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The Mehriz Sand Ramps: A Late Quaternary Palaeoenvironmental Archive of Extreme Aridity and Glacial Legacy in Central Iran

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This study examines the influence of late Quaternary climate changes, local topographical features, and wind dynamics on the formation, development, and activity of sand ramps situated south of Yazd, Central Iran. Research methods included extensive fieldwork, geomorphological and geological mapping, thin-section analysis, XRD studies, and evaluation of regional wind and precipitation data. The ramps formed under rapidly changing arid conditions during the late Quaternary, as indicated by the poorly weathered and unconsolidated aeolian sands and the absence of alluvial or colluvial layers within the deposits. Their formation and evolution were strongly controlled by topography, lithology, wind patterns, and episodes of extreme cold and aridity. Mineralogical analyses show dominant quartz, feldspar, mica, and biotite in the lower sand sheet layers, pointing to a source from mafic rocks outcropped in glacial cirques and valleys above 2,200 m a.s.l. These rocks weathered during glacial periods, and the resulting sediments were transported downslope by ice tongues and runoff. During subsequent arid periods, winds redistributed the finer sediments over short distances, depositing some as sand sheets at the base of slopes, while others were carried up mountain slopes or across ridges to accumulate on the leeward sides. A shift from mafic minerals in the lower layers to calcite-rich surface layers reflects a change in environmental conditions over time. The current limited activity of the ramps suggests they are relict features, formed during past periods of intense drought, when extreme aridity provided the necessary conditions for their accumulation.

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1. Introduction

Sand ramps represent geomorphic formations that differ fundamentally from other dune types in terms of their location, morphology, genesis, stratigraphy, sediment characteristics, mineralogical composition, grain shape, and the environmental and temporal conditions under which they form (Sharifi Paichoon, 2019). Two major distinctions are related to the duration and climatic context of their formation. While dunes often form progressively and remain active over extended timescales, sand ramps generally develop during a single short Quaternary phase (Batamane *et al*., 2012), resulting in their relict and largely inactive nature in most studied regions (Lancaster and Tchakerian, 1996; Thomas *et al*., 1997; Turner and Makhlouf, 2002; Berking and Schütt, 2011; Del Valle *et al*., 2016; Sharifi Paichoon, 2019).

Following their relatively short formation periods, environmental conditions such as humidity, wind regime, sediment supply, and topography often changed, inhibiting further ramp development. Consequently, global research has shown that each ramp system exhibits unique environmental and geomorphological characteristics, making generalizations between regions unreliable.

Most sand ramps develop on windward slopes, where aeolian sediments accumulate progressively (Clemmensen *et al*., 1997; Bertram, 2003; Telfer *et al*., 2012; Bateman *et al*., 2012; Turner and Makhlouf, 2002; Kumar *et al*., 2017; Del Valle *et al*., 2016). In certain settings, however, sediments are transported across ridges to leeward slopes, forming descending ramps (Lancaster and Tchakerian, 1996; Thomas *et al*., 1997; Berking and Schütt, 2011; Ellwein *et al*., 2015). These patterns highlight the complex interplay of wind, water, and mass-movement processes involved in ramp evolution, suggesting their potential as archives of paleoenvironmental information.

While most sand ramps are stabilized relicts from past climatic epochs, others remain active or semi-active today (Sharifi Paichoon, 2019). Compared with dunes in hyper-arid regions, sand ramps demonstrate higher geomorphic stability due to post-formational environmental changes that limited further reworking. Conversely, dunes remain mobile, undergoing significant migration and morphological transformation. Globally, these landforms are rare and often their surfaces can be covered with alluvium or colluvium materials, leading to their classification as topographically anchored dunes, talus cones or alluvial (Bateman *et al*., 2012; Sharifi Paichoon *et al*., 2018). So, despite their geomorphic importance, many sand ramps remain insufficiently investigated. Three key parameters determine the scientific interpretation of any sand ramp: (a) the climatic conditions during its formation, (b) the source and pathways of sediment supply, and (c) the post-formational evolutionary changes (Wells *et al*., 1987; Lancaster and Tchakerian, 2003).

Studies have shown that sand ramps were largely created during cold glacial or periglacial episodes of the late Pleistocene under stronger wind regimes and lower temperatures than today (Thomas *et al*., 1997; Telfer *et al*., 2012; Berking and Schütt, 2011; Ellwein *et al*., 2015; Del Valle *et al*., 2016; Kumar *et al*., 2017; Sharifi Paichoon, 2019). However, some research attributes their formation to arid climatic conditions combined with suitable topographic features (Sharifi Paichoon and Tajbakhsh, 2018; Mehrshahi, 2020).

In terms of sediment origin, sand ramps differ from most dune systems because they primarily originate from local sources (Mehrshahi, 2000; Mehrshahi and Khosrowyani, 2010; Sharifi Paichoon and Dehghan, 2017). These sediments may be derived from adjacent rivers (Thomas *et al*., 1997; Pease and Tchakerian, 2003; Telfer *et al*., 2012; Bateman *et al*., 2012; Ellwein *et al*., 2015; Rowell *et al*., 2018a) or desiccated paleolakes (Lancaster and Tchakerian, 1996; Sharifi Paichoon *et al*, 2020b), transported by regional and local wind corridors

(Lancaster and Tchakerian, 1996). Over time, the availability of sediments from fluvial systems has fluctuated due to climatic variability (Pease and Tchakerian, 2003).

Initially, ramps develop as aeolian sand accumulations over short timescales on mountain slopes, later integrating colluvial, talus, and fluvial materials through hydrological and gravitational processes (Bateman *et al*., 2012; Del Valle *et al*., 2016; Kumar *et al*., 2017). Thus, their stratigraphy typically records mixed sedimentary origins, reflecting successive climatic oscillations and geomorphic responses.

The key factors promoting ramp formation include the availability of substantial sediment volumes (Thomas *et al*., 1997; Rendell and Sheffer, 1996; Telfer *et al*., 2012; Del Valle *et al*., 2016), favorable topography (Ventra *et al*., 2017), past climatic parameters (temperature, moisture & wind) (Bertram, 2003; Telfer *et al*., 2012; Berking and Schütt, 2011), and sufficient accommodation space (Bateman *et al*., 2012; Rowell *et al*., 2018a). Lithology and weathering processes during cold Quaternary periods also played crucial roles in sediment production (Telfer *et al*., 2012; Sharifi Paichoon and Tajbakhsh, 2018).

Because these formations developed under conditions differing from those of today, they provide valuable insights into Quaternary paleoenvironments in arid regions, where sedimentary and climatic records are often sparse (Rowell *et al*., 2018a). Although most ramps are now inactive, a few continue to evolve under current aeolian regimes (Lancaster and Tchakerian, 1996; Turner and Makhlouf, 2002; Sharifi Paichoon, 2019). This study investigates the formation of sand ramps in western Mehriz (south of Yazd) by addressing key questions regarding their genesis and environmental significance. Despite the presence of abundant sediment, adequate space, and strong winds, why do these ramps, situated on windward and leeward slopes as climbing and falling dunes, exhibit minimal activity? Examining these ramps is thus critical for exploring their value in reconstructing the paleoenvironment of a region with limited surviving archives of its past.

2. Geographical location and geological features

The sand ramps investigated in this study are situated in the eastern section of the Ibrahim Abad plain, located west of Mehriz city and south of Yazd city (Fig. 1). This plain covers an area of over 160 km^2. It is classified as a construction depression, surrounded by the massive Shirkouh Mountains to the north, south, and west (Fig. 2). In the eastern part, a linear mountain formation has emerged in the shape of a single ridge, resulting from the activity associated with the Baghdad Abad fault during the Pliocene epoch (Fig. 2). This mountain ridge varies in height, measuring less than 10 meters in the southern section and exceeding 120 meters in the northern areas. Composed of Eocene conglomerate sediments, commonly referred to as Kerman conglomerates (Figs. 3 & 4), the central sections of this ridge have experienced erosion or possible tectonic disruption. Consequently, during periods of heavy rainfall, runoff flows through the eroded areas of the mountain ridge (Figs. 2 & 12).

The highest peak of Shirkouh reaches approximately 4,100 meters, while the lowest elevation of the plain is about 1,500 meters. This significant elevation difference between the mountains and the plain has resulted in considerable climatic variation. For instance, the average annual temperature in the plain is approximately 18°C, whereas it drops to below 12°C at elevations exceeding 2,500 meters. Precipitation levels also reveal notable disparities; the plain receives roughly 70 mm of annual rainfall, while higher altitudes experience over 350 mm per year (Sharifi Paichoon, 2019; Fig. 15). Furthermore, the pronounced elevation gradient between the mountains and the plain has led to the formation of numerous large watersheds that function as vital water sources for the rivers traversing the plain. These rivers transport substantial quantities of weathered material from upstream, forming extensive alluvial fans (Sharifi Paichoon and Shirani, 2017). Currently, under the influence of prevailing climatic conditions—particularly the relatively low temperatures and consistent humidity—the plain is characterised by a notable vegetation cover.

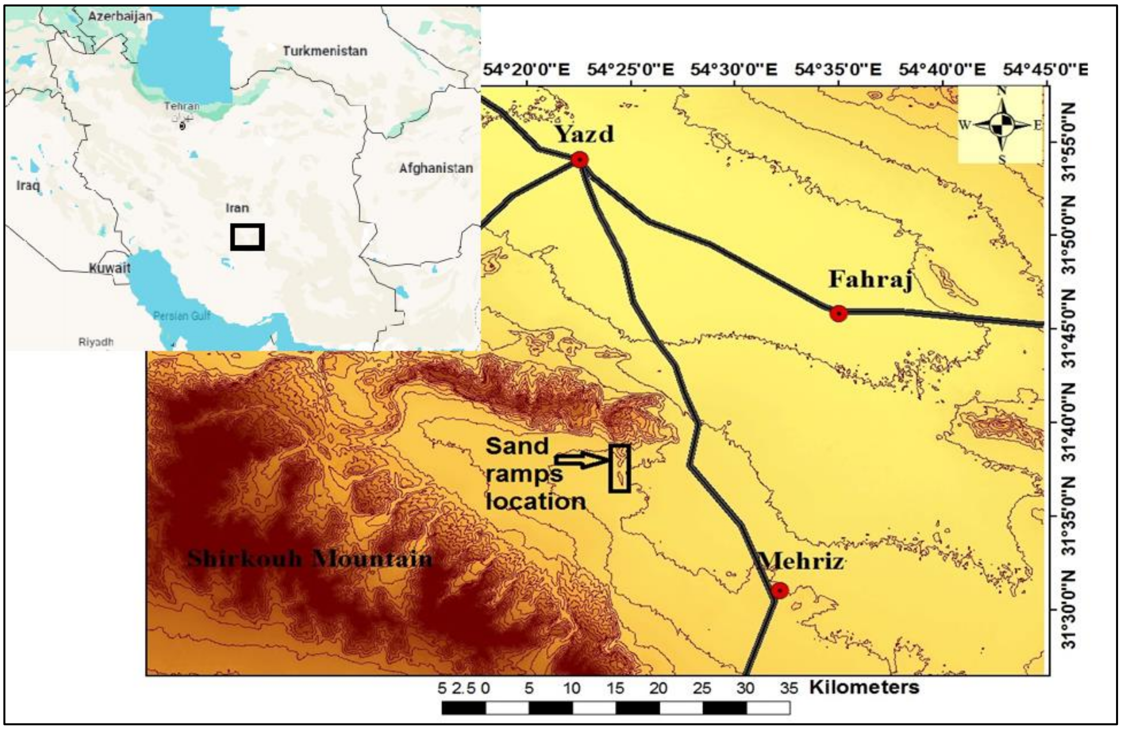


Fig 1. Location map of the study area in central Iran, south of Yazd city, and west of Mehriz city

Geologically, Shirkouh Mountain is classified as a batholith, covering an area exceeding 1,000 km². (Amini and Kalantari, 1997). This mass primarily consists of granite and granitoid rocks, covered by more than 3,000 meters of limestone and dolomite sediments from the Cretaceous period (Fig. 2). The batholith intrudes into the shale and sandstone formations of the Nayband group. Overlying the batholith are discontinuous layers of Cretaceous limestone, along with sandstone formations and conglomerates dating from the Upper Jurassic and Lower Cretaceous periods (Fig. 2). Initially, the Shirkouh batholith included remnants of earlier Jurassic batholiths; subsequently, during the progression of a Cretaceous Sea in the region, Lower Cretaceous conglomerates and limestones were deposited in a discontinuous manner. These sediments were later folded during the Laramide orogeny, leading to the formation of the Shirkouh mass (Sheibi and Esmaelly, 2009; Sheibi *et al*., 2013). In the areas surrounding the study region, limestone and dolomite deposits are predominant, while granite appears more sporadically at higher elevations in the mountains and within valley and glacial cirque depressions, which were outcropped by glacial processes during the Quaternary period (Sharifi Paichoon *et al*., 2018).

In the eastern part of the plain, particularly in the northeast, numerous sand ramps have developed on both the windward and leeward slopes of mountains that have risen as a result of tectonic activity (Fig. 3, photos A & B). In areas with elevations greater than 50 meters, sand is predominantly found at the foot of the mountains as sand sheets, although some have climbed up the slopes (Fig. 3, photos F & I), and some have passed over the mountain ridge and settled on the leeward slope. In some areas of the plain, such as the southeastern section where the mountain height drops below 20 meters, all the sedimentary sands have passed over the mountain ridge and are located on the leeward slopes (Fig. 3, photos C, D & E).

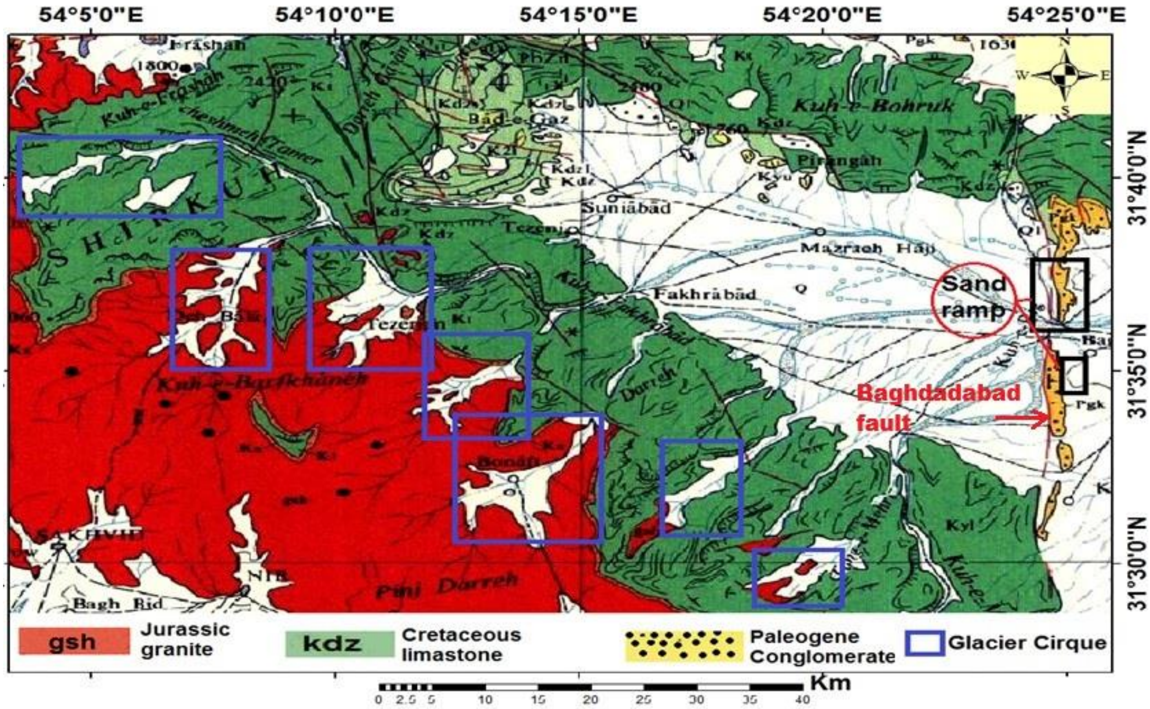


Fig. 2. The geology map of the studied region

A key aspect of the sand ramps and sand sheets in this region is their semi-active nature, as they are infrequently covered by vegetation or alluvial and colluvial materials (Fig. 3, photo G). Unlike sand ramps found in adjacent areas or other parts of the world, which are often hardened (Thomas *et al*., 1997), weathered, or entirely obscured by vegetation and sediment, the ramps in the study area exhibit distinct characteristics (Sharifi Paichoon, 2019). Furthermore, the sand sheets at the foot of the mountains are composed purely of sand, lacking any alluvial or colluvial deposits or signs of vegetation (Fig. 3, photo I). Notably, the leeward ramps in the southeastern part of the plain are completely stabilized, despite the absence of protective covers such as plants or coarse sediments. These unique features have transformed the ramps into a recreational area that attracts many visitors (Fig. 3, photos C & D).

3. Materials and methods

This research primarily relies on field surveys conducted over the past few years. The study area was visited multiple times during this period across different seasons. Additionally, various resources were utilized, including Google Earth images, topographic maps of the region at a scale of 1:50,000, geological maps at a scale of 1:100,000 (from Nair and Yazd), and a digital elevation model (DEM) with a resolution of 15 meters (Fig. 5). By integrating these maps with field observations, a geomorphological map of the study area was created using ArcGIS software (version 10.4) at two distinct scales (Fig. 11). This map effectively illustrates elevations, sedimentary and alluvial plains, valleys, sand sheets, and both climbing and falling dunes.

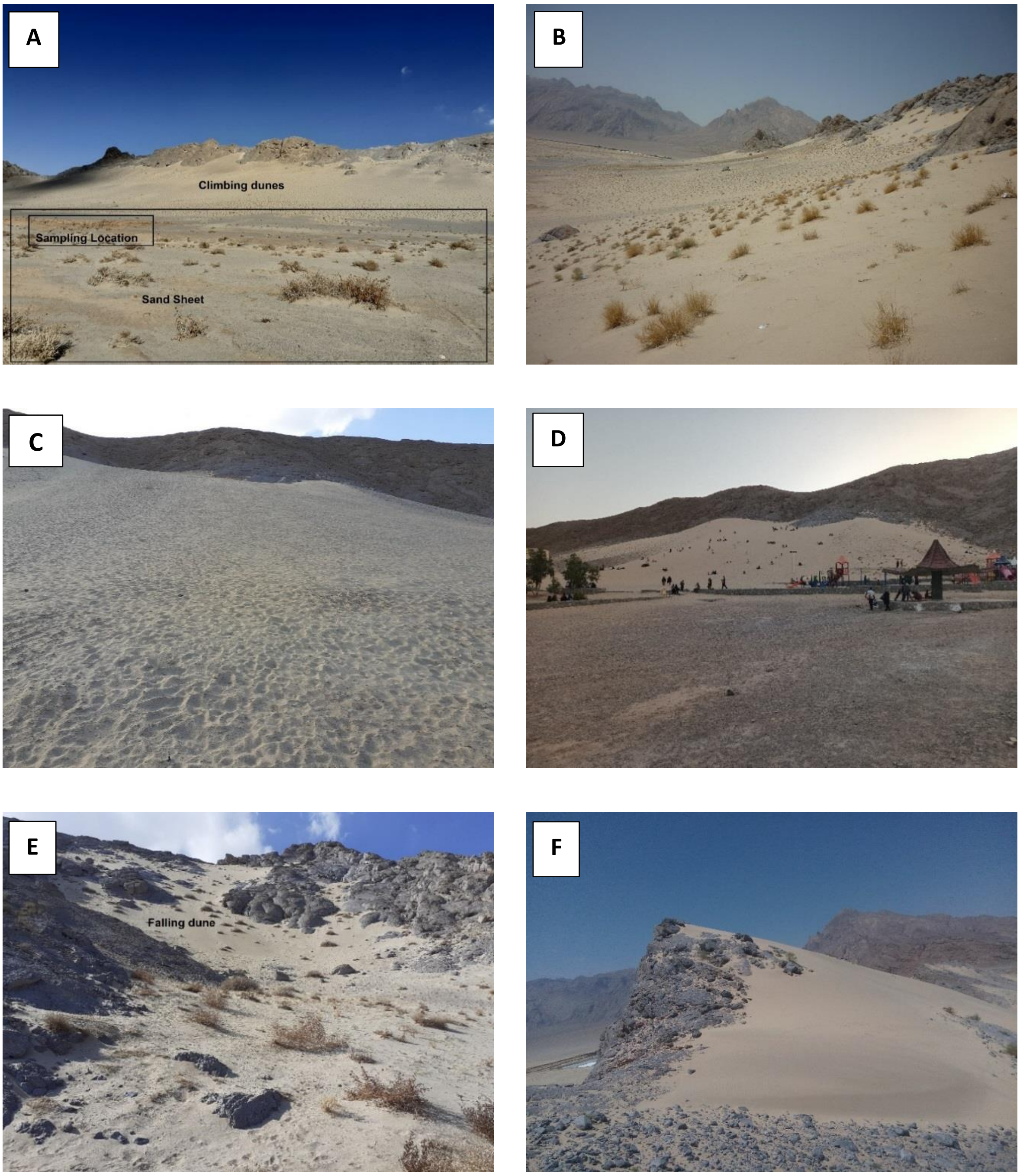


Fig. 3. Photo (A) shows a general view of the climbing dunes and the sand sheet at the foot of the mountain. Photo (B) depicts the placement of climbing sands on the windward slope, where new vegetation has grown. Photos (C) and (D) illustrate a leeward dune (a falling dune) in the eastern parts of the studied plain, which is currently used as a recreation centre. Photo (E) shows a falling dune. Photo (F) shows a small quantity of sand climbing up the slope and then settling on the leeward side. Photo

Fig. 3. Continued. (G) demonstrates that the vegetation cover currently stabilizes the sand and reduces wind activity. Photo (H) depicts a mini nebkha on the studied plain, formed during the dry

To investigate the sedimentology of dunes, sediment samples were collected from the study area at three locations: a) climbing dunes (located on the windward slopes), b) falling dunes (found on the leeward slopes), and c) sand sheet at the foot of the mountain (Figs. 1, 3 & 11). These samples were collected during the dry seasons of 2021 and 2023. Specifically, 10 sediment samples were taken from an artificial trench, which had a depth of 350 cm and was created for sand extraction, located at the geographic coordinates 54° 24' 52'' E and 31° 36' 58'' N (as indicated by GPS; Figs. 1 & 4; Table 1), 12 samples were taken from the sediment on the windward slope at various distances and heights (Fig. 4), and 4 samples were collected from the sediments on the leeward slopes (Fig. 4). Sediment samples from both climbing and falling dunes were collected at depths of approximately 50–60 cm. To achieve this, pits of comparable depth and roughly 50 cm in diameter were excavated. From each pit, 200–300 g of sand was carefully retrieved using a shovel, and subsequently, they were packed in small plastic bags and transported to the laboratory for analysis.

In the laboratory, sediment samples were first dried in an oven set to 105 °C. Subsequently, they underwent granulometric analysis through dry sieving to determine the grain size distribution of the samples. This process utilized stainless steel sieves, incorporating a series of mesh sizes: 2000, 1000, 500, 250, 125, and 63 μm. Each sample was subjected to sieving on a vibratory shaker for 15 minutes. The percentage of sediment retained on the sieves at various intervals was then entered into the Gradistat program (Blott and Pye, 2001). The Folk method (1957) was also used for classifying, naming, and analyzing the sediments, as well as calculating statistical parameters such as the mean, mode(s), sorting (standard deviation), skewness, and kurtosis. Grain size parameters were calculated logarithmically using the Method of Moments (phi scale). Cumulative distribution curves for the sediments of the studied sand ramp in different areas were also generated. Particle size analysis was conducted to evaluate particle size distribution (Singh & Singh, 2021), the proportion of various grain sizes, and to construct the grain size distribution curve. To determine the composition and major elements of minerals, X-ray diffraction (XRD) analysis was employed. Seven samples were collected from sediments in the study area, including two samples from climbing dunes (one from the middle and another from the upper slope), one sample from the middle and one from the lower part of falling dunes, and three samples from a sand sheet at depths of 50, 170, and 350 cm. The sediment samples were placed in clean boxes and transported to the Geological Analysis Laboratory at Tarbiat Modares University. Upon arrival, the samples were thoroughly air-dried before being ground into a homogeneous powder using a mortar and pestle. This powdered material was subsequently packed into an aluminum sample holder and analyzed using the Philips X'Pert MPD XRD system from the Netherlands, which utilized a copper tube with a wavelength (λ) of 1.54056 Å, a step size of 0.02°/s, a voltage of 40 kV, and a current of 40 mA.

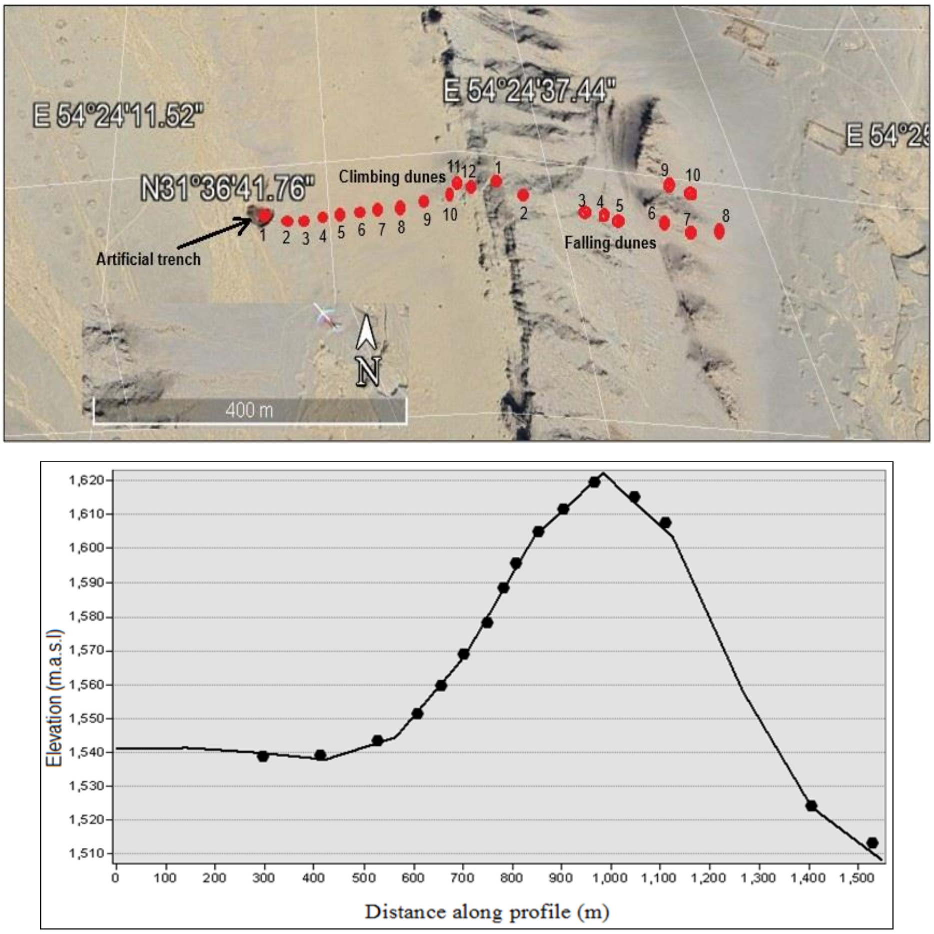


Fig. 4. Shows the location of the samples taken for analysis from the ascending and descending sands.

Modelling the bulk sediment XRD patterns provides insights into the environmental and depositional histories (Solotchina *et al*., 2009). In addition, to analyze the micromorphology and identify the minerals present in the sediments along with their characteristics, thin sections were prepared from a total of 14 sediment samples collected from all studied sections. These samples included sediments from both climbing and falling dunes, as well as from the sand sheet. After preparing the thin sections, the samples were observed under a polarizing microscope at various magnifications (Fig. 9). The findings from the mineral analysis were then compared with lithological data obtained from geological maps and field studies to determine the origins of the sediments found in the ramp and to understand the processes involved in their formation. Given the significant impact of climatic factors, particularly temperature and humidity, on the activity and development of sand ramps, a graph was created to illustrate the variations in temperature and precipitation. Additionally, using data from eight meteorological stations over 30 years (1990-2020), including Yazd, Mehriz, Tengechenar, Garizat, Taft, and Tezerjan, an isohyetal map was generated to depict the annual rainfall distribution across different areas of the region, as humidity is a key factor influencing the activity of these features. In addition, windrose diagrams for both annual and seasonal wind patterns at the Yazd synoptic station were generated over a 30-year period, from 1990 to 2020 (Fig. 12). These diagrams were created using WRPLOT software, based on averaged wind data, to illustrate the frequency, speed, and direction of the winds. They demonstrate the influence of both prevailing and secondary winds on the formation and development of sand ramps. Furthermore, the analysis of these diagrams helps to identify local winds, the pathways of sand transport, and the processes involved in ramp formation.

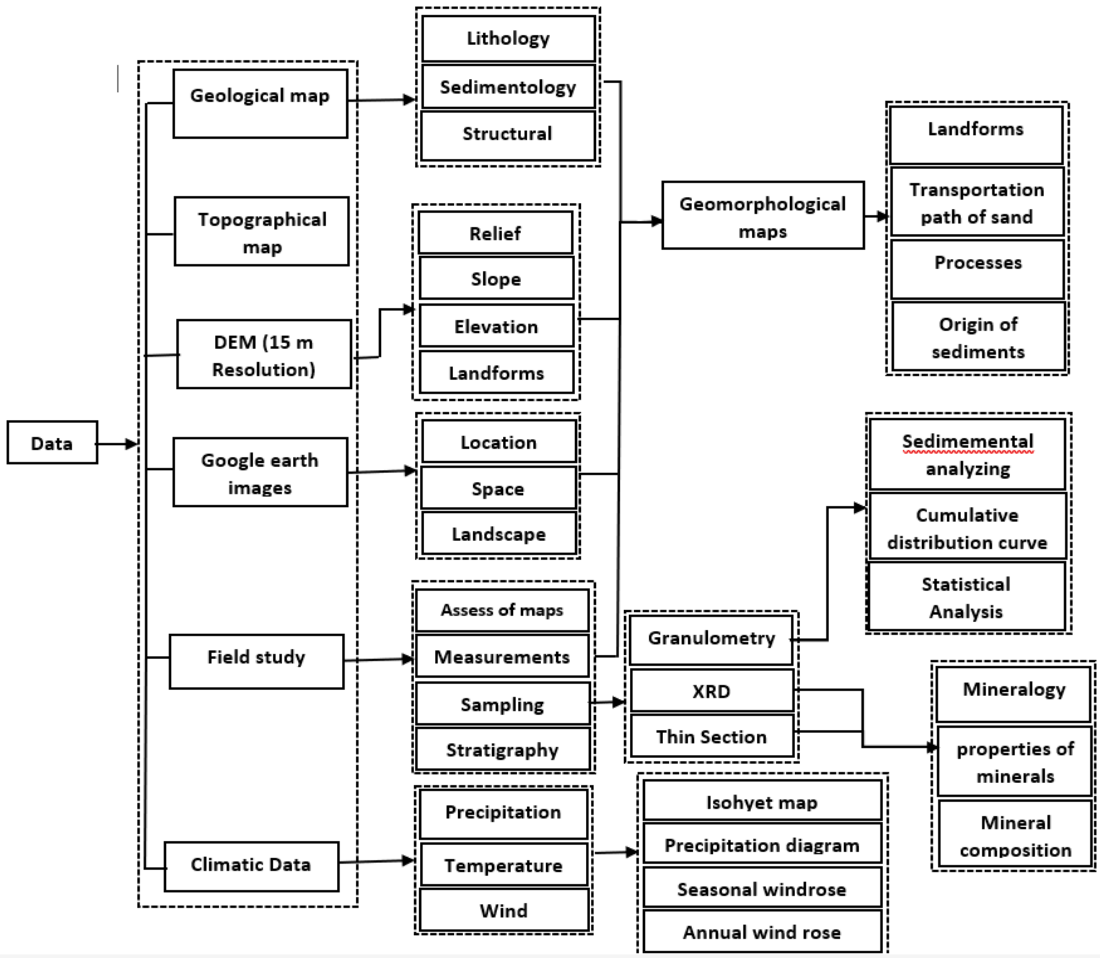


Fig. 5. Flowchart illustrating the data collection process and stages of the research

4. Results

4.1. Granulometry of sediments

The physical characteristics of these sediments are presented in Table 1. The granulometric analysis revealed a significant reduction in the size of the surface sediments, from the downstream areas of the plain to the upper sections of the slope, nearing the peak. Specifically, the average sand grain size was approximately 350 microns (2 Q) in the plain, around 250 microns (2.4 Q) on the windward slope and near the peak, and 1.5 Q in the lower portions of the slope. In the latter case, the sands exhibited poor sorting due to the presence of gravel and coarse sand (Tab. 1 & Fig. 6).

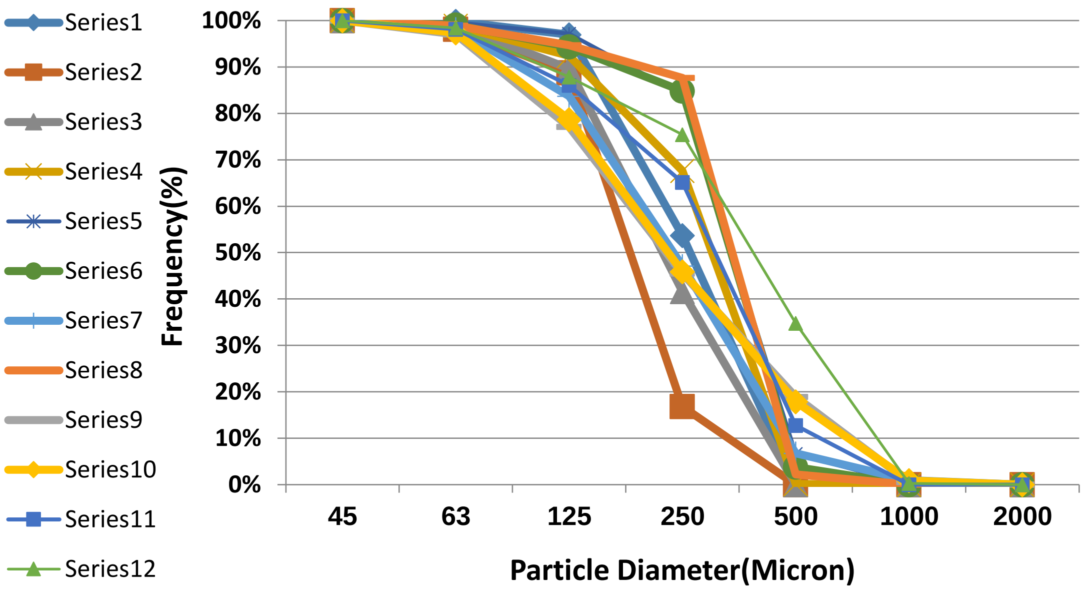


Fig. 6. Cumulative distribution curves of the sand grain size on the studied ramp of the windward slope

However, sediments on the windward slope near the peak lacked gravel or coarse sand. In other words, the sediment grains were extremely well sorted (Tab. 1 & Fig. 7). An analysis of the sediments from a 350-cm deep trench in the sand sheet at the foot of the slope revealed a significant decrease in grain size from the surface to depth. This reduction may be attributed to the strong prevailing winds and the proximity of sand sources in the present compared to the past (Table 1 & Fig. 7).

An analysis of sand grains at different elevations along the mountain slope revealed that the grains on the lower windward slope are larger than those near the peak (Tab. 1). Moreover, the windward slopes contain weathered sediments in the form of rock fragments intermixed with the sands. In contrast, the sand sheet at the foot of the mountain exhibits a strong correlation between grain size and depth, with smaller grains predominantly found at greater depths. This variation suggests the influence of intense winds during the more recent Holocene epoch, as previously documented.

To gain a deeper understanding of the sediment grain characteristics on the slopes and in the sand sheet, normal and cumulative distribution graphs were generated for each sample. These graphs clearly illustrate variations in sediment properties across different locations. Surface sediment samples, whether from climbing or falling dunes, exhibit well sorting, with very well-sorted sediments observed near the mountain peak, while larger grains (gravel-sized) are deposited within the plain. On the windward slopes, sorting quality decreases due to the deposition of weathered sediments from higher rock formations on the mountain. In the vertical layers of the sand sheet, sediment grain size gradually decreases from the surface downward (Table 1; Fig. 7). Despite the poor sorting observed in the 3.5-meter layer within the plain, this layer contains neither alluvial deposits nor distinct sand layering. This observation suggests continuous sedimentation processes and prolonged arid conditions during the Holocene period.

Table 1. Mineralogical characteristics of sediments using Thin Section and XRD Analysis

Sample		Description	Gravel	V coarse sand	Coarse sand	medium sand	fine sand	Silt	Mean (ϕ)	Mode (ϕ)	Sorting (ϕ)	Skewness(ϕ)	Kurtosis (ϕ)
Grain-size characteristics of surface sediments of climbing dune	1	Fine Sand	0.0	0.0	10.3	31.4	55.1	3.2	2.283	2.491	1.077	0.007	0.911
	2	Medium sand	0.0	0.0	12.9	52.3	33.1	1.8	1.885	1.496	0.962	0.250	1.104
	3	Slightly gravelly sand	2.2	0.9	16.7	27.6	50.3	2.4	2.036	2.491	1.81	-0.058	0.914
	4	Gravelly fine sand	6.3	0.5	17.3	25	48.4	2.6	1.945	2.491	1.389	-0.155	1.038
	5	Medium sand	0.0	0.0	2.5	85.2	11.3	1.0	1.555	1.496	0.506	0.241	1.426
	6	F. Gravelly M. sand	0.0	1.0	5.9	40.5	51.0	1.7	2.102	1.496	0.910	0.074	0.961
	7	Medium sand	0.0	0.0	4	80.8	14.3	0.9	1.566	1.496	0.529	0.238	1.406
	8	Very coarse sand	0.0	45	20.4	12.4	15.7	6.5	0.813	0.500	1.491	0.652	0.653
	9	Medium sand	0.0	0.0	0.3	67.4	31.2	1.1	1.872	1.496	0.705	0.358	1.023
	10	Fine sand	0.0	0.0	0.1	41.8	57.3	0.8	2.140	2.491	0.740	0.039	0.912
	11	sand	0.0	0.0	0.0	17.2	81	1.7	2.44	2.491	0.600	-0.014	1.390
	12	Medium sand	0.0	0.0	0.2	53.8	45.9	0.1	1.970	1.496	0.630	0.096	0.743
Grain-size characteristics of vertical sedimentary layers of sand sheet	1	Sand, 350 cm depth	0.0	0.0	10.3	31.4	55.1	3.2	2.283	2.491	1.077	0.007	0.911
	2	V.F.G. Fine sand (320 cm. depth)	0.0	1.1	2.4	39.4	55.2	1.9	2.143	2.491	0.815	0.062	0.924
	3	Fine Sand (290 cm. depth)	0.0	0.0	7.0	31.5	59.4	2.1	2.234	2.491	0.936	-0.024	0.999
	4	Medium sand (240 cm. depth)	0.0	0.0	11.1	37.6	48.2	3.1	2.128	1.496	1.040	0.099	0.966
	5	V.F.G. Medium sand (210 cm. depth)	0.0	0.0	7.0	31.5	59.4	2.1	2.234	2.491	0.936	-0.024	0.999
	6	Slightly gravelly sand (170 cm. depth)	0.0	3.9	23.7	32.3	35.5	4.5	1.833	1.496	1.290	0.157	0.843
	7	V.F.G.Coarse Sand (120 cm. depth)	0.0	0.0	11.1	37.6	48.2	3.1	2.128	1.496	1.040	0.099	0.966
	8	V.F.G. Medium sand (90 cm. depth)	0.0	1.3	25.2	34.7	35.5	3.4	1.805	1.496	1.207	0.164	0.884
	9	V.F.G. Medium Sand (60 cm. depth)	0.0	1.2	10.6	42.7	43.8	1.6	1.971	1.496	0.964	0.108	1.032
	10	Slightly gravelly sand (20 cm. depth)	0.0	2.8	36.4	27.9	31.6	2.2	1.596	0.498	1.214	0.250	0.829
Leeward sand	1	Slightly gravelly sand (170 cm. depth)	0.0	3.9	23.7	32.3	35.5	4.5	1.833	1.496	1.290	0.157	0.843
	2	V.F.G.Coarse Sand	0.0	12.2	28	27.5	30.8	1.5	1.407	0.498	1.287	0.065	0.917
	3	(120 cm. depth)	0.0	0.6	19.2	45.1	34.2	0.8	1.712	1.496	0.925	0.062	1.008
	4	V.F.G. Medium sand	0.0	1.3	25.2	34.7	35.5	3.4	1.805	1.496	1.207	0.164	0.884

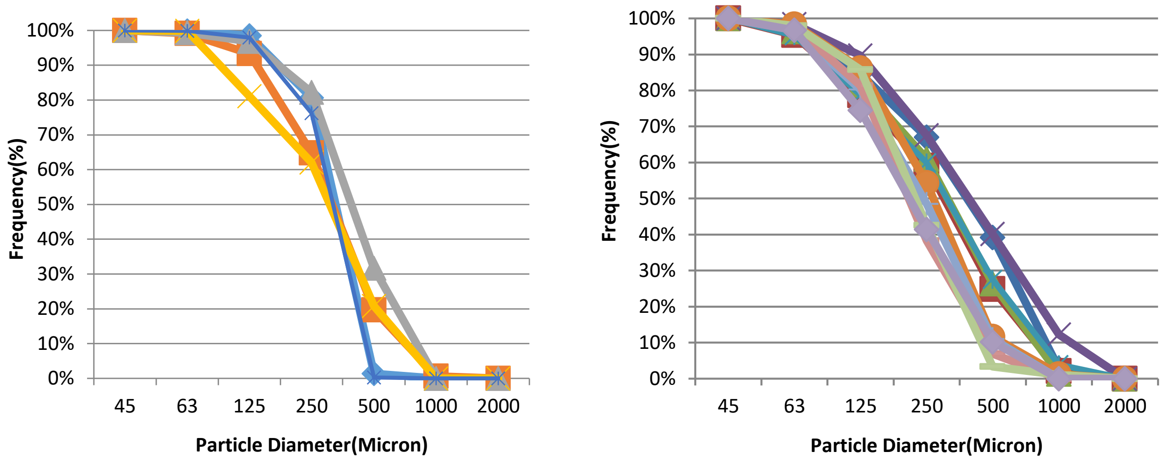


Fig. 7. Cumulative distribution curves of sand grain size in the studied ramp on the leeward slope (left diagram) and the sand sheet profile (right diagram).

4.2. Analysis of the physical and chemical properties of sediments

4.2.1. X-Ray diffraction analysis

X-ray diffraction analysis was conducted to examine the elemental composition and crystal structure of the sediments. The results indicate that the mineral composition of the studied trench within the sand sheet is relatively uniform, especially at depths greater than 1 meter below the surface. The primary minerals identified in this section, in order of abundance, are quartz, albite, and calcite. In contrast, the upper layers of the sedimentary trench (sand sheet) exhibit a higher concentration of dolomite minerals. In the climbing and falling dunes, the proportions of calcite and dolomite increase significantly (Fig. 8). Furthermore, sediments from the windward slopes near the peak and the leeward slopes contain clinochlore minerals.

Minerals formed from the decomposition of biotite, and with a smaller contribution from feldspars, reflect changes in the sediment's mineralogy caused by shifts in environmental conditions. Additionally, muscovite minerals are notably abundant in the sediments from the upper sections of the windward slope. Albite content is lower in trench sediments near the surface and in sediments on both the windward and leeward slopes, likely due to the weathering of mafic minerals under current conditions of increased humidity. However, unweathered biotite minerals are preserved in the deeper layers of the sand sheet (Fig. 8).

4.2.2. Thin section analysis

The chemical and physical properties of the sediments were examined using thin sections and a polarizing microscope to magnify the sediment grains. Significant variations were observed in the sediments from the surface of the plain to the peak of the mountain along the windward slope. The surface sediments of the plain were found to have a higher concentration of feldspar and biotite compared to quartz and calcium carbonate (Fig. 9, Photos 1, 2, & 3). Additionally, some clay particles were observed (Fig. 9, Photos 1 & 2). The feldspars, especially the alkaline varieties, and the biotites showed little evidence of weathering and remained largely intact (Fig. 9, Photos 1-3). The sediments also contained small quantities of quartz and calcium carbonate, along with occasional rock fragments (Figs. 1-3). This suggests minimal wind-driven displacement, indicating that the sediments have remained near their source. Notably, the calcium carbonate particles in this area are highly rounded, setting them apart from other sediment types in terms of origin and transport distance. As the elevation increases, the

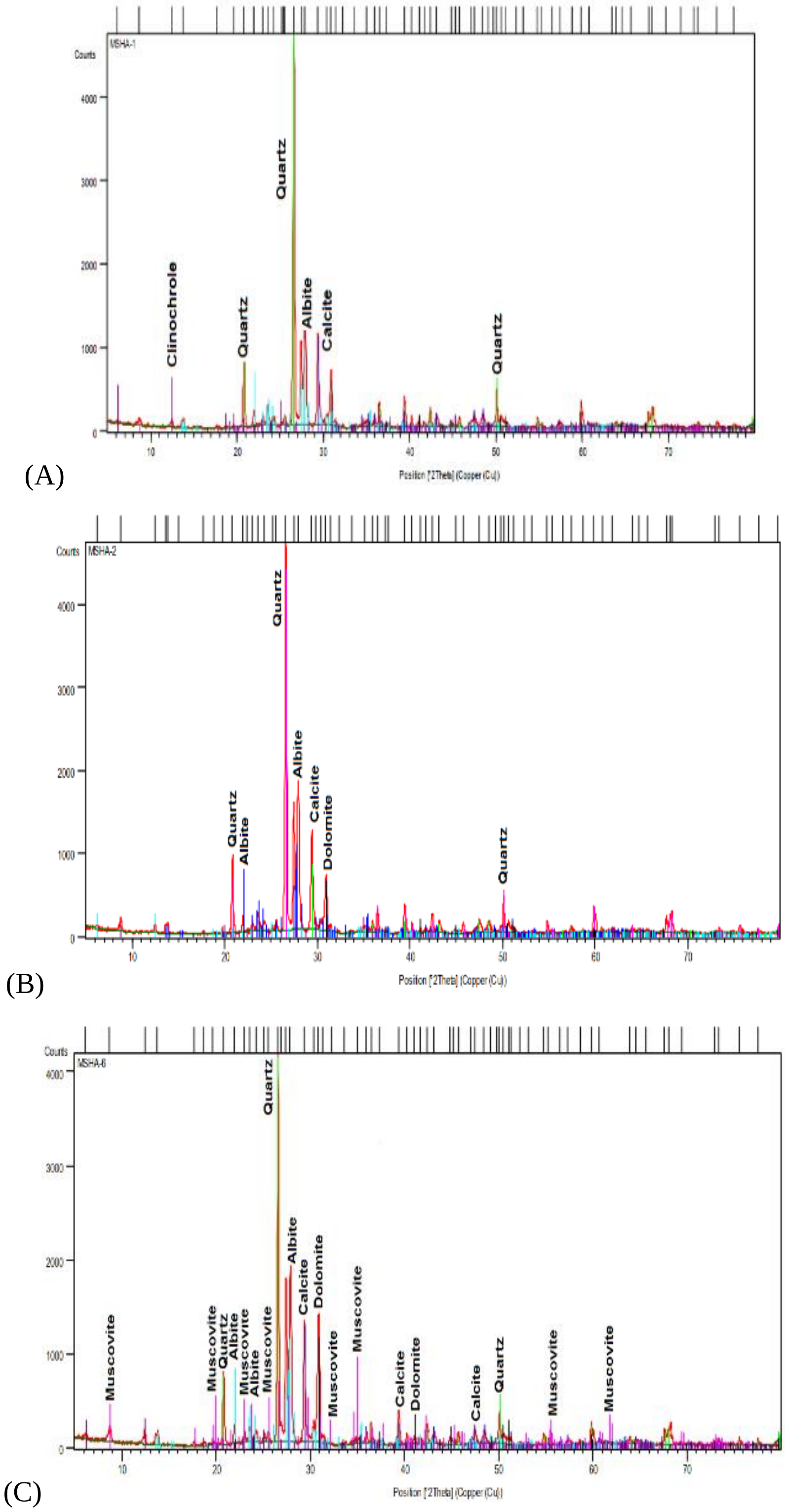
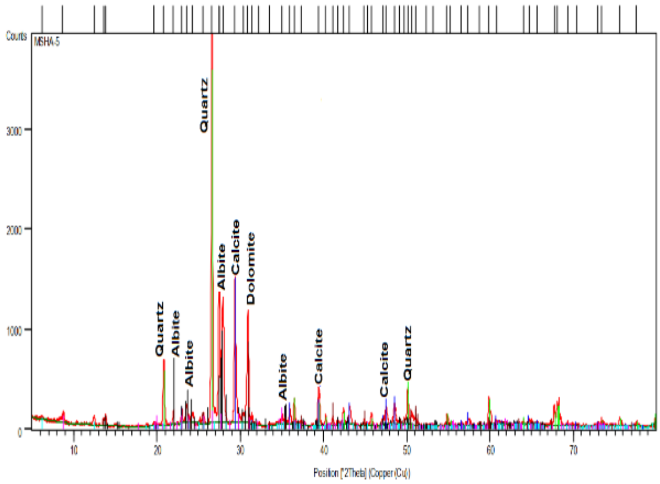
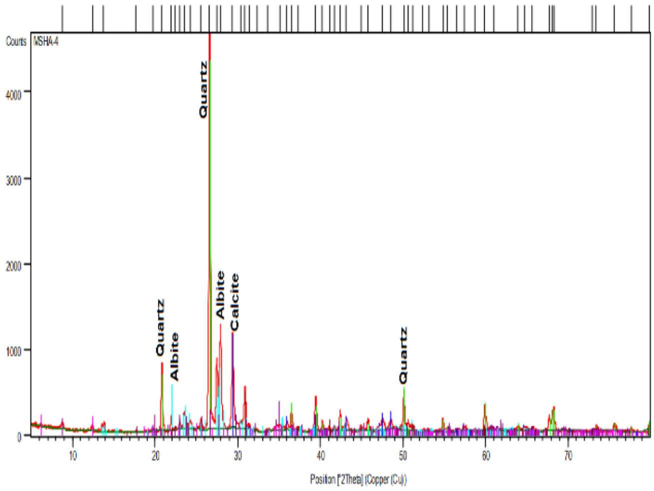


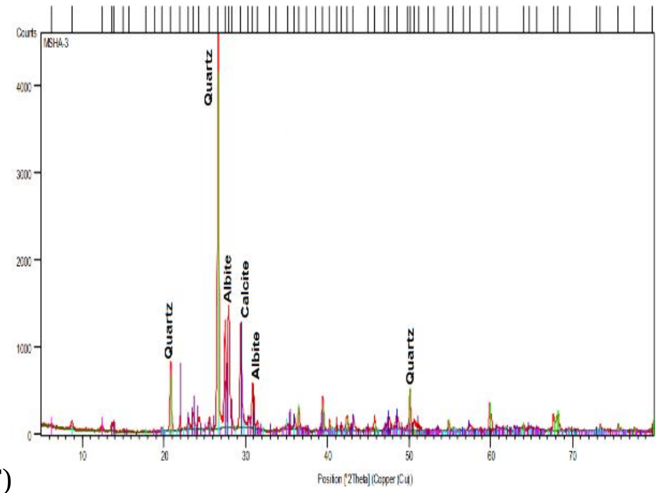
Fig. 8. X-ray diffraction (XRD) spectra of sediments collected from the studied area, with peak positions and corresponding minerals indicated by colored arrows. This figure shows: A) Sediments from the downstream section of the leeward slope within the plain, containing Quartz, Albite, Calcite, Dolomite, and Clinochlore; B) Sediments from the middle section of the leeward slope, containing Quartz, Albite, Calcite, and Dolomite; C) Sand sheet sediments at a depth of 3.5 meters, containing Quartz, Albite, and Calcite;



(D)

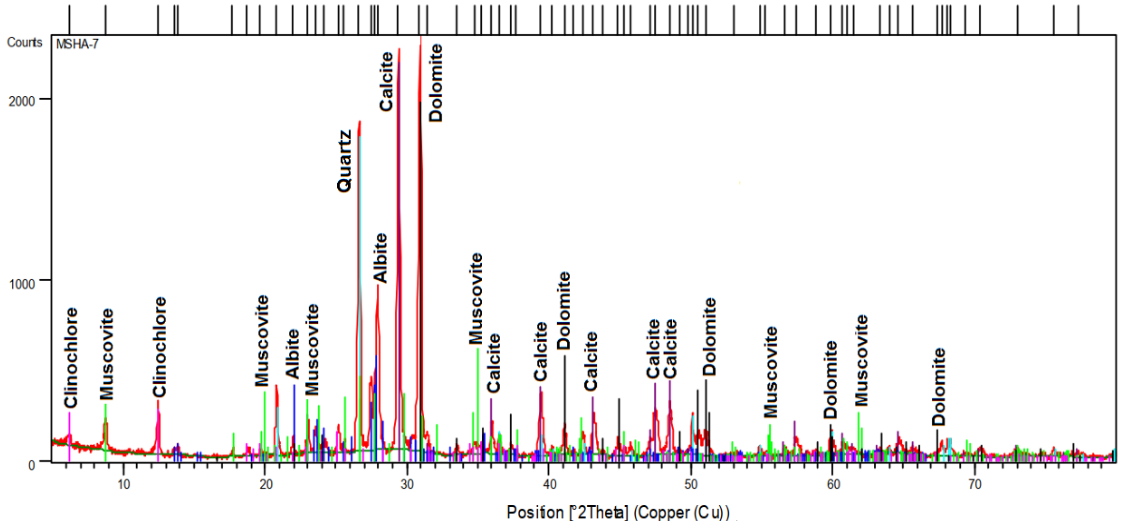


(E)



(F)

Fig. 8. Continued. D) Sand sheet sediments at depths of 1.5 to 2 meters below the surface, containing Quartz, Albite, and Calcite; E) Sand sheet sediments at a depth of 0.5 meters below the surface, containing Quartz, Calcite, and Dolomite; F) Sand ramp sediments from the middle section of the windward slope, containing Quartz, Calcite, Dolomite, Muscovite, and Albite;



(G)

Fig. 8. Continued. G) Sand ramp sediments from the upper section of the windward slope near the mountain peak, containing Calcite, Dolomite, Quartz, Muscovite, and Feldspar.

proportions of calcium carbonate and quartz rise relative to feldspar and biotite, with no clay present in the sediments (Fig. 9, Photos 3-14). Quartz particles become more rounded, and the grain size decreases significantly. For instance, near the peak, on both the windward and leeward slopes, the grains are very small and rounded, containing limited feldspar and biotite, which appear heavily weathered. However, the calcium carbonate content increases substantially in these areas (Fig. 9, Photos 4-6, 13 & 14). The sands in this section of the ramp are well-sorted in terms of mineral composition (Fig. 9, Photos 6, 13 & 14).

The sediments in the vertical profile of the sand sheet, at a depth of 3.5 meters, were analyzed physically and chemically using thin sections and a polarizing microscope. The analysis revealed an increase in feldspar content, particularly alkaline varieties, along with biotites and muscovites, as the depth increased. These minerals, along with quartz, showed minimal weathering and remained largely intact (Fig. 9, Photos 7 & 8, depicting sediments at approximately 3.5 meters depth). Moreover, rock fragments were observed in the lower layers (Sample 8). The intact state of the feldspar minerals and their lack of weathering is likely due to the extreme aridity prevailing during the sand sheet's formation. Moreover, the sharp, unrounded edges of the particles suggest minimal transportation by either wind or water runoff (Fig. 9, Photos 11-14). The surface sediments and layers near the ground show a significant decrease in feldspar content, with extensive weathering attributed to increased humidity. Conversely, these layers contain higher amounts of calcite and coarser sand grain sizes (Fig. 9, Photos 10-12). Limestone particles, unlike other sediment materials, are completely rounded, indicating they have been transported over long distances. Calcium carbonate in this region appears in two distinct forms: larger, more crystalline grains and smaller particles (Fig. 9, Photo 12). This suggests that these particles have experienced multiple phases of displacement over different periods. Some limestone grains may have originated from upstream conglomerates of the sand ramp, transported after weathering and disintegration, while others could have come from more distant sources. The increase in grain size of the wind-blown sediments suggests that contemporary winds are faster and more intense than those in the past.

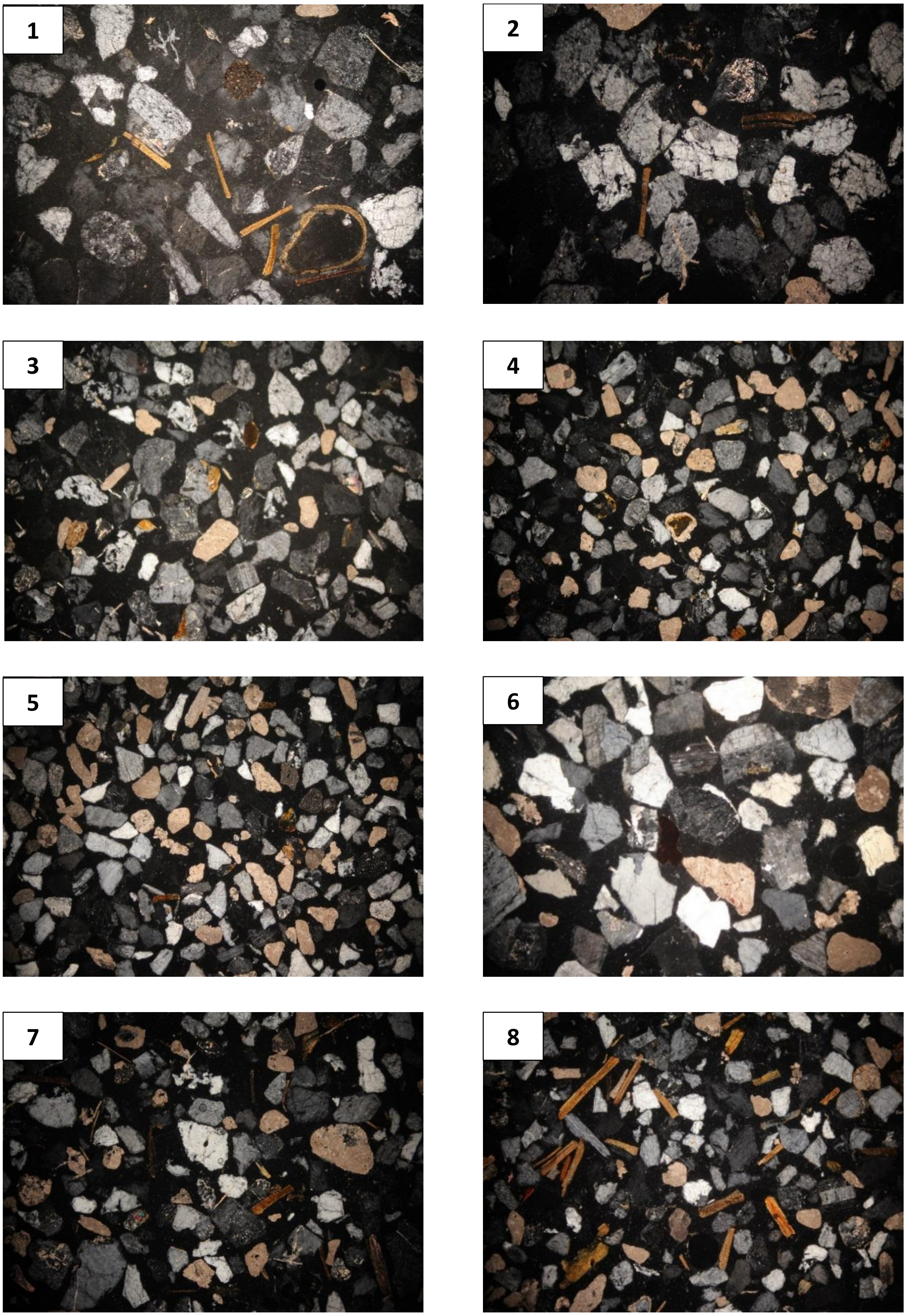


Fig. 9. Photos from the thin-section analysis of sediment minerals in sand ramps and the sand sheet, taken at various magnifications and angles using a camera installed on a polarizing microscope

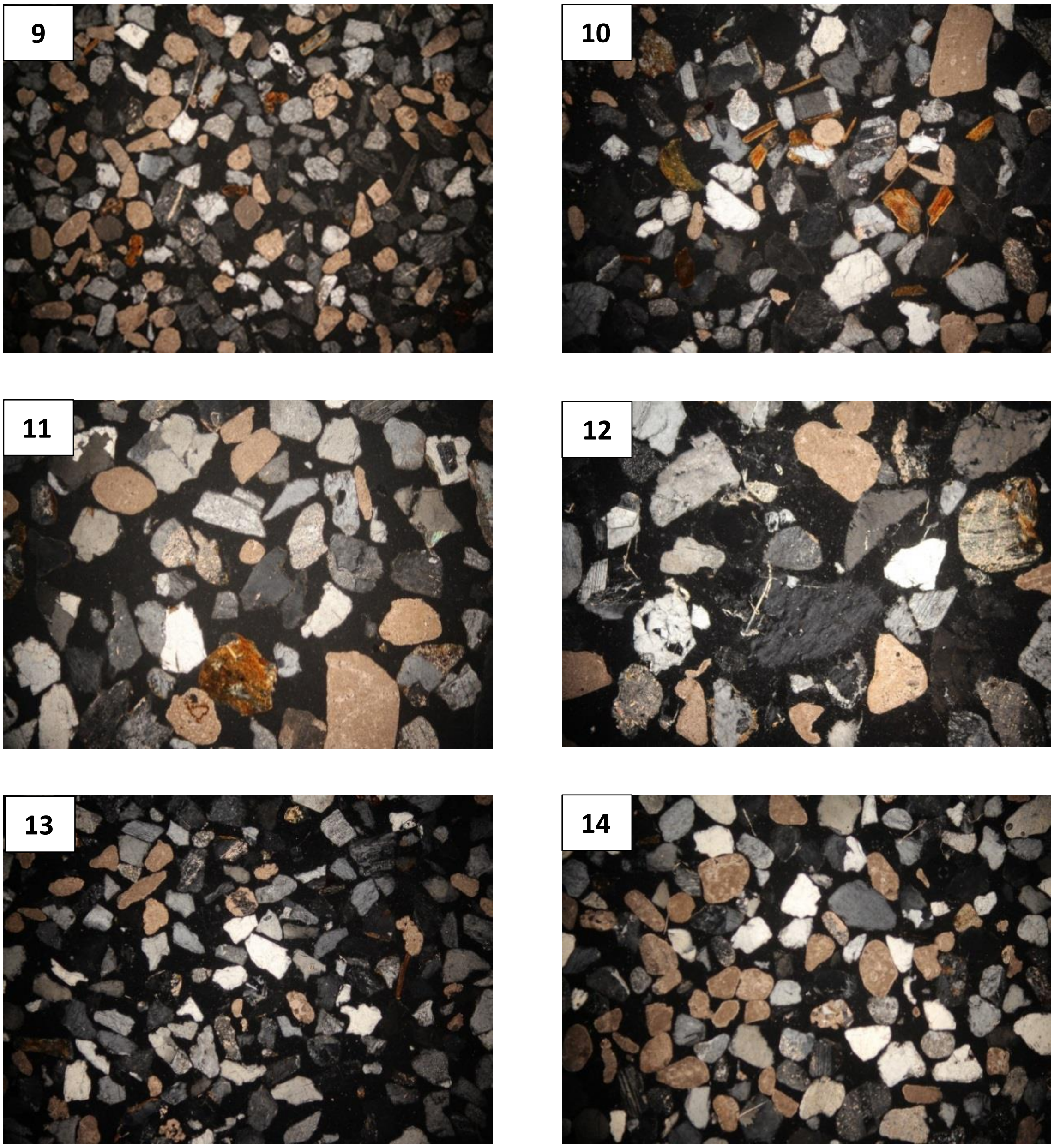


Fig. 9. Continued

4.3. Mineral composition and morphoscopy of sediment grains

The mineralogical composition and morphoscopic characteristics of the sand materials were examined using various samples collected from longitudinal and vertical profiles of the sand ramps and sand sheet sediments. Feldspar and quartz were identified as the dominant minerals in the sediments of the plain. A notable decrease in grain size was observed as one moved from the sand sheet toward the mountain peak. Biotites are abundant in the sand sheet and remain largely unweathered due to low humidity. Only quartz and calcite grains were observed near the mountain peak and on the leeward slope. Smaller grains displayed more pronounced signs of abrasion (Fig. 10).

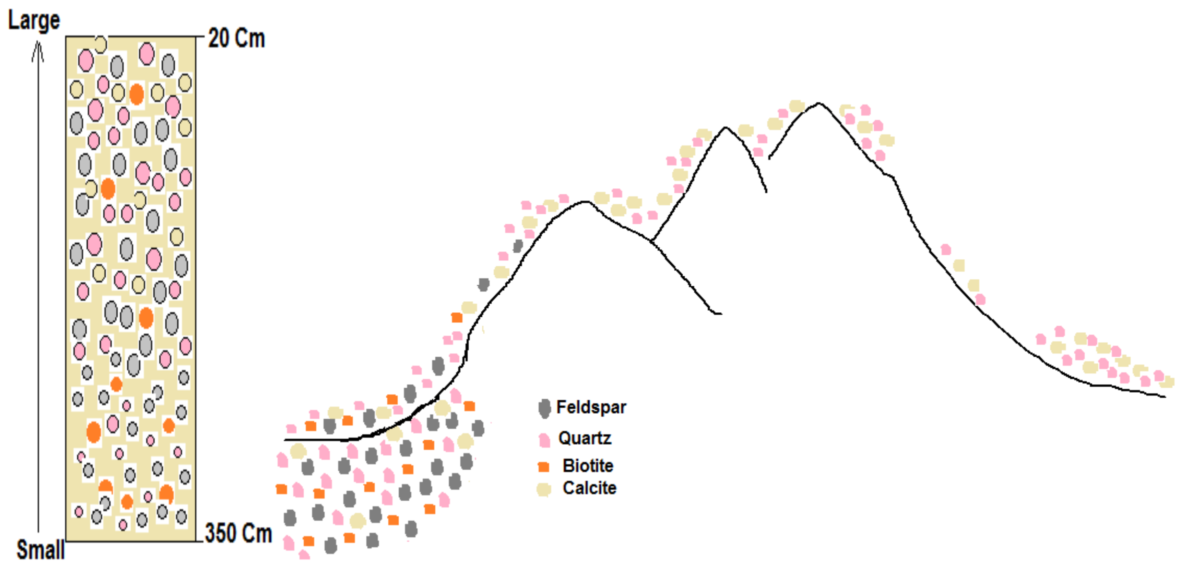


Fig. 10. Schematic presentation of sedimentary grain composition at various altitude levels, including the windward slope, leeward slope, and the sand sheet at the foot of the mountain.

4.4. Preparation of a geomorphological map

A geomorphological map of the area was created using geological, topographical, and Digital Elevation Model (DEM) maps, Google Earth imagery, and field observations. This map delineates the topography, the locations of landforms such as mountains and plains, regional lithology, alluvial fans, watersheds, major rivers, and sand ramps (Fig. 11). The geomorphological map reveals that a significant amount of weathered material, derived from upstream limestone and granite rocks, was transported to the plain during the Quaternary period, forming numerous extensive alluvial fans. During dry periods, the abundant sediments undergo wind erosion, primarily due to the lack of moisture and vegetation. The mountainous barrier in the eastern region of the plain obstructs the movement of these sands. As a result, these sands were deposited as a sand sheet at the foot of the mountain in the past. Some surface sediments were transported across the windward slope, occasionally crossing the mountain ridge and settling on the leeward slope, forming climbing and falling dunes. Furthermore, as shown on this map, most of the elevations surrounding the studied plain are covered by limestone. Granite formations are outcropped in the elevations and upper streams of the catchment area, particularly within cirque depressions. These rock outcrops date back to the colder glacial periods of the Quaternary, during which the stones underwent intense weathering due to cryoclastic processes (Sharifi Paichoon, 2018). During this period, following the destruction of the overlying limestones, the granite rocks underwent severe weathering and degradation due to glacial activity, with their sediments being transported downstream by glacial tongues and runoff. A large proportion of the sands found in the sand sheet, exceeding a height of 3 meters, can be attributed to this period and predominantly originated from mafic rocks (Figs. 2 & 11). In contrast, the sediments in the alluvial fans on the plain primarily consist of limestone, a feature also evident in the surface sands found on the climbing and falling dunes.

Table 2. Results of granulometry of the studied sand ramps.

No.	Sampling location	Morphology of dune	Height of samples	Thickness of sands (approximate)	Composition of minerals	frequency of minerals	Mineral weathering	Origin of sediments	Notes
1	Leeward ramp (at the foot of the valley in the downstream)	falling dune	at about 5 m above the level of the plain (1505 m a.s.l)	70 cm	Quartz, Albite, Calcite, Dolomite, Clinochlore,	Quartz, Calcite Dolomite,	sever	limestone & dolomites, mostly alluvial fans	Calcium carbonate and quartz minerals are abundant; some calcites recrystallised, exhibiting multimodal characteristics and transported over multiple periods. These calcites are highly rounded, while feldspar and biotite are rarely observed.
2	Leeward ramp (at the Middle parts of the slope	falling dune	At 60 m above the level of the plain (1565 m a.s.l)	40 cm	Quartz, Albite, Calcite, Dolomite	Calcite Quartz, Dolomite	sever	limestone & dolomites, mostly alluvial fans	Calcium carbonates are multimodal and large, exhibiting varying degrees of roundness and being transported over long distances.
3	Sand sheet	horizontal layer	At a depth of 3.5 m from the ground (1535 m a.s.l)	350 cm	Quartz, Alkline feldspar, Biotite, Albite, Calcite, Rock fragment	Alkline feldspar, Biotite, Muscovite	very little	mafic rocks, mostly river sediments	Mafic minerals exhibit minimal weathering, suggesting arid conditions and rapid formation. The mineral grains are angular with little rounding, indicating that they have undergone short wind transport distances. Intact biotite and feldspar suggest limited displacement and short formation times. The sands originate from nearby rivers.
4	Sand sheet	horizontal layer	At a depth of 1.5-2 m from the ground (1537 m a.s.l)	350 cm	Quartz, Alkline feldspar, Biotite, Albite, Calcite, Rock fragment	Quartz, Alkline feldspar, Biotite	very little	mafic rocks, mostly river sediments	Mafic minerals exhibit minimal weathering, suggesting arid conditions and rapid formation. The presence of rock fragments suggests a lack of weathering due to extreme aridity.
5	Sand sheet	horizontal layer	At a depth of 50 cm from the ground (1538 m a.s.l)	350 cm	Quartz, Calcite, feldspar, Dolomite, Albite	Quartz, Alkline feldspar, Calcite	Slight	mafic rocks, mostly river sediments & a small number of alluvial fans	The grains in the upper layers are larger than those in the lower layers, indicating an increase in wind intensity and speed over time. Feldspar and biotite show reduced volumes, indicating greater weathering and the potential presence of moisture during or after formation, possibly from surface water infiltration. Additionally, calcite mineral grains appear more rounded.
6	windward ramp (at the Middle parts of the slope)	climbing dune	At about 55 m above the level of the plain (1576 m a.s.l)	140 cm	Quartz, Calcite, Feldspar, Dolomite, Muscovite	Quartz, Calcite Dolomite,	sever	limestones, mostly alluvial fans	Rounded calcite minerals exhibit the highest volume, followed by quartz, which has a higher volume due to its increased durability against weathering. In contrast, feldspar minerals experienced a notable reduction, decreasing to approximately 5%.
7	windward ramp, near the peak of the Mountain	climbing dune	At about 105 m above the level of the plain (1596 m a.s.l)	70 cm	Calcite, Dolomite Quartz, Albite, Muscovite, Clinochlore	Calcite, Quartz, Dolomite	sever	Limestones, mostly alluvial fans	The considerable rounding of calcite minerals, along with variations in rounding extent and grain size, suggests the transportation of calcite sediments over extended periods and across significant distances.

As indicated by the geomorphological map of the area, a key factor contributing to the formation of ramps in the region is the uplift of the Kerman conglomerate and the creation of a relatively linear mountain barrier (exceeding 100 meters) in the eastern section of the plain (Figs 2 & 11). The significant amount of sand deposits found in the northeastern regions of the plain, in the form of sand sheets and climbing and falling dunes, highlights the importance of regional winds. Local southwest winds played a role in transporting the sands toward the northwest of the plain, while the prevailing northwest and west winds transformed them onto the slopes. Some of these sediments were deposited on the plain near the mountain, while others climbed the slope and settled on the windward slopes. The situation is markedly different in the southwestern portion of the plain. This region exhibits a significantly lower concentration of sand, with all aeolian sands traversing the mountain ridge and depositing on the leeward slope due to its lower elevation. The accumulation of fine and pure sands has transformed this dune (ramp) into a popular leisure and tourism destination.

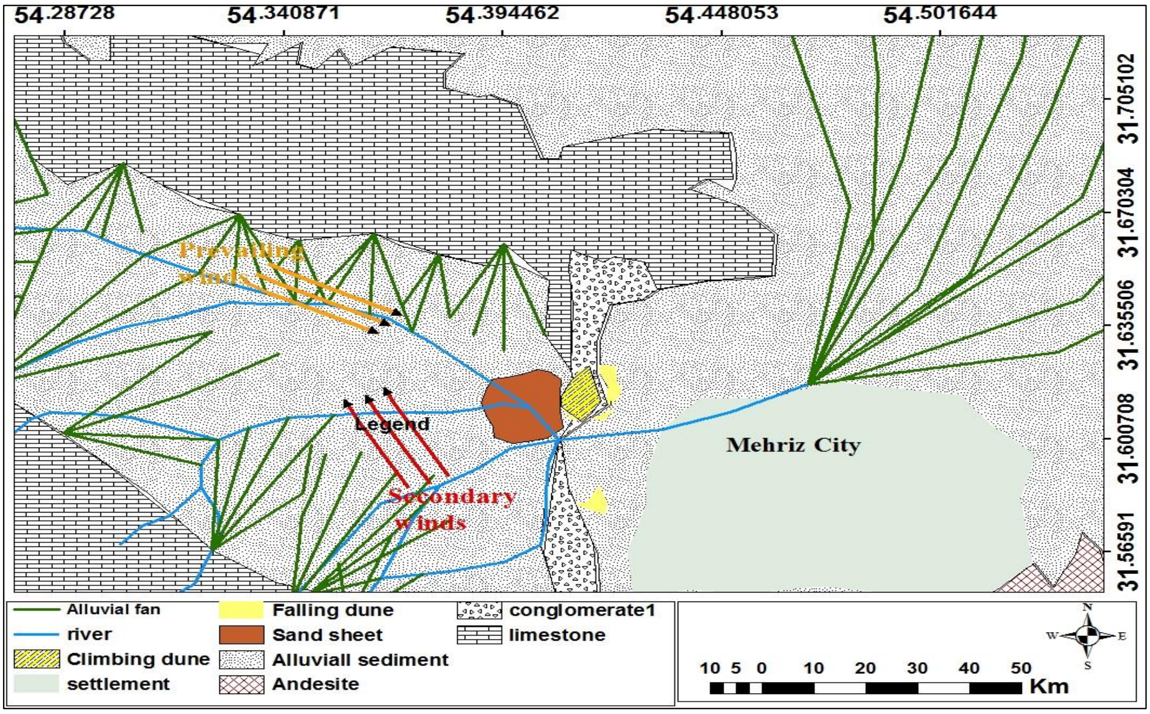


Fig. 11. Geomorphological map of the studied area, showing the location of the sand ramps (climbing and falling dunes), the raised fault ridge that contributed to the formation of the sand ramps, as well as large and numerous alluvial fans and dry rivers.

4.5. The role of different factors in the formation and development of sand ramps

This study examines the key factors influencing the formation of sand ramps in the study area. Field investigations, along with the analysis of geological, topographical, and geomorphological maps, mineralogical analysis, and regional wind and humidity information. The following section provides a detailed description of each:

4.5.1. The role of Quaternary glacial processes in the formation of sand ramps

Many of the ramps in the study area formed during the late Quaternary, likely in the early Holocene. Mineralogical analyses reveal that the sand grains primarily consist of quartz, feldspar, biotite, and mica, with calcite minerals found in small quantities within the aeolian sands, particularly in the lower and older layers. Field observations and geological maps indicate that limestone and dolomite outcrops are common in the surrounding plains, whereas granite formations are prominently outcropped upstream of the Shirkouh Mountains, particularly in glacial valleys and cirque depressions. During the Plio-Pleistocene era, the weathering and destruction of upper Cretaceous limestone layers led to the gradual outcrops of Shirkouh's massive granite formations. These rocks, being susceptible to the low temperatures of glacial climates, underwent intense weathering, resulting in the development of numerous large depressions (cirques and valleys) within the granite and granitoid masses of Shirkouh (Sharifi Paichoon *et al*., 2017; Sharifi Paichoon, 2018; Figs. 2 & 11). Ice tongues and runoff carried the weathered materials from these cirques and glacial valleys into the plain, forming extensive alluvial fans (Fig. 11). This suggests that a significant portion of the sediments composing the sand ramps originated during past cold periods. During pluvial phases, several dry rivers traversed the plain, transporting upstream sediments, primarily weathered granites from the cirques. These sediments, deposited in alluvial fans and along dry riverbanks, have since been exposed to strong winds, particularly from the late Quaternary onwards. Sediment transportation by wind primarily occurred during periods of extreme dryness when vegetation cover was drastically reduced.

4.5.2. The role of local winds in the formation of the sand ramps

Based on the wind rose analysis of the study area, the prevailing winds, including those from the northwest and west, are similar to those found in other regions of central Iran. However, during colder seasons, the wind direction shifts to the southeast, increasing in speed and intensity, which leads to heightened wind erosion (Fig. 12). These varying wind patterns—northwest, west, and southeast—play a role in the formation of dunes and sand fields. In contrast, north and south winds have minimal frequency and speed, characterizing them as secondary winds (Fig. 12). Data from the Yazd Synoptic Station and the corresponding wind rose indicate that southwest winds exhibit the lowest frequency, speed, and intensity. In contrast, some prevailing and seasonal winds exceed speeds of 100 km/h (Sharifi Paichoon *et al*., 2020a; Omidvar, 2010). These winds not only move sand through erosive processes but also contribute to the region's aridity. While sand ramps are primarily formed by the prevailing regional winds, the transportation of sand across the plain and along dry riverbanks is mainly driven by secondary and local southwest winds. These winds consistently move substantial amounts of sediment from various areas of the plain toward the northeast. Subsequently, west and particularly northwest winds transport these sediments up to the windward slope and even transfer some to the leeward slope. As a result, compared to the regional winds, the local winds play a significantly more important role in depositing sand and forming sand sheets and ramps in the studied plain. The wind roses depicted in Figure 12 illustrate the prevailing regional winds in the study area.

This scenario is evident in the studied region during recent dry years. In these years, a significant decrease in humidity leads to reduced vegetation on the plain, triggering wind erosion (Fig. 13). As a result, a small quantity of sand is transported to the northeast of the plain due to the influence of regional and local winds. Some of these sand particles climb the mountain slope and form ramps. However, in more recent years, the growth of vegetation has impeded the movement of aeolian sands (Fig. 13).

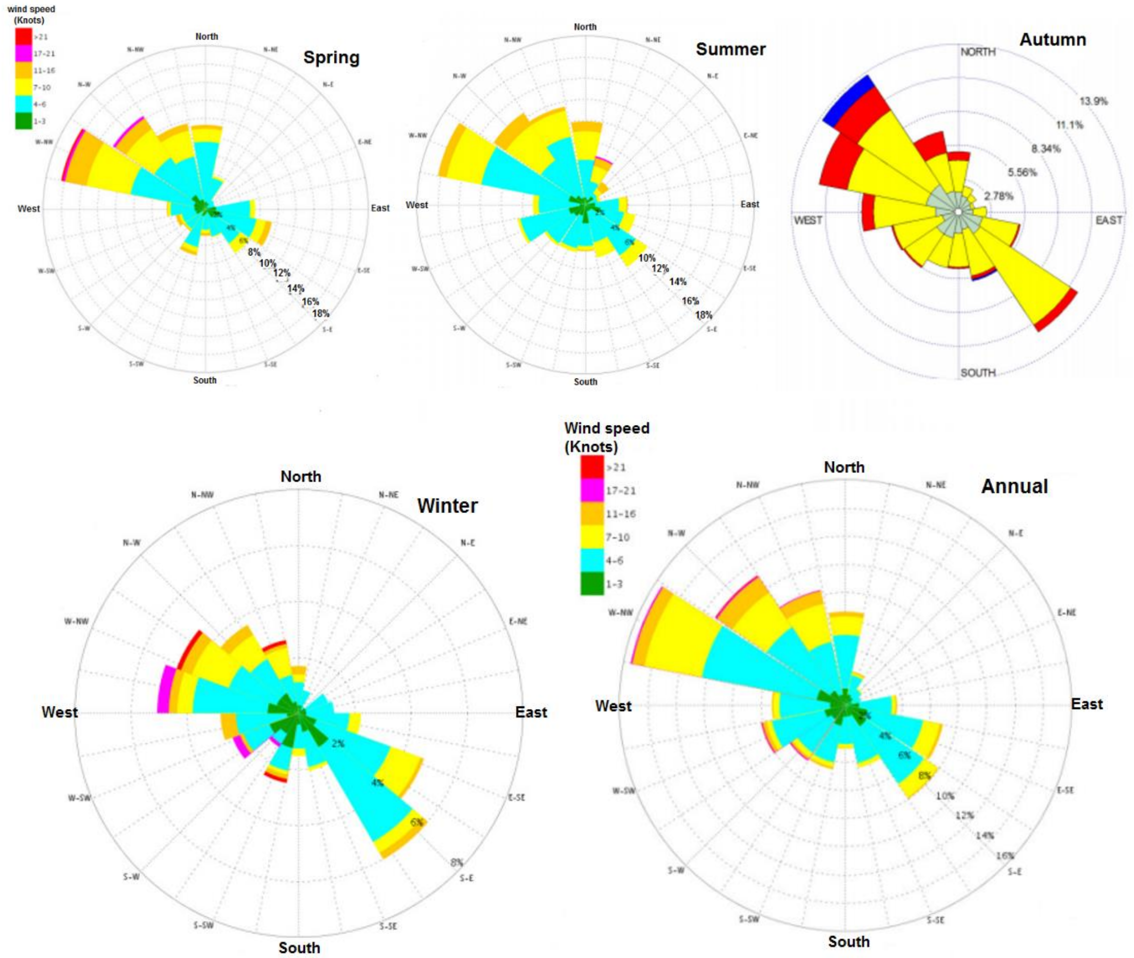


Fig. 12. Annual and seasonal windrose of Yazd synoptic station.

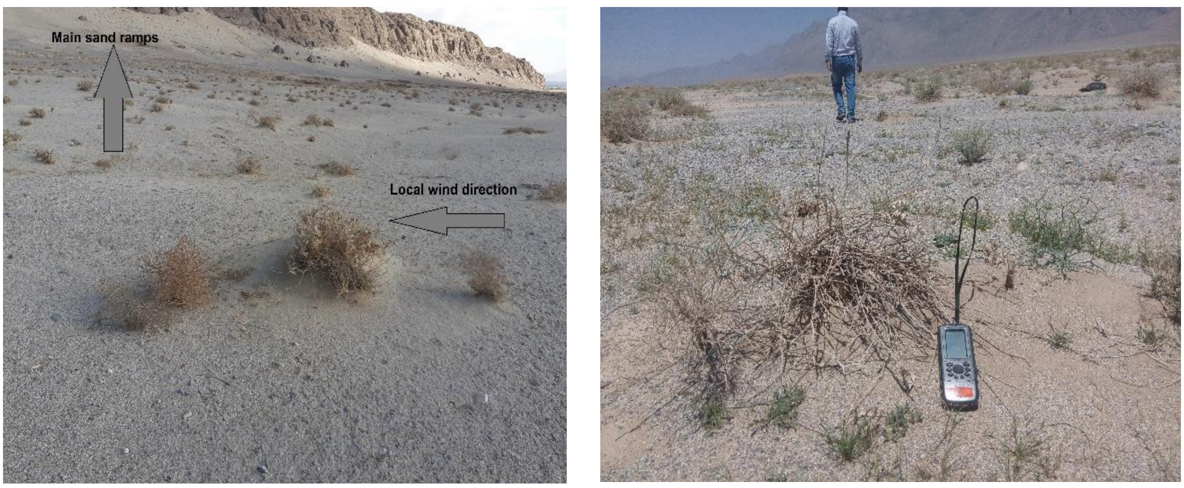


Fig. 13. Shows the influence of local winds on the deposition of sand ramp sediments (left photo); The right photo highlights how alternating periods of drought and wet years affect wind activity. During dry years, increased wind activity leads to the formation of mini-nebkas, while in wetter years, vegetation growth reduces wind activity.

4.5.3. The effects of climate change on the formation of sand ramps

The region's arid conditions in the study area can be attributed to several factors, including a) its geographic location within the high-pressure subtropical belt, b) its substantial distance from moisture sources, and c) its position on the leeward side of the extensive Alborz and Zagros Mountain ranges in the north and west. Annual precipitation in the region, as recorded by a nearby meteorological station approximately 30 km away, is below 60 mm. In contrast, the Mehriz station, located 5 km from the study area, reports an annual precipitation of around 70 mm. However, at higher elevations, annual rainfall exceeds 250 mm (Fig. 14).

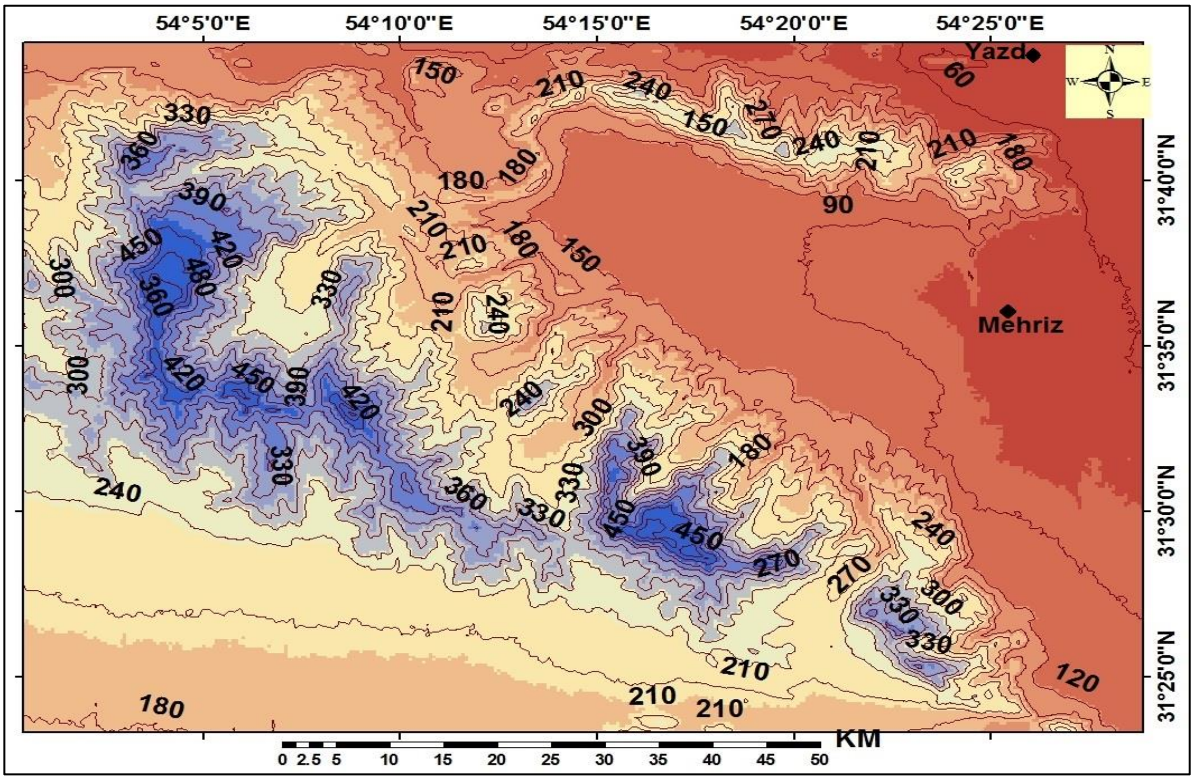


Fig. 14. Isohyet map of the study area, prepared using data from six meteorological stations: Yazd, Mehriz, Tengechenar, Garizat, Taft, and Tezerjan.

Regarding humidity in the region, a significant challenge is the notable variability in precipitation levels observed across different periods. Analysis of numerical data and corresponding graphs indicates that annual precipitation levels can decrease to as low as 20 mm in some years (Fig. 15). Furthermore, precipitation in central Iran is not evenly distributed throughout the year; instead, a substantial amount occurs within a single day or over a few days, which is insufficient to maintain adequate humidity levels and support vegetation growth. Occasionally, rapid rainfall associated with the Indian monsoon occurs in the summer months within a short timeframe, but a significant portion of it evaporates. These dry conditions can intensify, leading to prolonged droughts that may persist for several years. For instance, data from meteorological stations highlight that central Iran experienced drought circumstances from 2000 to 2016 (Fig. 15). Under such conditions, decreased humidity levels lead to reduced vegetation, increased wind activity, and heightened sand transport. Currently, the sand ramps in the area are relatively inactive and classified as semi-active. The existing climate, with around 70 mm of annual precipitation and average temperatures of 20°C, is not conducive to the development of sand ramps. Despite the limited rainfall, Ebrahim Abad Plain, which serves as the sand source for the ramps, exhibits dense vegetation due to lower temperatures, mitigating wind erosion. However, during dry years with decreased vegetation, erosive wind actions intensify. Stronger and more frequent winds lead to the gradual development of the ramps during these years. Consequently, the formation of these ramps can be traced back to severe dry periods in the past when annual precipitation was below 30 or even 20 mm, and vegetation was scarce. The sediments in the sand ramps and sheets lack compaction, weathering, and hardening, indicating their origin during the severe dry periods of the late Quaternary and possibly the early Holocene.

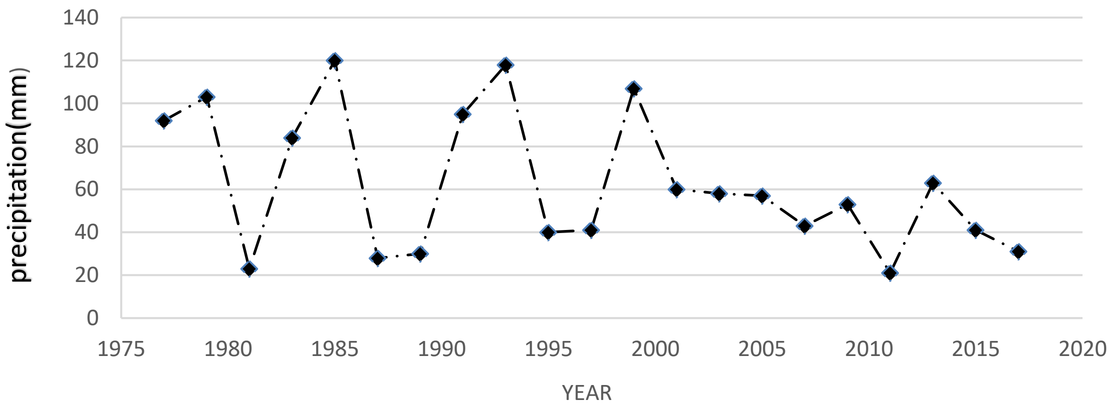


Fig. 15. Chart depicting Annual precipitation Changes in Yazd meteorological station

5. Discussion

The region investigated in this study, similar to the Mojave Desert in the United States, is identified as one of the world's primary areas for investigating sand ramps and has attracted more research attention than most other regions (Sharifi Paichoon, 2019; Thomas *et al*., 1997). However, only a limited number of sand ramps within this region have been studied in detail (Sharifi Paichoon, 2019). The Mehriz area, the focus of this research, contains a variety of sand ramps that differ significantly from those studied in other parts of the world, making it a valuable site for further investigation. Notably, while most sand ramps globally are covered by vegetation, alluvial, or colluvial deposits, obscuring direct analysis (Lancaster and Chakerian, 1996; Sharifi Paichoon, 2019), the sand ramps in this area, whether climbing or falling dunes are largely bare and exposed. With minimal recent gravel deposits, they offer a unique opportunity for straightforward observation and analysis.

Many of the sand ramps studied globally were formed under cold glacial and pre-glacial conditions in the past (Thomas *et al*., 1997; Berking & Schütt, 2011; Telfer *et al*., 2012; Ellwein *et al*., 2015; Del Valle *et al*., 2016; Sharifi Paichoon, 2019). These ramps, typically found on mountain slopes, are often hardened and weathered. In contrast, the sand ramps in the study area are relatively young, likely dating back to the dry periods of the late Quaternary or even early Holocene. As a result, minerals such as feldspars, biotites, and muscovites remained intact, showing no signs of weathering or hardening. Additionally, the sediments of both the ramps and the sand sheet at the mountain's foot exhibit uniformity, lacking any alluvial or colluvial layers (Fig. 4). While earlier research suggests that sand ramps are typically composed of aeolian, fluvial, and colluvial deposits (Bateman *et al*., 2012; Lancaster & Tchakerian, 1996), the sediment homogeneity observed in these ramps is often attributed to their rapid formation over a short time (Sharifi Paichoon, 2021; Table 1).

The formation and development of sand ramps have largely ceased due to changes in climatic and environmental conditions. However, field surveys in the study area indicate that these ramps remain partially active, classifying them as semi-active. Research conducted in the Ebrahim Abad Plain has shown that during dry years, vegetation diminishes, exposing numerous alluvial fans with substantial sediment deposits, thereby creating conditions suitable to wind activity (Sharifi Paichoon & Shirani, 2017). For instance, a prolonged drought in central Iran from 2000 to 2015 led to widespread vegetation loss, allowing wind processes to dominate the study area and other parts of central Iran. During this time, the sand ramps in the region expanded. Periodic droughts in central Iran, therefore, trigger ramp activity by limiting vegetation growth on sand deposits (Sharifi Paichoon, 2019).

Based on the results of the region's climate, the annual precipitation in the study area is currently less than 70 mm, occasionally dropping below 30 mm in the depressions of the surrounding playas (Fig. 13). The average temperature in the region is approximately 20°C, rising above 30°C during the summer, which exacerbates the arid conditions. Despite this, the plain supplying sediments to the ramps presently exhibits relatively robust vegetation, mitigating the impact of wind erosion on the ramps (Fig. 1, photo G, and Fig. 11). As a result, these ramps remain relatively stable, and their development is slow under prevailing dry conditions, unlike the active sand dunes found in central Iran (Sharifi Paichoon *et al*., 2020). In contrast to earlier studies suggesting that sand ramps are influenced by a "window of opportunity" characterized by abundant sediments and adequate space (Bateman *et al*., 2012), the primary factor driving the formation and development of these landforms is the absence of moisture or persistent aridity. Although the region has an abundance of available sediments, significant ramp development occurs only during years of severe drought.

It was also observed that in sections of the area with lower elevations, such as those below 20 meters in the southeastern part of the plain, sandy sediments have ascended to the peak, descended the leeward slope, and accumulated along the slope and at the foot of the mountain. Furthermore, a substantial quantity of sand has climbed elevations above 100 meters and settled on the windward slope in the northeastern part of the plain (Fig. 1, photos A, B, & F). This evidence suggests that sand ramp formation is influenced by several factors, including the volume of available sediment, sufficient space for sand accumulation, and topographical features. However, the most important factor in their formation appears to be closely tied to the duration and severity of drought periods. The current inactivity of ramps in this arid region implies that their development likely occurred during prolonged droughts. Under such past conditions, contrary to Thomas *et al*. (1997), winds do not appear to have been stronger than they are today. Granulometric analyses indicate that present-day winds are stronger than those at the time of the ramps' formation. This is evidenced by the coarser grain size of surface sediments compared to those in the lower layers of the sand sheet trench (Table 1).

Windrose data from the region (Fig. 12) indicate that west, northwest and southeast winds are the prevailing winds. Nonetheless, the extensive sand sheet located in the northeastern section of the plain suggests that southwest winds have been instrumental in sediment accumulation. Specifically, these southwest winds transport a large amount of sediment toward the northeastern plain, after which the dominant regional northwest and west winds drive the sediment further eastward, settling it on the slopes. The distinct topography restricts the influence of intense seasonal southeast winds on sand ramp formation. Findings by Sharifi Paichoon *et al*. (2018) and Sharifi Paichoon (2019) further emphasize that local winds (southwest winds) play a key role in forming the dunes and ramps in central Iran. The results indicate that the study area (Mehriz station) is only slightly affected by dust storms, which generally lack a dominant direction. Based on annual sand rose data, sand transport is mainly governed by west–east erosive winds. In winter, however, despite the limited number of dust storm days, the transport direction shifts to southwest–northeast (Saremi Naeini, 2017). It appears that much of the sand is carried northeastward during a few days of winter episodes and subsequently redirected westward by prevailing winds, ascending the nearby mountain slopes.

The analysis of the sand ramp's mineral composition indicates that the sediments originate from granites and granitoids located in the Shirkooh Mountains at elevations above 2200 m (Fig. 4). The surrounding rock formations are mainly composed of limestone and dolomite (Fig. 4). During glacial periods, the weathering of granite formations in high valleys and cirques occurred. Subsequently, ice tongues and runoff transported these weathered materials to the plains (Sharifi Paichoon *et al*., 2017; Sharifi Paichoon, 2019), particularly along river channels. In the dry late Quaternary and probably early Holocene periods, strong winds carried these sediments onto the slopes (Fig. 4). As a result, the surface sediments differ considerably from those in the lower layers in terms of physical characteristics. The surface layer's sediments exhibit a broader range of compositions, including significant amounts of fine-grained sand and calcium carbonate. Furthermore, the surface grains are more rounded and less sorted than those in the lower sediment layers. The diversity of surface sediments, along with their increased roundness and the presence of coarser limestone particles, suggests multiple sources and indicates that these sediments have been subject to stronger winds and have travelled greater distances than those in the past. In contrast, the lower layers of the sand sheet consist of unweathered and unrounded feldspar, biotite, muscovite, quartz, and rock fragments, implying that these grains were transported only short distances by wind.

6. Conclusion

This study identifies the sand ramps in the investigated area as some of the few active ramps in central Iran and possibly worldwide. Their genesis dates to the late Quaternary–early Holocene, coinciding with a rapid aridification phase. Evidence for this includes the lack of sediment hardening and weathering, the absence of alluvial–colluvial inputs, and no traces of vegetation within aeolian deposits. The formation and evolution of these ramps were strongly controlled by local geomorphic and climatic factors, such as topography, lithology, wind regime, and aridity. The presence of quartz, feldspar, mica, and biotite in deeper layers of the sand sheet indicates sediment derivation from igneous sources exposed in high-altitude glacial cirques (>2200 m a.s.l.). During glacial periods, weathered material was transported by ice tongues and runoff, later reworked by winds during dry Quaternary phases. Regional and local winds redistributed fine sediments: Local southwest winds carried them to the northern parts of the studied plain, while regional winds transported them eastward. Some of the sand settled at the foot of the slope, forming a sand sheet, while other portions climbed up the mountain slopes, with additional sand crossing ridges and descending on the leeward slope. Thus, the large volume of sand sediments in the northeastern parts of the plain, compared to the southeastern parts, demonstrates the influence of local winds.

The spatial distribution of climbing and falling dunes, especially the formation of extensive sand sheets in the northeastern plain adjacent to mountain slopes >100 m, highlights the topographic control on ramp development. In contrast, the southeastern sector exhibits limited sand cover, except for a large stabilized ramp formed in a leeward valley, underscoring the geomorphic role of slope configuration. Mineralogical analyses reveal notable feldspar, biotite, and muscovite in subsurface sediments, replaced by calcite and dolomite near the surface, indicating post-depositional environmental changes. The presence of mafic minerals signifies deposition during cold glacial periods, while clinochlore, formed through weathering of feldspars and biotites, appears exclusively in surface sediments of the climbing and falling dunes.

Thus, contrary to earlier studies (e.g., Bateman *et al*., 2012) that identified available sediments and space as the "window of opportunity" for ramps to form and develop, this study's findings suggest that severe drought served as that opportunity. Moreover, unlike the findings from earlier studies (e.g., Thomas *et al*., 1997), which highlighted strong winds as a key factor in the formation of ramps in central Iran, the current coarse-grained surface sediments suggest that wind strength is now greater than it was in the past, based on comparisons with the deeper sand sheet layers. Despite the region's strong seasonal winds, numerous alluvial fans, and fine sediment availability, the ramps exhibit limited modern activity under ~60 mm of annual rainfall. This implies that they are relict features, formed under severe droughts with precipitation likely below 20 mm/year. Unlike previous findings (e.g., *Bateman et al., 2012*), which emphasized sediment availability and accommodation space as primary "windows of opportunity," this study suggests that severe aridity was the main driver. Furthermore, contrary to *Thomas et al. (1997)*, who linked ramp formation to intense winds, the coarse surface grains indicate that present winds are stronger than those prevailing during ramp genesis. Distinct from most global counterparts, the studied ramps lack alluvial or colluvial capping, vegetation, and soil cover, while adjacent plains remain densely vegetated. This points to both the relative youth and ongoing dynamism of these ramps under modern arid conditions.

Finally, the findings confirm that sand ramps are highly sensitive paleoenvironmental indicators, recording past droughts that significantly influenced human settlement, vegetation, and fauna in central Iran. Hence, they represent key targets for archaeological, geoarchaeological, and environmental reconstructions of late Quaternary climates.

Data Availability Statement
Data is available on request from the author.

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Ethical considerations
The author avoided data fabrication and falsification.

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Conflict of Interests
The author declares no conflict of interest.

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