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NATURAL AND ANTHROPOGENIC FACTORS OF THE DEVELOPMENT OF ERG CHEBBI

Abstract: Estimation of the factors determining the development of Erg Chebbi, especially the influence of the human activity on the increase of the deflation intensity in the source areas, were the aim of the studies presented in this paper. This erg, occurring in the south-eastern part of Morocco along the border with Algeria, is formed by 13 star dunes and complex transversal dunes, the latter developed in the margins of the erg, mainly in its eastern and southern parts. On the basis of the textural analysis of the dune and basement material, the degree of aeolization of the sediments and their source areas were determined. The results of the investigations indicated high degree of aeolization and allochthonous source of the sediments which formed the dunes in Erg Chebbi. This is evidenced by high uniformity of the dune material within individual forms and in the erg as a whole, moreover by relatively large grain diameter, good sorting, negative values of the skewness index suggesting absence of the local fine-grain material supply and generally low participation of the local material poorly resistant to abrasion in the dune sediments. Taking into account the climatic conditions (mainly the wind velocity and direction) it was found that the areas of the vast hamadas, i.e. Guir in the east and north-east, and Kem-Kem in the west and south-west are the main source regions of the material building the star dunes in Erg Chebbi. These areas are largely not populated, and recently did not suffer any sudden changes of the natural conditions. Desertification of the source areas may be connected with the global climate changes and only in this context one may discuss the indirect human influence on the development of Erg Chebbi. Initial accumulation of the dune material was connected with the surface morphology of this area. Erg Chebbi formed in the lowest part of the depression, where two factors forcing sedimentation of the material transported by wind were present – this means the shallow or surface-reaching ground water and vegetation connected with these water conditions.

The obtained results indicate as well the significant difference of the textural features of the dune sediments occurring in the surroundings of Erg Chebbi and the basement sediments. The dunes form a system with a distinct, linear shape connected with the network of the river beds. The source of the material of these dunes is connected with the material transported formerly by rivers, which subsequently became episodic rivers. One found that the present-day

absence of flow in the river beds, which are source of material for these dunes, is connected with the decrease of precipitation and degradation of the plant assemblages, the latter resulting in poorer retention of water, and only in slight degree – with decrease of water supply caused by the local human activity.

On the basis of the performed studies one also found that the fast change of certain environmental factors in the area of Erg Chebbi, resulting from strong recent anthropopression, was not in the past and is not presently of any real importance for the development of this dune field.

Key words: dune development reasons, star dunes, dune sediment source, sediment textural features, Erg Chebbi, NE Morocco.

1. Introduction

The determination of the basic factors influencing the development of Erg Chebbi was the aim of the recent studies. The estimation of the anthropopression in the present-day development of this dune field was the most important question, which has been formulated at the start of the studies. To solve this problem, one determined the source of the aeolian material. Subsequently, knowing the alimentation areas, it was possible to analyse the physical-geographic features of these areas, considering especially the factors, which influenced the intensity of the deflation process. The next stage of the investigation concerned the possible changes of these factors, what could determine to an important degree the development of Erg Chebbi. The recognition of the reasons for these changes, especially the answer, if these changes result directly or indirectly from the human activity, was the last but very essential part of these works.

Erg Chebbi is situated in the southeastern part of Morocco, close to the Algerian border, to the southeast from the settlement of Rissani and the Tafilalt region (Figure 1).

Erg Chebbi is the sole dune field in Morocco to which the term „erg” is applicable, though considering its size; it is one of the smallest ergs of the Sahara Desert. It comprises 13 star dunes of the total surface of 110 km² (the maximum meridional length is ca. 18 km, and the maximum longitudinal width ca. 9 km). Thus its surface is ten to dozens times smaller than the surface of the other Saharan ergs. The maximum height of the dunes does not exceeds 200 m, reaching a half of the height of the highest dunes in the Sahara Desert (Photo 1).

2. Physical-geographic characteristic of the region

Erg Chebbi is situated in an extensive tectonic-karst-deflation depression of the average depth of 400 m (Figure 1). From the east side it is bordered by a distinct escarpment of the vast, flat hamada of Guir, from the south by hamada of Dra and from the west by the Kem-Kem hillocks. The surface of the depression is generally flat, scarcely cut by the network of the beds of the episodic rivers and inclined from the north (750 m a.s.l.) to the south (675 m a.s.l.).

Beyond the material of the aeolian origin, the floor of the depression is filled by the recent and Pleistocene sediments of the rivers and periodic lakes, mainly the muds of the alluvial flats (Figure 2). The older part of the depression filling consists of the Pleistocene alluvial fans and pediments formed in pluvial periods. Large, central, slightly elevated area is built by Upper Carboniferous dark gray clayey shale with intercalations of the fine-grained sandstone and red ferric-mineral-bearing fan sediments. Other sediments of the bedrock, as shown in the map (Figure 2) occupy distinctly smaller surface (Barczuk et al. 2006).

Climatic conditions of the considered region are typical of the continental hot desert climate. There occur characteristic great temperature changes both in annual and daily cycles. At Rissani Station, 30 km to the north-west from the Erg Chebbi, the maximum average temperature during a year was in August (45.3°C) and the minimum one – in January (-4.1°C). The daily temperature changes in the summer may exceed 30°C for air and 50°C on the surface of the sandy soil (Benmohammadi 2001). So high temperatures cause strong evaporation, which in this region may achieve almost 3000 mm per year. Precipitation is very irregular. At Rissani one noted the total annual precipitation from 12.3 to 152 mm (average 70 mm) with a distinct increase of the precipitation sums in September to November and in March and April. Direction and velocity of wind are the most important elements of the climate influencing the development of the dune fields. At Rissani one noted 36.2% of windy period with the velocity lower than 1 m·s⁻¹, 34.1% with the velocity from 1 to 4 m·s⁻¹, 20.7% with the velocity from 4 to 6 m·s⁻¹ and 9% with the velocity exceeding 6 m·s⁻¹. A significant velocity of wind has been observed from March to September with the highest values (an average exceeding 6 m·s⁻¹) in April, June and August. The active wind (>4 m·s⁻¹) blows from two opposite directions: SW and NE (Benmohammadi 2001).

The depression is watered by Oued (Wadi) Ziz, flowing in a broad valley. It is one of the longest rivers in Morocco, and it was a permanent river to the Moroccan-Algerian border till the beginning of 1970s. Clastic material is supplied together with water to the depression, especially during the large inflows connected with snow melting in the High Atlas, dewatered by Oued Ziz. This material was accumulated in the discussed area in large quantities. The accumulation decreased distinctly, when in the early 1970s one of the largest dams in Morocco has been built near the town of Errachidia. The regulation of the flow caused that Oued Ziz below the Rissani settlement changed into an episodic river. Fluvial transport of the material to the depression currently takes place only by short episodic rivers having their sources in the escarpments bordering the depression. These rivers are numerous, however the flow in them appears every dozen or so years due to low, irregular precipitation and intense evaporation. Construction of the Hassan Abdahil Dam led to extinction of Dajet Srji, what extended significantly the area sensitive to deflation. Broad bed of the Ziz River filled mainly by the sandy material after drying is the area of development of the aeolian processes as well. Absence of supply to the ground waters caused the lowering of the ground water table in the central, lowermost part of the depression in the center of the Erg Chebbi dunes. Till the end of the 1990s several small lakes periodically filled by water

existed in the center of the erg. Presently, water appears in them rarer and rarer and the water table of ground waters systematically goes down. Water supply to the oases in the marginal zone surrounding the erg by the currently expanding system called *foggar* is another reason for the lowering of the ground water table in the area of the erg (Photo 2). Scooping of water, like in the ancient Persia 2300 years ago (Oleil 1994), goes by digging several-meter-deep and several-kilometer-long channels, which drain ground water and lead it gravitationally toward the oases.

Vegetation in the considered area is very scarce. The reg area is almost completely without plants, because of lack of water and deflation, precluding soil formation. Rare grassy vegetation may be found on the dunes even at the height of dozens of meters. Apparently, the relatively favorable conditions for this type of plant are connected with its low water needs and the substrate suitable for the grass occurring there. Water supply comes mainly from dew, which in the continental hot climate in the winter months forms relatively regularly on the surface of the dunes. Compact vegetation cover may be found only within the oases – in the places with shallow ground water table or with systematic artificial watering.

3. Description of the dune forms

The dunes forming Erg Chebbi belong to the star type, consisting of several branches and very small apical surface (Photo 3) (Barczuk et al. 2006). Due to variable wind directions occurring in this area it is difficult to indicate the side of the prevailing steeper slopes. On the basis of the own observations it is concluded that somewhat longer slopes with the inclination of the natural accumulation angle (which in the case of Erg Chebbi is 30-31°) (Photo 4) occurs on the side facing the erg interior, independently of the dune location with respect to the sides of the world. Between the dunes, inside the erg one observed numerous transversal dunes with the relative height from few to a dozen meters and variable directions of their axes. It seems that the changes of the air mass flow forced by the star dunes, as the obstacles are the reason for this variability. Within Erg Chebbi the inter-dune surfaces filled by the aeolian material prevail. Very small parts of the reg without aeolian accumulation occur exclusively in the central part of the erg within the episodic lakes (Photo 5).

Dunes surrounding Erg Chebbi, especially those in its eastern and southern margin, belong mainly to the complex transversal variety with the maximum height up to 20 meters (Photo 6). Their occurrence is connected with the large episodic river, presently embracing Erg Chebbi on its eastern side (Figure 3).

4. Methods

The determination of the source of the sediments and evaluation of the degree of their degree of aeolization i. e. the degree of transformation of the source sediments in the aeolian ones (Mycielska-Dowgiałło 1992) have been made on the basis of the analysis of the textural features of this sediment (Mycielska-Dowgiałło, Rutkowski 1995). Forty five samples of the dune and basement sediments have been

collected (Figures 1 and 4) to analyze their granulation, and, in the selected samples, their mineral composition. Results of the granulation analysis yielded the frequency and cumulative granulation curves in the scale of probability (Mycielska-Dowgiałło 1995). On this basis the granulation indices according to the Folk and Ward (1957) formulae were calculated, i. e. the grain diameter (M_z), standard deviation (σ_1) and skewness (Sk_1).

The laboratory investigation included analysis of granulation and analysis of mineral compositions of the dune and basement sediments.

The granulation analysis has been made by means of the laser particle counter „Analysette 22” produced by Fritsch. Use of the laser method of the grain measurement to the complete analysis of the sample was possible due to the aeolian origin of the studied material. The maximum grain diameter of the studied sediment did not exceed 1 mm. The results of the triple measurements of each sample have had deviations not exceeding 5%. Somewhat greater error was found for the measurements of the basement sediments; the latter though had smaller grains than those of the aeolian material, however, are formed from less durable clayey material.

Microscope analysis of so-called granular preparations was the main investigating method allowing the determination of the mineral and lithologic composition of the dune and basement sediments. This analysis is widely used in the sedimentary rocks petrology (Barczuk 1992, Kosmowska-Ceranowicz, Buchmann 1982), but especially profitable application it has found in the studies of the sediments, which underwent the aeolian processes (Chlebowski, Lindner 1992, Chlebowski et al. 2002). Samples of the material taken for the laboratory analyses were initially, before the making of the granular preparations, analysed under binocular. Mineral and lithologic composition of the sand samples was made without separation of the individual grain classes because of the insignificant fractional differentiation of the components of the studied sediments. Preparations were made from the samples which were analysed in the context of their structure, texture and mineral composition by means of various polarizing and scanning microscopy techniques, described e.g. by Borkowska and Smulikowski (1973) as well as by Dear et al. (1966). For obtaining the complete identification of the lithoclasts and individual minerals one analysed such features of the minerals like habits, cleavage, color, pleochroism, refractive indices, birefringence, light extinction angle, optic axes, optic sign etc.

5. Results

On the basis of the performed analyses of the grain diameter one found that the prevailing majority of the material forming Erg Chebbi, independently of the height of the dunes, has grains within the ranges from 0.5 to 0.2 mm (1-2.32 Φ). This is the fraction which dominates in mature Saharan ergs but distinctly coarser than in the dune sediments of the region of Coude du Dra (Dłużewski 2003). The dune forms occurring in the area surrounding the investigated erg have distinctly larger fractional variation and somewhat higher participation of the finer grain material, namely in the grain class from 0.5 to 0.063 mm (1-4 Φ).

Sediments of the basement if the investigated area bear typically distinctly finer material than the dune sediments. This is mainly the material of the dust and clayey fractions (<0.032 mm; $>5\Phi$) connected with the accumulation in the stagnant water of the lakes and even in small depressions without external drainage.

On the basis of the frequency curves one may conclude the distinct absence of the connection between the basement sediments and the sediments building Erg Chebbi and only a limited connection between the sediments of the dunes bordering the erg and the basement sediments dominating in the depression.

Analysis of the cumulative curves of the granulation of the studied sediments from the star dunes indicates the important participation of the grains transported by saltation (Mycielska-Dowgiałło 1995). These are the grains of the diameter from 0.8 to 0.2 mm ($0.2-2.32\Phi$). Grains of the fraction below 0.2 mm ($>2.32\Phi$) are transported in suspension; however, participation of this fraction generally does not exceed 2%. The curves indicate absence of the material transported by dragging and rolling.

The shape of the cumulative curves of the grain sizes of the studied material from the dunes in the area surrounding the erg is similar. One may, however, indicate an insignificant decrease of the maximum grain size transported by floating to 0.125 mm (3Φ).

Cumulative curves of the basement sediments have distinctly different shapes. They show clearly lesser inclination evidencing by far poorer sorting of the basement material, if compared with the material of the dunes. The transport of the grains was dominated by floating.

On the basis of the cumulative curves one calculated the granulation indices according to the formulae proposed by Folk and Ward (1957). The values of the mean diameter of the grain classes (M_z) of the sediments building the dunes of the studied area may be evaluated as similar each to other. They range mainly from 0.315 to 0.4 mm ($1.67-1.32\Phi$) in the southeastern part of the erg and in the low transversal dunes surrounding Erg Chebbi (Tables 1a, 1b). The star dunes located in the northern and northwestern parts of the erg are built from slightly coarser grains of the diameter ranging from 0.315 to 0.5 mm ($1.60-1.00\Phi$) (Tables 1c, 1d). Coarser material is typical of the lower parts of the star dunes as well, what may be related to the supply of such grains from the apical parts of the dunes due to intense deflation of the finer grains. Thus, the dunes of Erg Chebbi have typically greater average diameter of the grains than the dune sediments in the region of Coude du Dra (Dłużewski 2003), and similar to the majority of the large Saharan ergs (Pietrow 1976, Coque 1962, Barczuk, Dłużewski 2001). Comparing the average diameter of the grains of the material occurring in the dune sediments at Erg Chebbi, one should say that it is distinctly larger than in the areas of the deserts in Middle Asia (Kara-Kum, Kyzyl-Kum), Central Asia (Alshan, Kashgar Valley), Indian Peninsula (Thar), Levant (Negev), South Africa (Namib, Kalahari), Australia (Great Desert in Victoria, Great Sandy Desert, Simpson Desert), where the grain class of 0.1 to 0.25 mm ($3.32-2\Phi$) prevails (Pietrow 1976, Coque 1962). Mean value of the grain diameters comparable to that from the Saharan ergs, Erg Chebbi inclusively, was found only in the Atacama Desert in South America (Finkel 1959). This may come from distinctly greater transporting ability (wind force), which is typical of the Saharan areas or from significantly coarser source material.

Table 1. Granulation indices of the dune sediments: M_z – average grain diameter, σ_1 – standard deviation, Sk_1 – skewness; calculated on the basis of the formulae of Folk and Ward (1957)

a. Star dune (height 157 m) – southeastern part

Number of sample	4a	11a	2a	10b	9a	8a	7a	6a	5a	3a	1a
Relative height [m]	7	10	20	40	60	80	100	120	137	157	157
σ_1	0.57	0.63	0.47	0.52	0.57	0.51	0.57	0.57	0.45	0.51	0.53
M_z	1.33	1.83	1.63	2.41	1.54	1.60	1.41	1.40	1.63	1.67	1.36
Sk_1	0.72	-0.13	-0.59	-0.19	-0.31	-0.67	-0.26	-0.37	-0.51	-0.32	-0.28

b. Transversal dunes surrounding Erg Chebbi

Number of sample	12a	13a	14a	16a	17a	18a	19a
Relative height [m]	2	1	3	1	5	4	2.5
σ_1	0.68	0.76	0.66	0.58	0.57	0.59	0.73
M_z	1.63	1.37	1.35	1.78	1.67	1.58	1.78
Sk_1	0.17	0.40	0.29	0.32	-0.19	0.03	0.08

c. Star dune (height 120 m) – northern part

Number of sample	26b	27a	28a	29a	30a	24a	25a
Relative height [m]	Base	20	40	60	80	100	120
σ_1	0.55	0.51	0.61	0.48	0.42	0.48	0.54
M_z	1.11	1.15	1.21	1.32	1.39	1.72	1.46
Sk_1	-0,11	0.06	-0.29	-0.50	0.11	-0.42	-0.66

d. Star dune (height 160 m) – northwestern part

Number of sample	40a	42b	41a	37a	35a	43a	38b	34a	36a	39a
Relative height [m]	Base	27	40	60	80	100	120	140	150	160
σ_1	0.66	0.49	0.50	0.51	0.45	0.51	0.48	0.52	0.42	0.47
M_z	1.02	1.35	1.44	1.45	1.54	1.52	1.38	1.60	1.54	1.35
Sk_1	0.21	-0.81	-0.78	-0.57	-0.44	-0.54	-0.51	-0.25	-0.38	-0.63

As it was mentioned, the basement is built from significantly finer material than the dunes. Average grain diameter for the basement sediments is from 0.004 to 0.15 mm i.e. 8.03-2.71 Φ (Table 2). So fine sediment was probably accumulated in basins without outflows.

On the basis of the values of the standard deviation (σ_1) one may conclude that sorting of the majority of the sediment of the star dunes is at the border between the material moderately and well sorted (Tables 1a, 1c, 1d). Lower dunes occurring

Table 2. Indices of the basement sediments granulation, surroundings of Erg Chebbi: M_z – average grain size, σ_1 – standard deviation, Sk_1 – diameter; calculated on the basis of the formulae of Folk and Ward (1957)

No of sample	15a	20a	21a	22a	23a
Depth [m]	0.10	0.40	0.60	0.80	0.35
σ_1	1.17	2.48	1.45	2.01	2.59
M_z	2.71	4.03	8.03	6.24	4.89
Sk_1	1.59	2.02	0.36	0.11	0.06

in the northern margin of Great Eastern Erg in Tunisia (Dłużewski 2004) and from 0.2 to 0.45 in the deserts of south-western Asia (Dymowska et al. 1984).

Sediments of the basement are poorly or very poorly sorted (Table 2), what confirms the preliminary supposition on their accumulation in very poorly energetic environment.

Distinctly negative values of the skewness indices (Sk_1), as shown in the Tables 1a, 1c and 1d, rarely found in the areas of the hot deserts, indicate that in the dune sediment of Erg Chebbi the material of the coarse fraction prevails over that of fine fraction with respect to the fraction of maximum abundance. This may be connected with sorting of the source sediments and their enrichment in the fractions of coarse grains, as well with great transporting force of wind. Sediments of the dunes occurring in the surroundings of the erg have mostly positive values of skewness (Table 1b), thus the prevalence of the finer material with respect to the grain class of the highest abundance is apparent. Very high values of the skewness index have the sediments of the basement (Table 2). This may indicate the supply of the fine material directly from the basement to the dunes in the surroundings of Erg Chebbi, but also lower dynamics of the transporting environment at lower height. This is confirmed by the skewness index values for the material collected in the lowermost parts of the star dunes (Tables 1a, 1c, 1d).

6. Mineral and lithologic composition of the sediments

A number of the mineral components were distinguished in the studied sediments like monocrystalline and polycrystalline quartz, gypsum, feldspars as well as lithic components or lithoclasts, mainly ferruginous-clayey clasts and various limestones and marls.

Monocrystalline quartz is the dominating component in all the investigated samples collected from the dune sediments. Its participation in the sediments of the star dunes ranges from 65% to 82% (Figures 5 and 6). A comparable participation, ca. 70%, was noted in the dunes surrounding the erg. The participation of monocrystalline quartz in the basement sediments is clearly lower and equals ca. 50% in the surface bed and deeper only few percent (Figure 7).

in the neighborhood of the erg have somewhat lower i.e. moderate sorting (Table 1b), what may indicate shorter aeolian transport of this material. Sorting of the material of the investigated dunes may be evaluated as slightly poorer, if compared with the sorting typical of the material of the majority of the dune areas in the hot deserts, which is from 0.28 to 0.39 in the Western Desert in Egypt (El-Baz et al. 1982), from 0.35 to 0.53

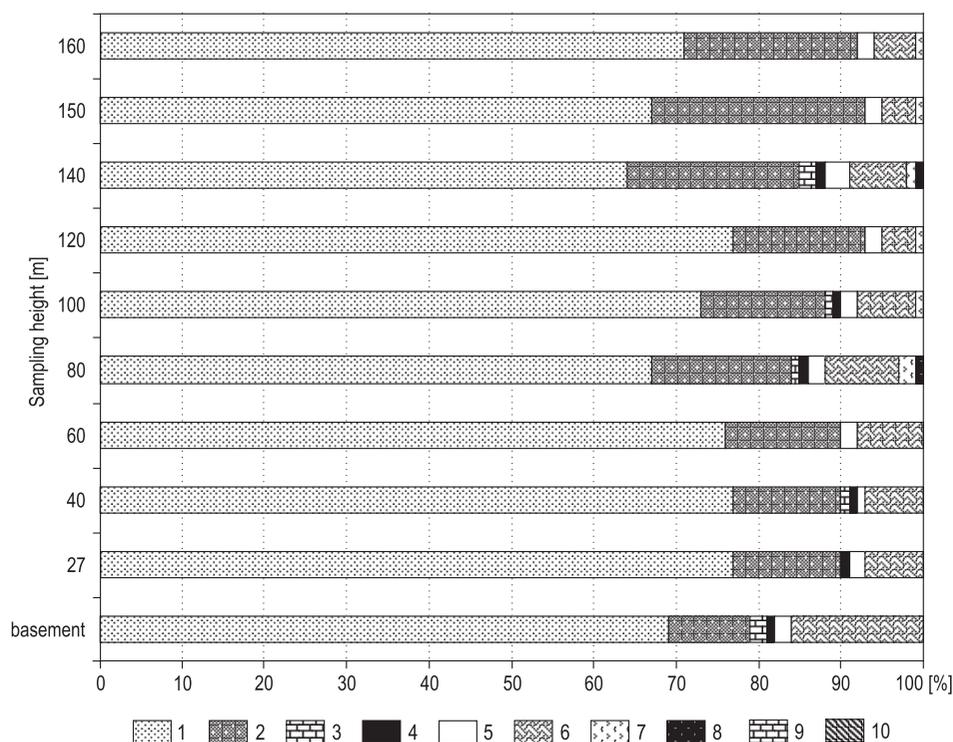


Figure 5. The mineral-lithologic composition of the dune sediments from a star dune in the north-western part of Erg Chebbi; samples 34-43

Explanations: 1 – quartz (monocrystalline), 2 – quartz (polycrystalline), 3 – gypsum, 4 – feldspars, 5 – heavy minerals, 6 – ferruginous-clayey clasts, 7 – marls, 8 – chemogenic limestones, 9 – organic limestones, 10 – others.

The grains of the monocrystalline quartz have quite uniform size and optic and crystallographic features. The grains of the coarser fraction are better rounded than those of the fine fraction. Some grains contain gas-liquid inclusions and occasional inclusions of iron compounds.

Determination of the source of the monocrystalline quartz is extremely difficult because of its physical properties and common occurrence. Quartz belongs to the components of very high resistance to physical and chemical destructive factors of weathering and transport. It may be transported for very long distances, thus it is a very good index of the so-called mineralogical maturity of the sediments. Very high content of quartz in sediment jointly with characteristic set of heavy minerals and other textural features may evidence multiple redeposition of the detritic material. Clastic material of such features could pass even several sedimentary-diastrorphic cycles. This appears e.g. from the fact, that all components of low resistance had been removed from the sediment in these processes which became enriched in the most resistant components, especially in most common quartz.

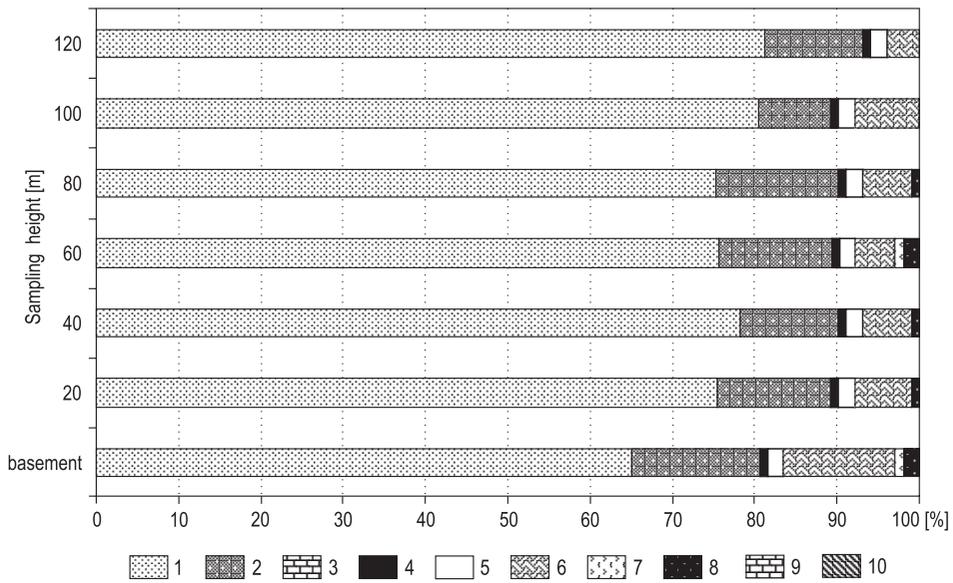


Figure 6. The mineral-lithologic composition of the dune sediments from a star dune in the northern part of Erg Chebbi; samples 24-30

Explanations: 1 – quartz (monocrystalline), 2 – quartz (polycrystalline), 3 – gypsum, 4 – fieldspars, 5 – heavy minerals, 6 – ferruginous-clayey clasts, 7 – marls, 8 – chemogenic limestones, 9 – organic limestones, 10 – others.

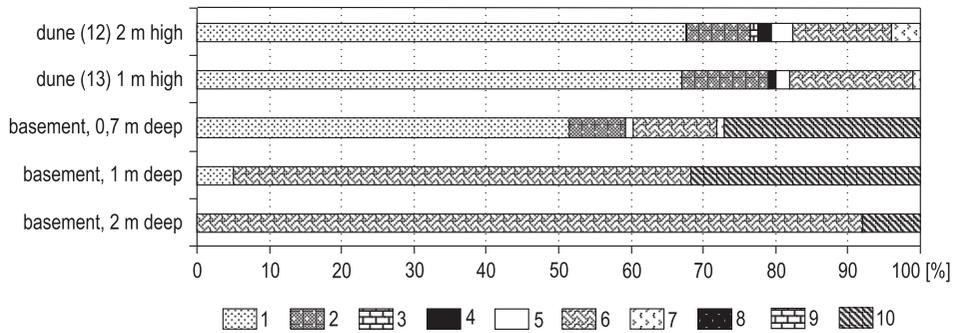


Figure 7. The mineral-lithologic composition of the dune sediments from the Erg Chebbi surroundings: sample 12 – single transversal dunes 2 m high, southern area; sample 13 – single barchanoidal dunes, south-eastern area; samples 62 a, b, c – excavation north of the Hassi Labied settlement, western area

Explanations: 1 – quartz (monocrystalline), 2 – quartz (polycrystalline), 3 – gypsum, 4 – fieldspars, 5 – heavy minerals, 6 – ferruginous-clayey clasts, 7 – marls, 8 – chemogenic limestones, 9 – organic limestones, 10 – others.

Polycrystalline quartz is characterized by mosaic texture of individual grains. Its participation in the sediments of the star dunes is distinctly lower than the content of the monocrystalline quartz and equals from 10% to 27% (Figures 5 and 6). Content of this component in the dunes surrounding the erg is ca. 10%, and in the basement sediments it occurs only in the surface bed (Figure 7).

Origin of the polycrystalline quartz may be various. Grains of mosaic texture may origin e.g. during metamorphic transformation of sandstone into quartzite. However, mosaic quarts frequently form by hydrothermal crystallization as so-called vein quartz. Unfortunately, the distinguishing these two kinds of quartz in the form of clasts in sandy sediments is extremely difficult, because in microscope image they are very similar. Presence of the polycrystalline quartz in the sediment has the meaning similar to that of the monocrystalline quartz, if the genetic and environmental features are considered. The both kinds of quartz have similar resistance to physical and chemical weathering, and to transport. Only few types of polycrystalline quartz are slightly less resistant than monocrystalline quartz, but the difference is small.

The total content of monocrystalline and polycrystalline quartz in the sediments of the star dunes is from 80% to even 95%, being similar to that in other Saharan ergs (Pietrow 1976, Coque 1962) and distinctly higher than in the dunes of the Coude du Dra region (Barczuk, Dłużewski 2003).

Ferruginous-clayey clasts occur in the studied dune sediments as brown aggregates of the random texture and rarer of the parallel or even shaly texture. Its content in the sediments of the star dunes is low and equals from 7% at the height of ca. 20 m to 4% in the apical parts of the dunes (Figures 5, 6). Content of this component is distinctly higher in the sediments at the base of the dunes, reaching ca. 13-17% (Figures 5 and 6) as well as in the dunes surrounding the erg, where the content is the same i.e. 13-17% (Figure 7). Ferruginous-clayey clasts in the basement sediments occur more frequently than in the dune sediments. Their content in the surface bed is ca. 30%, and deeper reaches even more than 90% (Figure 7).

These components have low resistance to destruction, thus they must come from local alimentation areas. Probably most of them are sediments formed in water of limited flow or stagnant, recently occurring as fragments of iron-stained clayey shale. Their occurrence in the basement sediments is connected probably with sedimentation in water reservoir, which occurred in this area till the end of 1980s. Water flowing to this lake both by Oued Ziz and superficially from the surrounding area during rare rains submitted fine detritic material, colored in red by dispersed iron compounds, common in strongly oxidizing desert environment. Ferruginous-clayey clasts formed this way are good indices both the environment in the places of their formation and (due to low resistance to abrasion) and short transport of the sediment.

Other components like gypsum, feldspars, marls, various kinds of limestone occur in the studied dune sediments in trace amounts. Their contents only occasionally exceed 3%, and in most samples they were not found. Relatively high contents of heavy minerals (up to 2%) were found in dune sediments, what may confirm high dynamics of the process.

7. Discussion

The obtained results indicate very high degree of aeolization of the sediments building the dunes of Erg Chebbi that means the accumulation in dynamic aeolian environment during a long period.

This is evidenced in peculiar by:

- very uniform dune material both within individual forms and within the whole dune field and small variation of the granulation indices,
- large grain diameter,
- good sorting,
- negative values of sorting, indicating absence of the supply of local fine material,
- low content of the mineral components poorly resistant to abrasion in the studied sediments.

Moreover, the studies evidenced very large difference in mineral and lithologic composition of the sediments building the dunes of Erg Chebbi and the sediments of the basement occurring in the surroundings of the erg. Thus it seems that the fine-grained sediments of the basement occurring in the close neighborhood of the erg are not source areas for the star dunes.

Development of Erg Chebbi is connected with long-lasting supply of allochthonic material. On the basis of the obtained results and considering the climatic conditions (mainly direction of wind and its force) one may say that the areas of vast hamadas Guir in the east and Kem-Kem in the southwest are the main sources of the material building the star dunes in Erg Chebbi. These are the areas of the gradual desertification, which presently caused almost complete degradation of the vegetation cover. Continental hot climate favors physical weathering and causes decay of rocks to fine fragments sensible to deflation, which is not prevented by vegetation, vanishing there.

These areas mostly not populated due to extremely unfavourable natural conditions and political situation in the Moroccan-Algerian borderland were not affected by human activity. Desertification of these alimentation areas may be connected with the global climate changes and only in this context one may indicate the indirect influence of human activities on the deflation process.

Analysis of the physical-geographic features of the area which hosts the material, building presently the dunes of Erg Chebbi pointed to several factors of high importance to the dune formation. It seems that the area morphology was the most important feature: Erg Chebbi developed in the lowest part of the depression. This fact was undoubtedly connected with two factors favouring the accumulation of the aeolian material – very shallow (or even at the ground surface) water table causing easy wetting of the surface beds and thus development of another factor of extreme importance for sandy material accumulation i.e. vegetation.

One may conclude that the rapid change of the natural environment during last thirty years in the part of the depression occupied by Erg Chebbi, which was caused by construction of the dam on the Ziz River, did not and still does not influence in recognizable degree the development of this dune field.

The studies of other, small dune fields occurring in the depression in the neighbourhood of Erg Chebbi indicated that their formation was connected with the local material sources which were mainly the presently dry fluvial sediments occurring in the beds of the recently episodic oueds (Photo 6). This is shown by mineralogical a lithological accordance of the sediments and by distinctly linear arrangement of the dune fields coincident with the shape of the riverbed. Analysis of the natural environment of the region have shown that decrease of flow in the numerous in this area but short oueds is connected mainly with lower precipitation and with degradation of the vegetation cover which diminished retention of water in the considered area, and only in small part with decreasing supply of water from outside. About the connection of the intensive development of the dune fields with the decrease of flow in the Ziz River bed resulting from the dam construction one may say exclusively in the context of the dune fields on the western side of Erg Chebbi: the bed sediments of Oued Ziz are the material source for these fields. Supposedly the absence of flow in Oued Ziz resulted in part in decrease of the ground water table in the lowermost part of the depression; this may suggest that the dam influenced the development of the dune fields in this part of the depression. Nevertheless it is excluded that the dam construction might have influenced the development of the dune fields in the areas where ground waters were not supplied from Oued Ziz, though such idea has been suggested in certain publications. The mentioned fields occur mainly in the eastern part of the depression. Moreover it seems that independently from the localization of the dune fields surrounding Erg Chebbi their development may be currently very dynamic. It results from the fact that beside the direct or indirect influences of the human activities, the alluvial bed sediments are now dry and thus very sensitive to deflation.

Distinct linear spectral border along the marginal zone of Erg Chebbi and the surrounding dunes suggests absence of mixing of the material in the zone of contact.

8. Conclusions

On the basis of the performed investigations it was found that the development of Erg Chebbi is connected in a significant degree with global climate changes. The obtained results do not indicate that the local human activity, which influenced during the last 30 years the changes of the natural environment of the studied area, should be also a factor responsible for the erg development. The results of the studies available till present and pertinent to the development of the dune fields in the vicinity of ErgChebbi indicate that the influence of the local anthropopression on their expansion is only partial and concerns mainly the dune fields in the western part of the erg.

The advanced analysis of the problem is recently the subject of the detailed studies carried in the current scientific project realized by the present authors.

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