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Geomorphology of El-Hebal Dune Field, SE Eastern Desert, Egypt

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ABSTRACT

There are four small dune fields (350-500 km²) in the SE Eastern Desert of Egypt, of which El-Hebal Dune Field is one of them. This dune field occupies a semi-closed basin at the foothills of the Red Sea Mountains. This paper will primarily analyze the geomorphological aspects of El-Hebal Dune Field to reveal its unique characteristics which distinguish it from other dune fields in this region, and in other parts of Egypt. The analysis of the geomorphological characteristics of this dune field relies on the interpretation of Landsat and Google Earth images supported by field measurements and sampling dune sands. The analysis of the available data revealed that this dune field is composed of 14 compound bundles trending NNE-SSW. All of them are composed of dunes of various forms, mainly linear, barchans, and lee dunes. Each bundle is composed of five to eight thin linear dunes which dismantle into barchans at their lower sections. Lee dunes represent a prominent aeolian form developed in this dune field due to the prevalence of low sandstone ridges lying perpendicular to wind direction. The growth and unification of lee dune led by time to the development of the linear dunes. Barchans developed at the downwind sections of the linear dunes. They are relatively smaller than others in other sand seas and in most dune fields in Egypt, with short horns and slip faces or without. Sand is derived from two main sources: the fluvial sediments deposited by wadis on the bahada and along the beaches of the Red Sea, and a secondary external source, from which sand is brought by the coastal current running along the Red Sea western coast in the southern direction. According to available evidence, a Holocene age is suggested for the development of this dune field.

KEYWORDS

El-Hebal Dunes; Eastern Desert; Egypt; Linear dunes; Barchans; Lee dunes

ARTICLE HISTORY

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Introduction

Egypt covers the northeast corner of Africa and occupies an area of about one million square kilometers. It is divided into four regions: the Nile Valley, the Western Desert, the Eastern Desert, and the Sinai Peninsula (Figure 1).

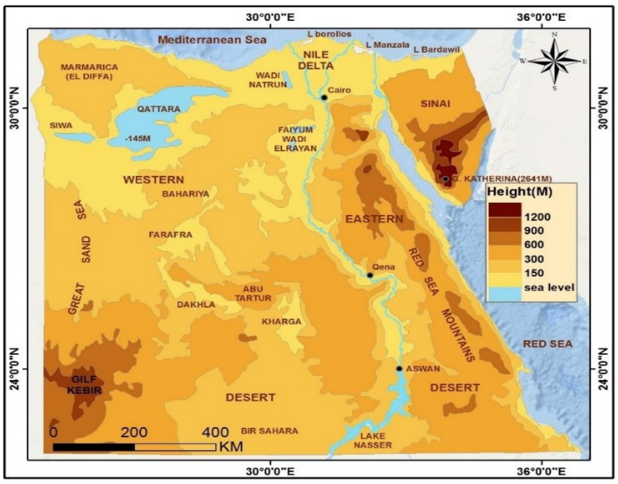

Figure 1. Relief Map of Egypt.

Sand accumulations cover about one-fifth (± 20 %) of total land mass. These sand accumulations were classified as sand seas where sand cover exceeds 50 % of its total area (< 5000 km²), and dune fields which cover areas less than that of sand seas, and where dunes cover less than 50 % [1]. Accordingly, there are six sand seas and ten dune fields in Egypt (Figure 2). This figure shows that most of these sand bodies were developed in the Western Desert, with only one sand sea in N Sinai, while the Eastern Desert accommodates five small dune fields of which four are concentrated in the SE of this Eastern Desert. El-Hebal Dune Field is one of these four dune fields (Figure 2).

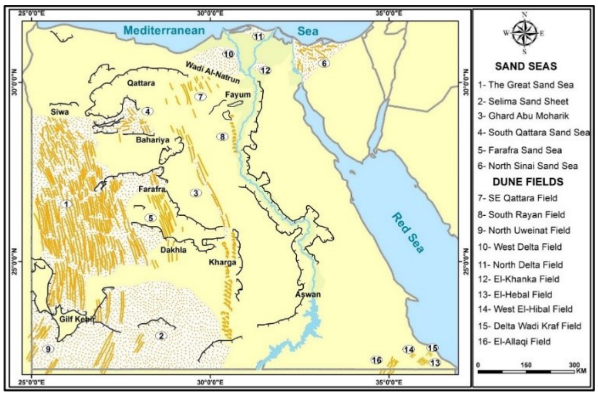

Figure 2. Sand Seas and Dune Fields in Egypt.

Till recently, only two dune fields were known in this remote region of the SE of the Eastern Desert [2]. These two fields are El-Hebal and West El-Hebal fields (Figure 2 & Figure 3). However due to the availability of high-resolution images

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of Google Earth, another two small fields of short linear dunes, barchans, fixed barchanoids, and nebkhas were discovered. The first one occupies the northern part of the Delta of Wadi Kraf (Figure 2 & Figure 3), and the second field lies to the south of Wadi El-Allaqi. The dune field of El-Hebal (I-Hubal as written on topographic maps, scale 1:500,000 according to the pronunciation of Locals) was discovered by Ball while conducting the topographic survey of this corner of the Eastern Desert in the early years of the 20th Century. It is first mentioned in the literature by Ball in treating blown sand in the southeastern desert, but without giving any information on dune characteristics [3]. This dune field acquired its name El-Hebal (The Ropes) from Locals because the width of the linear dunes of this field is relatively thin. It lies at a few kilometers to the SE of the Delta of Wadi Kraf.

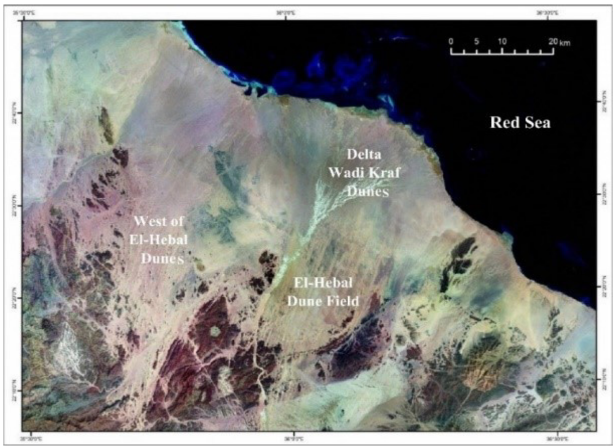

Figure 3. Space image shows three dune fields of SE of the Eastern Desert of Egypt. (Source: Google Earth 2021)

Previous Studies

Previous studies are very few and started relatively recently. None of these studies aimed to study this dune field only. This is due to two factors: the first is its location in the Halayeb region in the SE corner of the Eastern Desert of Egypt, which makes it inaccessible due to the long distance that should be cut from Cairo. The second factor is that nearly all Egyptian Geomorphologists never heard about it, because it was cited in the book of Ball on the SE region of the Eastern Desert [3]. The first study after that of Ball was a section in a PhD Thesis on the geomorphology of the region of Halayeb [3,4]. Although this study introduced some data on some of the geomorphological aspects of the El-Hebal dune field, it is still unpublished as a separate study. The new data provided by this PhD study are used and cited in the present study. El-Hebal Dune Field is introduced as one of the dune fields in Egypt in three studies on sand seas and dune fields of Egypt [1,2,5]. In these three studies, the main aspects of El-Hebal Dunes were discussed, depending on data collected from fieldwork and extracted from topographic maps and Landsat- TM and Google Earth images. However, due to the lack of some necessary data such as those of wind regime, and some data on Lee dunes morphology, it was not possible to present this study for publication at an earlier date.

Previous studies showed that this dune field acquired unique geomorphologic aspects that differ from other dune fields and sand seas in Egypt and are not known to aeolian researchers. Therefore, this paper will treat and analyze these specific aspects to reveal the characteristics of the local environment that led to the birth and development of El-Hebal Field with its unique aspects. It depends on the data collected from space images of Landsat-TM and Google Earth, topographic maps scale 1:50,000 and field measurements and the collection of some sand samples. Also, a comparison will be made between the geomorphic aspects of El-Hebal Dunes and those of other sand seas and dune fields in Egypt and some other deserts.

Location of El-Hebal Dune Field

All previous studies of El-Hebal Dune Field followed Ball's definition of this dune field [1-5]. Ball considered this dune field to be composed only of the 14 compound bundles of linear dunes (Figure 4) [3]. Seen on space images (Google Earth and Landsat) and topographic maps, scale 1:50,000 (Sheet NF 37 11c), this field lies in a semi-closed basin at the foothills of the Red Sea mountains. This basin is open from the north and surrounded by high grounds from other directions. The floor of this basin rises from 50-100 m asl in the upwind section to 100-150 m asl in the central section, and then to 250-300 m asl in the southern downwind section. Re-examination of the images of Google Earth (2021) of El-Hebal surroundings made it possible to discover a new significant geomorphological characteristic of this dune field. It was found that some dunes extend -in the southern direction through a gap in the high ground that bounds the field from the south and continues till the Egyptian-Sudanese boundaries and enter the Sudanese Territories. This fact indicates that the dune field of El-Hebal is not confined to the part adopted by Ball and some previous studies. By adding the area of this new southern extension, the total area of El-Hebal Dune Field becomes about 500 km². The main dune field starts at ~ 20 km from the coastline of the Red Sea (Latitudes 22° 28' / 22° 26' N) and extends inland for ~ 25 km (Latitude 22° 15') (Figure 4). When the new extension is added, the southern limit reaches Latitude 21° 55'.

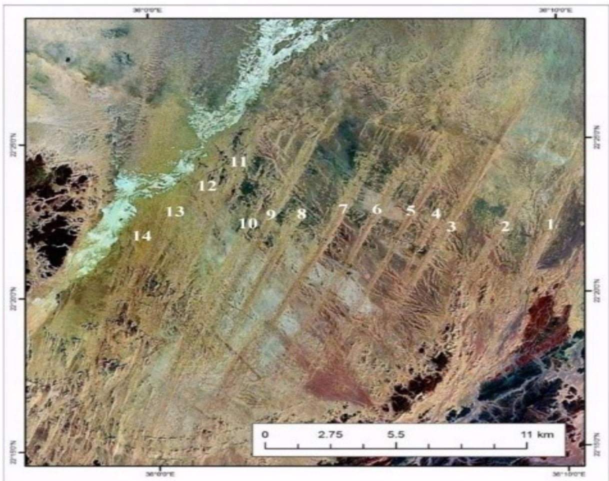

Figure 4. Landsat-TM image show El-Hebal Dune Field to the east of Wadi Kraf. (See Table 3 for the dimensions of dune bundles)

Topographic Setting

The dune lines of this field started to develop on the Bahada plain and intruded into the foothills of the Red Sea Mountains in a semi-closed basin. The surface of the ground rises gradually

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from about 50 m asl at the upwind section of dunes to about 250-300 m asl at the downwind section of the dune field. Also, this basin is characterized by the presence of low-lying rocky ridges trending NNW-SSE perpendicular to the dune trend (Figure 5). When crossing these ridges, sand is trapped at their leeward side forming lee dunes. Drainage lines start braiding in the basin of the dune field at the foothills of the Red Sea Mountains, where they are crossed by dune lines, indicating that the dunes started to develop after the stoppage of water flow and the onset of the arid conditions. but some recent drainage lines are checked by dune ridges. Only a few of these drainage lines cross the Bahada Plain and reach the coastline, forming deltas such as that of Wadi Kraf.

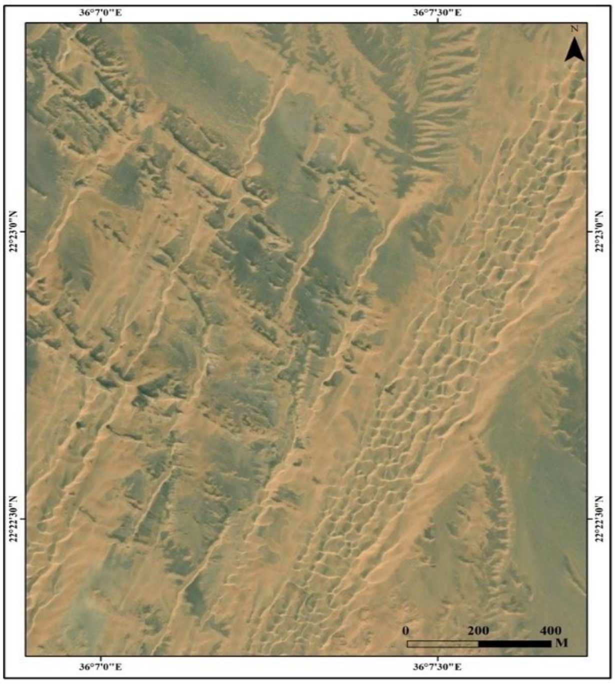

Figure 5. A section of El-Hebal Dune Field Showing a part of a dune bundle, lee dunes, and rocky ridges trending perpendicular to dune orientation (Source: Google Earth 2021).

Wind Environment

Unfortunately, no wind data are available from the Egyptian Meteorological Authority for the two local Meteorological stations of Shalatin in the north and Halayeb in the south. These two stations lie at the upwind section of El-Hebal Dune Field along the Red Sea coast. Therefore, it was necessary to find another source for climatic data. Luckily, wind data are available on the Website of NASA. To guarantee that the climatic data obtained from this Web Site represents the wind environment in the El-Hebal region, a geographic location (N 22° 22' 2.9'', E 36° 04' 28.7'') was chosen in the heart of El-Hebal Field to represent the whole dune field. After examining the available data, wind categories with velocities less than 11 knots were excluded. This is because, according to previous studies, they cannot move the average grain size prevalent in dunes, which is 0.25-0.5 mm [6]. Winds with velocities higher than this threshold velocity are called in previous studies "Sand Moving winds" and are summarized in Table 1 as percentage occurrences of the total wind occurrences [6,7].

Table 1. Percentage Occurrence of Sand-Moving winds in the Region of El-Hebal.

Directions (Degrees)	Wind Velocity (Knots)				
	11-16	17-21	22-27	28-33	Total
345-014	6.70	0.90	0.06	0.0	7.66
015-044	10.20	0.60	0.01	0.0	10.81
045-074	2.90	0.10	0.00	0.0	3.00
075-104	0.40	0.00	0.00	0.0	0.40
105-134	0.20	0.00	0.00	0.0	0.20
135-164	0.10	0.00	0.00	0.0	0.10
165-194	0.10	0.00	0.00	0.0	0.10
195-224	0.10	0.00	0.00	0.0	0.10
225-254	0.10	0.10	0.01	0.0	0.21
255-284	0.80	0.20	0.01	0.0	1.10
285-314	3.40	0.90	0.02	0.0	4.50
315-344	3.50	0.20	0.01	0.0	3.80
Total	28.50	3.00	0.12	0.0	31.62

(Source: NASA web site: power.larc.nasa.gov/data-access-viewer/)

It can be seen from this Table that wind regime can be described as "Wide Uni-Modal", and that less than one third of all wind occurrences can move sand grains. The table also show that most (90%) of the sand-moving winds fall within the weakest category (11-16 knots). Although wind blows with various velocities from all directions with different percentages, the highest frequencies come from the eastern and northeastern directions (21.47%). This is in accordance with the general dune orientation in the El-Hebal dune field (Figure 6 & Table 1).

To determine the effect of surface wind on moving sand, sand drift potentials were calculated by the following equation [6]:

$Q \alpha V^2 (V - V_t) t$, where:

Q = annual rate of sand drift, V= wind velocity, V_t = threshold wind velocity for sand, t = time wind blows from any direction as a %

This equation is applied for each wind velocity and for all 12 directions of the summary, and the results are recorded in Table 2. The resulting number is called by Fryberger Drift Potential (DP) and the units as Victor Units (VU) since wind velocities are treated as vectors [6]. Table 2 indicates the following facts:

1. The total vector units of the total sand drift potential (165 VU) indicate a weak-energy wind environment in this region according to the classification of wind environments in arid regions by Fryberger [6]. When compared with DP in Kharga and Dakhla, it was found that of Kharga is much higher (intermediate-energy wind environment 245.37 VU), while that of Dakhla is much lower (very weak-energy wind environment 72.92 VU) [7].

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2. More than 50% of Sand Drift Potential comes from two directional groups (345° - 014° & 015° - 044°).
3. Although the percentage of wind occurrences is higher (10.81%) in the category 015°- 044° than in the category 345° - 014° (7.66%), the DP is reversed in the two categories. This is because - as Table 2 shows – of the occurrence of higher percentages in the two wind categories 17-21 & 22-27 knots which increase sand drift from these two directions.
4. Although wind occurrences are much higher in wind Category 11- 16 knots than that in wind category 17-21 knots, the total sand drift of wind velocity of category 17 – 21 knots is nearly equal to that of wind category 11-16 knots.

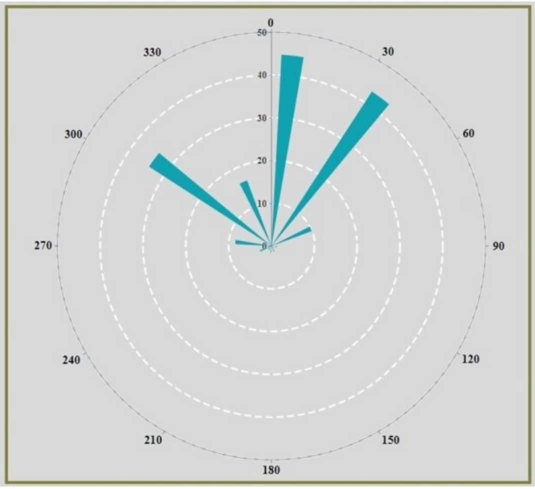

Figure 6. Sand Rose of El-Hebal Dune Field (Drawn from Table 2).

Table 2. Sand Drift Potentials (Vector Units) in El-Hebal Dune Field.

Direction (degree)	Velocity Category (Knots) 11 – 16	17– 21	22 – 27	28-33	Total
345-14	18.35	22.02	4.39	0	44.76
15-44	27.92	14.39	0.72	0	43.03
45-74	7.95	1.82	0.25	0	10.03
75-104	1.02	0.33	0	0	1.35
105-134	0.51	0.26	0.04	0	0.81
135-164	0.36	0.34	0.34	0.39	1.43
165-194	0.35	0.8	0.38	0	1.52
195-224	0.25	0.63	0.21	0	1.09
225-254	0.32	1.27	0.72	0.58	2.88
255-284	2.21	5.37	0.89	0	8.46
285-314	9.23	23.4	1.44	0	34.06
315-344	9.54	6.16	0.63	0	16.34
All directions	78.02	76.76	10.01	0	164.79

Dune Forms

Small-scale space images and topographic maps show that the El-Hebal dune field is composed of 14 longitudinal parallel units composed mainly of linear dunes (Figure 4). Their length, width, and orientation are recorded in Table 3.

Table 3. Some Morphometric Features of El-Hebal Dunes

Sl. No.	Length (km)	Width (km)	Orientation (Degrees)	Sl No.	Length (km)	Width (km)	Orientation (Degrees)
1	4.0	0.50	28	8	17.3	0.65	25
2	14.0	0.40	22	9	14.2	0.50	25
3	4.9	0.30	28	10	18.7	0.60	24
4	11.5	0.60	27	11	11.0	0.40	24
5	4.2	0.45	28	12	13.0	0.35	20
6	10.2	0.55	25	13	3.2	0.30	20
7	11.9	0.45	27	14	5.8	0.80	20
Source: Google Earth 2021				**Average**	10.0	0.49	24

Source: Measurements made on Landsat-TM image (see Figure 4).

This table shows that the length of these units is relatively short, varying between 3.2 km and 18.7 km, with an average of 10 km. The table also shows that they have relatively wide breadth, ranging between 0.3 km and 0.8 km, with an average of 0.49 km. On the contrary, high-resolution space images (Google Earth 2021) show that the dune system is not as simple as shown on small-scale tools. These images of Google Earth show that the dune system is composed of three dune forms: linear, lee dunes, and barchans. These three dune forms are not independent of each other, rather they developed in a system in which the dune form transforms into the other one in a unique physical environment of geology, topography, and wind system as will be shown in the following analysis.

Linear dunes: characteristics and mode of development

Each of the 14 longitudinal units is composed of several sinuous linear ridges, running parallel to each other (Figure 5). Generally, each unit is composed of 5-8 sinuous linear ridges with sharp crests. Although some of them are short, uniting with others, the sand ridges are organized in a neat parallel pattern (Figure 5). In the meantime, the spacing of these sinuous linear dunes (average 100 m) does not change along any of the main compound units in El-Hebal Field. Although other compound longitudinal dunes are composed of several linear ridges in other sand seas and dune fields in Egypt, the occurrence of the parallel pattern of the linear dunes in all main compound units is unique in El-Hebal Dune Field and needs interpretation [1,8]. From the available data, the most probable interpretation for such a unique characteristic is that the upwind sections of the main compound units are composed of several parallel lee dunes, which developed on the lee side of the bedrock ridges. The lee dunes grew over time and extended in the downwind direction which is SSW. This growth of Lee dunes in the downwind direction results in the unification of the upwind Lee dunes with the downwind ones. Since this process occurs instantly along the same line, the result is the unification of all Lee dunes lying along each other, developing linear dunes. The combination of both the bedrock ridges and the development of parallel lee dunes beside each other, and the availability of sand supply explain why all sinuous linear ridges of the compound units in El-Hebal dunes are parallel along any of the compound units (Figure 7).

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Figure 7. A Field photograph showing the straight slip faces atop one of the linear dunes

The sinuosity of the linear dunes is another aspect that characterizes this dune field. Though linear dunes keep their orientation all along their extension, in detail they are characterized by sinuosity (Figure 5). This aspect can be explained by the wind regime. The following treatment will depend on previous studies on wind regimes that develop linear dunes, and on the wind regime and morphological characteristics of El-Hebal sinuous dunes. These dunes developed sharp crests, and a straight slip face on one side and a convex slope on the other side (Figure 7). This cross-section may be reversed not only from one locality to another along the dune, but also at the same locality. It is well established in previous studies that linear dunes develop in bi-directional or wide unimodal regimes [9,10]. In this study, it was found that the wind regime of El-Hebal Dune Field is wide unimodal which is following the results of previous studies. This wind regime develops zones of net erosion and net deposition on both sides of dunes. Therefore, peaks and saddles develop along the dune, which advance downwind in the resultant drift direction [11]. This process leads to the sinuosity of dunes.

Lee dunes

Lee dunes develop at the lee side of different obstacles, such as small and large hills, wadi sides, escarpments, boulders, and vegetation bushes [9,10,12-14]. In El-Hebal dune Field, they are formed on the lee side of two different obstacles. The first is on the leeward side of low-lying ridges that extend at right angles to the dominant wind direction which is from NNE as indicated by the analysis of wind data and dune orientation (Figure 5). The second group of lee dunes developed at the lee side of small hills. This occurs in the downwind sector of El-Hebal Field, where so many small hills were detached at the foothills of the Red Sea Mountains.

The length of lee dunes varies between several tens of meters to several kilometers. Although length depends on the height of the obstacle as indicated by some previous studies, it is not proportional to height in some localities [12]. In many cases, the length of the lee dune is longer than expected according to obstacle height. Most probable, this is due to the wind environment. In localities where wind is strong, the relationship between the two variables is also strong, since wind coming from both sides of the obstacle removes any sand accumulating at the tip of the dune. On the contrary, in a weak-energy wind environment, sand deposition may continue because weak winds cannot remove it. Another probable interpretation is the unification of two lee dunes running consecutively to each other along the same line. Therefore, when the upwind dune grows faster than the downwind one because it traps more sand, it catches the downwind dune and makes a longer lee dune (Figure 5).

Barchans

High-resolution images of Google Earth revealed that the downwind section of all linear dunes of El-Hebal Field is composed of barchans (Figure 8). This is following the results of previous studies in Egypt and in some other deserts [2,8,9,15]. As indicated by these previous studies, the availability of sand in these downwind sections is relatively limited. Due to this shrinkage in sand supply, linear dunes dismantle into small sand hillocks, which develop over time into crescent barchanoids / barchans. In the following section, three aspects of barchans (Form, Dimensions, and Movement) are analyzed.

Form and dimensions of barchans

Barchans developed in the downwind sections of El-Hebal dunes (Figure 8). Although having a slip face / leeward slope and windward slope, they are characterized by some aspects that make them different from other barchans in other dune fields/sand seas in Egypt. As can be observed from (Figure 9), the barchans of El-Hebal Dunes are characterized by three aspects. The first is that most of barchans are semi-circular in form, and the second is that they have very short horns. The third aspect is that they are smaller compared to other barchans in other dune fields/sand seas in Egypt. The first two aspects are probably attributed to the fact that dunes while advancing southwards, move on surfaces that are getting higher. Therefore, the wind that blows along the two sides of the windward slope gets weaker and deposits its load on the dune body instead of carrying it to the horns. Consequently, horns and dune length grow at a slower rate in the downwind direction, leading to the development of short horns and to the change in dune shape to become wider and circular/semi-circular in shape. The third aspect is verified by measuring the length and width of a sample of 32 dunes from El-Hebal barchans.

Figure 8. A space image showing Barchans of the downwind sections of some linear dunes in El-Hebal Dune Field (Source: Google Earth 2021)

It showed that their average length and width are 40 and 57 m consecutively and vary in length between 20 and 120 m and in width between 30 and 70 m. Similar dune fields where small barchans dominate were reported in some other deserts, such as Iraq, Mauritania, and Peru, without Interpretation [7]. When compared with barchans in Dakhla and Kharga in the Western Desert, it was found that the average width for a sample of 50 barchans in either locality is 173 m and 228 m consecutively [8]. Why the barchans of El-Hebal are smaller than those of Kharga

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and Dakhla? The answer to this question lies in the multi-variant of the environment of El-Hebal Dune Field, which simply means that several factors in this region control the size of the barchans.

The limited sand supply which comes from the Red Sea beach is the first variable. As indicated in the study which deals with wind environment, nearly two-thirds of the effective wind that can move dune sands comes from a wide uni-direction (345º-14º & 15º-44º), and most (more than 50 %) of the potential sand drift comes also from the same direction. This indicates that the wind drifted sands from the beaches of the Red Sea inland to form El-Hebal Dunes. However, this source of sand is very limited since it originated from wadi sediments coming from the Red Sea Mountains. It is already known that wadis issuing from the Red Sea Mountains and debouch into the Red Sea are small with limited discharge and sediments.

Secondly, the barchans, which developed at the downwind sections of linear dunes are in the early stages of the cycle of development. Previous studies on the cycle of development of barchans showed that, in their initial stage, barchans look like small hillocks of sand with very gentle sides all around [2,16]. In the youth stage, dunes start developing a crescent shape with short horns and a small slip face, which is the case of El-Hebal Barchans (Figure 9). Therefore, it can be inferred that barchans occupying the downwind section of the linear bundles of El-Hebal are still in the early /youth stage of development. It can also be inferred that the whole field is a young field of dunes still in its youth stage.

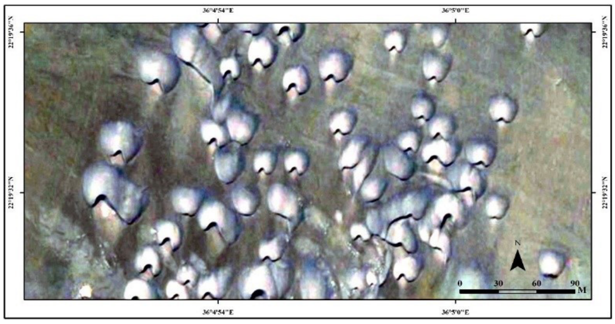

Figure 9. A sample of barchans of the downwind section of El-Hebal Dunes. (Source: Google Earth 2021)

The cross-sections of some barchans of El-Hebal Field (Figure 10A) show that they bear similar characteristics as those of the initial and early youth stages of the cycle of development of barchans. When compared with those of Kharga barchans (Figure 10B), although some cross sections bear the aspects of early stages of development, other sections represent mature barchans with a long concave-convex windward slope, a steep slip face (32°-33°) and a height of several meters.

The third factor is the weak wind environment (164 VU) of El-Hebal Field. According to the classification of Fryberger sand drift potential less than 200 VU for any wind environment is classified as weak [6]. As a result of this factor, sand drift is weak, and the supply of sand from the Red Sea beaches will be always limited, and eventually, dunes will grow and move downwind at a slower rate compared to dunes in areas of intermediate or high wind environment. Therefore, the analysis of the aspects of movement of barchans in El-Hebal Field and its relationship with dune size is pertinent.

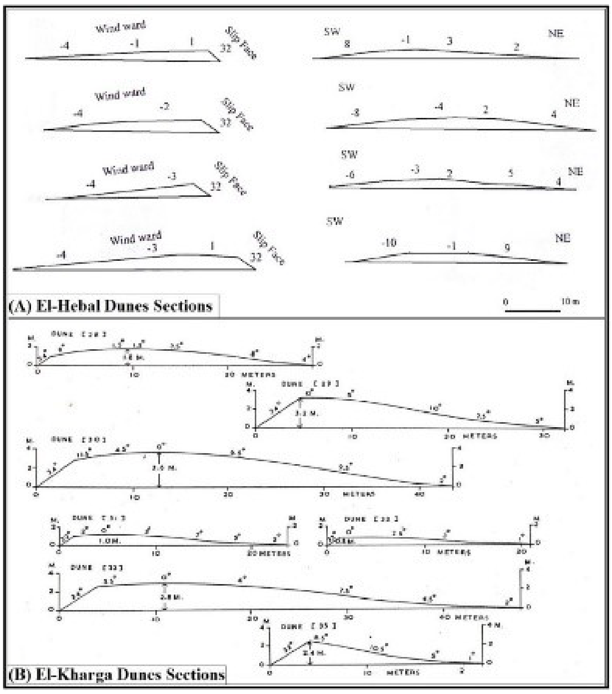

Figure 10. Cross-sections of some barchans in El-Hebal Dune Field and Ghard AbuMoharik in Kharga (Source: A: Abdel-Hamid 2001; B: Embabi 1976-1977).

Movement of Barchans

The advancement of barchans in the downwind direction is a phenomenon that makes this form of dunes unique and different from others. The movement of barchans drew the attention of many arid geomorphologists, not only because they are one of the fascinating and significant dune forms, but also because they are cited as a threat to human activities. This is why studies of barchans and their movement in Egypt started very early at the end of the nineteenth century and the beginning of the twentieth century, in areas where they acted as a threat to human activity [17,18]. Since then, studies of the movement of barchans have been focused on Kharga (the southern section of Ghard Abu Mohark), Dakhla (the southern section of Farafra Sand Sea), and in Sinai (North Sinai Sand Sea).

In El-Hebal Dune Field no attempt was made till recently when high-resolution images of Google Earth became available on the internet free of charge. An attempt was made to investigate this aspect of El-Hebal barchans [19]. In this study, a section of one of the linear bundles was examined by two sets of Google Earth images, 7 years apart (2009-2016), to recognize the same barchans on both sets of images (Figure 11). The examination of the two sets of images makes it possible to recognize 32 barchans on both. When overlaid on each other, it became clear that all ba1rchans were displaced/moved from their original location, and that this movement was towards the downwind direction (Figure 11 and 12). The total distance of displacement was measured in meters, then divided by the number of years, i.e., the time lapsing between the dates of the two Google images, to get the annual displacement.

The analysis of the values of annual displacement reveals that barchans of El-Hebal moved downwind at different rates, ranging between 7.5 and 25 m / year. Variations in dune

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displacement in previous studies in various deserts of the world were interpreted by dune size, in other words, large dunes move at a lower rate compared to smaller ones because of the difference in the quantity of sands accommodated. Thus far, no mathematical model to calculate the quantity of sand in dunes to correlate it with the distance of displacement.

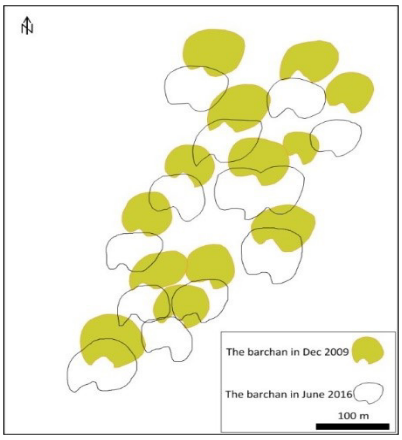

Figure 11. A sample of Barchans which were recognized on two series of Google Earth images showing dunes displacement.

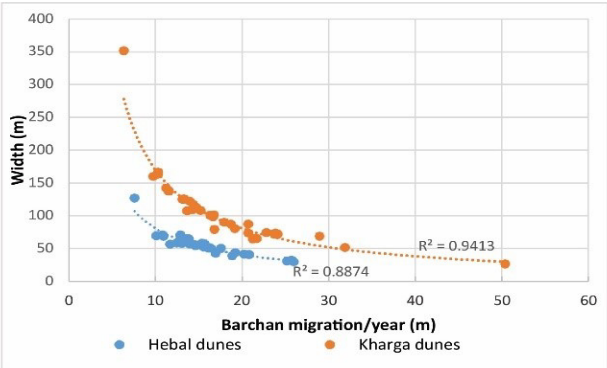

Figure 12. A scatter diagram showing the relationship between dune displacement and dune size (width) in El-Hebal Field and Kharga Depression.

Therefore, dune height or width of dune was taken as a parameter to represent dune size in previous studies. Due to difficulties in measuring the height of barchans in El-Hebal Field, maximum width was measured for the same dunes of the sample of which their displacement was measured. To correlate both variables (distance of movement and width of dune), a scatter diagram is drawn, and a correlation coefficient is calculated (Figure 12). The result is that dune size is the main factor controlling the rate of dune movement in a certain wind environment, in agreement with findings from previous studies. When compared with a sample of Kharga Barchans (Figure 12), both follow the same rule, although the barchans of El-Hebal move at a slower rate than those of Kharga. This difference can be explained by the difference in the energy of the wind environment, where that of El-Hebal is weak and that of Kharga is intermediate.

In addition to the weak energy of the wind environment of the region of El-Hebal dunes, there are two other factors controlling the low rate of movement of barchans characterizing the environment of El-Hebal dunes. First, while barchans move in the downwind direction, the surface of the foot slopes of the Red Sea Mountains is getting higher, resulting in deceleration of the wind speed and consequently the rate of dune movement. Second, Google images show that the windward slope of barchans is darker than the leeward side, indicating the concentration of heavy minerals on the surface of the windward slope. Most probably, this is due to a fact which is that weak-energy wind can carry sand composed of light minerals leaving the heavy mineral sand as a lag on the surfaces of the windward side. This lag represents a shield for the lower layers of sand in the dune body, resulting in the deceleration of dune advancement.

Sand Properties

The analysis of sand properties depends on two sets of samples. The first one is small (4 samples) and was collected from one of the linear dunes (3 samples), and one sample from the nearby beach of the Red Sea coast during the 1996 trip [2]. The second group of samples is much larger (104), because the collected samples include other sand forms: sand sheets, sand ripples, nebkas, and inter-dune areas, and were collected during the 1991 trip [4]. Despite its smaller size, the first set of samples has two advantages over the larger one. The first is that their sands were subjected to mineralogical analysis, and the second advantage is that one of the samples is collected from the nearby beach of the Red Sea for comparison with dune sands. Although both sets of samples were collected about 30 years ago, they still represent the El-Hebal Dune field. This is because no evidence was found to show that wind conditions changed during this last short period from the early nineties of the 20th Century till the present day, resulting in a change in grain size or mineral composition.

Grain size

Table 4 summarizes the grain size characteristics of the four sand samples collected from the El-Hebal Dunes and the Wadi Kraf Beach. It can be seen from this table that the grain size is fine to very fine, and the mean size is fine where it ranges between 2.4 and 2.7 ø. This size is smaller than the sand grains of other sand seas in Egypt, where most of them fall within the medium to fine fractions [2,20]. This is due to the weak energy of wind in El-Hebal Field, which can deflate only fine very fine sand fraction.

Table 4. Grain size of sands of El-Hebal Dunes and Beach sands in SE Eastern Desert.

Sample Location	Mean Size (ø)	Sorting (ø)	Grain Size (ø) 2	3	4	5	Total(%)
1) 22° 26' 03" N 34° 07' 00" E	2.7	0.32	1.20	84.40	14.3	0.10	100
2) 22° 25' 20" N 36° 08' 45" E	2.4	0.36	1.86	82.65	17.2	0.17	100
3) 22° 16' 35" N 34° 07' 00" E	2.7	0.33	1.40	82.51	14.7	1.39	100
4) Beach 22° 23' 18" N 36° 25' 32" E	2.6	0.43	9.30	74.70	15.0	0.15	100

The table also shows that the sorting of all samples is very good, except for the good beach sample. As indicated in

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previous studies [2,9,10], sorting becomes worse as the sand gets either finer or coarser. This is the case of beach sand, whose sorting is worse than other samples because it contains a much higher percentage of medium-sized sand fraction than others. The interpretation of this difference lies in a weak wind energy environment. In this environment, wind deflates fine –very fine sand fractions and carries them inland to form El-Hebal dunes, while coarser fractions are left behind on the beach. It was also found that there is a change in grain size along the same dune line, where there is a slight tendency to be finer southwards [4]. Coarser sand (0.19 ø) is found in dune corridors. Most probably, this sand originated from local fluvial deposits on which the dunes were developed [4]. It was also found that the dune surface is composed of a one-grain layer of coarser sand than the lower layers [4]. This is due to the weak-energy wind which carries fine sand from the surface layer and coarse sand is left behind.

Mineral composition

Although El-Hebal sands are composed of so many minerals such as magnetite, hematite, pyroxene, epidote, zircon, rutile, and garnet, it was found for study to group them into two groups: opaque and non-opaque (Table 5). It is clear from this table that most heavy mineral samples are composed of non-opaque minerals; however, they account for only one-third of the beach sample. On the contrary, the opaque minerals form most of the beach samples. This is because opaque minerals are heavier due to their high bulk specific gravity. The table also shows that the percentage of the ZTR minerals in the dune samples is significantly less than that in the beach sample. These minerals are known as the ultra-stable minerals. This characteristic indicates that the sands passed a few cycles of deposition, and consequently, the dunes are relatively recent [2,20]. Upon comparing these findings and those of some other sand seas or dune fields in Egypt mentioned in previous studies, it was found that the ZTR of the sands of El-Khanka dune Field in the SE of the Nile Delta is low (7.8 %) as that of El-Hebal Dunes which indicates similarity in age (Figure 13). On the contrary, the ZTR percentage of the Great Sand Sea, Ghard Abu Moharik, and Farafra Sand Sea is more than 50 % in each of them, indicating that their dunes passed several cycles and that the dunes are relatively old [2]. Of the ZTR group, the detailed composition of the beach sample shows that it is composed of Zircon only. Since it is an ultra-stable mineral, the weak energy wind of El-Hebal Dunes deflates only very fine particles while larger ones are left on the beach. It is known that zircon mineral is found in most igneous rocks with good hardness. This indicates that beach sands originated from the nearby Red Sea Mountains which are formed mainly of igneous and metamorphic rocks.

Table 5. Some aspects of mineral composition of El-Hebal dunes and beach sands.

Sample Number	Non-Opaque	Opaque	ZTR (1)
(1)	84.70	15.30	3.60
(2)	67.54	32.46	4.80
(3)	79.51	20.49	2.06
Beach Sample(4)	36.71	63.29	22.98

(1) ZTR: Zircon, Tourmaline, and Rutile as a percentage of non-opaque totals.

Figure 13. Prevailing marine currents in the Red Sea.

Sources of Sand

Sources of aeolian sands are classified into local/internal and external sources [15]. Taking into consideration all the previous characteristics of dune and beach sands, the geomorphological aspects of El-Hebal Field, and the wind environment it can be concluded that the sands of the dunes were derived from external sources. The wind rose indicates that sand is carried out from a source lying in the NNE and northern directions. Here, there is no other locality where sand is available except Red Sea beach. Upwind heads of El-Hebal Dune Field lie only 20 km from the Red Sea coast with wind blowing mainly from N & NNE indicating that the sands of El-Hebal Dunes come from beach sands. These beach sands were brought from the Red Sea Mountains and were laid down as deltaic sediments by fluvial action. The mineral composition of dune sand indicated that it has been originated from a source rich in heavy minerals, which is the beach sands. Beach sands originated from two sources: the first is the fluvial sediments eroded from the nearby Red Sea Mountains [5]. The second source is the sands which are derived from the Egyptian beaches along the Red Sea Coast that were carried out by the N-S coastal current (Figure 13). A probable local source for the sand of the inter-dune corridors is the disintegrated sandstone which forms the NW – SE ridges crossed by dune lines. Also, this local source – most probably contributed a minor percentage to the sands of dune lines of El-Hebal Field.

Age of Dunes

When the dunes of El-Hebal start to develop? All evidence points to a relatively recent age. First, topographic maps (scale 1: 50000) and space images show that the dune lines cross the lower reaches of the drainage lines which cut across the Bahada plain of the Red Sea Mountains. This indicates that the dunes of El-Hebal were formed after wadis stopped flowing when present arid conditions were well established since about 5000 – 3500 years BC [1,8]. Second, the shape of barchan dunes and their morphological characteristics indicate that they are still in the

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early stages of development. When compared with those envisaged in the cycle of barchan development, it was found that the characteristics of El-Hebal Dunes are quite like those of the early and youth stages in the cycle of development [5, 17,19]. Along with this characteristic, in the examination of barchans on high-resolution images of Google, no complex dunes were found, and very rare compound barchans were recorded. Also, the cross sections of El-Hebal barchans are quite like those of dunes which are still in their early stages of development in the Kharga Depression. Third, the low percentage of the ultra-stable heavy minerals indicates that the sand passed only a few cycles and consequently the dunes are relatively recent.

These characteristics all point to the recent development of dunes, and El-Hebal Dune Field is young. Most probably, this field of dunes started to develop with the onset of the Holocene arid conditions since 5000 – 3500 BC [21,22]. During this recent arid phase of the Holocene, similar dunes in age developed atop older (Pleistocene) and wider lines of linear dunes in the sand seas and some field dunes in Egypt, such as the Great Sand See [2,23,24].

Conclusions

El-Hebal Dune Field is unique among all Egyptian dune fields because it developed in a local environment with elements that worked together to produce this unique landscape. Pre-topography of the Red Sea Mountains, the foothills of the mountains, the Bahada, and the nearby Red Rea coast are the most significant aspects of this region. Other characteristic topographic features that influenced the development of El-Hebal Dunes are the low sandstone rocky ridges trending NNW-SSE, the drainage lines of previous water flow which carried sediments from the mountains and spread them on the surface of the Bahada and Red Sea beaches, and the residual hills detached from the feet of the mountains. Another aspect of the local environment is the weak-energy winds and the wide unimodal wind regime in which wind blows from N and NNE directions. Such directions are perpendicular to the orientation of the low rocky ridges. With wide unimodal weak-energy winds blowing from North and NNE, sands were reworked and returned inland as aeolian materials to form dunes of various forms, organized in a set of bundles parallel to each other, and controlled by the topography of the foothills of the Mountains. This process started to work with the onset of the present arid period of the Holocene, since 5–3.5 ka years BC. This age makes this field one of the youngest among others in Egypt and is equal to the age of the silk dunes atop the Pleistocene linear dunes in most of the Egyptian sand seas such as the Great Sand Sea.

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No potential conflict of interest was reported by the authors.

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