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First identification of yardangs in the Dakhla region (Southern Morocco)

Première identification de yardangs dans la région de Dakhla (Sud du Maroc)

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Abstract. Yardangs are among the most spectacular features of aeolian landscapes, occurring in numerous areas on Earth as well as on other solid planets. Yardangs are teardrop-shaped hills whose orientation reflects prevailing winds. The combined action of deflation and abrasion in sparsely vegetated desert areas favours the formation and evolution of these aeolian features, resulting in their characteristic regular morphologies.

This paper presents the first identification of the yardangs carved in Quaternary formations of the Moroccan Sahara. This preliminary study focuses on describing their geomorphology (length, width, distribution, etc.) and lithology. In addition, the statistical analysis of morphometric parameters provides valuable information for further research in this western region of the Sahara Desert.

Keywords: Yardangs, Geomorphology, Quaternary, Moroccan Sahara.

Résumé. Les Yardangs sont parmi les formes d'érosion éolienne les plus spectaculaires, présentes dans de nombreuses localités sur la terre ainsi que sur d'autres planètes solides. Les yardangs sont des collines en forme de larme dont l'orientation exprime celle des vents dominants. L'action combinée de la déflation et de l'abrasion dans une zone désertique à végétation éparse peut permettre la formation et l'évolution de ces formes d'érosion éolienne.

Cet article présente une première identification des yardangs sculptés dans les formations quaternaires du Sahara marocain. En outre, ce travail préliminaire apporte des éléments sur leurs caractéristiques topographiques (longueur, largeur, distribution, etc.) et lithologiques. L'analyse statistique des paramètres morphométriques fournit des informations utiles pour des investigations futures sur cette partie occidentale du Grand Sahara.

Mots-clés : Yardangs, Géomorphologie, Quaternaire, Sahara marocain.

INTRODUCTION

Yardangs are aeolian erosional features in the form of wind-abraded ridges of cohesive material (Cooke *et al.* 1993, Parsons and Abrahams 1994, Goudie 2004). These aeolian landforms are composed of alternating ridges and corridors and have been reported from numerous arid regions on Earth and other planets, including Mars, Titan and Venus (Ward & Greeley 1984, Greeley *et al.* 1995, Ding *et al.* 2020, Paillou & Radebaugh 2013). Yardangs develop at different scales, from micro-yardangs (centimetre scale) to meso-yardangs (metre scale) or even mega-yardangs, also referred to gullies, which can be tens of metres high and several kilometres long (Goudie 2007, Laity 2009). They occur in several lithologies, ranging from soft materials to hard rocks (Whitney 1985), with meso-yardangs possibly form in heterogeneous rocks, while mega-yardangs are mostly developed in resistant material (e.g., Goudie 2007, Laity 2011, Ding *et al.* 2020).

Yardang development is accelerated during arid and windy periods and interrupted during wet and warm periods. This phenomenon is thought to be related to climatic fluctuations and changes in atmospheric circulation induced by variations in solar radiation on an orbital scale (Pelletier *et al.* 2018, Ding *et al*. 2020). As yardangs record the prevailing wind direction during their formation and typically development in less than 10 thousand years, they can also serve as palaeoclimatic indicators (Lancaster *et al.* 2002, Laity & Bridges 2009, Laity 2011).

Numerous studies have reported the presence of yardangs in the African Sahara, in Mali (Riser 1985), Tchad (Mainguet 1968, 1970) and other countries (Ding *et al.* 2020). In the southern Moroccan region of Dahkla, aeolian landforms described as networks of small depressions shaped by the wind and isolated residual mounds formed of Pleistocene sediments, have been reported (Ortlieb 1975, p. 24). These forms, suggestive of yardangs, are referred to as "Aguerguer" by the local inhabitants, and this term used on topographic map to name this kind of landform on the southern Morocco. More specifically, the term "Aguerguer" is used by some authors to name a region of southernmost coastal Morocco, from Cap Barbas to Cap Blanc, characterised by such a landscape of low-elevation sandstone hills (Hébrard 1973, Ortlieb 1975). However, to date, no study has explored these landforms in detail.

Here we report the first meso-yardangs in southern Morocco and provide a statistical analysis of their main morphometric characteristics as well as the general lithological aspects of these aeolian abrasion forms developed in Quaternary formations.

REGIONAL SETTING

The study area is located between 21°75’ to 22°18’ North and 16°25’ to 16°59’ West, about 30 km from the town of Bir Gandouz (Fig. 1). The coastal strip is a tropical arid zone tempered by an oceanic influence, with annual rainfall not exceeding 50 mm (HCP 2018). The region is dominated by northerly winds with an annual frequency of 73%. These winds prevail from March to November, with dominant direction ranging from N-NNE as recorded at Dakhla, some 230 km north of the study area, to N-NNO as recorded at Nouadhibou, 100 km southward (Ozer 1996). These trade winds coming from the sea are at the origin of a notable humidity (60% to 90%) reinforced during the night; this moisture is linked to the high daily thermal amplitude. Together, these elements produce temperate climatic conditions in the Atlantic Band (“Monographie de la region de Eddakhla Oued Eddahab 2018”). Humidity can drop to 20% from December to March due to a warm, dry continental wind (E and SE) locally called the Chergui (Williams *et al.* 2016). Vegetation in the coastal strip is very scarce due to the strength of the winds, while Saharan acacia (*A. albida, A. ehrensbergiana, A. radiana*) and other Saharan tree species occur more inland.

The general landscape is a plain with rare prominent reliefs. The coast from Dakhla to Mauritania is composed of alternating beaches and cliffs interrupted by lagoons (sebkhas). Further inland, sandy sheets organized in single and compound barchan dunes and alternating rocky plains cover the land surface. Geologically, this area is a part of the western Tarfaya-Lâayoune-Ad-Dakhla sedimentary basin of the Saharan domain (Michard *et al.* 2008, Davison & Dailly 2010). This NE-SW oriented basin comprises sedimentary rocks accumulated from the Cretaceous period to the present (Elboudali *et al.* 2018).

The coastal plain is particularly noticeable in the study area, where it develops over a width of a little less than 50 km, forming a flat surface increasing progressively inland eastward (Fig. 2). According to Ortlieb (1975) and Hébrard (1973), this plain corresponds to the top of the El Aïouj limestone formation, which includes intertidal to infralittoral limestones formed in the late Middle Pleistocene (Aioujian stage in the regional stratigraphy). A 10 to 15 km wide strip adjoining the shoreline surmounts this plain to form the so-called Aguerguer

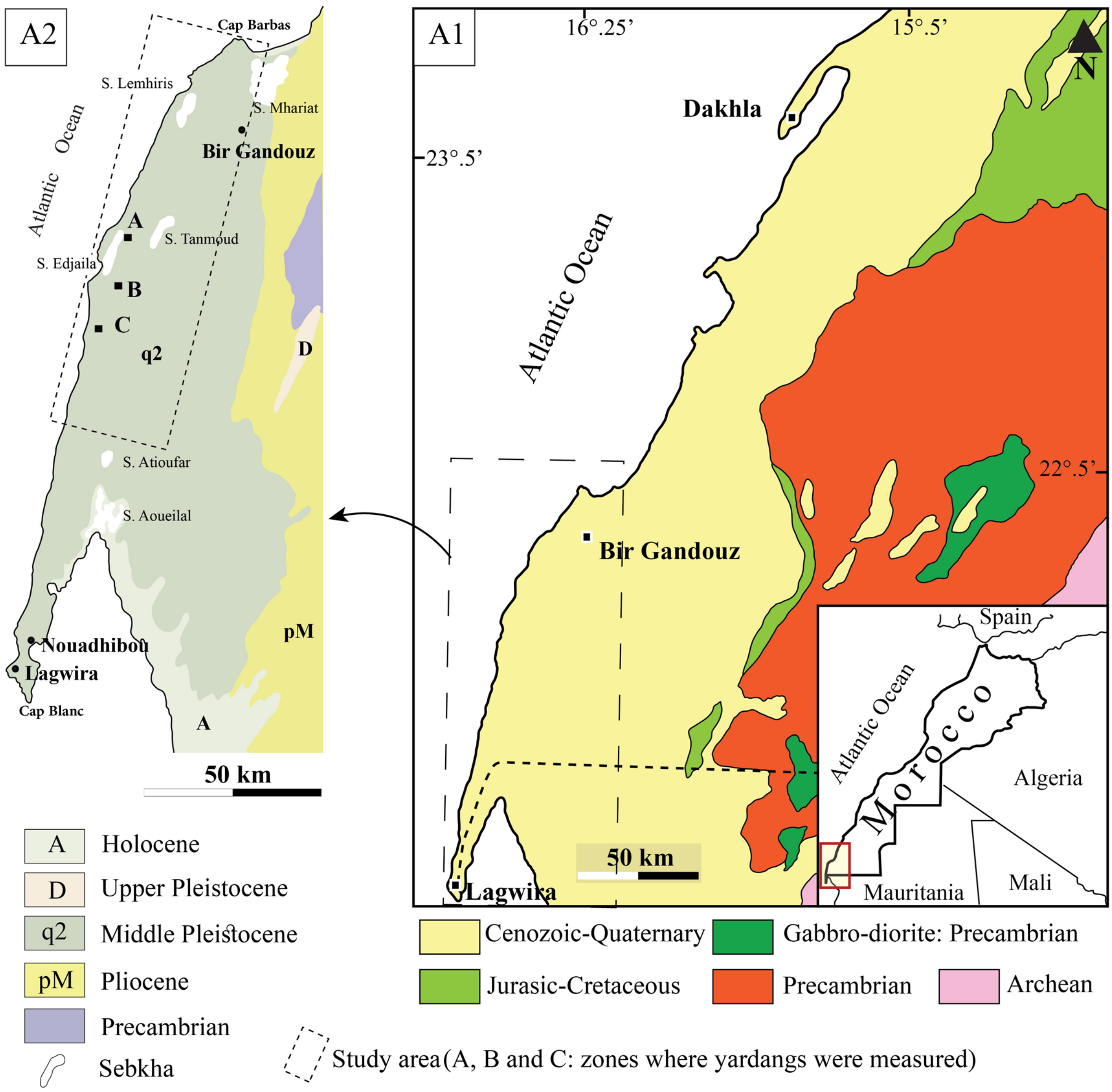

Figure 1. Simplified regional geological map A1 (from Saadi, 1982, modified) and geological map A2 of the study area (from Saadi *et al.* 1985, modified).

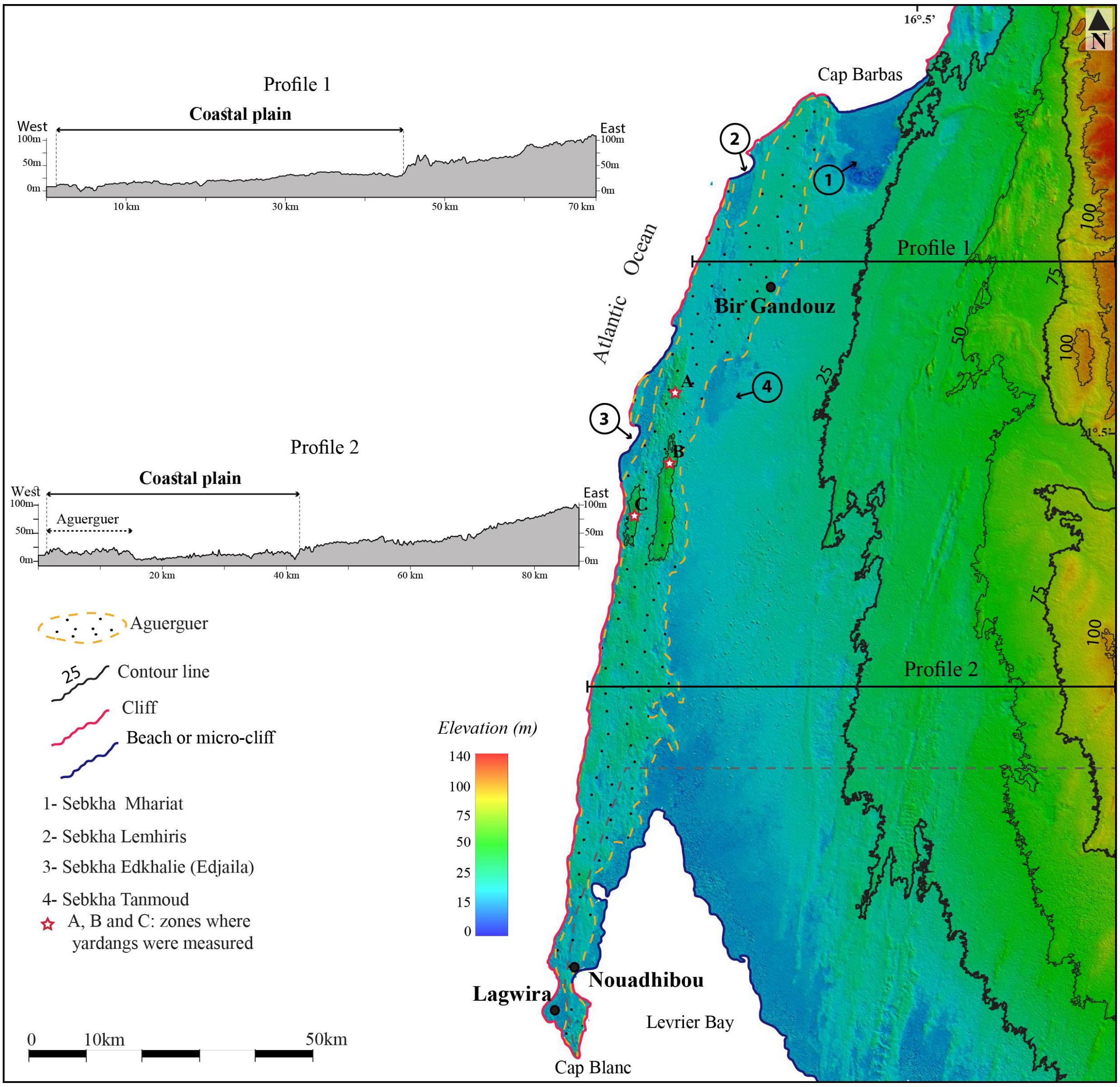

Figure 2. Digital elevation model and topographic profiles of the study area.

region, which is characterised by the presence of sandstone mounds shaped in aeolianites. From the south of Bir Gandouz to Lagwira, these aeolianites, which outcrop continuously, are known as the “Aguerguer sandstone”. They correspond to coastal dune deposits interspersed with incipient palaeosols including terrestrial gastropods and fragments of extinct giant Ostrich shells (Tessier *et al.* 1971) and are interpreted as a regression facies of the Aioujian stage (Hébrard 1973, Ortlieb 1975).

METHODS

High-resolution satellite images (Landsat, 15m) were used to observe the land surface and perform geomorphological analysis of the Dakhla Oued Eddahb region using the Google Earth software. Moreover, the sparse vegetation in this desert region facilitates morphological measurements of the observable yardangs (meso-yardang). For each of the three 1.5 km^2 locations (A, B and C in Figs. 1 and 2), the erosion features in relief (mounds) were distinguished from the accumulation features (sand sheet) on satellite photos (Google Earth Pro). In addition to their teardrop morphology, the mounds are identified on photographs by their rocky surface underlined by numerous small escarpments, which distinguish them from the inter-mound corridors mainly covered by a residual pavement with numerous bushes, sheets of quick sand or, sometimes, trains of transverse dunes.

Four parameters were selected to characterise yardangs (length, width, orientation, density) in three distinct 1.5 km^2 areas (A, B and C). The main statistical analyses performed on these landforms are summarised in Table 1. The densities were calculated using the Parzen method, also known as kernel density estimation (e.g., Hall *et al.* 1987, Węglarczyk 2018).

A field mission was carried out in February 2021 to more closely observe the morphology and determine the lithology and sedimentologic structure of the yardangs. This field mission also allowed a detailed observation of the rock surfaces constituting these mounds, with a view to determining the morphogenic processes involved in the formation of the yardang.

RESULTS

Geomorphology

In the Aguerguer area from the south of Bir Gandouz to Lagwira, several metres long and wide features can be classified as meso-yardangs. These wind-sculpted residual hills are characterised by a "teardrop" (also called "whaleback") morphology (Barchyn 2018, Ding *et al.* 2020). These shapes slope from their steep windward side to their gently sloping leeward end (Fig. 3). Measurements taken in the field show that Yardangs have an average height of between 1 m and 7 m, with their maximum width most often occurring towards the front end.

Some yardangs have two or more small, several metre-high prominences at their top, which over time become individualised ridges (Fig. 3). Wind erosion increases the space between the ridges, generating new yardangs separated by a corridor. When establishing morphological parameters, no distinction was made between simple yardang and yardang with prominences, as they reflect evolutionary stages of a same feature and not different types of features. Corridors represent the inter-yardang spaces and commonly appear flat. These later are occupied by migrating dunes of different sizes (Fig. 3, A).

Yardang lengths measured at the three localities range between 17 and 467 m, with a mean value of 55 to 144 m. The yardangs are longer in zone A, with average lengths being roughly double those in the other two zones. On the other hand, the yardang length in these latter two zones is relatively similar (Tab. 1, Fig. 4). There are no significant differences in the yardang width between the three localities, except that the width range is greater for zone A (Tab. 1, Fig. 4).

The aspect ratio (length versus width; e.g., Li *et al.* 2016, Pelletier 2018) demonstrates that length is about three times greater than width in all three areas (Tab. 1, Fig. 4). Most yardang morphologies have a value ranging between 2:1 and 3:1. This pattern is even more evident as the length of the yardangs increases, in accordance with previous studies concerning meso-yardangs that exhibit a similar 3:1 ratio value (Laity 2009).

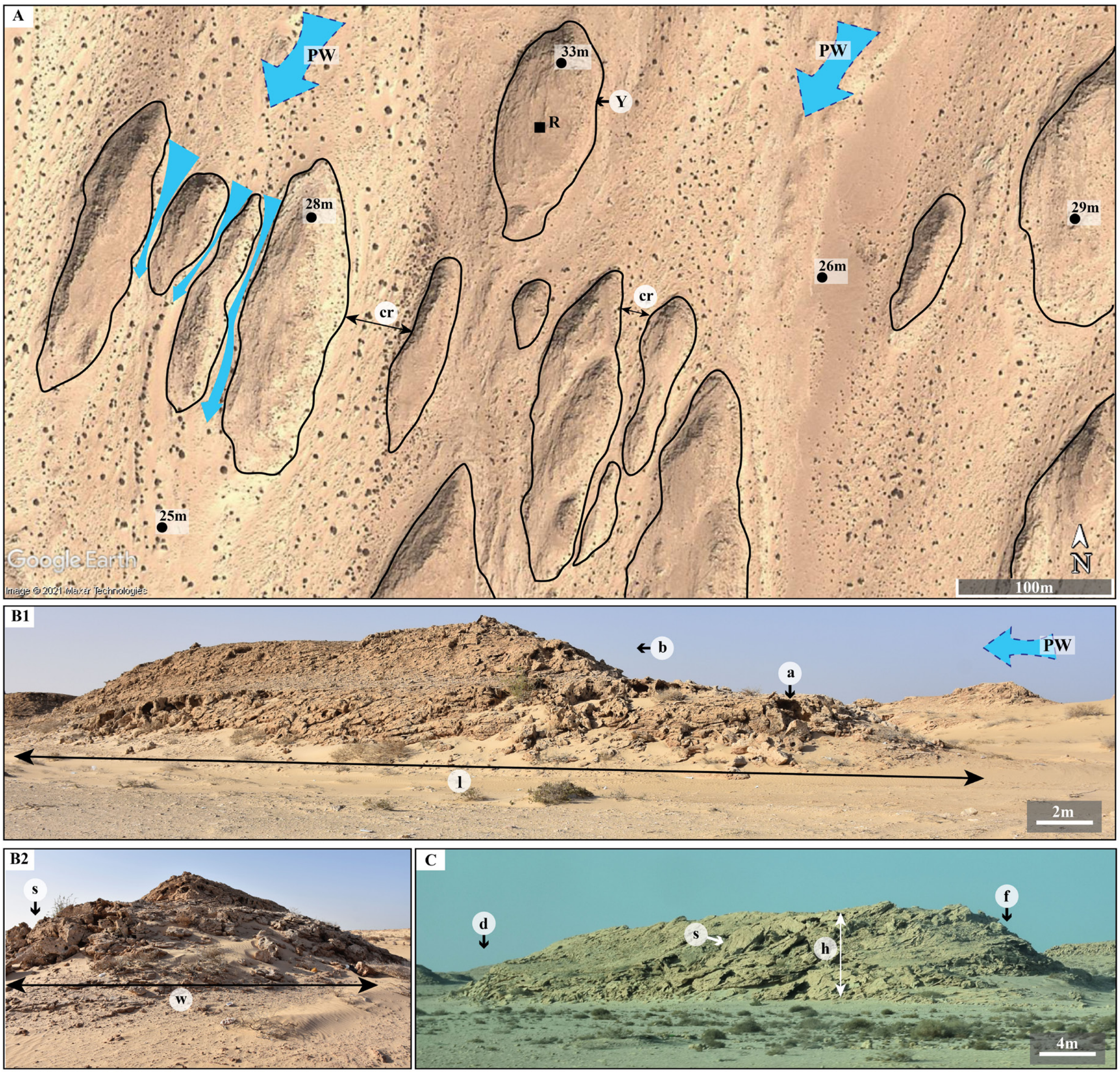

Figure 3. Yardang morphologies in the Dakhla Oued Eddahab.

(A) Satellite image, **PW**: predominate wind direction, **cr**: corridor, **Y**: yardang, **R**: location point (21°50.822'N, 16° 53.686'W), **(B1)** longitudinal view of yardang with prominence, **a**: alcove, **b**: boss, **l**: length, **(B2)** frontal view of the same yardang, **w**: width details, **s**: slump blocks, **(C)** simple yardang, **d**: distal part, **h**: height, **f**: front, **s**: slump blocks.

Taking their length as the main axis, the yardangs of all three zones are primarily oriented between 15° NE and 30° NE (Fig. 5). This pattern differs slightly from the direction of present prevailing wind regimes, which are typically characterised by a unimodal N-NNE component (Fig. 5).

Wind is an important factor in the formation and evolution of the yardang morphology. The aggressiveness of the winds is added by the Cape effect. The orographic cape area, such as Cap Barbas (Fig. 2), allows for a significant increase in wind strength downstream (e.g., Weisrock 1982; Moujane *et al*. 2011). The discrepancy between the dominant orientation of the yardgans and the direction of the present prevailing winds can be explained by the change in the atmospheric circulation regime. In the field, the difference in orientation between the current winds and the paleowinds (responsible for the formation of the yardangs) could be documented by observing the orientation of the yardangs and the nearby dune fields, with the barkhan dunes indicating the direction of the current prevailing winds (Fig. 6). Such a juxtaposition of aeolian features is present a few tens of kilometres further south of the study areas, where it can be observed that the yardangs have the same NNE orientation as in the study areas, while the barkhan dunes show a northerly wind direction, in accordance with the current prevailing wind direction (Fig. 6).

Mapping the distribution of yardangs in the three zones according to the midpoint of the length axis demonstrates these features groups in clusters aligned with the prevailing wind direction (Fig. 7). While each yardang is oriented NNE, the clusters of yardangs are aligned N-S in the three zones. Note also the increase in the concentration of yardangs, and thus a correlative decrease in inter-yardangs spacing in the two southern zones B and C compared to the more northerly zone A. These two characteristics suggest a current action of northerly winds by deflation, leading to the formation of corridors in which sand masses in transit can migrate, while the yardangs are preserved with their original orientation between the corridors.

In addition, to the formation of corridors between yardangs as mentioned before, it is important to note the presence of

Table 1. Statistical summary of measured morphological parameters. **SD:** Standard deviation, **CV:** Coefficient of variance.

		Zone A	Zone B	Zone C
Length (m)	Range	24-467	14-166	17-360
	Mean	114	55	68
	Mode	86	48	57
	SD	86	26	43
	CV	0.76	0.47	0.64
Width (m)	Range	5-148	8-80	6-93
	Mean	37	21	24
	Mode	27	18	20
	SD	28	10	14
	CV	0.77	0.49	0.58
Aspect ratio	Range	0.5:1-7.9:1	0.5:1-11.1:1	1.4:1-6.7:1
	Mean	3.3:1	2.8:1	2.9:1
	Mode	3.1	2.5	2.7
	SD	1.1	1.4	0.8
	CV	0.33	0.49	0.29

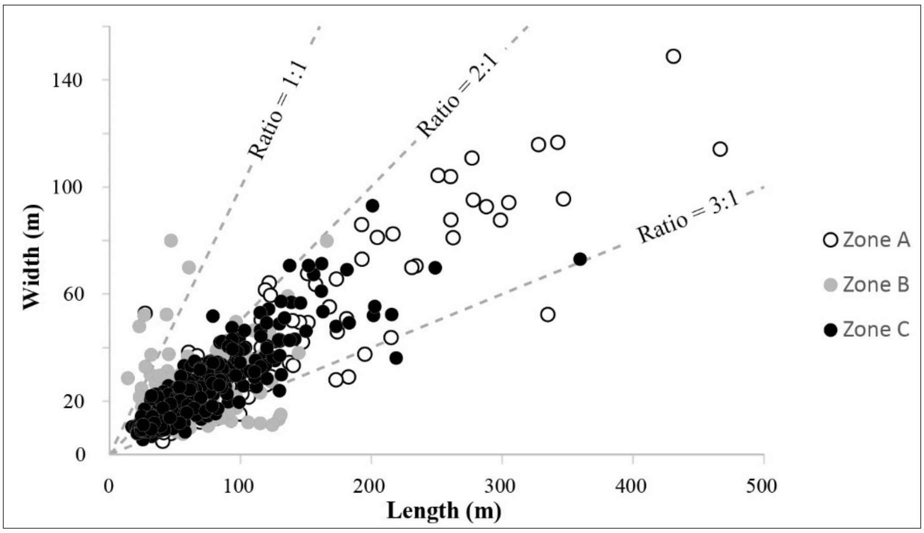

Figure 4. Aspect ratio (lengths: widths) of yardangs in the Dakhla Oued Eddahab region.

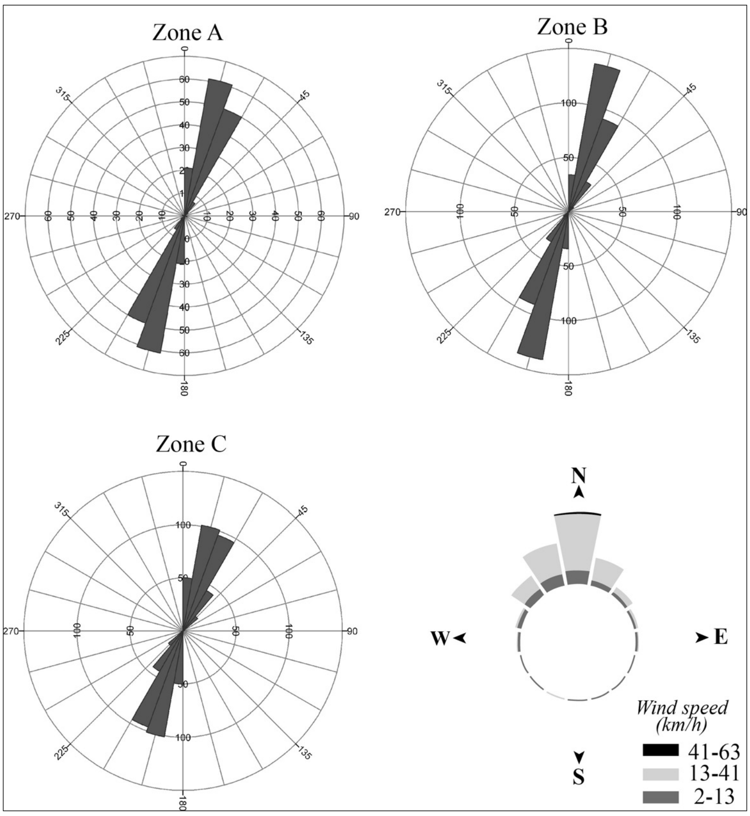

Figure 5. Frequency distribution of yardang directions in the three zones and frequency distribution of present wind speed in the coastal region of Nouadhibou (https://fr.windfinder.com).

huge flat surfaces (Fig. 6) and the formation of depressions and sebkhas such as sebkhat Anmoud and sebkhat Aoueilal (Fig.1), which demonstrate and illustrate the importance of the wind deflation in this area.

Lithology

The lithogy of yardangs in the southern region of Dakhla Oued Eddahab is mainly in the form of aeolianites and marine calcarenites (Fig. 8). The latter rocks are well consolidated due to a high proportion of shell debris, the dissolution of which leads to the formation of a cement that binds biogenic and silicoclastic elements.

The aeolianite (sandstone) that forms the upper portion or the major part of the yardangs is characterised by successive layers of cross-bedded and horizontally-bedded sands as well as the presence of rhizoliths and continental shells, especially at the top of the yardangs. These features make it possible to recognize in these aeolianites the sandstones of Aguerguer (Hébrard 1973, Ortlieb 1975). In addition, all sides of the yardangs display alveoli indicative of "honeycomb weathering", which vary in size from a few centimetres to a metre. The increase in the size of these alveoli generates alcoves that are frequently degraded through breakage, with the resulting blocks slumping down the sides of the yardang (Benito *et al.* 1993, Ritley & Odontuya 2004, Laity 2009). These dissolution features can be observed in many arid zones, where they are referred to as *karst à alveoles* (Salomon 2006, p. 160), which some authors explain by more humid conditions in the past (Rognon 1979, Alimen 1987, Williams *et al.* 2016). However, the development of these forms could also be interpreted as the effect of salt, especially since coastal winds are known to be salt laden. These salt crystals accumulate on the rock surfaces and produce cracks, which subsequently facilitate the degradation of the outcrop (e.g., Weisrock 1982).

However, the abrasion of yardangs by sand remains the main factor of their formation (Fig. 9). This phenomenon can be observed on two scales: at the scale of the outcrop, and at the level of the rock surface. Winds loaded with sand and gravel are blasting tops and sides of the yardangs to widen the corridors between them. At the level of the surface of the rocks, it could be observed the effect of the polishing in form of an external polished and dark colored surface (yellowish, grayish), while the inside of the rock is whitish. While the perforation of the yardang surfaces by alveoli suggests that these mounds are old, these aeolian surfaces indicate that these though ancient yardangs, are still in the process of being shaped by the wind.

The internal structure of the aeolianite layers corresponds to a large-scale cross lamination with slip faces displaying well-developed foreset laminae, dipping at a maximum angle of 0° to 34°. These features are typical of the barkhanoid dunes (Mckee 1966, Pye & Tsor 2008 and Fig. 8). Furthermore, the internal structure of the eolianites indicates that the paleowinds, under which these eolianites were formed, were northerly winds. This direction is broadly comparable with the direction of the winds that shaped the yardangs as well as the current winds (Fig. 4). This means that these three elements

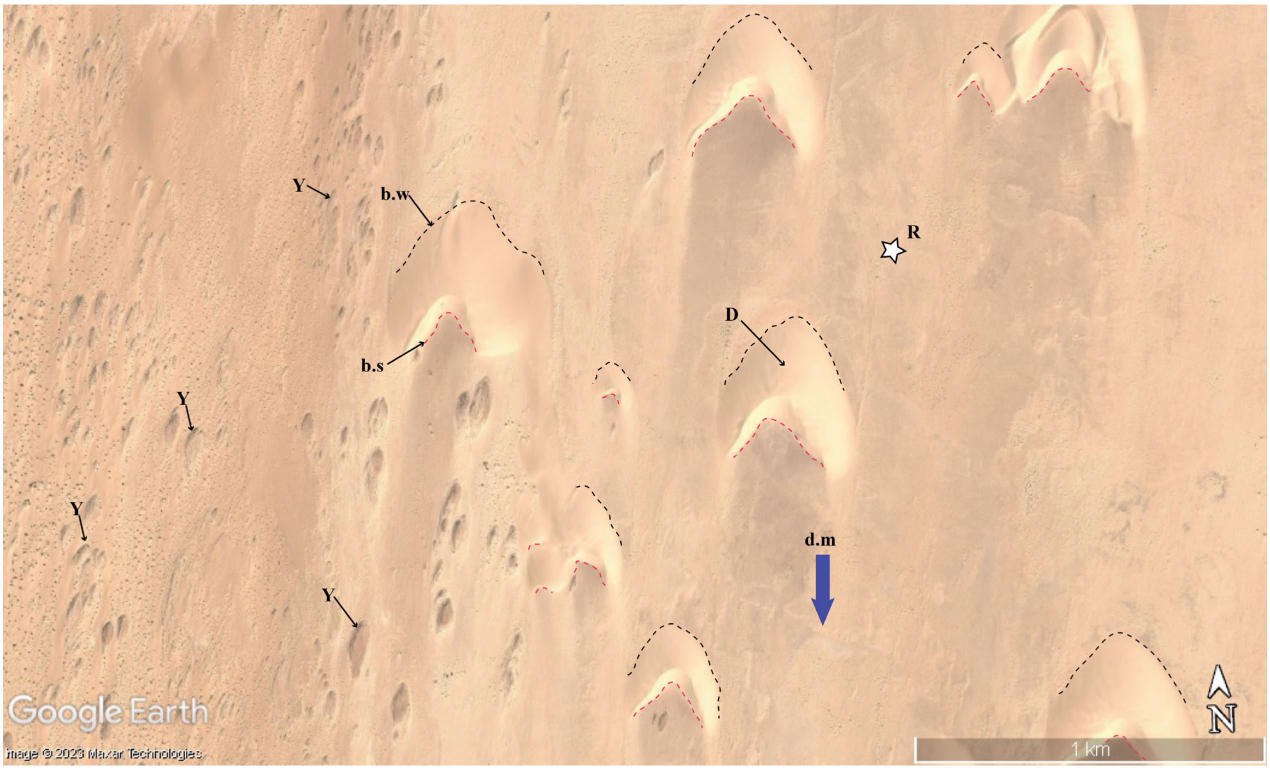

Figure 6. Yardangs and barkhan dunes south of Bir Gandouz (google earth image, 03/2012). **d.m**: dunes mouvement **b.w**: basal limit of windward side, **b.s**: basal limit of slip face, **D**.: Barkhan dune, **R**: reference point (21°43’45.20”N; 16°52’20.47”O) **Y**: yardang.

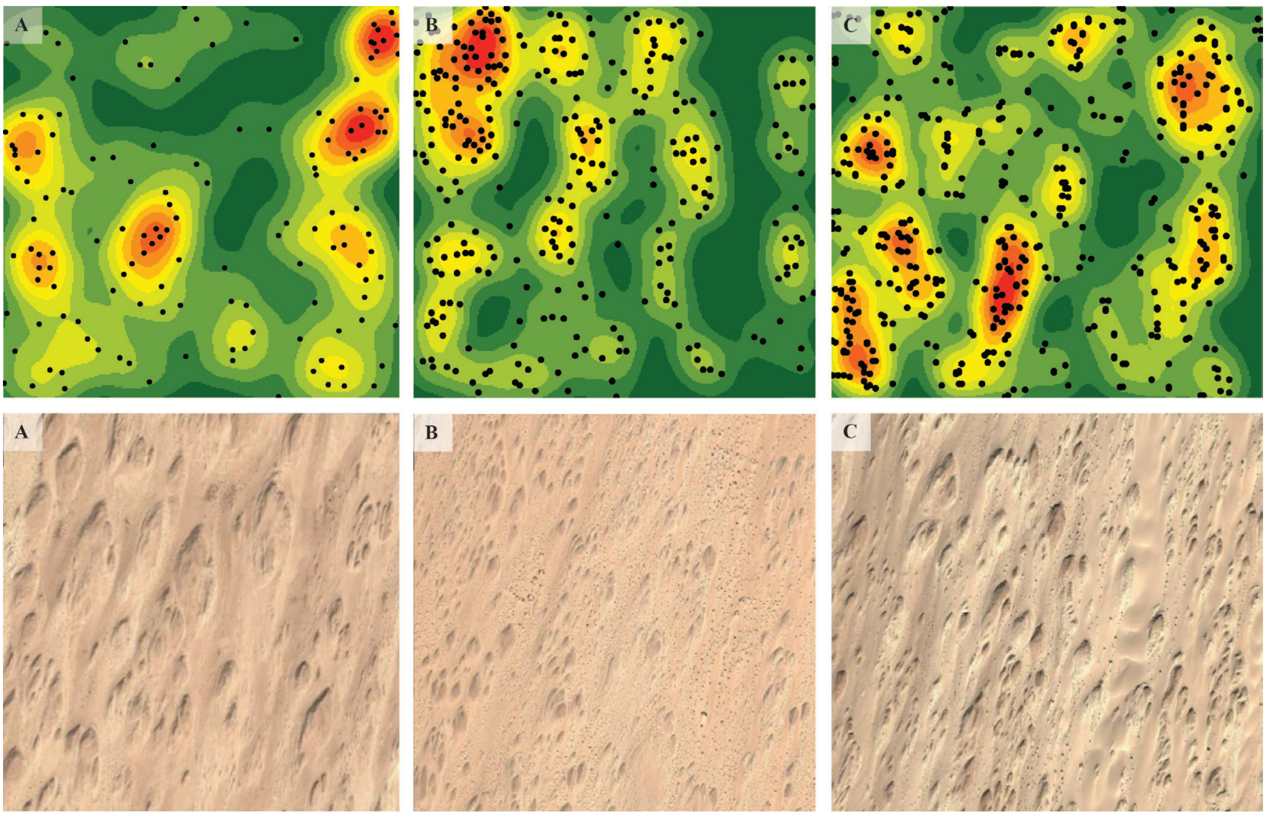

Figure 7. Yardang kernel density maps and Google Earth images of the three zones A, B and C. The black dots on the density maps represent the centroid of each yardang. The maps and images are at the same scale (1.5 km x 1.5 km).

of the landscape were all formed under the control of the trade winds, even thought, there may have been slight differences in the prevailing winds over the ages. This morphometric data therefore highlights the relative stability of the wind regime in this area since at least the late middle Pleistocene (i.e. the estimated age of the Aguerguer sandstone, cf. Hébrard 1973, Ortlieb 1975).

The basal portion of the yardangs is generally composed of marine calcarenites. These harder rocks present multiple lithologies in relation to the high richness of biogenic grains, sometimes corresponding to cemented lumachelle and occasionally beach sandstones rich in complete shells or debris. All these facies are consistent with the El Aiouj limestone, which is known regionally to underlie the Aguerguer sandstone (Ortlieb 1975).

Lithology played an important role in the overall formation and evolution of the yardangs. The carbonate content of the rocks favored the dissolution of biogenic elements and the formation of a "honeycomb weathering" aspect. The topography of the region has tilted east-to-west and the absence of river networks excludes the hypotheses of fluvial erosion. The evolution of yardangs can follow two trajectories: the retreat of the front and subdivision. The front retreats by slumping, the wind scouring the soft layers, with the more consolidated layers subsequently overhanging and breaking off into small slumps. In addition, yardangs in the Dakhla region can thus be considered as mature according to the genetic model of Ding *et al.* (2020).

A MODEL OF YARDANG DEVELOPMENT

The current morphological aspect of the yardangs has undergone several stages of modeling. Based on data from our fieldwork and on previously proposed models for different parts of the world (e.g. Ward & Greeley 1984, Laity 2009, Dong *et al.* 2012, Ding *et al*. 2020), the evolution of these aeolian features in the coastal fringe to the south of Dakhla appears to have gone through at least three stages:

(1) Initiation to embryonic stage: During this phase, the very powerful winds hollowed out corridors in the pre-existing irregularities and fractures in the topography. This led to the formation of escarpments and segmented surfaces (Fig. 10).

(2) Juvenile to adolescent stage: Continued erosion and wind deflation was accompanied by the dissolution of carbonated rocks (chemical alteration). During this stage, the morphology of the region underwent major modifications, including the development of mega-ridges (mega-yardangs) as a result of these surface geodynamics.

(3) Mature to recession stage: This is the current phase in which these morphologies appear as typical yardangs. The enlarged corridors between the yardangs and the formation of two or more small prominences at their top, which over time become individualized ridges, testify to slightly different prevailing wind directions from those that originated the yardangs, showing that different wind phases have contributed to shaping this landscape as well as the old age of the yardangs. The decrease in the size of these morphologies towards the south of the region are consistent with a recession phase. The yardangs will disappear little by little and the surface will give way to mobile dune fields.

The annual rate in which the yardangs are sculpted is influenced by numerous factors that are difficult to untangle (e.g., Wang *et al.* 2011, Pelletier *et al.* 2018). For example, lithology obviously plays an important role, as yardang formation is faster in soft materials than in hard rocks (e.g., Laity & Bridges 2013, Barchyn & Hugenholtz 2015). However, deducing a formation rate for the yardangs in the Dakhla region is currently impossible. However, as these features are carved in Late Middle Pleistocene rocks, it is safe to assume that they were shaped, discontinuously, throughout the Upper Pleistocene up to the Present.

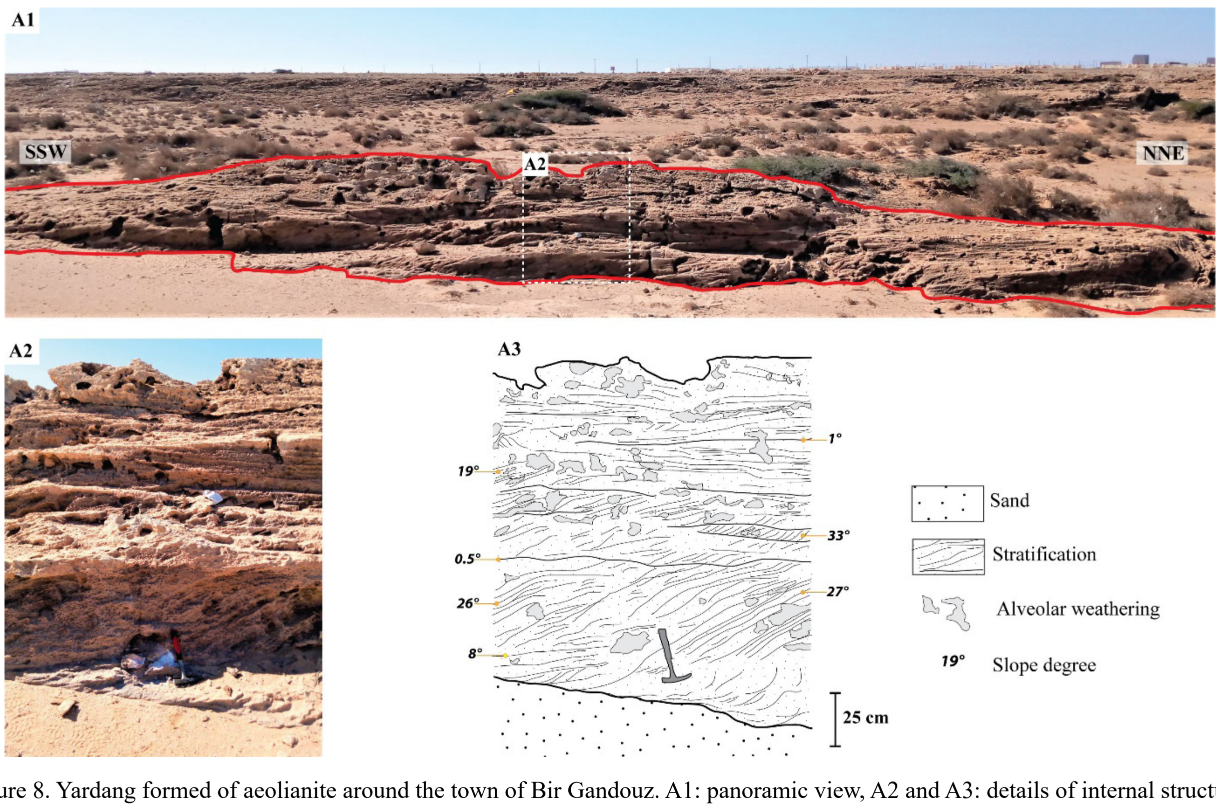

Figure 8. Yardang formed of aeolianite around the town of Bir Gandouz. A1: panoramic view, A2 and A3: details of internal structures.

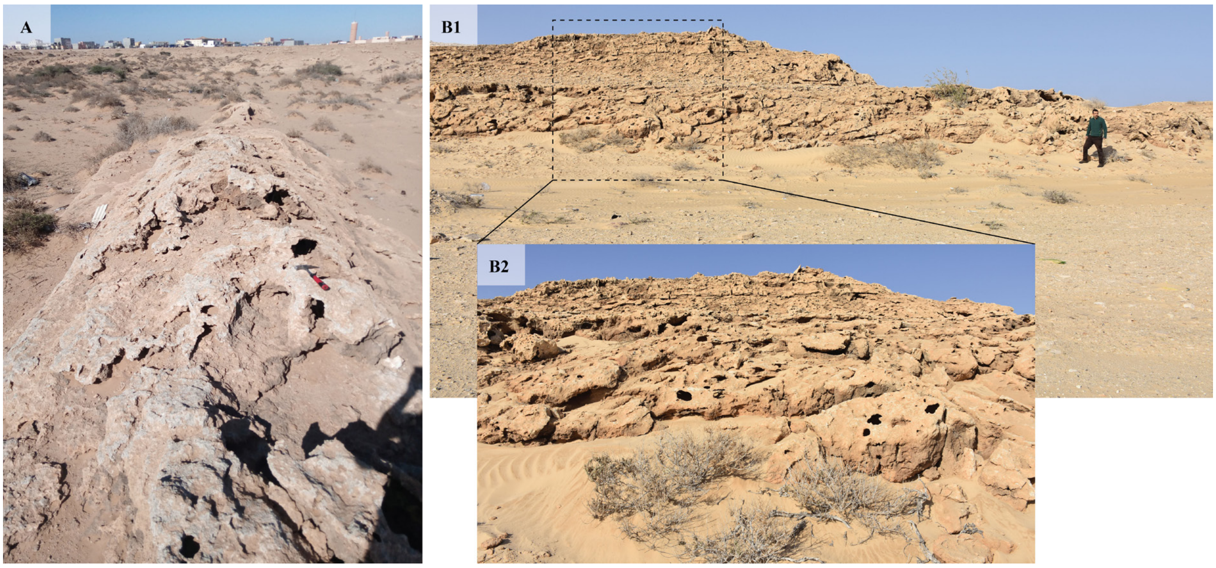

Figure 9. Erosion of the yardang surface. **A:** photo near to the Bir Gandouz city, **B1**, **B2**: photo and its detail at about 60 km south of Bir Gandouz (on the national road n°1).

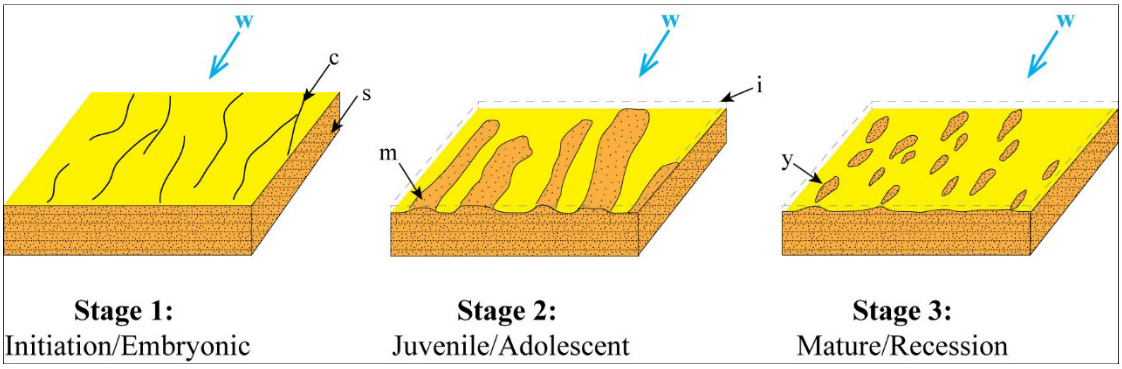

Figure 10. Evolutionary model for the Dakhla yardangs. **c**: couloirs, **i**: initial topographic level, **m**: mega-yardangs, **s**: substratum, **y**: current yardangs.

CONCLUSION

The Dakhla region, particularly the coastal zone, is characterised by a relief composed of well-streamlined yardangs. These landforms display a typical whaleback or teardrop shape with their long axes oriented parallel to the strongest and prevailing regional wind (NNE), while their main axis is oriented slightly obliquely to the present prevailing regional winds, suggesting the old age of the formation of these forms.

However, our observations show that these mounds are still being shaped by the wind, but with the appearance of directions consistent with the current prevailing winds, for example in the formation of small prominences at their tops. This documents that the yardangs in this study area are neither fossil forms nor recent forms, but ancient forms that cumulate different stages of shaping.

Several factors (topographic, lithological and climatic) favour the development of these morphologies, foremost of which are (1) a flat topography with sparse or no vegetation, (2) a relatively unidirectional high speed wind charged with sand particles, and (3) the low wind resistance of most of the rocks, especially the dune sandstones.

The present study will provide the basis for future research on this type of aeolian landforms. In particular, the dating of the Aguerguer sandstone from which they are carved would help to clarify the chronology and evolution of these yardangs. Furthermore, a detailed study will be required on controlling factors like tectonic and lithology, while the microscopic analysis of facies would give more information on post-depositional diagenesis and paleoenvironmental changes.

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REFERENCES

Alimen H. 1987. Evolution du climat et des civilisations depuis 40 000 ans du nord au sud du Sahara Occidental (premières conceptions confrontées aux données récentes). *Quaternaire*, 24(4), 215–227.

Barchyn T.E. & Hugenholtz C.H. 2015. Yardang evolution from maturity to demise. *Geophysical Research Letters*, 42, 5865–5871.

Barchyn T.E. 2018. Modeling the mechanisms behind yardang evolution. *Journal of Geophysical Research: Earth Surface,* 123, 4, 618–621.

Benito G., Machado M.J. & Sancho C. 1993. Sandstone weathering processes damaging prehistoric rock paintings at the Albarracin Cultural Park, NE Spain. *Environmental Geology*, 22(1), 71–79.

Cooke R.U., Warren A. & Goudie A.S. 1993. *Desert geomorphology,* CRC Press, 534 p.

Davison I., & Dailly P. 2010. Salt tectonics in the Cap Boujdour Area, Aaiun Basin, NW Africa. *Marine and Petroleum Geology*, 27, 2, 435–441.

Ding Z., Zhao J., Wang J. *et al.* 2020. Yardang on Earth and its implications to Mars: A review. *Geomorphology*, 107230.

Dong Z., Lv P., Lu J. *et al.* 2012. Geomorphology and origin of yardangs in the Kumtagh Desert, Northwest China. *Geomorphology*, 139, 145–154.

Elboudali N., Zouhri S., Gingerich P.D. *et al.* 2018. Foraminifères planctoniques : clé de la nouvelle datation du membre" Guerran" de la formation Samlat d'Ad-Dakhla (Domaine saharien, Maroc). *Bulletin de l'Institut Scientifique*, *Section Sciences de la Terre*, 40, 21–37.

Goudie A.S. 2004. *Encyclopedia of Geomorphology*. Routledge, London and New York.

Goudie A.S. 2007. Mega-Yardangs: A global analysis. *Geography Compass,* 1(1), 65–81.

Greeley R., Bender K., Thomas P.E. *et al.* 1995. Wind-related features and processes on Venus: summary of Magellan results. *Icarus*, 115(2) 399–420.

Hall P., Watson G.S. & Cabrera J. 1987. Kernel density estimation with spherical data. *Biometrika*, 74(4), 751–762.

HCP (Haut commissariat au plan) 2018. Monographie de la région de Eddakhla Oued Eddahab 2018, 181 p.

Hébrard L. 1973. *Contribution à l'étude géologique du Quaternaire du littoral mauritanien entre Nouakchott et Nouadhibou, 18°-21° latitude Nord. Participation à l'étude des désertifications du Sahara*, Documents des Laboratoires de Géologie de la Faculté des Sciences de Lyon, 71(1), 210 p.

Laity J.E. & Bridges N.T. 2009. Ventifacts on Earth and Mars: Analytical, field, and laboratory studies supporting sand abrasion and windward feature development. *Geomorphology*, 105(3–4), 202–217.

Laity J.E. 2009. *Landforms, landscapes, and processes of aeolian erosion. In Geomorphology of desert environments*. Springer, Dordrecht, 597–627.

Laity J.E. 2011. Wind erosion in dry lands. In David S.G. (Ed.) - *Arid zone geomorphology: Process, form and change in dry lands*, 3rd Edition. Thomas, 539–568.

Laity J.E. & Bridges N.T. 2013. Fundamentals of aeolian sediment transport: Abraded systems. In: Shroder J. *et al.* - *Treatise on Geomorphology*. *Aeolian Geomorphology*, 11, 269–286, Academic Press, San Diego, California.

Lancaster N., Kocurek G., Singhvi A. *et al.* 2002. Late Pleistocene and Holocene dune activity and wind regimes in the western Sahara Desert of Mauritania. *Geology,* 30(11), 991–994.

Li J., Dong Z., Qian G. *et al.* 2016. Yardangs in the Qaidam Basin, northwestern China: Distribution and morphology. *Aeolian Research*, 20, 89–99.

Mainguet M. 1968. Le Borkou. Aspects d'un modelé éolien. *Annales de Géographie*, 77(421), 296–322.

Mainguet M. 1970. Un étonnant paysage : les cannelures gréseuses du Bembéché (N. du Tchad). Essai d'explication géomorphologique. *Annales de Géographie,* 79, 58–66.

McKEE E.D. 1966. Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). *Sedimentology,* 7(1), 3–69.

Michard A., Saddiqi O., Chalouan A. *et al.* 2008. *Continental evolution: The geology of Morocco: Structure, stratigraphy, and tectonics of the Africa-Atlantic-Mediterranean triple junction*, 116, Springer.

Moujane A., Bentamy A., Chagdali M. *et al.* 2011. Analysis of high spatial and temporal surface winds from Aladin model and from remotely sensed data over the Canarian upwelling region. *Télédétection,* 10(1), 11–22.

Ortlieb L. 1975. Recherches sur les formations plio-quaternaires du littoral Ouest-saharien: 28°30′-20°40′ lat. N. Travaux et Documents de l'O.R.S.T.O.M., 48, 298 p., IRD Editions, Bondy

Ozer, P. 1996. Evolution des directions et des vitesses des vents de 1951 à 1994 sur la façade Atlantique de l'Afrique de l'Ouest du sud du Sénégal au nord de la Mauritanie. *Publications de l'Association Internationale de Climatologie,* 9.

Paillou P. & Radebaugh J. 2013. Looking for Mega-Yardangs on Titan: A Comparative Planetology Approach. *European Planetary Science Congress*, 8.

Parsons A.J. & Abrahams A.D. 1994. *Geomorphology of desert environments.* Springer, Dordrecht, 831 p.

Pelletier J.D., Kapp P.A., Abell J. *et al.* 2018. Controls on yardang development and morphology: 1. Field observations and measurements at Ocotillo Wells, California. *Journal of Geophysical Research: Earth Surface*, 123, 694–722.

Pye K. & Tsoar H. 2008. *Aeolian sand and sand dunes*. Springer Science & Business Media, 458 p.

Riser J. 1985. Le rôle du vent au cours des derniers millénaires dans le bassin saharien d'Araouane (Mali) (Wind action during the last millenaries in the Saharian basin of Araouane - Mali). *Bulletin de l'Association de Géographes Français,* 62(4), 311–317.

Ritley M.K. & Odontuya E. 2004. Yardangs and dome dunes northeast of Tavan Har, Gobi, Mongolia, *GSA Abstracts with Programs*, 36(4), 33.

Rognon P. 1979. Evolution du relief et paléoclimats depuis 40 000 ans sur la bordure nord du Sahara. *Bulletin de l'Association de Géographes Français*, 56(462), 205–214.

Saadi M. 1982. *Carte structurale du Maroc.* Direction des mines et de la géologie, Edition du Service géologique du Maroc.

Saadi M., Hilali E.A., Bensaıd M. *et al*. 1985. Carte Géologique du Maroc 1/100.0000. *Notes et Mémoires du Service Géologique du Maroc*, (8), 260 p.

Salomon J.N. 2006. *Précis de karstologie*. Presses Univ. de Bordeaux.

Tessier F., Hébrard L., & Lappartient J.R. 1971. Découverte de fragments d'œufs de *Psanuaornis* et de *Struthio* dans le Quaternaire de la prequ'île du Cap Blanc (République islamique de Mauritanie). *Comptes rendus de l'académie des Sciences de Paris, série D*, 273, 2418–2421.

Wang Z.T., Wang H.T., Niu Q.H. *et al.* 2011. Abrasion of yardangs. *Physical Review E*, 84(3), 031304.

Ward A.W. & Greeley R. 1984. Evolution of yardangs at Rogers Lake, California. *Geological Society of America Bulletin*, 95, 7.

Węglarczyk S. 2018. Kernel density estimation and its application. *ITM Web of Conferences*, 23, 8 p.

Weisrock A. 1982. Signification paléoclimatique des dunes littorales d'Essaouira-Cap Sim (Maroc). *Revue de Géomorphololgy Dynamique,* 31(3), 91–107.

Whitney M.I. 1985. Yardangs. *Journal of Geological Education*, 33(2), 93–96.

Williams R.H., McGee D., Kinsley C.W. *et al.* 2016. Glacial to Holocene changes in trans-Atlantic Saharan dust transport and dust-climate feedbacks. *Science advances*, 2(11), 1600445.

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