Geomorphology of the Tafilalt Basin, South-East Morocco – implications for fluvial–aeolian dynamics and wind regimes

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ABSTRACT

The hyper-arid Tafilalt Basin, South-East Morocco, is dominated by two ephemeral fluvial networks and several ergs with various dune forms from barchans to mega dunes. Especially the genesis of the star dunes remains an open research question. Therefore, a new multisheet geomorphological map describes the surface dynamics in the basin. Identification of major surface features was done with remote sensing data and on-site surveys. The analyses were used to identify all different landscape units. Additionally, aeolian features are emphasized to deduce current wind directions. The identification of two opposite wind fields was possible and a spatial correlation in the fluvial-aeolian system is detected. The border of the opposite wind fields crosses Erg Chebbi. Hence, the star dunes are under the influence of a multimodal wind system. Overall, this new geomorphological map strengthens the understanding of the fluvial-aeolian interaction in the Tafilalt Basin and sets a baseline for ongoing in-depth studies.

1. Introduction

The Tafilalt Basin, South-East Morocco, provides an ideal landscape setting to extensively study the interaction of fluvial–aeolian dynamics in desert environments. The area shows hyper-arid climate conditions but also frequent fluvial sediment input due to rainfall events in the High Atlas. Here, fluvial–aeolian interaction and dependencies can be evaluated exemplarily and can be extrapolated at different scales. The occurrence of a wide range of different dune fields across the area allows at the same time a detailed investigation of the wind regime. In addition, the Tafilalt Basin is home of the prominent Erg Chebbi at its center, as one of the smallest sand seas (erg) of the Sahara (Fryberger & Ahlbrandt 1979). It has a prominent dune morphology with 14 major star dunes, but its origin is mostly unknown. Only preliminary explanations concerning sand trapping due to water and soil moisture of the ephemeral Lake Yasmine north of Erg Chebbi exist (García-Rodríguez & Antón, 2014), but cannot account for the dune morphology in general. It can be hypothesized that the erg with its star dunes, like other star dune fields (comp. Goudie et al., 2021), represents a remnant of a formerly larger sand cover (comp. Zhang et al., 2016). To test and research these hypotheses as well as the evolution of the Erg Chebbi and its star dunes, the general geomorphological mapping of the Tafilalt Basin sets the baseline for in-depth investigations of landscape development in the past and present.

Geomorphological maps presenting a systematic inventory of landforms, often in several layers, are a vital investigation method for the scientific understanding of landscapes and their evolution (Barsch & Liedtke, 1980; Verstappen & Zuidam, 1968; Wright, 1972). Normally divided into a large-scaled morphogenetic map and small-scaled morphodynamic maps, they describe earth surface evolution under past to modern climates with regard to morphography, morphometry, morphogenesis, morphodynamics, and morphochronology. In addition, they can include anthropogenic landforms and additional information like vegetation cover, groundwater or land use (Dramis et al., 2011). For our study area, the Tafilalt Basin, an area of roughly 14,000 km², no geomorphological maps exist up to know. Medium-scaled geomorphological maps (map scale from 1:25,000–1:250,000), displaying large landscape units in full extension, are best suited for presenting surface processes and landscape evolution. This allows the identification of all major process spaces but requires customized generalization. Due to the defined map scale, a combination of remote sensing techniques (satellite/aerial-photograph interpretation) and field survey for ground check is suggested and implemented (Dramis et al., 2011; Verstappen, 1977).
Thus, the presented medium-scaled map set (1:175,000) is used to describe the geomorphology in the study area of the Tafilalt Basin. Major geomorphological units summarizing fluvial, gravitational/dun- 
dative, aeolian and residual processes (e.g. alluvial 
plain, basin floor, piedmont, mountain rock slopes, 
hamada) are mapped via automatic and manual mor-
phometric analyses as well as field surveys. This serves 
as a process-orientated overview of the study area. In 
addition, by the identification of all sand fields and lar-
ger ergs, associated dune forms and their spatial 
relationship to hydrology, major dune-forming wind 
directions and large-scale wind regions are mapped.

2. Study area

The Tafilalt Basin is located in South-East Morocco in 
an extensive basin structure of the most eastern Anti-
Atlas foreland (cf. Figure 1). The basin is described as 
a tectonic depression 700 m above sea level (Barczuk 
et al., 2008). Its basement is built up by Paleozoic 
mostly clastic rocks of variscan origin (Fal et al., 
2019; Fetah et al., 1986; Saadi, 1982). The basin is bor-
dered by Neogene and Cretaceous sediments with 
large flat hamada surfaces. Quaternary deposits can 
be found on alluvial fans and plains of the ephemeral 

rivers Ziz and Rheris, in addition to extensive pedi-
ments and larger sand/dune field deposits (Adnani 
et al., 2016; Barczuk et al., 2008; Robert-Charrue, 
2007). Overall, the basin floor is flat but slightly 
inclined to the south. From a geomorphological per-
spective, it is dominated by the river system of Oued 
Ziz and Oued Rheris, which originate at the Atlas 
Mountains watering the greater Tafilalt oases before 
they desiccate in the central basin and further south. 
Aeolian features are abundant and mostly represented 
by sand fields with complex barchans and transverse 
dune morphologies. An exception is Erg Chebbi, the 
largest sand field in the central depression with 14 
compound star dunes. Smaller but noteworthy sand 
fields are Erg Znagui and Erg Ouzina further south 
along the alluvial plains of the Oued Ziz.

The basin climate is continental hyper-arid (BWh 
after Köppen and Geiger) with potential evaporation 
rates above 2500 mm/y. Precipitation is scarce, varies 
between 30 and 140 mm/yr and concentrates unreliably 
in the autumn to winter months with strong single flood 
events. The daily temperature average is around 20 °C, 
but varies strongly between day and night as well as 
during seasons. Maximum temperature can reach up 
to 50°C, especially above sand surfaces (Alali & Benmo-
hammadi, 2013; García-Rodriguez et al., 2014).

Figure 1. Location of the Tafilalt Basin in the eastern Anti-Atlas with typical surface features A: Wadi system near an escarpment of the Hamada du Guir B: Basin floor and star dunes in the central depression C: Erg Ouzina with alluvial plain of the Oued Ziz in the background. Data Source: Landsat 8 RGB false color composite highlighting sand cover (Band 7,4,2), own photography Oct 2018 and February 2020. The main map (supplement) is marked by the white rectangle.
regime at the border of the Saharan desert near Jabel Bahrim (comparable to the Tafilalt Basin) is described as bimodal (SW-WSW/NEENE) with max wind speeds of 17.7 m/s (Schulz & Fink, 2016).

3. Materials and methods

Landscape classification and identification of major sand cover was done via remote sensing on two different scales (1:5000 and 1:175,000) and on-site survey in October 2018 and February 2020. Data from TanDEM-X (Rizzoli et al., 2017), Landsat 8 (courtesy of the U.S. Geological Survey), Sentinel 2 (Copernicus Sentinel data 2018, processed by ESA) and ESRI Basemap Service were used to create the presented multi-sheet map set. Used data, basic workflow and deduced surface mapping features are summarized in Figure 2. Main analyses and digital mapping were all done with ArcMap 10.4.

3.1. Morphometric analyses and classification

Base layers and terrain parameters (slope classification, elevation contours 50 m breaks) were built by using the freely available WorldDEM with a spatial resolution of 90 m (Wessel et al., 2018). This is a sufficient spatial resolution for the presented map scale (1:175,000) and to identify pediments and connecting morphogenetic surfaces, which are most abundant in the Tafilalt Basin. In a first step, we calculated basic terrain inclinations (comp. Main Map Supplement C) with the Slope Tool creating a new Raster data set, which was reclassified in different units of the Pediment Association. In the presented map we used a slope classification separating the Pediment from higher and lower surfaces orientated at mean inclinations after (Dohrenwend & Parsons, 2009). Breaks were set at >5° hill slope, 1° – 5° Pediment, <1° tributary basin and< 0,5° alluvial plain. In a final step and for the presented map, all resulting layers were generalized with a smoothing filter of 500 m tolerance, which excludes single features with a diameter less than 3 mm on the printed map scale increasing map readability and clarity.

3.2. Sand cover identification and dune mapping

For the identification of sand cover, we used a Landsat 8 RGB false color composite (Landsat 8 RGB Band 7,4,2 comp. Main Map Supplement A) as this band combination is in particular highlighting sand-covered regions. The identified areas went through a detailed analysis on high-resolution satellite images (mosaic compilation in ESRI Basemap) with manual mapping of dune crest orientation at a much higher resolution of 1:5000 (comp. Figure 3). Each individual dune crest was analyzed and a generalized main wind direction for each sand field was deduced. Barchanoid forms, which result from a unimodal wind regime (e.g. Munyikwa, 2005; Tsoar, 2001; Wiggs, 2001), are particularly suitable for this purpose. Resulting orientations were exemplified crosschecked on-site during two field surveys in 2018 and 2020.

3.3. Fluvial system and active streams

The ephemeral active fluvial system was mapped in two ways, morphometrical via WorldDEM and based on the Normalized Difference Moisture Index (NDMI) provided by Sentinel 2 Data reflecting moisture in active wadis from recent precipitation event in September 2018. Calculations of the NDMI were proposed by Gao (1996). Automatic mapping was done with D8 flow routing proposed by (O’Callaghan & Markab, 1984). Major automatic working steps included calculations with Spatial Analyst Hydrology tools of flow directions, flow accumulations and with the Raster Calculator. The resulting vector-based stream network was also generalized with a 500 m tolerance in order to increase the map readability.

4. Main geomorphological units

Main geomorphological units in the Tafilalt Basin can be divided into four spatially close and connected sections. They are summarized in aeolian features and landforms (multiple sand fields with diverse dune forms), ephemeral fluvial systems with its two major streams, secondary wadis and alluvial plain as well as multiple fluvial/gravitational surfaces summarized in the Pediment Association (hill slopes, Pediment, basin floor) and residual surfaces (hamada) on the surrounding plateaus.

4.1. Dune features [aeolian]

Erg Chebbi is with 110 km² the largest dune field in the basin followed by smaller Erg Znagui (13 km²) and Erg Ouzina (16 km²) along the Oued Ziz. Furthermore, 87 smaller sand fields were identified in the presented study area, which are dominated by barchans or longer transverse dunes (comp. Figure 3A). Some sand fields do not display distinct dune types, which are therefore classified as undifferentiated sand cover (comp. Figure 3B). Larger more complex compound star dunes are present in Erg Chebbi (comp. Figure 3C) and Erg Ouzina (comp. Figure 1C). With the exception of Erg Chebbi, all dunes are spatially closely related to the ephemeral fluvial systems of Oued Ziz and Oued Rheris, indicating fluvial sediments as a potential main source of dune sands and a strong correlation between the fluvial and aeolian processes spaces. This is a striking feature in arid environments.
Figure 2. Data Overview, Workflow description and derivate morphological surface features.

Figure 3. Identification of dune types at three locations of the Tafilalet Basin comparing on-site photo, ESRI basemap orthophoto and manual crest mapping. A: Barchans on the basin floor, B: Undifferentiated dune fields in Erg Znagui, and C: Star dunes in the Erg Chebbi (cf. Figure 1). Deduced wind directions from crest line orientation at barchan sand fields. Data source: Own photography and ESRI, DigitalGlobe, GeoEye, i-cuved, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community for satellite image.
compare for example, Al-Masrahy and Mountney (2015), Liu and Coulthard (2015) and are an important source for the detection of different sediment source in the area (Adnani et al., 2016). Smaller aeolian features like sand sheets, single barchans and nebkhas are found along the main wadis but are, due to their small sizes, not displayed at the presented map scale. However, through manual generalization onto larger signatures losing, in the presented large-scale map, singular unimodal dune crest signatures, relevant data (main wind direction in sand field) can be displayed, which is necessary for the interpretation of regional wind dynamics.

The dune crest analyses enable the identification of prevailing wind directions on medium-scaled maps in local wind fields and can be used for case studies in remote and hardly accessible regions where reliable recent wind data/stations are missing. In general, the overall formation of different morphological dune types like crescentic (barchan), transverse, linear, reversing, star and parabolic dune is complex and controlled by several major more local factors like suitable sediment production and availability, wind intensities and direction as well as vegetation cover (comp. Lancaster, 2005; McKee, 1979). They form dune patterns, for example on larger sand cover, of simple, compound and complex forms with each class representing an increasing morphological complexity (McKee, 1979). Yet their dune crest alignments reflect, with exception of the star dunes, the dominant sand transport and associated wind direction/ regime quite clear (Fryberger & Ahlbrandt 1979; Lancaster, 1983).

Migrating dunes like crescentic, transverse and parabolic dunes result from a unimodal wind regime whereas linear dunes are associated with a bimodal system (e.g. Bubnerzer & Bolten, 2008; Munyikwa, 2005; Tsoar, 2001; Wiggs, 2001). More stationary dunes like star dunes are expected to be formed also under a bimodal to multi-directional wind regime (Dong et al., 2013; Goudie et al., 2021; Lancaster, 1989a, 1989b, 2005; Tsoar, 2001; Zhang et al., 2016). In consequence, migrating dunes, especially barchans with their typical semicircular shape, are suitable to identify the recently dominant unimodal wind direction via orthophotos and satellite data (Blasco et al., 2020). This can be applied to the abundant sand fields in the basin, which are dominated by free barchans and located on the alluvial plain. Since barchan orientations result from constant unimodal winds over several years (Goudie, 2020), the ESRI basemap can be used despite the fact that it represents an satellite image mosaic. Yet, it remains a qualitative analyses and description and cannot replace quantitative wind speed measurements. In addition, on-site knowledge and research is highly recommended in the creation of process-orientated maps at this large scale, since it facilitates the identification of aeolian features and is necessary to validate remote sensing results (Dramis et al., 2011). Beyond the methodological aspects the presented map enables the analyses of bimodal wind fields in our study area which are necessary for the forming of more complex dune forms (Lancaster, 2005; McKee, 1979; Tsoar, 2001).

Apart from Erg Chebbi in the central depression and Erg Ouzina, all sand fields can be divided into two general groups with opposite mean crest orientations. One group North-East of the erg, in the South Tafilalt Basin, displays barchans mostly travelling South-West. The second group South-East and West of the erg, near and in the Anti-Atlas, travels in opposite direction to the North-West. In parts, for example in the alluvial plain near the village of Rissani, sand fields with opposite barchan orientations are only 10 km apart. They obviously indicate a border between different wind systems correlating with regional wind dynamics further south-west near the village of Jebel Brahim (Puy et al., 2018; Schulz & Fink, 2016). After the analyses of all sand fields, this border can be identified throughout the central depression dividing it into two major wind regimes. Erg Chebbi with its prominent star dunes can be located at this border spanning from Erfoud through the basin along the village of Taouz and onto the Hamada du Guir.

4.2. Drainage network [fluvial]

Oued Ziz and Oued Rheris dominate the basin, forming an extensive alluvial plain dominated by whitish fluvial sediments in the North-West between the Atlas Mountains and the eastern parts of the Anti-Atlas, often referred as Tafilalt Valley (Baidder et al., 2016). Representing two drainage systems of the High Atlas Mountains, they are spatially close in the Tafilalt Basin where they merge at its eastern border. The associated alluvial plains are not only the main source region for the local sand supply and adjacent dune field, but also an important source of dust. Thereby, the fine material (< sand) of the alluvial deposits is blown out and can be deposited in greater distances, which is an important process all over the Sahara Desert (Lavi Bekin et al., 2020). Tributary wadis of both systems form an extensive ephemeral fluvial network eroding the rocky hilltop remnants of the Anti-Atlas, forming abundant Inselbergs in the West and elongated escarpments in the East of the Tafilalt. In comparison to Oued Rheris, the Oued Ziz is dominantly shaping the central basin depression. Its secondary wadis cut mainly into the escarpments at the eastern and southern rim of the basin, namely of the Hamada du Guir and the Kem-Kem. This results in constantly retreating escarpments and the formation of an enlarging basin over longer geological timescales.
4.3. Pediment Association [fluvial, denudative, gravitational]

Pediments Association features are found in the whole basin but are most abundant in the western part of the basin where the Anti-Atlas is eroded extensively, forming a plain landscape with several Inselberg clusters. After Cooke’s concept of Pediment Associations (Cooke, 1970) this summarizes three main surface features in close genetic correlation. A sediment source region with rocky hill slopes dominated by vertically cutting streams and strong erosion, the pediment itself as morphological most stable component, and the tributary basin floor with mostly accumulation. The latter is being divided into the basin floor and the alluvial plain which is highly dominated by the two major streams (cf. Chapter 4.2). In this open erosional-depositional system, the pediment itself can also be divided into an upper erosional (glacis d’erosion) and lower depositional part (glacis d’accumulation). The differentiation is difficult on site and on this map scale not possible. Therefore, the pediments in total are orientated at their mean surface inclinations (cf. Chapter 2). Nevertheless, they occur in multiple locations in the Tafilalet Basin where sufficient inclinations, for example at mountain ridges, Inselbergs and escarpments, enable the establishment of erosion and transport (comp. Figure 4 A, B, C). They are cut and divided by ephemeral streams, which divide them in several fan-shaped lobes around their central mountainous source areas.

4.4. Plateau/Hamada [residual]

Large plateaus surrounding the basin, namely Hamada du Guir in the East and Kem-Kem in the South are best characterized as residual surfaces. Often referred to as desert pavements (Mabbutt, 1977), these larger flat unvegetated surfaces are dominated by coarse debris, characteristic for Saharan hamada’s. This dominance results from one or several stone concentrating processes due to deflation, wash, upward migration of stones, cumulic pedogenesis and subsurface weathering (Dixon, 2009). In addition, several circular solutional depressions known as dayas (Elbelrhiti et al., 2020; Goudie, 2010; Mitchell & Willmott, 1974) are found randomly in the Hamada du Guir. Overall, they are too small to be displayed on the presented map scale.

5. Conclusion

Different mapping scales were used in the presented geomorphological map and its supplements (satellite image, topography, slope) in order to describe the current geomorphological dynamics in the arid environments of the Tafilalet Basin. Four main process units of fluvial, gravitational/denudative, residual and aeolian systems where identified in the basin and mapped. From a spatial point of view, all sand fields are close to the fluvial systems of Oued Ziz and Oued Rheris, indicating a strong correlation between the fluvial and aeolian processes areas. This indicates sedimentological connections, assuming that sediments are provided by the ephemeral fluvial system from the Anti-Atlas, the Pediments as well as the surrounding hamada surfaces and are subsequently blown out locally. In consequence, a relatively young Holocene to recent aeolian age for several sand fields close to wadis can be assumed since a reasonable travel distance is not present. Contradicting, Erg Chebbi, located not directly close to Oued Ziz and Rheris, may be of different origin and age. The detailed mapping of dune forms on the smaller scales (compared to other map features) is able to give detailed information about the wind regime. Here, the mapped minor sand fields, which are mostly characterized by unimodal dune types (barchans and transverse dunes), can be divided into two groups of opposite wind directions with a dominance of south-western and north-eastern winds. In consequence, the basin can be divided into two regions with the complex

![Figure 4](image-url)
mega dunes of Erg Chebbi in between as possible consequence of an at least bimodal wind system. Overall, the geomorphological map provides an ideal setting to describe the spatial interaction of fluvial–aeolian processes in desert environments and is, in addition, particularly suited as base for in-depth investigations of the landscape development in the past and present.

**Software**

All data, parameters and base map features were calculated and drawn with ArcMap 10.4.1. Post production of all maps, layout and cartographical optimization was done with Adobe Illustrator Package CS5. The latter was used for all figures and tables in the presented publication.

**Data availability statement**

The data that support the findings of this study are available from the corresponding author, [Herzog, Manuel], upon reasonable request.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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