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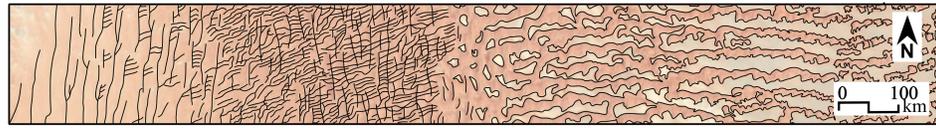
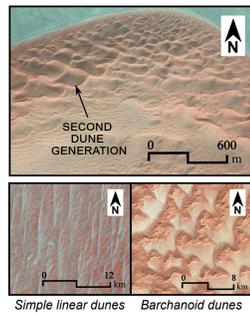


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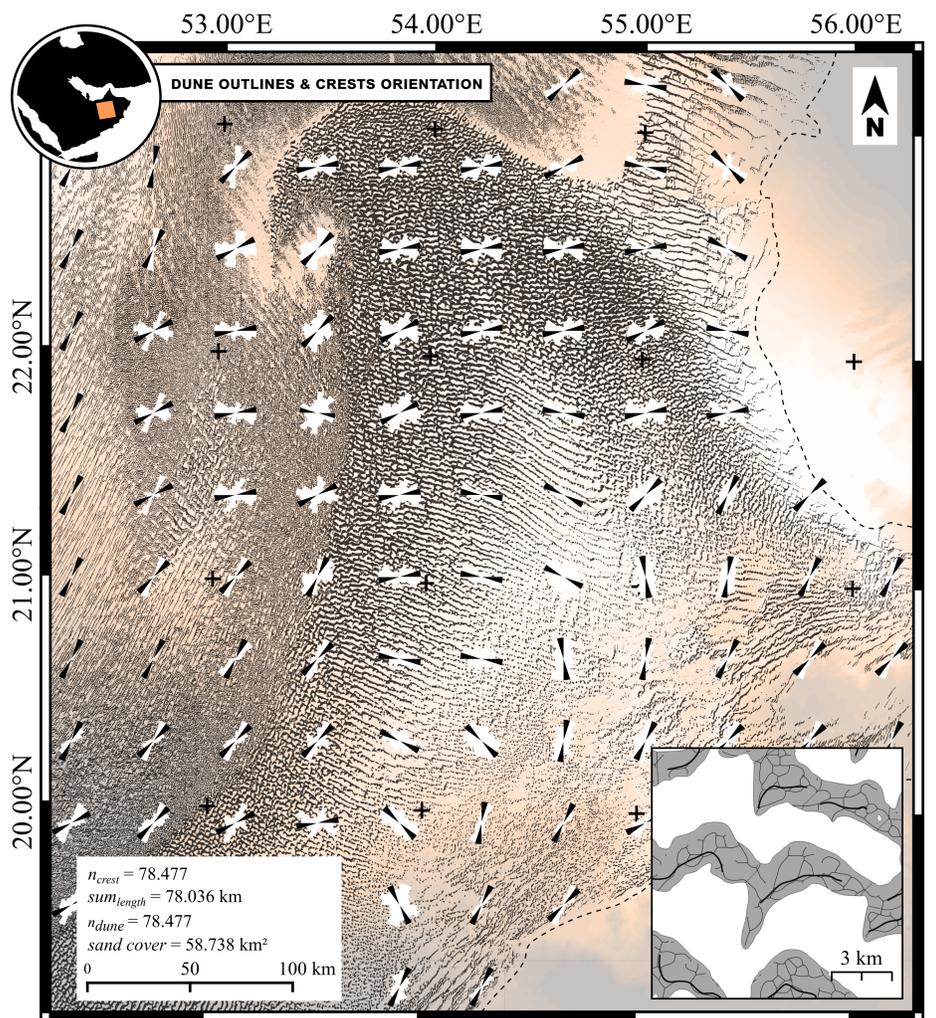
Deep Learning: A new tool for mapping and analysis of dune fields (e.g. Rub'Al Khali sand sea)

INTRODUCTION & PROBLEMATIC

Geometry and spatial organisation of dunes are controlled by the interaction between a moving fluid (shear stress) and granular sediments (quantity, size and shape of particles). Dunes are ubiquitous on planetary surfaces, shaping repetitive patterns at different scales. Spatial and volumetric mapping and analysis of these bedforms is therefore essential to better understand i) their formation processes and ii) their spatio-temporal evolution. Bedform mapping studies are usually focused either on a dune field scale (i.e. main geometric patterns) or on a few selected dunes (i.e. slope, outline, crestlines, etc.), but never encompassed both scale. Indeed, numerous maps are produced by manual digitizing (e.g. crestlines, outlines, slip faces) which is very time-consuming and biased by mapper subjectivity. Here, we propose an automatic method of dune outlines, crestlines and slip face mapping from DEM based on Artificial Intelligence (AI) which allows instantaneous, massive and integrated extraction of several properties from local scale (each single dune) to regional scale (dune field). We illustrate our AI protocol capabilities, reproducibility and accuracy on the Rub'Al Khali sand sea.

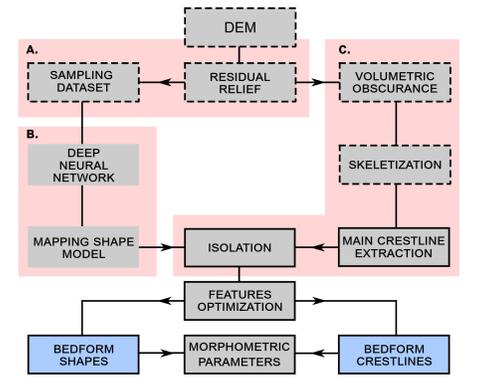


RUB'AL KHALI AUTOMATIC MAPPING & MORPHOMETRIC PARAMETERS



PROTOCOL WORKFLOW

1. Computation of *Residual Relief* (RR) to filter the regional topographic trend from the dune relief;
2. Segmentation of dune outlines from RR using a Deep Learning algorithm (Shumack et al., 2020);
3. Computation of *Volumetric Obscure* (VO ; Rolland et al., 2022) to enhance high inflexion points corresponding to dune crestlines;
4. Skeletonization of dune crestlines from VO and extraction of main crestline;
5. Computation of dune parameters (e.g. width, length, height, crests orientation) from the mapping results.

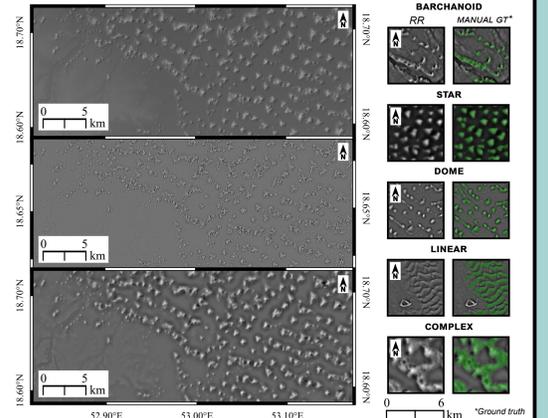


A. RESIDUAL RELIEF CONCEPT & SAMPLING

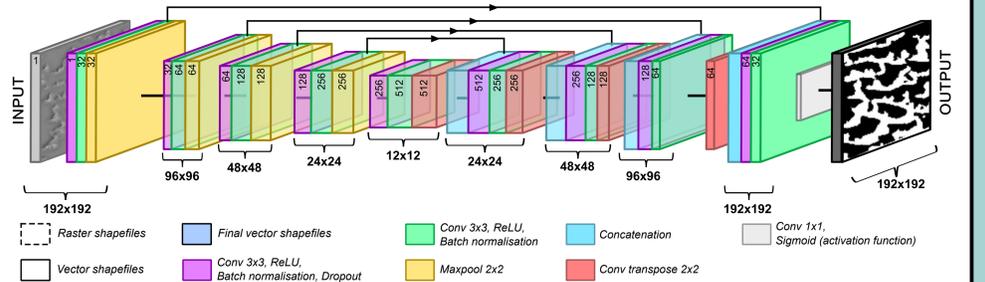
Dune fields show superimposed generations of dunes (m to km-scale) producing complex topographic signal on DEMs. Each dune scale patterns can be analysed independently if the topographic signal is disentangled.

We computed it on 100 training samples that are then used as learning data set to map the dune outlines. The samples are selected from four arid regions and cover a large range of dune types (barchanoid, star, dome, linear and complex dunes).

Each sample represent a DEM on which dunes are identified and digitalized manually. This manual mask is considered as a "ground truth" reference by the Deep Learning algorithm.



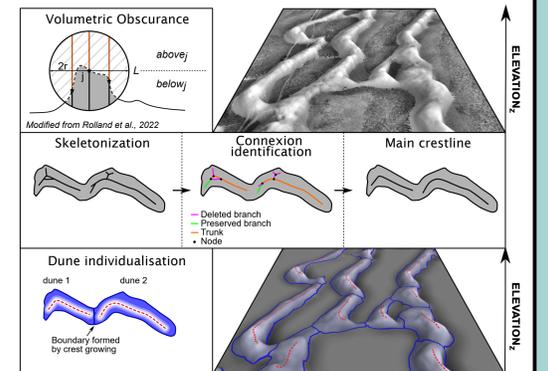
B. DEEP LEARNING ALGORITHM



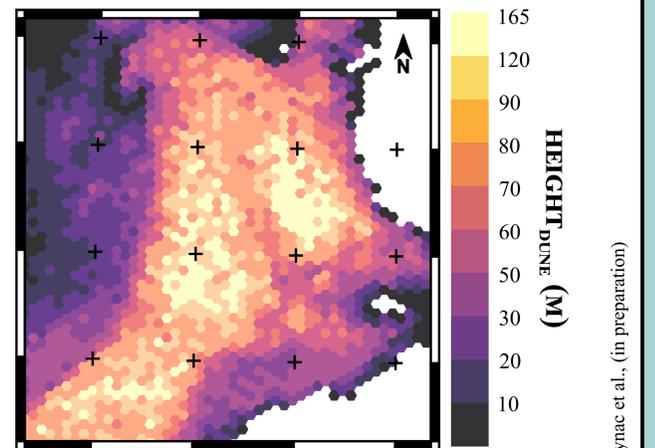
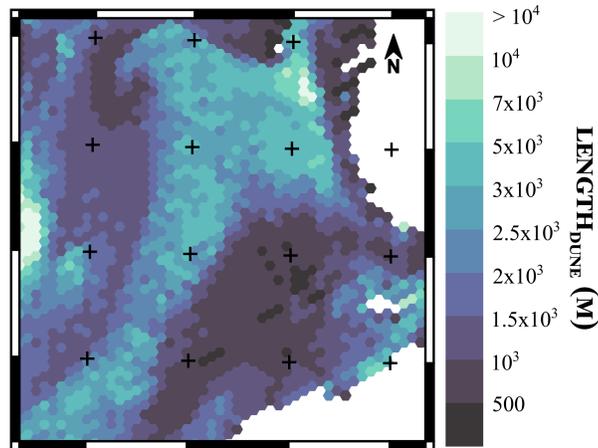
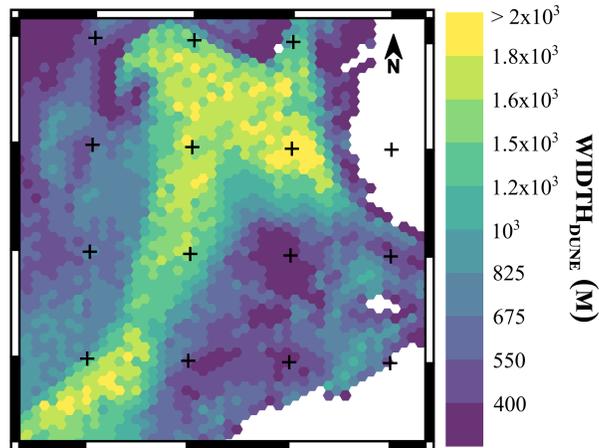
C. VOLUMETRIC OBSCURE APPROACH & SKELETIZATION

The crestlines extraction is based on the Volumetric Obscure algorithm (Rolland et al., 2022). The tool calculates for each pixel on a DEM the ratio between the volume below and above the topography in a sphere of a given radius centred at a given point of the topographic surface.

The output raster is reduced to a branched skeleton from an automated algorithm that analyzes the branch connectivity of each bedform crestlines to keep the longest segment.



Geographic projection system: WGS84/UTM 40N



RESULTS

| Metrical performances of the protocol from manual references | | | | |
|--|------------|--------------|-------------|---------------------|
| Metric | Recall (%) | Accuracy (%) | Quality (%) | Crest deviation (°) |
| Mean | 87,1 | 90,9 | 69,1 | 11 |
| Median | 92 | 91,7 | 69,4 | 8 |

Deep Learning performances

After the DNN training, the mapping model is assessed from 20% of the samples, demonstrating good performances: 92% of precision, 87% of recall and 70% of mapping quality.

Crests location & layout

Automatically extracted crestlines show low directional dispersion (11°) regarding manually digitized ones (considered as "ground truth").

Morphometric features

We automatically mapped more than 78,000 dune outlines and crestlines, on an area of more than 58,000 km². This is the first map ever of width, length, height and orientation of 78,000 dunes of the Rub'Al Khali desert, showing:

- Mean crestlines direction of 81° (range: 45°-135°) for high dunes (>70m) and of 35° (range: 171°-180°) for smaller dunes (<70m);

- Dune widths changes from 400 m to 1.8 km following a S to N gradient;

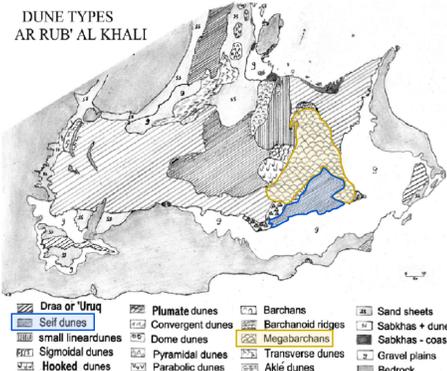
- A central area with a very consistent pattern of wide (>1.2 km), very long (>2 km) and high (>70 m) dunes;

- A south area with a very consistent pattern of narrower (<600 m), shorter (< 1 km) and a height gradient that decreases to the south (70 to 20 m);

- Consistency with previous studies
Our detailed morphometric measurements at the dune field scale shows:

- between the central area pattern of our work and the megabarchan area identified in dune field scale previous studies;

- between the south area pattern of our work and seif dunes area identified in dune field scale previous studies.



CONCLUSION & FURTHER WORKS

This protocol demonstrate good performances to map various and complex dune forms. This work is an original production that completes atlases of this region present in the literature the morphological boundaries mapped from aerial/satellite images (Barth, 2001; Glennie, 1970; McKee, 1979).

Only a few detection problems were noticed, and these were caused on by the DEM's resolution limit in a few specific locations, which produced a weak dune signal. This protocol may be used in the future on hydraulic and extraterrestrial dunes.

