Introduction: Dunes provide a unique set of information about local wind regimes on planetary bodies where in-situ meteorological measurements are scarce. Wind directional variability and sediment availability are known to control the dune growth mechanism and the subsequent dune shape and orientation [1,2]. In zones of high sediment availability (i.e., mobilizable sediment in the inter-dune areas), dunes grow in height perpendicularly to the maximum gross bed-form-normal transport [3]. This dune growth mechanism is henceforth referred as BI, the “bed instability mode”. In contrast, in zones of low sand availability (i.e., non-mobilizable bed in the inter-dune areas), dunes elongate in the direction of the resultant sand flux by deposition at the dune tip of the sediment, which is transported along the crest. This dune growth mechanism is henceforth referred as F, the “fingering mode” [4].

On Mars, dunes cover an area estimated around 975,000 km² [5-7] of which 86% belong to the North Polar Region. Fifty years of Martian surface observation show that dunes are still active on Mars [8]. In Polar Regions, because of the seasonal CO₂ cap, sediment transport may only occur from late spring to early autumn, hence during approximately 30% of a Martian year [8]. Modern winds on Mars are therefore supposed to contribute to shape sand seas. Nevertheless, wind regimes on Mars are still under debate. Actually, they essentially rely on the predictions of Global Circulation Models (GCM).

Here, we show that both dune growth mechanisms coexist on Mars and that there is a strong dependence of dune orientation on sediment availability. We use this dependence at two different sites at the border of the largest sand sea to infer new constraints on the local multi-directional wind regimes.

Methods: To link dune morphology to the local sediment cover, we study the north polar region of Mars where dunes are mostly composed of unaltered basaltic [9-10] and andesitic [11] grains. At the border of the largest sand sea, in the boreal circumpolar region, we choose a zone of transition in terms of sediment availability and wind direction (Fig. 1a). We focus on two specific dune fields located at 79°N-235°E and 79°N-247°E (Fig. 1b). In these two dune fields which are less than 140 km apart, bright areas correspond to the Martian bedrock and dark areas correspond to thick sediment layers. From the images of the Context Camera (CTX) on-board the Mars Reconnaissance Orbiter (MRO), we extract dune orientations directly from the identification of crest-lines and estimate the sediment cover using the ratio of dark pixels to the total number of pixels, helped by the statistics of the brightness distribution within the images. The sediment cover around each dune is computed over a circle centered at the middle of the crest with a radius equal to the largest wavelength observed in the dune field.

Figure 1: Martian Polar Regions of interest. a. Dune fields and dune coverage around the Martian North pole. Black lines show the wind direction inferred from geomorphic features and dunes [12]. b. Studied dune fields. c. Close-ups on dunes with different orientations in site 1 (left) and site 2 (right).

To determine dune orientation on Mars using the methodology based on the two dune growth mechanisms [1,2], we interpolate to small-time scales the near-surface winds predicted from the Laboratoire de
Météorologie Dynamique (LMD) GCM [13]. In addition, we use the geographic limits of the CO₂ polar cap during one Martian year to restrain our analysis to the seasons of possible sediment transport, when no CO₂ ice is deposited on the surface [14].

Results: In both sites, where there is no bedrock in the inter-dune, we clearly observe linear dunes with a wavelength around 400-500 meters and a North-South orientation. Wherever bedrock is apparent between linear dunes, their orientations change (Fig. 1c). On site 1, linear dunes may break-up into barchan dunes, which are all migrating to the East considering the orientation of their horns. On site 2, there are asymmetric barchan dunes (finger dunes) that elongate and migrate to the South-West considering their longest arms and the orientation of the slip face of their mobile head, respectively.

Dune orientation with respect to sediment cover is shown in Figs. 2a,d. In both sites, there is a dependence of dune orientation on sediment availability and a significant difference in dune alignment between zones of high and low sediment cover (pink lines in Figs. 2a,d). Nevertheless, two distinct behaviors can be observed: in site 1, there is a continuous transition in dune orientation, whereas in site 2, there is a sharp transition for sediment cover ranging from 60 to 80%. This difference in behavior can be emphasized using the standard deviation of an error function, which is 100 times larger in site 1 than in site 2.

Using the outputs of the GCM [13], the predicted dune orientation agrees with observations for both dune growth mechanisms in site 1. In site 2, the wind regime does not significantly change. Yet the predicted orientation for finger does not match at all orientation observed in the field.

Discussion: Thanks to the high contrast between the dune material and the non-erodible ground in high latitude on Martian dune fields, this is the first time that the dependence of dune orientation on sediment availability is observed and quantitatively investigated. Field examples shown in Figs. 1 reflect the diversity of dune shape and orientation that could be produced in the polar regions of Mars. Changes in dune orientation according to sediment cover demonstrate that the two dune growth mechanisms coexist on Mars and that the two sites under investigation have been exposed to multi-directional wind regimes. This dependence takes different forms for different dune-fields, indicating that sediment cover alone cannot be the sole control parameter for dune orientation. Dune field boundary conditions and the long-term erosion-deposition rates along the sediment transport pathways should also be taken into account. At the borders of the largest sand sea on Mars, we can now distinguish two main features from the relations between dune orientation and sediment cover:

- Outbound elongation of finger dunes (site 1).
- Inbound migration of finger dunes (site 2).

Most importantly, these dune features may be related to the wind regimes and the long-term evolution of dune fields to provide new constraints on local climate conditions.

![Figure 2](image.png)

**Figure 2:** Dune crest orientation function of sediment cover for site 1 (a) and site 2 (d). Squares are mean values computed in non-overlapping sliding windows. Dark green lines are the best fit to the data using the error function. Horizontal lines give the predicted dune orientation for F and BI using dunes (violet) and the outputs of GCM (gray). (b, e) Wind roses extracted from GCM. (c, f) Flux roses computed from the GCM winds. Arrows show the predicted dune orientation for F (black) and BI (red).