**Formation, transport and mineralogical evolution of basaltic sands on Earth and Mars.**

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**Introduction:** Sand deposit are widespread on Mars and are found in various environments, including for example the northern plains, the cavity of impact craters [1], or in the vicinity of volcanic edifices [2]. Sand grains were likely formed at different periods of the Mars history. In some cases, they have been probably buried and the sands can be seen spreading out of recently exposed outcrops of more or less consolidated sandstone layers. The present sand mass on Mars represents a potential record of recent and older environments. Indeed, sand composition, physical properties and pathways record their modes of formation and their modes of transport and sedimentation. However, in many situations investigated so far, sand sources sand pathways, and sand formation chronology remain unclear. For instance, the dune fields at Noachis Terra have been recently investigated [3]. According to this study, the origin of sands can be glacial and/or volcanic, but probably not lacustrine. The sand sources are said to be probably regional and local but no sand pathways can be identified. This example illustrates the need for a deeper understanding of volcanic sand formation and transport on the Earth to understand the story of sands and their relationships to the Mars climate changes.

We present in this paper a brief review of the distribution of sand deposits on Mars. Potential mechanism on Mars are considered, and their relative importance are evaluated. Then, a case study of basaltic sand formation and evolution is presented from three field campaigns in Iceland achieved in during the years 2004-2006. The chemical analysis demonstrates that Eldborgir lava is the source of the sand. The morphologic and mineralogical observations show how sand grains were derived from the advance and retreat of glaciers abrading recent lava flows from the Eldborgir volcano. Eolian transport has affected the mineralogy of sands relatively to the lava. A similar mechanism is likely to occur on Mars, explaining the differences of the spectral signature within dunes fields and between the volcanic rocks and the derived volcanic sands.

**Potential sand formation mechanism:** We first recall the possible mechanisms for the formation of sand on Mars given present and past likely environments:

- Volcanic activity, pyroclastic deposits can produce large amount of fine and large particles (ashes to scoria) which are then classified as sands. This process can be probably considered as a major contribution to the present mass of sands.

- By fragmentation during the strong shock waves, impact catering is an efficient process to produce particles, in particular the small ones responsible for the gardening of the superficial layers.

- Aeolian activity and abrasion or preexisting rocks. This requires the presence of sand grains formed by another process, but wind abrasion features have been found at all scales on Mars.

- Fluvial transport. Events associated with the valley networks or large outflow channels might have contributed to the formation of the present sand mass.

- Loess and some quantity of sands are also generally produced at the base of glacier to the basal sliding of by the erosive power of ice deformation and by the flow of water under the glacier on the Earth. The rate of ice deformation and the activity of water at the present surface temperature are probably not sufficient to produce sands below the glaciers. It is not yet certain is glacial flow has occurred at the base of the polar ice caps, the temperature being controlled by a poorly know heat flux on Mars. However, under the warmer climate in the past would have probably leaded to the flow of polar caps and would have probably leaded to the flow of equatorial glaciers.

- Any combination of these processes could be also invoked for the sand formation.

**Distribution of sands on Mars**

Sand is usually recognized by the dune fields, even if sand deposits do not form dunes systematically. A sea of sand extends around the north polar cap, the dunes field being covered in winter by $CO_2$ frost. Isolated or more developed dune fields are also found in numerous crater floors of the mid-latitude northern and southern hemispheres, e.g. the famous dune fields of Proctor, Hershell, Lowell, Kaiser, or Gale craters in the south, or Inuvik and Moreux craters in the north. Sand deposit can be also found along the wall of Valles Marineris, and dunes fields have been reported in Melas, Coprates, Ganges and Juventae Chasma, as well as in Noctis Labyrinthus. The caldera of large volcanoes can be also a sink for volcanic sands, as

evidenced by the black dunes of Syrtis Major. Examples of sand dunes found on the Rabe crater floor are given in Fig. 2, polar sand dunes and sands in the floor or northern impact craters are given in Fig. 3. For all the sandy regions the same key questions can be asked:
- Where is the source of sand?
- In which environment sand has been produced?
- Where are the sand transport pathways? Are those sands transported locally, regionally or globally?
- What are the relationships between the sands of the rocks?
- How the mineral, chemical and thus spectral signature differ between the sands and the source rocks?
- When did the sand form?
- Is sand still produced on the Mars surface under the present conditions?

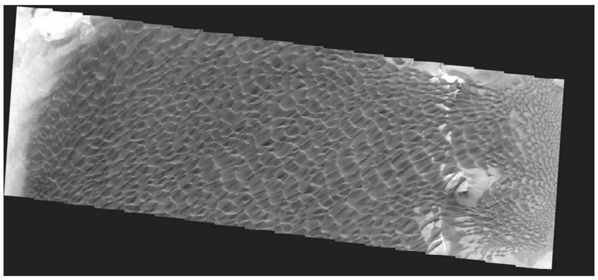

*Fig. 2. Dunes on Rabe crater floor on Noachis Terre (-43.7°N, 34.7°E). Image size: 17.7x62.7 km.*

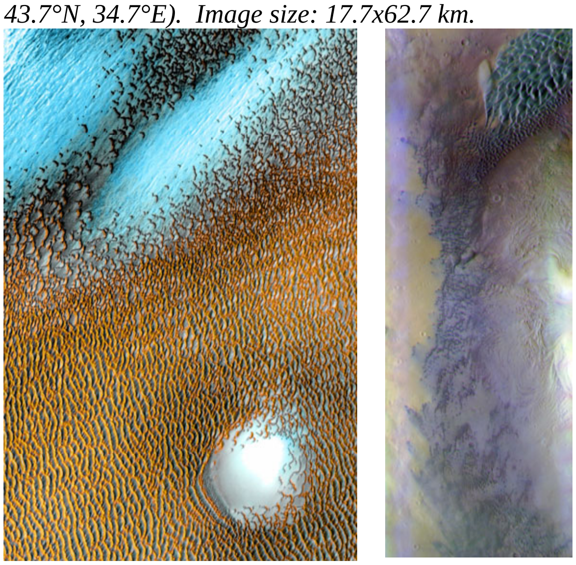

*Figure 3. Example of sand dunes. Left: North dunes deposits, right : Moreux Crater Dunes.*

To answer this question on Mars, our approach is to investigate:
1) The mineral composition of sands and rocks in the vicinity by spectral observations.
2) The surface properties of sand (grain size) by thermal and photometric observations.
3) The morphology of dunes and sand deposits
4) Terrestrial analogs of volcanic sands to establish criteria to recognize mechanism of formation, and to understand the mineralogical evolution of sands relative to the source rocks during formation and transport.
This abstract focuses on the part (4) and we report a case study south of the Eldborgir volcano, with the implications for the study of Martian sands. The source of sands in Iceland is also an opened question which has to be investigated for itself.

**A case study of in Iceland: Elborgir lava field**.

The determination of the source rock can by first suggested by the wind direction determined from eolian morphology (slip faces of dunes, or ripples). Then, the chemical and mineralogical analysis (microprobe) of sand and potential sources would confirm the actual origin of sand. Due to the large variety of volcanic rocks in Iceland, the source are potentially diverse.

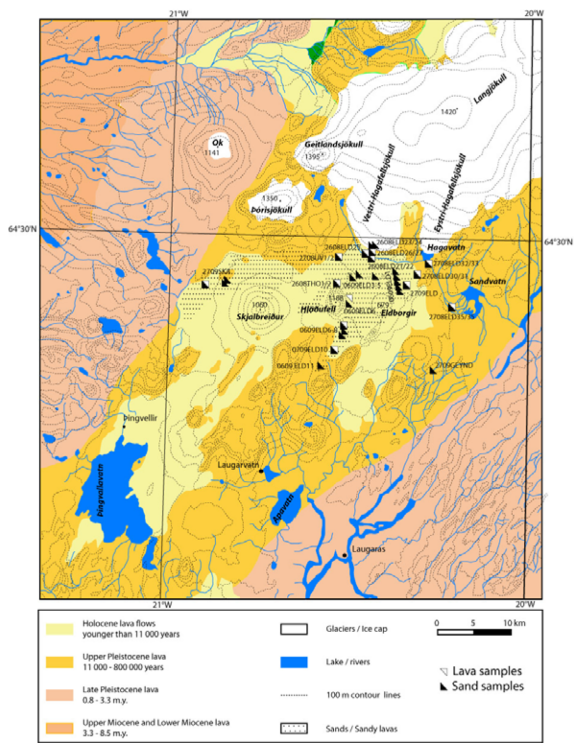


*Figure 4. Geological map with the location of sand and rocks samples at Eldborgir shield volcano.*

The investigated region is situated south-west of the Langjokull glacier. Pleistocene lavas composed the basement on which the glacier flows. More recent magmatic event along the present axis of the rifting zone is responsible for the formation of the Skjabreiður volcano and the event more recent (about 9000 years old) Eldborgir shield volcano (3000-4000 years old). The caldera of the low Eldborgir shield can be seen on the left of the Fig. 5. The lava field emanating from the Eldborgir volcano is covered by few tens to probably few meters of sands in some places. The sand deposit extends at the north to the present glacier front and about 10 km south of it. During fieldwork, we faced a sand storm of medium intensity (as seen in Fig. 5). The winds during the storm came from the southwest. However, the ripples orientation shows that prevailing winds are generally from the northeast and correspond to the strong catabatic winds from the glaciers (see Fig. 6). This wind direction was also often observed during the field campaign, especially when the weather was clear. Given the direction of prevailing winds, we had to determine if the sands originate from the recent Eldborgir lava flow or from older lava flows which are today covered by the glacier.

*Figure 5. Eldborgir lava flow and drifting sands during strong southwestward winds.*

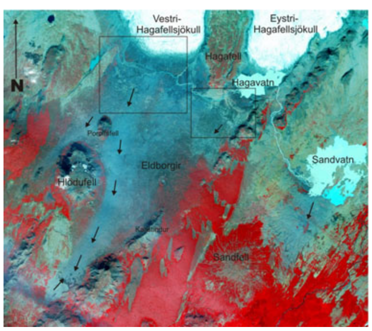


*Figure 6. Spot image with eolian directions from ripples orientations (size of the image is 15*15 km).*

**Chemical comparison of sand and Eldborbir lava.** *Chemical and mineralogical analysis (Fig. 7&8).* The chemical analysis (CRPG, Nancy) of sands and rocks show first that the major and minor elements of Elborgir lava and sands are generally strongly correlated. Then, two chemical elements, Ni and Mg are systematically enriched in the sands compared to the lava. However, this enrichment is not constant and seems to vary with the distance to the glacier. The observation of thin sections of rocks and sands suggested that the Ni and Mg enrichment is related to the increase amount of Olivine in the sands.

*Mineralogical effect of eolian transport.* The Fig. 9 demonstrates that the enrichment of olivine in the sand is explained by eolian transport of the sand found at the front of the Glacier.

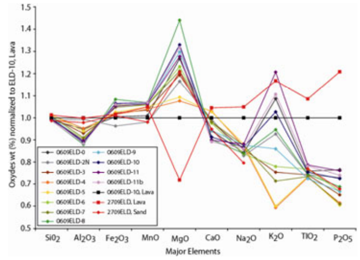


*Figure 7. Major elements analysis normalized to Eldborgir lava composition.*

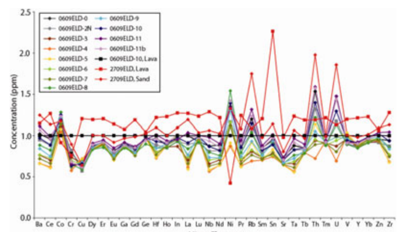


*Figure 8. Minor and trace elements analysis normalized on Eldborgir lava composition.*

An index of olivine enrichment equal to the average of the enrichment of MgO and Ni in the sand relative to the lava is plotted against an index of eolian sorting. The index of eolian sorting corresponds to the variance of the frequency distribution of grain sizes (in microns$^2$). This graph strongly suggests that highly sorted sand (with the lower variance in their grain size distribution), which have experiences more eolian transport correspond to the strongest enrichment in Olivine.

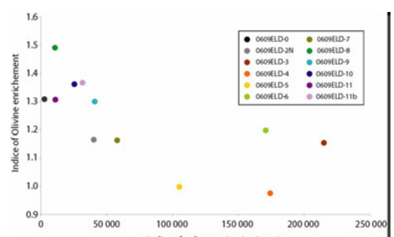


*Figure 9. Indice of olivine enrichment as a function of the eolian sorting. The most sorted material corresponds to the most enriched in olivine.*

**Origin of sand: insights from morphologic observations at the glacier front.** At the northern edge of the lava field, lavas stops before the glacier outwash plains. The lava front is not clearly visible and is buried by the latest alluvial sediments from the glacier. Nevertheless, interactions between the glacier and the Eldborgir lava flows have not been reported so far.

Glacial grooves are found in addition to eolian abrasion features on some lava rocks (Fig. 10). This grooves are localized immediately south of the glacier. Rocks exposed more south display only the grooves resulting from eolian abrasion (Fig. 10). Moraines can be also observed on the field and on satellite images (Fig. 11). The observation of erratic blocks is consistent with a glacial origin of southern deposits during glacier advances. We conclude that a part of the Eldborgir lava has been buried at least once beneath the glacier front extending at least 1 km more to the south since the last 3000 years. These observations strongly suggest that the glacier front which was much more advanced in the past has eroded the lava flow of Eldborgir. This hypothesis also explains why we could not observe a lava flow front at the front of the glacier.

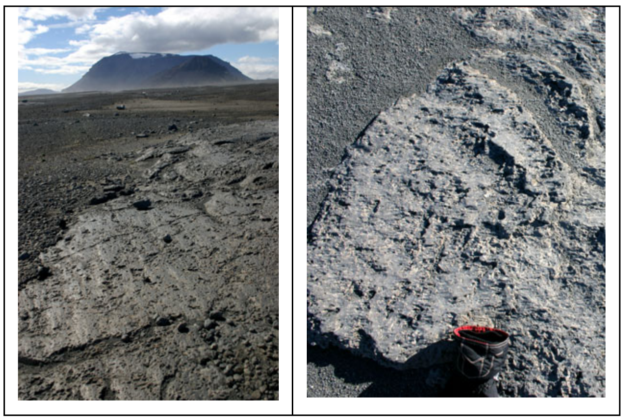

*Figure 10. Left: Grooves over lava flows at the northern edge of Eldborgir lava. View is to the south. Right: deep eolian abrasion features on volcanic rocks.*

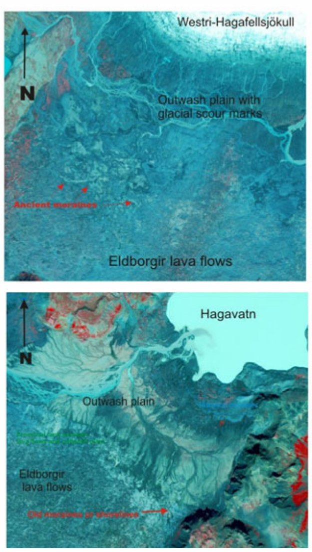


*Figure 11. Map with glacial features and lava flows. (a) At the northern edge facing the westin-hagafellsjökull (b) At the NE edge facing the Hagavatn and the Eastin-hagafellsjökull.*

**Conclusion.** *Formation and transport of Eldborgir sands.* The distribution of moraines and erratic blocks at the glacier front demonstrates that Eldborgir lava flows formed during a period of glacier recession. Glaciers advances following that period have likely buried and eroded the front of the Eldborgir lavas over about 1 km large southward and 10 km long. The retreat of the glacier has left eroded blocky and sandy material forming in part the alluvial sediments of the outwash plain. The sand grains left at the base of the glacier were then transported by catabatic and prevailing winds along the Eldborgir lava field, extending south of the source region. The drifting sand on the lava was then very efficient to abrade the lava over at least ten centimeters in some places (very deep abrasion features are observed). The abrasion eventually increased significantly the volume of basaltic sands initially produced by the glacier. The sorting of sands during eolian transport was responsible for the increasing amount of olivine in the sands relative to the lava.

*Implications for sand formation and transport on Mars.* First of all, we observed that advances and retreats of glaciers on lava flow are efficient to produce sand, loess forming alluvial deposits. When these deposits are with the strong catabatic winds blowing on the fresh lava flows, large amount of sand can be produced in probably less than a few hundred of years, on the Earth. It would be exciting to be able to find past environments on Mars where similar a mechanism was responsible for the formation of volcanic sands, keeping in mind that the main difference between terrestrial and Martian glaciers are the activity of liquid water. The chemical and mineral composition of sands derived from the lava source remained a good indicator of the nature of volcanic rocks. However, eolian transport, and probably eolian sorting has eventually resulted in an increase of the olivine concentration in the sand relative to the lava. The mechanism responsible for olivine concentration is not clear (preferential transport depending on grain size, preferential weathering of other components of the rocks, in particular the glassy component, and further work should be done in this direction to understand how this process could translate into the Mars environment.

**References:** [1] Fenton, L. K. (2005), J. Geophys. Res., 110, E11004, doi:10.1029/2005JE002436. [2] Poulet, F., et al., (2003), Astron. Astrophys., 412(19–23), doi:10.1051/0004-6361:20031661. [3] Fenton, L. K., et. al (2005) J. Geophys. Res., 110, E06005, doi:10.1029/2004JE002309. Themis images are extracted from Christensen, P.R., N.S. Gorelick, G.L. Mehall, and K.C. Murray, *THEMIS Public Data Releases*, Planetary Data System node, Arizona State University, <http://themis-data.asu.edu>