Final report of the OTKA/NKFI COOP_NN_116927 project titled
"Sedimentary analysis of Mars using
Earth analogues, and connection to European space project"

During this research project the following topics were developed in synergy with each other: 1. development of field surveying instrument, 2. laboratory analysis of field collected samples, 3. extrapolation to Mars to support the activity of ExoMars rover, 4. joint work with ESA experts and other researchers from foreign institutes to interpret the major findings and apply them to future missions.

Development of a borehole-wall scanner

An instrument was developed in this project (Fig. 1) capable of scanning borehole walls with diameter ranging from 2.7 to 5.0 cm, and record the wall with 0.1 mm spatial resolution down to a 2 m depth. Figures 2-5 show the mechanical motor (Fig. 2), various parts before assembling (Fig. 3), the telescopic rod (Fig. 4) and the complete system in the field (Fig. 5). The instrument was used at several sites, including Hungary (Kelemenszék szikes, Kiscelli Agyag Formáció, Törökbálint Homokkő Formáció, Mogyoródi vulkanikus tufa), at the Atacama and Tabernas Deserts.

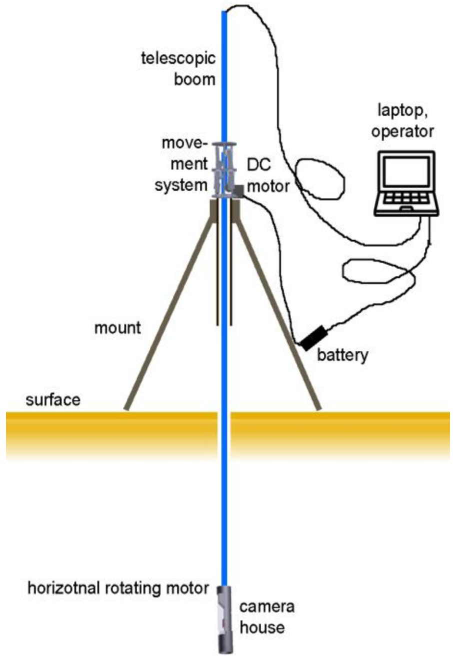

Figure 1. Generalized structure of the instrument.

The analyses of images recorded by the instrument revealed those basic information types, which will be acquired during drilling and related scanning performed by the ExoMars rover on the red planet using its MaMISS instrument. Among the recorded features grain size distribution, grain deformation, aggregation, phyllosilicate grains attached to larger grain surfaces and some layering were identified. The recorded borehole-walls showed wide range of appearance with various structures, including drilling artefacts and fallen out segments pointing to the cohesion of target rocks.

The acquired scans in the boreholes helped to separate the sedimentary and volcanic target types. It was also demonstrated how the obtained context information can be linked to laboratory analyses results. A first paper on how the instruments could support field activity was presented in Open Astronomy, a peer reviewed journal.

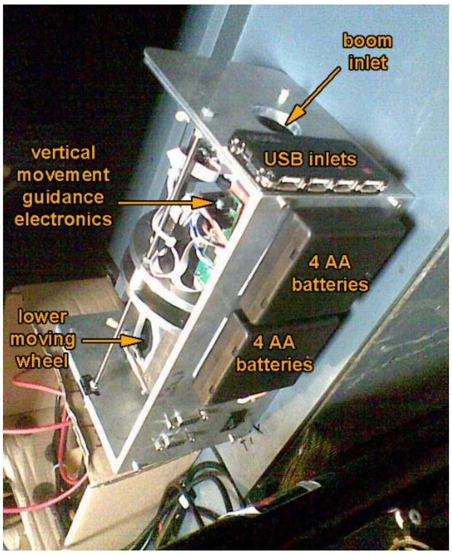

Figure 2. Sideway image of the motor and wheel system

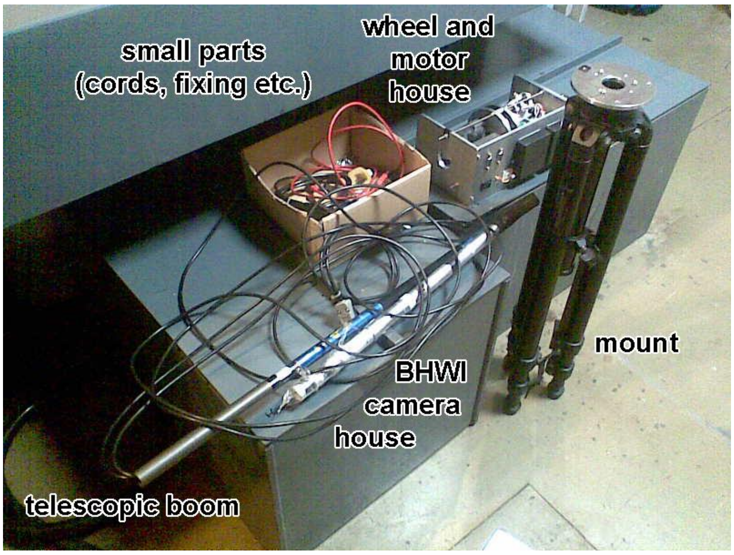

Figure 3. The main parts of the instrument kit for travel.


Figure 4. Aluminum “strut” that replaced the telescopic boom

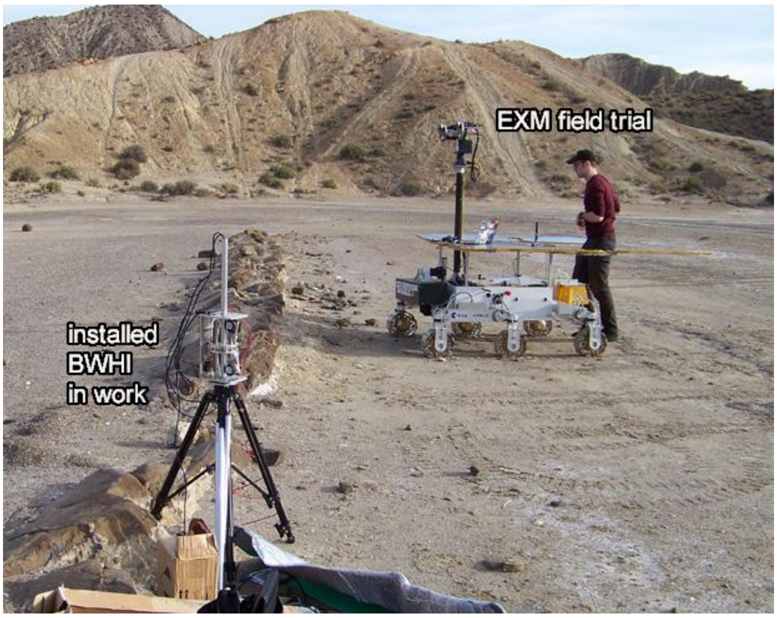

Figure 5. The instrument at work at the Tabernas filed site during the EXOFIT campaign (2018 autumn)

Field works

Field activities were realized in Hungary, Morocco, Chile (Atacama Desert) and Spain (Tabernas Desert and Sao Miguel Island). Among the targets evaporate rich desiccated terrains and volcanic terrains including tuffs, weathered andesite, and basalt-andesite sites were surveyed. Desiccated ephemeral lake basins were also surveyed in the Ojos del Salado volcano in the Atacama-desert, and in the Tabernas Desert in Spain. During this work geomorphological analysis, sample collection, together with drilling and borehole wall scannings were realized. The results covered wide range of topics: a Mars relevant new water flow regime could be discovered, evaporates showed variable water content, and wet weathering products in volcanites, including smectites in the basalts of Sao Miguel Island were found.

Based on **morphology and their spatial occurrence** of borehole-wall images (Figure 6), the following groups could be separated of grain occurrence:

a) larger (mm sized) roughly rectangular shaped grains → in volcanic/magmatic targets,
b) similar sized rectangular grains occurring close to each other as a densely arranged group, what could be sedimentary but also magmatic/volcanic in origin, here the later was observed only,
c) small (sub mm) isometric grains with size around the limit of spatial resolution → occurs in several target material types,
d) larger (mm sized), very rugged outline grains → in sedimentary targets, possibly aggregates loosing parts along their outer edges,
e) larger (mm sized or above) grains with many further attached small grains, with small voids between them could be aggregates, and demonstrate fractal-like appearance,
f) similar pattern to "e" group but on larger area of the borehole-wall (also presenting somewhat "fractal pattern") and also points to sedimentary origin,
g) grains far away from other grains are more characteristic for sedimentary than volcanic/magmatic sites.

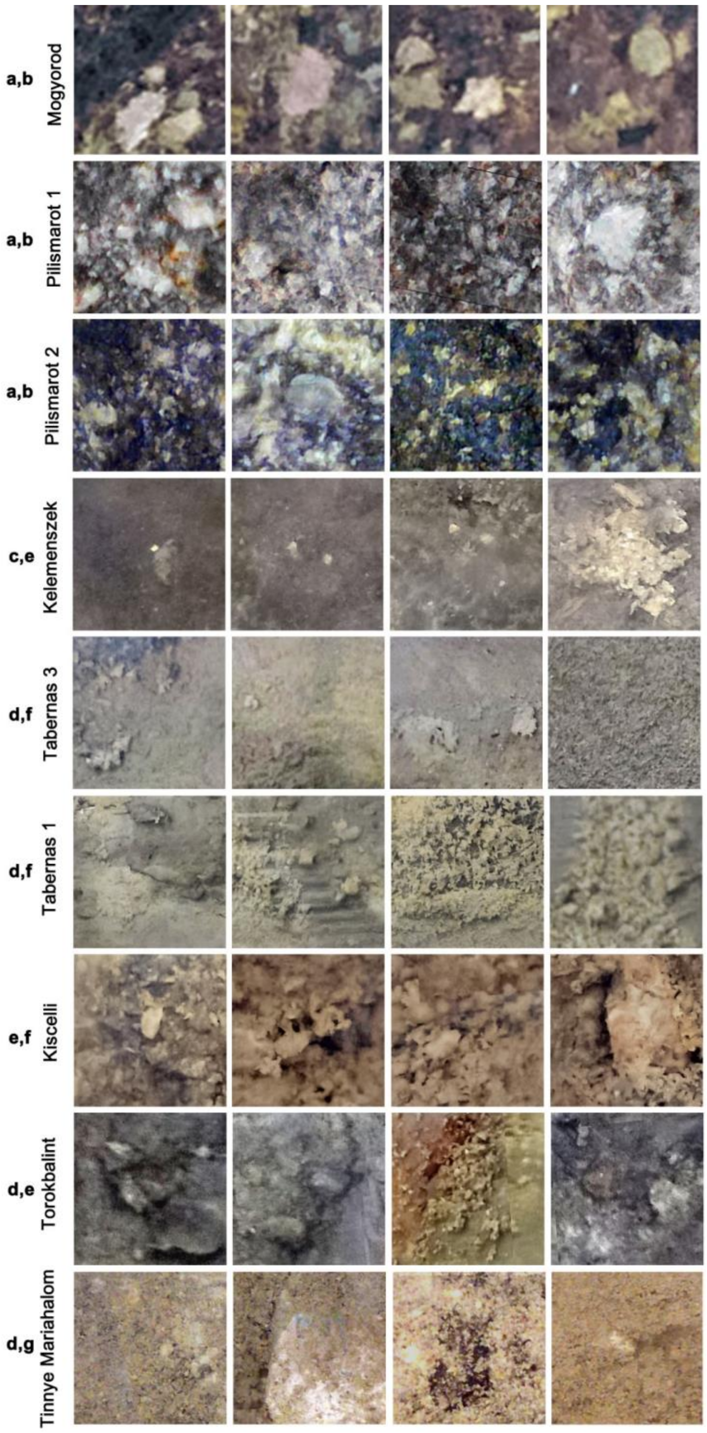

Figure 6. 5x5 mm sized examples for the grain arrangement types, where the first three rows are volcanic, the lower six rows are sedimentary sites.

The above listed observations reveal that some characteristic of the grains may indicate the origin. Some examples are visible in Figure 6 grouped according to the above listed categories.

Figure 6 also shows the general differences between magmatic and sedimentary sites. While magmatic ones are more homogeneous and do not show large aggregates, sedimentary type sites are more heterogeneous in appearance, and can have relatively large aggregates. Smeared grains occur only here, and small scale surface heterogeneity produced fractal-like pattern exclusively emerges in this group.

Laboratory works

The particle size, shape, surface texture and composition of aeolian and fluvial sedimentary samples were analyzed and compared using optical microscope-based automatized image analysis, in order to suggest indicators providing means to discriminate these two transport modes on Mars. The principal goal was to assess if such indicators – established on Earth – could be used on Mars aiding interpretations on the origin of sediments analysed by the ExoMars 2020 rover during its mission. Wind and water transported sand from, respectively, the Sahara Desert and Maros river bar in Hungary were investigated and treated as mainly aeolian and fluvial end-members. In addition, two Mars-analogue aeolian and fluvial basaltic sediments from Iceland were analysed in a similar way (Figure 7).

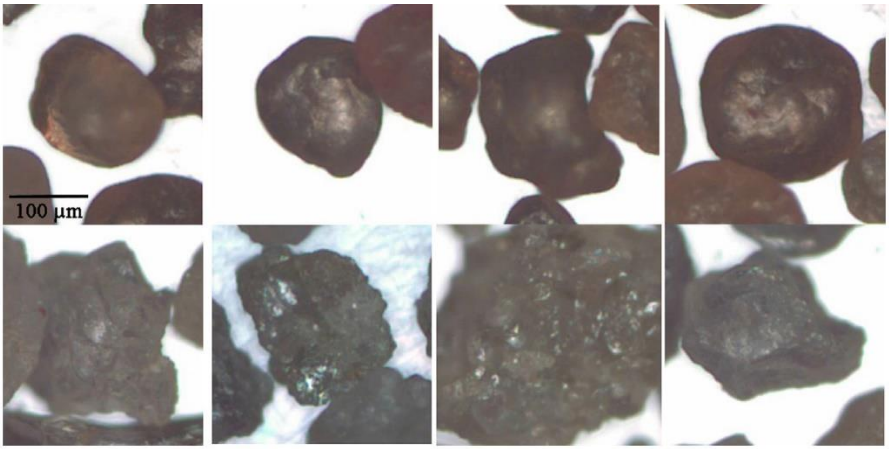

Figure 7. Example particles from the different size classes in Sahara sand (top) and Maros sand (bottom). Inset dimensions are 1 x 1 cm. Note the different surface textures and grain shapes.

Our analyses demonstrated that useful parameters for the distinction of aeolian and fluvial transport included the degree of sorting, the grain diameter/perimeter ratio, circularity (reflecting the sphericity of the grains) and convexity (showing roughness of the grains) of particles. Mature aeolian sands are always well-sorted with high diameter/perimeter ratios since they are dominated by rounded grains. Differences were observed in both surface textures and the range of mineral compositions, wherein the aeolian samples reflect a more mature state. Separation of the two Icelandic samples with different origins was less straightforward due to both shorter transport distances and the fact that the fluvial sample was made of scoria, although intermixing of grains with a probable aeolian origin could also be determined. These characteristics of grain size and shape parameters are potential indicators which enable rough separation of the two transport modes, and their determination is shown to be feasible using high resolution Close-UP Imager (CLUPI) observations by the rover. Nonetheless, knowledge of the geological context – for instance sedimentary facies, layering, sorting of the sediments and grain shape – is a requirement for proper interpretations. These sedimentary features could partly be determined by the instruments onboard the rover: MaMISS, CLUPI and PanCam.

Differences between aeolian and fluvial grains are expected to be more pronounced on Mars than on Earth due to the episodic and likely short-term subaqueous transport, as opposed to the long-term activity of wind. However, future interpretations of the ExoMars 2020 rover images of Martian sedimentary grains will be hampered by the limited knowledge of fluvial/aeolian transport on Mars. Based on our results, future research should focus on determining the dominant transport mode of any sediment and the degree of grain mixing, which strongly influenced by the transport mode.

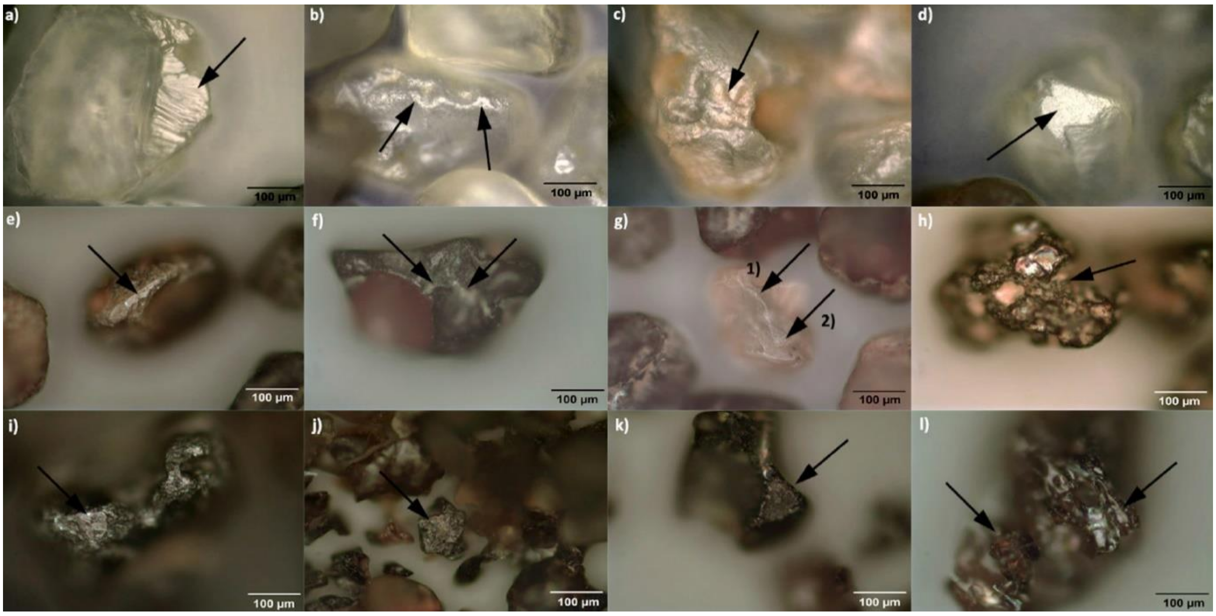

Figure 8. Some morphological features on different grains from Maros (a), Sahara (b, c, d), ISAR aeolian (e, f, g, h) and ISAR fluvial sand (i, j, k, l). Images obtained by optical microscope with 20 times magnification. The arrows show the specific identification marks of upturned plates in the Maros (a) sand, Sahara sand (d), ISAR aeolian (e, g – 2 row) and ISAR fluvial grains (i, j, k); meandering ridges on the Sahara sand (b) and ISAR aeolian grains (f, g – 1) row). Crystalline overgrowths can be seen in (c). Examples of the more problematic grains from the ISAR samples can be seen in h) and l).

The analysis of Mars-relevant basaltic grains transported by water and wind were compared, using optical microscopy, Raman and EPMA instruments (Figure 8). Results of the microscopic grain surface analysis were also compared to those on quartz and identified some features already recognized on quartz in different environments on Earth (conchoidal fracture, different steps or marks (fluvial); upturned plates, bulbous edges, chemical precipitation, dissolution etching (aeolian)). However, several previously non-classified ones were also identified. The large diversity of grain surface micro-morphological features is more difficult to interpret than those using only quartz grains, but several exist (aeolian: upturned plates, bulbous edges; fluvial: conchoidal fractures, percussion marks) that support the separation of wind and fluvial transport agents. This may support the environmental reconstructions on Mars. The relationship between grain surface types and morphological features observed on borehole-wall scans should be further developed for paleo-environmental reconstructions on Mars by the sampling of ExoMars rover.

Further, more detailed analysis of grains from 0.5 mm to 1 mm in size showed much more diverse and exotic surface micromorphology than that of quartz (Figure 9 and 10). Some quartz type micro-textures could be identified by SEM pictures: conchoidal fracture, different steps or marks (fluvial); upturned plates, bulbous edges, chemical precipitation, dissolution etching (aeolian). We found several micro-textures, which were not similar to the precious features like cracked surface, isometric shape with rough surface pattern, depressions with different size and shape.

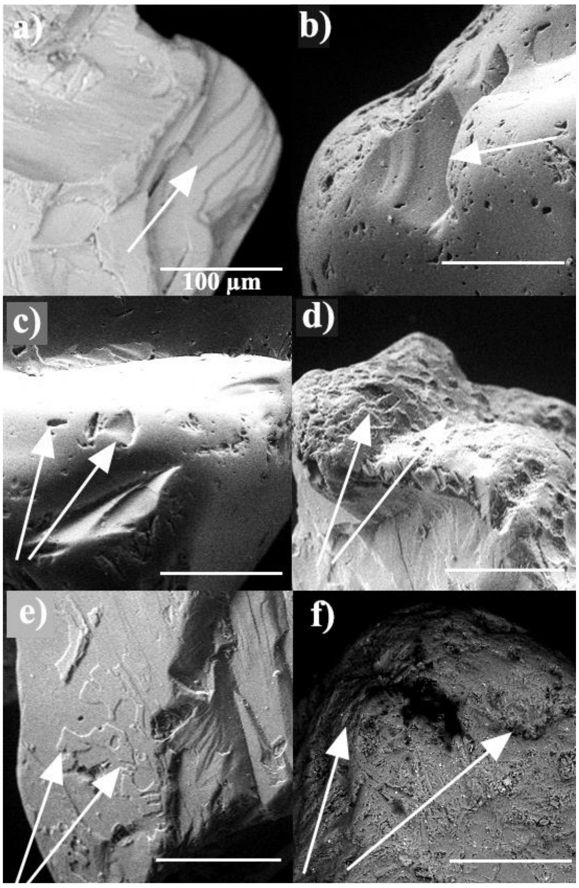

Figure 9. Some identification marks on different fluvial grains from Azores Islands. The specific identification marks are the straight steps (a), conchoidal fracture (b), percussion marks (c), dissolution etching (d), precipitation features (e) and the isometric shape with rough surface (f) can be seen on the pictures. The white arrows show the identified micromorphologies,

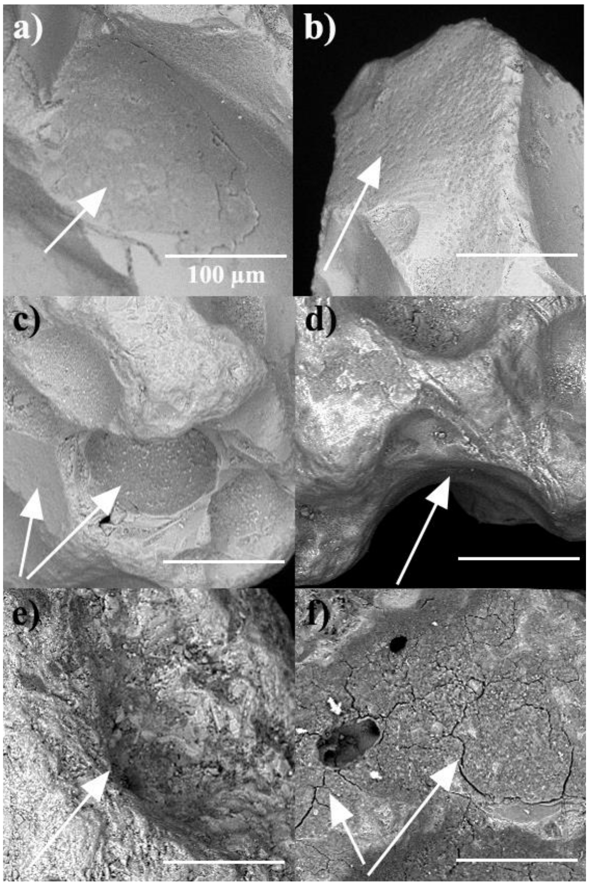

Figure 10. Some identification marks on different aeolian grains from Iceland. The specific marks are the precipitation features (a), dissolution etching (b), large voids and abraded surfaces (c), bulbous edges (d), depressions (e) and cracked surfaces (f) can be seen on the pictures. The white arrows show the specific micromorphologies,

Discussion

Using the results of grain size and shape observations, identification of the related transport mode is possible on Mars, as the difference between mature fluvial and aeolian basaltic grains seem to follow major characteristics on those observed on Earth. The CLUPI detector onboard the rover must use large enough magnification. As displayed in Figure 11, major characteristics in grain shape can be identified above a certain magnification. The potential discrimination of transport types could further be improved by the analysis of micro-morphological features on grain surfaces. However, this would need further improvements in our knowledge on surface features of basaltic grains.

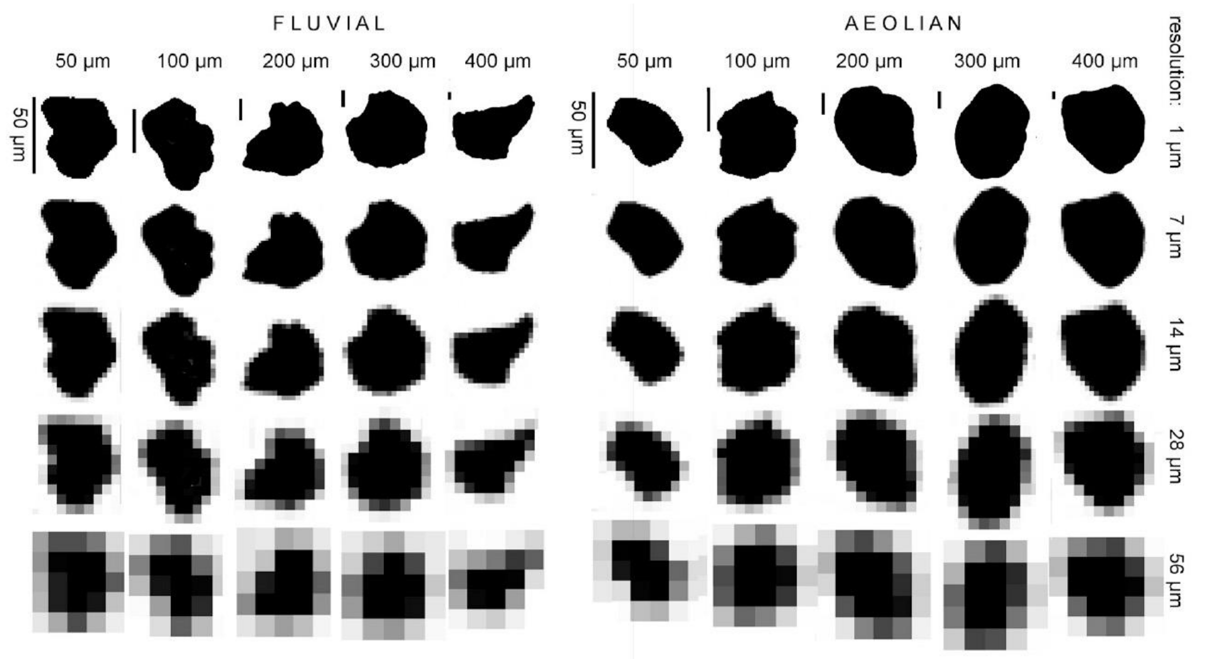

Figure 11. Images of aeolian and fluvial grains of different size with spatial resolutions of 1, 7, 14, 28 and 56 µm. Approximately 14 µm is the planned maximal resolution of CLUPI.

While the imaged grains (separated from their original environment they were embedded) do not provide sedimentary information beyond the physical scale of the grains; layering, imbrication and vertical trends in the borehole gained by the wall scanning provide various context related sedimentary information. Comparison of the expected findings of an optical and infrared borehole-wall scanning could provide relative insight into the potential information that can be gained solely from the collected sample ("no scan" column, Table 1).

Table 1. Comparison of various observable characteristics of optical ("opt. scan" column) and infrared ("IR scan" column) borehole-wall scanning, and the lack of borehole-wall data using information only from the investigated sample ("no scan" column, only laboratory analyses). The used values: 0 - no data, 1 - moderate, 2 - robust information.

characteristics	**opt. scan**	**IR scan**	**no scan**
original grain separation	2	1	0
grain size	2	1 or 0	1
grain orientation	2	1 or 0	0
transport mode identification	2	1 or 0	1
presence of aggregations	1	0	0
cement between grains	2	1	1
vertical trend	2	1	0
layering	2	1	0
mineral type identification	0	2	2
hydrated minerals	0	2	2
clay fraction	1	2	2
weathering products	1	2	2
erosion, desiccation surfaces	2	1	0

Table 1 demonstrates that MaMISS (onboard the rover, IR column) will have a chance of providing unique information which otherwise could not be gained by the mineral analysis of other instruments like MicrOmega and Raman ("no" column). These latter provide similar datasets, which are not really complementary to each other in identifying sedimentary features. It is worth mentioning that MaMISS will focus on the infrared region, where the optically identified features are less obvious and could be more difficult to identify.

4.1 Mission relevant technical suggestions

Based on the lessons learned during the comparison of field and laboratory results in this project, we demonstrated that recording the borehole-wall with optical instrument during/after drilling on Mars will potentially support the paleo-environment reconstructions with data types and specific information that would have otherwise been lost during the common laboratory analyses of samples collected from the borehole. These imaging data will be complementary to compositional data gained subsequently. Because of the lack of plate tectonism and low geothermal gradient on Mars, even Ga old sediments should provide observable features, which are especially important for targeting Mars sample return and later crewed Mars missions. The achieved findings provide suggestions to optimize working strategies, which are mainly related to the complementary characters of imaging and compositional data. These strategic findings are listed below.

- The heterogeneities of borehole-walls shown by **optical analysis reflect mainly structural and not compositional differences**. These structural differences point to depositional conditions, with changing grain sizes related to the transport energy, encrustation during deposition, and sediment remobilization processes. In the workflow of EXM sample transport, imaging with CLUPI will be taken from the sample delivery position.
- In most cases the alternation of sedimentary layers is related to the change in the depositional environment without substantial change in the composition.
- The relative importance of **information loss during sampling and crushing** will be the highest at the sedimentary type scenario sites, less at the regolith type sites and even less at the volcanic scenario sites.
- Occurrence of fine grains has specific importance: phyllosilicates as important targets might be smeared during drilling. The mechanical behaviour of such minerals could be linked to compositional data. Clay-sized grains could also appear in the borehole-wall dataset as **small grains attached to the surface of larger ones**. This binding may be lost during crushing and retained only for a subordinate fraction of clay sized grains in the pulverised sample.
- **MicrOmega** instrument onboard the rover is able to make targeted analysis of specific grains (grains of interest); the borehole-wall scanning could provide useful information on their potential occurrence along the vertical column.

International collaborations

In September 2018, we contributed to the ExoMars rover field testing in the Tabernas Desert, Spain, where borehole wall scanning was performed using the instrument developed in this project (Figure 11).

Although the three drillings were made in resembling target rock types, they still seem to be different in appearance, as demonstrated in Figures 13-15.

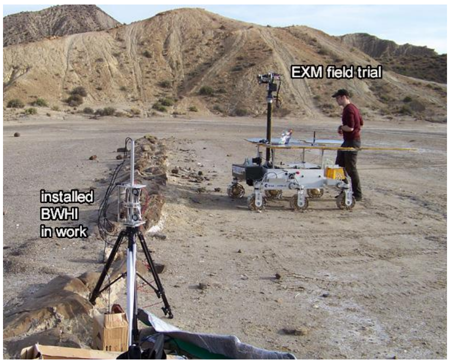

Figure 12. The BHWI (left) with the test rover (right)

Figure 13. Mosaic of the Tabernas 1 site.

Figure 14. Mosaic of the Tabernas 2 site.

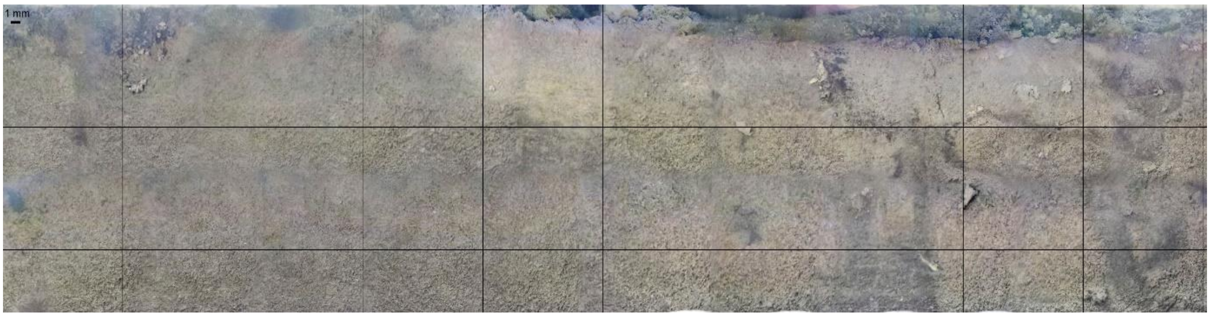

Figure 15. Mosaic of the Tabernas 3 site.

Supported by the results gained in drilling and borehole-wall analysis in this project, Kereszturi A. project member was invited to participate in the mission proposal of NASA, titled Gangotri, which is aimed at drilling a middle latitude ice-rich site on Mars.

Further international collaborations were realized under the project:

- joint evaluation of rock type appearance with CLUPI camera simulator (will be onboard the rover) using the sample collected at Azores Island, together with Keyron Hickman Lewis (Centre de Biophysique Moléculaire, CNRS Orleans Campus, France),
- joint compositional analysis of ESA2C samples with ESA and Natural History Museum of London.

These two subprojects are ongoing and results are expected in the near future.

National collaboration:

- instrument development: joint activity with BME, BMFSZ and Kolorprint Ltd

- PhD courses held at ELTE University, Mohammed Amine Ettahri produced a landing site evaluation work for the Mawrth Vallis region of ExoMars rover
- MSC courses at ELTE University: Steinmann Vilmos produced a student research work on the Oxia Planum candidate landing site, evaluating outcrop occurrence and slope angle values
- Joint field work was realized with researchers of ELTE (Atacama Desert, Nagy Balázs, Leél-Össy Szabolcs, Aszalós Júlia),