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**Review of the PhD dissertation**

**"Aeolian Transport on Mars in Meridiani Planum"**

**submitted by MSc. Joanna Kozakiewicz**

## Scope and purpose

NASA's Opportunity rover landed at Meridiani Planum, which like many places on Mars, has abundant sand cover, resulting in bedforms some of which may still be active in spite of the low atmospheric pressure of Mars. This PhD dissertation is about determining constraints on sand dynamics at Meridiani Planum, as an example of a bedform-rich area on Mars, and also on planetary bodies having an atmosphere. It discusses the current existence, mechanisms, and intensity of aeolian erosion in relation to its morphological expression, wind transport, and article properties.

## Structure and content

The main body of text is short. It introduces and synthesizes the work, and is followed by two published (long) articles which expose the main methods (article 1) and results (article 2).

- **The main body of text** presents the objectives of the work. The state of knowledge section provides all the necessary information on Mars, the state of the art in the understanding of aeolian transport, and the geological description of the study area in relation with the results obtained by Opportunity. It goes then to a rather comprehensive literature review on the rocky materials and aeolian transport at the Opportunity landing site specifically.

The data and methods are then shortly presented (details are mostly in Article 1). A broad range of methods were used in the dissertation, all oriented toward constraining aeolian transport as accurately as possible. This diversity includes semi-automatic determination of grain shapes using a new algorithm (described and tested in Article 1), spectrometric and geochemical analysis, and photogrammetric analysis, all using the relevant datasets from the Opportunity rover instruments. The results of numerical models of wind velocity arising from published literature were also used.

The methods were applied to all the sediments located along the Opportunity traverse. The results (published in Article 2) highlight a lack of sands of medium size, which is attributed

to trapping in the interior of the larger craters. The bedform types are classified and correlated with grain size abundances, density, and shape, and with results obtained in previous works.

- **The first article**, published in Springer's *Earth Science Informatics*, presents the Particle Detection and Measurement (PADM) algorithm for semi-automatic grain size and shape determination. Since Joanna Kozakiewicz studied aeolian transport along the whole Opportunity traverse, measuring tens of thousands of individual grains, it is readily understandable that a new, semi-automatic algorithm had to be developed for this work. The methodological background in the article clearly shows the shortcomings of earlier methods, and the need to developed a more suitable and simpler method to serve the objectives of the PhD work. The steps of the PADM algorithm are presented. The algorithm is tested using synthetic binary images, and against outputs obtained by two algorithms developed earlier and applied to three terrestrial sands of different properties. After demonstrating the efficiency (speed and quality of results) of the PADM algorithm, it is finally applied to images obtained by the MAHLI and MI images on Opportunity. A graphical interface was developed for PADM, which makes it readily usable by the community.

- **The second article**, published in Journal of Geophysical Research – Planets, exposes the results of the application of the PADM algorithm to 70 000 individual sand grains on 184 sediment targets along the 45 km-long Opportunity rover traverse, to which additional methods published in the literature are added. Grain analysis made use of all the image data available on the Opportunity payload. This includes images from the microscope imager of Opportunity (MI), the stereoscopic panchromatic images from the rover Navigation Camera (NAVCAM), and the panchromatic and colour composite images of the Panoramic Camera (PANCAM). Images are complemented by chemical analysis coming from the Alpha Particle-X-ray spectrometer (APXS), located with the Front Hazard Avoidance Camera (FRONTCAM). The APXS data were used to retrieve grain density via CIPW norm calculation.

Three image targets were identified: regolith, hard rock, grain on rover magnets. The sand grains were studied for granulometry, shape (circularity, aspect ratio, roundness), composition, density and geomorphological occurrence, making meaningful grain population statistics possible using four parameters: mean, standard deviation, skewness, and kurtosis.

It emerges from this analysis that Opportunity crossed two sand units, which differ in FeO content, and also, for the coarser sand grains only, in size and shape. The similarity of parameters for fine sands is interpreted as a consequence of easier small size particle transport and blending by wind.

From the three grain populations, a bimodal grain size distribution was found, with a quasi-absence of grains of medium size, in contrast with sands along the Curiosity rover traverse

in Gale crater. It is argued that among the hypotheses that would explain this observation, the most likely is grain saltation to the interior of impact craters outside the Opportunity traverse, where the steep walls acted as a trap and favoured their accumulation in dunes.

The joint examination of grain parameters and statistics allows the author to infer formation mechanisms for coarse-grained sand ripples, and discuss them in great detail.

The supplementary material annexed to the second article discusses issues arising in applying the methodology to real sand particles, and also makes available all the details of the analyses performed.

**Evaluation**

The subject and objectives are well introduced before the two articles. The structure is good and the writing concise and pedagogical, the approach is logical and rigorous, which makes the manuscript enjoyable to follow.

Both articles are published in very good peer-reviewed journals. The PADM algorithm was thoroughly tested, which makes the reader of the second article confident in the results presented.

The robustness of the methodology and the very large number of sand grains investigated make the statistics reliable, and the level of details which can be achieved in characterizing aeolian transportation and sedimentation is remarkable. The explanation given to the surprising absence of medium-sized sand grains is one of the most interesting results of this work, shedding light into overlooked aspects of sand dynamics on Mars. The quality of the information obtained from grain parameters and statistics benefits the analysis of the formation of coarse-grained ripples, which is discussed with excellent scientific control.

I was perhaps the most impressed by the general approach. After the dissertation objective is defined, we get a long paper which develops the new methodology that was required to pursue this objective using rover data. Then, we get an even longer article (30 pages along with 27 pages of supplementary material) which demonstrates the results. This simple structure gives coherence, robustness, and clarity to the work. While there was enough material to publish more papers, this doctoral thesis showcases the efficacy of producing fewer, higher-quality papers, which not only strengthens scientific inquiry, but also improves readability and amplifies the impact of the research.

*Wind as a Geological Process on Earth, Mars, Venus and Titan* is a seminal book written by Ron Greeley and James Iversen and published forty years ago. The work conducted in this PhD as reported in this dissertation reminds me, and may be viewed as, a major update to some of the most interesting and promising chapters of this book. It has implications for the future understanding of the dynamics of aeolian bedform on Venus and Titan too, as well as on Pluto and cometary nuclei, as claimed in the introductory and synthesis chapter at the beginning of the manuscript. After reading the second article, I would have been

delighted to have a word more on such perspectives. Joanna Kozakiewicz also entertains the prospect of implementing artificial intelligence techniques to fully automate the PADM algorithm "in the future". I would be happy to hear whether such a future is in her own plans.

The PhD dissertation of Joanna Kozakiewicz sheds an original light into the problem of aeolian dynamics on Mars, demonstrating a thorough mastery of the underlying concepts. It shows that she has the method, skills and breadth of view allowing her to continue research as a leading specialist in the dynamics of aeolian processes.

This is an excellent work, and this dissertation fulfils all the requirements for the degree of a Doctor of Philosophy as specified in *art. 13 ust. 1 Ustawy z dnia 13. 03. 2003 r. o stopniach naukowych i tytule naukowym oraz stopniach i tytule w zakresie sztuki*. Therefore, I give my express recommendation for the admission of the candidate to the defence of this dissertation for the degree of a Doctor of Philosophy.

Daniel Mège, 03.04.2024 r.