Theses of Ph.D. Dissertation titled

REMOTE SENSING AND MORPHOLOGY:

GIS-based integration of orbiter datasets for the investigation of ice-related slope features on Mars

ANDRÁS SIK

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I. INTRODUCTION, OBJECTIVES

Mars is the most extensively investigated, most dynamically changing and most exciting planetary body of our cosmic environment. From the last years of the XX. Century, minimum half of the resources expended for the exploration of the Solar System has been oriented to the research of this peculiar world. I became a geographer partly because of this planet: in the secondary school's astronomy club we discussed about its surface morphology more and more often, and among my subjects the geography was in the strongest relation with the examination of the planets and moons. During my university years this relation deepened, I have analyzed the planet's surface morphology in my diploma thesis and along my Ph.D. studies as well, meanwhile I became the member of the Mars Astrobiology Group (a research team operated in Collegium Budapest – Institute for Advanced Study and supported by the European Space Agency), which deals with a hypothesis developed by Hungarian scientists about the habitability of the recent Martian surface conditions.

Thus my dissertation represents only a part of my Mars-related research activity, furthermore besides my own results contains general chapters as well. Its objectives are the following:

- brief overview in Hungarian language of the milestones of Mars research and of our widely accepted, up-to-date knowledge about the planet;
- detailed description of the remote sensing/GIS methodology and data sources' web pages needed for the analysis of the planet's surface, which hopefully constitute useful guidance for the beginner Mars scientists of the future in the more and more complicated labyrinth of different Martian space probes, instruments, spatial reference systems, data sources and file formats;
- development of a computer-assisted methodology – and as far as I know, in Hungarian language gap-filling documentation of it – which allows the integrated management, map visualization and interpretation of satellite images and other type of planetary datasets from different orbiters by a general purpose GIS software package running on Microsoft Windows operation system;
- by the usage of this methodology presenting some morphological analysis examples of the mid-latitudinal regions' periglacial debris aprons and interpreting their origin based on four study areas;
- by this methodology as well, the morphological analysis and interpretation of the active surface processes in the slope streaks forming on the subpolar regions' dark dune fields, based on four study areas;
- illustrating that recently detailed morphological analysis can be carried out already on other celestial bodies' surfaces as well, so planetary science could be considered as the planetary extension and as a promising future sub-discipline of physical geography.

II. METHODOLOGY, or HANDBOOK FOR BEGINNER MARS SCIENTISTS

The investigation of planet Mars recently – instead of telescopic observations – carried out by space probes. For my eight study areas, I have selected and downloaded the optical satellite images, digital terrain models (DTM) and other type of planetary datasets acquired via remote sensing techniques by orbiters' instruments from public internet databases, then I have processed, integrated and analyzed them in ESRI ArcGIS Desktop 9.3 GIS software environment.

Meanwhile I had to solve many technical problems, mainly because of the files' different spatial reference systems (spheroid, graticule, projection), scales and format parameters (byte order, spectral resolution, file layout, pixel type, processing level, extension) – so I compiled a detailed, handbook-styled technical description representing all the practical experiences I have gathered over the years in the processing of different Martian data sources.

After the overview of the available global Mars maps, internet data sources, web-based data search opportunities and specifications of the most commonly used datasets, I have explained every step of the data integration methodology I suggest to apply:

- opening a new Data Frame in ArcMap, changing the store option for path names to relative;;
- setting the spatial reference system of the Data Frame;
- creating a new File geodatabase in ArcCatalog, into which every raster-, vector- or table-format data source can be loaded, except the extremely large file sized MRO HiRISE images;
- MGS MOLA DTM is the most practical basemap, because in the last years the MOLA spatial reference system became a widely accepted standard in the world of Martian GIS;
- changing the Data Frame's display units to „Decimal Degrees" – for the easier orientation on the surface of the planet;
- setting the central meridian of the Data Frame (0° is the practical choice);
- in ArcCatalog, its own spatial reference system should assigned every data file;
- integrating the global coverage footprint files of the different data sources;
- based on these, selecting and downloading all available data files for the analyzed region;
- if needed, georeferencing of these data files, following the MGS MOLA DTM → MGS MOC WA → MO THEMIS → MEX HRSC→ MRO CTX → MGS MOC NA → MRO HiRISE sequence;
- performing the GIS analyzes and storing their results in the File geodatabase;
- 3 dimensional visualization of the results.

III. CONCLUSIONS

III.1. Methodology

Data processing

1) I have briefly reviewed the milestones of Mars research and our widely accepted, up-to-date knowledge about the planet, as well as the basic principles of its remote sensing/GIS-based investigation.
2) During the compilation of my practical experiences and the detailed morphological analysis of my selected eight study areas I have processed approximately 400 data files with diverse data type, spatial reference system or projection, scale, file structure and extension, acquired by 11 instruments on four different orbiter space probes. From these I have created one global and eight local MARSGISs and corresponding .MXD format ArcMap documents, respectively, which altogether represent about 75 GB of scientific data (this amount could be stored on 16 standard capacity DVD, therefore I have used a HDD hardware for archivation purposes).
3) I successfully accomplished the GIS-based integration, map visualization and interpretation of satellite images and other type of planetary datasets from different orbiters without the usage of any special planetary computer program, only by a general purpose GIS software package running on Microsoft Windows operation system, namely the ESRI ArcGIS Desktop 9.3 platform. During this I came to the conclusion that the MOLA spatial reference system should be uniformly used in any Martian GIS (but with an IAU2000 ellipsoid radius-based spheroid-shaped body, instead of the IAU2000 ellipsoid itself), and for global MARSGIS the Equirectangular (Simple Cylindrical) projection is the best choice, while for local MARSGIS Polar Stereographic or Sinusoidal projections seem to be practical – depending on the latitude value of the analyzed Martian region.
4) It turned out that the most complicated data source to integrate into any MARSGIS is the TRDR-type hyperspectral files of MRO CRISM instrument, for which – based on my own practical experiences – I have developed and documented a multi-step procedure in details.
5) In my opinion MRO CTX data files are the best option for context image of an analyzed region because in almost every case these are higher quality than any other low resolution data sources. Moderate quality, but more spectacular color context image maps should be generated as the RGB composite of the red, green and blue optical band MEX HRSC raster files, which is worth to pan-sharpen by the corresponding panchromatic nadir image, accordingly (I have generated this for all of my study areas).

6) During the past several years I have suggested two different regions as targets for the MRO HiRISE camera through a public web page and the team which operates the instrument has acquired both of those in 2007, so I was able to use them in my research.

Accuracy

7) The registration accuracy can be considered as a fundamental quality indicator of the integration of orbiter datasets with different spatial reference system or scale, and the correct setting of the appropriate projection parameters can only ensure the necessary level of this indicator between low resolution data sources, while in the case of high resolution images or when temporal surface changes are investigated, unfortunately some kind of manual georeferencing method is needed.
8) It seems, that the comparison of the numerous MGS MOC NA images (acquired between 1997 and 2006) with the MRO HiRISE images (started to become available after 2006) in order to search for the temporal changes of the surface morphology is not really feasible, mainly because of the different scales of the two data sources.
9) I conclude that the DTMs from different data sources are in good correlation with each other in my study areas. The absolute height of a surface point could be measured with highest reliability from the individual MGS MOLA profiles, topographic comparisons between distant regions should be based on the MGS MOLA DTM – which has global coverage, but an interpolated dataset, and for the morphometrical analysis of a study area the higher resolution MEX HRSC DTM is the most practical choice (if that is available) – which is the result of stereogrammetric processing of optical satellite images (I think that the "random noise"-like local roughness of this latter data source should be smoothed by the pixel-based averaging of the height values from the MGS MOLA DTM and from the MEX HRSC DTM).

III.2. Periglacial debris aprons

Morphology

10) Based on the detailed morphological and morphometrical analysis of four different study areas I conclude that the three different types of the periglacial debris aprons of Martian mid-latitudinal regions (LDA, LVF, CCF) are developed in the same way in the past of the planet: as a result of the slow downslope movement and plastic deformation of rock-ice mixtures with cemented inner structure, their three different types in turn are consequences of the „relief forcing" of their topographic neighborhood. Besides, I think that the extensive landforms' structure is not homogeneous, but rather these are the joining systems of smaller debris flows originating from different source locations.

11) By analyzing the Greg crater and the Protonilus study area I conclude that the position of the periglacial debris aprons is determined mainly by two parameters: the topography (slope) and the insolation (aspect). This implies that solar radiation-driven processes – which I consider to be the melting of H_2O and mechanical weathering – play a key role in their formation.
12) I have observed on the debris tongues of the Greg crater and on the debris apron surrounding the Euripus Mons as well, that their surface fabric is changing similarly between the source and the distal regions: becomes older and more eroded in downslope direction. In my opinion these different surface fabric-types can be matched very well with the patterned ground morphologies of the terrestrial periglacial regions.

Activity

13) In the four study area I was not able to detect any recent changes in the surface morphology of the periglacial debris landforms – in spite of the 0,25 m/pixel scale of the MRO HiRISE images showing apron surrounding the Euripus Mons in two different seasons of the same Martian year which I have compared to each other, and despite the good correlation between the two independent spectrometer datasets which indicate that the surface temperature can be slightly higher than 0 °C for the warmest short summer period in this study area.
14) In my view the reason of the debris aprons' unchanging morphology is, that their uppermost material (down to a few meter depth) is not containing enough water ice for the temporary emergence of an active layer on the top of them – which is in good correlation with the results of a previous research investigated the global variation of the near-surface H_2O-content on the planet.
15) Based on these I think, that the debris tongues of the Greg crater and the debris apron surrounding the Euripus Mons are nowadays to be considered as inactive landforms, but some part of their past water ice reservoir still can be present in their interior – for example, in the debris apron surrounding the Euripus Mons, whose volume based on my calculation is about 2 587 km^3, even 2 000 x 10^9 t frozen H_2O can be stored. But in the current climatic conditions their ice content is sublimating gradually so they become more and more eroded and finally fossil landforms – but if a slow global warming is really taking place on the planet, then in the near future they can even become active again.
16) Unfortunately the available data sources of the lineated valley fill in the Nilosyrtis study area did not allow the investigation of its recent activity, however I consider the concentric crater fill in the Protonilus study area as a certainly old, fossil landform, which completely lost its past water ice content from the near-surface debris layers, so its former morphology is recently eroded by aeolian processes and is buried by a gradually thickening erosional mantle.

Evolution

17) Taking into account the fact that more and more eroded surface fabric-types can be observed in the downslope direction I conclude that the periglacial debris aprons could have moved so slowly, that the extremely small intensity Martian erosional processes were able to alter their surface material significantly during their displacement – which implies that the sudden, episodic mass movement-styled events can be ruled out as the explanation for their origin (because in that case the erosional degree of their morphology would be uniform on their entire surfaces).

18) Based on terrestrial analogs I estimate that the small debris tongues in the Greg crater could have been developed during about 0,5-1,5 million years, while the formation of the much larger debris apron surrounding the Euripus Mons (for which I calculated 2 587 km^3 as its volume) lasted approximately for 100-300 million years (this is in good correlation with the impact crater size-frequency distribution-based ages of some similar landforms in the study area). So the periglacial debris aprons most probably formed in the last period of the Amazonian epoch of the Martian evolution history and therefore can be considered as one of the youngest landform-types of the planet. Although they are similar to the slope features of ice-containing debris material on Earth from many aspects, the Martian landforms are orders of magnitude older than their terrestrial counterparts and during their long-lasting active periods they transformed the fretted terrains (originating from the previous, Hesperian epoch) to morphologically diverse and topographically complex landscapes.

19) Nowadays the Martian periglacial debris aprons are not equilibrium landforms which means that at the time of their formation the climatic conditions differed from the recent surface environment – presumably the average temperature was lower during those periods. So the assessment of the formational time sequence of the analyzed, varying ages landforms could facilitate the more accurate reconstruction of the planet's evolution history. I consider the concentric crater fill of the Protonilus study area as the oldest analyzed landform which could have been formed more hundred million years ago – based on the gully locations of the crater wall, perhaps in a period in which the planet's obliquity was higher than the 38,3° Martian latitudinal value of the crater itself (because in this case during the warmest periods of the summer the solar radiation arrived to the region from the north, therefore the crater walls with southern exposure were the most shady ones and the summer insolation only at these locations did not melted completely the winter H_2O accumulation, so gully formation was possible there from the slow melting and seeping of the frozen H_2O). Namely the increasing obliquity causing the warming of the polar regions so their water ice reservoirs start to sublimate and so water vapor is released into the atmosphere, which later freezes out to the surface in the Martian mid-latitudinal regions, resulting in ice-related landforms, among others debris aprons as well.

20) Based on the erosional degree of its surface fabric, I estimate the age of the lineated valley fill of the Nilosyrtis study area to be maximum 25-50 million years, so it was formed later than the concentric crater fill of the Protonilus study area and the debris apron surrounding the Euripus Mons, respectively. Besides, the ages of its several tens of meters thick morphological formations with different height and line of bearing become older from the edge to the centerline of the valley floor indicating that the lineated valley fill was formed in more phases, with temporal interruptions between them – most likely because of the climatic changes occurred in the meantime. I think that this landform is not the debris-covered remnant of a former valley glacier network, but rather the braided system of smaller debris flows which on the one hand showing striped pattern parallel to the retreating boundary line of the valley walls, growing in perpendicular direction to and therefore abutting each other at the centerline of the valley, then finally overlapping each other partially, and on the other hand undergoing longitudinal displacement not because of processes related to glacier formation but only because of the „relief forcing" of their topographic neighborhood.
21) The youngest periglacial debris aprons of the four study areas can be found in the Greg crater. In my opinion these debris tongues was formed in the latest period of the planet's evolution history, maximum 5-10 million years ago, when the obliquity – based on numerical modeling – fluctuated around a much larger value for a long period than it is today.
22) Based on these I think, that the detailed morphological and morphometrical analysis of the periglacial debris aprons of Martian mid-latitudinal regions can effectively contribute to the clearer understanding of the planet's evolution history. The investigations carried out in the frame of my research activity partly reinforce the more and more widely accepted hypothesis that for several periods in the last 200-300 million years the obliquity of planet Mars was significantly higher than it is today, which in the polar regions caused warming while in the mid-latitudinal regions resulted in ice accumulation in the near-surface layers and in the formation of valley glacier networks. But taking into account my observations, none of the four study areas experienced glacier formation in the past, therefore my conclusion is that the different type and -aged debris features of these study areas emerged in periglacial surface environment and developing in it since that time as well.

III.3. Dark slope streaks

23) Based on the detailed morphological and morphometrical analysis of four different study areas I conclude that the dark slope streaks observed on the dune fields of the sub-polar Martian regions are the surface signatures of the pore volume-filling recent downslope seepage of at least a microscopic quantity of liquid interfacial H_2O appearing temporarily during the spring-summer

melting period of the water ice contained in the near-surface material. The slope streaks only appear on the dark dune surfaces and in my opinion the "seepage model" developed by the Mars Astrobiology Group (to whose members I belong to since 2003) can consistently explain their observed characteristics.

24) By analyzing the Konkoly crater study area I conclude that during the summer the dark dune field is colder in average than the surrounding flat terrain, which I consider as the consequence of the dune's water ice content, and since its surface temperature at some locations can be slightly higher than 0 °C, its ice reservoir has the chance to become partly melted at the beginning of the summer season.

25) By the comparison of high resolution optical images acquired during two consecutive spring period in the Konkoly crater study area I confirmed, that the development of the dark slope streaks is mainly determined by the surface temperature, because their changes follow a similar spatial and temporal pattern in the different Martian years.

26) Based on the detailed morphometrical analysis of the dune field inside the Russell crater I think, that the elongation and size of the dark slope streaks is influenced by the topography (slope) and the insolation (aspect) as well: the length of features situated on differently tilted terrains is proportional to the slope angle and below 8° of topographic gradient only circle-shaped dark dune spots develop, and by comparing the similarly tilted southwestern and southeastern slopes, the larger slope streaks always can be seen on the southwestern (in other words warmer) locations. This implies that a solar radiation-driven process – which I consider to be the melting of H_2O – plays a key role in the formation of the dark slope streaks. Moreover, the dune's composition can be an important parameter as well, because the streaks are observable in parallel configuration with the contour lines of the dune, which might indicate the layered structure of the slope and thereby the changing atmospheric H_2O-content during the formation of the different levels of the dune's material.

27) By analyzing the seasonal changes of the study area located near to the Escorial crater I conclude that the growth in the length of the dark slope streaks can reach 4-8 m during a Martian day in the spring period – and so they are really the areas of active surface processes.

28) Based on the compositional analysis of the dark dune field inside the Inuvik crater I found that the available spectral data sources can be successfully used for the separation of the different surface materials, furthermore that the temporal changes of the uppermost layer's composition are in good correlation with the seasonal processes monitored on the optical satellite images. So it is my opinion that the "seepage model" can be further confirmed by the results of this hyperspectral remote sensing technique as well, which is to be considered as an indirect material analysis method.

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29) Based on my research I came to the final conclusion that the periglacial debris aprons of Martian mid-latitudinal regions and the dark slope streaks observed on the dune fields of the sub-polar Martian regions are equally ice-related slope features and their development can be explained by the same process, which is the partial melting of the H_2O-content in the shallow subsurface layers. But the debris aprons are larger and ancient landforms developed in the last few hundred million years by slow mass movements of a few tens or some hundreds of meters thick rock-ice mixtures, while the slope streaks are smaller and recently active features which are the results of the fast downslope seepage of the few mm- or cm-deeply located, liquid interfacial H_2O. In my opinion both types of features can be considered as reliable locations and reachable sources of frozen and/or liquid H_2O reservoirs to be found on the planet, and their future investigation has important theoretical aspects (on the one hand, the detailed understanding of the different climatic conditions from the current surface environment in the late period of the Martian evolution history, on the other hand the planet's ancient habitability and hypothesized life forms) and practical significance (the landing site selection of the planned future human expeditions) as well.
30) Furthermore, the morphological analyses in my Ph.D. Dissertation clearly demonstrate that GIS methodology can be effectively applied in the detailed investigation of other celestial bodies' surfaces as well, so planetary science could be considered as the planetary extension and as a promising future sub-discipline of physical geography.

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