A COMBINED TOPOGRAPHIC-THEMATIC MAP OF THE CENTAURI AND HELLAS MONTES AREA, MARS

Hartmut Lehmann[a], Stephan van Gasselt[b], Stephan Gehrke[a] , Jörg Albertz[a],
Gerhard Neukum[c] and the HRSC Co-Investigator Team

[a] Technische Universität Berlin, Geodesy and Geoinformation Science, Germany –
{stephan|h.lehmann|albertz}@igg.tu-berlin.de
[b] Freie Universität Berlin, Institute of Geosciences, Germany – {vgasselt|gneukum}@zedat.fu-berlin.de

Commission IV, WG IV/7

KEY WORDS: Extra-terrestrial, Planetary, Cartography, Geology, Software, Orthoimage, DEM/DTM

ABSTRACT:

Since January 2004, *Mars Express* brings us an unprecedented wealth of spectacular multispectral digital image data of high resolution as well as systematic stereo coverage of the Martian surface. During the past two years, the High Resolution Stereo Camera (HRSC) on board of Mars Express covered more than half of the Martian surface, whereas 27% of the data already obtained is provided in resolutions better than 20 m/pixel. HRSC images are processed systematically to various data levels. Based on these products, high-quality large-scale topographic and thematic image maps are generated. The standard map series for the *Mars Express* Mission is the *Topographic Image Map Mars 1:200,000*, which covers the planet's surface in 10,372 individual map sheets.
The Centauri and Hellas Montes assembly of remnant massifs, located at 97° east and 38° south, has been interpreted as crustal uplifts and ejected material from the Hellas impact event in early Martian history. Recent investigations of this area resulted in the discovery of a degraded caldera complex, a structure, which has formerly been interpreted as impact crater structure. The discovery of this collapsed caldera feature bears new implications on the evolution of the Eastern Hellas rim assembly.
The geologic map sheet of the Centauri and Hellas Montes area is spread from 95°00' to 97°50' eastern longitude and 36°45' to 39°45' southern latitude. This new thematic map project is realized in a close co-operation between the German Aerospace Center (DLR) in Berlin-Adlershof, providing photogrammetric processing, the Institute for Geosciences, Remote Sensing of the Earth and Planets, Freie Universität Berlin for the geoscientific interpretation and the Institute of Geodesy and Geoinformation Science, Technische Universität Berlin, responsible for all cartographic aspects.
With the map of the Centauri and Hellas Montes area the authors present a new design in thematic planetary cartography.

KURZFASSUNG:

Seit Januar 2004 sendet die ESA-Raumsonde *Mars Express* eine Fülle an atemberaubenden multispektralen digitalen Bilddaten in hoher Auflösung und mit 5facher Stereoabdeckung von der Marsoberfläche. In den vergangenen Jahren hat die High Resolution Stereo Camera (HRSC) an Bord der Raumsonde *Mars Express* mehr als die Hälfte der Marsoberfläche erfasst, wobei 27% der aufgenommenen Daten mit einer Auflösung besser als 20 m/Pixel vorliegen. HRSC Bilddaten werden systematisch in unterschiedlichen Verarbeitungsstufen prozessiert. Basierend auf diesen Daten wurden bereits verschiedene großmaßstäbige topographische und thematische Karten hergestellt. Das Standard-Kartenwerk für die *Mars Express* Mission ist die *Topographic Image Map Mars 1:200,000,* welche die Marsoberfläche in 10 372 einzelne Kartenblätter abbildet.
Die im östlich des Hellas Impaktbeckens gelegenen Restbergmassive der Centauri and Hellas Montes Region, bei 97° Ost und 38° Süd, werden als Zeugen impaktbezogener Krustenhebung und Ejektamaterial interpretiert. In einem Teilgebiet der Region wurde im Rahmen von aktuellen Untersuchungen möglicher Kriechstrukturen eine stark degradierte Caldera entdeckt. Während der vulkanischen Aktivitätsphase wurde vermutlich weiträumig Material in der Centauri und Hellas Montes Region abgelagert, welches zur Bildung von Kriechstrukturen beigetragen hat. Es ist wahrscheinlich, dass Ausflussaktivität in der nahen Umgebung mit Aufschmelzungsprozessen infolge des Vulkanismus im Zusammenhang stehen. Es sind deutliche Hinweise erkennbar, dass Flanken der vulkanischen Struktur später kollabierten und die Umgebung mit Hangrutschungen und Lawinen überdeckte.
Das thematische Kartenblatt des Centauri und Hellas Montes Gebietes erstreckt sich über einen Darstellungsbereich von 95°00' bis 97°50' östlicher Länge und 36°45' bis 39°45' südlicher Breite. Die Karte wurde in Kooperation mit dem Deutschen Zentrum für Luft- und Raumfahrt (DLR) in Berlin-Adlershof, verantwortlich für die photogrammetrische Verarbeitung der Bilddaten, dem Institut für Geowissenschaften, Fachrichtung Planetologie und Fernerkundung, Freie Universität Berlin, für die geowissenschaftliche Interpretation und dem Institut für Geodäsie und Geoinformationstechnik der Technischen Universität Berlin realisiert, welches die kartographische Umsetzung dieses Projekts koordiniert und ausgeführt hat.
Mit dem vorliegenden Kartenblatt des Centauri und Hellas Montes Gebietes präsentieren die Autoren ein weiteres Gestaltungsbeispiel aus dem Bereich der planetaren Kartographie.

1. INTRODUCTION

Since recent decades the exploration of our solar system enjoys a steadily increasing scientific and public interest. *Mars Express* is one of several space missions being planned or in operation at this stage. With its entry into the operational orbit in January 2004, *Mars Express*, which is the first European Space Mission ever, bestows us an abundance of spectacular data of Mars Neukum et al. (2004). For cartographic purposes however the unprecedented wealth of spectacular multi-spectral digital image data of high resolution as well as systematic stereo coverage of the Martian surface are of substantial interest. In the scope of this recent large-scale mapping program the German "High Resolution Stereo Camera" (HRSC) on board of *Mars Express* has been especially designed to meet photogrammetric and cartographic requirements. As a necessary basis for precise topographic mapping the data proved to be well suited for the derivation of Digital Terrain Models (DTM) as well as color orthoimage mosaics. During the past two years, the HRSC covered more than half of the Martian surface, whereas 27% of the data already obtained is provided in resolutions better than 20 m/pixel. HRSC images are processed systematically to various data levels. Based on these products, high-quality large-scale topographic and thematic image maps are generated. The *Topographic Image Map Mars 1:200,000* is the standard map series for the *Mars Express* Mission, which represents the surface of planet Mars in more than 10,000 individual map sheets.

Basic principle of the Topographic Image Map Series 1:200,000 is a well designed cartographic concept developed at the Technische Universität Berlin in close cooperation with colleagues from German Aerospace Center (DLR), Institute of Planetary Research, Berlin.

In addition to the need for precise high-quality topographic image maps a continuously increasing requirement for thematic maps is evident. At first instance thematic map activities are presently focused on the preparation of geological and geomorphological maps.

For realizing these challenges the cartographic software package *Planetary Image Mapper* (PIMap) which has been developed at Technische Universität Berlin, again proved its operational capability.

With the map of the Centauri and Hellas Montes area the authors present a new design in high-quality thematic cartography which benefits from the quality of HRSC images and DTMs as well as the sophisticated cartographic concept and the flexibility of PIMap.

2. CARTOGRAPHIC CONCEPT

In planetary cartography maps are usually based on image data. In the case of *Mars Express* color orthoimage mosaics as a result of photogrammetric processing (e.g. *Scholten* et al., 2005) have been used predominantly.

A sophisticated cartographic concept was developed and forms the basis for the topographic image map series, the *Topographic Image Map Mars 1:200,000*, as well as for thematic maps (Lehmann, H., 1996, Albertz, J. et al., 2004). The Martian reference body for planimetry is a rotational ellipsoid as defined by the International Astronomical Union (IAU) which is the *Mars IAU 2000* ellipsoid. An areoid (Martian geoid) is defined as the topographic reference surface for heights. Equal-area map projections are used for compiling the map sheets. Because of its useful mathematical and graphical properties, the *Sinusoidal* projection is applied to map sheets between 85° north and 85° south. For mapping the polar regions the *Lambert Azimuthal* projection was selected. In principle, the cartographic concept perfectly meets all requirements for both mapping features and regions of special interest as well as particular HRSC orbits that don't fit with the sheet line system. Map sheets of the *Topographic Image Map Mars 1:200,000* series easily can be subdivided into quarters or sixteenth for maps in scales 1: 100,000 or 50,000.

The softwarepackage *Planetary Image Mapper* (PIMap) comprises all cartographic processing steps such as compilation and nomenclature of the map content including contour lines, generation and placement of graphical elements, e.g. naming of surface features, including the map frame and all necessary marginal elements for every single map sheet.

PIMap Input Data:

- Initialization file (mandatory!)
- Orthoimage mosaic
- Digital Terrain Model (DTM)
- Planetary features: topographic names and landing sites
- Map series definitions

More details with regard to the topographic map production process with PIMap are presented in the companion paper by Gehrke et al.(2006c).

Whereas only few post processing steps are required to generate high quality topographic maps, at present the integration of thematic data is mainly an interactive process.

3. CENTAURI AND HELLAS MONTES AREA

The Centauri and Hellas Montes assembly of remnant massifs, located at 97° East and 38° South, have been interpreted as crustal uplifts and ejected material from the Hellas impact event in early Martian history.

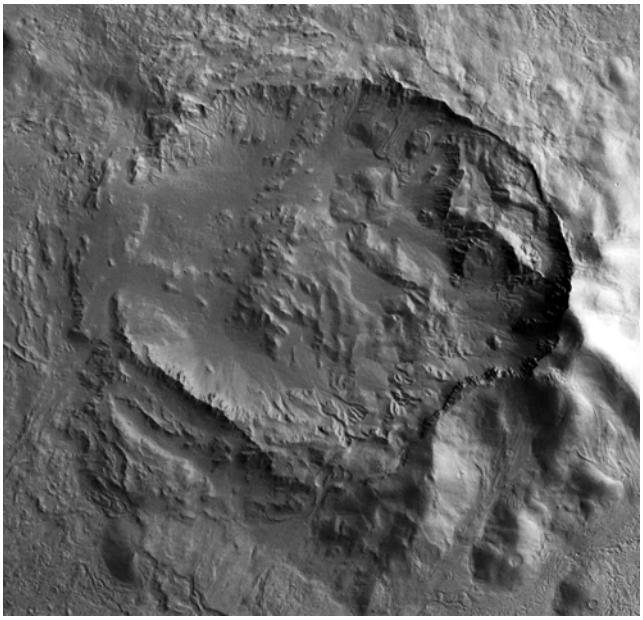

Fig. 1: HRSC Nadir scene from the eastern Hellas Montes area. Degraded caldera complex, orbit 2510, image width is 50 km.

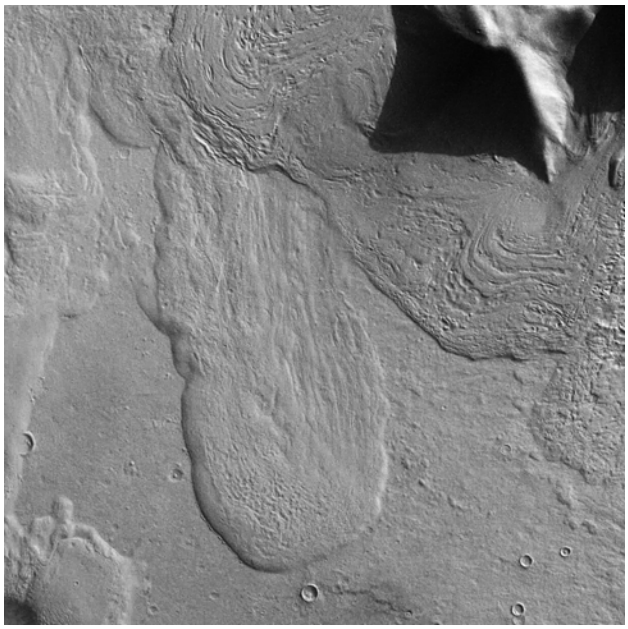

Fig. 2: Debris tongue, image width is 23 km.

Subsequent mechanisms led to formation of adjacent lobate debris aprons which are considered to be composed of a debris-ice mixture with rheological similarities to terrestrial rock glaciers. Recent investigations of this working area resulted in the discovery of a degraded caldera complex, formerly been recognized as impact crater structure. The discovery of this collapsed caldera feature bears new implications on the history of the Eastern Hellas rim assembly. The region was covered in HRSC orbits 2510, 2466 and 0506.
Especially the recently obtained data from orbits 2510 and 2466 provided highly detailed insights into the small-scale morphology of this area.

3.1 Geologic and Geomorphologic Setting

The Eastern Hellas Planitia area is one of the locations on Mars which have been discussed by many scientists in a wide field of geologic and geomorphologic topics. Landforms and geology of that area are primarily related to the Hellas Planitia impact event which occured early in Martian history and formed one of the largest impact basins in the solar system (e.g., Greeley and Guest, 1987; Tanaka et al., 1992). Subsequently, volcanic processes and resurfacing of landforms connected to several volcanic edifices shaped the area (e.g., Greeley and Crown, 1990; Crown, 1991; Crown and Greeley, 1993). Outflow activity connected to the Dao, Niger and Harmakhis Valles (Price, 1992; Bleamaster and Crown, 2004) as well as the contributory Reull Vallis caused ongoing resurfacing and transport of large volumes of water and debris (Leth and Treiman, 1997; Mest and Crown, 2001).
Within these settings, the most prominent landforms of the Eastern Hellas assemblages are characterized by smoothly shaped isolated complexes of remnant massifs with a relief of several hundreds to thousand metres which are interpreted as uplifted crust or ejected material connected to the Hellas impact event (Greeley and Guest, 1987). These remnants are situated among large complexes of coalescing debris aprons indicative of viscous creep and deformation. These debris aprons are interpreted as possible rock glacier analogues (Squyres, 1978, 1979; Squyres and Carr, 1986; Crown and Stewart, 1995; Crown et al., 2002; van Gasselt et al., 2002; Mangold, 2003). Rock glaciers and associated landforms on Earth are connected to alpine and high-latitude periglacial environments (Wahrhaftig and Cox, 1959; Haeberli, 1985; Vitek and Giardino, 1987; Barsch, 1987, 1988). They represent mass-transport systems composed of mixtures of debris and ice in various amounts. Their possible analogues on Mars have been discussed with a focus on their origin and amount of ice and/or water as well as the incorporated debris. The global distribution of debris aprons has been shown on Viking data (Squyres, 1978, 1979). Highest-resolution data provided by the Mars Orbiter Camera experiment on Mars Global Surveyor (Malin et al., 1992) gave further insights into the style of emplacement, and the textural inventory. Topographic profiles derived from Viking stereo data as well as topographic data provided by the Mars Orbiter Laser Altimeter onboard Mars Global Surveyor (Smith et al., 2001) furthermore showed convex-upward profiles indicating stresses and deformation values similar to terrestrial glacial systems (Squyres, 1978; Mangold et al., 2002).
Among these more or less spatulate populations of debris aprons, a particular landform located just north of the Reull Vallis and east of the Harmakhis outflow channel head looks slightly different in terms of (a) general shape, (b) textural inventory and (c) morphometry. Emplacement styles ranging from rock glaciers, debris avalanching and debris flows have been discussed recently (Crown et al., 1992; Baratoux et al., 2002; Degenhardt and Giardino, 2003; van Gasselt et al., 2006). There are few textural and morphometric hints that an origin as debris avalanche is plausible although contemporary or later creep deformation assisted by interstitial ice has to be considered also. It is interpreted that the 35-kilometer depression in the North is not related to an impact event as interpreted in earlier maps (Greeley and Guest, 1987; Crown et al., 1992) but is connected to a highly-degraded volcanic edifice. Size ratios and rim characteristics differ significantly from common impact craters. Large landslide deposits in the west and south of the caldera indicate collapse of the western rim during multiple events.
This interpretation has several implications on the geomorphology of the eastern Hellas Planitia area. The Harmakhis Vallis head is situated directly west of the caldera complex and its formation can directly be associated with volcanic activity in this area. Furthermore, sources for debris incorporated into the debris apron are probably connected to early volcanic activity and possible ash-flow deposits. Interstitial ice then caused ongoing deformation and remobilization with the consequence that surfaces are generally considered young as suggested by crater-size frequency data (Baratoux et al., 2002; van Gasselt et al., 2005).

3.2 Geologic and Geomorphologic Mapping

In contrast to geologic maps, geomorphologic maps and a combination of both consist of a two-dimensional representation of various surface units which may be similar in lithologies, i.e., composition, but different in terms of morphology, shape and texture. Image data from the HRSC instrument (Neukum, G. et al., 2004) as well as highest-resolution data from the Mars Orbiter Camera (Malin et al., 1992) and THEMIS instruments (Christensen et al., 2004) have been utilized to perform mapping in this area in order to show various landslide units in connection with massifs from which they are derived. It is obvious that different landslide units as well as remnant massifs consist of identical lithologies,

however, different stages of emplacement and therefore different superpositions have to be pointed out clearly in order to understand the genetic evolution of the Hellas/Centauri Montes areas. For mapping, HRSC based stereo data has been used to generate red-cyan anaglyphs. The parallaxes caused by stereo angle of 18.9° between HRSC nadir and first stereo-channel significantly improved separation of various units and helped to understand relative positions of individual units. Higher-resolution data have been mainly utilized for delineating unit boundaries more precisely.

Geomorphologic definition of Mass-Wasting Units differentiated for the map project:

- **Lobate Debris Apron (lda)**
  debris material with large volumes of interstitial ice, deformation similar to terrestrial rockglaciers
- **Debris Tongue Units (dt)**
  remobilized landslide material connected to caldera collaps
- **Harmakhis and Reull debris infill (hrf + hrv2)**
  erosional debris and landslide material filling the Harmakhis and Reull Valles channel systems. Partly derived from the Centauri Montes, partly derived from caldera collapse
- **Intra-Caldera debris (icd)**
  erosional debris and landslide material from the interior of the caldera complex
- **Reull Vallies infill (rvf)**
  debris and wall rock material of the Reull Vallis unit
- **Centauri Montes debris unit (undivided) (cd)**
  erosional debris from the Centauri Montes complex
- **Margins of Centauri Montes debris units (cdm)**
  lobate shaped debris units connected with margins of the Centauri Montes debris unit
- **Crater-impact ejecta (e)**
  ejecta material, partly incorporated into landslide deposits
- **Crater infill (cf)**
  concentric-crater fill units and crater floor deposits
- **Debris unit (du)**

4. MAP SHEET LAYOUT

For the generation of this thematic map the cartographic software system, the *Planetary Image Mapper* (PIMap) has proven to be an essential and valuable map production tool. Due to the flexibility of the product center point, map dimensions, and scales can be freely defined thus providing a remarkable cartographic freedom in constructing maps in different projections, sheet lines (quadrangles), scales and dimensions.
Following the map series *Topographic Image Map Mars 1:200,000* as a guideline our new geomorphologic map project is mainly based on its technical specifications concerning reference body for planimetry, reference surface for heights, map projection and many aspects with regard to the grid systems and nomenclature.
The work area on which our interest is focussed has been mapped out between 95° to 100° Eastern longitude and 36° to 40° Southern latitude. From the available HRSC data covering that region, orbit 2510 has been chosen for map generation. However a thin strip at the eastern border of the orbit data does not range exactly up to the 100° Eastern longitude meridian.

It is intended to render the thematic content according to well established cartographic experience with respect to an easy readable and well-defined representation. In mapping processes by means of a map series, with a necessarily fixed sheet lines system, consequently, the appearance of relevant topographic features of special interest are often affected by those sheet lines. In contrast to map sheets of map series in general, the map project of the Centauri and Hellas Montes area is laid out as an individually defined map sheet. According to the coverage of recently obtained data of orbit 2510 and a variety of pragmatic aspects as well, the map scale was defined to be 1:300 000.
This is certainly a compromise considering the fact, that the work area has to be presented in one individual sheet for optimal overview in the distinctive style of the layout features of the standard map series *Topographic Image Map Mars 1:200,000.*
Considering all design aspects and technical specifications this geologic map project of the Centauri and Hellas Montes area results in a map surface spread from 95°00’ to 97°50’ Eastern longitude and 36°45’ to 39°45’ Southern latitude.

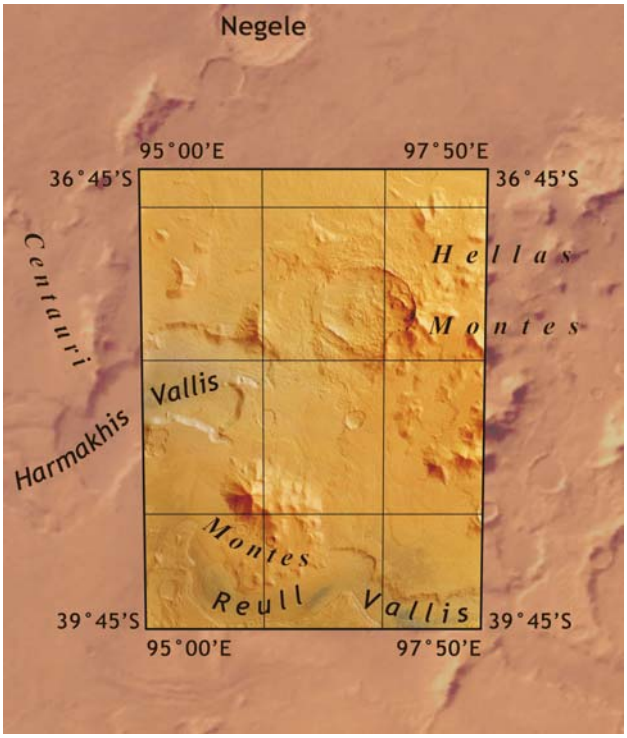

Fig. 3: Location and dimension of the topographic basis for the map project of the Centauri and Hellas Montes area in Sinusoidal projection. (Background Imagery: Viking data, adapted for presentation)

Presentation of the geomorphologic context is arranged in such a way that only selected thematic features are depicted within the map surface by means of discrete color. As is common practice in thematic mapping the remaining areas, not relevant for geomorphologic interpretation, are not assigned as a further class in the interpretation key. Instead of that it was decided to represent those areas by the topographic color imagery resulting in a combined topographic-thematic map.

5. CONCLUSION AND OUTLOOK

The wealth of challenging data acquired by HRSC since January 2004 still fascinates scientists and the public as well. Nearly 30% of HRSC imagery reveals spatial resolution better than 20 m/pixel. Since then various image maps have been generated mainly intended for scientific purposes within the HRSC Science Team. Most of the maps already produced are map sheets in the range of the standard map series *Topographic Image Map Mars 1:200,000* or derivatives with different sheet lines or/and scale. At the present time however a steadily increasing demand for thematic maps, especially geologic and geomorphologic maps, is in evidence. Current work is focused on further adjustments of PIMap which come up through requests and demands arising within the science team during the ongoing experiment. Particularly for future thematic mapping, further investigation will be concentrated on developing additional customized (tailor-made) software modules to supplement PIMap, which proved so far its reliability and performance in planetary map generation.

But at the same time it is implied that agreements and standardizations in geologic/geomorphologic interpretation, nomenclature and methodology for cartographic representation have to be formulated as requirements.

REFERENCES

Albertz, J., Gehrke, S., Wählisch, M., et al., 2004: Digital Cartography with HRSC on Mars Express. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Istanbul, Vol. XXXV, Part B4, pp. 869-874.

Albertz, J., Gehrke, S., Lehmann, H., et al., 2005a. Precise Topographic and Thematic Maps of Planet Mars. *Proceedings XXII International Cartographic Conference*, A Coruña.

Albertz, J., Attwenger, M., Barrett, J., 2005b. HRSC on Mars Express – Photogrammetric and Cartographic Research. *Photogrammetric Engineering & Remote Sensing*, Vol. 71, No. 10, pp. 1153-1166.

Baratoux, D., Mangold, N., Delacourt, C., Allemand, P., 2002. Evidence of liquid water in recent debris avalanche on Mars. Geophys. Res. Lett. 29, 60–1.

Barsch, D., 1987. Rock glaciers: an approach to their systematics. In: Giardino, J., Shroder, J., Vitek, J. (Eds.), Rock glaciers. Allen & Unwin, London, pp. 41–44.

Barsch, D., 1988. Rockglaciers. In: Clark, M. (Ed.), Advances in periglacial geomorphology. Whiley, Chichester, pp. 69–90.

Bleamaster, III, L. F., Crown, D. A., 2004. Morphologic Development of Harmakhis Vallis, Mars. In: Mackwell, S., Stansbery, E. (Eds.), Lunar and Planetary Institute Conference Abstracts. p. 1825.

Christensen, P. R., Jakosky, B. M., Kieffer, H. H., Malin, M. C., McSween, Jr., H. Y., Nealson, K., Mehall, G. L., Silverman, S. H., Ferry, S., Caplinger, M., Ravine, M., 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. Space Science Reviews 110, 85–130.

Crown, D. A., 1991. Volcanism in the eastern Hellas region of Mars: The geology of Hadriaca and Tyrrhena Paterae. Ph.D. Thesis.

Crown, D. A., Greeley, R., 1993. Volcanic geology of Hadriaca Patera and the eastern Hellas region of Mars. J. Geophys. Res. 98, 3431–3451.

Crown, D. A., Pierce, T. L., andScott C. Mest, S. B. Z. M., 2002. Debris aprons in the eastern hellas region of mars: Implications for styles and rates of highland degradation. In: Lun. Planet. Sci. Conf. Abstracts. Vol. 33. p. 1642, print.

Crown, D. A., Price, K. H., Greeley, R., 1992. Geologic evolution of the east rim of the Hellas basin, Mars. Icarus 100, 1–25.

Crown, D. A., Stewart, K. H., 1995. Debris aprons in the eastern hellas regionof mars. In: Lun. Planet. Sci. Conf. Abstracts. Vol. 26. pp. 301–302,

Degenhardt, J. J., Giardino, J. R., 2003. Subsurface investigation of a rock glacier using ground-penetrating radar: Implications for locating stored water on Mars. J. Geophys. Res. 108 (E4), 17.

Gehrke, S., Neukum, G.., 2005. Das Kartographische Softwarepaket „Planetary Image Mapper“ (PIMap). *Photogrammetrie – Fernerkundung – Geoinformation*, 5/2005, pp. 417-422.

Gehrke, S., Lehmann, H., Köhring, R., et al., 2006a: Iani Chaos in Three Scales – A Topographic Image Map Mars and its Subdivisions. *Lunar and Planetary Science (LPSC) XXXVII*, Houston, Paper #1325.

Gehrke, S., Lehmann, H., Köhring, R., et al., 2006b: Large-Scale Topographic Maps of Iani Chaos, Mars. *Proceedings 5th Turkish-German Joint Geodetic Days*, Berlin.

Gehrke, S., Wählisch, M. Lehmann, H., Albertz, J., Roatsch, T., 2006c: Generation of Digital Topographic Maps of Planetary Bodies. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Goa, Vol.36, Part 4, Commission IV, WG IV/7

Greeley, R., Batson, R.M., 1990. *Planetary Mapping*. Cambridge University Press, Cambridge.

Greeley, R., Crown, D. A., 1990. Volcanic geology of tyrrhena patera, mars. J. Geophys. Res. 95, 7133–7149.

Greeley, R., Guest, J. E., 1987. Geologic map of the eastern equatorial region of mars. U.S. Geol. Surv. Misc. Inv. Series Map-I-1802-B.

Haeberli, 1985. Creep of mountain permafrost: internal structure and flow of alpine rock glaicers. Mitt. der Versuch. f. Wasserbau, Hydrol. und Glaziol. Zürich 77, 142.

Lehmann, H., 1996: A New map Series for Planet Mars-Concept and realization of the “Topographic Image Map Mars 1:200,000”. *The International Archives of the Photogrammetry, and Remote Sensing*, Vienna, Vol. XXXI, Part B4, pp. 497-502.

Leth, P. T., Treiman, A. H., 1997. Geology of the Reull Vallis Region of Mars - Evidence for Mid-Noachian sheet floods. In: Lunar and Planetary Institute Conference Abstracts. p. 807.
MIPL, 2006: www-mipl.jpl.nasa.gov (accessed: June 2006).

NASA, 2006. Planetary Data system. *pds.jpl.nasa.gov* (accessed: June 2006).

Neukum, G., et al., 2004. The High Resolution Stereo Camera of Mars Express. *ESA Special Publication SP-1240*.

Porco, C. C., et al., 2004. Cassini Imaging Science: Instrument Characteristics and Anticipated Scientific Investigations at Saturn. *Space Science Review*, Vol. 115, pp. 363-497.

Scholten, F., Gwinner, K., Roatsch, T. et al., 2005. Mars Express HRSC Data Processing – Methods and Operational Aspects. *Photogrammetric Engineering & Remote Sensing*, Vol. 71, No. 10, pp. 1143-1152.

Malin, M. C., Danielson, G. E., Ingersoll, A. P., Masursky, H., Veverka, J., Ravine, M. A., Soulanille, T. A., May 1992. Mars Observer Camera. J. Geophys. Res. 97, 7699–7718.

Mangold, N., Allemand, P., Duval, P., Geraud, Y., Thomas, P., 2002. Experimental and theoretical deformation of ice-rock mixtures: Implications on rheology and ice content of Martian permafrost. Planet. Space Sci. 50, 385–401.

Mest, S. C., Crown, D. A., 2001. Geology of the Reull Vallis Region, Mars. Icarus 153, 89–110.

Neukum, G. and Jaumann, R. and the HRSC Co-Investigator and Experiment Team, 2004. HRSC: the High Resolution Stereo Camera on Mars Express. Vol. SP-1240. ESA, Ch. 1, pp. 17–36.

Price, K. H., 1992. Geologic Mapping of Part of Harmakhis Vallis Region, Mars: Evidence of Multiple Drainage Events. In: Lunar and Planetary Institute Conference Abstracts. p. 1107.

Smith, D. E., Zuber, M. T., Frey, H. V., Garvin, J. B., Head, J. W., Muhleman, D. O., Pettengill, G. H., Phillips, R. J., Solomon, S. C., Zwally, H. J., Banerdt, W. B., Duxbury, T. C., Golombek, M. P., Lemoine, F. G., Neumann, G. A., Rowlands, D. D., Aharonson, O., Ford, P. G., Ivanov, A. B., Johnson, C. L., McGovern, P. J., Abshire, J. B., Afzal, R. S., Sun, X., 2001.

Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars. J. Geophys. Res. 106, 23689–23722.

Squyres, S. W., 1978. Martian fretted terrain - Flow of erosional debris. Icarus 34, 600–613.

Squyres, S. W., 1979. The distribution of lobate debris aprons and similar flows on Mars. J. Geophys. Res. 84, 8087–8096.

Squyres, S. W., Carr, M. H., 1986. Geomorphic evidence for the distribution of ground ice on Mars. Science 231, 249–252.

Tanaka, K. L., D. H, S., Greeley, R., 1992. Global stratigraphy. In: Kieffer, H. H., Jakosky, B. M., Snyder, C. W., Matthews, M. S. (Eds.), Mars. Univ. Arizona Press, pp. 345–382.

USGS, 2006a: *astrogeology.usgs.gov* (accessed: June 2006).

USGS, 2006b: Map-a-Planet. pdsmaps.wr.usgs.gov (accessed: July 2006)

van Gasselt, S., Hauber, E., Jaumann, R., 2002. Morphology and Topography of Fretted Terrain at the Dichotomy Boundary in Tempe Terra, Mars: Quantitative Morphology of Slope Aprons and Mesas. In: Lunar and Planetary Institute Conference Abstracts. p. 1856.

van Gasselt, S., Hauber, E., Neukum, G., HRSC Co-Investigator Team, 2006. Origin and Nature of a Debris-Tongue in Hellas Montes, Mars. In: Mackwell, S., Stansbery, E. (Eds.), 37th Annual Lunar and Planetary Science Conference. p. 2417.

van Gasselt, S., Hauber, E., Reiss, D., Scholten, F., Neukum, G., The HRSC Co-Investigator Team, 2005. Slope Morphologies of the Hellas Mensae Constructs, Eastern Hellas Planitia, Mars. In: Mackwell, S., Stansbery, E. (Eds.), 36th Annual Lunar and Planetary Science Conference. p. 2090.

Vitek, J. D., Giardino, J. R., 1987. Rock glaciers:a review of the knowledge base. In: Giardino, J. R., Shroder, J. F., Vitek, J. D. (Eds.), Rock Glaciers. Allen & Unwin, pp. 1–26.

Wahrhaftig, A. L., Cox, A., 1959. Rock glaciers in the alaska range. Geol. Soc. Am. Bull 70, 383–436.

ACKNOWLEDGEMENT

The research project *Software Development and Technical Support for Cartographic Data Processing* at the *Technische Universität Berlin* is funded by the German *Bundesministerium für Bildung und Forschung.* This project is part of the research program *High Resolution Stereo Camera (HRSC) on the Mars Express Orbiter* under the guidance of Principal Investigator Prof. Gerhard Neukum, Freie Universität Berlin.

For this study, the HRSC Experiment Team of the German Aerospace Center (DLR) in Berlin has provided map-projected HRSC image and DTM data.