CHAPTER 7

Data Analysis and Methods for Data Interpretation

Methods of data processing, combination and interpretation are extensively covered in the appropriate section in each of the chapters in part III on *Investigations of Key Areas* of this thesis. The possibilities of data fusion and the variety of ways that lead to essentially identical results are far too extensive to be covered here. General approaches and background issues are addressed in the following section shortly and references are provided for the reader for further in-depth inquiries. The method to be applied depend on the specific questions and the solution to obtain best results vary accordingly. For details the reader is referred to part III of this work and especially to chapter 8 on *Seasonal Variations of Polygonal Thermal Contraction Crack Patterns in a South Polar Trough, Mars* regarding the combination of data such as THEMIS, MOC, MOLA and TES within a variable seasonal context. Geomorphometric methods at the limit of accuracy have been extensively applied in chapter 10 on *Current State and Disintegration of Rock-Glacier Landforms in Tempe Terra/Mareotis Fossae, Mars*. Methods for image data mosaicking, especially MOC-NA in combination with HRSC image data, have been applied widely in chapter 9 on *Cold-Climate Modification of Martian Landscapes: A Case Study of a Spatulate Debris Landform in the Hellas Montes Region, Mars* as well as in chapter 11 on *Lineated Valley Fill at the Martian Dichotomy Boundary: Nature and Degradation*.

7.1. Selection and Fusion of Data

Search for required image data is performed by the use of a global planetary GIS that has been set up by the author at the group at Freie Universität Berlin in order to localize data efficiently and to extract and pass on the gathered information for subsequent raw data processing. The latter step is performed using VICAR or ISIS environments as described in chapter 6 about data processing. Many data issues in the GIS-based workflow are supplemented by several utilities taken care of data im- and export and extraction of raw data and label information.

The choice for "the right" GIS was based on personal experience regarding modifiability of the GIS environment for other than terrestrial purposes, im- and export functionalities, implementation of subroutines and 3rd-party software, the usability for other users and finally the availability of licenses at the institute of Geosciences at the Freie Universität. The choice was made for ESRI's ArcGIS software as several other GIS solutions have been tested but considered not to suffice the requirements.

The freely accessible data repository of the USGS, Astrogeology Branch, Flagstaff was a very helpful source for planetary data and issues regarding references and workflow. Proprietary HRSC data or data that is not updated within a promptly after team release, such as MOC and THEMIS, are imported using own scripts to allow for up-to-date information, as well as userdefinable data selection fields.

The selected appropriate data is either directly re-processed and displayed in the GIS environment for direct analyses or it is re-processed from scratch to maintain initial quality and accuracy. All data processing prior to work performed on map-projected image data cannot be handled using the GIS anyway and is therefore restricted to the VICAR/ISIS software environments. Depending on the specific problem that is addressed, image data, predominantly HRSC, THEMIS and MOC raw data, are selected within the GIS, processed using VICAR/ISIS software routines and are re-imported into the planetary GIS for further interpretation and analyses.

Other data, such as gridded data sets or data in non-gridded arrangements such as MOLA PEDR topography tracks or TES data are generally processed using either experiment-specific software (Vanilla toolkit or MOLA tools), VICAR routines implemented at DLR, Berlin and/or third-party environments such as GMT, to generate gridded data and which can then be imported into the GIS for combination with image data.

Many of the experiment teams make use of their own definition of a reference system (e.g., MOC is defined by IAU94 with planetographic latitudes, TES by IAU94 with planetocentric latitudes, MOLA is defined by IAU2000, table 6.1) consisting of different definitions of the reference ellipsoid, coordinate systems (west vs. east), latitude systems (planetographic vs. planetocentric), and different definitions of the central meridian. Even with the most recent US flagship mission MRO, experiment teams make use of different body definitions.

Although such problems can be solved mostly during later processing, it is a cumbersome process of having to re-adjust data every time new data releases or new processing levels become available. In consequence, most of the data are stored twice, one set being the original version, one set being the adjusted one so that later data combination processes are manageable within a bearable amount of time. Reference used throughout this work is provided by the IAU2000 definition (*Seidelmann et al.*, 2002).

7.2. Geomorphologic and Geologic Mapping

Geologic mapping of planetary surfaces comprises in general the separation of units that are different relative to neighboring units in respect to color and albedo, textural properties (roughness), and structural inventory and failure to do so can lead to unexpected results and misinterpretation of the local geology (*Skinner and Tanaka*, 2003; *Tanaka and Skinner*, 2003). To achieve trustworthiness and accuracy, all data that cover a certain region are generally combined and compared to each other so that a consistent and coherent image of that area is obtained. This process of course also includes the usage of already published maps and digital map data.

Most planetary maps, however, are a combination of geomorphologic and geologic maps and represent a simplified two-dimensional representation of the actual setting of the study area by combining either lithologies or geomorphologic units. Geomorphologic and geologic mapping requires information about relief either as topographic data represented by digital terrain models or as stereo data as represented by epipolar images. Geologic mapping focuses on the compositional properties of certain units, and with the help of new high resolution three-dimensional data, mappers are able to obtain information on strike/dip relationships of individual subunits, e.g., layers, and to reconstruct the relative positions of geologic units in a certain area more precisely or to investigate the nature of a unit in more detail (e.g., *Fueten et al.*, 2005, 2006). Stratigraphic information connected with absolute ages is obtained using methods described in section 7.4. In order to obtain information on the relationships of geological units, geologic mapping, i.e., the separation of different units, has to be performed first.

While geomorphologic maps are more connected to the representation of surface processes that shaped landscapes and can therefore well be obtained using topographic in combination with image data, geologic mapping does require additionally information on the compositional properties. Information on this can in principle be obtained using color data of planetary surfaces but this has its natural limitations as seen in Viking and MOC-WA times where only a few color channels were available. High-resolution spectrometer data became available in the last few years, especially the OMEGA mapping-spectrometer instrument on Mars Express operating in the visible and near-infrared range using 352 contiguous spectral elements with pixel sizes of about 350 m to 5000 m at the surface (*Bibring et al.*, 2004; *Bibring et al.*, 2004) or the thermal infrared imaging spectrometer THEMIS onboard Mars Odyssey (*Christensen et al.*, 2004; *Christensen*, 2006) operating in nine bands. These new tools, high-resolution three-dimensional information as well as high-resolution spectrometer data allow for mapping processes that also include rock-stratigraphic units, information that was lacking during earlier mapping approaches (*Wilhelms*, 1987, 1990; *Tanaka et al.*, 1992).

Once a set of consistent data are available, mapping is performed using the existing planetary ArcGIS environment or by using vector-based tools that allow for later lossless data import in the ArcGIS environment. This process also allows for changes and adjustments that need to be incorporated later when new data needs to be incorporated. The mapping process itself is naturally connected to the question that is raised and except for some locations where crater-size frequency measurements have been performed in this work, no 'true' geologic mapping has been conducted. Depending on scale, data availability and data quality, this process was handled in different ways and is described accordingly in the section of part III. Results of that work are shown in e.g., chapter 9 on page 131 on the *Cold-Climate Modification of Martian Landscapes* as well as in publications on the technical issues of that mapping process (*Lehmann et al.*, 2006b,a).

7.3. Geomorphometric Methods

Geomorphometric methods were applied on a global scale and at few local sites to derive, e.g., depths, volumes, areas and lengths, slopes, and distances of certain surface features, such as in chapter 10 on page 155 on *Current State and Disintegration of Rock-Glacier Landforms in Tempe Terra/Mareotis Fossae, Mars*. While lengths, widths and areas can be determined using image data with the help of correctly map projected data and virtually any software that is able to count pixels, volumetric measurements also require elevation data of comparable quality.

The technical aspects covering the derivation of such values are not explained in detail in chapter III and need some more clarification. As time has brought up new image data containing much better orientation data than those products from earlier instruments, a combination of data became necessary and manageable. Some data analyses presented in this work were initially performed on the basis of Viking pre-MDIM 2.1 image mosaics that were missing a correct geometric control (*Zeitler et al.*, 1999) and that needed to be combined to MOLA topographic data. As MOLA has provided a new standard reference for Mars, the older Viking data needed to be shifted accordingly. As deviations were not equally distributed across the planet, rubbersheeting methods had to be applied which were carried out using the DLR VICAR enhancements to obtain not only a somehow-rectified image but a piece of projected image data that can be reprojected afterwards and combined by maintaining its geometric and cartographic integrity. This process does not need to be stressed in more detail as it is commonly used in terrestrial photogrammetry software packages, although usability differs quite noticeably. With the release of the MDIM 2.1 and its corrected reference, such problems vanished thus far.

As soon as different data sets have been brought to the same reference and scale by using either rubbersheeting adjustments or by simply adjusting geodetic and cartographic parameters, data can be either imported into the planetary GIS environment or to proprietary software written at DLR[1] for combination of topographic and image data. Contrasting to modern GIS environments, that software uses pixel-based derivation of geomorphometric parameters as it does not make use of map parameters (except for map scales).

[1] *dtmtool* by K. D. Matz or *HRSCview* by G. Michael

This results in an unusual behavior and unexpected results if data products have not been prepared taking account of the correct mapping parameters. Modern GIS environments handle such issues by treating data not as fixed map projected alignments of image pixels but as data entities connected to a reference body. Due to such discrepancies, measurements performed prior to the use of a GIS as discussed in part III were re-calculated and adjusted appropriately. Using modern environments, the derivation of volumes and areas as well as angles and distances are a matter of point-and-click methods and are appropriately described in reference handbooks.

Important aspects of geomorphometry are error estimates. In almost none of the work published on geomorphometry on Mars thus far, error estimates are provided. Measurements of distances and areas as well as planar angles rely on the image data used and errors can be easily estimated to within one or two pixels of deviation. Volume measurements, however, should not be over-interpreted and should currently be considered as estimates only.

Beside the geomorphologic validity of performing such measurements and the problem of selection of an appropriate reference plain, a combination of image data at small scales with topographic data at much coarser resolution can not lead to exact results if image data is used for the digitization process. Errors can hardly be estimated and are controlled by not only the vertical accuracy of any dataset but also on artifacts introduced by terrain model interpolation or by faulty tracks in the case of MOLA. Data presented in chapter 10 on page 155 on *Current State and Disintegration of Rock-Glacier Landforms in Tempe Terra/Mareotis Fossae, Mars* are therefore treated very cautiously.

Proper measurements of lengths are vital for crater-size frequency analyses making digitization of image data using pixel-based software tools problematic. Distances derived from computer-based crater-size measurements are often overestimated by up to 20% when compared to measurements obtained with the stereo-comparator equipment at FUB as some tests have shown. Such errors lead to considerably older derived ages for geologic units. This problem can be solved by multiplying the image scale by a factor of at least two to three so that measurements are performed on "sub-pixel" level.

Tests have shown that the results compare closely to analog measurements using stereo-comparator equipment. However, increasing the zoom factor in the display and measurement software usually does not help as the lengths are measured on the basis of the true pixel extent.

7.4. Chronostratigraphic Methods

Chronostratigraphy has not been a focus of this work and only few age determinations have been performed mainly because the landforms discussed herein are of such a young age that extensive age determination work would not significantly contribute to the understanding of surface processes. There are however cases where age determinations were very helpful and where no data has been published before, such as, e.g., in chapter 12 on page 183 on *Geomorphic Evidence for former Lobate Debris Aprons at Low Latitudes on Mars: Indicators of the Martian Paleoclimate* or in chapter 10 on page 155 on *Current State and Disintegration of Rock-Glacier Landforms in Tempe Terra/Mareotis Fossae, Mars* or in chapter 11 on page 171 on *Emplacement History and Degradation of Lineated Valley Fill at the Martian Dichotomy Boundary, Deuteronilus Mensae*.

The topic of age determinations is extensively covered by Werner (2005) discussing not only aspects of the geologic history of Mars but also issues regarding fundamentals of crater-size frequency analyses, impact of contamination of surfaces by secondary craters and implications on age determinations as well as the treatment of erosional ages.

The common chronostratigraphic methods applied are based on the fact that projectiles in the solar system accumulate on planetary surfaces through time which results in old surfaces showing a higher impact crater density than younger ones. By measuring the amount and sizes of impact craters per area, estimates on the surface age are possible within cer-

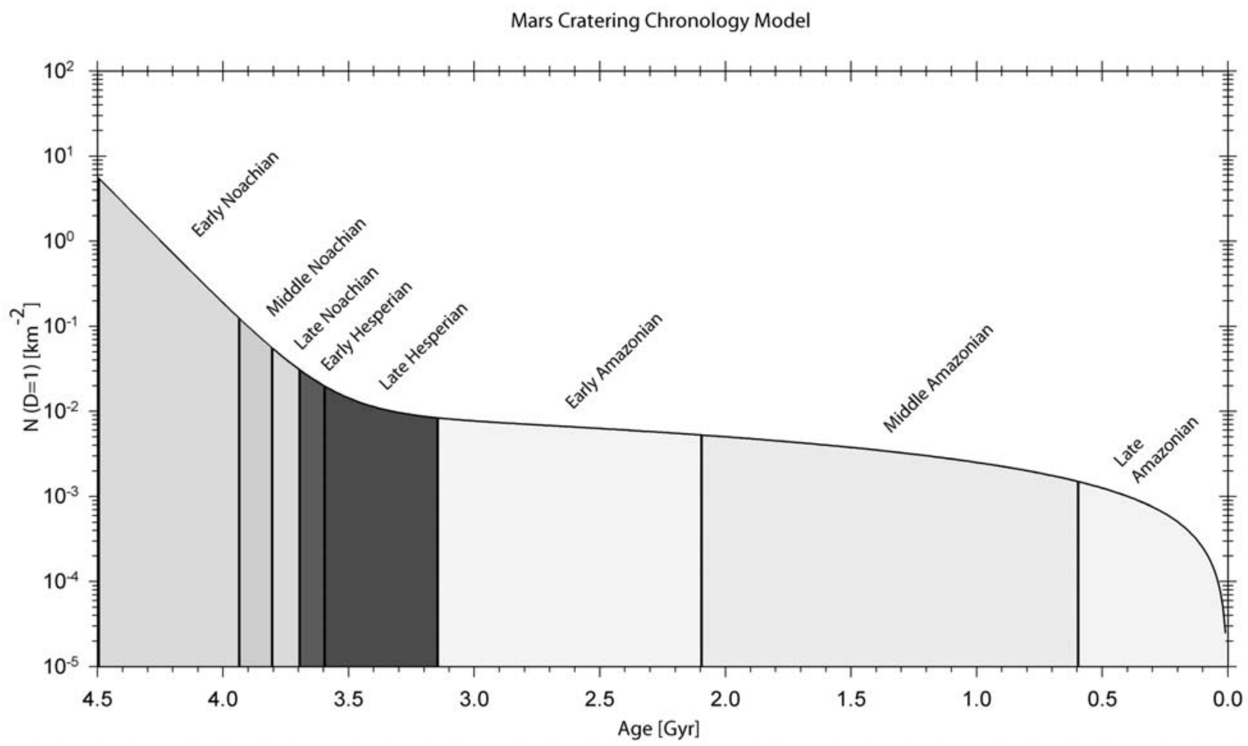

Figure 7.1.: Martian chronology model, modified after (*Hartmann and Neukum*, 2001).

tain model-boundary conditions (*Neukum and Wise*, 1976; *Neukum and Hiller*, 1981). The method of age derivations on the basis of impact-crater size frequencies is based upon work by e.g., *Shoemaker and Hackman* (1962); *Baldwin* (1964); *Hartmann* (1966a,b); *Neukum and Dietzel* (1971) and is in principle applicable to all solid-surface objects in the solar system and depends on estimates of the impact flux. Absolute ages were obtained by correlating ages derived from size-frequency measurement to radiometric ages obtained from the Moon of Apollo lunar surface samples (*Neukum*, 1983).

Geological units on a planetary body, such as Mars, are correlated to each other by comparing crater-size frequencies per area unit at a given diameter (e.g., $N_{(D\geq1km)}/km^2$) which gives relative crater-retention ages. These values can be compared on a global scale as done by e.g., *Scott and Tanaka* (1986); *Greeley and Guest* (1987); *Tanaka et al.* (2005).

Resurfacing processes of geologically active planets cause obliteration of traces of impact craters and therefore have an influence on the measured surface age so that the age measured becomes the resurfacing age and not necessarily the age of formation of that specific unit (*Öpik*, 1966; *Hartmann*, 1971; *Soderblom et al.*, 1974; *Neukum et al.*, 1975). This fact has to be kept in mind when mapping is conducted and there are several prerequisites that need to be met before age determinations can be performed: measurements provide trustworthy results if (a) the area forms a homogeneous surface that is not covered or resurfaced significantly by younger processes (e.g., aeolian material, lava flows), (b) the area is not contaminated by clusters of secondary impact craters and (c) the area consists of a unit that has been emplaced by one and the same process (e.g., flood plains).

Measurements on slopes are valid to a certain degree only as the true size of an area depends on the slope angle. Apart from that, the image on which crater sizes are measured must fulfill the basic technical requirements to allow for measurements, i.e., the chosen map projection must represent true lengths.

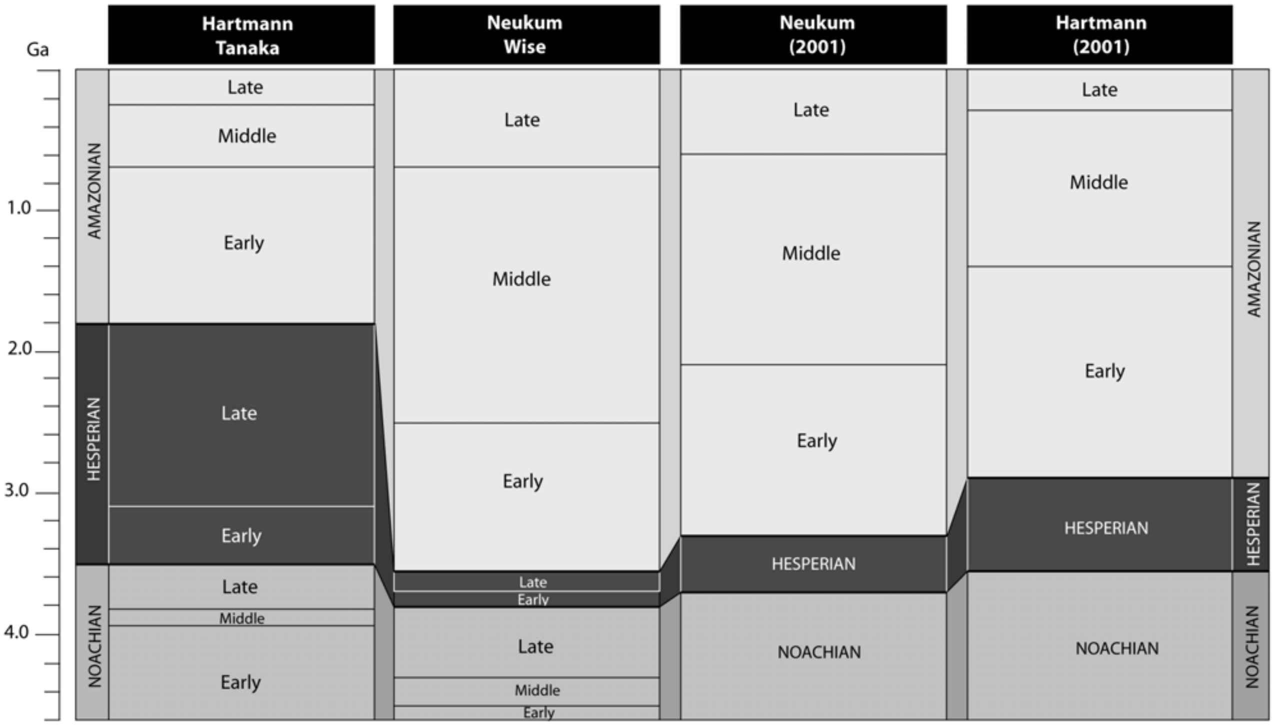

Figure 7.2.: Stratigraphic column and model ages of systems on Mars, stratigraphy after Hartmann and Tanaka as cited in *Hiesinger and Head* (2004), *Neukum and Wise* (1976); *Hartmann and Neukum* (2001); modified after *Hiesinger and Head* (2004).

For Mars, the crater-size frequency distribution was set up initially by *Neukum and Wise* (1976) and was later modified by *Ivanov* (2001) and is approximated by

$$\log_{10}(N) = a_0 + \sum_{n=1}^{11} a_n \left(\log_{10}(D)\right)^n \quad (7.1)$$

with

a_0	=	$f(t)$	a_6	=	$1.016 \cdot 10^{-1}$
a_1	=	-3.1970	a_7	=	$6.756 \cdot 10^{-2}$
a_2	=	1.2570	a_8	=	$-1.181 \cdot 10^{-2}$
a_3	=	0.7915	a_9	=	$-4.753 \cdot 10^{-3}$
a_4	=	-0.4861	a_{10}	=	$6.233 \cdot 10^{-4}$
a_5	=	-0.3630	a_{11}	=	$5.805 \cdot 10^{-5}$

By fitting this curve in log(N) direction (y-axis), a_0 can be determined and values for crater-size frequencies at the reference diameter can be obtained. Relative ages are then extracted by using an appropriate chronology model (figure 7.1). In order to obtain absolute ages for Mars, the Lunar production function needed to be transferred to fit Martian conditions with the help of crater-scaling laws and under the assumptions that the population of projectiles for the inner planets remains the same as for the Moon (*Neukum and Wise*, 1976; *Hartmann*, 1977; *Neukum*, 1983; *Ivanov*, 2001; *Hartmann and Neukum*, 2001). Modifications of this basic model contain also radiometric ages from SNC meteorites found on the Earth (*Bogard and Johnson*, 1983; *Becker and Pepin*, 1984; *Marti et al.*, 1995, e.g.,). This transfer results in a chronology curve from which ages based on the relative production function fit can be obtained (figure 7.1) and put into a stratigraphic context (figure 7.2).

The absolute systematic errors in ages due to the uncertainty of the Martian cratering chronology is about 100 Ma for ages older than 3.5 Ga (steep branch in figure 7.1) and up to a factor of two in the constant range (*Neukum et al.*, 2004; *Werner*, 2005). □