Part III.

Re–Assessment of the Martian Stratigraphy

In **Part III, Re–Assessment of the Martian Stratigraphy**, the crater count results obtained during this investigation will be described, and some key results outlined. A summarizing discussion and interpretation will be given in Part IV, The Evolutionary History of Mars.

The earlier problems of assessing the geologic stratigraphy is introduced by a case–study: the Athabasca Valles. The geologic history of this former candidate landing site of the Mars Exploration Rover landers (MER) will be interpreted. Difficulties and possibilities of data "merging" are shown. This investigation is based on Viking and MOC imagery, and displays the gap in the range between 100 m up to 1 km of determining crater frequencies, due to differently resolved imagery. As outlined in Part II, linking different data sets, we overcame these difficulties due to the newly available imagery received during the Mars Express mission (HRSC experiment) and complementing image data taken by the Mars Odyssey Mission (THEMIS experiment). The latest geologic interpretation (based on MOC and HRSC imagery) for the youngest plains on Mars (Elysium Planitia) is indicating a "frozen sea", and which supports our earlier interpretations for the Athabsaca Valles region (Chap. 12).

The morphologic diversity of Martian impact craters imposes the possiblity to study target influence on the crater size–frequency distribution. A comparative study of the early heavy bombardment as well as the formation of Mars and the Earth's moon is based on the investigation of basin ages and their occurring frequencies. In comparison to the lunar record, it was possible to strengthen the applied chronology model and show the similar planetary evolution of the Moon, and Mars (as recorded by basin ages and their numbers) and most likely the entire inner solar system (Chap. 13). The detailed geologic history of Gusev crater, one of the actual MER landing sites, will also be given. This basin is situated at the highland–lowland dichotomy boundary, and special features such as crater depth will be evaluated (Chap. 13.2). Morphologic differences for large craters were found to be correlated with the dichotomy that splits the Martian surface into the northern lowlands and the southern highlands.

The advantage of additional datasets, e.g. from the Mars Orbiter Laser Altimeter (MOLA), is that they have initiated an enormous mapping effort and new interpretations of the geologic history of the Martian northern hemisphere (Tanaka *et al.*, 2003). Based on these attempts, the ages of all newly mapped geological units will be presented (Chap. 14), including a detailed study of the dichotomy boundary between 330°E and 90° E (Chap. 14.2), as well as a detailed study of major units of the northern plains units, Acidalia and Utopia Planitiae. Their geologic evolution, morphologic characteristics, and giant polygonal patterned troughs will be discussed along with the possible existence of a Martian ocean (Chap. 14.3).

The mophological appearance of the dichotomy boundary has been modified in many places either by volcanic, fluvial or glacial processes. The Medusae Fossae Formation, massive deposits along the boundary, has been studied (Chap. 14.4). Some of the largest outflow channels in the Chryse region have been investigated in greater detail (Chap. 14.5), in order to better understand their individual evolution, and to set a time–frame for the development of the lowland plains. Special type regions such as Amazonis Planitia and Hesperia Planum will be discussed in conclusive interpretations together with the crater size–frequency distribution measurements, in order to understand the geological evolution of the northern lowlands.

Finally, an overview of the volcanic evolution on Mars will be given based on the interpretation of caldera and volcanic surface ages determined from High Resolution Stereo Camera data (received from the Mars Express mission up to now). These results will be compared to earlier measurements based on Viking imagery. The Tharsis, Elysium, and Highland volcanic provinces will be discussed with emphasis on their differing evolution (Chap. 15). Additionally, interrelated glacial and/or fluvial activities are the focus of this study (Chap. 16).

A comprehensive summarizing discussion and interpretation of the global evolutionary history of Mars will be given in Part IV.

12. Athabasca Valles: A Case Study

Athabasca Valles has been studied as one of the candidate landing sites for the Mars Exploration Rover landers (MER) (Werner *et al.*, 2003a,b). The Athabasca Valles system is thought to be an outflow channel system that dissects Cerberus Planitia, a volcanic region of Elysium Planitia (one of the youngest regions on Mars). It is located in an area between 200° and 220° W and extends from the equator to 15° N. The area of interest has been mapped by Greeley and Guest (1987) as primarily younger channel and flood–plain material (unit Achu) of Amazonian age, following Scott and Tanaka (1986). They have interpreted it as fluvial deposits, where distinct albedo patterns probably represent channels with bars and islands. Especially in the west mottled zones represent deposition from ponded terminus of fluvial systems. Contrary to this interpretation, Plescia (1990) describes the Cerberus Formation to be of volcanic origin and points out corresponding surface morphologies, including lobate edges of the unit and the embayment relation of the unit with adjacent older units. Low–viscosity lavas from the Elysium volcano group northwest of the plains have flooded this region and filled the topographic depression. Plescia's (1990) interpretation is supported by Schaber (1980) who describes the radar and thermal characteristics to be similar to those interpreted as flood basalt provinces (e.g. Syrtis Major).

The main valley of the Athabasca Valles system strikes in a NE–SW direction, but also discharges to the Cerberus Plains at an elevation of about –2700 m in a southeast direction following the overall topography. The possible origin of the valley correlates with Cerberus Fossae, a set of sub–parallel grabens or extensive en–echelon fissures striking NW–SE at an elevation of about –2450 m. The fissures may have developed during the rise of the Elysium volcano bulge. Burr *et al.* (2002) identified relatively fresh lava extrusions from Cerberus Fossae associated with the channel origin.

Isolated, irregularly shaped remnants with a maximum elevation above the plain of 1000 m are embayed by plains material and dominate the western and eastern part of the investigated area (see Fig. 12.1). While the southeastern plains slope very gently to a topographic low of –2750 m, the southwestern region is blocked by a sudden rise to an elevation of about –1900 m.

Methodology: For a comprehensive study of the stratigraphic relationships, all available datasets have been combined: MDIM–2 Viking imagery, MOLA based digital elevation models and shaded relief maps, as well as MOC wide– and narrow–angle (MOC–NA up to April 2003, e18–release) imagery of the Mars Global Surveyor spacecraft. The resolution of all the different datasets was set to 231 m/pixel. Longitude and latitude shifts in the Viking and MOC wide–angle imagery were corrected on the basis of the digital elevation model using rubbersheeting methods. For small–scale features and the verification of area boundaries obtained by geological and geomorphological mapping, selected MOC narrow–angle shots were used to achieve higher precision in this highly differentiated terrain. The main mapping procedure was initially performed using Viking and MOC–WA imagery. In order to distinguish different units, various albedo features were analyzed. MOC–WA images were more satisfactory than Viking imagery due to reduced noise. Finally, area boundaries were adjusted using MOLA–derived data and the close views of MOC–NA imagery. For detailed studies, the MOC–NA images M04/02002 and M12/01869 which cover the plains units surrounding the valley and the proposed valley rim at a resolution of 3–5 meters/pixel, were mapped in order to possibly obtain even younger ages, requiring higher image resolution.

Geologic History of Athabasca Valles: In order to determine the stratigraphic relationships and the origin of the valley, ages were measured for different geological units in the region of Athabasca Valles. Details of the mapping results, interpretation of the geological units as well as a detailed age discussion is given in Werner *et al.* (2003a,b). Athabasca Valles was analyzed comprehensively to understand the chronostratigraphic relationships and explore different episodes of resurfacing. The results of the crater statistics investigation contradict the classic assumption that the Athabasca Valles were excavated by one or a few possibly ongoing catastrophic outflow events. As discussed by Berman and Hartmann (2002), various athors cited the age of the Cerberus plains to be Middle or Late Amazonian (around 0.6 Ga), showing signs of even younger resurfacing episodes. Continual volcanic activity accompanied by fluvial activity is a more likely interpretation. In the imagery, we could record the end of several resurfacing events in stratigraphically differing areas and establish the following geological history: The main channel has been incised into the Cerberus volcanic plains with an average plains age of 3.6 Ga. The main fluvial or glacial erosion processes ended 2.6 Ga ago. This result shows that the age of the valley system is itself older than commonly believed. One major, possibly fluvial event occurred 1.6 Ga ago in the topographically lower volcanic plains southwest of the valley. The valley was episodically covered by lavas, until 0.9 Ga, with a few younger episodes 30 Ma ago. The surface texture south of the valley system suggests a younger, possibly fluvial overprinting of the volcanic texture 30 Ma ago. The youngest volcanic activity is dated to about 3 Ma ago. With the latter ages we have not only been able to confirm earlier age estimates by Hartmann and Berman (2000); Berman and Hartmann (2002), but also shown that the valley system itself has undergone a period of two billion years that was dominated by volcanic processes in the most recent times. More erosional episodes might be found if one examines the "terraces" of the streamlined islands. The age determination favors the hypothesis that the streamlined features are erosional remnants. The interpretation of recent fluvial activity could not be verified within the geological units we could identify on the imagery (described in Werner *et al.*, 2003a). However, the ejecta pattern of a few larger craters superimposed on the lava blankets, that cover the valley floor might suggest the presence of water. The results contradict the assumption that the Athabasca Valles were excavated by one or a few possibly ongoing catastrophic outflow events, as claimed by Burr *et al.* (2002).

Cerberus Fossae fissures West of Athabasca Valles: Murray *et al.* (2005) investigated an area west of Athabasca Valles. This plains region has been interpreted earlier by Plescia (1990); Hartmann and Berman (2000); Berman and Hartmann (2002) to be volcanic plains. We could confirm that this plains unit formed about 3.6 Ga ago (Murray *et al.*, 2005), and similar ages were found for plains units in the Athabasca Valles region (Burr *et al.*, 2002; Werner *et al.*, 2003a). It is thought that the Cerberus Fossae fissures on Mars were the source of both lava and water floods two to ten million years ago (Werner *et al.*, 2003a). Nevertheless, based on HRSC and MOC data we were able to observe a strong resurfacing event. The crater size–frequency distribution yields a surface age of about 5 Ma, similar to ages we found in the Athabasca region. Evidence for the resulting lava plains has been identified in eastern Elysium, but seas and lakes from these fissures and previous water flooding events were presumed to have completely evaporated and sublimed. The surface morphology recognized in the HRSC and MOC imagery indicate that such lakes may still exist and resemble terrestrial ice floes. We infer as discussed in detail by (Murray *et al.*, 2005) that the evidence is consistent with a frozen body of water, with surface pack-ice,

Table 12.1.: Summary of all surface ages found for certain units. They correspond to the different isochrones shown in Fig. 12.1 (solid lines). The measured surface age of 0.9 Ga were found in units of all imagery and establish a good connection between high– and low–resolution images.

Unit	Unit Age(s)*				
Viking - Area 1	3.6		0.9		
MOC - WA - Area D		2.6	0.9		
MOC - m1201869 Area 1					0.003
MOC - m1201869 Area 12				0.03	
MOC - m1201869 Area 5			0.9	0.03	
MOC - m0402002 Area 1			0.9		

* in Ga (= billion years)

in southern Elysium around 5°N–latitude and 150°E–longitude. The frozen lake measures about 800 km times 900 km in lateral extent and may be up to 45 metres deep, similar in size and depth to the North Sea (Murray *et al.*, 2005). We also could confirm on the basis of crater counts, that the "ice–plates" are slightly older than the inter–plate areas (for details see Appendix C).

12.1. Implications for the Martian Crater Size–Frequency Distribution and Age Determination

Our interpretation of crater statistics data based on determining absolute surface ages by applying the Martian cratering chronology model presented by Hartmann and Neukum (2001) led to results similar to Hartmann and Berman (2000); Berman and Hartmann (2002) for comparable regions in the Athabasca system. This supports the reliability of the different approaches to determining surface ages using crater statistics.

Additionally, these counts (Fig. 12.1), both on Viking imagery at large crater sizes and MOC imagery at small crater sizes, consistently fit the currently established Martian production crater size-frequency distribution proposed by Neukum *et al.* (2001) and Ivanov (2001). A surface age of 0.9 Ga was measured in units of all high– and low–resolution images (Table 12.1). This constitutes an excellent first order test for the general validity of the Martian size-frequency distribution and cratering chronology model by Neukum *et al.* (2001) and Ivanov (2001). It also demonstrates the difficulty of linking surface units mapped in different image resolution and relating crater frequencies measured from these two datasets. Now, the gap can be filled by the High Resolution Stereo Camera (HRSC) imagery, which covers huge areas at high resolution (up to 11 meters/ pixel), where medium–resolution Viking–mosaics do not existed.

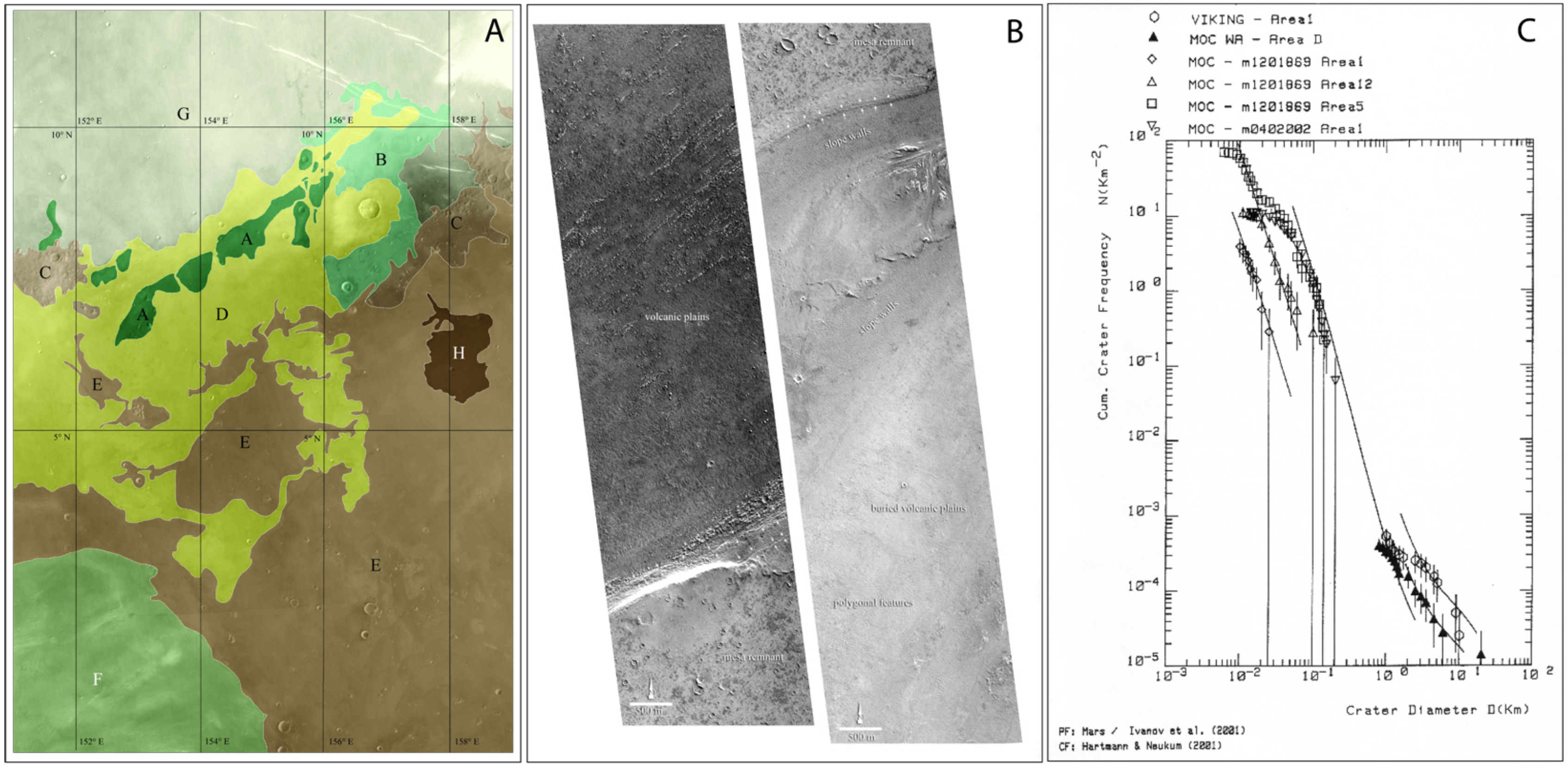

Figure 12.1.: The Athabasca Valles system: (A) Mapped on MOC-WA imagery. (B) MOC-NA image M12/01869 centered at 8.31°N 154.46°E shows a traverse across a mesa remnant near the upper Athabasca Valles system. (left), the northern part, shows the main valley floor. The dark plain (plf) is flooded with volcanic lava. The transition to the mesa remnant is characterized by a steep escarpment that expose of several remnant layers (white arrows). (right) the mesa slopes more gently than the northern slope towards brighter plains. The slope walls (sw) are cut by a set of very narrow subparallel ridges, which resemble small dunes. At the base of the southern slope a streamlined island (si) can be observed, which is clearly defined in the east and rather diffuse at its western margin. Sets of small valleys branch at the front of the island. The channels spread in a southern and western direction onto older lava plains. (C) The crater size frequency distribution of a few prominent ages measured for the Athabasca Valles area. These are selected to give an impression regarding the range of ages. The ages represented by the isochrons are given in table 12.1.