Part IV.

The Evolutionary History of Mars

Part IV, **The Evolutionary History of Mars**, summarizes the temporal development of the Northern Lowlands and the global volcanic evolution in relation to the decay of the magnetic field, the actual dynamic shape of Mars, as well as their implication to the general evolution of the planet Mars. The interplay of volcanic activity, the northern lowland formation, together with the formation of the dichotomy are put into the context of earlier investigations (see also Part III). New findings with respect to the evolution of Mars are described, and in part, a new view of the most recent evolution will be outlined. An outlook to further investigations and the importance of our findings will also be discussed.

In this thesis, the frequency of craters forming on geological units are used to investigate the sequence of events in various regions of Mars, including

- the lowlands occupying the northern hemisphere, and the outflow channel activity of adjacent regions
- the dichotomy boundary separating the lowlands and highlands
- the global volcanic record, and
- recent fluvial, glacial, hydrothermal, and volcanic processes and their interplay

Except for the chronostratigraphic classification of these regions, this effort has resulted in the determination of the Martian crater size–frequency distribution over the entire measurable diameter range (tens of meters to hundreds of kilometers). Regarding the "contamination" due to secondary cratering in our crater counts, we found, in agreement with Hartmann (2005), that the conclusion by McEwen *et al.* (2005b) that the age determination is impossible, is not valid (Part II).

All absolute ages derived in this thesis are based on the assumption that Mars and the Earth's moon have had a similar bombardment history with respect to the time dependence of impact rate and the source of impactors; therefore, the transfer of the lunar cratering chronology to Mars appears valid. We tested this idea by comparing the early lunar and Martian cratering record, which had a characteristically higher impactor flux than today. The impactor flux for this period between 4.1 Ga (Apollo 16 landing site) and 3.15 Ga (Apollo 12 landing site), has been calibrated for the Moon based on radiometric ages. These have been determined for samples collected on the lunar surface at various landing sites and brought to Earth.

Additional knowledge is gathered by studying large impact basins (larger than 250 km in diameter) that only formed during the so–called heavy bombardment period. On the Moon, these basins did not form any later than about 3.9 Ga ago, and we found a similar situation for Mars. The number of large impact basins per age period appears to be in the correct proportion between the Moon and Mars data. However, on Mars the oldest crustal structures we observe today are no more than 4.2 Ga old, whereas we can probably date the lunar surface back to 4.3 or 4.4 Ga. On Mars the earlier record has been erased by endogenic and surface erosional processes. This implies that the transferred Martian cratering chronology relates the crater frequencies and absolute ages correctly in the exponentially dominated part of the cratering chronology model (before about 3.5 Ga; the higher flux period). For the younger period (younger than about 3.5 Ga) two facts support the validity of the cratering chronology model: (1) the estimates of the asteroidal impactor population has increased in number over the last years (2) their orbital evolution is better known, so that the transfer of the lunar model to Mars now has a good statistical basis. Applying this model we can derive surface ages for volcanic and fluvial landforms of large areal extent. A good agreement with meteorite ages of volcanic origin and aqueously altered minerals is found.

17. Stratigraphic Type Areas Re–Visited

Based on imagery from Mariner and Viking missions, the Martian stratigraphic system has been established (originally by Condit (1978) and later refined by Tanaka, 1986). As no direct measurements of absolute ages of Martian rocks are available (except a few of SNC meteorites), model ages of the stratigraphic system and series are based on estimated projectile flux. Relative ages are measured by means of superimposed crater frequencies and transferred to absolute ages applying the established chronology model (Hartmann and Neukum, 2001). The formal definition of Martian time–stratigraphic units started with a 1:25M-scale map of Mars by Scott and Carr (1978), divided into Noachian, Hesperian and Amazonian units. The exposed base of the Arcadia Formation defines the base of the Amazonian system. Re–measurements in Arcadia Planitia revealed resurfacing processes (as suspected by Tanaka, 1986), which shifted the age boundary of the Lower Amazonian (for comparison see Fig. 17; Hartmann and Neukum, 2001).

For the epoch–boundary definition, cumulative crater frequencies at certain diameters (and larger) for a specific type unit have typically been utilized. In all map approaches, the registration of surface units to an epoch by relative or even absolute ages is based on the predicted cumulative crater frequencies at diameters of 16 km, 5 km, and 2 km (Tanaka, 1986). To classify smaller or younger units, where none of these diameter classes are present, a "minus–two" slope has been formerly suggested in order to extrapolate the crater size–frequency distribution to the smaller–size ranges (e.g. Tanaka *et al.*, 2005). All our measurements show that such a simple approach is invalid; see detailed discussion of the "true" shape of the Martian crater size–frequency distribution in Chapter 11. At least a segmented power–law (Hartmann, see Chapter 4) or a polynomial expression (Neukum, see Chapter 4) is much more adequate for describing the complex structure of the Martian crater size–frequency distribution, as predicted by Hartmann, Neukum, Ivanov and others (see Chapter 4).

We have re–mapped some key geologic units, including Amazonis and Acidalia Planitiae, Hesperia Planum as well as Noachis Terra. In the following, the results of crater size–frequency measurements, which we used to re–examine the age boundaries of the stratigraphic epochs, will be discussed.

17.1. Ages of Martian Basins and the Noachian Epoch

As discussed in Chapter 13, the large lunar basins were produced no later than about 3.8 to 3.9 Ga ago and the situation is similar for Mars. In the case of Mars, most basins formed before 3.9 Ga, based on crater size–frequency distributions and the applied cratering chronology model. When comparing the frequencies of relevant impact basins on Mars and on the Moon for the period prior to 3.9 Ga, roughly similar number of bodies hit the Moon and Mars per surface area. According to our investigation, much of the oldest surface areas on Mars, the Martian southern highlands (e. g. Noachis Terra), were formed at around 4.0 to 4.2 billion years ago during the period of the heavy bombardment. This implies that no surface is found to be older than 4.2 Ga. Radiometrically determined ages for Martian meteorites indicate that some rock ensembles are as old as 4.5 Ga (Chapt. 6.1), i.e. part of the surface material survived from that time until today though no structural relationship is visible any more.

As discussed in Chapter 13, the transferred chronology model supports the idea of a marker horizon, as suggested by Wetherill (1975). An upper limit of surface ages based on crater counting has been introduced by these measurements of the crater size–frequency distribution in Noachis Terra and the number and ages of the large impact basins on Mars. The average age of the Martian highlands, derived from a size–frequency distribution of basin diameters compiled by Barlow (1988a), is about 4.1 Ga.

The boundary between the Middle and Upper Noachian Epoch is defined by the unit assigned as Npl2, which can be found in Noachis Terra as well, adjacent to Npl1 units (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). One of the Noachian type regions is indicated as Npl1, which is the Noachian unit representing the boundary between Lower and Middle Noachian around 4 Ga ago. For the large–crater range (> 2 km) measured in Npl2, we obtained an age of about 3.9 Ga (boundary between the Middle and Upper Noachian). Inspection of the smaller–size range (< 2 km) indicates depletion of craters due to resurfacing, e. g. by erosion as is visible in the valley networks and deposition (inter–crater plains).

17.2. The Hesperian Epoch

Hesperia Planum is the type region for the Early Hesperian period. The crater size–frequency distribution for this region (Hr), based on old Viking data supplemented by high-resolution (17 m/pxl) THEMIS imagery, revealed resurfacing in the smaller crater–size range. The age for this plains unit is 3.71 Ga and the resurfacing event ended 3.18 Ga ago. When comparing our crater frequencies to the corresponding boundary crater density ranges (see Chapt. 6.2), only an approximate agreement is found. Nevertheless, all boundaries were established based on Mariner 9 and Viking imagery. Therefore, crater frequencies below crater diameters of about 800 m were not considered due to the lack of global coverage at high resolution, to effects of erosion and deposition, and the possible but unresolved contribution of secondary craters. Considering only large craters, which are not affected by the above mentioned processes, requires a large sample area to allow for a statistically significant interpretation. On Mars, this is difficult in itself, especially for the younger regions where significant resurfacing occurred and only small patches of homogeneous surface are exposed.

Other regions such as the Northern Lowland units are of Hesperian age. Recent efforts by Tanaka *et al.* (2003) focused on remapping the geologic unit of the northern plain units, considering topographic and stratigraphic aspects rather than morphologic characteristics. They obtained new insights into geological processes and events and proposed four successive stages of lowland resurfacing that are most likely related to the activity of near–surface volatiles.

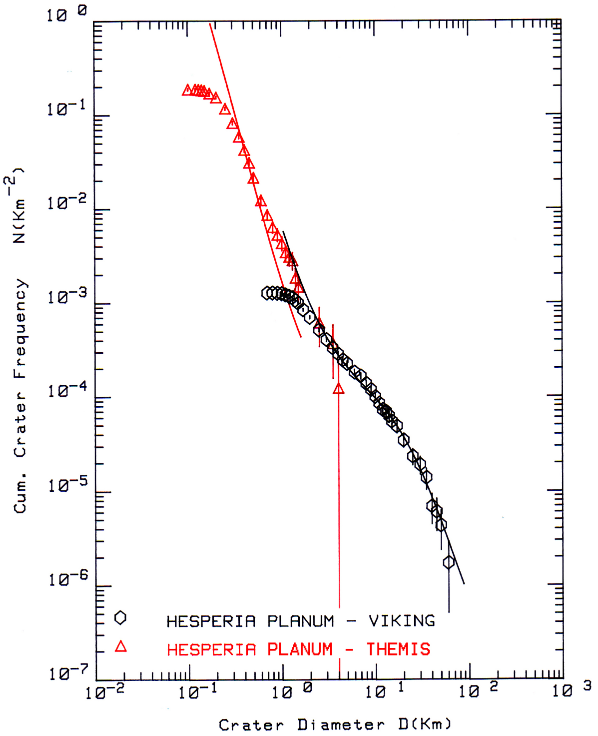

Figure 17.1.: The crater size–frequency distribution measured on Viking (black) and THEMIS (red) imagery. The plains age is about 3.7 Ga (black curve) and experienced a resurfacing event ending about 3.2 Ga ago (red curve).

Measured Crater Size Frequencies for the Type Locations

Series	Type Region	< N(1)	N(1)	N(2)	N(5)	N(16)	> N(16)	abs. Age
Upper Amazonian	Achu	ok	7	–	–	–	–	0.014 Ga
Middle Amazonian	Aa3, Aa2	–	resurf	39	18	–	–	1.15 Ga
Lower Amazonian	Aa1	–	528	292	95	18	older	3.5 Ga
Upper Hesperian	Hv(x)°, here Hvg	–	624	333	87	lack	lack	3.44 Ga
Lower Hesperian	Hr	resurf	4320	705	225	49	ok	3.71 Ga
Upper Noachian	Npl2	resurf	resurf	1040	417	120	older	3.88 Ga
Middle Noachian	Npl1	resurf	resurf	1180	544	245	ok	4.02 Ga
Lower Noachian	Nb	–	–	–	–	–	–	> 4.1 Ga

* N(D) = no. $\geq$ D/10^6 km^2 and Hv(x)° means Hvk, Hvg, Hvr, Hvm

Table 17.1.: The Crater frequencies for crater diameters equal to or larger than 2 km, 5 km, and 16 km as measured for the stratigraphic type areas, which outline the boundary conditions for the different geological epochs, type regions according to Scott and Tanaka (1986); Greeley and Guest (1987); Tanaka and Scott (1987).

As an example for the Northern Lowland units, we selected Acidalia Planitia (similar to Utopia Planitia), which is occupied by extensive areas of polygonal terrain, so-called giant polygons (a general chronostratigraphic interpretation of the new map approach is discussed in Chapter 14.6). Measurements of size-frequency distributions in areas covering polygonal terrain and surrounding units yield (crater retention) ages of 3.4 Ga in the medium-size range. We have obtained size–frequency distributions that appear to have an unusual deficiency of large craters compared to the proposed production function (Chapter 14.3). Such an observed distribution, which roughly follows a single power–law description (with a slope index close to –2), has been discussed for the northern lowlands and other younger Martian units. Barlow (1988b) and most recently Strom *et al.* (2005) argue that the change of the production function is due to a change in the projectile population after the heavy bombardment period. Combining the clearly visible crater population with the population of so–called ghost craters, buried craters causing ring-like grabens, yields an age of 3.8 Ga with resurfacing, which occurred until about 3.4 Ga ago. Similarly shaped distributions (compared with the stacked population distribution in polygonal terrain) are observed in regions with strong "excess" of craters in the larger diameter range (see Chapter 14.3). These distributions can be explained by extensive resurfacing (deposition) effects within a time span of roughly half a billion years. The difference compared with the giant polygon units is that the large craters are blanketed, while in the vicinity the large crater population is preserved mostly unmodified.

Other regions in the northern lowlands, earlier considered as Hv(x) members (Hvk, Hvg, Hvr, Hvm), appear to have formed between 3.8 Ga and 2.8 Ga (see Chap. 14.1). This implies that the causative and temporal formation of the northern lowlands is not completely uniform. Therefore, it is difficult to use any of these unit to define epoch boundaries. The problem is indicated in the inverse age results for the type regions for the Upper Hesperian and Lower Amazonian Epoch. The unit mapped as presumably younger surfaces, actually appears older based on crater counts. The variability of crater size–frequency distributions measured in the northern–lowland regions is mainly due to the deposition of variably thick layers (see Chapt. 14.3 for discussion), which in many places of the lowlands obscure the crater size–frequency distributions. Discussions (e.g. Strom *et al.*, 2005, and earlier by Barlow (1988b)) regarding the change in the projectile population between the period of heavy bombardment and younger times are based on the differing crater size–frequency distributions found in the Martian Lowlands and highland areas. In this thesis, crater counts have been performed to understand and support the stratigraphic relationships between different geologic units and to obtain a coherent view based on the relative crater frequencies. These are based on area sizes that mostly do not reflect the large diameter size range ($>$ 50 km) for surfaces younger than about 3.4 Ga (see Table 14.1). Therefore, a definitive answer as to the shape of the large crater size–frequency distribution cannot be given for the entire northern lowlands.

An ideal crater production function is very rarely found in the lowland areas. Even the surface of geologic units classified as Amazonian, e.g. Aa1, Aa2, Aa3, shows resurfacing events. In the large–scale distribution ($>$ 5km) kilometer–sized craters remain (obviously embayed by later deposits), but smaller–scale resurfacing also occurred, affecting craters below 1 km in diameter (unobservable in Viking imagery).

17.3. The Amazonian Epoch

Amazonis Planitia has been considered the type region for Amazonian ages. This youngest epoch, the Amazonian, includes an absolute time span of 3/4 of the geological record of Mars. Our crater size–frequency distributions reveal strong resurfacing events and a non–uniformity in age. This means that the Amazonian–Hesperian time–stratigraphic boundaries have to undergo careful revision.

In most of our investigations, based on high–resolution imagery (HRSC, THEMIS, and MOC–NA), large areas are occupied by volcanic units, that formed later than 500 Ma ago. Additionally, most surface morphologies associated with ice on the surface or subsurface ice (glacial), such as debris aprons, lineated valley fill, or possible rock glaciers, appear to be relics of the most recent "ice ages" on Mars (see Chap. 16). All landforms related to such processes have formed during the most recent 1/8 of the Martian geologic history.

Based on these results, a revision of the boundary key units is needed to find units that would best represent those youngest Amazonian epochs in high–resolution imagery. A new subdivision of the last three billion years of Martian geologic history (the Amazonian) may have to be considered.

This effort needs an established and unified crater production function, as discussed in Chap. 11. We could not confirm a separation between two different populations before and after the heavy bombardment period. All our measurements have been performed in coherent, uniform geologic units. We have never summarized measurements that ignored geological unit boundaries. Most of the measurements do not cover the large size range of the distribution that would allow us to judge the shape of that part of the distribution, since the areas are both too small and/or too young ($<$ 3.5 Ga) to obtain a statistically significant sample. In areas older and/or larger (e.g. Fig. 17.1), the coverage is extensive enough (statistically significant) to indicate that the shape in the large–size range confirms the shape as described by Neukum (1983); Neukum and Ivanov (1994); Ivanov (2001).