1. Abstract

This thesis was conducted in the framework of the German Research Foundation's priority program *Mars and the Terrestrial Planets* as part of the project *Chronostratigraphy of Mars*.

All global stratigraphic and geologic systems for Mars have been based on remote sensing data gathered during the Mariner 9 and Viking mission (Tanaka, 1986; Tanaka *et al.*, 1992a), culminating in three 1:15M–scale geologic maps by Scott and Tanaka (1986); Greeley and Guest (1987); Tanaka and Scott (1987). Generally, most of the surface–forming processes were placed in the early phase of the Martian evolution. Chrono–stratigraphic schemes for Mars are derived from imagery and crater frequencies observed during Mariner 9 and Viking missions, and however, led to a wide range of chronologic systems with no clear consensus on the absolute ages (Hartmann, 1973b; Soderblom *et al.*, 1974; Neukum and Wise, 1976; Hartmann *et al.*, 1981; Neukum and Hiller, 1981; Neukum, 1983; Strom *et al.*, 1992). Missions launched in the late 1990ies, such as Mars Global Surveyor and Mars Odyssey revealed very young volcanic surfaces, correlating in age with Martian meteorite crystallization ages (Hartmann, 1999a). Additionally, global topography (Smith *et al.*, 1999a,b, Mars Orbiter Laser Altimeter) and gravity data (Zuber *et al.*, 2000) as well as the discovery of strong remnant magnetization of the older Martian crust (Acuña *et al.*, 1999), implied a more continual and diverse evolution than previously thought.

Age determination techniques were initially developed for lunar applications during the late 1960s and early 1970s when automated and manned missions to the moon allowed for sample return of rock material. Radiometric rock ages (absolute ages) and correlation of these ages with crater size frequencies (relative ages) measured in units surrounding the landing sites, build standards for calibrating crater frequencies on the moon and other solid surface–bodies on a global scale.

The technique applied in this study has been developed and outlined by Neukum *et al.* (1975) for the moon and later other planets in general (Neukum, 1983). The methodical bases have been transferred to Mars (Neukum and Wise, 1976; Neukum and Hiller, 1981; Neukum, 1983; Neukum and Ivanov, 1994, and other solid–surface planetary bodies) and are the most reliable tools to define global age relations. Key is the single source of the inner solar system projectile population (asteroid belt,), was proven firmly (e.g. Neukum and Ivanov, 1994). However, the absolute chronology and absolute ages of different Martian stratigraphic units were known only crudely then due to the uncertainties primarily in the Martian impactor flux. In 2001, different approaches by Hartmann, Neukum and Ivanov to apply the underlying cratering chronology model and the lunar crater production function for the Martian case were successfully unified (Neukum *et al.*, 2001; Hartmann and Neukum, 2001; Ivanov, 2001). Nevertheless, due to limited coverage and resolution of the previously available imagery, it was not possible to measure the Martian calibration crater production function over a wide–enough crater size range. Now, imagery newly gathered by the High Resolution Stereo Camera (HRSC) experiment onboard ESA–Mars Express mission could be used. The experiment is capable to cover large areas at resolutions of up to 11 meter per pixel. The study presented here, was benefiting from the proprietary use of the HRSC imagery in the group of the Principal Investigator G. Neukum.

One major aim of this thesis was to improve and/or verify the existing chronostratigraphic system of Mars. The second major goal was to understand globally the geologic evolutionary history of Mars focusing on the volcanic and fluvial processes, determining consistent absolute ages and studying the sequence of events through time. This implies the photogeologic analysis of all available types of Martian imagery in order to cover the diversity of Martian landforms in time and space.

In order to unravel the evolutionary history of Mars, this study was notably concerned with testing the theoretically transferred lunar crater production function for the Martian case. As an outcome of this study the proposed Martian crater production function was proven over the entire (50 meters to 500 kilometers) crater diameter–size range by measurements and the time–independence of the Martian crater production function was confirmed. This was not possible earlier on the basis of the available imaging data . This result confirms that all craters have formed by a single projectile source from the asteroid belt. Any deviation (visible in kinks) from the confirmed Martian standard crater production function indicate resurfacing events. In such cases the method of age determination has been improved, and a procedure to derive the resurfacing age with high accuracy has been developed.

An additional topic has been to understand the contribution or "contamination" due to secondary cratering (craters generated by the ejecta of a "primary" crater). Constructing theoretical secondary crater size–frequency distributions and comparison with observed crater size–frequency distributions show that most models on secondary cratering ignore the time–dependence of the contributing number of secondary craters: An older surface would have a larger secondary contribution, because more abundant and larger primary craters must have contributed. Such a contribution which should also change the ratio of small–to–large crater frequencies is not observed. All measurements obtained in this and in other (similar) investigations, the data of which have been used in this thesis, have been performed in a crater–diameter range where at most 10% secondaries are contributing.

After proving the standard Martian crater production function, the applicability of the transferred cratering chronology model was tested. The formation ages of the large impact basins (diameters larger than 250 kilometers) on Mars have been determined and it is argued that these basins were formed no later than 3.9 Ga ago (1 Ga = 1^9 years = 1 billion of years). This result is in agreement with the situation on the moon and the general idea of a flux decay after the heavy bombardment period, the tail end of planetary formation. Hereby, the cratering chronology model has been affirmed once again. Independently, large volcanic surface units show crater frequencies and absolute ages derived from such measurements that are in very good agreement with crystallization ages of basaltic Martian meteorites. This support the applicability of the chronology model.

Applying these findings, the evolutionary history of Mars was studied in detail: Type areas of the Martian epochs (Noachian, Hesperian and Amazonian) such as Noachis Terra, Hesperia Planum, northern lowland regions, Amazonis and Elysium Planitia, have been examined. Of special interest were volcanic, fluvial and possible glacial processes. Therefore, the frequencies of craters superimposing geologic units in the northern hemisphere occupying lowlands and outflow channels were measured, as well as the dichotomy boundary separating the lowlands and highlands, following the new mapping approach by Tanaka *et al.* (2003); Tanaka *et al.* (2005) based on MOLA topography data. We aimedat understanding the role of water during the Martian geologic evolution.

Relics of episodic fluvial activity is observed as valley network systems in the highland regions (Carr, 1986). The spatial and temporal coincidence of these fluvial landforms and crustal remnant magnetization indicates that any precipitation potentially occurred in the presence of a dynamo–induced magnetic field. Despite the low gravitation of Mars a magnetic dipole–field kept the Martian atmosphere stable and possibly permitted a water cycle during the early Martian history (until latest 3.7

Ga ago). If a Martian ocean existed in the northern lowlands, it ceased before 3.7 Ga ago. While possible surface run–off manifested in the valley networks occurred until about 3.7 Ga, the latest forceful fluvial surface modification occurred during the formation of large outflow channels until 3.5 Ga ago. The latter, though, appears to have been triggered by volcanic activity in the vicinity of the largest volcanic province, the Tharsis rise. Similar correlations have been observed at a few highland volcanoes, e.g. Hadriaca Patera. The younger fluvial erosion is closely related to volcanic activity and occurred in episodes over the last 2 billion years. Extensive measurements at almost all volcanic constructs and in many volcanic plains allowed for the interpretation of the evolutionary history of Martian volcanic constructs. An interplay of volcanic processes with ancient and more recent fluvial and glacial activity is confirmed by our study. Globally, the volcanic activity started very early in the Martian evolution, major volcanic plains formed until about 3.7 Ga ago, e.g. Hesperia Planum. Most of the volcanoes show activity at least until 3.5 Ga ago. They achieved their present dimensions already at that time. Later volcanic resurfacing could not erase larger older impact craters and indicates that later volcanic activity was weaker than during the construct–forming period. Another major finding is that the volcanic activity on Mars continued until very recently (e.g. 2 Ma at the flanks of Olympus Mons, (Neukum *et al.*, 2004)), and is more wide–spread than believed earlier. The crystallization ages of basaltic Martian meteorites (about 180 Ma, 450 Ma and 1.3 Ga) confirm this finding. The enigmatic Medusae Fossae formation could be dated for the first time indicating that explosive volcanic eruption occurred even as recently as 1.6 Ga ago.

This thesis provides the first coherent view of the geological evolution of Mars, focusing on impact cratering, volcanic, fluvial and glacial processes. In addition to tectonics and aeolian dust distribution, such processes play a significant role in sculpting the Martian landscape. Notably the volcanic and related tectonic activity sheds lights on the internal dynamics and thermal evolution of planets.

By understanding the evolutionary history of Martian volcanic constructs, the formation time of large impact basins, as well as the evolution of the northern lowlands and the dichotomy boundary, essential time–markers have been gathered in this work. The global geological evolution of Mars is derived from ages determined in this work. As indicated by the Martian meteorite ALH84001, Martian crust had solidified around 4.5 Ga ago, but the oldest southern highland units reveal surface ages of only about 4.2 Ga.

The crustal dichotomy formed early during the crustal formation, but at least before the formation of the oldest impact basins Hellas and Isidis. The morphologically defined dichotomy between heavily cratered southern highlands and smooth northern lowland plains formed later. The basement of the northern lowland appears to be about 3.8 Ga old and was covered by two types of deposits later. Emplacement was partly due to fluvial activity during the outflow channel formation and ended about 3.5 Ga ago. Volcanic deposits emplaced through volcanic activity at the two volcanic centers Elysium and Tharsis contributed as well. Global volcanic activity is observed until about 3.7 Ga ago (volcanic plains formation in the highlands) and later activity focused on the volcanic vents in the Tharsis and Elysium region. Major volcanic activity over the last 3 billions of years is restricted to the large shield volcanoes in these two volcanic provinces and their vicinities. Fluvial landforms that formed later than 3.5 Ga (melting of subsurface ice) were triggered by volcanic activity.

This study revealed that the youngest epoch, the Amazonian, is reflected in a variety of landforms, and includes an absolute time span of three–quarters of the geological record of Mars. The crater size–frequency distributions measured in the northern lowlands reveal strong resurfacing events and a non–uniformity in age. This implys that the Amazonian–Hesperian

time–stratigraphic boundaries have to be revisited. In most of our investigations, based on high–resolution imagery (HRSC, THEMIS, and MOC–NA), large volcanic units have been formed later than 500 Ma ago. In addition, most surface morphologies associated to ice or subsurface ice (glacial and periglacial), such as lobated debris aprons, lineated valley fill, or possible rock glaciers, appear to be relics of the most recent "ice ages" on Mars. All landforms related to such processes have formed during the most recent eighth of the Martian geologic history. Based on these results, a revision of the boundary key units that would best represent those youngest Amazonian epochs in high–resolution imagery. A new subdivision of the last three billion of years Martian geologic history (considered Amazonian) should be considered.

Providing that the time–frame outlined in this study is correct, the timing for the thermodynamical evolution of Mars can be assessed. The apparent absence of plate tectonics on Mars and the presence of huge volumes of strongly magnetized crustal materials, requiring the presence of a strong dynamo field in ancient times, makes Mars an interesting planet to compare with the Earth or thermodynamical models for other terrestrial inner Solar System bodies.