15. Volcanic Activity on Mars

Martian volcanism, preserved at the surface, is extensive but not uniformly distributed (Fig. 15.1). It includes a diversity of volcanic landforms such as central volcanoes, tholi, paterae, small domes as well as vast volcanic plains. This diversity implies different eruption styles and possible changes in the style of volcanism with time as well as the interaction with the Martian cryosphere and atmosphere during the evolution of Mars. Many volcanic constructs are associated with regional tectonic or local deformational features.

Two topographically dominating and morphologically distinct volcanic provinces on Mars are the Tharsis and Elysium regions. Both are situated close to the equator on the dichotomy boundary between the cratered (older) highlands and the northern lowlands and are approximately 120° apart. They are characterized by volcanoes, whose morphologies are strongly analogous to basaltic volcanic landforms on Earth. The huge volcanoes in the Tharsis region (Olympus Mons, Ascraeus Mons, Pavonis Mons, and Arsia Mons) share many characteristics with Hawaiian basaltic shield volcanoes (Carr, 1973). They are constructed from multiple lobate flows of lava, generally show complex nested coalescing summit calderas of varying age, and gently slope on the order of a few degrees. Their eruption style is effusive and of a relatively non–explosive nature. The main differences between the Martian and terrestrial volcanoes are the greater sizes and lengths of flows of the Martian volcanoes, mainly due to higher eruption rates, the "stationary" character of the source (no plate tectonics) and the lower gravity.

Plescia and Saunders (1979) have summarized the chronology and classification of Martian volcanic activity based on the Viking imagery data. They grouped the volcanic landforms into (1) shield volcanoes (to be of basaltic composition), (2) domes and composite cones, (3) highland paterae, and related (4) volcano-tectonic features. Many plains units like Lunae Planum and Hesperia Planum are thought to be of volcanic origin, fed by clearly defined volcanoes or by huge fissure volcanism. Many small volcanic cone fields in the northern plains are interpreted as cinder cones (Wood, 1979), formed by lava and ice interaction (Allen, 1979), or as the product of phreatic eruptions (Frey *et al.*, 1979).

An overview of the temporal distribution of processes, including the volcanic activity as well as the erosional processes manifested by large outflow channels ending in the northern lowlands and sculpting large units of the volcanic flood plains has been given by Neukum and Hiller (1981). This will be discussed in this work together with new findings. Both Plescia and Saunders (1979) and Neukum and Hiller (1981) gave a chronological classification of the volcanic features on Mars. The difference between these two attempts is the applied reference crater production function. Plescia and Saunders (1979) based their reference crater production function on counts in the Lunae Planum region. As has been demonstrated by Neukum and Wise (1976) and Wise *et al.* (1979a), strong resurfacing obscured the crater size–frequency distribution of this region. Therefore, such an ambiguous calibration curve as used by Plescia and Saunders (1979) might result in wrong stratigraphic relationships, if applied on a more global scale.

Based on Mars Orbiter Laser Altimeter (MOLA) topographic data, Plescia (2004) reexamined the dimensions and volumes of all major volcanic constructs of Mars and could correct the earlier findings of the post–Viking era. During the first two years of the ESA Mars Express mission, the High Resolution Stereo Camera imagery data provides the first opportu–

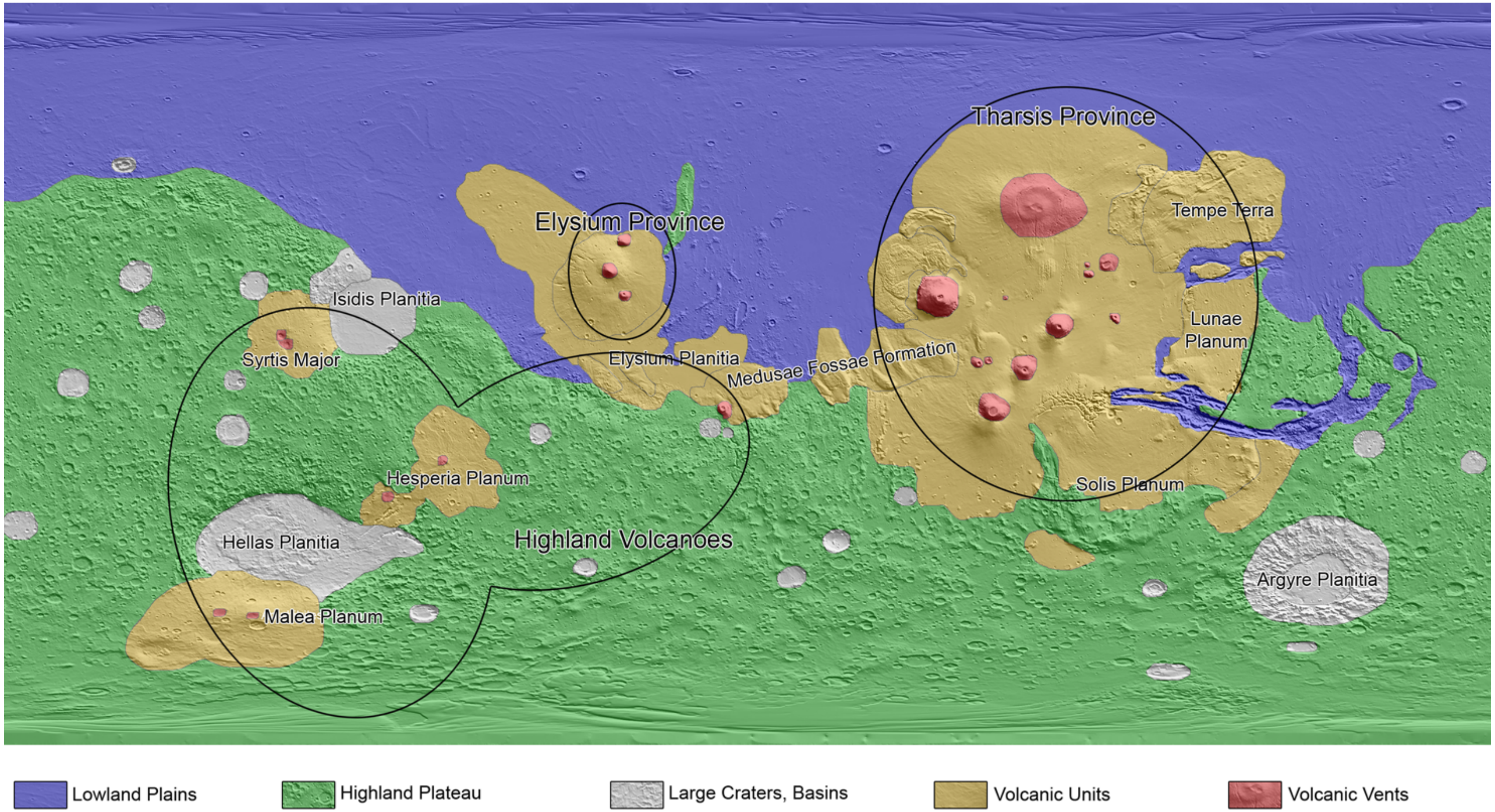

Figure 15.1.: The volcanic provinces of Mars are indicated in yellow. Known central vent constructs are displayed inred. The individual volcanoes are assigned in separate maps. The topographic dichotomy is shown in blue for the lowland parts and green for the highland parts. Large impact structures are shown in white. The background topography is given as a MOLA shaded–relief map.

nity for detailed insights into the morphology and topography of these volcanoes and their chronostratigraphic evolution.

Following the mapping of Spudis and Greeley (1977) and by Scott and Carr (1978), a synthesis of their results indicate that as much as 60% of the surface is covered with volcanic materials. The primary focus outlined in the following sections is on the evolution of the large volcanic provinces Tharsis and Elysium, accompanied by most other volcanic regions on Mars. An additional goal is to understand the interacting processes of erosion and deposition (related to volcanic and fluvial processes) with respect to new and old findings.

Based on the observation of superposition, cross–cutting relations, and, if available, on the number of superposed impact craters, Greeley and Spudis (1981) first described the volcanic history of Mars. To understand the volcanic evolution, caution must be given to the fact that the amount of volcanics represented by the enveloping youngest layer on top of the stratigraphic sequence and sometimes the crater size–frequency distribution reveal an earlier phase(s) by an embayed or flooded crater population.

The oldest unit considered in this investigation are the highland plateau units (e.g. Wilhelms, 1974). We found the oldest highland–plains units to be about 4.1 Ga old (Noachis Terra, see Chapter 17), which is roughly the time of emplacement of the largest Martian basins followed by the emplacement of so–called inter–crater plains 3.9 Ga ago. Most of the highland units range between 4.1 Ga and 3.9 Ga (see e.g. Chapter 17 or 13.2), roughly the decaying end of the heavy bombardment period. At that time, the erosional scarp of the dichotomy boundary between the highlands and lowlands most likely formed as has been suggested already by Zuber *et al.* (2000). Nevertheless, whatever caused the formation of the dichotomy escarpment, subsequent resurfacing acted differently along the boundary (see Chapter 14.2). The temporal overlap of extensive fluvial activity (e. g. valley networks) and volcanic episodes (e.g. highland paterae) is manifested in the observation of phreatomagmatic interaction e.g. at Tyrrhena Patera or at the flank base of western Elysium Mons (Wilson and Mouginis-Mark, 2003). The coincidence of the Hellas basin formation and the accumulation of highland paterae has been noted by Greeley and Spudis (1981), but we find that at least the later–stage patera activities were not triggered by the impact event itself.

Following the interpretation of the volcanic history outlined by Greeley and Spudis (1981) based on the Viking imagery, the plateau plains activity is followed by massive flood volcanism, which resurfaced large areas such as Lunae or Hesperia Plana and huge amounts of the Martian lowland areas. Massive volcanic constructs such as the Tharsis rise, notably Olympus Mons and Alba Patera, cover the dichotomy starting at least 3.8 Ga ago (the age of the aureole has been recalculated from Neukum and Hiller (1981)) and continuing to about 3.5 Ga (Alba Patera, see Section 15.1.1). The presence of the Aureole around Olympus Mons and the absence of such a feature around Alba Patera might indicate a changed environmental situation. The timing and existence of a Martian ocean in the northern lowlands is discussed (Chapter 14.3) and constrained temporally by the surface ages of the two differently appearing flank bases.

Both Martian volcanic centers are dominated by central vent volcanoes and surrounding plains–forming flows. Fracturing (graben formation) is related to the early structural uplift of the volcanic rises, although could be caused by younger volcanic activity (see below). While Greeley and Spudis (1981) found an agreement with a moon–like thermal history, we will show a more diverging evolutionary history of Mars.

All major volcanic constructs including Paterae and Tholi have been imaged in the first period of the ESA Mars Express mission. The ability to image simultaneously in color and stereo gives us the new opportunity to better characterize the geomorphology and chronostratigraphy of most volcanoes in the Tharsis and Elysium region and most highland volcanoes. We have remapped major parts of the volcanic shields and calderas on the basis of the high–resolution HRSC imagery in color and stereo, in combination with nested MOC imagery and the Super Resolution Channel (SRC) (as good as 2.5 m/pixel) of the HRSC.

15.1. The Tharsis Volcanic Province

The Tharsis region is the most dominating feature of the Martian topography and shows numerous volcanic constructs of different age and morphology:

15.1.1. Alba Patera

The northernmost is the fascinating volcano Alba Patera. It is an enormous volcanic shield with a base diameter of roughly 1100 km, more than the gigantic Olympus Mons. Compared to Olympus Mons, it is a wide but low–relief construct of about 6 km in height, with flank slopes of about 1°, and one of the largest calderas found on Mars (diameter of about 120 km). The surrounding flank grabens (Tantalus and Alba Fossae) extend in a North–South direction. The summit region around the caldera is characterized by extensive lava flows and local dendritic valleys. The construct is divided into two parts indicating at least two formation stages, one broad lower construct (about 4 – 5 km high) cut by the Fossae and marginal lava aprons (Ivanov and Head, 2003) and a much smaller summit shield (of about 1 km in height), which contains a caldera and is situated on top of a broad summit plateau of the lower construct.

Age determinations by Neukum and Hiller (1981) yielded surprisingly young ages based on Viking data. For comparision with the absolute ages derived in this thesis, the relative ages given on the basis of their crater retention ages $N_{cum}(D \geq 1 \text{ km})$ in Neukum and Hiller (1981) are recalculated applying the most up–to–date chronology model by Hartmann and Neukum (2001). At the western flank of Alba Patera, they found ages indicating at least four episodes of activity: about 3.4 Ga, 2 Ga, 800 Ma ago and as recent as 250 Ma ago. In our measurements based on Viking and HRSC data, we could confirm the maximum age of about 3.5 Ga (see Chapter 14.1). These results were based on Viking imagery measurements taken at the northern flank base of Alba Patera, most likely covering the dichotomy scarp observed elsewhere on the planet. Measurements based on HRSC imagery at the lower flank (north of the summit) support this oldest age found in low–resolution Viking imagery. All other crater counts have been performed in the upper part of the construct and indicate similar ages of about 1.1 Ga to 3 Ga, as reported by Neukum and Hiller (1981). Resurfacing, which is possibly related to the formation of sinuous channels, probably eroded through flowing lava (as observed on other Martian volcanoes). The youngest ages (of comparable range in Neukum and Hiller (1981)) are found in the closest vicinity of the large caldera, yielding two episodes that ended as recent as between 800 Ma and 180 Ma ago. This two–stage activity is supported by the summit caldera morphology, which has been interpreted by e.g. Plescia

Figure 15.2.: The MOLA shaded–relief map of Albor Tholus.

(2004) or Ivanov and Head (2003) to represent at least two major episodes of caldera formation and summit volcanic activity.

Alba Patera Flank Regions

Unit	N$_{cum}$(1km)	Age in Ga
1Ar1	1.23e-3/3.10e-4^{+}/9.09e-5^{+}	2.51/0.636^{+}/0.186^{+}
2Ar1a	6.13e-4/ 2.40e-4^{+}	1.26/0.493^{+}
2Ar2	1.45e-3/3.95e-4^{+}/1.26e-4^{+}	2.93/0.811^{+}/0.259^{+}
3Ar1	5.60e-4	1.15

$^{+}$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

Both the morphology, the shape and the ages suggest a complex geologic evolution of Alba Patera over most of the Martian history.

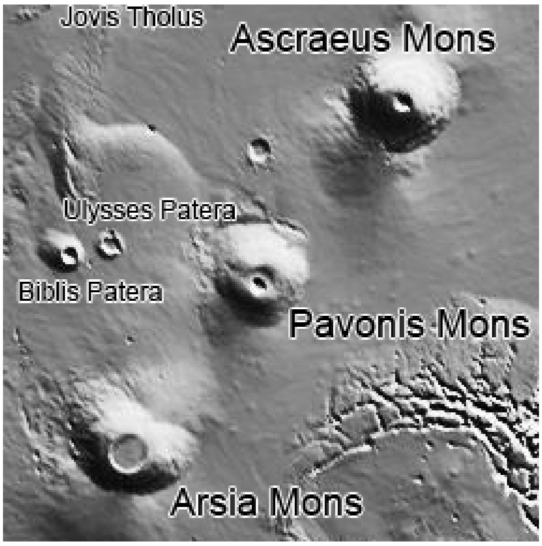

Figure 15.3.: The MOLA shaded–relief map of the Tharsis Montes: Ascraeus Mons, Pavonis Mons, and Arsia Mons.

15.1.2. The Tharsis Montes

Three large volcanoes named Ascraeus Mons, Pavonis Mons, and Arsia Mons constitute the Tharsis Montes. They are centered on top of the volcanic rise as a chain trending from northeast to southwest (where Ascraeus is the northernmost and Arsia the southernmost). Previous age determination by Plescia and Saunders (1981) and Neukum and Hiller (1981) indicated decreasing surface ages towards the northeast. Morphology, slope steepness and caldera complexity were used as arguments to judge Arsia Mons (a broad feature with low slopes and large simple caldera) as the oldest, while the others were considered as subsequently younger, due to their steeper slopes and more complex smaller central calderas.

Comparing the morphometric properties of Viking– and MOLA–derived summit elevations, large differences have been noted by Smith *et al.* (2001). Earlier determinations by the USGS based on Viking imagery (U.S. Geological Survey (USGS), 1989) had to be reduced for all large volcanoes in the Tharsis region (see e.g. Plescia, 2004).

Arsia Mons

The southernmost volcano of the Tharsis triplet is Arsia Mons with a summit height of about 18 km and relief height (compared to the surrounding plains) of about 11 km (second to Olympus Mons). It has a single caldera, the largest on Mars (diameter of about 120 km as first reported by Crumpler and Aubele (1978)). The main edifice has a width of about 430 km and is composed of the central shield and two aprons at the northeastern and the southwestern flank side, roughly following the great circle trend of the Tharsis Montes triplet. These aprons formed by lava flows extending from alcoves on the lower flanks of the main shield. They originated about 5 – 7 km below the summit. Both aprons appear at the tip of some flank depressions, which follow a line of nine low shields (relief of about 150 m) across the caldera floor along the same great circle trend as the Tharsis Montes themselves and roughly the axis of the aprons (Head *et al.*, 1998a,b). While the main edifice has slope angles of about 5°, the flank apron slopes range between 1° and 4°. At the flank base towards the west, a large aureole deposit appears, which is believed to have formed by glacial deposits (Head and Marchant, 2003). Thus far, we have not performed crater counts for these possible glacial deposits.

For the caldera floor, we found a surface age of about 130 Ma (Neukum *et al.*, 2004), which confirms earlier measurements by Neukum and

Caldera and Flank Ages of Arsia Mons

Unit	N$_{cum}$(1km)	Age in Ga
cal	6.23e-5	0.128
1Ar1	1.00e-4	0.206
1Ar2	3.13e-3/4.10e-4$^+$	3.54/0.841$^+$
2Ar1	9.43e-4/2.11e-4$^+$	1.93/0.432$^+$
2Ar2	1.68e-4	0.345
2Ar3a	9.21e-5	0.189
2Ar4	5.09e-5	0.104
3Ar1	3.02e-5	0.62
4Ar1	5.17e-4/1.37e-4$^+$	1.06/0.280$^+$
5Ar1	9.66e-4/2.79e-4$^+$	1.98/0.572$^+$
5Ar2	4.17e-4/7.13e-5$^+$	0.855/0.146$^+$

$^+$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

Hiller (1981). Construct–wide ages ranging between 100 Ma and 200 Ma have been found and are interpreted by us as the latest stage of the summit and flank eruptions. Earlier episodes stopped at about 500 Ma, 800 Ma, and 2 Ga ago. The oldest age is about 3.54 Ga and indicates the time when the period of major edifice construction ended.

Pavonis Mons

The middle one of the Tharsis Montes triplet is Pavonis Mons, having the lowest summit altitude of about 14 km and a relief compared to the surroundings at the foot of the shield of about 10 km. The two visible caldera depressions occupy an area of about 100 km in diameter and indicate the latest periods of summit activity. Based on crater counts, we determined that the caldera floor formation ended about 370 Ma ago for the larger one and about 80 Ma ago for the well preserved smaller caldera floor. The flanks have a slope angle of roughly 4°, but two lava aprons (similar to those seen at Arsia Mons) originate about 4 km below the summit region (slope of about 1°), aligned to the northeast–southwest fracture trend observed in that region. The southern flank is carved by prominent lava channels and smaller alcoves. The lava aprons and large units at the western flank bottom (towards which most of the lava flowed) are occupied by clusters of small low–shield volcanoes. These regions are associated with the youngest parts of the Pavonis Mons shield, which are reflected in many crater size–frequency distributions obtained on the flanks, aprons and small shields. All ages range between about 100 Ma and about 800 Ma. They appear to be strongly correlated temporally to the latest stage of summit activity. Ages range between 100 Ma and 450 Ma for a series of arcuate concentric grabens cutting across the lower northwestern flank, with lava flows barely covering the graben morphology.

Caldera and Flank Ages of Pavonis Mons

Unit	N$_{cum}$(1km)	Age in Ga
cal 1	1.79e-4	0.367
cal 2	4.02e-5	0.082
1Ar1	6.32e-4/2.52e-4$^+$/8.91e-5$^+$	1.30/0.516$^+$/0.183$^+$
2Ar1	3.14e-5	0.064
2Ar2	3.72e-4	0.763
2Ar3	3.36e-3/1.93e-4$^+$	3.56/0.395$^+$
2Ar4	6.03e-4	1.25
2Ar5	5.98e-4/1.77e-4$^+$	1.23/0.362$^+$
3Ar1a	4.99e-5	0.102
3Ar2	1.03e-4	0.212
3Ar3	4.64e-5	0.095
3Ar4	1.13e-4/4.33e-5$^+$	0.232/0.089+

$^+$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

In general, the main edifice was erected about 3.56 Ga ago, experiencing a strong resurfacing recorded in the crater size–frequency distribution about 1.2 Ga ago. Similar to Arsia Mons, an aureole–type deposition at the northern flank base is observed, but no ages were determined due to the lack of visible craters in the HRSC dataset.

Ascraeus Mons

With an elevation of about 18 km, Ascraeus Mons is the northernmost of the volcano triplet. Once again, marginal lava aprons are observed extending northeast and southwest at the flanks. Comparatively small aureole deposits are found at the northwestern flank segment as well. The flanks appear to have slope angles of about 7°. The summit caldera is complex compared to the other shield calderas and has at least six coalescing calderas. Strong tectonic features indicate a reworked caldera floor morphology, causing difficulties in a proper interpretation of surface age and the caldera formation time. We obtained ages ranging over the entire history of the volcano, starting about 3.6 Ga ago (when the main edifice was already emplaced) to as recently as about 100 Ma ago (Neukum *et al.*, 2004).

Caldera and Flank Ages of Ascraeus Mons

Unit	N_{cum}(1km)	Age in Ga
cal 1	1.93e-4	0.396
cal 2	1.04e-4	0.213
cal 3	5.07e-5	0.104
cal 4	1.13e-4/3.83e-4	0.233/0.785
cal 5	5.26e-5	0.108
cal 6	4.49e-5/5.03e-3	0.092/3.66
1	4.87e-5	0.100
2Ar1	2.15e-4/7.11e-5^{+}	0.44/0.145^{+}
2Ar2	xx/2.42e-4^{+}/8.99e-5^{+}	xx/0.496^{+}/0.184^{+}
2Ar3	3.01e-4/1.14e-4^{+}	0.617/0.233^{+}
3Ar1	9.24e-4/8.76e-5^{+}	1.90/0.179^{+}
3Ar2	7.62e-4/1.49e-4^{+}/1.06e-4^{+}	1.56/0.306^{+}/0.217^{+}
4	5.07e-4/1.66e-5	1.04/0.034^{+}

$^{+}$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

Most younger ages found for the caldera floors are present in measurements for the caldera surrounding summit unit, ranging between 100 and 800 Ma. Similar ages are found at the flanks. Some large flank units appear even younger, ranging between 50 and 100 Ma in age. A detailed investigation by Plescia (2004) reveals a complex history of flank eruption and apron formation; most units are covered by pronounced flow lobes. Low shield vents, alcoves and other volcanic activity are observed following the overall northeast–southwest trend manifested in the long axis of the triplet as observed at Arsia and Pavonis Mons already.

The Tharsis Montes in general

All three large shield volcanoes have a long complex volcanic history, in which the main shield formation ended about 3.55 Ga ago and was followed by many episodes of surface modification, which covered the edifice by many layers of lava flows. Only the last period of effusive eruption is recorded in terms of surface ages derived from crater counts. The youngest flank eruptions, which still produced an huge volume, and many scattered low shield vents indicate that the volcanoes were active until recently. Most likely, the Martian large shield volcanoes are dormant.

15.1.3. Olympus Mons

The largest and most prominent Martian shield volcano is Olympus Mons, which has a relief of about 22 km and a basal extent of about 800 km by 600 km, measuring the edges of the scarp surrounding the main edifice. The width is almost doubled if the enormous extent of the aureole deposit is considered (despite the unexplained formation process), which is dispersed over many hundreds of kilometers northeastward into the lowland units. The slopes are about 5° and up to 30° at the scarp. Based on HRSC data we performed extensive and detailed structural investigations of the scarp units, flanks and caldera (Neukum *et al.*, 2004; Basilevsky *et al.*, 2005) as well as a chronostratigraphic analysis of the entire edifice, focusing on the caldera, and the western and eastern scarp.

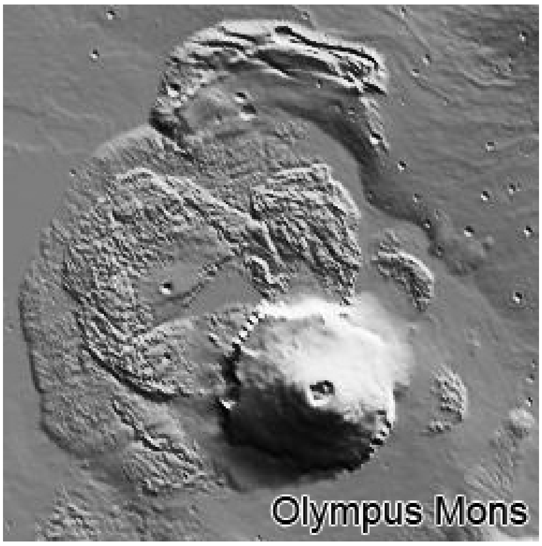

Figure 15.4.: The MOLA shaded–relief map of Olympus Mons.

The caldera of Olympus Mons consists of at least six coalescing depressions, which have been described in morphologic detail by Mouginis-Mark (1981) and suggest a sequence of at least six episodes of caldera collapse. Both of the smallest calderas appear very smooth in their floor morphology and were the last to form

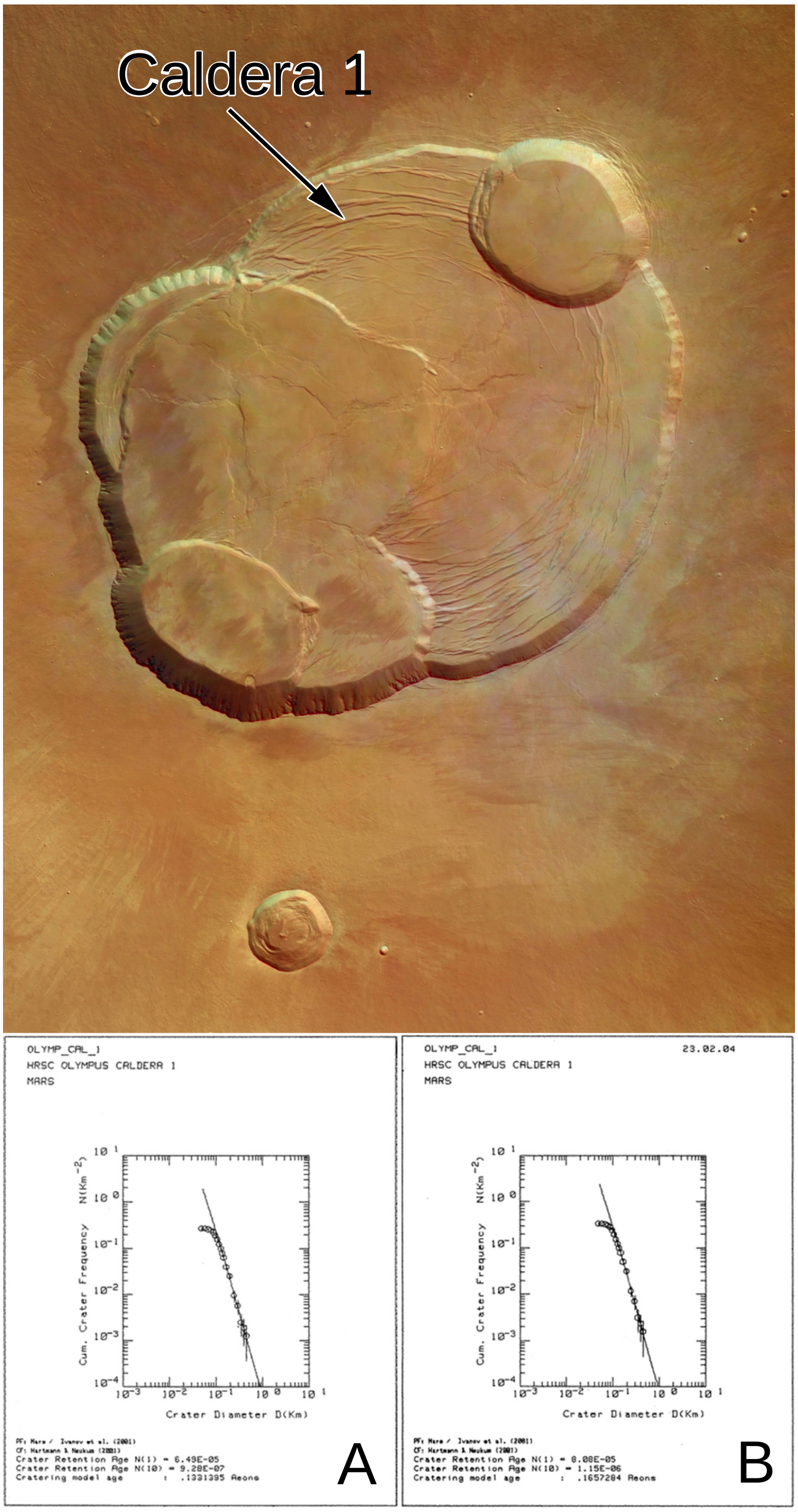

Figure 15.5.: The caldera of Olympus Mons. One of the larger kettles is reworked by tectonics, resulting in a modification of the reference area used to calculate the surface ages. Subset (A) shows the resulting age for the uncorrected area, and (B) for the corrected area used to calculate the age. A difference of 30 Ma is found, for a given age of 140 Ma, (A), and 170 Ma, (B).

in this sequence of collapses. The other sub–caldera floors have experienced strong tectonics, as seen by circular grabens in one of the larger depressions and wrinkle ridges that formed as compressional features spread over the center. Additionally, the floor has been surficially covered by volcanic flows from effusive fissure, resurfacing most of the caldera floors.

All our caldera floor crater counts appear to cluster at about 150 Ma (Neukum *et al.*, 2004), with a slight tendency to invert the expected morphological sequence. As described by Mouginis-Mark (1981), the larger calderas have been reworked by tectonics (graben, wrinkle ridges) and possibly volcanism. Therefore, the crater size–frequency distributions represent a lower limit of the surface formation. For example, in order to reduce the area which is occupied by grabens in the reference area, the crater–size frequencies per area of both large calderas are shifted to be the same, resulting in a slightly older surface age (see Fig. 15.5). A treatment considering the wrinkle–ridged units would have a similar effect, shifting the data for both large calderas towards higher crater–size frequencies per surface area. Nevertheless, to resolve the sequence of events set by the morphology, the crater–count statistics reach its limitations, if we work on statistically non differing crater–size frequencies. Only the morphologic situation could constrain the sequence, while the ages derived from a set of crater size–frequency measurements yield individual fit ages of around 150 Ma, but are statistically indistinguishable within the error limits.

Nevertheless, these results are in strong agreement with earlier measurements (Hartmann, 1999a; Hartmann and Neukum, 2001) based on MOC images in small areas of the calderas of Olympus Mons as well as Arsia Mons. This indicate that the summits of these edifices were essentially active almost in the geological present, the last 2 – 4% of Mars history. The vicinity of the caldera is characterized by superposing lava flows, which represent the latest active phases. Measuring the flank surface ages in four units around the caldera, the average surface age is oldest close to the caldera (resurfacing ended about 210 Ma ago), and shows an age of about 170 Ma further down–slope and elsewhere on the flanks. This appears not only morphologically, but also is reflected in the crater size–frequency distribution, which shows the coverage by lava flows is more effective further down–slope than in the close vicinity of the caldera. Here, besides a few large impact craters that are embayed by younger lava flows (one 10.5 km crater is visible in Fig. 15.5), the flank surface is not completely covered by flows (part of an older 700 Ma–aged surface survived). This observation is in agreement with widely observed flank eruptions on Mars and Earth. Using the observed crater size–frequency distribution, the effect of geological resurfacing is visible in the shape of the distribution Neukum and Horn (1976). The crater diameter (and derived rim height) at which the crater size–frequency distribution is affected, yield a thickness of an uppermost layer a few hundred meters. The summit plateau is truncated by an up to 7 km high scarp, which is present in most places, but is occasionally modified by lava–covering and flattening of the steep flanks. Detailed investigation of the western scarp morphology has been performed based on HRSC and MOC imagery (Neukum *et al.*, 2004; Basilevsky *et al.*, 2005). The western flank exposes at its edge a ridge and several smaller mesas. Ages found for the mesa surface suggest that they could be remnants of the very early and ancient proto–Olympus Mons. Ages of about 3.8 Ga were determined by measurements in the aureole (Hiller *et al.*, 1982), supporting the notion that most of the volcanic construct had been already emplaced very early in Martian history. Prominent and thin layering is visible at the steep slopes of the scarp, indicating the volcanic origin of the plateau. Different slope types have been identified by Basilevsky *et al.* (2005), while one type (S2 slope) is found only at the western flank of Olympus Mons. At the upper part, several chaos–like depression, are found from which channel–like grooves evolve downslope.

This morphology possibly relates to the influence of water (for details see Basilevsky *et al.* (2005) and Chapter 16). The ages derived from crater size–frequency measurements for the volcanic units on the flanks range between 500 Ma until very recently, indicating the flank was blanketed by several episodes about 500 Ma, 200 Ma, and 100 Ma ago. Many of the measured crater size–frequency distributions show, however, relatively flat distributions that indicate the steady (in terms of millions of years) supply of new lava flows (see Neukum *et al.* (2004) and Appendix C).

Flanks of Olympus Mons

Unit	N_{cum}(1km)	Age in Ga
The caldera vicinity		
ar1	3.47e-4/1.04e-4$^+$	0.712/0.213$^+$
ar2	1.13e-4	0.232
ar3	8.30e-5	0.170
ar4	6.51e-5	0.134
The eastern flanks		
plateau1	8.91e-5	0.183
plateau2	2.53e-4/9.44e-5$^+$	0.519/0.194$^+$
floor	8.60e-5/4.12e-5$^+$	0.176/0.085$^+$
The western flanks		
remnants	1.31e-2	3.83
flanks	2.17e-4 – 1.18e-6	0.445 – 0.002

$^+$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

The slope morphologies appear similar for the eastern and western scarp. Only the possibly water–related slope–type 2 does not exist (A. T. Basilevsky, 2005, pers. comm.). In a joint effort (map provided by S. van Gasselt, 2005) at the eastern flank units, crater size–frequency distributions were measured (Fig. B.11). The resulting ages indicate similar peak activities as observed at the western flank, but again the steady depositing of single lava flows is not easily described by these measurements.

In comparing the flank bases of the eastern and western flanks, one major difference appears: While on the western side most of the surface morphology, other than lava, indicates a glacial origin (for details see Neukum *et al.* (2004); Head *et al.* (2005) and Chapter 16), the eastern parts are dominated by fractures and channels that intersect the smooth plains and will be further discussed in Chapter 16.

15.1.4. The Tholi and Paterae on Tharsis

Eight Martian volcanoes are classified as shields: Olympus Mons, Ascraeus Mons, Pavonis Mons, Arsia Mons, Alba Patera, Biblis Patera, Uranius Patera, and Jovis Tholus. Besides these shields, a few dome–type volcanoes are also present in the Tharsis region. Northeast in the prolongation of the Tharsis Montes chain, the Uranius Group is located consisting of Uranius Patera, Uranius Tholus, and Ceraunius Tholus. To the south and east of the Tharsis Montes lies Tharsis Tholus. They all have a basal width of between 100 and 300 km in diameter and a relief of about 3 km (Uranius Patera and Uranius Tholus) and around 6 km (Ceraunius and Tharsis Tholi). Most have an asymmetric shape and a multi–stage caldera, occupying large portions of the entire (visible) construct. Many of their flanks are buried under lava flows of the surrounding plains, generated by the Tharsis Montes, so that the true dimensions remain unknown.

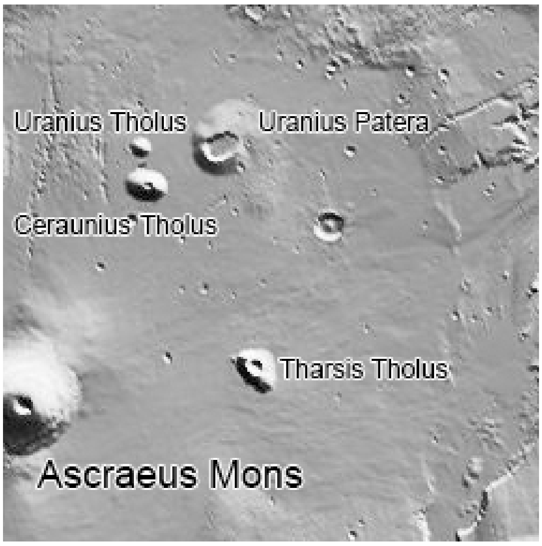

Figure 15.6.: The MOLA shaded–relief map of Tharsis Montes accompanying domes to the northeast: Uranius Patera, Uranius Tholus, Ceraunius Tholus, and Tharsis Tholus.

Uranius Patera appears to have a complex development, indicated by fan–shaped segments emanating from its complex caldera. Our age determination performed on low resolution HRSC limb observation data yield a shield and caldera age of about 3.7 Ga, while a resurfacing event which ended about 3.5 Ga ago affected the caldera and parts of the flanks. Higher resolution imagery by HRSC support the impression that even later resurfacing which is not related to volcanic activity has occurred.

Uranius Tholus is a small cone–like volcano having a two–stage caldera, representing at least two active phases. Our crater counts confirm that the construct had been built up by 4.04 Ga ago, while the caldera floor was emplaced before 3.9 Ga ago. A later event, ending about 3.5 Ga ago, renewed the surface of the cone by either late stage volcanic activity or surface erosion which is not evaluated at the image resolution given.

Ceraunius Tholus is striking to the eye by its prominent sets of radial troughs at its flank, partly leading into the elliptical crater Rahe which through the troughs was filled with lava piles at its bottom. A two–stage caldera indicate more episodic activity which is not revealed by crater counting. The volcanic construct had already been emplaced about 3.75 Ga ago.

Tharsis Tholus has a complex morphology and a uniqueness among Martian volcanoes because of its slumping blocks that segment the flanks. The volcano is an obstacle (embayed by lava flows of Ascraeus Mons) in the surrounding lava plains. The age determined by crater counts indicates that the visible part of the edifice had been emplaced no later than about 3.71 Ga ago.

Domes Northeast of the Tharsis Montes

Unit	N_{cum}(1km)	Age in Ga
Uranius Patera Caldera	6.11e-3/2.44e-3^{+}	3.70/3.45^{+}
Uranius Patera Shield	6.16e-3/3.21e-3^{+}	3.70/3.54^{+}
Uranius Tholus Caldera	1.93e-2	3.9
Uranius Tholus Shield	4.71e-2/2.81e-3^{+}	4.04/3.50^{+}
Ceraunius Tholus	7.50e-3	3.74
Tharsis Tholus	6.63e-3/3.17e-3^{+}	3.71/3.54^{+}

$^{+}$ treatment description see Chapt. 9.1

for imagery, area annotation and counts see Appendix B

West of the Tharsis Montes, another group of volcanoes (Biblis Patera, Ulysses Patera, and Jovis Tholus) is located. All are clearly embayed by younger lavas originating from the Tharsis Montes. The small volcanoes west of the Tharsis Montes became inactive before the latest stage of the Tharsis Montes activity. Only parts of the edifices are exposed to the surface, which is reflected in the low relief of 1 to 3 km above the surrounding plains.

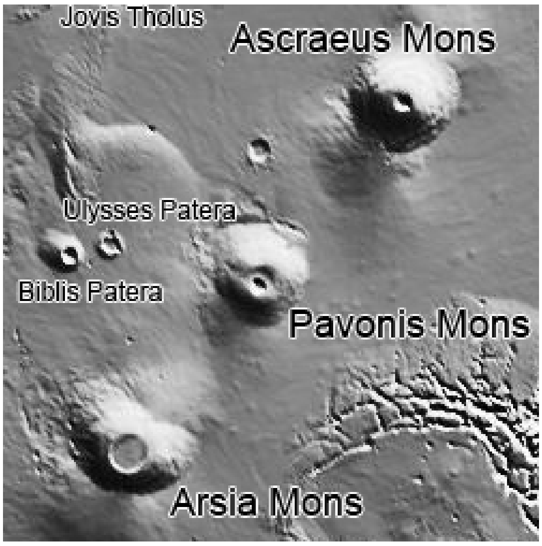

Figure 15.7.: The MOLA shaded–relief map of the Tharsis Montes and the accompanying domes Ulysses Patera, Biblis Patera, and Jovis Tholus to the west.

Biblis Patera ’s visible tip extends roughly 130 km by 180 km. Its asymmetrical exposure and caldera floor, lying 1 – 1.5 km below the surface of the surrounding plains might give a clue to the original extent of the edifice. Age determination for the caldera floor indicates that the remaining uppermost region formed before 3.68 Ga ago.

Ulysses Patera ’s morphology suggests that most of the edifice has been buried under subsequent lava flows fromed by Arsia Mons. Two large impact craters are visible on the flanks of the relatively small edifice. Crater counts on the flanks and the caldera yield an end of the edifice construction period about 3.73 Ga ago. Nevertheless, the presence of the two large craters implies that the edifice was emplaced even earlier (appr. 3.9 Ga ago).

Jovis Tholus , located further northeast, is an obstacle (embayed by lava flows of Arsia Mons) standing only 1 km above the surrounding plains. The caldera occupies most of the remaining cone, indicating large amounts of lava embaying the edifice. Crater counts were not performed for this volcano, since there is no HRSC coverage.

Domes West of the Tharsis Montes

Unit	N_{cum}(1km)	Age in Ga
Biblis Caldera	5.56e-3	3.68
Ulysses Patera	2.97e-2/7.22e-3^{+}	3.92/3.73^{+}
Jovis Tholus	no measurements	

$^{+}$ treatment description see Chapt. 9.1

for imagery, area annotation and counts see Appendix B

Our results indicate a more homogeneous picture regarding the evolution of the small Tharsis volcanoes than data collected by Neukum and Hiller (1981). Differences are possibly caused by the varying counting strategies, differing operators and variable image quality. Here, only a single operator performed all measurements at uniform image resolution. The overall impression from our measurements, that is the active period of those tholi and paterae stopped early in Martian history (before 3.7 Ga ago).

15.2. The Elysium Volcanic Province

This region is the second–largest volcanic province on Mars, situated in the northern lowlands. The volcanic province consists of three volcanoes: Elysium Mons, Hecates Tholus, and Albor Tholus. Further south, a fourth volcano, Apollinaris Patera, is located at the dichotomy boundary, surrounded by parts of the Medusae Fossae Formation. The Elysium volcanoes and Apollinaris Patera are classified as dome and composite volcanoes respectively, and considered to be constructed from lava that are more viscous than ordinary basalts. The domes are formed by multiple lava flows. Composite volcanoes formed possibly by interbedded lava and pyroclastic material. The enigmatic Medusae Fossae Formation is believed to be (besides other explanations, see Chapter 14.4) made up of possible pyroclastic deposits, spread widely at the dichotomy boundary with no clearly identified source.

The Elysium region has been described in detail by Malin (1977) based on Mariner 9 data. The three Elysium volcanoes are on top of a broad (about 1600 km wide) regional high, similar to the Tharsis rise. However, the structural situation has been compared to Alba Patera (Head *et al.*, 1998a) since the vent volcanoes are superimposed on the risen plateau in an off–center fashion. While Elysium Mons occupies part of the plateau, Hecates Tholus lies at the northeastern base and Albor Tholus at the southeastern margin. The two latter show some embayment contacts at their bases, keeping their complete basal extent hidden.

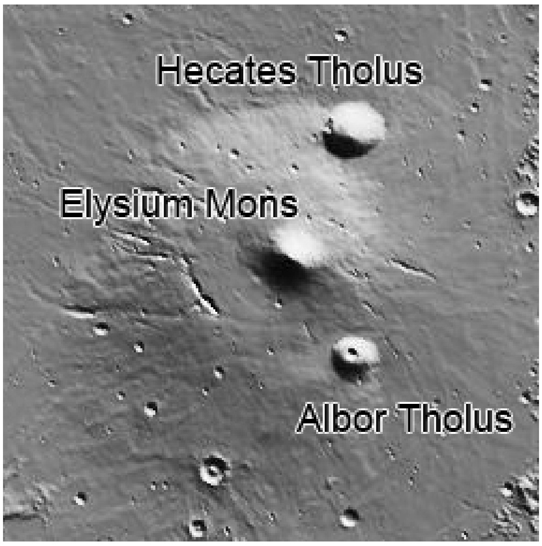

Figure 15.8.: The MOLA shaded–relief map of the Elysium volcanic province. In the north Hecates Tholus is located, in the center Elysium Mons, and towards the south Albor Tholus.

Elysium Mons

The largest of these three volcanoes is Elysium Mons, with a relief of about 14 km and flank slopes ranging between 1° and 10°. The simple summit caldera has a diameter of about 14 km and a shallow appearance. Radial and concentric troughs dominate the western (and partly eastern) flank of the regional high, but are possibly not related to the Elysium Mons. At the western flanks, lava flows extend several hundred kilometers into the northern lowland plains (Utopia Planitia, see Chapter 14.1), which had been associated with Elysium Mons. Fluvial features at the western flank base of the Elysium rise could be interpreted as formed by tectonically–driven release of ground–water or phreatomagmatic interaction. At the southeastern flank base, traces of tectonic grabens extend further in a radial fashion (Cerberus Fossae). They may have originated during the formation of the Elysium rise and are possibly still active, cutting through the youngest region of Mars, Elysium Planitia and the Cerberus plains, as discussed in Chapter 12. This area is discussed to be the youngest volcanic plains unit of Mars. In this very smooth region, large plates have been identified which were interpreted as a frozen sea (Murray *et al.*, 2005). Other nearby similar appearing plates (near the Athabasca Vallis system), though are smaller in dimensions, are interpreted as lava plates, (Werner *et al.*, 2003b,a). The subject remains controversial. The discovery of the impact crater Zunil, and its ejected boulders over an area of about 1600 km in width brought new attention to the secondary cratering issue (for discussion see Chapter 10.1).

Caldera and Flank Ages of Elysium Mons

Unit	N_{cum}(1km)	Age in Ga
Caldera	2.70e-3/7.80e-4	3.49/1.6^{+}
Northern flank	2.68e-3/7.86e-4	3.48/1.61^{+}
Flank (full)	xx/1.71e-3/8.00e-4	xx/3.21/1.64^{+}
Flank (detail)	6.41e-4	1.31

$^{+}$ treatment description see Chapt. 9.1

for imagery, area annotation and counts see Appendix B

The ages based on crater counts from HRSC imagery indicate the final activity of the emplacement of the main edifice at the latest 3.5 Ga ago, while the frequency of a few large craters yields an even older age (3.65 Ga). Both caldera and flank crater size–frequency distributions indicate a resurfacing event ending about 1.6 Ga ago. This is unrelated to the Elysium Mons vent activity, but possibly to an aeolian overprint. Most measurements based on Viking imagery (Chap. 14.1) confirm that the main construction phase had ended about 3.65 Ga ago and only the large flank eruption, flowing northwest and covering Utopia Planitia had formed over a period of 400 Ma and continued to as recently as 3.1 Ga ago.

Albor Tholus

The southernmost dome of these three volcanoes is Albor Tholus. The caldera diameter is about 35 km with a depth of 4 km, which is enormous with respect to its basal extent of about 150 km and relief of about 5.5 km. While the flanks appear convex, with slope angles of about 5°, the caldera–wall slopes range between about 20° and up to 35° (Chap. 7.4).

Caldera Ages of Albor Tholus

Unit	N_{cum}(1km)	Age in Ga
caldera 1	1.05e-3	2.16
caldera 2	2.3e-4	0.471
caldera 3	7.99e-4	1.64

for imagery, area annotation and counts see Appendix C

The caldera morphology indicates a smaller, younger caldera collapse. Ages found for the caldera floors indicate that the summit activity had ended about 500 Ma ago, with an earlier episode ending 2 Ga ago (Werner *et al.*, 2004b; Neukum *et al.*, 2004; Werner *et al.*, 2005b).

Hecates Tholus

The northernmost volcano is Hecates Tholus, located at the edge of the Elysium rise and connected to the lowlands. Numerous radial rills emanate from the top, interpreted as fluvial in origin (Gulick and Baker, 1990), but more recently viewed as eroding through lava flows (Williams *et al.*, 2005). With a relief of about 7 km, the roughly 180 km wide edifice exposes a small (13 km in diameter) and shallow (less than 500 m) multi–staged caldera. Our crater counts indicate a history of summit activity over the last billion years, while the flank age of 3.4 Ga tells us that the construct had been already emplaced at that early stage. Mouginis-Mark *et al.* (1982) studied Hecates Tholus extensively and suggested that the summit is covered with pyroclastic deposits post–dating the flank formation. The flanks appear convex, with slopes varying from 6° at the bottom to 3° at the summit. Detailed age determination for the northern flank of Hecates Tholus was initiated to understand the timing of the summit caldera activity and a possible side–caldera (Hauber *et al.*, 2005), not seen in earlier investigations. Imagery and topographic data from the HRSC revealed previously unknown traces of an explosive eruption at 30.8°N and 14.98°E, on the northwestern flank of Hecates Tholus. The northwestern flank has been mapped by us and studied in detail in terms of morphology and crater size–frequency distributions. Additionally, MOC–NA imagery has been used. We found that both caldera and flanks have similar surface ages. While the caldera indicate an active phase about 1 Ga ago, we find similarly aged deposits on the upper flank segment. Later caldera activities are not reflected in the surface ages of the summit vicinity, which indicates that they were less massive than the one occurring about 1 Ga ago.

Caldera and Flank Ages of Hecates Tholus

Unit	N_{cum}(1km)	Age in Ga
caldera 1	4.97e-4	1.02
caldera 2	1.57e-4	0.322
caldera 3	1.36e-4	0.28
caldera 4	4.4e-5	0.09
caldera 5	5.36e-5	0.11
Side–Caldera and Flanks		
caldera ejecta	1.74e-4	0.357
flank dissected	4.52e-4	0.927
Elysium plains	2.01e-4	0.411
Flank air fall	4.26e-4	0.874
glacier upper	2.39e-5	0.049
glacier lower	6.63e-5	0.136
gl northern	1.19e-4	0.245
gl southern	2.47e-5	0.051

for imagery, area annotation and counts see Appendix C

The eruption at the flank bottom created a large, 10-km-diameter caldera about 350 Ma ago. In the vicinity of the amphitheater–like depression, erupted deposits are found, which show this age. Glacial deposits partly fill the caldera and a younger adjacent depression. Details will be discussed in Chapter 16.

Apollinaris Patera

This volcano is situated at the dichotomy boundary (north of the impact crater Gusev; Chapter 13.2) and surrounded by the Medusae Fossae Formation (Chapter 14.4). It extends over roughly 190 km, and has a two–stage caldera of about 80 km in diameter. The northern rim is characterized by a small scarp facing towards the northern lowlands, resembling a small version of the Olympus Mons scarp. To the south, a lava apron has evolved, making up the youngest unit of the entire construct. Ages derived from our crater counts indicate that the last activity (at the fan and caldera) ended at about 3.71 Ga ago, while the entire volcano had been constructed by 3.74 Ga.

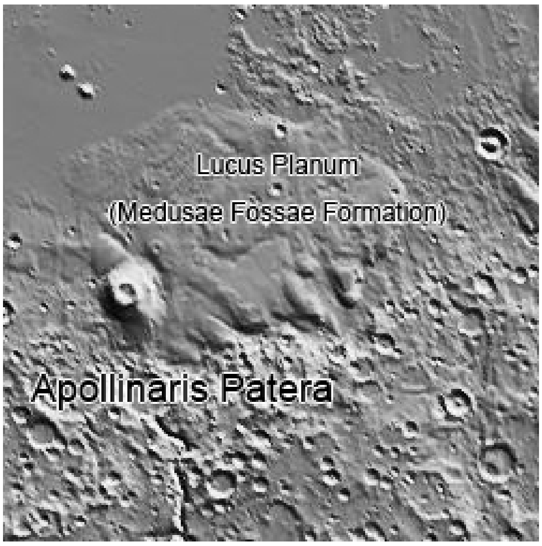

Figure 15.9.: The MOLA shaded–relief map of Apollinaris Patera and part of the Medusae Fossae Formation (Lucus Planum).

Even if the structure of these four volcanoes suggest assignment to one group, their evolutionary history, especially of Apollinaris Patera, is diverse. In the highland vicinity of Apollinaris Patera, a few small Noachian–aged volcanic domes (e.g. Zephyria Tholus) are located

Ages of Apollinaris Patera

Unit	N$_{cum}$(1km)	Age in Ga
Caldera small	(3.29e-2)/4.08e-3^{+}	(3.98)/3.61^{+}
Caldera big	6.82e-3	3.72
Shield	1.11e-2/7.58e-3^{+}	3.81/3.74^{+}
Fan (south)	6.65e-3	3.71

$^{+}$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

(Stewart and Head, 2001), which are consistent with a stratovolcano origin in which the edifice formed by mixed explosive and effusive eruptions. These observations make Apollinaris Patera different when compared to other highland paterae.

15.3. Highland Paterae

This category of central vent volcanoes has been defined by Plescia and Saunders (1979). Hadriaca and Tyrrhena Patera in addition to others constitute a group of highland paterae. These are low–relief broad features, possessing irregular summit calderas with outward radiating lobate ridges and numerous radial channels on their flanks. Morphology and topographic profiles are attributed to explosive volcanism related to phreatomagmatic processes, comprising ash flow deposits rather than lava flows. Sinuous channels similar to them on Tyrrhena Patera are interpreted as lava channels. Many features in the surroundings of Hadriaca and Tyrrhena Paterae are clearly related to fluvial or phreatomagmatic activity. Subsidence in the vicinity of channels carved by surface water indicates a close correlation between volcanic activity and the removal of surface and sub–surface material.

The Highland Patera group consists of Hadriaca and Tyrrhena Paterae east of the Hellas basin, Amphitrites and Peneus Paterae at the southern margin of the Hellas basin, and Syrtis Major Planum, characterized by two calderas (Meroe and Nili Paterae) and located west of the Isidis basin.

Hadriaca Patera

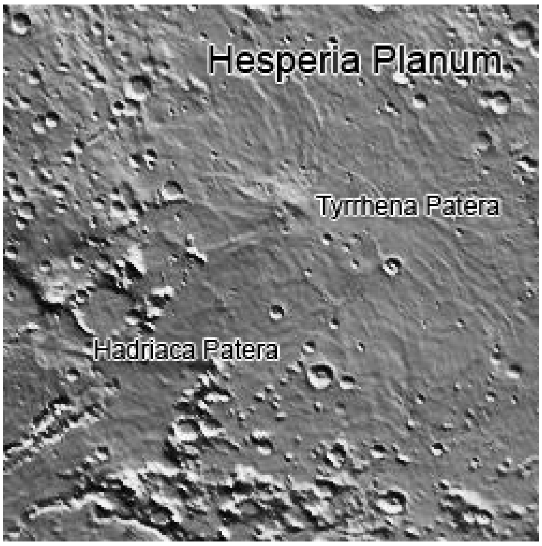

Figure 15.10.: The MOLA shaded–relief map of the Hesperia Planum. In its center Tyrrhena Patera is situated. Hadriaca Patera is situated in between this volcanic plain and the large impact basin Hellas Planitia.

This volcano caught our attention early in the MarsExpress mission. Hadriaca Patera was mapped earlier by Crown and Greeley (1993). Detailed chronostratigraphic investigations were performed on HRSC imagery and a revised map by Williams *et al.* (2005) was published. A very shallow caldera, about 90 km in diameter and surrounded by pyroclastic flows, is strongly modified by possible fluvial erosion. The presence of water is suggested by the existence of a complex trough system named Dao and Niger Valles and phreatomagmatic processes are observed by Zuschneid *et al.* (2005).

Ages of Hadriaca Patera

Unit	N$_{cum}$(1km)	Age in Ga
Caldera	5.26E-4 – 3.22E-3	1.08 – 3.54
Flank	5.62E-4 – 1.52E-2	1.15 – 3.86

data by Williams *et al.* (2005); Zuschneid (2005)

Crater counts yield episodic activity of mostly explosive (ash) eruptions in the earlier stage and later, more effusive eruptions observed in the caldera. The main edifice was constructed until about 3.9 Ga ago, while stages of activity ending about 3.7 Ga and 3.3 Ga ago are recorded in crater size–frequency distributions for the flank. The caldera floor had been emplaced by about 3.5 Ga ago. Following the formation of a wrinkle ridged surface, the caldera was covered by thin layers created by more effusive eruptions about 1.6 Ga ago. Subsequent resurfacing about 1.1 Ga ago is seen in most areas of the volcano. For a detailed discussion and more advanced geologic analysis see Williams *et al.* (2005) and Zuschneid (2005).

Tyrrhena Patera

This volcano, located at the volcanic ridged plains of Hesperia Planum, was already imaged in high–resolution in Viking–times and studied as a type–locality of highland paterae (Plescia and Saunders, 1979). Its basal extent is about 600 km, while its relief does not exceed 1 km. It has a central caldera, from which a large channel originates, suggesting a formation by lava erosion (Plescia and Saunders, 1979). The summit region is crested by layers of heavily eroded pyroclastic deposits. The flank morphology (radial shallow troughs) is similar to that of Hadriaca Patera.

Ages of Tyrrhena Patera

Unit	N_{cum}(1km)	Age in Ga
Caldera	1.85e-3/7.20e-4^{+}	3.29/1.48^{+}
Flank	2.32e-2/5.24e-3^{+}/1.43e-3^{+}	3.93/3.66^{+}/2.90^{+}
AhrF	1.79e-3/5.38e-4	3.26/1.10
He	6.94e-4	1.42
Nsu1+2	3.33e-2/3.04e-3^{+}/7.68e-4^{+}	3.98/3.53^{+}/1.58^{+}
Ns1	3.98e-3/1.25e-3^{+}	3.60/2.56^{+}
Ns2	1.96e-3/2.84e-3^{+}/9.07e-4^{+}	3.90/3.50^{+}/1.86^{+}
AHcf1	1.59e-3/5.88e-4^{+}	3.11/1.21^{+}
NsL1-4	2.52e-3/7.87e-4^{+}	3.46/1.61^{+}

$^{+}$ treatment description see Chapt. 9.1;
for imagery, area annotation and counts see Appendix B

The ages determined for the volcanic evolution of Tyrrhena Patera strongly resemble the episodic activity and time frame found for Hadriaca Patera. While the entire construct was emplaced early in Martian history (before 3.9 Ga ago), the flank deposition and erosion happened in periods ending at about 3.7 Ga and 3.3 Ga ago. The large channel was formed through the later stage of the effusive eruption about 1.7 Ga ago. Evidence for a later resurfacing event, about 1.1 Ga ago, can be found in many areas of the volcano.

Amphitrites and Peneus Paterae

The region named Malea Planum, south of the Hellas impact basin has a morphology typical of volcanic plains (e.g. Hesperia Planum) and displays the two well–defined calderas of Amphitrites and Peneus Paterae.

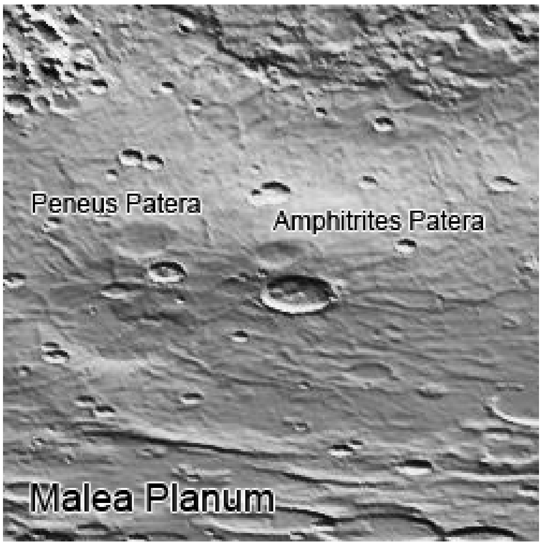

Figure 15.11.: The MOLA shaded–relief map of Malea Planum, a volcanic plain similar to Hesperia Planum. Two calderas of Amphitrites Patera and Peneus Patera are visible.

Ages for Amphitrites and Peneus Paterae

Unit	N_{cum}(1km)	Age in Ga
Amphitrites Caldera	7.69e-3/3.51e-3^{+}	3.74/3.57^{+}
Peneus Patera	no measurements	

$^{+}$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

They have low reliefs and very shallow flank slopes of about 1°. Other features in the plains unit are caldera suspects (Peterson, 1977). HRSC imagery covers only the Amphitrites caldera, for which crater counts yield an age of about 3.75 Ga and a resurfacing event ending about 3.6 Ga ago. This event probably was not due to volcanic activity.

Syrtis Major Planum

This plains unit was identified as a large volcanic region west of the Isidis impact basin (Greeley and Guest, 1987). Syrtis Major occupies an area of about 1100 km in diameter, and is characterized by two calderas, Meroe and Nili Paterae (Hiesinger and Head, 2002).

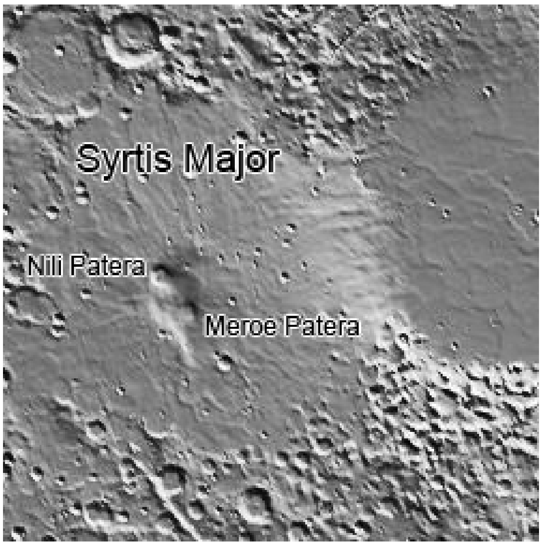

Figure 15.12.: The MOLA shaded–relief map of Syrtis Major Planum and the Meroe Patera and Nili Patera at its center.

They are located almost at the center of the very low shield inside an elliptical depression, which was not interpreted by Hiesinger and Head (2002), but to us appears to resemble an earlier–stage caldera. The plateau is characterized by wrinkle ridges similar to other volcanic plains (e.g. Hesperia Planum). Ages determined for the approximately 70 km diameter caldera of Meroe Patera yield an age of about 3.75 Ga, which probably indicates the end of the main volcanic activity. The crater size–frequency distribution measured for the caldera indicates a later resurfacing ending about 2.3 Ga ago, which we interpret as non–volcanic. Similar ages have been found by Hiesinger and Head (2004).

Caldera Age of Meroe Patera (Syrtis Major)

Unit	N_{cum}(1km)	Age in Ga
Meroe Patera	7.28e-3/1.13e-3^{+}	3.73/2.33^{+}

$^{+}$ treatment description see Chapt. 9.1
for imagery, area annotation and counts see Appendix B

15.4. Volcanic Plains

Four types of Martian volcanoes and their prevailing occurrences in the cratered terrain hemisphere (generally the southern hemisphere) have been described. Paterae, which are large low-profile volcanic structures, appear to be either older shield volcanoes or a unique type of volcano. 'Plains' volcanics represent low-volume eruptions that formed cones, low shields, and other small–scale structures. Flood volcanics are produced by high–volume eruptions, post–dating the older and more degraded plateau plains, and occur mostly as basin–filling materials. Plateau plains, the Martian inter–crater plains, contain many wrinkle ridges and floor–fractured craters. It has been suggested that volcanic processes as well as erosional processes have been important in obliterating small Martian craters (Greeley and Spudis, 1978). Further, volcanic products may constitute a significant fraction (up to 44%) of the surface rocks in the cratered terrain (Greeley and Spudis, 1978).

One of the typical examples of volcanic plains is **Hesperia Planum**. Typical wrinkle ridges are interpreted as resembling the morphology of lunar maria. Many ridges follow an irregular pattern, but some appear mostly circular and cover what are likely crater rims of a cratered plains unit that has been subsequently covered. Crater size–frequency measurements performed on Viking and THEMIS imagery suggest that the plains were emplaced before 3.7 Ga ago, but experienced a resurfacing event about 3.12 Ga ago (N_{cum}(1km)=1.60e-3, see Fig. 17.1). This emplacement age is valid for the entire Hesperia Planum unit. Another plains unit, a small region of Lunae Planum, yields an age of 3.5 Ga (see Table 14.1).

15.5. The Volcanic Constructs – Discussion of Results

The detailed volcanic evolution of most individual volcanic constructs on the Martian globe is described in Chapter 15. The crater count results and derived relative and absolute ages are given here and listed together with the imagery in Appendix B. In this section, a more general view of the derived geological evolution of Mars based on the volcanic evolutionary history will be discussed. Additionally, the possible correlation of volcanic processes with fluvial (and glacial) activity will be outlined. In Figure 15.13, all resulting crater counts gathered in this work are plotted together with measurements based on Viking imagery by other authors previously (as discussed in Chapter 15). The data used here were assembled by Neukum and Hiller (1981), evaluating measurements published by Blasius (1976); Carr (1976); Carr *et al.* (1977b); Crumpler and Aubele (1978); Masursky *et al.* (1977); Neukum and Wise (1976); Plescia and Saunders (1979); Wise *et al.* (1979b) and their own.

The novelty of the global data set presented and interpreted here is that counts have been performed by a single observer, are based on a single set of high–resolution imagery, and have had a single crater production function and chronolgy model applied. This guarantees a very coherent set of data and allows for a better comparision of the results and subsequent comparison to earlier measurements. Based on the results shown in Fig. 15.13, the following volcanic evolution for Mars is derived.

All volcanic constructs were formed and built up to their present size by very early time in the Martian history (before about 3.6 Ga ago). This implies that most of the volcanism had started about 4 Ga ago or even earlier. In that time period, the highland units had already been emplaced and inter–crater plains were formed. Possibly, even the basement of the lowlands had formed about that time (before 3.8 Ga ago). The **small tholi and paterae in the Tharsis region** are relics of such an early volcanic period. In their case, the vent production of magma stopped about 4 Ga ago and shows only in a few cases subsequent activity until about 3.7 Ga ago. Few of the tholi and paterae show later resurfacing, which is not clearly related to volcanic processes. Global volcanic activity during the early Martian history is manifested in many small shields or domes found e.g in the vicinity of Apollinaris Patera (Chap. 15) or in the Coracis Fossae, where we obtained ages of about 3.9 Ga (Grott *et al.*, 2005). For the other large Tharsis volcanoes, crater size–frequency distributions indicate that they reached their final size about 3.6 Ga ago, with later more or less intensive resurfacing of the flanks. A similar decrease in activity is found for the **highland volcanoes**: Meroe Patera (Syrtis Major), Amphitrites Patera and Apollinaris Patera, with no obvious volcanic activity occurring later than 3.65 Ga ago. Subsequent resurfacing is observed and could be related to a blanketing deposition of unkown origin, which is seen equally inside and outside the calderas. A more varied timing of events is observed for Hadriaca and Tyrrhena Paterae, situated east of Hellas in Hesperia Planum, a volcanic plain that formed about 3.7 Ga ago. The evolutionary history of both volcanoes appears synchronized in processes and timing. After the formation of a cone apparently composed of material from more explosive volcanic activity early in the Martian history (about 3.9 Ga ago, the very shallow broad shields were already constructed). Subsequent activity resurfaced the vicinity by possible ash deposition and by later carving channels into the unstable ash deposits until about 3.7 Ga ago. The eruption style changes later to a more effusive one as observed at their crest regions (about 3.5 to 3.3 Ga ago). Inside the Hadriaca caldera and at Tyrrhena Patera, the latest volcanic activity ended about 1.5 Ga ago, as indicated by the large caldera–flank channel on Tyrrhena Patera. The **Elysium volcanoes** formed before 3.6 Ga ago and reached their final size about 3.6 Ga ago. Extensive volcanic activity is observed at the western flanks of the

Elysium rise during a period between 3.4 and 3.3 Ga ago. Enormous volcanic flows expand into Utopia Planitia, while flank failures support the formation of channels by the release of water. The surrounding plains to the northeast (Arcadia Planitia) indicate subsequent volcanic flooding about 2.6 Ga ago, but the source remains unclear. The caldera and upper flanks of Elysium Mons formed about 3.5 Ga ago, showing a resurfacing about 1.5 Ga that cannot be related to volcanic activity because both ages are found inside and outside the caldera. Especially, measurements at Hecates Tholus, but also at Albor Tholus, indicate that volcanic activity occurred later than previously thought. Caldera and flank ages show subsequent resurfacing over the past 2 Ga, while at Hecates Tholus this happened even over the past 1 Ga until about 100 Ma ago. Elysium Planitia, a region southeast of the Eysium rise, appears as one of the youngest plains on Mars (formed between 10 and 30 Ma ago, see Fig. 10.3). The ages measured in this region are discussed, as a result of the discovery of crater Zunil and its numerous secondary–crater strewn field. As discussed in Chapter 10.1, the misinterpretation in age is less than a factor of two, if secondary craters were included in the measurements unwittingly. As discussed above, the small **Tharsis volcanoes** are classified as very old small tholi and paterae that are relics of the earliest volcanic activity in that region. Major parts of the large shield volcanoes have formed before 3.6 Ga ago. At all shield flanks, episodes of volcanic eruptions (flows) are observed, which have surface ages of between 500 Ma and 100 Ma. The youngest ages determined by the crater size–frequency measurements are about 2 Ma (Olympus Mons escarpment), suggesting that the volcanoes are potentially still active. For Alba Patera, the most recent flank resurfacing occurred about 200 Ma ago, possibly the result of volcanic activity. Caldera floor ages of the Tharsis Montes and Olympus Mons reveal that the latest vent activity happened between 200 Ma and 100 Ma ago. At the foot of Pavonis Mons, small shields are observed that formed about 300 Ma to 100 Ma ago. This latest extensive volcanic activity, observed in both large volcanic provinces (Tharsis and Elysium), correlates well with crystallization ages found for the basaltic Martian meteorites (Shergottites) and shows that the applied chronology model accurately reflect the surface ages.

For the first time, it was possible in this study to determine the age for the formation of the Medusae Fossae: 1.6 Ga. This correlates with late–stage activity of some highland volcanoes (Hadriaca and Tyrrhena Paterae) and at least some ages found at the flank of the Tharsis Montes. The same age is observed for some volcanic surfaces where no clear source can be identified (Elysium Mons, Meroe Patera). If the Medusae Fossae deposits are interpreted as pyroclastic ashes that are wide–spread over the planet and accumulated at the dichotomy boundary, it is possible that they could have been deposited as a thin layer in many places, for example, at the volcanoes. This possible final stage of global volcanic activity is maybe supported by the age of another group of Martian meteorites (Nakhlites).

Crater size–frequency measurements confirm that the most edifices were constructed over billions of years and are characterized by episodically repeating phases of activity that continued in both large volcanic regions almost to the present. A number of caldera floor and flank ages are clustered around 150 Ma, indicating a relatively recent peak activity period and practically coinciding with radiometrically measured crystallization ages of a group of basaltic Martian meteorites (Shergottites). The relation to the second group of Martian meteorites, the Nakhlites, remains more speculative. Most of the smaller volcanoes in the Tharsis region have been active in early Martian geological history, similar to most of the highland volcanoes. The long activity of Martian volcanoes correspondingly implies a long lifetime of the "feeding" source especially in the Tharsis region, that indicates a long and stable dynamic regime in the planet's interior.

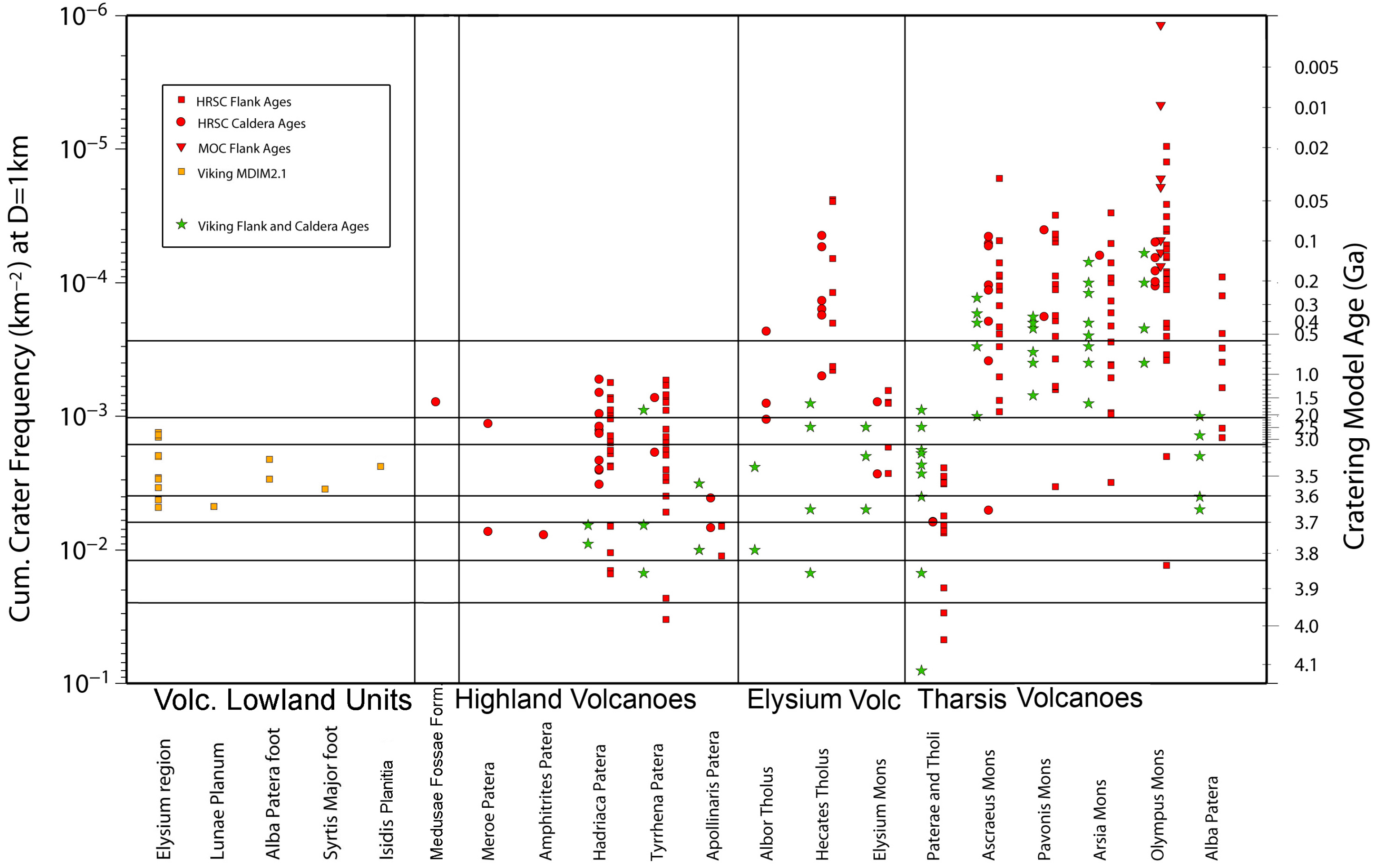

Figure 15.13.: Summary of crater frequencies N_{cum} (1 km) (left scale) and model ages derived applying the cratering chronology model by Hartmann and Neukum (2001) (right scale) for most of the volcanic constructs on Mars (red symbols) and a few volcanic plains units (orange symbols). The results are plotted for each individual volcano and grouped for Highland volcanoes, Elysium and Tharsis volcanoes. Additionally, the results for the Medusae Fossae formation and some volcanic plains are given. Most of the measurements were performed on HRSC imagery (red circles for caldera ages and red squares for flank ages). Measurements on MOC–narrow angle imagery for the flank ages (red triangle) give insight into the small crater size range. For comparison, earlier measurements based on Viking imagery are plotted as green stars. The latter are assembled by Neukum and Hiller (1981) and references therein. Horizontal lines show the epoch boundaries, see Chapter 5, Fig. 5.1.