14. Northern Lowlands, Highland–Lowland Dichotomy, and Fluvial Activity

Global Martian geologic mapping and stratigraphic analysis is based mainly on Viking Orbiter image interpretation (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987, see Chapter 6.2). One of the dominating features of the Martian surface is the ancient highland-lowland topographic and morphologic dichotomy, superimposed by huge impact basins and volcanic regions. The lowland region, roughly centered on the north pole, covers one third of the planet and is broadly characterized by a smooth, gently sloping surface at the km scale, below the mean planetary radius. Its origin has been attributed to tectonism as well as impact or mantle dynamics (e.g. Wise *et al.*, 1979a; Wilhelms and Squyres, 1984; Frey and Schultz, 1988), but any clear morphologic evidence has been obscured by subsequent resurfacing events. Based on new mission data, the interpretation of the northern lowlands gained new insights due to detailed topographic data of the Mars Orbiter Laser Altimeter (MOLA) and additional imagery of the Mars Orbiter Camera (MOC) (both onboard the Mars Global Surveyor space craft). Based on this new data, Tanaka *et al.* (2003) significantly revised the interpretation of the origin and age for a host of features in the northern lowlands. Their investigation culminated in a remapping of the northern plains of Mars and a preliminary interpretation of the resurfacing history. They relied mostly on a MOLA digital elevation model at a 1/128° resolution (about 500 m/pixel), while the physical interpretation is based on MOC–NA and high–res VIKING imagery ($<$ 100 m/pixel). A summary of the stratigraphy and distribution of the units is given in Tanaka *et al.* (2003). The main definition of the "new" lowland units is based on the topographic outline at an elevation of below –2000 to –5000 m. Major geographic features include the Borealis basin (Vastitas Borealis Formation), Utopia basin (Utopia Planitia), and Isidis basin (Isidis Planitia), implying that they all might have formed by large impacts. To the south, the plains are bounded by densely cratered highland terrain and the broad Tharsis rise, which includes Olympus Mons and the Alba Patera shield volcanoes. East of the huge volcanic Tharsis rise, Chryse and Acidalia Planitiae are located, characterized by old channel mouths as well as likely channel–related flood–plains and chaotic material. The bottom of the western flank of the Tharsis Rise is occupied by Amazonis Planitia and Arcadia Planitia, which extend westwards to the volcanic Elysium rise. The Elysium rise includes the Elysium Mons, Hecates Tholus, and Albor Tholus volcanoes, the largest volcanic constructs in the entire lowlands. To the south, Elysium Planitia surrounds the Elysium rise. Amazonis, Arcadia, and Acidalia Planitiae are merged to the Arcadia Formation, distinguished on the basis of morphology, albedo, and crater frequencies. The dichotomy boundary is intersected by Syrtis Major Planum, a broad shield volcano, and the impact basin Isidis Planitia. The rugged peaks of Lybia Montes surround the southern margin of Isidis Planitia.

The time–stratigraphic classification of the newly mapped northern hemisphere is based on the number of craters for each unit from the crater catalog published by Barlow (1988, revised 2001), which includes craters of +5 km in diameter. Tanaka *et al.* (2003) discuss the relevance of these crater frequencies with respect to their correctness and stated three problems in their approach: (1) the mis-registration of the MOLA–based geologic map and the VIKING–base of the crater catalog, which might attribute craters to a unit to which they do not belong or vice versa, affecting smaller units the most. (2) Taking the cumulative number for a single reference diameter (here 5 km and larger) instead of the entire crater size–frequency distribution, therefore any resurfacing will be obscured and need preselection of the craters to be counted. (3) The crater catalog already excludes highly degraded craters.

To investigate the full cratering record by using the crater size–frequency distribution as described in Chapter 8, it is not necessary to exclude or pre–sort crater populations. Any resurfacing will be visible in the crater counts as described in Chapter 9.1.

14.1. Northern Lowland Stratigraphy

In a joint effort, representative type areas for each geological unit were selected following Tanaka *et al.* (2003). A detailed study using crater size–frequency measurements for each unit to define a time–stratigraphic sequence is given here. Small patches representative of certain geologically mapped units and specific morphologic characteristics are distinguished. The patches are selected to contain a single geological unit and the simple outline is the basis for crater size–frequency distribution measurements. The basis for the surface age determination is the Viking – Mars Digital Image Model (MDIM 2.1) global dataset (a complete orthorectified mosaic) at a pixel resolution of 231 m/pxl. Based on our crater size–frequency measurements, the resulting surface ages and the time–stratigraphic relations of the investigated units are described here. Special focus has been given to four different zones, which represent different characteristics and evolution within the northern plains. The Chryse basin (zone 1), the Utopia basin (zone 2), the Amazonis and Elysium region (zone 3) and zone 4 representing the sequence between the north pole and Alba Patera.

14.1.1. The Geology of the Chryse Region (Zone 1)

The physiographic setting of this region is dominated by Chryse Planitia, a possible impact basin of about 2000 km in diameter. Many of the largest and prominent outflow channels on Mars drain into that nearly circular basin, which opens into the northern lowlands. Clear evidence for the impact origin cannot be found because rim characteristics have eventually been washed away by the fluvial activity (Fig. 14.1).

The extent of Chryse Planitia is outlined by four geological units (*Chryse unit 1 – 4*). The main characteristics of this basin are the scoured features and streamlined islands associated with the outflow channels. A system of deep, wide channels (Kasei, Maja, Shalbatana, Simud, Tiu, Ares, and Mawrth Valles) emanates from chaotic terrains and disappears into the lowlands. Chryse 1 and 2 units delineate plains deposits along the western and eastern margins of Chryse Planitia, characterized by wrinkle ridges, hummocky material, locally lobate scarps and tear–drop shaped islands. While Chryse 1 unit represents deposits from mass–wasting and local fluvial erosion of highland boundary surfaces, Chryse 2 unit was formed by debris flows and fluvial deposits. Further downstream, Chryse 3 and 4 units follow. They appear relatively smooth in the western part of Chryse (unit 3) and are marked locally by irregular grooves, knobs, low shields, and thin circular sheets (unit 4).

There are fluvial deposits in Kasei, Maja and Ares Valles, in the prolongation of Simud and Tiu Valles rapidly emplaced sediments (flood overrun), subsequent compaction, and mud volcanism modified the smooth appearance. A few of units relate directly to the outflow channel morphology (*Ares and Simud unit*). They contain the chaotic source regions and carved floors of the upstream part of Ares Vallis and other valleys. The Simud unit also includes some of the channel floors and large blocks and debris of older material disrupted and possibly transported by high–pressure fluids.

The channels originate from chaotic terrain and dissected highland plateau and boundary plains (*Noachis, Nepenthes, Lunae, and Lybia unit*). Most of the outflow channels do not end in the Chryse basin, but can be traced by the scoured features northward into Acidalia Mensa. The gradual disappearance is interpreted as possibly caused by the development of the Vastitas Borealis Formation.

This formation occupies most of the lowland region and has been mapped as a single unit merging four subunits, defined mainly by texture and albedo differences in earlier map approaches. The *Vastitas interior unit* is characterized by numerous low hillocks, arcuate ridges, dozens of circular depressions (ghost craters), pervasive hummocks, as well as grooved and mottled appearances. The *Vastitas marginal unit* forms plains and low plateaus along much of the outer margin of the interior unit. It has a more pronounced topography compared to the interior unit, showing troughs, knobs, and ridges. Both units are interpreted as sediments delivered over a large area by rapid emplacement due to outflow channel activity.

Many morphologies indicate high subsurface–volatile content and possible glacial, periglacial, lacustrine, or tectonic processes. Units such as the Noachis, Nepenthes and Lybia unit, are widespread throughout the mapped region, represent highland material, and grad from one into the other. The Noachis unit generally outlines rugged highland terrain surrounding most of the northern lowlands and is densely cratered. It resembles a mixture of volcanic and sedimentary material, which is covered by impacts. The Lybia unit has a similar appearance, but is more pronounced in topography, forming massifs and high–standing terrain within the Noachis unit. The Nepenthes unit consists of knobs and mesas of highland rock and interposed slope and plains material, which forms much of the highland/lowland margin. To the northeast, huge parts are covered by perhaps kilometer thick lava plains marked by wrinkle ridges. These belong to Lunae Planum and make up the Lunae unit in this zone.

These geologic–morphologic units are represented by 16 patches on which crater counts were performed. Their distribution and location are given in Fig. 14.1, image clips and resulting crater size–frequency distributions are given in Appendix A, and the ages and dimensions are summarized in Tab 14.1.

14.1.2. The Chrono–Stratigraphy of the Chryse Region

Most of the patches in this zone represent units belonging to the Chryse inner slope region (Fig. 14.1). Ages determined for image clips representing the Chryse 1 – 4 unit range between 3.83 Ga and 3.3 Ga. The ages found for individual units somewhat vary. For example, the Chryse 1 unit, represented by four patches (32, 33, 39, and 41) range between 3.83 Ga and 3.61 Ga. The imagery base and the resulting crater size–frequency distributions are shown in the Appendix A. The variation in age are explained by the visible change in morphology. All crater size–frequency distributions reveal surface ages slightly older than 3.6 Ga. For image clippings, where crater counts also indicate older ages (about 3.8 Ga), the surface morphology is not homogeneous. As for clip 33 and 32, smooth plains with wrinkle ridges and fluvial overprint are visible along with many knobs, which are widespread throughout the units. Particularly, the surface in the southern part of clip 33 resembles degraded highland terrain, which explains a very old surface age of 3.8 Ga.

Clippings representing Chryse 2 and 3 units generally fall into the same age range, but clip 35 appears especially young (3. 45 Ga) compared to the results of the other patches. Regions like Lunae Planum (mapped here as Lunae unit) are the background units for the carved channels of Kasei Valles. Their age indicates an outline for the start of the erosive phase of outflow channel activity. The Lunae unit clip indicates an age of 3.5 Ga and does

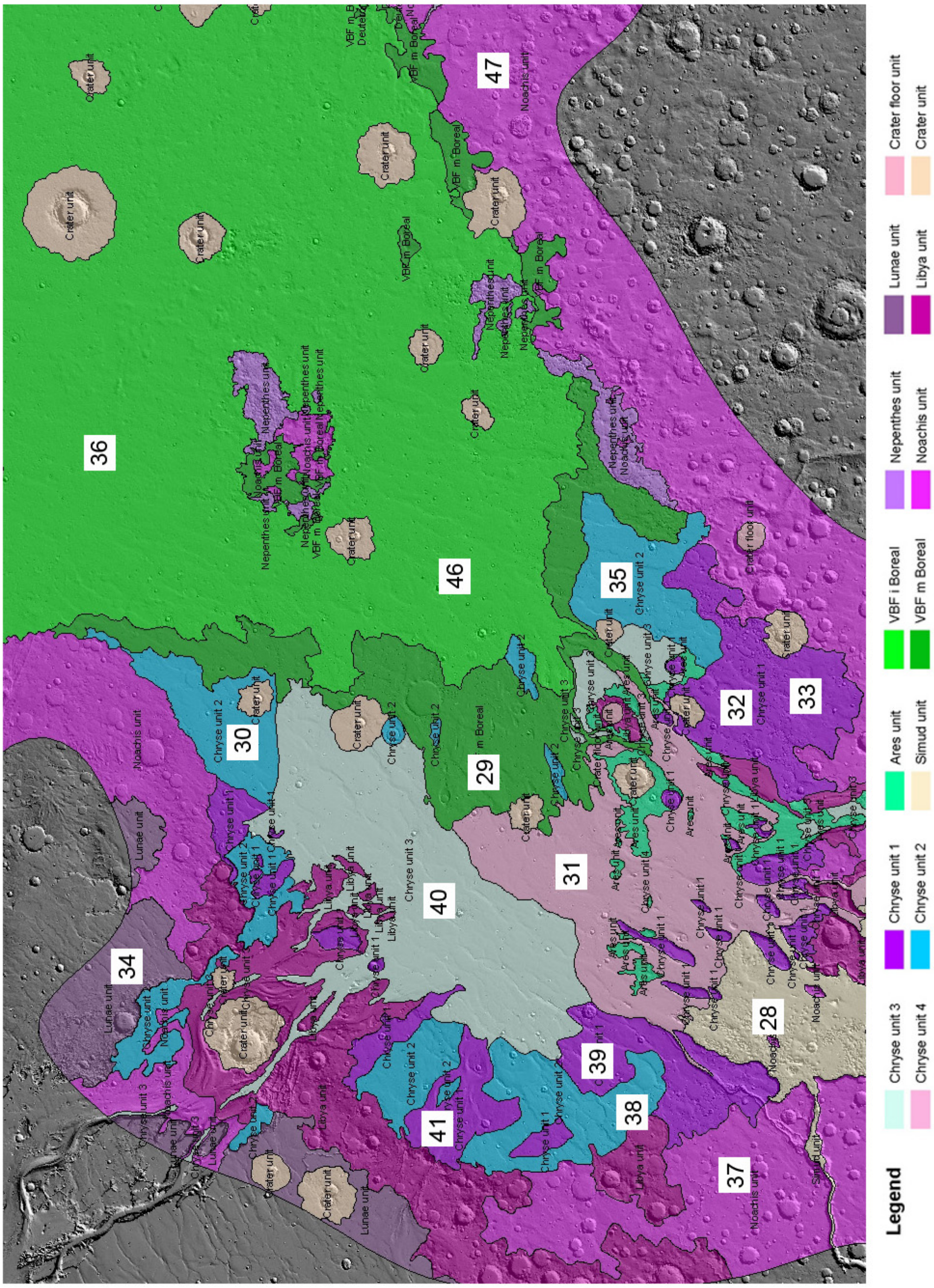

Figure 14.1.: The geologic map of the Chryse region as mapped by Tanaka *et al.* (2005) with numbered patches to indicate their locations. Here, Zone 1 is given. The results of the crater size–frequency distribution measurements are given in Table 14.1.

not support this idea. The volcanic activity that created this lava plain possibly was active over a longer period, ending subsequent to the formation of the Kasei channel system. As expected and already described by Tanaka *et al.* (2003), the oldest ages are found in the highland units (e.g. No. 47 and 37), which are heavily cratered. The geological interpretation of the Noachis unit (assumed to be the oldest by Tanaka *et al.* (2003) and earlier interpretations) indicates a long history of resurfacing and deformation, accounting for secondary erosional, depositional and tectonic features. These are characterized by high crater densities, valley networks, isolated depressions (which are possibly subdued eroded impact structures), as well as ridges, scarps, and troughs. The resurfacing activity is recognized in the crater size–frequency distribution, but not limited to a single episode (gradual deviation from the expected crater production function).

The naming follows the previous type region: Noachis Terra defining the Noachian Epoch. In Chapter 13 we discussed that there is no mapped unit older than about 4.1 Ga, which is close to the age found for Noachis Terra. In the Chryse region as well as in zones that will be discussed later, the oldest units are definitely about 4.0 ± 0.05 Ga old. The patches illustrating the outflow channel activity (Simud and Chryse 4 units) indicate resurfacing slightly younger ages, in the Chryse 4 unit, and which range between 3.6 and 3.4 Ga. It is likely that the erosive processes in Simud Vallis ended at about that time, but possibly later wide spread sedimentary deposition resurfaced the downstream region represented as Chryse 4 unit. The surface age gradually becomes younger towards topographic lows.

In general, all zones in the northern lowland units range between 3.6 Ga and 3.5 Ga, with a few exceptions in zone 2 and zone 3. These exceptions are correlated with morphologic units with a geologic origin that is clearly different than the lowlands characteristics. The gradual change in age correlated with the topographic change is represented by the different Chryse units (1 – 4). The Chryse units 1 and 2, occupying the possible rim region, are about 3.75 Ga old (patches 38, 33, and 32). Even within the Chryse unit 1, the age/elevation relationship is confirmed by the crater counts on patch 32, indicating a resurfacing event about 3.66 Ga ago.

This (3.66 Ga) is roughly the upper limit of the overall lowland age and is related to a constant height everywhere, which has been originally mapped as the Vastitas Borealis Formation grouping four morphologic end members (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). The lower–most region of the Chryse basin appears to be the youngest unit in that zone and is represented by a variety of units all resembling remaining flow features (lower parts of the channel systems) and other channel related units. On the basis of Viking imagery, resurfacing activity has not affected the Chryse region.

14.1.3. The Geology of the Utopia Basin and its Vicinity (Zone 2)

As the Chryse basin, the Utopia basin is also believed to be of impact origin and appears relative circular, about 3200 km wide and about 1 – 3 km deep. In both cases, rim features are not visible. The gravity anomaly maps for these two basins are very different. While the Utopia basin is similar to Isidis, Hellas and Argyre, and reveal typical high amplitudes indicating the general gravity feature of mascons, the anomaly of Chryse is not very distinct (Yuan *et al.*, 2001). The Utopia Basin is bounded by the crustal dichotomy to the south and west. Zone 2 includes, asides from the Utopia basin, the Isidis impact structure to the southwest, interrupting the dichotomy boundary followed westwards by the volcanic province Syrtis Major Planum. From the west, extensive volcanic flow units related to Elysium Mons (mapped here as *Elysium and Tinjar unit 1 and 2*) cover a huge amount of the Utopia basin area (Fig. 14.2). In Chapters 14.2 and 14.3, the highland–lowland

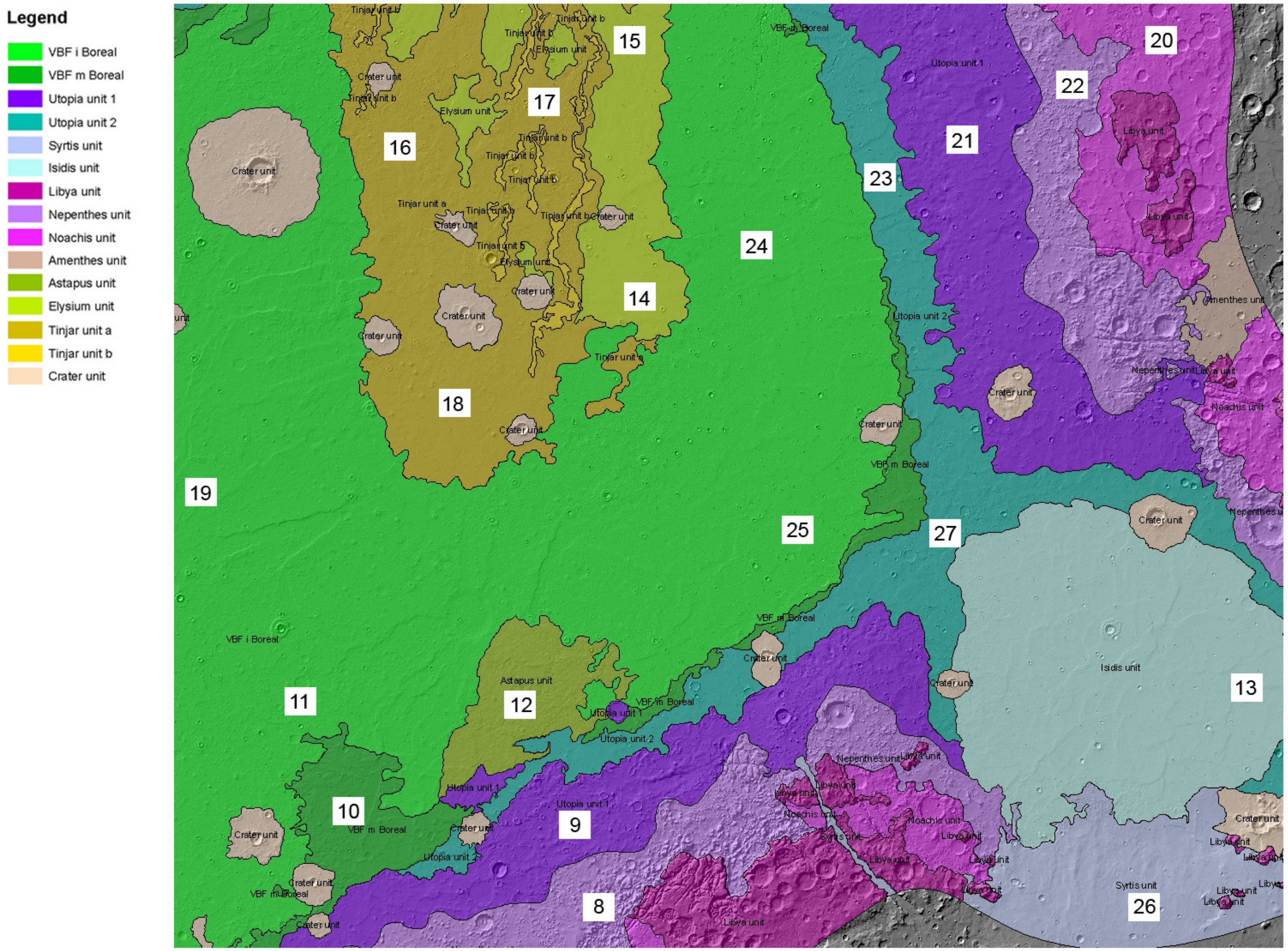

Figure 14.2.: The geologic map of the Utopia basin and its vicinity as mapped by Tanaka *et al.* (2005) and numbered patches to indicate their locations. Here, Zone 2 is given. The results of the crater size–frequency distribution measurements are given in Table 14.1.

boundary as well as aspects of the Utopia Planitia region will be discussed in detail.

The broadest and central area of the Utopia basin is part of the global Borealis province, which includes Vastitas Borealis, Planum Boreum, Utopia and Acidalia Planitiae. The Utopia basin defines two units (*Utopia 1 and 2 unit*) characterizing the southern, western and part of the eastern margin of Utopia Planitia, around most of Isidis Planitia and in parts of southern Elysium Planitia. Both units slope gently away from the highland margin. While Utopia 1 unit (closer to the highland margin) forms lowland plains deposits with irregular depressions, scarps many tens of kilometers long, and pancake domes, the lower parts of the Utopia 2 unit are marked by kilometer-sized knobs and mesas as well as depressions. These morphologies indicate erosion, transport and deposition of clastic material. Alongside, Isidis Planitia and Syrtis Major Planum are situated on the dichotomy boundary. Utopia 2 unit connects the Utopia and Isidis basins.

The *Isidis unit*, making up almost the entire Isidis basin plains, is marked by linear and arcuate ridges as well as chains of pitted cones, hundreds of meters wide, and wrinkle ridges. The basin plain is slightly tilted, with a height difference of about 300 m between the northeastern edge and the lower southwestern margin. The *Syrtis unit* covers the lower margin of Syrtis Major Planum. Flow tongues are visible in the east, including two 200 km long and roughly 30 km wide ridges with a discontinuous narrow depression along the crest. Northwards, the *Astapus unit* is separated from the global northern lowland outlining the Vastitas unit, due to its complex kilometer–scale irregular pits, grooves and ridges.

Besides the Syrtis Major volcanic province, the Elysium rise and flow features delineating units are found in this zone. The *Elysium unit* consists of extensive tongue–shaped flows, the volcanic edifices Elysium Mons, Hecates Tholus, and Albor Tholus, and their surroundings. Flows extending more than 2000 km into Utopia Planitia are separated from the Elysium unit, which is made up of the volcanic shield flows that extend from the vents, as dictated by the morphology of the region. *Tinjar a and b units* are flows typically emanating from mostly northwest–trending fissures and troughs of the Elysium Fossae. Tinjar b unit outlines broad, irregular channel systems of Granicus, Tinjar, Apsus and Hrad Valles, which most likely resulted from magma/volatile interaction and subsequent degradation. Highland units are present in Nepenthes, Noachis, and Lybia units around the Utopia basin. These units comprises heavily cratered highland units (*Noachis unit*), grading into dense knobs, mesas and local depressions (*Nepenthes unit*) to smooth, gently undulating plains (*Utopia 1 and 2 unit*). Mass–wasting is the major contributor to the modification of the circum–Utopia highland-lowland boundary (Skinner *et al.*, 2004).

14.1.4. The Zone–2 Chrono–Stratigraphy

In this zone, 19 patches, representing the geologic units and on which the crater size–frequency distributions were measured, are shown in Fig. 14.2. Imagery and crater size–frequency distributions are shown in Appendix A. The ages and dimensions are given in Tab. 14.1. Crater counts on patch no. 13 representing the Isidis floor unit give an age of about 3.4 Ga, while the basin itself originated at about 4 Ga ago (Table 13.3). Nili and Meroe Patera most likely fed the volcanic province Syrtis Major Planum. Their calderas have an age of 3.73 Ga with a resurfacing event ending 2.5 Ga ago and will be discussed in detail in Chapter 15.3. Here, the crater counts on the patch representing this region (No. 26) indicate an age of about 3.57 Ga, which is close to the latest stage activity of other Paterae volcanic constructs. The oldest surface age in this zone is again found in the Noachis unit (No. 20), that is the heavily cratered highland unit with an age of about 4 Ga.

Following a profile line roughly along the 120°E–meridian (starting with patch no. 20) the surface age gradually decreases with de-

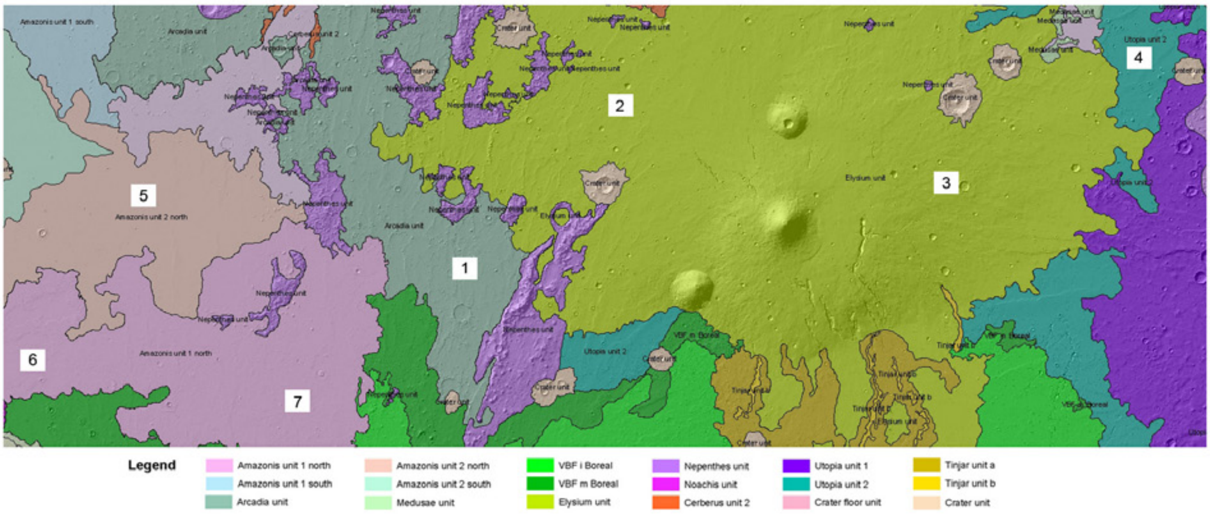

Figure 14.3.: The geologic map of the Elysium volcanic province and Amazonis Planitia as mapped by Tanaka *et al.* (2005) and numbered patches, to indicate their locations. Here, Zone 3 is given. The results of the crater size–frequency distribution measurements are given in table 14.1.

creasing elevation as has been observed in similar morphologic situations in the Chryse region. In Zone 2, the Vastitas Borealis Formation surface ages are the youngest of the investigated patches at about 2.8 Ga. The units related to possible rim parts of the Utopia basin, represented by patches east and west of the Isidis basin (Utopia unit 1, No. 09 and 21), appear to be slightly older at the eastern flank (∼ 3.75 Ga) compared to the 3.65 Ga at the western flank. The outline of Utopia unit 2 is supposed to define a morphologically uniform unit (No. 27 and 23), but the surface ages determined for various patches, representing Utopia unit 1, appear to better fit the surrounding unit ages rather than being homogeneous within this unit. A detailed investigation to understand its evolution as a single surface unit is needed and will be discussed for the western Utopia "rim" unit in Chapter 14.2. All patches (No. 8, 9, (10), 11, 12) resemble units, which also will be discussed in Chapter 14.2, but here they all appear to have an age of 3.65 Ga.

Following the profile line (∼ 120°E), patches representing the Elysium and Tinjar units, which have been interpreted as lava flows, erupted at the flanks of Elysium Mons. Ages of about 3.55 Ga have been measured, but most crater size–frequency distributions indicate that these units suffered a resurfacing episode, which ended about 3.3 Ga ago. During this episode, craters smaller than 3 kilometers in diameter have been erased. Similar ages are found in Zone 3, where similar morphologic units are classified.

In general, when translating the absolute surface ages described here (Tab. 14.1) to geologic epochs (Fig. 5.1), the origin of most of the surfaces represented by the patches in zone 1 and 2 are of Hesperian age except the highland units (Noachian age). Some of the units represented by patches (e.g. no. 19, 23, 24 and maybe even 25) are the youngest in Zone 2, are roughly 2.9 Ga old and considered of Early Amazonian age.

14.1.5. The Elysium Volcanic Province and Amazonis Planitia (Zone 3) – Geology and Chrono–Stratigraphy

The third zone of interest includes the volcanic province Elysium and surrounding plains units (Fig. 14.3). Three volcanoes, Elysium

Mons, Hecates Tholus and Albor Tholus as well as other local sources constituting this region, cover a rather large area of the northern lowlands with volcanic shield flows (see Chapter 15.2). The region lying to the west, between the Tharsis and Elysium rises, consists of Amazonis and Arcadia Planitiae. Amazonis Planitia has been the type region for the youngest of the Martian epochs. These extremely flat regional plains show some subtle, sinuous channels and are sparsely cratered (*Amazonis 2 north unit*). *Amazonis 2 south unit* consists of a sequence of lobate flows that are broad, long, planar, gently sloping and believed to be the result of voluminous lava flows in both units. *Amazonis 1 north and south units* are more rugged, consisting of material that is possibly lava or pyroclastic debris flows. Arcadia Planitia outlined as the *Arcadia unit* is more bumpy in its appearance and shows knobs organized in circular rings, resembling buried crater rims.

The volcanic units represented by patches no. 2 and 3 resemble volcanic flanks of the Elysium rise and give an age of about 3.6 Ga. A similar age is found for patch no. 4 (mapped as Utopia unit 2), which covers part of the plains unit discussed in relation to the Athabasca Valles. In these Athabasca Valles plains units, the same age of 3.66 Ga has been found in our earlier investigations (see Chapter 12, Werner *et al.* (2003b) and Murray *et al.* (2005)) and confirms the crater size–frequency distribution measurements in this study.

Patches representing units in the Amazonis Planitia, the western lowland vicinity of Olympus Mons, indicate ages of Middle to Late Amazonian (No. 5 and 6). While patch no. 7 resembles the same unit as patch no. 6 (Amazonis unit 1 north), it appears to be much older (∼3.35 Ga). In a separate measurement across the entire Amazonis Planitia, the classification of surface morphology correlated to different surface age units is observed (for the crater size–frequency distribution see Chapter 17). Strong resurfacing visible in the eastern part of Amazonis Planitia (close to the Olympus Mons Aureole) might require a remapping of earlier attempts, which described Amazonis Planitia as a wide homogeneous plan. The Arcadia unit represented by patch no. 1 appears to have an overall surface age of about 3.55 Ga.

14.1.6. Between Alba Patera and the North Pole (Zone 4) – Geology and Chrono–Stratigraphy

The northern periphery of the Tharsis region includes the broad volcanic edifice Alba Patera and its foothills, *Alba 1 and 2 units.* Alba 1 unit forms the northern part of the Alba Patera shield and comprises tens of kilometers wide and hundreds of kilometers long well defined sinuous flows. On the other hand, the Alba 2 unit appears more smooth due to flat lying deposits, most likely volcanic and atmospheric deposition (Fig. A.12).

Four patches cover a profile line between Alba Patera and the northern polar ice cap, roughly following the 270°E meridian, and making up the last zone discussed here. Again, the selected units follow the gentle slope down to the northern lowland average elevation. Ages based on the crater size–frequency distributions for patches no. 42, 43, 44, and 45 indicate a surface age of about 3.6 Ga. There is no gradual change in age coinciding with the observed elevation level. A surface age of 3.37 Ga, obtained from crater measurements closest to Alba Patera (patch no. 42) is the youngest. Morphology and ages between the pole and Alba Patera do not follow the typical highland–lowland boundary characteristics. It is most unlikely that similar geologic processes have acted to form this region compared to the dichotomy sector. While units between − 30°E to about 145°E are characterized by the transition between old Noachian heavily cratered highland terrain to Hesperian–aged lowland units, the cliff–like dichotomy boundary characteristics (if ever existed) of the other hemisphere are obscured or fully covered by volcanic (or other resurfacing) activity. The gradual rejuvenation of the observed surface ages is clearly represented by measured patches and will be discussed in de-

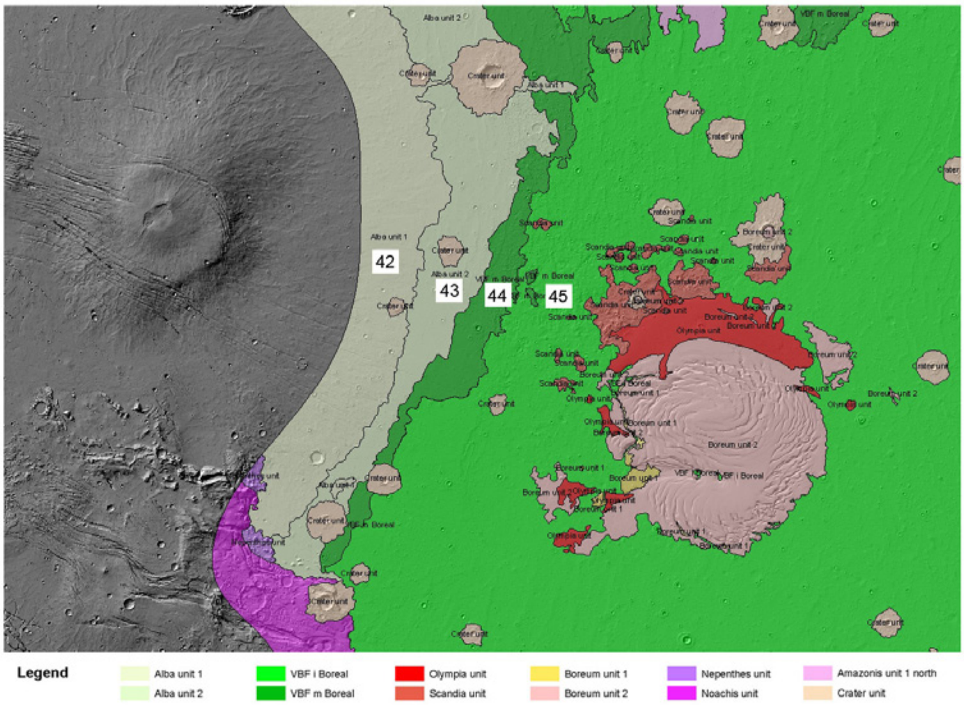

Figure 14.4.: The geologic map between Alba Patera and the North Pole as mapped by Tanaka *et al.* (2005) and numbered patches, to indicate their locations. Here, Zone 4 is given. The results of the crater size–frequency distribution measurements are given in table 14.1.

tail for the sector between – 30°E to about 90°E (Chapter 14.2).

14.1.7. The Viking–Based Chronostratigraphy of the Northern Lowlands, Summary

In the Chryse region, the 4 Ga ages are the oldest found in the highland units, which are heavily cratered with occurrences of small–scale resurfacing. The Chryse inner slope ages range between 3.8 and 3.3 Ga and tend to become gradually younger towards topographic lows. The units belonging to outflow channels have formed before 3.55 Ga ago. The units in continuation of flood plains appear slightly younger. Generally, the Vastitas Borealis Formation (entire plains) is about the same age (3.5 to 3.6 Ga). The lava unit (Lunae Planum) has been formed until 3.5 Ga ago. Nevertheless, many mapped units (mainly outlined topographically) are not homogeneous in age, which is supported by the morphologic diversity of those units.

The Utopia basin and its vicinity indicate similar ages. The bounding highland plains are about 4 Ga old. As in the Chryse region, the Utopia floor age ranges between 3.5 and 3.6 Ga, with older slope units (about 3.75 Ga). Again, a gradual decrease in ages towards topographic lows is observed, with a minimum age of about 3 Ga. Volcanic flows and phreato–magmatic activity (Elysium flank flow units) occurred about 3.5 Ga ago followed by a later phase between 3.4 and 3.1 Ga. The Syrtis Major flank measurements indicate a similar age of 3.55 Ga, while the surface of Isidis Planitia is slightly younger (3.45 Ga; correlating with low topography).

The plains around Elysium are partly type units for the youngest epochs of Martian history. The Elysium flanks and surrounding plains (Arcadia) are about 3.5 to 3.6 Ga old, Results of the Crater Size Frequency Measurements

#	Geologic Unit	Area	Dmin	Dmax	N_{total}	N_{cum}(1km)	Age in Ga*
Results of the Crater Size Frequency Measurements in Zone 1							
28	Simud unit	50726.2	1.0	7	32	3.68e-3	3.58
29	VBF m Boreal	52994.8	1.2	17	35	2.88e-3	3.51
30	Chryse unit 2	36427.9	1.0	17	30	6.05e-3	3.69
31	Chryse unit 4	45069.9	.9	17	55	3.60e-3/1.79e-3$^+$	3.58/3.25$^+$
32	Chryse unit 1	51014.5	.6	50	102	7.93e-3/4.73e-3$^+$	3.75/3.64$^+$
33	Chryse unit 1	48678.8	1.1	20	91	1.29e-2	3.83
34	Lunae unit	27171.1	.8	12	69	2.80e-3	3.50
35	Chryse unit 2	56505.1	.9	17	74	2.46e-3	3.45
36	VBF i Boreal	74655.6	1.0	25	58	3.75e-3	3.59
37	Noachis unit	29945.0	.9	35	121	2.99e-2	3.97
38	Chryse unit 2	15803.8	.9	10	40	8.61e-3	3.76
39	Chryse unit 1	20638.5	1.0	13	39	5.03e-3	3.66
40	Chryse unit 3	56970.1	.9	17	80	3.33e-3	3.55
41	Chryse unit 1	54653.5	1.0	20	69	4.07e-3	3.61
46	VBF i Boreal	121418.3	.6	25	152	2.73e-3	3.49
47	Noachis unit	78954.8	.8	70	168	4.83e-2/1.82e-2$^+$	4.04/3.89$^+$
Results of the Crater Size Frequency Measurements in Zone 2							
08	Nepenthes unit	53657.1	.8	25	67	4.81e-3	3.65
09	Utopia unit 1	48843.0	1.2	25	61	4.93e-3	3.65
11	VBF i Boreal	59549.1	1.7	17	26	4.28e-3	3.62
12	Astapus unit	87457.7	1.3	10	54	4.17e-3	3.61
13	Isidis unit	24149.6	1.1	12	27	2.37e-3	3.43
14	Elysium unit	308995.3	.5	9	84	2.95e-3/1.44e-3$^+$	3.52/2.92$^+$
15	Elysium unit	36978.4	.6	5	51	2.95e-3/1.33e-3$^+$	3.52/2.71$^+$
16	Tinjar unit a	81279.5	1.1	20	34	3.43e-3	3.56
17	Tinjar unit a	55842.5	1.0	12	45	4.24e-3/2.00e-3$^+$	3.62 /3.34$^+$
18	Tinjar unit a	133574.7	1.4	9	24	1.98e-3	3.34
19	VBF i Boreal	229742.8	1.7	17	31	1.38e-3	2.82
20	Noachis unit	21906.1	1.1	25	69	5.07e-2/2.97e-2$^+$	4.05/3.97$^+$
21	Utopia unit 1	30605.7	.8	13	111	8.76e-3	3.76
22	Nepenthes unit	25494.6	1.0	13	45	1.22e-2/3.21e-3$^+$	3.82/3.54$^+$
23	Utopia unit 2	31268.1	.8	17	45	1.47e-3	2.97
24	VBF i Boreal	39105.5	.6	7	74	1.42e-3	2.88
25	VBF i Boreal	25959.0	.7	8	74	4.38e-3/2.02e-3$^+$	3.43/3.35$^+$
26	Syrtis unit	84612.8	.8	10	182	3.51e-3	3.57
27	Utopia unit 2	75724.3	.9	35	57	3.66e-3	3.58
Results of the Crater Size Frequency Measurements in Zone 3							
01	Arcadia unit	129442.5	1.4	20	43	3.28e-3	3.55
02	Elysium unit	133562.1	.6	20	226	4.84e-3	3.65
03	Elysium unit	130913.1	.035	35	126	2.88e-3	3.51
04	Utopia unit 2	61866.9	.9	10	90	5.21e-3	3.66
05	Amazonis unit 2 north	230947.7	.5	20	20	7.09e-4/5.30e-4	1.45 or 1.1
06	Amazonis unit 1 north	110484.1	1.1	13	11	2.09e-4/1.41e-4$^+$	0.95/.29$^+$
07	Amazonis unit 1 north	178776.8	2.0	17	16	1.93e-3	3.32
Results of the Crater Size Frequency Measurements in Zone 4							
42	Alba unit 1	127810.7	1.3	20	62	2.10e-3	3.37
43	Alba unit 2	139594.4	.8	30	57	2.95e-3	3.52
44	VBF m Boreal	44302.2	1.4	13	15	4.73e-3	3.64
45	VBF i Boreal	86840.6	1.5	60	29	3.31e-3	3.55

$^+$ treatment as described in Chapt. 9.1 — * billion years

Table 14.1.: This table lists the absolute ages and other statistical parameters for the patches shown in Fig. 14.1 to A.12. All measured crater size–frequency distributions for all patches, including the fit of the crater production function and the resulting age, are shown in Appendix A.

while the youngest plains unit, Amazonis Planitia, cannot be treated homogeneous in age and morphology. We found ages ranging between 3.3 Ga and 400 Ma even if mapped as a single unit.

Between the North Pole and Alba Patera, younger ages in topographic lows (3.64 and 3.55 Ga) are found. While the Alba Patera construct possibly hides the dichotomy boundary, the typical gradual age change towards lows is not observed, but two episodes of volcanism occur (3.37 and 3.52 Ga).

In general, the northern lowland units (in all zones) range between 3.6 Ga and 3.5 Ga, while decreasing age down–slope towards topographic lows are observed. The typical morphology of the dichotomy boundary has been partly covered/erased by volcanic, fluvial, or cratering processes (reflected in ages), while the fluvial activity could not cause resurfacing as effectively as the volcanic process. Usually the morphology and ages correlate well and the new mapping attempt to assign the lowlands as a generally uniform (mapped as Borealis inner unit) unit appears to be valid. Nevertheless, it is unlikely that the lowland surface formation occurred during a single event. Elevation levels and morphology are not necessarily related. Therefore, mapping following the elevation level is misleading, especially in units composed of multiple geological processes.

14.2. The Highland–Lowland Dichotomy Boundary between –30°W and 270°W

The dichotomy boundary is defined as separating the heavily cratered highlands and the northern lowlands observed in Viking imagery. The origin of the Martian dichotomy is unclear, but it has been argued that it was formed by a number of large impacts (e.g. Wilhelms and Squyres, 1984; Frey and Schultz, 1988; McGill, 1989) or internal dynamics (e.g. Wise *et al.*, 1979a; McGill and Dimitriou, 1990; Sleep, 1994; Zhong and Zuber, 2001; Zuber, 2001). MOLA–topography data have revealed a difference in elevation between the northern and southern hemisphere of about five kilometers (e.g. Smith *et al.*, 1998). Especially in the eastern hemisphere (Terrae Sabaea and Cimmeria), the dichotomy boundary is characterized by a prominent scarp and possible extensional and compressional features (Watters, 2003), while other parts in the western hemisphere appear to have gentle slopes (Terra Arabia).

If the dichotomy boundary had once been a global band, in some localities the characteristically steep escarpment is covered by two large volcanic provinces (the Tharsis and Elysium region) and a few impact structures (e.g. Isidis Planitia) or impact basin suspects (e.g. Chryse Planitia). Here the boundary section between Chryse Planitia and Isidis Planitia (30°W to 270°W, and 17.5°N to 60°N) is investigated in detail. An overview is given in Fig. 14.5.

The investigated area is bordered by the large outflow channels in the west. The line of the steep escarpment morphology is interrupted by the Isidis impact basin and the volcanic Syrtis Major complex. The boundary continues almost halfway around Mars in its typical appearance. It is partly covered by the enigmatic Medusae Fossae Formation, which is interpreted as pyroclastic deposits of unknown origin (Greeley and Guest, 1987) or as remnant of ancient polar deposits (Schultz and Lutz, 1988), as discussed later in Chapter 14.4.

Compared to the typically steep escarpments in Terra Cimmeria, the Arabia Terra region appears fairly reliefless. Arabia Terra is associated with a low thermal inertia, which is thought to be due to fine–grained material, centered on 20°N and 330°W (Palluconi and Kieffer, 1981). Spectral information (gathered by the Thermal Emission Spectrometer onboard Mars Global Surveyor) indicated a hematite–rich surface (Christensen *et al.*, 2000). The Neutron spectrometer (onboard 2001 Mars Odyssey) found a hydrogen–enriched (possible water/ice–enriched) region (Feldman *et al.*, 2002; Mitrofanov *et al.*, 2002; Boynton *et al.*, 2002). Basilevsky *et al.* (2003) attributed the decreased epithermal neutrons in the Arabia Terra region (and also in the Medusae Fossae region southwest of Olympus Mons) to chemically bound water, but we found no clear relation to any surface geology (Basilevsky *et al.*, 2004, revealed by MOC–NA imagery). Nevertheless, a region in Arabia Terra close to the equator, Meridiani Planum, has been selected as the MER Opportunity landing site. The finding of so–called blueberry spherules are interpreted as the source of the orbital detection of hematite (Squyres *et al.*, 2004a). Additionally, the formation of jarosite, a hydroxide sulfate mineral found at the landing site (Klingelhöfer *et al.*, 2004) and the deposition scenario requires the presence of liquid water (Squyres *et al.*, 2004a).

Theoretical modeling based on thermal inertia and albedo suggest ground ice might be more stable than elsewhere at the same latitudes, even if obliquity changes are considered (Mellon and Jakosky, 1993, 1995). Compared to other Noachian–aged areas on Mars, Arabia Terra is almost devoid of so–called valley networks. They are believed to be drainage systems, cited as evidence for a formerly wetter and warmer Mars. Two genetic processes for the formation of valley networks are discussed, both involving fluvial activity: surface runoff and water sapping (Mars Channel Working Group, 1983). The lack of networks in Arabia Terra and circumferential Hellas is correlated to the low–lying nature of these areas compared to the generally higher elevation of Noachian units, with a separation elevation of about 1000 meters (summarized by Carr, 1996).

14.2.1. Geology

Our detailed investigation was initiated because of the varying general topography of the dichotomy boundary in Arabia, Sabaea, and Cimmeria Terrae. The transition between both surface morphologies discussed here are separated not causatively but coincidentally by the most prominent impact structure of the northern lowlands, Lyot (roughly centered at the 330°W longitude). A possibly related separation is found in the region of Deuteronilus Mensae. This separation is visible in the derived bouguer anomaly and calculated crustal thickness (Neumann *et al.*, 2004), which was already pointed out by Janle (1983). The heavily cratered highlands are nearly everywhere thicker than 60 km, while the lowland crust has been derived to range between 20 to 40 km. West of 330°W longitude, the crustal–thickness change correlates with the topography, while the crustal thickness of the Arabia Terra region relates to the lowlands, while the surficial appearance is similar to typical highland morphology (heavily cratered).

The existence of outflow channels in the Chryse region demanded a sink region. To find the sink, the search was focused on the smooth northern–lowland plains. Large polygonally–fractured ground (McGill, 1985, for further discussion see Chap. 14.3), mottled plains, patterned ground, terraces and stepped massifs, backflow features, and layered sediments are indicators for a possible, temporary, ancient Martian ocean (Carr, 1996). Shoreline candidates, separating smooth lowland areas from highland units, were traced along the dichotomy boundary (Parker *et al.*, 1989). The key area of this investigation has been Deuteronilus Mensae, exhibiting both gradational (Rossbacher, 1985) and fretted terrain (Sharp, 1973) boundary types. Westward, the boundary is defined by gradational material and to the east by fretted terrain.

Typical of fretted terrain are uplands dissected into a complex pattern with steep escarpments separating upland remnants from low–lying plains. Debris flows (lobate debris aprons) extend about 20 km away from the escarpments. Examples can be found in the northern hemisphere in the Deuteronilus-Proteronilus Mensae region (280 – 360 °W) in the Mareotis Fossae region (50 – 90 °W), Acheron Fossae regions (130 – 140 °W), and in the Phlegra Montes (180 – 200 °W), but also around rim massifs of Hellas and Argyre basin and smaller crater rims. Their creeping appearance is attributed to entrained ice, but this has not been proven (Squyres, 1979; Lucchitta, 1984). These features are thought to be indicators for an earlier wetter Mars (Squyres, 1979).

The goal of this investigation is to attribute ages to the characteristic dichotomy units and to figure out if the different occurrence in topography and crustal structure is supported by measured crater–size frequencies and derived absolute ages. Many interpretations for the evolution of the dichotomy escarpment are focused on the eastern part, such as continental rifting, thrust faulting, or breakup margins (e.g. McGill and Dimitriou, 1990; Sleep, 1994). The western parts are thought to be subduction zones (Sleep, 1994). Therefore, the dichotomy–related units were mapped according to Tanaka *et al.* (2003) and their revised version (Tanaka et al., 2004, pers.comm.). The unit delineation for the age determination is based on Mars Global Surveyor data, which are the MOLA–topography and MOC-WA imagery. Mainly topographic data, but also morphologic and albedo aspects, were considered to outline the geologic units on the global Viking MDIM 2.1 photomosaic. Following the unit description and annotation of Tanaka *et al.* (2003), a brief overview for the unit appearances in the investigation area is given below (Fig. 14.5):

Highland material, undivided (unit HNu): typical ancient highland terrain marked by large craters, isolated depressions, ridges, scarps, and troughs. It can be interpreted as a mixture of volcanic and sedimentary material, showing a long resurfacing history of cratering, erosion, deposition and tectonic deformation. Assigned under *B*, an area around Nili Fossae has been investigated. Morphologically, it repeats knobby–unit characteristics, but is influenced by the Isidis basin and the volcanic construct Syrtis Major.

Knobby unit (unit HNk): consists of knobs and mesas, which are dissected highland remnants with steep escarpments, separating upland remnants from low–lying plains along the highland–lowland boundary. Processes such as fracturing and collapse due to basal sapping of volatiles and mass-wasted debris are likely.

Boundary plains unit 1 and 2 (unit Hb1 and Hb2): Both belong to the northern lowland plains in the map of Tanaka *et al.* (2003). Boundary plains unit 1 is considered to be the oldest exposed northern–plains unit adjacent to older highland and plateau materials. It is closely related to the steep escarpment of the dichotomy boundary itself, gently down–sloping away, and is missing in the northwestern Arabia Terra region. Ridges, scattered knobs up to a few hundreds of meters high, indicate volatile-assisted slope processes. Boundary plains unit 2 is chiefly identified as smooth plains material, marked by wrinkle ridges, coalescing with the base of boundary plains unit 1 if present. Northwest of the Arabia Terra region, the unit embays highland material (unit HNu). The fretted trough floors of Deuteronilus Mensae form a continuous surface with the unit Hb2 surface in northwestern Arabia, where they are not covered by apron material. *Apron material* (unit Aa) includes smooth, sloping deposits along the base of high-standing scarps of Deuteronilus Mensae (lobate debris aprons).

Younger chaos material (unit Act) is represented in a smaller area at the boundary of this investigation area. It usually occupies depressions tens to hundreds of kilometers across and tens to a few hundreds of meters deep in the Acidalia Mensa and includes polygonal fractures, knobs, and irregular scarps.

The majority of the northern lowlands, the Vastitas Borealis Formation, is mapped here as *hummocky member* (unit AHvh). This unit is characterized by numerous low hillocks, arcuate ridges and patches of grooves hundreds of meters wide forming networks of polygons several kilometers (see Chap. 14.3). This unit may be an area where a standing body of water (ocean /mud ocean) has most affected the surface morphology.

We use crater–count results to revisit the earlier age interpretation and to understand if the surface ages yield any clues about different timing of the evolution of the eastern and western part of the dichotomy–boundary units discussed here.

14.2.2. Chronostratigraphy

The crater counts have been performed on Viking–MDIM–2 imagery, which remains the most convenient in terms of image contrast. The mosaic was reprojected in a Lambert–two–parallel projection and divided into eight sheets. Ages were determined for the individual units on different sheets. For some units crater–size frequencies vary from sheet to sheet and yielded slightly varied absolute ages (see Fig. 14.5). These age ranges can be caused by the individual timing of pertinent geological processes. Nevertheless, measuring ages on Viking imagery of relatively low resolution (231 m/pxl) does not permit a discussion of any resurfacing events acting on the removal of craters in the small–size range (less than about 1 kilometer in diameter). Craters smaller than 1 km in diameter will not be reliably detected due to the resolution limit. We do not rule out that resurfacing processes have modified the surfaces after their formation. For a better interpretation, the sub-results (individual crater size–frequency distributions) were summed to get the size–frequency distributions and ages for the entire unit, summarized in Table 14.2. The individual results are given in Fig. 14.5 and will be discussed below.

Dichotomy Surface Ages

Unit	Area	N_{total}	N_{cum}(1km)	Age
HNu	$1.91\ 10^6$	3356	1.54e-2	3.86 Ga
HNk	$1.35\ 10^6$	1480	5.55e-3	3.68 Ga
Hb1	$0.78\ 10^6$	455	3.41e-3	3.56 Ga
Hb2	$1.34\ 10^6$	676	6.73e-3	3.73 Ga
Hb2			$2.72e\text{-}3^+$	3.49^+ Ga
AHvh	$2.47\ 10^6$	1746	2.07e-3	3.37 Ga
Aa	$0.29\ 10^6$	152	1.17e-2	3.82 Ga
			$7.16e\text{-}3^+$	3.73^+ Ga
Act	$0.92\ 10^6$	716	4.80e-3	3.65 Ga
B	$0.13\ 10^6$	151	1.01e-2	3.80 Ga
Lyot			2.22e-3	3.40 Ga

$^+$ treatment description see Chapt. 9.1

Table 14.2.: The absolute ages and other statistical parameters summed for all units. In this table the ages are given as an average age for the entire unit. In Fig.14.5, the individual results of the age determination are labeled. Unit boundaries, sheet boundaries and absolute ages measured sheetwise are labeled in Fig.14.5 and are discussed in the text.

Surface Ages at the Dichotomy Boundary: Ages found in this study area range between about 4 Ga and 3.1 Ga. In general, grading in age from old to young is correlated to an elevation change from the highlands, across the dichotomy towards the lowlands (in a south–to–north direction). The second general observation is a reduced age within a single geological unit in the western part compared to the the eastern parts.

The highland units assigned as HNu have been previously considered to consist of rock units that cannot be distinguished morphologically or stratigraphically in order to place them in the Noachian or Hesperian epoch. Our crater counts were performed on four sheets containing the HNu unit. They yield surface ages, which range between 3.98 Ga to 3.89 Ga. These Middle to Early Noachian ages are found elsewhere (see Chapters 14 and 13) and are in good agreement with an almost homogeneously formed highland plateau, where the surface forming processes are dominated by impact cratering. The crater size–frequency distribution measured close to the Isidis basin reveals the oldest surface age, followed by resurfacing reflecting an eventful history, since the impact basin formation. In the eastern part northward from the highland plateau, the escarpment foot is occupied by the knobby unit HNk, which is closely related to the highlands. It originated through dissection of highland plateau units. Here, we observe a broader age range between 3.83 Ga to 3.67 Ga. Areas measured closer to the escarpment appear older than those more distant from the cliff. Larger craters are still visible on the remaining blocks and mesas of the dissected highland plateau, while in the areas further away smooth lowland plains dominate the terrain. After summing all crater counts for this unit, the surface age of about 3.68 Ga is Early Hesperian, with the mesa surfaces

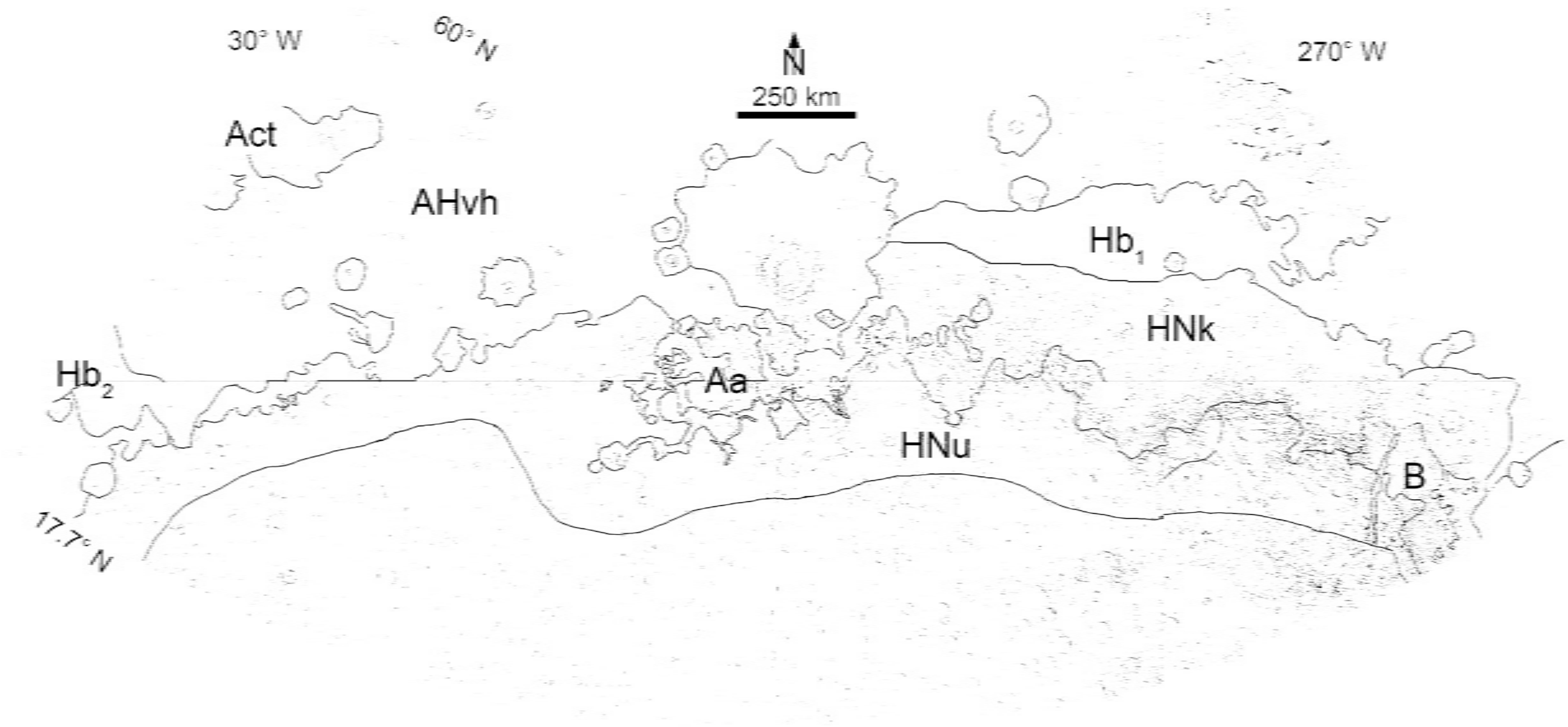

Figure 14.5.: The dichotomy boundary between 30°W to 270°W and 17.5°N to 60°N. Geologic units are delineated following Tanaka *et al.* (2003) on the basis of Viking and MOC–WA imagery and topographic information (MOLA). The huge area was split into eight sheets and ages were determined for each subset separately. The absolute ages (individual results of age determination for each subunit) obtained are labeled in the map for each subunit. Ages resulting for the entire geologic units (by summing the crater counts of the subsets respectively) are listed in Table 14.2.

surfaces Noachian in age. Earlier interpretations considered these units as Hesperian-Noachian, similar to the highland plateau surfaces.

Further north the geological unit considered as boundary unit 1 (Hb1) appears. Both morphologies making up the units Hb1 and HNk are not found in the western part of our investigation area. Here, the trend of younger surface ages towards topographic lows in the lowlands is apparent (as described earlier, Chapter 14). The surface age derived from crater counts is 3.56 Ga, deviating within the individually mapped units between 3.61 Ga and 3.55 Ga (Early to Late Hesperian). A slight absence of large craters is observed, a phenomenon that is known for other units in the Martian lowlands (see Chap. 14.3). The youngest age of 3.48 Ga, measured in the eastern part, is found in the mapped unit AHvh, which has been considered as Amazonian – Hesperian. Here, the largest variation between the western and eastern part of the investigation area is found (west of 330 °–meridian, the crater counts indicate a surface age of 3.2 to 3.14 Ga). Especially in the western part, a deviation from the measured crater size–frequency distribution compared to the crater production function is found in the larger crater–diameter range. This absence of large craters is found in the Acidalia (and Utopia) region and was confirmed by crater counts in units of this area, e. g. in units Hb1, AHvh, Act, which will be discussed in terms of surface and crater formation in the following chapter.

Impact crater or basin Lyot is of comparable age (3.4 Ga), as has been discussed in Chapter 13. The crater counts summed over the entire unit AHvh, representing the northern–lowland unit, yield a surface age of 3.37 Ga. Unit Act, Acidalia Colles (around 20°W and 50°N), is related in morphologic appearance more to the highland remnants, which is reflected in the surface age of 3.65 Ga as well. Earlier, this unit was considered Amazonian, but our age suggests an Early Hesperian age. Compared to the eastern part of the investigation area, only a single boundary unit (Hb2) is present. The ages for this unit range between 3.74 and 3.68 Ga, Late Noachian to Early Hesperian. The summed crater size–frequency distribution of the entire geologic unit gives a surface age of 3.73 Ga and an apparent major resurfacing event occurred before 3.53 Ga ago.

In the Deuteronilus region, assigned here as Aa, one obtains very old ages (see Table 14.2) if measuring all craters on mesas and the lower units together, but if just the lowland parts are considered, the age is as young as the lowland units west of Lyot (about 3.2 Ga).

Summary: The separation between the eastern and western part of the investigated dichotomy boundary area, indicated in morphology, topography and gravity anomalies, has been confirmed by our crater counts. Nevertheless, a convincing interpretation for the origin of these differently evolved boundary parts could not be found.

14.3. Giant Polygonal Trough Units in the Northern Lowlands

Utopia, Elysium, and Acidalia Planitiae (parts of the northern lowlands) are occupied by extensive areas of polygonal patterned terrain, so-called giant polygons. Originally, this polygonal fractured terrain was observed on the Mariner 9 B-frames (Mutch *et al.*, 1976) and revealed, accompanied by other morphologies, that large portions of the Martian surface have been formed by the action of water. Later, high–resolution Viking photographs resolved in greater detail locations and the morphology of the giant polygons. They consist of 200 to 800 meter wide steep–walled and flat–floored troughs, some tens of meters deep, and 5 to 30 km in diameter (Pechmann, 1980). They are distributed around 45°N, 15°W (southeastern Acidalia Planitia); 36°N, 255°W (northwestern Elysium Planitia); 49°N, 233°W (Utopia Planitia). These mid–latitude polygons differ mainly in scale from the permafrost–related polygonal pattern in the polar regions (Rossbacher and Judson, 1981).

Various hypotheses for their origin have been proposed, including thermal cooling and contraction in permafrost (Carr and Schaber, 1977; Carr *et al.*, 1976), desiccation of water–saturated sediments (Morris and Underwood, 1978), cooling of lava (Morris and Underwood, 1978; Masursky and Crabill, 1976; Carr *et al.*, 1976), or tectonic deformation (Mutch *et al.*, 1976; Carr *et al.*, 1976). Pechmann (1980) has shown that none of these terrestrial analogs would lead to a satisfactory description of the mechanisms and scales involved. McGill and Hills (1992) were able to explain the observed large size of the polygons and could account the stresses responsible for the polygon troughs by plate–bending and finite–element models, which indicate the shrinkage of desiccating sediments or cooling volcanics accompanied by differential compaction over buried topography. The giant polygonal pattern is accompanied by ring or double–ring like graben structures, which are assumed to be buried craters and have been used to estimate the thickness of the overburden (McGill, 1986; McGill and Hills, 1992). Another explanation for the origin of undulating surfaces and polygonal crack patterns of this size is based on formation through Rayleigh convection in rapidly emplaced water–rich sediments (Lane and Christensen, 2000). A third force, elastic rebound, which implies the relaxation of the northern Martian lowlands crust after huge water or ice bodies have disappeared, may have accompanied or driven the formation of these large crack patterns (Hiesinger and Head, 2000).

The discussion regarding how giant polygons have formed is linked to the question of did large standing bodies of water and/or catastrophic flood events exist in the past.

14.3.1. Geology

All three sites are located in the northern lowland plains of Mars. This plain assemblage, following the interpretation of Scott and Tanaka (1986) and Greeley and Guest (1987), was deposited in the Late Hesperian. Textural and albedo differences as well as morphologic characteristics have been used to map different members of the so-called Vastitas Borealis Formation. The giant polygon terrain occupies regions mapped as grooved member (Hvg), one of four members that resembles grooves and troughs forming curvilinear and polygonal patterns as much as 20 km wide (Tanaka *et al.*, 1992a, in later attempts modified to a single unit, Vastitas Borealis formation, (Tanaka *et al.*, 2003)). Pechmann (1980) described the geological environment of the three localities in detail and concluded that the polygonal troughs intersect units of all other Vastitas Borealis members, but appear to be similar in morphology at all localities. The age relation of troughs to superimposed craters indicates that the polygon formation occurred immediately after the deposition (McGill, 1986). Lucchitta *et al.* (1986) suggest that the material is of sedimentary origin and was deposited in a standing body of water, emphasizing the areal relation between topographic low regions in the northern plains, polygonal terrain and outflow channels. Carr (1986) describes the capability of the outflow channels to supply immense volumes of wet sediments to the lowland region. Crater counts indicate a coincidence between outflow events and origination of the polygonal terrain (Neukum and Hiller, 1981). The age determination of McGill (1986) indicated, that the channels, which might have fed the lowland region, were cut into a surface that is younger than the polygonal terrain.

Giant–Polygon Terrain Database: The investigation is based on geological mapping of the giant polygon units and measuring their crater size–frequency distribution based on the Viking–MDIM–2 global mosaic and MOLA–topographic information. In the case of the Utopia region, a mosaic made of 28 high-resolution Viking frames (orbit 430Bxx) with a pixel resolution of 15m was prepared. To cover the full range of crater sizes (in this case from 50 km down to 10 m), additional information

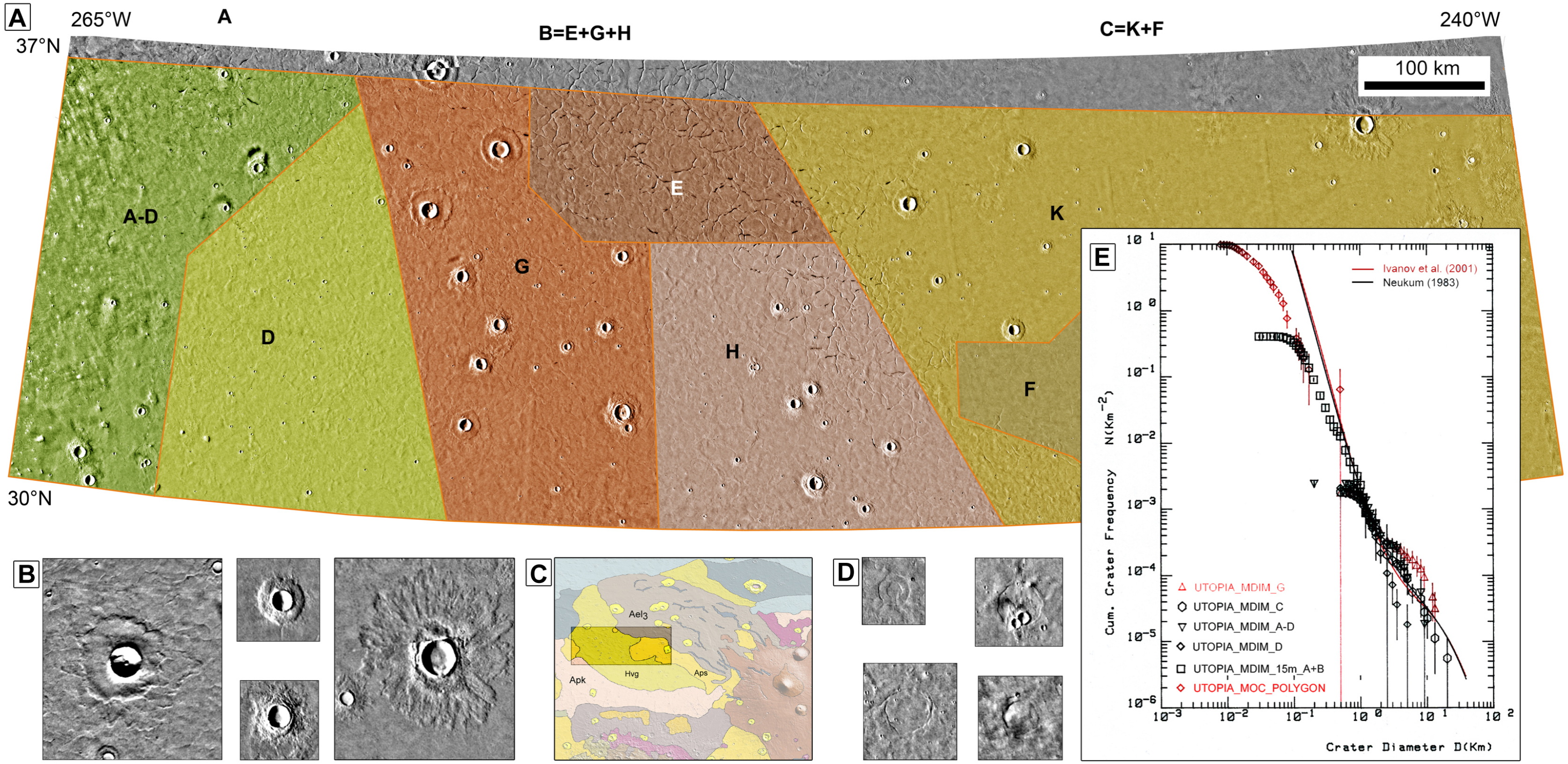

Figure 14.6.: Areas were selected (A) in the central part of the Utopia Planitia (C) according to their diverse crater morphology. Examples are given in (B). Parts of the areas of giant polygons are characterized by ring– or double–ringed graben features, as shown in subset (D). Evaluating the crater size–frequency distributions of these selected areas, a diversity of crater distributions especially in the large–size range is found (E). Few of large craters have been found.

were retrieved from two MOC–NA images M08/03489 (30.90°N, 113.28°E) and E04/02201 (32.66°N, 111.02°E), which superimpose the 15m-VIKING mosaic at a pixel resolution of 3.03m and 6.14m, respectively.

14.3.2. Crater Morphologies

The crater forms on Mars as in Utopia Planitia do largely vary and show a range of complex morphologies. Craters smaller than about 14 km appear bowl–shaped, like simple craters on the Moon or Mercury. A similar size–range for the transition from simple–to–complex interior crater morphology in the Martian lowland plains has been noted by Wood *et al.* (1978). In principle, central peak morphology is expected for craters larger than 5 km (Pike, 1980a), but has been observed for craters as small as 1.5 km in diameter in heavily cratered highland units (Mouginis-Mark, 1979). Craters larger than 15 km are not present in the investigated areas.

The ejecta morphology is slightly dominated by single– or double–lobed ramparts, so–called fluidized ejecta blankets that are believed to indicate the presence of volatiles (see Chapter 7.4, e. g. water ice or water in the subsurface (Carr *et al.*, 1977a)). A number of craters show ballistically emplaced ejecta, spreading outward over distances less than a crater diameter. For both groups, no clear diameter dependence is found. For a few of the larger craters, no ejecta are visible at the given image resolution, meaning they had been formed before the surrounding surface unit was emplaced. They appear "flooded" by later deposits. Examples are shown in Fig. 14.6 B and D.

Among the giant polygonal troughs, circular grabens with diameters between 8 km and 30 km can be found. These are believed to be fracture patterns of counterdrawing buried craters (Carr, 1981; McGill, 1986), yielding a regional cover thickness of about 600 m (McGill and Hills, 1992). These single– and double–ringed grabens are associated with slight topographic depressions seen in the MOLA topography (Buczkowski and McGill, 2002). Based on modeled graben spacing of double-ringed troughs, Buczkowski and Cooke (2004) suggested a cover thickness of 1–2 km. Additionally, the topographic data from MOLA revealed the presence of roughly circular basins in both the Martian highlands and lowlands, which are usually not associated with any structural feature in image data. These so–called Quasi-Circular Depressions are candidates for large, buried or deeply eroded impact structures (e.g. Frey *et al.*, 2002).

Crater Size–Frequency Distributions in the Utopia Region: Based on the Viking–MDIM–2 imagery, we performed new crater size–frequency measurements and determined ages in selected areas of the Utopia region, which cover polygonal terrain and surrounding units (Fig. 14.6 A and E). All crater size–frequency distributions of the selected units converge in the smaller crater diameter size range and give an age of 3.4 Ga. This plains age is observed in many measurements in other lowland regions and is also confirmed by the measurements of the crater size–frequency distribution in the 15m–Viking mosaic. A later resurfacing event is observed in that distribution, which is also supported by the crater counts on the MOC-NA image.

For the larger–crater diameter–size range (larger than 3 km), a variety of shapes for the crater distribution is observed in different units of Utopia, confirming earlier observations by McGill (1986). These all correlate with the presence of giant polygons and other surface structures, indicating resurfacing processes have been acting in a different manner. The diversity or deviation from the expected crater production function (Neukum *et al.*, 2001; Ivanov, 2001) for the larger–crater diameter–size range (larger than 3 km) most likely relies on different target properties or the geologic evolution of the area. A few of these units show an "excess" of larger craters in the crater size–frequency distribution (Fig. 14.6 A and E, Unit G). These units yield an age of 3.8 Ga. The measured small–size converging distri-

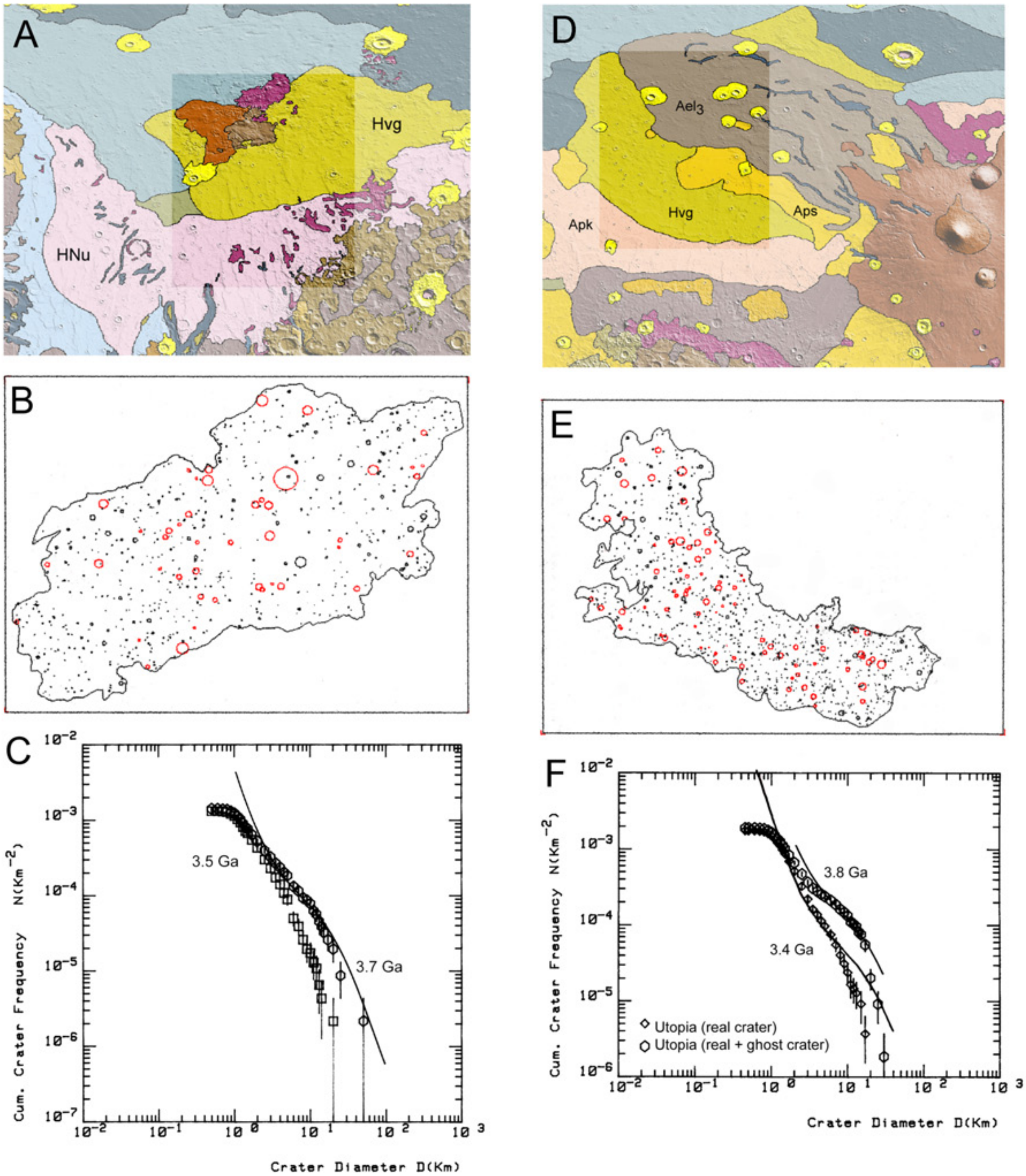

Figure 14.7.: (A,D) The geologic unit Hvg (following Scott and Tanaka (1986) and Greeley and Guest (1987)) in the Acidalia Planitia (left) and in the Utopia Planitia (right) are shown. The detailed outline and the visible (real) craters are indicated in black, the so–called ghost craters in red (subset (B,E), left Acidalia, right Utopia region). In subset (C,F) the resulting crater size–frequency distributions for the visible (real) crater distribution (quadrangular) are given, a clear lack of large craters is observed. Indicated by circles, the summed distribution of visible (real) craters and the most–likely buried crater population (ghost craters) are shown.

butions lead to an age of 3.4 Ga and indicate a resurfacing event that is detectable in all units.

Crater Size–Frequency Distribution in the Polygonal Terrain Measuring the region of polygonal terrain in the Utopia and Acidalia Planitiae, we obtained crater size–frequency distributions that appear to have an unusual deficiency of large craters, as compared to the proposed production function. For the polygonal terrain in Utopia and Acidalia Planitiae, we first measured the crater distribution of clearly visible craters and obtained an age of 3.4 Ga. A lack of large craters is especially observed in the polygonal terrain. Additionally, the distribution of the ringed–graben structures was measured assuming that they are the "counterdrawn" crater population of the underlying surface or basement. The distribution of visible craters was stacked with the population of so-called ghost craters for both regions in Utopia and Acidalia Planitiae. The sum of the visible and ghost crater population yields an age of 3.8 Ga, an age observed in regions where a lack of craters in the larger diameter range is not observed (Figures 14.7). This implys that at the centers of the Utopia basin and Acidalia Planitia large amounts of deposits were emplaced, while in their surrounding most likely the basement of the lowlands is exposed.

Existence of an Ancient Martian Ocean? Irrespective of the cause of the diversity or obscuration of the measured crater size–frequency distribution in the larger–size range compared to the expected crater production function, it occurred between 3.4 and 3.8 Ga in areas where poligonal terrain is observed. These distributions can be explained by extensive resurfacing effects within a period of roughly half a billion years, covering the earlier crater population by a 1–km or even 2–km thick layer. In other regions in Utopia, ring–graben structures and lack of large craters are not observed. These units appear to be at the outer edge of the Utopia basin. This conforms with the existence of a proposed ocean in the northern lowlands and fits the interpretation that the polygons emerged through desiccation and differential compaction of sediment over buried topography. It also implies slow emplacement (period of sedimentation over roughly 400 Ma) of sediments, so that the formation of the giant polygonal pattern is unlikely to be due to Rayleigh convection during the deposit emplacement as suggested by Lane and Christensen (2000). The elastic rebound of the crust as a driving force is possible, but supports the formation of the pattern after the disappearance of a possible ocean. Nevertheless, for elastic rebound to be effective in fracturing the surface, a relatively sudden removal of the surface load is required. Considering the analysis of the northern lowland plains units, a relation between younger ages and topographic lows has been observed. These ages were found to cover an age range between 3.6 and 2.8 Ga, which would imply a very slow water regression. Nevertheless, most younger surfaces appear to have formed through volcanic deposition. An effect directly related to elastic rebound might be unobserved in localized areas such as where the giant polygons are distributed.

14.4. The Medusae Fossae Formation

Along the equator between the Tharsis and Elysium volcanic centers in the Elysium–Amazonis Planitiae region, the highland–lowland boundary is superimposed by massive deposits. These deposits define an extensive unit of somewhat enigmatic origin, named the Medusae Fossae Formation (Scott and Tanaka, 1986). In general, the formation appears as a smooth and gently undulating surface, but is partly wind–sculpted into ridges and grooves. MOLA–based topographic data indicate a thickness of the deposit of up to 3 km. It is commonly agreed that the materials forming Medusae Fossae were deposited by pyroclastic flows or similar volcanic air–fall materials (Greeley and Guest, 1987) and could be a remnant of ancient polar layered deposits of a polar cap which has been once close to the equator (Schultz and Lutz, 1988). Westward of Arsia Mons close to the equator, we find the highland–lowland boundary. An area between 140 °W and 150 °W was imaged by the HRSC during orbit 895 (Fig. 14.8 A) and orbit 917 (Fig. 14.8 B). Both orbits almost completely overlap. The plateau area of the volcanic massif is partly covered by lava flows and partly dissected by valleys, which were most likely carved by fluvial activity (Fig. 14.8 A and B). The remains of water-bearing inner channels are visible in the center of the valleys and at the bottom of the massif (Fig. 14.8 C and D). Superposition of the lobate-fronted pyroclastic flows indicates that the water erosion ended before deposition. A subsequently formed impact crater near the massif shows ejecta blankets that were spread as a flow over parts of the plateau, implying water or ice in the subsurface at the time of impact (see Chapter 7.4).

At the highland-lowland boundary between the old volcanic plateau region and Amazonis Sulci, part of the widespread deposits of the Medusae Fossae Formation (MFF) are shown. At this part of the highland–lowland boundary, the volcanic plateau fed by the southernmost Tharsis Montes volcano Arsia Mons is dissected by several valleys that were most likely carved by running water. Senus Vallis, for example, is shown in detail where the latest–stage inner channel is still visible (Fig. 14.8 C). Abus Vallis resembles a channel of similar type. At its mouth, the steepness of the walls or the narrowness of the valley prevent observation of the channel floor, due to the insolation and shading situation when the image was taken. Nevertheless, the remains of the last stage of water activity can be traced as a small channel at the floor of the lowland plain (Fig. 14.8 D). Additionally, the emplacement of pyroclastic flows is visible in this detail. The action of water erosion ended before the emplacement of the pyroclastic flow. These small channels accompany a larger valley system called Mangala Valles, discussed in Chapter 14.5. Impact craters with pronounced ejecta blankets are the youngest features of the stratigraphic sequence that can be observed in these images. They have well preserved ejecta blankets showing a lobate appearance, which is believed to indicate the presence of water or water ice in the impacted target. As a crater forms on a flat surface, it expands in a circular fashion. Due to the topography of the impact site, the shape of the crater during expansion was disturbed by the walls of the plateau and resulted in a somewhat asymmetric (oval) shape. The distribution of ejecta resembling the wings of a butterfly, is due to a non-vertical impact (less than 45 degrees, e.g. Melosh (1989)).

We performed crater size–frequency distribution measurements for the lava–covered plateau section and parts of the pyroclastic–flow units that formed Medusae Fossae. The resulting ages indicate about 3.1 Ga for the last lava coverage of the plateau and 1.6 Ga for parts of the Medusae Fossae Formation. The latter is also found as a surface age for Medusae Fossae Formation units found in the Gusev vicinity. A single global formation around 1.6 Ga ago of the enigmatic Medusae Fossae Formation is most likely. Both ages provide a time frame for the fluvial activity in that region, using stratigraphic information on superposition and intersection, as discussed above.

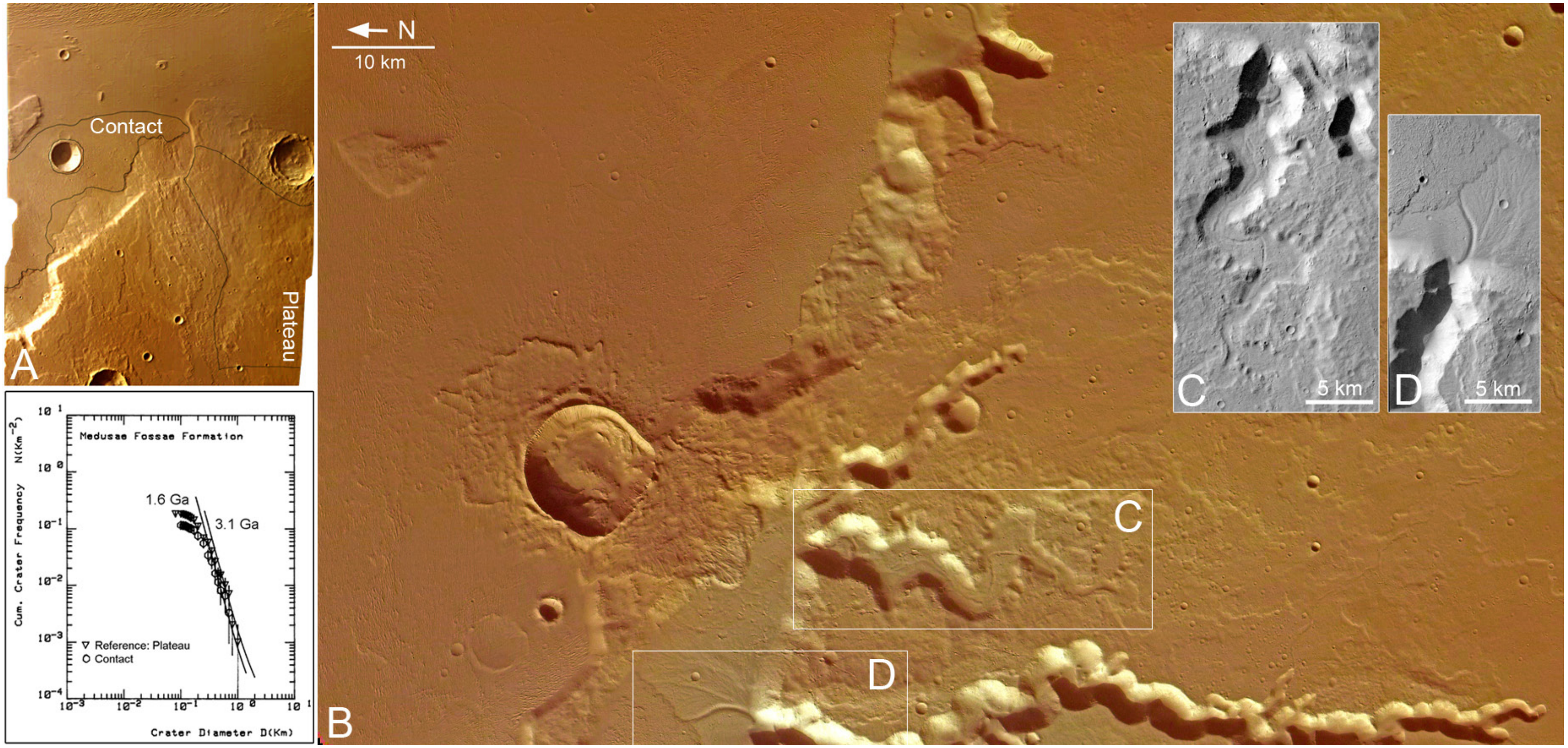

Figure 14.8.: Parts of the Medusae Fossae Formation (MFF) at the dichotomy boundary (between 140 °W and 150 °W close to the equator) west of Arsia Mons: Subset A imaged in orbit 895 shows the volcanic plateau, the dichotomy boundary and possibly volcanic ash flow belonging to the Medusae Fossae Formation. Areas where crater counts have been performed are indicated and their resulting surface age is shown in the diagram below. Image subset B is the continuation westward of subset A. Details C and D show two small channels dissecting the plateau region. So–called inner channels are also present.

14.5. Outflow Channels: Mangala, Kasei, and Ares Valles

One type of channel–system unit is associated with the outflow–channel development occurring from Valles Marineris to Chryse Planitia, while a few occur along the western and southern margin of Amazonis Planitia. It is proposed that the active period of the channels was during the Hesperian and Amazonian (Tanaka *et al.*, 1992b), postdating the development of valley networks. (Baker, 1982) argues that outflow channels are large–scale complexes of fluid–eroded troughs. They appear to have emanated from discrete collapse zones known as chaotic terrain, which sometimes occupy the floor of chasmata. The chaotic terrain generally consists of kilometer–sized knobs and irregular mesas, which gives the impression of tilted blocks of former plateau rocks. Indicators such as channel relics, floodplains along the channel courses, depositional streamlined bars, and erosional islands led to the interpretation that channel system forming floods originated from aquifer outbreaks (Carr, 1979). Many morphologic features hint at diverse erosive forces such as winds, debris or mud flows, glaciers, lavas, however, catastrophic flooding became commonly accepted (for a detailed discussion see e.g. Baker *et al.*, 1992). Some channel systems show no obvious source regions, but possibly emanate at fracture and fissure zones (see discussion in Chap. 12). Most source–region situations are believed to be causatively related to volcanic processes, not only due to the close spacial occurrence especially in the Tharsis vicinity. Observed landforms such as scour marks or chaotic zones can also be considered to be caused by glacial or periglacial processes as well as (sub–)surface mobilization of volatiles.

Here, we studied the predicted causative relationships by age determination, based on HRSC and MOC imagery and digital terrain models. Therefore, three outflow channels (Ares, Kasei, and Mangala Valles) and their individual source regions have been studied in more detail:

Ares Vallis, a typical outflow channel example, is the easternmost channel, originating in the Iani Chaos region. These chaotic terrains are thought to be the characteristic source morphology for outflow channels. **Kasei Valles**, one of the largest valley systems on Mars, shows a more exceptional source region. This system originates in a large chasma–structure, Echus Chasma, where no clear evidence for chaotic terrain can be found. Nevertheless, chaotic terrain is apparent further downstream. Robinson and Tanaka (1990) proposed that the channel formed by catastrophic drainage of a lake in Echus Chasma. HRSC imagery revealed a blanketing by a volcanic layer and possible indications for a previous standing body of water (see Fig. 14.10).

Lastly, the **Mangala Valles** outflow system located southwest of the Tharsis bulge is discussed below. The source region is not characterized by chaotic terrain, but is found further downstream and has been previously related to Memnonia Fossae tectonic features interpreted as en–echelon fissures (compare Chapter 12). This is the only outflow channel extending into the highlands; no continuation is found in Amazonis Planitia, part of the lowland region. Despite the relatively high–resolution of the Viking imagery (Mangala medium-resolution observation, 40 m/pxl), the source region of Mangala is poorly resolved. Nevertheless, Carr (1979) discussed the sudden onset character of water release due to groundwater, which had been released by penetrating a possible permafrost seal. Artesian pressure below the sealed surface amplified the groundwater release after the surface was disrupted by either tectonic activity or melting of the ice seal by dyke emplacement, a volcanic process visible on Earth. HRSC imagery (orbit 286) revealed details of the source region and confirms the onsetless release of water; no surface run–off is observed (Fig. 14.9).

The Mangala Valles outflow channel system is considered, due to a comparable source configuration, to be an analogue to the Athabasca Vallis outflow channel, which has been success-

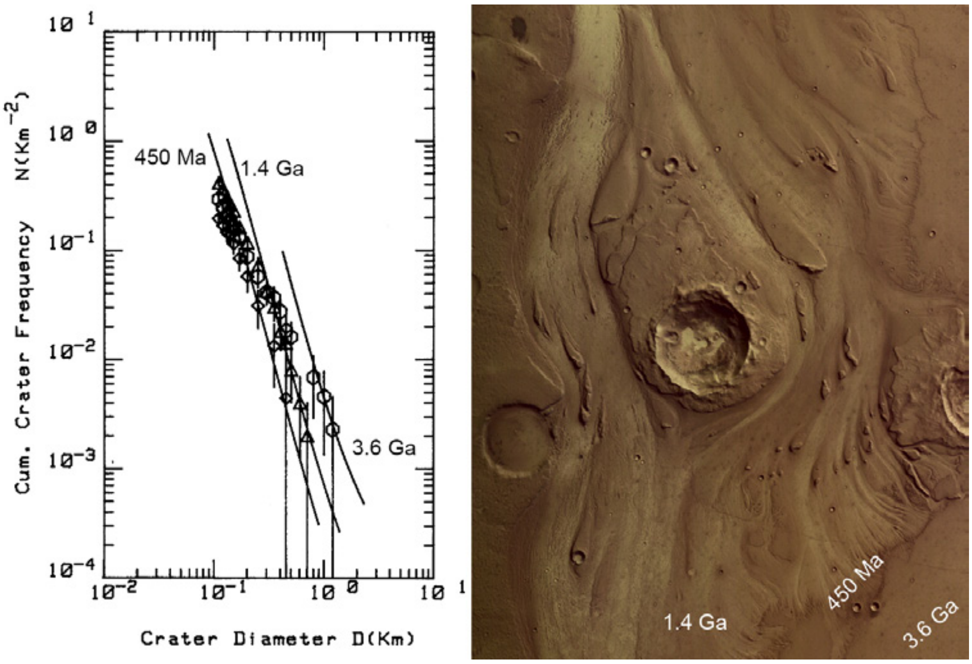

Figure 14.9.: A mid–stream part of Mangala Valles: The HRSC imagery (orbit 286) shows source–region details confirming the onsetless release of water and no surface run–off in the old volcanic plateau region. Crater size–frequency distributions in the channel and secondary source region (lower right corner) indicate episodic erosive activity.

fully investigated in terms of the chronostratigraphy of events and its morphologic inventory (Chap. 12, Werner *et al.*, 2003a). The volcanic plateau, fed by Arsia Mons, generally has an age of about 3.6 Ga. This is similar to Athabasca, where the surrounding plateau fed by Elysium Mons or Albor Tholus formed before 3.6 Ga ago. Crater size–frequency measurements in the source regions of the Mangala Valles system provided ages with major resurfacing periods between about 1.4 Ga for the floor units and as young as about 450 Ma for the secondary source region (Fig. 14.9). Besides the morphologic implications on channel formation, which could be triggered by volcanic activity (e. g. dyke emplacement), age determinations additionally support the correlation between volcanic and fluvial action (see Chap. 16). Temporally, the Athabasca Vallis system itself appears younger in its fluvial and volcanic origin (Chap.12, Werner *et al.*, 2003a), than the Mangala Valles system.

For **Kasei Valles**, we studied the source region Echus Chasma (Fig. 14.10) in terms of morphologic and chronostratigraphic relationships and the main channel region of the Kasei Valles outflow system. The western part of Echus Chasma and its surrounding plains were covered by the HRSC orbit 97, (Fig.14.10). The source region is characterized by a basin-like catchment, in which water from the surrounding plateaus was captured. The plateau is dissected by numerous erosive rilles, which resemble possible valley networks (channels carved by precipitation and surface run–off). Large sapping valleys support the idea of active fluvial processes in that region. From the morphologic observations in HRSC and MOC image data, it seems likely that the Chasma was once filled by a standing body of water, as suggested by Robinson and Tanaka (1990). While Mangold *et al.* (2004) interpreted the regional crater size–frequency distribution to show a Hesperian age, based on a larger portion of

Figure 14.10.: Echus Chasma, the source region of Kasei Valles: The HRSC imagery (orbit 97) show dissected plateaus, sapping valleys, and other morphologic indications for fluvial activity.

the surrounding plateau, we found a resurfacing of the surrounding plateau at about 1.5 Ga, possibly related to fluvial activity. A later resurfacing event, recognizable in crater size–frequency distributions measured on the surrounding plains and on the Chasma floor, is as young as about 90 Ma. The surrounding plateaus could be composed of volcanic ash and lava, as indicated by spectrophotometric investigations of the dark material appearance (T. McCord, 2004, pers. comm.). The distribution of this dark material implies a transport mechanism (either fluvial or aeolian) that moved material downward to the floor or upward to the plateau. Both directions are likely, but a few features at the Chasma walls appear to be related to a downward movement, possibly assisted by fluvial processes. Although the Kasei Valles outflow system and the mechanisms of formation have been studied for decades (summarized by Baker *et al.*, 1992), the formation of this outflow channel system is still debated.

Central parts of the Kasei Valles area (e.g., Sacra Sulci, see Appendix A.1) have shown mesoscale morphologies that strongly support theories of formation by glacial flow or glacial interaction with the ground surface. The morphologic interpretation is reinforced by crater size–frequency measurements in selected areas, which show lava plains in the central Kasei Valles area that are as young as about 1.3 Ga and traces of possible glacial resurfacing with similar ages (between about 1.8 and 1.3 Ga). This suggests a long-lasting period of glacial activity and the co–occurrence of glacial and volcanic processes (see Appendix for details). This work supports theories by e. g. Lucchitta (1982, 2001); Woodworth-Lynas and Guigné (2003) for a glacial origin.

Wagner *et al.* (2004) studied the **Hydraotes Chaos** area, the source region of Simud Vallis and the central circum-Chryse outflow channels. Measurements of the erosion–level, indicated by block and mesa heights, show a correlation between height and ages. Dominated by the episodic activity of significant amounts of flowing water (e.g. Ori and Mosangini, 1998), most of the former mesas and highland units had by then been eroded more or less down to the valley floor level. This process started about 3.7 Ga ago and ended between 400 Ma and 200 Ma ago. On the basis of image data of various instruments with the help of very high–resolution digital terrain models derived from HRSC data, it appears that water may have caused collapse of the surface by the removal of subsurface material, as indicated by variations of surface elevations and tilt angles of individual remnant blocks.

In a joint effort (together with Neukum, Zuschneid, and van Gasselt at Freie Universität Berlin), the **Iani Chaos** region, feeding Ares Vallis, was investigated in a similar manner. It is a chaotic terrain east of Hydraotes Chaos. Crater size–frequency measurements revealed episodic activity at the northern terminus of the Iani Chaos, starting as early as 3.5 Ga ago and ending 50 Ma ago. The upstream areas of the Ares Vallis outflow channel show ages in the range of 650 Ma to 40 Ma. The youngest are most likely aeolian surface modifications. Such an interpretation for Ares and Tiu Valles was outlined already by Marchenko *et al.* (1998).

The higher resolution HRSC imagery allowed us to understand processes resurfacing the circum–Chryse outflow channels subsequent to their formation. They were formed already early in the Martian history, before 3.5 Ga, as discussed in Chapter 14. Possibly, Mangala and Athabasca Valles are exceptional, not only due to their differently appearing source regions, but also in their continual activity.

14.6. Implications of the Evolutionary History of the Highland–Lowland Boundary, and the Northern Lowlands

The evolutionary history of the northern lowlands and the bordering highland–lowland dichotomy will be summarized here.

Following Tanaka *et al.* (2003) and their revision (Tanaka *et al.*, 2005), four zones were studied: the Chryse region, the Utopia basin, plains between the Elysium and the Tharsis volcanic provinces, and a profile between Alba Patera and the north pole. In all regions, the bordering highland units (Noachis and Nephentes units) are the oldest. Additionally, a detailed study of the dichotomy boundary between the Chryse and Isidis Planitiae was undertaken. While the Noachis unit formed during a period between 4.05 and 3.8 Ga ago, the slightly younger Nephentes unit is 3.8 to 3.5 Ga old. Most likely, the Nephentes unit, which belongs to the highland plateau, underwent resurfacing, such as inter–crater plains formation (volcanic), or erosion by surface run–off water (valley networks), and originally formed as early as the Noachis units. All ages discussed in this thesis, gathered for the lowlands and partly modified boundary units, are plotted in Fig. 14.11. Horizontal lines indicate the epoch boundaries as described in Chap. 5. In general, the formation of the most relevant surfaces in the lowlands ended between 3.75 Ga and 3.5 Ga ago. Exceptions are found in Amazonis Planitia, some channel systems (Mangala and Kasei Valles), and other areas that formed through volcanic deposition (< 3.5 Ga).

Following the description in Chap. 14.1, the dominant ages found for surfaces in the Chryse region and Utopia Planitia range between 3.6 Ga and 3.5 Ga, as for the majority of the northern lowland units. Detailed studies of the giant polygonal terrain observed in the Utopia and Acidalia Planitiae indicate that the distribution of visible craters and the ring–graben structures (ghost craters) yield the same basement ages as it is exposed closer to the highland–lowland dichotomy boundary where no thick deposit layer is expected. Most of the lowland units are covered by deposits about 1–2 km or even more thick. Results found in relation to the polygonal terrain conforms with the existence of a proposed ocean (possibly mud ocean etc.) shortly after the crustal formation of the northern lowlands (details in Chapter 14.3). In general, the northern lowland units (in all zones) show gradual changes to younger ages continuing down–slope towards topographic lows. These ages cover an age range between 3.6 and 2.8 Ga. That could imply a gradual water regression. Regardless, most of the younger units in the northern lowlands are considered volcanic in origin, arguing against the ocean theory during the Amazonian Epoch (younger than 3.1 Ga). More arguments for the timing of the possible existence of an ancient Martian ocean is found by investigating the outflow channel activity and related ancient, fluvial processes. The Chryse inner slope ages are found to range between 3.8 and 3.3 Ga and tend to become gradually younger towards topographic lows. The units belonging to outflow channels formed before 3.55 Ga ago. The units in continuation of flood plains appear to be slightly younger, while the Vastitas Borealis Formation is of about the same age. The Utopia basin and its vicinity indicate similar ages. The Utopia floor ages range between 3.5 and 3.6 Ga, with older slope units (about 3.75 Ga) and in a broader unit between 3.8 Ga and 3.4 Ga, as discussed above. Major deposition in the northern lowlands were not driven by emplacement of sediments during the outflow channel formation which ended between 3.5 and 3.6 Ga ago. In such case the difference between basement and visible surface must be smaller (cp. Utopia giant polygonal terrain).

Volcanic flows and phreato–magmatic activity (Elysium flank flow units) occurred about 3.5 Ga ago, followed by later phases between 3.4 and 3.1 Ga ago. The Syrtis Major flank measurements indicate a similar age of 3.55 Ga, while the surface of Isidis Planitia is slightly younger (3.45 Ga).

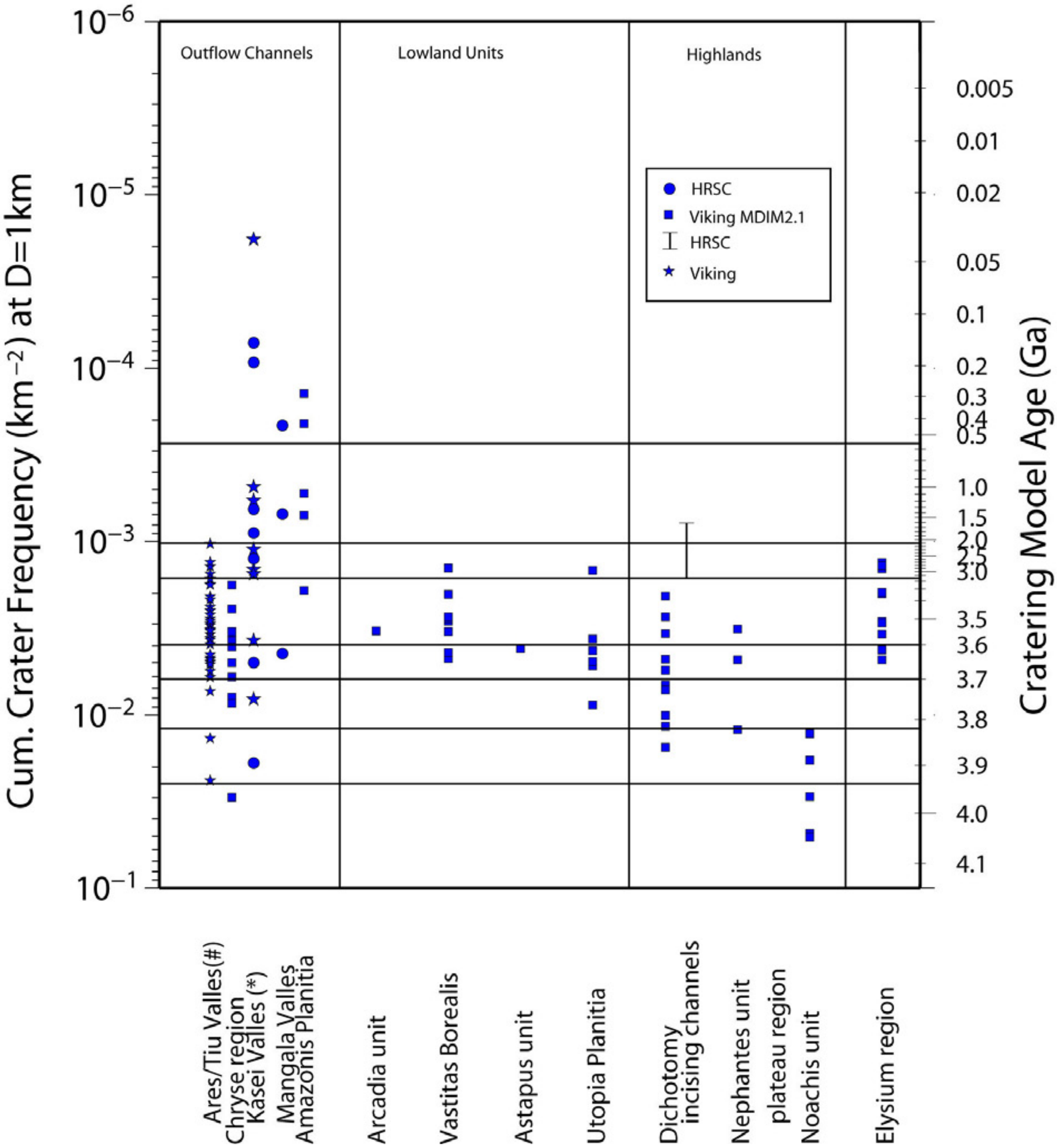

Figure 14.11.: Summary of crater frequencies N_{cum} (1 km) (left scale) and model ages derived applying the cratering chronology model by Hartmann and Neukum (2001) (right scale) for outflow channels, lowland units, and highland areas. These measurements have been performed mainly on Viking MDIM2.1 mosaics (blue squares) and for detailed studies of outflow channels on HRSC imagery (blue circles). This dataset is accomplished by detailed studies in Ares and Tiu Valles (blue stars, # Marchenko *et al.*, 1998), measured on Viking imagery, and Kasei Valles (blue stars, ⋆ Lanz, 2003) measured on Viking and MOC imagery. Horizontal lines show the epoch boundaries, see Chapter 5, Fig. 5.1.

The plains surrounding Elysium are partly type units for the youngest epochs of the Martian history. The Elysium flanks and surrounding plains (Arcadia) are about 3.5 to 3.6 Ga old, while the youngest plains unit, Amazonis Planitia, cannot be treated as homogeneous in age and morphology. The ages range between 3.3 Ga and 400 Ma, even if mapped as a single unit. Their origin is of volcanic nature. Measurements between the North Pole and Alba Patera are generally consistent with age of the entire northern lowlands (Vastitas Borealis Formation). Alba Patera volcanic eruptions might have covered the dichotomy boundary in two episodes (3.37 and 3.52 Ga) indicate that major parts of Alba Patera formed early in the Martian history (cp. Chap. 15).

The bordering highlands are about 4.0 Ga old. The steep escarpment characterizing the highland–lowland dichotomy boundary into segments might have once been present around the globe. Examining the dichotomy between 330° E and 90° E (between Chryse and Isidis Planitiae) a morphologic difference of the regions eastward and westward of the impact basin Lyot is found. This separation is seen in morphology, topography and gravity anomalies (cp. Zuber *et al.* (2000)) and has been confirmed by these crater counts. Nevertheless, a convincing interpretation for the origin of this differently evolved boundary parts can not be given. The typical morphology of the dichotomy boundary has been partly covered/erased by volcanic, fluvial, or cratering processes, which is reflected in ages measured in this work (see Part IV for final discussion). The fluvial activity, e.g. in the Chryse region, was less effective in resurfacing as the volcanic processes, e.g. Tharsis region.

The highland units formed before 4 Ga ago and supposedly the lowland basement formed at about the same time. Generally, surface ages of about 3.6 to 3.5 Ga are observed, which correlates with the major activity period of the outflow channels, dominating the landforms in the Chryse region. Other resurfacing related to water (valley networks) in the highland units acted before 3.7 Ga ago.

The dichotomy boundary formed before major volcanic activity (Olympus Mons aureole formation at about 3.8 Ga ago). Three volcanic provinces superpose either the lowlands (Elysium), possibly the dichotomy itself (Tharsis) or are situated at its closest vicinity (Syrtis Major), and interact with the lowlands (Apollinaris Patera). Volcanic activity and deposition of flood lavas in the lowlands continued after 3.5 Ga ago. Exceptionally strong resurfacing due to volcanic activity occurred in Amazonis Planitia, with ages ranging between 3.0 Ga and less than 400 Ma.

As discussed above, the lowland deposit formation ended between 3.8 Ga and 3.4 Ga ago, but is as young as 2 Ga locally. Additional information for the time frame for the existence of a Martian ocean is indicated in the flank base morphology of the volcanoes located along the highland–lowland boundary. Here, the action of valley networks, possibly formed by precipitation, is visible in the highland areas or at the flanks of older volcanoes (e.g. most likely Hadriaca, Tyrrhena, Apollinaris and possibly Alba Paterae).

Alba Patera and the Elysium rise show smooth slopes, characterized by superposing lava flows or similar volcanic morphologies. On the other hand, the flank base of e.g. Olympus Mons, lowland–sides, are characterized by a prominent so–called aureole. The Apollinaris Patera flank base show similar morphologies, forming a steep escarpment at the flanks towards the lowlands. While the "undisturbed" flank formation of Alba Patera and the Elysium rise occurred before 3.55 Ga ago, the Olympus Mons aureole formed at about 3.8 Ga ago and the lowland-side flanks of Apollonaris Patera at about 3.75 Ga ago, while the last episode manifested in a southward erupted lava fan at about 3.71 Ga ago (details in Chapter 15). Additionally, all ages measured in the closest vicinity of the steep dichotomy escarpment are around 3.7 Ga.

These ages fit the temporal constraint for the possible existence of any kind of Martian ocean that disappeared before 3.75 Ga or more exactly 3.71 Ga ago (Apollinaris flank age). This would imply that the large outflow channels (they have formed until 3.5 Ga ago) did not feed a large ancient ocean at later times anymore, but a general water cycle, including precipitation and surface run–off (valley networks), could still have existed then (further discussion in Part IV).

Any resurfacing ages related to outflow channels younger than about 3.5 Ga could not significantly contribute to most deposits found in the lowlands. Studies of Kasei Valles (Lanz, 2003) and the joint mouth of Tiu and Ares Valles (Marchenko *et al.*, 1998) resulted in similar findings. Major parts of the channels were excavated before 3.5 Ga ago, while any subsequent resurfacing (fluvial and or volcanic) only marginally shaped the inner landforms and surfaces of the channels. Subsequently, volcanic processes dominate the deposition in the northern lowlands, e.g. in Amazonis Planitia, as flows in Utopia Planitia (source Elysium) and, for example, the filling of Gusev crater.

At the dichotomy escarpment, in the Hellas depression, and in the vicinity of Olympus Mons (but also at many other large Tharsis volcanoes), the most recent resurfacing is related to morphologies associated with possible glacial or ice–related landforms or volcanic activity, as discussed in the next chapters.