Chapter 11
The Terrestrial Planets

Angelo Pio Rossi, Stephan van Gasselt, and Harald Hiesinger

11.1 Introduction

11.1.1 Comparing Terrestrial Planets

Comparative Planetology deals with the study of similarities and differences across various Solar System bodies and on the processes acting through time over them. Some of these processes, such as asteroid and comet bombardment (Chap. 7) or space weathering (Chap. 9) act on several or all of them, some only on individual (Chaps. 8 and 9) planets, moons (Chap. 12) or small bodies (Chap. 13).

For the structure of this chapter we chose to discuss the terrestrial planets and their satellites in terms of their geological evolution with time. We start with ancient times and end with modern times. Orthogonal to this time line, we describe the processes and their effects acting on each planetary body. This approach was chosen to facilitate the comparison among the studied objects by discussing the geological evolution of a planet in the context of the others. Our home planet, Earth, will serve as a reference framework and important anchor point for our comparative planetology studies because it is the best studied object for which we

A.P. Rossi (✉)
Jacobs University Bremen, Campus Ring 1, 29795 Bremen, Germany
e-mail: an.rossi@jacobs-university.de

S. van Gasselt
National Chengchi University, No. 64, Sec 2, ZhiNan Rd., Wenshan District, Taipei 11605, Taiwan
e-mail: svg@nccu.edu.tw

H. Hiesinger
Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany
e-mail: hiesinger@uni-muenster.de

A.P. Rossi, S. van Gasselt (eds.), *Planetary Geology*, Springer Praxis Books,
DOI 10.1007/978-3-319-65179-8_11

have knowledge gained from hundreds of years of sample analyses, mapping efforts, drilling, mining, and remote sensing, to name only a few sources of information.

Comparing the entire suite of terrestrial planets requires to individually characterize each of them and the processes acting on them through time. However, there are several limitations involved in such a reconstruction, partially due to the discontinuous and fragmentary nature of the accessible geologic records and the lack of enough well-contextualised field data. In this context, increasingly high-resolution remote-sensing coverage is important, in order to better map the nature and the stratigraphic relationship between surface units (Chaps. 2 and 5). Such information has to be augmented by in situ observations, sample return, and ideally by human exploration.

The degree to which we know the geology of individual terrestrial planets is variable: it largely depends on the amount, quality, and resolution of available remote sensing data, as well as on a possibly available ground truth. Moreover, the reconstruction of the geological history of any planet relies on time-consuming geological mapping (Chap. 4), whose pace is different for different planets. Even for some of Earth's most covered and best mapped countries, some of the base geologic maps are decades old, and refresh times are counted in several years to decades. For planets, systematic geologic mapping is affected by time lags of the same order of magnitude. On certain planets, such as Venus, even the stratigraphy is relying in some cases on workarounds involving the relative sequence of deformational events rather than the sequence emplacement of geological units.

The Moon's and Mars' geological histories have been studied for several decades and with continuously improving data coverage (Chap. 4), crossing Petabytescale. Mercury has only recently been studied with modern remote sensing data, and detailed regional and global mapping is taking place in these years. In fact, its very first global geologic map based on data from the last decade has been recently produced. Venus is globally mapped in its basic units, but its complexity, especially for older, more heavily deformed terrains requires newer higher resolution observations (Fig. 11.1).

Terrestrial planets, also known as inner or rocky planets share several characteristics: they are mainly composed of silicates, they are located relatively close to the Sun, they show evidence for past or present vigorous volcanism and tectonicsm (Chap. 8), and at least half of them hosts or hosted a stable hydrosphere at some point during their evolution (Chap. 9). These, among other conditions (Chaps. 10 and 14), contributed to their present or potential habitability. Earth's Moon is included in this chapter because it is part of the Earth–Moon system, being genetically and partially geologically linked to the Earth from very early times. The relative sizes of terrestrial planets determine to a certain extent their respective fate, with the smaller bodies, and, in the case of Mercury, also with the smaller relative mantle thickness, ended their geological activity earlier, while larger ones continued until very recently or are still active.

The current distribution of topography (hypsometry) of the terrestrial planets reflects their integrated geological history (Fig. 11.2). Although largely driven by endogenic processes (Chap. 8), surface processes and surface-atmospheric processes interaction had a strong role in shaping them at geological timescales

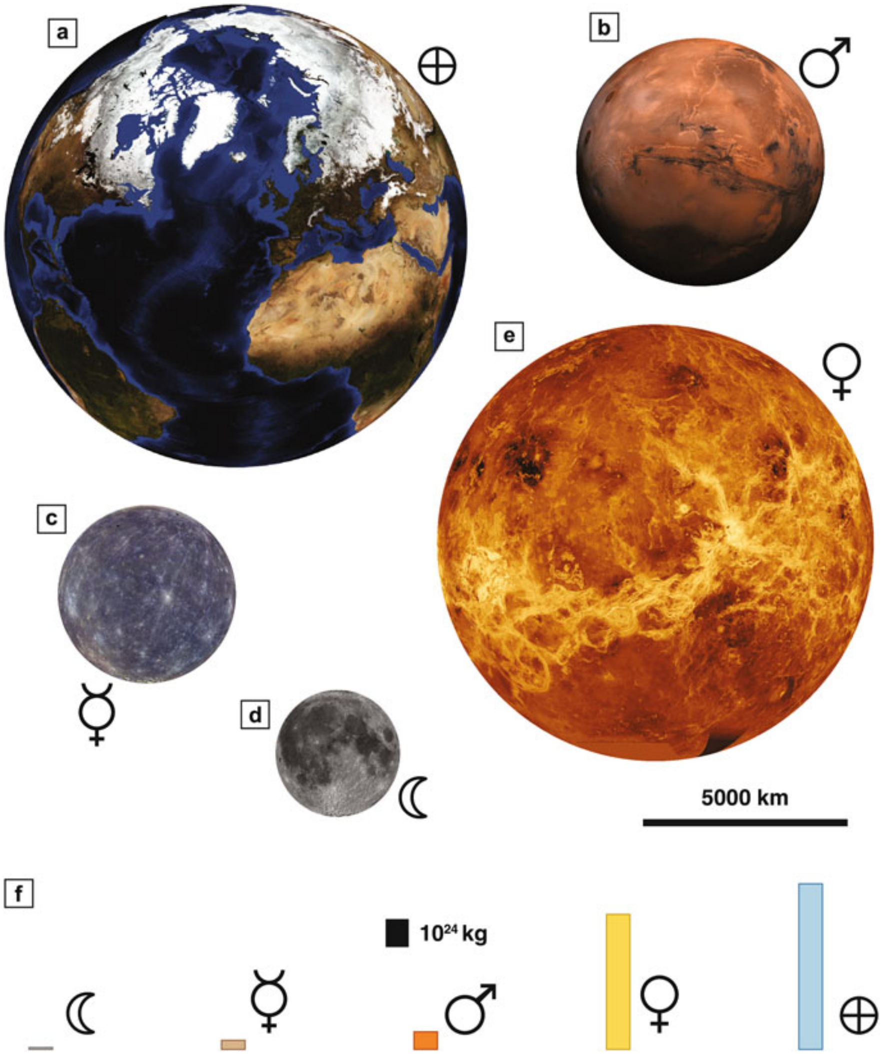

Fig. 11.1 Terrestrial planets compared, on images or renderings with negligible atmospheric masking of the surface; (**a**) Earth Blue Marble, obtained from MODIS data and bathymetry data of Earth; (**b**) Mars as seen by Viking, centered on the 5000 km long Valles Marineris canyon system; (**c**) Mercury in enhanced MESSENGER color; (**d**) The lunar nearside showing the two main different terrains, highlands and maria; (**e**) Venus, artificially colored Magellan radar backscatter image of an hemisphere. Sources: (**a**) NASA. (**b**) NASA Viking Orbiter, USGS. (**c**) NASA Messenger. (**d**) NASA/LRO/LROC. (**e**) NASA Magellan

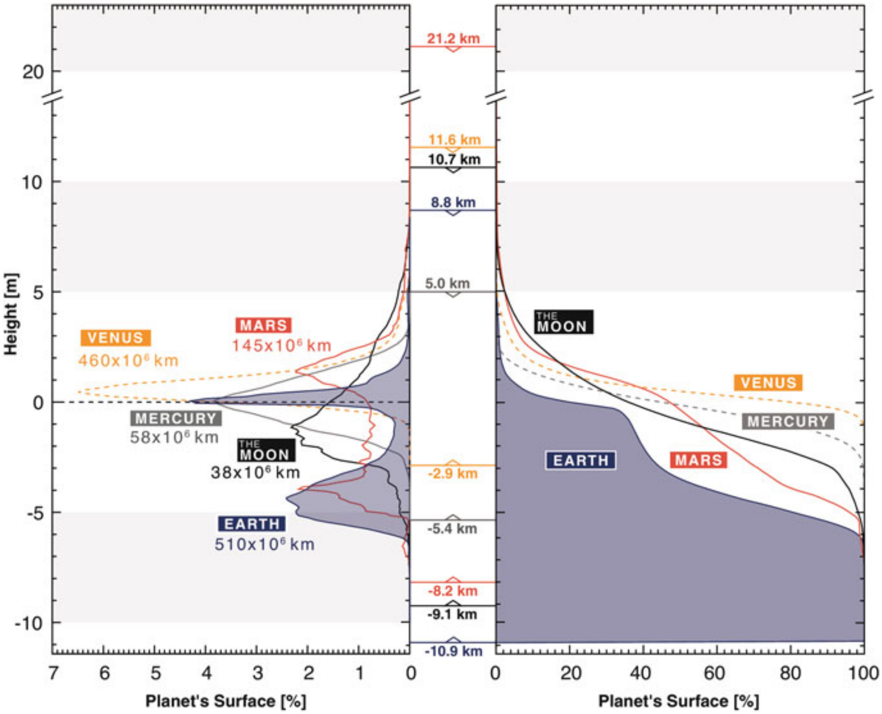

Fig. 11.2 Hypsometric curves of the terrestrial planets and the Moon. Source: Mercury: NASA/Messenger/MLA; Venus: NASA/Magellan/SAR Altimeter; Moon: NASA/LRO/LOLA, Earth: NOAA/ETOPO-1, (Amante and Eakins, 2009); Mars: NASA/MGS/MOLA

(Chaps. 9 and 10). However, the overall surface age of each terrestrial planet varies depending on its individual history (Fig. 11.3). The spatial distribution of stratigraphic units also reflect this (Fig. 11.4). When comparing the hypsometric curves of the terrestrial planets, it can easily be seen that the topographic height distribution for Earth and Mars have a distinct bimodal shape (Fig. 11.2a) while for the Moon, Mercury and Venus the distribution is unimodal and symmetric with individual maxima around the median. For Earth this characteristic shape is related to the distribution of land masses (i.e. continents) and oceans. Although is tempting to use this observation as an argument in favour of a Martian ocean, the bimodal shape is more likely related to a large impact or the result of mantle convection (Chap. 8), differentiating northern lowlands for southern highlands. In the cumulative view, the martian bimodal shape is less well pronounced when compared to Earth.

With the exception of Venus, the impact histories of the terrestrial planets are similar to a great extent, although with exact timing possible variations, in their first few hundred million years, but dramatically diverge afterwards. Such divergence

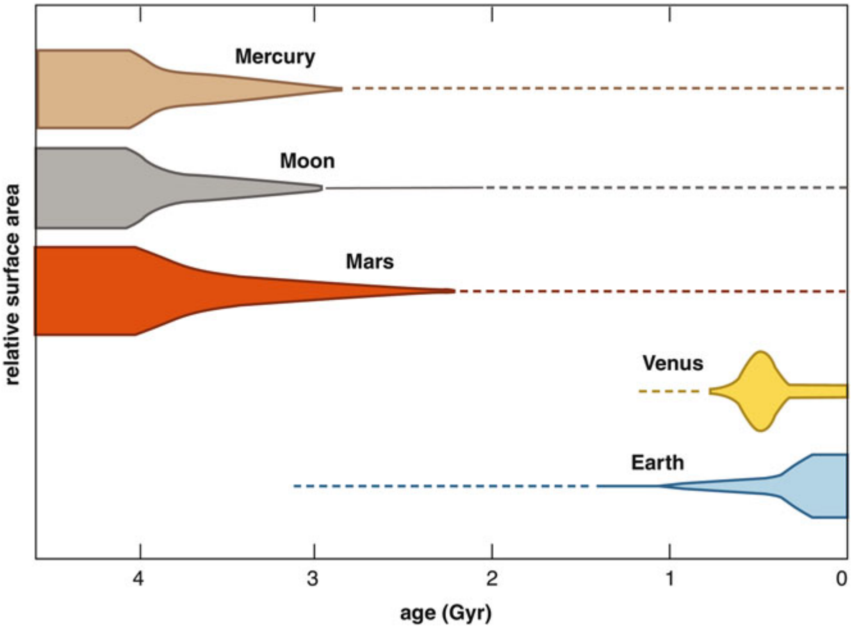

Fig. 11.3 Evolution of surface area age for all terrestrial planets and the Moon through time. Source: Redrawn from Head (1999)

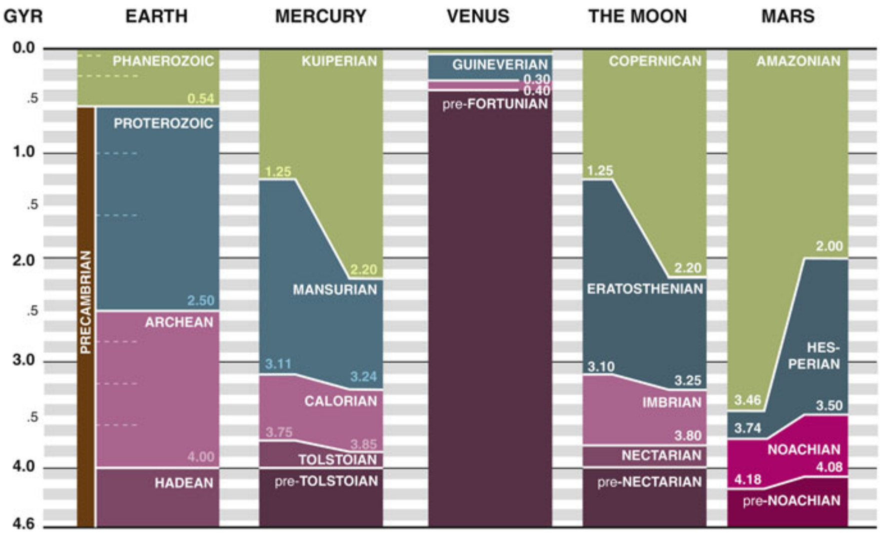

Fig. 11.4 Chronostratigraphic comparison of the Terrestrial planets. Source: Modified after van Gasselt and Neukum (2011)

is not related to the external impact cratering dynamics, but mainly to internal dynamics causing partial to total obliteration of earlier cratering record (Chap. 1).

11.1.2 Timing of Events: Cratering Histories

The stratigraphies of all terrestrial planets and the Moon have been established and calibrated, respectively, with impact crater size-frequency distribution measurements on their surfaces and radiometric dating (Chaps. 2 and 7). The latter has only been possible by returning samples from well-characterized landing sites on the Moon that allowed for the correlation of cumulative crater frequencies and the radiometric/exposure ages of the samples. This chronology curve can be adapted to other planets to date their surfaces. On Mars, a well-dated candidate crater has been proposed as source of the Shergottite-type meteorites (Chap. 6). If correct, this would indirectly provide a calibration point for the martian chronology. Another indirect absolute age determination on Mars has been achieved by NASA's Mars Science Laboratory (MSL) rover, finding ages consistent with those of the area dated with crater size-frequency on remote sensing orbital data (Fig. 11.4).

The relative preservation of surface units belonging to a certain chronostratigraphic subdivision (Fig. 11.4) depends much on the dynamics and the geological activity on each planet or moon: Extremely old terrains, formed during the earliest phases of crust formation are preserved (Fig. 11.5) on large parts of the Moon (Pre-Nectarian to Nectarian), Mercury (Pre-Tolstojan, Tolstojan) and to a significant portion of Mars' surface (Noachian).

Correlating events and evolution across the terrestrial planets is difficult and for reasons of processes specific to each planet it is not necessarily meaningful. However, impact processes in the Solar System, with their variations through space and time shaped all rocky planets in a first order similar way, particularly in the first few hundred million years (Fig. 11.5), although synchronicity might not have been exact. The impact flux (Chap. 7) had its source mostly in the asteroid belt with smaller contributions from comets (Fig. 11.6).

Other endogenic and surface processes also occurred on more than one planet, but at different times and with slightly to largely different boundary conditions. For example, early Mars is often compared to ancient Earth in terms of liquid water availability and results from the MSL rover suggest large reservoirs of water and possibly O_2 in the atmosphere or in near-surface environments.

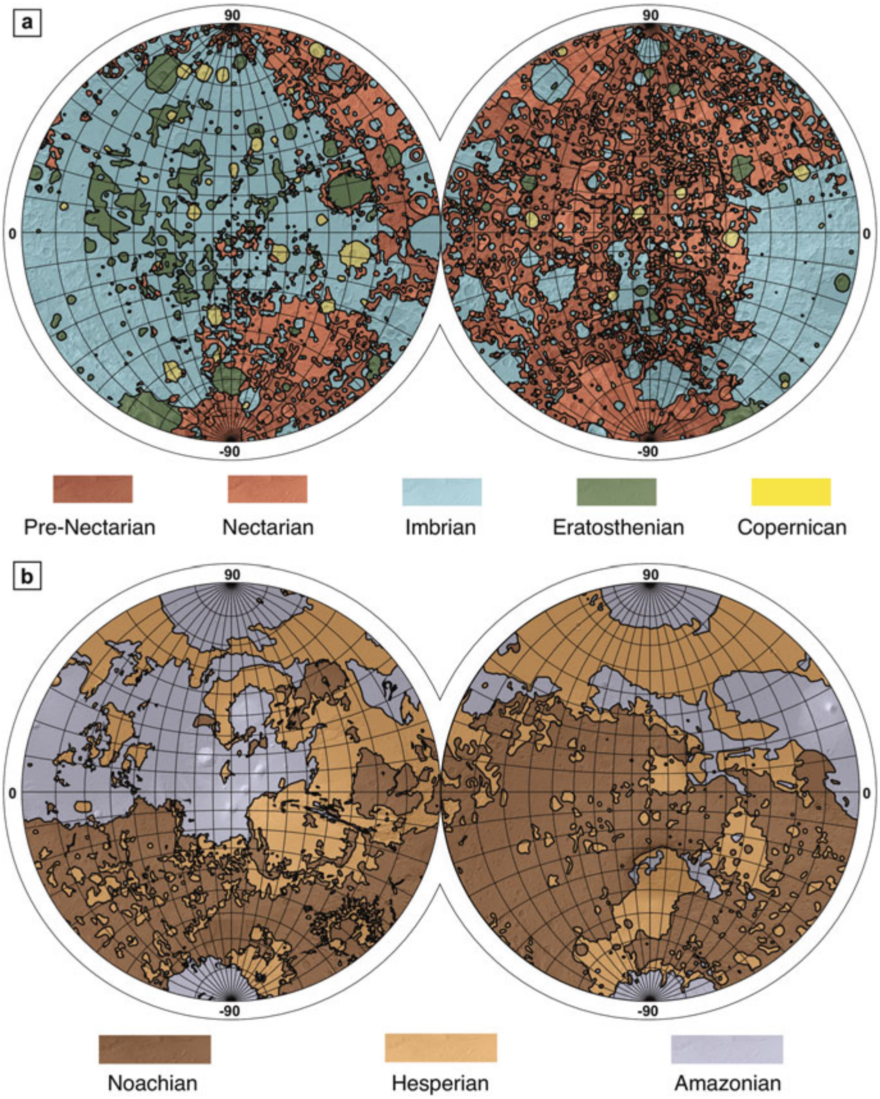

Fig. 11.5 Global surface ages, based on Fig. 11.4. (**a**) The Moon. (**b**) Mars. Sources: (**a**) After Fortezo and Hare (2013) and references therein, also quoted in Fig. 8.12. (**b**) After Tanaka et al. (2014)

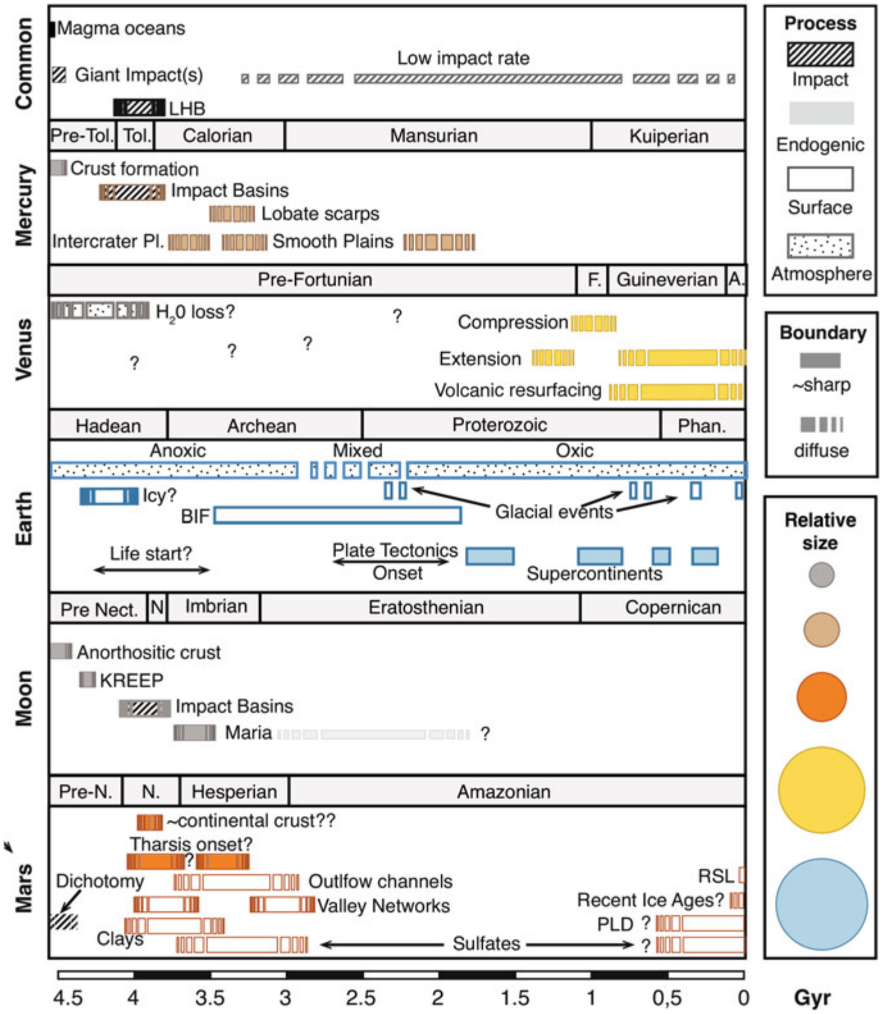

Fig. 11.6 Synoptic view of progesses acting on Terrestrial planets through time (see Chaps. 7–9): Dominating processes through time for the terrestrial planets and the Moon. See also Fig. 14.2. Source: Art and Nisbet (2012); Shearer et al. (2006); Nance et al. (2014); Basilevsky and Head (1998); Ehlmann et al. (2011); Fassett and Head (2008); Carr and Head (2010); Hoffman and Schrag (2002); Wilhelms et al. (1987); Neukum et al. (2001); Sautter et al. (2015); Head et al. (2007); Van Kranendonk et al. (2012); de Kock et al. (2009)

11.2 Early Phases

11.2.1 Formation and Magma Oceans

The very earliest times of Solar System formation are recorded only in meteorites (Chap. 6). Early solid aggregates in the Solar System were micrometersized. Collisions among those particles progressively produced larger bodies, reaching tens to hundreds of kilometers, forming so-called *planetesimals* (Chap. 1). Continuing collisions of these relatively large bodies resulted in both catastrophic disruption (Chap. 7) and planetesimal fragmentation as well as accretion into even larger, 10^3 km-sized planetary bodies, eventually leading to the formation of the terrestrial planets over time.

The initially violent phases of the formation of terrestrial planets (Chap. 1) led to global impact-generated melting involving a substantial thickness, producing so-called magma oceans. Those magma oceans affected also planetesimals in the first few million years of Solar System evolution. In the case of the terrestrial planets, it is assumed that the depth of these magma oceans that were produced by global melting were on the order of tens to hundreds of kilometers.

The subsequent cooling of a magma ocean (Fig. 11.7) led to the formation of a primary crust: its closest and most well-preserved example are the bright highlands of the Moon, composed of relatively light-toned anorthosite, as compared to darker maria basalts (Chap. 8). Individual crystals (zircons) formed during the cooling of Earth's magma ocean are as old as the Hadean (Fig. 11.4). However, most of the early geologic record is lost on Earth due to plate tectonics, the atmosphere, and life. Thus, with these factors missing, the Moon is an excellent body to study the very earliest history of the Earth–Moon system by investigating its primary crust.

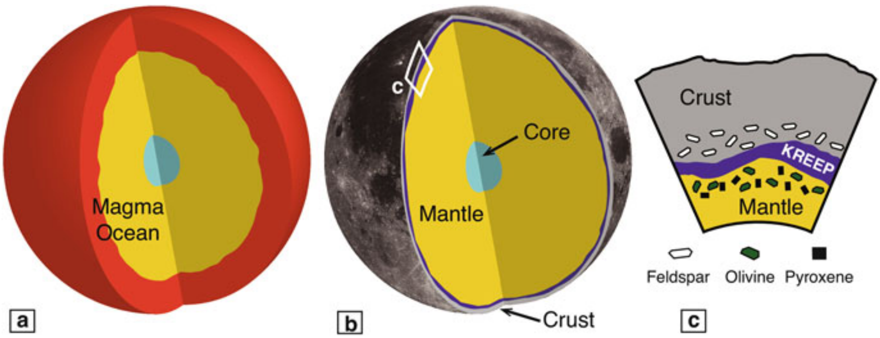

Fig. 11.7 Magma ocean of the Moon: (**a**) Initial state of lunar Magma ocean following its accretion after the giant impact; (**b**) final state of the Moon, with the original *primary* crust solidified from the magma ocean producing light-coloured, anorthositic highlands; (**c**) In the process incompatible elements are concentrated in the so-called KREEP layer, evident in the area of Oceanus Procellarum (Procellarum KREEP Terrain). Source: redrawn after Geiss and Rossi (2013)

Magma ocean conditions lasted between a few to several million years. Earth's crust existed most likely already 4.4 Gyr ago and the magma ocean, following the Moon forming impact around ∼4.5 Gyr ago lasted most likely for no more than 100 Myr. The crystallisation of the lunar magma ocean, that was likely to be at least few hundred km deep, left anorthositic highlands, which are still preserved. The presence of the ancient magma ocean on the Moon is also supported by the unusual concentration of incompatible elements in certain terrains, reflecting a reservoir at depth of KREEP (K, Rare Earth Elements, Phosphorous). The relative concentration of those elements on the surface of the Moon could be mapped using Gamma Ray spectrometry. Although their concentration occurred at depth, KREEP materials were brought to the surface through later volcanism.

The inaccessibility of Venus' most ancient geological record (Figs. 11.4 and 11.6) does not allow for collecting evidence of its potential magma ocean. Mercury's very think mantle (Chap. 10) provides some constraint on the eventual size of its ancient magma ocean. Mars' magma ocean occurred early, few million years after the formation of the Solar System. The southern highlands of Mars represent the oldest portion of its preserved crust (Fig. 11.5), but only recently and only very small outcrops of anorthosites have been found on Mars, mainly in deep units uplifted by central peaks in large craters. Due to its dynamic nature, Earth lost all direct evidence of its magma ocean. However, it likely had a magma ocean at least several tens of kilometers deep.

11.2.2 Giant Impacts

The first phase of intense impact flux on the terrestrial planets is also known as the period of *Early Bombardment*. Impacts of bodies of different sizes, up to planetesimals of several hundred kilometers were common during the formation of the terrestrial planets. Large and catastrophic impact events during the first several million years are also recorded in the most ancient meteorites (Chap. 6). Such giant impacts differ from basin-forming events in scale, producing such large-scale damages that globally affected the planetary body or even disrupted it. The giant impact that likely resulted in the formation of the Moon is a good example. The giant impact hypothesis of the origin of the Moon predicts that some 50–100 Myr after the formation of Earth (4.5 Gyr), a Mars-sized body, *Theia*, impacted Earth and caused substantial damage but did not fully disrupt Earth: the resulting debris re-accreted to form Earth's Moon (Fig. 11.8).

The giant impact hyphothesis, as of today the most widely accepted for the origin of the Moon, could also be used to explain the structure of Mercury. Such an impact on Mercury could have resulted in a relatively thin mantle and a large iron core (Chap. 10). Giant impacts were large enough to be able to completely disrupt or globally affect the involved planetary bodies, with variable final fate of impactor and target depending on relative mass and encounter geometry.

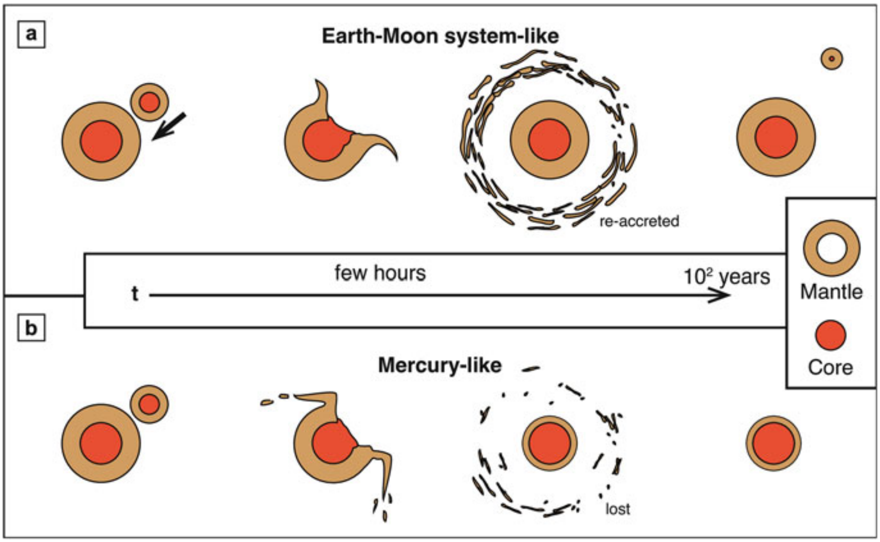

Fig. 11.8 Giant impact, roughly exemplifying the possible role of an impact of a large planetesimal on a terrestrial planet, e.g. (**a**) in the case of Earth, a Mars-sized planetesimal, *Theia* is very likely to have led to the formation of the Moon; (**b**) the same process with different boundary conditions could result e.g. no re-accretion of mantle material, as it possibly occurred on Mercury early in its history

The giant impact on the Earth and comparable ones across other terrestrial planets, to a smaller extent contributed to the current compositions of mantles and to a larger extent to crusts of planetary bodies. The actual timing of the Moon-forming impact could have been relatively late, according to recent estimates up to 100 Myr after the initial formation of the Solar System.

11.2.3 Basin Formation

On the basis of Apollo and Luna samples a phase of intense bombardment at 3.9–4.0 Gyr has been proposed. Also known as the *Late Heavy Bombardment (LHB)* or the *Lunar Cataclysm*, most of the large basins on the Moon were supposedly formed during this time period. To explain this unusual spike in impact rate, outer Solar System dynamics have been suggested (Chap. 7 and excursion therein). According to this model, the giant planets and their gravitational interactions and resonances resulted in a perturbation of the asteroid belt and the Oort cloud (Chap. 1) to produce more projectiles to hit the Moon during this time period.

If it occurred, the Late Heavy Bombardment might have most likely affected all terrestrial planets with a comparable intensity, and, in the case of Earth, with

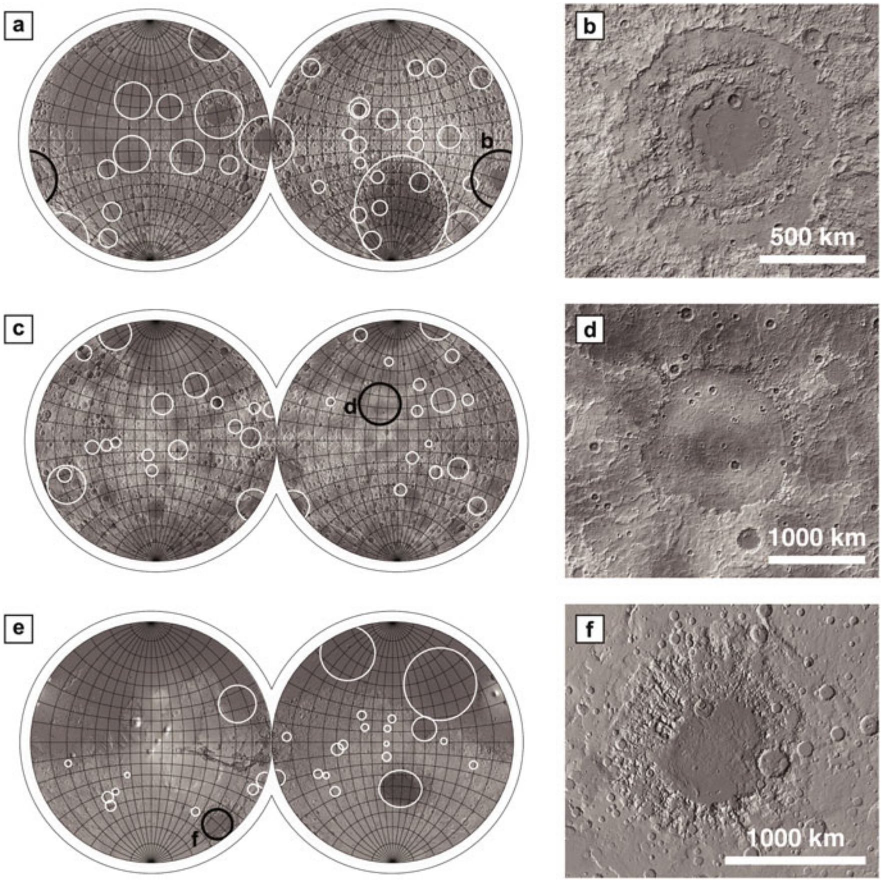

Fig. 11.9 A selection of large basins with various degrees of preservation and modification across the terrestrial planets. (**a**) For the Moon basins formed around 3.9 Gyr ago; (**b**) The lunar Orientale basin, an exemplary multi-ring impact basin of almost 1000 km diameter; (**c**) Mercury basins of ages close to that of the potential LHB; (**d**) The largest impact basin on Mercury, Caloris Planitia, has a diameter of about 700 km and less prominent rings when compared to lunar basins; (**e**) basins on Mars with ages comparable to that of the hypothesized LHB; (**f**) Argyre Planitia, 1800 km in diameter, appears more modified than similar counterparts on the Moon and Mercury, due to erosional and depositional processes. Sources: (**a**), (**c**), (**e**) Werner (2014). (**b**) NASA/LRO/LOLA. (**d**) NASA/MessengerMLA. (**f**) NASA/MGS/MOLA

possible partial or total sterilization (Chap. 14). This might have been the case also for the other terrestrial planets should life had been present back then.

Large impact basins, several hundreds to thousands of kilometres in diameter, are variably well preserved on the terrestrial planets (Fig. 11.9). If a *stratotype* of the LHB existed, the Moon would be the place for it: Large basins, well visible due to both lithological and structural differences to the surrounding primary anorthositic crust, are formed across a relatively short time span around 3.9 Gyr ago.

Mercury's basin are not as clearly outlined as those on the Moon and are different in morphology due to differences in gravity and internal structure. They have less well-developed rings and they are also more modified by global contraction occurring after their formation. On Mars, there are about 30 large basins of ages close to 4 Gyr (Fig. 11.9). They are less pristine than those on Mercury and the Moon, and this might be related to their strong post-impact modification either by volcanism or by erosional and depositional processes, such as ancient glacial activity potentially associated with Hellas and Argyre Planitiae. Consequently, partial or total obliteration of large basins on Mars might have occurred.

As with most other processes mentioned in this chapter, Venus' geological impact basin record is largely lost or not accessible by current data. So far, on Venus no large basins have been unambiguously detected, although one has been recently suggested based on contextual geological information. In fact, the largest confirmed impact crater, Meade, has a diameter of less than 300 km and is far younger than the age of a potential LHB on Venus. Also, the extensive later modification of Venus' surface might hinder the discovery of possibly heavily deformed craters in its oldest terrains.

Earth's geodynamics, dominated for most of its history by plate tectonics and its related crustal and lithospheric recycling, erased all morphological and structural signatures of any potential large impact structures. On Earth, plate tectonics itself possibly started with much smaller plates than those of today, due much more vigorous mantle convection (Chaps. 8 and 10). A possible trigger for early plate tectonics could have been the occurrence of large impact basins around ~4 Gyr ago, close to the Hadean–Archean boundary (Fig. 11.4). The actual onset of modern plate tectonics is not well-constrained and estimates range from around 1 Gyr ago to about 4 Gyr, implying that it is potentially unrelated to the intense bombardment of the Hadean. The possible effects of the LHB on Earth today are only recorded in single crystals preserved in ancient terrains, after cycles of erosion and sedimentation have been modifying the original surface. The concepts of magma oceans, giant impacts and the LHB all condensed from detailed studies of lunar samples and remote sensing data as well as meteorites (Chap. 6). Without human or robotic sample return missions and access to the Moon, all those hypotheses could not have been developed in the same way.

Impact rates decreased through the history of the Solar System, although details are still debated (Chap. 7). Nevertheless, one of the cumulative effects of continued impact bombardment—both at large and small spatial/temporal scales—is the fragmentation of target rocks, which produces the other *regolith* layer. The regolith comprises the uppermost portion of planetary crusts, progressively and cumulatively disrupted by impacts of variable sizes, for geological timescales. Although the dominating process to form the Moon's regolith is impact-related physical disruption of existing material, other processes are active and are contributing to the uppermost portion of the regolith, also known as lunar soil. There are several definitions for the term *soil*, ranging in nature from granulometric to engineering-related properties: This is in contrast to the usage on Earth where it is mostly related to the development of an organic layer. The size range of individual

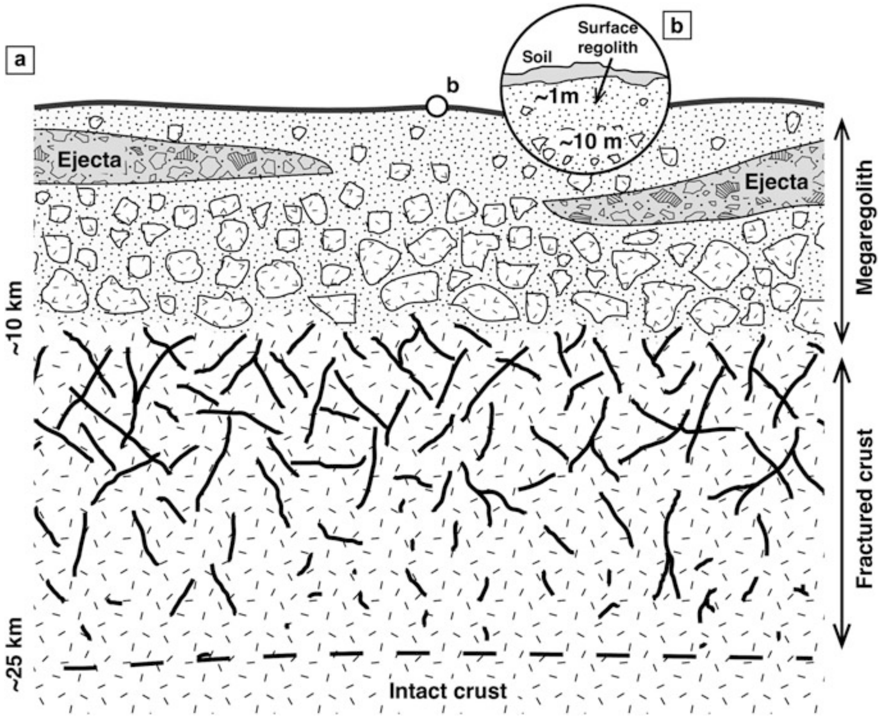

Fig. 11.10 Regolith and megaregolith development on planetary surfaces: (**a**) large-scale structure of the regolith/mega-regolith of the Moon. Regoliths/megaregoliths on other terrestrial planets, i.e., Mercury and to a lesser extent Mars, are also dominated for most of their geological history by impact cratering and, thus, should show similar characteristics; (**b**) enlargement of the uppermost portion of the crust, and the surface regolith. Source: after Hiesinger and Head (2006), Hörz et al. (1991)

components within the regolith and the megaregolith varies between microscopic (e.g., few micrometers) to extremely large, kilometre-sized or more (Fig. 11.10). In this respect, the fine-grained surface of planets is referred to as *regolith* whereas the heavily impact-disrupted upper crust down to tens of kilometers, is referred to as *megaregolith*. Regoliths progressively developed and they are the result of a cumulative set of processes, mainly driven by impacts. With the development and growth of the regolith, the underlying bedrock is increasingly protected from the effects of subsequent impacts craters smaller or comparable in size to that of the regolith thickness. Processes contributing to the progressive lunar soil formation (Fig. 11.10) include spallation, local fusion that cements granules into agglutinates as well as physical weathering due to temperature changes (Chap. 9), contributing to particle comminution specifically in the upper finer-grained portion of the regolith (soil).

On Venus the thick and dense atmosphere hindered small regolithforming impacts to reach the surface, while the record of megaregolith formation might have been erased by the geologically recent vigorous resurfacing by mantle overturn. On Mars, the presence of an impact-generated, deep regolith (megaregolith) acted most likely as a subsurface reservoir for the martian hydrosphere. Without this regolith reservoir, the martian hydrosphere would have shrunk much earlier due to atmospheric loss by solar wind activity, in particularly as no significant magnetic field protected the planet for most of its history (Chap. 10). On the Earth, the preservation of a regolith or megaregolith layer has been prevented by its very dynamic crustal recycling as well as erosional and depositional processes acting throughout its geological history. Thus the terrestrial regolith, i.e., the soil, is produced by non-impact processes.

11.2.4 Secondary Crust Formation

After a period ranging from a few tens of Myr to a few Gyr and following the formation of an early crust and rigid lithosphere (Chap. 10), partial melting of the mantle and resulting basaltic eruptions produced a second type of crust on essentially all terrestrial planets (Chap. 8). This secondary crust is still very well preserved on the Moon, Mercury, and Mars at forms volcanic plains. For example, secondary crust constitutes the large basin-filling mare basalts on the Moon and may also be represented in large portions of Venus' surface. On Earth, secondary crust mostly builds up the ocean floors, hot spots, and other basalt plains. The accommodation space to host such secondary crusts for most terrestrial planets is provided by large impacts, producing multi-ring basins, in addition to the melt produced within the impact process itself (Chap. 7).

The duration of volcanic activity on the terrestrial planets is roughly scaled with their relative size and mass, and thus, their heat capacity. Small objects cool faster than larger objects due of their larger surface-to-volume ratio. Consequently, volcanism ceased rather early, possibly before $\sim$3.5 Gyr on Mercury, below 3 Gyr and up to about 1.2 Gyr locally on the Moon (Fig. 11.11), and it lasted longer on Mars (most Amazonian units on Tharsis, as in Fig. 11.5).

Earth's modern secondary crust is mostly present on the ocean floors (Fig. 11.12). Historic ocean floors do not exist anymore as such as they have been consumed and closed by plate subduction and collision. On Earth, only few witnesses of even older, pre-plate tectonics crusts still exist. The remains are embedded in very old deformed terrains by processes active on Earth but presumably not on other terrestrial planets, with the exception of Venus. Secondary crust on the Earth was able to form even before the onset of modern plate tectonics, although the one preserved and formed today is linked to it.

The surface of Venus today is covered to more than 70% by volcanic plains (Fig. 11.12) that formed during a relatively recent, not well constrained time period roughly estimated somewhere between 100 Myr and $\sim$1 Gyr. According to the model of *convective mantle overturn*, it was suggested that this global resurfacing event took place over a geologically short period (Chap. 8). It is possible that the

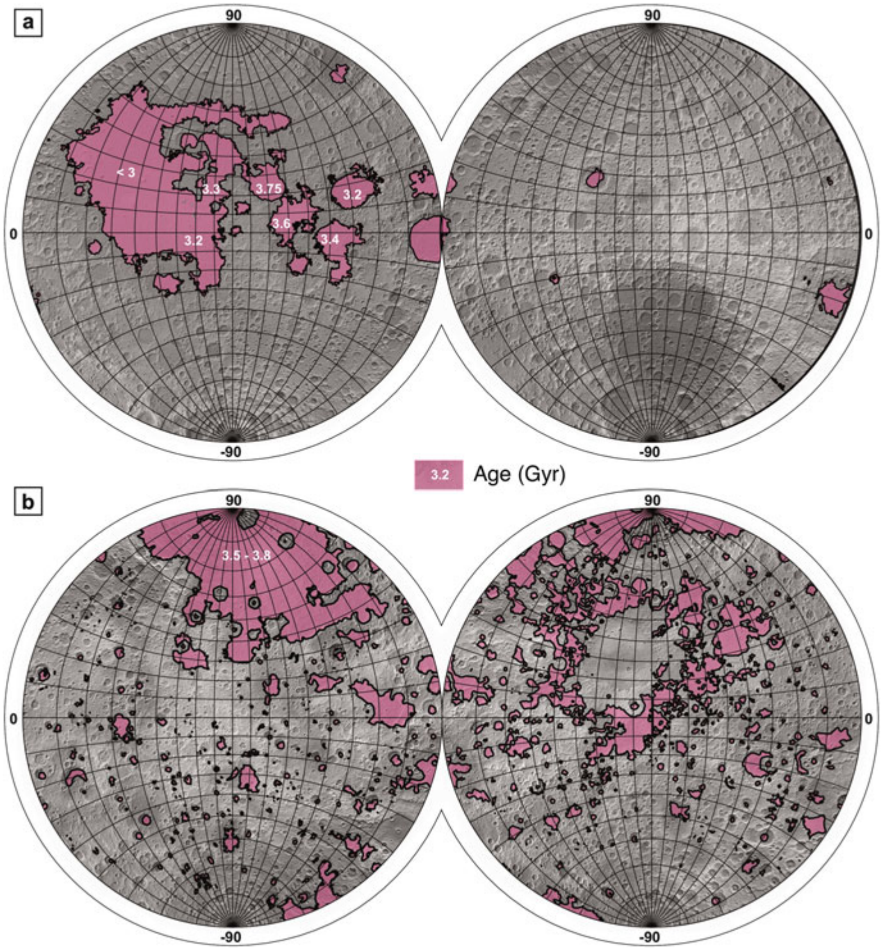

Fig. 11.11 Secondary crusts, composed of basaltic volcanic plains on terrestrial planetary bodies: (**a**) the Moon, see also sources of Fig. 8.12; (**b**) Mercury, smooth plains. Sources: (**a**) Fortezo and Hare (2013), see also sources in Fig. 8.12. (**b**) Procter et al. (2016), ages from Marchi et al. (2013)

event was not instantaneous or that several instances occurred. Nevertheless, some older terrains appear to have not been involved in such resurfacing and are still preserved, to an unknown extent. Today, these terrains are surrounded by more recent volcanic units with variable amounts of deformation (Chap. 8).

11.2.5 Continents and Planetary Counterparts

On Earth, the most evolved type of crust, i.e., continental crust, formed initially in relatively small volumes, which increased with time. It has been suggested that continental crust is only formed on planetary bodies that developed tectonic

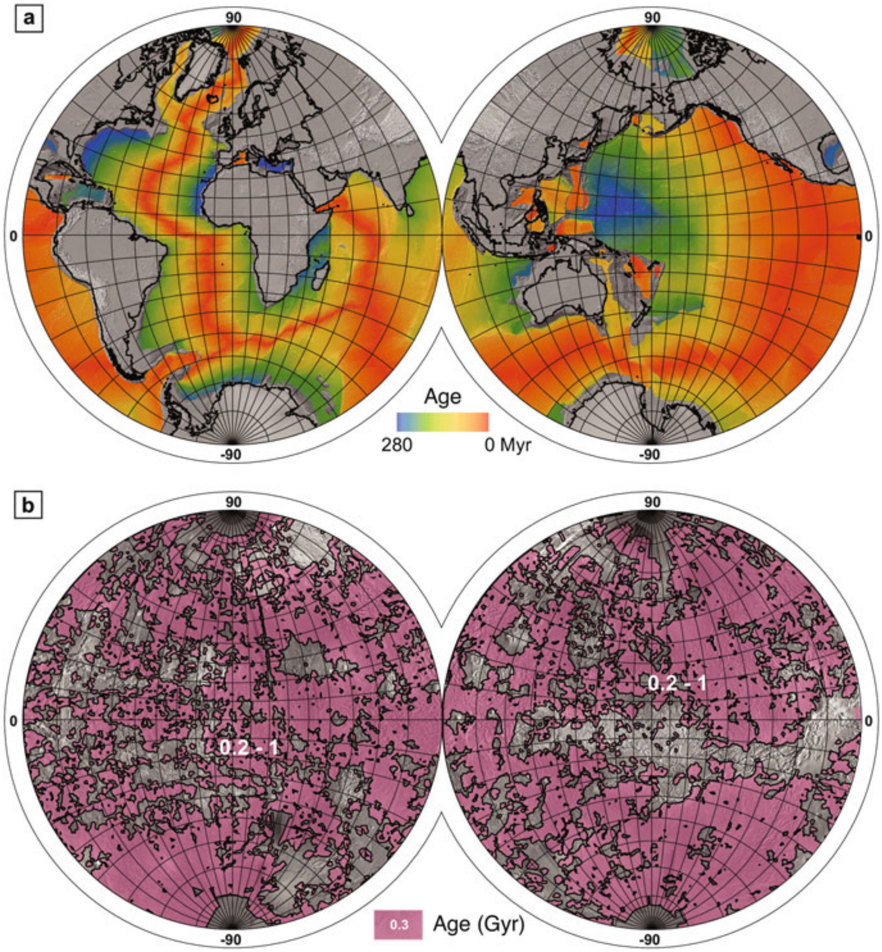

Fig. 11.12 Secondary crusts on the terrestrial planets: (**a**) Earth's recent crust, formed by partial melting of the mantle, is covering the oceanic floor. Older oceanic materials is recycled or embedded/obducted by plate tectonics and related mountain building; (**b**) Venus volcanic plains, covering about 70% of Venus' surface, have relatively young ages of up to several hundred million years, locally possibly much younger. Sources: (**a**) Müller et al. (2008), color-coded after Kovesi (2015). (**b**) Ivanov and Head (2011), courtesy M. Ivavov; age from Kreslavsky and Head (2015)

plates, i.e., Earth. However, on Mars, there is evidence of remnants of an ancient material compositionally comparable to Earths continental crust. Together with the formation of an evolved (tertiary) crust, this points to the possibility of an early onset of continental-like crust formation, which was possibly aborted after short time, and thus was not preserved in large geologically active bodies. Additional evidence of plate-like tectonics on Mars and large-scale horizontal movements such as those characteristic on Earth are ambiguous. Venus surface also does not provides unambiguous evidences for plate tectonics. Although individual geologic and geodynamic features might be shared, locally, or regionally, they are not organized in a global framework (Chaps. 8 and 10).

Exhumation of old portions of the crust on the terrestrial planets is also achieved mainly through impact cratering, while on Earth plate convergence and collision allows for more efficient, although localised, exhumation of deep material, from several tens or even hundred (e.g. in large collisional chains) of kilometres of depth. Over geological timescales, eolian erosion can also cause significant exhumation, for example on Mars.

Venus displays few large continental-like terrains, called *tesserae*, (Fig. 11.13) that, among all terrestrial planets, are most similar to Earth's cratons. However, to date, no evidence (see Chap. 8) of comparable horizontal movement has been identified and accurate compositional information of the oldest terrains on Venus is lacking.

Given the different tectonic settings, mountain building among terrestrial planets and the Moon works very differently: on the Moon and Mercury local high relief is commonly produced by the formation of concentric rings associated with craters and large basins. Localized contraction is present on both Mars and, even more on Venus (Fig. 11.13). On the Earth, however, plate boundary interaction produces most topographic and structural relief as well as exhumation. Also, very ancient remains of terrestrial secondary crust are spread or squeezed into orogens with varying degree of preservation.

Orogenic and collisional processes, synchronously active in relatively small regions of the Earth's surface (i.e., *orogens*), are very effective in exhuming older or deeper portions of the crust, for example, by squeezing through or *obducting* crustal material. Over geological timescales, the areas affected by orogenic processes can grow and can form very large rock bodies (Fig. 11.13). Orogens create topographic highs subject to erosion that eventually expose deeper units and, at the same time, cause isostatic uplift due to the removed mass. Still, ancient orogens and their record are preserved and accessible. Once (for rocks from former oceanic domains) or since (for continental collision) these orogens are embedded into continental crust, they are less prone to be lost in the recycling of plate tectonics. On other terrestrial planets such recycling does not occur, although it could partly apply to Venus, associated possibly to the most intense localized compression.

On terrestrial planetary bodies, impact craters can serve as boreholes in the ground, exposing deep geological units. The original depth of such an exposed uplifted or ejected unit can be derived from measuring the size of the impact because its sampling (excavation) depth is well constrained by the crater size (Chap. 7).

On the terrestrial planets, the rock cycle might be affected in different ways on each planet, depending on its activity and geologic nature. In terms of basaltic production, the most common endogenic process, we observe significant spatial and temporal differences on the respective planets. Similarly, metamorphism, i.e., the solid-state changes of existing rocks can also be different. While products of impact metamorphism (Chaps. 6 and 7) are ubiquitous on the Moon, Mercury, and Mars because of the very large number of craters, they are restricted to the immediate vicinity of impact craters on Earth and Venus. Eolian sedimentary processes require

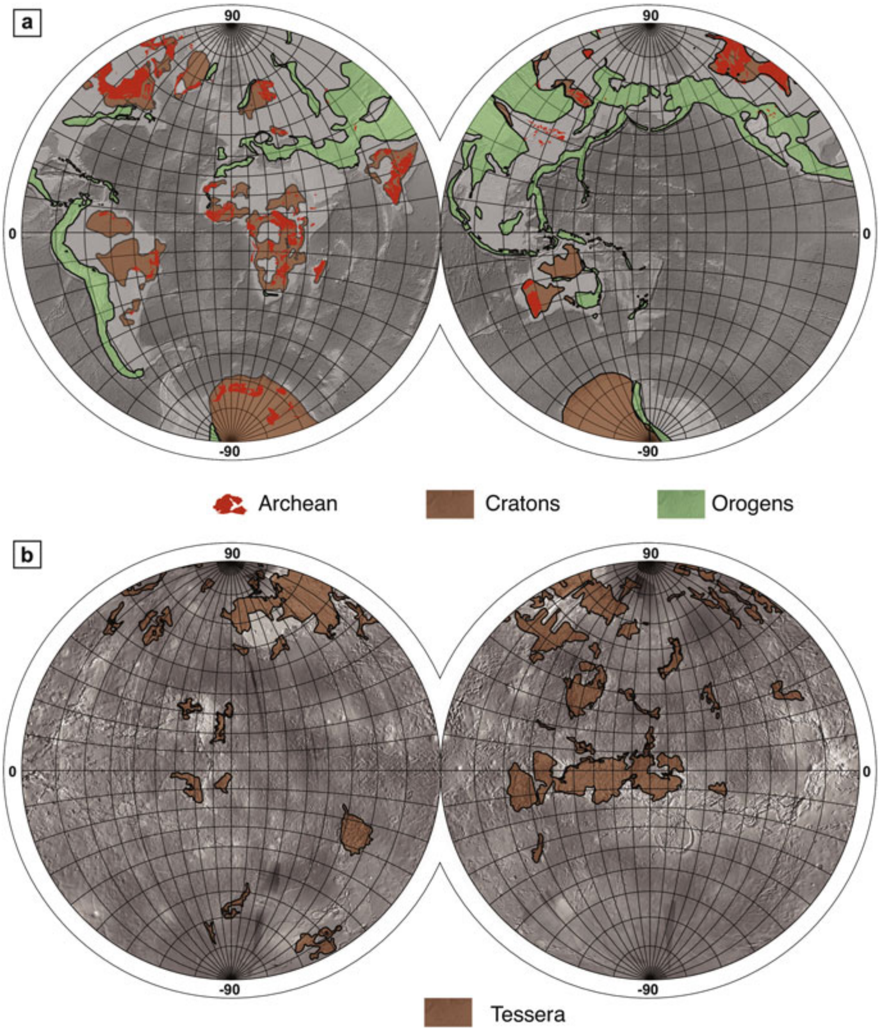

Fig. 11.13 Large-scale collisional features, orogens and cratons on Earth compared to Venus: (**a**) Global distribution of cratons and collisional orogens on Earth, as well as distribution of Archean rocks; (**b**) Venus' tessera terrain is highly deformed, it is older than the surrounding plain units, and occupies about 8% of the surface. Sources: (**a**) USGS. (**b**) Ivanov and Head (2011) courtesy M. Ivavov

a dynamic atmosphere and thus are mostly limited to Mars and Earth. Although Venus also has an atmosphere, the lack of sufficient sand-sized particles and observational effects of the radar data limit the detected number and mobility of sand dunes.

Physical and chemical weathering (Chap. 9) occurred both during different phases of the terrestrial planets' evolution. Today, chemical–physical weathering is occurring on Venus surface and its highest mountain ranges might experience chemical weathering, resulting in the formation of radarbright peak areas. Mars' water-driven chemical weathering occurred mostly during the Noachian, while physical weathering continued throughout its history. On Earth, both kinds of weathering were constantly active for its entire history, mainly driven by climate. Climatic effects should be expected also on Mars, in addition to its long-term interior dynamics (Chap. 10), although their chronologic interplay is difficult to disentangle from their cumulative effect on the surface and near subsurface.

The evolution of sedimentary processes through time is very relevant also for future exploration, both for the possible link with life formation and their role in the creation of valuable resources (Chaps. 14 and 15).

11.2.6 Ancient Hydrologies and Surface Alteration

Among the terrestrial planets, Mars and Earth are the only planetary bodies that are located within the habitable zone. Thus, they have substantial amounts of water/ice that can interact and modify their surfaces. Most sedimentary processes (Chap. 9) are linked to an active hydrological cycle. Earth has such a cycle since very early in its history, most probably already during the Hadean and presumably even during periods of enhanced meteoritic bombardment, close to 4 Gyr ago. Throughout its history Earth most likely exhibited a surface that was covered at least to some extent by water.

Few billion years ago also Venus might have hosted a substantial amount of water on its surface and atmosphere, but the geological record of such possible ancient habitable Venus, suggested by recent climatic models, is unaccessible.

The Noachian period on Mars might bear resemblance to the earliest times of Earth's history, particularly before the onset of plate tectonics and life (Chap. 14). Even today, Mars resembles Earth in terms of processes that act on its surface, e.g., eolian, glacial, periglacial, volcanism, etc. (Chap. 2). However, the exact conditions during the Noachian are difficult to reconstruct without extensive ground truth and reliable proxies. There are several lines of evidences for water-related alteration and hydrated mineral formation, even pedogenesis, but the exact temperature and pressure ranges as well as the actual compositions are debated.

During the Noachian, Mars (Fig. 11.4) was characterized by a thicker atmosphere than today and, at least for few hundred million years, an internal magnetic field to protect the atmosphere (Chap. 10) from being eroded by large impacts, trapped in the subsurface or scavenged by the solar wind, though various processes. Atmospheric loss on Mars occurred for over 3.5 Gyr, and for comparable times also on Venus. However, Venus does not have an internal magnetic field to protect its atmosphere from escape but was able to replenish its atmosphere by outgassing associated with volcanism (Chaps. 8 and 10). Actual mechanisms leading to atmospheric escape by solar forcing are complex, ranging from thermal effects to microscopic effects of the solar wind particles on atmospheric constituents, including photochemical escape, sputtering, ionisation, etc.

The complexity of the geological history of Mars and Venus is only second to that of Earth. In fact there are only two terrestrial planets with an ancient or present hydrological cycle and sedimentary processes, both erosional and depositional: Earth and Mars.

Mars' valley networks, comparable to Earth's drainage systems have commonly been interpreted to be linked to surface runoff and with variable contribution of groundwater (sapping, see Chap. 9) or surface ice-melting. They tend to be shallow, less than 100 m in depth and up to hundreds of km in length, with several networks reaching a few thousand kilometers in length. They are concentrated at low to mid-latitudes on Mars, typically in the highlands in the southern hemisphere, south of the dichotomy boundary (Fig. 11.14). Often, they are spatially and geologically associated with putative palaeolakes.

The D/H ratio measured on Venus has been interpreted to indicate substantial water loss in its past. If this loss of water did not occur too early, it might be plausible that Venus once hosted large bodies of water, developed a sedimentary cycle, and even might have been habitable (Chap. 14). However, this remains highly

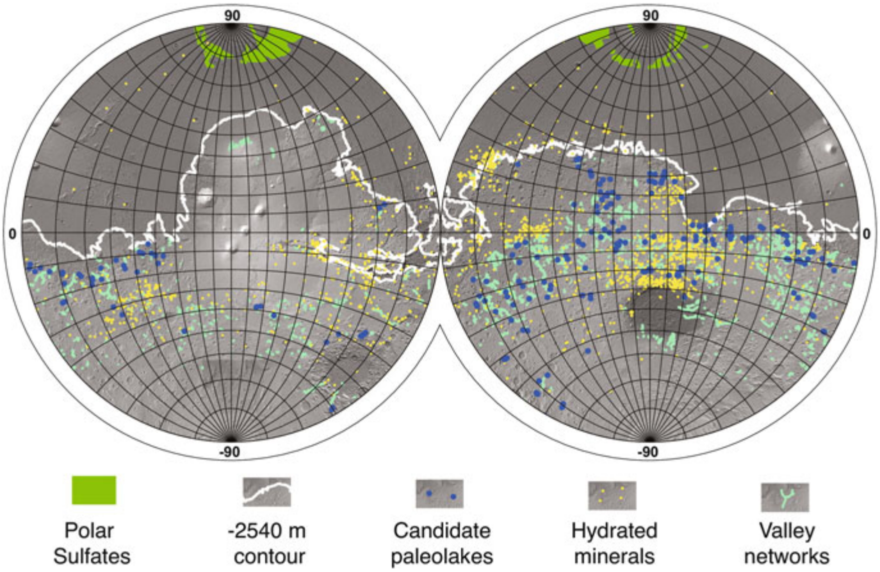

Fig. 11.14 Spatial distribution of selected geomorphologic features (paleolakes, valley networks) and mineralogical evidence (sulfates, hydrated minerals) in support of an ancient hydrosphere on Mars. *White line* is the −2540 m contour line, roughly demarcating the northern lowlands and the southern highlands. Source: Sulfate map courtesy J. Flahaut, after Massé et al. (2012); MGS MOLA contour after Di Achille and Hynek (2010); hydrated minerals compiled by Carter et al. (2013); Valley networks from Hynek et al. (2010); Open basin lakes from Fasset and Head (2008)

speculative because of the nature of crustal recycling on Venus, i.e., convective mantle overturn that erased all evidence for such scenarios.

On Earth, we have evidence for an ancient, stable, long-term sustained hydrosphere and related geological processes for at least the last 4 Gyr. For the same time period, Mars also shows evidence of relatively long-term liquid water stability at its surface, including erosional and depositional features such as valley networks, longitudinal valleys, outflow channels, deltas, paleolakes, or even putative temporary oceans as well as hydrated minerals (Chap. 9, see Fig. 11.14).

Sedimentary basins on Earth are mostly linked to plate tectonics (there are currently very few impact crater-hosted lakes, such as Bosumtwi in Ghana). However, in the Hadean and Archean, particularly before the onset of plate tectonics, it is likely that more impact basins existed on Earth. On Mars, numerous impact craters hosted palaeolakes as indicated by the deposits these paleolakes left behind. The exact estimate of the duration of such paleolakes is still a matter of debate and it ranges from transient to several Myr.

Geomorphologic evidence for water on Mars is abundant, has been recognized and investigated since the 1970s, and incudes large-scale fluvial and lacustrine features as well as glacial features, for example, in Argyre and Hellas Planitiae.

Additional evidence for water on Mars is provided by modern spacecraft that spectrally investigated the composition/mineralogy of the martian surface. As a result, numerous minerals were identified that were formed by water-related alteration of existing rocks (e.g., clay minerals) as well as primary deposition (e.g., carbonates). Although carbonate minerals have been detected in martian meteorites at a microscopic scale since decades (Chaps. 6 and 14), their orbital detection came later and is spatially limited to a few occurrences. Thus, despite the substantial amounts of water on Mars, widespread carbonate buildups like those on Earth never formed on Mars or were later destroyed. For example, perchlorates, as detected at the Phoenix landing site, might have hindered the formation of carbonates.

Many Noachian volcanic units on Mars (Fig. 11.5) display water-related alteration of their original basaltic composition, resulting in various types of phyllosilicates, including clays. Specific vertical distributions of those mineral associations have been detected regionally and have been interpreted as results of varying liquid compositions or the potential development of soil (*pedogenesis*).

On Mars, such alteration are limited to rather ancient times while they are common and ubiquitous on today's Earth. The absence of evidence for hydration in deposits later than Noachian can be explained, for example, by only a short-term intermittent presence of water that was unable to cause enough alteration in rocks. The exact environmental conditions for ancient Mars are still poorly constrained. For example, instead of the canonical *wet and warm* climate, early Mars could have been *cold and icy*, even if it was locally wet, and could have formed large-scale temperate glaciers (Chap. 9) with tremendous effects on surface alteration.

11.3 Intermediate, Diverging Histories

Interplanetary stratigraphies, although they follow similar patterns on the Moon and Mercury (Fig. 11.4), are not easy to correlate as geologic processes of similar nature acted asynchronously across the terrestrial planets. The timing, duration, and extent of volcanism, for example, is connected to the internal structure of a planet, its size, water content, and thermal characteristics, to name but a few. Similarly, the occurrence and nature of tectonism depend on the internal structure, the related stress field, the heat loss mechanism, and to some extent tidal deformation. Other processes are specific to planets that can hold an atmosphere, including fluvial, lacustrian, glacial, and eolian processes. Considering the common distant sources of the main impact-forming projectiles (i.e., the asteroid belt and the Oort cloud), it seems plausible that impact cratering might have affected the planets to a first order homogeneously. However, at closer inspection, the effects of the dense atmosphere on Venus, the distance of the planets from the Sun, different sizes and gravity, and many other factors affected the geological histories of the terrestrial planets.

Very early phases of complete surface layer melting, i.e., a magma ocean, and very intense bombardment by asteroids and comets are common to all terrestrial planets. The geological evolution of each planet then started to diverge, slowly or abruptly, depending on the studied processes. In the middle ages of planetary evolution, flood volcanism on the Moon and Mars, for example, continued to be active at different boundary conditions and eruption/depositional rates. During this phase, Mars and Earth divert progressively in terms of dominant active processes, although some of them act for comparably long times and even today (see also Chap. 2).

Although most geological evidence of liquid surface water is restricted to the Noachian or early Hesperian, some palaeolakes and valleys on Mars still occurred during the Hesperian. On Mars, the role of groundwater and subsurface hydrology became increasingly important during this phase as surface water became increasingly unstable.

11.3.1 From the Surface to the Subsurface

On Mars, the progressive loss of atmosphere and water over the last 4 Gyr, along with the associated reduction in atmospheric pressure and decrease in temperature, made liquid water unstable on the surface but stable in solid and vapor form. Beside atmospheric loss, water was also lost to the subsurface: Mars' crust, with its high porosity due to the impact-generated megaregolith (locally or regionally capped or sealed by other units, such as volcanic lava flows or sedimentary layers) acts as water reservoir (aquifer), of presumably local, regional, or even global scale. As temperatures dropped with time, the upper part of the water-saturated crust eventually became part of the cryosphere. Depending on, for example, the local heat flow, heat conductivity, and surface temperatures, some models predict that the cryosphere sealed off possible liquid water beneath. Thus, it is plausible that there is still liquid water beneath the several kilometers thick martian cryosphere.

During the Noachian recharge of subsurface acquifers on Mars was achieved most likely through precipitation. As surface runoff became increasingly ineffective from most of the Hesperian onwards, aquifer recharge was also affected. Nevertheless the amount of subsurface water available when the Martian hydrological cycle stopped working, either in liquid or solid form, allowed for release of subsurface water at the surface through complex processes.

In addition to early lacustrine systems on Mars that have formed in crater basins, and large-scale surface runoff responsible for generating the global valley network distribution (Fig. 11.14) between the Noachian and the Hesperian, larger-scale catastrophic water outflow also occurred on Mars. These outflow channels possibly resulted in short-term ponding. The duration and extent of such ponding is still under debate and range from local deposits to hemispherical oceans. On the basis of absent large-scale water-related mineral alteration, both in distal and proximal portion of the large outflow features on Mars (Fig. 11.15), it has been argued that it is unlikely that the outflow channels produced long-lasting stable bodies of water on the surface.

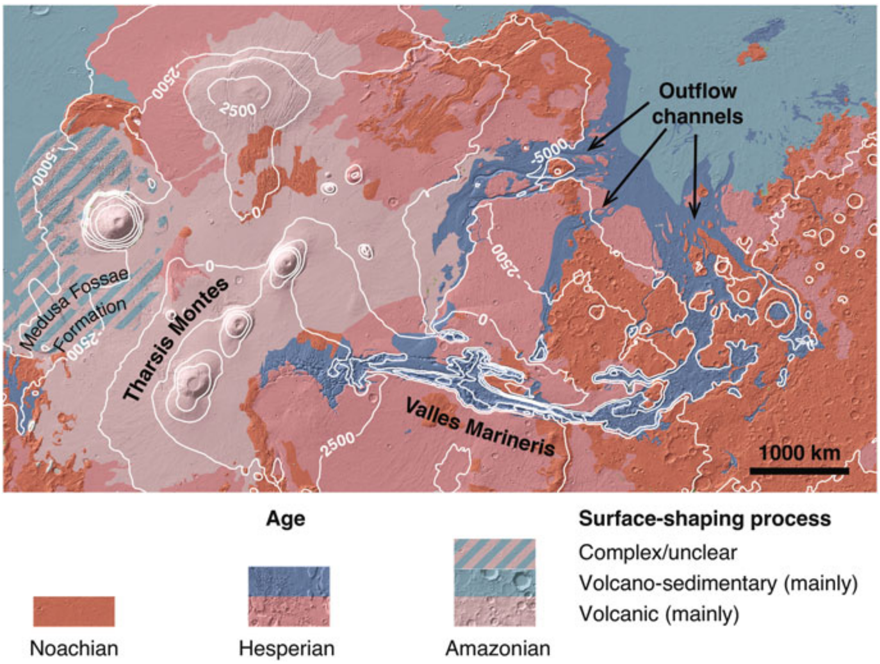

Fig. 11.15 Interaction of volcanic, tectonic and (catastrophic) sedimentary processes on Mars. Source: data adapted from Tanaka et al. (2014); design inspired by Carr (1996)

Interpreted in the literature as partially ice-carved or even volcanically-carved, outflow channels (Fig. 11.15) are largely considered to be the result of a catastrophic release of water from the subsurface, in one or more events. In this model, igneous processes or impact heating lead to melting of the cryosphere and the release of large amounts of subsurface water within short periods of time. Famous terrestrial analogues are known from Iceland (*jkulhlaups*) and Missoula, Washington. For example, the large, Tharsis province that was volcanically active for long times (Chap. 8) is spatially correlated with most outflow channels. Other smaller outflow channels are associated with regional (e.g., the circum-Hellas volcanic province) or local (e.g., Mangala Fossae) volcanic centers or dikes (Chap. 8).

Closely related to outflow channels are the *chaotic terrains*, located in many Hesperian and Amazonian craters along the dichotomy boundary (Fig. 11.15). Chaotic terrains vary in scale, from a few kilometers to hundreds of kilometers. In some cases it is linked to previous impact basins (e.g., Aram Chaos), in others it occurs as irregular depression, possibly due to the coalescence of several craters. Thus, in addition to heterogeneities within the megaregolith of the first several tens of kilometers of Mars' crust, the deformation within chaotic terrains is likely due to pre-existing impact-related structures (Chap. 7).

Several major outflow channel source areas are close to the Valles Marineris canyon system (Chap. 8). Some outflow channels were active only once, while others were active multiple times, as long as sufficient impact and/or volcanic heat and volatiles in the crust were present. Eventually Mars ran short of one or the other locally or regionally, thus, outflow channel activity did not last until the very recent geological past. Subsurface ice/water was not necessarily replenished, although volcanism might have continued later than the formation of outflow channels. In places where multiple episodes of outflow from roughly the same source occurred, the magnitude of floods in most cases became increasingly smaller, suggesting reservoir depletion with time.

Chaotic terrain and related liquid water-carved outflow channels are characteristic of Mars and have no counterpart in the inner Solar System, apart from some analogues on Earth that are associated with submarine slope failures. Some icy satellites display similar features, and were formed by disruption, however, in a very different geological context (Chap. 12). Chaotic terrain is widespread in a some regions on Mars possibly caused by the combined effect of low to midlatitude subsurface water release from the cryosphere in combination with volcanic, Tharsis-driven triggering of melting (Chap. 8). Although the occurrence of chaotic terrain appears to be spatially associated with outflow channels (Fig. 11.15), it exhibits various stage of development, from initial cracking to highly eroded mesa and knob morphologies. For a discussion of the role of collapse in Mars' chasmata and chaotic terrain see Chap. 8.

Since the shutdown of Mars' global magnetic field (Chap. 10) about 4 Gyr ago, the atmosphere of Mars has been continuously eroded by the solar wind. Such a change in global environmental conditions across the Noachian and Hesperian resulted in different geological/geochemical conditions and also in changes in dominant mineralogy. For example, widespread sulfates have only been formed since the Hesperian—in some places in close vicinity of phyllosilicates—when available water became increasingly rare. Although these minerals can be reasonably well detected from spectrometers in orbit around Mars, landing missions will ultimatively provide ground truth for the occurrence of these minerals (Chap. 5).

The occurrence of sulfates has been interpreted as evidence for a very specific environment on Mars' surface and subsurface, i.e., more acidic conditions for most of its post-Noachian geological history. Some of the sulfates at low latitudes, for example those in Valles Marineris, are of Noachian to Hesperian age, and were either formed by primary or secondary processes. Others such as those in Terra Meridiani could be linked to evaporitic processes (Chap. 9). Finally, some are much younger and related to recent deposits, such as the circum-polar sulfate deposits linked to recent to active eolian landforms (Fig. 11.14). These sulfates possibly represent lag materials previously altered by and within ice rather than liquid water.

One large difference across terrestrial planets with an atmosphere (Venus, Earth, Mars) is the production of carbonates as local, regional, or global sinks of CO_2, either now or in the past. On Earth, life effectively supports the precipitation of carbonates to form extensive carbonate deposits. On Mars, the formation of carbonates is more local, at smaller scale, and most likely inorganic. On Venus, carbonates are unknown (Chap. 14).

11.3.2 Cryosphere and Water Loss

The existence of a past hydrological cycle on Mars is supported by several lines of geological evidence. On the basis of numerous studies it became clear that water was temporally stable at the surface, decreased in availability, some was lost to space, and some built up a partially global cryosphere.

The original amount of water on Mars surface has undergone large and difficult to quantify losses, with some models suggesting 95–99% loss of surface water. Today, some of this water is either stored in the subsurface cryosphere or was lost from the upper atmosphere. The many widespread outflow and collapse features, largely Hesperian and Amazonian in age, might have a common origin related to the release and recharge of subsurface water/ice, with an overall long-term volatile depletion. Mars' cryosphere has a much wider geographical and topographic distribution than on Earth, where the cryosphere is concentrated in higher latitudes and at high altitudes. Using radar sounding and neutron spectrometers, different spatial scales of the cryosphere could be explored, ranging from the first meter of regolith, as observed with neutron spectrometers to kilometer vertical scale as observed with orbital sounding radars (Chap. 3).

Some models predicted that the martian highlands were ice-covered for long periods of time during the Noachian, somewhat similar to the so-called snowball Earth state (Fig. 11.6). If correct, interaction between vigorous volcanism and such an ice cover could have produced liquid water early in Mars' history without puncturing the cryosphere as was the case to form the outflow channels mostly during the Hesperian.

Unlike geologically less diverse bodies such as the Moon and Mercury, Mars and Earth experienced, for most or all of their history, interactions between different geologic processes at multiple scales (Fig. 11.15). The interaction between distinct endogenic and exogenic geological processes through time produced the current surfaces on Mars and Earth (Fig. 11.17). The cumulative growth of continental crust on Earth in the last 4 Gyr and the growth of its younger oceanic crust are rather late events when compared to the surface ages on Mars. On dynamic Earth, geologic processes are still active and ongoing today whereas Mars' geologic activity is mostly ancient.

The progressive growth of continental crust and the plate tectonics-driven mobility of continents through time have a tremendous impact on climate, contributing to large-scale ice caps and global ice ages (Fig. 11.6). Those large-scale events, about 1.2 Gyr ago, are still preserved in the geologic record of Earth. Much shorter timescales are involved in recent ice ages, on Earth as well as on Mars.

Planet-wide or global climate changes occurred on three of the terrestrial planets, Venus, Earth, and Mars. These climate changes occurred at multiple temporal scales and are either linked to the large-scale configuration of lithospheric plates or driven by a variety of dominating processes, including orbital dynamics (Mars), endogenic activity or climate-endogenic coupling (Venus). On Earth, also effects of human activity are discussed to contribute to climate change (Fig. 11.16).

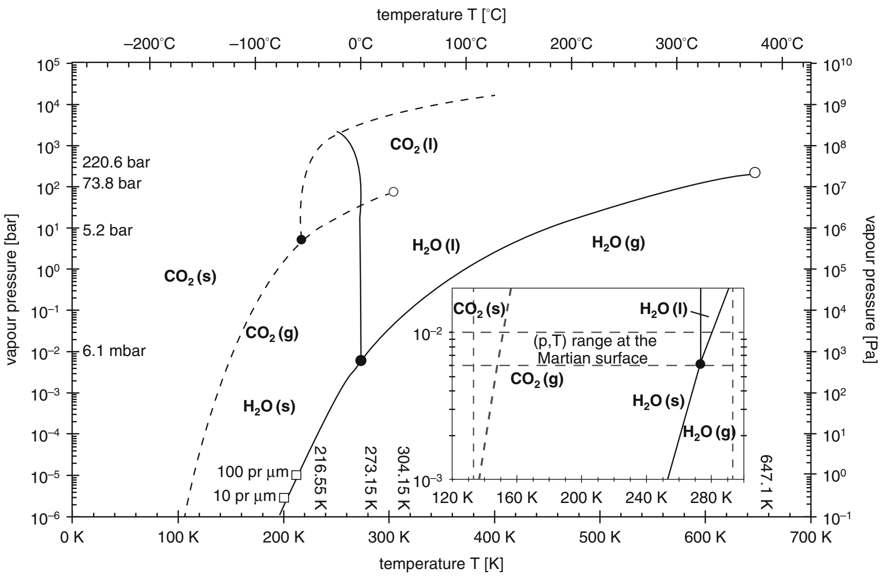

Fig. 11.16 Phase diagram for water and carbon dioxide as well as frost-point temperatures for a well-mixed atmosphere and 10 pr µm and 100 pr µm atmospheric water vapor. *Filled and empty circles* are respectively critical and triple points. Source: figure from van Gasselt (2007) and reference therein

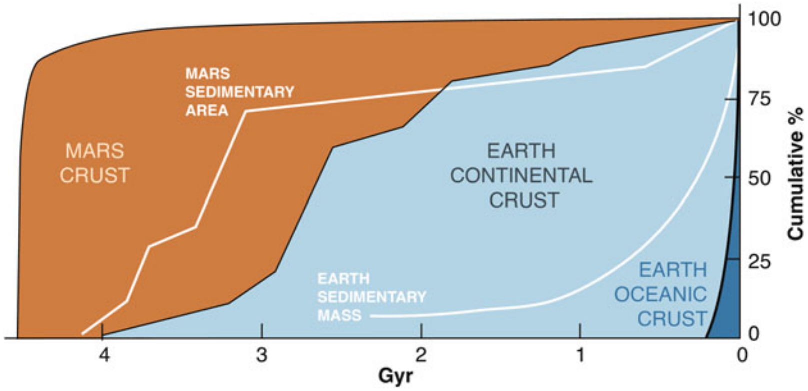

Fig. 11.17 Relative comparison of Earth's and Mars' crust production through times and sedimentary rocks. Volumetric information available on Earth is lacking on Mars, thus surface area as measured on global geological maps is used. Source: modified from McLennan (2012), after Taylor and McLennan (2009)

Globally acting sedimentary processes as recorded by extensive sedimentary deposits are preserved and more or less accessible only on Earth and Mars. Although Venus might host ancient sedimentary deposits as well, they still need to be identified. On Earth and Mars, the amounts of sedimentary rocks produced through time follow the respective degree of preserved geological activity (Fig. 11.17). Mars, for example, had an early intense period of global geological activity followed by less intense regional and local geological processes. While volcanism lasted quite long, until the recent geological past (∼10–100 Myr), most sedimentary rock formation dates back to the Noachian/Hesperian, with far less steep production rates in the Amazonian. Earth's sedimentary record is best preserved in the Phanerozoic, while its present oceanic basins are of even younger age (Fig. 11.12).

11.4 Recent Phases

Each planet has seen its own geological evolution and the timing of geological processes is not necessarily contemporaneous among these objects. On Earth, the last billion years make up a substantial part of its recorded history, during which endogenic activity (Chap. 8), life (Chap. 14), modern sedimentary processes (Chaps. 2 and 9), and most modern plate tectonics processes occurred. In contrast, for the Moon, the last billion years is a period of extremely low activity, characterized by continued impact bombardment and small-scale volcanic activity. Similarly, Mercury also shows evidence for low activity during this time, although some late-stage local volcanic processes have been discovered on its surface.

Mars on the other hand, has experienced quite some geological activity, although not comparable with the activity taking place in the Noachian and Hesperian. For example, most of the volcanism linked to the Tharsis province is Amazonian in age (Fig. 11.4), and the observed polar caps are also considered to be recent features.

Large-scale plate tectonics dynamics have been linked to long-term climatic conditions on Earth. The assemblage of supercontinents occurred several times (Fig. 11.6) since the Proterozoic (e.g. Rhodinia, Pangaea) and was associated with large-scale continental glaciations (Fig. 11.6). Possibly, similar phases of glaciation also occurred much earlier, i.e., associated with older supercontinents.

On a different time scale, of few million years or less, Quaternary ice ages on Earth are globally recorded in landforms and the geological record, e.g. in proxies from sediment cores.

The absolute magnitude of astronomical variations leading to terrestrial ice ages is relatively small. The tidal locking and synchronous rotation (Chap. 1) of the Earth-Moon system stabilizes the inclination of Earth's spin axis obliquity, that varies only within little more than two degrees. On Mars, due to the lack of sizeable moons, such a stabilizing effect is not present and the range of variation of its obliquity over timescales of few million years can be of several tens of degrees. Such variations had large impacts on Mars' cryosphere and overall volatile distribution in the subsurface, surface, and atmosphere. The location of polar caps during late Amazonian ice ages on Mars could have been in different geographic positions. However, because the locations of potential palaeo-polar caps are not well established, there exist different interpretations of specific widespread geological units, such as the Medusa Fossae Formation (Fig. 11.15), ranging from volcaniclastic to glacial.

During higher obliquity periods, larger amounts of volatiles were injected into Mars' atmosphere, possibly resulting in snow precipitation, at least locally. Such short term (few million years) snow accumulation could produce glaciers, whose possible geomorphologic traces have been identified on Mars in several locations (Chap. 9). Evidence of widespread recent periglacial features on Mars also exist. Permafrostrelated features are very common in the mid and high latitudes on Mars. In particular, features such as gullies, which on Earth are often linked often to near subsurface ice melting or precipitation of snow, are widespread in higher mid latitudes. Although their exact mechanism of formation is debated, they were active in the very recent geological past, possibly during or after higher obliquity phases with increased subsurface ice melting. Alternatively, dry processes or liquid water sources have also been suggested for explaining their development.

On Mars, chasmata and canyon development continued locally into the Amazonian. It is also plausible that, volatiles were exchanged between the polar caps, the ice in the regolith, and the atmosphere. The dynamics of such exchange processes were also linked to climatic variations. Recent processes on Mars include the formation of perchlorates, very reactive compounds detected for the first time on the northern plains at the Phoenix landing site, (Chap. 15). In the presence of ice, these perchlorates could result in brines formed near the surface (Chap. 9).

It has been proposed that brines might be responsible for the formation of recurring slope lineations (RSL), i.e., flow-like surface changes on sloped surfaces. These RSL features have been detected in different locations and are spatially associated with the presence of hydrated salts. Although possible sources of water responsible for such flow features on present Mars are not clear (subsurface, atmosphere), their current state of activity has been well-documented.

Aeolian processes occur on three out of four terrestrial planets (Earth, Mars, and Venus), and are also active on some icy satellites (Chap. 12), and might even affect the surface on comets (Chap. 13). Active depositional features are documented on Mars and are likely on Venus. Unlike on Earth where aeolian sand tends to be largely made of quartz and igneous minerals are rather rapidly weathered, Mars' dunes are mostly composed of basaltic sand. On Earth, deserts and sand seas occur predominantly at relatively low latitudes; on Mars there is a clustering of dune fields close to the north polar cap (Fig. 11.18). On Venus, aeolian depositional features were not yet imaged in enough detail to resolve their characteristics.

Surface-atmosphere interaction is important on all major terrestrial planets, including presentday weathering. In particular, transient and local, but very widespread phenomena such as dust devils are responsible for large amounts of dust injected into the lower atmosphere of Mars, with possible effects on the climate.

In the last billion years, little geologic activity occurred on Mercury and the Moon. Such activity is mostly limited to impacts (e.g., the formation of the lunar Copernicus crater in the last few hundred Myr), local mass wasting, and the effects of space weathering on the surface regolith, including implantation of ions from the solar wind (Chap. 15). Mass wasting driven by gravity, impacts and possible internal activity is an ongoing process occurring at low pace, on several terrestrial planetary bodies, such as Mars and the Moon. Recent mass wasting processes were imaged on the Moon, while active avalanches on polar deposits were imaged on Mars by orbiters several times. On the other hand, in the very same last billion years or so Venus experienced most of its recorded geological activity. The basis for reconstructing Venus' global history and evolution is largely geological mapping (Chap. 4), but the integrated study of its climate and atmospheric evolution, including modelling, is important too (Chap. 11).

On Venus, the earliest unit preserved, the tessera terrain, covers approximately 8% of Venu's surface (Fig. 11.13), and recorded early large-scale contractional and extensional phases, likely during geologically short, very intense deformation phases. Substantial deformation also affected the earliest post-tessera volcanic plains. This deformation was concentrated locally and resulted in ridge belts (Chap. 8). On Venus, the detailed geological history can only be described in a relative sense, not chronostratigraphically, because the homogeneous and random distribution of impact craters does not allow dating of specific surface units. Regional to global events of extension and compression alternate in the youngest units and localized extension associated with volcanic rises (e.g., similar to what occurs on Earth) is present. Overall, it appears that volcanic and tectonic processes recorded on Venus' surface were active globally. Similar to other terrestrial planets other than Earth, their magnitude appears to have decreased with time.

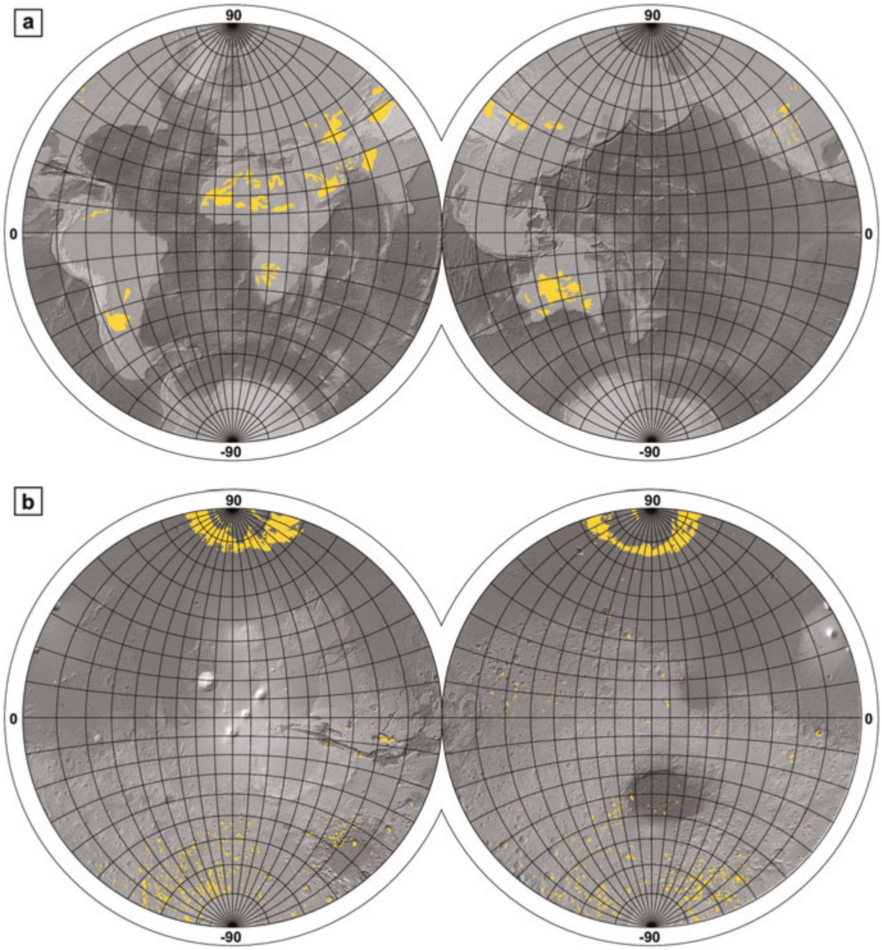

Fig. 11.18 Aeolian processes and products are present on Earth, Mars and Venus. The largest deposits are present on Earth and Mars; (**a**) global map of sand seas on Earth; (**b**) global occurrence of sand dunes on Mars. Sources: (**a**) data from Sun and Muhs (2007). (**b**) Hayward et al. (2007, 2010, 2012)

In its recent geological past (less than 1 Gyr), Venus experienced a more or less global volcanic resurfacing that erased almost all existing terrains as well as the evidence for the early geologic history. The coupled endogenic and atmospheric evolution produced a very pronounced climate change. Although ancient, pre-resurfacing surface conditions are not accessible anymore, the isotopic record of the atmosphere and numerical climatic models hint at possibly very different conditions, compared to today's greenhouse.

The range of documented active processes on the terrestrial planets is wide (Table 11.1): space weathering and continued impact cratering are the most

Table 11.1 Comparison of recent and current processes on the terrestrial planets and the Moon

Body	Endogenic	Surface	Surface/atmosphere
Mercury	None	Space weathering, volatile escape/exchange in polar areas	Loss to exosphere
Venus	Recent, possibly active volcanism	Aeolian processes, surface physical and chemical alteration	
Earth	Plate Tectonics, volcanism	Active hydrology and sedimentary cycle	Ample surface-atmosphere interaction, alteration, pedogenisation
Moon	Low seismic activity, recent volcanism?	Space weathering, mass wasting	Volatile escape/exchange in polar areas
Mars	Recent Volcanism, possibly recent/present seismic activity (?)	Active aeolian processes	Volatile exchange between polar caps, regolith and atmosphere, possible local surface brines

Impact processes are not included because they are ubiquitous on all planets with the exception of Venus, where most small impactors never reach the surface because of the thick atmosphere (see Chaps. 8 and 10)

important processes on virtually airless bodies (the Moon, Mercury) while surface-interior and surface-atmospheric interaction is important on other planets (Venus, Earth, Mars).

11.4.1 Planetary Global Change and Perspectives

Planetary sciences and geology traditionally address long-term and large-scale evolutionary aspects of planets, although uncertainties are often high, particularly for targets or processes observed for the first time (Chap. 1). Data of planets such as Mars have by now excellent spatial and temporal coverage, although not always continuous.

One of the messages conveyed by the cumulated geological understanding of the terrestrial planets is that both internal and external dynamics globally affect the planets. Examples of the latter include increased phases of impact cratering (e.g., LHB), related to both enhanced atmospheric erosion and surface disruption or subsurface mobilization. Internal processes such as global partial melting of the mantle and resurfacing on Venus as well as plate tectonics on Earth have/had profound, long-lived global consequences for the entire planet. In Earth's case, the onset of life triggered changes both in the geosphere and atmosphere (Chap. 14).

Recent to current processes across terrestrial planets that bear certain resemblance, although at largely different spatial and temporal scales, include, for example: The greenhouse effect (Venus, Earth), and recent climatic cycles (Mars, Earth). The extreme climatic conditions and greenhouse effect on Venus are mainly linked to its geodynamics. On Earth, the change from a CO_2-rich atmosphere to a nitrogen/oxygen atmosphere is related to the evolution of life. Recent, non negligible effects on the geologic evolution of Earth are linked to human activity. Thus, the formalization of anthropogenic effects in the geological records has been discussed lately and might eventually result in a formal stratigraphic epoch name (Chap. 2). On Mars, recent climate cycles and their effects on surface landforms are well-recorded and are similar in scale and processes to those on present glacial or periglacial areas on Earth, particularly to selected, very cold and very dry locations such as the Dry Valleys in Antarctica (Chaps. 2 and 9).

As much as the traces of human activities would most likely be retained in Earth's geological record, human artifact on other planets such as spacecrafts, structures and tools left behind on the Moon (Chap. 5), are likely to be preserved for geological timescales.

Speculating on the geological future of terrestrial planets is less difficult for the Moon and Mercury compared to the other terrestrial objects. Because the Moon and Mercury are small bodies that already cooled to large extents, not much internal geological activity is expected to take place on them. Venus, is characterized by episodic convective mantle overturn that recycles the surface at global scales. Although little to no volcanic activity is currently observed, at time scales of hundreds of million years or billion years, it is expected that Venus will experience periods of extreme activity. On Earth, geologically long-term changes in the tectonic regime, such as a stop of plate tectonics and an evolution toward a stagnant lid regime (Chap. 10) could be a few billion years ahead. Thus, overall changes in the atmosphere and the near subsurface, for example, with the release of volatiles from ground or seabed reservoirs (e.g., chlathrates) are more likely in the geological near term. The effects of those changes might be substantial and even tragic for mankind. The related geological record is likely to be condensed just on relatively thin deposits, although globally correlated.

The understanding of Earth-like planets such as Venus and Mars can shed light on both past and future processes, whose record is incomplete or absent on Earth. The Moon is unique in that it is history book of more than 4.5 Gyr Solar System evolution which retains a geological record that is very complementary to ours. The growing understanding of the most remote terrestrial planet, Mercury, can inform us on how Earth evolved compositionally, e.g., with respect to a late delivery of carbon by a C-rich planetesimal, with similarity to Mercury, also more C-rich, compared to other terrestrial planets. The growing evidence from astronomical observations of terrestrial exoplanets enormously widens the range of possible geological boundary conditions; the most accessible examples though, are those in the Solar System.

Take-Home Messages

Terrestrial planets share several characteristics, including a variably preserved impact cratering history, silicate volcanism and tectonic deformation driven by very diverse geodynamics.

The bulk of the geological activity is concentrated at different age ranges for different planets: intense and violent early phases for all planets, followed by variable phases of volcanism, deformation and, for Mars and Earth, sedimentary activity.

The Moon, Mercury, and to a large extent also Mars allow access to the geological record of the early Solar System. Earth and Venus retain little information about the first hundred Myr of Solar System history but have a better record of the most recent several hundred Myr.

Beside impact cratering, volcanism and tectonism dominated the geological evolution of all terrestrial planets and the Moon, particularly during the first 1–2.5 Gyr. Mars exhibits large-scale volcanic activity that continued past the first 2.5 Gyr. Venus and Earth are the two planets that were most recently/currently volcanically active.

Sedimentary processes linked to a transient or stable hydrosphere are recorded on Earth and Mars. Venus could have hosted a hydrological cycle during its early phases of geologic evolution, but evidence for such a cycle has been erased from its geological record.

The level of current activity is variable on the terrestrial planets. Apart from the present low impact rate, common to all planets, Mercury and the Moon are the least active. Venus is possibly active both volcanically and tectonically. On Mars and Earth numerous geologic processes are active today.

Global, often catastrophic changes are documented, within different geological boundary conditions, on all terrestrial planets.

Further Readings

Arvidson, R.: Aqueous history of Mars as inferred from landed mission measurements of rocks, soils, and water ice. J. Geophys. Res. Planets. **121**(9), 1602–1626 (2016). doi:10.1002/2016JE005079.

Balme, M., Gallagher, C., Hauber, E.: Morphological evidence for geologically young thaw of ice on Mars: a review of recent studies using high-resolution imaging data. Prog. Phys. Geogr. **37**(3), 289–324 (2013). doi:10.1177/0309133313477123.

Basilevsky, A.T., Head, J.W.: The geologic history of Venus: a stratigraphic view. J. Geophys. Res. Planets **103**(E4), 8531–8544 (1998). doi:10.1029/98JE00487

Carr, M.H.: Channels and valleys on Mars: cold climate features formed as a result of a thickening cryosphere. Planet. Space Sci. **44**(11), 1411–1423 (1996). doi:10.1016/S0032–0633(96)00053-0

Carr, M.H., Head, J.W.: Geologic history of Mars. Earth Planet. Sci. Lett. **294**(3), 185–203 (2010). doi:10.1016/j.epsl.2009.06.042

Carr, M.H., Head, J.: Martian surface/near-surface water inventory: sources, sinks, and changes with time. Geophys. Res. Lett. **42**(3), 726–732 (2015). doi:10.1002/2014GL062464

Ehlmann, B.L., Edwards, C.S.: Mineralogy of the Martian surface. Annu. Rev. Earth Planet. Sci. **42**(1), 291–315 (2014). doi:10.1146/annurev-earth-060313-055024

Elkins-Tanton, L.T.: Magma oceans in the inner solar system. Annu. Rev. Earth Planet. Sci. **40**(1), 113–139 (2012). doi:10.1146/annurev-earth-042711-105503

Farley, K.A., et al.: In situ radiometric and exposure age dating of the martian surface. Science **343**(6169), 1247166 (2014). doi:10.1126/science.1247166

Geiss, J., Rossi, A.P.: On the chronology of lunar origin and evolution. Astron. Astrophys. Rev. **21**(1), 1–54 (2013). doi:10.1007/s00159-013-0068-1

Gregg, T.: (2015). Planetary tectonics and volcanism: the inner solar system. In: Schubert, G. (ed.) Physics of Terrestrial Planets and Moons. Treatise on Geophysics, vol. 10, Chap. 9, pp. 307–325, 2nd edn. Elsevier, Oxford (2015). doi:10.1016/B978-0-444-53802-4.00187-1

Grotzinger, J., Hayes, A., Lamb, M., McLennan, S.: (2013). Sedimentary processes on Earth, Mars, Titan, and Venus. Comp. Climatol. Terr. Planets **1**, 439–472 (2013)

Hansen, V.L.: Impact origin of Archean cratons. Lithosphere **7**(5), 563–578 (2015). doi:10.1130/L371.1

Hansen, V.L., Young, D.: Venus's evolution: a synthesis. Geol. Soc. Am. Spec. Pap. **419**, 255–273 (2007). doi:10.1130/2006.2419(13)

Hartmann, W.K.: The giant impact hypothesis: past, present (and future?). Philos. Trans. R. Soc. Lond. A Math. Phys. Eng. Sci. **372**(2024) (2014)

Helbert, J., Hauber, E., Reiss, D.: Water on the terrestrial planets. In: Schubert, G. (ed.) Physics of Terrestrial Planets and Moons. Treatise on Geophysics, vol. 10, Chap. 11, pp. 367–409, 2nd edn. Elsevier, Oxford (2015). doi:10.1016/B978–0-444-53802-4.00174-3

Hiesinger, H., Head, J.W.: New views of lunar geoscience: an introduction and overview. Rev. Mineral. Geochem. **60**(1), 1–81 (2006). doi:10.2138/rmg.2006.60.1

Lasue, J., Mangold, N., Hauber, E., Clifford, S., Feldman, W., Gasnault, O., Grima, C., Maurice, S., Mousis, O.: Quantitative assessments of the martian hydrosphere. Space Sci. Rev. **174**(1), 155–212 (2013). doi:10.1007/s11214-012-9946-5

McLennan, S.M., et al.: Geochemistry of sedimentary processes on Mars. Sediment. Geol. Mars **102**, 119–138 (2012)

Reiss, D., Lorenz, R., Balme, M., Neakrase, L., Rossi, A.P., Spiga, A., Zarnecki, J. (eds.) Dust Devils. Space Sciences Series of ISSI, vol. 59, 426 pp. Springer (2017). ISBN: 978-94-024-1133-1, ISSN: 1385-7525

Smrekar, S.E., Stofan, E.R., Mueller, N., Treiman, A., Elkins-Tanton, L., Helbert, J., Piccioni, G., Drossart, P.: Recent hotspot volcanism on Venus from VIRTIS emissivity data. Science **328**(5978), 605–608 (2010). doi:10.1126/science.1186785

Steffen, W., Leinfelder, R., Zalasiewicz, J., Waters, C.N., Williams, M., Summerhayes, C., Barnosky, A.D., Cearreta, A., Crutzen, P., Edgeworth, M., Ellis, E.C., Fairchild, I.J., Galuszka, A., Grinevald, J., Haywood, A., Ivar do Sul, J., Jeandel, C., McNeill, J., Odada, E., Oreskes, N., Revkin, A., Richter, D.D., Syvitski, J., Vidas, D., Wagreich, M., Wing, S.L., Wolfe, A.P., Schellnhuber, H.: Stratigraphic and Earth System approaches to defining the Anthropocene. Earth's Futur. (2016). doi:10.1002/2016EF000379

Taylor, S.R., McLennan, S.: Planetary Crusts: Their Composition, Origin and Evolution, vol. 10. Cambridge University Press, Cambridge (2009)

Way, M.J., Del Genio, A.D., Kiang, N.Y., Sohl, L.E., Grinspoon, D.H., Aleinov, I., Kelley, M., Clune, T.: Was Venus the first habitable world of our solar system? Geophys. Res. Lett. (2016). doi:10.1002/2016GL069790

Werner, S.C., Ody, A., Poulet, F.: The source crater of Martian Shergottite meteorites. Science **343**(6177), 1343–1346 (2014). doi:10.1126/science.1247282

Wilhelms, D.E., John, F., Trask, N.J.: The geologic history of the Moon. USGS Professional Paper, vol. 1348. U.S. Geological Survey. http://ser.sese.asu.edu/GHM (1987)

Wordsworth, R.D., Kerber, L., Pierrehumbert, R.T., Forget, F., Head, J.W.: Comparison of warm and wetİ and cold and icyİ scenarios for early Mars in a 3-D climate model. J. Geophys. Res. Planets **120**(6), 1201–1219 (2015). doi:10.1002/2015JE004787