18. Results, Prospects, and Applications

This thesis provides a coherent view on the geological evolution of Mars, focusing on impact cratering, volcanic, fluvial, and glacial processes. In addition to tectonics and aeolian dust distribution, theses processes play a significant role in sculpting the Martian landscape. Notably the volcanic and related tectonic activity sheds lights on the internal dynamics and thermal evolution of planets. By understanding the evolutionary history of Martian volcanic constructs, the formation time of large impact basins, as well as the evolution of the northern lowlands and the dichotomy boundary, essential time–markers are gathered in this work. After having provided a time–frame of surface processes, the timing for the thermodynamical evolution of Mars can now be assessed.

The apparent absence of plate tectonics on Mars and the presence of huge volumes of strongly magnetized crustal materials, requiring the presence of a strong dynamo field in ancient times, makes Mars an interesting planet to compare with Earth or other terrestrial inner Solar System bodies.

One of the most startling planetary scientific discoveries in recent years was the observation of strong Martian crustal magnetism (Acuña *et al.*, 1999). Though an internal dynamo is not currently active, Martian crustal palaeo–sources are orders of magnitude stronger than lunar fields, as strong or stronger than any terrestrial crustal fields. The properties of the current crustal magnetization provide information regarding the geologic processes responsible for its formation, while constraints on the time history of the dynamo will provide information about the thermal history of the interior and in turn will provide vital information concerning Mars's formation and dynamic evolution. Finally, the history of the dynamo may prove relevant to atmospheric loss through time, with implications for climate (and astrobiological considerations). Understanding the age distribution of Martian magnetic anomalies will allow us to determine the history of the Martian dynamo and consider the implications for the formation as well as the geologic and climatic evolution of Mars as will be outlined below.

Many aspects of the scenario of the early and subsequent evolution including internal dynamics of Mars has been discussed earlier (most recently e. g. by Spohn *et al.*, 2001; Solomon *et al.*, 2005; Nimmo and Tanaka, 2005). Usually, the timing is based on educated guesses, while the results of this thesis essentially push the time–frame forward. The evolutionary geologic history of Mars based on ages gathered in this thesis is given in Fig. 18.1.

The visible crustal age in the southern highland unit, carrying the strongest remnant magnetization, appears to have formed before 4.1 to 4.2 Ga (Chapt. 13), while the oldest known Martian meteorites indicate a crustal age of about 4.5 Ga (Chapt. 6.1). Most of the southern highland areas, showing weaker magnetization, are subsequently resurfaced (by fluvial erosion and possibly volcanic deposition). Crater counts yield ages around 4.0 Ga. While the absolute ages for this period do not differ very much, the relative ages from crater frequencies differ up to a factor of two. Crater counting methods, nevertheless, cannot account for any evolution earlier than documented in the crustal formation. Due to the high impact flux, saturation may have been reached and the net accumulation may be indetermined, thereby limiting this method of age determination to about 4.3 Ga. In this investigation no surface is found to be older than 4.2 Ga (Chapt. 13).

The Martian dynamo must have been active before 3.9 Ga. The cessation of the magnetic field seems to be correlated with the formation of the large impact basins, Hellas, Argyre, Isidis

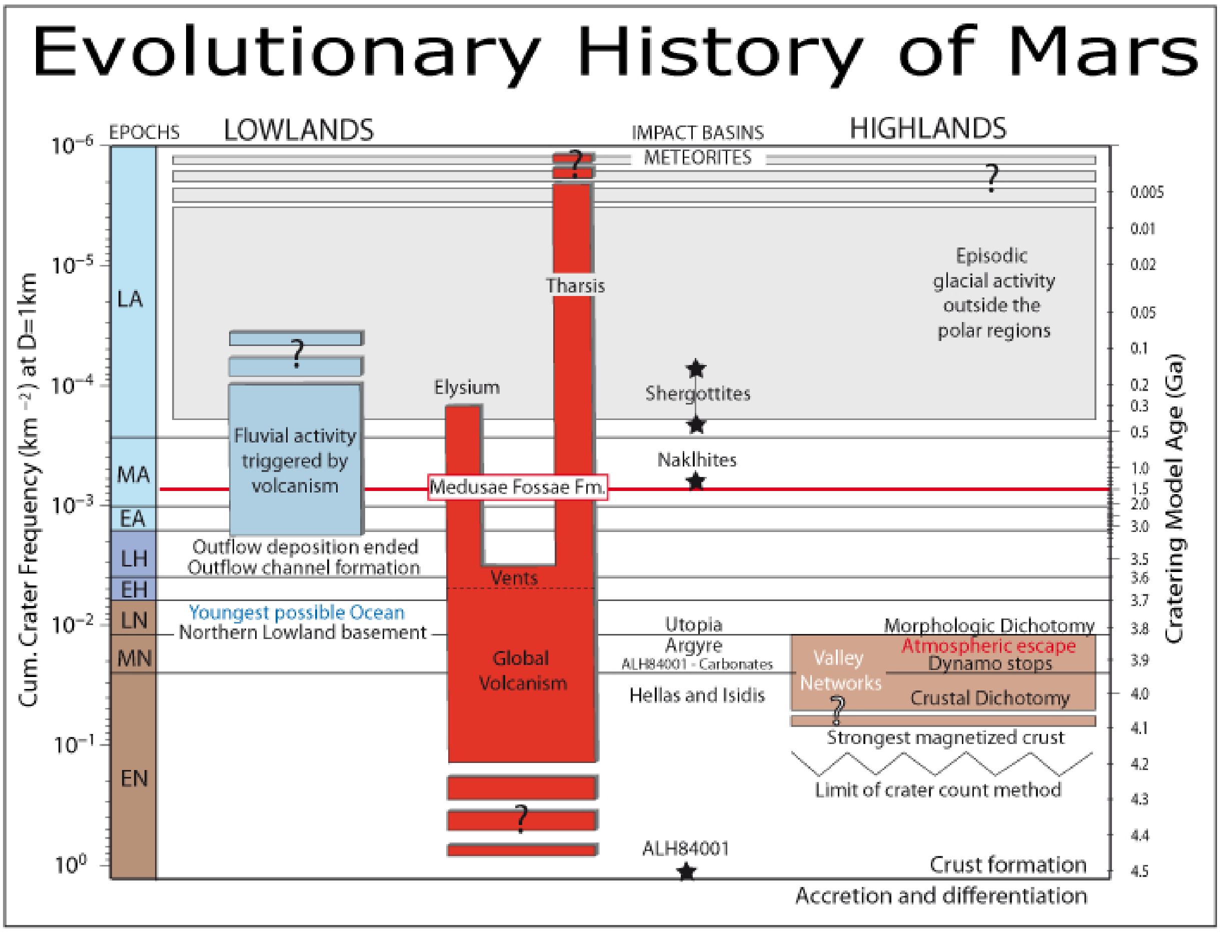

Figure 18.1.: The global geological evolution of Mars derived from ages determined in this work. It is distinguished between the evolution of the lowlands and highlands. Impact basin formation and meteoritic crystallization ages are indicated as time–markers. The volcanic evolution is shown separately because the volcanic history is independent of these two crustal units. Tectonic features are strongly related to the volcanic activity and not specifically discussed in this figure. The *Medusae Fossae formation* and *episodic glacial activity outside the polar regions* are not particularly identified in any of the hemispheres. Similarly, aeolian features appear planet–wide and are not specifically related to any epoch. Generally, a decay of such an activity is observed. Ages are given according to the cumulative crater frequency (left) and in absolute ages (right), additionally, the geologic epoch boundaries are shown (following Tanaka *et al.* (1992a), LA, MA, EA, assign Late, Middle, and Early Amazonian, LH and EH stand for Late and Early Hesperian, and LN, MN, and EN for Late, Middle and Early Noachian. No ages older than about 4.15 Ga are found in this investigation.

and Utopia (Chapt. 13). They are devoid of long–wavelength magnetic anomalies (observed at spacecraft height of about 150 km on average). At least Hellas and Isidis formed about 4.0 Ga ago, while Argyre and most likely Utopia are younger. Nevertheless, the period of cooling of a melt pocket formed by such a large impact event and the temperature drop below the Curie temperature (blocking of a remnant magnetization), could take as much as a few 100 Ma (Reese *et al.*, 2004). The formation time of the crater and the drop below the Curie temperature of the formed melt body is therefore not identical, and hence large basins are not the best time–marker for the cessation of the dynamo (they provide a minimum age). Further confirmation is found at volcanic constructs. Hadriaca Patera shows magnetic signatures, supporting a cessation of the dipole field around 3.9 Ga. Similarly, the basins are used as time–marker for the formation of the crustal dichotomy, reflected in the north–south varying crustal thickness. The observed crustal (thickness) distribution was established early and was modified through these impacts. Nevertheless, this study could not confirm a simultaneous formation of the early lowland and highland crust. The formation of the morphologically defined dichotomy is most likely happened at a different time–scale (Chapt. 14.2). Subsequently, further modification (e.g. crustal thickening) occurred through volcanic activity in the two large volcanic provinces Tharsis and Elysium. No quasi–circular depressions were mapped (Frey *et al.*, 2002), but similar methods were used to define the age differences between visible surface and underlying basement which formed about 3.4 Ga and 3.8 Ga ago, respectively (Chapt. 14.3). The age difference between the highlands and the presumed basement of the lowlands is roughly 200 Ma, based on crater counts. In favour of a crustal formation in the lowlands after the cessation of a dynamo, the results gathered in this thesis fit better.

Plains formation and surface ages of the small tholi and paterae in the Tharsis region indicate that there globally volcanic activity had occurred since 4.1 Ga ago and continued to about 3.7 Ga. All volcanic constructs were emplaced to its now observed size before 3.55 Ga ago (with the exception of Olympus Mons which lost part of its outer shield before 3.7 Ga ago). Most volcanic plains (e.g. Hesperia Planum) were emplaced before this time (Chapt. 15). The end of this period of global volcanic activity is correlated with the outflow channel formation. Generally, the erosive process by fluvial activity and the global volcanic activity decreased after 3.5 Ga. In the northern lowlands the layer of deposits formed during that time and grew to a thickness of possibly a few kilometers in the depressions (Chapt. 14.1). Valley networks are found dominantly in highland regions and are believed to be older than the outflow channels.

In the presence of a self–sustained magnetic field (requiring a partly fluid core) the atmosphere is more stable against solar wind. On Earth (or Venus) the gravitational effect is strong enough to keep an atmosphere even without a dynamo, while on Mars major atmosphere escape probably occurred within 50 – 100 Ma, after the cessation of the dynamo. Any possibly existing water–cycle then vanished due to the atmospheric loss. Escarpments found at Olympus Mons and Apollinaris Patera indicate different environmental conditions during their formation compared to Alba Patera and the Elysium bulge. While the slopes of Alba Patera and the Elysium region formed before 3.6 Ga ago, the aureole of Olympus Mons formed around 3.8 Ga ago. The surface of Apollinaris Patera is older than 3.7 Ga (Chapt. 15). Any ancient ocean in the northern lowlands disappeared before 3.7 Ga ago (Chapt. 14.1), either froze, or a substantial fraction of the water was lost to space as the atmospheric D/H ratio suggests (Owen *et al.*, 1988). The ages of valley networks, believed in general to be older than outflow channels, support this idea of an at least episodically existing water–cycle on early Mars (Chapt. 14.6).

Younger resurfacing is dominated by volcanic activity which triggered subsurface water release and allowed for additional ice deposition, but permanently liquid on the surface of Mars is impossible after the atmosphere was lost (Chapt. 16).

Hand in hand with the understanding of the time frame of the decay of the Martian magnetic field, the thermal evolution and the internal dynamics are more constrained. While large–scale convection in the mantle is responsible for the continuous reshaping of Earth's surface through plate tectonics, plate tectonics is currently not observed on Mars. There are speculations that the dichotomy boundary is a

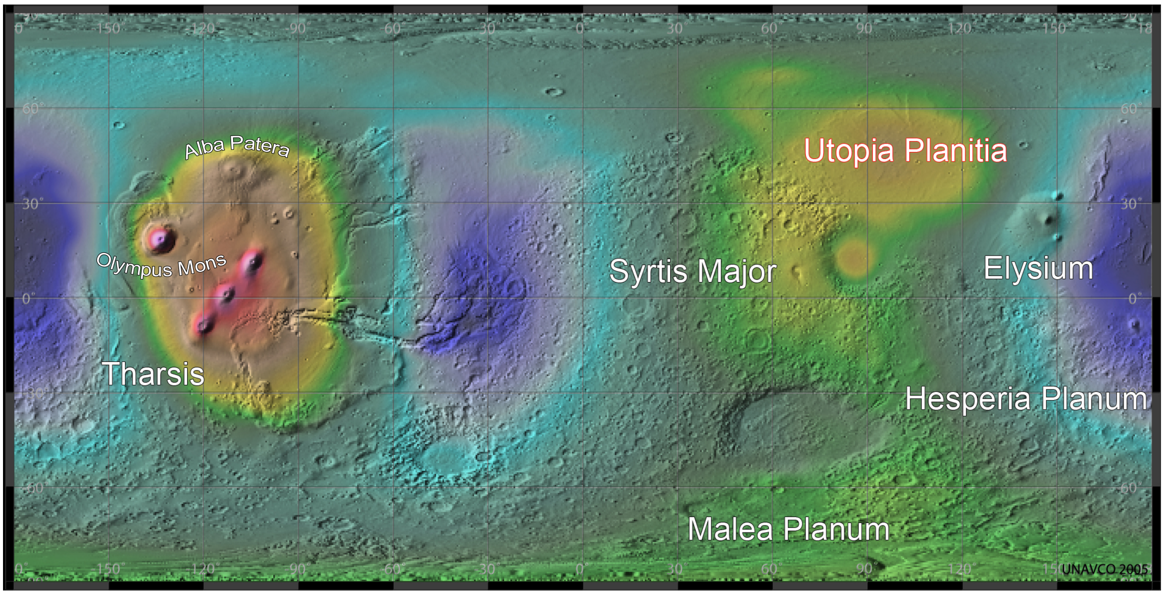

Figure 18.2.: Mars Laser Altimeter Topographic data (shaded relief) with a superimposed areoid (red is high, blue low);(map provided by UNAVCO; http://jules.unavco.org). Volcanic regions are marked. A correlation of possibly still active volcanic provinces and a high areoid is obvious in the Tharsis region, and probably a local high in the Elysium region. Olympus Mons and Alba Patera are situated along the margin of the areoid high as seen from many LIPs from Earth.

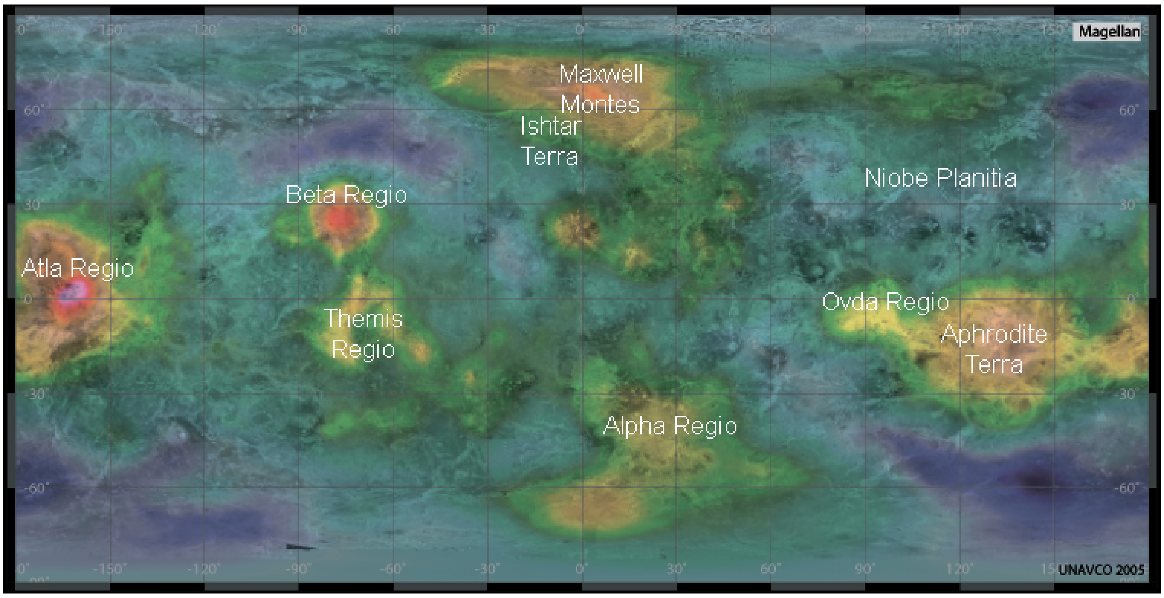

Figure 18.3.: Magellan radar maps (gray scale) with a superimposed Venusian geoid (red is high, blue low);(map provided by UNAVCO; http://jules.unavco.org). Prominent features are marked. A correlation of possibly still active volcanic provinces and a high geoid are obvious in e.g. Beta Regio or Atla Regio. These local highs are associated to mantle dynamics as seen from many Large Igneous Provinces on Earth.

relic of ancient plate tectonics, including global–scale resurfacing through Rayleigh–Taylor instabilities or other long–wavelength convections that formed the northern lowlands. The crust (or basement rock) formed earlier than the visible surface implies. Furthermore, ancient plate tectonics was suggested (Sleep, 1994) due to the magnetic anomaly pattern in the highlands (Connerney *et al.*, 1999), despite lacking equivalent surface morphologies. Any visible tectonics, regional tectonics or local deformational features, are usually associated with volcanic constructs, but no landforms are convincingly associated with ancient plate tectonics such as subduction zones, mountain belts or mid–ocean ridges.

On Mars, volcanism is extensive, but not uniformly distributed, and includes a diversity of volcanic landforms. The Tharsis and the Elysium regions are two volcanic provinces that are topographically dominating (Fig. 18.2), situated close to the equator on the dichotomy boundary between the cratered (older) highlands and the northern lowlands (about 120° apart). A possible correlation of young volcanism and aeroid (Mars geoid) highs could suggest upwelling mantle dynamics, contradicting a volcanism driven by a thick insulating crust. The regions, where upwelling might be indicated in the areoid, are characterized by volcanoes whose morphologies are strongly analogous to volcanic landforms on Earth. The huge volcanoes in the Tharsis region (Olympus Mons, Ascraeus Mons, Pavonis Mons and Arsia Mons) have many characteristics that strongly resemble Hawaiian shield volcanoes. The main difference between the Martian and terrestrial volcanoes are the size and length of the flows, mainly due to high eruption rates, the "stationary" character of the source (no plate tectonics), and possibly the lower gravity.

In this thesis, the results for the evolutionary volcanic history provides a time–frame for the general thermal evolution of Mars. In the early Martian history, it is evident that volcanism occurred planet–wide and most volcanic regions were emplaced before about 3.5 Ga ago. It is also demonstrated that the Elysium and Tharsis regions experienced volcanic activity until very recently (i.e. 200 to 100 Ma ago, even in a few places, until 2 to 3 Ma ago), suggesting that the most recent activities (over the last 500 Ma of Martian history) are more wide–spread than previously believed (detailed in Chapt. 15 and 15.5).

In order to explain the internal dynamics of planets, especially that of Mars, the following scenario (Spohn *et al.*, 2001) is required:

After accretion, a planet differentiate into a core, mantle, crust and atmosphere/hydrosphere of unknown conditions. Several accretion and differentiation models are known, usually, time scales of 20 to 50 Ma are involved. Mars's today's mass and moment–of–inertia factor supports the differentiated structure. The subsequent thermal evolution or cooling history is transferring heat by heat conduction and by thermal convection to remove the heat generated by radioactive nuclides and to cool the interior.

Large–scale convection has been considered to form a crustal dichotomy as derived from Mars Global Surveyor gravity and topography data. Numerical models show, simultaneously to a cooling core, the mantle flow is dominated by widely distributed down–welling. Broad local upwelling flows is commonly found in internally heated convection models. In the case of Mars, a hotter (or superheated) core allows for a spinel-perovskite phase transition, even though Mars's temperature and pressure schemes are not well–defined. This boundary might amplify large–scale and localization of upwelling flows as well as might allow for a strong dynamo in the early history of Mars. Later volcanism might no longer be driven by up–welling mantle convection (plumes) but due to crustal thickness growth and buoyancy. Although speculative and not proven for Mars, a similar scenario has been considered for Venus, where global resurfacing occurred due to thickening of the lithosphere until the internal heat excess forces a global lithospheric overturn or continuous volcanic activity covering the surface planet–wide. Both ideas compete but no final proof for one or the other case can be given through gravity. etc., (Fig. 18.3).

In this sense, Earth appears unique among the terrestrial planets in possessing plate tectonics. Possibly, its mantle convection regime produces convective stresses to generate failure in the rigid surface boundary layer. The forces of plate tectonics are not fully understood but the plate tectonics are driven by mantle convection with feedback provided by subduction. The processes requires a rigid lithosphere. Other planets appear to be in a stagnant–lid regime; a regime which is characterized by the formation of a nearly immobile lid on top of a convective mantle, that occurred due to large viscosity of the upper thermal boundary layer. Venus e.g. globally shows young surface (based on crater counts) indicating a crustal subsidence event or planet–wide volcanic eruptions during the most recent 1 billion years. A correlation of the youngest volcanic units and geoid highs is observed. Such local highs are associated to mantle dynamics.

For Mars, the following sequence of events is suggested: Major volcanic (voluminous) activity occurred globally. The cessation of the magnetic dynamo is followed by possible super–plume activity in the Tharsis region (and Elysium region). The last observed global volcanic activity ended around 3.6 Ga ago. Plains–forming activity ended even earlier. Locally, more recent activity is observed in Elysium, Tharsis and possibly at Hadriaca and Tyrrhena Paterae. A more detailed discussion is given in Chapter 15.5. Models suggest that the persistence of mantle convection stopped after the core cooled / the dynamo ceased as a consequence of too–low heat flow across the core–mantle boundary. Volcanism and magmatism continued as on Venus, in places where thick insulating crust formed. As on Earth, thermochemical heterogeneities at the core–mantle boundary could be the reason for localized upwelling. Comparable (localized) volcanic activity on Earth, Large Igneous Provinces (LIPs) result from catastrophically rapid dissipation of great quantities of internal heat, and they are not related to surficial plate tectonic processes. It has been shown (Burke and Torsvik, 2004) that there is a strong spatial correlation between LIP eruption sites for the past 250 Ma (corrected for the effects of plate tectonics) and the low seismic velocity regions (s–waves) at the core–mantle–boundary (Fig. 18.4). Timescales for mantle dynamics (plume formation) and plate tectonics are on the order of a few hundreds million years, which can be derived from ocean floor ages, hot spot ages, and formation and break–up of super–continents.

There are considerable similarities in the geoid patterns and lowermost density heterogeneities (Figure 18.4) on Earth, particularly around Africa, where there is no recent subduction, as well as on Mars. On the other hand, recent work has suggested that areoid anomalies have rather shallow origin (Zhong, 2002). On Earth, a combination of rheological models based on mineral physics and density models based on seismic tomography explains a large part of the geoid shape.

Experiences gathered through investigations on Earth will have an impact on the interpretation of findings on other planets where little detail is known. By comparatively studying Earth and Mars, the source of geoid and areoid undulations will allow a better understanding of a possible relation between lowermost mantle density anomalies and surface volcanism, and constrain crustal thickness for Mars and improve models of its thermal evolution. In most models of Mars's interior, a simple three–layered structure is assumed. Chemical boundaries or boundaries related to pressure or temperature well understood, but must differ from the Earth's structure due to size and gravity differences (see discussion by Spohn *et al.*, 2001).

A comparison of dynamical patterns reflected on the planet's surface, and of its gravity anomalies and geoid patterns allow for a better understanding of the thermal evolution of planets. The results of this thesis strongly support that Mars is a planet which takes its place between the two end–members of planetary evo-

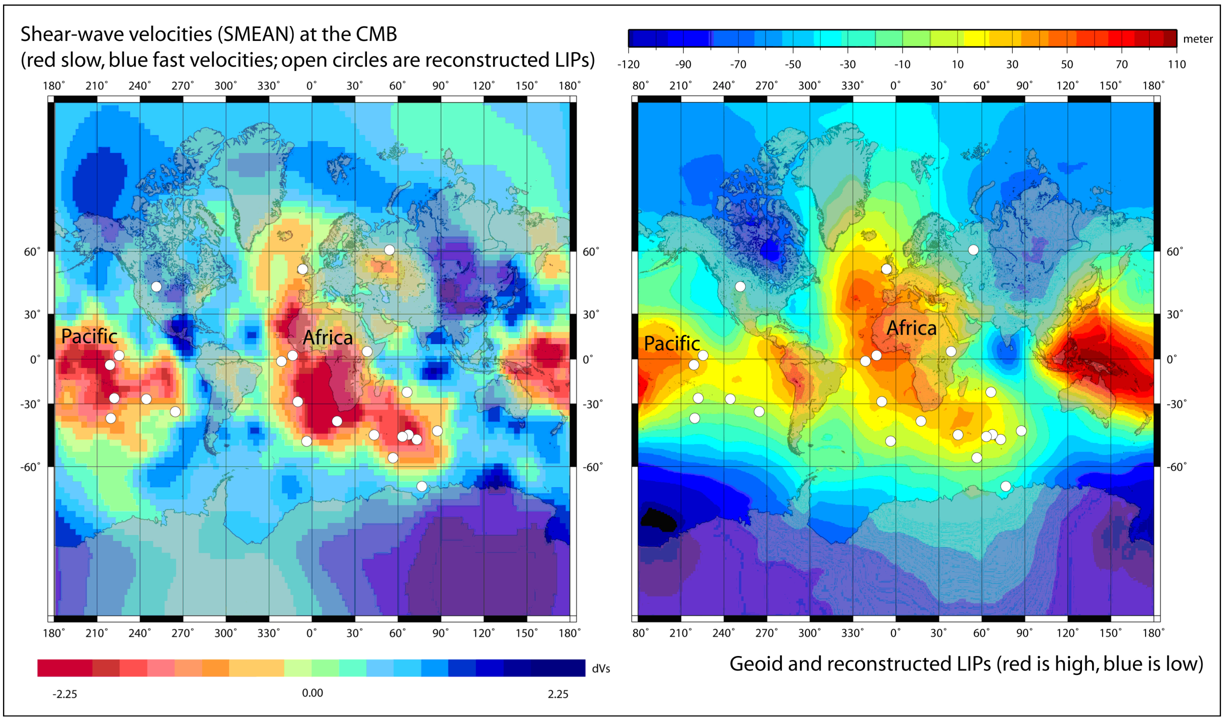

Figure 18.4.: Left: SMEAN shear wave velocity anomaly model for Earth, near the core–mantle boundary, about 2800 km depth (Becker and Boschi, 2002). Right: Earth geoid. Open white symbols are reconstructed Large Igneous Provinces (LIPs) updated from Burke and Torsvik (2004) using a revised palaeomagnetic reference model.

lution: While Mercury and the Moon appear to record the early history of the Solar System, and show no signs of water relevant to their evolution, Mars at least shows a very diverse surface history. It is most likely the only planet whose surface feature show the total record of both internal and external processes from the beginning of its existence 4.5 Ga ago until now. The role of water in its early history is unclear, but evidence for surface action of water is clear. Presently, water and ice is probably hidden in the subsurface and apparent in the polar caps. Episodic volcanic activity allows for water release and ice deposition. Venus and Earth are two end-members which show very young surfaces. The major difference is the presence of water. While Venus is presumably dry, the hydrosphere on Earth might be key to plate tectonics.

The validity of theories concerning (deep) plume activity and plate tectonics versus stagnant–lid and crustal thickening could gain additional support from the comparison between planets. Ultimately, these results will contribute to the knowledge of similarities and differences between two planets, and thus improve our understanding on how each one of them evolves thermally in its interior and geologically on its surface.