CHAPTER 7 FORMATION AND EVOLUTION OF ILDS

Chapter 4 dealt with the investigation of the different ILDs by considering many of their characteristic parameters, chapter 5 displays sets out their characteristics in comparison and considers the similarities and discrepancies among them and chapter 6 discusses the various formation hypotheses against what was observed on ILDs.
ILDs occur along weak crustal zones (Fig. 70) like Valles Marineris in a volcano-tectonic environment (Sect. 2.4.1) and in chaotic terrains (Sect. 2.4.2). Faults and fractures are very common in the subsurface favouring groundwater movements and possible upwellings. A potential model for the formation and evolution of ILDs was deduced from observations made in this thesis, integrating the former state of knowledge into the Martian history. Overall, many features may relate to lacustrine deposits (Sect. 6.5), as mentioned above, but a lacustrine formation in a) closed or b) partly closed basins requires sulphur-enriched water for the generation of sulphates. Varying concentrations of the input source (e.g. by confined aquifer) could also explain the lack of hydrated sulphates or haematite in some ILDs. Therefore a formation as spring deposits seems most probable. Only both processes combined would explain the formation of ILDs. At the same time, the potential aeolian input is not excluded, i.e. also the volcanic component (e.g. ash from Tharsis).

1) ILDs are present in depressions of the Hesperian-aged surfaces that are affected by chaotic terrain. These depressions are either located in the central or peripheral troughs of Valles Marineris (Ganges 1-5, Capri/Eos) and interconnected areas (Aurorae) or in Noachian-aged craters (Aram, Aureum 1+2, Iani 1-3, Arsinoes).

2) Layering is present throughout the ILDs at all scales and implies the occurrence of multiple events which is ensured by the activity of large outflow channels from the Late Hesperian into the Amazonian.

3) There are different mineral assemblages as the ILDs show

- a) PHS + kieserite (4 ILDs: Aram, Aureum 2, Ganges 1, Capri/Eos)
- b) PHS + kieserite + haematite (7 ILDs: Aram, Aureum 2, Iani 2+3, Ganges 1, Capri/Eos)
- c) kieserite (Aurorae)
- d) none of the named minerals (3 ILDs: Arsinoes, Ganges 2+4)
- e) insufficient data for 4 ILDs (Aureum 1, Iani 1, Ganges 3+5).

Hydrated sulphates and haematite occur spatially and stratigraphically closely related and within the sulphate unit or below as a lag deposit with low albedo (contacts are not clearly identifiable), which argues for a deposition under acidic aqueous conditions. The sub-horizontal layering requires deposition under low-energy conditions. If all ILDs, whether containing hydrated sulphates and haematite or not, formed by a similar formation mechanism, then fluids of different compositions might explain the mineralogical differences.

4) A formation in lacustrine environments is favoured as ILDs are located at elevations (-5200 m to -500 m) below the surrounding plateau rim. These localities correspond to closed depressions (most chaotic terrains), b) where no significant inflow from the plateau was identified and to open rift basins located in Valles Marineris. But there are exceptions a) the rift-basin lake (Capri/Eos, Ganges 1-5, Aurorae, Fig. 80 and b) the closed-basin lake (Aram Aureum 1+2, Iani 1-3, Arsinoes, Fig. 79).

5) Since the whole area is a tectonic setting starting at the huge volcanic region of Tharsis and passing into Valles Marineris, the chaotic terrains and the outflow channels, the whole crust is tectonically affected which most probably supported subsurface flow. Flow must have occurred widely and areally since cross-bedding and gradation do not appear. In Fig. 78, there are at least 3 possibilities of how to fill the depressions in which ILDs were formed as inflow from the plateau is excluded.

1. Water may either derive from confined aquifers [*Carr*, 1979] that were cut by erosion of the wall rock material and subsequently drained into the basins. Since a warm and wet Mars with a dense atmosphere and active valley networks [*Carr and Clow*, 1981] was assumed for the Noachian, water derived from atmospheric precipitation and leaked into the crust (e.g. Lunae Planum at 10.4N/66W). Given the high porosity resulting from the intense disruption of the crust by the heavy bombardment, huge amounts of water may have been stored. Its catastrophic release in the Late Hesperian (Table 3) lead to the formation of the chaotic terrain and the large outflow channels that drained into the Chryse region.

2. The volcanic activity of Tharsis and its location upslope to Valles Marineris may have enabled the lengthwise movement of subsurface floods. Following the hydraulic gradient within aquifers and rising up as hydrothermal fluids along tectonic or collapse structures such as faults, fractures and fissures.

3. An additional input could be a permafrost layer within the wall rock which was subsequently melted by insolation. The wall material would have been destabilised, causing slope failure into the basin.

According to figure 78, the input is strongly associated to a) volcano-tectonic activity, b) temperature (melting of ice by insolation) and c) Tharsis floods and later regressive erosion (sapping) of the outflow channels and carving of higher outflow channels which may have lead to a further release into the basin.

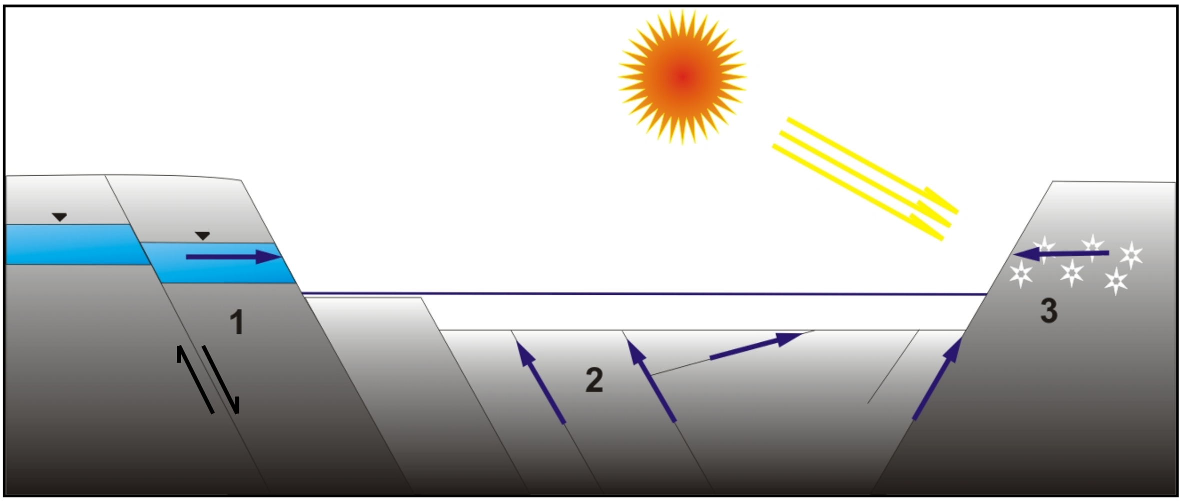

Figure 78: Model of the potential input sources for a deposition in a closed lacustrine basin. Confined aquifers that were released by erosion. Subsurface flows coming from Tharsis and resulting in hydrothermal fluids that rise along faults. Melting of a permafrost layer located in the wall rock accompanied by destabilisation and slope failure.

6) Under Martian conditions, the dehydration of PHS preferentially results in an amorphous PHS rather than kieserite. The crystallisation of amorphous PHS to kieserite is a long-term process, but kieserite in turn is easily converted back into PHS by water absorption [*Vaniman et al.*, 2004]. Kieserite has been found on steep, high-albedo, thickly bedded outcrops of high thermal inertia (Fig. 37A) massive and exhibiting slope forming strata. PHS was detected interlayered with kieserite in Ganges 1, Aram, Aureum 2, Capri/Eos but slope-forming: it mostly has a lower albedo, smoother appearance, and is distinctly layered (Fig. 38A). Thus it is rather likely that the PHS must have formed out of kieserite by water absorption. This would also be consistent with observations as kieserite is heavily affected by rock break-up through frost weathering and thus water absorption and conversion to PHS is facilitated (increased surface area).
Kieserite could have formed by evaporation at temperatures of 30-50°C under acidic (sulphidic) aqueous conditions (Sect. 3.2.2). The conversion into PHS is assumed to take place at much lower temperatures [*Chipera and Vaniman*, 2006] when water or surface moisture was present. To obtain layering, these processes must have repeated. With incoming water, the sulphates could be partially eroded and redeposited. Their lower density lets them settle at last, thus layering is formed [*Warren*, 2006]. Furthermore, reworking of material and incorporation of pre-existing intrabasin material could have occurred. Aeolian input (e.g. volcanic ash) would also be possible on a volcanically active Mars.

7) These processes (Fig. 78) could explain the presence of differently enriched fluids and rock material. The compositions of the respective input source depend on the drainage area. But one can imagine that flows from volcanic centres such as Tharsis could be more enriched in ions (e.g. sulphidic) that could have favoured acidic water conditions and thus the formation of sulphates.
Especially for Ganges Chasma within which some ILDs show hydrated sulphates and haematite but others lack them (cf. 3), this model is likely. There could be a possible correlation between the spectrally featureless ILDs (Arsinoes, Ganges 2+4), the discharge

areas and heavily eroded ILDs (flutes, grooves; Fig. 61, 71). On the contrary, ILDs that are located in more protected areas show sulphates (Sect. 5.6). The sulphate-rich deposits also show higher effects of rock break-up (e.g. by frost weathering) which could be explained by the occurrence of water (volume expansion leading to rock break-up, Fig. 69).
The ILDs that are neutral in the spectral range of CRISM (Arsinoes, Ganges 2+4) do not contain hydrated sulphates or iron-rich minerals. Since Ganges 2+4 are found at elevations more or less below Ganges 1 (kieserite + PHS + haematite), it is clear that they would be expected below Ganges 1 where no kieserite is present (whereas Ganges 5 is expected within →kieserite?; lacking mineralogical data). Thus, the composition of Ganges 2+4 is highly speculative and their TI is not correlated to certain other parameters. Besides showing a high albedo, they are heavily fluted and Ganges 2 shows hardly any rock break-up (for Ganges 4 the state of rock break-up is unknown since data are lacking, Fig. 69). Hence, they may derive from precipitation of potential sulphur-poor leakage water from the walls (Fig. 78.1). Both Ganges 2+4 are located in the discharge regions (contrary to sulphate-rich that are more protected). Thus, ILDs that lack hydrated sulphates (Sect. 5.6, 5.5) are located mostly in the discharge regions where deposition possibly is prevented by strong current so that they are directly eroded. This could be the case for Ganges 2+4. For Arsinoes the TI is low and it is heavily disrupted indicated by erosion (flutes and grooves). Since there is a morphological similarity between the top of Arsinoes and Aram (cap rock material) it might be explained why Arsinoes is spectrally featureless in the VNIR (spectrally featureless cap rock, the same for Aram; Sect. 5.6). For Capri/Eos, this does not apply, as it is also located in discharge region but nevertheless it is sulphate rich and heavily affected by rock break-up.
For Iani 1 mineralogical data lack, but similar to Ganges 3+5, it shows a high TI, high albedo and is heavily fluted and located in the discharge region of Ares Vallis, which may explain its heavily disrupted appearance. It is approximately at the same elevation range as Iani 3 (and Iani 2) which show PHS and haematite. Aureum 1 also lacks mineralogical data, but in comparison with Aureum 2 (similar cap rock) it could be deduced that below the cap unit PHS, kieserite and haematite could be found (Fig. 65).

It is confirmed that ILDs with both sulphates show different associations of PHS and kieserite with respect to which is on top of the other.

- Capri/Eos shows PHS which is taken to be below kieserite. Since Capri is situated in the discharge amongst Valles Marineris flow and drainage, water that ponded in a lake for a while [e.g. *Harrison et al.*, 2008[1]] could have converted kieserite to PHS in the lowermost part.
- Ganges 1, Aureum 2 and Aram show kieserite below PHS which suggests that after the formation of the kieserite, no more water ponded within their basins that could have produced PHS (favoured at lower temperature). For Aureum 2 mostly the sulphates are interlayered and based on 6) kieserite converted into PHS by water absorption (surface humidity).
- Iani 2+3 show PHS indicating more cold and humid climate during its formation.

[1] Fluvial features are observed in that region west and south of Capri/Eos. The ponding described by *Harrison et al*. (2008) however occurred in the Amazonian after the formation of the ILD.

- The region in which only kieserite occurs (Aurorae) was apparently not much affected by aqueous processes or surface moisture after the kieserite formed since otherwise PHS would have formed. Thus, it was possibly mantled after its formation and exhumed when dry conditions dominated, i.e. after the outflow channel activity ceased (Mid-Amazonian).

Haematite represents regions where near-neutral groundwater caused diagenesis of Fe- and sulphate-bearing rocks as observed for Meridiani Planum and thus may have formed the haematite. *Glotch and Christensen* (2005) reported on a chronology derived from haematite that gets younger from east to west: Hence, from Meridiani Planum (Noachian) via Aram Chaos (Hesperian) to Valles Marineris deposits (Hesperian/Amazonian). Therefore there the pH changes from acidic (kieserite formation) to neutral when haematite was formed in chaotic terrains and Valles Marineris. This could be explained by the varying input shown in figure 78.

8) The stair-stepped morphology is observed on ILDs studied (Fig. 36F) and is ascribed by alternating strata of competent and incompetent material. As shown in Chapter 6, a volcanic contribution in the form of ash could also feasibly to be incorporated into the basin deposits since so-called tuff-like weathering was observed. Its deposition in an aqueous (acidic) system could also form sulphate.
Within the closed basins of Aureum 2 and Aram, convolute-like bedding is observed in indicating density contrasts of materials and fast sedimentation and covering of denser water saturated material. The upper less dense sediment sinks irregularly and dehydrates, forming crests and troughs in the process. Some small-scale folding is observed within layers, especially in Ganges 1+2, but in Iani 1 as well and is ascribed to intense deformation of sulphates during the accumulation of the deposit, since the mechanical behavior of salt and sulphate is susceptible to soft deformation at ambient or low temperatures (T< 200C, e.g. *Warren*, 2006). A spectrally neutral cap rock is present on many ILDs displaying vugs and sharp crests. This could imply that both a clastic and an aeolian component were involved in ILD formation, as mentioned above. Sedimentation would have to be fast to retain interstitial water (Sect. 5.1). Precipitated evaporite grains experience the same erosional, transport and depositional processes as siliciclastics and carbonates, since many evaporites contain sedimentary bedforms (Sect. 5.1). Thus, these structures do not imply that the cap rock unit exclusively consists of siliciclastics. Spectral detection may also be hampered by aeolian material or even the presence of spectrally neutral evaporites such as anhydrite or halite (Sect. 3.2.2, 5.6).

9) The outflow channel activity was most extensive in the Late Hesperian and stopped in the Middle Amazonian [*Head et al.,* 2001]. The present Mars is cold and dry and water is no longer stable on its surface (Table 6, Fig. 4). Aeolian processes are now among the most dominant on Mars marked by their indicative features such as yardangs, dunes, grooves, flutes and pits on the ILD surfaces. Due to the high temperature amplitude on Mars (Fig. 4), its thin atmosphere and the instability of water on the surface, mechanical weathering (e.g. frost weathering) is very extensive and since moisture is lacking, chemical weathering rather is absent (e.g. unweathered mafic minerals: olivine, pyroxene). On

HiRISE images rock break-down in the form of meter-sized boulders and talus is well observed in ILDs and clearly indicates consolidated material that is undergoing weathering (Iani 1-3, Aureum 2, Ganges 1, Capri/Eos, Aram). Because of the diurnal surface temperatures of -90°C to -3°C (annual maximum temperatures; derived from BT) frost weathering (Sect. 5.5) is favoured on the ILDs. In fact, the degree of rock break-up, into hardly (group 2) and heavily affected (group 1) by rock break up resulting in boulders and disrupted surfaces, can be correlated to ILDs with hydrated sulphates (Fig. 69, 71).
Subsequently, erosion affected weak zones and fractures within the ILDs (Fig. 80). The fact that erosion, either by effluent water and/or wind (aeolian abrasion, Sect. 2.3.1) did take place is proven by flutes, grooves, yardangs and surface pits. Thus, erosional processes (Sect. 2.2.2, 2.3.1) affected ILDs differently and caused their present shapes as shown in figure 80. ILDs (in Valles Marineris) are exposed in different locations within depressions indicating erosion was more extensive on the rift shoulders (Ganges 1), preferentially occurred along cracks and other contact points (Capri/Eos, Ganges 2-4), or was more intense in the central part up to the base rock (Ganges 5). There the other ILDs in the eastern chaotic terrains are mostly (except for Aureum 1) located near the centre of the depressions indicating erosion was more efficient in marginal parts of the depressions.

10) Based on the stratigraphic relationship between the Valles Marineris floor and the chaotic terrain, deposition of the material must have first taken place in the Late Hesperian when the chaotic terrains and outflow channels formed. Actually, the crater dating showed a young Amazonian age for ILDs due to few impact craters on their surfaces (Sect. 5.8). Since ILDs are heavily affected by erosion this age corresponds to their erosional ages but not to their depositional ones. Further, after the erosional activity by outflow channels ceased, erosion by wind dominated on the dry and cold Mars. Thus assuming an age of at least 2 Ga starting from the time the outflow channel activity ceased to the present, then the highest erosional rate of 0.00004 μm/a [*Golombek and Bridges,* 2000] would erode 2 cm. Even when assuming a magnitude higher (20 cm) it is much lower than 1 m (out of 300-3600 m of the ILD thickness). This is in contrast to when the Hesperian erosion rates of 0.02 μm/a [*Arvidson et al.*, 1979] are applied resulting in an erosion of 10-30 m. Thus since the Mid-Amazonian (cessation of outflow channels) ILDs experienced no basal erosion. It is shown that ILDs are certainly older than the Amazonian as confirmed by erosion rates that were relatively high in the Hesperian. Local effects may explain the distribution of thicknesses. Since around 2 Ga are passed between ILD formation and their present appearance it has to be considered that few episodic events of hydrothermal input and thus evaporation would have been enough to explain the high thicknesses of ILDs (e.g. Ganges 1, Capri/Eos).

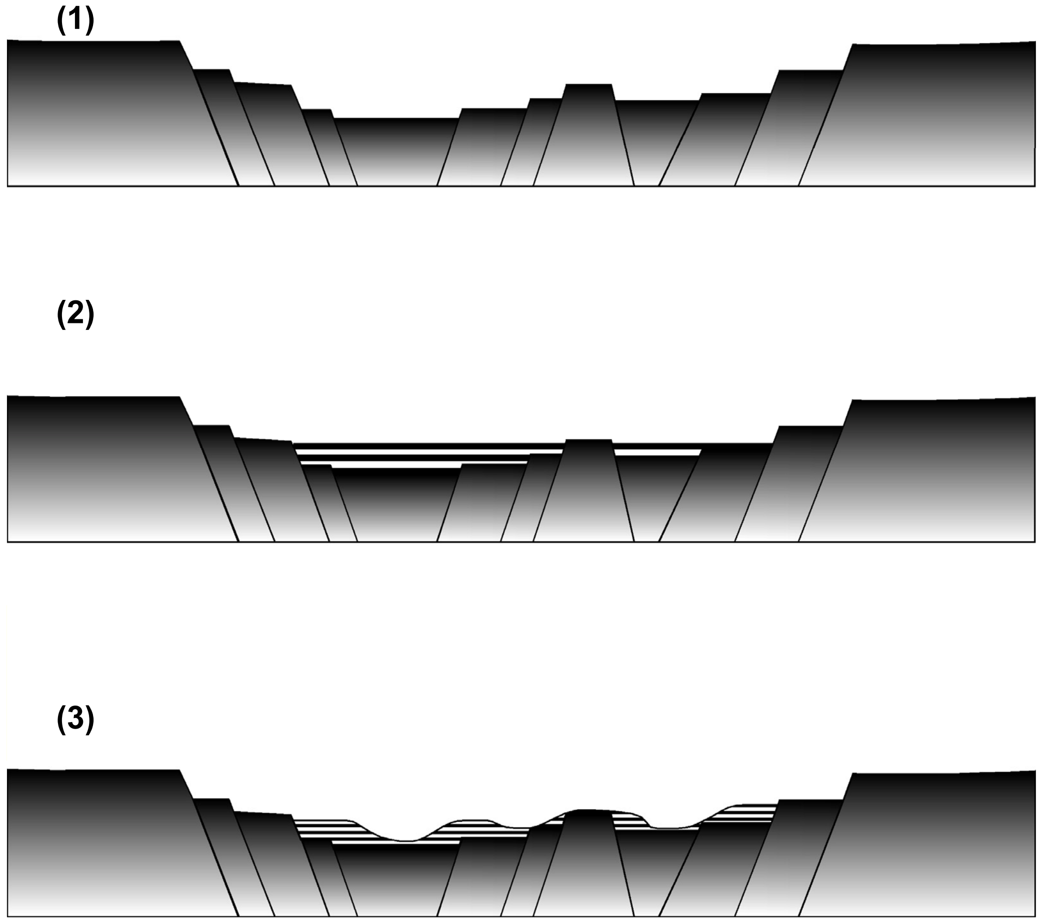

Figure 79: Formation model for ILDs. (1) ILD material deposited after chaotic terrain was formed (Sect. 5.8) irregularly. Water is derived from several sources (cf. Fig. 78): confined aquifer or melted ice layer in the walls or by hydrothermal fluids rising along fractures and faults. (2) Deposition of ILD material took place under low-energy aquatic conditions enabling horizontal layering. The reworked material that was present in the basin before is incorporated in deposition. (3) Then water vanished and left behind the ILD that was subsequently eroded by wind to form flutes, yardangs or grooves (Sect. 5.1). As confirmed by studying outflow channels [*Andrews-Hanna* and Phillips, 2007a] these events occurred episodically, enabling the formation of stair steps (Fig. 5.1). With incoming water, sulphates were partially eroded and redeposited. Their lower density lets them settle last, thus layering occurs [*Warren*, 2006]. Furthermore, reworking of material and incorporation of pre-existing intrabasin material (crater, chasma) followed. ILDs that lack hydrated sulphates (Sect. 5.6, 5.5) are located mostly in the discharge regions where deposition is possibly prevented or they are directly eroded when it has a low density like sulphate and there are strong currents.

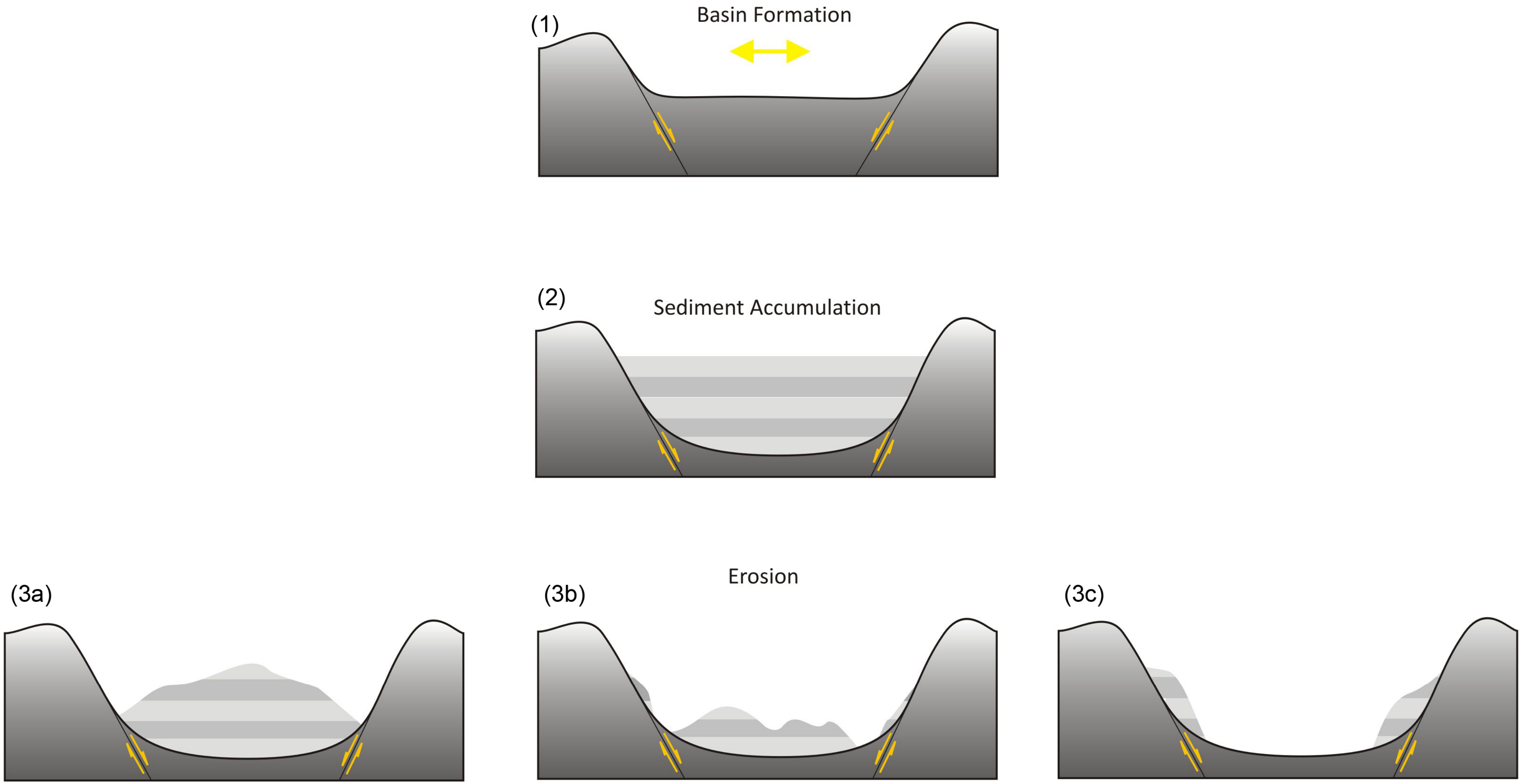

Figure 80: ILD formation and evolution. Here the setting for the Valles Marineris ILDs is shown. The present distribution of ILD material within the basin however is comparable to ILDs in the eastern chaotic terrains (located in central or marginal parts). (1) Extensional stress regime causes rifting and basin (graben) evolution. (2) Accompanied sediment accumulation (potentially wall rock-, aeolian, volcanic material e.g. by fissure eruptions) within the rift basin. Collapse of terrain (formation of chaotic terrain, cf. Fig. 79; resulting in catastrophic release of water forming the outflow channels). Basin fill with water enabling deposition under subaqueous conditions.

Water derived from several sources (Fig. 78). Required sulphur sources could be groundwater upwellings/springs (hydrothermal fluids) providing gases and ultimately brines (Fig. 78). Sulphate formation took place by evaporation (since material in the pre-existing basin is incorporated, possible alteration of volcanic material to form sulphates; aeolian input from Tharsis (ashes) may also have occurred syn-sedimentary →tuff-like weathering, cf. Sect. 6.2). (3) Erosion by effluent water and wind apparently affected the ILDs differently. ILDs are exposed in different locations within depressions indicating erosion was more extensive on rift shoulders (3a) present in Ganges 1, preferentially occurred along cracks and other contact points (3b) present in Capri/Eos, Ganges 2-4, or was more intense in the central part up to the base rock (3c) present in Ganges 5.

CHAPTER 8 OUTLOOK

A comparison of several ILD parameters showed that ILDs feature morphologies that are similar, such as stair-stepped configurations, undulating strata, layering on any scale, erosion and weathering patterns (flutes, grooves, yardangs, boulders and talus, angular joints) although their setting (craters, chasmata), erosional shape, thermophysical properties, and occasionally their mineralogy are different.

Based on the observations quoted in this thesis, a continuative detailed CRISM/HiRISE study considering different layers in ILDs may provide possible further correlations between ILDs. Moreover, in future missions the detection of further anhydrous minerals might shed more light on Martian climatic conditions, since each mineral indicates certain thermodynamic conditions which it requires for its formation, thus telling us about the formation of ILDs. Apparently, the detection of hydrated and iron-rich minerals does not require only a fresh eroded surface, as it is precisely the fresh eroded ILDs with no more than a thin aeolian cover that are spectrally neutral (different mineralogy: other evaporites or anhydrous-, iron-free silicates). Therefore, it is necessary to know which minerals the spectrally neutral ILD surfaces consist of. In addition, it would be very interesting to know whether ILDs solely consist of sulphates. Furthermore, a hydrological model which, adapted to Martian conditions, investigates the amount of water and vapor that is required to produce these huge thicknesses present in ILDs would be useful in weighing different formation hypotheses in the balance.

In summary, there are several open questions that may be solved by future research, using additional data from future Mars missions:

Do ILDs solely consist of sulphates and haematite or are there additional saline minerals like halite, sylvite, and anhydrite that indicate lacustrine evaporation? Alternatively, are there silica minerals like plagioclase that directly indicate a volcanic origin?

What is the mineralogy of the spectrally neutral ILDs?

Do the layers have different mineralogies? Is there a correlation between these layers?

What does this mean for Martian climatic conditions and the formation of ILDs?

What is the amount of water and vapor required to produce such thick layers of, for instance, sulphates that are present within ILDs?