CHAPTER 6 FORMATION MODELS

Several formation models are discussed which postulate sedimentary and/or volcanic processes for the formation of ILDs (Sect. 1, 2.4).

Thus, ILDs are suggested to be

- To be ancient deposits of glacial, lacustrine or aeolian origin that are exposed due to erosion [*Malin and Edgett*, 2000];
- made of volcanic material (subaeric pyroclastic volcanism [*Peterson*, 1981; *Chapman and Tanaka*, 2002; *Hynek et al.*, 2002]; subglacial volcanism [*Chapman and Tanaka*, 2001] or volcanic flows [*Lucchitta*, 1981; *Lucchitta et al.*, 1992; *Lane and Christensen*, 1998]), lacustrine deposits [*McCauley*, 1978; *Nedell et al.*, 1987; *McKay and Nedell*, 1988],
- spring deposits [*Rossi et al.*, 2007; 2008], or
- formed by salt diapirism [*Milliken et al.*, 2007].

6.1 ANCIENT DEPOSITS

ILDs were observed within and coming out from under the walls of Valles Marineris and thus were assumed by *Malin and Edgett*, 2000 to be as old as the wall rock: Noachian. They proposed that the ILDs formed initially by deposition initially in impact craters that were buried and then exposed by erosion after Valles Marineris formed in the Early Hesperian (Sect. 2.4.1). This interpretation departs from previous MGS observations by *Lucchitta* (2001) who ascertained ILDs as young as Hesperian or Amazonian in age and thus that they were deposited after Valles Marineris formed.

Observations of the ILD morphology, albedo, elevation, consolidation and mineralogy in comparison to wall rock material should unravel, whether the ancient deposits hypothesis is valid for these ILDs. The stratigraphic relationship between ILD and chasma floor, wall rock, and chaotic terrain should indicate if ILDs are ancient deposits.

There is one ILD in Valles Marineris (Ganges 5) which is exposed on the wall rock. It is heavily eroded from the wall rock as visible on light-toned patched on the wall material, indicating it had an original much larger extent. It is partially covered by smooth aeolian material but the contact to the wall rock is observed since the surface of the ILD is rough and affected by erosion into yardangs is therefore different from the wall rock, which appears unaffected by aeolian erosion. The walls are weathered into a spur-and-gully morphology [*Malin*, 1976; *Peterson*, 1981]. In contrast to the low albedo wall rock, Ganges 5 shows a higher albedo. Besides, Ganges 5 occurs at a similar elevation range to those ILDs nearby (Fig. 65) and for which the relationship to the floor and chaotic terrain is clearer. That means Ganges 5 is exposed-3800 m to -3500 m, whereas Ganges 1 is exposed from -4100 m to -500 m. Considering the high elevation of Ganges 1, it is probable that its extent was much higher and thus once covered Ganges 5 (Fig. 65). In addition, there are similarities to Ganges 1 (thin mesas on top, grooved, flutes, yardangs). Ganges 5 is also not plainly exposed along the walls but occurs domed on them. Based on the named arguments, the ancient deposit hypothesis is not conclusive.

6.2 PYROCLASTIC DEPOSITS

Pyroclastic fall deposits[1] form as fallout of volcanic fragments ejected from a vent or fissure by a magmatic explosion. Such volcanoes are mostly explosive and sub-aerial, and the material is deposited on land [*Tucker*, 2001]. There are two types: fall deposits derived from eruption plumes ejected explosively from a vent, producing a plume of tephra and gas, and ash-cloud fall deposits that result in part from ash clouds rising from a moving pyroclastic flow. Flow and surge deposits are moved by pyroclastic gravity currents [*Reading*, 1996]. Surge deposits result from highly expanded turbulent gas-water-solid currents with low particle concentrations [*Tucker*, 2001]. They are generally thin and fine-grained, usually draping the topography, and accumulate more thickly in depressions. Their grain size and bed thickness decrease away from the volcano, and erosive bases and channel structures are common. They display a massive appearance, poor sorting, and plateau-forming or valley-filling morphology [*Füchtbauer*, 1988]. Surge deposits are restricted to depressions but may thin out laterally, whereas flow deposits follow the topography and are deposited in depressions (Fig. 73). Generally, pyroclastic rocks, such as basaltic tuffs, are primarily composed of olivine, clinopyroxene and plagioclase[2] [*Füchtbauer*, 1988; Sect. 3.2.2].

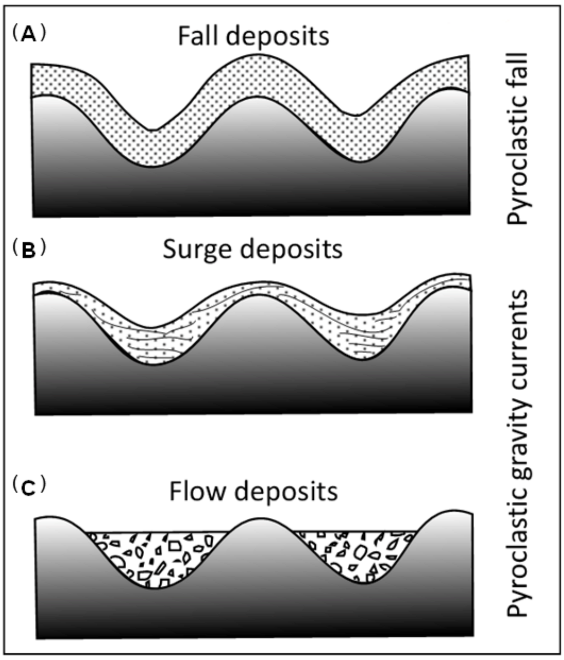

Figure 73: Pyroclastic deposition models modified after [*Reading*, 1996]. Deposits show different geometries: (A) Fall deposits cover the landscape with a blanket of the same local thickness (like snow). (B) Transport and deposition of surges and highly diluted pyroclastic flows is concentrated in depressions. (C) High-

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[1] Pyroclastic deposits are classified and named by grain size (ash < 2 mm, lapilli 2-64 mm, bombs and blocks > 64 mm), sorting, and their chemical and mineralogical composition [*Füchtbauer*, 1988].

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density pyroclastic flows follow the topography in transport and deposition (like water).

The pyroclastic theory was proposed by *Peterson* (1981) for Hebes Chasma (1.8°S/283.2°E; Fig. 2) implying a thick sequence of ash-flow deposits formed the ILD. The horizontal layers were assumed to consist of more resistant welded tuff, the volcanic source was supposed beneath the chasma or within the Tharsis area [*Peterson*, 1981]. Tuff-like weathering phenomena on ILDs were also observed by *Chapman* (2007) who compared them to terrestrial analogues.

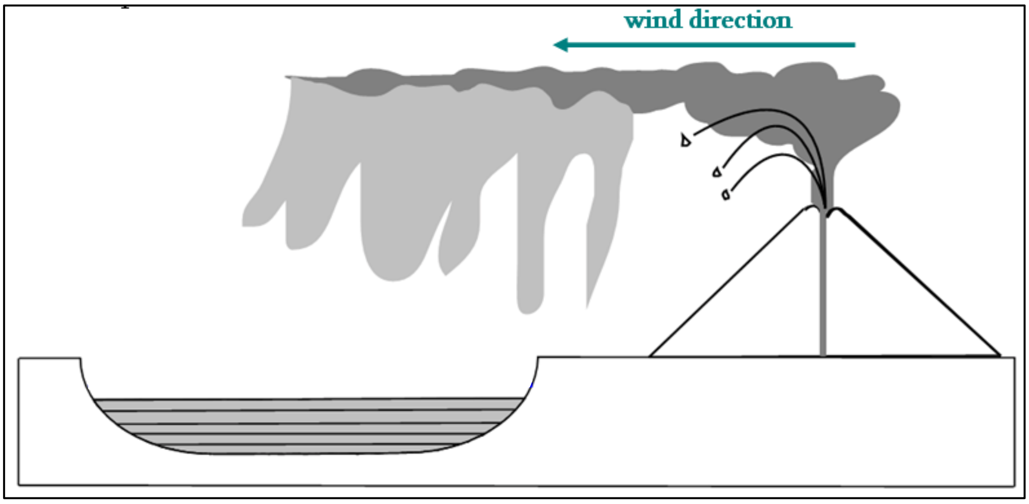

Figure 74: Sketch showing a possible ash deposit model. Pyroclastic deposits are transported away from the eruption column as differently-sized fragments (ash, lapilli, bombs, or blocks). Deposition takes place in the downwind direction.

Characteristics of pyroclastic deposits that can be observed on Mars:

- Gradual decrease in bed thickness away from the site of eruption,
- plateau-forming, valley filling, draping morphology,
- welding in tuffs close to the vent (if derived from high-temperature magma and/or rapid accumulation),
- volcanic source (e.g. cinder cones),
- individual isopachs and isopleths forming more or less regular ellipses that are elongated in the downwind direction of elongation away from the vent defining the dispersal axis of the deposit [*Sigurdsson et al.*, 2000].

Stair-stepped morphologies (implying alternating strata of incompetent and more competent material) are displayed by all ILDs (Sect. 5.1) and could be coincident with weathering phenomena that have been reported from tuffs on Earth. Flutes were observed at 8 out of 14 ILDs (Aram, Iani 1, Arsinoes, Ganges 1-5, Sect. 5.1) possibly resembling weathering marks that are also observed on terrestrial ash flows. In contrast to ash flows (Fig. 73C) but possibly rather similar to ash fall deposits (Fig. 73A), ILD material apparently deposited conformably upon the original curved surface (chaotic terrain; Sect. 5.8), which is observed at best in the chaotic terrains of Aram, Iani, Arsinoes, Aureum and Aurorae (e.g. Fig. 36A). Local volcanic sources have not been identified and the large volcanic regions of Tharsis and Elysium (Fig. 2) are 3500 – 7000 km (Tharsis) and 9900 –

12000 km (Elysium) away. Thus it is questionable whether those could be the volcanic source responsible for the ILD formation since ILDs show thicknesses of 300-3600 m (Ganges 5-Ganges 1). But since the lower gravity (Table 1) on Mars also affects the properties of lava eruptions and flows and magma should rise much faster and flow more easily and for longer distances than on Earth it may be also applied to ash transport and deposition. Mafic minerals such as pyroxene and olivine were not found in 10 out of 14 ILDs (Sect. 5.6). Sulphates (7 out of these 10: Aram, Aureum 2, Iani 2+3, Aurorae, Ganges 1 and Capri/Eos) do not correspond to common primary composition of pyroclastic minerals but sulphates may weather from ash deposits. Haematite (6 out of these 7 ILDs: Aram, Aureum 2, Iani2+3, Ganges 1, Capri/Eos) may also be a weathering product. The mineralogical composition of 4 ILDs is unknown because there is insufficient data (Sect. 3.2.2). Layering geometry measurements were performed for 3 ILDs (Iani 3, Ganges 1, Capri/Eos; Fig. 46A, 53J; Sect. 5.7) and indicate that the layering is sub-horizontal (Iani 3, Ganges 1) with < 10° and more inclined for Capri/Eos < 18°. In Capri/Eos outward dipping indicating draping processes (cf. Sect. 5.7) cannot be excluded since again higher resolution data are required.

Characteristics for tuff-like weathering (alternating competent and incompetent strata) were found in all ILDs. Those that show weathering marks (flutes) known from terrestrial ash flows are 8 ILDs (Aram, Iani 1, Arsinoes, Ganges 1-5).

6.3 SUBGLACIAL VOLCANISM

Sub-glacial volcanic edifices like those known from Iceland can be subdivided into (i) table volcanoes and (ii) ridge-shaped hyaloclastite[1] deposits [*Bourgeois et al.*, 1998]. Table volcanoes – the sub-glacial equivalents of shield volcanoes - are the product of central vent eruptions and form roughly circular, steep-sided volcanoes and flat-topped mountains (tuyas, Sect. 2.5). Mostly they consist of a pile of pillow-lavas and hyaloclastites surrounded by volcanic breccia. These volcanoes rise up to the ice surface - assuming there is a sufficient magma supply - and are topped by flat aerial lava flows emplaced above the ice cap. Their height indicates the ice thickness at the time of their emplacement. Hyaloclastite ridges – the sub-glacial equivalents to eruptive fissures - are located along the tectonic trend as they are related to central volcanoes situated in the currently active rift zones. Like table volcanoes, they consist of fragmented pillow lavas and hyaloclastites. Often, there is no cap because activity was not sufficient or intense enough to reach the ice surface [*Bourgeois et al.*, 1998].

Sub-glacial volcanism was proposed for the formation of ILDs by *Chapman and Tanaka* (2001), *Komatsu et al.* (2004) and *Chapman* (2007) based on the tectonic origin of Valles Marineris and morphological similarities to terrestrial glacio-volcanic features. *Komatsu et al.* (2004) reported on near-horizontal basalt layers comprising the cap while the underlying hyaloclastite unit is rather inclined [*Komatsu et al.*, 2004].

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[1] Hydrated tuff-breccia; consisting of a bulk of solidified, fractured, glassy lava (mostly composed of sideromelane and palagonite).

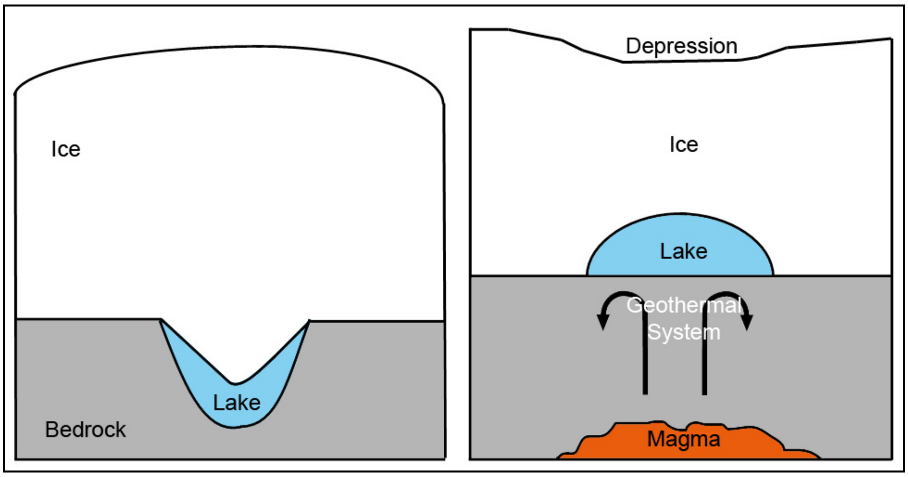

Figure 75: Main types of sub-glacial lakes. *(left)* A stable lake, *(right)* an unstable lake draining into jökulhlaups[1]; modified after *Bjoernsson* (2002). The ice above the volcano melts due to hydrothermal activity, causing a depression in the glacier surface. Melt water either drains continuously to the glacier margin or accumulates in a sub-glacial lake located beneath the glacier surface depression.

Expected characteristics of sub-glacial volcanic landforms on Mars:

- Tuya morphology (flat top, steep flanks),
- comprised of pillow-lavas and hyaloclastites surrounded by volcanic breccia,
- near-horizontal flat to dome-shaped cap of lava flows above more inclined hyaloclastites,
- layering in lower parts and cap well developed,
- located along the tectonic trend.

Observations of ILD morphology and mineralogy could indicate whether they show typical features of sub-glacial volcanism. However, it cannot be checked whether mafic glasses are present as amorphous materials do not have crystalline structures and thus feature no mineral absorptions. Since they are composed of pillows, plagioclase and pyroxene and olivine could be present. Plagioclase is spectrally featureless in the spectral range of OMEGA and CRISM (Sect. 3.2.2).
A tuya-like morphology indicated by flat top and steep sides is present in 5 out of 14 ILDs (Aram, Aureum 2, Iani 2, Ganges 1, Capri/Eos; Fig. 30A, Sect. 5.1) and thus a potential similarity to sub-glacial volcanoes (Fig. 13) described above. Four out of these 5 ILDs (Aram, Aureum 2, Ganges 1, Capri/Eos) show a cap unit (Fig. 30D, Sect. 5.1): a similarity to table volcanoes. Layering is present throughout the ILDs. Mafic minerals such as olivine and pyroxene are absent in 10 out of 14 ILDs (Aram, Aureum 2, Iani 2+3, Aurorae, Ganges 1, Capri/Eos, Arsinoes, Ganges 2+4). There is insufficient mineralogical data for 4 ILDs (Iani 1, Aureum 1, Ganges 3+5). Pyroxene was found only in loose aeolian material that covers the ILD surface (Ganges 1, Arsinoes; Fig. 53G, 49C). In addition, sulphates and haematite are not common minerals formed by sub-glacial volcanic processes. Layering geometry measurements performed on 3 ILDs (Iani 3, Ganges 1, Capri/Eos) show sub-horizontal layering (<10°). For Ganges Chasma the lower part (7-9°) is not significantly

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[1] Glacial lake outburst flood; it forms when water dammed in a glacier or moraine is released e.g. by subglacial volcanic eruption.

more inclined than the cap (4-6°). Capri/Eos however is heavily disrupted and shows a complex structure but there the lower part also is not more inclined than the top.
Five ILDs (Aram, Aureum 2, Iani 2, Ganges 1, Capri/Eos) show morphological similarities with sub-glacial volcanoes (flat top and steep flanks, cap). However the main features (caldera, vents) are not present.

6.4 AEOLIAN DEPOSITS

Aeolian deposits generally indicate dry periods [*Bahlburg and Breitkreuz*, 1998]. They are transported by wind (via suspension, saltation, reptation) and often form sand dunes which, in turn, are characterised by fine-grained sands (cf. 2.3.1). Sand accumulates in dunes, whereas silt and dust settle down as mantling coverings [*Bahlburg and Breitkreuz*, 1998]. Aeolian dunes feature cross-bedding. On Earth, they are mainly composed of silica quartz, whereas on Mars, dunes show mafic minerals such as olivine and pyroxene [*Tirsch et al.*, 2008]. Sulphate (gypsum) was found in north polar dunes where it occurs only in small portions on their surface and is supposed to originate from underlying gypsum-rich bedrock [*Roach et al.*, 2007].
For Mars an aeolian origin for ILDs was proposed by *Peterson* (1981) due to possible large-scale cross-bedding visible in the floor deposits in between Candor and Ophir Chasma (6.5°S/289.1°E and 4°S/288°E). The material was assumed to derive from global or localised dust storms (Sect. 2.3.1).

Characteristics of aeolian deposits:

- Good sorting,
- sand sheets, ripples, duneforms,
- large sand deposits (ergs) mostly associated with topographic or structural trough or obstacle,
- siliceous minerals, mafic minerals;
- mostly unconsolidated.

Observations of morphology, consolidation and mineralogy of ILDs should clarify whether they display characteristics of aeolian deposits. Siliceous minerals like quartz, as a main component in terrestrial dunes, cannot be detected in VNIR – the spectral range of CRISM and OMEGA (Sect. 3.2.2).
All ILDs surfaces show the effects of wind erosion in the form of yardangs, flutes, grooves and pits (Sect. 5.1). Aeolian deposits are commonly observed on their tops (e.g. ripples). ILDs differ from the Martian dunes of Noachis and Arabia Terra (44.7°S/10°E and 22.8°N/5°E, Fig. 2) as well as from dune fields surrounding them (e.g. at Ganges Chasma, Fig. 55B, 56A). Their immense heights of 300-3600 m (Ganges 5-Ganges 1, Sect. 5.4), high albedo, and a TI (304-498 SI) that corresponds to consolidated and rocky material (Sect. 5.5) contrasts them against dunes. Meter-sized boulders (affirmed by 8 ILDs: Aram, Aureum 2, Iani 1-3, Aurorae, Ganges 1) and talus (all out of Ganges 5) at the base of steep

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Thus, ILDs are suggested to be
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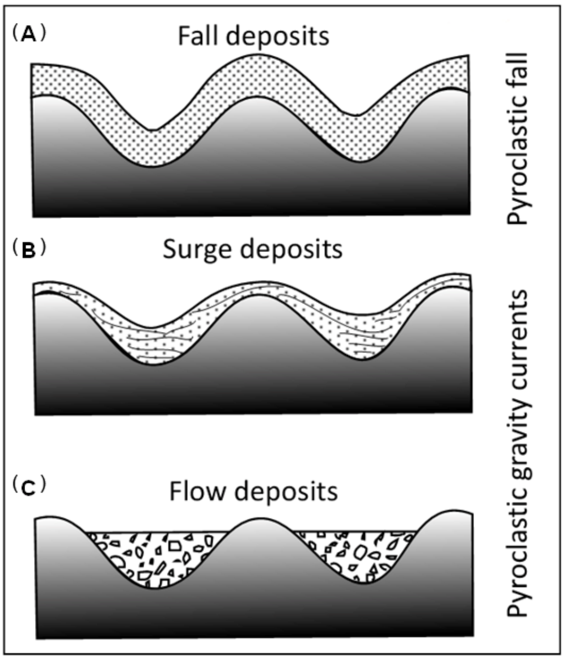

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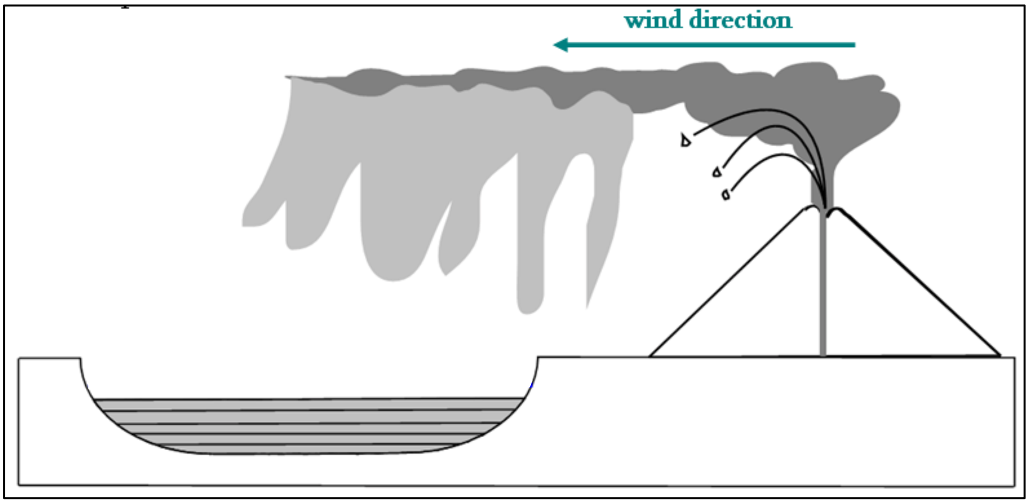

Figure 74: Sketch showing a possible ash deposit model. Pyroclastic deposits are transported away from the eruption column as differently-sized fragments (ash, lapilli, bombs, or blocks). Deposition takes place in the downwind direction.

Characteristics of pyroclastic deposits that can be observed on Mars:

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6.3 SUBGLACIAL VOLCANISM

Sub-glacial volcanic edifices like those known from Iceland can be subdivided into (i) table volcanoes and (ii) ridge-shaped hyaloclastite[1] deposits [*Bourgeois et al.*, 1998]. Table volcanoes – the sub-glacial equivalents of shield volcanoes - are the product of central vent eruptions and form roughly circular, steep-sided volcanoes and flat-topped mountains (tuyas, Sect. 2.5). Mostly they consist of a pile of pillow-lavas and hyaloclastites surrounded by volcanic breccia. These volcanoes rise up to the ice surface - assuming there is a sufficient magma supply - and are topped by flat aerial lava flows emplaced above the ice cap. Their height indicates the ice thickness at the time of their emplacement. Hyaloclastite ridges – the sub-glacial equivalents to eruptive fissures - are located along the tectonic trend as they are related to central volcanoes situated in the currently active rift zones. Like table volcanoes, they consist of fragmented pillow lavas and hyaloclastites. Often, there is no cap because activity was not sufficient or intense enough to reach the ice surface [*Bourgeois et al.*, 1998].

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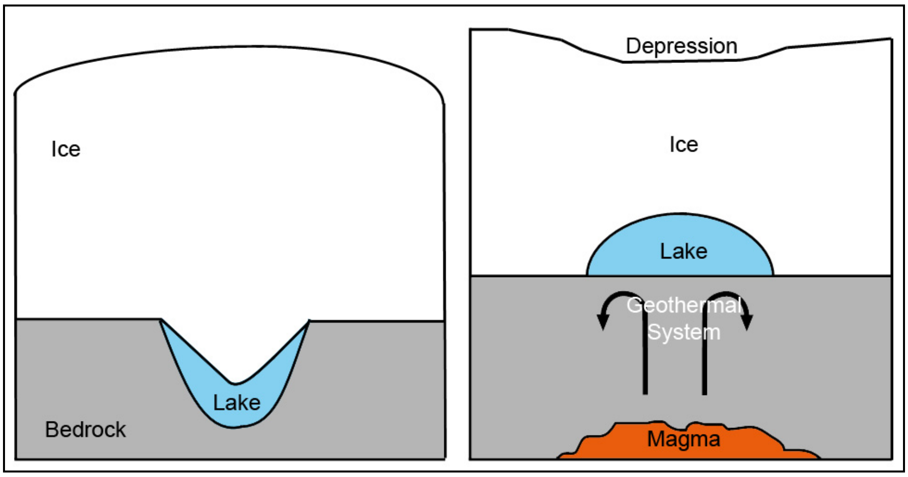

Figure 75: Main types of sub-glacial lakes. *(left)* A stable lake, *(right)* an unstable lake draining into jökulhlaups[1]; modified after *Bjoernsson* (2002). The ice above the volcano melts due to hydrothermal activity, causing a depression in the glacier surface. Melt water either drains continuously to the glacier margin or accumulates in a sub-glacial lake located beneath the glacier surface depression.

Expected characteristics of sub-glacial volcanic landforms on Mars:

- Tuya morphology (flat top, steep flanks),
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[1] Glacial lake outburst flood; it forms when water dammed in a glacier or moraine is released e.g. by subglacial volcanic eruption.

more inclined than the cap (4-6°). Capri/Eos however is heavily disrupted and shows a complex structure but there the lower part also is not more inclined than the top.

Five ILDs (Aram, Aureum 2, Iani 2, Ganges 1, Capri/Eos) show morphological similarities with sub-glacial volcanoes (flat top and steep flanks, cap). However the main features (caldera, vents) are not present.

6.4 AEOLIAN DEPOSITS

Aeolian deposits generally indicate dry periods [*Bahlburg and Breitkreuz*, 1998]. They are transported by wind (via suspension, saltation, reptation) and often form sand dunes which, in turn, are characterised by fine-grained sands (cf. 2.3.1). Sand accumulates in dunes, whereas silt and dust settle down as mantling coverings [*Bahlburg and Breitkreuz*, 1998]. Aeolian dunes feature cross-bedding. On Earth, they are mainly composed of silica quartz, whereas on Mars, dunes show mafic minerals such as olivine and pyroxene [*Tirsch et al.*, 2008]. Sulphate (gypsum) was found in north polar dunes where it occurs only in small portions on their surface and is supposed to originate from underlying gypsum-rich bedrock [*Roach et al.*, 2007].

For Mars an aeolian origin for ILDs was proposed by *Peterson* (1981) due to possible large-scale cross-bedding visible in the floor deposits in between Candor and Ophir Chasma (6.5°S/289.1°E and 4°S/288°E). The material was assumed to derive from global or localised dust storms (Sect. 2.3.1).

Characteristics of aeolian deposits:

- Good sorting,
- sand sheets, ripples, duneforms,
- large sand deposits (ergs) mostly associated with topographic or structural trough or obstacle,
- siliceous minerals, mafic minerals;
- mostly unconsolidated.

Observations of morphology, consolidation and mineralogy of ILDs should clarify whether they display characteristics of aeolian deposits. Siliceous minerals like quartz, as a main component in terrestrial dunes, cannot be detected in VNIR – the spectral range of CRISM and OMEGA (Sect. 3.2.2).

All ILDs surfaces show the effects of wind erosion in the form of yardangs, flutes, grooves and pits (Sect. 5.1). Aeolian deposits are commonly observed on their tops (e.g. ripples). ILDs differ from the Martian dunes of Noachis and Arabia Terra (44.7°S/10°E and 22.8°N/5°E, Fig. 2) as well as from dune fields surrounding them (e.g. at Ganges Chasma, Fig. 55B, 56A). Their immense heights of 300-3600 m (Ganges 5-Ganges 1, Sect. 5.4), high albedo, and a TI (304-498 SI) that corresponds to consolidated and rocky material (Sect. 5.5) contrasts them against dunes. Meter-sized boulders (affirmed by 8 ILDs: Aram, Aureum 2, Iani 1-3, Aurorae, Ganges 1) and talus (all out of Ganges 5) at the base of steep scarps (Sect. 5.5, 5.1) also indicate high consolidation. Another discrepancy arises as 10 out of 14 ILDs lack mafic minerals like pyroxene and olivine of which Martian dunes are composed. Similarly horizontal stacking of hydrated sulphates is not established in aeolian deposits. The aeolian deposits hypothesis is not consistent with observations on the ILDs.

6.5 LACUSTRINE DEPOSITS

McCauley (1978) proposed a model for a lacustrine origin of Valles Marineris ILDs based on their horizontal nature, the continuity of bedding and the interconnected trough systems. This model implies deposition of aeolian and eroded wall rock material as well as volcanic ash from the Tharsis region (Fig. 2) and into a low-energy aqueous environment. Sulphate minerals in lacustrine deposits on Earth are mostly accompanied by other evaporite minerals such as carbonates[1] and halite. Halite and chlorides in general, cannot be detected due to the limited spectral range of CRISM and OMEGA (Table 8).

Typical characteristics of lacustrine deposits expected on Mars:

- channels, deltas (open-basin lake),
- cross-bedding, horizontal layering (unless post-depositional tilting occurred),
- located in depressions,
- flutes, grooves
- hydrated minerals.

Observations of ILD morphology, elevation and mineralogy could detect similarities to lacustrine deposits. No inflow channels were identified, thus the water that filled the depressions in which ILDs are observed. Thus, the water to fill the depressions would have had to be derived from elsewhere (e.g. released aquifer, melting of ice in the wall rock, groundwater upwelling). Cross-bedding is not observed but all ILDs show sub-horizontal bedding (Sect. 3.2.3) favouring low-energy aqueous environments. Flutes and grooves are present on some ILD surfaces (8 ILDs: Ganges 1-5, Arsinoes, Aram, Iani 1) indicating fluvial erosion affected the ILDs (fluvial erosion is also observed on the floor of Capri/Eos Chasma (south of the ILD) and Ganges Chasma (between Ganges 4+5). Morphologies resembling to convolute-like bedding was observed in Aureum 2, Aram and in few parts of Iani 1, and indicate differences in the consolidation of material and density and predicts water-saturation of according sediments. Mostly ILDs are situated in or near the centre of the depressions (12 ILDs out of 14), but 2 out of 14 ILDs (Ganges 5,

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[1] On Mars, several instruments including TES (Sect. 3.1.5) have tried to detect carbonates. The first small amounts of carbonates were detected by TES but only in the Martian dust [*Bandfield et al.*, 2003]. The formation of carbonates requires warm, wet and alkaline to neutral pH-values [*Matthes*, 2001) - conditions similar to those of clay minerals which were found on the Noachian surface by OMEGA [*Poulet et al.*, 2005]. Recently, CRISM [*Ehlmann et al.*, 2008] detected small amounts of carbonate in close association with clay minerals, showing that the acidic aqueous cycle of the Hesperian [*Bibring et al.*, 2006] did not affect all environments on Mars. On the other hand, sulphates were found on surfaces of Hesperian age (Fig. 3; *Bibring et al.*, 2006) and need an environment (wet, acidic pH-values, Sect. 3.2.2) in which carbonate may only be present dissolved.

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Aureum 1) are in more marginal parts. This might be an effect of erosion and possibly display the original much greater extent of the ILDs. All ILDs are located in depositional areas below the surrounding plateau rim (Fig. 63, 64). Therein hydrated sulphates were found in 7 out of 14 ILDs (Aram, Aureum 2, Iani 2+3, Aurorae, Ganges 1 and Capri/Eos). Sulphates require aqueous conditions for their formation and are also common terrestrial evaporite minerals (Sect. 3.2.2). The occurrence of hydrated sulphates in turn indicates sufficient water or humidity may have been present up to a certain elevation which is -3000 m for Iani 2 and Iani 3 and -500 m for Ganges 1 (Fig. 65). This is the upper limit at which hydrated minerals are observed in Valles Marineris and the eastern chaotic terrains. The original uppermost elevation of hydrated sulphate could be higher than measured. Layering geometry measurements were performed for 3 ILDs (Iani 3, Ganges 1, Capri/Eos; Fig. 46A, 53J; Sect. 5.7) and indicate that the layering is sub-horizontal (Iani 3, Ganges 1) with 10° and more inclined for Capri/Eos < 18°, which could be consistent with deposition under quiescent conditions.

The lacustrine hypothesis appears very likely since there are many arguments: hydrated minerals (for 7 out of 14 ILDs: Aram, Aureum 2, Iani 2+3, Aurorae, Ganges 1 and Capri/Eos), location in depressions below the surrounding plateau (all ILDs). Flutes and grooves on their surfaces are present for 8 ILDs (Ganges 1-5, Arsinoes, Aram, Iani 1).

6.6 SPRING DEPOSITS

On Earth, the majority of spring deposits is of non-thermal origin and built from low-temperature minerals dissolved in groundwater [*Crumpler*, 2003]. Their formation is associated with warm (hydrothermal) springs that mostly produce water at or near ambient temperature (5-30°C). They are restricted to regions where significant vertical discontinuities (like faults) enable water to reach the surface, which also could have occurred on Mars where hydrothermal fluids could rise along these weak crustal zones through fissures or vents [*Rossi et al.*, 2007; 2008]. *Bourke et al.* (2007) reported on spring mounds in Dalhousie/Central Australia which consist of carbonates, clays, gypsum and iron oxides and are capped by protective carbonates. There are various morphologies (domes, pitted cones, mesas) as the process of volume accumulation is constrained by geometry variations and the dynamics of point sources.

Characteristics of spring mounds:

- Present in regions that show vertical discontinuities (faults),
- mostly carbonates (travertine), clays, gypsum, iron oxides capped by carbonates,
- domes, pitted cones, mesas, terraced mounds;
- thickness of several to hundreds of meters.

Observation of the ILD morphologies, mineralogy and thickness will show similarities and differences to spring deposits. Since carbonates on Mars are rare and restricted to old, Noachian outcrops (cf. Sect. 6.5) and since the Hesperian most likely was dominated by acidic aqueous conditions (Sect. 2.1, Fig. 3), which favoured the formation of sulphates, carbonates are not expected in ILDs.

ILDs share some features of spring mounds as 5 out of 14 ILDs (Aram, Aureum 2, Iani 2, Ganges 1, Capri/Eos; Fig. 30A, Sect. 5.1) show mesa morphology and 6 out of 14 ILDs (Aram, Iani 1+3, Arsinoes, Aurorae, Ganges 1) have dome-shaped profiles. Pitted surfaces are also observed on 4 ILDs (Aram, Iani 3, Ganges 2, Capri/Eos) but not cone morphology. Around 2 ILDs (Iani 2+3) are distinctly terraced ILDs are also present. The thicknesses of ILDs are a few hundred meters (300-800 m) for 6 ILDs (Aram, Aureum 1, Iani 2, Ganges 2, Ganges 4+5) which would be comparable to spring deposits and much higher (1000-3600 m; Fig. 65) for the remaining 8 ILDs (Aureum 2, Iani 1+3, Arsinoes, Aurorae, Ganges 1+3, Capri/Eos). The mineralogical composition of 4 ILDs (Iani 1, Aureum 1, Ganges 3+5) is not known due to insufficient data. Nevertheless, on Earth there are spring deposits that show gypsum and iron oxide as well. But there, hydrated Mg-sulphates and haematite were found in 7 out of 14 ILDs (Aram, Aureum 2, Iani2+3, Aurorae (no haematite), Ganges 1, Capri/Eos). Mineralogically, the presence of haematite would be comparable to terrestrial springs. However, the source areas define the ion concentration of the springs is define by the respective, the presence of Mg-sulphates instead of Ca-sulphates. Thus for Mars where sulphates were found in several locations associated with ILDs, the groundwater which is enriched in sulphidic ions rather than in carbonaceous might produce sulphate-rich springs.

A formation by spring deposits would be coincident with ILD observations for 10 ILDs (Aram, Aureum 2, Iani 2+3, Ganges 1, Capri/Eos, Aurorae, Ganges 3-5) even if the high thicknesses are different to spring deposits. However, the characteristic mineralogy and morphology is coincident.

6.7 SALT DOMES

On Earth, ground movements within salt layers from the Mesozoic, particularly the Upper Permian (Zechstein) in Central Europe, are well known to form salt domes. The cause for salt doming is gravity. When flowing material contrasts in density with its surroundings (Fig. 77) a sediment overburden of about 1,000m is needed to initiate salt flow [*Bahlburg and Breitkreuz*, 1998]. The mean density of halite salt is ~2.2g/cm³ and, contrary to shale or other flowing material, it does not change its density with increasing lithostatic pressure and depth because it has almost no pore volume [*Suppe*, 1985]. Salt rises near discontinuities within the overlying strata (lineaments of brittle deformation and cross-points). Within the source area of the salt supply, the overlying strata gravitate and normal faults (pear-, mushroom-shaped or elongated salt banks) are formed. If there is an inadequate salt supply, the salt dome contracts and becomes trapped and isolated in the overlying strata. *Warren* (2006) described the cap rock found on large salt plugs covering the top of the intrusion as (from bottom to top) halite followed by fractured anhydrite, gypsum, and vuggy calcite (Fig. 76). There, gypsum forms by rehydration of anhydrite and calcite forms from an anhydrite precursor via bacterial sulphate reduction.

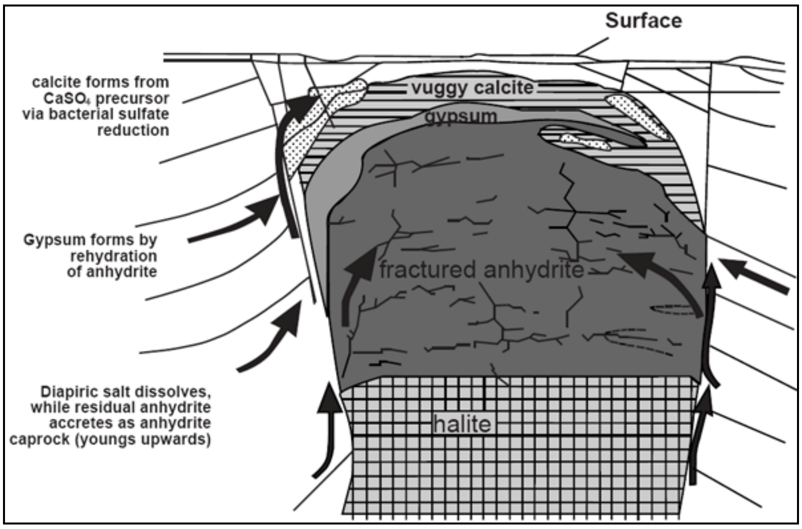

Figure 76: Cap rock zonation after *Warren* (2006). Cap rock forms by the dissolution of the upper part of the salt structure. Once salt supply dwindles the rate of rise slows and is flushed by undersaturated phreatic waters (black arrows). Dissolution of the halite leaves behind anhydrite that then accretes into an anhydrite cap rock. The upper portion of the anhydrite unit rehydrates to gypsum that is then converted to limestone by bacterial sulphate reduction.

Milliken et al. (2007) reported that the salt diapirs of Great Kavir/Iran show morphological similarities to ILDs in Candor and Melas Chasma, west of the research area (at 6.5°S/289.1°E and 10.3°S/287.3°E) in Valles Marineris (Fig. 2, 10). *Beyer et al.* (2000) assume that an overburden of at least 100 m is required on a 500 m-thick salt deposit to produce salt domes in Candor Chasma. Anhydrite – cannot be detected by CRISM or OMEGA (Table 8).

Characteristics of salt domes expected for Mars:

- Present along of weak crustal zones,
- density contrast between salt and surrounding,
- caprock: mostly anhydrite (from bottom to top: halite, anhydrite, gypsum).

Observations of ILD morphology and mineralogy could unravel whether ILDs could be salt domes. Anhydrite – cannot be detected by CRISM or OMEGA (Table 8). The presence of halite, which is responsible for salt doming, cannot be ascertained since it is featureless in the spectral range of CRISM and OMEGA. Thus, although this mineralogy is within the spectral range of CRISM or OMEGA (Sect. 3.2.2) and the low resolution of TES, the presence of halite, which is responsible for salt doming, cannot be ascertained.

A density contrasts[1] between sulphates found in 7 ILDs and the Martian crust would be present and could have enabled salt dome formation for at least 7 ILDs (Aram, Aureum 2, Iani 2+3, Aurorae, Ganges 1, Capri/Eos; 3 are spectrally featureless in the spectral range of CRISM and OMEGA, 4 ILDs: insufficient data), but these are not composed of gypsum (but PHS and kieserite). Eight out of 14 ILDs (Aram, Aureum 1+2, Ganges 2-4, Capri/Eos) are capped by massive-appearing materials (Sect. 5.1, 5.6) which could represent the salt plug.

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[1] Densities: Kieserite: 2.6 g/cm^3, PHS→epsomite: 1.7 g/cm^3; basalt: 3.1 g/cm^3; *Rösler*, 1984).

Eight out of 14 ILDs (Aram, Aureum 1+2, Ganges 2-4, Capri/Eos) would fit in the hypothesis since they show a cap rock. But the salt dome hypothesis seems not conclusive since the salt then must have been formed long before the outflow channel activity started (before the Late Hesperian) since otherwise the material rather would be eroded. In addition, the conditions for sulphate formation at that time were assumed rather unlikely (Sect. 2.1).

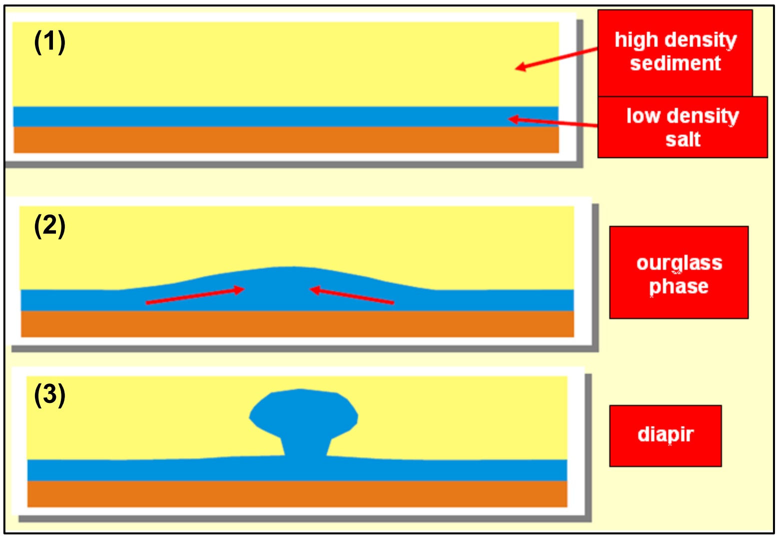

Figure 77: Sketch of a salt dome formation. (1) There are density discrepancies between the salt and the overlying sediment burden as salt retains its density with increasing depth and sediment thickness, while the density of the surrounding material - such as shale - increases. (2) The salt starts flowing underground and accumulates along discontinuities within the overlying strata. (3) A diapir forms when the salt rises and is blocked by overlying strata. Modified after *Heubeck* (2005).

Deposition of ILD material - discussed here - in Valles Marineris most probably occurred in an a) open-basin or rift lake or b) closed basin lakes (mostly in craters) and thus water must have derived from a confined aquifer as proposed by *Carr* (1979) or from in the basin walls or from melting of ice. Both systems have their outflow channels (Ares-Tiu-Simud Valles: 10.3°N/334.2°E-15.7°N/324.3°E-10.1°N/322.5°E) that drain into the Chryse Region (Fig. 2).

BASED ON OBSERVATIONS: WHICH HYPOTHESIS IS THE MOST ADEQUATE?

There is one ILD in Valles Marineris (Ganges 5) which is exposed on the wall rock but its heavily eroded style (yardangs, flutes, grooves) is much different from the wall material (spur and gully morphology). Further are there differences in albedo and TI. Besides, Ganges 5 shows similarities to Ganges 1, which is exposed on the floor and at a similar elevation range (Fig. 65) which may indicate Ganges 1 once reached the wall rock and thus overtopped Ganges 5 in elevation. Therefore, the ancient deposits hypothesis is unlikely.

Stair-stepped morphologies, which may be ascribed to tuff-like weathering, are observed in all 14 ILDs and possible characteristic weathering marks are present in 8 out of 14 ILDs (Aram, Iani 1, Arsinoes, Ganges 1-5, Sect. 5.1). Nevertheless, there is no local volcanic source and the huge volcanic centres of Tharsis and Elysium are > 3500 km away.

Characteristic mafic minerals such as olivine and pyroxene were not found. However, a general volcanic contribution in the form of ash (possibly from Tharsis) cannot be ruled out since Mars is affected by volcanic processes and the ILD localities (chasmata, chaotic terrains) are genetically and chronologically associated with Tharsis (Sect. 2.4). In this case, then the ash must have weathered into sulphates.

Table volcano-like morphologies were observed in 4 out 14 ILDs (Aram, Aureum 2, Ganges 1, Capri/Eos) but the required mafic minerals (olivine and pyroxene) are not present. What argues against sub-glacial volcanism (Sect. 6.3) is the lack of volcanic features like calderas or vents. Similarly main glacial edifices (e.g. eskars, moraines or wall rock striation), which are present in glacially affected Martian regions like the South Pole, the Argyre, Hellas and Elysium region [*Head et al.*, 2001; *Jaumann*, 2003] are lacking.

ILDs do not demonstrate characteristics of aeolian deposits. The indicative morphologies lack and no similarities with Martian dunes are observed (e.g. morphology, consolidation, albedo, mineralogy, height). Even if ILDs were aeolian material that was formed somewhere else and transported and cemented, they would rather show sulphate surface coatings than massive deposits of stacked sub-horizontal material.

A lacustrine origin may be feasible since aqueous deposition is indicated by the hydrated sulphate minerals observed in 7 out of 14 ILDs (Aram, Aureum 2, Iani 2+3, Ganges 1, Capri/Eos) and since all ILDs occur in depressions and are overtopped by the surrounding plateau rim (Fig. 63, 64). There would be three different scenarios: a) open-basin lake: 7 ILDs (Aurorae, Ganges 1-5, Capri/Eos) and b) closed-basin lake (Aram, Aureum1+2, Arsinoes) and 3) other depressions (Iani 1-3). Sub-horizontal layering (Sect. 5.7) could indicate quiescent conditions during deposition.Convolute-like bedding is observed in Aureum 2 and Aram and indicates different consolidation of material and density contrasts as well as water-saturated sediments. The lacustrine hypothesis thus could be adequate when input (to produce sulphates) is ensured e.g. by confined aquifers within the wall rock.

The spring deposit hypothesis combines morphologic and mineralogical characteristics of 6 ILDs (Aram, Aureum 2, Iani 2+3, Ganges 1, Capri/Eos). When disregarding the abundant carbonaceous springs, this hypothesis seems reasonable to explain the mineral diversity (locally enriched hydrothermal fluids) and wide distribution of ILDs in closed basins (craters) and open basins (Valles Marineris). Potentially, Martian brines are more enriched in magnesium and iron resulting from the mafic crust and causing a higher magnesium sulphate concentration and acidic conditions. There, the formation of sulphate is preferred at the expense of carbonates and other salts.

Mineralogical similarities to salt domes could be present since sulphates were observed on ILDs (kieserite, PHS), but these are not known from terrestrial salt domes. Even if these sulphates were salt domes, it suggests that they were formerly buried and rose later on. It is questionable how this could be put in context with the formation of chaotic terrains, Valles Marineris and the outflow channels since then they must have formed in the Noachian.

After all formation hypotheses that focus on the ILDs, this is the first study that concerns with mineralogical observations which lead to a potential formation and evolution of ILDs. For the discrimination between potential formation hypotheses the mineralogy is essential since minerals require certain kinetics which are characteristic for their formation and which thus provide insights into the prevalent environmental conditions at that time. Morphology is especially important as it may show the morphological context and can be very useful when compared to terrestrial analogues. Indicative morphological features then lead to possible formation scenarios that could have occurred in this area on Mars. The formation in a lacustrine environment is best explained in combination with spring deposits (hydrothermal fluids entering the system). These processes lead to the formation of ILDs in a) open rift basins and interconnected areas and b) in (more or less) closed depressions (Aram, Aureum, Arsinoes, Iani 1-3).