Taking n ¼ 0.04 as commonly used for a rough non-vegetated bedrock, the result gives a value of Q ¼ 0.5 10^6 m^3/ s. Taking extreme values of n ¼ 0.01 and 0.07 would result in values from 0.3 to 2 10^6 m^3/s. The value of QE0.5 10^6 m^3/s should thus be taken as a rough estimate of the maximum discharge rate possible through the valley.

6.2. Discharge rate on the flood plain

On the grooved plains, the flood appears as a sheet flow and might not have been as deep as in the valley. The largest teardrop island (A) and grooves are erosion markers that can be used to estimate the flow depth. However, they are topographically subtle structures not visible on HRSC or MOLA DEM. The teardrop-shaped island is also invisible on MOLA profiles because it is located in a gap in between individual profiles. Grooves can be compared to the surrounding landforms in Fig. 7c. Here, the 100 and 200 m high highland residual hills are not affected by the flow limiting the flow thickness to smaller depth. On HRSC close-ups, grooves are apparently of similar height as the rim of the 500 m diameter crater in their surroundings (Fig. 4a). Estimating the rim height of this crater size would give an order of magnitude for the grooves height, so for the flow depth too. The height of crater rim (Hr) is related to the crater diameter (D) according to Hr ¼ $0.036D^{1.01}$ on the moon (Melosh, 1989) and Hr ¼ $0.03D^{0.96}$ for small Martian craters (Garvin et al., 1999). On the basis of the diameter of the impact crater of 500 m, the height would be about 18 m using the first relation or 12 m using the second. Thus, we use a value of 1575 m for the flow thickness. We assume for the calculation a flow width of 10 km, which is the lateral extent of the grooves, and a slope of 0.51 measured locally. The calculation gives a value of about 1.3 10^6 m^3/s for n ¼ 0.04 and a depth of 15 m, with extreme values of a minimum of 0.4 10^6 m^3/s using n ¼ 0.07 and 10 m of depth to a maximum of 8 10^6 m^3/s using n ¼ 0.01 and 20 m of depth. This estimation of about QE1 10^6 m^3/s is consistent with the value obtained for the valley of QE0.5 10^6 m^3/s: discharge rates are consistent with an initial sheet flow that was later partially sequestered inside the valley to the east while it was still flooding the plains to the southeast.

6.3. Comparison with other floods

The calculated peak discharge rates in the range of magnitude of 1 10^6 m^3/s for the flood system are 100–1000 times lower than those calculated for large Martian outflows such as Kasei or Ares Vallis with values of up 10^9 m^3/s (Komar, 1979), but they are similar to the values found for late episodes of floods in Kasei Vallis (Williams et al., 2000). These discharge rates are also in the range of calculated peak discharges of terrestrial megafloods, smaller than the glacial surge of Lake Missoula in the Scabland region with 20 10^6 m^3/s (Baker, 1973), and similar to the overflow of Lake Bonneville with 1 10^6 m^3/s (O'Connor, 1993) and to the largest reported sub-glacial eruption in Iceland with 0.7 10^6 m^3/s (Waitt, 2002a, b). These two latter comparisons show that the North Syrtis outflow, despite being not as large as most of the Martian outflows, is an important flood.

7. Discussion: Stratigraphic relationships, age and origin the flood

7.1. Age relationships

The Early Hesperian epoch is defined by a crater density of N(5)=125–200, i.e. 125–200 craters larger than 5 km in diameter per million square kilometers, or N(2)= 1200–750, i.e. 1200–750 craters larger than 2 km per million square kilometers (Tanaka, 1986). Crater densities found for Syrtis Major Planum are of N(5) ¼ 15476 (Hiesinger and Head, 2004), or N(5) ¼ 124716 (Mangold et al., 2000), or N(5) ¼ 100 for the main activity episode (Greeley and Guest, 1987), which all put Syrtis Major volcanic plains in the Early Hesperian. Using the new HRSC images, the area of 4300 km^2 is too small to derive a N(5) age, whereas our crater count gives an N(2) ¼ 11607520, which also indicates an Hesperian age, but seems to be slightly older than previous estimates.

The age of the volcanic plains does not give the age of the flood itself but a maximum age. Most craters are fresh and not affected by the aqueous flows, but the presence of the two teardrop-shaped islands shows that two impact craters, at least, were present before the flood, thus implying a hiatus of time between the lava plain formation and the catastrophic flood. It is therefore unlikely that the floods formed as a direct consequence of the underlying lava emplacement. Nevertheless, the presence of fresh lava lobes in the SW and North of the studied region (Fig. 6) suggests that the volcanic activity continued in the region after the flood occurred. In that case, the flood might have formed in between two distinct episodes of activity of Syrtis Major lavas, in the Hesperian epoch.

7.2. Origin of the flood

The origin of this flood over Syrtis lava flows is difficult to understand as it is for many other outflow channels, but the interpretation is complicated by the poor knowledge of the source area. Here, different hypotheses can be proposed such as (1) a subsurface origin due to ground ice melting or groundwater release by either increasing geothermal activity or heating by lava flows; (2) a subsurface origin due to tectonic pressurization by seismic activity; (3) a regional rise of the water table; or (4) a melting of glaciers present at the surface by incoming lava flows. Hypotheses involving a lake overflow are not discussed hereafter because of the lack of evidence in favor of such a lake in the surroundings.

The magmatic activity and presence of dikes driving lavas to the surface might be the best candidate to trigger outflows on Mars (Wilson and Head, 2004). The presence of chaotic terrain (Fig. 9b), or putative aqueous flows coming from underneath lavas (Fig. 9a) may favor a subsurface origin. These putative source areas suggest that water was stored in the ground of Syrtis either as liquid water, or as water ice that subsequently melted due to the magmatic activity. This questions if such water was stored inside Syrtis lavas or in the underlying bedrock. An important parameter is that the lava plains on which the outflow formed are located in the vicinity, only 20 km, of the Noachian highlands–lavas boundary. Clay minerals are known to exist in the crust of the Nili Fossae region (Poulet et al., 2005; Mangold et al., 2007) suggesting that water might have existed in this region before the Syrtis Major lavas were emplaced. Clay minerals present below the lava flows could have contributed to increase the liquid water storage ability of the subsurface. Thus, at this location, lava could have buried a Noachian crust in which abundant water, as liquid or ground ice, was stored.

A recent work (Hanna and Phillips, 2006) shows that outflows might form when the tectonic pressurization due to fault movements would progressively create the subsurface drainage under pressure (Hanna and Phillips, 2006). This hypothesis requires water to be liquid to occur. A large fracture (Fig. 2) appears to cross the highlands north of the study region and might have been a source of seismic activity. However, this fracture does not cross the surface of lava plain. Whether this fracture played as a blind fault after its burial is impossible to demonstrate, and the source of fluid is difficult to explain from a blind fault. Thus, the tectonic pressurization hypothesis is here not as convincing as it is for outflows clearly controlled by major fractures such as for Mangala or Athabasca Valles.

A third hypothesis is that the remobilization at surface of subsurface liquid water might have occurred due to a regional rise of the groundwater table. The exact reason of a water table rise is uncertain, and the result of rovers study on the Terra Meridiani area suggests that modifications of the water table on Mars might have occurred (McLennan and 31 colleagues, 2005). Sapping valleys exist in the Nili Fossae region showing the possibility of groundwater activity (e.g. Mangold et al., 2006, 2007). Nevertheless, we do not observe other flood signatures connected to these sapping valleys, so this hypothesis does not well explain the occurrence of the single outflow channels on the volcanic terrain.

An alternative explanation to the three subsurface processes proposed is that surface ice stored as glaciers over lava flows might have triggered floods. Glacial surges are the most frequent processes to trigger catastrophic floods on Earth (e.g. O'Connor, 1993). This hypothesis could explain the sudden presence of flood features north of the DV: if a glacier was present at this location, the first grooves would be located at the glacial front. However, we do not observe any glacial landforms such as moraines or eskers that could support this hypothesis either locally at the north of DV source area, or at any locations of the Nili Fossae-Syrtis Major region. This hypothesis is therefore much more speculative than the subsurface triggered floods.

From the present set of observations, we conclude that the exact formation mode of the flood incising Syrtis Major lava flows remains uncertain. We favor the first hypothesis, the role of the volcanic heating, involving water ice melting and/or liquid water pressurization below lavas, as suggested by the presence of the chaotic terrain, the restriction of the aqueous flows to lava plains and the presence of lava flows unaffected by fluvial features that might form later. The presence of this outflow close to the region of Nili Fossae at a location where the lava is likely thin is certainly not a coincidence: the source of water might be found in the basement below the lava flows. This hypothesis could also explain why the inferred flood features are only observed in the Syrtis region. Indeed, the overall volcanic region of Syrtis Major is devoid of any other fluvial landforms, as observed with new datasets. The flood might sign an activity at the periphery of the bulge due to interactions with the basement.

At this point, it should be noted that most outflow channels on Mars are observed in connection with volcanic regions. Late Amazonian outflows have been identified in the Cerberus plain (Athabasca Valles, Marte Valles) in close relation with recent volcanic activity (e.g., Burr et al., 2002). Other examples were found on HRSC images at the southeastern margin of Olympus Mons (Basilevsky et al., 2006). Many outflow channels are connected to Hesperian volcanism, such as Dao Vallis and Harmakhis Vallis around Hadriarca Patera, or Hebrus Vallis around Elysium Mons. Recently, a paleoflood activity has been identified using HRSC images over the Hesperia Planum. Hesperian plain (Ivanov et al., 2005) and volcanic cones have been identified in the chaotic region of Margaritifer Terra (Meresse et al., 2008). All these outflows seem to be genetically related to the formation of volcanic plains or their thermal consequences. Nevertheless, Syrtis Major Planum, as well as Hesperia Planum, are some of the oldest locations on Mars where water activity seems to have been negligible. According to the identification of new outflows in Hesperia Planum (Ivanov et al., 2005) and now in Syrtis Major Planum (this study), it appears that some locations previously identified as among the driest on Mars once had local hydrological activity characterized by quick fluid discharge and flood at the surface. This activity might outline the interactions between the volcanic activity and the water rich basement presently buried beneath the lavas.

8. Conclusion

HRSC images of the northern Syrtis Major region at the contact with the Nili Fossae highlands display erosional features such as grooves, teardrop-shaped islands and valleys. These landforms display similar directions indicating a likely coeval activity different from lobate lava flows where observed. We interpret these landforms as due to a flood event that likely took place in the Hesperian period. Flow landforms of 410 km long and few km wide are consistent with main topographic slopes in most locations. Peak discharge estimates of about 1 10^{6} m^{3}/s are in the range of terrestrial mega-floods. To date, the most likely origin invokes subsurface water mobilization and discharge due to volcanic activity and subsequent pressurization. The observation of an aqueous flood is unusual in the Syrtis Major region, which is a generally dry region dominated by volcanic landforms and mafic minerals. This identification is comparable to the recent identification of outflow channels by HRSC/MEx data in different volcanic plains in the Hesperia Planum, Elysium Mons or Tharsis regions. It shows how frequent is this process even in regions previously supposed to be very dry and devoid of aqueous flows. This outflow occurred in the periphery of the region, possibly as an expression of water storage buried in the underlying basement rocks.

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