4.3. History of gully activity

It has long been established that obliquity is the most influential of the three climate drivers (e.g. Kieffer and Zent, 1992) and thus our results suggest that gully activity along PF slopes would have been favored during phases of peak obliquity $\geqslant 35°$. This occurred most recently in the period between ~0.5 and 2.1 Ma (Fig. 10). This period is consistent with age estimates of gully activity elsewhere on Mars (Reiss et al., 2004; Schon et al., 2009). In comparison, the model results suggest that the EF gullies were only active prior to 5 Ma when the obliquity cycles would peak to $\geqslant 45°$ (Fig. 10). Hence the most recent phase of EF gully activity occurred at an earlier period than was experienced by the PF gullies. This is consistent with the higher number of superimposed craters and a more degraded appearance of EF gullies relative to PF gullies. Even during 5–10 Ma, obliquities of 45° were only achieved for 20 kyr during each ~110 kyr obliquity cycle relative to the 70 kyr spent at obliquities >35° during the same time period. Hence the limited accumulation period and lower frequency of activity may account for the vast difference in gully morphology between the EF and PF slopes and the associated lower EF slope erosion rates would explain the steeper EF slopes relative to the PF slopes. Due to the lesser but still significant influence of eccentricity (wavelength ~2 Ma) on insolation, not all of the periods of high obliquity will correspond to the same amount of insolation (Fig. 10) (see also, Kreslavsky et al., 2008). Therefore, gully activity is expected to vary in response to this over the last 20 Ma.

4.4. Spatial representation of the model results

Fig. 11a shows the spatial distribution of the polar facing and equator-facing gullies that display the most prominent differences in the geomorphological characteristics that were described above. The two end member gully types were mapped based on the following morphological characteristics: PF end member gullies (highlighted in red in Fig. 11a) were defined by broad alcoves that contain multiple tributaries that coalesce to form single large sinuous channels. EF gullies (highlighted in blue in Fig. 11a) were defined by linear channels that originate from the base of well-defined cuspate alcoves that occur in the rock unit. The difference in valley depth (Fig. 3) appears to have had a limiting affect on both gully types. Hence, the two end members were not defined by specific scale ranges as both groups were affected by the lengths of the slopes they were on. The gullies on slopes not highlighted in Fig. 11a consisted of morphologic characteristics representative of both end member types. Fig. 11b–d shows the model results based on the aspect and slope values for the study site derived from a 200 m/pixel HRSC Digital Elevation Model. The value represented on the maps is the time taken for the temperature to increase from 150 K to the melting point. Hence, the smaller the value the higher the potential for gully activity to have occurred (assuming that a dust layer is produced over the snowpacks to reduce the albedo sufficiently). Larger time periods will increase the effect of loss through sublimation, reducing the volume of the snowpack, possibly to the point at which it is completely removed before melting could occur. Regions of no activity (such as EF slopes at obliquities <45°) correspond to conditions where either the temperature never become cold enough for CO_2 frost to form or the melt point is never achieved. The model results show good agreement with the map of gully morphology (Fig. 11a). In addition to representing the spatial distribution of the extreme insolation environments experienced by EF and PF slopes, Fig. 11 also provides an insight into gully formation at other orientations. Gullies on east- and west-facing slopes experience gully activity index values between those of the PF and EF slopes, which is consistent with the gullies on these slopes consisting of morphologies between the two end members.

5. Summary and conclusions

The top-down melting model of gully formation presented here is consistent with the morphological variations displayed in the study area and provides a potential timeframe for gully activity over the last 10 Ma which may yield an insight into morphologic variations observed elsewhere on Mars. Furthermore, continued high-resolution modeling will help to elucidate the more detailed processes that operate in this environment on Mars, such as those seen in the Antarctic Dry Valleys (ADV). For example, wind on Mars may be a means of concentrating precipitation into snowpacks in a manner similar to that seen in the ADV (e.g., Morgan et al., 2008; Dickson et al., 2007b; Head et al., 2007; Levy et al., 2007). Furthermore, more work needs to be done in comparing the way in which snow, dust, and other sediment accumulates and melts in the ADV so that models of accumulation and melting on Mars (e.g., Williams et al., 2008, 2009) optimize their geological realism. Additionally, katabatic winds, which are particularly developed over both martian and Antarctic slopes, yield competing effects on the stability of ice. On the one hand, slope winds are known to contribute to the transport and formation of snowpacks. On the other hand, katabatic flow results in a warmer atmosphere above the slope by adiabatic compression (Nylen et al., 2004; Marchant and Head, 2007; Spiga and Forget, 2009), which might favor melting. Further modeling would also address the influence of atmospheric circulation over complex terrains on the formation of clouds and on the precipitation budget. Integration of these comparative terrestrial and martian analysis will provide new insights into recent water-related processes on Mars.

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