Subsequently, atmospherically-derived water is introduced to the gully–polygon system. Topographically-depressed polygon troughs are shaded environments that could cold-trap atmospheric water frost (Hecht, 2002) and/or act as topographic obstacles, concentrating wind-blown particulate ice (Head et al., 2008)—expanding the extent and thickness of seasonal frost accumulations imaged in this survey. Under appropriate obliquity- and slope-dependent peak insolation conditions (Hecht, 2002; Kuzmin, 2005; Levy et al., 2007a; Morgan et al., 2008) this ice, concentrated in polygon troughs, could melt to produce short-lived, ephemeral, liquid water. Peak insolation conditions occur when the solar angle is normal to the surface slope. Gully–polygon systems commonly occur on steep, $\sim 30^\circ$ slopes (Dickson et al., 2007a), making them strong candidates for recent surface melting of atmospherically emplaced volatiles (Hecht, 2002). Crater-retention age dating of recent gully deposits similar to those included in this study indicates gully activity within the past 1–2 Ma, although flows may have occurred as recently as 300 ka (Riess et al., 2004; Schon et al., 2009).

As in the Antarctic Dry Valleys, martian polygon troughs appear to concentrate and direct the transport of metastable surface- and near-surface, meltwater, creating annexed polygon troughs (Levy et al., 2008b). Short-lived water transport in annexed troughs (Figs. 8 and 9) could easily transport unconsolidated polygon trough and wedge sediments, contributing to sediment deposition in small terminal fans. Over time, annexed trough channels would converge towards trunk channels (Fig. 9b, compare left and right), forming braided annexed channels. Braided channels would produce larger fans than those formed from isolated annexed troughs by collecting sediment from several separate channels, and by increasing the volume of water available to move sediment. These fan deposits would still be relatively thin, and would be easily cut or dissected by the continued growth of underlying polygon cracks (Fig. 10b).

Continued erosion within annexed troughs would provide an increasingly large sheltered environment for accumulation and subsequent melting of ice and windblown snow (Figs. 6 and 9b). Eventually, braided channel walls would be widened, creating an elongated alcove with one or more incised channels (Fig. 6). Material eroded from elevated alcoves would be deposited in a distal fan, which could remain thin enough to permit continuing dissection by thermal contraction crack expansion. Elongate alcoves are analogous to gully-related concavities or nivation hollows in the ADV (Figs. 1 (inset) and 2b). The presence of polygons in elongate alcoves, but not in widened alcoves (below) suggests that some ice-rich latitude-dependent mantle material remains intact in these alcoves.

This process would continue for as long as climate conditions remained capable of generating liquid water or brines that remained metastable long enough to flow (e.g., Mellon and Phillips, 2001; Hecht, 2002; Costard et al., 2002; Christensen, 2003; Kreslavsky and Head, 2007; Burt et al., 2008). The longevity of briny fluids on Mars is strongly dependent on solute depression of the freezing temperature (potentially supporting liquid flow at temperatures as low as -20 to $-50\,^\circ\mathrm{C}$, depending on salt chemistry and concentration; Burt and Knauth, 2007) and reduction in evaporation rate to support persistent fluvial activity (potentially as slow as 0.04 mm/h at $-25\,^\circ\mathrm{C}$; Ingersoll, 1970; Sears and Chittenden, 2005). Eventually, alcove mantle material would be fully eroded, exposing original scarp/crater-wall surfaces (Fig. 5). Exposed crater and mantle material in these large, steep alcoves might fail in response to gravitational sliding, as well as in response to surficial fluvial erosion, producing large fans beneath leveed channels (Morgan et al., 2007b). Extensive fan deposition may bury polygons, cutting off underlying thermal contraction cracks from the fan surface exposed to seasonal thermal cycling, and leading to the generation of a network of new polygons (fine fractures present on some large fan surfaces that are discontinuous with the polygon network surrounding the fan). Other large fans lack any polygonal patterning, suggesting that fan emplacement may have been rapid enough to prevent the formation of syngenetic polygons (MacKay, 1990).

As climate conditions became colder and drier (Forget et al., 2007), fluvial and erosive processes would decrease and eventually cease in the gullies. In the absence of gully flow and infiltration refreshing buried ice-cemented permafrost, enhanced sublimation on equator-facing slopes would desiccate shallow permafrost, reducing sediment cohesion, and ultimately resulting in subdued gully and polygon textures in response to aeolian erosion. In degraded gully–polygon systems (e.g., Fig. 11) polygons are lost from view before gullies (owing to the larger size of gullies) suggesting that polygons may have interacted with gullies even more commonly than is currently observed.

In summary, this model provides a mechanism for the development of martian gullies that occur in association with polygonally patterned ground. Morphological similarities between martian gully–polygon systems and the closest morphological and climatological analog on Earth (gully–polygon systems in the ADV), suggest that the martian examples may have formed and developed on slopes underlain by ice-cemented permafrost. In both cases, a top–down source for gully-carving water is implied, as geomorphological evidence suggests limited melting of the underlying ice-cemented substrate.

6. Conclusions

Observations of gullies and polygons from Antarctic field work and analysis of HiRISE image data suggests the following stratigraphic and temporal relationships between gullies and polygons: (1) polygons pre-date alcove excavation in some gullies; (2) polygon troughs form traps for ice and windblown snow that can become sources of meltwater for gullies; (3) polygon troughs have been annexed and eroded by some channels, indicating that channel formation occurred on a polygonally patterned surface; (4) fan embayment and dissection relationships indicate that some fans formed on polygonally patterned surfaces; and (5) polygon development continued during fan emplacement. Using morphologically similar gully–polygon systems in the ADV as a guide, the stratigraphic relationships between gullies and polygons observed in the HiRISE images suggest that the martian gullies analyzed in this study developed on slopes underlain by polygonally-patterned, ice-cemented permafrost. Interactions between martian gullies and polygons are analogous to those documented in ADV gully–polygon systems.

No evidence was seen for significant melting of underlying ice-cemented permafrost on Earth or Mars. Additionally, no evidence of subsurface groundwater release (e.g., Malin and Edgett, 2000; Heldmann and Mellon, 2004; Heldmann et al., 2007) from beneath the ice table was observed at HiRISE resolution. No paired aquacludes or intensive substrate layering abutting gully channels or alcoves was observed in gully–polygon system sites, which included crater rims, crater walls, and isolated central peaks, nor was scour associated with high-pressure water release observed. Rather, the locations of gullies on Mars are strongly associated with the presence of a mantling unit that is commonly polygonally-patterned. These lines of evidence suggest an atmospherically emplaced, top–down source for fluids involved in martian gully evolution on polygonally-patterned surfaces, comparable to hydrological processes observed in the Antarctic Dry Valleys. On Earth and Mars, the presence of polygons is not shown to be directly causal of martian gully formation, but to be diagnostic of top–down gully water sources, and to amplify the key processes of gully formation: accumulation of water ice and the channelized transport of melt water.