Thus, polygonally-patterned LDM surfaces on Mars may consist of both equilibrium landforms and relict landforms. Current ice table depth is set primarily by climate and salts (Jakosky and Carr, 1985; Mellon and Jakosky, 1995; Mellon et al., 2004, 2009; Hudson et al., 2009a). Accordingly, the deposition of meters-thick ice deposits cannot be readily accounted for by currently operating geomorphic processes, and implies an older, slightly different, set of "ice age" climate conditions (e.g., Head et al., 2003). This difference between martian depositional and modification conditions over time and space is analogous to microclimate processes governing the growth and development of sublimation polygons forming atop debris-covered glacier ice in Antarctica (Marchant et al., 2002). In this terrestrial case, ice involved in polygon formation is deposited in equilibrium with the glacial accumulation zone microclimate conditions (e.g., a depositional environment) and is transported by glacier flow into warmer conditions at lower elevations, resulting in a gradual deepening of ice table depth (Marchant et al., 2002). At each step, the polygonally patterned frozen substrate is approaching local equilibrium with prevailing microclimate conditions.

Geomorphological response of the landscape to changing microclimate conditions over time and space is a hallmark of equilibrium landform processes. Accordingly, polygonally-patterned surfaces on Mars represent a range of cold desert processes, of which some are active and some are relict. Active, developing landforms forming under prevailing martian climate conditions over the past ~1–2 Ma can be considered potential martian equilibrium landforms. Other, relict, landforms provide insight into past climate conditions that have been preserved by the cold and hyperarid surface conditions acting over the past millions to hundreds of millions of years.

## 5. Outstanding questions in martian polygon studies: integrating lander data

Despite significant progress over the past decade in decoding the geological, climatological, and astrobiological significance of martian thermal contraction crack polygons, several questions remain points of continuing investigation. Lander-scale chemical and morphological analysis of LDM surfaces (Fig. 15) (e.g., Bonitz et al., 2008; Boynton et al., 2009; Hecht et al., 2009; Smith et al., 2008, 2009) raises questions regarding the local microstructure of LDM deposits.

Following the Viking Lander 2 (Mutch et al., 1976; Marchant and Head, 2007), the Phoenix lander has provided a unique first-look at permafrost processes operating on the surface of the martian polar plains (Smith et al., 2008, 2009). Critical results from the mission include the detection of an icy surface present beneath thin, overlying, dry sediments (Smith et al., 2008, 2009; Lemmon et al., 2008; Mellon et al., 2009); complex soil chemistry comparable to that observed in terrestrial cold and arid terrains (Boynton et al., 2009; Hecht et al., 2009; Kounaves et al., 2009); and weather/climate conditions consistent with the generation of a range of cold-desert landforms (Smith et al., 2008, 2009; Lemmon et al., 2008; Mellon et al., 2009). Questions remain, however, as to the abundance, origin, and subsurface distribution of the observed ice, the history of liquid water at the landing site, the age and stability of the landing site surface, and the relationship between the landing site and the martian latitude-dependent mantle (LDM).

Application of geomorphological techniques and principles developed in terrestrial permafrost settings (e.g., the Antarctic Dry Valleys, Berg and Black, 1966; Sugden et al., 1995; Marchant et al., 1996, 2002; Sletten et al., 2003; Kowalewski et al., 2006; Marchant and Head, 2007; Swanger and Marchant, 2007; Kowalewski, 2009; Swanger, 2008) can be usefully applied to lander-scale exploration of martian polar terrains (e.g., Levy et al., 2009e). For example, stable (non-churning) and vertically ablating surfaces are typical of extremely ice-rich permafrost surfaces in some portions of the Antarctic Dry Valleys (see Section 2.4)—particularly those in which sublimation is the dominant water phase transition. Terrestrial permafrost geomorphology experience provides a guide to geomorphic features observed on the martian surface that may suggest stable, vertically ablating, ice-rich permafrost (Fig. 15a and b) (Brook et al., 1993; Sugden et al., 1995; Marchant et al., 2002; Marchant and Head, 2007). Pitted rocks are present at the Phoenix site (Fig. 15c), and have been interpreted as vesicular boulders (Arvidson and Mellon, 2008). Alternatively, these boulders may have been pitted by a range of surficially-acting physical processes, such as salt weathering, that typically forms mm-to-cm-scale pits on static rocks in Antarctic environments on timescales from ~1 to 4 Ma (Matsuoka, 1995; Staiger et al., 2006; Head and Kreslavsky, 2006; Marchant and Head, 2007). This age for pitted rocks at the Phoenix landing site would be consistent with predictions of geologically recent coeval development of LDM and boulder piles (see Section 4.2). Next, although preliminary cobble and boulder counts at the Phoenix site have been interpreted to indicate thorough reworking of the surface by dry cryoturbation (Heet et al., 2009; Mellon et al., 2008b), the presence of cobbles and boulders overlying fine sediments, even in polygon interiors, strongly suggests the formation of "desert pavement" surfaces, typical of vertically ablating arid surfaces (Fig. 15a and b) (McFadden et al., 1987; Sugden et al., 1995; Marchant and Denton, 1996; Marchant et al., 2002). Pavement surfaces are ablational, consistent with the paucity of aeolian depositional ripples at the site reported by Arvidson and Mellon (2008)—although light-toned, smooth "dust pools" are abundant around the lander, and may be analogous to flat-lying sand accumulations typical of Antarctic polygonally-patterned terrains (Marchant et al., 2002; Levy et al., 2006). Additionally, linear groups of boulders and cobbles present at the Phoenix site appear analogous to the surface expression of relict polygon trough locations found in vertically-ablating Antarctic tills (Marchant et al., 2002). Surface manifestations of relict polygon wedges would not be preserved in a well-mixed, cryoturbated sediment column. Lastly, tightly clustered groups of cobbles and boulders at the landing site appear analogous to disintegrated boulders (or "puzzle rocks") common in Antarctic, arid terrains—clasts that are weathering in situ with minimal disarticulation by cryoturbation (Fig. 15d) (Staiger et al., 2006; Marchant and Head, 2007, Fig. 10). Taken together, these landforms provide strong evidence for a stable, non-churning permafrost surface at the Phoenix landing site.

As with sediment and rock analyses, observations of thermal contraction crack polygons resolved in exquisite detail by landers such as Viking Lander 2 and Phoenix provide insight into permafrost-related processes occurring in the upper centimeters of the martian LDM. Troughs emerging from polygon interiors that orthogonally intersect adjacent polygon troughs indicate that the Phoenix landing site surface has undergone more than one generation of polygon fracture formation, consistent with models predicting ongoing thermal contraction cracking (Fig. 15e) (Mellon, 1997). Ongoing fracturing, preferential sublimation of buried ice at fracture locations, winnowing of dry sediment into surface furrows (Fig. 15f), and periodic slumping of clasts into polygon troughs (typical of terrestrial sublimation polygons, e.g., Marchant et al., 2002) may account for both polygons observed at the site with both cobble/boulder-covered interiors overlying fines, as well as for troughs observed with cobble cover. If sublimation polygons are present at the Phoenix landing site (e.g., Levy et al., 2008c), a surface history dominated by vertical ablation of ice-rich subsurface material, rather than by cyclic cryoturbation, is strongly implied.