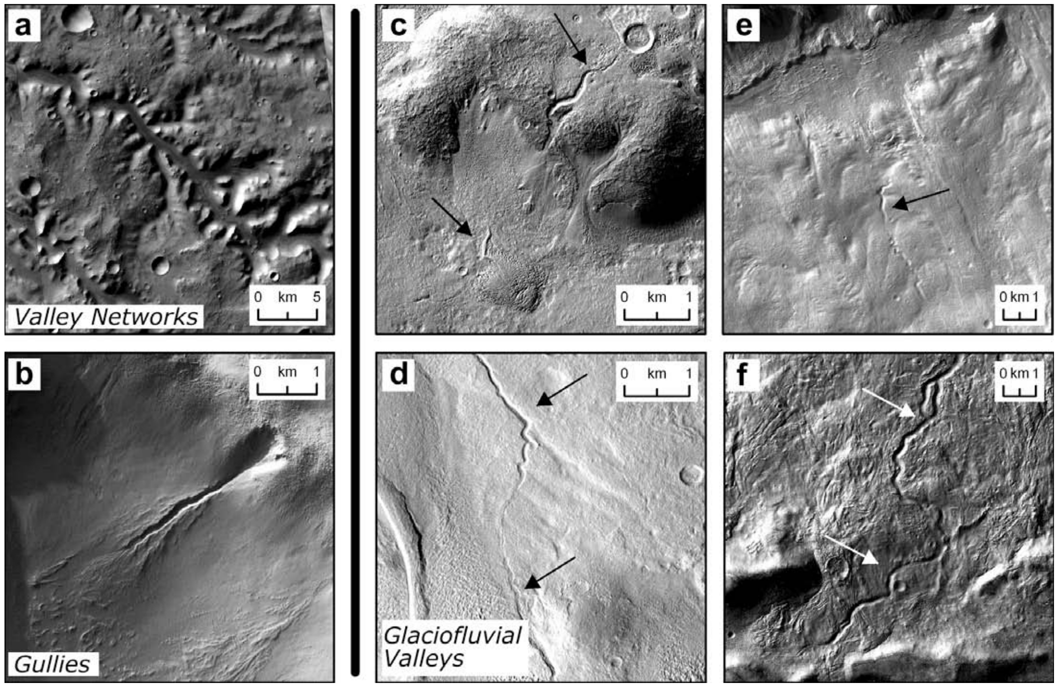

Fig. 1. Examples of features on Mars interpreted to be formed by liquid water (CTX image number): (a) valley networks at −10.6°E, 22.8°S (P21_009049_1580), (b) a gully on a crater rim at −104.6°E, 47.9°S (P18_008077_1317); and possible glaciofluvial features, (c) 11.7°E, 39.7°S (P15_006807_1391), (d) 164.4°E, 39°N (P17_007658_2175), (e) 58.3°E, 29°S (B01_010075_1498), and (f) −158°E, 42.8°S (P12_005877_1391). Locations for the glaciofluvial examples (and others in the paper) are shown on the distribution map, Fig. 11.

(Shean et al., 2007). Two preferred insolation geometries include terminal cliff faces (Fountain et al., 1998; Lewis et al., 1999) and lateral margins where ice abuts steep bedrock slopes, the latter enable diffuse radiation to warm proximal ice surfaces. By way of comparison, we note that meltwater channels in association with wet-based glaciers typically incise thick deposits of proglacial outwash, and show anastomosing and/or braided patterns with multiple channels (Denton et al., 1993; Dyke, 1993). Channels from cold-based glaciers are typically shorter, fewer in number, and straighter (e.g., Dyke, 1993; Skidmore and Sharp, 1999; Atkins and Dickinson, 2007). Given the relative paucity of debris entrained in most cold-based glaciers, lateral and proglacial channels may represent the only evidence for cold-based glaciation (Kleman, 1994; Kleman and Borgstrom, 1994; Atkins and Dickinson, 2007).

The key factors controlling the formation and evolution of surface meltwater and resultant streams from cold-based glaciers include: (1) elevation (temperature-dependence of melting; Fountain et al., 1998, 2006; Lewis et al., 1998; Marchant and Head, 2007), (2) adjacent topography (controlling the focus and orientation of meltwater streams as well as the influx of solar radiation in areas with considerable relief), (3) substrate type (till, bedrock, polygonal ground, etc., controlling the amount and type of erosion and pattern of streams; Atkins and Dickinson, 2007; Levy et al., 2008), and (4) ice temperature (controlling the overall amount of meltwater produced). The presence of supraglacial debris, if sufficiently thick, can serve to decouple underlying ice from atmospheric warming and prevent meltwater production (e.g., Kowalewski et al., 2006).

The main requirement for initiating top-down melting on Mars is sufficient insolation to raise extant ice to its melting temperature, since the thin atmosphere has little heat content and minimal effect on surface temperatures. One factor that may aid reaching the melting temperature is if it is depressed by salts (e.g., Ingersoll, 1970; Knauth and Burt, 2002; Kreslavsky and Head, 2009). Sulfates and other salts species are known to be common at the martian surface (e.g., Clark and Van Hart, 1981; Rieder et al., 1997; Clark et al., 2005), and may be transported and deposited onto ice by the martian atmosphere (similar to atmospheric deposition of salts in Antarctica today; Bao et al., 2000). Additionally, the factors listed above for melting of terrestrial cold-based glaciers likely play a role in enabling top-down melting of cold-based glaciers on Mars.

1.2. Low-to-mid-latitude cold-based glaciation on Mars

Observations from Mars orbit have increasingly led to the recognition of the importance of non-polar ice and glaciation at low-to-mid-latitudes (e.g., Squyres, 1979; Lucchitta, 1981; Head and Marchant, 2003, 2006; Milliken et al., 2003; Pierce and Crown, 2003; Kargel, 2004; Hauber et al., 2005, 2008; Head et al., 2005, 2006, 2009; Shean et al., 2005, 2007; Levy et al., 2007; Kadish et al., 2008; Dickson et al., 2008; Fastook et al., 2009). Regions in both the northern and southern hemispheres are characterized by numerous lobate-debris aprons and lineated valley fill deposits, interpreted as debris-covered glaciers (Head et al., 2006, 2009; Head and Marchant, 2006) based on morphologic and topographic evidence, and terrestrial analogs. Concentric crater fill in similar regions may also have a similar origin (e.g., Squyres and Carr, 1986; Levy et al., 2009). Stratigraphy and crater counting suggest that these features were last active during the Late Amazonian, with crater retention ages younger than a few hundred million years (e.g., Mangold, 2003; Head et al., 2005; Levy et al., 2009). Modeling suggests that ice accumulation and glacial flow is favored at low-to-mid-latitudes during periods of higher obliquity (Forget et al., 2006; Madeleine et al., 2009), and climate and glacial flow models have successfully reproduced the locations and characteristics of major areas of glaciation (Fastook et al., 2009) assuming specific spin-axis/orbital configurations reasonable for Mars in the recent past (Laskar et al., 2004). Terrestrial analogs in hyperarid, cold polar deserts, such as the Antarctic Dry Valleys, support the interpretation that these deposits on Mars were predominantly a result of cold-based glaciation (Marchant and Head, 2007). Generally cold-based activity is inferred because features are almost pristinely