that the formation of LDA and LVF involves both talus and ice, but there is disagreement as to the amount of ice: One end-member calls on formation by ice-assisted creep of talus (often defined as producing a "rock glacier") (e.g., Squyres, 1978, 1979), while another end-member calls on formation as debris-covered glaciers, (predominantly glacial ice with a cover of sublimation lag or till) (e.g., Head et al., 2006a,b). Here we develop criteria to distinguish between these end-members and investigate a wide range of occurrences to assess the origin of LDA and LVF.

Although temperate glacial and periglacial climates and analogs can offer insight into these environments, the extremely cold and hyper-arid conditions on Mars are more likely to be related to environments in which cold-based glaciation is the dominant process and temperatures are virtually always below the freezing point of water (e.g., Marchant and Head, 2007). Terrestrial cold-based glacial analogs have recently been applied to the analysis of fan-shaped deposits on the NW flanks of the Tharsis Montes and Olympus Mons, and have been interpreted to represent extensive tropical mountain glaciers formed by enhanced snow and ice deposition during periods of high obliquity in the Amazonian (Williams, 1978; Lucchitta, 1978; Head and Marchant, 2003; Neukum et al., 2004a,b; Shean et al., 2005, 2007; Head et al., 2005; Milkovich et al., 2006; Forget et al., 2006; Kadish et al., 2008).

Additional Earth glacial analogs have been used to develop criteria for the recognition of glacial deposits in various topographic and environmental settings on Mars (Marchant and Head, 2006). These criteria have recently been applied to the assessment of the fretted terrain, one of the hallmark morphologies of the highland–lowland boundary region in the northern mid-latitude Deuteronilus–Protonilus Mensae area (30°–50° N and 10°–75° E) (Fig. 1). An increasing awareness of the possible role of glacial deposits on Mars (e.g., Lucchitta, 1981, 1984; Head and Marchant, 2003; Marchant and Head, 2007) led to investigation of the question of whether the accumulation of snow and ice, and resulting glacial activity, could account for some of the observed characteristics of the LDA and LVF in the fretted terrain. In one area analyzed (Fig. 1, point 1) (~37.5° N, 24.2° E) (Head et al., 2006a) evidence was presented that lineated valley fill formed in multiple accumulation zones in breached craters, alcoves, and tributary valleys and flowed laterally down-valley forming a major trunk system that was characterized by compression of ridges at constrictions, tight folds at converging branches, and a lobate, convex-upward terminus. In a second area (Fig. 1, point 2) (~40.5° N, 34,5° E) (Head et al., 2006b), a single integrated glacial flow system was documented covering ~30,000 km^2 and consisting of multiple, theater-headed, alcove-like accumulation areas, converging patterns of downslope flow into several major valley systems, and broad piedmont-like lobes where the LVF extended out into the adjacent lowlands. The features and deposits in these two areas were interpreted to represent intermontaine valley glacial systems dating from earlier in the Amazonian.

An additional detailed morphological analysis of a 70,000 km^2 region just east of the area treated by Head et al. (2006b) (north-central Deuteronilus Mensae, south of Lyot, in the vicinity of Sinton Crater; Fig. 1, point 5) was described by Morgan et al. (2009), and is characterized by the distinctive sinuous ~2 km-high plateau scarp boundary, outlying massifs to the north, and extensive fretted valleys dissecting the plateau to the south. These features are modified by processes that form LVF in the fretted valleys, and LDA along the dichotomy scarp and surrounding the outlying massifs. High-resolution HRSC image and topography data show that LVF and LDA deposits are comprised of the same material, show integrated flow patterns, and originate as debris-covered valley glaciers; the proportion of ice and debris involved is high and a significant amount of ice (hundreds of meters) is likely to remain today beneath a thin cover of sublimation till. There is depositional evidence to suggest glacial highstands at least 800 m above the present level, implying previous conditions in which the distribution of ice was much more widespread. In Nilosyrtis Mensae, farther east along the dichotomy boundary (Fig. 1, points 9, 10), LVF and LDA show stratigraphic, topographic, and textural relationships that indicate extensive glaciation along the boundary and multiple phases of glacial overprinting during the late Amazonian (Levy et al., 2007). Evidence was analyzed and presented for the regional integration and flow of LVF material and its interpretation in the context of cold-based glaciation in the Antarctic Dry Valleys.

The synthesis of these areas led to several additional questions: 1) What was the original thickness of the glacier ice? 2) How much ice-surface lowering, through sublimation, retreat and ice loss, has occurred to bring the LDA and LVF surfaces to their presently observed levels? 3) Have there been multiple periods of glaciation, and if so, over what time periods? Preliminary analyses (e.g. Marchant and Head, 2008) suggested that the LDA and LVF might be parts of a larger phase of glaciation, during which glacial ice was much thicker and perhaps completely filled the valleys. Dickson et al. (2008) described evidence for glacial thickness maxima and multiple glacial phases in the Coloe Fossae region of the dichotomy boundary (Fig. 1, point 7). They documented the topography associated with a sloping lobe interpreted to be evidence of a glacial highstand that was part of a LVF glacial landsystem. The elevation difference between the upper limit and the current surface of the LVF at the study site is ~920 m and Dickson et al. (2008) interpreted this difference to reflect the minimum amount of ice-surface lowering of the valley glacier system during downwasting and retreat. Consistent with a general lowering of the ice surface are multiple moraines and/or trimlines, and changes in LVF flow patterns, including local flow reversals, as the ice retreated and decreased in thickness. Furthermore, the clear superposition of several lobes out onto the current surface of the LVF indicates that a smaller-scale phase of glaciation followed the lowering of the valley glacial landsystem. These data suggest that the major Late Amazonian glaciation that produced LVF in this region involved significantly larger amounts of glacier ice than previously thought, and that subsequent, less extensive glaciation followed (Dickson et al., 2008).

2. Synthesis of criteria for recognition

On the basis of these studies and using a range of terrestrial analogs most likely to apply to the recent cold-desert environment of Mars (e.g., Marchant and Head, 2006, 2007), the following criteria have been developed to assist in the identification of debris-covered glacial-related terrains on Mars. We first list the features (Fig. 2), followed by the interpretation of each, listed in parentheses: 1) alcoves, theater-shaped indentations in valley and massif walls (local snow and ice accumulation zones and sources of rock debris cover) (Fig. 2A), 2) parallel arcuate ridges facing outward from these alcoves and extending downslope as lobe-like features (flow-deformed ridges of debris) (Fig. 2B), 3) shallow depressions between these ridges and the alcove walls (zones originally rich in snow and ice, which subsequently sublimated, leaving a depression) (Fig. 2B, C), 4) progressive tightening and folding of parallel arcuate ridges where abutting adjacent lobes or topographic obstacles (constrained debris-covered glacial flow) (Fig. 2B, C), 5) progressive opening and broadening of arcuate ridges where there are no topographic obstacles (unobstructed flow of debris-covered ice) (Fig. 2B, C), 6) circular to elongate pits in lobes (differential sublimation of surface and near-surface ice) (Fig. 2B, C), 7) larger tributary valleys containing LVF formed from convergence of flow from individual alcoves (merging of individual lobes into LVF) (Fig. 2A), 8) individual LVF tributary valleys converging into larger LVF trunk valleys (local valley debris-covered glaciers merging into larger intermontaine glacial systems) (Fig. 2A), 9) sequential deformation of broad lobes into tighter folds, chevron folds, and finally into lineated valley fill (progressive glacial flow and deformation) (Fig. 2B, C), 10) complex folds in LVF where tributaries join trunk systems (differential flow velocities causing folding) (Fig. 2B, C), 11) horseshoe-like flow lineations draped around massifs in valleys and that open in a downslope direction (differential glacial