is much more similar to these developed in graben locally along the dichotomy boundary in the Deuteronilus–Protonilus region (e.g., Coloe Fossae; Fig. 6) than along the boundary scarp or in channels and crater walls there (Head et al., 2006a,b; (Figs. 3–6)).

2) Lineated valley fill and piedmont-like deposits: In environments in Acheron where slopes increase, such as in the dome-like structure at the eastern end, structures and morphologies differ. Here, linear debris aprons are developed in the graben but rapidly turn and flow downslope to create lineated valley fill and, where the graben open to the surrounding plains, large piedmont-like lobes (Fig. 7A, E). In this perspective view, the large piedmont-like lobate debris apron emerges from the graben, flows around an obstacle, and spreads out into a large lobe about 30 km wide. A similar fan is formed just to the north, from flow emerging from the wide graben there (Fig. 7A). Thus, in these cases, linear LDA produce LVF which in turn forms large lobes as the LVF flows downslope and out onto the surrounding plains.

3) Post-Acheron Impact Craters: In this environment, numerous post-Acheron impact craters show evidence of the same type of lobate fill (Fig. 7F, G) as seen in the crater on the floor and wall of the graben (Fig. 7B, D). The northern parts of these craters show interior wall and floor textures (central uplifts, wall terraces, floor roughness) typical of relatively fresh impact craters. The southern walls and floor, however, are almost completely obscured by a darker smoother material forming lobate deposits extending from the inner wall down on to the crater floor. In detail, the deposits are characterized by the same lobate ridged texture seen elsewhere in LDA; the lobes also follow local topography on the crater floor (Fig. 7F, G).

3.5.1. Range of environments in which LDA occur

These occurrences broaden the longitude range in which northern mid-latitude LDA and LVF are observed extending the range sufficiently to suggest that the deposits may be common globally at other similar longitudes (Fig. 1; Squyres 1979), and thus may be related to broad climate latitudinal change rather than specific conditions related to the dichotomy boundary scarp. These occurrences also broaden the geological setting to include additional linear graben (see also Coloe Fossae, Fig. 6) and emphasize the importance of occurrence inside superposed impact craters, and north-facing slopes.

3.6. Assessment of other regions in the 30°–50° N latitude range

The presence of valley glaciers could be due to local environmental conditions in which the accumulation of snow and ice was favored (e.g., Hecht, 2002). The widespread distribution of these glacial systems in the Deuteronilus–Protonilus highland region (Fig. 1), however, suggests that conditions were much more regional, extending across a significant latitude band. To address the question of whether climatic conditions conducive to glacial activity extended beyond the Deuteronilus–Protonilus region, we undertook a broad review of the remaining longitudes at these latitudes and found abundant evidence of local and regional Amazonian glacial deposits in the following areas (Fig. 1), including: 1) Elysium Rise: Hecates Tholus (Fig. 1, point 11): A 45 km wide depression at the base of Hecates Tholus is host to a series of debris-covered glacial deposits (Hauber et al., 2005). 2) Phlegra Montes (Fig. 1, point 12): Debris-covered glacial deposits are located along the scarp of the montes as well as surrounding individual massifs there (e.g., 30°–50° N, 160°–167° E) (Safaeinili et al., 2009). Craters with concentric crater fill show evidence of the former presence of significant thicknesses of ice (overtopping crater rims) in this region (e.g., Dickson et al., submitted for publication). 3) Arcadia Planitia (Fig. 1, point 13): Degraded mountains in central Arcadia contain LDA-LVF deposits (e.g., 35°–40° N, 185°–190° E). 4) Tempe Terra Region (Fig. 1. point 15): LVF and LDA of apparent glacial origin occur in numerous places in the graben and mountains in this region (e.g., 45°–52° N, 280°–300° E) (van Gasselt et al., 2002; Chuang and Crown, 2005). 4) Instances have also been reported of remnant LDA-like features formed of ice at even lower latitudes (Hauber et al., 2008).

4. Discussion and conclusions

The following characteristics are typical of lobate debris aprons and lineated valley fill: 1) Lobate debris aprons (LDA) can be subdivided into linear (along-valley walls and degraded crater walls) and circumferential (around isolated massifs); 2) LDA commonly form from numerous parallel individual flow lobes emanating from alcove-like indentations in massif and valley walls; 3) in some cases LVF glacial systems clearly merge with linear LDA; 4) in some cases linear LDA derived from opposite valley walls merge and flow down-valley; 5) in massif clusters, circumferential LDA often meet those from adjacent massifs, merge, and then flow downslope, forming piedmont-like lobate terminations in the adjacent lowlands.

The relationships described and shown in Figs. 2–7 suggest that linear LDA and LVF are intimately related in morphology and modes of origin. Evidence of melting associated with LDA and LVF in the Arabia Terra region is extremely rare, but in one location in this region (Fig. 6G), several small channels are seen draining from the front of LDA; the unusually abundant pitting in the LDA here and the frontal pits at the location of the small channels suggests that a significant component of ice was involved in the formation of these deposits (e.g., Pierce and Crown, 2003; Mangold, 2003; Li et al., 2005). Among the hypotheses outlined above for the origin of LDA and LVF (e.g., groundwater-fed mobilization, ice-assisted rock creep, ice-rich landslides, rock glaciers, and debris-covered glaciers), we interpret the evidence documented here to support a major role for debris-covered glaciers. Formation of LDA by accumulation of snow and ice in alcoves, and in tributaries along the flanks of valley walls led to the formation and outward flow of glacial ice; debris falling from the talus slopes above became concentrated and deformed to create the lineated glacial debris cover. As LDA grew and coalesced, they merged between massifs and in valley centers, and began to flow down-gradient, forming LVF, ultimately creating large valley glaciers with divides, local piedmont-type glaciers, and very large valley glacial landsystems (Head et al., 2006a,b). The location and distribution of these features (Fig. 1) strongly suggest regional intermontaine valley glacial systems whose locations are dictated by topographic configurations (dichotomy boundary scarps, massifs, valleys and craters) conducive to accumulation and preservation of snow and ice and the formation of rock debris cover (Benn et al., 2003). Several topographic and morphologic relationships suggest that some valley glacial systems may be partly fed from local plateau icefields (Figs. 2C, 8).

In summary, the Deuteronilus–Protonilus region (Fig. 1) was an area of active and very widespread glaciation during parts of the Amazonian. The strong geomorphic similarities between lobate deposits along the dichotomy boundary between 30° and 50° N with terrestrial cold-based glaciers and glacial deposits has led to hypotheses for geologically recent (Late Amazonian-age) mid-latitude glaciation (e.g., Head et al., 2006a,b). The key to these studies has been to identify individual landscape elements on Mars and to match them with terrestrial counterparts (e.g., Marchant and Head, 2007). Building on this work, the next logical step is to integrate a landsystems approach (e.g., Evans, 2003), whereby assemblages of landforms over wide spatial scales may be used to deconvolve the evolution and maturation of glacial cycles on Mars. The characteristics of these features compare quite favorably to terrestrial counterparts that formed during the build up, maturation (glacial overriding of mountain topography), and ultimate sublimation of Miocene-age cold-based glaciers in the Antarctic Dry Valleys (ADV) (Denton et al., 1993; Marchant et al., 1993). During the waning stages of this glacial overriding event, alpine glaciers formed in the lee of emerging nunataks and at the head of alcoves in otherwise ice-free valleys. Rockfall along the sides of these alcoves, in concert with sublimation of dirty ice, produced classic debris-covered glaciers (e.g., Marchant and Head,