compressed and merge into LVF, flowing downslope to become broad distal lobes; in this region, there is a topographic and flow divide separating north- and south-flowing LDA and LVF. Evidence for an apparently superposed LDA with abundant ridges and a distal moraine-like feature is seen emerging from an alcove in the middle right (Fig. 5F). In other cases where mesas are close together (Fig. 5H), flow lines emerging from alcoves rapidly bend downslope and join other alcove and valley tributaries, compressing and deforming to create LVF.

Our analysis suggests that linear LDA and LVF are intimately related in morphology and modes of origin. The very close relationship of LDA source regions with alcoves (Fig. 5B, D, G), and the wide range of associated features (e.g., concentric ridges (Fig. 5B, G), pits (Fig. 5B–E), moraine-like features (Fig. 5B, D, G), piedmont-like lobes (Fig. 5E), merging of flowlines into LVF (Fig. 5F, H), etc.) all suggest an integrated system, beginning in alcoves and ending in distal lobes. We thus interpret the evidence documented here to support a major role for debris-covered glaciers. As LDA grew and coalesced (Fig. 5B–E, G), they merged between massifs and began to flow down-gradient, forming LVF (Fig. 5F, H), ultimately creating valley glaciers with divides (Fig. 5F, H) and integrated glacial landsystems (e.g., Head et al., 2006a,b) (Fig. 5A).

3.4. Coloe Fossae region (Fig. 1, location 7; Fig. 6)

A distinctive region along and just south of the dichotomy boundary is characterized by a series of narrow linear graben extending for about 200 km NW-SE (Fig. 1, point 7) (Coloe Fossae; 36–42° N 53.5–58° E). We compared the LDA and LVF found here with areas characterized by mesas (Ismeniae) and broad sinuous valleys (Mamers) of the fretted terrain, and to Acheron Fossae, an area of LDA/LVF development outside northern Arabia Terra. The scarp defining the main dichotomy boundary, and the mesas that extend to the north, are both characterized by classic examples of LDA. Along the scarp, LDA, seen at Viking resolution to be broad aprons, are revealed to be characterized by multiple individual lobes (Fig. 6B, top; Fig. 6C. bottom) extending 5–7 km from scarp alcoves into the surrounding plains; characteristics include proximal radial ridges, distal concentric ridges, and irregular pits and depressions (Fig. 6B, C). In some cases (Fig. 6C, bottom) there is clear evidence of a younger, smaller set of lobes extending 3–4 km out on top of the broader 10–12 km lobes. Along the north–south portion of the scarp (Fig. 6A, F) LDA extend from the scarp about 16 km out into the adjacent lowlands; here there is evidence for extensive pits and irregular depressions, often following the radial and concentric ridged texture.

Similar relationships are seen along the mesas that characterize Protonilus Mensae, the region in front of the scarp. LDA are formed of multiple individual lobes distinctly related to alcoves (Fig. 6D) with radial, concentric and pitted textures, with small-scale pitting particularly abundant on the distal margins. More than one generation of lobe formation is also suggested by the stratigraphic relationships with a smaller (4–6 km) more distinctive set of lobes extending out over the larger more extensive (16–18 km) lobes (Fig. 6D). At some mesas (Fig. 6E), LDA are deflected around massifs and join LDA that are forming from the mesa itself. Portions of the proximal parts of these two peripheral lobes (Fig. 6E, bottom) are similar to LVF textures; in addition, LDA extending downslope from the eastern part of the mesa are being deformed into folds and incorporated into the along-valley flow of the broad lobe (Fig. 6E lower right). Within the graben of Coloe Fossae, the surface texture is much more linear and wavy (Fig. 6H) than that typical of the more lobate LDA surrounding mesas and more similar to LVF. Similar relationships are seen in Acheron Fossae (described below), where viscous-flow floor texture in flat, straight-walled graben form typical linear LDA, due to the fact that local alcoves are minimized in the straight graben wall. This linear LDA texture forms from LDA converging from the walls and meeting in the center; as at Acheron, where slopes steepen, the linear LDA can flow down-valley, often forming distal lobes. The waviness in the lineated valley fill (Fig. 6) can often be related to small irregularities in the graben walls. Central structures in the lineated LDA include broad folds, some of which appear to be breached, forming axial depressions (Fig. 6H, arrows; compare to Fig. 6E).

In cases where scarps and mesas are in close proximity, LDA forming on opposite slopes rapidly merge and form LVF (Fig. 6B, bottom). LDA formed in a topographically constrained area such as a sloping impact crater interior (Fig. 6F, bottom) show evidence of compression against the distal rim of the crater, diversion to the North, and flow out into the surrounding region to form an LVF-like texture. The linear LDA on the floor of Coloe Fossae (Fig. 6H) are testimony to the fact that LVF can originate from valley walls and form LVF-like textures.

3.5. Acheron Fossae region (Fig. 1, location 14; Fig. 7)

LVF and LDA of glacial origin are common in association with the graben and massifs (Fig. 7). Acheron Fossae are a series of arcuate parallel graben on a rise north of Olympus Mons (217–237° E; 34–40° N). The graben floors are characterized by viscous-flow-like features (Kronberg et al., 2006) resembling LDA and LVF. We analyzed the floors and walls of the graben composing Acheron Fossae, examining the viscous-flow-like features there and assessing their morphology, topography, relation to underling topography, slope and orientation. We also compared the graben floor structures to lobate deposits found on the pole-facing slopes of impact craters superposed on the Acheron Fossae region (Fig. 7A). Three types of viscous-flow features are seen in the Acheron region and differ somewhat from the classic LDA and LVF in Deuteronilus Mensae (Squyres, 1979); we focus on the eastern half of Acheron (Fig. 7A) to illustrate these:

1) Linear LDA: Distinctive lobate features are observed on the graben floor (Fig. 7B). The ridged texture of these features is generally parallel to the graben walls and is somewhat sinuous but does not commonly form the discrete fold-like lobes typical of many LDA (Squyres, 1979; Lucchitta, 1984; Pierce and Crown, 2003; Head et al., 2006a,b). The reason for this appears to be the distinctly straight linear walls of the graben, which do not form the alcoves that are common on sinuous valleys and their tributaries in the Deuteronilus region (Figs. 3–6); in these areas alcoves appear to serve as distinctive accumulations zones for snow, ice and rockfall, and thus are the emergent point of the lobes forming the individual folds within the broader LDA. Do the linear LDA show significant lateral movement? Fig. 7B–D shows a 7–8 km diameter impact crater on the floor and rim of an ~8 km wide graben; here, in the perspective view (Fig. 7D), the linear LDA form on the north-facing graben wall and extend across the floor, over the rim, and down into the impact crater over a distance of ~6–7 km. There is also evidence that linear lobate debris aprons are forming on the south-facing slopes, although they tend to be less prominent. The nature of the linear LDA developed on the floors of Acheron Fossae

Fig. 8. A. Net ice accumulation (mm yr^{-1}) predicted in Mars atmospheric general circulation model simulation x_{ref} = (35°, 0.1270°, 2.5, TMG), superposed on the map by Squyres (1979), which shows the specific location of several different types of ice-related features. LDA and LVF stand for lobate debris aprons and lineated valley fill. See also Fig. 1A, which shows the areas of widespread glaciation documented in this and related papers. Indicated regions: 1. Tempe Terra, 2. Deuteronilus Mensae, 3. Nilosyrtis Mensae, and 4. Phlegra Montes. B) Water ice accumulation during L_s = 180–360° period (mm). C. Water ice sublimation during the L_s = 0–180° period (mm). From Madeleine et al. (2009). D). In this perspective view, a series of lobate viscous-flow features (lobate debris aprons and lineated valley fill) are observed along the dichotomy boundary of Mars, where the southern highlands (background) meet the northern lowlands (foreground). Multiple lines of geologic evidence suggest that these features were formed by glacial activity. The scarp is ~1500 m high, and the scene is ~25 km across along the scarp face. Image is composed of CTX data from the Mars Reconnaissance Orbiter draped over MOLA topographic data from Mars Global Surveyor, with no vertical exaggeration. See also Fig. 2C. CTX orbit P05_002902_2199_XI_39N306W, centered at 53.9° E, 40.6° N.