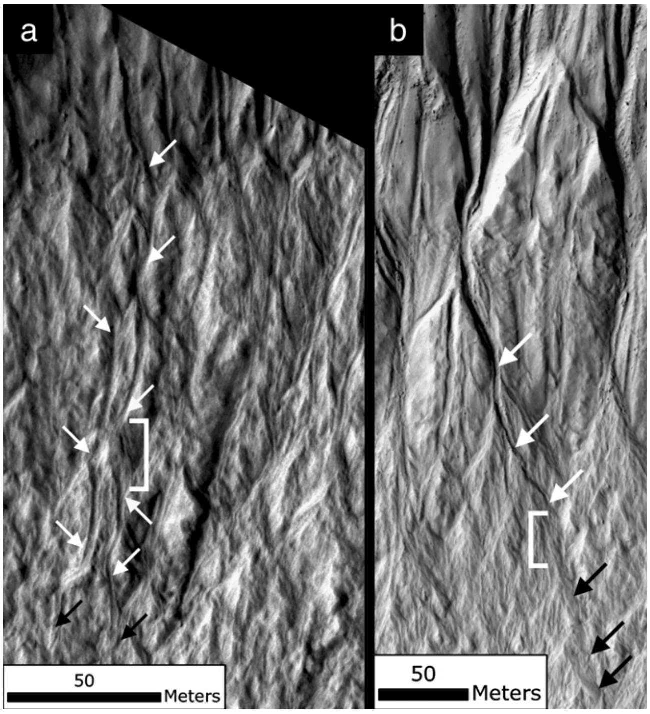

Fig. 8. Lobate flows (black arrows) emanating from channels that can be traced upslope (white arrows). Brackets indicate portions of the channel that appear to have been covered with fan-forming sediment subsequent to lobe and channel emplacement. a) The right set of arrows trace lobes through channels over a gully fan surface, to a gully channel, while the left set of arrows traces a channel that is overprinted by the toe of the gully fan. b) Lobes traced over a gully fan surface to the gully channel. Both panels excerpted from PSP_007148_2245, with north towards image top, down-slope towards image bottom, and illumination from the lower left.

the morphological signatures of varying amounts of liquid water, and changing degrees of sediment cohesion provides a baseline for determining whether the Protonilus Mensae gullies and lobes are strong candidates for martian debris flow deposits.

5.2. Characteristics of debris flows and other mass movements

On Earth, a debris flow is characterized by the transient movement of a debris-rich water and rock slurry, often displaying periodic pulses or surges, that deposits sediments within confined channels, as levee deposits, and in terminal lobes with steep snouts and margins, as flow slows and stops (Johnson and Rodine, 1984; Coussot and Meunier, 1996). Debris flows are distinguished from fluvial processes, such as stream flow and hyperconcentrated flows, in that debris flows are temporally transient phenomena that form abruptly (Coussot and Meunier, 1996). The water content of debris flows is typically 10–50% by mass, in contrast to hyperconcentrated flows or fluvial erosion that have water contents of 75–99% by mass (Coussot and Meunier, 1996). Debris flows in which sediments and water move as a single, coherent phase, may be followed by a tail of hyperconcentrated flow (in which sediment and water move at different speeds), resulting in near-instantaneous modification and erosion of debris-flow deposits (Coussot and Meunier, 1996).

Debris flow deposits are distinguished from dry (liquid-water-free) processes, such as avalanches and landslides, in that sediments in debris flow deposits are well-mixed, poorly sorted, and show no preservation of primary stratigraphy or bedding (Coussot and Meunier, 1996). Additionally, deposits from dry processes such as avalanches and landslides are typically found down-slope of "crown-scarps" or a detachment scarp—while wet debris flow deposits are rarely associated with detachment scarps (Coussot and Meunier, 1996). Water-free mass movements rarely display sinuosity in channelized segments (Mangold et al., 2008a). Water-free mass-movements such as dry, granular flows, typically terminate in lobate or digitate snouts on relatively steep slopes (typically >20°), governed by the angle of repose of the material (Felix and Thomas, 2004; Mangold et al., 2008a; Pelletier et al., 2008); in contrast, water-lubricated debris flows terminate in lobate snouts on considerably shallower slopes of ~10° or less, as governed by the critical shear strength of the water-debris fluid (Mangold et al., 2008a).

Terrestrial debris flows typically originate from one of three causes: 1) transition from a fluvial or hyperconcentrated flow into a debris flow due to a sudden addition of energy (e.g., a flash flood in a sediment-choked drainage system), 2) transition of a landslide into a debris flow by liquefaction of a coherent mass of sediment in response to a sudden addition of water (e.g., a slump occurring after heavy rains), or 3) mobilization of loose sediments by a sudden pulse of water (the "fire-hose effect") (Johnson and Rodine, 1984). These debris-flow initiators commonly are associated with particular environments in which debris flows are observed (e.g., flash-floods in arroyos or box canyons, landslides on high-retentivity soil slopes, etc.).

5.3. Identification of Protonilus Mensae lobate deposits as debris flow deposits

On the basis of the morphological characteristics outlined above, we interpret the Protonilus Mensae lobate deposits to be debris flow lobes (Johnson and Rodine, 1984; Coussot and Meunier, 1996). The lobes are defined by abrupt snouts that terminate on low angle slopes, and which emerge from leveed channels, and display variable-width (pulsed) channel deposits and stacked flow fronts. The lack of delicate fluvial bed and channel structures and the presence of sharply defined snouts strongly implicates debris flows over hyperconcentrated flows in the formation of the lobate deposits. We cannot rule out the possibility that some upslope, channelized sediment may have been deposited as subsequent hyperconcentrated flows; however, stream terraces, cut banks, and island erosion are not observed in these deposits. The lack of coherent blocks of pasted-on terrain or of boulders or layered blocks of mesa materials in the lobes suggests that dry mass wasting (e.g., a landslide) cannot readily account for the formation of the lobes. Further, the lobes terminate on slopes well below the angle of repose of dry sediment. Lastly, the lobes are considerably thicker than, and are more rounded than the thin, cuspate, and digitate termini typical of (potentially) dry martian granular flow features (Pelletier et al., 2008).

If the Protonilus Mensae lobate features are debris flows, formed by a moving mixture of water and sediment, how do they compare to terrestrial debris flows in terms of critical shear strength? Shear strength can be calculated from debris flow deposits by the approach outlined in Johnson and Rodine (1984):

$$k = T_c \gamma_d \sin\delta \qquad (1)$$

where k is the critical shear strength, T_c is the thickness at which the deposit ceased being able to flow, γ_d is the "reconstituted" (wet) weight of the sediment (taking 3.69 m/s^2 as acceleration due to martian gravity), and δ is the angle of the slope upon which the lobe came to rest. T_c was measured using shadow measurements of lobate snouts visible in HiRISE image data, yielding a mean thickness of ~1.6 m ($N=20$). At the shadow-measurement locations, a co-registered HRSC stereo digital elevation model was analyzed to determine δ, resulting in a mean value of 14°. Lastly, γ_d was taken to be 2×10^3 kg/m^3, a typical value for fine-grained (boulder-free) terrestrial debris flow deposits (Johnson and Rodine, 1984) and broadly similar to the wetted density of martian dust and dust simulants (Allen et al., 1998; Richter et al., 2006). Based on these results, the Protonilus Mensae lobes have a shear strength of