~3×10^3 N/m^2 (with a range of 1–6×10^3 N/m^2). Typical terrestrial debris flows (admixtures of water and debris) have a range of shear strengths between 2 and 20×10^3 N/m^2—with finer-grained debris flows lacking boulders populating the lower portion of the range (Johnson and Rodine, 1984, Pelletier et al., 2008).

5.4. Water content, sources, and geological setting

Beyond the mechanical similarities outlined above, what is the morphological evidence for the presence of liquid water as a component in the Protonilus Mensae mesa debris flows? The distinct thickness and roundness of the distal lobe snouts is strikingly similar to wet debris flow snouts observed in terrestrial environments (Fig. 4) (Johnson and Rodine, 1984, Coussot and Meunier, 1996). This morphology is atypical of thin surface flows on Mars that may or may not contain a liquid phase (Pelletier et al., 2008). The low-angle slopes on which the flows terminate (~14°) are also strongly suggestive of water-lubricated flows. Lastly, the initiation of gully channels on the high, steep slopes of the latitude-dependent mantle and pasted-on terrain is consistent with a lowering of the stability regime of the pasted-on material in developing gullies—a lowering which is typically accomplished in terrestrial environments by over-pressurization of pores and lubrication by liquid water (Johnson and Rodine, 1984, Coussot and Meunier, 1996; Lanza et al., in press).

What is the relationship between the distal lobes and the gullies located upslope—and to what extent can wet debris-flow processes be inferred in the formation of the gullies? The contacts between lobes, channels containing lobes, and gully fans are complex. Some lobes terminate downslope of the fans and emerge from incised channels that can be traced to the toe of a gully fan (Fig. 5), raising the possibility that these lobes formed by the remobilization of fan sediments. In contrast, some channels from which lobes emanate can be traced onto gully fans. Small, lobate structures are present atop some gully fans (Fig. 5), suggesting that some lobe-forming flows have traveled across a gully fan surface. Finally, in rare cases, channels from which lobate deposits emanate can be traced directly to a gully channel (Fig. 8), implying that the source of debris and water for the debris flow lobe is located within, or in the source region of, the gully channel above the gully fan.

Given this complex set of stratigraphic relationships, we suggest that the sediments present in both the gully fan deposits and the lobate flows observed in the Protonilus Mensae study site originate as sediments mobilized during incision of gully channels and erosion of pasted-on material. On gully fans, the presence of both small lobes, and more complexly fluted surface textures suggests that the fans may have formed by the deposition of sediments from a repeated combination of small, short-run-out debris flows, interspersed with lower energy fluvial or hyperconcentrated flow deposition. In contrast, the distal lobes are interpreted to represent relatively more energetic, high-volume debris flows, with longer run-outs, that form in discrete events. The episodic deposition of fan sediments by low-energy flows, and erosion of fan sediments by higher-energy flows can account for the fluted and sculpted surface texture typical of the Protonilus Mensae fans, while the repeated activity of water-rich fan-forming deposition events can account for the meandering or sinuous character of some gully channels (Mangold et al., 2008a,b).

What is the origin of water and debris for the observed debris-flow deposits? The incision of gully channels into pasted-on terrain, coupled with a lack of gully channel tributaries, and thinning of pasted-on terrain towards the tops of the gully channels, suggests that melting of ice present in latitude-dependent mantle (Head et al., 2003) pasted-on deposits (Christensen, 2003) and mobilization of the lithic component may be involved in debris-flow generation. The presence of closely-spaced, but non-anastomosing gully channels suggests that source material and melting was concentrated in loci of debris-flow generation, rather than slope-wide (which could have resulted in more generalized slope failure or slumping). Melting would be enhanced on the steep slopes from which pasted-on terrain is absent due to an increase in direct insolation (Hecht, 2002). Cross-cutting and cut-off relationships between gully channels suggest that melting of pasted-on material was episodic, rather than a singular event, consistent with other gully fans observed on Mars (Head et al., 2008; Schon et al., 2009). A debris-flow process resulting from melting of latitude-dependent mantle pasted-on terrain was anticipated by Costard et al. (2002). Although precise comparison of gully channel, fan, and lobe volumes is precluded by the large difference between topography resolution and image data resolution, order of magnitude estimates suggest that the combined volumes of fan and lobe deposits are comparable to the volume of latitude-dependent mantle material removed by gully channel incision.

What does the timing of the flows indicate about the climate conditions prevailing during lobe deposition and the potential sources for gully and lobe-forming water? Dating of the gully fans and lobate deposits to ~500 ka links the gullies and lobes to the waning edge of the last major (~35°) martian obliquity excursion (Laskar et al., 2004). This period within the past ~2 Ma is characterized by the formation of a large number of gully systems on Mars (e.g., Riess et al., 2004; Head et al., 2008; Schon et al., 2009), and to the degradation of the martian latitude-dependent mantle (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003) (manifested in Protonilus Mensae as pasted-on terrain (Christensen, 2003)).

While climate conditions over the past ~2 Ma have generally been exceptionally cold and dry at the Protonilus Mensae study site (Haberle et al., 2001; Costard et al., 2002), recent work has demonstrated the possibility of generating liquid water from the melting of surficial ice deposits sufficient to produce gully-scale flow in protected micro-environments (Hecht, 2002; Dickson et al., 2007a,b; Marchant and Head, 2007; Morgan et al., 2007b; Head et al., 2008; Levy et al., 2009b; Williams et al., 2009). Costard et al. (2002), Christensen (2003), and Williams et al. (2009) have used subsurface thermal models to predict shallow subsurface melting of ice-rich pasted-on terrain. The range of slope, latitude, surface ice presence, and orientation conditions sufficient to generate meltwater by the top-down melting of surficial ice outlined by Hecht (2002), Dickson et al. (2007a), Head et al. (2008), and Williams et al. (2009) are all met by the Protonilus Mensae site, suggesting that gully and debris flow water may be sourced by the melting of shallow, debris-rich ice under optimum insolation conditions. The lack of tributaries feeding many of the Protonilus Mensae gully channels, coupled with a lack of large alcoves, suggests that the localized accumulation of windblown particulate ice that has been suggested to be an important factor in other martian gullies (Hecht, 2002; Dickson et al., 2007a; Head et al., 2008; Levy et al., 2009b) was not a significant factor in the formation of these unusual gully deposits.

One remaining question raised by this analysis is why debris-flow deposits are present at the Protonilus Mensae site, but are not observed in other gully terrains on Mars—including those forming on isolated mesas, or elsewhere in latitude-dependent mantle and pasted-on terrain. One possibility may be unusually high deposition of atmospheric water ice in Protonilus due to regional climate variation (e.g., Madeleine et al., 2007, in press), leading to high melt volumes, and abnormally energetic flows. This possibility is consistent with the presence of a broad range of ice-related features formed over the past ~100 Ma in the greater Protonilus region, including lineated valley fill and concentric crater fill (Head et al., 2006a,b; Dickson et al., 2008). Alternatively, complex wind patterns between mesas in fretted terrain may enhance deposition of wind-blown particulate ice (e.g., Morgan et al., 2007a, 2008), or the presence of nearby mesas may increase the thermal radiation incident on surface ice, resulting in enhanced melting (e.g., Hecht, 2002; Williams et al., 2009). These deposits could also be unusually large, well-exposed examples of an end-member process that occurs at a smaller scale in other martian gullies, but does not leave well-preserved, coherent deposits there.