3. Glaciofluvial valleys in the context of valley network formation over time

The age of these glaciofluvial features is interesting because most of the fluvial record on Mars appears to be older, forming in the Noachian and early in the Hesperian (e.g., Pieri, 1980; Carr and Clow, 1981; Fassett and Head, 2008a). There are well-documented exceptions to the older fluvial features, however, and some Hesperian and Amazonian terrains on Mars show clear evidence for fluvial erosion. The most prominent examples are along the rim of Valles Marineris (Mangold et al., 2004, 2008; Weitz et al., 2008), the Valles Marineris interior (Quantin et al., 2005), on certain volcanoes (Gulick and Baker, 1990), and in the vicinity of some young craters (Mouginis-Mark, 1987; Brackenridge, 1993; Williams and Malin, 2008; Morgan and Head, 2009). Burr et al. (2009) also interpret the sinuous ridges associated with the Medusae Fossae Formation as young (late Hesperian to middle Amazonian), although constraining the age of fluvial activity is challenging because the material in which they are found is easy to erode and the ridges appear exhumed; an alternative view is that the lower units of the Medusae Fossae Formation may be relatively old (Early Hesperian or before; Kerber and Head, 2009).

The existence of demonstrably Hesperian to Amazonian-aged valley networks has led some workers to argue that the global climate conditions responsible for early valley network formation (which may be warmer and wetter than today) lasted well into the Hesperian or even Amazonian (e.g., Craddock and Howard, 2002). Conversely, other researchers have suggested that the existence of these younger valleys may mean that the Noachian/Early Hesperian valley networks could have formed under a climate more similar to the modern cold, hyperarid than is commonly inferred (Carr and Head, 2003; McEwen et al., 2007b). Furthermore, it is likely that many of these fluvial features, particularly those associated with volcanic edifices, do not represent fundamental changes in the atmosphere of Mars, but rather represent local conditions related to the internal supply of heat to melt snow and ice accumulated on volcanoes during obliquity-driven climatic excursions (e.g., Fassett and Head, 2006, 2007b).

Thus, it is important to place the previously known young valleys and the possible glaciofluvial valleys described here in context in terms of both age and their climate implications. Most of the crater ages and stratigraphic data for these valleys suggest that they are Amazonian in age. In a few instances, these constraints *require* an Amazonian age, such as where a valley incised a glacial moraine in a young crater and where a valley incised the surface of the lobate-debris apron in Acheron Fossae.

In terms of climate requirements, the glaciofluvial valleys we observe are less integrated, and typically far smaller than mapped ancient valley networks (Fig. 1). The ancient valleys on Mars also existed in an environment which allowed for large (and widely distributed) lakes to exist on the surface (Fassett and Head, 2008b, and references therein). The glaciofluvial valleys are also sparsely distributed, though not uncommon, at latitudes >26° in each hemisphere (Fig. 11). These characteristics suggest they may not have required stable liquid water; instead, perhaps their formation only required transient metastablity (e.g., Hecht, 2002). Their direct association with cold-climate features is also an argument for their formation in a cold-climate similar to the martian climate today. As has been long noted, most surfaces of Amazonian and Hesperian age lack any indication of fluvial modification (e.g., Pieri, 1980; Carr and Clow, 1981), so the 'wet' conditions that formed these features must be far more limited than the Noachian or earliest Hesperian valley systems. We thus discount the likelihood that transient regional to global rainfall is a reasonable explanation

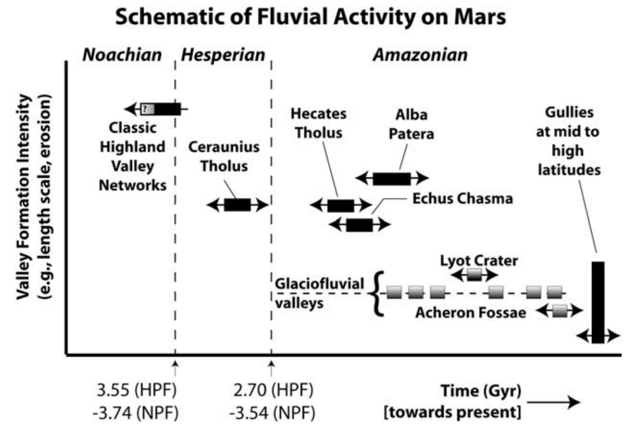

Fig. 12. A schematic representation of valley network intensity over martian history, modified after Fassett and Head (2008a). Ancient, highland valley networks date predominantly to the end of the Noachian or earliest Hesperian, and the last widespread activity appears to have ended by the Early Hesperian. The long-term intensity of valley network activity in the earlier Noachian is not known. There are several regions that experienced punctuated valley formation after the end of this early period, such as on the plateau above Echus Chasma, on the volcanoes Hecates Tholus, Ceraunius Tholus, and Alba Patera, and around several young craters (not shown). (Arrows are meant to give a sense that the actual age is unknown; age estimates for these young valleys generally overlap with each other based on formal statistics, but are not consistent with Noachian formation; see detailed crater counts in Fassett and Head (2008a).) The age of valleys in Lyot crater are estimated to be younger than 800 Myr in the Hartmann system or ~1.5 Gyr in the Neukum system based on crater counting of the unit they incise (Dickson et al., 2009). The valley cutting across the Acheron Fossae lobate-debris aprons (Fig. 8) are also constrained by the age of the apron to be younger than approximately ~100 Myr (best estimates for the age of the apron is ~80 Myr in the Neukum system or ~110 Myr in the Hartmann system). The evidence we present in this paper requires the existence of small scale, low-intensity valley formation at some points during the Amazonian as well – perhaps in a periodic manner during or following peak periods of mid-latitude glacial activity.

for the observed valleys. Instead, the source of water for forming these valleys is almost certainly the nearby available inventory of glacial ice.

Thus, under some conditions in the Amazonian, melting of surface or near-surface ice must have been possible. The local nature and morphological distinctiveness of these small, glaciofluvial valleys (and other young valley systems) continue to support the view that Noachian valleys formed in a different climate from what characterized Mars during the Amazonian. In Fig. 12, we present an updated schematic diagram for the history of valley formation on Mars, illustrating changes in erosion intensity over time. We emphasize that the glaciofluvial valleys we describe here, as well as the other examples of young valley networks on Mars, appear to be qualitatively different from Noachian valley networks and very recent Amazonian gullies, and represent a distinctly different type of fluvial activity. In sum, the diverse record of valley formation on Mars shows a long history of surface erosion under a range of conditions, and new spacecraft data will undoubtedly lead to a greater understanding and appreciation of this record.

4. Conclusion

We document the existence of small, glaciofluvial valleys associated with major Amazonian ice deposits in the mid-latitudes of Mars. The meltwater production that formed these valleys may be due to anomalous insolation conditions in climatic microenvironments. The formation of these features demonstrates the diversity of geomorphic processes that have occurred on Mars, despite what remains strong evidence for long-term cold and dry condi-