preserved underneath glacial deposits (tills) and characteristic features such as drop moraines are commonly observed (Head and Marchant, 2003).

The SHARAD radar sounder has recently provided new geophysical support for the geological interpretation that some of these glacial features in both hemispheres remain ice-cored, covered by only a thin, meters- to decameters-thick surface lag (Holt et al., 2008; Plaut et al., 2009; Safaeinili et al., 2009). This is a remarkable result considering that the crater populations on the surface of these features imply crater retention ages of greater than 100 Myr, and subsurface ice is presently unstable against sublimation in the regions where they are found (e.g., Mellon and Jakosky, 1995). The reasons for this ice preservation are uncertain but may reflect low long-term average net sublimation rates that led to highly diminished rates of ice loss due to increasing sublimation till thickness (Helbert et al., 2005), and/or long periods of higher obliquity in the last 1 Gyr. Ice thicknesses were also much greater during peak glacial conditions (Dickson et al., 2008; Marchant and Head, 2008) and glacial ice may have been much more widespread than that preserved in lobate-debris apron and lineated valley fill deposits today (Head et al., 2009).

Despite the abundant evidence for ice emplacement, glaciation, and the long-term survival of ice in these regions, there has been little evidence of concomitant melting and runoff. Indeed, until recently, the most compelling evidence that has been presented for glaciofluvial activity is a series of Hesperian age, braided ridges in the south circum-polar Dorsa Argentea Formation (Head and Pratt, 2001; Ghatan and Head, 2004) and large sinuous ridges in Argyre Planitia (Kargel and Strom, 1992; Hiesinger and Head, 2002; Banks et al., 2009). Along with these eskers, long valleys also emanate from the margins of the Dorsa Argentea Formation. These are interpreted to represent Hesperian drainage of meltwater discharge from a south circum-polar ice sheet (Head and Pratt, 2001; Ghatan and Head, 2004). These features appear likely to pre-date the widespread Amazonian ice deposits discussed above. Other evidence for limited melting associated with glacial deposits involves volcano–ice interactions (e.g., Chapman and Tanaka, 2002; Head and Wilson, 2007), in which subglacial and/or englacial volcanism led to melting and the formation of small drainage valleys (Shean et al., 2005).

Most recently, Dickson et al. (2009) described evidence for small valley-forms in a distinctive microenvironment on the floor of Lyot crater in the northern mid-latitudes. The most plausible sources of fluid for forming these valleys are ice-rich mantling deposits on the crater floor or lobate-debris aprons, which are probable debris-covered glaciers, along the crater walls. In the case of Lyot, the observed valleys are known to be young (Amazonian), both because of the youthful age of the Lyot crater itself (which sets an absolute upper limit), as well as crater counts on the material the valleys incise (Dickson et al., 2009). The unique microenvironment of Lyot, which is a very deep crater and is thus among the highest atmospheric pressure regions on Mars (Haberle et al., 2001; Lobitz et al., 2001), has been interpreted to be a factor in allowing liquid water to transiently exist there.

Here, we describe a broad survey of a distinct class of valleys associated with features interpreted to be ice-related that we interpret to be glaciofluvial (features whose origin is related to glacial meltwater). Fig. 1 shows these candidate features as well as examples of valley networks (Fig. 1a) and gullies (Fig. 1b) for comparison. The key differences between the features we describe here and classic Mars valley networks are the much smaller size of candidate glaciofluvial valleys, and their limited drainage development: valleys commonly have few or no tributaries and many originate at a single source point. The glaciofluvial features we describe here also have clearly distinct morphologies from martian gullies in that they lack alcoves and most lack fans (Malin and Edgett, 2000), and occur on shallowly-sloping regions beneath ice-related landforms, rather than on the steep (20–30°) interior slopes of crater walls.

The most common class of valley features we recognize occur at the margins of materials interpreted to be of glacial origin and are small (50–400 m wide) and short (<∼10 km in length) (Fig. 1c–e). Our primary observational data are images from a survey of Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) data (Malin et al., 2007), examined through the first eight PDS releases (through mission part P22; ∼15,000 images were examined). For specific features, we also incorporate data from MRO High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007a), the Mars Odyssey Thermal Emission Imaging System (THEMIS) (Christensen et al., 2003), the Mars Express High Resolution Stereo Camera (HRSC) (Neukum et al., 2004), and the Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 1999).

The requirements for features to be included in our survey as candidate glaciofluvial features are a direct inferred relationship with current or past glacial deposits and characteristics suggesting that they formed by the action of flowing water (based on aspect, sinuosity, formation of branching networks, etc.). We exclude the gully features (Malin and Edgett, 2000), which form on much steeper slopes and are morphologically distinct, although melting of snowpack or ice is a possible origin for these features (Lee et al., 2001; Costard et al., 2002; Christensen, 2003; Head et al., 2008; Williams et al., 2009).

2. Observations

2.1. Examples of small valleys in and around craters

The most common setting in which we observe potential glaciofluvial valleys is on the interior and exterior of mid-latitude craters that are typically tens of kilometers in diameter. On Mars, the geological setting and slope conditions that such mid-latitude (25–55°) craters provide appear to have been preferred microclimates for both ice accumulation (e.g., Squyres and Carr, 1986; Levy et al., 2009) and melting (e.g., Costard et al., 2002).

2.1.1. Valleys within and outside an 80-km crater, 11.8°E, 40°S

Fig. 2 shows a series of small valleys on the interior of an unnamed 80-km crater. There are clear signs of past glacial ice on the crater interior, particularly viscous flow features (e.g., Milliken et al., 2003) that are perched high on the interior crater rim (elevation range ∼1100–2200 m), and large lobate flows on the crater floor (elevation range ∼−110 m to ∼500 m) (Fig. 2a and b). Stratigraphic relationships suggest that the viscous flow features are younger than the broader lobes on the crater floor, implying multiple episodes of ice activity in this location (e.g., Head et al., 2008). The potential glaciofluvial valleys begin at muted alcoves (Fig. 2c–f) beneath viscous flow features at MOLA elevations of ∼150 m and ∼350 m. Thus, these valleys are interpreted to have formed during earlier phases of glaciation, when ice was more widespread and meltwater was available to incise the observed features. There are also very small valleys on the crater exterior (Fig. 2b); since these emerge from hollows filled with stipple-textured material, similar to the texture of glacial remnants on the crater interior and ice-rich material seen elsewhere (e.g., Mustard et al., 2001), they may also have resulted from melting ice.

The valleys on the crater interior have near-constant widths and few or no tributaries, consistent with being fed by point sources. The longest valleys are ∼5 km in length, and the slopes of the observed valleys floors are between 2° and 6° (much lower than slopes for gullies on Mars, ∼18–40°; e.g., Dickson et al., 2007; Parsons et al., 2008). At the termini of certain valleys (Fig. 2c–f), small