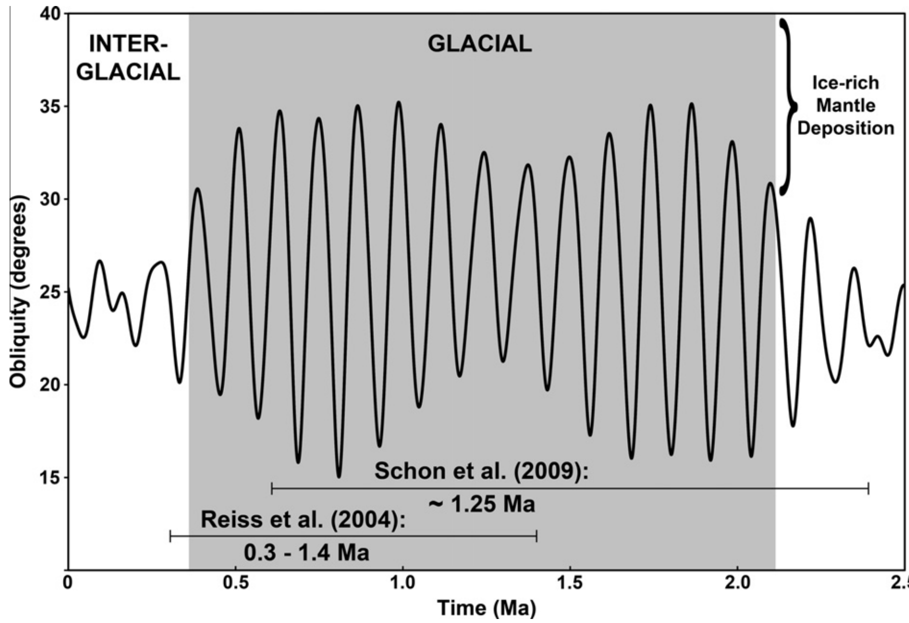

Fig. 1. Obliquity variations of Laskar et al. (2004) and suggested climate epochs of Head et al. (2003). Higher obliquity and higher amplitude variations in the recent past (0.4–2.1 Ma) define episodes of mid-latitude ice stability (e.g., Mellon and Jakosky, 1995) during which the deposition of multiple ice-rich mantling layers has been interpreted from geological evidence. Meltwater derived from degradation of this mantling unit is interpreted to be one source of meltwater responsible for gully formation, along with later snow in gullies. This chronology is consistent with gully dating via superposition and chronostratigraphic markers that provide maximum gully ages (Reiss et al., 2004; Schon et al., 2009a,b).

latitude). These relationships suggest that gully chronostratigraphy (Fig. 1) can provide important links to climate history and the processes that form and modify gullies. Here we use new observations of alcove-less gullies to suggest a candidate source of water for gully formation using chronostratigraphic constraints.

3. Gullies in a stratigraphic context

The locale in Fig. 2 (∼35°S, 131°E) provides an informative setting for an analysis of the stratigraphic position of gullies in relation to the deposition and erosion of these widespread ice-rich mantling deposits. At this location, secondary impact craters from the formation of Gasa crater established a stratigraphic marker horizon, which can be used to constrain gully timing and coincident degradation of mantling materials. Stratigraphic markers, such as these secondary craters, are important tools in chronostratigraphy because they represent a layer or event that was simultaneously emplaced over a wide area in different depositional environments; such markers on Earth include large volcanic eruptions that produce ash/bentonite marker beds and geochemical-stratigraphic markers formed by the widespread deposits of impact cratering events. Gasa secondary craters (Fig. 2) are pervasive on the crater floor and rim, but are much less well-developed, degraded, or absent on the crater wall and much of the gully fan deposits.

What is the broader context of this stratigraphic marker on Mars? Mid- to high-latitude geomorphology of latest Amazonian age on Mars is characterized by ice-related processes and landforms including a pervasive ice-rich mantling unit first identified in global maps of surface roughness (Kreslavsky and Head, 2000) that show topographic smoothing at high latitudes; evidence for this mantle is also seen in visual imaging (Mustard et al., 2001; Kreslavsky and Head, 2002; Milliken et al., 2003). Head et al. (2003) synthesized these observations into a theory of recent obliquity-driven "ice ages" on Mars that is supported by global circulation model studies (Mischna et al., 2003; Levrard et al., 2004) and models of ice stability (Schorghofer, 2007). Additional evidence supporting extensive atmospheric deposition of ice is provided by Gamma Ray Spectrometer (GRS) data of ice abundances that far exceed reasonable pore space volumes (Boynton et al., 2002), observations by Phoenix of massive ice just below the surface (Smith et al., 2009), observations of sublimation-type contraction crack polygons at the Phoenix landing site (Levy et al., 2008), observations of layering within the mantling unit (Schon et al., 2009b), and contemporary observations of new mid-latitude impact craters which expose a nearly pure ice substrate that is observed to sublimate upon exposure (Byrne et al., 2009; Dundas and Byrne, 2010). The formation of the stratigraphic marker is clearly coincident with the period of time during which this ice-rich mantling deposit was emplaced at these latitudes (Fig. 1).

4. Degradation of the latitude-dependent mantle

Analysis of the crater floor, wall, and rim (Fig. 2A) show the presence of the regional latitude-dependent ice-rich mantle on the floor and crater rim; these areas are also characterized by pervasive superposed secondary craters from Gasa crater (e.g., Schon et al., 2009a) (Fig. 2A, top and bottom), a relationship that dates much of this mantle emplacement to pre-Gasa history (Fig. 1). Also observed on the crater wall are several scarps that face up-slope, and have very irregular, sinuous to digitate borders. The most prominent example occurs near the base of the crater wall and consists of a generally continuous scarp facing up-slope with a sinuous outline (right-hand side of Fig. 2A). Examination of the broad crater wall reveals an additional but less distinctive scarp in the middle part of the crater wall (Fig. 2A). The boundary of this scarp is much more digitate than the boundary of the scarp at the base of the wall; indeed, examination at higher resolution shows that this scarp is composed of two to three smaller digitate scarps (Fig. 2D, top). In the upper part of the crater wall, two or three additional scarp-like trends are seen, some relatively continuous for hundreds of meters, and others less continuous (see Fig. 2A, upper left in particular). We interpret these scarps to be the eroded remnants of the multiple layers shown to comprise the latitude-dependent mantle and documented in many places elsewhere in areas where the mantle is undergoing erosion (e.g., Schon et al., 2009b). In this scenario, the wall surface represents an area of mantle undergoing degradation, and the scarps represent the exposed remnants of mantle layers. The stratigraphic relationships indicate that the layers higher up on the wall represent progressively older depositional layers.

Detailed analysis of the state of preservation of the pervasive secondary craters from Gasa crater in this area provides further insight. Secondary craters on the floor are well preserved (Fig. 2A, bottom; D, bottom), but secondaries lying above the scarp at the base of the crater wall appear more irregular and incomplete (Fig. 2C, middle; D, middle), consistent with their modification by erosion and degradation of the mantle layers. Areas higher on the crater wall display even more degraded secondary craters (Fig. 2C, top; D, top) or little evidence of secondaries at all (Fig. 2A, middle and top), while other orientations of the crater wall preserve a smooth mantle texture and many secondaries (Fig. 2A, far right). Analysis of the stratigraphic relationships of the gully fan deposits and the mantle layers modified by secondaries from Gasa (Fig. 2A; B, bottom; C, bottom; D, bottom) shows that portions of the fans are clearly superposed on, and thus post-date, the emplacement of secondaries.

Together, these observations are consistent with (1) the region being mantled by an ice-rich latitude-dependent deposit, (2) pole-facing crater-wall slopes having the ice-rich mantle preferentially degraded, (3) the scarps representing the margins of layers composing this progressively degraded mantle, (4) the mantle undergoing significant degradation following the Gasa crater-forming event that emplaced the secondary craters in this region, and (5) gully activity (portions of gully fans) continuing to occur following the Gasa cratering event (Fig. 1).

The primary crater that is the source of the secondary craters superposed on the mantle (and thus representing a marker event in the region) is the Gasa impact crater, located ∼100 km to the southwest. The crater size frequency distribution on Gasa ejecta indicates that this event occurred ∼1.25 Ma with uncertainty in the production function for small craters yielding a range of 0.6–2.4 Ma (Schon et al., 2009a). Unambiguously superposing the stratigraphic marker are portions of the gully fans (Fig. 2A).