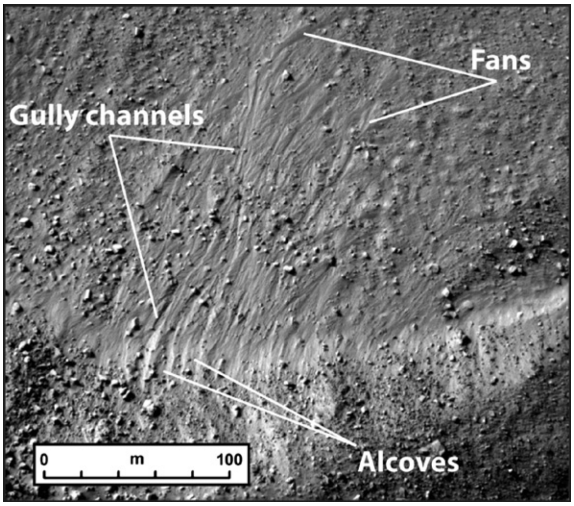

Fig. 11. Small gullies along a debris-covered mound on the floor of the southern valley. The gullies display the three morphologic components of other martian gullies: alcove, channels and fan (Malin and Edgett, 2000a). The small size of these features suggests they are geologically very young, though they might have been active at the same time as the larger gully systems along the upper slopes of the valley walls. HiRISE image: PSP_006926_1320.

boulders (Fig. 11). The slope between the boulders appears smooth and frequently displays fine scale eolian ripples (wavelength of 1 m), suggesting that the gullies are incised into a dust rich layer.

The second type of small gully is located along the side of a dune-covered mound within the southern valley complex (Fig. 12). The dunes are linear with a wavelength of ~3 m. Smaller ripples with a wavelength of ~1 m are present orthogonal to the dune crests, suggesting that the dominant winds that formed the dunes were bidirectional, perpendicular to each other, or that the larger dune forms are relict. The gullies are only comprised of channels, and do not exhibit well-developed alcoves or depositional fans. The channels are ~200 m long, 3 m wide, are bounded by levees, and display largely linear courses except for small-tight meanders (Fig. 12). The level of incision of adjacent channels differs, suggesting that some of the channels were abandoned in favor of other courses. The gullies are orientated in the same direction as the dunes and are of a similar width, suggesting that the dune structure strongly influenced gully formation.

The crisp and unweathered nature of these two groups of gullies, and their small scale, supports the interpretation that they are very young. It is therefore possible that they formed at the same time as the other larger-scale gullies, or alternatively they may result from more recent activity. If they were formed by snowmelt as has been proposed for the larger gullies by Morgan et al. (2010), then smaller volumes of melt would have been required. One explanation for the origin of these smaller gullies (Figs. 11 and 12) may relate to the localized climate effects associated with elevation. The apices of the larger gully alcoves (i.e. the uppermost section of the channels) are at an altitude of around 500 m, whereas the smaller gullies have been found at −1000 m. Both of these values are within the elevation range for gullies that occur elsewhere on Mars (−5000 to +3000 m, Dickson et al., 2007). Nevertheless the 1500 m elevation range between these two gully groups within the study area may be important; the atmospheric lapse rate on Mars is low, and so there is no appreciable surface temperature gradient between these two altitudes. However, the atmospheric-pressure decrease with elevation is significant with regard to water stability. Lobitz et al. (2001) derived an expression for the relationship between elevation and surface pressure on Mars, constrained by the Viking 2 Lander pressure measurements:

$$P(z, L_s) = P_{VL2}(L_s)exp(-(z - z_{VL2})/H) \quad (2)$$

where H is the scale height for Mars, 10.8 km, $P_{VL2}(L_s)$ is the surface pressure at the Viking 2 Lander site at solar longitude L_s (fit to a polynomial curve), and z_{VL2} is the MOLA-derived altitude at the Viking 2 Lander site (−4 km). We used this in conjunction with the one-dimensional version of the atmospheric Laboratoire de Météorologie Dynamique (LMD) GCM (Forget et al., 1999) to plot the present annual difference in climate (average pressure, maximum surface temperatures) between the two elevations of gully alcoves in temperature and pressure space (Fig. 13). Assuming both gully types were formed by snowmelt, we chose albedo and thermophysical properties consistent with a thin dust covered snowpack (see Fig. 13 caption for values). Modeling work by Williams et al. (2008, 2009) has demonstrated that a lag of dust would form on the surface of a snowpack under martian conditions due to sublimation. Both elevations experience limited diurnal periods in the spring when conditions are above the triple point, though this period is more significant for the smaller gullies (Figs. 11 and 12). Further modeling is required to determine if these conditions would be sufficient to permit the melting required to form the small gullies (e.g. Williams et al., 2008, 2009).

4.1.2. Comparisons with other martian gullies

Aspect-dependent gully morphology has been documented elsewhere on Mars. Hale Crater, for example, displays the same relationships between well-developed, deeply-incised, pole-facing gullies and smaller, more subdued gully-like forms on equator-facing slopes (Reiss et al., 2009). The origin of the equator-facing features in Hale Crater is unclear (they do not have incised channels, and are superimposed by impact craters) and may be related to the impact event itself, in a manner similar to the proposed formation of Mojave Crater fluvial features (Williams et al., 2004). The gullies

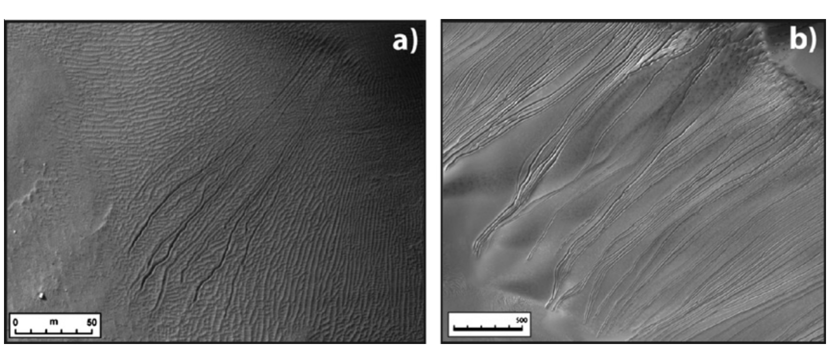

Fig. 12. Small-scale gullies along sand dunes. (a) These gully systems are morphologically different from gullies elsewhere in the study area, although they are similar (despite being an order of magnitude smaller) to gullies observed on Russell Crater dunes (b). Left image: HiRISE: PSP_006926_1320. Right image: HiRISE: PSP_007018_1255.