Gullies and RSL: Gullies on Mars are kilometre-scale erosion-deposition systems located on steep slopes, comprising a source area (alcove), transport channel and terminal fan(s) or lobe(s) (debris apron) [1]. Their morphological similarity to water-carved gullies on Earth meant they were hailed as signs of groundwater seepage on their initial discovery, however since that time the role of water in their formation has been debated [e.g., 2,3]. Recent imaging has revealed that gullies are active at the present day [4,5] and this activity occurs during winter when temperatures are too cold for liquid water or brine to form or flow, this suggests a possible role for CO₂ ice in their formation [6–8]. Recurring Slope Lineae (RSL) are dark streaks located on steep slopes that grow during warm seasons to hundreds of metres in length [9] for several metres of width. They originate at rocky outcrops on the steepest slopes in the equatorial- and mid-latitudes [10–12]. Once they stop growing, they fade and reoccur in the following year, although not necessarily in exactly the same location or with the same extent. Their incremental growth and link to hydrated perchlorates [13] has led numerous researchers to propose liquid water/brine as responsible for the origin and growth of RSL, despite the low availability of water in the soil or atmosphere at the time of their formation. Alternate hypotheses struggle to explain the morphology or seasonal growth of RSL [14,15].

Hale Crater: Hale Crater has a 150x125 km oblate form and is located at 36° latitude in the southern hemisphere of Mars adjacent to the Argyre impact basin. The impact creating Hale is estimated to have happened 1 Ga [16] although it could be younger [17]. Hale Crater is superposed on the Uzboi Vallis system, which is thought to have been a conduit for large volumes of water as well as containing a lake system [18]. The crater ejecta and floor deposits show morphological evidence consistent with water being present in the regolith at the time of the crater’s formation:

- Pitted deposits on the floor and in the ejecta, interpreted to be the result of volatile escape during the interaction of the hot ejecta with water [19].
- Sub-kilometre fans associated with crater massifs (inviscid flows) attributed to overland flow directly following the impact [20], and
- Fluidised ejecta deposits, thought to originate from the melting of ice within the hot ejecta [16,17]. In addition, Hale Crater contains a range of much younger landforms consistent with the episodic or the intermittently meta-stable presence of surface/near-surface water ice and/or liquid water: including: protalus ramparts [21], scalloped depressions [22], small-scale lobes (possibly due to solifluction) [22], low-centred polygons [22], km-scale gullies [21,23,24] and RSL [13]. As a result of their morphological work Reiss et al. [21] concluded that the gullies probably formed by melting of near surface ice or snow under recent episodes of high obliquity. Kolb et al. [24] modelled the formation of new bright slope deposits at the termini of gullies and concluded that “wet sediment-rich and water-rich flows could produce the observed bright deposits”; however, flows of dry materials could not be excluded. These deposits lie below the angle of repose.

Hale Crater is one of the few sites on Mars where active gullies [25] and RSL [13] are observed concurrently. Typically the RSL occur on the equator-facing slopes of the central peak, whereas the active gullies are located on the eastern crater rim (Fig. 1). The density of the gullies in Hale surpasses that in any of the surrounding regions [26]. Hence, our choice of this region to perform a detailed morphological and morphometric study of the gullies and RSL in the context of the longer aqueous history of Hale Crater.

Data and approach: We use a mosaic of seven CTX derived digital elevation models at 20 m/pix generated via the ISIS-SocetSet method described in Kirk et al. [27] at the Natural History Museum in London. Our analysis is performed in a local sinusoidal projection to minimise projection distortion. Gullies are mapped as polygon features as described in [26], in addition channel length, fan length, incision width are recorded. RSL were mapped as polygon features from HiRISE images. Slope maps were derived with window sizes of 3, 9, 15 and 21 pixels [28] and an aspect map with a window of 21 pixels.

Preliminary results and discussion: Gullies in Hale crater are dominantly pole-facing, with a significant population E-W (more W- than E-facing) and rare equator-facing gullies. The RSL face predominantly polewards with a slight west-facing preference, they are occasionally found on other orientations. Gullies and RSL occasionally are observed in close spatial association. Both landforms have their source areas in steep rocky hillslopes. Hillslopes with gullies have
maximum (9x9) slopes ranging from 15–65°, averaging 36° and for RSL the slope range is 7–50° with an average of 33°. Considering the substantial difference in scale between these landforms (Fig. 1) the slope statistics for the two landforms are indistinguishable. Fig. 2 shows that gullies tend to be longer and less dense in their distribution when there host hillslope is steep. We found that gully fans also tend to be longer when the hillslope is steep. Together these results suggest that these steep slopes are particularly favourable for gully-forming processes, such as the accumulation or destabilisation of volatiles.

**Conclusions and future work:** The strong orientation preference for both gullies and RSL suggests a dominant role of insolation in their formation as suggested by previous workers with a preference for sunset-facing slopes. The fact that gully-deposits lie below the angle of repose, suggests a fluidising component is involved in their emplacement. The minimum slope angles for RSL are also below the angle of repose, but this finding needs to be verified with higher resolution HiRISE elevation data. In addition, we will examine the catchment properties of both of these landforms and for gullies the material into which they incise to further investigate the possible triggering factors for the flows creating these landforms.

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Figure 1: (a) Overview of Hale Crater, CTX image mosaic. (b) Slope map from CTX elevation data with gullies and RSL superposed, legend to right. (c) gullies in Hale Crater. (d) RSL in Hale Crater.

Figure 2: The maximum slope against (a) the maximum channel length and (b) the density of gullies, for hillslopes with gullies in Hale.