Martian gullies: a comprehensive review of observations, mechanisms and insights from Earth analogues

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Abstract: Upon their discovery in 2000, Martian gullies were hailed as the first proof of recent (i.e. less than a few million years) flowing liquid water on the surface of a dry desert planet. Many processes have been proposed to have formed Martian gullies, ranging from liquid-water seepage from aquifers, melting of snow, ice and frost, to dry granular flows, potentially lubricated by CO_2. Terrestrial analogues have played a pivotal role in the conception and validation of gully-formation mechanisms. Comparison with the terrestrial landscape argues for gully formation by liquid-water debris flows originating from surface melting. However, limited knowledge of sediment transport by sublimation is a critical factor in impeding progress on the CO_2-sublimation hypothesis. We propose avenues towards resolving the debate: (a) laboratory simulations targeting variables that can be measured from orbit; (b) applications of landscape-evolution models; (c) incorporation of the concept of sediment connectivity; (d) using 3D fluid-dynamic models to link deposit morphology and flow rheology; and (e) a more intense exchange of techniques between terrestrial and planetary geomorphology, including quantitative and temporal approaches. Finally, we emphasize that the present may not accurately represent the past and that Martian gullies likely formed by a combination of processes.

This review provides an overview of the research done on Martian gullies since their discovery by Malin & Edgett (2000), providing the backdrop to the papers in this Special Publication. The review specifically highlights how the use of terrestrial analogues has provided insight into the formation mechanisms of Martian gullies. The study of Martian gullies has been steeped in analogy to terrestrial landforms from the very beginning – starting with their naming as ‘gully’ (Malin & Edgett 2000). This name was chosen in reference to their resemblance to ‘spur and gully’ morphology on Earth, rather than referring to the terrestrial definition of gully as ‘a water-made cutting, usually steep-sided with a flattened floor’ (Mayhew 2015) which is ‘deep enough (usually >0.5 m) to interfere with, and not to be obliterated by, normal tillage operations’ (https://www.soils.org/publications/soils-glossary). In making our descriptions we use terms derived from terrestrial geomorphology to describe the characteristics of Martian gullies, which inevitably are rooted in the terminology used in the description of fluvial catchments and may suggest a fluvial origin. We attempt to make a reasonable balance between using process-neutral terms (which if taken to extremes are so generic as to be unhelpful) and terms that inevitably invoke a given process.

We start by providing a comprehensive review of the observational data collected on Martian gullies. Following this, we summarize their proposed formation mechanisms, along with the range of Earth analogues that have been used to gain insight into Martian gully formation. Within Earth analogues we include scaled physical laboratory simulations, which we argue play a similar role to flume experiments in understanding terrestrial geomorphic processes (e.g. Paola *et al.* 2009). We then undertake a short critical assessment of the limitations of such analogies, and highlight future avenues and challenges for research as a result of this review and discussions at the second ‘Martian Gullies and their Earth Analogues’ workshop held in London, June 2016.

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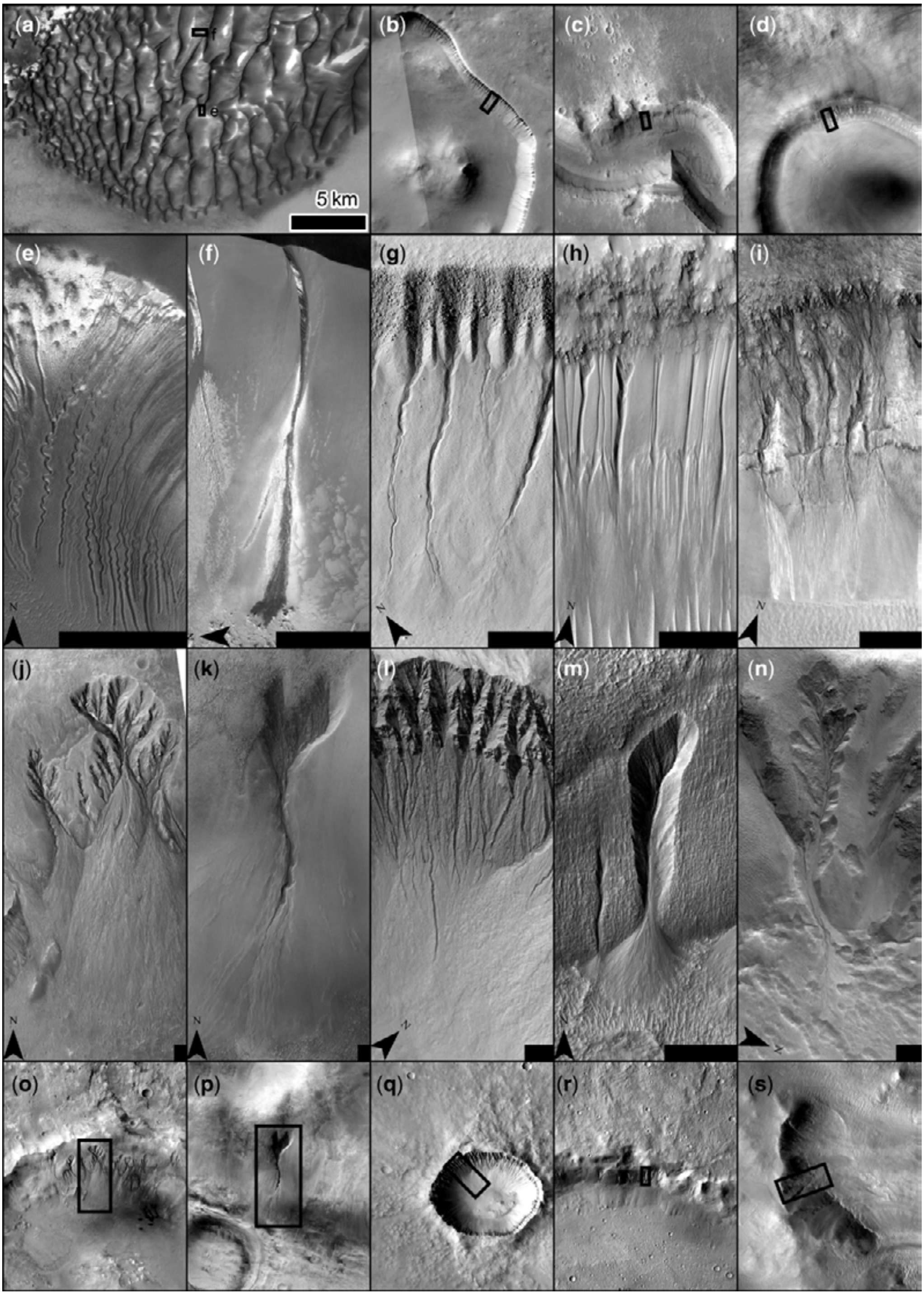


Fig. 1. Example images of gullies on Mars with context images. North is up unless indicated otherwise. The scales in images (b)–(d) and (o)–(s) are the same as indicated in (**a**). For images (e)–(n) all scale bars are 200 m. (**a**) Southern part of Kaiser Crater dune field in CTX image D07_030133_1330, black boxes indicate the locations of (e) and (f). (**b**) Part of the wall of one of the polar pits in Sisyphi Cavi in CTX image B10_013598_1092 with the black box

Review of key observations of Martian gullies

Morphology

Martian gullies are composite landforms that comprise an alcove, channel and depositional fan (also referred to as an apron in the Martian literature: Malin & Edgett 2000). They can be up to several kilometres in length, and their length seems to be controlled by the length of the hillslope available (Hobbs *et al.* 2013, 2017). Alcove zones can span up to 1 km cross-slope (Heldmann & Mellon 2004; Bridges & Lackner 2006; Heldmann *et al.* 2007; Yue *et al.* 2014; Conway *et al.* 2015). They occur in a wide range of settings, mostly in the mid-latitudes and sometimes in polar regions, ranging from the walls and central peaks of impact craters to valley walls, hills, dunes and polar pits (e.g. Malin & Edgett 2000; Balme *et al.* 2006). The main requirement for their occurrence being the availability of steep slopes exceeding *c.* 20°–30° (e.g. Dickson *et al.* 2007; Reiss *et al.* 2009*a*; Conway *et al.* 2015, 2017). Gullies can occur singularly but they usually occur in groups and can span whole hillslopes (Fig. 1e, g–i, l). Sites with gullies number nearly 5000, and it is estimated therefore that tens of thousands of gullies exist on Mars (Harrison *et al.* 2009).

What follows is a generic description of gullies on Mars, placing emphasis on their most commonly observed morphological features, while also summarizing the wide variation in morphology observed in Martian gullies. We begin our morphological descriptions with so-called ‘classic’ gullies, which are the most abundant (98% of the database of Harrison *et al.* 2015) and show the widest variation, then follow with descriptions of two uncommon, but remarkable, gully types: linear dune gullies (33 sites globally, 0.6%: Pasquon *et al.* 2016) and polar-pit gullies (1% of Harrison *et al.* 2015) (see Fig. 1e & g, respectively).

Gully alcoves are generally theatre-shaped depressions, whose upslope extent is located at the hillcrest or mid-slope within the hillslope on which they are located. They can be incised into the bedrock, often exposing numerous metre-scale boulders, or into slope-side deposits, such as the latitude-dependent mantle (LDM) or sand (e.g. Aston *et al.* 2011; de Haas *et al.* 2013, 2015*a*, 2017; Núñez *et al.* 2016*b*). The LDM is believed to be an ice-rich mantling unit of which the most recent layers were deposited during climate excursions, which happened in the last few millions of years (see the subsection on ‘Associated landforms’ later in this section). Some variations in gully source material are related to host-crater age, and lead to contrasting gully–alcove morphology (de Haas *et al.* 2017).

Alcoves often lead to chutes in which channels are developed, and these channels then lead onto the depositional debris fan, or apron. Here, as in the terrestrial literature, we make a distinction between ‘channels’ and ‘chutes’. We define channels as erosional incisions which should indicate the bankfull level of the fluid and therefore can be taken to represent a single ‘event’ (Fig. 2d). Chutes, on the other hand, are analogous to valleys in lowland geomorphology; they are erosional incisions representing the ensemble of erosional events and do not represent bankfull conditions. It should be noted, however, that incised channels cannot always be reliably identified and hence the confusion between chutes and channels in the Martian gully literature, which is likely to be related to the rapid reworking of the Martian surface. Where chutes are classified as channels, this can lead to erroneous application of terrestrial geomorphological laws developed for channels. Channels extend from within the alcove and onto/across the depositional

Fig. 1. *Continued*. indicating the location of (g). (**c**) Part of Nirgil Vallis in CTX image F08_038957_1517 with the black box indicating the location of (h). (**d**) A 12 km-diameter crater in Acidalia Planitia, CTX image F21_043861_2326 with the black box indicating the location of (i). (**e**) Linear dune gullies on a dune in Kaiser Crater with frost visible in the upper-left corner, HiRISE image ESP_028788_1325 at Ls 173°. (**f**) A classic gully also on Kaiser Crater dune field with a new deposit outlined by a bright halo, HiRISE image ESP_027944_1325 at Ls 139°. (**g**) Gullies on the wall of a polar pit in Sisyphi Cavi, HiRISE image ESP_049531_1090. (**h**) Gullies on the wall of Nirgil Vallis, HiRISE image ESP_038957_1515. (**i**) Gullies originating at the bedrock layer on the inner wall of an impact crater, HiRISE image ESP_045193_2325. (**j**) A gully system spanning *c.* 4 km in length with a large tributary catchment in HiRISE image ESP_013894_1410. (**k**) Gully which does not extend up to the slope crest in HiRISE image ESP_014312_1320. (**l**) Gullies extending into alcoves incised into the bedrock of Galap crater in HiRISE image PSP_003939_1420. (**m**) Gullies entirely contained within deposits of the LDM in HiRISE image PSP_002514_1420. (**n**) Gullies surrounded by pitted ground in the LDM in HiRISE image ESP_026097_2310. (**o**) Part of the wall of a 19 km-diameter crater in Terra Sirenum in CTX image B11_013894_1412 with the black box indicating the location of (j). (**p**) Mesa in Nereidum Montes in CTX image B12_014312_1323 with the black box indicating the location of (k). (**q**) Galap Crater in Terra Sirenum in CTX image B09_012971_1421 with the black box indicating the location of (l). (**r**) Inner wall of Bunnik Crater in Terra Sirenum in CTX image P04_002659_1418 with the black box indicating the location of (m). (**s**) Inner wall of Lyot Crater in CTX image D19_034800_2310 with the black box indicating the location of (n). HiRISE image credit: NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

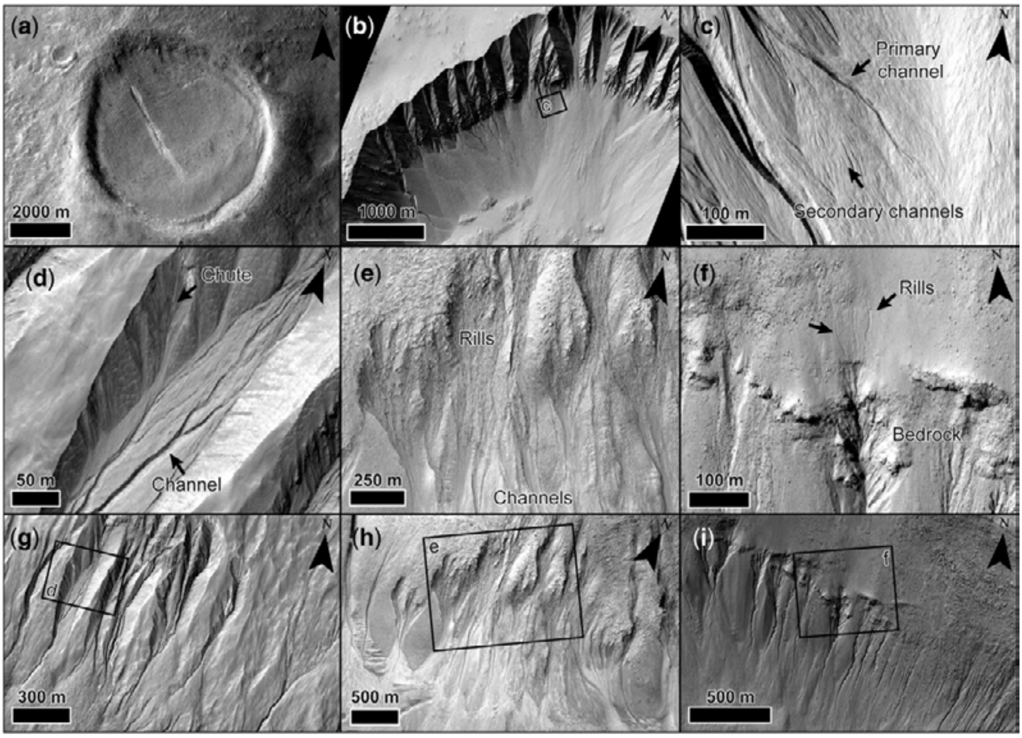


Fig. 2. Alcove zones of gullies on Mars. (**a**) An individual gully located within LDM inside an impact crater on a south-facing slope in the rim materials of the Argyre Impact Basin. The alcove of this gully comprises a single incision or chute. HiRISE image ESP_013850_1415. (**b**) Gasa Crater whose rim hosts numerous gully alcoves incised into the bedrock. The location of (c) is given by the black box. HiRISE image ESP_014081_1440. (**c**) Detail of chutes and channels emerging from the alcoves in Gasa Crater onto the fans below. Discontinuous secondary channels can be identified on the fan as well as primary channels which are still connected to the chutes and alcoves. (**d**) A gully incised into LDM, where the channels are located within a chute. The chute walls have mass-wasting scars. HiRISE image PSP_005616_1440. (**e**) A gully system where the alcoves are poorly defined topographically, but instead comprise many coalescing rills which come together to form the primary channels mid-slope. HiRISE image ESP_022685_1400. (**f**) Gullies on a crater wall which appear to originate at bedrock outcrops, yet on closer inspection rills can be seen above the outcrops upslope of their parent gullies. HiRISE image PSP_006261_1410. (**g**)–(**i**) Context images for panels (d)–(f) using the same HiRISE images. HiRISE image credit: NASA/JPL/University of Arizona.

zone. It has been stated in the literature that gully channels become narrower in a downslope direction (Hartmann *et al.* 2003) but, in fact, it is usually the incised chutes that narrow downslope. In many cases the upper part of Martian gullies lack a true alcove, as described above – the upper escarpment, or break in slope, is missing. Such gullies are usually characterized by a source area where many small channels emerge gradually from rocky hillslopes and come together to form a single chute (Fig. 2e, f). Gilmore & Phillips (2002) initially reported the origin of gully channels at outcropping bedrock layers. However, with higher-resolution images, in many cases it can be seen that the channels originate (often as barely distinguishable rills) above the bedrock layer (Dickson & Head 2009) (Fig. 2f).

Downslope of the alcoves, at the point where deposition dominates over erosion due to lower gradients, a depositional fan is present. These can be wide cone-shaped deposits of sediments, which originate at the apex where the chute intersects with the hillslope (e.g. Figs 1j, m & 2b). Similar to alluvial fans on Earth, these deposits ‘fan out’ from the apex in plan view and have a convex cross-slope curvature. Such gully fans are often dissected by entrenched, steep-walled, channels. Both primary and secondary channels (the latter being abandoned, formerly active, channel systems) can often be identified on gully-fan surfaces (Fig. 2c). The fans of adjacent gullies can merge downslope forming a bajada, a continuous deposit at the foot of the hillslope. Additionally, many gullies lack wide, fan-shaped deposits, but have more restricted deposits, which are longer in the downslope direction than they are wide. These deposits can be digitate in shape, or indistinctly blend into the surrounding terrain.

Polar-pit gullies (Fig. 1g) are notable not only for their high-latitude location, but they also have a distinctive morphology and morphometry. This type of gully is only found in south polar pits, which form the only steep topography at latitudes polewards of 60° S (Conway *et al.* 2017). These pits are believed to be formed by collapse of the terrain induced by subglacial volcanism (Ghatan & Head III 2002). The gullies incised into the walls of these polar pits are characterized by regularly spaced rounded alcoves which often reach the top of the slope and when they do, on their inner slopes, are comprised of metre- to decametre-scale rounded boulders. The base of the alcove sometimes leads into a chute, and the deposits more often than not form a bajada of continuous fan-deposits. Channels are slightly sinuous and lead out onto the fan, where sometimes other channel segments can also be seen. Many studies, however, do not distinguish these gullies from classic gullies elsewhere on Mars (e.g. Auld & Dixon 2016).

Linear dune gullies (Fig. 1e) are the most uncommon and distinctive subtype of Martian gullies. They are only found on dark sandy slopes, either dune slip faces or sand-covered slopes in the southern hemisphere (Fig. 1a, e, f) (Pasquon *et al.* 2016). They are dominated by a long parallel-sided leveed channel, which varies little in width along its length. This channel either directly follows the hillslope gradient or possesses some considerable sinuosity (Pasquon *et al.* 2016). The alcove is rarely wider than the channel and often comprises poorly expressed tributary rills. The channel terminates downslope abruptly and the ‘apron’ simply comprises the bounding levee, although in some cases the channel is perched (an erosional landform within the depositional landform) (Jouannic *et al.* 2015). Channel terminations can be in the form of pit chains, or can be surrounded by pits. The longest examples are found on the extraordinary Russell Crater megadune (Reiss & Jaumann 2003; Gardin *et al.* 2010; Reiss *et al.* 2010*a*; Jouannic *et al.* 2018), which rises up to 500 m in height (Gardin *et al.* 2010). As for classic gullies, their length seems to be limited by the size of the hillslope available. They often occur alongside gullies with a ‘classic’ morphology (Fig. 1a, e, f) and there are some cases where intermediate forms can be found.

Typically, gully-alcove slopes on Mars exceed 20° (Heldmann & Mellon 2004; Dickson *et al.* 2007; Heldmann *et al.* 2007; Conway *et al.* 2015), while gully-fan slopes range from 5° to 25° (Kolb *et al.* 2010*a*; Conway *et al.* 2015; Gulick *et al.* 2018), with channels spanning the whole range of slopes. Conway *et al.* (2015) found that gullies whose alcoves extend up to and erode into the bedrock of a crater wall tend to have the steepest alcove and apron slopes (>23° and >20°, respectively). Polar-pit gullies are distinctive as they tend to have lower alcove and debris apron slopes (<25° and <12°, respectively) compared to the population as a whole. Pasquon *et al.* (2016) reported alcove slopes for linear gullies of 14°–25° and mean slopes of 9°–17° along the whole profile, which are consistent with the general population of Martian gullies.

As with any classification system, there are forms that do not fit neatly into the descriptions provided above. In the most generic sense, Martian gullies are a form of gravity-driven mass-wasting system, where material is removed from the top and transported towards the base of the hillslope. However, they are distinguishable from simple fall deposits (scree, talus or colluvium) by the presence of the transport channel and/or chute, as pointed out by Malin & Edgett (2000), and the presence of a depositional fan below the dynamic angle of repose (Kokelaar *et al.* 2017). Hence, it has generally been acknowledged that a channel is the essential attribute for identifying a Martian gully (e.g. Balme *et al.* 2006). Alcoves (with a spur and gully morphology) are common in bedrock escarpments across Mars and the Moon (Dickson & Head 2009; Sharpton 2014) (Fig. 3). Hillslopes that are contiguous with those hosting well-developed gullies can themselves show morphologies that, without the context of their neighbours, would not necessarily be classified as gullies (Fig. 4). These slopes have poorly developed and discontinuous channels, which have limited sinuosity trending directly downslope. Such features are also found in isolation, often in the equatorial regions of Mars (Rummel *et al.* 2014; Auld & Dixon 2016) (Fig. 4c), and have usually been omitted from global-scale catalogues of Martian gullies (e.g. Harrison *et al.* 2015). Treiman (2003) classified some equatorial features as gullies, such as alcoves with aprons in the calderas of the Tharsis volcanoes and the light-toned layered mounds in Candor Chasma (Fig. 4a). These equatorial features have channels – a downslope trending linear depression – yet they lack the steep banks and morphological complexity of their mid-latitude counterparts, and more closely resemble terrestrial dry mass-movement chutes (refer to the subsection on ‘Dry granular flow’ in the next section), and hence have not generally been classified as gullies.

As discussed in more detail in the following subsection, gullies have small-scale morphologies indicating many episodes of deposition and erosion. In addition, relict versions of whole gully landforms have also been reported. In order to be identifiable

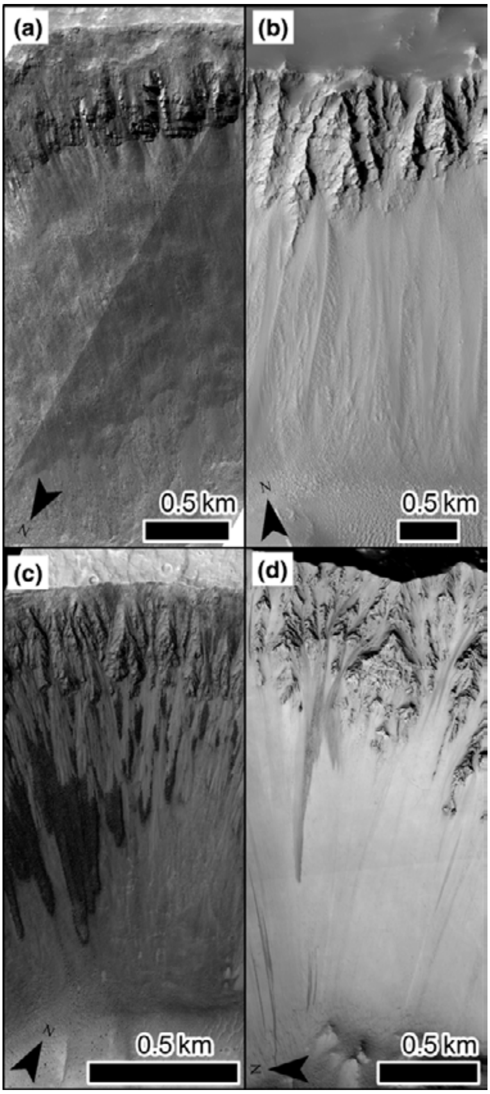


Fig. 3. Spur and gully morphology on Mars and the Moon. (**a**) Inner wall of Dawes Crater on the Moon, with spur and gully features identified by Senthil Kumar *et al.* (2013) in LROC NA image M175104387. (**b**) Wall of Noctis Labyrinthus on Mars, showing extensive evidence of aeolian activity in the form of ripples on the talus slope, HiRISE image ESP_028805_1725. (**c**) Inner wall of a *c.* 6 km impact crater at 2° S in Libya Montes, showing tongues of granular material extending downslope, HiRISE image ESP_014412_1780. (**d**) Inner wall of a 21 km-diameter central pit crater, mentioned in the pristine crater catalogue of Tornabene *et al.* (2018), where the dark slope streaks originating at the top of the talus slope are thought to be triggered by a recent rockfall. HiRISE image PSP_010037_1965. HiRISE image credit: NASA/JPL/University of Arizona. LROC image credit: NASA/GSFC/Arizona State University.

as relict gullies, some aspect of the channel has to be identifiable, strengthened by identification of associated relict fans and/or alcoves.

Detailed morphology

The arrival of the High-Resolution Imaging Science Experiment (HiRISE) instrument in orbit around Mars in 2006 which returns 0.25–0.5 cm/pix images of the Martian surface (McEwen *et al.* 2007*a*) has allowed the morphology of Martian gullies to be catalogued in great detail. Here we describe commonly observed metre- to decametre-scale features associated with the channels and depositional parts of gullies.

The chutes and channels of gullies can be highly sinuous (Figs 1e & 5a) (Arfstrom & Hartmann 2005; Mangold *et al.* 2010). Many authors report both V-shaped incisions (e.g. Dickson & Head 2009; Hobbs *et al.* 2013) and tributary organization of channels/chutes (e.g. Malin & Edgett 2000; Morgan *et al.* 2010). Terraced cutbacks and longitudinal bars (Fig. 5c) (Schon & Head 2009), and more rarely levees (Fig. 5b) (Hugenholtz 2008; Lanza *et al.* 2010; Levy *et al.* 2010; Johnsson *et al.* 2014; Sinha *et al.* 2018), have also been reported as attributes of gully channels. In systems with well-developed fans, the chute and base of the alcove can become backfilled with sediment. In these sediment-choked systems, channels tend to be discontinuous and braided within the confining chutes (McEwen *et al.* 2007*b*); good examples of this are seen in Gasa Crater (Fig. 5d). Braiding of channels is also seen on the fans and in shallow upslope tributary systems (Levy *et al.* 2009; Gallagher *et al.* 2011).

Digitate deposits, either as part of a fan or on their own, are often reported as characterizing the terminal part of Martian gullies (Dickson & Head 2009) (Fig. 6a, b). Deposits often ‘spill over’ the sides of channels (Stewart & Nimmo 2002), but deposits are also re-incised by channels. A distributary organization of channels is associated with gully deposits (McEwen *et al.* 2007*b*), and metre-sized boulders can be common on their depositional surfaces (McEwen *et al.* 2007*b*; de Haas *et al.* 2015*d*). Sometimes distinct depositional lobes are also observed with high relative relief (Lanza *et al.* 2010; Levy *et al.* 2010; Johnsson *et al.* 2014; Sinha *et al.* 2018) (Fig. 6a). The surfaces of Martian gully fans can often be divided into segments with different ages, based on cross-cutting relationships and morphological differences between segments (Schon *et al.* 2009*a*; de Haas *et al.* 2013, 2015*d*; Johnsson *et al.* 2014). This observation shows that gullies form in multiple episodes: that is, they are separated by enough time to have been modified by other processes, rather than in one event (Schon & Head

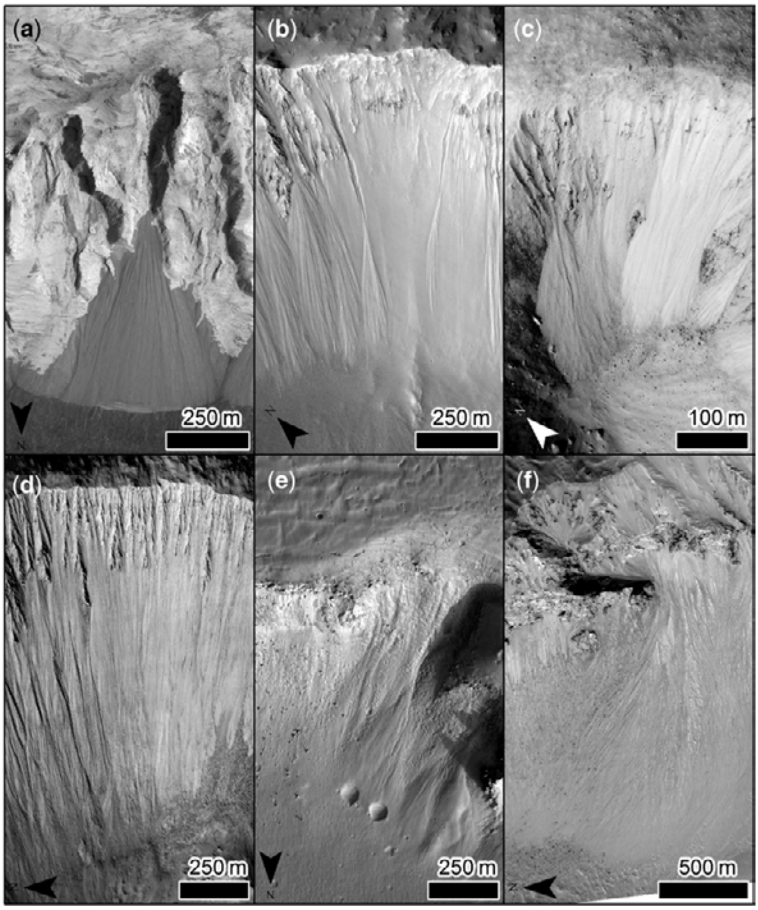


Fig. 4. Gully-like landforms at equatorial latitudes (a–c) and adjacent to mid-latitude gully systems (d–f) on Mars. (**a**) Alcove into an interior layered deposit in Ganges Chasma with an associated fan of dark sediments, HiRISE image ESP_032324_1715. (**b**) Inner wall of a 5 km-diameter crater at 14° S, with linear incisions (channels) and associated fans on the crater wall, HiRISE image ESP_046433_1655. (**c**) An isolated alcove–channel–fan system within an 800 m-diameter crater superposed on an ancient valley leading northwards into the Isidis Basin at 2° S, HiRISE image ESP_036987_1825. (**d**) Alcove–channel–fan systems on the west-facing wall of Istok Crater adjacent to a series of well-developed gullies (Johnsson *et al.* 2014), HiRISE image PSP_006837_1345. (**e**) Alcove–channel–fan systems on a north-facing wall within Asimov Crater, where south-facing gullies are abundant (Morgan *et al.* 2010), HiRISE image ESP_016657_1330. (**f**) Alcove–channel–fan systems on a west-facing portion of Hale Crater's rim adjacent to large well-developed gully systems (Kolb *et al.* 2010*b*), HiRISE image ESP_012597_1435. HiRISE image credit: NASA/JPL/University of Arizona.

2011) (Fig. 6c). This assertion is also supported by the presence of terraces within gully chutes. The surfaces of gully fans are, in many instances, heavily degraded (de Haas *et al.* 2015*d*; Dickson *et al.* 2015), mainly by weathering and wind erosion, but also they may be covered by LDM deposits. Gully channels can be crossed by fractures within the LDM and superpose other similar fractures (Dickson *et al.* 2015) (Fig. 6d). As a result, gully-fan surface morphology is often dominated by secondary, post-depositional, processes. Interpretation of the primary formation processes of gullies based on fan-surface characteristics may be misleading for the often long-inactive Martian gullies, and interpretation of surface morphology should be approached with care (de Haas *et al.* 2015*d*).

Because the channel and associated deposits are the parts of the gully landform that have the least relative relief, it has the poorest preservation potential, making relict gullies hard to substantiate. Dickson *et al.* (2015) identified inverted gully channels in >500 sites polewards of 20° S. These ridges are

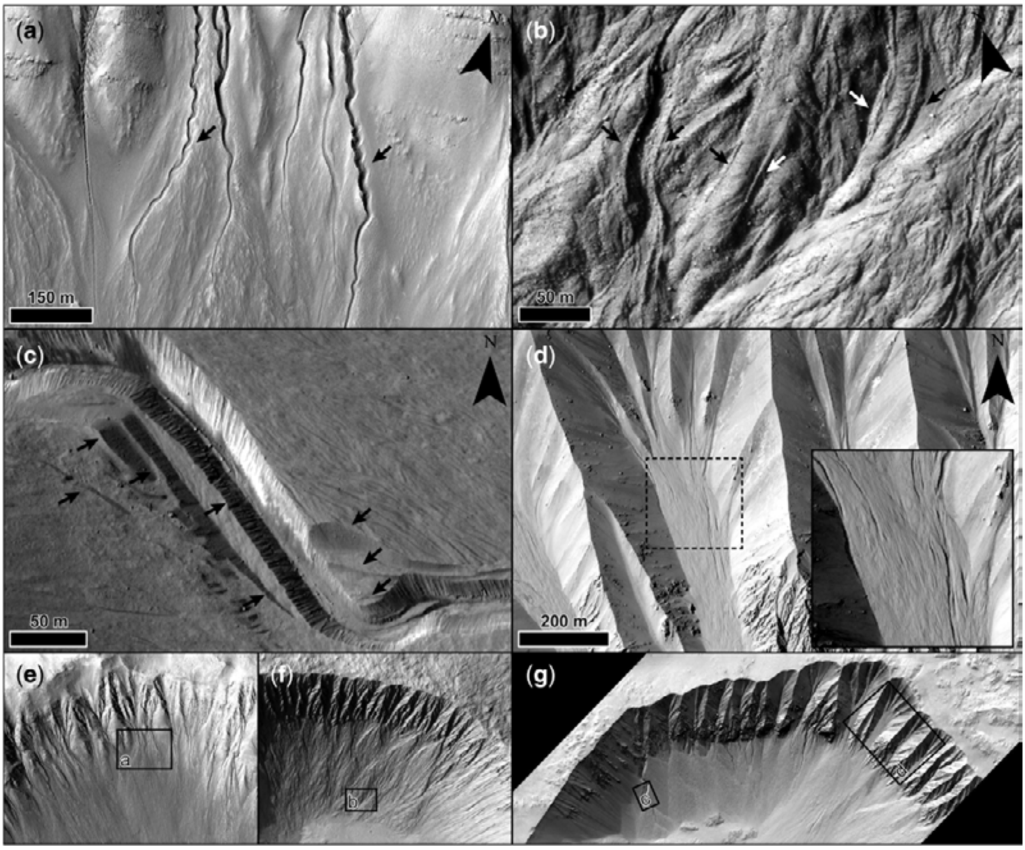


Fig. 5. Martian gully channel features. (**a**) Highly sinuous gully channels highlighted by black arrows in HiRISE image PSP_003464_1380. (**b**) Channels with well-developed lateral levees in Istok Crater highlighted by black and white arrows in HiRISE image PSP_006837_1345. (**c**) Terraces in a gully fan channel in Gasa Crater highlighted by black arrows in HiRISE image ESP_014081_1440. (**d**) Braided channel pattern on a gully fan surface in Gasa Crater in HiRISE image ESP_014081_1440. (**e**)–(**g**) context images for (a)–(d). HiRISE image credit: NASA/JPL/University of Arizona.

present on pole-facing slopes between 40° S and 50° S, and are probably being revealed from under the LDM. Dickson *et al.* (2015) further reported the burial of whole gully systems beneath LDM and present two examples of this. Many other authors have reported apparently infilled alcoves next to distinct or active gully systems (e.g. Hoffman 2002; Christensen 2003; Auld & Dixon 2016; de Haas *et al.* 2017), which they interpret as relict gully systems.

Associated landforms

Martian gullies do not occur in isolation but in association with, and often with superposition relationships to, a range of other morphological features, which we briefly summarize here (in order of descending size). Of the same order of scale or larger than Martian gullies are viscous-flow features (VFFs) (Squyres 1978) which encompass a wide range of features, of which the subtype glacier-like forms (GLFs) (Hubbard *et al.* 2011; Souness & Hubbard 2012; Souness *et al.* 2012) are the most similar in scale to gullies. Martian gullies occur in the same latitude band as GLFs and crater-filling VFFs (Levy *et al.* 2014), and recent work has shown that gullies tend to be sparse where lobate debris aprons (a large subtype of VFFs) and GLFs are dense (Conway *et al.* 2017). From surface morphology and topography alone, VFFs are believed to be debris-covered glaciers (e.g. Squyres 1979; Mangold 2003*a*; Morgan *et al.* 2009) and radar data have confirmed that the ice under the debris is almost pure (Plaut *et al.* 2009). Gullies are sometimes observed adjacent to or topographically above such features (Fig. 1d, i) but rarely intersect them. Gullies only occur in *c.* 12% of craters filled with VFFs, despite occupying

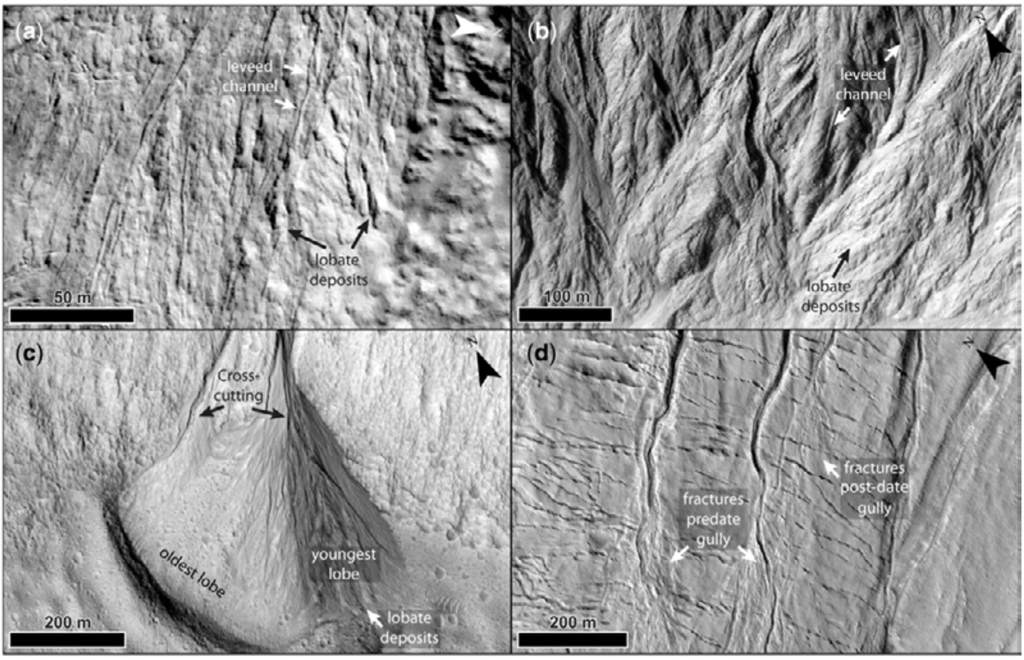


Fig. 6. Depositional features and cross-cutting relationships, indicating Martian gully formation over multiple flow events. (**a**) & (**b**) Multiple superposed channels with lateral levees ending in well-defined lobate deposits on gully fans in Hale Crater (after Reiss *et al.* 2011) and Istok Crater (after Johnsson *et al.* 2014), respectively: (a) HiRISE image PSP_006822_1440 and (b) HiRISE image PSP_006837_1345. (**c**) Cross-cutting channels and gully-fan sectors of different ages on a gully fan in Artik Crater (after Schon & Head 2011 and de Haas *et al.* 2013) (HiRISE image ESP_012314_1450). (**d**) Gully-fan deposits predating and post-dating fractured washboard terrain (after Dickson *et al.* 2015) (HiRISE image PSP_005943_1380). HiRISE image credit: NASA/JPL/University of Arizona.

the same latitude band. Spatulate depressions or arcuate ridges are thought to represent the end moraines of now ablated GLFs (Hartmann *et al.* 2014) and often occur at the foot of gully systems (Arfstrom & Hartmann 2005; Berman *et al.* 2005; Head *et al.* 2008; de Haas *et al.* 2017) (Fig. 7c, e). Gully fans superpose these arcuate ridges and sometimes form on their downslope scarps (Fig. 7d).

In Utopia Planitia and the Agyre region of Mars (Soare *et al.* 2007, 2017; Pearce *et al.* 2011), gullies occur in close association with 100 m-scale polygonized depressions that are linked to the ablation of excess ice – so-called thermokarst or scalloped depressions (Fig. 8c). Similarly, Soare *et al.* (2014*b*) found that 100 m-scale mounds they interpreted to be caused by ice-heave (pingos) also occurred in association with gullies in the Argyre region (Fig. 8d).

Many gullies are intimately associated with the LDM (Aston *et al.* 2011; de Haas *et al.* 2015*a*, 2017; Dickson *et al.* 2015) and dissected LDM (Mustard *et al.* 2001; Milliken *et al.* 2003). The LDM is characterized by a terrain-draping unit which infills decametre- to 100 m-scale topographical lows and smoothes the topography at high latitudes (Kreslavsky & Head 2002). It is often associated with polygonally patterned ground at the metre- to decametre-scale, which is thought to be caused by thermal contraction in ice-cemented soil (Mangold 2005; Levy *et al.* 2009). Initially, the term ‘pasted-on terrain’ was used to refer to the polygonally patterned terrain into which gullies are incised (Christensen 2003) but this has later been incorporated into the catch-all term of ‘LDM’. Although an in-depth discussion of the LDM is beyond the scope of this paper, it should be noted that: multiple generations of LDM deposits are thought to exist (e.g. Schon *et al.* 2009*b*); and although the LDM is generally attributed to airfall deposits of ice nucleated on atmospheric aerosols (Kreslavsky & Head 2002), some aspects of the LDM argue for ice enrichment through freeze–thaw cycling (Soare *et al.* 2017). Several lines of evidence (aside from the crack morphology) have led most researchers to agree that polygonally patterned ground indicates an ice-rich terrain, including: newly formed impact craters, discovered using the Context Camera (CTX), have been found by Compact Reconnaissance Imaging Spectrometer for

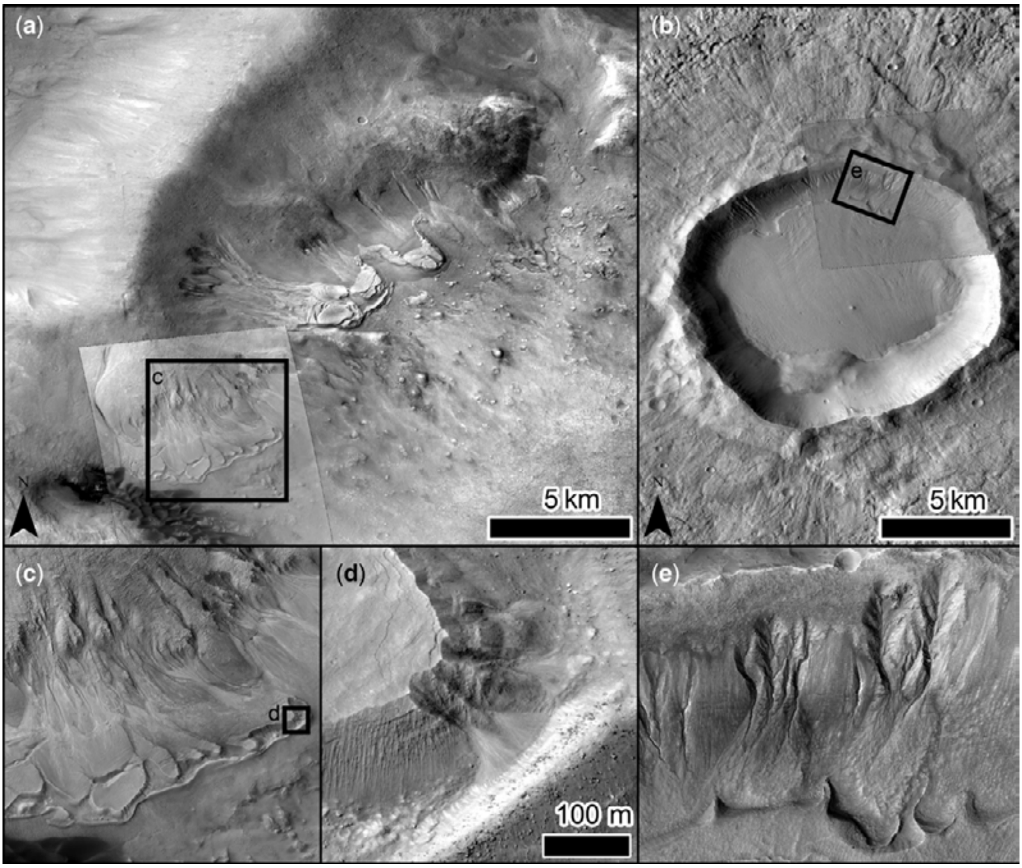


Fig. 7. The relationship between arcuate ridges and Martian gullies. (**a**) Overview of a ridge in Nereidum Montes with arcuate ridges downslope of gullies on its eastern flank. HiRISE image ESP_022685_1400 overlain on CTX image G11_022685_1402. (**b**) Overview of a 9 km-diameter crater in Terra Sirenum, containing a 'viscous flow feature' (VFF), with gullies upslope of arcuate ridges on its pole-facing wall. HiRISE image ESP_022108_1410 overlain on CTX image B07_012337_1408. (**c**) Detailed view of gullies upslope of a complex of arcuate ridges, whose fans superpose the terrain hosting the ridges. The location of (d) is indicated by the black box. (**d**) Small gully-like landforms on the scarps of the arcuate ridges. (**e**) Detailed view of the gullies upslope of the arcuate ridges, where the gully fans appear to be backfilling the spatulate depression behind the ridges. HiRISE image credit: NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

Mars (CRISM) and HiRISE to have excavated subsurface water ice (Byrne *et al.* 2009); *in situ* discovery of ice associated with polygonally patterned ground by the Phoenix lander (Mellon *et al.* 2009); and the spatial correlation between high ice content as inferred from the neutron spectrometer data and polygonally patterned ground (e.g. Mangold 2005).

Not all gullies are found in association with LDM, yet large proportions are: Levy *et al.* (2009) reported that just over 50% of gullies in their survey (all HiRISE images 30°–80° north and south latitude) are associated with polygonally patterned ground. Polygonal patterns are found on the inner slopes of alcoves and chutes of gullies, as well as in the terrain that the gullies incise (Fig. 9b). Their fan deposits superpose polygonally patterned ground and sometimes relict fan deposits show polygonization (Fig. 9c). Volume-balance arguments indicate substantial volatile loss in gully systems incised into this type of terrain (Conway & Balme 2014; Gulick *et al.* 2018), implying excess ice in the ground at these locations. The lowest latitudinal limit of gullies coincides with the edge of the dissected LDM (Milliken *et al.* 2003) but also with the lowest latitude extension of VFFs (Levy *et al.* 2014). Head *et al.* (2003) noted that the LDM superposes crater-bound VFFs, yet the LDM may superpose gullies and also be dissected by gullies (Dickson *et al.* 2015). Hillslopes with pasted-on material or LDM are often associated with arcuate

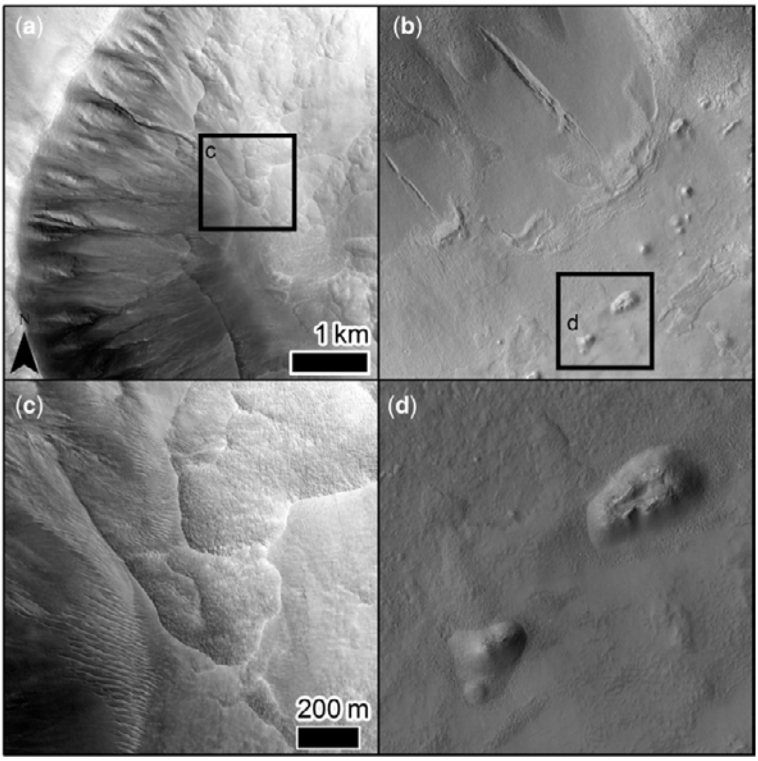


Fig. 8. The relationship between gullies and scalloped depressions and pingo-like-mounds. The scale indicated in (a) is the same in (b), and also the same for (c) & (d). North is up in (a)–(d). (**a**) A 9 km-diameter crater in Utopia Planitia reported by Soare *et al.* (2007) containing gullies and scalloped depressions. HiRISE image ESP_016113_2305. (**b**) Pingo-like mounds and gullies on a massif in the Nereidum Montes reported by Soare *et al.* (2014*b*). HiRISE image ESP_020720_1410. (**c**) Detailed view of scalloped depression located downslope of the gullies, with polygonized floor and steep cuspate margins, particularly on the pole-facing slope. (**d**) Detailed view of the pingo-like mounds, where the right-hand example has a collapsed summit and both have fissures at their summits. HiRISE image credit: NASA/JPL/University of Arizona.

ridges at the base of the slope, but also smaller-scale landforms informally termed 'washboard terrain' encompassing parallel series of across-slope trending fractures thought to represent crevasses (Arfstrom & Hartmann 2005; Hubbard *et al.* 2014; Dickson *et al.* 2015) (Fig. 9d).

Landforms intimately associated with periglacial conditions (those conducive to freeze–thaw cycling in the ground) have been reported to occur in close proximity to, or in association with, Martian gullies. These landforms are generally on the metre- to decametre-scale, and the frequency of their association with gullies numbers in the tens, rather than in the hundreds, as for the features mentioned above. Cross-cutting and intimate association has been reported between gullies and: (1) lobate forms (including stone garlands), which are attributed to solifluction processes where the top part of the soil profile creeps downslope due to repeated thawing (Gallagher & Balme 2011; Gallagher *et al.* 2011; Johnsson *et al.* 2012; Soare *et al.* 2014*a*) (Fig. 10d); and (2) sorted stone stripes where clasts are gathered at the edge of convection cells in the soil caused by freeze–thaw cycling (Gallagher *et al.* 2011) (Fig. 10e). Gullies are also reported to occur in close proximity to other sorted patterned grounds, including sorted stone circles and nets, and rubble piles (Gallagher *et al.* 2011; Balme *et al.* 2013; Barrett *et al.* 2017).

Finally, gullies are often found on the same slopes as recurring slope lineae (RSL) (e.g. McEwen *et al.* 2011; Ojha *et al.* 2015; Dundas *et al.* 2017*a*), which are downslope-propagating dark streaks typically a few metres to tens of metres wide and hundreds of metres long (Fig. 10f). They only occur on the steepest slopes and originate at rock outcrops in terrains that have high thermal inertia (interpreted to have low dust cover). Their behaviour

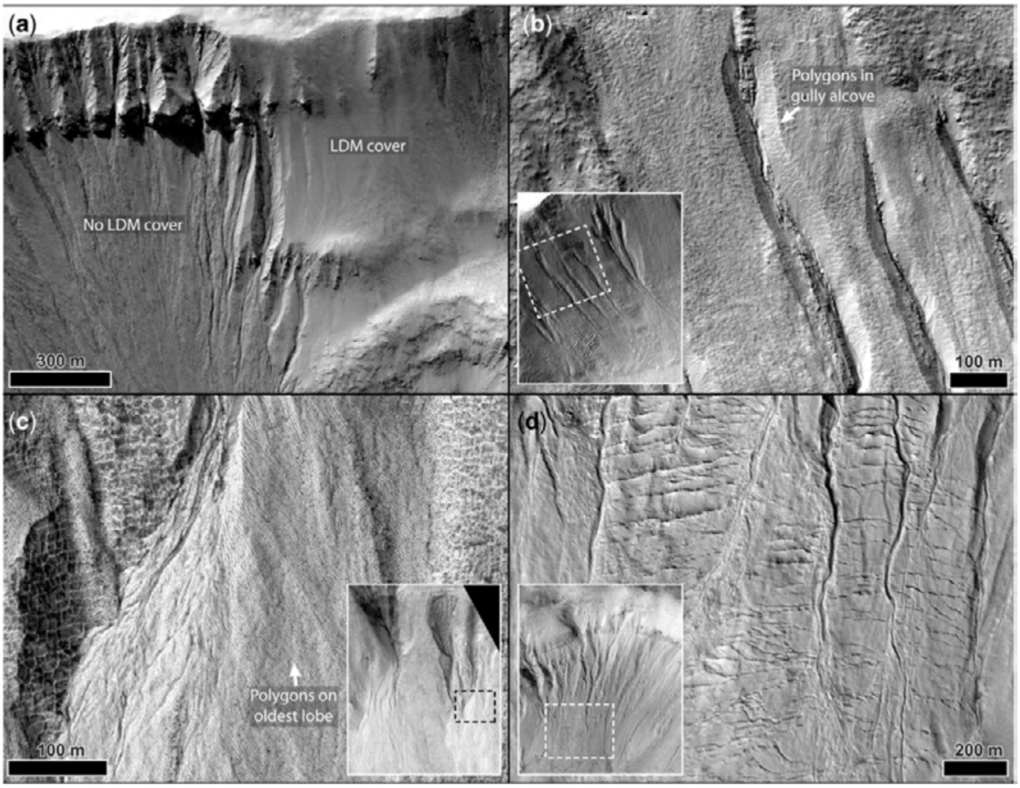


Fig. 9. Relationship between gullies and LDM deposits. (**a**) Gullies with and without LDM cover in Domoni Crater (HiRISE image ESP_016213_2315) (after de Haas *et al.* 2017). (**b**) Polygonal ground in gully alcoves in Langtang Crater (HiRISE image ESP_023809_1415) (after de Haas *et al.* 2017). (**c**) Polygons on an inactive gully-fan lobe (HiRISE image PSP_002368_1275) (after Levy *et al.* 2009). (**d**) Washboard terrain superposing old gully-fan deposits, while being covered by younger gully-fan deposits (HiRISE image PSP_005943_1380; see also Fig. 6d) (after Dickson *et al.* 2015). HiRISE image credit: NASA/JPL/University of Arizona.

distinguishes them from other mass-wasting phenomena; they grow during the hottest times of the year, fade during the cold season and reoccur at the same (or nearly the same) place each year (Grimm *et al.* 2014; Stillman & Grimm 2018). RSL generally occur superposed on gully alcoves. No change in relief is associated with RSL, so they are thought to transport only small amounts of sediment (if any). Some RSL propagate over sandy fans and occasionally slumps are also found on these fans, but their relationship to RSL remains unclear (Chojnacki *et al.* 2016; Ojha *et al.* 2017). RSL are also found on steep slopes without gullies, most notably those in Valles Marineris (McEwen *et al.* 2014; Chojnacki *et al.* 2016; Stillman *et al.* 2017).

Global trends

Gullies are found on steep slopes polewards of *c.* 30° in each hemisphere (Harrison *et al.* 2015) (Fig. 11). Between latitudes of 30° and 40°, pole-facing gullies are strongly dominant; whereas from 40° to the pole, gullies are mostly equator-facing but also exist in other orientations (Conway *et al.* 2017). Gullies are found across all elevations on Mars but are notably absent within their general latitudinal distribution from the Tharsis Bulge and the Hellas Basin (Heldmann & Mellon 2004; Dickson *et al.* 2007; Heldmann *et al.* 2007). The latter is due to the absence of steep slopes, and the former seems to be an effect of surface thermal inertia (Conway *et al.* 2017). The general paucity of gullies in the northern hemisphere can be directly attributed to the lack of steep slopes in that hemisphere (Conway *et al.* 2017).

Although gully morphology varies widely (Fig. 1), there seems to be no distinctly identifiable trends with latitude and/or orientation (Balme *et al.* 2006). Obvious exceptions to this general rule are the polar-pit gullies. There are hints in the literature as to gullies with different degradation states having different

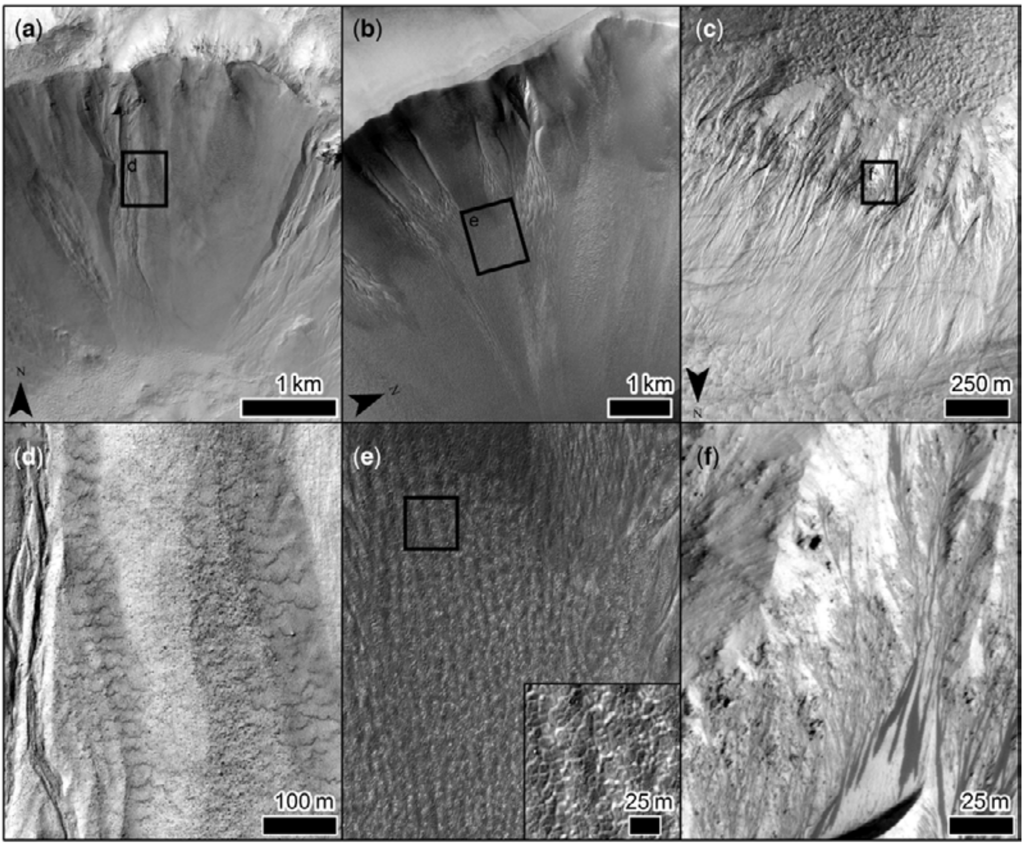


Fig. 10. The relationship between gullies and lobes, patterned ground and RSL. (**a**) Gullies in Ruhea Crater in HiRISE image ESP_023679_1365, where the black box marks location of (d). (**b**) Gullies in a 20 km-diameter crater in Acidalia Planitia, HiRISE image ESP_045997_2520 overlain on CTX image B01_010077_2520, where the black box marks the location of (e). (**c**) Gullies on the central mounds of Lohse Crater in HiRISE image PSP_006162_1365, where the black box marks the location of (f). (**d**) Lobes on the terraces in the chute walls of gullies and on the surrounding terrains as first reported in Johnsson *et al.* (2018). (**e**) Stripes between the gully fans first reported in figure 12 of Gallagher *et al.* (2011). The inset box shows that clasts make up the lower-albedo parts of the stripes. (**f**) RSL in the alcoves of gullies, first reported in figure 14 of Ojha *et al.* (2014). HiRISE image credit: NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

latitudes/orientations but this remains to be fully substantiated. Bridges & Lackner (2006) and Heldmann *et al.* (2007) did note that gullies in the northern hemisphere were more degraded in appearance than those in the southern hemisphere. Levy *et al.* (2009), Morgan *et al.* (2010) and Raack *et al.* (2012) reported that for the southern hemisphere, equator-facing gullies seemed more degraded than the pole-facing ones.

Compositional data

Harrison *et al.* (2015) showed that gullies are more prevalent on terrains classified as high thermal inertia, interpreted as being low dust, low albedo, and with grain sizes of between 60 μm and 3 mm (Putzig *et al.* 2005; Jones *et al.* 2014). Harrison *et al.* (2017) found that fans associated with active gullies in Gasa Crater have higher thermal inertia than other gully fans, yet lower thermal inertia than talus slopes. The hysperspectral imaging system CRISM has been used to examine the composition of the materials in and around gullies (Barnouin-Jha *et al.* 2008; Núñez *et al.* 2016*a*; Allender & Stepinski 2017, 2018), and suggested that: (1) gullies are hosted on a wide range of geological materials; (2) in some cases, gullies expose underlying rock and move it downslope; (3) many other gullies show no spectral difference to their surroundings; and (4) there is no systematic association between hydrated minerals

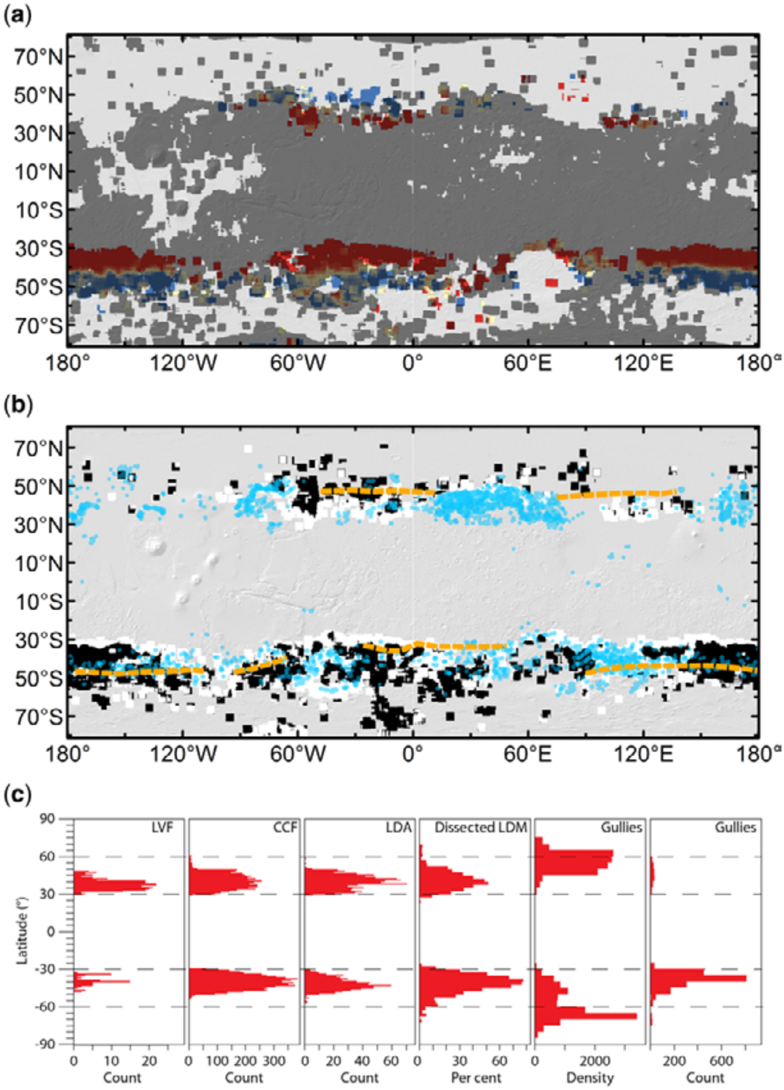


Fig. 11. Global gully trends on Mars. (**a**) Map showing the orientation of gullies and their relationship to the occurrence of steep slopes; the data are from Conway *et al.* (2017). Red colour indicates gullies are 100% pole-facing, blue are 100% equator-facing and yellow are 50–50%. Darker shades are the locations where there are more steep slopes and lighter shades are the locations where there are fewer. In detail, the number of pixels with 20° slopes derived from projection-corrected Mars Orbiter Laser Altimeter (MOLA) data was counted inside a 250 km moving window, which was then normalized by the true area of that moving window. The cutoff between the two shades is 3×10^{-3} steep pixels per km^2. MOLA hill-shaded relief is in the background for context. (**b**) Comparison between the location of gullies (black–white), large glacier-like forms (blue) and the roughness boundary of Kreslavsky & Head (2000) as an orange dashed line, thought to represent the equatorwards limit of the LDM. The number of gully sites per km^2 of steep slope are given in black and white, where black is >250 and white is <250. The glacier-like forms are compiled from the catalogues of van Gasselt (2007), Souness *et al.* (2012) and Levy *et al.* (2014). MOLA hill-shaded relief is in the background for context. (**c**) Histograms showing the latitudinal distribution of glacier-like forms (LVF, lineated valley fill; CCF, concentric crater fill; LDA, lobate debris aprons are all from Levy *et al.* 2014), dissected latitude-dependent mantle (LDM) from Milliken *et al.* (2003), slope-normalized gully density from Conway *et al.* (2018*b*) and raw counts of gullies from Harrison *et al.* (2015). LVF, CCF and LDA are given as the number of landforms per 1° latitude bin. Dissected LDM is given as the percentage of MOC image per 2.5° latitude bin. Gullies are given as the mean number of sites per steep slope and counts in 5° latitude bins.

and gullies even in the new light-toned deposits found in some gullies. Heldmann *et al.* (2010) used CRISM data and also confirmed that recent light-toned deposits in Penticton Crater have no spectral differences to the surrounding material. It should be noted that the lack of systematic observations of hydrated or brine spectral signals in gullies does not mean that these materials are absent (Massé *et al.* 2014) – hydrated signatures rapidly disappear under Martian conditions and a spectral signal can easily be obscured by a surface coating of millimetres of dust, which is abundant and pervasive on Mars.

Fan *et al.* (2009) investigated the relative water content of four gully sites compared to their surrounding areas and found by using statistical analysis of OMEGA hyperspectral data that the gully sites had elevated water contents. Dickson & Head (2009) used colour HiRISE images to identify the seasonal accumulation of frost in the alcoves and channels of two gully systems, and in one case they used CRISM to confirm its composition as water ice. Vincendon (2015) reported both seasonal water ice and CO_2 ice in association with active gullies. Dundas *et al.* (2017*b*) also find from HiRISE image data that active gullies are commonly associated with seasonal ice deposits. Sometimes these ices are observed in the alcoves of generally equator-facing gullies, but the frost is located on pole-facing sections of their alcoves (Fig. 12). These results are in general accordance with those obtained for surfaces on Mars in general. Carrozzo *et al.* (2009) observed from OMEGA data that low-latitude ice condensation occurs preferentially on shadowed (i.e. pole-facing at the present day) slopes between 30° S and 30° N. Kuzmin *et al.* (2009) used thermal emission spectrometer (TES) thermal inertia data to map water ice at the surface, and reported widespread water ice condensation on the surface occurring in winter between 40°–50° S and 40°–50° N, particularly in the northern hemisphere, which is consistent with spectral observations (Appéré *et al.* 2011).

Temporal context (age and activity)

Gullies are geologically very young landforms that formed within the last few million years. This is inferred from the conspicuous lack of superposed impact craters on gullies (e.g. Malin & Edgett 2000), superposition relationships with polygons, dunes and transverse aeolian ridges (e.g. Malin & Edgett 2000; Reiss *et al.* 2004), their occurrence in young impact craters that formed within the last few million years (Johnsson *et al.* 2014; de Haas *et al.* 2015*b*, 2017; Conway *et al.* 2018*a*), and the presence of secondary craters related to recent crater impacts as marker horizons on gully lobes (Schon *et al.* 2009*a*). Geologically young gully deposits are present in both very young and very old host craters (<1 Ma–>1 Ga), and their size is unrelated to host-crater age (Grotzinger *et al.* 2013; de Haas *et al.* 2017). While the spatial distribution of Martian gullies has been extensively studied and quantified, their temporal evolution is poorly understood. Documenting the temporal evolution of gully systems had already been noted as one of the main outstanding questions and avenues for advancement regarding the understanding of Martian gullies by Dickson & Head (2009), yet very few papers have addressed this topic since then. de Haas *et al.* (2017) show that after their formation in fresh craters, gullies may go through repeated sequences of: (1) LDM deposition and reactivation; and (2) glacier formation and gully removal (Conway *et al.* 2018*a*),

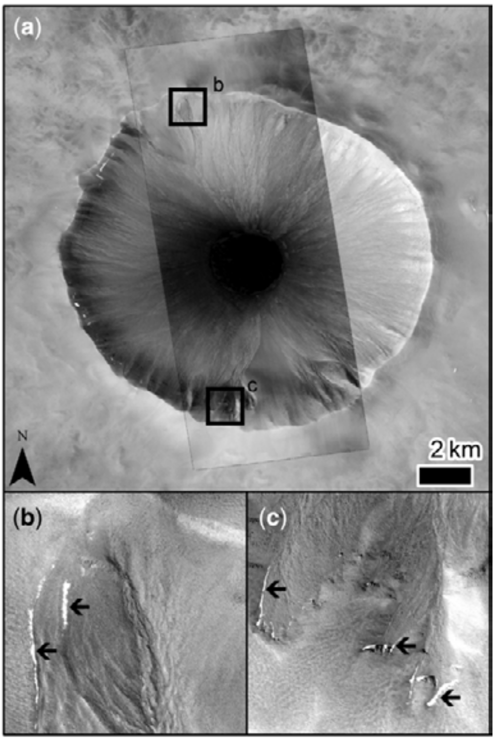


Fig. 12. Frost visible in equator-facing and pole-facing alcoves of gullies in a 12 km-diameter crater located in the northern hemisphere in Acidalia Planitia. (**a**) Overview in HiRISE image ESP_052090_2450 overlain on CTX image P18_007995_2448. (**b**) Frost in the equator-facing alcove (black arrows), but only on the facets of the alcove that do not directly face the equator. (**c**) Frost in the pole-facing alcove (black arrows), located at the most sheltered positions. HiRISE image credit: NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

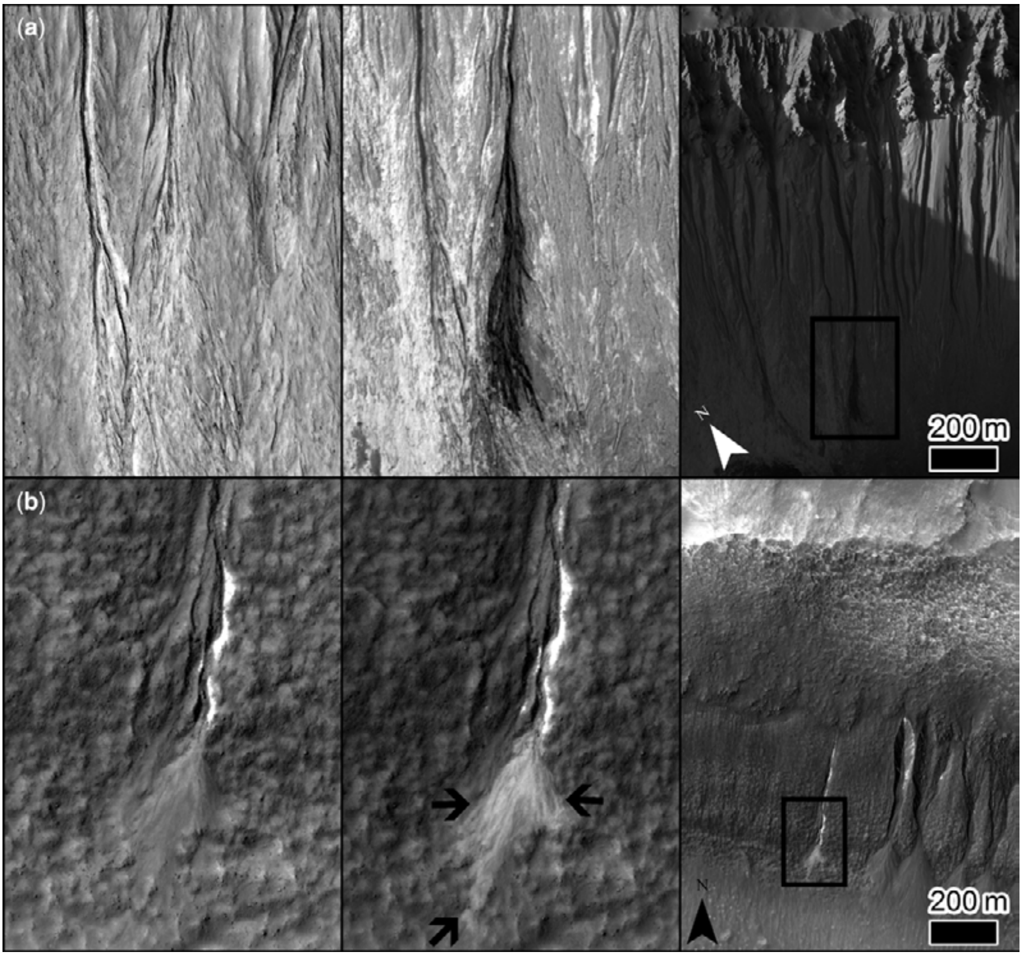


Fig. 13. Present-day activity in Martian gullies. Images have been selected to best highlight the new morphology, so are not necessarily the closest in time. For each row the leftmost image is the ‘before’ image. The middle image is the ‘after’ image, which is the same image used in the overview panel located on the far right. (**a**) A new dark flow, which is superposed on seasonal frost on the crater wall making it particularly visible even though the slope is in shadow. HiRISE images ESP_022688_1425 (before) and ESP_027567_1425 (after and overview). (**b**) New relatively light-toned deposits on a gully fan, highlighted by black arrows in the middle panel. HiRISE images ESP_014368_1435 (before) and ESP_031919_1435 (after and overview).

followed by the formation of new gully systems. In general, gullies in host craters that are younger than a few million years have not been affected by LDM or glaciation (type 1), gullies in host craters of a few million years to a few tens of millions of years have been affected by LDM but not by glaciation (type 2), and gullies in host craters of more than a few tens of millions of years have been affected by both LDM and glaciation (type 3). These various types of history are reflected in the gully morphology: type 1 gullies have large alcoves with rough surfaces that cut into bedrock and extent up to the top of the crater rim (Figs 11 & 2b); type 2 gullies are similar but are visually softened by a veneer of LDM deposits (Figs 1h, k & 9a); and type 3 gullies lay within the former extent of glaciers, as indicated by the presence of, for example, arcuate ridges and sublimation till, and have elongated, V-shaped alcoves that often do not extend all the way up to the crater rim (Figs 7b, e & 8b).

Repeat imaging of Martian gullies has revealed that mass transport is occurring within these systems at the present day (Reiss & Jaumann 2003; Malin *et al.* 2006; McEwen *et al.* 2007*b*; Diniega *et al.* 2010; Dundas *et al.* 2010, 2012, 2015, 2017*b*; Reiss *et al.* 2010*a*; Raack *et al.* 2015; Pasquon

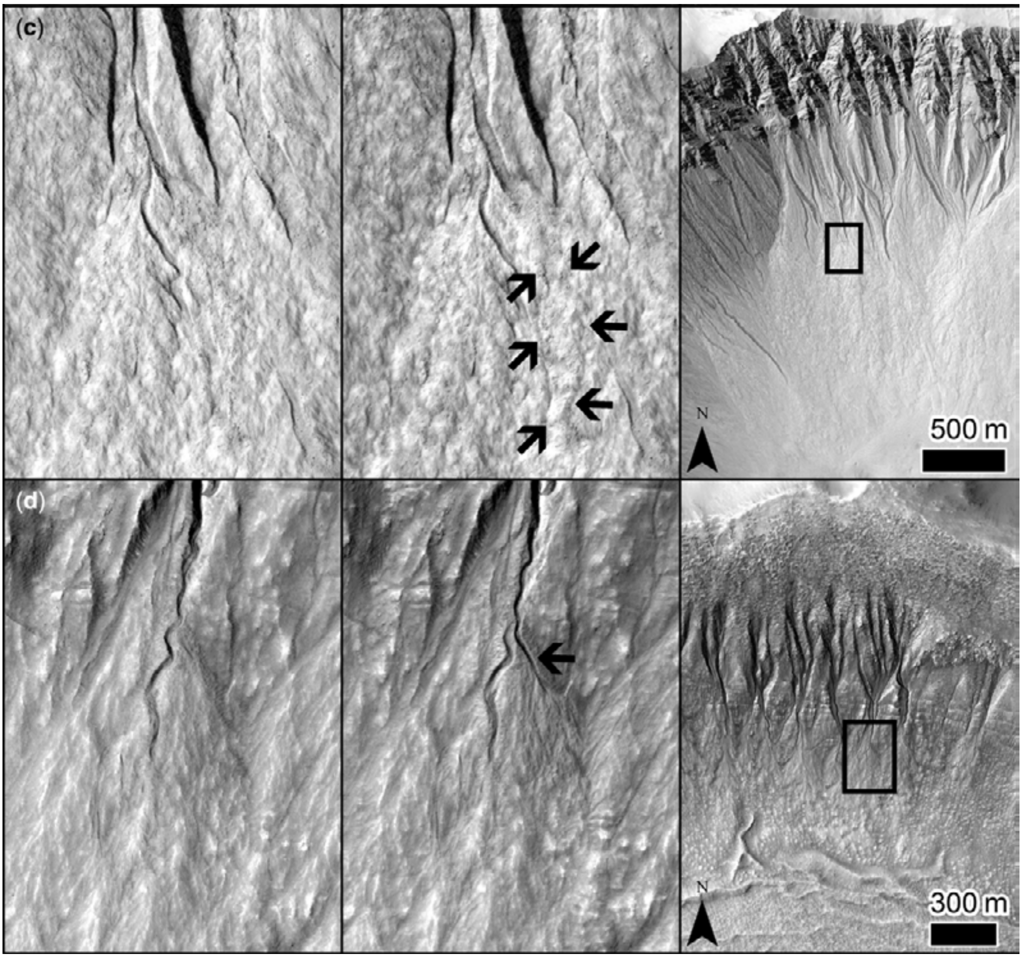


Fig. 13. *Continued*. (**c**) New massive deposit on the fan of a gully in Galap Crater, outlined in the middle panel by arrows; this new deposit is lobate and contains boulders. HiRISE images PSP_003939_1420 (before) and ESP_032078_1420 (after and overview). (**d**) A newly incised channel branching off a pre-existing gully, highlighted by a black arrow. HiRISE images ESP_013115_1420 (before) and ESP_032011_1425 (after and overview). HiRISE image credit: NASA/JPL/University of Arizona.

et al. 2016). Activity within gullies on dark sandy substrates in the southern hemisphere is particularly remarkable, with both 'classic' and 'linear' gully sites showing some kind of mass transport every Mars year. In this Special Publication, Pasquon *et al.* (2018) show that the timing and nature of the activity of the classic gullies on dark sand dunes differs from that of linear dune gullies. Classic dune gullies are generally active in local winter (Diniega *et al.* 2010; Pasquon *et al.* 2018), and their activity is characterized by smaller metre-scale slumps into the chute/alcove and large alcove-clearing events that leave upstanding deposits on the debris fan (Pasquon *et al.* 2018). Linear dune gullies are active as the seasonal surface frost finally sublimates from the surface (solar longitude (Ls) *c.* 200°, early spring), and their activity is characterized by the elongation of channels, and the appearance of new pits and new channels. Linear gullies with no changes are also observed. Volume-balance arguments dictate that entire linear gully systems can be produced on the order of tens of Mars years (probably slightly longer for the large systems on the Russell megadune) and classic gullies on the order of hundreds of Mars years (Pasquon *et al.* 2018). Hence, it is likely that these dune gully systems are a product of the present climate system. It is also worth noting that the north polar dune fields are also remarkably active, yet the timing and character of this activity differs from the southern hemisphere

(Diniega *et al.* 2017). Here, alcove–fan systems only tens to hundreds of metres in length form on dune slip faces in autumn or early winter. Their formation seems to be linked to the first deposits of the seasonal CO_2 ice. Channels are occasionally visible at the limit of resolution; hence, this is why these features would not usually be classed as Martian gullies.

Polar-pit gullies are also more active than classic gullies elsewhere (Hoffman 2002; Raack *et al.* 2015). Their activity is characterized by the gradual progression of relatively dark sediment deposits over the seasonal ices during the latter part of winter. These dark deposits are visible as topographical relief once the ice has been removed. Not all polar-pit gullies are active at once, which led Raack *et al.* (2015) to surmise that the process must be supply limited rather than environment limited.

Activity in classic gullies was first documented in the form of 'bright white deposits' in Mars Orbiter Camera data (Malin *et al.* 2006). These deposits appear on the depositional apron of the gully, have a digitate outline, no detectable relief and no distinct source zone (Fig. 13b). Since then, repeat images by HiRISE have detected movements that appear both 'bright' and 'dark' in the red wavelengths (Fig. 13a, b), and can have various colour hues including 'blue' and 'yellow'. These movements include deposits with no detectable relief, but also deposits with upstanding lobate edges containing boulders (Fig. 13c), the evacuation of sediment infilling channels and, in one case, the incision of a new channel (Dundas *et al.* 2010, 2012, 2015, 2017*b*) (Fig. 13d). Activity is rarer in the northern hemisphere and so far none of the observed modifications have engendered any detectable alteration in relief (Dundas *et al.* 2017*b*). Source areas for these movements cannot usually be identified, although occasionally failure scars are present. Crown fractures have been identified in the alcoves of Gasa Crater (Okubo *et al.* 2011), where the gullies are particularly active (Dundas *et al.* 2017*b*), suggesting slope instability as a trigger for movement. Because activity in classic gullies is so sporadic, there are only about 40 examples where timing can be constrained to within 3 months and the activity tends to occur in winter or during defrosting at that latitude (Dundas *et al.* 2017*b*). Whether these observations of activity in classic gullies represent the process that forms the whole gully landform is currently under debate.

Review of proposed Martian gully-formation mechanisms and their terrestrial analogues

Multiple models have been put forth in an attempt to understand how geologically youthful gully features could have formed on Mars. Our view of Martian gullies has improved over time since their initial discovery thanks to long-term monitoring and higher-resolution data, which is reflected by the wealth of data on their morphology and spatial distribution presented above. Accordingly, the models of formation that have been put forth have evolved over time as well. Terrestrial analogy has played a key role in developing these formation models and also in testing them against observations. It was the analogy to systems on Earth carved by liquid water that sparked the initial controversy about gully formation as corroborated by the flurry of comments on the initial discovery paper (Doran & Forman 2000; Hoffman 2000; Knauth *et al.* 2000; Saunders & Zurek 2000). The reason this claim was so controversial, and remains so, is that our understanding of Mars' surface environment dictates that liquid water should not be thermodynamically stable – it should only be present in its gaseous or solid forms (Hecht 2002; Richardson & Mischna 2005). Climate models have shown that liquid water could be transiently stable, but the locations where this is predicted do not match with the locations of gullies (e.g. Richardson & Mischna 2005; Stillman *et al.* 2014). Authors have therefore proposed that landforms resembling terrestrial water-carved landforms could be formed on Mars by other fluids or even without fluids – a concept termed 'equifinality'. One of the reasons that multiple hypotheses for formative mechanisms are conceptually viable is the steepness of the relief and the instability of surface materials under steep gradients. Hence, any appreciable applied force might be capable of causing bulk flows. It is now generally accepted that gullies are formed by a fluid, presently thought to be H_2O liquid or CO_2 gas. In this section, we first summarize the arguments which show that gullies on Mars are not formed by a completely dry granular flow. We then go on to present the arguments made in favour of liquid-water mechanisms and the models outlining the origin for this water. Finally, we outline the arguments made in favour of CO_2-based fluids for gully formation. Each of these subsections will emphasize the role that terrestrial analogues have played in developing these working hypotheses.

Dry granular flow

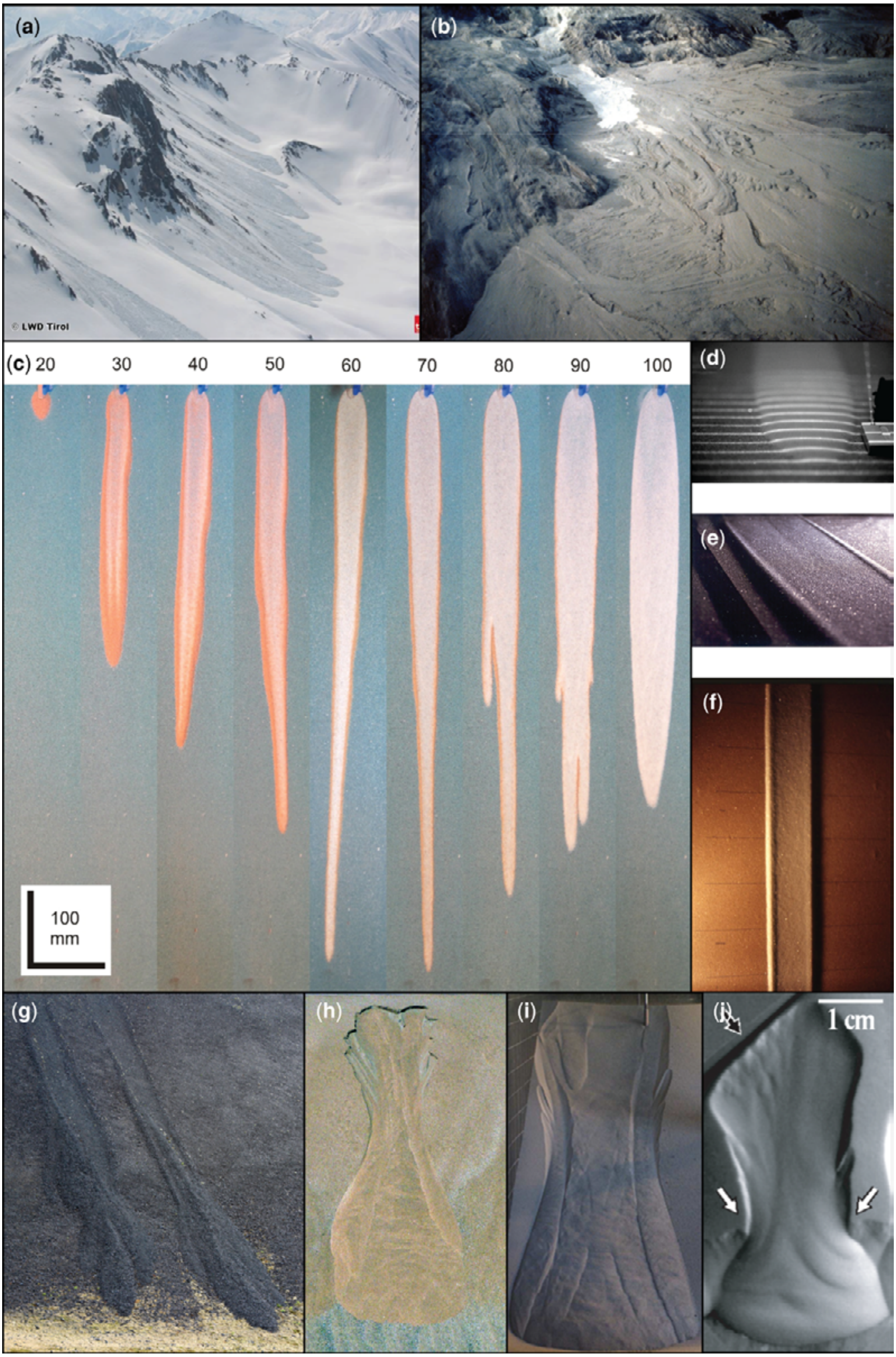
Treiman (2003) proposed entirely dry flow as the agent behind Martian gully formation based on the difficulty of sustaining liquid water under recent climate conditions. He explained the leveed channel morphology of Martian gullies with reference to the terrestrial analogues of pyroclastic flows and dry snow avalanches as examples of natural dry granular flows (Fig. 14a, b). However, McClung & Schaerer (2006, p. 134) note that 'dry snow avalanches tend to travel in straight lines rather than being deflected by topography, such as gullies'. Observations of snow avalanches by Kochel & Trop (2008) as Mars analogues in the Wrangell Mountains in Alaska also point to some differences: avalanches have very straight, wide channels, with broad levees, the terminal deposit is often square-lobate showing no digitate break-offs. These landforms are similar in morphology to those produced by dry granular flow in experiments (e.g. Félix & Thomas 2004; Kokelaar *et al.* 2014) (Fig. 14c–e) and numerical modelling (Gueugneau *et al.* 2017).There is also disagreement in terrestrial literature as to whether dry granular flow models are even valid for snow avalanches, which almost inevitably involve some phase changes (e.g. Naaim *et al.* 2003; Hutter *et al.* 2005; Platzer *et al.* 2007; Gauer *et al.* 2008), and wet snow avalanches can behave like, and have a similar morphology to, debris flows (Bartelt *et al.* 2012) (covered in the next subsection). The same is true for pyroclastic flows, which are fluidized by hot pressurized gas in the pore space (either trapped on catastrophic collapse of the ash column and/or continually produced from the hot volatile volcanic products) (e.g. Sparks & Wilson 1976; Siebert *et al.* 1987; Mellors *et al.* 1988). We will come back to the pyroclastic analogy within our discussion concerning the fluidization by CO_2 gas evolved by sublimation (see the subsection on 'CO_2 gas-fluidized flow' later in this paper).

Shinbrot *et al.* (2004) also supported a dry granular flow model based on the fact that both Martian gullies and dry mass-movement features on terrestrial sand dune slip faces (Fig. 14g–i) have leveed channels (e.g. Sutton *et al.* 2013*a*). Shinbrot *et al.* (2004, 2007) used a spinning disc to simulate the lower cohesion induced by lower gravity, and generated features with wide, shallow channels and gentle lateral levees (Fig. 14). However, other authors have found that Martian gullies in detail are morphologically distinct from dry features on Earth and dry mass-movement features elsewhere on Mars (Fig. 3), as detailed below. Martian gullies show evidence for flows that divert around an obstacle and reintegrate after passing it (i.e. braided), which requires a certain flow thickness, viscosity and fluidity that according to our present knowledge is not achievable in dry flows even under low gravity (Brusnikin *et al.* 2016). Dry granular flows do not behave in this manner unless they are sufficiently thick and fine-grained such that van der Waals forces are many orders of magnitude larger than intergranular friction and grain weight (Johnson *et al.* 1971; Derjaguin *et al.* 1975; Campbell 1990). Conway & Balme (2016) compared the morphometries of the catchments of Martian gullies to dry mass-wasting features on Earth (talus slopes), on the Moon and ungullied crater walls on Mars, and found that Martian gullies were statistically dissimilar from these nominally 'dry' landforms. The runout of dry granular flows should not extend very far beyond slopes greater than the dynamic angle of repose (*c.* 20°: Pouliquen 1999; Kleinhans *et al.* 2011), which has been confirmed to be the case for dry avalanches on the Moon (Kokelaar *et al.* 2017), yet the majority of Martian gully fans are shallower than this. Conway *et al.* (2015) measured a median slope of 14° for 67 gully fans, and Kolb *et al.* (2010*a*) concluded that 72% of the 76 fans they studied were likely to be emplaced by fluidized flows. It should be noted that Pelletier *et al.* (2008) and Kolb *et al.* (2010*b*) found that the new bright deposits reported by Malin *et al.* (2006) in the Penticton and Hale craters occur on steep enough slopes to be attributed to dry granular flows. The general consensus among the Mars gully community today is that gullies do not form via an entirely dry granular flow mechanism, although dry mass-movement processes could occur within pre-existing gullies today (Harrison *et al.* 2015). Dry granular flows remain a reasonable mechanism for spur and gully landforms, which often lack channels/chutes.

Liquid-water gullies

Martian gullies are similar to terrestrial analogue landforms carved by water, which has led researchers to propose a number of water-related flow processes for their genesis. It should be noted that the ubiquity of precipitation involvement, directly or indirectly, in such analogues makes extrapolation to Mars somewhat questionable. In the first part of this subsection, we discuss the arguments that have been made in favour of each of these water-based flow processes in light of their terrestrial analogues (see 'Fluvial flow, debris flow, slushflow, brines and other exotic fluids' below). Whether or not similar landforms can be produced by other non-water-flow processes will be discussed in Section 'CO_2 related mechanisms'. Following this we discuss the possible origins of this water along with their terrestrial analogues (see the subsections on 'Release of water at high to moderate obliquity' 'Release of groundwater from aquifers', 'Melting of near-surface ground ice' and 'Melting of snow' later in this section).

Fluvial flow, debris flow, slushflow, brines and other exotic fluids. The involvement of water in the formation of Martian gullies has from the start been driven by their similarity to terrestrial water-generated landforms. On Earth, the two main flow processes responsible for the downslope transport of sediment are fluvial flows and debris flows. When we refer to fluvial flows we mean flows in which the sediment concentration is sufficiently low that the fluid behaves like a Newtonian fluid and sediment entrainment solely occurs via shear stress exerted on the bed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© LWD Tirol
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by the fluid – generically referred to as the stream power law (e.g. Hack 1957; Sklar & Dietrich 1998; Whipple & Tucker 1999). Debris flows, on the other hand, are flows where the sediment to water ratio, typically *c.* 20–60% water by volume (Costa 1984; Iverson 1997; Pierson 2005), is sufficiently high that the rheology of the fluid changes and it behaves more like a Bingham plastic or a viscous fluid (e.g. Iverson 1997, 2014; Ancey 2007). Steep first-order catchments on Earth are often dominated by debris-flow processes, which leave an identifiable morphological fingerprint on the landscape (Jackson *et al.* 1987; Lague & Davy 2003; Mao *et al.* 2009). Slushflow is a special kind of debris flow where some of the clastic material is replaced by ice (Rapp 1960; Nyberg 1989; André 1990; Decaulne & Sæmundsson 2006). In the most general sense, brines can replace water in both fluvial flows and debris flows, so could also be a component of the sediment transport in Martian gullies. In addition, there is a range of more 'exotic' processes that cannot occur on Earth, revealed in scaled-physical models in the laboratory, which could be active in Martian gullies. In the following subsections, we will discuss these different sediment-transport processes, how they have been applied to Martian gullies and the relevant terrestrial analogues.

Fluvial flow. Once produced, liquid water has been shown by multiple authors to have a residency time of up to a few hours on the Martian surface under the temperature and pressure conditions of both the present and the geologically recent past (e.g. Carr 1983; McKay & Davis 1991; Haberle *et al.* 2001; Hecht 2002; Heldmann 2005). This duration combined with the evidence for multiple events required to form Martian gullies leaves plenty of scope for water to form Martian gullies.

There are uncountable numbers of erosion–deposition systems on Earth that comprise the generic elements of a source alcove, a transportation channel and a depositional apron/fan, especially if no scale or slope constraints are imposed. In searching for kilometre-scale systems in which only first- or second-order catchments are developed, as for Martian gullies, it becomes clear that in many cases the depositional part of any given terrestrial system has been removed by other parts of the hydraulic system (located in the sea, or a lake, or eroded by a trunk river). This fact alone indicates that Martian gully systems are water-starved compared to those on Earth and do not form part of a larger connected hydraulic system.

Terrestrial gullies formed by fluvial flow comparable in scale and structure to those on Mars have been reported from a wide variety of sites with a large range of climatic settings (Table 1), ranging from cold or hot deserts to relatively humid mountain environments. In addition to the plan-view similarity between fluviatile terrestrial gullies and Martian gullies, authors have noted similarity in catchment properties (Conway & Balme 2016), long profiles (Yue *et al.* 2014; Conway *et al.* 2015; Hobbs *et al.* 2017), cross-sectional properties (Yue *et al.* 2014), fan slopes, channel organization and channel features, such as streamlining, terracing and braiding (Kumar *et al.* 2010; Gallagher *et al.* 2011; Reiss *et al.* 2011). Note, however, that features such as terraces are also common on terrestrial debris-flow fans (Fig. 15e–h).

Following from these similarities, several authors have used terrestrial-inspired fluvial erosion models to infer the discharge and therefore the amount of water required to form gullies (Heldmann *et al.* 2005; Parsons & Nimmo 2010; Hobbs *et al.* 2014). These models are based on knowledge obtained via

Fig. 14. Dry mass-wasting features on Earth. (**a**) Dry powder avalanches in the European Alps taken from the European Avalanche Warning Services (© EAWS, http://www.avalanches.org/eaws/en/includes/glossary/glossary_en_all.html). The hillslope length is several hundred metres. (**b**) Deposits from 17 October (light grey) and 7 August pyroclastic flows at Mount St Helens; from figure 294 of Lipman & Mullineaux (1981). Lobe widths are of the order of several tens of metres. (**c**) Experimental granular flows, where numbers across the top denote the percentage of fines (white 150–250 µm ballotini) in natural sand (300–355 µm quartz); adapted from figure 4 of Kokelaar *et al.* (2014). Top-down photographs of a 29° inclined plane where the mixture was dropped to give initial velocity. (**d**) Deposits of experimental granular flow of microbeads released onto an inclined plane at 25° as described in Félix & Thomas (2004); photo credit Nathalie Thomas. Lobe width *c.* 8 cm. (**e**) & (**f**) Two views of a leveed channel created by an experimental granular flow of microbeads released onto an inclined plane at 25°, experiments described in Félix & Thomas (2004). In (e) the distance between the levees is *c.* 17 cm and in (f) there is a 10 cm interval between the lines. Photographs courtesy of Nathalie Thomas. (**g**) Granular-flow deposits at the foot of the scree slope on the western face of Hafnarfjall in Iceland. The channel width is approximately 2 m. Photograph taken by S.J. Conway. (**h**) Dune slip face avalanche on a dune in the Namib Desert near Walvis Bay; the avalanche is approximately 50 cm long. Photograph taken by S.J. Conway. (**i**) Experimental slip face avalanche on a slope of 34° with a mean sand of diameter of 277 µm. Taken from figure 2 of Sutton *et al.* (2013*b*), with permission from John Wiley & Sons. Avalanche is approximately 2 m long. (**j**) Granular flow under simulated low-gravity conditions (spinning disk), taken from figure 1 of Shinbrot *et al.* (2004; © 2004 National Academy of Sciences).

Table 1. *Summary of Earth analogues used for comparison to Martian gullies, including the climate and which gully formation model they have been used to support*

Continent	Authors	Location(s)	Climate type	Ground conditions	Process	Trigger	In support of:
Antarctica	Dickson *et al.* (2007, 2017); Levy *et al.* (2007, 2009); Marchant & Head (2007); Morgan *et al.* (2007); Dickson & Head (2009)	McMurdo Dry Valleys	Hyperarid cold polar desert	Permafrost at 35–45 cm	Pure water flow	Insolation	Surface melt, influence of brines, no rain, snow drifting
Antarctica	Harris *et al.* (2007)	McMurdo Dry Valleys			Groundwater and surface flow of brines	Meltwater	Shallow groundwater
	Lyons *et al.* (2005)				Groundwater seep	Melting of subsurface ice	Shallow groundwater
Antarctica	Hauber *et al.* (2018)	Northern Victoria Land	Hyperarid cold polar desert	Permafrost	Debris flows, percolation	Meltwater	Meltwater from ice and/or snow, highlight as analogue
South America	Heldmann *et al.* (2010)	Atacama Desert, Chile	Arid desert	Dry	Debris flows	Rare rain event	Fluvial processes
South America	Oyarzun *et al.* (2003)	Atacama, Chile, Road from Copiapó to Maricunga	Arid desert	Dry	Mudflow		Water in gullies from the surface or groundwater
South America	de Haas *et al.* (2014, 2015*d*)	Atacama Desert coast, northern Chile	Arid desert	Dry	Debris flow	Rare rain events	Role of secondary modification on fan morphology
South America	Conway & Balme (2016)	Quebrada de Camarones, Atacama, Chile	Arid desert	Dry	Dry rockfalls	Unknown	Counter-example for water hypotheses from morphometrics
South America	Pacifici (2009)	Santa Cruz region, Argentinean Patagonia	Arid steppe highlands	Proglacial deposit, unknown if ice			Highlight as an analogue
South America	Pilorget & Forget (2016)	Lascar, Chile	Desert	Dry	Pyroclastic	Volcanic eruption	CO_2
South America	Stewart & Nimmo (2002)						Counter-example, supports instead water hypotheses
North America	Costard *et al.* (2002, 2007*a*)	Jameson Land, East Greenland	Dry periglacial	Thick permafrost, active layer 1 m	Debris flows	Melting permafrost	Melting in the near surface
North America	Lee *et al.* (2001, 2002, 2004, 2006)	Devon Island, High Arctic; valleys and Haughton impact	Polar desert climate	Talus	Debris flows	All temperature triggered (very transient)	Surface snowmelt
				Talus	Snow gullies	Snow gullies, surface snowmelt	
North America	Osinski *et al.* (2006)	Arctic Canada		Permafrost			Highlight as an analogue
North America	Andersen *et al.* (2002)	Axel Heiberg Island, Canada	Polar desert climate	Permafrost 600 m thick	Brine flow from groundwater		Groundwater
North America	Heldmann *et al.* (2005)	Axel Heiberg Island, Canada		Permafrost	Brine flow from groundwater		Brines
North America	Grasby *et al.* (2014)	Ellesmere Island, Nunavut, Canadian High Arctic	Polar desert	Permafrost	Fluvial	Spring	Groundwater

North America	Soare *et al.* (2007, 2014*a*, *b*, 2018)	Tuktoyaktuk, NWP, Canada	Thermokarst – degraded permafrost areas	Permafrost and substantial segregated ice lenses	Long-term temperature increase and thaw	Possibly insolation triggered snowmelt, or permafrost melting	Melting near surface
North America	Hugenholtz *et al.* (2007)	Bigstick Sand Hills – SW Saskatchewan, Canada	Continental	Permafrost	Debris flow	Snowmelt and niveo-aeolian	Melt
North America	Hugenholtz (2008)	St Pierre Valley, Gaspé region, Québec	Continental, humid	Talus, possible permafrost	Frosted granular flow	Temperature oscillations around freezing	Frosted granular flow
North America	Kochel & Trop (2008)	Wrangell Mountains, Alaska	Supraglacial	Substantial snow and ground ice on debris fans	Icy debris flow	Rainfall	Generic process analogue
					Snow avalanche	Solar heating	
North America	Conway *et al.* (2011*b*); Conway & Balme (2016)	St Elias Mountains, Alaska	Periglacial	Talus, discontinuous permafrost	Rockfalls	Unknown	Counter-example for water hypotheses from morphometrics
North America	Hooper & Dinwiddie (2014)	Great Kobuk Sand Dunes, Alaska	Subarctic		Debris flow, fluvial	Snowmelt and niveo-aeolian	Near-surface melt
North America	Conway *et al.* (2011*b*, 2015); Conway & Balme (2016)	Front Range, Colorado	Mountainous periglacial	Talus	Debris flow	Unknown	Water hypotheses from morphometrics
North America	de Haas *et al.* (2015*d*)	Panamint Valley, Death Valley, California	Desert		Debris flow, secondary aeolian modification		Role of secondary modification on fan morphology
North America	Conway *et al.* (2011*b*, 2015); Conway & Balme (2016)	San Jacinto Fault, Death Valley, Lucerne Valley and Anderson Dry Lake, California	Desert	Dry	Fluvial	Precipitation	Water hypotheses from morphometrics
North America	Eyles & Daurio (2015)	Ubehebe Crater, Death Valley, California	Desert	Dry porous volcanic products	Fluvial gullies associated with protalus ramparts		Highlight as an analogue in terms of snow-driven processes
North America	Kumar *et al.* (2010); Yue *et al.* (2014); Conway & Balme (2016)	Meteor Crater, Arizona	Arid, wetter in past	Dry	Fluvial and debris flow	Rainfall, snowmelt and springs	Water hypotheses, debris flow
Europe and North America	Treiman (2003)	Adventdalen, Svalbard, Norway; Ashcroft, Colorado			Snow avalanches		Dry granular flow
Europe	Hauber *et al.* (2009, 2011*a*, b); Reiss *et al.* (2009*b*, 2010*b*, 2011); Johnsson *et al.* (2012, 2014); Conway & Balme (2016)	Svalbard, Norway	Arctic desert	Permafrost	Fluvial and debris flow		Water hypotheses, meltwater, snowmelt fluvial, debris flow, influence of freeze–thaw cycles, landscape assemblage in periglacial environment
Europe	Hartmann *et al.* (2003)	Esja Plateau, Iceland	Periglacial	Ground sometimes frozen	Debris flow	Snowmelt, connected to drainage,	Water hypotheses

(*Continued*)

Table 1. *Summary of Earth analogues used for comparison to Martian gullies, including the climate and which gully formation model they have been used to support (Continued)*

Continent	Authors	Location(s)	Climate type	Ground conditions	Process	Trigger	In support of:
Europe	Conway *et al.* (2011*b*, 2015); Conway & Balme (2016)	Westfjords and Tindastóll, Iceland	Fjordlands, periglacial	Talus	Debris flow	Snowmelt, heavy precipitation	Water hypotheses from morphometrics
Europe	Mangold (2003*a*, *b*)	Southern French Alps	Alpine	Talus	Debris flows		Debris flow
Europe	Marquez *et al.* (2005)	La Gomera, Canary Islands	Warm and wet	No ice, dry talus with calcrete	Fluvial	Aquifer outflow	Groundwater
	Conway *et al.* (2015)						Water hypotheses from morphometrics
Oceania	Hobbs *et al.* (2014)	Island Lagoon near Woomera, Australia	Semi-arid		Fluvial	Overland flow	Water and dry
		Pasture Hill, New Zealand	Periglacial		Fluvial	Frost processes, rain, snowmelt	
	Hobbs *et al.* (2013)	Lake George escarpment, Australia	Arid		Surficial runoff		Water and LDM melt
	Hobbs *et al.* (2015)	All three of the above					Water and melt
	Hobbs *et al.* (2016)	Cooma, Australia	Arid		Runoff	Rainfall	
Asia	Komatsu *et al.* (2014)	Lonar Crater, India	Tropical savanna	Humid soils	Debris flow, fluvial	Groundwater and overland flow	Highlight as an analogue
Asia	Xiao *et al.* (2017)	Qaidam Basin, Tibetan Plateau (NW China)	High-elevation desert		Fluvial	Rainfall	Highlight as an analogue
Asia	Anglés & Li (2017)	Qaidam Basin, Tibetan Plateau (NW China)	High-elevation desert				Overland flow or melt
Asia	Sinha *et al.* (2018)	Ladakh Himalaya	High-elevation desert	Talus and alluvial fans	Debris flow	Snowmelt	Debris flow from snowmelt
Asia	Yue *et al.* (2014)	Xiuyan Crater, NE China	Humid, continental	Humid soils	Fluvial	Precipitation	Water hypotheses and dry processes
	Wang *et al.* (2013)						
Several	Hugenholtz & Tseung (2007)	Escuer fan in central Spanish Pyrenees, intense thawing of frozen sand Canada, New Zealand, beach sand fans triggered by groundwater, Spain base of cliffs with ephemeral groundwater			Debris-flow-dominated alluvial fans		Debris flow

The analogues are listed by continent and then by site (in descending latitude) and grouped by team where appropriate.

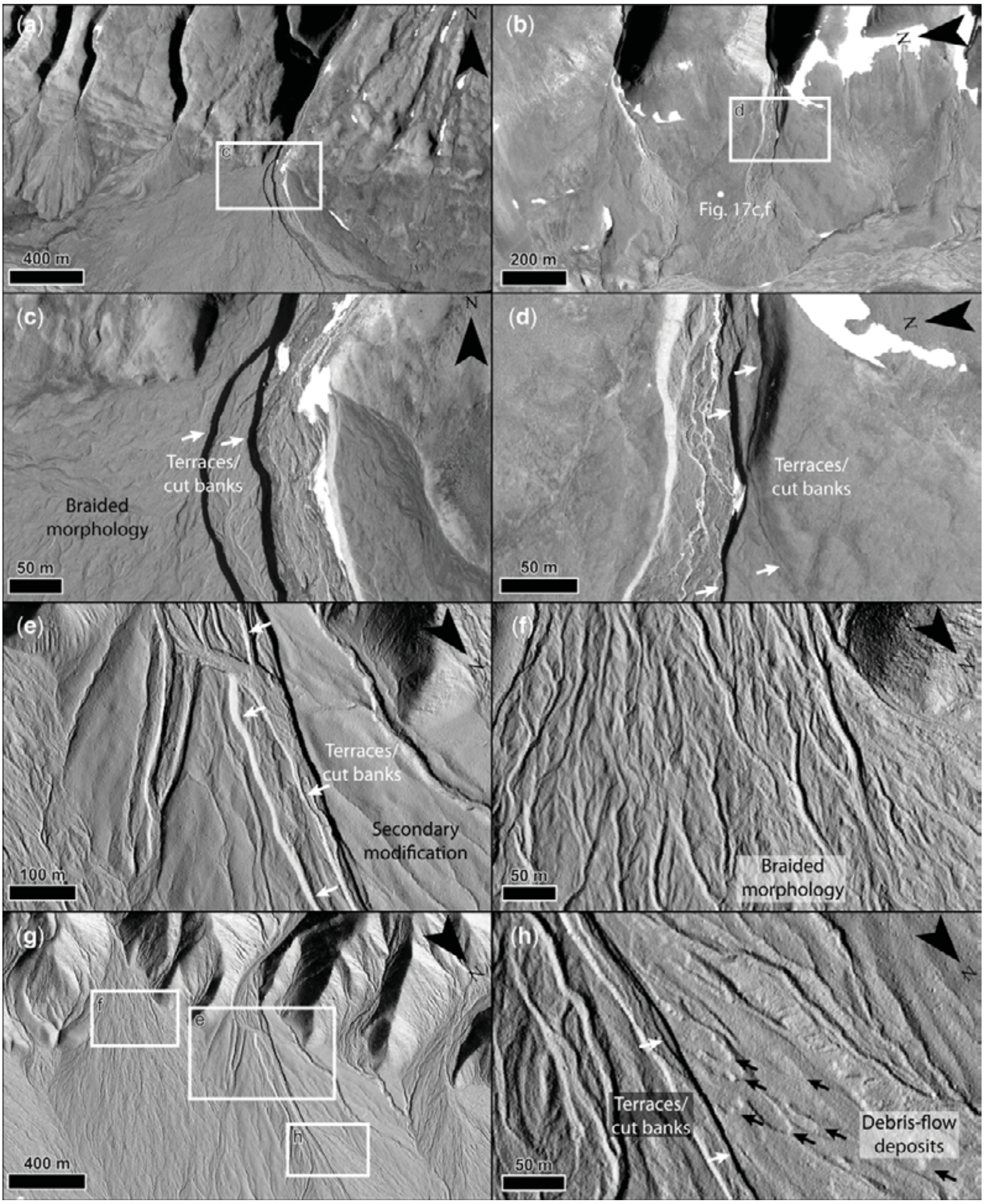

Fig. 15. Terraces and braided morphology in gullies on Earth. (**a**)–(**d**) Fluvial fans in the periglacial environment of Svalbard, showing braided channel morphology, terraces and cut banks. (a) & (c) show a fan in Adventdalen; (b) & (d) show a fan in Bjørndalen (see also de Haas *et al.* 2015*c*). Source: HRSC-AX orthoimages from DLR (German Aerospace Centre), see Hauber *et al.* (2011*a*) for details. (**e**) & (**f**) Hillshaded images of debris flow and fluvial fan in the arid Saline Valley (Mojave Desert, USA). (**g**) & (**h**) show terraces and cut banks on a debris-flow fan; (f) shows braided channel morphology on an adjacent fluvial fan. Source: EarthScope Southern & Eastern California Lidar Project (http://www.opentopography.org).

field or experimental data on Earth in fluvial fluid flows with low sediment content and link channel geometries to flow discharge.

Debris flow. Debris-flow analogue sites for Martian gullies are dominantly located in arid, periglacial or glacial climates. Many authors have noted the key characteristics (Fig. 16): (1) lateral levees; (2) lobate or digitate deposits; and (3) poorly sorted gravel or coarser-sized sediments as deposits (Hartmann *et al.* 2003; Costard *et al.* 2007*a*; Kochel & Trop 2008; Reiss *et al.* 2009*a*), which are attributes often seen in Martian gullies. Heldmann *et al.* (2010) drew an analogy between mudflows in the Atacama and the new light-toned deposits on Mars (Malin *et al.* 2006). They found that the higher albedo mudflow was a smooth deposit, with 90% fines compared to 78% fines in the surrounding material, and that the deposit and surrounding material were spectrally indistinguishable – thus, a viable hypothesis for the origin of the light-toned Martian gully deposits. In contrast, the Atacama debris flows described by Oyarzun *et al.* (2003) have very marked topographical effects, and form an elevated digitate fan deposit and a channel with lateral levees, similar to those described in glacial and periglacial environments.

Multiple types of morphometric analyses that reference terrestrial data have already been applied to Martian gullies, and they imply predominant gully formation by debris flows. They include slope–area relationships (Lanza *et al.* 2010; Conway *et al.* 2011*b*), gully width–depth relationships (Yue *et al.* 2014), channel sinuosity (Mangold *et al.* 2010), the short length of gullies (Heldmann *et al.* 2005) and the often steep depositional slopes of the fans (>15°) (e.g. Heldmann & Mellon 2004; Dickson *et al.* 2007; Lanza *et al.* 2010; Levy *et al.* 2010; Conway *et al.* 2015). These analyses are in contrast to many analyses of surficial morphology, suggesting a formation by fluvial flows (e.g. Heldmann & Mellon 2004; Reiss *et al.* 2009*a*, 2011). All these studies make strong references to Earth analogues in order to define the morphometric properties distinctive to debris flows. The fact that Martian gullies bear a resemblance to terrestrial systems carved by fluvial flows and by debris flows is not surprising because, first, systems on Earth (and likely Mars) are polygenetic and, secondly, as detailed below, primary formation processes can be masked by secondary ones.

Terrestrial studies inform us that the effectiveness of secondary modification depends on the ratio between the characteristic timescales to build morphology by primary deposition and to modify

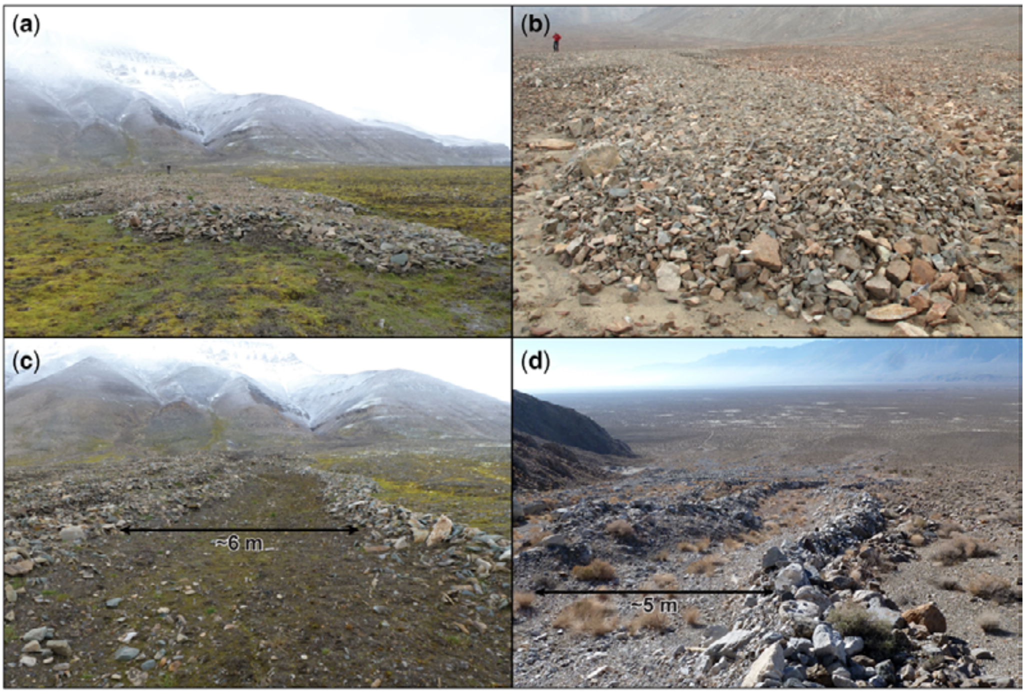

Fig. 16. Debris-flow deposits on Earth. (**a**) Debris-flow lobe deposit on a fan surface in the periglacial environment of Svalbard. (**b**) Debris-flow lobe deposit in the Chilean hyperarid Atacama Desert (reprinted from fig. 2 of de Haas *et al.* 2015*d*, © 2015, with permission from Elsevier). (**c**) Debris-flow channel with clearly defined lateral levees on Svalbard. This channel is connected to the lobe shown in (a). (**d**) Debris-flow channel with well-defined levees on the dolomite fan in the Mojave Desert (USA).

morphology by secondary processes (de Haas *et al.* 2014). Alluvial fans, whereon the return periods of primary geomorphic activity are low and/or whereon secondary processes are highly effective, are therefore most susceptible to secondary modification. In extremely dry environments where rates of geomorphic activity are low, such as in terrestrial deserts and on Mars, surfaces are often modified by secondary processes. Secondary modification of alluvial fan surfaces can result from multiple processes, such as wind erosion, fluvial erosion and weathering (Blair & McPherson 1994, 2009; de Haas *et al.* 2013, 2014, 2015*b*, *d*). Which of these processes dominate secondary reworking differs between sites. On Earth, for example, de Haas *et al.* (2014) described a debris-flow fan in the Atacama Desert with a surface that has primarily been reworked by weathering and fluvial runoff. This fan is relatively wind-sheltered, however, and many other fan surfaces in terrestrial deserts are heavily modified by wind (e.g. Anderson & Anderson 1990; Blair & McPherson 2009; de Haas *et al.* 2014, 2015*d*; Morgan *et al.* 2014). Inactive parts of alluvial fans in the high-Arctic, periglacial, environment of Svalbard are also prone to secondary modification (de Haas *et al.* 2015*c*). Here, secondary reworking mainly results from snow avalanches, weathering and periglacial conditions in the topsoil resulting in the formation of patterned ground, solifluction lobes and hummocks on inactive fan surfaces. The origin of long-inactive and modified fans can be determined by sedimentological analysis of stratigraphic exposures because reworking is superficial and barely recorded in the subsurface (Blair & McPherson 1994, 2009; de Haas *et al.* 2014). Wind scour can be an aid in revealing such stratigraphic relationships.

Similar to terrestrial fan systems, the morphological signatures of the primary processes forming Martian gullies may thus have been removed and/or masked by secondary processes (Fig. 17). High-resolution HiRISE images (*c.* 0.25 m/pix) enable the recognition of large boulders and large-scale stratigraphic layering in sedimentary outcrops on Mars, and thereby sedimentological subsurface analyses. Sedimentological analysis of outcrops in gully fans in 51 HiRISE images widely distributed over the southern mid-latitudes shows that the sedimentology visible in incised sections of many gullies is consistent with debris-flow sedimentology as observed on Earth (de Haas *et al.* 2015*d*). The great majority (96%) of outcrop exposures in gully fans fed by catchments, comprising bedrock and hosting boulders, contain sedimentological evidence for debris-flow formation. These exposures contain many randomly distributed large boulders (>1 m) suspended in a finer matrix, and, in some cases, lens-shaped and truncated layering. This may explain the long-lasting discrepancy between morphometric analyses that imply Martian gully formation by debris flows (e.g. Lanza *et al.* 2010; Mangold *et al.* 2010; Conway *et al.* 2011*b*) and frequent observations of fan surfaces lacking clear debris-flow morphology, suggesting formation by fluvial flows (e.g. Dickson & Head 2009; Levy *et al.* 2010; Reiss *et al.* 2011).

In a similar fashion as for fluvial flows, authors have used terrestrial relationships between channel geometries and discharge/flow velocity for debris-flow dynamics to infer the water content and associated reservoir size for Martian gullies (Miyamoto *et al.* 2004; Levy *et al.* 2010; Mangold *et al.* 2010; Jouannic *et al.* 2012). Further, by using terrestrial knowledge of the size frequency and sediment concentrations of debris flows not only can the water reservoir be estimated, but also the timing and cadence of gully activity (de Haas *et al.* 2015*b*).

Slushflows and other exotic fluids. Both slushflows and icy debris flows have been proposed for Martian gullies inspired by their observation on Earth (Kochel & Trop 2008; Auld & Dixon 2017) (Fig. 18). Icy debris flows have the same morphological attributes as debris flows but some of the transported solids are ice – this leads to a small amount of deflation of the deposits post-deposition (Kochel & Trop 2008). The deposits of such flows are similar to those of wet snow avalanches (Fig. 18) but for wet snow avalanches the only remaining morphology is low-concentration clasts (e.g. Decaulne & Sæmundsson 2010; Decaulne *et al.* 2013; Laute & Beylich 2013) (Fig. 18h) that through repeated action can result in a recognizable avalanche debris cone (de Haas *et al.* 2015*c*) (Fig. 18g). On Earth, these cones are built by a combination of processes (Luckman 1992; Stoffel *et al.* 2006), so the contribution of avalanches to the sediment budget can be hard to ascertain. Slushflows are somewhat similar to debris flows in that they contain a small amount of liquid water compared to solids; however, those solids are not just sediments but relatively large quantities of snow and ice (>70%). This leads to a number of differences with debris flows: they can initiate on slopes as low as 10° (Elder & Kattelmann 1993) (Fig. 18a), and, although they can have lateral levees, the deposits tend to be chaotic with no clearly defined downslope boundary (Larocque *et al.* 2001). Like debris flows, they can occur in a hillslope or torrent-fan system (Fig. 18b). Physical-scale experiments under terrestrial atmospheric conditions have been performed by Auld & Dixon (2017), and show that slushflow could account for some of the erosional and depositional features of Martian gullies. Auld & Dixon (2017) allowed a mixture of liquid and ice to run over an erodible sediment bed, so the concentration of sediment approaches that for an

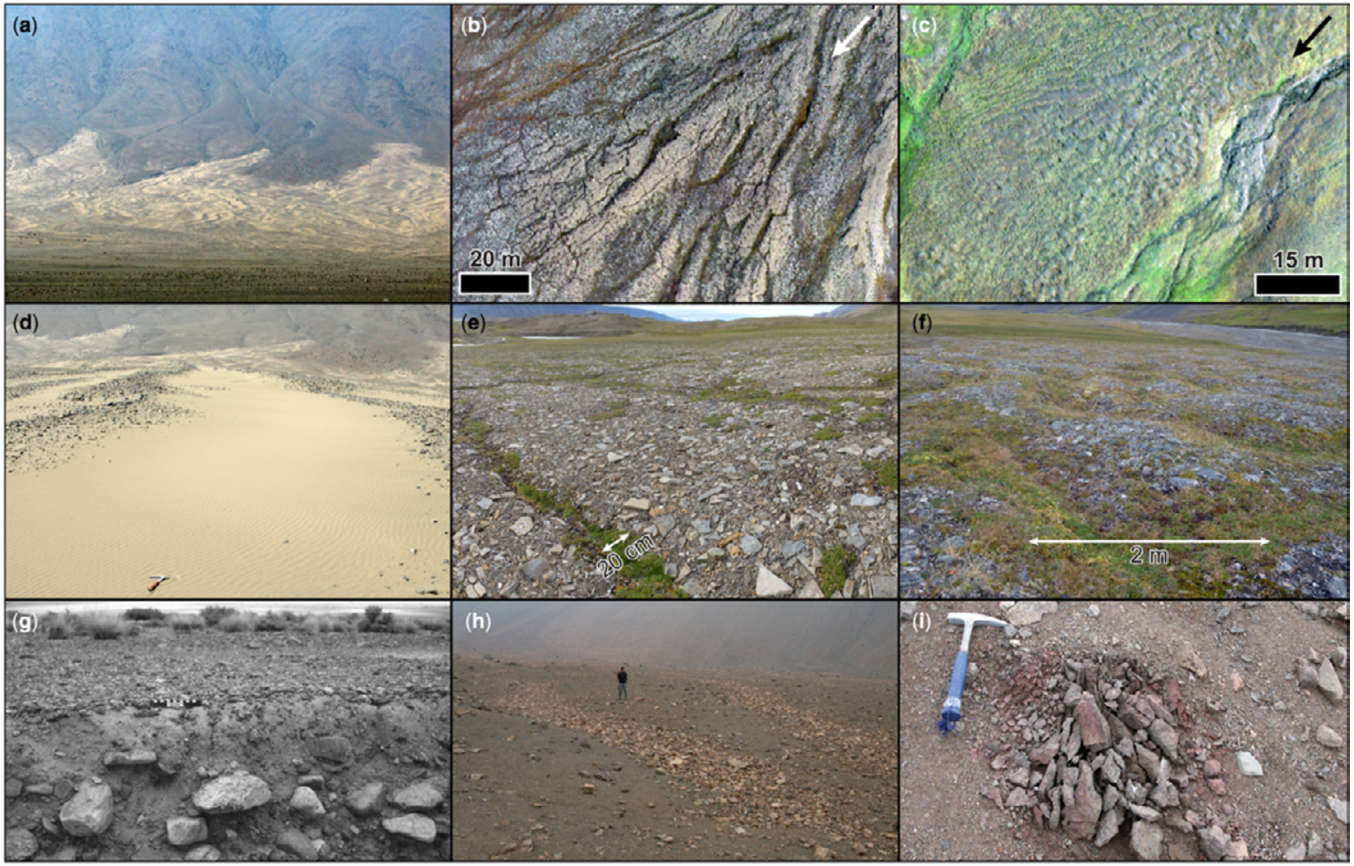

Fig. 17. Secondary, post-depositional modification of fan surfaces on Earth, masking the original depositional morphology. (**a**) Debris-flow fan surfaces covered by aeolian sand, in the Atacama Desert, Chile (reprinted from fig. 11 of de Haas *et al.* 2015*d*, © 2015, with permission from Elsevier). (**b**) Polygonal ground on top of a debris-flow fan surface in Svalbard. (**c**) Hummocks on top of a fluvial fan surface in Svalbard. (**d**) Detail of the fan shown in (a). (**e**) Detail of polygonal ground on the fan in (b). (**f**) Detail of hummocky ground on the fan in (c). (**g**) Desert pavement on top of a debris-flow fan surface in Nevada (USA) (reprinted from fig. 14.15a of Blair & McPherson 2009 with permission from Springer, © 2009). (**h**) Fluvial channels on a debris-flow fan surface in the Atacama Desert, Chile, as a result of secondary runoff; the person used for scale is 1.85 m tall (from fig. 11 of de Haas *et al.* 2015*d*, © 2015, with permission from Elsevier). (**i**) Broken-down clast on the surface of a debris-flow fan as a result of salt weathering in the Atacama Desert, Chile (reprinted from fig. 7 of de Haas *et al.* 2014, © 2014, with permission from Elsevier). (b), (c), (e) & (f) are reprinted from figure 15 of de Haas *et al.* 2015*c*, © 2015, with permission from Elsevier.

icy debris flow rather than a slushflow which has a lower sediment concentration and less topographical relief than an icy debris flow.

For icy debris flows, avalanches and slushflows, there should be substantial ice content within the deposited debris. This high volatile content could account for some of the features of Martian gullies, including the slope-orthogonal fractures (Figs 6d & 9d) and the presence of thermal contraction polygons on the debris fans (Fig. 9c). However, ice exposed at the surface of Mars would also sublimate and therefore Martian gully fans should also show signs of sublimation, including disruption of surface textures, pitting and possibly collapse structures, which are not systematically observed.

Scaled-physical models have been used to explore the effects of the Martian atmospheric pressure on the sediment-transport capacity of liquid water. Martian surface air pressure and temperature are generally below the triple point of water, and this means that water is transient and unstable – often termed metastable (Hecht 2002) – and therefore boils. Frozen soil conditions lead to reduced infiltration, which can lead to both overland-flow and debris-flow processes at much lower discharge than if the soil was above freezing (Gabet 2000; Védie *et al.* 2008; Conway *et al.* 2011*a*; Jouannic *et al.* 2015) (Fig. 19a–c). Laboratory simulation experiments have shown that boiling leads to three processes that are not experienced by water flows on Earth (Massé *et al.* 2016; Raack *et al.* 2017; Herny *et al.* 2018): grain saltation at the flow boundary; granular avalanches triggered by the saltation and gas production; and, finally, sediment levitation (Fig. 19d). All three processes can act together to lead to much more efficient sediment transport than the equivalent for stable water, and no terrestrial field analogues exist for these sediment-transport mechanisms.

Depressed freezing temperatures. The potential influence of brines on the morphology of water-eroded features has not been addressed in great detail via terrestrial analogy. In their studies of the Antarctic Dry Valleys, Marchant & Head (2007) noted that the water flowing in streams could be saline, but did not remark on any influence this had on the morphology of the system compared to systems developed with non-saline water. Similarly, Lyons *et al.* (2005) and Harris *et al.* (2007), and Pollard *et al.* (1999) in Arctic Canada, noted that springs were forming channels with saline waters, yet did not make a full morphological analogy to Martian gullies or a comparison to pure water springs. Levy *et al.* (2011) did study the morphology of saline water tracks in the Antarctic Dry Valley, but noted that their relief was weak. Salts are not the only mechanism through which the freezing point of water can be depressed. Water inside the pore space of sediments can exist in a supercooled state (Oyarzun *et al.* 2003; Kossacki & Markiewicz 2004; Kereszturi & Rivera-Valentin 2012; Kereszturi & Appéré 2014). Water in a porous medium can have freezing points as low as 233 K (−40°C) (Cahn *et al.* 1992; Maruyama *et al.* 1992) without excessive salinity due to the presence of a kinetic barrier, preventing crystallization in pore spaces where the kinetic energy is considerably lowered (Morishige & Kawano 2000). However, to our knowledge, no cases have been reported terrestrially where such interstitial water can trigger downslope sediment flows. Highly concentrated acidic water, such as that suggested by results from the MER-A and B rovers, can also result in a freezing point much lower than that of pure water (e.g. Squyres *et al.* 2006). Using a scaled-physical model, Benison *et al.* (2008) examined the sediment-transport capacity of acidic solutions, and found that because these solutions were more dense and viscous than pure water they carved deeper and narrower channels, yet still produced generically gully-like features. They noted that these solutions could also form isolated pits in the sediment bed.

In principle, the sediment-erosion and sediment-transport processes caused by a brine should have similar mechanisms to those caused by pure water, as long as the brine is sufficiently dilute to remain in the Newtonian regime. A similar argument can be made for debris-flow processes occurring with brines. However, landscape-scale features with high solute concentrations are limited to hot springs on Earth (e.g. Fouke *et al.* 2000) and, to a lesser extent, rare overland flow events in deserts where salt has had time to accumulate at the surface (e.g. Callow 2011). The effect of brines on geomorphic processes has, to our knowledge, not been isolated. An expectation from terrestrial geomorphology is that because we have a good knowledge of the physical processes that govern erosion and deposition by water that account for fluid viscosity, fluid and particle densities, and gravitational acceleration, it should be relatively simple to transfer this knowledge to brines and then to other worlds (Julien 2010; Grotzinger *et al.* 2013); although, recent low-gravity work has started to throw doubt on this expectation (Kuhn 2014).

Release of water at high to moderate obliquity. The bottom-up and top-down gully-formation mechanisms described in following subsections (on ‘Melting of near-surface ground ice’, ‘Melting of snow’ and ‘Melting of H_2O frost’) share a common final water-release mechanism: freeze and thaw under the different climate conditions experienced at high to moderate orbital obliquity on Mars. Mars has an axial tilt which has a much greater amplitude of

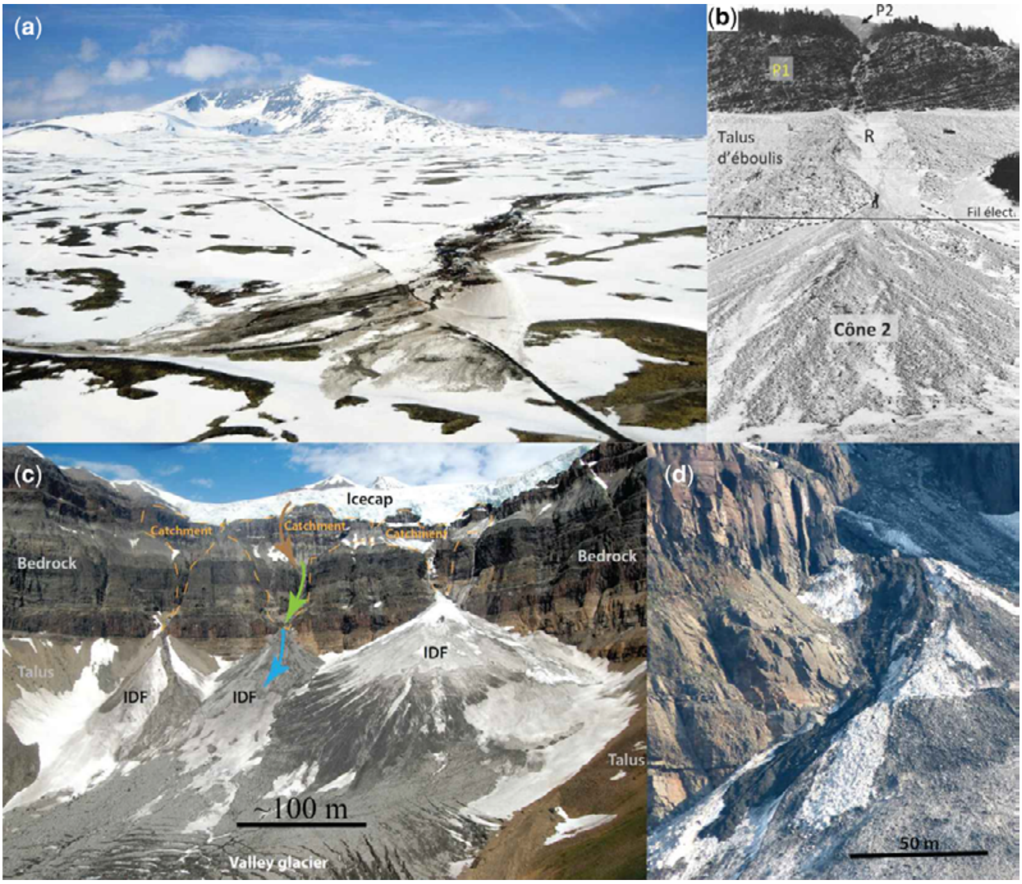

Fig. 18. Geophysical flows involving ice on Earth. (**a**) Low-gradient slushflow cutting across the Snøheim road in Norway, taken from https://reccoprofessionals.files.wordpress.com/2011/05/slush_flow_no.jpg (**b**) Gully dominated by slushflow processes on the NW flank of Mount St Pierre, Québec (Canada) studied by Hétu *et al.* (2017) and taken from figure 15 of the same paper – the person is for scale. (**c**) Cirque at McCarthy Creek, Wrangell St Elias National Park, Alaska studied by Kochel & Trop (2008): the right fan is dominated by avalanche processes and the left one by icy debris flows, taken from figure 1 of Kochel *et al.* (2018) where IDF stands for 'icy debris fan'. (**d**) Icy debris flow on the middle fan shown in (c); taken from figure 7B of Kochel *et al.* (2018).

oscillation than that of the Earth (23° ± 10° in the last 5 myr compared to 23° ± 1 for the Earth: Fig. 20) due to the lack of a large stabilizing Moon (Laskar & Robutel 1993; Laskar *et al.* 2004). Variations in axial tilt on the Earth are a component of 'Milankovitch cycles' that are known to strongly influence climate, including mean annual surface temperatures and volatile distribution (Berger 1988). Mars' stronger variation in axial tilt is therefore assumed to have a commensurately stronger influence on its climate (Head *et al.* 2003; Forget *et al.* 2006), with Head *et al.* (2008) making a direct comparison to glacial–interglacial cycles on Earth. At higher orbital obliquity, the polar caps receive more insolation in summer and can be completely destabilized, redistributing their volatiles via the atmosphere to the lower latitudes, resulting in a more vigorous atmospheric circulation, higher atmospheric pressure and humidity (e.g. Dickson 2014; Madeleine *et al.* 2014). These changes in atmospheric conditions bring Mars' surface much closer to the triple point, making freeze–thaw cycling and transient liquid water more likely (e.g. Costard *et al.* 2002; Richardson & Mischna 2005).

This mechanism enables authors to reconcile the observations that mid-latitude gullies are dominantly pole-facing and that higher-latitude gullies have a weaker equator-facing preference, as these are the places where insolation conditions are expected to favour melt. Costard *et al.* (2002) initially invoked

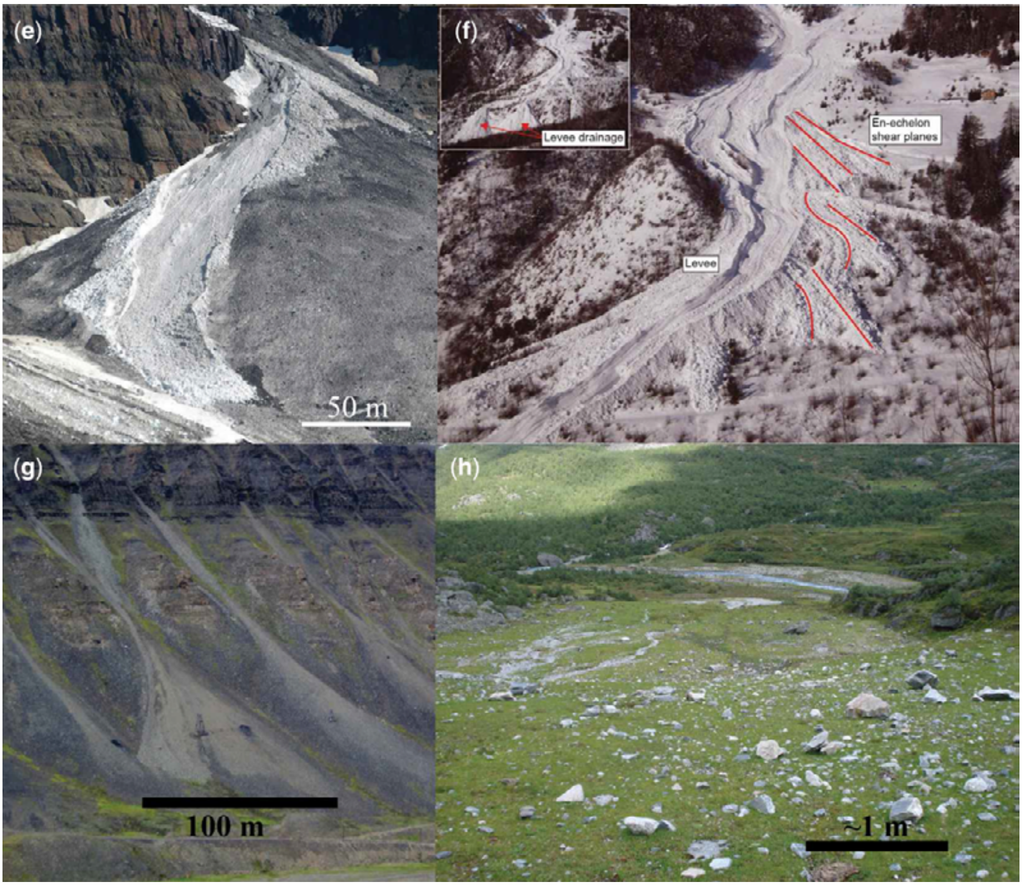

Fig. 18. *Continued*. (**e**) The fan in the middle of (c) with a fresh wet snow-avalanche deposit showing lateral levees and lobate snout, taken from figure 4A of Kochel *et al.* (2018). (**f**) Wet snow-avalanche deposit in Vallée de la Sionne in Switzerland showing complex morphologies, including lateral levees and overbank deposits; taken from figure 1 of Bartelt *et al.* (2012, with permission from Cambridge University Press). House in the top right is for scale. (**g**) Snow-avalanche-dominated debris fans in in Longyeardalen, Svalbard (after fig. 7c of de Haas *et al.* (2015*c*), © 2015, with permission from Elsevier). (**h**) Isolated boulders deposited by snow avalanches in Erdalen, Norway, taken by A. Decaulne on 27 August 2010. The largest rocks in the foreground are approximately 30 cm across.

orbital obliquities of 45° or more (which last occurred more than 5 myr ago) to account for these trends. The Costard model finds that the only locations on Mars that would experience daily mean temperatures higher than the melting point for ice (273 K) are the mid- to high latitudes on pole-facing slopes, where gullies are indeed observed. However, the Costard model does not predict the observed onset of equator-facing gullies polewards of 40° latitude (Conway *et al.* 2017). More recent studies have shown that more moderate obliquities of 30°–35° which have occurred in the last hundreds of thousands of years can provide good matches to these orientation observations (Williams *et al.* 2009; Conway *et al.* 2018*b*), but invoke much shallower melting conditions.

Release of groundwater from aquifers. The shallow aquifer hypothesis was first proposed by Malin & Edgett (2000), and then expanded upon by Mellon & Phillips (2001) and Goldspiel & Squyres (2011). This model involves an aquifer confined by an impermeable rock layer and a dry overlying regolith (to provide thermal insulation) lying upslope from a ridge. At a point close enough to the surface toward the ridge where ground ice is stable, an ice plug forms. Obliquity-induced freeze–thaw cycles lead to increased fluid pressure within the aquifer, eventually fracturing the ice plug and allowing water from the aquifer to burst out of the side of the slope and run downhill, forming a gully. Goldspiel & Squyres (2011) concluded that this model could only function if the aquifer were briney, or had high permeability

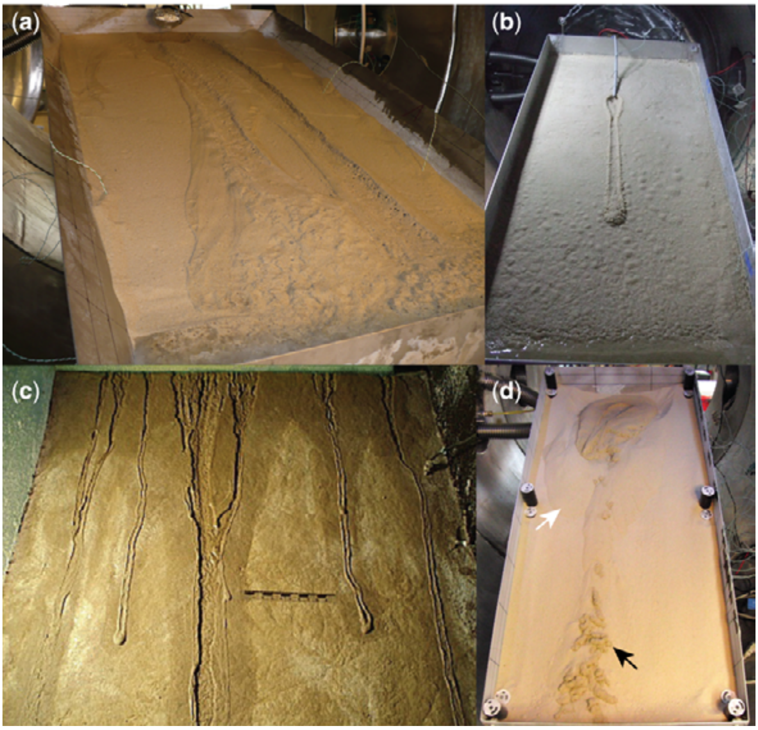

Fig. 19. Physical-scale models of Martian gullies. (**a**) Sediment transport engendered by liquid water over fine sand at 14° slope under low pressure (*c.* 7 mbar) and low sediment temperature (−25°C) reported in Conway *et al.* (2011*a*). Water at the base of the flow has frozen solid, and the flow propagated over a lens of frozen saturated sediment. Bubbles formed by boiling were frozen into this mixture as the flow progressed. The tray is 1 m in length. Photograph taken by S.J. Conway. (**b**) Sediment transport engendered by liquid water over an active layer several millimetres deep formed in saturated frozen fine sand at 14° slope under low pressure (*c.* 7 mbar) reported in Jouannic *et al.* (2015). Bubbles visible across the surface are formed by gas produced within the sediment by boiling. The tray is 1 m in length. Photograph taken by G. Jouannic. (**c**) Figure 4 from Védie *et al.* (2008, with permission from John Wiley & Sons) showing channels on a sloping active-layer formed in a frozen bed of silt caused by pulses of water from a perched aquifer. Top of the slope is 55 cm across and the experiments were performed under terrestrial pressure. (**d**) Sediment transport engendered by liquid water over fine sand at 20° slope under low pressure (*c.* 9 mbar) and elevated sediment temperature (*c.* 25°C) reported in Raack *et al.* (2017) and Herny *et al.* (2018). The white arrow points to sediment displaced by dry avalanches triggered by grain saltation at the flow front, and black arrow points to saturated pellets levitated on cushions of gas released by boiling. The tray is 1 m in length. Photograph taken by C. Herny.

(like that of gravel) or high initial temperature (high geothermal heat flux).

Another flavour of this model was proposed by Gaidos (2001), where a deep aquifer is confined by an impermeable rock layer on the bottom and the cryosphere (Clifford 1993) on the top. Decreasing heat flow in the subsurface leads to expansion of the cryosphere; pressurizing the confined aquifer to the point of fracturing the cryosphere. The liquid water from the aquifer then travels upwards through the fractures due to increased pore pressure until low vertical stresses or failure of the surrounding rock occur, at which point the water begins moving laterally and a sill of liquid water forms. If the sills reach the surface on a slope, the water is expelled and gullies form. Hartmann *et al.* (2003) proposed a shallow aquifer formed by localized geothermal melting of ground ice. Debris flows would then be triggered either by the direct rapid release of water to the surface or by saturation-induced failure. The fact that water travels along impermeable layers in the subsurface and exits at cliff faces in Iceland (Hartmann *et al.* 2003; Decaulne *et al.* 2005), and gully-like forms were located downslope, was used as a direct support for their hypothesis.

Grasby *et al.* (2014) reported on landforms resembling Martian gullies (alcove–channel–apron) being formed by springs fed by a sub-permafrost

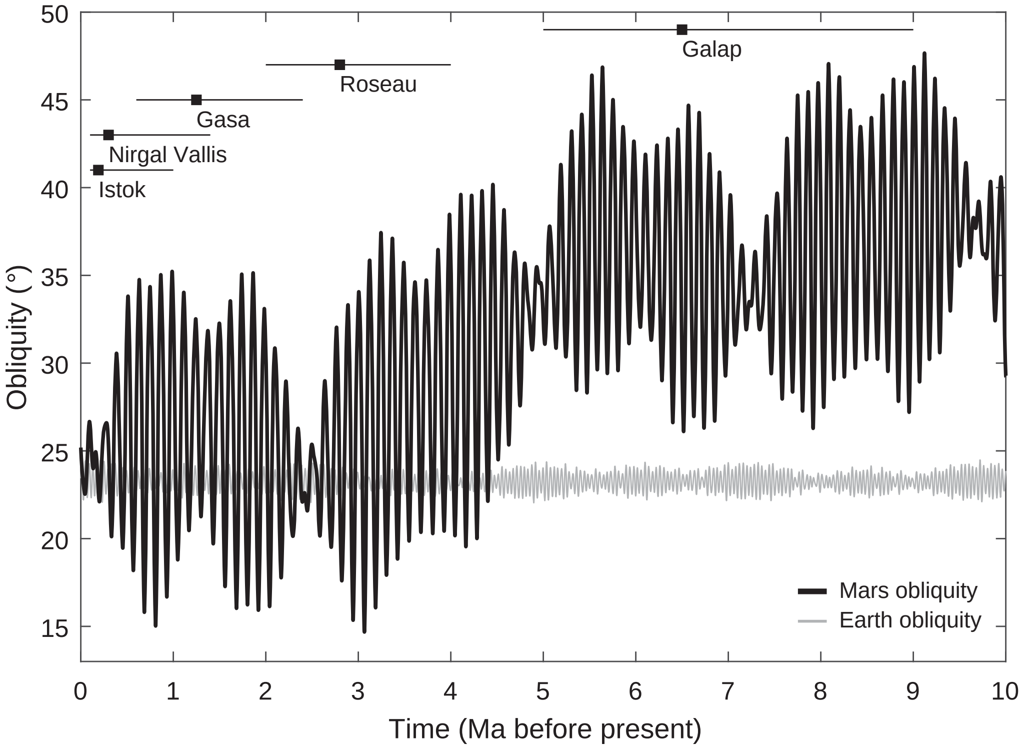

Fig. 20. Martian and terrestrial obliquity during the past 10 myr (Laskar *et al.* 2004), along with estimated maximum gully ages. Maximum gully ages based on crater impact ages: Istok Crater (Johnsson *et al.* 2014), Gasa Crater (Schon *et al.* 2009*a*), Roseau Crater (de Haas *et al.* 2017) and Galap Crater (de Haas *et al.* 2015*a*). The maximum gully age based on a superposition relationship with the Nirgal Vallis dune field is from Reiss *et al.* (2004).

groundwater circulation system in the Canadian High Arctic (Fig. 21). This goes one step further than other authors who used terrestrial analogues to demonstrate that springs can bring water to the surface in environments considered as analogous to Mars in the High Arctic and Antarctica (Andersen *et al.* 2002; Heldmann *et al.* 2005; Lyons *et al.* 2005; Harris *et al.* 2007), and did not attempt to draw a morphological analogy. Coleman *et al.* (2009) used a scaled-physical model to simulate gullies formed by the emergence of water from an underground aquifer. Their experiments were performed in sand under terrestrial temperature and pressure, and they concluded that gully-like landforms could be produced by aquifer flow at the base of a cliff.

Observations of gullies occurring at rock outcrops and at consistent heights below local highs (e.g. Gilmore & Phillips 2002; Heldmann & Mellon 2004; Marquez *et al.* 2005) used as support for the aquifer hypothesis have since been shown to be an artefact of imaging quality or far from systematic (with the majority of gully systems extending to the highest local elevation). The shallow aquifer model cannot easily account for the occurrence of gullies on isolated central peaks and massifs (e.g. Balme *et al.* 2006), and recharge mechanisms are problematic without invoking a deep-cryosphere connection. However, invoking a deep cyrosphere creates the additional problem that seeps should also be observed on surfaces other than steep hillslopes. Neither the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) nor the Shallow Radar (SHARAD) sounder have detected evidence for shallow aquifers on Mars (Nunes *et al.* 2010). Despite these difficulties, this model has recently been revived to account for the occurrence of possibly water- or brine-animated ‘recurring slope lineae’ (Stillman *et al.* 2016, 2017).

Finally, terrestrial analogues have also been used to argue against the groundwater hypothesis. Treiman (2003) used terrestrial analogues to argue that the geological structure of craters is unsuitable for directing seeps to the surface – the layers dip away from the inner crater wall (Kenkmann *et al.* 2014). Secondly, the observation that gullies occur across

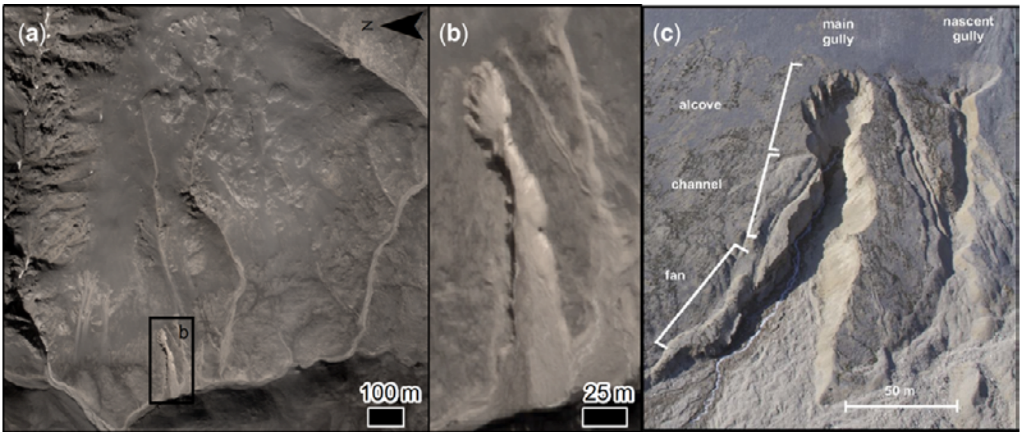

Fig. 21. Gullies as a result of aquifer seepage at Ice River, Nunavut, Canadian High Arctic. (**a**) Satellite image overview of the zone containing the gullies with the box indicating the location of (b). Image credit Quickbird-2 © 2011 DigitalGlobe, Inc. (**b**) Detail of the gullies. Image credit Quickbird-2 © 2011 DigitalGlobe, Inc. (**c**) Oblique aerial view taken from figure 4A of Grasby *et al.* (2014).

a wide range of bedrock geologies which should have widely varying permeability makes a universal aquifer hypothesis unlikely. Earth, which is a similarly geologically complex planet, does not host such integrated groundwater systems.

As pointed out by Baker (2001), based on global trends in gully distribution and orientation alone, it is hard to rule out the groundwater hypothesis because the source of the water is hidden and the release mechanism is the same as that proposed for the melt-based hypotheses. Despite the many convincing arguments against this hypothesis, only *in situ* investigation could completely rule out aquifers as a source of water in Martian gullies.

Melting of near-surface ground ice. A few different models of melting of near-surface ground ice to produce gullies have been proposed. In the model of Costard *et al.* (2002), warming of the surface at an obliquity of 45° lasts long enough for the temperature wave to penetrate far enough to melt ground ice. The meltwater then saturates the regolith and produces debris flows once critical shear stress is reached. Gilmore & Phillips (2002), on the other hand, proposed a model where water from melting ground ice percolates through the regolith until encountering an impermeable layer, at which point it travels laterally along the layer until it exits at the surface where the layers are exposed, such as in a crater or valley wall. However, this model suffers the structural problems raised for the aquifer models (see the subsection on ‘Release of groundwater from aquifers’ earlier in this section).

Costard *et al.* (2002, 2007*a*) cited debris flows which they inferred to be produced via melting of ground ice in Greenland as terrestrial analogues in support of this hypothesis. Védie *et al.* (2008) and Jouannic *et al.* (2012, 2015) pointed to the formation of the active layer (defrosted upper portion of permafrost) as key in forming this kind of mass flow on Martian sand dunes. Studies by Hugenholtz *et al.* (2007) and Hooper & Dinwiddie (2014) in SW Saskatchewan, Canada and in the Great Kobuk Sand Dunes in Alaska have shown that debris flows can be initiated by melting of niveo-aeolian (wind-driven snow) within sand dunes. Gallagher & Balme (2011) noted the similarity in terms of morphology and landform assemblage between retrogressive thaw on Earth (Fig. 22) and gullies in the northern hemisphere of Mars. However, the wide, shallow depressions with minimal channelized flow of typical terrestrial retrogressive thaw slumps are dissimilar to most Martian gullies. Yet, as shown by Figure 22, such failures could be an initiation point, or component, of the sediment cascade in Martian gullies.

Terrestrial landscapes with gullies where active-layer formation is key to the morphogenesis of the component landforms have also been used to support this model of gully formation. One of the often-cited case studies is Svalbard (Hauber *et al.* 2011*a*, *b*; Reiss *et al.* 2011; Johnsson *et al.* 2012; Balme *et al.* 2013), where thaw is central to forming solifluction lobes, sorted patterned ground and pingos, and debris flows may be triggered by active-layer detachment (de Haas *et al.* 2015*c*). The landscape also contains debris-covered glaciers and polygonally patterned ground, which, although not related to thaw, attest to the ice-enrichment of the surface environment. These authors identify each of these

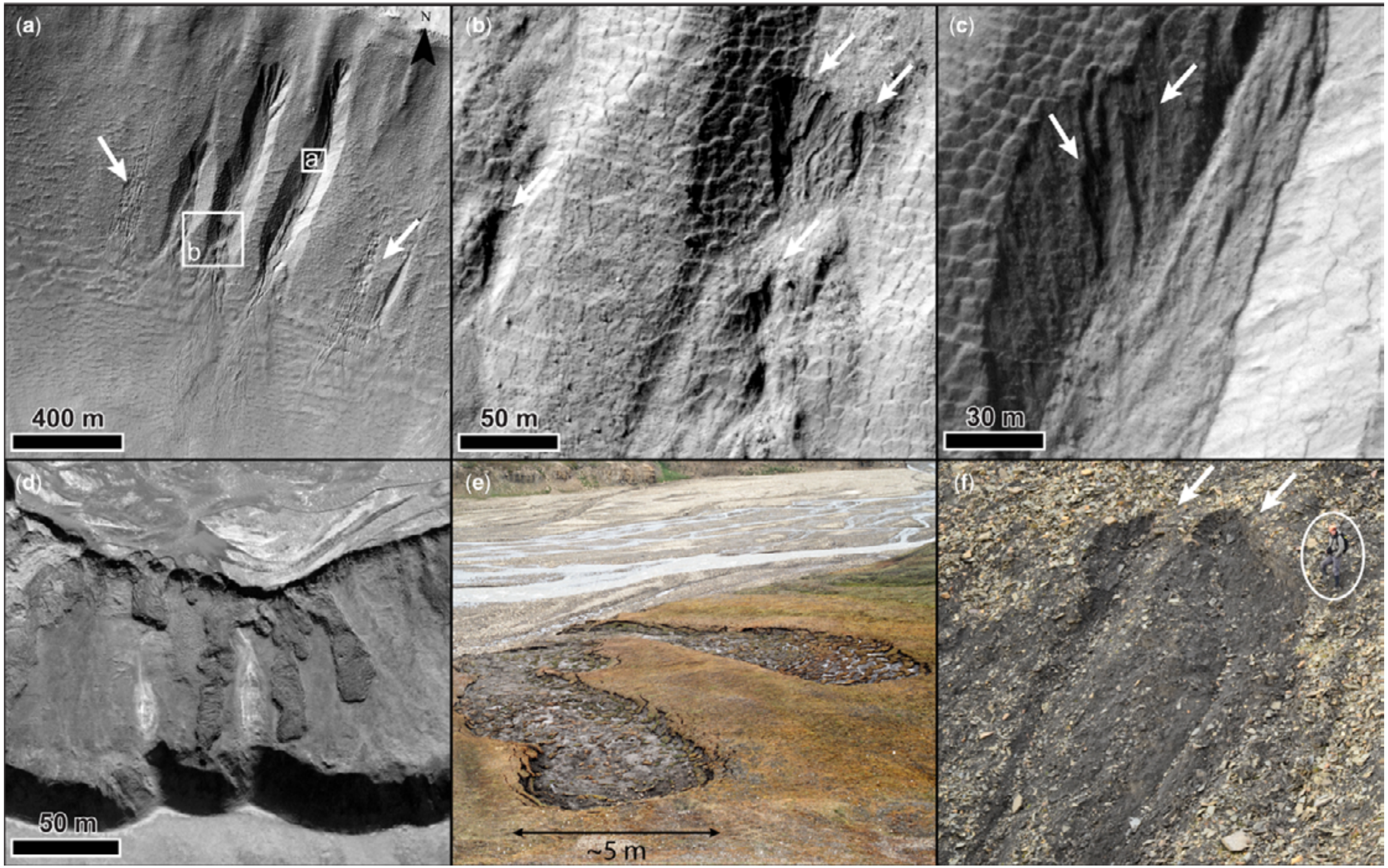

Fig. 22. Active-layer detachment on Earth and potentially on Mars. (**a**) Gullies and candidate active-layer detachments (indicated by white arrows and boxes) in Yaren Crater as seen in HiRISE image ESP_024086_1360 (after Johnsson *et al.* 2018). (**b**) Detail of shallow landslides from possible active-layer detachments in the lower gully alcove. (**c**) Possible active-layer detachment scars in the upper alcove. (**d**) Active-layer detachment slides in Hanaskogdalen, Svalbard (from Hauber *et al.* 2011*a*). (**e**) Photograph of two active-layer detachment slides in (d) (reprinted from fig. 12 of de Haas *et al.* 2015*c*, © 2015 with permission from Elsevier). (**f**) Active-layer detachment on a steep slope near Svea, Svalbard (reprinted from fig. 12 of de Haas *et al.* 2015*c*, © 2015 with permission from Elsevier). HiRISE image credit: NASA/JPL/University of Arizona.

landscape elements on Mars, where they also highlight the similar spatial arrangement and scale of the landforms. Gallagher & Balme (2011) did not draw on a specific terrestrial analogue, but referred extensively to terrestrial landscapes and the interrelationship typically reported between landforms to build the case that gullies in high northern latitudes may be formed by processes analogous to retrogressive thaw slumping. Soare *et al.* (2007, 2014*a*, *b*, 2017) have used landscapes in the Tuktoyaktuk peninsula, northern Canada, to argue that Martian gullies are an element of a landscape resulting from freeze–thaw cycling, which also includes, high-centred polygons, pingos and thermokarst depressions (Fig. 23).

In order for this hypothesis to be valid, melting needs to be possible in the top metres of the ground on Mars. Modelling by Mellon & Phillips (2001) showed that the depth of the 273 K isotherm is always above the depth of any near-surface ground ice that might exist at these latitudes, under both present-day conditions and under past conditions at high obliquity. Similarly, Kreslavsky *et al.* (2008) examined the orbital conditions which would permit an active layer to form and concluded that these conditions last occurred >5 myr ago, and, hence, do not

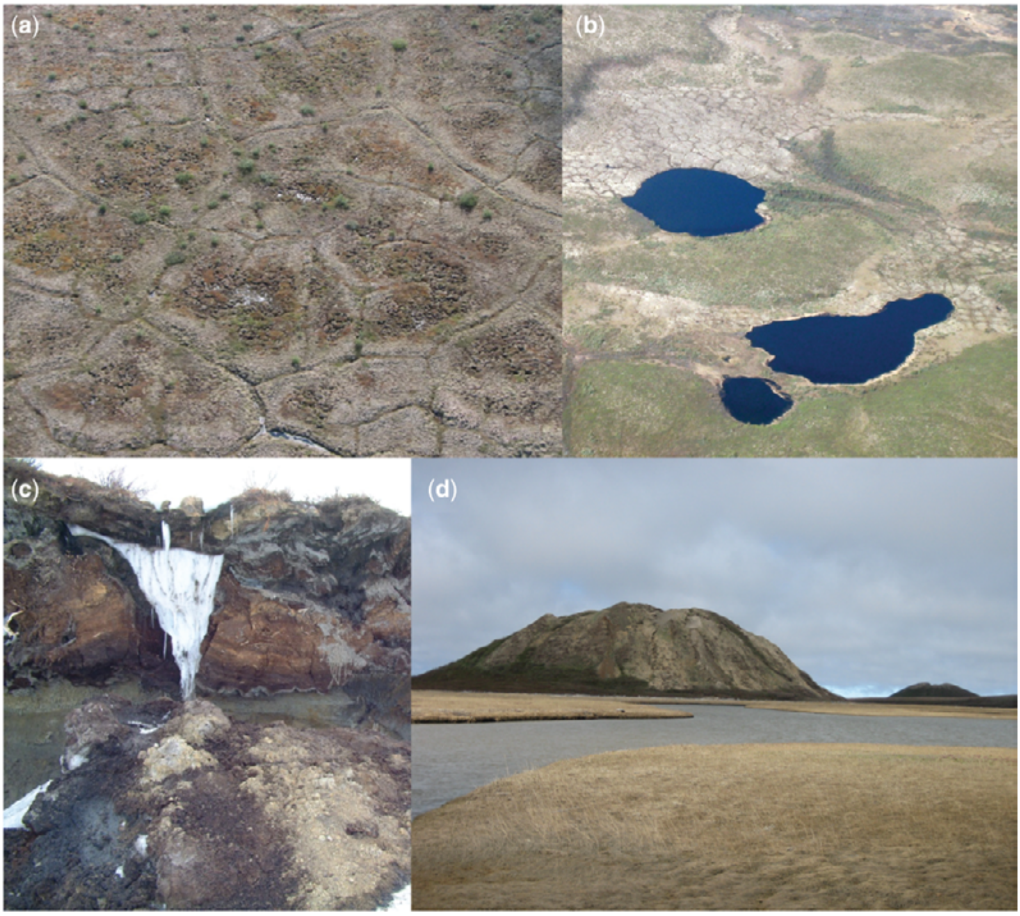

Fig. 23. Periglacial landform assemblage in northern Canada. (**a**) High centred polygonally patterned ground, Tuktoyaktuk Coastlands, with meltwater visible in polygon troughs, taken from figure 14 of Soare *et al.* (2014*a*, © 2014 with permission from Elsevier); polygons are *c.* 20–50 m across. (**b**) Alases or thermokarstic depressions (Tuktoyaktuk Coastlands) surrounded by polygonally patterned ground, reprinted from figure 2 of Soare *et al.* (2015, © 2015 with permission from Elsevier). The thermokarst lake in the background is *c.* 100 m across. (**c**) Cross-section though a polygon margin revealing the ice wedge (*c.* 2.5 m across at the top), Tuktoyaktuk Coastlands, taken from figure 13 of Soare *et al.* (2014*a*, © 2014 with permission from Elsevier). (**d**) Ibyuk Pingo with Split Pingo in the background, Northwest Territories, Canada, taken from figure 7 of Soare *et al.* (2014*b*, © 2014 with permission from Elsevier).

provide a good explanation for Martian gullies. Further, Mellon & Phillips (2001) also found that temperatures high enough to melt ice would only be attained if the ice were composed of 15–40% salts. Melting due to the presence of salts is also inconsistent with the latitudinal distribution of gullies, as they would be expected to form at all latitudes over a range of obliquity regimes in this case (Mellon & Phillips 2001). If the process that initially formed gullies is responsible for the activity we observe today, the Costard *et al.* (2002) model cannot be invoked as gullies are active at Mars' current obliquity. Any models involving melting at or near the surface would also imply that gully activity would be expected in summer (as is the case for terrestrial snowmelt-initiated debris flows in Iceland, which peak in the summer: Rapp 1986; Decaulne & Sæmundsson 2007; de Haas *et al.* 2015*c*), and the seasonal constraints of all of the new gully flows known to have formed within a single Mars year demonstrate that they are forming in autumn, winter or very early spring (Harrison *et al.* 2009; Diniega *et al.* 2010; Dundas *et al.* 2010, 2012, 2015). If the present-day activity in gullies is separate from their initial formation mechanism, however, then these issues do not pose a problem for the ground-ice model as it could be valid during periods of higher obliquity.

Melting of snow. Melting of snow as the genesis of gullies was first proposed by Lee *et al.* (2002) and Hartmann *et al.* (2003) based on the resemblance of Martian gullies to those on Devon Island and Iceland, respectively, created by snowmelt (Fig. 24a, b). Christensen (2003) (later expanded by Williams *et al.* 2009) invoked snowmelt by proposing that gullies were created by the melting of dust-covered snowpacks that formed at high to moderate obliquity (*c.* 35°), remnants of which are preserved as LDM deposits on gullied crater walls today. Head *et al.* (2008) also proposed a model involving surface meltwater, in which the last glaciation of Mars resulted in debris-covered glaciers forming against the polewards-facing walls and on the floors of mid-latitude craters. When the climate changed, the glaciers stopped accumulating and flowing, leaving alcoves exposed on the crater walls. Residual surface ice and snow in these alcoves then melted to form gullies. Schon & Head (2012) advocated this model based on the correlation between the calculated age of one particular gully they studied and the emplacement time of dust-ice-covered mantling deposits. The presence of an intimate relationship between glaciers and gullies is further supported by de Haas *et al.* (2017), who show that glacial activity often removes gully deposits (leaving only the crown of the gully alcoves exposed) but that gullies subsequently rapidly form within the formerly glaciated crater wall (Conway *et al.* 2018*a*). The support and caveats of these models are the same as those discussed in the previous subsection on 'Melting of near-surface ground ice'.

Overland flow of water sourced from snow meltwater in the dry valleys of Antarctica produces many of the features associated with gullies on Mars: channel sinuosity, V-shaped incision, lateral levees (although their topographical expression is small) and fan-shaped deposits. Marchant & Head (2007), amongst others, argued that the cold dry climate of the Antarctic Dry Valleys makes them a particularly suitable analogue for Mars, which very few other terrestrial analogues can match. In this location, gully alcoves are observed to form traps for windblown snow and ice, otherwise known as nivation hollows (e.g. Christiansen 1998; Lee *et al.* 2004; Dickson *et al.* 2007). Because of the aridity of the dry valleys, there are usually high concentrations of salt at the surface, which cause any water flow to be salty (Marchant & Head 2007). The authors argue that this could also be the case on Mars and would favour gully formation via snowmelt. The assemblage of landforms found alongside gullies in the Dry Valleys, including notably polygonally patterned ground and glacial landforms, has also been used to support this environmental analogue as a process analogue to gullies and their associated landforms on Mars (Marchant & Head 2007; Levy *et al.* 2009) (Fig. 24c).

Védie *et al.* (2008) performed scaled-physical experiments designed to simulate the formation of Russell Crater's linear dune gullies under ambient Earth pressure and low temperature (Fig. 19). They found that snowmelt as a water source did not produce morphologies distinct from other water sources (perched aquifer, melting of ground ice). A similar conclusion was reached by Sinha *et al.* (2018), who compared debris flows generated by snowmelt in the arid Himalaya to gullies with a similar morphology on Mars. These studies imply that snowmelt is hard to distinguish from other near-surface sources of water by morphology alone and, hence, it would be difficult to detect its influence in the formation of Martian gullies.

Melting of H_2O frost. Kossacki & Markiewicz (2004) investigated whether gullies could have formed from seasonal melting of accumulated H_2O frost under favourable pressure and wind-speed conditions. In this model, H_2O frost transitions to the liquid phase after the complete removal of the overlying CO_2 frost layer (which deposits atop H_2O frost seasonally on Mars). CO_2 frost can remain on crater walls into late spring. Once insolation increases above a certain intensity (in late spring/early summer) the last CO_2 frost sublimates away, which could result in the rapid heating (and melting)

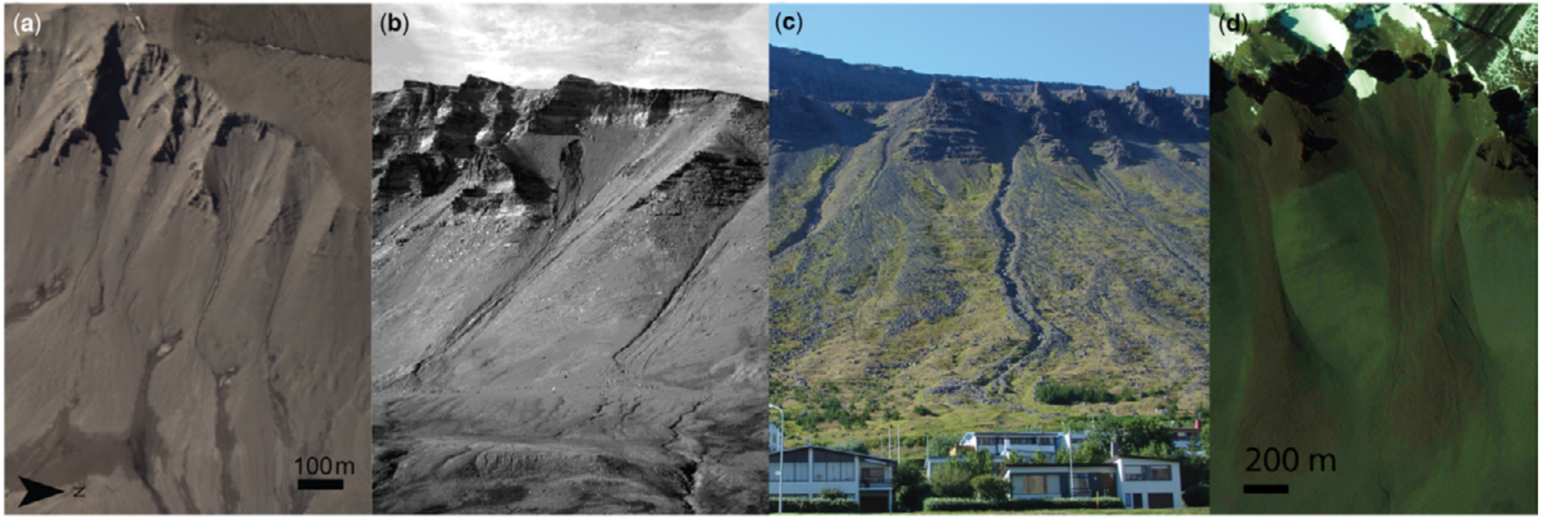

Fig. 24. Gullies on Earth generated by snowmelt. (**a**) Satellite images of the gullies shown in (b). Image credit GeoEye-1 © 2013 DigitalGlobe, Inc. (**b**) Debris flows in Jameson Land, Greenland, which occurred by the infiltration of melting snow during the summer season, taken from figure 10.4 in Costard *et al.* (2007*a*, with permission from Cambridge University Press). (**c**) Debris flow on the slopes above Ísafjörður in NW Iceland triggered by rapid snowmelt in 1999 (track #1 of Decaulne *et al.* 2005), photograph taken by John Murray in 2007. (**d**) Gullies studied by Levy *et al.* (2009) in Wright Valley, Antarctica. Polygonal patterned ground visible on the plateau and the depositional fans. Image credit GoogleEarth, DigitalGlobe.

of the underlying H_2O frost. The presence of salts within the water ice could aid in lowering the melting temperature and favour this process. The estimated maximum volume of liquid that could be generated by this melting is <0.2–0.55 kg m^{-2} depending on latitude, which Kossacki & Markiewicz (2004) stated was not enough to generate any surface flow but could affect the cohesive properties of the surface layer of the slope. With an average precipitable water-vapour abundance of only *c.* 10 µm in the current Martian atmosphere (Jakosky & Farmer 1982; Jakosky & Barker 1984); other authors have also argued that frost accumulation and subsequent melting would not likely to be significant enough to saturate the regolith to the point of slope failure, but rather the dampening would lead to increased cohesion (e.g. Dundas *et al.* 2015). The darkening of the surface by this dampening has been hypothesized to be the origin of RSL on Mars (McEwen *et al.* 2011), where downslope percolation of small amounts of water explain the gradual growth of these relatively dark features. A terrestrial analogue for this kind of water percolation was reported by Levy *et al.* (2011) in the form of water tracks in Antarctica. These water tracks are saline, and are supplied by the melting of snow, pore ice and ground ice. They have also been used as analogies for Martian linear gullies on dark sand dunes – where a dark halo is observed to appear at the same time as new/modified gully tracks (Jouannic *et al.* 2018). Pasquon *et al.* (2016) termed these dark halos 'RDF' or recurrent diffusing flows. Jouannic *et al.* (2018) also use an unusual example of snowmelt on a glacier as a process analogue for the formation of new 'perennial rills' within these RDF; however, they leave open the question of which fluid is involved.

Recent scaled-physical models under Mars pressures have revealed that the metastable nature of water on Mars means that more sediment transport could occur than might be expected from stable water (Massé *et al.* 2016; Raack *et al.* 2017; Herny *et al.* 2018). Therefore, the main argument against the meltwater hypothesis – that melting surface frost cannot produce enough water for surface flow – may be somewhat ameliorated if these processes are indeed active.

The argument that frosts are too thin (because of the low atmospheric humidity) to explain the size of Martian gullies has some potential counterarguments, as follows: water vapour abundance in the Martian atmosphere is highly variable, dependent upon the time of day, season and local conditions (e.g. Smith *et al.* 2009). Due to its low concentration in the atmosphere and its variability, modelling the distribution of water vapour in the past is challenging (e.g. Madeleine *et al.* 2014; Steele *et al.* 2017), particularly under high obliquity when the water cycle is predicted to be more intense (e.g. Haberle *et al.* 2003). Hence, it is challenging to make any solid statements about frost availability at Martian gully sites in the past. Further, present-day measurements of water vapour from orbit are likely to be unrepresentative of transient and local surface conditions, which would be sufficient to generate small amounts of melt, as argued in the RSL literature (McEwen *et al.* 2014; Chojnacki *et al.* 2016). Wind redistribution of seasonal frosts could also increase the local thicknesses of frosts, somewhat analogously to the melting of snow hypothesis discussed in the previous subsection. Equally, the distribution of surface frosts is highly sensitive to small variations in topography, so despite the general prediction that frost should not accumulate on equator-facing slopes as they are never deeply shadowed (Schorghofer & Edgett 2006), observations of frost are made on equator-facing slopes (Dundas *et al.* 2017*b*) (Fig. 12). Terrestrial analogy dictates that only episodic optimal conditions are required and they can produce significant landscape change (Marchant & Head 2007; Levy 2015).

CO_2-related mechanisms

Carbon dioxide is the major constituent of the Martian atmosphere and condenses onto the surface at the high latitudes every winter. Its sublimation in the spring is believed to responsible for sediment transport in the form of 'spiders' (e.g. Piqueux *et al.* 2003; Kieffer *et al.* 2006; Portyankina *et al.* 2010), and dark spots and flows on polar dunes (e.g. Kereszturi *et al.* 2009; Gardin *et al.* 2010; Kossacki & Markiewicz 2014). CO_2 frost is known to extend continuously from the pole to latitudes of 50° in mid-winter (e.g. Piqueux *et al.* 2015) and is found on steep pole-facing slopes from latitudes from 50° to 30° (Vincendon *et al.* 2010*b*). Hence, its geographical distribution matches that of gullies and the timing of recent gully activity in Martian winter matches with its presence. The polar-pit gullies and classic dune gullies are the only examples where the tight constraint on timing leaves CO_2 as the only unambiguous candidate to account for the sediment movements observed in these systems. However, as discussed in the earlier subsection on 'Morphology' (in the 'Review of key observations of Martian gullies' section), polar-pit gullies are somewhat different from the majority of gully systems, so the processes that form them may differ from those active in other gully systems.

Based on the timing of observed present-day gully activity (generally in winter coinciding with periods when CO_2 frost is on the ground), a CO_2-based process for gully formation is favoured by Diniega *et al.* (2010), Dundas *et al.* (2010, 2012, 2015, 2017*b*), Pasquon *et al.* (2016) and Raack *et al.* (2015). A CO_2-related process is supported by the observation of a higher level of activity in the south-polar-pit gullies (Raack *et al.* 2015) compared to those in the mid-latitudes, as more frost is deposited on slopes at higher latitudes. South polar pits should host *c.* 1 m of CO_2 frost accumulation in winter (Hoffman 2002), which is significantly more than lower latitude gullies, where micrometres of accumulation are predicted (Vincendon *et al.* 2010*a*). However, CO_2 frost has not been detected spectroscopically at latitudes equatorwards of *c.* 34° S (Vincendon *et al.* 2010*b*), and present-day gully activity has been observed at latitudes as low as 29° S. Dundas *et al.* (2015) did note that CO_2 frost processes might simply be the dominant driver of activity within pre-existing gullies today, and not the process by which they initially formed.

In the following subsections we will present the various CO_2-driven mechanisms of gully formation that have been proposed. We start with liquid CO_2, which has now been rejected on the grounds of thermodynamics, but is presented here because the authors used terrestrial analogues to support their arguments. We then present mechanisms that involve the gravitational displacement of solid CO_2 with or without the evolution of CO_2 gas. Finally, we detail the mechanisms that primarily involve the transport of sediment by gas evolved from CO_2 sublimation.

Release of liquid CO_2 from shallow aquifers. Musselwhite *et al.* (2001) proposed that Martian gullies formed via the outbreak of liquid CO_2 from near-surface 'aquifers'. In this model, similar to the shallow groundwater model of Malin & Edgett (2000) described in the earlier subsection on 'Release of water at high to moderate obliquity', liquid CO_2 builds up in an aquifer behind a dry ice 'dam' that forms at the point in the subsurface where liquid CO_2 is no longer stable. Seasonal and/or obliquity-cycle-driven heating weakens the dry ice 'dam', eventually resulting in the rapid release of liquid CO_2 to the surface. Upon reaching the surface, the CO_2 would rapidly vaporize, forming a gas-supported flow that entrained rock and ice, carving a gully as it moved downhill. The authors argue for CO_2 over H_2O as the gully-carving agent on Mars, because CO_2 is the most abundant volatile on the planet. This model was quickly dismissed due to the difficulty in both accumulating and sustaining significant amounts of either condensed CO_2 or CO_2 clathrate-hydrate in the Martian crust (Stewart & Nimmo 2002). Stewart & Nimmo (2002) stated that gas-supported flows of this nature would have velocities much too high to create morphologies observed in Martian gullies, and would be expected to result in forms more like terrestrial pyroclastic flows than the fluvial/debris flow forms of gullies (Stewart & Nimmo 2002). Therefore, they used the dissimilarity of a terrestrial landform to Martian gullies in order to counter the hypothesis proposed by Musselwhite *et al.* (2001). They particularly point to the visual dissimilarity between the deposits of the Mount St Helen's pyroclastic flows and the depositional fans of Martian gullies (Figs 6 & 14).

CO_2 frost avalanches, blocks and frosted granular flow. Ishii & Sasaki (2004) proposed that avalanches of solid CO_2 frost could gradually carve gullies over time by 'scratching' into the surface as chunks of frost fell during periods of sublimation (i.e. spring into summer). Frost avalanches have also been proposed as gully formation/evolution mechanisms by some authors based on HiRISE observations of frost-dust avalanches on a north polar scarp (Russell *et al.* 2008) and the hypothesis of Costard *et al.* (2007*b*) that 'dark streaks' observed over frost in gullies are dry avalanches. However, present-day CO_2 frost avalanches on scarps of the northern polar layered deposits have not been observed to form any gully-like features (Russell *et al.* 2008). Because these avalanches do not involve a volatile phase, their behaviour and morphology should be similar to that of dry granular flows and therefore this model has been discounted on the same grounds (see the subsection on 'Dry granular flow' earlier in this section).

A different type of sublimation-induced CO_2 ice avalanching has been suggested as the formation mechanism behind linear dune gullies, such as those on the dunes in Russell Crater (Diniega *et al.* 2013). In this model (originally proposed by Hansen *et al.* (2011) for mass-movement features on the north polar erg of Mars) blocks of CO_2 ice dislodge from the top of the dune in springtime due to sublimation induced by solar heating. The blocks then travel downslope, levitating on a cushion of CO_2 gas, carving leveed linear channels. The authors use a field-simulation analogue to support their hypothesis, where the authors placed decametre-scale sublimating blocks of CO_2 ice on terrestrial dune fields (Fig. 25) and produced similar narrow leveed channels (and terminal pits). These pits have also been reproduced in laboratory simulations with sublimating blocks of CO_2 ice (Mc Keown *et al.* 2017). As discussed in the subsections 'Morphology' and 'Temporal context (age and activity)' in the earlier section on 'Review of key observations of Martian gullies', the peculiar morphology and precise timing of the activity of linear gullies suggests that their formation process is different to the other Martian gullies, so this mechanism has not been applied to the general population of gullies.

Hugenholtz (2008) proposed frosted granular flow as a gully-formation mechanism on Mars based on terrestrial observations (Fig. 26). Frosted granular flow is a rare type of mass movement on Earth where clasts are lubricated by thin frost coatings, facilitating downslope movement. They tend

Fig. 25. Sliding sublimating CO_2 ice blocks down dunes as analogues for Martian linear gullies, frames were captured from the video included as Supplementary video 4 in Diniega *et al.* (2013), where a block is released over a 20° slope on Kelso Dunes, California; the person at the dune brink is for scale. Black arrows point to the block at each time step, labelled t1–t4.

to occur in the fall and spring when the air temperature oscillates around freezing (273 K) at times of relatively high humidity on snow-free surfaces (Hétu *et al.* 1994; Hétu & Gray 2000). Hétu *et al.* (1994) noted four conditions required for frosted granular flow: (1) unconsolidated sediment easily mobilized downslope; (2) a slope gradient at or near the angle of repose in the source region; (3) frost accumulation on the unconsolidated grains; and (4) a trigger for mass movement – on Mars this could be, for example, rockfall (Hétu *et al.* 1994), point-source defrosting (Costard *et al.* 2007*b*), vapour-induced instability (Hoffman 2002) or avalanching of CO_2 frost (Ishii & Sasaki 2004). Locations of repeated flows typically either follow pre-existing channels or, when diverted by obstacles, create new channels. Grains ranging in size from fine-grained sand (*c.* 0.0007 cm) to large clasts (20 cm) can be mobilized by these flows on slopes as low as *c.* 25°; however, frosted granular flows predominantly transport gravel-sized grains (Hétu & Gray 2000; Hugenholtz 2008). As for debris flows, kinetic sieving results in the accumulation of large clasts at the flow margins and on the surface of frosted granular flows. Frosted granular flows are reported to exhibit levees, straight to sinuous channels, concave profiles and digitate terminations (Hétu *et al.* 1994; Hétu & Gray 2000), which are similar to debris flows. Seasonal H_2O frost accumulates as far north as 13° S in the winter (Vincendon *et al.* 2010*a*), and early morning frost has been observed on the ground by the Opportunity rover at 2° S (Landis 2007), covering the entire latitude range where gullies are found in the southern hemisphere. Hugenholtz (2008) proposed that CO_2 frost rather than water-ice frost may be the lubricating mechanism for frosted granular flows on Mars. However, this seems unlikely because only thin diurnal night-time CO_2 frost has been detected at latitudes lower than *c.* 34° S (Vincendon *et al.* 2010*b*; Piqueux *et al.* 2016). Additionally, CO_2 frost does not accumulate in the mid- to high latitudes in areas that are never deeply shadowed at any point in the year (Schorghofer & Edgett 2006), and gullies are found on equator-facing slopes where CO_2 frost is not predicted to accumulate. In addition, frosted granular flow seems unlikely as a principle driver for gully formation based on their morphology. The morphology of frosted granular-flow channels and deposits are very similar to that of classic granular flows described in the subsection on ‘Dry granular flow’ (earlier in this section) and lack the morphological complexity shown by typical Martian gullies, including tributary networks, deep incisions, streamlined forms and terraces (Figs 2, 5 & 6).

CO_2 gas-fluidized flow. Hoffman (2002) and Cedillo-Flores *et al.* (2011) proposed that gullies in at least Mars’ polar regions, such as those in the south polar pits of Sisyphi Cavi, formed by fluidization of aeolian sediment deposited atop CO_2 frost once the frost begins to sublime in springtime (Fig. 27). This model requires a slope covered with CO_2 frost, which is then subsequently mantled by sediment, sand or dust via aeolian transport from adjacent non-frosted slopes. The frost layer rapidly sublimes due to heating of the overlying lower-albedo material. This introduces instability to the slope, triggering mass movement. Mechanical heating as the material moves downslope generates more CO_2 vapour, acting as a lubricant to allow the mass to behave like

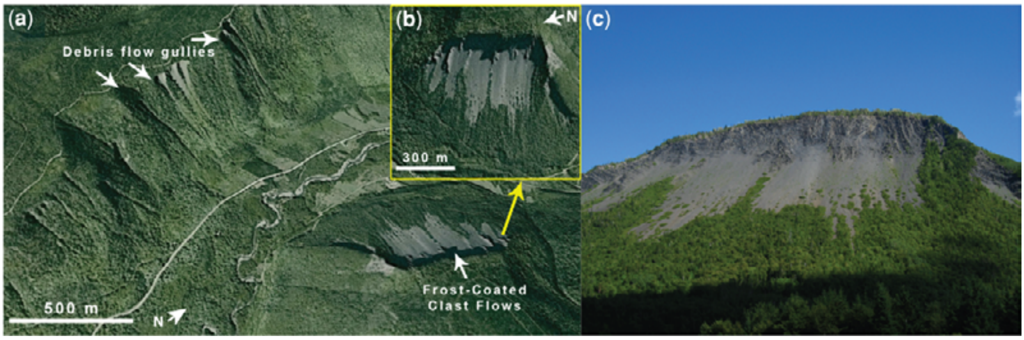

Fig. 26. Hillslopes with frosted granular flow in the St Pierre river valley in Québec, investigated initially by Hétu & Vandelac (1989) and Hétu *et al.* (1994), and reported as a terrestrial analogue by Hugenholtz (2008). (**a**) Overview of the hillslopes with debris flows and talus slope with frosted granular flow, and (**b**) zoom showing the talus slope. (**c**) Photograph of the talus slope taken by Maxime Chevalier. (a) & (b) are modified from Harrison *et al.* (2015, fig. 2.15) with image credit: Google Earth/CNES/Spot.

a fluid and carving a channel. This model differs from that of Musselwhite *et al.* (2001) in that it only invokes surface CO_2 ice based on the aforementioned thermodynamic difficulty in sustaining CO_2 ground ice on Mars.

Recent activity within polar-pit gullies coincides with periods of defrosting (Hoffman 2002; Raack *et al.* 2015), which has led to the suggestion that CO_2 defrosting is capable of initiating mass movement of the underlying sediment (rather than sediment deposited atop it). Hoffman (2002) suggested that the closest terrestrial analogue to this sort of gas-fluidized flow is a density flow, and presents submarine turbidity channels for their morphological similarity to Martian gullies, where the submarine landforms display sinuous channels (Fig. 28) and distributary fans.

Following along the same lines, Pilorget & Forget (2016) proposed a model where CO_2 ice condenses onto the surface in autumn, gradually forming a continuous slab. Sublimation at the base of the slab ice occurs due to differential solar heating of the underlying regolith because the slab ice is relatively transparent to sunlight. Some of the resulting CO_2 gas diffuses into the regolith, trapped between impermeable permafrost and the overlying CO_2 slab ice. In mid-winter, CO_2 ice begins to condense in pore spaces within the upper few centimetres of the underlying regolith. Pressure builds up to a point where the CO_2 gas ruptures the overlying ice, forming jets of CO_2 gas that could destabilize the slope and cause a fluidized debris flow. This was inspired by the model of sub-slab sublimation that has been proposed for the formation of south polar spiders (Piqueux *et al.* 2003; Kieffer *et al.* 2006). Pilorget & Forget (2016) described this type of gas-supported flow as being akin to a terrestrial pyroclastic flow (Fig. 14). They noted that not every 'eruption' of CO_2 gas would be expected to generate a gully, but multiple eruptions in the same place could occur due to re-condensation, leading to repeated events within an individual gully system. In fact, in the case of Russell Crater dune gullies, their model predicts eruptions on a daily basis from Ls 150° to 205°, which coincides with the appearance of dark flows but not linear gully activity (Jouannic *et al.* 2018; Pasquon *et al.* 2018). One of the prerequisites for this model is the presence of a CO_2 ice slab, which is not expected at the mid-latitude sites where the majority of active gullies are located and is not easily applicable to gullies on equator-facing slopes in the mid-latitudes, where CO_2 if present is likely to be spatially discontinuous and thin (Dundas *et al.* 2017*b*; Conway *et al.* 2018*b*).

As argued by Hoffman (2002), density currents, such as pyroclastic flows and submarine turbidity currents, are the nearest analogy for sediment transport by sublimating CO_2. Numerical models have shown that pyroclastic flows on Earth behave like dense granular flows, and produce a broad central linear channel with lateral levees and terminal lobes (Félix & Thomas 2004; Mangeney *et al.* 2007). Terrestrial laboratory experiments of the fluidization of dry material with CO_2 gas (Cedillo-Flores *et al.* 2008; Sylvest *et al.* 2016, 2018) similarly produce features morphologically similar to dry sand flows on terrestrial dunes, as the gas rapidly escapes (Fig. 14). Further work is needed to ascertain whether CO_2 sublimation can produce long-lived fluidization and therefore morphologies similar to Martian gullies. It has been hypothesized that the repeated action of discrete granular flows can produce connected networks (Shelef & Hilley 2016) and complex channel geometries as seen in Martian gullies and terrestrial equivalents. As stated by Hoffman (2002, p. 321), 'quantitative diagnostic criteria must be developed to distinguish between the morphologies produced by subaerial flows and those of density flows'.

Summary of gully-formation mechanisms

Since their discovery, many processes, often based on terrestrial analogues, have been proposed by a variety of authors to understand the formation of gullies on Mars. Hypothesized geomorphic-flow processes range from completely dry to various types of water- and CO_2-lubricated flows. To fully understand gully formation, these processes need to be able to account for activity in gullies at the present day as well as during past, higher-obliquity, conditions.

At present, dry flows have been ruled out as a predominant gully-forming mechanism because of the typical gully-fan slopes, which are well below the dynamic angle of repose, and gully morphology that is inconsistent with dry-flow morphology. Dry flows are nevertheless likely to contribute to the upper part of the sediment cascade in Martian gullies. Present-day gully activity is intimately linked to CO_2 defrosting, and therefore CO_2 is likely to play a role in the formation of many present-day flows. However, this process is not able to account for the distribution of the full gully population, such as gullies on equator-facing mid-latitude slopes. Liquid water should not be thermodynamically stable under current Martian conditions, and therefore is unlikely to account for present-day gully activity. On the other hand, during periods of higher obliquity in the past, climate models predict that snow and ice should have been stable down to *c.* 30° of latitude, consistent with the global distribution of gullies. Moreover, under these conditions snow and ice was probably able to melt, and thereby form gullies.

In short, as extensively discussed above, there is no single gully-formation mechanism that is consistent with all the observations of the full gully population on Mars. Like on Earth, it is therefore likely that multiple processes operate within gullies and that the predominant mechanism could change over time, under changing atmospheric conditions, as a result of variations in orbital forcing.

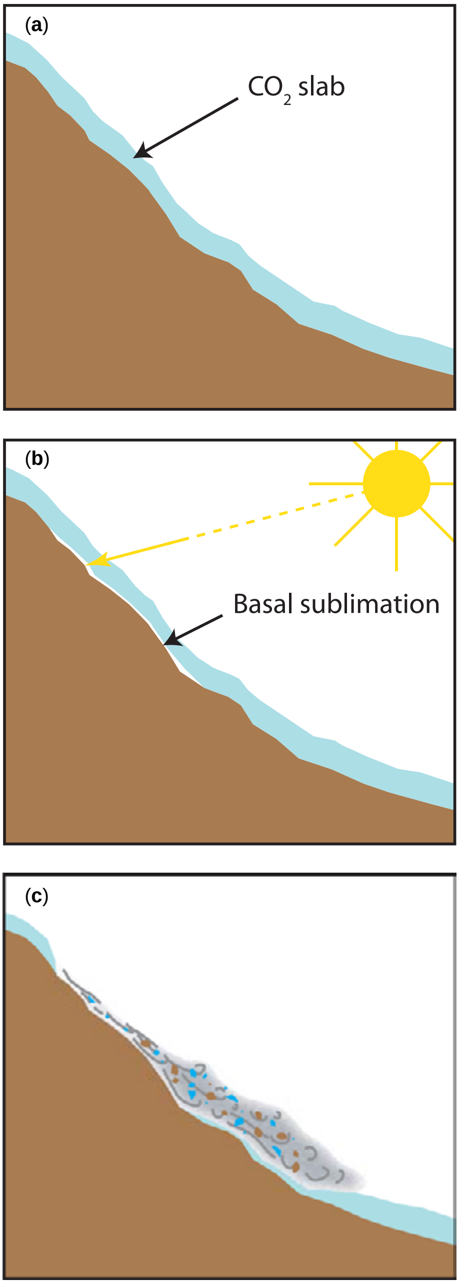

Fig. 27. CO_2 gas-lubricated flow model as described in Hoffman (2002). (**a**) In winter CO_2 slab ice is deposited on the Martian surface. (**b**) Sunlight (yellow arrow) penetrates through the surface CO_2 frost (light blue) and warms the underlying regolith (red-brown). This causes the frost layer to sublimate at its base, destabilizing the slope and generating an avalanche. (**c**) A mixture of the CO_2 frost, gas and entrained debris move downslope, with the frost continuing to degas and generating a vapour-lubricated flow.

The role of earth analogues in gully research

Earth analogues: their advantages and their limitations

A full review of the usefulness of Earth analogues in planetary science is outside the scope of this review and we refer interested readers to more detailed works on this topic (e.g. Baker 2014). Here we discuss particular issues that have arisen repeatedly

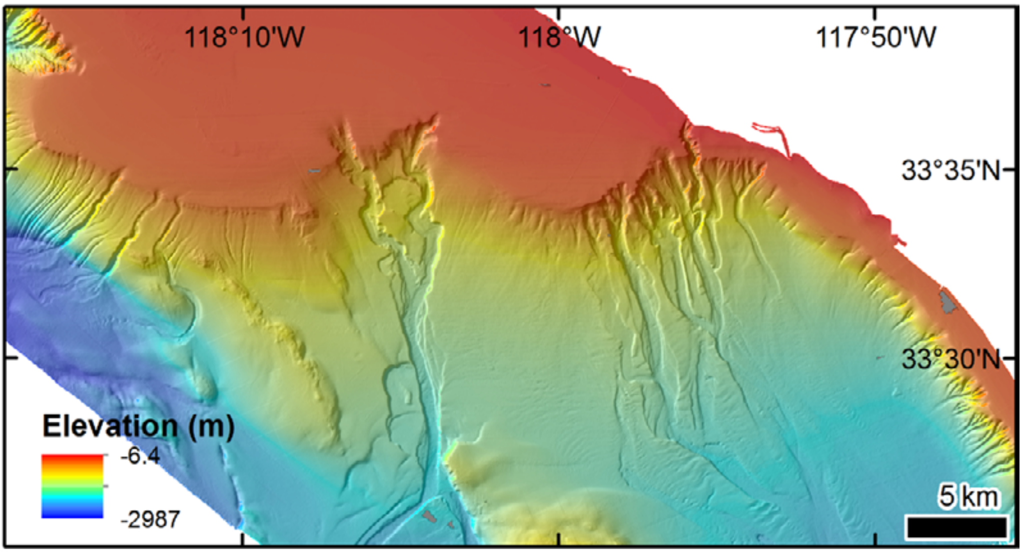

Fig. 28. Submarine gullies and canyons. Data from the United States Geological Survey (USGS) showing the bathymetry of the Los Angeles, California Margin surveyed between 1996 and 1999, and detailed in Gardner & Dartnell (2002).

during our review of the Martian gully literature. Earth analogues have been intensely used to construct working hypotheses regarding the processes and fluids that lead to gully formation on Mars. Different types of terrestrial analogy have been used and we have pulled out these general themes, where most papers on Martian gullies use one or more of these approaches:

- plan-view morphology at the landscape-scale or feature-scale;
- three-dimensional (3D) or plan-view morphometry;
- environmental analogues;
- landscape assemblages;
- physical-scale experiments;
- empirical laws from terrestrial studies.

Out of these types of analogues, the ones that rely on plan-view morphology are the most controversial because of equifinality, whereby similar landforms can be produced by widely different processes (Chorley 1962). A case in point is that pyroclastic flows have been interpreted to be both similar and unlike Martian gullies by different authors (‘Dry granular flow’ and ‘CO_2 gas-fluidized flow’) (Stewart & Nimmo 2002; Treiman 2003; Pilorget & Forget 2016). The fact that widely different processes can result in leveed channels with lobate terminal deposits on Earth (including debris flows, lava flows and pyroclastic flows: Fig. 29) suggests that various physical processes can be responsible for a similar morphology. However, once the morphometry, upslope landforms and landscape setting of these lobate deposits are taken into account, the similarity with the alternative landform is reduced (Baker 2017). Hence, using a combination of morphological and morphometric similarities at a range of spatial scales can establish a more robust analogy (Mutch 1979; Zimbelman 2001), and is an approach that has been adopted by many researchers working on Martian gullies. To build a successful analogy, full similarity over a range of scales and processes is not required: that is, not every aspect of the target landscape needs to be reproduced (e.g. climate, geology, soil, topography). In the case of Martian gullies, Antarctica is the nearest environmental analogue (low temperatures and humidity: e.g. Marchant & Head 2007), Iceland forms a better geological analogue (basalt bedrock: Hartmann *et al.* 2003), and impact craters form the best analogue in terms of topographical and structural setting (e.g. Osinski *et al.* 2006), and all of these have been used to gain fruitful insights into Martian gully formation.

The debate over carbon dioxide as an active agent of morphological change in Martian gullies highlights one of the potential limitations of Earth analogy. That is, can we successfully argue that liquid water is involved in Martian gullies by using Earth analogues if we cannot provide the counterpoint of landscapes created by CO_2 sublimation or, at least, gas-supported flows? In this case, are terrestrial analogues helpful at all or simply

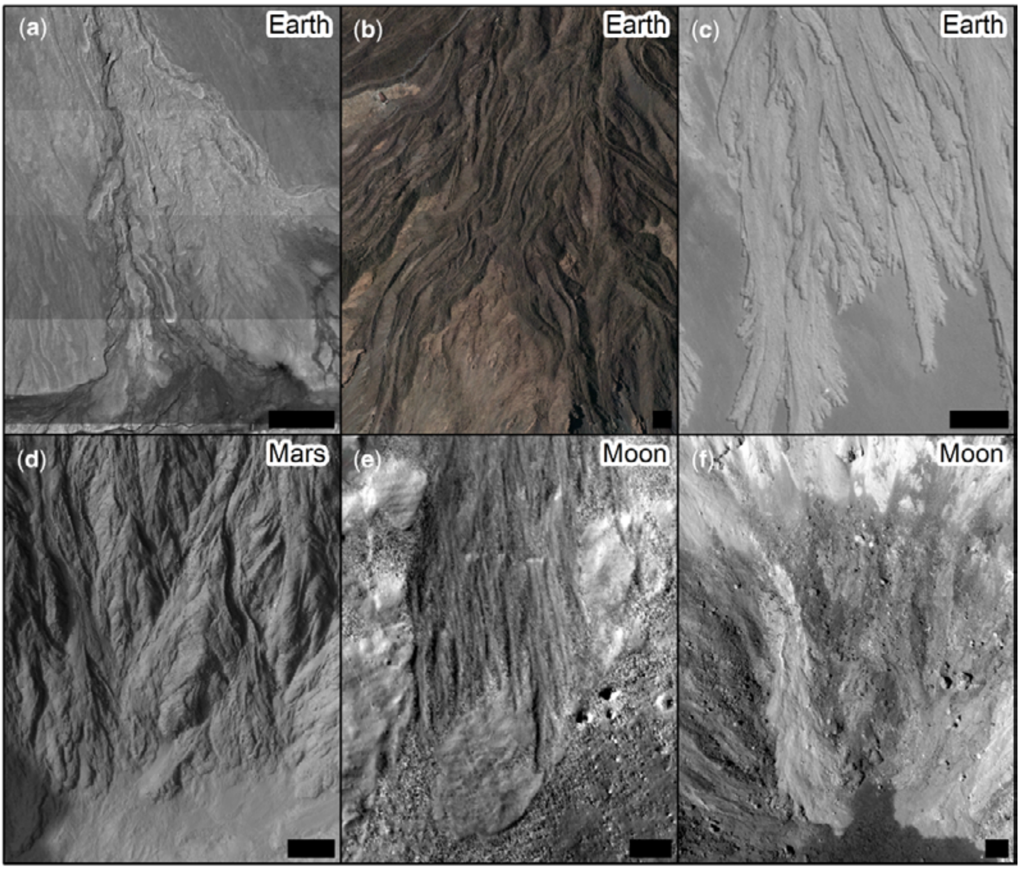

Fig. 29. Channelized deposits from different processes on different planetary surfaces; scale bars are 50 m in all cases. (**a**) Debris-flow deposits in Svalbard, image credit DLR HRSC-AX campaign. (**b**) Lava flows on Tenerife, aerial image courtesy of IGN, Plan Nacional de Ortofotografía Aérea de España. (**c**) Self-channelling pyroclastic deposits at Lascar volcano, Chile, Pléiades image. (**d**) Depositional lobes in Istok Crater on Mars, where channels (likely to be from debris flows) are formed as part of the depositional fans, HiRISE image PSP_007127_1345. (**e**) Fingering granular flows on the Moon, likely to be self-channelling dry granular flows (Shinbrot 2007), LROC image M167036896. (**f**) Lobate deposit and associated channel on the Moon, perhaps from impact melt or ejecta processes, LROC image M143676946. HiRISE image credit: NASA/JPL/University of Arizona. LROC image credit: NASA/GSFC/Arizona State University.

misleading? Analogy (Hesse 1966) can still be useful: although not providing definitive explanations, it does provide a source of hypotheses that move geological research into productive lines of inquiry (Gilbert 1896). We argue that for terrestrially rare or unknown processes, further progress can be made by using numerical modelling and scaled physical models (which we consider here as a subtype of terrestrial analogy). Laboratory experiments can be used to determine if the physical processes governing sediment transport by CO_2 sublimation are indistinguishable from those driven by water as the interstitial fluid. Substantial work is required, however, to both properly understand the physics that govern these processes and then to appropriately scale up the processes observed in the laboratory to assess if they can indeed produce the landforms we observe.

Establishing a terrestrial analogue allows us to exploit the depth of knowledge on that process in order to respond to Mars-specific questions. For example, based on an analogy between fluvial and Martian gullies, Parsons & Nimmo (2010) and Hobbs *et al.* (2014) applied empirical terrestrial relationships between discharge and fluvial-channel dimensions to estimate the water required to form Martian gullies. Yet, success of empirical approaches depends on whether the empirical parameters are inherently terrestrial. Recent work in low-gravity parabolic flights has highlighted, for example, that the empirical drag coefficient used when estimating the settling velocity of particles in a flow is dependent on gravity, when previously it was believed to be independent (Kuhn 2014). Therefore, particles under Martian gravity settle more quickly and have a much narrower distribution in settling velocities (for a given range of particle shapes and sizes) than would be predicted by applying the empirical settling velocity. Nevertheless, applying terrestrial empirical laws can give important insights into gully formation and evolution, as long as interplanetary differences are carefully considered.

Future directions

The work reviewed in this paper shows that terrestrial analogues have played an important role in Martian gully research. We consider transporting both terrestrial analogies in terms of landscape-process interpretation, but also in terms of the methodologies used to interpret the formative environment, as a fruitful avenue that should continue to be exploited in future Martian gully research. We have also identified five further avenues where we think further research could yield important insights.

Terrestrial experience tells us that separating individual landscape-forming processes from one another is disingenuous. For instance, fluvial flows can evolve into debris flows via gradual incorporation of loose debris downslope (firehose effect or bulking: Godt & Coe 2007; Coe *et al.* 2008). Erosion of bedrock is typically limited during fluvial- or debris-flow events in steep catchments, landslide processes are a common prerequisite for making sediment available in catchments (Benda & Dunne 1997) and the bedrock is initially weakened by weathering (Phillips 2005; Matsuoka & Murton 2008). Those loose sediments are then removed by debris flow or fluvial processes; the efficiency of such sediment cascades is defined as ‘connectivity’ (e.g. Cavalli *et al.* 2013). We advocate that progress can be made in Martian gully research by considering the landform as a series of sediment cascades and the connectivity of the landscape as a whole system (Heckmann & Schwanghart 2013; Bennett *et al.* 2014). In considering the cascade of sediments relatively little work has focused on establishing terrestrial analogues and understanding the processes in the erosional part of Martian gullies (i.e. the alcoves). A notable exception is the study by Okubo *et al.* (2011), who examined the potential triggers of landslides in alcoves to supply sediment to Martian gullies in Gasa Crater. However, these authors did not consider the fate of the sediments post-failure. The increasing availability of high-resolution digital elevation models (DEMs) of Martian gullies is opening up the opportunity to study the connectivity and sediment cascades from source to sink using both morphological and morphometric techniques.

The increasing availability of DEMs of Martian gullies also offers another opportunity – the possibility of employing landscape-evolution models to understand gully formation. Such an approach has been applied in the study of the degradation of Martian impact craters via fluvial systems driven by rainfall (Howard 2007). However, this approach has yet to be applied to Martian gullies. Martian gullies are ripe for this application because of two recent innovations: (1) the increasing use of synthetic DEMs as a starting point for landscape-evolution models (Hillier *et al.* 2015), allowing gullies to be simulated in undisturbed topography; and (2) the recognition that landscape-evolution models can be driven by stochastic discrete-flow events (Shelef & Hilley 2016), rather than flow driven by continuous variables. The use of landscape-evolution models could help us to explore the age of gullies, the climate drivers and the expected sedimentary packages relevant for understanding the rock record on Mars.

Similarly, there is a wide range of advanced 2D to 3D numerical models that are used to simulate dry and wet sediment-gravity flows on Earth over realistic topography (e.g. debris flows, grain flows and snow avalanches) (O’Brien *et al.* 1993; Christen *et al.* 2007, 2010; Iverson & George 2014; Mergili *et al.* 2017). Such models can correct for Martian gravity and, in combination with high-resolution DEMs, can be used to infer the initiation and flow conditions that led to the formation of deposits on Martian gully fans. Such analyses could shed new light on the palaeoclimatic conditions leading to gully formation. Yet, despite their great potential, only Pelletier *et al.* (2008) used one such model, FLO-2D, to infer the volumetric water content in recent flow deposits in a crater in the Centauri Montes region. An important application of such models would be distinguishing between fluvial flow, debris flow and gas-supported flow based on the extent and thickness of the observed deposits.

Scaled-physical models are another area where we think that significant progress can be made in understanding the processes that form Martian gullies. Lapotre *et al.* (2017) highlighted that natural water flows on Earth cover a narrow range of fluid densities, viscosities and grain densities, and they inevitably occur under terrestrial gravity, which means that the effects of these different parameters on flow behaviour is hard to assess from terrestrial observations alone. Laboratory experiments allow us to vary such parameters. In addition, certain physical processes can be isolated and studied in detail in order to understand the basic underlying mechanics. The relative importance of the driving variables can be assessed experimentally (in terms of rates, frequency and magnitude) and the physical equations can be used to explore the parameter space guiding future laboratory work. Gravity can be adjusted via the use of parabolic flights and has been used to study granular flows under Martian gravity (Kleinhans *et al.* 2011), but has not yet been extended to fluidized flows. The study of sediment transport by CO_2 sublimation is in its infancy, and is of particular importance for breaking the impasse between liquid water v. CO_2 for forming and modifying gullies. The potential role of brines and metastable fluids in sediment transport on Mars is also an area where significant work remains. An important area for future work will be using experiments to place limits on slope angles and grain sizes for deposition and erosion caused by different transport mechanisms, which can then be compared to slope and grain-size observations of Martian gullies. Laboratory simulations exploring how volatiles such as CO_2 and water vapour interact with the Martian regolith and respond to changes in surface temperatures are also needed to understand the processes involved in triggering the sediment cascades we observe in Martian gullies. Laboratory studies also present the advantage of being able to study the dynamic component of sediment transport, which is severely lacking on Mars where the gap between images can be several sols but is usually at least several months.

The formative processes of gullies and their spatial distribution have been extensively studied and quantified (e.g. Heldmann & Mellon 2004; Balme *et al.* 2006; Dickson *et al.* 2007; Kneissl *et al.* 2009; Harrison *et al.* 2015), while only a few studies have addressed their temporal evolution (de Haas *et al.* 2015*b*, 2017; Dickson *et al.* 2015). Focusing on the temporal evolution of gullies is an important avenue of future research, as the dominant formative mechanism of gullies may change over time and because gullies may interact with other processes over time. Recent work by de Haas *et al.* (2015*b*, 2017) shows that crater dating provides a promising tool for unravelling gully-formation mechanisms as long as the considered temporal resolution is large enough to be resolved via crater counting.

Conclusions

In this review we have summarized the main hypotheses proposed for Martian gully formation, and the role that Earth analogues have played in conceiving and developing these hypotheses. There remains a debate in the community between the role of CO_2 and liquid water in forming gullies. Using terrestrial analogy alone, liquid water is the most plausible candidate, yet current modifications in gullies occur at times of year when surface liquid water is unlikely. Sediment transport by sublimating CO_2 lacks a terrestrial analogue; hence, it is difficult to judge whether the morphology of all Martian gullies could be produced by this mechanism. Knowledge from Earth tells us that landforms are not made by a single process, and that the processes can vary in space and in time. Hence, we believe that the present processes in gullies probably do not accurately represent those active in the past. An urgent effort is required to ascertain the sediment-transport capacity of CO_2-supported flows on Mars and its resulting landforms to make progress.

We find that on balance terrestrial analogies are useful for understanding the complexity and interplay of processes involved in creating gullies on Mars – such insights are difficult to obtain from remote sensing, numerical modelling or laboratory studies alone. We emphasize that caution should be taken in applying these analogies, and the important environmental differences between Earth and Mars must be taken into consideration.

We highlight six particular areas where we think progress can be made in Mars gully research in the near future:

- Laboratory simulations using scaled-physical models, focusing specifically on exploring variables that can be observed from orbit.
- The use of landscape-evolution models which are specifically adapted to recent and past Martian climate.
- Application of the concept of sediment connectivity, with specific emphasis on the insights that can be gained from the erosional landforms of Martian gullies with reference to Earth analogues.
- Application of advanced 2D and 3D numerical sediment-gravity flow models to back-calculate the conditions leading to observed gully deposits.
- Cross-fertilization of concepts and methodologies used in terrestrial geomorphology to the study of Martian gullies.
- Quantitative analyses of the temporal evolution of Martian gullies, and the identification and exploration of terrestrial analogues representative of Martian gullies during different time periods.

The activity of Martian gullies extends from the present day back to the last few million years, and they are geographically widespread. Therefore, understanding the processes that shape them has the potential to unlock the secrets of Mars' recent and past climate, hydrosphere, and habitability.

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