Martian gullies and their Earth analogues: introduction

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Abstract: Martian gullies are widespread landforms in the mid-latitudes of Mars. When the first reports of these kilometre-scale features were published in 2000, they were controversially hailed as a sign of recent flows of liquid water on the surface of Mars. This supposition was contrary to our understanding of recent environmental conditions on Mars, under which water should not exist in its liquid form. In response to their discovery, researchers proposed a wide range of scenarios to explain this apparent paradox, including scenarios driven by CO_2, climate change or the presence of a liquid water aquifer. This Special Publication is a collection of papers arising from the topics discussed at the Second International Workshop on Martian Gullies held at the Geological Society, London. A review paper opens the Special Publication and thereafter the papers are presented under three themes: Martian remote sensing, Earth analogues and laboratory simulations. This Special Publication establishes the state of the art in Martian gully research, presents the latest observations and interpretations of the present-day activity and long-term evolution of Martian gullies, explores the role of Earth analogues, highlights novel experimental work and identifies future avenues of research. The importance of gullies as a potential marker of habitable environments on Mars underlines their importance in framing space exploration programmes.

The First International Workshop on Martian Gullies, the ‘Workshop on Martian Gullies: Theories and Tests’, was held on 4–5 February 2008 at the Lunar and Planetary Institute in Houston, Texas, USA. Its purpose was to bring together researchers examining gullies (Malin & Edgett 2000) and to discuss progress with respect to the various hypotheses in circulation. At that time, the formation of gullies (Fig. 1) by top-down melting under a past climate regime was favoured over the aquifer theory. Hypotheses involving dry processes, including CO_2-supported flows, had been gradually abandoned due to dissimilarities with dry processes on the Moon and Earth. Two major discoveries disturbed this consensus after the workshop: (1) the realization that present-day Martian gullies were active during winter, when water is highly unlikely to be present in its liquid form, and that the activity could not simply be attributed to dry mass wasting (e.g. Dundas *et al.* 2015), which re-established dry processes as a candidate for forming Martian gullies; and (2) the discovery of recurring slope lineae, which are active at the present day and were initially linked to the seepage of liquid water (McEwen *et al.* 2011). These recurring slope lineae reanimated the dry v. wet gully formation debate.

This Special Publication came together as a result of the Second International Workshop on Martian Gullies, entitled ‘Martian Gullies and their Earth Analogues’, held at the Geological Society in London during the Geological Society’s Year of Water. The aim of the workshop was to revisit the debate on the formation of Martian gullies in the light of new research and new data gathered since the last workshop. Martian gullies (Fig. 1) remain a highly attractive and dynamic research topic because of

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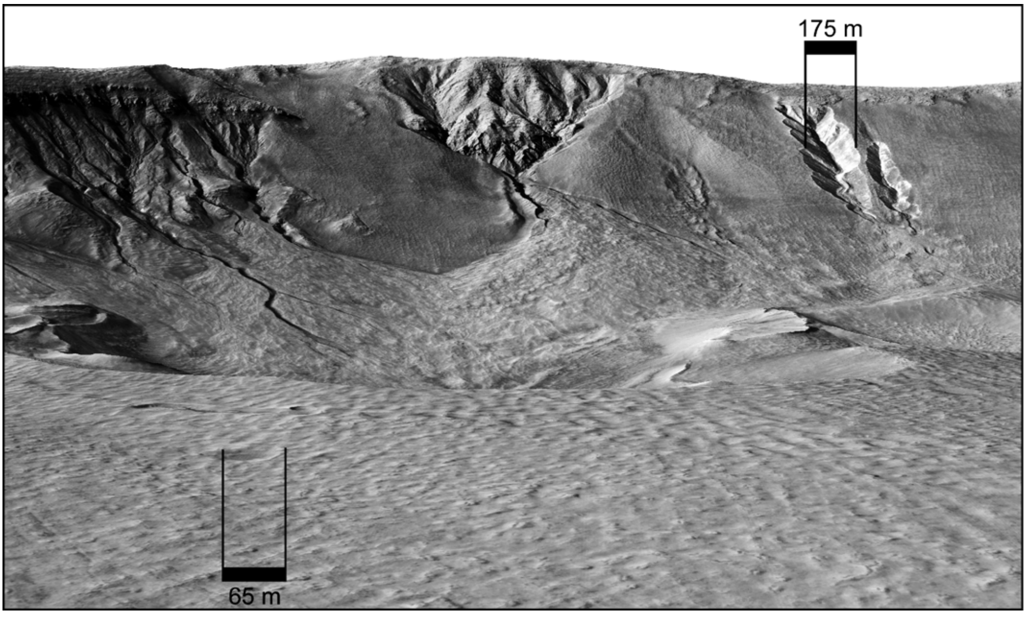

Fig. 1. Perspective view of gullies in Niquero Crater on Mars in HiRISE image ESP_030021_1410 (credit NASA/JPL/UofA) overlain on a digital elevation model from Conway *et al.* (2018*a*) with scale bars located in foreground and background for ease of reference.

their potential as indicators of liquid water on the surface of Mars and elsewhere (e.g. Scully *et al.* 2015). Water is the principal ingredient for life and finding evidence for it drives the exploration programmes of national space agencies, such as the famous 'Follow the Water' slogan of the National Aeronautical and Space Administration and the ambitious ExoMars programme of the European Space Agency. The importance of gullies in space exploration is highlighted by the fact that gullies are explicitly mentioned in the Findings of the Mars Special Regions Science Analysis Group White Paper, which lists Martian 'special regions' where visiting spacecraft need to take additional precautions because 'terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant Martian life forms' (COSPAR 2002, 2005 – see summary in Rettberg *et al.* 2015; NASA 2005). The possibility of liquid water forming gullies on Mars has enormous implications for the climate and history of Mars and how they are recorded in its rocks, the alteration of rocks and meteorites from Mars and the availability of resources for human habitation. Understanding Martian gullies could therefore be important not only for our understanding of the planet, but also in the design of future space missions and the selection of landing sites.

This Special Publication represents a cross-section of the work presented at the Second International Workshop on Martian Gullies. It opens with a review paper (**Conway *et al.* 2018*c***) summarizing the research performed to date on Martian gullies and an assessment of the issues that need to be resolved to progress our understanding of these controversial landforms. This initial paper deals with the three major points of discussion that arose at the workshop: (1) terminology; (2) our understanding of sediment transport by fluids, including CO_2; and (3) the usefulness and limits of Earth analogues in studying Martian gullies. The book is then split into three major sections: Martian remote sensing, Earth analogues and laboratory simulations.

Martian remote sensing

This is the longest section of the Special Publication and is representative of the approaches used in the community studying Martian gullies. The latest results on the present-day activity of Martian gullies, including constraints on the timing and frequency of activity, are covered by four papers (**Dundas *et al.* 2017**; **Diniega *et al.* 2017**; **Jouannic *et al.* 2018**; **Pasquon *et al.* 2018**). **Dundas *et al.* (2017)** present an overview of gully activity and posit that CO_2 sublimation processes drive present-day activity. The other three papers focus on the activity of gullies on dunes on Mars. This activity is shown to be annual and seasonal and is probably linked to the action of CO_2, but with the possibility of water action left open in some cases. As a counterpoint to recent activity, the timing of the formation of gullies in the last few million Mars years was also discussed at the workshop and is reported by **de Haas *et al.* (2017)**, who suggest that water may have been the preferred candidate for the formation of gullies in the (recent) past. Papers are also presented covering the analyses of remote sensing data and provide new constraints for the development of gully formation models, including global topographic data (**Conway *et al.* 2017**), thermal inertia (**Harrison *et al.* 2017**), landform assemblages (**Soare *et al.* 2018**) and a detailed hydrological analysis of topographic data (**Gulick *et al.* 2018**). These papers lead to the conclusion that water is the most likely agent producing Martian gullies, particularly in the light of new modelling work that leverages such results (Conway *et al.* 2018*b*).

Earth analogues

The Earth analogues presented at the workshop and included in this Special Publication include Antarctic water flows in Victoria Land (**Hauber *et al.* 2018**) and the McMurdo Dry Valleys (**Dickson *et al.* 2017**) and Himalayan debris flows generated by snowmelt (**Sinha *et al.* 2018**). The Earth analogues discussed at the meeting, but not included in this book, were submarine landforms (Gales *et al.* 2012), gullies in Meteor Crater, dune processes in Egypt and alluvial fans in Svalbard (Hauber *et al.* 2011) (Fig. 2). These analogues contribute significantly to our understanding of the processes and environmental constraints under which such landscape features can form and aid in formulating hypotheses that can be tested via Martian or laboratory studies.

Laboratory simulations

Small-scale Earth analogues, provided by laboratory simulations of the processes that could form Martian gullies, were also a notable topic of the workshop. Laboratory simulation papers are presented here on understanding sediment transport by CO_2 sublimation (**Sylvest *et al.* 2018**), metastable water (**Herny *et al.* 2018**) and slush flows (**Auld & Dixon 2017**) – all potential processes for forming and modifying Martian gullies. Experiments with sliding CO_2 blocks were also presented at the workshop, but these have been published elsewhere (McKeown *et al.* 2017). These blocks are thought to be an active agent in the formation of the 'linear' gullies found on dunes, a peculiar sub-type of Martian gullies.

Discussion and conclusions

This Special Publication contains a cross-section of the latest work on Martian gullies. The subjects presented at the workshop, but not encapsulated by the papers within this Special Publication, include: the implications of global climate model results for the formation of Martian gullies, which have been seminal in establishing the obliquity paradigm (Costard *et al.* 2002) and bolstering the CO_2 hypothesis (Pilorget & Forget 2016); numerical modelling of the flows that form Martian gullies (Pelletier *et al.* 2008; Mangeney *et al.* 2010); the role of dry processes, including wind and dust, in gully formation

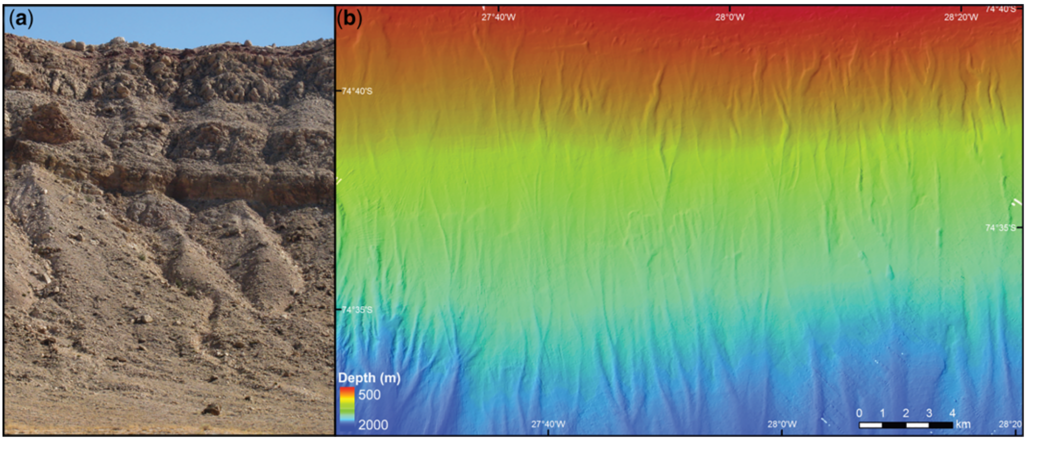

Fig. 2. Terrestrial analogues for Martian gullies. (**a**) Gullies in Meteor Crater, Arizona, USA. The boulder in the foreground is *c.* 4 m across. Image credit: Marisa Palucis. (**b**) Sun-illuminated multi-beam bathymetry showing submarine gullies on the southern Weddell Sea continental margin, Antarctica. Acquisition system Kongsberg EM122. Frequency 12 kHz. Grid cell size 30 m. Image credit: Jenny Gales.

and modification (Treiman 2003; De Haas *et al.* 2015); the spectral identification of volatiles and minerals at active gully sites (Vincendon 2015); the reporting of controversial equatorial Martian gullies (McEwen *et al.* 2018); and the link between the generation of recurring slope lineae and gullies and gullies as a landform within a paraglacial time series (Jawin *et al.* 2018; Conway *et al.* 2018*a*). The breadth of the topics covered in this Special Publication, at the workshop and in the wider literature attest to a continuing interest in these familiar, yet enigmatic, landforms. This Special Publication provides a key reference to those new to the field as well as inspiration for future research, because it:

- establishes the state of the art in the field in the initial review paper (**Conway *et al.* 2018*c***), identifying knowledge gaps and future avenues of research;
- presents the most up-to-date observational data of Martian gullies from remote sensing and provides the latest interpretations of these data;
- describes a range of terrestrial analogues as potential processes and environmental analogues, which aid in formulating and testing hypotheses about the formation and modification of Martian gullies; and
- presents novel laboratory simulations giving insights into the dynamics of potential gully-forming processes, observations that are inaccessible via remote sensing.

The interpretation of the processes that form Martian gullies will continue to shape future space exploration. In the near term, new insights are expected from the Colour and Stereo Surface Imaging System (CaSSIS) onboard the Trace Gas Orbiter, part of the European Space Agency's ExoMars programme, which started acquiring data in 2018. The colour imaging ability of CaSSIS will allow easier detection of new activity in gullies (Tornabene *et al.* 2018), acquisitions at different times of day (Thomas *et al.* 2017) and promises a deeper investigation into the roles of seasonal and diurnal ice and frost in present-day gully activity. The designated three-dimensional data from CaSSIS will allow a more systematic study of gully morphometry. The papers gathered in this Special Publication show that gullies are an important area of continuing research and space exploration: they are a key landform in unravelling Mars' recent (million-year range) hydrological cycle and climate and therefore the habitability and potential for life on modern-day Mars.

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