PROCESSES AND MORPHOLOGIES OF ICELANDIC GULLIES AND IMPLICATIONS FOR MARS

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ABSTRACT

Iceland provides an excellent natural laboratory for studies of debris flows and other steep slope water-related transport processes. These phenomena are important for the understanding of terrestrial landscape evolution. Basic morphological similarities between Icelandic gullies and controversial, potentially water-related gullies on Mars suggest that Icelandic gullies may also offer insight into the conditions and mechanisms of Martian gully formation. An understanding of how different processes lead to different morphologies in Iceland could identify diagnostic features to help fingerprint the range of processes operating on Mars. Aerial photographs of study sites in Iceland, along with on-site temperature sensors, provide information about the evolution of gully morphology and timescales of gully activity. We use our preliminary observations to investigate the roles of snowmelt, rainfall, and topography in shaping Icelandic steep-slope features.

INTRODUCTION

Debris flows are water-mobilized gravity flows that carry a poorly mixed slurry of rock and sediment downslope. They are one of the major landforms that influence the shape of high-latitude slopes (Åkerman, 1978; Rapp, 1986), and they are ubiquitous in Iceland. Their distinctive signature morphology consists of a chute-like head alcove, a channel (often raised with levees), and a conical debris apron; taken together, these constitute a 'gully'. Other steep-slope processes active in Iceland include snow avalanches, nivation, gelifluction, rockfall, and fluvial erosion. Many of these processes overlap spatially with debris flows, competing to shape the morphology of gullies.

Previous studies of debris flows in Iceland (e.g. Decaulne and Sæmundsson, 2007) have focused on their natural hazard relevance. We intend to explore the geomorphologic roles of steep-slope processes in Iceland, and we will investigate the potential relevance of these terrestrial processes to gullies and gully-like forms on Mars.

In 2000, Malin and Edgett published images of alcoves, sinuous channels, and debris aprons photographed by the Mars Orbiter Camera (MOC). They championed these gullies as evidence of recent liquid water flowing across the surface of Mars. Substantial controversy ensued, as the planetary science community argued over how the gullies had formed and whether liquid water was involved. Three main end-member hypotheses emerged: liquid water from a subsurface aquifer (Malin and Edgett, 2000; Heldmann, 2007), runoff from melt of snow deposited during a high-obliquity period (Christensen, 2003; Dickson et al., 2007), and dry granular flow (Treiman, 2003). The pitch of the discussion was heightened with Malin et al.'s (2006) announcement of new, bright deposits in two gullies that had appeared since the last set of photographs was taken in 1999.

In the absence of primary data on Martian gullies beyond orbital imagery and spectral analysis, terrestrial analogs have proven to be a valuable resource for testing new ideas about Martian gullies. Previous terrestrial analog studies include Costard et al.'s (2002) work on debris flows in Greenland, Hartmann et al.'s (2003) study of gullies in Iceland, and the work of Head et al. (2007) in the Antarctic Dry Valleys. With its easy accessibility, Iceland offers an excellent opportunity to study a broad range of steep-slope features and to test their viability as Martian analogs (Black and Thorsteinsson, 2008).

Simple debris flows are the Icelandic landform most similar in appearance to the classic Martian gully. Debris flows require ample water, which is in limited supply on Mars, although liquid water runoff at the Martian surface is possible with the assistance of a plugged aquifer (Malin and Edgett, 2000; Heldmann et al., 2007) or a brine *(*Marchant and Head, 2007). But we stress the diversity of steep-slope processes in Iceland, many of which require little or no liquid water to activate. As Åkerman (1978) has pointed out, gully activity on Earth may have fluctuated since the end of the last glaciation. The basic gully structures may be several thousand years old (Rapp, 1987). However, as our results will show, many processes continue to substantially modify gully morphology in the present day. It is therefore important to identify and describe the full range of these ongoing erosional, transport, and depositional processes. An understanding of how different processes lead to different morphologies in Iceland could provide diagnostic features to help identify the range of processes operating on Mars.

With these considerations in mind, the ultimate goals of our investigation are as follows:

- To gain an understanding of the mechanisms of gully formation and their relationship to gully appearance. The basic mechanisms driving debris flows in Iceland have been described by Decaulne and Sæmundsson (2007), and they include: rain on snow, snowmelt induced by a rapid temperature increase (>10ºC in 24 hours), and long-lasting and/or intense rainfall. The morphological expression of these various causes, however, requires further study.

- To analyze gully activity over longer timescales.
- To characterize the evolution of gully morphology.

METHODOLOGY

We combine ongoing field measurements and observations with analysis of aerial photographs provided by Landmælingar Íslands (LMÍ).

The field measurements include snow density, snow temperature, gully-bottom temperature, slope, and the basic dimensions of the gully. Gully-bottom temperatures are obtained with two electronic temperature sensors, one on Ármannsfell and one on the eastern part of the Esja massif. These Starmon-type sensors have an accuracy of ±0.05°C and they take a temperature reading every minute. We have installed them in the bottom of gully channels, in the hope that episodes of meltwater flow in the gullies will leave a temperature signature. We expect that any snowmelt events resulting in top-to-bottom flow should appear as periods of constant near freezing temperature. The goal of our field measurement program is to assemble a record of changes in gully activity and morphology over the course of a full year, thereby illuminating any seasonal dependence.

The aerial photographs (e.g. Figure 2) promise additional insights into rates of gully formation, stages of activity and dysfunction, and areal distribution. They range in scale from roughly 1:20,000 to 1:60,000. Complete coverage of Iceland is available at intervals of roughly 10 years, from 1945 onwards.

RESULTS

Field Observations

Substantial volumes of windblown snow accumulate in the alcoves and channels of Icelandic gullies. Excavation of a gully on Mt. Esja showed that snow depths at the top of the channel were greater than 2.5 meters, even when the adjacent slope was bare. Observation of other Icelandic gullies indicates that this degree of concentration is not unusual. Nivation (snow wash) and focused snow avalanches may be important geomorphic factors as a result (Rapp, 1986). Nivation over millennia may be a primary agent in shaping the scalloped alcoves where Icelandic gullies originate. Snow density and snow temperature profiles from gullies in Southwest Iceland show temperate spring snow packs, with snow responding to air temperature in the top few centimeters but stabilizing at or slightly below zero degrees Celsius throughout the remainder of the profile. Densities range from 0.26 kg/m^3 to 0.554 kg/m^3.

Icelandic gullies vary in cross-section from V-shaped to U-shaped channels. Luckman (1977) has observed that repeated, concentrated snow avalanches may produce U-shaped chutes, which cannot be easily explained by running water. Among the V-shaped channels, there is a wide spread in depth/width ratios. This may prove a fruitful area for additional measurement.

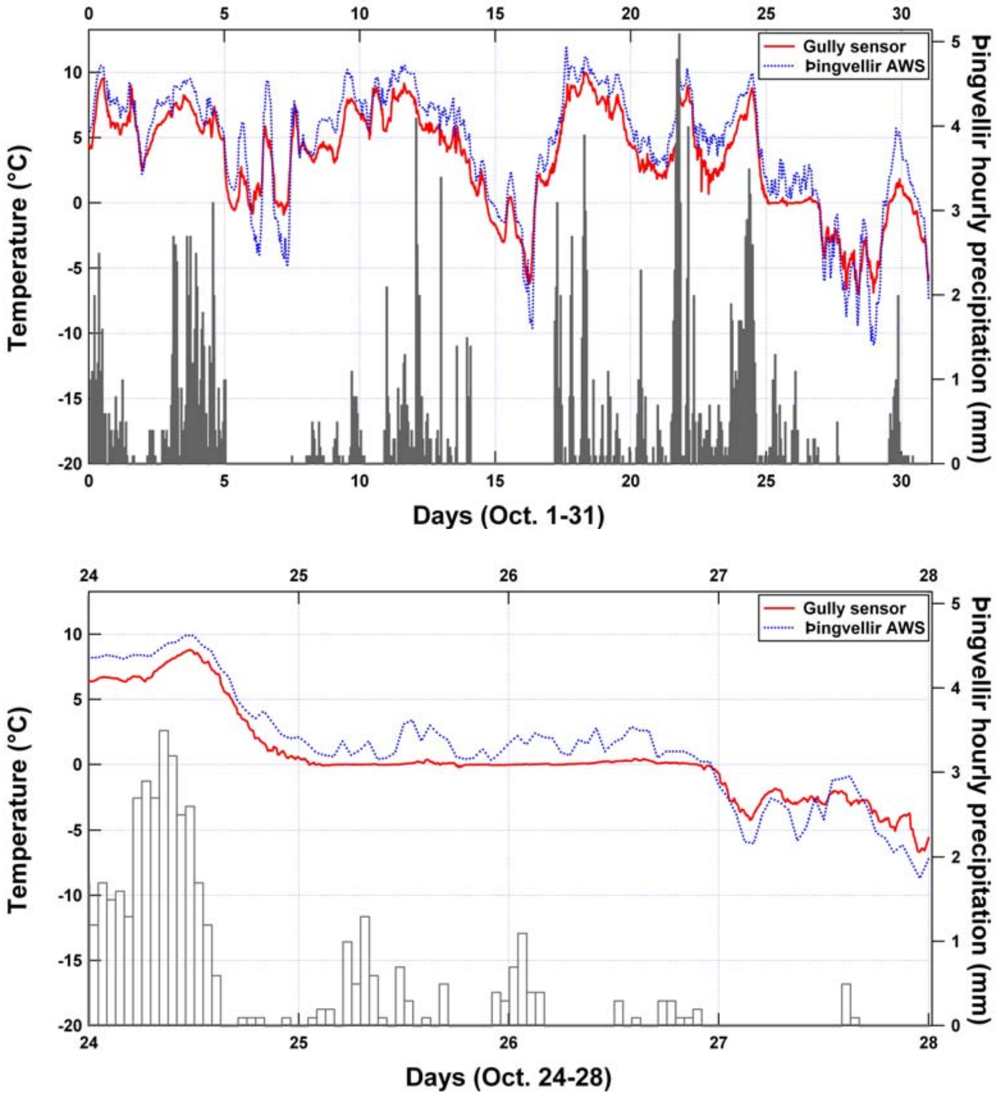

Figure 1. (Top): October temperature measurements from a sensor at Ármannsfell (elev. ~400 m) along with hourly precipitation (gray bars) and temperature at the nearby Þingvellir weather station.

Figure 1. (Bottom): An enlargement of a period of potential gully flow.

Unlike on Mars (Christensen, 2003), older, degraded, and inactive gullies are clearly present in Iceland. Previous authors have used lichen to estimate the elapsed time since the most recent debris flow activity, finding recurrence intervals ranging from 40-500 years in north Sweden (Rapp, 1986).

The temperature sensors reveal one potential episode of flow in the Ármannsfell gully on October 26-27, shown in Figure 1. The three days preceding October 26 were unusually warm, with heavy precipitation (Figure 1). Precipitation on the day preceding the anomaly was especially heavy. We infer that a combination of a warm air mass passing through the area and heavy rain may have triggered snowmelt in the alcove and channel, leading to runoff in the gully. However these results must be viewed with care, as a snow pack around the sensor could also cause zero temperature readings.

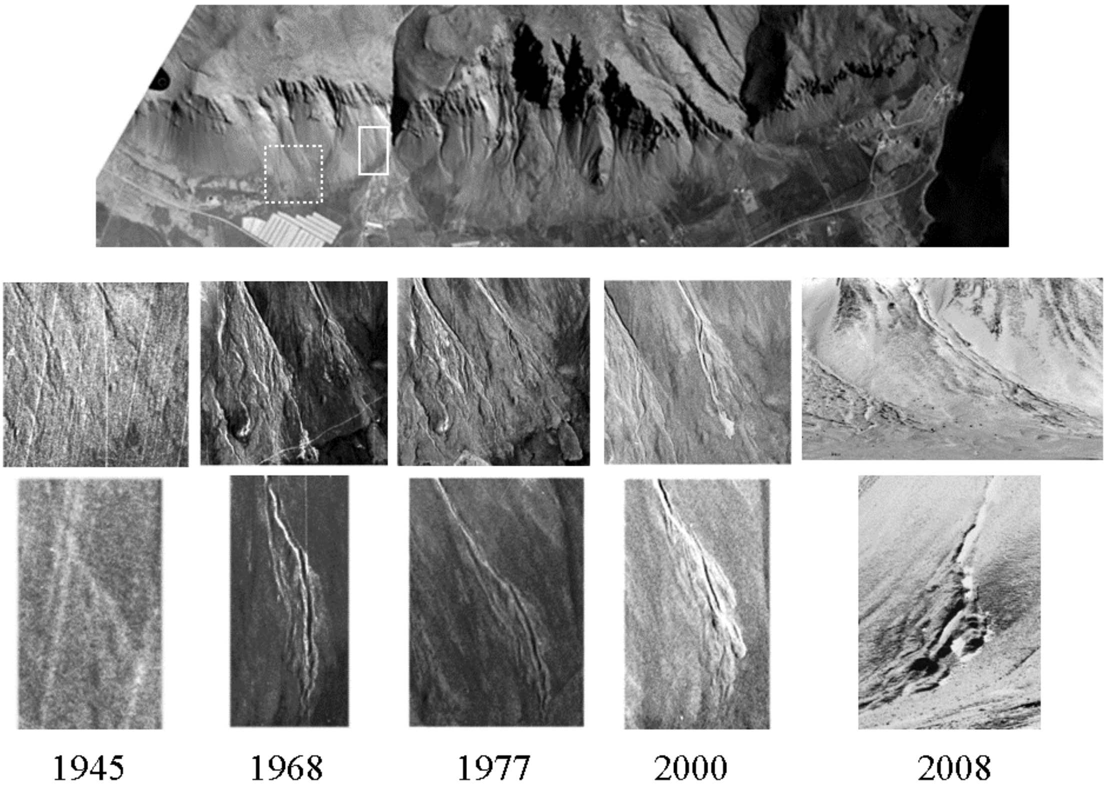

Figure 2. The image at the top provides context of the ~6 km western face of Mt. Esja; the second row and third row present close-ups of fan morphology at two sites in 1945, 1968, 1977, 2000, and 2008. 2008 images are ground-based from January; all other images are aerial, and taken during the summer (courtesy of LMÍ). The gully sites in the second and third rows are indicated by the dashed and solid rectangles, respectively, in the context image. Note the decadal-scale changes in the main channels through the debris aprons, and the snow-filled channels in the 2008 images.

The fact that there is rarely only one process at work, even in the same gully, has complicated our efforts to isolate cause and morphological effect.

Orientation does not appear to have a strong effect on large-scale gully distribution in Iceland, although certain faces at specific sites host more gullies than others. Similarly, geology is not a major control either: gullies are found both on hyaloclastic formations and layered basalts. Interestingly, gullies can also occur when there is no upslope drainage network, supporting the role of snow accumulation and melt as a primary driver of gully formation in some cases.

Observations from Aerial Photographs

Analysis of aerial photographs helped us to bracket the timescales of change in Icelandic gullies. On a decadal scale, changes in debris aprons and distal channels were plentiful. Over the course of 50 years, one small new debris flow track appeared on a ~6km face of Mt. Esja (Figure 2, top). We also identified a transient set of intriguing parallel incisions, which appeared and disappeared in tens of years.

Clearly, Icelandic gullies are being actively modified on decadal timescales in the present day. But equally noticeable was the lack of major changes in the landscape of the slope. We did not identify any changes in alcove morphology, and the number of major gullies and channels remained static. We therefore suggest that primary development of gully morphologies occurs on much longer timescales than those for which aerial records are available.

Figure 2 presents close-ups (from 1945, 1968, 1977, 2000, and 2008) of two adjacent sites on Mt. Esja. Changes in the channel paths through the debris aprons, and new debris deposits, are visible at both sites. Whipple and Dunne (1992) argue that debris fan morphology reveals flow rheology: debris-rich flows roughen fan surfaces, and flows with high sediment loads fill in channels, leading to avulsion and the creation of new depositional termini. Time-staggered aerial photographs like those in Figure 2 allow us to analyze the evolution of debris aprons. We observe that individual deposits tend to be rounded and lobate, but as individual deposits accumulate, leading to distal channel avulsion, the overall debris apron may become digitate. This process is illustrated in the bottom sequence of Figure 2.

DISCUSSION

Implications for Iceland

Rapp (1960) and Åkerman (1978) have noted that present rates of talus formation in Spitsbergen seem too low to be consistent with the observed debris fans. They suggest that talus development might be substantially enhanced during periods of increased debris availability. In recent decades glaciers in Iceland have been retreating, possibly due to climatic warming (Sigurðsson et al., 2007). Where valley glaciers retreat to expose slopes, sediments and debris may be released, leading to local increases in the rate of debris apron formation and/or debris flow activity in Iceland. Reported debris flow activity in Iceland has increased in historical time (Decaulne and Sæmundsson, 2007); however it seems likely that this is largely an artefact due to better record-keeping.

Our observations serve to reinforce the diversity of the processes that help to shape Icelandic gullies. Hydrologically, subsurface aquifers do not appear to play a large role in Icelandic gullies. The sources of liquid water are primarily surface runoff and snowmelt.

Figure 3. New bright deposits in a gully in Terra Sirenum on Mars (Malin et al., 2006; HiRISE PSP_004229_1435). Note the digitate terminus.

Implications for Mars

The nature of contemporary gully activity on Mars is one of the major questions in the Mars community today. Terrestrial analogs provide several potential agents as alternatives to liquid water. Snow avalanches, for example, can be facilitated by snow concentration in gullies previously shaped by water.

Pelletier et al. (2008) modelled one of Malin et al.'s (2006) new bright deposits (shown in Figure 3). They found that dry granular flows or very sediment-rich flows produced morphologies more consistent with the observed deposits than the morphologies produced by water-rich flows. Dry granular flows terminated in distributary fingers like those seen in Figure 3, whereas water-rich flows were more strongly controlled by topography and terminated in the same, lowest, location. However, Pelletier et al. (2008) were modelling a single flow event. In Iceland, most gullies appear to host multiple flow episodes. As Figure 2 shows, water-related flows can produce digitate termini; the fingers accrue in separate flows, as deposition blocks old channels and causes avulsion.

Running water, rock glaciers, and gelifluction may all help to erode or remove terrestrial debris aprons. In the absence of any of these processes, debris aprons would likely have been removed during the last glaciation (Rapp, 1986). Thus the maximum age of Icelandic debris aprons may be assumed to be on the order of 10,000 years ago, when the Weischelian glaciation ended. In this context, questions about the age of Martian gullies become vexing. It is difficult to estimate the rate of removal of debris on Mars, especially large debris, but certainly it is much lower than on Earth. Martian gullies do overlay most other young features, including dunes in some cases. However, as our work shows, many other processes can be activated *by the presence of a gully*. The original genesis of Martian gully structures could thus have occurred several tens of millions of years ago, while more recent snow and ice deposition and rockfall may be promoted by the topography of the gully, maintaining a low level of activity.

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