

MARS GULLY ANALOGS IN ICELAND: EVIDENCE FOR SEASONAL AND ANNUAL VARIATIONS.

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Introduction: When in 2006 Malin et al. [1] reported images showing higher-albedo deposits in gullies that had lacked them in photographs taken 4-5 years previously, the controversy over the formation mechanisms for the gullies did not abate [2-7]. These images did, however, provide strong evidence for some contemporary activity of the gullies, in addition to underlining the following pressing questions: (i) What is the rate of Martian gully formation, (ii) is gully formation episodic or continuous, (iii) is gully formation fast or slow, (iv) how has the rate of gully formation changed over time, and (v) what factors govern the rate and morphology of gully formation?

Previous workers have reported the existence of Mars gully analogs on Earth, in particular in Greenland [7], Iceland [8] and Antarctica [9,10]. However, many of these studies have been limited in scope or duration. Here, we will present the preliminary findings from a longer-term study of Icelandic Mars gully analogs (September 2007 to June 2008), with a goal of identifying clues to the formation mechanisms for a range of gully morphologies, along with rates of gully formation and degradation.

Methodology: In order to assess the seasonal alterations in Icelandic gullies, we have established a network of 11 gully sites. The sites encircle the island. The more accessible sites near to Reykjavik are visited on a monthly basis, whereas the more remote sites are monitored on a seasonal basis. We also installed two electronic temperature sensors, one on Ármannsfell, a 766-meter high mountain ~50 km northeast of Reykjavik, and one on Langahlið, a 527-meter high slope ~20 km south of Reykjavik. Both sites are Upper Pleistocene hyaloclastite formed by subglacial volcanism. As shown in Figure 2, the sensors were placed in the bottom of the gullies near the debris aprons to catch any top-to-bottom flow; the Ármannsfell sensor rests on bedrock. The *Starmon* sensors have an accuracy of $\pm 0.05^\circ\text{C}$ and they take a temperature reading every minute. Any snowmelt events resulting in top-to-bottom flow should appear as periods of constant near-freezing temperature.

These field approaches will be supplemented by analysis of aerial photographs, which we hope to have completed by Spring 2008. These photographs promise additional insights into rates of gully formation, stages of activity and dysfunction, and areal distribution. Complete coverage of Iceland is available at intervals of roughly 10 years, from the 1940s onwards.

Observations and Discussion: The fall of 2007 has been anomalously wet in Iceland. Rainfall equivalent precipitation in September in Reykjavik reached 163 mm and 175 mm in October, roughly double the 1961-1990 averages. These conditions, by increasing the available water inventory, should increase any water-related gully activity.

Insights from Field Observations. The scale and morphology of many Icelandic gullies are extremely similar to Martian examples. Channels originate in deep alcoves in blocky escarpments or shallow alcoves that collect snow in winter, and terminate in digitate debris aprons (see Figure 1). Gully systems range from several hundred meters to a kilometer in length, which is comparable to gully sizes on Mars [2]. Multiple terminal deposits and braided channels and debris aprons suggest several discrete episodes of flow. Unlike on Mars [4], older, degraded, and inactive gullies are



Figure 1 (top). A gully in the Tindastóll range in northern Iceland. Note the snow-filled alcove and channel, the levees, and the debris apron in the foreground. **Figure 2.** A temperature sensor deployed on bedrock on the floor of a gully on Ármannsfell.

clearly present in Iceland. Vegetation is one valuable indicator of dormancy that is unavailable to us on Mars. As Figure 1 shows, substantial volumes of wind-blown snow (1-2 meters depth) collect in gully channels, even when nearby slopes are snow-free.

Initial investigations of Icelandic gullies did not focus on snow-related features, as snowmelt phenomena were considered unviable on Mars [8]. Recently, theories of high-obliquity Martian snow deposition and melt [4,5] have been proposed as explanations of the Martian gullies. Opponents suggest that the production of significant volumes of runoff from snow would be difficult on Mars [6]. Snowmelt gullies appear to be plentiful in Iceland; they tend to originate upslope in a shallow concavity, often with braided depressions feeding into a central channel without levees. Similar morphologies also exist on Mars [2]. Further investigation of morphologies associated with snowmelt in terrestrial analogs may shed light on whether there is evidence for a similar process on Mars.

Hartmann et al. [8] found that evidence from Icelandic gullies agreed with Costard et al.'s [7] hypothesis of obliquity-induced melting of ground ice and consequent debris flow. We suggest that the prevalence of two distinct morphologies in Iceland—debris flow gullies and snowmelt gullies—may also be the case on Mars. Martian microclimates [10] might have allowed snow to exist on some slopes and ground ice to melt on others simultaneously during the last high-obliquity period; this is consistent with the wide variety of gully forms observed on Mars.

Insights from Temperature Measurements. Initial monitoring of the Ármannsfell gully during the months of October and November captured one anomaly with the characteristics we predicted for a snowmelt event, as described above. Beginning October 26th around 1 a.m. and continuing until October 27th around 10 p.m., the temperature flatlined at 0°C, with only a few small excursions, no greater than $\pm 0.4^\circ\text{C}$. Although the Pingvellir weather station (~4 km away) also recorded air temperatures near freezing during this period, the temperatures at the weather station show greater variability. As Figure 3A shows, the stable temperature during this time period resembles no other section of the temperature profile between September 30 and November 5. The likelihood that such an anomaly would occur at exactly 0°C by coincidence seems extremely low. We conclude that this section of the temperature profile represents a likely period of snowmelt flow in the gully, with flow reaching at least to the apex of the debris apron where the sensor was located.

The three days preceding October 26 were unusually warm, with heavy precipitation (Figure 3A). Precipitation on the day preceding the anomaly was

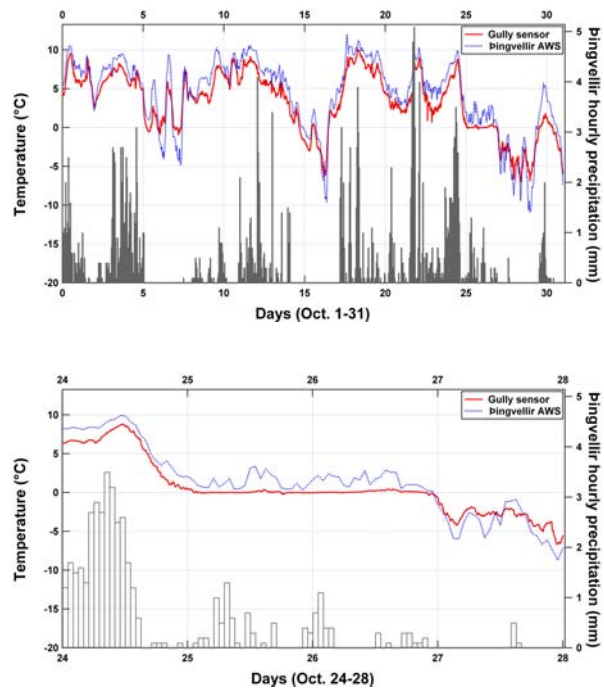


Figure 3A (top). October temperature measurements from a sensor at Ármannsfell (elev. ~400 m) along with hourly precipitation (gray bars) and temperature at the nearby Pingvellir weather station. **Figure 3B.** An enlargement of a period of potential gully flow.

especially heavy. We hypothesize 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. Results from several seasons of monitoring should provide a more complete picture of the conditions and frequency of gully activity.

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