Thermal inertia variations from gully and mass-wasting activity in Gasa crater, Mars

Tanya N Harrison, Livio Tornabene, Gordon Osinski, Susan J Conway

► To cite this version:

Tanya N Harrison, Livio Tornabene, Gordon Osinski, Susan J Conway. Thermal inertia variations from gully and mass-wasting activity in Gasa crater, Mars. The Geological Society, London, Special Publications, 2019, 467 (1), pp.199-210. 10.1144/SP467.8 . hal-02270629

HAL Id: hal-02270629

<https://hal.science/hal-02270629>

Submitted on 8 Jan 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Thermal inertia variations from recent gully and mass wasting activity in Gasa 2 Crater, Mars

3 Tanya N. Harrison^{1†}, Livio L. Tornabene¹, Gordon R. Osinski^{1,2}, and Susan J. Conway³

4 ¹*Centre for Planetary Science and Exploration, Department of Earth Sciences, University of Western Ontario*

5 ²*Department of Physics and Astronomy, University of Western Ontario*

6 ³*Laboratoire de Planétologie et Géodynamique, Nantes, France.*

7 [†]*Current affiliation: NewSpace Initiative, Arizona State University, Tempe, AZ, USA*

9 1. Introduction

10 Gullies are incised channel features with source alcoves and depositional fans
11 found on slopes in the middle and high latitudes of Mars [*Malin and Edgett*, 2000]. Their
12 morphology is highly suggestive of liquid water having been involved in their initial
13 formation. This includes features such as banked, sinuous, and terraced channels,
14 superelevation of gully deposits, and terminal deposits travelling across slopes much
15 lower than the angle of repose for dry material [e.g., *Malin and Edgett*, 2000; *Heldmann*
16 *and Mellon*, 2004; *Malin et al.*, 2006; *McEwen et al.*, 2007], although dry and frost-
17 related processes have also been proposed [e.g., *Treiman*, 2003; *Hugenholtz*, 2008;
18 *Cedillo-Flores et al.*, 2011; *Dundas et al.*, 2012, 2015]. They also appear to be
19 geologically youthful, typically lacking craters and superposing recent aeolian features
20 such as transverse aeolian ridges [e.g., *Malin and Edgett*, 2000; *Reiss et al.*, 2004; *Schon*
21 *et al.*, 2009]. The unexpected observation of new light-toned flows in two pre-existing
22 gully channels with the Mars Global Surveyor (MGS) narrow angle Mars Orbiter Camera

(MOC NA) [Malin *et al.*, 2006] led to monitoring efforts to look for gully activity in an attempt to constrain how gullies on Mars may have formed, and how they are evolving today.

Carrying on the monitoring efforts of MOC NA, the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) [Malin *et al.*, 2007] routinely monitors 617 locations across both hemispheres at a pixel scale of 6 m for present-day gully activity [Harrison *et al.*, 2009]. The High-Resolution Imaging Science Experiment (HiRISE) aboard MRO [McEwen *et al.*, 2007] monitors approximately 500 of these locations at a pixel scale of ~0.25–1 m [Dundas *et al.*, 2016]. Thus far, present-day activity ranging from the movement of boulders [Dundas *et al.*, 2015] to the deposition of material on aprons and incision of new small channel segments [e.g., Malin *et al.*, 2006; Harrison *et al.*, 2009; Dundas *et al.*, 2010] has been observed in 38 separate locations over the past decade. Of these, Gasa Crater has been the most active site observed on Mars to date, making it of particular interest for studying the process(es) behind gully formation and activity. In this study, we investigate whether differences in thermal inertia across different segments of gully systems, combined with morphological and colour observations with HiRISE, can provide some constraints of the physical characteristics associated with recent activity within gullies in Gasa. We also investigate thermophysical differences between slopes in Gasa dominated by gully activity compared to those predominantly modified by dry mass wasting processes. Thermal inertia can be used to model the grain size and/or induration of the upper (~1 to 10 cm) of surface materials [e.g., Ferguson *et al.*, 2006]; as such, this dataset can help us to better understand the mass movement processes occurring on the slopes within Gasa Crater.

46

47 **2. Setting and Previous Work on Gasa Crater**

48 Gasa Crater is a ~7 km impact crater centred at 35.7°S, 129.4°E (Figure 1), which
49 lies within the floor deposits of the older, infilled and degraded Cilaos impact crater (~19
50 km-diameter). Despite extensive gully activity on its northern wall, Gasa appears
51 morphologically well preserved [e.g., *Tornabene et al.*, 2006, 2012] consistent with a
52 young modeled age. Crater counts on the continuous ejecta blanket of Gasa yield a crater
53 retention age of 0.6–2.4 Ma, with a best-fit age of 1.25 Ma, possibly coinciding with the
54 last glacial maximum on Mars [*Schon et al.*, 2009]. Relatively unmodified secondary
55 craters and a lack of evidence for pasted-on deposits on the pole-facing wall suggest that
56 Gasa Crater formed after the last major episode of latitude-dependent mantle
57 emplacement in the southern mid-latitudes [*Schon et al.*, 2009; *Schon and Head*, 2012].
58 The floor of Gasa hosts pitted deposits of the type extensively documented by Tornabene
59 et al. [2012]. Such deposits are thought to represent primary crater-related deposits,
60 which are interpreted to form from the interaction of impact melt with volatiles
61 originating from the target [*Boyce et al.*, 2012; *Tornabene et al.*, 2012]. The preservation
62 of these deposits, especially atop the ejecta blanket, support the interpretation that Gasa is
63 not only geologically youthful, but well preserved.

64 Cilaos Crater, within which Gasa Crater sits, hosts gullies on its pole-facing walls.
65 These gullies formed within the pasted-on mantle emplaced before the formation of Gasa.
66 However, in some places the Cilaos gullies appear to superpose Gasa ejecta, suggesting
67 that gully activity in the region occurred both before and after the formation of Gasa [i.e.,

Schon and Head, 2012]. The pole-facing walls of Gasa host many gullies, with morphologies suggesting fluidized flows (such as debris flows) may have played a role in their formation [*Kolb et al., 2010; Lanza et al., 2010; Conway et al., 2011*]. The gullies within Gasa incise into the underlying bedrock [*Okubo et al., 2011*], unlike many other gullies on Mars that are observed within “pasted-on” crater wall mantling deposits [i.e., *Christensen, 2003; Dickson et al., 2015*]. Features interpreted as crown fractures, which represent extensional strains from downslope movement of rock in terrestrial mass movements, are observed in association with gully alcoves on the northeast wall of the crater, but not with the north/northwestern wall gullies. This may imply that the northeastern wall is the least stable in the crater [*Okubo et al., 2011*]. The equator-facing crater walls are steeper (Figure 1B) and display features with morphologies consistent with dry mass wasting processes observed within other well-preserved (non-gullied) craters similar in size to Gasa [e.g., *Tornabene et al., 2016*]. Gasa Crater has the highest asymmetry in backweathering rates of its pole-facing vs. equator-facing walls (factor of ~60) of all craters analyzed by de Haas et al. [2013], suggesting its gullied pole-facing wall is eroding at a much faster rate than the non-gullied equator-facing wall.

2. Methods

Thermal inertia is defined as:

$$I = (k\rho c)^{1/2}$$

where k is the thermal conductivity, ρ is the bulk density, and c is the specific heat capacity of the surface material. Units are in $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$, herein shortened to “thermal

inertia units” (TIU). On Mars, thermal inertia is most strongly controlled by the thermal conductivity of a material, which ranges over 3–4 orders of magnitude, while specific heat capacity and density only vary by a factor of ~3 for rocks and soils [e.g., *Wechsler and Glaser*, 1965; *Neugebauer et al.*, 1971; *Wechsler et al.*, 1972; *Presley and Christensen*, 1997b]. As such, thermal inertia is strongly controlled by the particle size of a material, with bulk conductivity varying as a function of the solid, radiative, and conductivity of interstitial gas. Solid and gas conductivity play the largest role under martian conditions [*Wechsler et al.*, 1972], predominantly controlled by the relationship between the particle size and the pore size relative to the mean-free path of a gas (~5 μm at martian surface pressures). When grain sizes are small enough that the pore size is about the same or smaller than the mean free gas path, heat transfer becomes inefficient due to a lower frequency of collisions between gas molecules and grains in the material. Thermal conductivity of fine-grained materials is also lowered due to the higher number of grain-to-grain contacts per unit length [*Jakosky*, 1986; *Presley and Christensen*, 1997a]. For grains larger than ~5 μm , thermal inertia is controlled by the size of a particle relative to the diurnal thermal skin depth (~1 cm for sand and ~10 cm for rock) [e.g., *Hardgrove et al.*, 2009]. This results in fine-grained, unconsolidated materials having lower thermal inertia values than coarse-grained and/or well-indurated (cemented) materials, although it is important to note that thermal inertia values alone are non-unique [e.g., *Ferguson et al.*, 2006 and references therein]. High resolution images provide additional insight on the texture and grain size of thermal inertia units.

Quantitative thermal inertia (TI) at 100 m per pixel was measured on standard data products calculated from Thermal Emission Imaging System (THEMIS) night-time

IR data [Christensen *et al.*, 2004] with an overall accuracy of ~20%, precision of 10–15%. THEMIS TI values are generally consistent with MGS Thermal Emission Spectrometer (TES) and the Mars Exploration Rovers mini-TES derived thermal inertia values [Fergason *et al.*, 2006]. We analysed the 32-bit 100 m/pixel THEMIS thermal inertia images [Fergason *et al.*, 2006; Christensen *et al.*, 2013] using the map sampling function in the Java Mission-planning and Analysis for Remote Sensing (JMARS) software package [Christensen *et al.*, 2009]. Gasa Crater was chosen both based on the size of its gully aprons, and because it is one of the few sites on Mars where present-day gully activity has been observed in multiple locations within the same crater over several Mars years [Dundas *et al.*, 2010, 2015]. Gully fan segments were mapped morphologically using HiRISE images ESP_014081_1440 and ESP_039531_1440 for complete clear-atmosphere, low shadow, and low emission angle ($<3^\circ$) coverage of the crater, with the HiRISE and THEMIS TI datasets each manually georeferenced to the THEMIS daytime IR 100 m global map (version 12) in JMARS. The HiRISE images were extremely contrast stretched during mapping to enhance details within the gully fans. Additional map creation was completed using ArcMap 10.2.

Due to differences in calibration between images and slope effects on absolute THEMIS thermal inertia values [Fergason *et al.*, 2006], we focus this work on the relative differences in thermal inertia between individual gully aprons and lobes within aprons using a single THEMIS TI strips covering Gasa (image ID I09926012, quality rating 5, acquired on 10 March 2004 at $L_s 2.48^\circ$ —near the start of southern autumn when surface frost has not been deposited at these latitudes). Only images with a quality rating of 5 or higher (7 being the highest possible rating), assigned by the THEMIS team, were

considered for use. Polygons were drawn covering portions of gully aprons, distinguishing between the youngest (stratigraphically topmost) apron deposits and the underlying older apron deposits (Figure 2). These polygons were drawn to intentionally subsample the apron deposits due to the difference in resolution between THEMIS TI and HiRISE in order to minimize sampling from surrounding pixels covering other aprons. Using the map sampling feature in JMARS, the thermal inertia values for pixels within each polygon were extracted. This map sampling function works such that if a pixel is more than 50% contained within the sampling polygon, its value is included in calculations; otherwise, the pixel is not counted [Scott Dickenshied, *personal communication*¹].

3. Results

3.1 General thermal inertia conditions within Gasa Crater

The materials within Gasa exhibit a wide range of thermal inertia values (Figure 3). The lowest values, averaging ~312 TIU, correspond with what is likely to be unconsolidated fine-grained deposits that have settled atop of—but not infilling or obscuring—pitted materials on the crater floor. The highest TI values correspond with bedrock exposures in the crater walls, particularly along the southwestern (non-gullied) wall and within the gully alcoves of the pole-facing walls. Thermal inertia values of gully aprons on the pole-facing wall have average thermal inertias ~60–75 TIU lower than the talus on the equator-facing wall (Figure 4; Table 1), suggesting the gully aprons are

¹ Scott Dickenshied a Scientific Software Designer at ASU and one of the lead developers for JMARS.

dominated by finer-grained material than the talus slopes. The gullied walls as a whole have a lower average thermal inertia than the non-gullied walls, consistent with observations by Lanza et al [2011] regarding differences in thermal inertia values of gullied vs. non-gullied crater walls. However, the alcoves of gullied and non-gullied walls have similar high TI values, generally greater than 460 TIU. Moderate TI values correspond with coarse-grained, unconsolidated talus on the equator-facing walls, consistent with preliminary morphologic and thermophysical mapping results by Tornabene et al. [2016] in non-gullied well-preserved craters. HiRISE IRB colour imaging of Gasa supports this interpretation. In HiRISE IRB images, yellows correspond to surfaces that are richer in ferric-bearing materials (in many cases due to coatings or the presence of fine-grained martian “dust”) while blues correspond to ferrous-bearing materials [Delamere et al., 2010]. The gullied walls of Gasa are generally yellower in the HiRISE IRB than the non-gullied walls (Figure 6), suggesting the gullied walls are potentially more dust-covered than the non-gullied talus slopes.

3.2 Thermal inertia and recent gully activity

Analysis of 66 individual gully fan segments show that in Gasa, the average thermal inertia values of the youngest apron deposits are generally ~20–40 TIU higher than the older underlying/surrounding deposits (Figures 4B–5). Present-day gully activity has been documented in gullies #10, 12, and 19 (as labelled in Figure 3) by Dundas et al. [2010, 2012, 2015]. All three of these have aprons with areas of concentrations of higher TI (yellow patches in Figure 3) relative to other fans/fan segments, although they are not

the only gullies with high TI fan segments. This could suggest that additional gullies within Gasa have been recently active, but not within the period of monitoring by CTX and HiRISE. It should be noted that the THEMIS image used in this study was acquired in 2004, before the changes documented by Dundas et al. [2010, 2012, 2015] occurred; therefore, we are not seeing the most recent changes that have occurred within Gasa with this THEMIS dataset.

4. Discussion

The observation of lower thermal inertia values for older fan deposits in martian gullies, combined with HiRISE IRB colour results, suggests that martian gully deposits decrease in thermal inertia over time due to deposition of atmospheric dust. Thermal mapping of alluvial fans in Death Valley by Hardgrove et al. [2009, 2010] found that older fan deposits had a *higher* thermal inertia than younger deposits, as their fine-grained component had been eroded away by aeolian (i.e., deflation) and fluvial processes. On Mars, the opposite effect appears to be the case, as the rate of dust deposition greatly exceeds the rate of deflation. This is consistent with estimates based on *in situ* surface investigations. The Mars Exploration Rovers [Kinch et al., 2015] and Phoenix [Drube et al., 2010] found an average dust deposition rate of 0.02–0.06 μm per sol, whereas deflation rates calculated from the Pathfinder [Golombek and Bridges, 2000] and the Mars Exploration Rovers [Golombek et al., 2006, 2014] are only ~ 0.1 nm/Myr in the Amazonian.

Another process likely acting to reduce the thermal inertia of martian gully fan lobes is the rapid breakdown of fan material. Denudation of inactive fans in both terrestrial hot-arid and cold polar desert environments results in the creation of a smooth desert pavement on fan surfaces as weathering and erosion proceed [e.g., *Matmon et al.*, 2006; *Frankel and Dolan*, 2007; *de Haas et al.*, 2013]. *de Haas et al.* [2013] calculated denudation rates in the Amazonian of 0.89 m/Ma, which would result in subduing small-scale morphology on gully fans on timescales of <1 Ma. This smoothing effect would be expected to lead to a lowering of thermal inertia values as larger grains in fan deposits break down. On Earth, debris appears to break down more quickly in cold polar desert (periglacial) environments relative to hot-arid deserts due to the action of snow avalanches, permafrost, and freeze-thaw cycles [*de Haas et al.*, 2014, 2015]—decades [e.g., *André*, 1990, 1995; *Luckman*, 1992] as opposed to thousands or hundreds of thousands of years [*Matmon et al.*, 2006; *Frankel and Dolan*, 2007]. Recurring snow avalanches can erode debris flow levees on Earth in as little as ~20–40 years, whereas debris flow levees in areas that do not experience snow avalanches can be preserved for hundreds to thousands of years [e.g., *André*, 1990, 1995; *Luckman*, 1992]. A similar process could potentially occur on Mars with dust avalanches, although slope streaks (thought to represent dust avalanches) are not typically observed in conjunction with martian gullies. Rapid breakdown of gully deposits may also explain why characteristic features of debris flows (i.e., levees) are only observed in a few martian gullies [e.g., *Levy et al.*, 2010] despite morphological parameters suggesting debris flows as a likely candidate process for gully formation [e.g., *Lanza et al.*, 2010; *Conway et al.*, 2011, 2015; *de Haas et al.*, 2014].

223

224 **5. Implications and Future Work**

225 Gasa Crater exhibits clear variations in thermal inertia across its walls, controlled
226 by the material properties and the types of dominant mass movement processes occurring
227 on each wall. The youthful gully fan lobes display thermal inertia values ~20–40 TIU
228 higher than adjacent older eroded and dust-covered lobes. The talus aprons from mass
229 wasting in Gasa have thermal inertia values ~60–80 TIU higher than gully aprons. The
230 results of this study thus suggest that repeated THEMIS day/night IR imaging
231 coordinated with MRO observations could be used for surface change detection. In the
232 case of gullies large enough to be resolved in the THEMIS IR, acquiring at least 1–2
233 images (in order to ensure at least 1 of acceptable quality is returned) at the beginning
234 and end of each season in both hemispheres would be ideal as gully activity appears to be
235 seasonally constrained to autumn through early spring [e.g., *Harrison et al.*, 2009;
236 *Diniega et al.*, 2010; *Dundas et al.*, 2010, 2012, 2015]. Analysis of thermal inertia
237 differences could aid in selecting or refining sites for monitoring by CTX and HiRISE,
238 and the ~5 m/pixel Colour and Stereo Surface Imaging System (CaSSIS) aboard the
239 European Space Agency’s ExoMars Trace Gas Orbiter [*Thomas et al.*, 2014].
240 Additionally, the thermal imaging of Hardgrove et al. [2009] revealed structure within
241 alluvial fans in Death Valley not distinguishable in visible images. This, combined with
242 the results of our study, may make a case for sending a higher-resolution thermal imager
243 to Mars on a future orbiter, as it could prove to be a valuable asset to study the structure
244 of gullies and deltas/alluvial fans, all of which are found in abundance on the planet.

245

246 **Acknowledgements**

247 T. N. Harrison acknowledges funding for this project from the Vanier Canada
248 Graduate Scholarship and the Amelia Earhart Fellowship. Feedback from Colin Dundas,
249 Phil Stooke, and Catherine Neish helped to improve this manuscript.

250

References

André, M.-F. (1990), Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry, *Polish Polar Res.*, 11(3–4), 345–363.

André, M.-F. (1995), Holocene climate fluctuations and geomorphic impact of extreme events in Svalbard, *Geogr. Ann. Ser. A-PHYSICAL Geogr.*, 77(4), 241–250.

Boyce, J. M., L. Wilson, P. J. Mouginis-Mark, C. W. Hamilton, and L. L. Tornabene (2012), Origin of small pits in martian impact craters, *Icarus*, 221(1), 262–275, doi:10.1016/j.icarus.2012.07.027.

Cedillo-Flores, Y., A. H. Treiman, J. Lasue, and S. M. Clifford (2011), CO₂ gas fluidization in the initiation and formation of Martian polar gullies, *Geophys. Res. Lett.*, 38(L21202), doi:10.1029/2011GL049403.

Christensen, P. R. (2003), Formation of recent martian gullies through melting of extensive water-rich snow deposits, *Nature*, 422(6927), 45–48, doi:10.1038/nature01436.

Christensen, P. R. et al. (2004), The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission, *Space Sci. Rev.*, 110, 85–130, doi:10.1023/B:SPAC.0000021008.16305.94.

Christensen, P. R., E. Engle, S. Anwar, S. Dickenshied, D. Noss, N. Gorelick, and M. Weiss-Malik (2009), JMARS – A Planetary GIS, *Am. Geophys. Union, Fall Meet. 2009*, abstract #IN22A-06.

Christensen, P. R., R. L. Fergason, C. S. Edwards, and J. Hill (2013), THEMIS-Derived

272 Thermal Inertia Mosaic of Mars: Product Description and Science Results, *44th*
 273 *Lunar Planet. Sci. Conf.*, Abstract #2822, doi:10.1029/2006JE002735.

274 Conway, S. J., M. R. Balme, J. B. Murray, M. C. Towner, C. H. Okubo, and P. M.
 275 Grindrod (2011), The indication of Martian gully formation processes by slope-area
 276 analysis, *Geol. Soc. London, Spec. Publ.*, 356(1), 171–201, doi:10.1144/sp356.10.

277 Conway, S. J., M. R. Balme, M. A. Kreslavsky, J. B. Murray, and M. C. Towner (2015),
 278 The comparison of topographic long profiles of gullies on Earth to gullies on Mars:
 279 A signal of water on Mars, *Icarus*, 253, 189–204, doi:10.1016/j.icarus.2015.03.009.

280 Delamere, W. A. et al. (2010), Color imaging of Mars by the High Resolution Imaging
 281 Science Experiment (HiRISE), *Icarus*, 205(1), 38–52,
 282 doi:10.1016/j.icarus.2009.03.012.

283 Dickson, J. L., J. W. Head, T. A. Goudge, and L. Barbieri (2015), Recent climate cycles
 284 on Mars: Stratigraphic relationships between multiple generations of gullies and the
 285 latitude dependent mantle, *Icarus*, 252, 83–94, doi:10.1016/j.icarus.2014.12.035.

286 Diniega, S., S. Byrne, N. T. Bridges, C. M. Dundas, and A. S. McEwen (2010),
 287 Seasonality of present-day Martian dune-gully activity, *Geology*, 38(11), 1047–1050,
 288 doi:10.1130/G31287.1.

289 Drube, L. et al. (2010), Magnetic and optical properties of airborne dust and settling rates
 290 of dust at the Phoenix landing site, *J. Geophys. Res.*, 115, E00E23,
 291 doi:10.1029/2009JE003419.

292 Dundas, C. M., A. S. McEwen, S. Diniega, S. Byrne, and S. Martinez-Alonso (2010),
 293 New and recent gully activity on Mars as seen by HiRISE, *Geophys. Res. Lett.*,

294 37(7), L07202, doi:10.1029/2009GL041351.

295 Dundas, C. M., S. Diniega, C. J. Hansen, S. Byrne, and A. S. McEwen (2012), Seasonal
 296 activity and morphological changes in martian gullies, *Icarus*, 220(1), 124–143,
 297 doi:10.1016/j.icarus.2012.04.005.

298 Dundas, C. M., S. Diniega, and A. S. McEwen (2015), Long-term monitoring of martian
 299 gully formation and evolution with MRO/HiRISE, *Icarus*, 251, 244–263,
 300 doi:10.1016/j.icarus.2014.05.013.

301 Dundas, C. M., S. Diniega, A. S. McEwen, C. J. Hansen, and S. Byrne (2016),
 302 Monitoring martian gullies: Implications for formation and evolution, in *Martian*
 303 *Gullies and Their Earth Analogues*, London, United Kingdom.

304 Fergason, R. L., P. R. Christensen, and H. H. Kieffer (2006), High-resolution thermal
 305 inertia derived from the Thermal Emission Imaging System (THEMIS): Thermal
 306 model and applications, *J. Geophys. Res. E Planets*, 111(12), 1–22,
 307 doi:10.1029/2006JE002735.

308 Frankel, K. L., and J. F. Dolan (2007), Characterizing arid region alluvial fan surface
 309 roughness with airborne laser swath mapping digital topographic data, *J. Geophys.*
 310 *Res.*, 112, F02025, doi:10.1029/2006JF000644.

311 Golombek, M. P., and N. T. Bridges (2000), Erosion rates on Mars and implications for
 312 climate change: Constraints from the Pathfinder landing site, *J. Geophys. Res.*, 105,
 313 1841–1853.

314 Golombek, M. P. et al. (2006), Erosion rates at the Mars Exploration Rover landing sites
 315 and long-term climate change on Mars, *J. Geophys. Res.*, 111(E12),

316 doi:10.1029/2006JE002754.

317 Golombek, M. P., N. H. Warner, V. Ganti, M. P. Lamb, T. J. Parker, R. L. Fergason, and
318 R. Sullivan (2014), Small crater modification on Meridiani Planum and implications
319 for erosion rates and climate change on Mars, *J. Geophys. Res.*, *119*(12), 2522–2547,
320 doi:10.1002/2014JE004658.

321 de Haas, T., E. Hauber, and M. G. Kleinhans (2013), Local late Amazonian boulder
322 breakdown and denudation rate on Mars, *Geophys. Res. Lett.*, *40*(14), 3527–3531,
323 doi:10.1002/grl.50726.

324 de Haas, T., D. Ventra, P. E. Carbonneau, and M. G. Kleinhans (2014), Geomorphology
325 Debris- flow dominance of alluvial fans masked by runoff reworking and
326 weathering, *Geomorphology*, *217*, 165–181, doi:10.1016/j.geomorph.2014.04.028.

327 de Haas, T., M. G. Kleinhans, P. E. Carbonneau, L. Rubensdotter, and E. Hauber (2015),
328 Surface morphology of fans in the high-Arctic periglacial environment of Svalbard:
329 Controls and processes, *Earth Sci. Rev.*, *146*, 163–182,
330 doi:10.1016/j.earscirev.2015.04.004.

331 Hardgrove, C., J. Moersch, and S. Whisner (2009), Thermal imaging of alluvial fans: A
332 new technique for remote classification of sedimentary features, *Earth Planet. Sci.*
333 *Lett.*, *285*(1–2), 124–130, doi:10.1016/j.epsl.2009.06.004.

334 Hardgrove, C., J. Moersch, and S. Whisner (2010), Thermal imaging of sedimentary
335 features on alluvial fans, *Planet. Space Sci.*, *58*(4), 482–508,
336 doi:10.1016/j.pss.2009.08.012.

337 Harrison, T. N., M. C. Malin, and K. S. Edgett (2009), Present-day gully activity

338 observed by the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX), in
 339 *Bulletin of the American Astronomical Society, DPS Meeting #41*, p. 1113.

340 Heldmann, J. L., and M. T. Mellon (2004), Observations of martian gullies and
 341 constraints on potential formation mechanisms, *Icarus*, 168(2), 285–304,
 342 doi:10.1016/j.icarus.2003.11.024.

343 Hugenholtz, C. H. (2008), Frosted granular flow: A new hypothesis for mass wasting in
 344 martian gullies, *Icarus*, 197, 65–72, doi:10.1016/j.icarus.2008.04.010.

345 Jakosky, B. M. (1986), On the thermal properties of Martian fines, *Icarus*, 66, 117–124,
 346 doi:10.1016/0019-1035(86)90011-4.

347 Kinch, K. M., J. F. Bell III, W. Goetz, J. R. Johnson, J. Joseph, M. B. Madsen, and J.
 348 Sohl-Dickstein (2015), Dust deposition on the decks of the Mars Exploration
 349 Rovers: 10 years of dust dynamics on the Panoramic Camera calibration targets,
 350 *Earth Sp. Sci.*, 2, 144–172, doi:10.1002/2014EA000073.

351 Kolb, K. J., A. S. Mcewen, and J. D. Pelletier (2010), Investigating gully flow
 352 emplacement mechanisms using apex slopes, *Icarus*, 208, 132–142,
 353 doi:10.1016/j.icarus.2010.01.007.

354 Lanza, N. L., G. A. Meyer, C. H. Okubo, H. E. Newsom, and R. C. Wiens (2010),
 355 Evidence for debris flow gully formation initiated by shallow subsurface water on
 356 Mars, *Icarus*, 205(1), 103–112, doi:10.1016/j.icarus.2009.04.014.

357 Lanza, N. L., H. E. Newsom, and M. M. Osterloo (2011), The systematic effects of
 358 martian gravity on hillslope materials and mass movement processes, *42nd Lunar*
 359 *Planet. Sci. Conf.*, abstract #2383.

360 Levy, J. S., J. W. Head, J. L. Dickson, C. I. Fassett, G. A. Morgan, and S. C. Schon
 361 (2010), Identification of gully debris flow deposits in Protonilus Mensae, Mars:
 362 Characterization of a water-bearing, energetic gully-forming process, *Earth Planet.*
 363 *Sci. Lett.*, 294, 368–377, doi:10.1016/j.epsl.2009.08.002.

364 Luckman, B. H. (1992), Debris flows and snow avalanche landforms in the Lairig Ghru,
 365 Cairngorm Mountains, Scotland, *Geogr. Ann. Ser. A-PHYSICAL Geogr.*, 74(2/3),
 366 109–121.

367 Malin, M. C., and K. S. Edgett (2000), Evidence for recent groundwater seepage and
 368 surface runoff on Mars, *Science*, 288(5475), 2330–2335,
 369 doi:10.1126/science.288.5475.2330.

370 Malin, M. C., K. S. Edgett, L. V. Posiolova, S. M. McColley, and E. Z. N. Dobra (2006),
 371 Present-day impact cratering rate and contemporary gully activity on Mars, *Science*,
 372 314(5805), 1573–1577.

373 Malin, M. C. et al. (2007), Context Camera Investigation on board the Mars
 374 Reconnaissance Orbiter, *J. Geophys. Res.*, 112(E5), E05S04,
 375 doi:10.1029/2006JE002808.

376 Matmon, A., K. Nichols, and R. Finkel (2006), Isotopic insights into smoothening of
 377 abandoned fan surfaces, Southern California, *Quat. Res.*, 66, 109–118,
 378 doi:10.1016/j.yqres.2006.02.010.

379 McEwen, A. S. et al. (2007), Mars Reconnaissance Orbiter's High Resolution Imaging
 380 Science Experiment (HiRISE), *J. Geophys. Res.*, 112(E5), E05S02,
 381 doi:10.1029/2005JE002605.

382 Neugebauer, G., G. Münch, H. H. Kieffer, S. C. Case Jr., and E. Miner (1971), Mariner
 383 1969 infrared radiometer results: Temperatures and thermal properties of the
 384 Martian surface, *Astron. J.*, 76(8), 719–749.

385 Okubo, C. H., L. L. Tornabene, and N. L. Lanza (2011), Constraints on mechanisms for
 386 the growth of gully alcoves in Gasa crater, Mars, from two-dimensional stability
 387 assessments of rock slopes, *Icarus*, 211(1), 207–221,
 388 doi:10.1016/j.icarus.2010.09.025.

389 Presley, M. A., and P. R. Christensen (1997a), Thermal conductivity measurements of
 390 particulate materials 1. A Review, *J. Geophys. Res.*, 102(E3), 6535–6549,
 391 doi:10.1029/96JE03303.

392 Presley, M. A., and P. R. Christensen (1997b), Thermal conductivity measurements of
 393 particulate materials 2. Results, *J. Geophys. Res.*, 102(E3), 6551–6566.

394 Reiss, D., S. van Gasselt, G. Neukum, and R. Jaumann (2004), Absolute dune ages and
 395 implications for the time of formation of gullies in Nirgal Vallis, Mars, *J. Geophys.*
 396 *Res. E Planets*, 109(6), 1–9, doi:10.1029/2004JE002251.

397 Schon, S. C., and J. W. Head (2012), Gasa impact crater, Mars: Very young gullies
 398 formed from impact into latitude-dependent mantle and debris-covered glacier
 399 deposits?, *Icarus*, 218(1), 459–477, doi:10.1016/j.icarus.2012.01.002.

400 Schon, S. C., J. W. Head, and C. I. Fassett (2009), Unique chronostratigraphic marker in
 401 depositional fan stratigraphy on Mars: Evidence for ca. 1.25 Ma gully activity and
 402 surficial meltwater origin, *Geology*, 37(3), 207–210, doi:10.1130/G25398A.1.

403 Thomas, N. et al. (2014), The Colour and Stereo Surface Imaging System (CaSSIS) for

404 ESA's Trace Gas Orbiter, in *8th International Conference on Mars*, p. abstract
 405 #1067, Pasadena, CA.

406 Tornabene, L. L., J. E. Moersch, H. Y. McSween, A. S. McEwen, J. L. Piatek, K. A.
 407 Milam, and P. R. Christensen (2006), Identification of large (2-10 km) rayed craters
 408 on Mars in THEMIS thermal infrared images: Implications for possible Martian
 409 meteorite source regions, *J. Geophys. Res. E Planets*, *111*(10), 1–25,
 410 doi:10.1029/2005JE002600.

411 Tornabene, L. L., G. R. Osinski, A. S. McEwen, J. M. Boyce, V. J. Bray, C. M. Caudill, J.
 412 A. Grant, C. W. Hamilton, S. Mattson, and P. J. Mouginis-Mark (2012), Widespread
 413 crater-related pitted materials on Mars: Further evidence for the role of target
 414 volatiles during the impact process, *Icarus*, *220*(2), 348–368,
 415 doi:10.1016/j.icarus.2012.05.022.

416 Tornabene, L. L., J. L. Piatek, K. T. Hansen, S. J. Hutchinson, N. G. Barlow, G. R.
 417 Osinski, S. J. Robbins, and A. S. McEwen (2016), Visible and thermophysical
 418 characteristics of the best-preserved martian craters, part 1: Detailed morphological
 419 mapping of Resen and Noord, *47th Lunar Planet. Sci. Conf.*, abstract #2879.

420 Treiman, A. H. (2003), Geologic settings of Martian gullies: Implications for their origins,
 421 *J. Geophys. Res.*, *108*(E4), 8031, doi:10.1029/2002JE001900.

422 Wechsler, A., and P. Glaser (1965), Pressure effects on postulated lunar materials, *Icarus*,
 423 *4*, 335–352, doi:10.1016/0019-1035(65)90038-2.

424 Wechsler, A. E., P. E. Glaser, and J. A. Fountain (1972), Thermal properties of
 425 granulated materials, in *Thermal Characteristics of the Moon*, *Prog. Astron.*

426 *Aeronaut.*, vol. 28, edited by J. W. Lucas, pp. 215–241, MIT Press, Cambridge, MA.

427

Figure 1. (A) Subframe of CTX G06_020661_1440_XN_36S230W covering Gasa Crater and Cilaos Crater, within which it lies. Blue and red lines mark the MOLA elevation transects in B. North is up. (B) MOLA elevation profiles across Cilaos and Gasa Craters (blue line) and only across Cilaos Crater (red line).

Figure 2. Example of younger (stratigraphically higher) and older (underlying) lobes within an individual gully fan in Gasa Crater. Yellow box in A shows context for B. Note the rough surface texture of the younger lobe compared to the underlying older portion of the fan. Subframes of HiRISE ESP_014081_1440.

Figure 3. (A) CTX G06_020661_1440_XN_36S230W with THEMIS-derived thermal inertia overlaid atop it, centred at 35.7°S, 129.4°E, showing Gasa and Cilaos craters. (B) Closer view of Gasa as marked by the white box in A. Numbered gullies indicate locations of activity documented by Dundas et al. [2010, 2012, 2015]. Dots indicate each documented gully (numbered clockwise from the eastern wall from 1–28; individual numbers omitted for space).

Figure 4. (A) Polygons denoting areas sampled for thermal inertia values of gully/talus aprons (white), alcoves (teal), and the entire wall (alcoves and aprons, dotted black). Yellow polygon on the crater floor denotes pitted material. (B) Fan segments for gullies (blues) and talus slopes (purples) and corresponding thermal inertia ranges. Basemap for both A and B is a mosaic of subframes of CTX G06_020661_1440_XN_36S230W and HiRISE ESP_014081_1440 and ESP_039531_1440.

448 Figure 5. Mean thermal inertia values for the 66 mapped gully fan segments in Gasa
449 Crater with standard errors shown. Dot colours correspond to the legend in Figure 4B.
450 Fans were numbered clockwise from the western wall of the crater.

451 Figure 6. HiRISE IRB colour of gullied wall (B) and talus on slopes from mass wasting
452 (C). (A) CTX G06_020661_1440_XN_36S230W with HiRISE ESP_020661_1440
453 overlaid for context. White boxes denote the locations of B and C, with C rotated 180°
454 for easier comparison to B. White arrow in B denotes a new gully flow in Gasa
455 documented by Dundas et al. [2012], formed in Mars Year 30 between Ls 109–152°.
456 Note its blue appearance compared to the surrounding fan deposits.

Table 1. Average thermal inertia (in TIU) of gullied (N) and non-gullied (SW and SE) walls in Gasa Crater

	Gullied Wall (N)				Non-Gullied Wall (SW)				Non-Gullied Wall (SE)			
Segment	Mean [Std Error]	Max	Min	Std Dev	Mean [Std Error]	Max	Min	Std Dev	Mean [Std Error]	Max	Min	Std Dev
Aprons	379 [2]	574	280	45	454 [2]	537	357	30	436 [4]	607	324	54
Alcoves [†]	470 [3]	720	336	71	502 [5]	722	351	61				
Entire Wall	418 [2]	720	275	74	482 [3]	722	357	52	433 [4]	607	324	54

[†]The SE wall of the crater hosts no alcoves.

Figure 1

Figure 2

[Click here to download Figure Figure 2-Gasa Older vs Younger Fans HiRISE.jpg](#)

Figure 3

[Click here to download Figure Figure 3-Gasa Thermal Inertia.jpg](#)

Figure 4

Figure 5

Figure 6

[Click here to download Figure HiRISE IRB Gullied vs Non-Gullied Walls.jpg](#)