



Producing Dust through Simulated Glacial Abrasion of Basalt Clasts with Implications for Mars

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Abstract

Multiple processes have been proposed for the genesis of dust on Mars, including volcanic eruptions, eolian abrasion, bolide impacts, and glacial grinding. Atmospheric dust has a significant impact on climate that is heavily dependent on the particle size distribution (PSD) of the dust. Therefore, we ask, do different dust-generating mechanisms produce different dust PSDs and, consequently, different impacts on the climate? Glacial grinding is the erosive process of clasts embedded in the base of a glacier sliding across bedrock or subglacial sediment. We use basalt clasts as analogs to assess sediment production via experimental glacial grinding. We cut small (3 cm), flat- and point-tipped fabricated clasts from five distinct basalts and used a novel experimental apparatus to abrade them across a basal rock slab representing bedrock. Pointed clasts generally produced more sediment than flat clasts, as did clasts with vesicular textures compared to those with nonvesicular textures. The resulting PSDs show that most dust samples exhibit a primary mode, between 20 and 50 μm . These results indicate a tendency toward silt production from rock-on-rock grinding of basalt, akin to the conditions at the base of a wet-based glacier. Results were compared to sediment PSDs from other potential dust-producing mechanisms. Simulated glacial grinding of basalt generates proportionally $\sim 50\%$ more fine dust ($< 2.5 \mu\text{m}$) than simulated eolian abrasion of basalt sand. Results from these experiments suggest that if widespread wet-based glaciation existed on Mars, the dust produced would have influenced the climate, although the net radiative effect is unknown.

Unified Astronomy Thesaurus concepts: [Glaciers \(2303\)](#); [Dust formation \(2269\)](#); [Glaciation \(2302\)](#); [Planetary surfaces \(2113\)](#); [Surface processes \(2116\)](#)

1. Introduction

Mars is known for its red dusty shroud, with dust covering much of its surface and commonly blanketing the planet in global storms (P. R. Christensen 1986; K. L. Tanaka 2000; H. E. Gillespie et al. 2020). C. E. Newman et al. (2022) liken dust and its importance to the Martian climate to the role of the hydrological cycle on Earth's climate. While modern Mars has a thinner atmosphere and thus a subdued ability to transport coarse dust compared to Earth, dust–climate interactions might have been more like those on Earth in the distant past. On Earth, atmospheric dust exerts direct radiative effects that both warm and cool a planet's surface and atmosphere, influence precipitation and cloud formation, and initiate ice nucleation (D. Rosenfeld et al. 2001; J.-L. Dufresne et al. 2002; M. L. Eastwood et al. 2008; F. Conen et al. 2011; M. Tang et al. 2016; J. F. Kok et al. 2017, 2023). After deposition, dust can change the surface albedo, especially of ice and snow, and could deliver nutrients to soils and oceans if a biosphere ever existed (C. S. Bristow et al. 2010; N. Mahowald et al. 2011; G. S. Okin et al. 2011; S. M. Skiles et al. 2018). Additionally, dust deposits in the rock record provide geologists with evidence of past processes that created and transported dust, as well as information about the local environment, such as climate, and mechanisms of dust deposition, e.g., shallow water, topography, or biological capture and stabilization (D. R. Muhs 2013; D. Jordanova et al. 2022). The influence of dust on climate varies depending on the dust characteristics, especially particle size distribution (PSD) and composition (J. F. Kok et al. 2023).

For example, finer dust ($< 2.5 \mu\text{m}$) typically exerts a cooling influence through scattering of shortwave solar radiation, whereas coarser dust ($> 2.5 \mu\text{m}$) more likely exerts a warming effect by absorption of longwave radiation (N. Mahowald et al. 2014; A. A. Adebisi & J. F. Kok 2020).

Many processes have been proposed to generate dust on Mars, including volcanic eruptions, eolian abrasion, bolide impacts, and glacial grinding as potential major contributors (N. T. Bridges & D. R. Muhs 2012). These dust production processes may have temporal limitations. For example, impact-related dust likely occurred primarily in the earlier pre-Noachian and Noachian times and diminished to lower constant rates through the Hesperian and Amazonian (N. G. Barlow 2010). Similarly, extensive wet-based, erosive glaciation may have been limited to the Noachian and Hesperian, although evidence suggests that sporadic wet-based glaciation persisted in the Amazonian (C. Gallagher & M. Balme 2015; F. E. G. Butcher et al. 2017, 2020, 2021; K. E. Scanlon et al. 2018; A. Bouquety et al. 2019; S. Z. Woodley et al. 2022). Explosive volcanism generally predominated in early Martian history (Noachian–Hesperian), although some Amazonian pyroclastic deposits have been proposed (P. Brož et al. 2021). Eolian abrasion likely prevailed over much of Mars's history, especially in the absence of a significant biosphere to assist in stabilizing soil surfaces, and eolian abrasion has likely been the dominant form of dust production since Mars became arid (N. T. Bridges & D. R. Muhs 2012; C. Charalambous 2015; C. E. Newman et al. 2022).

Measuring PSDs of dust on Mars poses a significant technical challenge, especially for dust deposited in the ancient rock record. The particle size of dust suspended in the modern Martian atmosphere has been modeled with remote sensing techniques using data collected from satellites, rovers, and landers, and these



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approaches generally indicate that the bulk of atmospheric dust is $<2.5\ \mu\text{m}$ (R. T. Clancy et al. 2003; M. J. Wolff & R. T. Clancy 2003; M. A. Kahre et al. 2008). However, measuring in situ PSDs of fine, dust-sized sediments is not possible because of the limited resolution of rover- and lander-based imaging sensors. Generally, silt-sized and smaller particles are too fine to see and count (F. Rivera-Hernández et al. 2019; C. M. Weitz et al. 2022; A. Vaughan et al. 2023). Additionally, these surveys are limited to two-dimensional photographs, as no viable method exists to measure the PSD of a volume of sediment remotely. Two-dimensional photographs of the surface of a soil or sand dune may not be representative of the PSD of its internal volume (C. M. Weitz et al. 2022). While the coarse dust component of soils and dunes may not be as active as it was in the past, it has likely influenced the climate and geological cycles on Mars. Currently, the best way to investigate the PSDs of the dust fraction of Mars and their potential influence is to recreate them using analog processes of production, which is the goal of this study and the eolian abrasion experiments by S. M. Adams & G. S. Soreghan (2025, in preparation).

Given that the characteristics of dust determine its climatic influence, we consider the following question in this work: do different dust-generating mechanisms produce dust populations with distinguishing characteristics? Perhaps one process produces an abundance of fine dust that would reflect and scatter more incoming shortwave radiation in the atmosphere and thus exert a cooling effect, whereas a different process might produce dust with a warming influence. In this study, we conducted experiments with basalts that replicate the process of sediment production via glacial grinding. We then compare these results to dust and sediment PSDs from volcanic eruptions, lunar regolith, and previous eolian abrasion experiments.

1.1. Experimental Background

Given the difficulty in studying Mars and its dust and surface processes in situ, we rely on analog studies to replicate the process of glacial grinding. Historically, only a small number of studies have conducted experiments designed to replicate glacial grinding of rocks with the goal of examining and describing the PSDs of produced sediment (W. H. Mathews 1979; J. S. Wright 1995; I. F. Jefferson et al. 1997; A. G. G. Lee & E. H. Rutter 2004). These studies generally relied on small ring-shear devices to grind sand grains or used grinding wheels of rock to produce new sediment (Mathews 1979; J. S. Wright 1995; I. F. Jefferson et al. 1997; A. G. G. Lee & E. H. Rutter 2004).

Experiments by J. S. Wright (1995) using a ring-shear device on crushed, sand-sized Brazilian vein quartz produced only traces of silt in most of the experimental runs. This was surprising since glacial grinding had been assumed to produce significant amounts of fine sediment (I. J. Smalley & C. Vita-Finzi 1968). In contrast, similar grinding experiments by I. F. Jefferson et al. (1997) using a carbide disk mill on disaggregated sands from Cretaceous sandstone produced abundant silt. The stark difference in the results between these two studies motivated R. Kumar et al. (2006) to conduct another series of experiments using a ring-shear device similar to that used by J. S. Wright (1995) but with the mature sedimentary sands used by I. F. Jefferson et al. (1997); this resulted in the production of abundant silt. They concluded that Brazilian vein quartz lacks internal crystal defects known as

Moss defects, while the Cretaceous sands have internal crystal defects that promote breakage along these planes of weakness to form silt. Moss defects, named after A. J. Moss, who first observed and described them, are small fractures present in plutonic quartz that promote breakage during physical abrasion (A. J. Moss & P. Green 1975).

Other experiments have studied rock-on-rock glacial erosion. W. H. Mathews (1979) used a device that turned a wheel of ice with embedded sand between two tablets of limestone, but this study did not describe the resultant PSDs of produced sediment. A. G. G. Lee & E. H. Rutter (2004) used an apparatus that turned two rock wheels of the same lithology such that they abraded against one another under a weighted load. They abraded wheels of granite, two types of schists, and three types of sandstone. They measured the PSDs of the sediments produced with a laser particle size analyzer (LPSA), and none of the modes fell within the traditional loess range of 20–50 μm . Modes of $\sim 10\ \mu\text{m}$ occurred in some samples, but the majority exhibited modes of either $<10\ \mu\text{m}$ or $\sim 100\ \mu\text{m}$.

Given that previous glacial grinding experiments focused on lithologies commonly found on Earth, and considering the many unknowns surrounding the histories of both dust and climate on Mars, we investigated dust produced via simulated glacial grinding to determine if glacial grinding of basalt could influence the climate of ancient Mars. We compare the experimental glacial grinding PSD results to dust created via simulated eolian abrasion of basalt sands, dust PSDs from previous volcanic eruptions, and lunar regolith (created by meteorite and micrometeorite bombardment) to determine if our experimental glacially derived dust and its influence on the climate would be different (W. I. Rose & A. J. Durant 2009; A. Costa et al. 2016; S. M. Adams & G. S. Soreghan 2025, in preparation; J. C. Laul et al. 1987).

2. Methods

2.1. Sample Collection and Preparation

Five basalt samples were collected to capture a range of textures and geologic ages, as such variability might mimic rocks subject to glacial erosion on Mars or the early Earth (Figure 1). For the grinding experiments, four small clasts were cut from each of the five samples to represent small gravel-sized angular clasts at the base of a glacier. In this work, we define “clast” as a small rock, machine-cut to an elongated shape with either a flat or pointed tip. Each clast is approximately 3 cm long and 1 cm wide, resulting in a surface area on the top surface of approximately 1 cm^2 . Although care was taken to form each clast to uniform dimensions, the limitations of cutting and grinding such small pieces create subtle variations of 1–3 mm in overall length and $<10^\circ$ of variation for pyramidal point angles, introducing a realistic element of natural variation. The four clasts for each sample were cut to create two with flat tops and two with four-sided pyramidal points. Figure 2 shows a representative subset of pointed clasts from each sample type and captures the range of variation in wear after grinding. The Appendix (A1–A5) illustrates before-and-after images of all clasts used in the experiments.

MG1 was collected from a basalt plug near Cañon City, Colorado, mapped as a tertiary basalt of Pliocene or Miocene age (J. D. Horton et al. 2017). It is aphanitic with thin bladed plagioclase, pyroxene, and trace olivine. The basal slab used

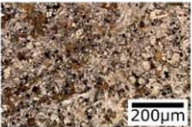
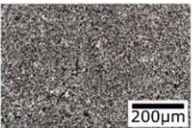
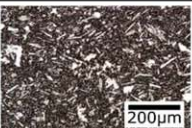
Sample Name	Location	Age	Texture	Formation	Lat	Long	Thin Section Photo
MG-1	Colorado	Pliocene or Miocene	Aphanitic basalt, sparse labradorite and olivine	Mapped as Tertiary Basalts	38°24'18"N	105°16'05"W	
MG-2	Virginia	Jurassic	Aphanitic, very fine texture	Mt. Zion Church Basalt	38°48'47"N	77°38'47"W	
MG-3	Virginia	Precambrian	Aphanitic high Ti Meta basalt	Catoctin Formation	38°41'43"N	77°53'27"W	
MG-4	Hawaii	Holocene	Aphanitic, glassy	Puna Basalt	19°21'44"N	155°21'46"W	
MG-5	Hawaii	Holocene	Aphanitic, glassy, vesicular, blades of feldspar	Kau Basalt 1852 eruption Mauna Loa	19°31'11"N	155°35'2"W	

Figure 1. Sample names used in the text and corresponding locations of collection, age of the rocks, textures of the rocks, parent formation, location of sample collection, and photomicrographs showing the minerals and texture of each lithology. Larger images of photomicrographs are provided in the Appendix (A6–A8).

for abrasion for all samples is also made of MG1 basalt. MG2 is of Jurassic age and collected from the Mt. Zion Church Basalt in Virginia. MG2 is microcrystalline, and the ground mass of the microlitic texture in the Mt. Zion Church Basalt comprises plagioclase and augite (A. M. Davis et al. 2001; S. Southworth et al. 2007). MG3 is from the Precambrian Catoctin Formation in Virginia (A. M. Davis et al. 2001). Our MG3 samples are aphanitic with bladed plagioclase lathwork, chlorite, and pyroxene. MG4 is from the Holocene Puna Basalt in Hawaii and was collected from the Ka'u Desert (D. R. Sherrod et al. 2021). It is aphanitic and vitric and has large, bladed plagioclase lathwork surrounded by a microlitic ground mass of plagioclase, pyroxene, and glass. MG4 has small ($\sim 100 \mu\text{m}$) vesicles as well. MG5 is Holocene in age and was collected from Mauna Loa, Hawaii. The basalt is assumed to be from the 1852 eruption of Mauna Loa and was collected near the summit (D. R. Sherrod et al. 2021). MG5 is aphanitic, vitric, and highly vesicular, with vesicles as large as 1 cm diameter. MG5 has large, bladed plagioclase lathwork that commonly appears radial and thicker elongated plagioclase crystals suspended in a glass ground mass.

2.2. Experiment Design

Figure 3 illustrates the experimental apparatus. A clast is mounted to the base of a piston attached to a platform that, when weighted, has a combined mass of 5 kg. The piston is depressed through an open shaft mounted to a wheeled cart. The mass on the platform is transferred through the piston to the clast. The clast tip rests on and abrades across a flat basal rock slab (the MG1 basalt) representing bedrock. The basal slab is seated within a tub containing sufficient distilled water to inundate the slab surface to help trap produced dust and to replicate wet friction experienced by wet-based glaciation,

similar to the wetting of wheels by A. G. G. Lee & E. H. Rutter (2004) in their grinding experiments. The cart is pulled by hand, which slowly drags the stylus across the stationary rock slab at 2 cm s^{-1} ($6.31 \times 10^5 \text{ m yr}^{-1}$). Flow velocities for wet-based glaciers can vary over several orders of magnitude depending on a number of factors, with surging glaciers such as Greenland's Jakobshavn Isbræ moving in excess of 10 km yr^{-1} and small alpine glaciers ranging in velocity from ~ 30 to 500 m yr^{-1} (I. Joughin et al. 2018; R. Millan et al. 2019, 2022). Thus, our experiments employ velocities ranging from 10 to 10^4 times the speed of natural wet-based glaciers, surging glaciers, and ice streams. The clast is pulled forward for 20 cm then pushed backward for 20 cm. This process is repeated several times to achieve a total travel distance of 5 m.

The 5 kg vertical load creates a $\sim 50 \text{ N}$ contact force between the clast and basal slab. This is comparable to the 22 kg load weight used by W. H. Mathews (1979) and the 1–3 kg range used by A. G. G. Lee & E. H. Rutter (2004), which produced ~ 20 – 60 N normal forces on their experiments. For ring-shear experiments, J. S. Wright (1995) loaded the device with 10–15 kg of weight, and R. Kumar et al. (2006) used a normal load of 15 kg for most of their experiments. Additionally, using an equation from D. D. Hansen & L. K. Zoet (2019) for drag/contact force and the older equations they modified from P. A. Watts (1974) and B. Hallet (1979), our contact force mimics the approximate range of contact forces (10–100 N) predicted for small spherical clasts (~ 1 – 2 cm radius) contacting the bed of wet-based glaciers.

The contact force is in the predicted range of ~ 10 – 100 N according to D. D. Hansen & L. K. Zoet (2019) for small (1–3 cm radius) spherical clasts using equations for drag and contact forces used by P. A. Watts (1974) and B. Hallet (1979).

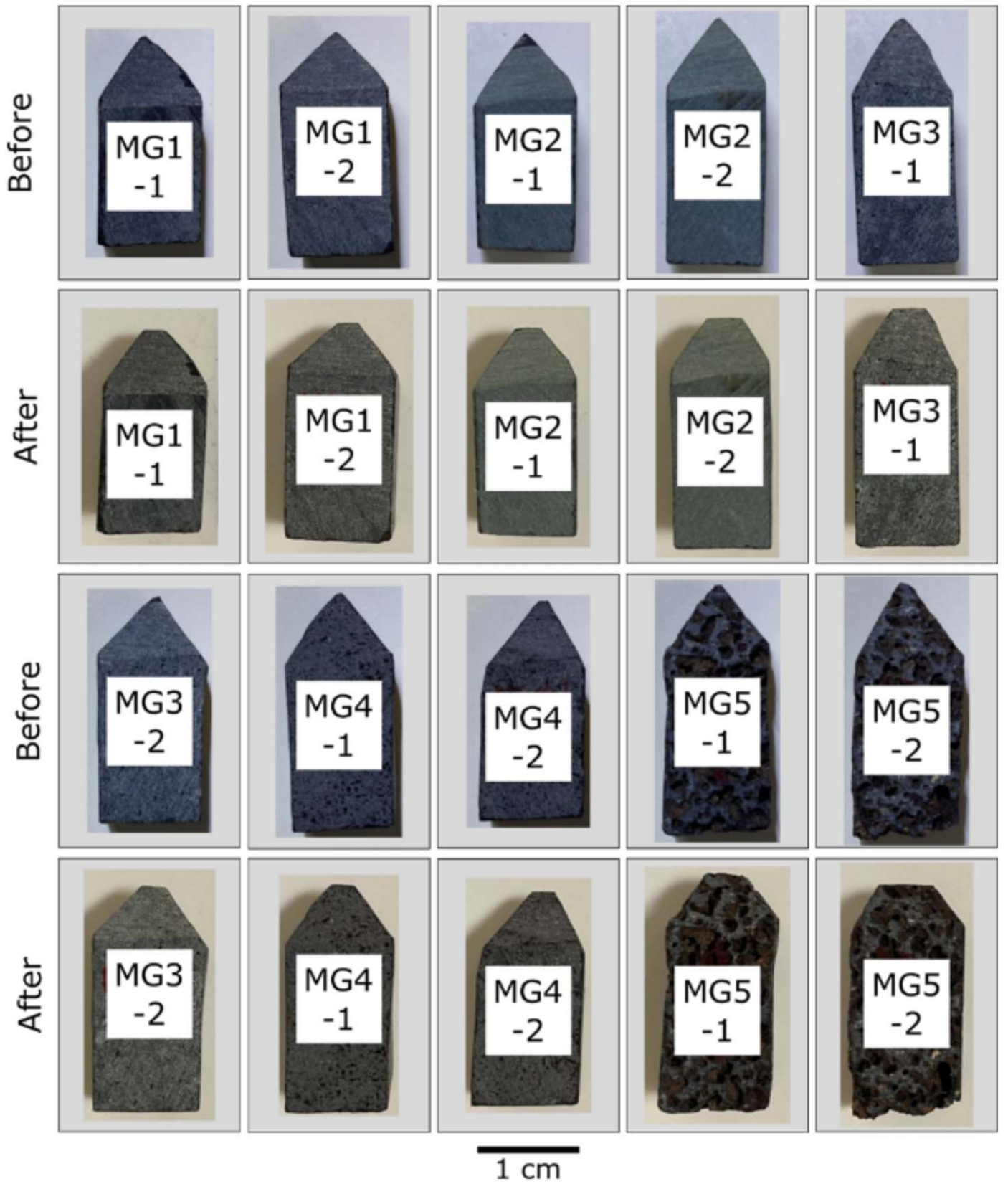


Figure 2. Before-and-after photographs of basalt clasts used in the grinding experiments. Each sample is approximately 1 cm wide and 3 cm tall.

We use equations from D. D. Hansen & L. K. Zoet (2019),

$$F_c = F_b + F_d, \quad (1)$$

where F_c is the contact force, F_b is the buoyant force due to gravity and is considered negligible for clasts under 0.5 m in diameter, and F_d is the drag force and for small clasts is

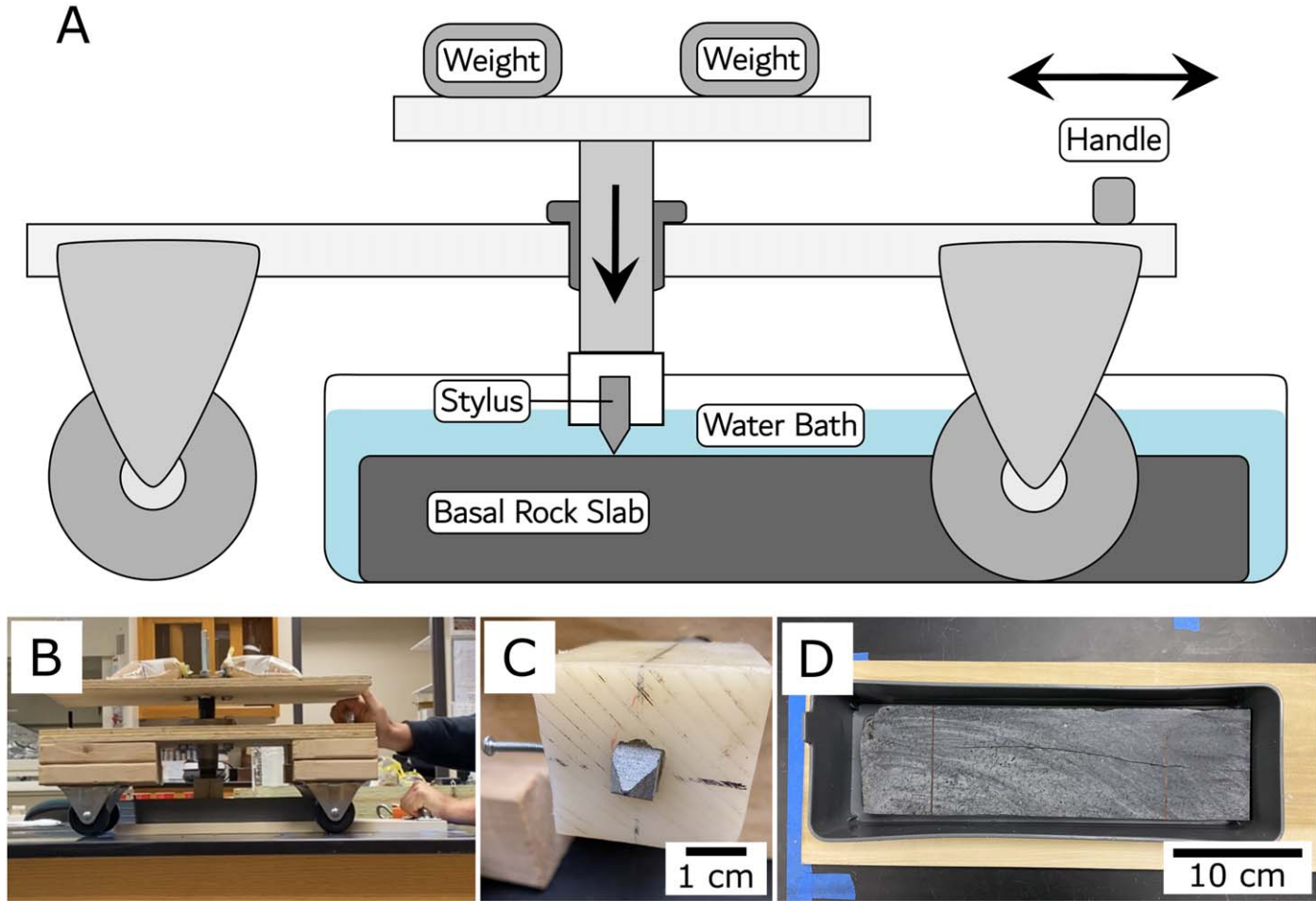


Figure 3. (A) Schematic of glacial abrasion device showing the cart used to move the clast (“stylus” as labeled above) across the basal rock slab, which sits in a basin of water. The clast is pressed into contact with the basal slab by a weighted piston that transfers ~ 5 kg of weight to the clast, producing a ~ 50 N contact force. Panel (B) illustrates the abrasion device during operation. The basal slab is held in place while the cart is pulled and pushed, dragging the clast across the basal slab in 20 cm lengths for a combined travel distance of 5 m. Panel (C) shows a mounted clast in the base of the piston. Panel (D) shows the basal slab inside the water basin. The water basin rests inside a hole cut in a thin board so the slab is held in place while the clast moves.

equivalent to the contact force regardless of ice thickness (D. D. Hansen & L. K. Zoet 2019),

$$F_d = \frac{4\pi\eta_i u_v r^3}{r_*^2 + r^2}, \quad (2)$$

where

$$r_* = \left(\frac{\rho_l}{\rho_l + \rho_i} \frac{3\eta_i C K}{\rho_i \mathcal{L}} \right)^2. \quad (3)$$

We assume the same variable values from D. D. Hansen & L. K. Zoet (2019): $\eta_i = 3.15 \times 10^{12}$ Pa s, $u_v = 500$ mm a^{-1} , $\rho_l = 1000$ kg m^{-3} , $\rho_i = 917$ kg m^{-3} , $\mathcal{L} = 3.3 \times 10^5$ J kg^{-1} , $C = 0.074$ K MPa^{-1} , and $K = 2.5$ W m^{-1} K^{-1} , where η_i is the ice viscosity, u_v is the ice velocity, ρ_l is the density of water, ρ_i is the density of ice, $\mathcal{L}$ is the latent heat of ice fusion, C is the Clapeyron slope, and K is the thermal conductivity of ice and rock averaged, and we calculated contact forces for clasts with radii from 1 to 2 cm to be between 9 and 72 N. Thus, the contact force created by our vertical load is similar to that expected in a subglacial clast of similar size.

After reaching 5 m of travel distance, loose sediment produced by the experiment resides on the wet slab surface

or in the water-filled basin and is collected by rinsing with deionized water into a 2 liter beaker. The water and sediment settle for 24 hr, after which time the water is decanted and discarded, and the remaining wet sediment mixture is centrifuged to concentrate it in one 50 ml centrifuge tube.

To measure the sediment mass produced from each grinding experiment, wet samples were rinsed into preweighed small plastic vials, frozen, and then freeze-dried to remove water. The vials were then weighed a second time with the dry sediment mass now in the vial. Problems arose owing to mass loss from the plastic vials during freeze-drying that exceeded the (very small) produced sediment volumes of some samples, resulting in negative mass values for five of the 20 samples (MG2-1, MG2-3, MG2-4, MG3-3, and MG3-4). These (MG2 and MG3) samples produced very little sediment because they are much harder than the other samples. MG2 was hard enough to produce very little sediment from even the pointed clasts. The MG3 samples produced measurable sediment from the pointed clasts but not the flat clasts. To correct for the mass error, 10 empty vials were weighed before and after freeze-drying to obtain an average mass loss of 8.21×10^{-3} g. This mass loss was then added to the mass of sediment samples. This brought MG3-3 to a positive mass value. The remaining four samples

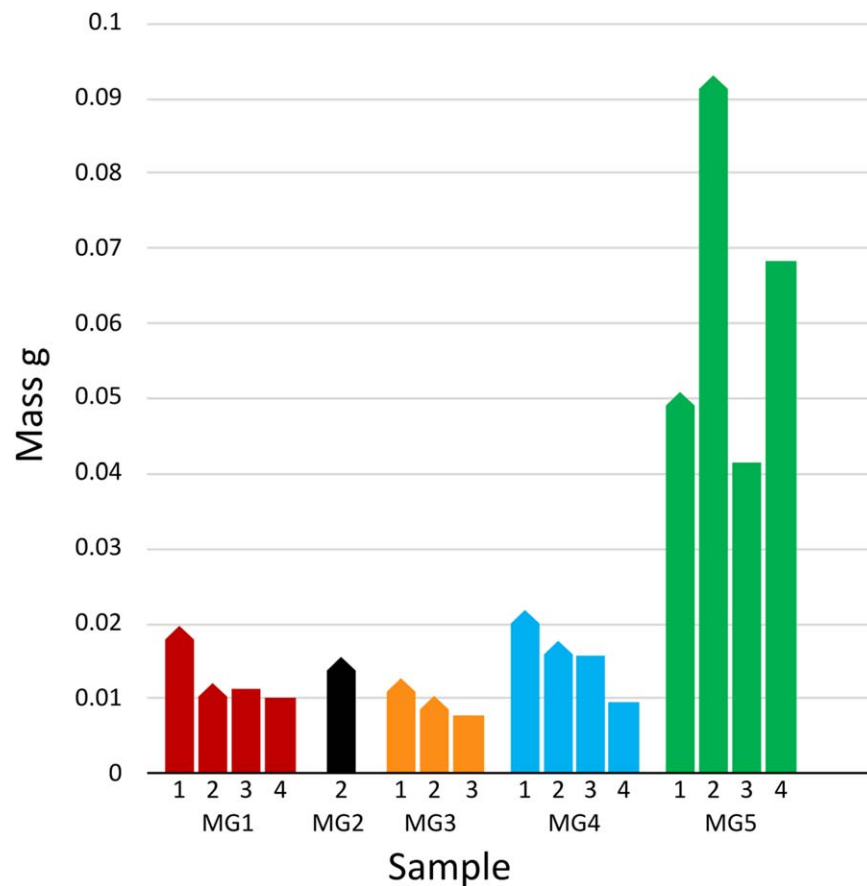


Figure 4. Mass of sediment produced from the abrasion of each clast. Columns with points represent pointed clasts, and flat columns represent flat clasts. Samples not shown had masses below our measurable threshold.

with negative values are excluded in mass calculation averages and figures.

PSDs of the sediment produced from each sample were measured using a Malvern Mastersizer 3000 LPSA after adding 5% sodium hexametaphosphate as a dispersant. Samples were measured using the Small Volume Module pump at 2500 RPM. Samples were added to the Small Volume Module pump using a 3 ml pipette, agitating the sample in the bulb of the pipette before adding each drop of slurry to the pump, ensuring that a well-mixed representative subsample was measured by the LPSA.

3. Results

3.1. Sediment Mass Produced

The grinding experiments resulted in removal of 2–4 mm of material from the tips of the pointed (pyramidal) clasts (Figure 2), while flat clasts showed <1 mm of wear. Pointed clasts generally produced more sediment than flat clasts, with the exception of MG5-4 (a flat clast; see Figure 4 for detail). MG5 clasts (from Hawaii) with vesicular textures produced significantly more sediment (0.04–0.09 g) than the nonvesicular samples (0.008–0.02 g). Pointed nonvesicular clasts produced sediment masses from 0.01 to 0.02 g, while flat nonvesicular clasts produced sediment masses from 0.008 to 0.015 g. Samples of MG2 and MG3 produced too little mass to detect due to mass loss in the plastic vials used to freeze-dry samples.

The basal slab exhibited visible wear in the form of small grooves along the path of the clast transect, although no large

grains or clasts were dislodged from the slab during abrasion. These observations suggest that the sediment contributed from the slab likely comprises entirely fine (<63 μm) material.

3.2. Sediment PSDs

Although several samples had low masses, all samples produced sufficient material for LPSA measurement. With all PSDs plotted together in Figure 5, the distribution curves show bimodal and multimodal distributions with variation in curve shape within the same sample type, variation within the same clast shape, and variation among different sample types. While the sediment produced is poorly sorted with significant variation among sample distribution curves, some patterns emerge. For example, 16 of the 20 samples exhibit a primary mode in the supercoarse (10–63 μm) dust range, primarily between 20 and 50 μm . Three of the four that fall outside this range are in the coarse (2.5–10 μm) dust range. Most curves exhibit multiple modes, and these curves generally exhibit primary and secondary modes in the coarse and supercoarse dust ranges. Additionally, secondary and tertiary modes occur, typically clustered at $\sim 0.5 \mu\text{m}$ (clay) and between 200 and 300 μm (fine-to-medium sand). Averaging the PSDs produces a curve with a primary mode of $\sim 24 \mu\text{m}$ and subtle modes in coarse and giant dust ranges (Figure 5).

When comparing PSDs across sediment-producing processes (Figure 6), similarities and differences emerge. In the sand or giant dust fractions, lunar regolith has a secondary mode in fine sand compared to ground basalt samples, while the volcanic sediments have primary modes near 1000 μm . The eolian

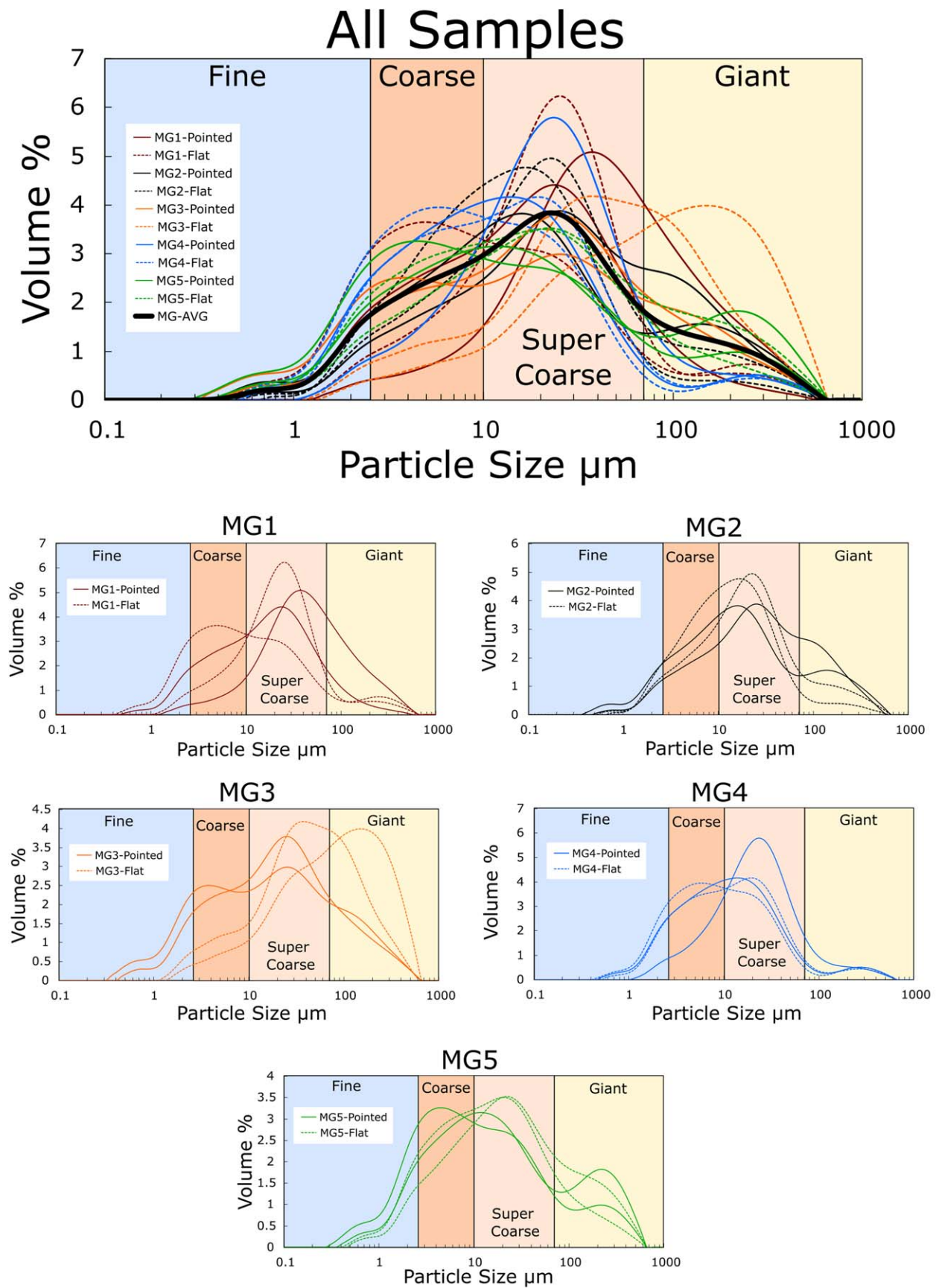


Figure 5. PSDs of all samples are shown in the top plot with the average PSD of all samples in black. Pointed clasts are solid lines, and flat clasts are dashed lines. PSDs of each lithology type and their corresponding clasts are shown in the bottom five PSD plots. Each sample shows the PSD of four samples, two from pointed clasts (solid) and two from flat clasts (dashed).

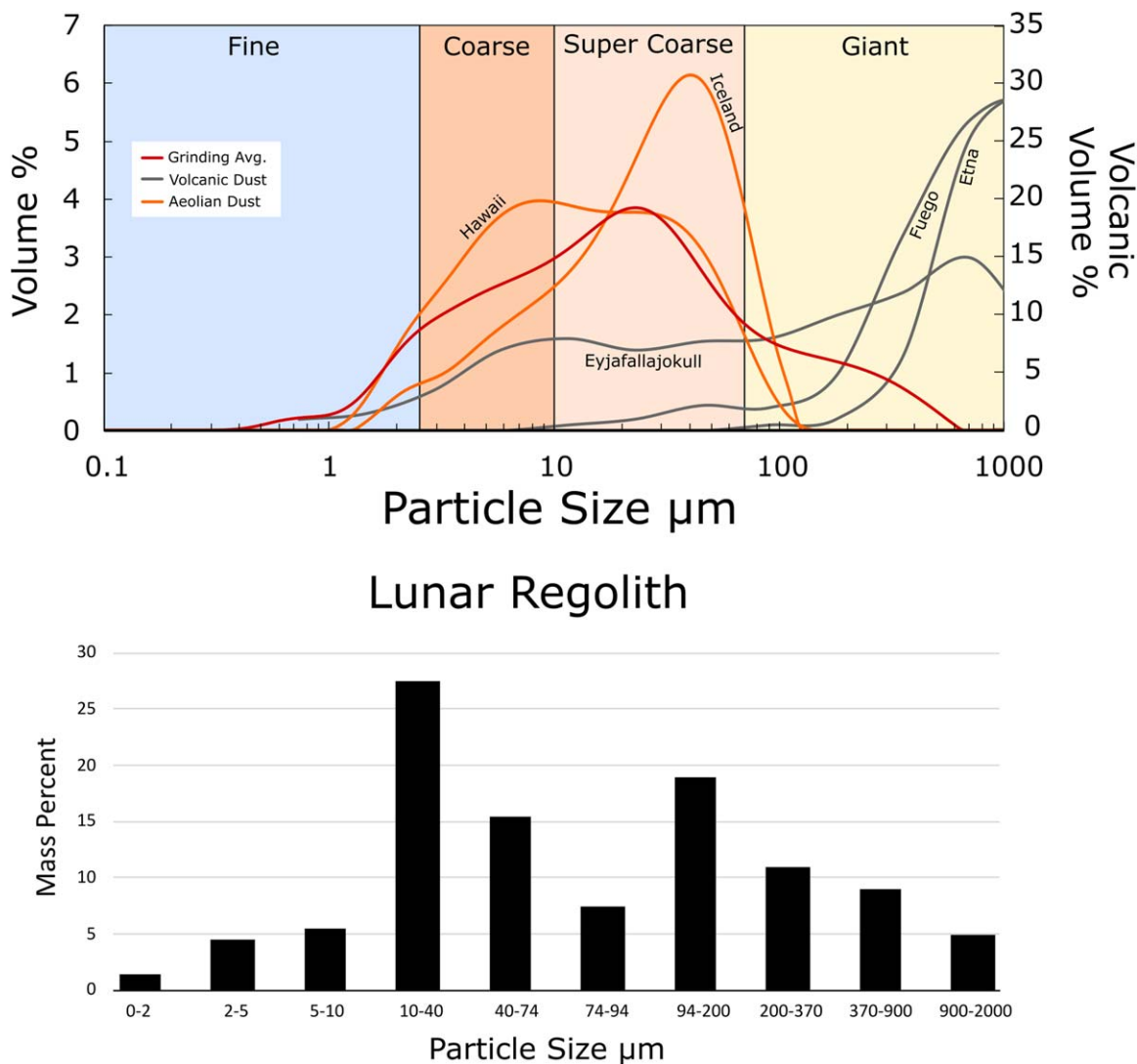


Figure 6. The average PSD of glacial grinding samples from this study is shown in red compared with PSDs of volcanic dust from different eruptions, lunar regolith, and dust from experimental eolian abrasion of basalt sands from Hawaii and Iceland (S. M. Adams & G. S. Soreghan 2025, in preparation). Note that lunar and volcanic PSDs are plotted with a different volume percent axis on the right. W. I. Rose & A. J. Durant (2009) and A. Costa et al. (2016) Eolian data from S. M. Adams & G. S. Soreghan (2025, in preparation), volcanic data adapted from W. I. Rose & A. J. Durant (2009) and A. Costa et al. (2016), lunar regolith adapted from J. C. Laul et al. (1987).

samples do not show a sand peak because the sediment was sieved at 63 μm to isolate the dust-sized fraction, although S. M. Adams & G. S. Soreghan (2025, in preparation) did produce new fine sand in the eolian abrasion experiments.

All processes produced PSD modes in the supercoarse (10–67 μm) fraction. The Iceland eolian abrasion dust and the volcanic dust exhibit slightly coarser modes, $\sim 50 \mu\text{m}$, while Hawaiian eolian abrasion dust, lunar regolith, and ground basalt modes cluster near 30 μm . Ground basalt, Hawaiian eolian abrasion dust, lunar regolith, and Eyjafallajökull volcanics exhibit modes in the coarse dust fraction. Iceland eolian abrasion dust and ground basalt have slight modes in the fine dust range, with the ground basalt producing a finer mode near 0.5 μm and Iceland dust at 2 μm .

3.3. Mass Fractions

Figure 7(A) shows mass fractions, calculations that sum volume percents in the particle size ranges designated as fine (<2.5 μm), coarse (2.5–10 μm), supercoarse (10–67 μm), and

giant (>67 μm) following the size categories for dust proposed by A. Adebisi et al. (2023). The LPSA size category that falls nearest to the supercoarse/giant boundary is 67 μm , so we use this cutoff for “dust” rather than more standard classifications (e.g., 62.5 μm). Density differences among dust grains in an individual dust sample are negligible; therefore, volume percent equates to mass percent. For example, 50% of a sample’s volume would also contain 50% of that sample’s mass. Significant variation in mass percent occurs within the sample type and clast type. Generally, supercoarse dust (10–67 μm) composes the largest fraction, followed by coarse dust (2.5–10 μm), then giant grains (>67 μm), with fine dust (<2.5 μm) composing the smallest fraction. A few samples have more giant grains than supercoarse dust, but the trend generally holds across sample and clast types.

Figure 7(B) illustrates the mass fractions recalculated to show only the dust fraction (<67 μm). Supercoarse dust is generally the largest fraction with a range from $\sim 40\%$ to 85%, coarse dust is the second-largest fraction with a range from

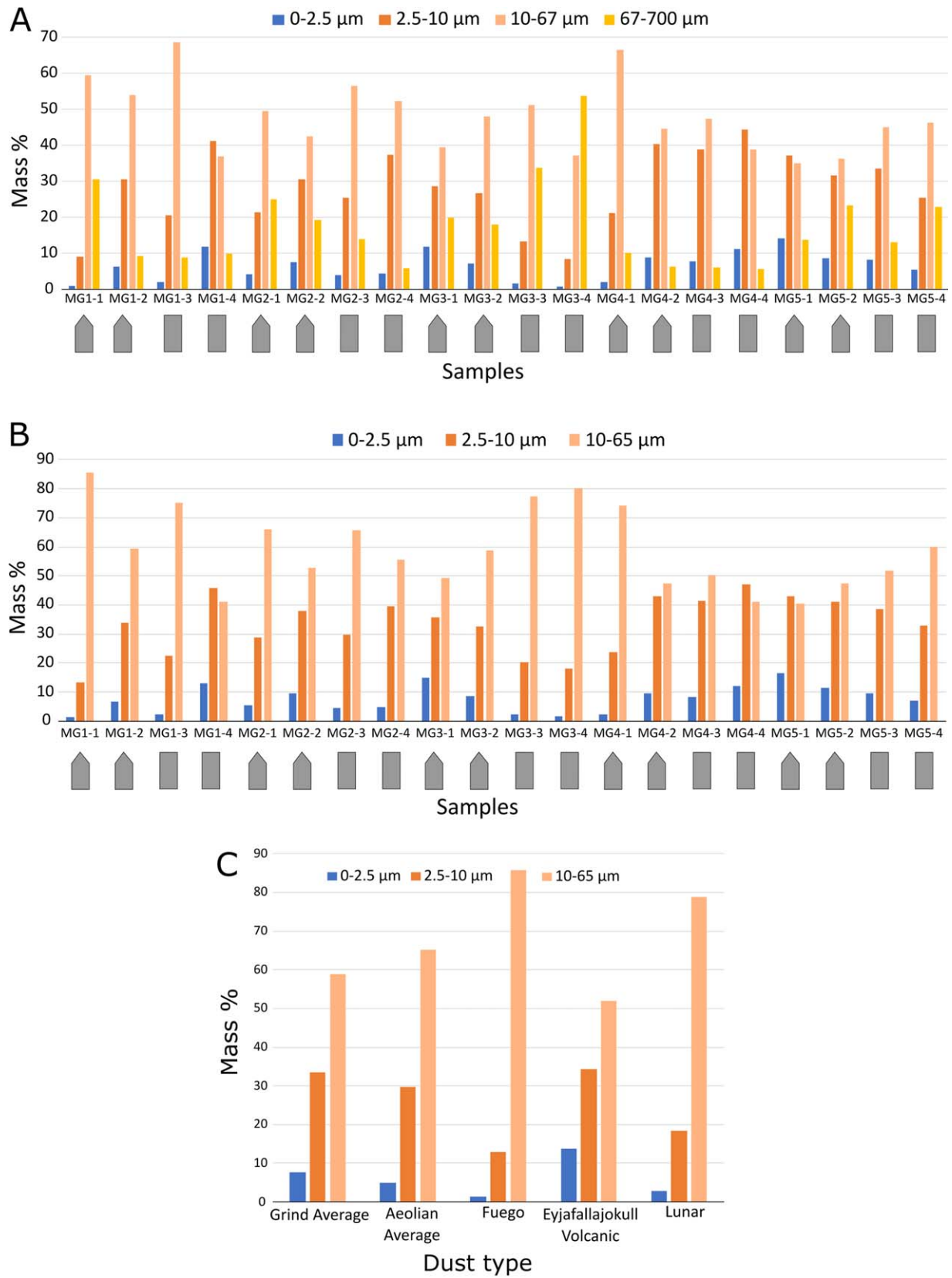


Figure 7. Panel (A) shows the fractional masses from each sample abraded in this study. These fractional mass percent values are calculated using volume percent results from the measured PSDs and summing the fractions within the given ranges. Panel (B) shows the fractional masses of each sample renormalized for the $<67 \mu\text{m}$ mass. Panel (C) compares the fractional mass of the average PSD produced from glacial grinding of basalts to fractional masses from dust produced via eolian abrasion of basalts, volcanic eruptions, and lunar regolith.

~15% to 45%, and fine dust is the smallest fraction with a range of ~1%–15%.

Focusing on the dust fraction ($<67\ \mu\text{m}$) enables comparison of the mass fraction averages from these basalt grinding experiments with the mass fraction averages from previously published experiments and dust fraction PSDs from volcanic eruptions and lunar regolith. Figure 7(C) compares the glacial sample averages to average mass fraction results from eolian abrasion experiments on basalt sands (S. M. Adams & G. S. Soreghan 2025, in preparation), the Fuego 1974 and Eyjafjallajökull 2010 volcanic eruptions (W. I. Rose & A. J. Durant 2009; A. Costa et al. 2016), and lunar regolith (J. C. Laul et al. 1987). The key difference between the PSDs of dust formed by experimental eolian abrasion and those of dust formed by experimental glacial grinding is that the experimentally produced glacial dust has ~50% more fine dust ($0\text{--}2.5\ \mu\text{m}$) on average than dust produced from experimental eolian abrasion. Fuego volcanic dust has a slight fine dust fraction and the least amount of mass in the coarse dust fraction. Eyjafjallajökull has the highest fraction of fine dust, the highest fraction of coarse dust, and the lowest fraction of supercoarse dust. Lunar regolith has more fine and coarse dust than Fuego 1974 volcanic dust but less fine dust and coarse dust than glacial, eolian, and Eyjafjallajökull volcanic dust.

4. Discussion

4.1. Martian Glaciation

Wet-based glaciers on Earth produce large volumes of sediment (B. Hallet et al. 1996; D. I. Benn & D. J. A. Evans 2013), and if wet-based glaciers existed on Mars, we assume they too would have produced abundant sediment. Wet-based glaciation enables the sliding and grinding of rocks against bedrock at the base of a glacier. Wet-based glaciers do not occur on modern Mars and likely have not existed in abundance there for over 1 billion yr (F. E. G. Butcher et al. 2017; C. E. Newman et al. 2022). However, they were likely more common in the Noachian and Hesperian, given observations of abundant sinuous ridges interpreted as eskers, indicative of wet-based glaciation (K. E. Scanlon et al. 2018). A. Bouquety et al. (2019) identified abundant erosive features interpreted as cirques and glacial valleys of late Noachian–Hesperian age. While no wet-based landforms such as eskers or moraines occur linked to these valleys, the presence of deep cirques and valleys suggests significant erosive action by the responsible glaciers. Late Amazonian features interpreted as eskers could indicate sporadic more recent wet-based glaciation (C. Gallagher & M. Balme 2015; F. E. G. Butcher et al. 2017, 2020; S. Z. Woodley et al. 2022; A. G. Galofre et al. 2024; A. O. Warren et al. 2024). A. G. Galofre et al. (2022) suggested that the lack of bedforms linked to wet-based glaciation on Earth is to be expected on Mars because more efficient subglacial drainage would prevail under conditions of Martian gravity. The efficient subglacial drainage reduces the ability for water pressure to rise, which is needed to reduce basal friction and increase sliding. Accordingly, A. G. Galofre et al. (2022) suggested that glacial sliding rates would be a factor of $20\times$ slower than on Earth, implying that weathering rates by Martian glaciers would be lower by a factor of 20–400 relative to those on Earth.

While the sediment masses produced from our experiments are generally small, the wear rates of $\sim 0.1\ \text{mm m}^{-1}$ for flat clasts and $\sim 0.6\ \text{mm m}^{-1}$ for pointed clasts are sufficiently high to erode the entire clast in $\sim 50\text{--}300\ \text{m}$ of travel distance, which would produce $\sim 8\text{--}10\ \text{g}$ of sediment. Glacial-like forms exist at the kilometer scale on Mars, implying sufficient glacial grinding to produce significant dust if wet-based sliding occurred (S. Brough et al. 2016; A. Bouquety et al. 2019).

The vesicular MG5 samples produced 2–4 times more sediment than the nonvesicular samples. The vesicles reduce the density and structural integrity of the clast, and, under the same force as the other samples, these clasts erode faster. Despite making more sediment, the PSDs of MG5 do not differ significantly from the other samples.

We expected pointed clasts to produce more sand and coarse sediment owing to the susceptibility of the asperity to failure by crushing or shattering attributable to the downward force concentrated on the point. However, no clear pattern between coarse sediment production and pointed clasts resulted. Flat clasts did not produce significantly more fine dust, which we hypothesized as likely based on prior experiments by A. G. G. Lee & E. H. Rutter (2004), who produced sediment with abundant fines when they ground granite wheels together. For most samples, the majority of produced sediment falls in the silt range ($4\text{--}63\ \mu\text{m}$). Our results suggest a natural tendency toward silt production from the abrasive action of rock-on-rock grinding under conditions similar to those prevailing at a glacier bed. These results also show sediment modes in the typical loess range ($20\text{--}50\ \mu\text{m}$) with an average mode of $\sim 24\ \mu\text{m}$, which mimics common modes of quartz-rich loess deposits on Earth (T. Sprafke 2023). On Earth, glacial abrasion has contributed vast quantities of dust and silt to major loess deposits within the relatively short span of the Pleistocene. If Mars experienced tens of millions or hundreds of millions of years with wet-based glaciation, abundant dust and silt are likely products.

When comparing our experimental design to the conditions of subglacial abrasion prevailing in nature, the biggest difference is clast velocity. In nature, the abrading clast could move with the ice in an alpine glacier at velocities between ~ 1 and $300\ \text{m yr}^{-1}$, perhaps up to $500\ \text{m yr}^{-1}$ for a surging glacier (R. Millan et al. 2019, 2022; F. Troilo et al. 2024). Our clasts abrade at a velocity of $\sim 1700\ \text{m day}^{-1}$ ($620,500\ \text{m yr}^{-1}$), significantly faster (by >3 -fold) than the fastest-moving alpine glaciers today. We note, however, that glacial velocities are reported as averages, typically measured with GPS or modeled with satellite remote sensing techniques over days to years (R. Millan et al. 2019, 2022; F. Troilo et al. 2024). The instantaneous velocity of an individual clast and its pattern of movement are unknown. Stick-slip motion in glaciers causing prolonged rapid movement phases resulting in microseismic events has been observed (O. V. Sergienko et al. 2009; J. Umlauf et al. 2021; M. Köpfli et al. 2022). During these events, portions of ice can move $0.5\ \text{m}$ in 30 minutes ($1.7\ \text{cm minute}^{-1}$) when observed from above (O. V. Sergienko et al. 2009). Accordingly, clasts at the base of the ice may move faster than $1.7\ \text{cm minute}^{-1}$ during individual microseismic events.

While the clasts in our experiments have faster velocities than those of an alpine glacier or ice sheet, we have no reason to suspect that this faster velocity is creating sediment PSDs dissimilar to those of typical glacial sediment. What might

differ is the abrasion rate of the clast and the rate of sediment produced over a given distance. Our experimental wear rates of 0.6 (pointed) to 0.1 (flat) mm m^{-1} are similar to those documented in A. G. G. Lee & E. H. Rutter (2004), where wear rates were 0.02–0.24 mm m^{-1} for their granite wheels and up to 75 mm m^{-1} for sandstone wheels.

4.2. Comparison of Dust Production Mechanisms

The tendency to produce silt from glacial abrasion of basalt may exist in other mechanical weathering processes. S. M. Adams & G. S. Soreghan (2025, in preparation) found through experiments that eolian saltation and abrasion of basalt sand produces abundant silt-sized ($<63 \mu\text{m}$) dust. The average fractional mass categories of fine, coarse, and supercoarse dust approximate those produced from our glacial grinding experiments, although grinding produces $\sim 50\%$ more fine dust ($0\text{--}2.5 \mu\text{m}$) than eolian abrasion (Figure 7(C)). Lunar regolith, wherein dust is created by perpetual impacts of meteorites and micrometeorites, also exhibits a significant mass fraction in the silt range (E. Grün et al. 2011; E. G. Sorokin et al. 2020). Explosive volcanic eruptions can produce large volumes of dust-sized particles, depending on the type of eruption. For example, basaltic eruptions with low viscosity and low volatile content are less explosive and thus typically do not produce significant amounts of fine dust. In contrast, magmas with silicic compositions, high volatile contents, and/or magmas that interact with water are more explosive and produce more fines through violent fragmentation during eruptions and pyroclastic flows (W. I. Rose & A. J. Durant 2009). The Etna and Fuego PSDs in Figure 6 are representative of low-viscosity basalt and basalt–andesite magmas and produce very little dust of $<63 \mu\text{m}$ (A. Costa et al. 2016).

Evidence of past explosive volcanism on Mars has been observed; however, it is relatively rare compared to evidence for effusive low-viscosity volcanism and eruptions that were generally concentrated in the Noachian and Hesperian (P. Brož et al. 2021). The volume of dust-sized sediment produced by volcanoes on Mars remains unclear, although some dust deposits have been interpreted as such, including the large Medusa Fossae Formation (L. Kerber et al. 2011; L. Ojha & K. Lewis 2018). It is also possible that volcanic dust on Mars is less abundant than dust generated by other mechanisms. The rarity of evidence for explosive volcanism suggests that volcanic dust may be a minor component on Mars compared to dust generated by other mechanisms.

While L. Ojha et al. (2018) suggested that large bolide impacts are ineffective for producing dust-sized particles based on fragmentation models from H. J. Melosh (1989), smaller meteorite or micrometeorite impacts may contribute to dust on Mars given significant time with a thin atmosphere, and A. G. Tomkins et al. (2019) show that Mars likely has a much higher flux of metallic micrometeorites compared to Earth. PSDs of lunar regolith, which is highly influenced by micrometeorite bombardment, show that $\sim 50\%$ of the sediment is $<74 \mu\text{m}$ (J. C. Laul et al. 1987; E. Grün et al. 2011; E. G. Sorokin et al. 2020). This suggests that meteorite impacts on Mars could produce modest amounts of fine sediment.

PSDs of experimentally ground basalt are less uniform when compared to PSDs from eolian abrasion of basalt. PSDs of samples of basalt sand abraded by S. M. Adams & G. S. Soreghan (2025, in preparation) in an eolian abrasion chamber tend to mimic one another with minor variation in

curve shapes and modes. In contrast, PSDs and modes of ground basalt can vary by tens to hundreds of microns. Two distinct curve shapes were observed in the eolian abrasion PSDs, one typical of the coarser Hawaiian sand and one typical of the finer Icelandic sands. PSDs of experimentally ground basalt suggest that glacial grinding of basalt produces relatively more fine dust than eolian saltation and effusive basaltic volcanism and comparable amounts of fine dust relative to lunar regolith.

Across several different weathering mechanisms and rock compositions, coarse ($2.5\text{--}10 \mu\text{m}$) and supercoarse ($10\text{--}67 \mu\text{m}$) dust are common products, whereas fine dust ($<2.5 \mu\text{m}$) is limited. This likely reflects the very significant energy required to mechanically break rock and minerals into particles finer than $2.5 \mu\text{m}$ —conditions that are rarely met (L. M. Tavares & R. P. King 1998).

4.3. Implications for Climate

While determination of the magnitude of the influence of glacially derived dust on Martian climate remains challenging, we can compare the possible effects relative to other dust sources. Experimentally ground basalt dust produces relatively more fine dust ($0\text{--}2.5 \mu\text{m}$) and more coarse dust ($2.5\text{--}10 \mu\text{m}$) than dust produced from eolian abrasion. The abundance of fine dust could cause more of a cooling effect through scattering of shortwave solar radiation, although the increase in coarse dust would also contribute to warming via absorption (A. A. Adebisi & J. F. Kok 2020). Presumably, there exists a ratio of fine to coarse dust at which their relative radiative impacts (warming versus cooling) cancel out, but this remains unknown. Since a dust plume is dynamic, with PSD evolving with time and transport distance as coarser dust falls out of suspension, fine dust may have a greater impact on climate because it persists in the atmosphere longer. Modeling the climate impacts of experimentally produced dust PSDs is beyond the scope of this work. However, our results suggest that if widespread wet-based glaciation existed on Mars, the dust generated from those glaciers would have likely influenced the climate through inputs of abundant fine and coarse dust. This dust would influence precipitation and cloud formation, alter ice albedo, and affect atmospheric temperatures (J. F. Kok et al. 2023). Modeling by R. D. Wordsworth et al. (2015) suggests that atmospheric dust could have contributed to the warming required for liquid water on early Mars.

Several mechanisms capable of abundant dust production were likely operating on early Mars, although the relative importance of each process likely changed through time. For example, early dust produced by bolide or meteorite impacts in the Noachian may not have persisted into the Amazonian if the produced dust was sequestered in sedimentary basins. While all mechanisms produce relatively large volumes of coarse dust capable of producing a warming effect on early Mars, as the dominant dust-producing mechanism shifted, the relative proportion of fine dust would have also shifted. This change in the coarse–fine ratio could have had a significant impact on the climate.

5. Conclusion

Widespread evidence exists of wet-based erosive glaciation on Mars, although the physical and temporal extent of wet-based glaciation remains uncertain. Our experiments suggest that glacial grinding produces distributions of sediment similar to PSDs of dust from eolian saltation and micrometeorite impacts but that

glacial abrasion is 50% more effective by volume percent at producing fine dust ($0\text{--}2.5\ \mu\text{m}$) compared to eolian abrasion, micrometeorite impacts, and nonexplosive basaltic volcanism. While explosive volcanism on Earth can produce significant dust, especially fine dust, the extent of explosive volcanism on Mars remains poorly resolved. If wet-based glaciation was extensive on Mars, our results show that a significant amount ($\sim 40\%$) of the dust produced would be $<10\ \mu\text{m}$ and capable of long-distance transport in the atmosphere, where it would influence the climate. The $>2.5\ \mu\text{m}$ fraction composes $\sim 33\%$ of the dust produced and could have contributed to atmospheric warming, thereby assisting in maintaining a warmer climate with liquid water and wet-based glaciation. However, it also proportionally produced more fine dust ($<2.5\ \mu\text{m}$) than eolian abrasion and micrometeorite impacts, which could have contributed to a cooler climate.

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Appendix

Clast before and after Grinding: Rock Sample Photomicrographs

Photos of abraded clasts before and after grinding experiments (Figures A1–A5) and photomicrographs of basalt samples used as clasts for grinding in experiments (Figures A6–A8).



Figure A1. Sample series MG1 clasts before and after grinding. Clasts on the top row are before grinding, and clasts on the bottom row are after grinding. Clasts are approximately 1 cm wide and between 2 and 3 cm tall.



Figure A2. Sample series MG2 clasts before and after grinding. Clasts on the top row are before grinding, and clasts on the bottom row are after grinding. Clasts are approximately 1 cm wide and between 2 and 3 cm tall.



Figure A3. Sample series MG3 clasts before and after grinding. Clasts on the top row are before grinding, and clasts on the bottom row are after grinding. Clasts are approximately 1 cm wide and between 2 and 3 cm tall.



Figure A4. Sample series MG4 clasts before and after grinding. Clasts on the top row are before grinding, and clasts on the bottom row are after grinding. Clasts are approximately 1 cm wide and between 2 and 3 cm tall.



Figure A5. Sample series MG5 clasts before and after grinding. Clasts on the top row are before grinding, and clasts on the bottom row are after grinding. Clasts are approximately 1 cm wide and between 2 and 3 cm tall.

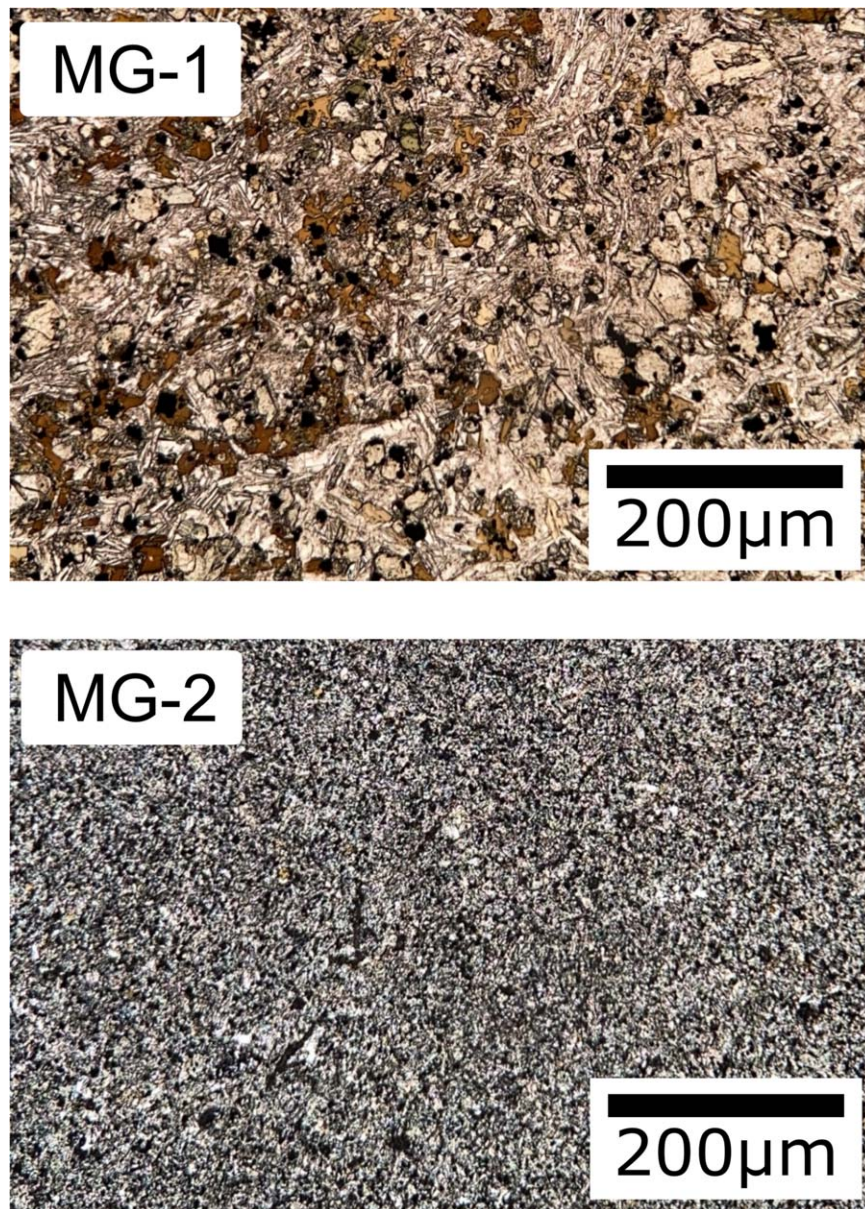


Figure A6. Photomicrograph images for samples MG1 and MG2. MG1 is the top photo, and MG2 is the bottom photo.

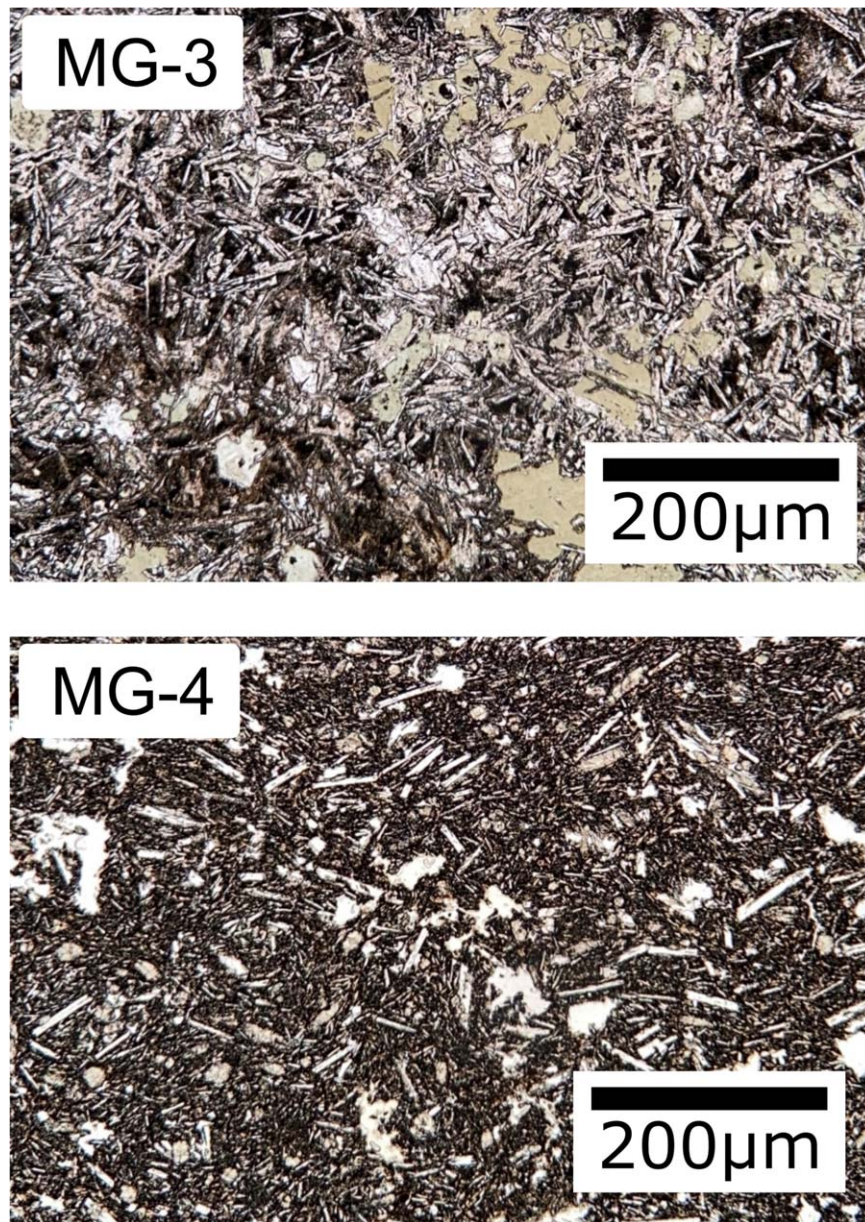


Figure A7. Photomicrograph images for samples MG3 and MG4. MG3 is the top photo, and MG4 is the bottom photo.



Figure A8. Photomicrograph images for sample MG5.

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