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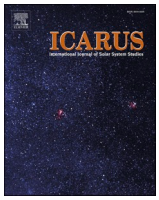

Mineral abrasion experiments at Mars relevant temperatures

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A B S T R A C T

The aeolian transport of sand generates fine material through abrasion. On Mars this process occurs at lower temperatures than on Earth, however, there is minimal data on the effects of temperature on aeolian abrasion rates. Here, results are reported of laboratory experiments where a suite of single-phase, Mars relevant minerals (feldspar, olivine, pyroxene, quartz and opal) were exposed to conditions simulating aeolian abrasion at temperatures common to the Martian surface (193 to 293 K). Our results suggest that mineral specific differences in solid phase parameters result in non-similar changes in abrasion rates with temperature. We propose this will ultimately exert a control on the composition and reactivity of the Martian surface.

1. Introduction

The reactivity of the Martian surface is central to interpretations of its habitability. The presence of oxidants has been proposed to influence surface reactivity (Klein, 1978), exerting a control on the presence of organic material at the surface (Oyama and Berdahl, 1977). The generation of H_2O_2 through the reaction of fractured silicates with water has been shown to depend strongly on mineralogy (Hurowitz et al., 2007; Edgar et al., 2022a). This mineral dependent reactivity also holds for the mechanochemical generation of other oxidants such as •OH (Hendrix et al., 2019) and perchlorate (Edgar et al., 2022b). The abrasion of sand in laboratory experiments simulating aeolian transport on Mars leads to a reduction in grain size (Merrison et al., 2010; Merrison, 2012) and an increase in surface area; with surface area and reactivity positively correlated (Bak et al., 2017). Together this suggests that controls on the abrasion rates of minerals will influence the reactivity of the Martian surface over time.

The mechanical properties of minerals exhibit known variability with temperature. Increases in indentation hardness with decreasing temperature are well documented for quartz (Evans, 1984), feldspar (Huang et al., 1985) and olivine (Evans and Goetze, 1979); significantly, each of these studies report non-zero and non-similar rates of change of hardness at the lowest temperatures tested. The effect of subnormal temperatures (90 and 194 K) on the crushing strength of a variety of minerals was investigated by Weigle (1949) who presented changes of –72 % (halite) to +517 % (serpentine). In experiments simulating aeolian abrasion at reduced temperatures, minerals abraded at lower temperatures produce less fine material (Edgar et al., 2022a), however, a systematic investigation of mineral resistance to abrasion at Mars relevant temperatures has not previously been conducted.

Here, our understanding of aeolian abrasion on Mars is extended through a series of simulated abrasion experiments targeting a suite of Mars relevant minerals (feldspar, olivine, pyroxene, quartz and opal; e.g., Rampe et al., 2020) at temperatures recorded in-situ on Mars (193 to 293 K; Martínez et al., 2017).

1.1. Experimental procedure

This study involved the simulated saltation of 5 different single-phase minerals: olivine, pyroxene, feldspar, quartz, and opal. The quartz, olivine and feldspar used in this study were obtained from Northern Geological Supplies Ltd., UK, the pyroxene was from a collection at The Great Northern Museum, Newcastle, UK, and the opal was obtained from Fantasia Mining, USA. All minerals were identified by X-ray diffraction with the olivine, pyroxene and feldspar further analysed by X-ray fluorescence, for full details see supplementary information. Minerals were crushed in a Tema disc mill and sieved to collect the sand sized fraction (125–300 μm) typical of grain sizes found in active aeolian sediments on Mars (Weitz et al., 2018). This was followed by immersion in water, sonication to remove adhered fine material, and subsequent drying at 70 °C for 48 h. Minerals were added to purpose made 10 cm length quartz ampoules in 10 g aliquots (Supplementary Fig. 1).

Ampoules were then sealed with Bellco butyl rubber stoppers (part

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no. 2048-11800A). Ampoules had hypodermic needles inserted through the stoppers before being frozen and then placed in a freeze dryer for 24 h to ensure removal of all water, with the needle then removed. The ampoules were connected to a vacuum/gassing line and evacuated to $<8 \times 10^{-3}$ mbar, monitored using an Edwards APG100-XM Active Pirani Gauge. 7.0 mbar of a certified gas mix (± 5 %; BOC) containing 96.05 % CO_2, 1.9 % Ar, 1.9 % N_2 and 0.15 % O_2 was then introduced, measured by an Edwards ASG2 Active Strain Gauge. This gas mixture replicates the mixing ratios in the Martian near surface atmosphere as measured by the SAM instrument on Curiosity (Mahaffy et al., 2013).

A rig to mechanically abrade granular material under conditions simulating saltation was developed following Merrison (2012) (Supplementary Fig. 1a). Ampoules were fastened tangentially to discs pinned to an axle rotating at 40 rpm. Each full rotation caused two inversions of the ampoule resulting in the contents falling from one end to the other under gravity. For a 75 day experiment this equated to ~8.6 $\times 10^6$ inversions. The mechanical power input of each inversion can be approximated as the specific gravitational energy (*Eu*) of the grains as they fall the length of the ampoule (h) under gravity (g), corresponding in this instance to ~0.8 W Kg^{-1}. The power transferred from the wind to grains at the threshold of saltation has been estimated to be ~0.05 W Kg^{-1} (Iversen and Rasmussen, 1999), hence these experiments simulated ~3.3 years of continuous sand mobilisation at threshold wind speeds on Mars. Sand grains on Mars potentially travel with significantly higher velocities at impact and it should be recognised that these experiments represent the transfer of sand at threshold wind speeds (e.g. Waza et al., 2023). The rigs were housed and operated within incubators for temperature control at 193, 223, 253, 273 and 293 K. Incubators had side ports allowing the rotator axle through the wall leaving the motor outside at room temperature. Temperatures within incubators were monitored with PT100 temperature probes (−100 to 450 °C ± 0.2 %) connected to an Omega OM-CP series data logger.

After 75 days of simulated saltation samples were removed from the ampoules and individually passed through a 125 μm sieve, i.e., the lowest diameter mesh that original samples would not pass through. The mass of each fraction (above and below 125 μm) was then weighed to 4 decimal places. There was inevitably some loss of fine material in the transfer processes. For example, any fines that adhered to the inside of the ampoules would not be measured; similarly, it is possible that some of the ampoule material would have been abraded and added to the fine fraction. To account for this, the fine fraction was calculated as the start mass of mineral minus the coarse fraction after abrasion. The wt% of mineral abraded are reported as:

$$\frac{\text{Mass of fine fraction}}{\text{start mass}} \text{ x } 100\ (\%) \quad (1)$$

All abrasion experiments were run in triplicate and the data is reported as the mean of three experiments.

2. Results & discussion

Prior studies of the reactivity of Martian surface materials have suggested that mineralogy plays a key role in determining its reactivity (Hurowitz et al., 2007; Hendrix et al., 2019; Edgar et al., 2022a). An understanding of the mechanisms that generate fresh mineralogical material is therefore necessary to evaluate the Martian surface environment. The experiments described here were conducted under the range of temperatures encompassing the diurnal and seasonal temperature variations recorded in situ on Mars (193 K to 273 K; Martínez et al., 2017). The tested range also includes the IUPAC standard temperature (~ 273.15 K) and the temperatures commonly encountered in laboratories, i.e., 'benchtop' temperatures (typically ~288 K to 293 K).

After 75 days of simulated abrasion a fraction of each of the minerals, at each of the tested abrasion temperatures, were reduced to below their starting grain size (125 μm; Fig. 1; Supplementary Table 3). The sub-125 μm fraction recovered from each of the experiments abraded at 193 K

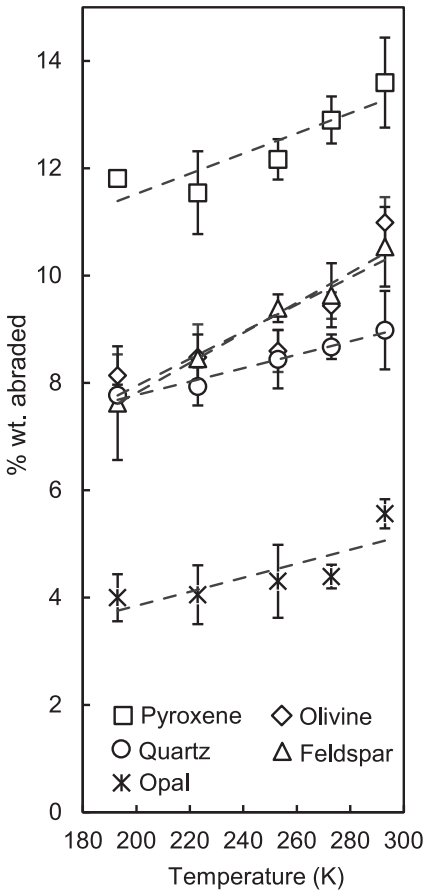

Fig. 1. wt% abraded to below 125 μm plotted against temperature of abrasion. All minerals as per key. The trend lines are least squares best fits. Error bars show ± 1 SD (n = 3). Data are provided in Supplementary Table 3.

was significantly (*t*-test; $p < 0.05$) less than that recovered from sands abraded at 293 K. At each temperature, the most fines were consistently recovered from pyroxene (maximum = 13.6 ± 0.8 % at 293 K; Fig. 1) and the least were consistently generated from opal (minimum = 4.0 ± 0.4 % at 193 K; Fig. 1). Olivine, feldspar and quartz generated similar quantities of fine material and were not consistent in the order of fine generation across the temperature range. For example, olivine generated more fines than feldspar at 293 K but not at 253 K, whilst quartz generated less fines than feldspar at all temperatures except for 193 K (Fig. 1; Supplementary Table 3). The difference between minimum and maximum fine material recovery between 293 and 193 K was mineral specific and ranged from a maximum of a 28.1 ± 0.5 % for opal to a minimum of 13.1 ± 0.8 % for pyroxene (Supplementary Table 3).

Dust agglomerates have been observed in prior experiments of a similar design (Merrison, 2012) which were not observed in this study, although a white veneer was found to form in some of the quartz experiments on the ampoule walls (Supplementary Fig. 1b). We suggest that this discrepancy may result from the different selection of the ampoule material; prior studies have utilised glass which is less resistant to abrasion than the quartz used here and may have subsequently added more significant volumes of material to their experiments.

In prior experiments of a similar design the hardness of the material has been interpreted as driving abrasion (Merrison et al., 2010; Merrison, 2012; Edgar et al., 2022a,b). The silicates used in this study have Mohs hardness between ~5.5 and 7, however, there was no correlation between the Mohs hardness of the material and the amount of fines produced. For example, the Mohs hardness of both pyroxene and opal are between 5.5 and 6.5 and these two minerals consistently generated the most and least fines respectively. Olivine and quartz, have a Mohs

hardness of ~7 and both generated more fines than opal and less than pyroxene (Table 1). The lack of correlation between Mohs hardness and total abrasion reported here indicates that other mechanical properties of the minerals play a more dominant role in determining absolute abrasion rates.

Prior studies investigating the effects of temperature on the Vickers hardness of different minerals have shown that a decrease in temperature results in an increase in hardness (Supplementary Fig. 2). These studies also show non-similar rates of change in hardness with temperature, i.e., the rate of change in hardness with temperature is different for different minerals (Weigle, 1949; Evans & Goetze, 1979; Huang et al., 1985; Kranjc et al., 2016). Broz et al. (2006) demonstrated a non-linear relation between Mohs number and Vickers hardness, and also with fracture toughness. As the abrasive process involves normal and shear contact components, both material properties will govern abrasion rates. The results presented here are consistent with these observations (Fig. 1). If changes in mineral hardness with temperature is driving mineral specific changes in abrasion rates, the composition (and subsequently the reactivity) of the fine fraction of Mars' regolith produced through aeolian abrasion may be temperature dependant. We note that our experiments have been designed to investigate differences in the abrasion response of minerals to varying temperature at a specific impact velocity (u) close to threshold wind speeds on Mars. The amount of fresh surface area generated by an individual impact is proportional to the kinetic energy of the impactor, i.e. to the square of the particle velocity ($\sim u^2$) (e.g. O'Hara-Dhand et al., 2010). Dust generation can then be modelled as a product of the kinetic energy per mass of sand, and the sand transport rate, which is itself proportional to the square of the wind speed ($\sim u^2$) (e.g. Merrison et al., 2012). The resulting strong dependence of dust generation on wind speed ($\sim u^4$) suggests that differences in particle velocity will dominate differences in the abrasion rates of minerals on Mars. Our new data indicates that under a specific wind regime, abrasion rates will respond to changes in temperature.

As well as the properties of the solid phases in these experiments, the properties of the fluid phase have the potential to influence mineral abrasion rates. Abrasion rate is proportional to the kinetic energy of the impacting particles and ultimately related to wind speed (e.g., Greeley et al., 1982; Merrison, 2012); the impact velocity in these experiments could be affected by the fluid phase by changes in both the Reynolds number, through fluid drag (e.g., Lamb et al., 2012); and the particle Stokes number, through viscous dampening (e.g., Davis et al., 1986; Schmeeckle et al., 2001). These two parameters are in turn a function of temperature dependant fluid properties such as gas density and viscosity, important considerations for studies of aeolian transport on Mars (Lapotre et al., 2017; Sullivan et al., 2020). The effects of temperature on the fluid phase may therefore be controlling the rates of abrasion in these experiments via changes in impact velocity. As the properties of the fluid would vary systematically with temperature, the non-similar changes in abrasion rates for the different minerals reported here suggest a mineral specific solid phase parameter relating impact velocity to abrasion rate. If the cause of the changes in abrasion rates are a mineral specific function of impact velocity, this yields an alternative proposition: fine material generated through aeolian abrasion is mineralogically distinct when generated at different impact velocities. It is also possible that both effects described here are recorded within the presented data.

Table 1
Maximum and minimum abrasion rates and Mohs hardness of each mineral.

	% wt. Abraded		Mohs Hardness
	Minimum	Maximum	
Pyroxene	11.81 ± 0.00	13.59 ± 0.84	6
Olivine	8.14 ± 0.39	10.99 ± 0.47	7
Quartz	7.77 ± 0.20	8.98 ± 0.73	7
Feldspar	7.62 ± 1.06	10.54 ± 0.74	6.5
Opal	4.00 ± 0.44	5.56 ± 0.27	5.5

Further experiments to separate and elucidate these processes will be of broad interest to planetary scientists.

3. Conclusions

After simulated saltation equivalent to ~3.3 years of continuous sand movement on Mars, experiments performed at Earth ambient temperatures (~ 293 K) produced more fine material than experiments performed at Mars ambient temperatures (193 K); signifying that temperature should be considered in any future experiments simulating Martian abrasion. The non-similar changes in abrasion rates presented here suggest a solid phase parameter is exerting a control on the abrasion of minerals. Silicate minerals with similar Mohs hardness' can generate different quantities of fine material, suggesting that Mohs hardness is not a practical predictor of abrasion potential. We suggest that increases in mineral hardness with temperature reduce abrasion rates at lower temperatures, or alternatively, that there is a mineral specific response in abrasion rates to impact velocity. In both cases the rate of change is non-similar between minerals which will lead to variations in Martian surface reactivity, ultimately driven either by temperature, wind speed, or both.

CRediT authorship contribution statement

J.O. Edgar: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **J.A. Gould:** Investigation. **K. Badreshany:** Investigation. **S.P. Graham:** Methodology, Investigation. **J. Telling:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used in this study is made availible in the supplementary information

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.icarus.2024.116238.

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