

Stress histories control rock-breakdown trajectories in arid environments

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ABSTRACT

Rock and boulder surfaces are often exposed to weathering and /or rock-breakdown processes for extremely long time periods. This is especially true for arid environments on Earth and on planetary bodies such as Mars. One important, but largely unexplored, gap in knowledge is the influence of past stress histories on the operation of present rock-breakdown processes. Do rocks in the same area with different stress histories respond equally to newly imposed environmental conditions? This study investigates the influence of different physical and chemical stress histories on the response of basalt to salt weathering. We designed a four-stage approach of pre-treatment, field exposure, weathering simulation, and post-treatment: (1) physical, chemical, or no pre-treatment in the laboratory; (2) 3 yr exposure in either a hyper-arid sandy or salt-pan environment in the Namib desert (Namibia); (3) 60 cycles of a hot desert salt weathering simulation; and (4) desalination. Salt uptake and rock breakdown was assessed at each stage through comparison with baseline observations of mass, internal strength (Dynamic Young's modulus) and surface morphology (three-dimensional microscopy). Clear differences in block responses were found. Physically pre-treated blocks (especially those left in the salt-pan environment) experienced the highest loss of strength overall, chemically pre-treated blocks showed the greatest mass loss in the sandy environment, and freshly cut blocks gained strength during exposure in the desert and maintained this during the experiment. These results imply that stress history matters for predicting breakdown rates, with humid, arid, and saline legacies influencing subsequent breakdown in distinctive ways.

INTRODUCTION

Rock-breakdown processes such as physical and chemical weathering are important agents of geomorphic change, producing erodible sediment and influencing slope instability. Rates of rock breakdown in arid environments are generally slow (e.g., ~1 mm k.y.⁻¹; Ryb et al., 2014), although 'hot spots' of locally wet, salty conditions have much higher breakdown rates (e.g., ~10–150 mm k.y.⁻¹; Viles and Goudie, 2007). In arid environments on Earth, salt weathering is an important rock-breakdown process (Goudie, 1993; Warke, 2007), as are thermal stresses from differential insolation (identified as a likely cause of boulder cracking by Eppes et al. [2010, 2015], and shown experimentally to cause deterioration in pre-stressed blocks by Viles et al. [2010]) and wind abrasion. Similarly, experimental, observational, and modeling studies show thermal cycling to be an important cause of rock breakdown on dry planetary bodies such as Mars (Viles et al., 2010; Eppes et al., 2015; Molaro et al., 2015), in addition to eolian abrasion (Bridges et al., 2014) and salt weathering (Jagoutz, 2006). The relative importance of these different rock-breakdown processes and their dynamics over space and time have not yet been clearly evaluated.

The term 'stress history' has been used to describe how the legacy of past processes influences response to current weathering (Warke, 2007). For example, rocks exposed to long periods of chemical weathering in wetter phases may respond more quickly to eolian abrasion in subsequent drier periods than rocks without that history. Or, rocks that have experienced extensive thermal cycling in arid conditions may break down more rapidly than other rocks when exposed to salt weathering associated with wetter conditions (Warke, 2007). Such stress histories may partially explain spatial and temporal patterning in rock-breakdown rates and styles in arid environments, and help explain variability of landscape evolution in geomorphic settings such as desert pavements (Viles and Goudie, 2013) and alluvial fans (Eppes and McFadden, 2008) over decadal to millennial time scales. What is lacking is empirical evidence of how different stress histories affect subsequent weathering trajectories.

This paper evaluates the influence of stress histories on a relatively resilient rock type (basalt) found widely on Mars and in many Earth deserts (e.g., northern Namibia and Saudi Arabia). Specifically, we assess how legacies from past environmental conditions (wetter, drier, or more

saline) influence breakdown rates. We utilize a novel methodology (combining sequential laboratory and field experiments) to address the following questions: (1) how do past histories of chemical weathering (by acid) or physical weathering (by thermal cycling) influence subsequent rock breakdown in eolian and salt-rich environments, (2) how does exposure in eolian or salt-rich environments influence subsequent salt weathering, and (3) how can such influences on weathering trajectories best be quantified experimentally?

METHODS

Basalt Sample Groups and Simulation of Stress Histories

Following Viles et al., (2010), a freshly quarried, fine-grained, dense, olivine-bearing basalt with plagioclase phenocrysts from China was used as the experimental substrate. Similar basalts are found in several desert environments on Earth, and are recorded from Gusev crater on Mars (McSween et al., 2006). One large basalt block was cut into small blocks (9.0 × 2.5 × 2.1 cm) and divided into seven sample groups, each comprising three replicates. Prior to experimental salt weathering, each group was subjected to a distinctive stress history, divided into two phases: (1) laboratory pre-treatments, and (2) field exposure (Fig. 1).

In the pre-treatment phase, physically pre-stressed sample groups (coded 'P') simulated diurnal thermal cycling typical for arid Earth and Mars environments. Blocks were subjected to five cycles of heating to 300 °C followed by quenching in water (following Viles et al. [2010], after Warke [2007]). Chemically pre-treated groups (coded 'C') replicated long-term weathering hypothesized to occur under past acid fog conditions on Mars (Tosca et al., 2004; Horgan et al., 2017) and in wetter phases in Earth deserts. Blocks were oven-dried and immersed in 2M H₂SO₄ solution for 48 h. Additional groups (coded 'N') had no pre-treatment.

In the field exposure phase, samples were exposed to hyper-arid conditions for 3 yr (September 2008 to August 2011) at two contrasting field sites in the Namib Desert, Namibia (Fig. 1).

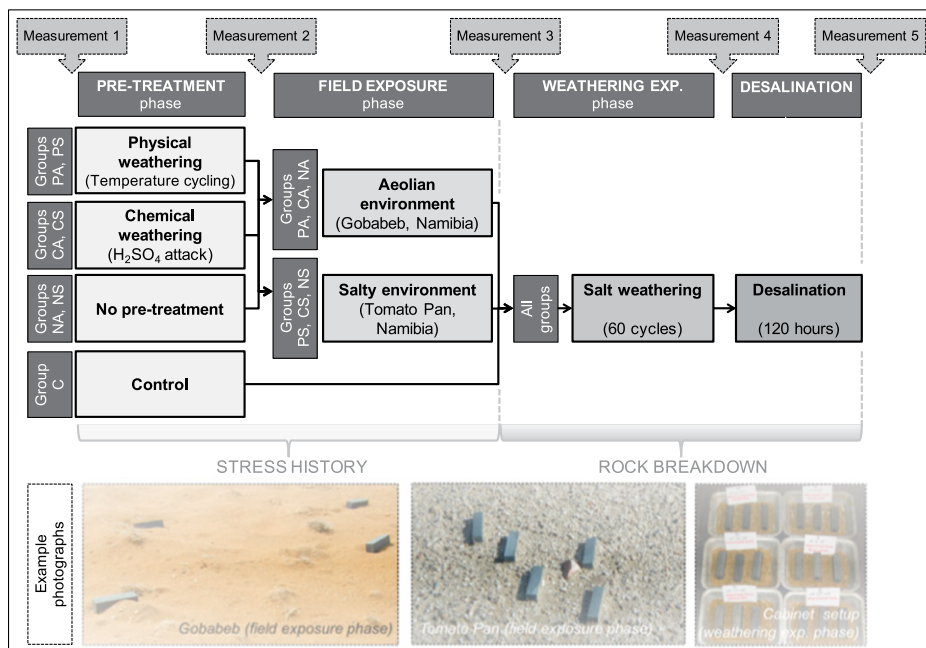


Figure 1. Summary of sample groups and experimental phases.

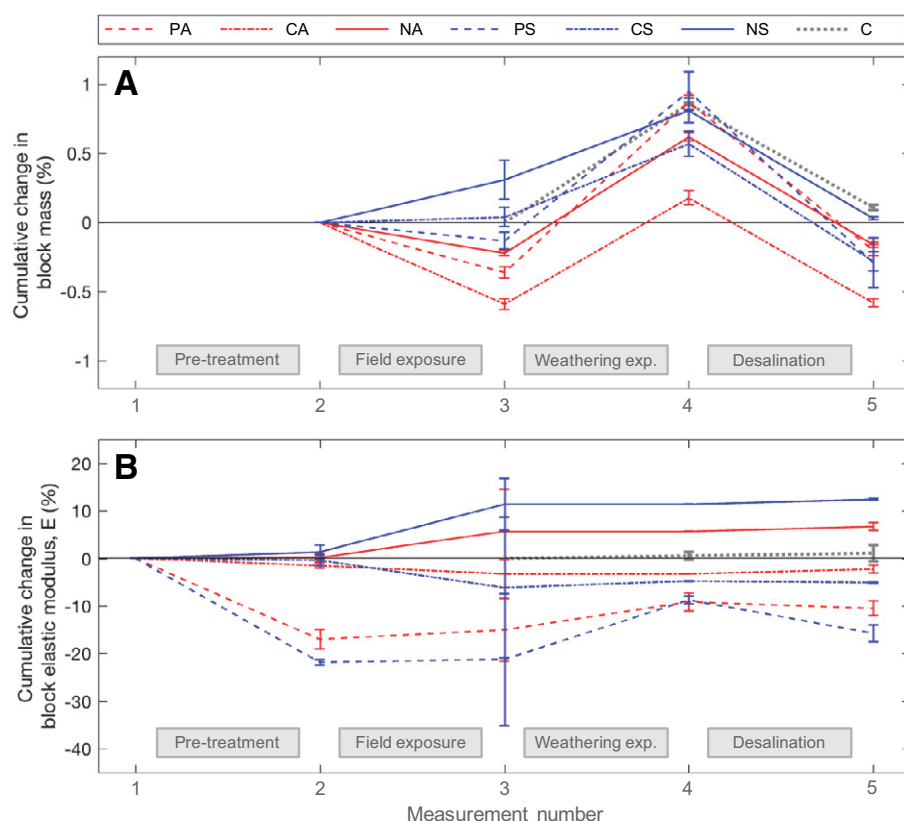


Figure 2. A: Cumulative change in block mass (%) relative to baseline after each stage. Note the distinctive behavior of physically pre-treated blocks (dashed lines). B: Cumulative change in E modulus (%) relative to baseline after each stage. Note the clear differences in behavior between physical (dashed lines), chemical (solid lines), and no (dot-dash lines) pre-treatment histories. See text for further details. PA, PS—physical pre-treatment; CA, CS—chemical pre-treatment; NA, NS—no pre-treatment; C—control.

Three sample groups with different pre-treatment histories (PA, CA, and NA) were placed on a sandy surface at the Gobabeb field site at the northern tip of a linear dune system in western Namibia (25.5602°S, 15.0403°E), which experiences regular, strong easterly winds. Blocks were placed orthogonal to the prevailing wind, to maximize eolian abrasion. The other three groups (PS, CS, and NS) were placed on a gravel surface in Tomato Pan near Swakopmund (22.6741°S, 14.5278°E), a salt-rich coastal environment, receiving regular fog precipitation (Viles and Goudie, 2007). Control blocks (C) received no pre-treatment or field exposure (Fig. 1).

Weathering Experiment and Desalination

In the weathering experiment phase, blocks from all seven groups were subjected to 60 cycles (23–72 °C, 100–30% relative humidity [RH]), in an environmental cabinet (Sanyo-FE 300H/MP/R20) based on climate data from Wadi Digla, Egypt, and the Negev Desert, Israel (Goudie, 1993). A full 24 h day was compressed into an 8 h cycle by reducing the length of time at near-constant temperatures (cf. Viles et al., 2010), to preserve a natural rate of temperature change (~0.2 °C/min) during periods of maximum heating and cooling. A 40W infrared lamp was switched on for half of each cycle to simulate natural heat transfer via solar radiation, and convective heating by surrounding air. All samples (including group C) were placed on 300 g of coarse sand mixed with sodium sulfate (Na_2SO_4) to a 1:10 weight ratio, in a tray (cf. Goudie et al., 2002). Na_2SO_4 is found in both terrestrial and Martian surface soils, and is known to be an effective weathering agent. To simulate fog as an important source of moisture and heat transfer, Na_2SO_4 solution (14% w/w, weight per weight) was sprayed after every third cycle. Sample groups were separated to prevent possible interactions, and rotated every 8 h to ensure equal exposure to any slight variations in conditions in the cabinet. The final desalination phase (two 48 h cycles of immersion in distilled water) aimed to release salt taken up in field exposure and weathering simulation, as well as any weathered debris.

Monitoring Rock Breakdown

In order to assess changes in block mass over time (as a measure of salt uptake and physical breakdown and/or loss of material), oven-dry weights (at 40 °C) were measured (Oxford Research Plus balance, ± 0.01 g) before and after each phase. The elastic strength (E modulus or Young's Modulus) of the basalt blocks was also measured on the top surface of each block before and after each phase using a MK5 Grindosonic device, as an indicator of incipient breakdown (e.g., Goudie et al., 1992). Surface morphologies were quantified as roughness (areal roughness parameter, S_a) at 50 \times magnification for a

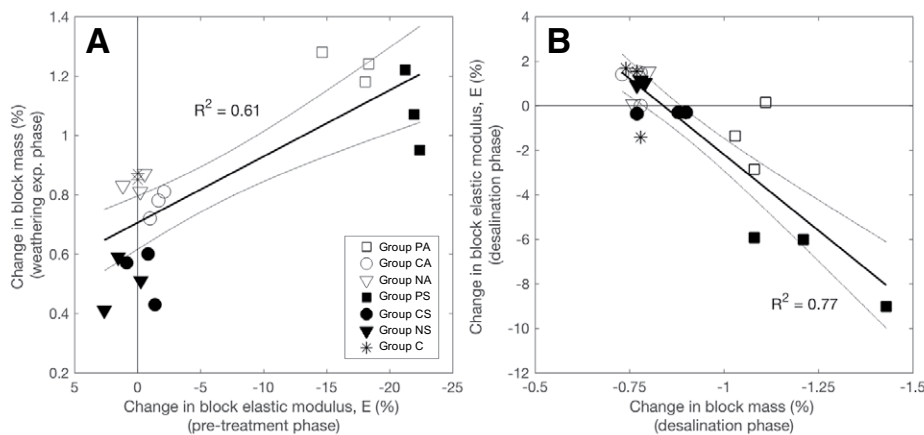


Figure 3. A: Change in E modulus (%) during the pre-treatment phase versus mass change (%) in the weathering experiment phase. B: Change in mass (%) versus change in E modulus (%) during the desalination phase. Dotted lines provide 95% confidence bounds around lines of best fit. PA, PS—physical pre-treatment; CA, CS—chemical pre-treatment; NA, NS—no pre-treatment; C—control.

sub-sample of blocks (Keyence 6000 series 3-D microscope).

RESULTS

Figures 2 and 3 summarize how previous stress histories of chemical (by acid) or physical (by repeated thermal cycling) weathering imprint onto subsequent phases of weathering in eolian and salt-rich environments. Acid pre-treatment simulates the production of a less-resilient weathering rind through long-term chemical weathering in humid conditions. Blocks pre-treated in this way were highly susceptible to eolian abrasion during field exposure (group CA lost weight and some strength), and slightly susceptible to salt weathering in the field and weathering experiment (group CS lost strength during field exposure and lost weight after desalination). Chemically pre-treated blocks also had rougher, more-pitted surfaces than the controls (Figs. 4D–4F; cf. Figs. 4G–4I; mean $S_a = 22.3 \mu\text{m}$, cf. $11.4 \mu\text{m}$). These results indicate that basalt clasts with legacies from humid conditions will be particularly sensitive to eolian abrasion during subsequent arid phases. Surface pitting will be visually obvious on such clasts.

Physically pre-treated blocks showed persistently different behavior during subsequent phases. They showed the greatest weight loss in the salty field exposure, the greatest increase in weight after the weathering experiment, and the largest fluctuations in strength over the different phases (PA and PS in Fig. 2). The relationships in Figure 3 imply that the legacy of micro-cracks imposed during physical pre-treatment heavily influenced salt uptake (group PS). Indeed, the slightly rougher surfaces of physically pre-treated blocks compared to controls (mean $S_a = 15.5 \mu\text{m}$) are interpreted as the surface expression of three-dimensional (3-D) micro-crack networks imparted by the pre-treatment (Figs. 4A–4C). These results indicate that basalt clasts with legacies from arid conditions will weather quickly through subcritical crack growth when conditions change to favor salt weathering.

Our results also demonstrate that exposure to salt-rich versus eolian environments influences

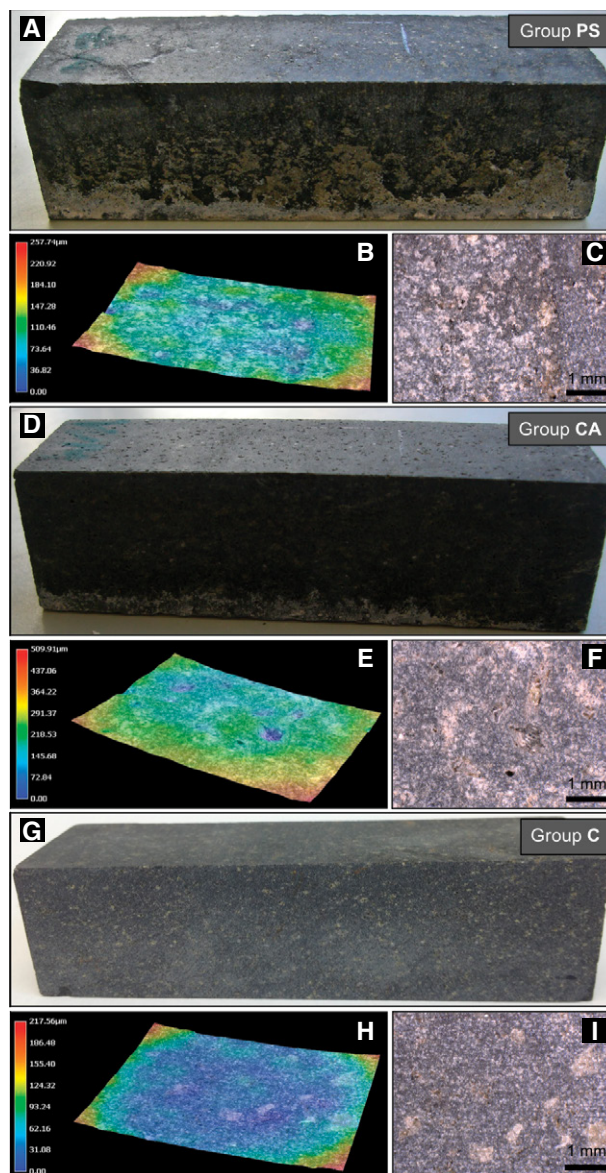


Figure 4. A: Visual and roughness changes in a group PS (physically pre-stressed) block after the experimental weathering phase, showing incipient salt weathering near the base and vein-like micro-cracks on the top surface. B: Three-dimensional (3-D) false-colored topographic image (50 \times) of a PS block after desalination, showing vein-like micro-cracks as shallow grooves. C: Same spot on block surface as in B, showing brownish, vein-like micro-cracks (50 \times). D: Group CA (chemically pre-treated) block after experimental weathering showing distinct surface pitting. E: 3-D false-colored topographic image (50 \times) of CA block after desalination showing depth of pitting. F: Same spot as in E, showing clear pitting (50 \times). G: Control (C) block before weathering experiment. H: 3-D false-colored topographic image (50 \times) of control block showing very low surface relief. I: Same spot as in H, showing regular, straight cutting traces (50 \times).

the subsequent response of blocks to experimental salt weathering. Three years of exposure to salt-rich hyperarid conditions led to enhanced weight loss after 60 cycles and desalination for both physically and chemically pre-treated blocks. Similarly, changes in strength at

each phase were more pronounced for blocks exposed in the salty environment (blue lines in Fig. 2B). These results indicate that saline conditions facilitate rapid subsequent rock breakdown, regardless of previous stress history, in comparison with eolian conditions. Thus, salt

weathering is an effective amplifier of inherited surface breakdown signatures.

DISCUSSION AND CONCLUSIONS

Our observations demonstrate how combining different measures of rock breakdown (both direct and indirect) can reveal useful information about weathering behavior. Weight-change data reveal differences between groups according to their field exposure history, whereas strength data differentiate between groups according to pre-treatment regime. Further, strength reduction provides an ‘early warning’ of subcritical crack growth and other hidden internal structural changes, which may eventually translate into surface morphological and/or weight changes. Micro-scale surface morphology observations further help relate reduced rock mass and strength to macro-scale landform erosion and slope instability. In the future, combined monitoring of weight, strength, and micro-scale surface morphology during field experiments, such as those carried out by Hedding et al., (2016), should lead to greater insights into the observed spatial and temporal variability of weathering.

Observations from Mars illustrate inter- and intra-site spatial variability in weathering that our research findings help to explain. Boulders from Gusev Crater show evidence of considerable breakdown, inferred to be from acid sulfate weathering and eolian abrasion (Ming et al., 2006), whereas those from Gale Crater show little evidence of chemical weathering, but more signs of physical weathering (Schmidt et al., 2014). Longer-term exposure to moist conditions at Gusev Crater has likely produced clasts susceptible to eolian abrasion; whereas the long history of predominantly dry conditions at Gale Crater has produced rocks susceptible to salt weathering. Intra-site variability in rock-breakdown features observed at both sites, such as the patchy occurrence of large-scale cracks at Gusev (Eppes et al., 2015), could also be explained by local differences in environmental histories—with boulders exhibiting long histories of dry conditions likely affected by micro-crack networks susceptible to cracking.

Complex patterns of weathering in extreme hot and cold desert environments on Earth may also be explained by our results. Hedding et al. (2016) found high inter-clast variability in weight-loss trends for 39 dolerite clasts over 7 yr on a nunatak in Antarctica, which may reflect differences in stress histories. Susceptibility of rocks to deterioration caused by thermal stresses, as inferred to be important on tonalite in Anza Borrego, California (Joo et al., 2016), and on dolerite in Antarctica (Lamp et al., 2017), may also vary according to their stress histories. Rocks that have experienced long-term very dry conditions are likely most prone to physical breakdown at these sites. Furthermore, our results illustrate the significance of salt weathering in these situations

as an amplifier of other weathering processes, which should be investigated further.

In conclusion, past exposure of basalt—whether to wetter conditions (simulated by chemical pre-treatments) or to hot dry conditions (simulated by physical pre-treatments)—affects the basalt’s response to subsequent eolian abrasion and salt weathering. Such differences help explain the spatial and temporal complexity of weathering behaviors within the range of environmental conditions observed in deserts on Earth and on Mars, and other planetary bodies that have experienced diverse, long-term stress histories.

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