Impact of textural patterns on rock weathering rates and size distribution of weathered grains

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Abstract

Rock texture has a critical influence over the way rocks weather. The most important textural factors affecting weathering are grain size and the presence of cracks and stylolites. These discontinuities operate as planes of mechanical weakness at which chemical weathering is enhanced. However, it is unclear how different rock textures impact weathering rates and the size of weathered grains. Here, we use a cellular automaton numerical model to simulate the weathering of rocks possessing grain boundaries, cracks, and stylolites. We ran simulations of both synthetic patterns as well as natural patterns of cracks, and stylolites. We found that for all patterns, weathering rates increase with the density of discontinuities. When the abundance of discontinuities was lower than ~25%, the synthetic patterns weathering rate followed the order: grid> honeycomb> Voronoi> brick-wall. However, for higher values of discontinuity density, all patterns exhibit similar weathering rates. We also tested the impact of the tortuosity of the pattern on weathering rates, and found rates to decrease with increasing tortuosity. In addition, we show that the rock textural pattern strongly impacts the detached grain size distributions. Rocks with an initial monomodal grain size distribution produce weathered fragments that are normally distributed. In contrast, rocks with an initial log-normal size distribution produce weathered grains that are log-normally distributed. For the natural rock patterns we tested, weathering changed the initial multimodal grain size distributions to lower modality distributions.

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2 weathered grains

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7 Highlights

- Numerical model simulating chemical weathering and grain detachment in rocks with
 different textural patterns.
- Weathering rate increases with increasing density of discontinuities.
- Mean size of detached fragments decreases with increasing tortuosity of the textural
 patterns.

13 Abstract

14 Rock texture has a critical influence on the way rocks weather. The most important textural factors affecting weathering are grain size and the presence of cracks and stylolites. These 15 discontinuities operate as planes of mechanical weakness at which chemical weathering is 16 enhanced. However, it is unclear how different rock textures impact weathering rates and the size 17 18 of weathered grains. Here, we use a numerical model to simulate weathering of rocks possessing grain boundaries, cracks, and stylolites. We ran simulations with either synthetic or natural patterns 19 of discontinuities. We found that for all patterns, weathering rates increase with discontinuity 20 density. When the density was $<\sim 25\%$, the weathering rate of synthetic patterns followed the order: 21 grid >honeycomb >Voronoi >brick-wall. For higher values, all weathering rates were similar. We 22 also found that weathering rates decreased as the tortuosity of the pattern increased. Moreover, we 23 show that textural patterns strongly impact the size distributions of detached grains. Rocks with an 24 initial monomodal grain size distribution produce weathered fragments that are normally 25 26 distributed. In contrast, rocks with an initial log-normal size distribution produce weathered grains

that are log-normally distributed. For the natural patterns, weathering produced lower modalitydistributions.

Keywords: Chemical Weathering, Grain Size, Fractures, Stylolites, Physical weathering,
Dissolution.

31 **1 Introduction**

Both natural and anthropogenic processes are affected by the rate at which rocks weather. Weathering rates impact the development of landscapes, the formation of soils, the fluid flow in aquifers and petroleum reservoirs, and the durability of buildings and monuments [1-3]. In addition, weathering rate plays a significant role in the global carbon cycle [4, 5], regulating atmospheric CO₂ on geological time scales [6]. Artificially accelerated weathering has even been suggested as a way of mitigating present-day anthropogenic carbon emissions [5, 7-9].

38 Weathering rates are affected by both chemical and physical mechanisms. Rocks comprising minerals that are susceptible to chemical processes, such as dissolution, oxidation, and 39 hydrolysis are expected to weather more rapidly than rocks comprising inert minerals [10-15]. In 40 addition, physical processes such as frost shattering, thermal expansion, and unloading [16-20] can 41 induce fracturing that causes mechanical weathering. Complicating matters further, chemical and 42 physical processes are often coupled [10, 21-24]. As the density of cracks increases, more mineral 43 surfaces are exposed to chemical reactions. At the same time, chemical dissolution along these 44 45 cracks increases the overall porosity and weakens the rock mechanically [25, 26], accelerating physical weathering. 46

At the microscopic scale, weathering rates are affected by discontinuities that include 47 crystalline defects, crystal edges and corners, and grain boundaries [27, 28]. For example, the rate 48 49 of dissolution along the edges and corners of a calcite spar was measured to be 1.7-3.6 faster than of the mineral face [29]. In polycrystalline rocks, grain boundaries were found to be an order of 50 magnitude more reactive than the bulk mineral [30-32]. In studies focused on rock weathering at 51 the submicron scale, enhanced dissolution at grain boundaries was shown to cause the mechanical 52 detachment of particles into the fluid phase [33-36]. Such chemo-mechanical rock weathering was 53 observed in micritic limestone, [37], however, particle detachment can occur in various types of 54 55 rocks with larger grain sizes and different mineral compositions [37-39].

At macroscopic scales, rock weathering is accelerated by other types of discontinuities such as cracks, joints, fractures, and stylolites [26, 40], which operate as planes of mechanical weakness and enhanced chemical weathering [20, 41, 42]. For example, Røyne et al. [21] showed that outcrop weathering is controlled by continual fracturing and production of surface area, which allows fluids to penetrate deeper into the rock and accelerate weathering rates.

While discontinuities are known to enhance weathering rates, the impact of different 61 patterns and textures remains unclear. Discontinuities often show spatial ordering and fractal 62 63 behavior [43-47], appearing in several superimposed networks reflecting the geological history of 64 the rocks [26, 48]. Typical patterns include conjugated sets of fractures, grid and ladder-like patterns, polygonal joints, and columnar joints [26, 48, 49]. Furthermore, similar patterns can have 65 different levels of connectivity depending on the spacing, orientation, length, and density of the 66 discontinuities. The convolution of these factors can be represented by tortuosity, which is a 67 measure of the geometric complexity of the pathways by which reactive fluids penetrate the rock. 68 High tortuosity is expected to lead to reduced weathering rates, while low tortuosity could intensify 69 70 weathering.

Here, we develop a cellular automaton model that simulates coupled chemo-mechanical weathering processes of rocks with different kinds of discontinuities and textural patterns. Specifically, we analyze the impact of the density and tortuosity of the discontinuities on the weathering rate. In addition, we examine how these parameters impact the size distribution of weathered rock fragments. We also discuss the implications for both surface and subsurface processes including soil and regolith production.

77 **2 Methods and data**

78 2.1 Model structure

To simulate the effects of chemo-mechanical weathering on rocks with different textures and grain size distributions, we used a model based on that described by Israeli and Emmanuel [39]. A 2-D cross-section of the rock was represented using a domain with 560*420 elements. Each element represented either a solid mineral, a discontinuity, or a fluid phase and is assigned a characteristic value.

In the simulations, chemical weathering only occurs in elements neighboring the fluid phase. In every time step, the probability that an element will dissolve depends both on the characteristic value of the element and the number of neighboring fluid elements. The dissolved elements are then reassigned as a fluid phase, and the domain is scanned for interconnected elements that are fully surrounded by fluid. These surrounded elements are considered to be detached physically and their elements are also reassigned to the fluid phase (Figure 1).

The discontinuities in the model are intended to represent grain boundaries, joints, cracks, or stylolites which are partially filled with cement. Thus, the discontinuities have an intrinsic strength that binds the rock together but they also dissolve more rapidly than the bulk rock, and this effect is included in the model.

The data from every simulation was saved as an object comprised of all the information from the simulation, including the rock's initial properties and the dynamic properties of the rock in every step. These properties include an image of the rock in every step, a list of pixels that were dissolved, location, and dimensions of detached fragments in every step. Using this object-oriented approach in MatlabTM, each simulation takes several minutes on a standard PC and the data is uploaded into a MySQL database facilitating analysis of the datasets.

100 2.2 Patterns of discontinuities

In our model, we used two kinds of discontinuity patterns: synthetic and natural (Figure 2). 101 Four different synthetic patterns were tested: (i) regular grid jointing; (ii) brick wall jointing; (iii) 102 103 hexagonal jointing, simulating columnar patterns common in basalts; (iv) Voronoi tessellation, representing a coarse-grained crystalline rock. Weathering was also simulated for 4 natural rock 104 105 patterns, obtained by binarization of outcrop images: (i) diagonal cracks; (ii) orthogonal cracks; (iii) stylolites oriented perpendicular to the weathering front; (iv) stylolites oriented sub-parallel 106 107 to the weathering front. The crack patterns are taken from two locations: drone images from McDonald limestone in Scotland [44] and a limestone outcrop at the south margin of the Bristol 108 109 Channel Basin, UK [50]. The stylolite patterns are derived from images of carbonate rocks from Israel, reported by Laronne Ben-Itzhak et al. [51]. 110

111 2.3 Model calculations

In the initial state of our simulations, we define a grain or block as a region bounded by discontinuities. We also define the discontinuity density as the proportion of discontinuity pixels

in the domain. For natural rock patterns in our simulations, this varies in the range 2% to 30%, 114 while for synthetic patterns this varies from 7% to 40%. For natural patterns, different values of 115 discontinuity density were obtained by cropping the images. In simulations using synthetic 116 patterns, discontinuity density is controlled by the number of grains in the domain: increasing the 117 number of grains increases the discontinuity density. 118

Six different realizations were carried out for each pattern type, and a total of ~ 6000 119 simulations were completed. At each step, we calculated the number of elements removed by 120 chemical weathering and by mechanical weathering. The dimensions and locations of each 121 detached grain were recorded. The available reactive surface in every time step was also calculated, 122 based on the location of the pixels that neighbor the reactive fluid. The data were then analyzed to 123 assess the weathering rate and the grain size distribution of the detached fragments. When 124 125 calculating the grain size distributions, we only considered detached clusters larger than 10 pixels, and the amplitude of each size bin represents the cumulative number of pixels of the individual 126 grains within the bin. This approach is similar, but not identical, to grain size distributions 127 determined by mass in unconsolidated sediments and soils [52, 53]. 128

129 For our model domains, we also calculated the tortuosity of the discontinuity patterns. There are several different definitions of tortuosity [54], and here, we adapted the definition of 130 131 Cooper et al. [55] based on the convolution of diffusive transport flow paths:

132

(1) $\tau = \epsilon \frac{D}{D^{\text{eff}}}$,

where ϵ is the discontinuity density, D is the intrinsic diffusivity of the discontinuity network, 133 while D^{eff} is the effective diffusivity through the bulk rock. We used the Tau Factor MatlabTM 134 application [55] to calculate the tortuosity based on our 2D images. 135

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3 Results and discussion 137

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3.1 Impact of discontinuity density on rock weathering rates

For all the rock patterns we tested, we found weathering rates to increase as the 139 140 discontinuity density increased (Figure 3). This result is not surprising since the dissolution rate along the discontinuities is more rapid than the dissolution rate of the bulk rock. Moreover, this is 141 consistent with field and experimental observations of weathering rates in fractured rocks [20, 21]. 142

Our simulations also show that the type of discontinuity pattern has a significant impact on 143 weathering rates (Figure 3), particularly at discontinuity densities <25%. For the synthetic patterns, 144 at any given value of discontinuity density, the rates followed the order: grid> honeycomb> 145 Voronoi> brick wall. In natural rock patterns, the order was less clear, although weathering in 146 orthogonal cracks was faster than in diagonal cracks, and weathering in perpendicular stylolites 147 was faster than in parallel stylolites. In addition, synthetic patterns generally weathered faster than 148 natural rock patterns. This is probably due to the irregular nature of natural patterns and their 149 inherently lower connectivity. 150

At discontinuity densities >25%, the weathering rates of all the patterns begin to converge. 151 This may be because at low discontinuity densities, the tortuosity of the pathways and their low 152 connectivity acts as a limiting factor. As the discontinuity density increases, connectivity is 153 expected to increase, facilitating the advance of the weathering front. Although the discontinuity 154 density is a critical parameter in determining weathering rates, our results suggest that additional 155 parameters related to the geometry of the patterns are also likely to impact the way rocks weather. 156 Specifically, for patterns in which the pathways are highly tortuous and poorly connected, rates 157 158 are expected to be slower.

159 3.2 Impact of tortuosity on weathering rates

160 In the simulations of synthetic rocks, each pattern type showed a decrease in weathering rate with increasing tortuosity (Figure 4a). Moreover, the rates grouped into two distinct trends: 161 162 (i) grid and brick wall, and (ii) honeycomb and Voronoi. This is probably due to the similarity in the geometry of the patterns within each trend. By contrast, for natural rock patterns, there is no 163 164 clear dependence of weathering rate on tortuosity for individual pattern types (Figure 4b). This could be related to the irregularity and anisotropy of discontinuities in natural patterns, which can 165 cause patterns with identical tortuosities to behave differently. In addition, the widely varying 166 discontinuity densities in the natural patterns could also mask the apparent impact of tortuosity. 167

To isolate the impact of tortuosity, we conducted a numerical experiment with simulations of synthetic patterns in which tortuosity changed systematically while maintaining the same level of discontinuity density (Figure 5). Starting with a regular grid, we introduced an offset in alternating layers to create brick wall patterns, which increased the tortuosity. In this method, the tortuosity varied from 1.95-2.75. In each offset, we ran six simulations with 3 different initial grain sizes: 2160, 234, and 108 pixels.

Our results show a near-linear decrease in the weathering rate as the tortuosity increases from 1.95 to 2.75 (Figure 6) for all the three grain sizes tested. Overall, the reduction in rate was 33%, 21%, and 27% for the 2160, 234, and 108 grain size simulations, respectively. This significant effect means that in addition to mineralogy and grain size, the tortuosity of the discontinuity pattern is likely to be a critical factor in determining the weathering rate in real rocks.

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3.3 Impact of discontinuity density and tortuosity on size of detached grains:

We found the mean detached grain size decreases non-linearly with increasing 180 181 discontinuity density for both synthetic and natural patterns (Figure 7). For the synthetic patterns, the detachment grain size drops by approximately 90% as the discontinuity density increases from 182 8% to 25% (Figure 7a). For natural patterns, there is a significant level of variability and the trend 183 is far less clear (Figure 7b). This is most likely a result of the differences between the initial 184 conditions in the synthetic patterns and those in the natural patterns: in the synthetic patterns, the 185 186 initial grain sizes are similar for any given discontinuity density, while in natural patterns, the initial grain size varies significantly. 187

The overall reduction of the mean detached fragment size with increasing discontinuity density is caused by two factors. The first is that increasing discontinuity density leads to a reduction in the initial grain size, which results in smaller detached grains. The second is that as the discontinuity density increases, the chemical weathering rate also increases, causing the grains to undergo more dissolution prior to detachment.

To test if tortuosity plays a role in the size of detached grains, we analyzed the results of the offset experiment described in Section 3.2 and found that the mean detachment size decreases with increasing tortuosity (Figure 8). This is because in patterns with higher tortuosity, chemical dissolution has longer time to act and reduce the size of the grains prior to detachment. This effect can be seen in the simulation snapshots in Figure 5: detaching grains in the grid simulation are larger than the detaching grains in the offset simulations.

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3.4 Impact of textural patterns on the size distribution of weathered grains

In all the rock patterns we tested, the grain size distribution of detached blocks was influenced by the rock textural patterns. For the synthetic patterns possessing an *initial* uniform grain size (grid, honeycomb, brick-wall), the *detached* grains showed a normal size distribution

(Figure 9 a-c). By contrast, for Voronoi patterns, the detached grain size distribution was lognormal, similar to the initial grain size distribution (Figure 9d). For the natural rock patterns we tested (stylolites and cracks), the initial block size distributions were multimodal. However, the size distribution of the detached fragments showed reduced modality (Figure 10). Our results are consistent with the findings of Palomares et al. [56] who showed that rocks with similar initial grain sizes fragment mainly along their uniformly distributed discontinuities, thus providing grains of uniform size, in contrast to rocks with anisotropic fabrics that do not disintegrate uniformly.

Grain size distributions of weathered grains strongly influence soil permeability and soil erosion [57]. Soils with a wide range of grain sizes are less permeable and erode less readily than soils with uniform grain size distributions [57]. Thus, we expect rocks with initial grid-like, or honeycomb discontinuity patterns to produce relatively uniform grain size distributions that form soils with higher permeabilities. By contrast, rocks with stylolites and cracks might be expected to produce soils that form impermeable layers.

216 Although there is significant variability, the grain size distribution of many soils and sediments often has a log-normal distribution [58, 59]. In our simulations, the only pattern that 217 218 weathered into fragments with log-normal distributions is the Voronoi pattern. These patterns are common in the polycrystalline rocks that provide much of the weathered material to sediments, 219 220 and it is likely that the log-normal distribution in sediments is influenced by the initial grain size distribution of the weathered rock. However, transport processes also strongly affect the size 221 222 distributions of sediments, [54], and we therefore expect the discontinuity patterns to have the strongest impact on the distribution of sediments that are relatively close to the source rock, such 223 224 as in fluvial fans.

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226 4 Conclusions

In this study, we used a numerical model that incorporates both chemical and mechanical weathering to investigate the impact of rock texture on weathering rate and the size of detached grains. Our results indicate that the weathering rate increases with increasing densities of discontinuities in the rock. We also found that increasing the tortuosity of the patterns lead to decreasing weathering rates. Moreover, we found a strong impact of texture on the detached grain size distribution, and that higher discontinuity densities leads to smaller detached blocks. This has practical implications for risk assessment near cliffs or stone edifices: rocks containing stylolites with spacings of several centimeters could present less of a risk than rocks containing fractureswith spacings of tens of centimeters.

The model we present here is a preliminary attempt to simulate the combined effects of 236 chemical and mechanical weathering, and we can identify some limitations to our approach. Our 237 simulations compare textures of different scales: the individual grains comprising a rock are often 238 micrometer or millimeter in scale, while joints and stylolites are often present at the centimeter 239 and meter-scale. Moreover, the time and spatial scales in the model are at present arbitrary, which 240 severely limits its predictive power. Calibrating the model, however, requires reliable field data, 241 which are difficult to obtain because of the long time scales associated with weathering. Future 242 work that focuses on improving the model by comparison with field-based measurements could 243 244 provide solutions to some of these challenges.

245 Acknowledgments and Data

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- publicly available in the Mendeley Data repository at DOI: <u>http://dx.doi.org/10.17632/v4jw2d9rbm.1</u>
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Figure 1:



Figure 1. Simulation of fluid-rock interaction. The bulk rock components are marked in yellow, rock discontinuities in black, and fluid in white. Cross sections of the rock are shown at 3 stages of the simulation: (a) initial state; (b) Step 220 and (c) Step 221. Chemical weathering dissolves the rock minerals slower than the discontinuities between rock clusters. When a cluster is surrounded by fluid it detaches from the surface and is removed from the simulation. Note that the black discontinuities dissolve more rapidly than the bulk rock.

Figure 2.



Figure 2. Examples of synthetic and natural rock patterns used in the simulations. The upper row represents synthetic rock textures of a grid (a), brick-wall (b), honeycomb (c) and realistic polycrystalline rock (Voronoi, d). The lower row is our model representation for natural rock images of diagonal cracks (e), orthogonal cracks (f), perpendicular stylolites (g), and parallel stylolites (h).

Figure 3.



Figure 3. Weathering rate as a function of discontinuity density in synthetic (red) and natural (blue) patterns. Each of the synthetic patterns shows a linear increase in weathering rate with the density of discontinuities. In the natural rock patterns, the trend is less clear. At lower discontinuity density, the weathering rate exhibits a strong dependence on the pattern.





Figure 4. Weathering rate as a function of tortuosity in (a) synthetic patterns and (b) and natural patterns. In the synthetic patterns there are two distinct groups. In the synthetic patterns, there are two distinct trends, in contrast to the natural patterns, which show no clear relationship.

Figure 5.



Figure 5. Snapshots of 3 simulations with different offsets and tortuosities. Each image shows the times step directly preceding a grain detachment event. The initial grain size is $\mu_0=2160$ pixels. Note the decrease in size of detached grains and in the difference in patterns of penetration of the reactive fluid into the rock. In addition, for the lowest level tortuosity the reaction front advances much more rapidly than at higher levels of tortuosity.





Figure 6. Weathering rate versus tortuosity in simulations with offset from grid (0% offset) to brick-wall (50% offset) and back to grid (100% offset), in three decreasing initial grain sizes $\mu_0=2160$ pixels (black), $\mu_0=234$ pixels (blue) and $\mu_0=108$ pixels (red).





Figure 7. Impact of discontinuity density on mean detachment size in (a) synthetic and (b) natural patterns. The synthetic patterns show a non-linear reduction in detachment grain size with increasing discontinuity density. In the natural patterns, the discontinuity abundance is less systematic, but the trend is similar.

Figure 8.



Figure 8. Mean detachment size as a function tortuosity in offset simulations for 3 initial grain sizes pixels (a) 2160 pixels; (b) 234 pixels; and (c) 108 pixels.

Figure 9.



Figure 9. Initial grain size distribution and size distribution of detached grains for synthetic rock patterns: (a) grid; (b) brick-wall; (c) honeycomb; and (d) Voronoi patterns. The initial distribution is shown by the solid red line, with the mean initial grain size indicated by the dashed red line. The standard deviation from the mean is shown by the shaded region. The size distribution of the detached grains is indicated by the solid gray line. The mean detached grain size is shown by the dashed gray line, and the standard deviation from the mean is indicated by the area shaded in gray.





Figure 10. Initial grain size distribution and size distribution of detached grains for natural rock patterns: (a) diagonal cracks; (b) orthogonal cracks; (c) perpendicular stylolites; and (d) and parallel stylolites. The initial distribution is shown by the solid red line, with the mean initial grain size indicated by the dashed red line. The standard deviation from the mean is shown by the pink shaded region. The size distribution of the detached grains is indicated by the solid gray line. The mean detached grain size is shown by the dashed gray line, and the standard deviation from the mean is indicated by the area shaded in gray. The weathering process decreases the modality of the distribution in all tested natural patterns.