Innovative applications of laser scanning and rapid prototype printing to rock breakdown experiments

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Abstract
We present the novel application of two technologies for use in rock breakdown experiments, i.e. close-range, ground-based 3D triangulation scanning and rapid prototype printing. These techniques aid analyses of form–process interactions across the range of scales relevant to breakdown (μm–m). This is achieved through (a) the creation of DEMs (which permit quantitative description and analysis of rock surface morphology and morphological change) and (b) the production of more realistically-shaped experimental blocks. We illustrate the use of these techniques, alongside appropriate data analysis routines, in experiments designed to investigate the persistence of fluvially-derived features in the face of subsequent wind abrasion and weathering. These techniques have a range of potential applications in experimental field and lab-based geomorphic studies beyond those specifically outlined here.

Introduction
Rock breakdown refers to the array of weathering and erosional processes that transform rock masses into sedimentary debris, including fluvial and aeolian abrasion and weathering. Exploring the link between rock breakdown process and form has been hampered by the difficulty in reproducing accurate physical models that reflect the true form of cobble-size clasts within the natural environment. Until now, field and laboratory experiments on weathering and abrasion have generally been limited to the use of idealized shapes composed of soft, erodible rock. While this approach is invaluable for elucidating the nature and relative rates of breakdown processes (such as salt weathering, see, e.g., Goudie, 2000; Goudie et al., 2002; or aeolian abrasion, see, e.g., Bridges et al., 2004a), the influence of a more complex surface topography cannot be adequately assessed. Surface morphology may be a key control on rock breakdown, through its influence on microclimate and therefore process operation (e.g. in cavernous weathering, Viles, 2005).

In this paper we present the novel application of two technologies, 3D triangulation scanning and rapid prototype printing, that, when combined, represent a significant development for experimental rock breakdown studies. Furthermore, we outline a range of analysis tools suitable for use on the datasets produced which help quantify and compare general and specific morphological attributes. The capability to generate high resolution, high accuracy topographic datasets using laser scanning enables quantitative analysis of rock breakdown across the broad range of relevant scales (micrometres to metres). This will help investigate any scaling relationships that may be important (Viles, 2001). Furthermore, laser scanning allows the creation of computer aided design (CAD) models of real clasts, which can be used to make prototype models. These models will enable the employment of realistic forms in both laboratory and field-based trials. Figure 1 outlines the sequence of techniques we have developed. The approach outlined here has enormous potential beyond that presented, particularly in geomorphological studies that incorporate physical models in their experimental design, such as exposure trials designed to monitor rates of abrasion and weathering or flume or wind tunnel studies that require realistic landscapes at smaller scales.
Innovative technologies for use in rock breakdown experiments

Figure 1. Sequence of techniques used in our rock breakdown studies.

Close-range, Ground-based 3D Laser Triangulation Scanning

3D laser scanning physically measures and catalogues the topographic expression of various surfaces without a priori assumptions of form, while its portability enables its use in both field and laboratory studies. Similar 3D laser scanning techniques (e.g., light detection and ranging (LIDAR)) are being used increasingly in geomorphological studies (e.g., MacMillan et al., 2003; Nagihara et al., 2004; Barlow and Hopkinson, 2005; Heritage and Hetherington, 2007) and its potential in rock breakdown studies has been noted elsewhere (Bridges et al., 2004b; Heslop et al., 2004).

In our experiments, basalt cobbles with features representative of fluvial transport (see Bourke et al., 2007a) were collected in the field and scanned using a Minolta 900 ‘triangulation’ laser scanner. The triangulation scanner is portable (21 cm × 41 cm × 27 cm), runs on AC power, scans from a distance of approximately 0·6 to 1·0 m and uses a series of interchangeable lenses to focus the scan area and increase (or decrease) resolution. The 3D laser scanning uses a ‘triangulation light block’ method that allows, at close range, the acquisition of 3D measurements with a maximum of 0·2 mm inaccuracy. Typical inaccuracy within individual scans using the mid-range resolution lens (used in this project) is approximately 0·35 mm (from Minolta specifications). Relative imprecision, from experience with this scanner, is about one-half to one-third of the inaccuracy. Target albedo and homogeneity also play a minor role in overall scan data precision; although there were no objective experiments to quantify this effect in this dataset, we assume this did not change between scan models. The production of complete point-clouds using shape-fitting software routines introduces additional imprecision and inaccuracy to the overall model, although overlapping information can be removed. The quantity of scan data overlap and experience of the scanning and modeling specialists play a role in final point-cloud precision and accuracy.

The scanner collects approximately 300 000 points per scan with a typical rock CAD model needing six or more scans to model completely. Separate scans are tied together using shape-fitting algorithms and target-based registration. Once scanned and registered, triangular irregular network (TIN) models of each rock are created at the highest resolution possible. In this way we are able to characterize surface morphometry at high accuracy, high precision, and high resolution. The scans create a model with a resolution of 0·23–0·40 mm.

The scanned data are utilized in two ways. First, we generated CAD models in preparation for rapid prototype printing. Second, the dataset was used to produce an accurate, high resolution topographic data set on which morphometric analyses were undertaken, both of the initial prototype and of the changes to it resulting from the wind abrasion experiments. Scan data permit the quantification of features at a range of scales (from micrometres to metres), thereby elevating the study of breakdown features from mainly qualitative to quantitative. In addition, we are able to measure experimental rates of breakdown with greater accuracy (micrometres) and isolate locations of enhanced rates of breakdown.
Prototype Printing

Rapid prototype 3D printing (also known as solid freeform fabrication) is a technique that manufactures objects by the sequential delivery of material to specific points in space. Rapid prototyping takes CAD models and transforms them into virtual cross sections. It then prints each cross section in physical space, laying down layers of liquid or powder material, building the model from a series of cross sections. The advantage of this process is the ability to create any geometry required. The technology is being used extensively in medical fields for tissue, cell and organ engineering (see, e.g., Nakamura et al., 2006; Boland et al., 2007). It is also used in architecture (see, e.g., Sass, 2007), industrial and art ceramics (see, e.g., Huson, 2006; Wang et al., 2007) and even in the communication of scientific concepts in education (e.g. Andersen et al., 2005). To our knowledge this is the first report of its use in geomorphic studies.

For our rock breakdown experiments, we used a Zcorporation 3D Zprinter 310. The models were composed of a gypsum powder and binding agent. The printer deposited layers 0.010 16 mm thick that gradually built up our rock model. Figure 2(c) shows a vesicular basalt cobble model. This rock model has 779 layers and took two hours to print for a cost of $40. The settling of the printed model along \( X, Y \) and \( Z \) is estimated to be 0.018 mm. The erodible composition of the model was important for our wind abrasion experiments, in order to produce observable change after short time periods. However, if a more resistant object is required, the final model can be coated with a medium strength cyanoacrylate liquid that binds the outer surface. In our pilot tests, these latter surfaces demonstrated minimal change during sandblasting in 30 m/sec winds for 40 minutes.

Analysis of DEM Data to Quantify Breakdown Features and Assess Change

Appropriate analysis routines such as fractal analysis, geometric morphometrics and simple linear measurements of mass loss that can be applied to the datasets produced by the laser scanning, rapid prototyping and experimentation techniques are explored in detail elsewhere and readers are referred to those publications (Bourke et al., 2007b; Ehlmann et al., 2008). Here we briefly present some approaches that we have found useful in our initial analysis.

We have used the three-dimensional virtual models of fluvial clasts (Figures 4 and 5) to undertake micro-topographic analysis using a geographical information system (GIS) platform. Non-shape variation such as position, orientation and scale are mathematically removed from the rock DEM by determining the overall trend of the rock surface, which is then subtracted from the DEM of the rock surface. Analysis of the residual model can then proceed to identify intrinsic morphometric properties.

General and specific morphometric techniques are employed, so that the entire surface, as well as its constituent features, are used to describe the clast. For example, the overall surface area of the rock is calculated and compared with its planar outline in order to evaluate surface complexity. We use micro-relief scaling to examine variations in elevation over changing horizontal scales. Previous studies (e.g. Weissel et al., 1994) have shown power-law scaling in topographic relief, shown in the equation \( y = cx^m \), where \( y \) represents vertical relief (average maximum height difference between points within a window of width \( x \)) and \( x \) represents horizontal scale, while \( c \) represents the amplitude factor (or \( y \) intercept) and \( m \) represents the scaling exponent (or slope). Topographic roughness may be determined using both \( c \) and \( m \) by calculating the area beneath the lines on a log–log plot by the equation.
Table I. Geostatistics generated from DEM of rock in Figure 3

<table>
<thead>
<tr>
<th>Morphometric measure</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sill</td>
<td>$4.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Range</td>
<td>17.4 mm</td>
</tr>
<tr>
<td>Surface area</td>
<td>7000 mm$^2$</td>
</tr>
<tr>
<td>Micro-relief (maximum minus minimum surfaces)</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Surface area</td>
<td>7000 mm$^2$</td>
</tr>
<tr>
<td>Planar area</td>
<td>3000 mm$^2$</td>
</tr>
<tr>
<td>Surface area:planar area ratio</td>
<td>2.3</td>
</tr>
<tr>
<td>Scaling exponent</td>
<td>0.716</td>
</tr>
<tr>
<td>$y$-intercept</td>
<td>0.72</td>
</tr>
<tr>
<td>Micro-topographic roughness</td>
<td>527-37 mm$^3$</td>
</tr>
<tr>
<td>Number of sinks</td>
<td>221</td>
</tr>
<tr>
<td>Mean sink depth</td>
<td>0.9 mm</td>
</tr>
</tbody>
</table>

The following are definitions of some terms used above. A sill provides a measure of the degree of vertical variation in the surface. High sill values indicate greater vertical relief. A range measures the extent of spatial autocorrelation of the surface. A small range indicates a narrow field of spatial autocorrelation; lateral extent of variation is small. A sink is a topographic low point in the surface identified through neighbourhood analysis. Micro-topographic roughness describes the vertical and horizontal scaling properties of the surface and quantifies the changes in vertical relief with changes in the horizontal extent of the surface. It is measured by calculating the area under the log-log plot.

Figure 3. DTM of vesicular basalt (Figure 2(b)). General and specific morphometric approaches are used to determine the topography of the surface and to identify vesicles (see Table I).
DEM. Adopting techniques used in hydrological modelling, topographic low points in a surface are used to identify sinks using GIS. In this case, these represented the low points within vesicles. Their pattern, distribution and relative depths can then be measured. The initial results of micro-topographic analysis of the sample rock are given in Table I.

Alongside the techniques discussed above, fractal analysis of a rock surface has the potential to characterize the scale-dependent nature of primary rock features, as well as the scales at which erosion affects the topographic signature of these features. Surface roughness has previously been used to characterize the surface texture of large-scale landforms such as lava flows (Shepard et al., 2001). Qualitatively, we observe that roughness varies with certain rock breakdown processes; e.g., aeolian abrasion produces smooth surfaces whereas granular disintegration produces rough surfaces at the millimetre scale. We are exploring the capabilities of three parameters to distinguish between breakdown phenomena and to derive quantitative signatures of process type, i.e. root-mean-square (RMS) height, RMS slope and the Hurst exponent ($H$), including breakpoints in $H$ (Ehlmann et al., 2008).

To examine the fractal characteristics of sample profiles extracted from the rock DEMs we constructed a series of variograms. Two cobbles sampled from the Ephrata fan in Washington show different surface morphologies. Sample B6, a sub-rounded vesicular basalt (Figure 4(a)), was sampled from the surface of the fan. Sample Q3, a sub-rounded granite clast (Figure 4(b)) was taken from a quarry trenched in the fan and by contrast has a relatively smooth surface. As expected, the two samples have distinctive trends: both variograms show a clear break in the log–log plots of RMS

![Figure 4](image_url)

**Figure 4.** (a), (b) Log–log plots of RMS slope against step size. (c), (d) CAD models of rocks B6 and Q3. Black lines indicate location of transect.
slope against step size (Figure 4(c), (d)), illustrating two distinctive roughness regimes at different scales. This suggests that, with adequate sample numbers, clasts that have experienced different process regime histories may be statistically separable on the basis of their roughness characteristics. Not only will this be a useful adjunct to studies interpreting environmental histories of landscapes on Earth, but it should also have wide applicability to datasets collected from Mars Exploration Rover stereo images.

Our analysis routines can also be used to investigate the rate and location of surface change in field and laboratory trials. In our experimental design we tested feature persistence under a range of environmental conditions such as sand abrasion, humidity and temperature cycles for both Earth and Mars (Bourke et al., 2007b; Viles et al., 2007). In our wind tunnel experiments, abraded targets produced by rapid prototyping were scanned following a number of runs in order to monitor change to the rock surface. The changes were quantified using a difference model between the original samples and the sample at the end of the breakdown experiments. The data were classified using standard deviation to show areas with greatest and least change in mass after the experiments were run with respect to the mean loss in mass (Figure 5). It is immediately apparent that there is differential erosion of features on the rock surface. Specific analysis of features is possible by extracting topographic profiles and measuring loss of mass at points along that line. For example, and perhaps intuitively, sharp ridge features show maximum abrasion. This type of analysis can be used to compare how different features may erode in order to determine the relative persistence of microtopographies within these features. By way of example, for ripple fracture features, which are essentially a ridge and swale topography, we find that ridge features abrade more rapidly than swales (Bourke et al., 2007b). We are also exploring further 2D and 3D analysis where the controls of curvature and aspect can be assessed.

Figure 5. Image of rock surface indicating locations of mass loss detected by laser scanning following wind abrasion experiments. A standard deviation classification was used. The mean loss of all cell values is 2.24 mm and was computed by subtracting the final sample grid from the 'before' sample grid. Values that are less than the mean loss are dark and values that are higher than the mean loss are lighter toned.
Discussion and Conclusion

The combination of close-range, ground-based LIDAR scanning with rapid prototyping and appropriate mathematical analysis techniques provides a powerful toolkit for improved understanding of rock breakdown. It allows us to produce large digital datasets and more realistic experimental targets. However, all new advances in techniques for geomorphologists come with a range of challenges. Notably, production of CAD models of 3D objects is time consuming and can be expensive, whilst the vast number of data points produced by laser scanning technology can make analysis very challenging. Furthermore, the prototypes differ from real cobbles in two important ways. First, they have an internal structure that is often very different from real clasts in terms of porosity, which may introduce artefacts into the breakdown process. Second, they only have the form of, in this case, fluvially transported clasts; they have not inherited the lithological properties (e.g. vesicles in basalt) or the stresses that might be induced by fluvial transport, which may affect their response to future aeolian abrasion or weathering. Despite these limitations, the approach outlined here is a significant step forward in rock breakdown studies. In addition, our future work will investigate the application of high-resolution (5–100 μm) X-ray computed tomography (HRXCT), which has been shown to reveal the internal 3D rock structure including porosity, fractures and heterogeneities (Wellington and Vinegar, 1987; Ketcham and Iturrino, 2005; Carlson, 2006).

In conclusion, we find that high resolution, high precision laser scanning produces data sets that have long been needed to identify, measure and monitor rock breakdown processes. The adjunct use of rapid prototype printing provides a way to create physical, 3D models of virtually any CAD model with precise detail, which should enhance the progress of rock breakdown simulations. Furthermore, it has enormous potential for use in many other physical model studies, where the morphology and morphometry of landforms at any scale can be faithfully reproduced.

Appropriate analysis routines to make the best use of the large datasets produced are still under development. It is hoped that such approaches can be used to compare disparate rock surfaces in order to characterize and distinguish different features based on their visually distinctive properties. Such quantitative descriptors may then be used to infer processes that were responsible for the measured morphology, and whether a particular morphology is related to a particular geological type. Such approaches will be invaluable for studies of rock breakdown both on Earth and on other planetary surfaces.

Acknowledgments

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References


Goudie AS, Wright E, Viles HA. 2002. The roles of salt (sodium nitrate) and fog in weathering: a laboratory simulation of conditions in the northern Atacama desert, Chile. *Catena* 48: 255–266.


