Fractal fingerprinting of joint and shatter-cone surfaces

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ABSTRACT

The branching patterns of radiating ridges on surfaces of tensile joints and shatter cones were simulated and quantified, and their scaling properties were examined in three dimensions by means of a technique new to geology, the slit-island method. Results show that the textures are fractal over a wide range of scales. Accordingly, an algorithm simulates growth of tensile fracture-surface features by combining a set of rules with an element of randomness. The simulated surfaces are fractal and strikingly similar to natural fracture surfaces. These and other complex branching patterns observed in geology are likely due to an interplay of deterministic and random processes.

INTRODUCTION

The advent of fractal geometry and the widespread availability of computers make it possible to quantify and model many of the highly complex textures observed in nature. Patterns that were until recently only imprecisely described can now be quantified by a number, the fractal dimension (Mandelbrot, 1982). For instance, the fracture surfaces of shatter cones and joints having irregular radiating ridges and distinctive branching patterns are here shown to be fractal. This observation is important because it leads to a new method of simulating the pattern-forming process. A central idea behind the formation of many of the fractal patterns in nature is that randomness plays an important role. Through computer simulation we demonstrate how rules for physically realistic growth combined with a random distribution produce results that are strikingly similar to the irregular branching pattern of ridges common to surfaces of joints and shatter cones. The random distribution used in the simulation corresponds to the distribution of defects in otherwise homogeneous rock. This work illustrates that the study of the interaction between determinism and randomness can lead to a better understanding of how patterning occurs on joints and shatter cones.

MEASUREMENT

The irregular ridges on fracture surfaces of joints and shatter cones radiate from the origin of the fracture, typically the site of a stress-concentrating heterogeneity. Joints are tensile planar fractures that may have irregular radiating ridges termed "plumose structure" (Fig. 1), whereas shatter cones are conical fracture surfaces with grooves and ridges in nested subcones, radiating from an apex (Fig. 2). Observation of these features shows that the textures are composed of many different-sized, similar parts—i.e., they are self-similar. This led to the idea that they might be fractal and to the measurement of their fractal dimension.

A generally ignored problem associated with measuring the dimensions of surfaces is variable scaling, or self-affinity (Voss, 1988). For self-affine surfaces, the geometric scaling is different along different axes. A familiar example of this phenomenon is Earth's crust. Viewed at a distance, the crust appears smoothly circular. As we zoom in, the apparent roughness increases. Accordingly, for small-scale models, one must use a vertical exaggeration to see crustal relief.

Lacking any method of precisely capturing the three-dimensional (3D) topographic data of the fracture-surface ridges in digital form, we overcame the problem of variable scaling by using the slit-island technique (Mandelbrot et al., 1984). The technique requires numerous two-dimensional sections through the 3D surfaces. The mathematical background, algorithms, and measurement programs for this technique and others are given in Roach (1992) and Roach and Fowler (1993). The slit-island method has been investigated in physics and material science (e.g., Pande et al., 1987; Lung and Mu, 1988; Meisel, 1991). Lung and Mu (1988) stated that the fractal dimension measured by slit islands does not correspond exactly to the actual fractal dimension of the surface, but Meisel (1991) refuted this claim, using theoretical mathematical examples. Despite this uncertainty, the slit-island method is fast becoming one of the standard procedures for quantitative measurement of surface topography. Certainly, it yields a measure that is useful to geologists because it goes beyond qualitative description, and serial sectioning is the only widespread practical method of studying 3D distributions in solid rock.

Because our interest is in the growth of the ridges, we chose to section fracture surfaces along planes parallel to the main plane

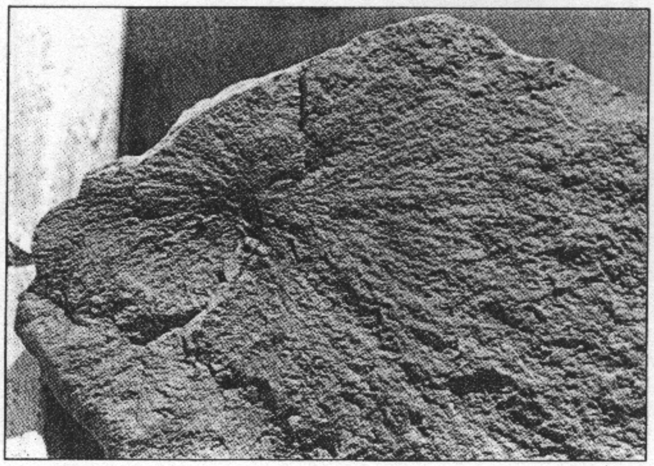

Figure 1. Plumose joint in arkose of Cambrian-Ordovician Potsdam Sandstone, Old Fort Henry, Kingston, Ontario; field of view is ~10 cm. Note that pattern radiates from quartz-grain origin.