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The influence of rock heterogeneity on the scaling properties of simulated and natural stylolites

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ABSTRACT

Stylolites are among the most prominent deformation patterns in sedimentary rocks that document localized pressure solution. Recent studies revealed that stylolite roughness is characterized by two distinct scaling regimes. The main goal of the present study is to decipher whether this complex scaling behavior of stylolites is caused by the composition of the host-rock, i.e. heterogeneities in the material, or is governed by inherent processes on respective scales, namely the transition from a surface energy to an elastic energy dominated regime, as theoretically predicted. For this purpose we have developed a discrete numerical technique, based on a lattice spring model, to simulate the competition between stress, strain, and dissolution during stylolite roughening. We varied systematically the quenched noise, initially present in the material, which controls the roughening. We also changed the size, amount, and dissolution rate of the heterogeneities introduced in our model and evaluated the influence on the scaling exponents. Our findings demonstrate that the roughness and growth exponents are independent of the exact nature of the heterogeneities. We discovered two coinciding crossover phenomena in space and time that separate length and time scales for which the roughening process is either balanced by surface or elastic energies. Our observations are consistent with analytical predictions and with investigations quantifying the scaling laws in the morphology of natural stylolites. The findings presented here can further be used to refine volume loss (compaction) estimates from the finite strain pattern of stylolites.

1. Introduction

Pressure solution in sedimentary rocks results in either intergranular or localized dissolution of material (e.g. Tada and Siever, 1989). The latter is responsible for the formation of stylolites, a frequent deformation pattern in sedimentary rocks (e.g. Stockdale, 1922; Dunnington, 1954; Heald, 1955; Park and Schot, 1968; Buxton and Sibley, 1981; Rutter, 1983; Railsback, 1993). Stylolites are rough interfaces that contain insoluble material (Fig. 1), which is considered to be the residuum of the dissolved rock (Railsback, 1993; and references cited therein). Stylolite initiation is still highly debated (e.g. Tada and Siever, 1989) but several mechanisms have been proposed that are in agreement with field observations: Formation (I) along preexisting anisotropies (Bathurst, 1987) (II) as anticracks (Fletcher and Pollard, 1981) that propagate due to stress concentrations at anticrack tips (even though this idea was challenged recently by Katsman et al., 2006) and (III) by stress induced self-organization (Merino, 1992; Railsback, 1998; Merino et al., 2006).

In the present study we quantify the roughness of simulated stylolites and study their dynamic development independent of the process leading to the localization of dissolution along a plane. Based on recent quantitative methods of stylolite roughness characterization (Renard et al., 2004; Schmittbuhl et al., 2004; Koehn et al., 2007; Ebner et al., in press) we use statistical tools to compare simulated and natural stylolites. In particular we study the influence of initial heterogeneity concentration in the host-rock on a) stylolite roughness, b) dynamic roughness growth and c) the correlation of crossover phenomena in space and time. To integrate the results of our study in the context of quantitative characterization we will first review the basic principles of our approach.

The exact classification of stylolites in the field is a difficult task because there is a wide range of geometries (e.g. Park and Schot, 1968) that are often transitional even within a single outcrop. Many previous studies (Park and Schot, 1968; Buxton and Sibley, 1981; Guzzetta, 1984; Tada and Siever, 1989; Railsback, 1993) used classification schemes that were based on visual descriptions of macroscopic features of stylolites. These classification schemes are

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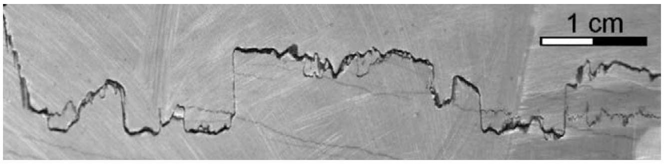

Fig. 1. Plane section of a bedding parallel stylolite in a jurassic limestone from Cirque de Navacelles (southern France). The rough interface is accentuated by a thin clay layer that is considered to be the residuum of the dissolved rock mass.

not quantitative and they are hard to compare since these studies focused on a variety of different aspects of stylolite formation. Recent studies, however (Drummond and Sexton, 1998; Karcz and Scholz, 2003) took a more quantitative approach using fractal concepts to describe the stylolite roughness in a statistical sense. They could describe stylolite roughness with a fractal scaling over several orders of magnitude, which means that their roughness is not dominated by a certain wavelength.

Renard et al. (2004) and Schmittbuhl et al. (2004) demonstrated that bedding parallel stylolite surfaces show a self-affine scaling invariance with characteristic Hurst exponents (also called roughness exponents). A self-affine rough surface is characterized statistically by the fact that points along the surface separated by a distance δx from each other are typically distant in the direction transverse to the surface by $\delta h = \delta x^{\alpha}$, where α is the roughness exponent. It was further noticed that two distinct scaling regimes exist that were characterized by two different Hurst or roughness exponents separated by a crossover-length (L), around the millimeter scale for the analyzed natural stylolites. Above this crossover, all investigated stylolites exhibit a Hurst exponent of about 0.5 meaning that they change relatively fast from being flat features on larger scale to being rough features on the smaller scale. Below the crossover-length the Hurst exponent is about 1.0, which means that the slope, or aspect ratio $\delta z/\delta x$, stays more or less constant. Schmittbuhl et al. (2004) and Renard et al. (2004) established from first principles of mechanics and chemistry a model for stylolite growth under the form of a stochastic partial differential equation (called in this case a generalized Langevin equation). This equation simulates the roughening of a stylolite surface as a competition between stabilizing forces (that keep the surface flat), which are controlled by long range elastic and local surface tension effects, and destabilizing forces (that roughen the interface) that are induced by pinning effects of material heterogeneities. The analytical solution of Schmittbuhl et al. (2004) reproduced the observed scaling behavior of natural stylolites and demonstrated that the two scaling regimes (characterized by the two different Hurst exponents) correspond to two thermodynamic regimes that are dominated by either surface or elastic energies on small and large scales, respectively (Renard et al., 2004; Schmittbuhl et al., 2004; Gratier et al., 2005). Based on the work of Schmittbuhl et al. (2004) it was demonstrated for the first time by Ebner et al. (in press) that the crossover-length of natural stylolites, which should be a function of the stress during stylolite growth, can be used to determine stress magnitudes and burial depth in sedimentary basins. The discrete numerical simulation technique of Koehn et al. (2007) enabled to study the dynamics of the roughening process through time revealing that the stylolite interface width w (defined in detail below) grows as a power law with time ($w \sim t^{\beta}$) with a growth exponent β of 0.5 in the surface energy dominated regime and a growth exponent of 0.8 in the elastic energy dominated regime. In addition the roughness growth may saturate so that the stylolites lose their memory for compaction or finite strain. It is important to notice that the roughness of simulated stylolites in this contribution is produced by heterogeneities in the material that pin the stylolitic interface due to slower dissolution rate constants, which are in competition with the surface and elastic energies which tend to flatten the surface (Koehn et al., 2007). Therefore the obvious question to ask is whether a variation of the quenched noise changes the scaling properties of the stylolitic interface?

Thus, in the present contribution we investigate the influence of different heterogeneities (namely the percentage of pinning particles, their pinning factor (defined below), and their size) on the scaling behavior, dynamic growth, and determined crossover-length of simulated stylolites.

2. Numerical model setup

The numerical technique that we use to simulate stylolite roughening is based on a lattice spring model coupled with a dissolution routine (Koehn et al., 2004, 2006, 2007). The model itself is embedded as a module in the *"Elle"* modeling-platform (Bons et al., 2008).

For computational reasons, to access large systems and analyze scaling laws over a large system size – resolution ratio, we will consider situations spatially invariant along one of the directions tangential to the stylolite – and effectively treat systems with two spatial dimensions. For the same reasons, we assume that the heterogeneity in the rock as well as the statistical properties of the stylolite surface can be represented in a 2D model, as shown in Fig. 2a, which contains a predefined flat interface filled with a confined fluid. Two blocks of particles are separated by a fluid pocket. Such a configuration is expected for example, in the case of a fluid pocket embedded between two low permeability sedimentary layers. This model system represents two solids or rocks that are pressed together by inward moving top and bottom boundaries, whereas the side boundaries remain fixed (uniaxial strain). A quenched noise (denoted by darker particles in Fig. 2a, b) is introduced by assigning a lower dissolution rate constant to a certain fraction of the particles (=pinning particles) and represents material heterogeneities initially present in the host-rock of natural stylolites.

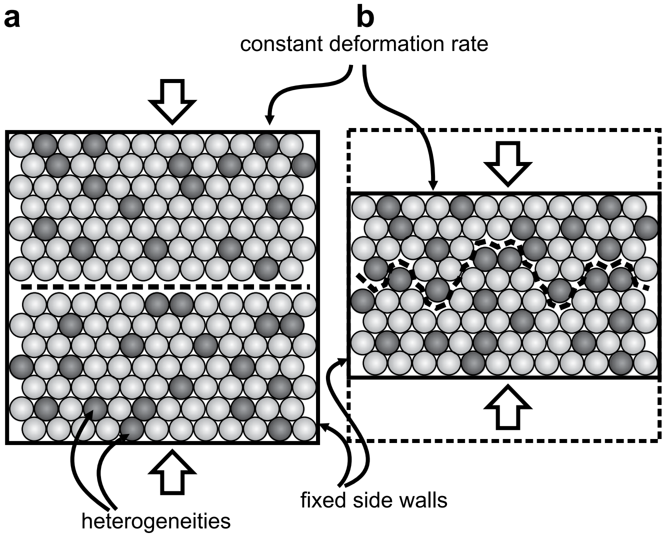

Fig. 2. Simplified sketch of the setup of the numerical model (modified after Koehn et al., 2007). The top and bottom walls of the box are moved inwards simultaneously to stress the system and initiate dissolution along the interface. a) Initial configuration of the setup showing a flat interface (dashed line). b) Configuration after a certain amount of compaction. The interface (dashed line) has developed a distinct roughness, note that the heterogeneities (darker spheres) accumulate along the interface.