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Stress-induced electric current fluctuations in rocks: a superstatistical model

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We recorded spontaneous electric current flow in non-piezoelectric Carrara marble samples during triaxial deformation. Mechanical data, ultrasonic velocities and acoustic emissions were acquired simultaneously with electric current to constrain the relationship between electric current flow, differential stress and damage. Under strain-controlled loading, spontaneous electric current signals (nA) were generated and sustained under all conditions tested. In dry samples, a detectable electric current arises only during dilatancy and the overall signal is correlated with the damage induced by microcracking. Our results show that fracture plays a key role in the generation of electric currents in deforming rocks (Cartwright-Taylor et al., in prep).

We also analysed the high-frequency fluctuations of these electric current signals and found that they are not normally distributed – they exhibit power-law tails (Cartwright-Taylor et al., 2014). We modelled these distributions with q-Gaussian statistics, derived by maximising the Tsallis entropy. This definition of entropy is particularly applicable to systems which are strongly correlated and far from equilibrium. Good agreement, at all experimental conditions, between the distributions of electric current fluctuations and the q-Gaussian function with q-values far from one, illustrates the highly correlated, fractal nature of the electric source network within the samples and provides further evidence that the source of the electric signals is the developing fractal network of cracks.

It has been shown (Beck, 2001) that q-Gaussian distributions can arise from the superposition of local relaxations in the presence of a slowly varying driving force, thus providing a dynamic reason for the appearance of Tsallis statistics in systems with a fluctuating energy dissipation rate. So, the probability distribution for a dynamic variable, u under some external slow forcing, β, can be obtained as a superposition of temporary local equilibrium processes whose variance fluctuates over time. The appearance of q-Gaussian statistics are caused by the fluctuating β parameter, which effectively models the fluctuating energy dissipation rate in the system. This concept is known as superstatistics and is physically relevant for modelling driven non-equilibrium systems where the environmental conditions fluctuate on a large scale. The idea is that the environmental variable, such as temperature or pressure, changes so slowly that a rapidly fluctuating variable within that environment has time to relax back to equilibrium between each change in the environment.

The application of superstatistical techniques to our experimental electric current fluctuations show that they can indeed be described, to good approximation, by the superposition of local Gaussian processes with fluctuating variance. We conclude, then, that the measured electric current fluctuates in response to intermittent energy dissipation and is driven to varying temporary local equilibria during deformation by the variations in stress intensity. The advantage of this technique is that, once the model has been established to be a good description of the system in question, the average β parameter (a measure of the average energy dissipation rate) for the system can be obtained simply from the macroscopic q-Gaussian distribution parameters.