Early warning signs for mining accidents: detecting crackling noise

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Abstract: Acoustic emission signals carry much of the information about collapsing cavities and progressing cracks in minerals. The acoustic noise signals are constituted by individual events, so-called ‘jerks’, which form a spectrum of ‘crackling noise’ with well-defined characteristics. The close connection between collapsing minerals under uniaxial stress and the spectra of crackling noise has been systematically investigated over the last 5 years on small samples but it is only a new paper in *American Mineralogist* that Jiang et al. (2017) have made a major breakthrough by using much larger samples and higher stresses. They show that the crackling noise changes its spectral parameters from the non-critical steady state to the all-important precursor regime before samples finally collapse. They showed that the noise distribution always follows a power law but that the exponents are different in the two regimes. Their work on coal and sandstone have hence shown that early warning signs can indeed be extracted from acoustic signals and thereby offer a new method to prevent mining accidents. **Keywords:** mining accidents, crackling noise, acoustic emission, collapse predictability

The prediction of mining accidents is one of the great outstanding problems for mineralogists. Accidents in coal and hard rock mining are particular severe with an alarming number of miners dying each year. Most of the deaths occur in developing countries, in China, and in rural parts of developed countries. Historically, one of the worst mining accidents occurred April 26, 1942 in the Chinese Benxihu (Honkeiko) Colliery (coal mine), killing 1,549 miners. Several of these accidents are related to the collapse of mine shafts. Such collapses are not fully preventable when large tectonic movements occur but the death toll can massively be reduced if the collapse can be predicted. A key research area for mineralogists is to identify any precursor events, therefore, which can identify markers to predict the collapse event over relatively short time spans.

This problem is closely related to the question of whether earth quakes have an early warning sign, such as biological activities of mechanical pre-tremors. Systematic in-situ investigations of these issues are difficult, however, because the events are mercifully rare and few data will be collected during or after a disaster strikes. In an alternative approach, Salje and his collaborators Jiang et al. (2017) transferred the investigation of collapse events into the laboratory where ‘lab-quakes’ replace the larger geological events (Baró et al. 2013).

This approach started in 2011 (Salje et al. 2011a) when Salje, together with his collaborators in Barcelona investigated the collapse of porous SiO_2 materials. These authors understood very quickly the close similarity between the collapse of mines and earth quakes with the crackling noise emitted from the sudden collapse of a porous cylinder under uniaxial stress. Similar work emerged from Ian Main’s group in Edinburgh (Bell et al. 2011) and others by doing model simulations (Kun et al. 2014).

The first aim by the Salje team was then to identify which minerals or mineral assemblies where prone to violent collapse. Furthermore, it was not clear what degree of porosity would lead to precursor effects and which would not.

In a first series of investigations, small samples of SiO_2 (the ceramic 'vycor') (Salje et al. 2011a, Baro et al. 2013), goethite (Salje et al. 2013), corundum (Castillo-Villa et al. 2013), sandstone (Nataf et al. 2014a), and berlinite (Nataf et al. 2014b) were studied and some universal behaviour was found: macroscopic observations show that the compression of porous materials leads to sudden partial collapses rather than a smooth elastic or plastic deformation. The partial collapse events are named 'jerks' and, within the context of out-of-equilibrium dynamics, have been classified as avalanche phenomena. Their statistical features are similar to crackling noise as reviewed by Sethna et al. (2001). Jerks were also seen not only under compression, but also under shear deformations where the microstructures of the sample change in sudden movements rather than continuously.

One of the experimental techniques that had been most successful in yielding an understanding of the statistical properties of jerks was the detection of the acoustic emission (AE) associated with the microcracks occurring in the samples. The compression of natural and synthetic porous mineral with 40% porosity have shown that the event energies and the times of occurrence are virtually indistinguishable from those of earthquake statistics, both concerning temporal correlations (aftershocks) and energy distributions. In particular, the distribution of event energies shows a Gutenberg–Richter behaviour, i.e. a lack of characteristic scales: the probability of a jerk with energy E follows $P(E) \sim E^{-\varepsilon}$ with $\varepsilon = 1.40 \pm 0.05$ for SiO_2 related materials. Larger exponents were found in corundum (up to 1.8) but the overall situation remained the same: in all samples one observed the power law distribution of jerks and correlations between the events, in particular near the end of the sequence when the final collapse was imminent. Salje and Dahmen (2014) provided a full theoretical description of the jerk statistics in disordered materials. The details of the acoustic emission mechanism are related to changes of microstructures and were derived by Salje et al. (2014) based on a simple theoretical model (Salje et al. 2011b).

These results pointed towards the possibility that correlation between the largest avalanches and corresponding foreshocks may occur in the case of high porosity (>80%). The experimental observations also lead to the first indication that large-scale major collapses could be predicted by the detection of acoustic signals in the case of geological materials constituted by crystalline (or amorphous) bulk phases with a highly porous microstructure. On the other hand, in case of samples with lower porosity, no such correlations were seen and avalanche prediction was deemed virtually impossible.

While these studies set out the pathway for collapse prediction, the breakthrough came after the technology to measure collapse jerks was scaled up to more realistic sample sizes. In the recent study by Jiang et al. (2017) these authors used a large scale hydraulic press with cylindrical samples sizes with 50 mm diameter and 100 mm length. The stress rate was as low as d□/dt = 8.5 kPa/s (1 kN/min) with a maximum stress of 300 kN. The experimental arrangement is such that even bigger samples under slower stress rates can be investigated so that the way is now open to test ‘realistic’ collapses while measuring the acoustic emission in the laboratory. Samples of coal and sandstone were measured and a very clear signal for the precursor effect was found. The large sample volume leads to a new phenomenon that was not possible to observe in small samples, which is the evolution of the event centers during the experiment. The results indicate that all avalanche characteristics can be divided into two groups, namely those at the early stages and those closer to the main failure event. Using eight AE detectors the authors found that the initial stages are characterized by randomly distributed event centers with large distances between them. The events are hence approximately randomly distributed in time and space. With increasing number of emission centres, clustering along the future collapse planes occur and the events become highly correlated. The energy exponents for the randomly distributed events are generally larger than those of the correlated events (uncorrelated 1.7 versus corrleated 1.5 for sandstone and uncorrelated 1.5 versus correlated 1.3 for coal). The power law dependence is emphasized by the averaged slope with Omori exponents $p = 0.84$ (sandstone) and $p = 0.95$ (coal). These values are typical for Omori sequences in natural earthquakes. The Båth's law is equally satisfied with the ratio of 1.2 between the energy magnitudes 4 of a main shock and an after shock.

The results of the research has two major implications. First, it shows that the prediction of collapse events is possible. The two indicators for an impending disaster, such as a collapse of a mining shaft or the collapse of a building, are the increase of acoustic emission of crackling noise and the change of its energy exponent. Both indicators can be measured easily by highly sensitive microphones attached to the material (sandstone sculptures, houses, coals seams, etc.). The signals need to be processed, which can be easily done using a simple computer device. The sensitivity of the method depends largely on the microstructural properties of the minerals: uniform but porous sandstone is much more sensitive to "early warning noise" than coal seams that contain a multitude of local cracks.

Second, we now understand crackling noise much better because a much more detailed measurement technique is available that allows the investigation of very large samples. The analogy of crackling noise of porous minerals with earthquakes is firmly established with the surprising additional feature: the energy exponent (or b-value in seismology) depends on the collectiveness of the collapse event. Local cavity collapse displays higher energy exponents than collective movements such in crack propagation and the formation of microfaults.

Once these issues are now clarified it is crucial that further research is undertaken using even larger samples and more acoustic detectors to clarify the collapse characteristics of minerals. A procedure could be to extract minerals or geological samples from mines and subject them to the same testing procedures. The statistical properties of the collapse such as the change of the power law exponent and possible changes in the Oromi and the Båth's law can then be registered. Then detectors can be introduced into the mines and permanently computer controlled. Whenever changes of the 'crackling noise' occur, it can be compared with the collapse characteristics and, if appropriate, warnings of impending collapse can be given.

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