debates

8 April 1999

E-MAIL CONTRIBUTIONS

Although this debate is now closed, the following contribution makes an interesting counterpoint to Ian Main's concluding remarks and so was held over for posting in this final week.

DIDIER SORNETTE

Predicting earthquakes requires an understanding of the underlying physics, which calls for novel multidisciplinary approaches at a level never yet undertaken. Notwithstanding past efforts in several countries in the last decades, I fail to see that the scientific community has used the full potential of artificial/computational intelligence, statistical physics, super-computer modelling, large scale monitoring of a full spectrum of physical measurements, coupled together with more traditional seismological and geological approaches to make a dent in the earthquake problem. What we have learned is that past failures in earthquake prediction reflect the biased view that it was a simple problem.

The alchemy of earthquakes

Paradoxes, misunderstanding, controversies often appear when restricted to the 'narrow' window of our present knowledge. Consider the example regarding the importance that Sir Isaac Newton attributed to alchemy as his primary research field, leading to the provoking statement by Geller in the first week of this debate that "Earthquake prediction seems to be the alchemy of our times".

The lesson I personally take from this example is that Newton was fundamentally right to expect that physical processes could lead to the transmutation of one element into another. However, physics and technology were not at his time sufficiently advanced and science had to wait for Becquerel and for the Curie's to open the modern 'alchemy' (nuclear science) era. The question then boils down to the fact that Newton lost his time pursuing a (valid) goal which was, however, out of his reach.

Similarly, we need fundamentally new approaches for understanding what are earthquakes, but hopefully less time might be needed to understand what is the 'alchemy of earthquakes', simply because we are so much better armed and science is progressing so much faster than ever before. I consider the understanding of earthquakes to be a requisite to the assessment of prediction potentials for two reasons. Simple 'black box' pattern recognition techniques have been tried repeatedly and have shown limited success, probably in part due to the poor quality and scarcity of the data. A fundamental understanding of earthquakes, not only of the source problem but of the full seismic cycles, is thus called for.

Only such an understanding could lead us to a quantitative assessment of the potentials and limitations of earthquake prediction, as chaos and dynamical system theory have helped in understanding (some of) the limits of weather forecasting. We are very far behind meteorology for two reasons:

1. we still have very limited precise quantitative measurements of the many parameters involved.
2. the physical phenomena underlying earthquakes are much more intricate and interwoven and we do not have a fundamental Navier-Stokes equation for the crust organization.

It is thus too early to state anything conclusive about the fundamental limitation of earthquake prediction.

Mechano-chemistry

Earthquakes are indeed very poorly understood. The standard theory is based on the rebound theory of earthquakes formulated by Reid in 1910 which was later elaborated as a friction phenomenon by Brace and Byerlee in 1966 with many recent developments using Ruina-Dieterich-type laws. This textbook picture still poses many fundamental paradoxes, such as the strain paradox[1], the stress paradox[2], the heat flow paradox[3] and so on[4]. Resolutions of these paradoxes usually call for additional assumptions on the nature of the rupture process (such as novel modes of deformations and ruptures) prior to and/or during an earthquake, on the nature of the fault and on the effect of trapped fluids within the crust at seismogenic depths (see ref. 4 and references therein). There is no unifying understanding of these paradoxes.

As recalled by Crampin in this debate, earthquakes depend on many geological and physical conditions. In particular, there is a lot of direct and indirect evidence for the prominent role of water, both mechanically (pore pressure) and chemically (recrystallization, particle effects, texture) and their probable interplay[4,5]. There is growing recognition that mineral structures can form and deform at much milder pressures and temperatures than their pure equilibrium phase diagram would suggest, when in contact with water or in the presence of anisotropic strain and stress (ref. 5 and references therein).

As an example, I have recently proposed[5] that water in the presence of finite localized strain within fault gouges may lead to the modification of mineral textures, involving dynamic recrystallization and maybe phase transformations of stable minerals into metastable polymorphs of higher free energy density. The interplay between mechanical deformation, activated chemical transformation and rupture opens new windows to look at earthquakes, beyond the (reductionist) mechanical paradigm.

Self-Organized Criticality

As mentioned by Bak in this debate, the SOC hypothesis has been suggested, on the one hand, on the basis of the observation of power law distributions, such as the Gutenberg-Richter law for earthquakes and the fault length distribution, and of the fractal geometry of sets of earthquake epicenters and of fault patterns, and on the other hand on the study of highly simplified models with somewhat similar scale-invariant properties.

The most interesting aspect of SOC is its prediction that the stress field should exhibit long-range spatial correlations as well as important amplitude fluctuations. The exact solution of simple SOC models[6] has shown that the spatial correlation of the stress-stress fluctuations around the average stress is long range and decays as a power law with distance.

Such models suggest that the stress fluctuations not only reflect but also constitute an active and essential component of the organizing principle leading to SOC. It is an intringuing possibility whether the observed increase of long-range intermediate-magnitude earthquake activity prior to a strong earthquake[7,8] may be a signature of increasing long-range correlations. This theoretical framework supports the view developed by Crampin in this debate that stress monitoring on large scale may be a good strategy.

Two important consequences can be drawn from the SOC hypothesis. First, at any time, a (small) fraction of the crust is close to the rupture instability. Together with the localization of seismicity on faults, this leads to the conclusion that a fraction of the crust is susceptible to rupture, while presently being quiescent. The quantitative determination of the susceptible fraction is dependent on the specificity of the model and cannot thus be ascertained with precision for the crust. What is important however in that the susceptible part of the crust can be activated with relatively small perturbations or by modification of the overall driving conditions. This remark leads to a natural interpretation of triggered[9] and induced seismicity by human activity in the SOC framework[10].

The second important but often ignored point is that, in the SOC picture, the crust is NOT almost everywhere on the verge of rupture and is not maintaining itself perpetually near the critical point. For instance, numerical simulations show that in discrete models made of interacting blocks carrying a continuous scalar stress variable, the average stress is about two thirds of the stress threshold for rupture. In these models, the crust is, on average, far from rupture. However, it exhibits strong fluctuations such that a subset of space is very close to rupture at any time.

The average is thus a poor representation of the large variability of the stress amplitudes in the crust. This leads to the prediction that not all perturbations will lead to triggered or induced seismicity and that some regions will be very stable. SOC models suggest that local stress measurements may not be representative of the global organization.

Criticality and predictability

In the present context, criticality and self-organized criticality, used in the sense of statistical physics, refer to two very different concepts, which leads to a lot of confusions, as seen in this debate. First, SOC is self-organized (thus there is no apparent 'tuning', see however ref. 11) while criticality is not. Second, the hallmarks of criticality are the existence of specific precursory patterns (increasing 'susceptibility' and correlation length) in space and time.

The idea that a large earthquake could be a critical phenomenon has been put forward by different groups, starting almost two decades ago[12-14]. Attempts to link earthquakes and critical phenomena find support in the demonstration that rupture in heterogeneous media is a critical phenomenon. Also indicative is the often reported observation of increased intermediate magnitude seismicity before large events (see Bowman and Samis's contribution to this debate and references therein).

Criticality carries with it the concepts of coarse-graining and universality, and suggests a robustness of its signatures when observed at sufficiently large scale. This is in contrast with the conclusion that one needs a detailed knowledge of the huge complexity of the geology and mechanics of fault systems (fault geometry, strength variations in the fault, zone material, rheological properties, state of stress, *etc*) to perform a prediction (see Crampin's contribution to this debate).

Criticality and SOC can coexist.

If rupture of a laboratory sample is the well-defined conclusion of the loading history, the same cannot be said for the crust where 'there is life' after large earthquakes. An illustration of the coexistence of criticality and of SOC is found in a simple sandpile model of earthquakes on a hierarchical fault structure[15]. Here, the important ingredient is to take into account both the nonlinear dynamics and the complex geometry.

While the system self-organizes at large time scales according to the expected statistical characteristics, such a the Gutenberg-Richter law for earthquake magnitude frequency, most of the large earthquakes have precursors occuring over time scales of decades and over distances of hundreds of kilometers. Within the critical view point, these intermediate earthquakes are both 'witnesses' and 'actors' of the building-up of correlations. These precursors produce an energy release, which when measured as a time-to-failure process, is quite consistent with an accelerating power law behaviour. In addition, the statistical average (over many large earthquakes) of the correlation length, measured as the maximum size of the precursors, also increases as a power law of the time to the large earthquake.

From the point of view of self-organized criticality, this is surprising news: large earthquakes do not lose their 'identity'. In this model[15], a large earthquake is different from a small one, a very different story than told by common SOC wisdom in which 'any precursor state of a large event is essentially identical to a precursor state of a small event and earthquake does not know how large it will become', as stated by Scholz and Bak in this debate.

The difference comes from the absence of geometry in standard SOC models. Reintroducing geometry is essential. In models with hierarchical fault structures[15], we find a degree of predictability of large events. Most of the large earthquakes whose typical recurrence time is of the order of a century or so can be predicted from about four years in advance with a precision better than a year.

An important ingredient is the existence of logperiodic corrections to the power law increase of the seismic activity prior to large events, reflecting the hierarchical geometry, which help 'synchronizing' a better fit to the data. The associated discrete scale invariance and complex exponents are expected to occur in such out-of-equilibrium hierarchical systems with threshold dynamics[16].

Of course, extreme caution should be exercized but the theory is beautiful in its self-consistency and, even if probably largely inacurate, it may provide a useful guideline. Hierarchical geometry need not be introduced by hand as it emerges spontaneously from the self-consistent organization of the fault-earthquake process[17].

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