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Earthquake precursors and crustal 'transients'

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For the public, the main question that seismologists should ask themselves is, "Can earthquakes be predicted?". *Nature*'s earthquake prediction debate follows this simple line of inquiry, although presented in a slightly more subtle form by Ian Main: "How accurately and reliably can we predict earthquakes, and how far can we go in investigating the degree of predictability that might exist?" This is still, however, a question formulated under social pressure. I argue that this question should be left to one side by scientists to allow progress in a more general and comprehensive framework, by studying the whole set of crustal instabilities — or 'transients' — and not only earthquake precursors.

First I shall outline the major observations relevant to this problem, and the two standard models for earthquake occurrence and predictability. I shall then comment briefly on these models and show how a more general approach could lead to a better understanding of earthquake predictability.

Relevant observations of crustal instabilities

O1: Continuous or transient aseismic fault slip is reported for several major faults that reach the Earth's surface[1]. This slip might involve only the upper few kilometres of the fault or, for some fault segments, it might involve the whole thickness of the brittle crust. The transient creep events occur at various time scales (hours, days or months).

O2: Silent and slow earthquakes observed at long periods show that significant transient, low-frequency slip events can occur on faults on a timescale of minutes[2]. The reported seismic nucleation phases, lasting from fractions of a second to seconds, seem to scale with the final rupture size, and sometimes with the dimension of the pre-shock cluster, if such a cluster exists[3].

O3: Fluid migration instabilities in the crust have been reported from studies of the mineralization of veins, near-surface measurements of groundwater geochemistry and pore-pressure measurements in deep boreholes[4,5]; non-hydrostatic pore pressure at depths of several kilometres is observed in many places.

O4: Seismicity is not a Poisson process: clusters of earthquakes can last from hours to years, and have reported dimensions from hundreds of metres to hundreds of kilometres[6]; seismic quiescence on various spatial scales has been reported to have occurred on a time scale of years[7].

O5: Earthquake sizes have power-law distributions (possibly up to some finite magnitude threshold).

O6: Size and roughness of fault segments follow power-law distributions; borehole logs of rock parameters (such as density and velocity) also reveal power-law distributions[8].

Two standard models

M1: Processes reported in O1 to O4, and their subsequent effects (such as ground deformation and electromagnetic effects) can sometimes be recognized (retrospectively) as being precursors to large earthquakes[3,9]. This is the basis for the preparation-zone paradigm in seismogenesis.

M2: Observations **O5** and **O6** provides the basis for self-organized critical models for the crust (SOC), or similar models leading to a chaotic system with a large degree of freedom, in which earthquakes are inherently unpredictable in size, space and time (such as cascade or avalanche processes)[10,12].

Many authors have convincingly shown that proponents of **M1** have not been very successful — if at all — in providing statistical evidence for such correlations between anomalies and earthquakes, nor for stating what would distinguish a 'precursor-type' from a 'non-precursor-type' anomaly[12]. Furthermore, it is difficult to explain how the size of the preparation zone, which is expected to be relatively small, can scale with the final size of large earthquake.

On model **M2**, my opinion is that proponents of seismicity's being nearly chaotic are not very convincing either, because their physical model of the crust is a crude, oversimplified one, from which the important mechanical processes reported in **O1** to **O4** are absent.

A generalized SOC model for the crust

To resolve this, one should consider SOC models applied to the whole set of instabilities in the crust (fluid, aseismic and seismic), not only to the seismic ones. In this more global framework, it would be surprising if the characteristic parameters of the slow instabilities that span a large range of scales (duration, dimension and amplitude) did not obey a power-law distribution, just as earthquakes do. Indeed, they all result from nonlinear processes developing on the same fractal structures: the system of faults and the rock matrix (**O5** and **O6**). Although we might have to wait for quite a long time before testing this hypothesis with enough observations, as deep aseismic slip or fluid transients are usually difficult if not impossible to detect from the surface, such a model does seem quite plausible.

Under this working hypothesis it can be suggested that each type of transient process might trigger not only itself in cascades, but might sometimes also be coupled to another: fluid instabilities triggering or being triggered by fault creep, earthquakes triggering or being triggered by fluid instabilities or transient fault creep triggering or being triggered by earthquakes.

Numerous observations support the existence of these coupled processes, mostly in the shallow crust, where aseismic processes are dominant[13,15]. Indirect evidence also exists deeper in the brittle crust, as some foreshock sequences seem to be triggered by aseismic slip[3]. The brittle-ductile transition zone might be another favourable location in which significant transient aseismic processes and seismic instabilities can coexist and be coupled on the fault system, because the faults zones there might exhibit unstable as well as stable frictional behaviour; interestingly enough, it also the common nucleation point for large earthquakes.

It can thus be proposed that models **M1** and **M2** can be merged into a more general framework of crustal instabilities, still within a SOC model, sometimes displaying coupled processes that lead, in favourable cases, to the observation of precursors to large earthquakes.

In such a model, the slow instability leading up to the earthquake is expected to remain unpredictable. However, if one were able to detect and monitor the progression of the slow instability, and to develop a physical model of the coupling process between the fluid or aseismic transient and the seismic nucleation, one might be able to predict some characteristics of the impending earthquake.

The remaining problem is the scaling of the precursors to the earthquake size, which could be tackled by considering that some of the large slow transients (size L1) might lead to seismic ruptures large enough for breaking a whole asperity (size L2 > L1), thus allowing dynamic propagation at least up to the next large barrier on the fault (distance L3 >> L2). The possible existence of probabilistic scaling laws between L1 and L2, and between L2 and L3, might be the condition for the existence of reliable precursors.

What should we do?

Clearly, geophysicists should focus on deciphering and modelling the physics of the frictional and fluid migration transient processes in the crust[16,17]. From the observational point of view, differential tomography with active sources or multiplets, dense arrays of continuous GPS receivers and of borehole strain meters and tilt meters, and deep borehole observations in fault zones (for tracking the role of fluids directly), might be the key to success.

Hence, to the question, "Is the reliable prediction of individual earthquakes a realistic scientific goal?", my answer would be in the negative, as this should not yet be a scientific target. However, to the more relevant question, "Is the understanding of crustal transients an important and realistic scientific goal?", I would answer in the affirmative, and add that significant progress in this field is required before questions about earthquake predictability can be answered realistically.

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