Proceedings of the
International Conference on Complex Systems
Nashua, NH, 21–26 Sept. 1997.

Y. Bar-Yam (ed.), New England Complex Systems Institute (1997) .
Also on-line in the *InterJournal*.

Emergence in Earthquakes

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We present a new theory of shallow earthquakes in which phase transformations allows the crust to store a fraction of the total released energy. These phase transformations also control the triggering nucleation phase. We briefly discuss consequences and comparisons with data.

1 Introduction

Research in earthquake prediction has a long history and is still very active in many parts of the world [1, 2, 3, 4]. Nourished by the fact that earthquake prediction has never really delivered [5], there is however a growing consensus [5, 6] that earthquake prediction might be utterly impossible in practice, due to the sheer complexity of the problem. From a scientific standpoint, this view is that of a Bayesian [7], for whom each failed attempt lowers the probability for the success of the next attempt.

Bayes'approach is warranted for stationary processes. Clearly, scientific progress is not in this class as testified by the long list of unexpected discoveries [8, 9]. According to standard wisdom, an earthquake is a sudden rupture in the earth's crust or mantle caused by tectonic stress. To understand the physics of earthquakes, it is thus necessary to know the state of stress in the crust. These premises are usually elaborated by models that attempt to account for seismological and geological data as well as constraints from laboratory experiments. However, stress is probably the least known of all geophysical fields, the failure criterion is still largely unknown and we do not understand the conditions that make a fracture propagate into big earthquakes. Furthermore, the mechanical view of earthquakes lead to important paradoxes, the strain paradox, the stress paradox and the heat flow paradox, that are difficult to account for, either individually or when taken together. Their resolution usually calls 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.

2 Role of Water and Phase transformations

What if some field other than stress was conducting the preparation of an earthquake? There is growing evidence [10, 11, 12, 13] of the importance of water as a key participant for decreasing normal lithostatic stress in the fault core and weakening rock materials by stress corrosion.

Here, we advance the novel concept that water has an additional role in the earthquake process, which is the alteration of minerals submitted to finite strains leading eventually to the phase transformation into other metastable minerals in out-of-equilibrium conditions. This transformation provides another route for storing energy during the earthquake cycle in the form of "chemical" energy. This new form of energy storage can be documented in details for the quartz to coesite transformation [14], shown to occur at seismogenic depth under finite deformations.

Under increasing strain, the transformed minerals eventually become unstable, as shown from Landau theory of structural phase transitions, and transform back explosively, creating a slightly supersonic shock wave propagating along the altered fault core leaving a wake of shaking fluidified fragments. As long as the resulting high-frequency waves remain of sufficient amplitude to fluidify the fault core, the mechanics of granular media teaches us that the elastic modulii and the shear strength of the granular fault gouge are substantially decreased in the presence of this shaking at acoustic pressure two order of magnitude smaller than the lithostatic value. This central zone is thus like a loose granular medium with low acoustic impedence, hence a trap of seismic waves. This weakening then triggers the rupture instability by unlocking the fault which starts to move and releases the elastic part of the stored energy. The healing of the fault is controlled by the duration of the shaking due to the trapped waves within the central zone. When the shaking dies off, the fault locks again and heals. This implies that the rupture propagation during the earthquake develops a pulse-like structure, with a pulse width increasing approximately proportionally with time since the inception of the earthquake.

3 Consequences and Predictions

In this theory, the fault slip is not triggered by reaching a stress threshold (corresponding either to friction unlocking or rupture nucleation), but rather by a chemical instability: as a consequence, any level of stress will activate the fault slip when the explosive phase transformation occurs. This theory allows one to rationalize many observations within a coherent framework, including the strain, stress and heat flow paradoxes [15], the observation that the

*Supported in part by NSF EAR96-15357 and NSF EAR97-06488

larger the recurrence time, the larger the stress drop [16], the shear heating observation [17], the seismic P-wave precursors [18], the fact that earthquakes occur preferentially in strong rocks [19], the existence of creeping fault sections and slow earthquakes [20], tilt anomalies [21], electric effects [3] and relation with deep earthquakes [22].

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