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WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

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THE PHYSICS OF EARTHQUAKE PREDICTION

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I. Introduction

Although most sciences have a well-developed phenomenology, physics is one of the few disciplines, if not the only one, that has a rich and well-developed theory that complements the phenomenology. Generally the successful models of theoretical physics have small numbers of degrees of freedom; there are many fine examples. I shall use the term physics to imply the construction of quantitative physical models of earthquake phenomena with small numbers of degrees of freedom.

In the field of seismicity, that is to say the area of earthquake occurrence, the phenomenology is rich. Complementary theoretical modeling of seismicity is still in its infancy. I propose to describe some of the recent developments in modeling that take advantage of the optimistic hopes that the number of degrees of freedom in such models be small. With regard to earthquake prediction, most government supported activity has been overwhelmingly of a phenomenological character; in the case of earthquake prediction, the phenomenological approach has assumed the robes of hope that the result will be serendipitous. It is my assumption that modeling will lay a stronger foundation to the problem than serendipidity. It is also my belief that modeling of the underlying physics will help to clarify whether some of the assumptions that are made in the name of phenomenological

prediction, are consistent with the underlying physical processes of the fracture and deformation of rocks.

Let me illustrate one of these assumptions. Let us suppose our interest is in the prediction of large earthquakes. These earthquakes occur so infrequently in the lifetime of man, or are preserved so incompletely in the fossilized historical record that, in some quarters, the assumption is made that small earthquakes are a scaled down version of large earthquakes; therefore, so the assumption goes, the statistics can be markedly improved by studying the smaller earthquakes, which are evidently more abundant. There are simple geometrical considerations why this assumption is untenable.

Modeling that takes into account the physics and chemistry of rheology and fracture as well as geometrical constraints can yield at several products:

1) understanding why certain types of clustering phenomenology occur: seismic gaps, swarms, foreshocks, etc., and testing of the hypotheses of phenomenology,
2) improvement in the present ways we do clustering analysis for precursory phenomena as well as the possible development of new types of precursors,
3) an attack on the Engineering problem, namely that of developing "routine" procedures for on-line prediction work. This last product must be statistical in nature, i.e. give probabilities of future occurrence in any given time-space-magnitude window using all data at hand, and updated with each new earthquake.

In the first of these tasks we are well along, as I shall describe. In the second, we have made no progress whatsoever thus far. In the third, we have had modest success, but only for the short-term prediction of small earthquakes, using a terribly oversimplified model of fracture.

II. Time-scales

Before embarking on our discussion of present efforts at modeling, let me indicate some constraints on the problem that can be derived from geophysics and physics. A selection from among the relevant constraints must include the following: First, that the surface of the earth is covered by a small number of very large, relatively rigid plates that are in motion relative to each other at rates of the order of cm/year. Earthquakes are non-uniformly distributed over the surface of the earth and are found at the frictional boundary between these plates. The plates themselves form the upper boundary layer of a large scale system of thermally driven convection. Earthquakes are a suddenly occurring fracture in a prestressed material and are irreversible events. This is a non-linear dissipative process and thus we may expect that some of the phenomenology of modern developments in non-linear science such as attractors, bifurcations, basins, transitions to chaos and the like, might occur in low-order theoretical models in the earthquake case as well.

Second, the energy release takes place over a wide range of scales, so much so that we invoke a scale that - for our purposes - is a logarithmic measure of the energy released; each magnitude unit corresponds to about a 60-fold ratio of energies. But the largest

earthquakes of the world all seem to have about the same size -- colloquially described as magnitude 8 events. But even earthquakes with magnitudes 6 to 6-1/2 are potentially destructive and can cause significant loss of life, as witness the Fruili earthquake. In some regions of the world, the largest earthquakes that can occur are no larger than magnitude 6 to 6 1/2 events. In any case, there is a maximum magnitude (or energy) for earthquakes in a given region. Since earthquakes are suddenly occurring fractures, this means that the size of the fractures also scales appropriately. The size of a magnitude 8 fracture is roughly 500 km, more or less, with a reduction by about a factor of 7 for each magnitude down to about magnitude 6 and perhaps beyond. Because of the logarithmic scaling and other arguments it will turn out that the distribution of almost all properties of earthquakes are self similar -- call them fractals if you wish -- and thus will give credence to statistical scaling arguments I have given above, were it not for the fact that the distributions are truncated. It is these largest scale size events that influences the occurrence of the smaller events.

Third, as a simple picture, we can infer that there are three time scales. The longest is that of plate tectonics which is the time scale for recurrence of the largest earthquake considered as a simple relaxation oscillator. This process regenerates of the energy lost in dissipation. These time scales are of the order of 100-500 years in active zones. At the other extreme, the fracture process itself can be considered to be a rapidly running transition from one state of elastic deformation to another. This time scale is of the order of the linear dimension of the crack divided by the velocity of elastic waves and is of the order of a few minutes for the largest earthquakes.

If earthquake prediction is to be successful, we must search for coupling between earthquake events. Aftershocks -- which are themselves genuine earthquakes -- are events triggered by a larger predecessor earthquake, and occur over intervals spanning days to months, and even longer, after the triggering event. The earthquake itself generates a redistribution of the stress field which takes place elastically, i.e. with the short time scale. Elastic redistribution of stresses could, in principle, trigger earthquakes at remote locations, but that would imply that coupling should take place on an unacceptably short time scale. Thus aftershocks as well as other phenomena imply the existence of a non-elastic coupling for stress redistribution, which give an intermediate time scale; we describe the cause of the intermediate time scale as being due to creep or viscosity.

The experimental properties of the creep or viscosity are as follows: In the later stages of the deformation of a rock subjected to a large shear stress it is found to undergo accelerated creep that terminates in rupture, if the confining pressure and temperature are not too large. The rates are much accelerated by the presence of interstitial water. The time to fracture depends on $\exp(\sigma V/kT)$ where σ and T are the shear stress and temperature. This result suggests that chemical kinetics or activation, is important. In fact microscopic examination of the rock fabric near rupture, shows evidence for recrystallization in the presence of the shear stress. Solution and recrystallization are dominated by chemical kinetics.

If a preexisting sharp crack is subjected to a large external stress, the crack grows with a velocity governed by $\exp(\sigma\sqrt{L}/kT \times \text{const})$ - where σ is the external stress and L is the length of the crack. This is once again evidence for the importance of chemical processes, especially if we note that the velocities are much increased if water is present near the crack tip. Water is present in sufficient amounts in the earth's crust to make accelerated creep a significant factor in the modeling. Accelerated, subsonic creep of this type in metals is called stress corrosion in the engineering literature.

III. Geometrical Constraints

We can summarize our discussion thus far as follows: the essential ingredients of any model should include

1) plate tectonics

2) non-elastic creep rheology

3) brittle (elastic) fracture

and 4) geometrical constraints of fracture sizes and orientations.

With regard to the latter feature, I remark that on a scale less than the largest fractures, Dr. Kagan and I have found that earthquake fault zones have three-dimensional structure that has a fractal distribution of sizes. The distribution of plate boundary features on a scale larger than the scale size of the largest earthquakes will not concern us directly in the present discussion. What the fractality implies is that a fault zone is not a plane, but indeed is a melange of barriers to extended rupture for cracks, or potential cracks, of a variety of scale sizes. It is also the case that small earthquakes, which we assume take place on the smaller cracks of the fractal melange, do not occur on what geologists have identified as the fault strand that will ultimately break in a large earthquake. One way to avoid this is to assume that the main fault is stronger than the surrounding region for a reason that invokes a process other than those we have discussed to now. The nature of this strengthening is probably identified now, but time will not permit my elaboration of this part of the total picture.

IV. Example I: Seismic Gaps

I now move to the description of several attempts at modeling of selected parts of the earthquake phenomenology, using models of low-order dimensionality. The examples are chosen from work at UCLA. One bit of such phenomenology is the observation of an extended period of quiescence before an impending large earthquake; an example is given by the regional seismic quiescence of Southern Mexico for several years before the M=7.8 Oaxaca earthquake of 1978. Professor Yamashita and I have modeled this problem as follows: Assume that we have a suite of pre-existing cracks of fractal size distribution that are also distributed along multiple planes. (The cracks are actually two-dimensional strips imbedded in a three-dimensional homogeneous elastic medium). The spaces between the lines are selected from the same population as the gaps on each line. At t=0 a sudden anti-plane stress σ_o is imposed on the region. The crack begins to grow under the influence of the velocity law $v=v_o \exp(K/Ko)$ (we actually use $v=v_o(K/K_o)^n$ with n a large number) where K is the stress intensity factor, and is the coefficient in the rate of fall-off of stress σ with distance x from the edge of a crack; in the neighborhood of a crack

tip, $\sigma \sim \sigma_o (L/x)^{1/2}$ where L is some length. The stress intensity factor at each crack tip is calculated by a pairwise approximation, and the cracks are allowed to grow. Because of the antiplane stress orientation, the cracks can only grow in their own planes; they cannot bend; this is a mathematical inadequacy on our part. As the crackss grow closer, the stresses in the gaps increase, and hence the rates of disappearance of the gaps accelerate. As long as the growth rates are slow compared to elastic wave velocities, the growth can be calculated quasistatically. At some point the velocity of growth approaches the sonic (elastic) velocity and the crack begins to radiate; this instant is the onset of an earthquake and we declare that the earthquake is instantaneous; i.e. we avoid solving the dynamical radiation problem and assume that the transition to a lower energy state by fusion of two adjoining cracks is instantaneous. The stresses in the redistributed crack system are now recalculated and the process continues until all cracks have fused into an array of master cracks that extend across the entire space.

If we have only one plane of cracks, we find that the smallest gaps disappear first with the release of small amounts of deformational energy stored in the gaps and their neighborhood. Fusion with larger cracks or through larger gaps releases larger amounts of energy, and these events occur later in the history; seismologists refer to this shift in the energy spectrum as a lowering of the b-value prior to the mainshock. In fact most of the fusions come just before the formation of the master event and a pattern of number of emission events as a function of time appears that is not unlike a foreshock sequence.

If we have several planes of cracks, we find that intermediate size events occur over the entire array, each with its own sequence of foreshocks. Although most of these events do not break completely across the line of cracks, sooner or later one of the planes of cracks must fracture by successive fusions completely across its own plane before the others. At this instant the cracks on the planes that are broadside to the through-going crack are cast in a reduced-stress shadow. The reduced stress lowers the rate of growth and fusion is effectively halted on the other crack planes. But inevitably, grow they must, and ultimately the velocities again approach sonic values at some later time. The period of quiescence terminates and finally a thorough-going fracture occurs on another plane. This event -- also preceeded by its own foreshocks -- is stronger than any of the preceding events, because the second through-going fracture occurs on a plane that is stronger than the first. The similarity of the output from the simulation of our model to the quiescence episode that preceded the large Izu earthquake is remarkable; this is of course fortuitous.

The fact that the cracks must remain "open" in this model does concern us. In the model the stresses are redistributed following a rupture event and these stresses remain localized essentially without change unless healing rates are rapid. The model requires that they are not. However healing rates are not well-determined experimentally. As additional comments, I remark that it is the largest cracks that influence the stress distribution of all the others. The occurrence of a major earthquake effectively zeros the stress fields of the smaller ones. In addition we note that the precursory episodes leading to the main shock involve stress fields that are extremely inhomogeneous. Models that do not have this feature -- that of inhomogeneity -- are likely to be unsuccessful.

V. Example II: Locked Faults

Let me give a second example that is designed to simulate the problem of a locked fault. Consider a two-dimensional array of lattice points with variable breaking strength at each site. Under the stress-corrosion model this corresponds to a variable critical stress intensity factor. Let the distribution of strengths have mean values that are high in one region and low in an adjoining region. Let the mean-square dispersion of healing strengths be the same in both regions; thus the dispersion in the model is a significant fraction of the mean breaking strength in the low strength region, and only a small fraction of the mean strength in the high strength region. Let the applied stress at each lattice point be a scalar quantity that is inhomogeneous due to redistribution from neighboring ruptures, and further let the stress increase at a uniform rate at all sites, during the time intervals between rupture/fusion events. A fracture is initiated at a lattice site after a suitable time delay after the critical state is reached. The fracture grows by the usual crack growth process under the influence of stress corrosion, and stops when a site is encountered at which the stress difference between strength and applied stress is greater than the redistributed stress due to the fracture. The redistributed stresses are short range terms. In the simulation, we find that the overwhelming majority of events occur in the low mean-strength regions and that these have an energy (or moment) distribution that is a power law if the site strengths are fractally distributed. Because of the high statistical dispersion of strengths in the low-strength region, a growing crack has a good chance of stopping within a short distance of the point of initiation; in other words, the magnitudes in the low-strength region are influenced by statistical effects and we can adjust these - via the dispersion - so that the crack almost never ruptures all of the way across the low-strength array.

On the other hand the reservoir of strengths in the high-strength region may be so great that it takes a long time for the applied stress to increase to the level of the breaking strength. Once rupture is initiated, the crack grows dramatically. Since the dispersion is small, the dynamical stress at the crack tip is sufficient to overcome the small fuctuations in strength in the path of the crack and the crack grows in a single event completely across the high strength array.

Thus in the low-strength region we have many events with a wide range of energies, while in the high strength region, we have no small events and only -- in this case -- periodic catastrophic events. The success of this model depends on the assumption that healing, that is the restoration of bond strength, takes place very rapidly after fracture; this is in contrast to the first model in which we assume restoration or healing occurs slowly in the time-scale of the sequence.

VI. Concluding remarks

These are but two examples of quite a large number of problems that we have been studying through modeling. Other questions that we have asked, and for which we have been able to obtain modest success through modeling include contributions to

a) understanding the causes of aftershock distribution
b) questions of the intermittency versus periodicity of the largest earthquakes in a given region
c) resolution of the Irwin/Griffith paradox for dynamical fractures

among others. The techniques we have applied include those of

a) Low-ordered dynamical systems of both deterministic and stochastic types which yield many of the familiar attributes of bifurcations, chaotic and periodic attractors, intermittency, basins, fractality, etc.
b) Renormalization group theory and the Ising model
c) Percolation theory
d) Critical branching processes

Dr. Kagan and I have also attacked the engineering problem of coupling these physics models of clustering to the on-line (if you will) processing of real catalogs for the purposes of developing genuine predictions. In this regard we have had only modest success: we have been able to predict future small earthquakes (that are at least larger than their predecessors) with a good statistical rate of success, but thus far the application of these fracture models to the prediction of large events has eluded us.

There are many unsolved problems, partly because of the large amount of phenomenology that we need to model, and partly because we do not yet know either the physics or how to model the physics. For example, we do not yet know how to incorporate the tensor character of the stresses into the models; once this is done we will have a better picture of the healing process, which remains a difficult issue. We do not know how to attack genuine three-dimensional models -- mainly because of the same computational limitations that afflict other areas of physics. With regard to the physics, we do not have a good picture of how fluids migrate in a region whose connectivity or tortuosity may be a variable according to the conditions of temporal closeness to the earthquake catastrophe. Indeed we do not know whether the dominant process for migration of water is due to H^+ diffusion or molecular diffusion. Finally, I remark that these efforts that I have been describing, attack isolated aspects of the full problem of patterns of seismicity on a piecemeal basis. There is the annoying doubt whether the full problem will turn out to be one of low-ordered dimensionality. If not, we may be up against a task that takes us out of the realm of present-day capabilities, or even that the problem of full-scale modeling to identify clustering may be unsolvable.

However the broad outline is clear. All models must involve several basic ingredients: stress redistribution due to fracture, time delays for the intermediate time scale processes, and long term plate tectonic effects. That much is clear. The excitement - and the variability of pattern - come in the geometrical expression of the models. The problems are non-linear in the extreme and therein lies the challenge and the charm.