A Search for Earthquake Precursors

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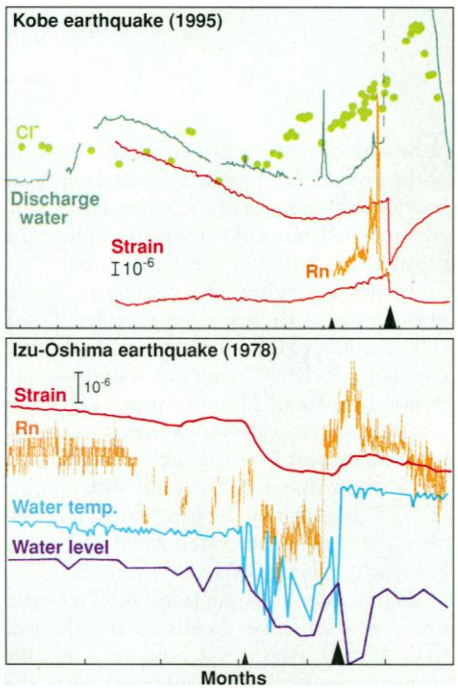
Geochemical and hydrological signals preceding significant earthquakes have been reported since the 1960s and played a prominent role in the successful prediction of the Haicheng earthquake in China (*1*). Such observations are part of monitoring programs in China, Japan, the former Soviet Union, and the United States. Yet, studies of these preseismic phenomena have been controversial for several reasons. Hydrogeochemical phenomena, while clearly strain indicators, do not have a well-understood relation to strain. They also exhibit "response heterogeneity" in that preseismic signals can be highly variable in space and time. Wells only meters apart can yield very different coseismic or preseismic water-level anomalies (*2*, *3*), and other wells change sensitivity over several years (*4*). Additionally, many preseismic signals are observed far from the impending earthquake, making it difficult to find a physical mechanism. And finally, the quality of studies in this field has been variable. Consequently, many researchers have dismissed precursory claims based on these data.

Recently, an impressive collection of precursory data from hydrogeochemical indicators that lends support to such claims was discussed at an international meeting at the University of Tokyo (*5*). Several presentations described efforts to understand and calibrate these indicators. A theoretical model was proposed to explain strain-induced anomalies in water chemistry (*6*). The postseismic degassing of He after the Kobe earthquake was simulated in the laboratory by subjecting granite to volumetric strain (*7*). Tidal forcing and barometric pressure were used to calibrate changes in water level (*2*, *3*, *8*, *9*), water temperature (*10*), flow in artesian wells (*11*), periodic geysers (*12*), and concentrations of Rn, CO_2, CH_4, N_2, H_2, He, Cl, and F (*13*). In many cases, these nontectonic effects could be successfully modeled and removed from the records.

Precursory data were presented for the Kobe earthquake of 17 January 1995 (magnitude M = 7.2). Covarying preseismic signals in ground-water discharge, Rn and Cl concentration, and strain were observed at three locations (all within the ultimate aftershock zone) beginning 3 months before the event (see figure) (*4*). These signals are remarkably similar to data collected for the earlier Izu-Oshima earthquake (M = 7.0, 14 January 1978). Comparable preseismic variations in ground-water level, temperature, Rn, and strain were seen at four different locations (25 to 50 km from the epicenter) beginning a month before the event (see figure).

Data were also presented for a M = 7.3 earthquake (11 July 1995) in the Burma-China border region (*14*, *15*). Accompanying two foreshocks were preseismic variations in Rn concentration, water level, water temperature, as well as leveling and line length. Precursors were observed out to several hundred kilometers and at about 30% of the observing stations. An official prediction was declared, and evacuation averted a substantial loss of life.



Precursory anomalies associated with **(top)** the *M* = 7.2 Kobe earthquake of 17 January 1995 (*21*). Ground-water discharge, two components of crustal strain (*22*), ground-water Rn, and ground-water Cl. The main shock (larger arrowhead) produced coseismic discontinuous change in all indicators. Precursory anomalies (smaller arrowhead) began about 3 months before the event. **(Bottom)** Similar precursory anomalies for earlier Izu-Oshima earthquake (Rn concentration, temperature, water level, and strain) began about 1 month before the main shock (*23*).

For the San Andreas fault system, preseismic and coseismic changes were reported for the 4 August 1985, M = 6.1 Kettleman Hills earthquake (*2*, *16*) from stations about 35 km from the epicenter. Two of four water-level sites and two of three volumetric-strain sites showed covarying precursory signals beginning 3 days before the event. A foreshock sequence followed the onset of the water-level anomalies. Another study discussed variations in the interval between eruptions from a periodic geyser located near the northern end of the San Andreas fault system (*12*, *17*). Coseismic and precursory changes were detected for three large earthquakes 100 to 200 km from the geyser, including the Loma Prieta earthquake (M = 6.9, 18 October 1989), for which a covarying preseismic extensometer signal was also observed. The precursors began 1 to 3 days before the events.

The above studies represent an encouraging trend toward improved data quality, more rigorous testing for the significance of anomalous signals, and accurate calibration. Most importantly, these observations support the contention that many preseismic anomalies are true precursors. They also imply that precursors indeed exhibit response heterogeneity [even in some of the clearest cases of precursory signals (*2*, *4*, *14*, *15*)] and are often too distant to have been caused by preseismic slip (*2*, *9*, *12*, *14*). Despite the absence of an adequate physical model for these effects, hydrogeochemical data are a promising means for observing precursory phenomena. Of 40 proposed precursors considered by the International Association of Seismology and Physics of the Earth's Interior (IASPEI) subcommission on Earthquake Prediction, only five were judged as significant. Of these, two were based on foreshocks (the only universally accepted precursory phenomenon), and two on hydrogeochemical indicators, namely the Kettleman Hills and Izu-Oshima studies mentioned above (*18*).

Precursors are important phenomena for addressing two fundamental and closely linked problems: the characterization of plate-boundary deformation and the nature of the earthquake preparation phase. These anomalies provide further evidence for an observable preparation phase, an essential condition for successful earthquake prediction. Response heterogeneity implies that the distribution of strain within a deforming zone is likewise heterogeneous; the existence of precursors at a distance suggests that strain transients constitute a significant component of plate boundary deformation and can propagate hundreds of kilometers.

These observations and their implications also suggest an observational strategy. Precursory phenomena have been detected primarily within on-land plate boundary deformation zones, where the epicentral region

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can be easily instrumented. These zones, distinct from the classic subduction-zone settings that account for most of the Earth's seismicity, need to be intensely monitored over a broad area. These data also point to the importance of faults on all scales (not just the largest) as promising locations for detecting precursors. Hydrologic phenomena naturally occur in faulted regions where water often flows readily. Hydrothermal areas denote relatively deep-seated faulting and are therefore of particular interest (*19*). Faults are also regions that by definition concentrate strain and thus should amplify coseismic and precursory deformation. Hydrogeochemical indicators may thus simply be in the right location (*20*). In several cases, borehole strainmeters have detected many of the precursors seen by hydrogeochemical phenomena. This provides a critical link with strain measurement and suggests that such strainmeters are particularly well suited for detecting precursors. In many ways, the onland San Andreas fault system, embedded within a relatively simple, well-studied, 1000 km by 200 km plate boundary zone, is ideal for the study of precursors. At present, however, this zone is only sparsely instrumented (in terms of hydrogeochemical and related strain instrumentation), especially when compared with seismogenic zones in Japan and China. In addition, sites have been concentrated primarily along one section of the San Andreas fault in association with the Parkfield Experiment.

For many researchers at the meeting, there was a sense of déjà vu, as if the Izu-Oshima and successfully predicted Haicheng earthquakes had recurred two decades later. The earlier events led to great excitement in the seismological community and a feeling that earthquake prediction was finally within our grasp. Yet, this goal has been elusive, gradually leading to strong skepticism, especially in the United States, about the prospects for prediction and even for detecting precursors. But this present pessimism, like the initial optimism, is probably excessive. We now realize that the earthquake prediction problem is not easy. Solving it requires a sound physical model and sound observations; these observations require patience as we wait for earthquakes to occur. Although we cannot avoid this waiting process, it can be accelerated considerably by casting a wider net—expanding observing programs to capture many more events and their precursors—and by fostering the kind of international cooperation seen at this meeting.

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How T Cells Count

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The surfaces of the antigen-presenting cells of the body offer a bazaar of foreign peptides, bound to their major histocompatibility complex (MHC) molecules, for the sampling and possible activation of the T cell population. To mount an immunological defense, T cells must recognize these foreign peptides. The T cell receptor (TCR) interacts with the foreign peptide–MHC complex, sometimes activating the T cell. How does the T cell know when the interaction should result in activation? In a report in this week's issue, Viola *et al.* (*1*) show that T cells "count" the number of TCRs engaged by the peptide-MHC complex and become activated when that number reaches about 8000.

In practice, TCR-peptide-MHC recognition is very sensitive. T cells, each with more than 10,000 TCRs that bind to a specific antigen, can respond if they recognize the peptide associated with as few as ~100 of the 100,000-odd MHC molecules on an antigen-presenting cell (*2–4*). Yet the interactions of TCRs with their ligands are weak, with dissociation constants of 10^{-6} M or less, suggesting that a TCR is engaged by its antigen for only a short time. In spite of this weak interaction, an individual T cell can distinguish variants of the same peptide, bound to the same MHC molecule, often responding to its optimal TCR ligand but not to a slightly altered form.

In fact, all mature T cells that recognize foreign antigens have TCRs that can also interact—even more weakly—with structurally related self antigens. Such an interaction with self peptide–MHC complexes in the thymus is essential to allow developing T cells to complete their maturation (*5*). How can enough information for several, critically distinctive responses be transduced by such a small number of weak interactions?

Last year, Lanzavecchia and colleagues (*6*) provided a striking clue toward resolving this problem. They found that each peptide-MHC complex did not bind stably to one complementary TCR complex but could engage multiple TCRs serially, ~100 to 200 TCRs per peptide-MHC complex. Because more TCRs are removed from the cell surface when there is more stimulating ligand, a lower limit for the number of binding events could be calculated by measuring the number of TCRs lost. These results indicated that TCR-ligand interactions are fundamentally dynamic and led to explanations of several features of T cell activation. First, they suggested that the moderately low affinity of binding might be an asset rather than a liability for T cell activation, enhancing the efficiency of rebinding by a small number of ligands. Second, they suggested that T cells might use multiple rounds of binding and dissociation to amplify small affinity differences for discrimination of optimal and altered peptide ligands. This mechanism would be particularly useful if T cells use "kinetic proofreading" to tell whether an optimal or a variant peptide ligand is binding (*7, 8*). Finally, they suggested a way to reconcile the brief encounters of individual TCR-ligand binding events with the requirement of T cells for several hours of stimulation before committing to an activation response (*9, 10*). All these predictions, however, depended on resolving a critical question: whether the removal (or "consumption") of so many

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