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EARTHQUAKE PREDICTION

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Earthquake prediction, hardly taken seriously as science in the United States before 1971, reached fledgling status in the period 1975 to 1978. By late 1974, most U.S. researchers in seismology were agreeing that earthquakes might be predictable on a scientific basis. Cautious optimism had in fact turned to rampant enthusiasm among some workers as evidence accumulated for many possible earthquake precursors and the theory of dilatancy seemed to explain most observations (see summaries by Bolt and Wang, 1975; Healy, 1975; Kisslinger and Wyss, 1975). Slower progress since 1974 has dampened the euphoria felt by some but a much more solid and broad foundation for a Prediction Program has now been constructed and a number of important cornerstones laid.

A new sense of urgency and relevancy for prediction research was created in December, 1975, when Castle et al. (1976) presented evidence that the elevation of a 12,000 square kilometer area in southern California had increased by 15 to 25 cm during the 1960's. Because this uplift lay astride a section of the San Andreas fault that has been essentially aseismic since a devastating earthquake in 1857 and because uplifts have been reported before other damaging earthquakes (e.g. Castle et al., 1974), the ominous suggestion was made that this uplift could be precursory to the next great California earthquake. Although scientists could not and still cannot be sure that the uplift is a precursor, concern was expressed from households in the uplifted area all the way to the White House and research scientists were suddenly asked to interact closely with public leaders, news media, and the general public. Staff of the U.S. Geological Survey (USGS) were invited to brief the President's Advisory Panel on Anticipated Advances in Science and Technology. The Director of the USGS met with the staff of the Governor of California to discuss implications of the observed uplift. The USGS and the National Science Foundation (NSF) were asked to transfer, for one year, $2.6 million from other programs over to earthquake research related to the Southern California Uplift and to develop a rationale for a national Earthquake Hazards Reduction Program (EHRP). A panel, convened by the President's Science Advisor, issued such a rationale (anonymous, 1976), which, together with the initiatives of Congress and the feeling of most seismologists that substantial progress was possible, helped bring about a threefold increase in funds during 1978 (Hamilton, 1978). Funding for earthquake prediction increased to a national level of $15.8 million, and the level of effort in the whole Earthquake Hazards Reduction Program funded by the USGS and NSF rose to a total of $53.2 million including prediction, hazards assessment, earthquake engineering, induced seismicity, fundamental studies of earthquakes, and research on how to stimulate the utilization of scientific results by the general public as well as studies of the socioeconomic impact of predictions.

Continued analysis of the uplift showed that between late 1972 and early 1974 the area of uplift increased to more than 50,000 square kilometers and the maximum uplift reached 45 cm (Castle, 1978; Holdahl, 1977). Then, by 1976, the whole area subsided to less than 50 percent

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of its maximum level. Subsequent analysis of leveling data from the early 20th century by R. O. Castle (oral communication, 1978) shows that a similar uplift occurred between 1902 and 1914 but that the southwest boundary lay along the coast near Lompoc and Long Beach where large earthquakes occurred in 1927 and 1933, rather than along the south front of the Transverse Ranges. It is interesting to note that this uplift partially subsided beginning in 1926, one and seven years, respectively, before the ensuing earthquakes. In early 1978, for the first time ever, all major level lines in southern California (over 4000 km long) were resurveyed in a three-month period by 36 survey teams to obtain an "instantaneous" overview of the uplift. The results are not yet in. Reduction of leveling data from other areas of the United States has also been intensified (Reilinger et al., 1977; Brown et al., 1977; Brown, 1978).

The observed uplift and subsidence agree closely with what geomorphologists would predict on the basis of landforms. The biggest surprise has been that 20 cm changes in elevation can occur in less than a year and perhaps even in less than a month. A number of models have been suggested that relate the elevation changes to earthquakes (Thatcher, 1976; Rundle, 1978; Rodgers and Chinnery, 1973; Wyss, 1977a) but insufficient data exist to prove or disprove any such relationship. Sieh (1978) found evidence in the uplifted area for six prehistoric earthquakes since the sixth century A.D. comparable to the 1857 event. Wehmiller et al. (1977), using amino acid dating of mollusks to determine the ages of marine terraces, found a rate of uplift of more than 10 mm per year during 40,000 years along the Ventura and Santa Barbara coasts, the highest rate recognized anywhere in the United States. Short-term changes in sealevel have also attracted attention; a possible precursor was noted before the 1933 Long Beach, California, earthquake (Nason, 1976) and before some earthquakes in Japan and South America (Wyss, 1976a, b).

Detailed measurements of changes in gravity have been made in southern California, especially in conjunction with the releveling effort (Strange and Wessells, 1976; Jachens, 1977). A localized increase in gravity southeast of Palmdale, California, of over 30 microgals was not accompanied by uplift (R. C. Jachens, oral communication, 1978). Furthermore, Brown et al. (1977) found only about 15 microgal change in gravity after the 1964 Alaska earthquake despite an uplift of about 50 cm. Thus although gravity measurements may provide an inexpensive way to measure elevation changes, these measurements may supply other information not yet understood and apparently more complex than simply changes in elevation and water level (Whitcomb, 1976a; Holdahl, 1976; Walsh and Rice, 1979).

Analysis of horizontal-strain data in southern California during the period of major uplift are inconclusive given the precision of available trilateration and geodimeter data. Thatcher (1976) found some evidence of anomalous compression in the early 1960's, but Savage and Prescott (1979), using other data, disagreed. Yearly Geodolite measurements made since 1972 on nearly 500 lines crossing faults in California show no significant deformation related directly to the uplift or to earthquakes (Savage et al., 1976; Savage et al., 1977; Savage and Prescott, 1978) but two very significant observations have been made. Thatcher (1979) basically agreed with the conclusion of Savage and Burford (1973) that rigid block displacements across major faults in central California provide a good first-order approximation to the regional deformation. Thatcher (1979) finds that a minimum of 3.3 cm motion per year occurs over a 60-km-wide zone that includes the creeping section of the San Andreas fault in central California, and that a small but not insignificant 20 percent of the displacement occurs outside of a 20-km-wide zone that includes the fault. Thus the deformation is primarily but not totally localized along at least part of the San Andreas fault. By inversion of the data, Thatcher estimates the rate of deep slip to be no more than 4.5 cm per year and finds that the possibility of elastic strain accumulation along the creeping part of the fault can not be unambiguously precluded. Savage et al. (1979) and Prescott et al. (1979) show that the regional strain-accumulation pattern consists of north-south compression and east-west tension in central California, as one would expect for the San Andreas fault, but that in southern California the strain pattern is north-south compression with little or no east-west tension.

Thatcher (1975a, b) finds evidence for deep aseismic slip prior to the 1906 San Francisco earthquake. He concludes that crustal deformation in northern California since 1906 can largely be accounted for by postearthquake effects lasting about 30 years, followed by continued strain accumulation in the San Francisco Bay region that decreases twofold 70 km to the north.

Slater and Huggett (1976) and Huggett et al. (1977) have developed a two-color laser ranging device capable of measuring daily changes in distance over about a dozen lines as long as 13 km with a precision of about 1 part in 10 . The results from recording near Hollister, California, since September 1975 show that strain is episodic and not continuous. The strain episodes can be attributed to fault slip at depth that may propagate upward. Several of these instruments will be installed during the next few years especially in southern California to try to measure the changes in strain over time.

More than 80 tiltmeters have been installed within 2 m of the surface near faults primarily in California, constituting the largest deployment of any type of instrument for prediction research during the early 1970's except for seismometers. These tiltmeters are sufficiently sensitive and stable but have proven very difficult to install in the ground such that rainfall and other atmospheric phenomena do not cause some relatively large noise signals (Wood and King, 1977). Furthermore, even if signals from the meters accurately reflect deformation in the immediate vicinity of the instruments, these signals may not reflect regional tectonic deformation (Wyatt and Berger, 1978). Nevertheless tiltmeters are the only widely deployed instrument that can give a nearly continuous measurement of deformation, and several distinctive anomalies preceeding earthquakes have been reported, especially before events of magnitude 4 and greater (Mortensen and Johnston, 1975; Mortensen and Johnston, 1976; Johnston et al., 1978). New tiltmeters are needed that can be placed at depths of perhaps hundreds of meters or that have a baseline along the surface of possibly a kilometer. Increased interest has arisen in monitoring lake levels precisely to detect tilt (Wilson and Wood, 1978).

A variety of new approaches to measuring changes in strain and stress were tried during 1975 to 1978 (Evernden, 1979) that ranged from continued operation of the laser strain meter at Pinon Flat (Beaumont and Berger, 1974), through short wire strain meters near the surface (Johnston et al., 1977), to vibrating-wire strain meters and a fluid-filled-bladder (flatjack) stress gauge, as well as overcoring methods for measuring absolute level of stress (Engelder et al., 1978; Sbar et al., 1979). So far the most definitive but also the most expensive technique used to measure the stress is hydraulic fracturing (Zoback et al., 1977, 1978). The most surprising result has been that stress differences at a depth of 250 m decrease approaching the San Andreas fault from approximately 55 bars at 20 to 35 km from the fault to 30 bars at 4 km and only 17 bars at 2 km (Zoback, 1978a).

Anomalies of 1 to 2 gammas in total magnetic field differences preceding earthquakes have been recorded, once at permanent stations and once in survey mode (Johnston et al., 1975; Smith and Johnston, 1976). The data are very sparse, however, and more observations are needed to establish whether they are typical or unique. Magnetic changes have not been observed during creep events on instruments within a few hundred meters of the fault (M. J. S. Johnston, 1978).

A variety of techniques for measuring resistivity have been tried in California (Fitterman and Madden, 1977; Corwin and Morrison, 1977; Mazella and Morrison, 1974; and Reddy, 1976). A decrease of 15 percent in resistivity during the month before a magnitude 4.2 event was observed by Mazella and Morrison (1974) just after their study began. However, Morrison et al. (1979) observed no anomaly above their 2 percent noise level before a magnitude 4 earthquake in December 1977 that was ideally situated under their array. Wang et al. (1975) found a decrease in resistivity of a few percent before frictional sliding of saturated granite blocks in the laboratory.

King (1978) reports increases in radon content of soil gas before regional earthquakes of magnitude 4 and 4.3. The rough correspondence of some of his anomalies with seasonal changes in barometric pressure and rainfall, however, have left many workers unconvinced.

Kovach et al. (1975) found some suggestion of precursory changes in well water level before local earthquakes. Over 25 wells were instrumented for prediction research between 1975 and 1978 but so far no earthquakes of magnitude 4 or greater have occurred near the wells.

The possibility of abnormal animal behavior before earthquakes attracted thorough discussion (Evernden, 1976) but although three serious research projects have been funded, they have not yet provided any definitive new data.

The installation and maintenance of seismographs make up the single greatest instrumentation effort in the earthquake program. About 400 seismographs with a peak-displacement response of approximately 17 cycles per second are located in California, and nearly 300 seismographs are scattered throughout most other seismic areas in the United States. Although these networks receive their major support from the prediction program, they are also funded by a variety of programs through several agencies. Thorough analysis of the data, especially in the larger networks, has become a far more difficult problem than data collection. Stewart (1977) developed a computer system that monitors signals from more than 100 stations and automatically locates local earthquakes immediately after they occur. Johnson (1978) programmed one computer to detect earthquakes and record the digital signals from more than 150 stations, and a second computer to process the data interactively. Systems similar to Johnson's are scheduled to be installed in six localities during 1979.

Operation of these and worldwide networks over long periods of time provides the baseline information required for identifying seismic precursors to earthquakes. The concept of seismic gaps has proved useful in locating regions along plate boundaries where large earthquakes are likely to occur and in estimating the greatest magnitude of the possible event (McCann et al., 1978 and 1979; Evernden, 1978b). Instruments are being installed cooperatively in gaps in the New Hebrides, Solomon Islands, India, Pakistan, Turkey, Taiwan, and Mexico in hopes of "trapping" a large earthquake. Instruments were installed in one gap (Ohtake et al., 1977b) just before an earthquake of magnitude 7.9 (Science News, 1978). The gap concept, however, does not help much in predicting the specific time of an event and efforts at refining the concept for this purpose have proved frustrating (Evernden, 1978b). Many authors report periods of relative quiescence in seismicity before the largest earthquakes in a general area but of increased seismicity in the prospective epicentral zone (Kelleher and Savino, 1975; Brady, 1976; Ishida and Kanamori, 1977; Engdahl and Kisslinger, 1977; Khattri and Wyss, 1977; Haberman and Wyss, 1979; McNally, 1977).

An increasing effort is being made to identify foreshocks, although no general agreement exists on what specifically is a foreshock. Jones and Molnar (1976) found that more than half of the large earthquakes around the world have one or more foreshocks large enough to be detected. McNally (1977) and Ishida and Kanamori (1977) showed that spatial and temporal clusters of earthquakes often precede large events. Lindh et al. (1978a) showed that in the three cases they studied, the ratio of the amplitude of SV waves to that of P waves is more scattered and has a different value for foreshocks than for main shocks. This change in ratio can be explained by a rotation of the stress axes with time. Thus the observations by McNally et al. (1978) of a significant increase in seismicity near the center of the Southern California Uplift, of a clustering of these events, and of a systematic rotation over time of the nodal planes for these solutions touched off speculation that these events were foreshocks to some major event related to the Southern California Uplift. The activity, nearly all of magnitude less than 3.0, however, subsided after 12 months, and this region has remained seismically quiet since November 1977. Efforts to identify migratory patterns of earthquakes have proved enticing but not useful as yet for specific predictions (Dewey, 1976; Brady, 1977).

Bufe et al. (1977) used a 14-year record of seismic slip on a small part of the Calaveras fault in central California to predict one magnitude 3 event successfully. Their method, however, did not continue to work. Thatcher et al. (1975) used seismic-slip distribution to point out two seismic gaps along the San Jacinto fault in southern California where the next earthquakes of magnitude 6 to 7 on this fault are likely to occur.

Velocity anomalies were reported by Aggarwal et al. (1975), Cramer and Kovach (1975), Wyss (1975a), Gupta (1975a, b), Wesson et al. (1977), Talwani (1979), Whitcomb (1976b), and Johnston (1978a, b). Anomalies were not found in a number of careful studies including those by McEvilly and Johnston (1973), Boore et al. (1975a, b), Engdahl (1975), Kanamori and Fuis (1976), Cramer (1976), Cramer et al. (1977), Bolt (1977), Steppe et al. (1977), Murdock (1978), and Lindh et al. (1978b). The clearest observations are in regions of shallow thrust faulting and specifically not in large strike-slip fault zones such as the San Andreas, where anomalies, if they exist, must be less than 2 percent. The size of a velocity anomaly may depend critically on the orientation of the fault and thus on how far the seismic waves recorded locally travel in the anomalous zone. Another possibility, however, is that velocity anomalies may occur in regions of high stress but be undetectable in regions of low stress.

Detection of velocity anomalies is complicated by large velocity changes near fault zones (Engdahl, 1975). Methods that are beginning to emerge for mapping these large velocity changes should be useful not only for detecting small travel-time anomalies, if present, but also for mapping fault structure (Aki and Lee, 1976; Engdahl and Lee, 1976; Crosson, 1976).

A major dispute in seismic source theory is whether the typical 10 to 100 bar stress drop during an earthquake occurs in a high ambient stress field of up to a kilobar or so or in a low ambient stress field of tens to hundreds of bars. A number of important observations since 1974 have helped to resolve this issue. Detailed seismic reflection studies provide evidence for a low-velocity zone at the depth of earthquakes in rocks adjacent to the creeping section of the San Andreas fault in central California (T. V. McEvilly, oral communication, 1976). Such a zone can best be explained by elevated pore pressure (A. Nur, oral communication, 1977), although elevated temperature may also play a role (Stewart and Peselnick, 1978). Thermal studies along the San Andreas fault, however, show that heat flow over the fault is not abnormally high, an observation suggesting low shear stresses and thus high pore pressure (Lachenbruch and Sass, 1973; Lachenbruch et al., 1978). Laboratory experiments indicate the onset of creep on faults before sudden earthquake like displacements (Byerlee, 1967; Dieterich, 1978). The implication may be that creep somehow initiates a sudden unstable motion resulting from a weakening of the fault's resistance to sliding. Theoretical modeling of the effects of pore pressure, as well as the strong dependence of water density on temperature, suggests that the effective confining stress on a breaking fault will drop rapidly to zero after only a few centimeters of displacement (Sibson, 1977; Raleigh, 1977). Thus the stress drop during an earthquake is likely to be complete. The observations mentioned above by Thatcher (1979) that most shear deformation occurs close to the San Andreas fault zone and by Zoback (1978a) and Zoback and Roller (1978b) that stress decreases approaching the San Andreas fault, add to the evidence for low stress in regions where earthquakes occur. Irwin and Barnes (1975) suggested that the presence of pore fluids at nearly lithostatic pressure in rocks of the Franciscan Formation along the San Andreas fault may distinguish creeping from locked sections of the fault.

These arguments should cause a careful rethinking of models of the earthquake process as to which possible precursors may be easiest to detect and also raise the possibility that the earthquake process along the San Andreas fault may differ fundamentally from that along thrust faults or faults not occurring near plate boundaries. Thus prediction techniques may vary from region to region. Detailed geologic and geophysical studies are underway in central California to determine the physical and structural properties of the San Andreas fault. A drill hole is planned to penetrate the epicentral region of shallow earthquakes in the upper 1 to 2 kilometers of the fault and to measure, among other things, the ambient pore pressure and stress. Laboratory studies of fault gouge have recently been stepped up (Peselnick et al., 1976; Wang et al., 1978; Wu, 1978).

Details of studies in rock mechanics and seismic source theory and their relation to earthquake prediction are discussed elsewhere in this volume as well as in two conference volumes edited by Evernden (1977, 1978a).

Although reliable methods of prediction may be a decade or more away, it is not too early to worry about how prediction research should interface with society. A panel on the Public Policy Implications of Earthquake Prediction (1975) pointed out a number of needs for immediate socioeconomic research and legislation to minimize the potential negative effects of a prediction. An unsubstantiated prediction actually caused negative results in Mexico (Garza and Lomnitz, 1978). The need to have potential predictions verified by a peer group of scientists has led to the formation of earthquake prediction evaluation councils by the USGS and the State of California (California Earthquake Prediction Evaluation Council, 1977). These councils have met several times but have not yet reviewed any specific prediction of a damaging earthquake. The State of California has passed a law (State Law 1267, 1976) limiting the liability of state employees who predict earthquakes. Haas and Mileti (1977a, b) underlined many of the potential problems of prediction by questioning a number of civic leaders and citizens on what their response would be to a specific prediction expressed as a scenario. The Working Group on Earthquake Hazards Reduction (1978) carefully catalogued the considerations and issues in formulating public policy and in implementing hazard reduction programs. These studies have brought earth scientists, social scientists, and policymakers together to discuss various problems and plans. Research will soon be stepped up in this complex area, hopefully in time for the first even tentative scientific prediction of a damaging earthquake in a populated area.

Thus, in overview, the earthquake prediction program in the United States has moved from a period of phenomenological observations during the early 1970's to a period of far more critical evaluation of instruments and observations and of greater emphasis on the mechanics of the earthquake process. Progress has been slow but steady. Improved observations have led to a far more detailed understanding of not only the strain field but also the stress field in seismic zones. Techniques are beginning to emerge for identifying foreshocks. The greatest frustration has been that, despite a major increase in instrumentation, no earthquake of magnitude 5.5 or greater has occurred directly under any densely instrumented region. Such observations in the future will probably lead to the most rapid advance in earthquake prediction research but solid progress is expected nevertheless as holes are drilled into the foci of some shallow earthquakes, as laboratory studies progress and as data are analyzed from the thousand or more instruments now operating. These instruments, in addition, are providing the required baseline data that in the future will allow differentiation of precursory anomalies from background noise. Development of borehole tilt and strain meters, more stable or absolute portable gravimeters, stress-measuring methods, and data-processing techniques should aid the empirical part of the program substantially. It is fair to say that the United States now has a serious National Earthquake Prediction Program consisting of a wide range of studies to record empirical observations of precursors and to develop a fundamental understanding of the physics of preearthquake and coearthquake processes.

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