fundamental guidelines for planning a multidisciplinary transect study of the region.

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# U.S.-Japan Quake Prediction Research

## Use of Real-Time Earthquake Information for Hazard Warning

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For the seventh time since 1964, a seminar on earthquake prediction has been convened under the U.S.-Japan Cooperation in Science Program. The purpose of the seminar was to provide an opportunity for researchers from the two countries to share recent progress and future plans in the continuing effort to develop the scientific basis for predicting earthquakes and practical means for implementing prediction technology as it emerges. Thirty-six contributors, 15 from Japan and 21 from the U.S., met in Morro Bay, Calif. September 12–14. The following day they traveled to nearby sections of the San Andreas fault, including the site of the Parkfield prediction experiment. The conveners of the seminar were Hiroo Kanamori, Seismological Laboratory, California Institute of Technology (Caltech), for the U.S., and Takeshi Mikumo, Disaster Prevention Research Institute, Kyoto University, for Japan. Funding for the participants came from the U.S. National Science Foundation and the Japan Society for the Promotion of Science, supplemented by other agencies in both countries.

The special theme for this seminar was the use of real-time information in the formulation of warnings of impending earthquakes and associated hazards. The papers and lively discussion ranged over the whole subject of earthquake prediction, from the fundamental physics of earthquake processes to the interface between science and society in the implementation of prediction technology. Tom Heaton, U.S. Geological Survey (USGS), who chaired the concluding discussion session, summarized the principal topics as:

- Seismicity sequences: foreshocks, aftershocks, and their relation to background seismicity.
- Characteristic earthquakes.
- Slip in subduction-zone earthquakes: where does it occur and how does it relate to the accretionary prism, sediment thickness, and other geological variables?
- Non-seismological precursory anomalies: strain, geoelectrical, and geochemical.
- The present capability to process and use real time data for predictions and warnings, including tsunami warnings.
- The fundamental physics of instabilities and creep (which couples back into all of the above topics).

Other topics that were addressed included new results from geological studies of active faults, advances in seismic instrumentation and technology for remotely accessing centralized digital data bases, and the correlation of Bouguer gravity anomalies with seismogenic zones and subsurface faults in Japan.

Publication of the extended abstracts of the seminar papers is planned, so only a topical summary is given here.

The earthquake prediction problem is treated on three time scales: long-term (decades), intermediate-term (a few years), and short-term (a few weeks to a few hours). The work reported during the seminar supports the general outlook that the most promising approaches to prediction, each applicable to one or more of these time scales, are geological studies of fault systems and paleoseismological studies, analysis of the time-dependent distribution of seismicity in space and time, observations of crustal deformation, which may be manifested by a variety of phenomena such as uplift, tilt, strain, and gravity changes. Specific precursory anomalies that might arise from changes in rock properties or ambient conditions as a major event approaches are still being sought and tested.

### Real-time Data Processing and Short-term Warnings

The capability to treat data in real-time and use the results for warnings, the special topic of this seminar, pertains primarily to short-term predictions, or even warnings that an earthquake has already occurred and that its effects (strong shaking, tsunami) will arrive soon at places away from the source. Modern data acquisition and computational systems have made real-time processing of earthquake-related data a reality in both countries, though not yet in general use in either.

Locations, magnitudes, focal mechanisms and other source parameters can be known within some tens of minutes after an event from the analysis of data telemetered to a suitably equipped center from either teleseismic stations or regional networks. Broadband data from even a single station can yield important (though not unique) results quickly.

The Japan Meteorological Agency (JMA) has installed a system called Earthquake Phenomena Observation System (EPOS) that can process 512 channels of seismic data and 512 channels of other data (for example, strain, tilt, sea-level) on an on-line real-time basis. EPOS is used for tsunami warning and earthquake prediction services. Recent tsunami advisories, a primary JMA responsibility, were issued within about 7 minutes of the earthquake occurrence. JMA is also responsible for the short-term prediction of the expected Tokai earthquake. For this task, the Agency monitors the data continuously and if anomalous changes are seen, the Earthquake Assessment Committee will be assembled promptly. Almost any data in EPOS, including real-time data, can be displayed on a large screen in the specially equipped room in which the committee meets. Thus the committee can quickly and efficiently assess the situation on the basis of the most recent observations.

Current seismic activity in the Tokai region has also been monitored continuously by university seismograph networks. The characteristic features of this seismicity, together with examples of focal mechanisms, were discussed in detail.

The National Oceanic and Atmospheric Administration and the U.S. Army Corps of Engineers are cooperating in a recently established program to monitor portions of the Aleutian trench with high potential for tsunamigenic earthquakes with bottom pressure recorders. The devices are capable of detecting the tsunami in deep water and the data can be rapidly transmitted to the Pacific Tsunami Warning Center, which has responsibility for warnings for the Pacific basin.

The current capabilities and the potential applications for the real-time processing of data from the dense regional university networks in several parts of Japan and the Southern California network were described to the meeting. The typical Japanese university analysis system, which is linked to a telemetered station network, automatically detects events, reads the arrival times of P and S waves, and locates the events. For example, the Tohoku University system locates about 9000 earthquakes per year. Reliability checks carried out by comparison to manual processing and comparison of the resulting seismicity distributions with those mapped from earlier work have shown the systems to be functioning very well.

The Southern California system is based on 250 telemetered stations, operated jointly by the USGS and Caltech. Currently about 15,000 events are located each year, with analysis completed within several days of real time. Systems under development should allow near real-time locations in the future.

From the prediction viewpoint, the payoff from near real-time processing comes from the ability to recognize anomalies that might denote the imminence of a strong event and to formulate a warning. The science has not yet had a full test of its capability to do this, but mechanisms to try are in place in both countries.

The prediction experiment at Parkfield, Calif. is the centerpiece of the current U.S. program. The project is designed to determine if short-term precursors to an earthquake in the magnitude 6 range can be detected and interpreted rapidly, to enable the USGS to make a closely timed prediction. The data from many sensors in the Parkfield area are telemetered to Menlo Park, where they are processed in almost real time. The experiment is an attempt at practical implementation of the results of much research during the past decade, and, if the results are positive, it is a step toward the development of an operational earthquake forecasting system. The observation and data handling system described to the seminar will certainly provide excellent data for research on earthquake processes, even if short-term prediction turns out not to work for the next Parkfield earthquake. The criteria established for making decisions on various levels of alert called for by the observations will also be tested as the experiment progresses. Finally, the effectiveness of the system established to communicate the prediction to the government of California and of their response will also be tested.

Many earthquakes are preceded by foreshocks, but identification of an event as a foreshock prior to the occurrence of the mainshock has proven to be a difficult and elusive task. An alternative approach that is being tried is to estimate the probability that, given the occurrence of a small-to-moderate earthquake, a larger event will occur near the same place shortly afterwards. This approach is a key element in the Parkfield plan, based on what occurred during the previous two

Parkfield earthquakes. Determinations of the spatial and temporal behavior of foreshock sequences and the regional history of foreshock occurrence are being combined in an effort to do real-time estimation of the increase of hazard implied by the occurrence of a moderate event in parts of California. A study of past foreshock sequences has revealed that, after the largest foreshock has occurred, these sequences decay in a manner very similar to aftershock sequences.

The California Earthquake Prediction Evaluation Council has developed a procedure for real-time, short-term predictions of large ($M \simeq 7.0$) earthquakes in eight identified seismic gaps in the state. The basis of the procedure is the assumption that every $M \simeq 6$ earthquake within 50 km of four gaps in southern California and every $M \simeq 5$ earthquake within 20 km of four gaps in northern California are foreshocks to a $M \simeq 7$ mainshock, to occur within 5 days. The predictions are issued as earthquake "advisories". The false alarm rate, judged from historical data, should be acceptable from the viewpoint of public reaction. Problems to be solved include the decision as to which gap will rupture when a postulated foreshock occurs, and what to do about differences in magnitudes for the same earthquake determined by different organizations.

A search for systematics among a large number of reported precursors to Japanese earthquakes, based on many different types of geophysical, geochemical, and geodetic observations, yielded a suggested relation, for short-term precursors (less than 40 days), for the probability of occurrence of a strong earthquake, given the observation of one of these precursors. Discussion brought out the principal problem with evaluating the significance of reported anomalies as true precursors. Many published reports, especially early ones, do not provide a basis for critically evaluating the validity of the report or any information on false alarms or failures to predict when the particular phenomenon is used.

The limit of a short-term real-time warning system is one that responds within tens of seconds of the occurrence of an earthquake, to provide a reliable estimate of the location, origin time, and size, and then calculate the area at risk, while the rupture is occurring. Signals from a network of instruments deployed along a fault (which, of course, must be pre-selected as having a high potential for a damaging earthquake), are monitored to detect promptly that something has occurred. The signals are used to track the rupture, locate the source, and estimate the seismic moment release in real time as the event progresses. Information that a potentially destructive event has occurred can be transmitted quickly to critical facilities, so that systems to limit or prevent damage can be actuated before the ground motion reaches the sites. A prototype system has been designed and tested on data from two recent California earthquakes and simulated data for the great 1857 event by a group at MIT.

## Prediction Research

The empiricism that characterized early prediction research is no longer acceptable in either country. Much of the research discussed at the seminar is directed toward gaining a fundamental understanding of seismogenesis that is adequate for interpreting observations of anomalies preceding earthquakes and the coseismic and post-seismic phenomena associated with strong earthquakes, as well as for designing future observation programs. Results of studies of subduction zones (a subject that has not figured prominently in the U.S. program), the San Andreas and associated faults in California, and intraplate events in the Japanese islands were presented and debated.

Geological investigations of active faults are one source of essential information. A seismotectonic zonation for upper plate events within the Japanese Islands, based on a geological investigation of the regional characteristics of active faults was offered. Improvements in dating techniques have led to a more precise chronology of earthquake ruptures on the southern San Andreas fault. A shorter average interval for the most recent 10 events (131 years) has been found, but also a much greater variability of the interevent times. The finding that these events tended to cluster in time, with long intervals between, reinforces doubts about the validity of using long-term average rates for estimating the current seismic hazard for this fault. On the other hand, the more precise dates increase the ability to correlate events between sites in efforts to evaluate the size of paleoseismic events.

Detailed gravity surveys in Japan revealed evidence of strike-slip movements on a latent active fault, as well as correlations between short wavelength negative Bouguer anomalies and microearthquake activity in some regions.

Hot discussion was provoked by a paper on the role of the accretionary prism and sedimentation rates on the distribution of seismic slip in subduction zones. In many subduction settings, an aseismic strip is observed to lie between the intra-plate activity near the trench and the abundant seismicity in the main thrust zone. The debate focused on whether this aseismic section can be explained as due to the presence of weak materials in the accretionary prism above the downgoing slab in all known cases.

The distribution of co-seismic fault slip can be estimated independently from direct geological observations, modeling of geodetic observations, and modeling of waveforms recorded by seismographs. A USGS study has looked at what each of these approaches reveals about the true fault slip. They have examined how the distributions, which often look quite different, can be reconciled, and how the combination can be used to document the complexities of fault rupture.

The details of the spatial and temporal distributions of earthquake sequences provide constraints on theoretical models of earthquake processes. Pre-mainshock distributions have been demonstrated to be a promising basis for intermediate-term predictions. Patterns observed prior to mainshocks and during the aftershock sequences were described for all of the tectonic settings mentioned earlier, with examples drawn from California, the Aleutian Islands, and Japan.

Results from Japan are mainly based on regional JMA observations and partly on local observations by university networks. Data from a number of large earthquakes around Japan support the concept that pre-event seismicity may vary according to three different patterns (quiescence, gradual increase, or concentrated swarm), depending on the region. In addition, there is evidence that variations in the long-term rate of seismicity observed concurrently in different regions might be attributed to slight changes in tectonic stress.

During discussions of case histories from northern and central California and from the central Aleutians, the participants seemed to accept the evidence that clusters of aftershocks tend to occur in the same places as clusters of events during the pre-mainshock period, and that this behavior is closely tied to the concept of a "characteristic earthquake." Rates of decay of aftershocks with time are being studied for possible ways in which to predict strong aftershocks in real time, as well as for the information these rates may contain about fault zone properties.

The rate of decay of the seismic signal recorded at local or regional distances is measured by an attenuation parameter called "coda Q." Temporal variations in coda-Q have been tested in various settings as a precursor. Recent work shows that the distribution of attenuation measured this way correlates well with seismicity, being low (high Q) in tectonically stable regions and high in young active areas. The temporal correlation is more complex, with cases of both higher and lower attenuation prior to a mainshock having been detected. The clustering of fractures before a mainshock may explain coda-Q changes, as well as seismicity precursors of various kinds.

The capability to determine rapidly the source parameters of large numbers of moderate to strong earthquakes, globally distributed, from broad-band digital seismograms has been put into routine use in the past few years. The large data base, containing consistently determined focal mechanisms, is valuable not only for general geodynamics research, but also for studies directed toward intermediate-term prediction.

Crustal deformation observations have been a key element in the Japanese prediction program from its beginning. Elevation changes observed on the Boso and Miura Peninsulas since 1923 have been interpreted in terms of subduction processes. This effort at "peninsula tectonics" suggests a periodic modulation of the secular variation, with a period of 19–20 years, and short-period variations related to time-dependent subduction processes. About 100 crustal deformation observatories use a variety of strainmeters and tiltmeters to monitor zones ofseismotectonic importance. The data are telemetered to the Earthquake Prediction Data Center at the Earthquake Research Institute, University of Tokyo. Data showing the subsidence of Omaezaki in the Tokai district since 1976 and uplift of the northeast sector of the Izu Peninsula since mid-1980 were displayed as products of leveling data analysis.

Work on non-seismological precursors to earthquakes, reported by Japanese participants, places more emphasis on fundamental studies than on correlations of anomalies with subsequent earthquakes. The investigation of resistivity, electrical potential, and geomagnetic anomalies in the neighborhood of faults are being carried out in an effort to clarify the role of groundwater in earthquake processes and in accounting for geoelectromagnetic changes that have been observed prior to some earthquakes.

Geochemical precursors, especially changes in radon concentration in groundwater, have been controversial and poorly understood (and often suspect) phenomena for a long time. No U.S. research on this topic was reported. One of the problems has been that observations at two sites at about the same distance from an epicenter might show an anomaly at one and not the other. Evidence of co-seismic and pre-seismic changes in radon concentration in a well or in soils on active faults in northeastern and southwestern Japan was presented. The observation of co-seismic changes in the well is not only interesting in itself, but the absence of any significant radon changes at another well about 50 km away on the same fault shows that, indeed, some wells are more sensitive than others to whatever produces the radon fluctuations. Such observations seem useful for identifying the best wells to use for future tests of the radon precursor hypothesis.

### Fault Physics and Instrumentation Development

Although many of the observational studies reviewed in the seminar have produced results that are important for understanding earthquake processes, few new theoretical results and no new laboratory findings were included. Two USGS papers considered fundamental aspects of faulting. One of these examined the role of fault creep, with emphasis on how creep acts to redistribute and concentrate stress around the strong points on the fault that ultimately fail to produce earthquakes. From the prediction viewpoint, an important conclusion is that intervals of time during which aseismic fault slip occurs should be regarded as periods of enhanced probability for an earthquake. The other study is part of a continuing effort to develop a comprehensive theory of earthquake nucleation, one that will account for the time dependence of foreshock and aftershock occurrence, as well as interevent times of mainshocks. An important suggestion from the work is that the duration of aftershock sequences are directly related to the recurrence time of mainshocks, a result that is supported by the data shown.

Development of new instruments is important for future progress in the two national prediction programs. The National Research Laboratory for Metrology, Tsukuba, has developed a facility for comparative performance tests of devices for geodetic measurements. Results from two years of operation of a laser extensometer and a laser distance measurement instrument in a specially prepared tunnel showed the close correspondence of the two, to within a few microstrains, but with an unexplained phase shift of about 48 days between the two sets of measurements. The multi-channel portable field unit that has been developed for the PASSCAL program of the Incorporated Research Institutions for Seismology was described and displayed.

Research on the social, economic, and political consequences of earthquake predictions has been underway in the U.S. from the earliest days of the prediction research program. A review of findings during the past 15 years revealed that long-term and short-term predictions, while eliciting different public responses, are not likely to have serious impacts on the target communities. Intermediate-term predictions (a few years) may have negative economic impacts, as well as positive effects.

### Future Plans

Plans for future prediction research efforts were discussed for the U.S. by R.L. Wesson, USGS, and for Japan by K. Ohtake, Geographical Survey Institute. The Sixth Earthquake Prediction Plan of Japan was presented to the Government very recently. The plan calls for a comprehensive program, in which observations and analysis will continue for specified Areas of Intensified Observation, with expanded efforts in both long-term and short-term prediction. The effort is to be supported by a variety of fundamental research studies, instrumentation development projects, and work on the prediction system.

The U.S. Five Year Plan, 1989–1993, for the National Earthquake Hazards Reduction Program was in the late stages of preparation at the time of the seminar. Therefore a less specific program plan was outlined. Instead "likely candidates for increased emphasis" during future years were put forward. These include geologic and seismologic studies for long-term prediction, geodetic measurements, borehole observations, rheology of faults zones, combined use of short-period and broad-band networks, and computer modeling of earthquake processes.

The participants came away from the seminar with a general feeling that, while there is very much work still to be done, especially on short-term predictions, much progress has been achieved in both national programs. Above all, there is no doubt as to the value to both countries of these more-or-less regularly scheduled opportunities for representatives of the active research communities to come together in a relaxed atmosphere, conducive to thorough airing of progress and problems.

Those contributing to the seminar were K. Aki (University of Southern California), H. Aoki (Nagoya University), W.H. Bakun (USGS), E.N. Bernard (NOAA/Pacific Marine Environmental Laboratory), A. Dainty (MIT), J.H. Dietrich (USGS), A.M. Dziewonski (Harvard University), W.L. Ellsworth (USGS), J. Fowler (Incorporated Research Institute for Seismology), F. Gonzalez (NOAA/PMEL), R.E. Habermann (NOAA/National Geophysical Data Center), Y. Hagiwara (University of Tokyo), K. Hamada (National Research Center for Disaster Prevention), A. Hasegawa (Tohoku University), T.H. Heaton (USGS), H. Ishii (University of Tokyo), D. Johnson (NSF), L.M. Jones (USGS), H. Kanamori (Caltech), Y. Kinugasa (Geological Survey of Japan), C. Kisslinger (University of Colorado), K.C. McNally (University of California, Santa Cruz), T. Mikumo (Kyoto University), D. Mileti (Colorado State University), K. Mogi (University of Tokyo), T. Oh'ishi (National Research Laboratory of Metrology), T. Ohtake (Geographical Survey Institute), Y. Okada (National Research Center for Disaster Prevention), K.E. Sieh (Caltech), L.R. Sykes (Columbia University), M. Tanaka (Geographical Survey Institute), W.R. Thatcher (USGS), K. Tsumura (JMA), H. Wakita (University of Tokyo), R. Wesson (USGS), T. Yukutake (University of Tokyo).

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# TER-QUA Climat Meeting

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Although the popular view is that the Earth is "warming up and drying out," tl present climate trend appears to be towa lower temperatures and more rain, accor to papers presented by Earth scientists wl met in Lincoln, Nebr., October 6–7.

Several speakers stated that actual data supporting the warming-up concept com from U.S. Weather Bureau stations, of w 97.5% are located in metropolitan areas where urban heat production is rising. Tl investigators found that the 2.5% rural st tions show a cooling history for the latest decades.

The participants were mostly geologists ographers, paleontologists, archeologists, others whose research is focused on the e fects (or results) of climate changes takin place at one time or another within the la 10–20 m.y.: the last portion of the Tertia period and all of the Quaternary period. Hence the name of the parent organizati TER-QUA. Many of these scientists are ir ested basically in the latest 100,000–150,0 years.

According to several of the speakers, th "greenhouse mechanism" is working very well—but not in the direction that many p ple have been assuming. The popular vie that industrial soot and gases collect in th mosphere, where they permit the passage incoming solar radiation but tend to block outbound heat losses. The result (if corre would be a warmer, drier climate, glacial melting, sea level rise, flooding of coastal ies, major crop failure, and widespread st vation.

Lee Smith, independent geologist (Hou ton, Tex.), observed in the opening paper that urban temperatures in the U.S. are ri ing because growing cities generate more heat than formerly, but that rural weathe stations show a cooling trend for the past years. He also reported that of 625 alpine glaciers checked periodically by the World Glacier Monitoring Service (Zurich, Switze land), a majority have been advancing sin the 1960s.

E. J. Zeller and G. Dreschhoff, polar sp cialists (University of Kansas, Lawrence), l been studying snow and ice layers from A arctica in order to collect evidence for changes in past solar activity. They report such evidence, for low solar activity in the years 1645–1715, for example, with well-known climate changes and noted that su changes were driven by natural causes.

William F. Tanner, coastal sedimentolog (Florida State University, Tallahassee), described coastal sediment sequences that de fine small sea level changes (about 1 m) ar hence probably climate changes, in the m recent 5000 years. The four most importa changes in that interval have been spaced 800–1000 years apart, all due to natural causes. The next one is due "any day" no he said, and apparently will be a sea level drop of roughly a meter.

Larry Martin, paleoecologist (University Kansas, Lawrence), pointed out that clima history on the Great Plains, over the last f tens of millions of years, has shown cycles