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Predicting Earthquakes: Science, Pseudoscience, and Public Policy Paradox

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Damaging earthquakes, while not frequent occurrences in the United States, cause great social disruption and economic loss. The Northridge, California, earthquake of January 1994, for example, was the most costly, damaging single disaster in the history of the United States. Although relatively few people were killed in the event (57), over 11,800 people received hospital treatment for earthquake-related injuries, while tens of thousands more went unattended. Segments of two major interstate freeways collapsed, resulting in several months of traffic nightmares for commuters and commercial trucking operations. An estimated 114,039 residential structures were damaged by the quake, 14,500 of which were unsafe for temporary or permanent occupancy. These damaged structures contained over 100,000 housing units; 30,000 were vacated or had significant structural damage, and another 30,000 were at risk of being removed from the building stock because of the expense of repairs (Comerio 1995). According to estimates from the California Governor's Office of Emergency Services (OES) in January 1996, approximately $25 billion in losses due solely to damaged structures and their contents had occurred. As of December 1995, 681,710 applications for state and federal disaster assistance had been received, more than double the amount in any previous single U.S. disaster. (The previous record for applications was 304,369 following Hurricane Hugo, which struck the Carolinas, Puerto Rico, and the Virgin Islands in 1989.) We have only to look at the Great Hanshin earthquake in Japan—one year later to the day—to see how an earthquake of only a slightly larger magnitude resulted in much greater losses (estimated at almost $100 billion) and caused much more serious social disruption, killing over 5,000 people, rendering almost 300,000 people homeless (over 10,000 of whom were still in temporary housing three years later), and creating industrial losses from which the region may take another decade to recover. And the August 1999 earthquake in western Turkey, which killed more than 17,000 people, demonstrates how utterly catastrophic a huge earthquake can be, especially in a region that is not adequately prepared.

Because many regions of the United States are exposed to earthquake hazards, and because few of the jurisdictions in those regions have incorporated seismic design into their building codes or have developed land-use plans that take seismic hazards into account, substantial national concern has developed about the vulnerability of our built environment to future seismic events, especially in major metropolitan areas. Because of its frequent experience with destructive earthquake events during the past century, the state of California has mandated certain types of earthquake preparedness and mitigation by its local governments, but it is clear that much more could be done. Without "reminders" like the Northridge quake that a region is at risk from a potentially dangerous threat, little policy activity is likely to take place, even though policy makers are aware of the hazard itself. There are always other, more commanding local problems—crime prevention, educational improvements, economic development, and job creation—that take precedence over seismic matters.

With valuable infrastructure and human lives at risk, scientists stepped forward in the early 1970s and offered to provide a short-term warning—of hours to days—that a destructive event was about to occur. While predictions could not save the built environment, the hope was that they could make it possible to evacuate buildings, shut down transportation systems, lower water levels in reservoirs, enable families to reassemble or to remain together, shut down production facilities safely, ready medical facilities, and put emergency response units on alert. The purpose of such warnings would be to lessen life loss, reduce secondary economic losses, and keep social disruption to a minimum. In areas outside of California where little seismic mitigation had taken place, prediction was often seen as a cost-effective response to a low-probability, high-consequence event. In California, prediction was seen as providing additional protection in a state that was actively trying to reduce its vulnerability.

The effectiveness of earthquake prediction as a tool for reducing earthquake impacts depends, in part, on developing community response plans that can be implemented when predictions are issued. The overarching policy issue—how to lessen earthquake losses to the built environment and social systems by disseminating forewarnings of future damaging earthquake events—has continued to be the focus of governmental efforts to deal with scientific forecasts, but the specific strategies considered have varied, often due to changes in scientific approaches to prediction.

This case study will trace the interwoven strands of scientific approaches and policy responses to earthquake predictions since the mid 1970s. The state of California has been the focus for concentrated research—in both earth science and social science—on earthquake prediction. Federal policy has played an important role in identifying priorities for both scientists and state and local government officials with respect to the impact of earthquake predictions on society.

Scientific Promise and Policy Response

Terminological Specification, Continuing Confusion

What is meant by the term *earthquake prediction?* Scientists have used a variety of words to describe their efforts to foretell earthquakes: a potential precursor (e.g., the Southern California uplift, popularly known as the Palmdale bulge), a hypothesis test, an experiment (e.g., the Parkfield segment of the San Andreas Fault throughout the 1980s), an earthquake watch (e.g., Parkfield), an earthquake advisory (e.g., the San Diego earthquake swarm), a forecast, a forewarning, and a heightened probability (e.g., San Francisco Bay Area and Southern California). These terms have usually been associated with legitimate scientific projections of future earthquake events; however, pseudoscientific predictions by amateur earthquake scientists (Henry Minturn for Los Angeles in 1976 and Iben Browning for the central United States in 1989) have also been issued using these same terms. Whether or not the source of or the basis for the announcement was scientifically "legitimate," policy makers and the general public have often responded similarly to these prediction events, regardless of what they were called.

In an attempt to clarify what would be desirable in a "credible" prediction from geoscientists, the Panel on Earthquake Prediction (1976) recommended that predictions from the scientific community should include six elements:

- *lead time*—a statement about how far in the future the earthquake will occur;
- *time window*—a statement about the time period, the dates between which the earthquake will occur;

- *magnitude*—a statement about the strength (measured on the Richter or similar scale) of the predicted earthquake;
- *location*—a statement of the geographical area in which the earthquake epicenter will occur;
- *impact*—a statement about the amount of damage that is likely to occur; and
- *probability*—a statement about the likelihood or confidence that the first five parameters will occur as specified.

However, by the early 1980s, members of the scientific community were already trying to retreat from this type of specificity, saying that predictions would be "messy" for years to come and that it was highly doubtful scientists would be able to meet these criteria. While it has been the intention of the earth science community to develop announcements that characterize a future event in these ways, it has been unable to do so. However, policy makers cannot wait until the ideal prediction can be formulated because they are faced with a variety of both legitimate and pseudoscientific forecasts of future (usually damaging) earthquake events for which they must prepare.

Advances in Prediction Science

Southern California residents were introduced to scientific accomplishments in the earthquake prediction field sporadically beginning in the early 1970s. Two examples illustrate the types of scientific advances that were being made and how the science of earthquake prediction was being portrayed to the lay public (including policy makers).

In November 1973, James Whitcomb, a geophysicist then at the California Institute of Technology, predicted a small quake in Southern California based on measured change in sound wave velocity as it traveled through subterranean rock layers. The prediction was considered semi-successful by scientific criteria because Whitcomb correctly identified the time period and area (San Bernardino—Riverside) of impact but not the magnitude (the actual event was smaller). One year later, two scientists from the United States Geological Survey (USGS), Malcolm Johnston and John Healy, were credited with accurately predicting that an earthquake of up to 5.0 magnitude would hit the Hollister area within a few days based on their review of magnetic field and tilt data. The next afternoon, a 5.2 earthquake occurred in Hollister. This accurate prediction was heralded in California newspapers as proof that scientists were on the verge of accurate earthquake predictions, including being able to predict time, location, and magnitude of coming quakes.

In the midst of this optimism, the USGS announced in 1974 that a substantial "uplift" had been discovered on a section of the San Andreas Fault in the Palmdale region of California's Mojave Desert. Similar phenomena had been observed prior to earthquakes in other parts of the world; and, given the large land area that the Southern California uplift covered, some scientists believed that it could be a precursor to a very large earthquake. Other scientists, however, called for intensified research in the area, because uplifts had also been discovered in other places that weren't accompanied by seismic activity. But the recognition of the Palmdale bulge focused public attention on the scientific efforts being made to forecast an earthquake in the not-too-distant future and on what could be done to lessen its impacts.

Throughout 1974 and 1975, the public was made aware of the experimental techniques and theories on earthquake prediction being used in Japan, the USSR, and China. The "successful" Haicheng prediction—made by the Chinese in February 1975 and credited with saving the lives of tens of thousands of people through widespread evacuation and precautionary measures—was touted as a significant contribution to prediction approaches (despite widespread scientific skepticism about this claim in the United States). Similarly, the Japanese were developing an earthquake prediction system, based on monitoring anomalies in Shizuoka prefecture, that included an automated warning system.

Then in April 1975, James Whitcomb, in a paper given at a scientific meeting, hypothesized that an earthquake in the 5.5–6.5 magnitude range could occur anytime within the next twelve months somewhere near the epicenter of the 1971 San Fernando earthquake. In the media, this hypothesis was referred to as a "prediction," a "forecast," and a "warning." A flurry of public attention followed this announcement, with both the public and state and local government officials trying to decide how to respond, especially since Whitcomb didn't want this situation portrayed as a "real" prediction but as the scientific experiment he believed it to be. This distinction was lost on a lay audience, including local policy makers trying to deal with public inquiries about what they would do about this prediction.

In early 1974, the National Academy of Sciences acknowledged the development of earthquake prediction studies and techniques and commissioned two panels to assess the scientific state-of-the-art (Panel on Earthquake Prediction 1976) and to provide an overview of the societal issues raised by earthquake predictions and of the potential social, economic, and political consequences that predictions might create (Panel on Public Policy Implications of Earthquake Prediction 1975). Both studies recognized that the science was still in its infancy and likely to be inaccurate for some time.

These efforts reflect the optimism of the early and mid-1970s and the expectation that scientific breakthroughs would allow predictions, at least in California, to be made within ten years.

The Formulation of a National Earthquake Policy

The scientific developments in California were taking place against a backdrop of destructive earthquake events that had substantial impacts on the national psyche. The 1971 San Fernando earthquake has been referred to as a "watershed" event in California. It was the strongest earthquake to strike an urban area in the United States in almost forty years; it damaged or destroyed structures that were thought to have been "earthquake-resistant" (i.e., constructed to withstand earthquakes); and it almost caused the collapse of the Van Norman Dam—the threat of which led to the evacuation of over 80,000 people for the several days it took to drain the reservoir. Had the dam failed during the earthquake, the resulting flood would have created the largest loss of life ever in the United States from a "natural" disaster.

During this period, earthquakes outside the United States also highlighted the damages and casualties that could result when a large-magnitude event hit a populated area—the earthquake in Guatemala City in February 1975, in which 23,000 people were killed and over a million left homeless; the earthquake in the Friuli region of Italy in May 1975, in which over fifty small towns were partially destroyed; and the two July 1975 earthquakes in the Tangshan region of China, which were estimated to have killed as many as 750,000 people and brought the heavily industrialized region to a complete standstill.

The California congressional delegation had introduced federal legislation aimed at providing funding for earthquake research in the mid-1970s, and the National Earthquake Hazards Reduction Act (P.L. 95-124) was finally passed in 1977 (and amended substantially in 1980). This act established the National Earthquake Hazards Reduction Program (NEHRP), making earthquakes the only natural hazard with a federal mandate to lessen their impacts.[1] One of the initial objectives of the act was:

> the implementation in all areas of high or moderate seismic risk, of a system (including personnel, technology, and procedures) for predicting damaging earthquakes and for identifying, evaluating, and accurately characterizing seismic hazards.

One of the specific research elements of the act required the "development of methods to predict the time, place, and magnitude of future earthquakes." The initial implementation of the act included the development of a plan for the "evaluation of prediction techniques and actual predictions of earthquakes" as well as "warning the residents of an area that an earthquake may occur." The 1980 amendments to the act referred to the importance of NEHRP's timely evaluation of predictions and the need to coordinate with state evaluation mechanisms (discussed below) in order to minimize confusion. From the passage of the act through the early 1980s, earthquake prediction was a major focus of NEHRP, and the USGS, which carried out the bulk of the prediction research, received by far the largest appropriation among the four federal NEHRP agencies.[2]

However, by the early 1980s, the USGS and the earth scientists involved in NEHRP were revising their optimism about their ability to make short-term earthquake predictions in the near future. In 1976, the Panel on Earthquake Prediction had written:

> The Panel unanimously believes that reliable earthquake prediction is an achievable goal. We will probably predict an earthquake of at least magnitude 5 in California within the next five years in a scientifically sound way and with a sufficiently small space and time uncertainty to allow public acceptance and effective response. A program for routine announcement of reliable predictions may be 10 or more years away. (p. 31)

But by 1983, the annual NEHRP report to Congress portrayed a different reality:

> Although significant progress has been made toward earthquake prediction, in general, a simple, highly reliable and universal formula for short-term prediction of earthquakes has not been found. (FEMA 1984, p. 35)

California Responds

As public and governmental interest in scientific information on earthquake prediction intensified in early 1975 and 1976, the Southern California media began to give much greater attention to prediction. State and local officials began to worry about what effects such announcements would have on the public and about how they would actually respond to these announcements. One well-known local politician in Los Angeles made the statement that a scientist shouldn't issue a prediction without being "100 percent certain" the earthquake would occur.

Other decision makers raised the concern that a prediction might actually cause greater harm to the local area than an earthquake, by causing people to "panic," property values to decline, and businesses and families to leave the area, some temporarily but others permanently.

Some social science research suggested the possibility of modest economic and social disruption (Haas and Mileti 1976, 1977). Other studies, however, concluded that this level of public disruption was unlikely (e.g., Turner et al. 1980; Kiecolt and Nigg 1982) and suggested that the public would more likely take a "wait and see" attitude and try to gather additional information to determine how to respond to such announcements.

Also, in response to the concerns about social disruption from a prediction announcement, state and local politicians and agencies began asking questions about what appropriate response should be made to prediction announcements. Part of their answer depended on how confident scientists were about the prediction (that is, on the level of probability attached to some future event), both in terms of theoretical development and the adequacy of data.

In order to provide this type of evaluation for public decision makers, the state of California established the California Earthquake Prediction Evaluation Council (CEPEC), chaired by the state geologist and consisting of government and university earth scientists. Based on CEPEC's assessment of a prediction, the governor would decide whether to mobilize state agencies and inform local municipalities. CEPEC was to function like a "science court," holding a hearing to review the scientific evidence on which a prediction was based and to determine whether there was an increased likelihood that an earthquake would occur during the predicted time window. CEPEC was to meet twice yearly to be updated by scientists about new techniques and theories and gain additional background information about forthcoming predictions. The establishment of CEPEC created a direct linkage between the earth scientists making and assessing predictions and decision makers responsible for public safety.

CEPEC was established early in 1975, principally because of the discovery of the Southern California uplift, and in mid-April of that year the council held its first hearing to review relevant scientific evidence. As a result of the hearing, CEPEC reported to the governor that a major earthquake could occur along the southern portion of the San Andreas Fault anytime within a decade, thus supporting the research of the USGS in this region. Although the CEPEC evalution was covered by the major media in Southern California, it seemed to provoke little public reaction. However, it did cause California's Seismic Safety Commission to issue an "advisory" to cities and counties in Southern California, encouraging them to enhance their earthquake preparedness and response planning.

Shortly after CEPEC's evaluation of the uplift, Caltech's James Whitcomb issued his "hypothesis test." Although the presentation of Whitcomb's prediction experiment was made to colleagues at a scientific meeting, it created much greater popular concern than the uplift, perhaps because it "fit" the more specific public expectation of what a prediction should be. For example, Whitcomb specified a time window of one year, as well as a magnitude range, for the event in a specific area of the Los Angeles basin. These factors made his prediction sound less ambiguous than the scientific information on the uplift, which came from a scientific organization (rather than a person), had a wide time window with an uncertain magnitude, and referred to a location in the Mojave Desert rather than an urban center (Turner, Nigg, and Paz 1986).

Public information-seeking was voracious after stories on Whitcomb were carried by the media. Both Caltech and USGS's Menlo Park office (in addition to local emergency management agencies) were inundated with requests about the meaning of the prediction and what people should be doing to protect themselves. Rumors also began to circulate during this period about actions that the government was supposedly taking (some of which were, incidentally, true) and about the likelihood that the earthquake would be larger than predicted.

In late April, CEPEC reconvened to consider Whitcomb's scientific evidence. On the basis of its review, the council concluded that the probability of an earthquake in the area Whitcomb identified was not significantly different than the average for similar geologic areas of California, although the council noted that the data were sufficiently suggestive to warrant Whitcomb's continued testing of his hypothesis.

The implications of this "cautious" evaluation for the general public were apparently ambiguous, with almost half of those who remembered hearing about the prediction still taking it "seriously" or "very seriously" a year later (Turner et al. 1986). For the state's Office of Emergency Services (OES) and the city of Los Angeles, however, there was a clear message: earthquake predictions are a fact of life and must be integrated into emergency planning processes. Later that year, the Southern California Earthquake Prediction Program (SCEPP) was established with funding from the Federal Emergency Management Agency (FEMA) to work with city and county governments to include prediction response in their earthquake preparedness planning.[3] The mayor of Los Angeles also established a blue ribbon Task Force on Earthquake Prediction in 1978 that met over the next five years, developing a draft of an earthquake prediction response plan in 1983 (Mattingly 1986). When the city of Los Angeles adopted a formal plan in 1989, it was the first local government in the country to have done so.

At the national level, federal legislation gave the director of the USGS the authority to issue an earthquake advisory or prediction to appropriate federal, state, and local government officials.[4] To support this authority, the USGS established the National Earthquake Prediction

Evaluation Council (NEPEC) in mid-1976. It was intended to provide the same function as CEPEC for regions outside of California and to coordinate with CEPEC when predictions were made for California.

Scientific and Policy Outcomes

The Parkfield "Experiment"—An Attempt at an Integrated Warning System

In the early 1980s, as earth scientists began to acknowledge that breakthroughs in earthquake prediction research were unlikely, they were also being pushed by Congress to develop a "prototype prediction network in Southern California" (FEMA 1983). Among the accomplishments identified in the 1982 NEHRP report to Congress was the recognition that earthquakes occur in "seismic cycles" on the southern San Andreas and that a "time-predictable" model was being developed to describe earthquake recurrence on a portion of the San Andreas near Parkfield, California.

In 1984, USGS scientists predicted, with 95 percent certainty, that a moderate earthquake (magnitude 5.0–6.0) would occur along the Parkfield segment of the San Andreas Fault between 1985 and 1993 (Bakun and Lindh 1985). This prediction was based on research that showed a twenty-two-year recurrence interval for moderate events along the Parkfield segment since the nineteenth century. The Parkfield prediction met all of the Panel on Earthquake Prediction's earlier criteria for a "true" prediction.

The area around Parkfield is quite rural, with sparse population and no engineered structures or multistoried buildings. This was a much different, simpler situation than a prediction targeted at a major metropolitan area. However, further analysis of the geologic data raised the concern that, on the basis of past events, an earthquake along the Parkfield segment could "trigger" a larger earthquake (of 6.5–7.0 magnitude) to the southeast along the San Andreas Fault, with potential impacts in seven highly populated counties covering a wide area of central California.

Because of this expanded concern about potential societal impacts, NEPEC evaluated the prediction in November 1984 and endorsed it as a "long-term" prediction; that is, the council concurred that there was sufficient scientific evidence that an earthquake in that area was likely to occur within the parameters specified. CEPEC, which was convened to review the prediction for the governor of California, issued a similar endorsement in February 1985. In concurrence with OES and the California Office of Mines and Geology, USGS issued the first public announcement of the prediction in April 1985 (Goltz 1985).

As this was the first officially endorsed earthquake prediction ever issued in the United States, OES contacted the four counties that could be most affected by a "triggered" earthquake to inform them of the prediction and to assure them that the state would be working with them on their response and warning plans.

OES initiated two policy activities related to the Parkfield prediction. First, in conjunction with the USGS, an imminent alert system was established, based on monitored geophysical activity—strain, tilt, fault creep, and foreshocks.[5] Based on predetermined levels of change in those measurements, alerts were to be sent to OES. The alert system provided for four levels of notification corresponding to increasing levels of probability of a shock within seventy-two hours. OES established different response criteria for each alert level and developed its own response plans (Office of Emergency Services 1990a, 1990b).

Second, OES began working with local jurisdictions in four of the at-risk counties, to prepare them to respond to the prediction. Two workshops were held for local officials in June and July of 1985 to inform them of the basis for the prediction and how the alert system would function. OES also hired a consultant to help the local governments draw up earthquake prediction response plans. These plans were to be developed for both a 6.0 and a 7.0 earthquake and for three time frames—long-term (which applied to the Parkfield prediction), short-term (days to hours), and very short-term (15–30 minutes) (e.g., Reitherman 1986a, 1986b).

From the system's inception in October 1985 through May 1987, forty level C and level D alerts (the two lowest levels) were issued to OES. Later, level A alerts, indicating a significant increase in the probability that a damaging earthquake was imminent, were issued on two occasions. The first, on October 19, 1992, expired three days later with no event occurring (Mileti and Fitzpatrick 1993). After the second level A alert in 1993 (also a false alarm), OES met with county emergency preparedness representatives to determine whether they wanted to continue with the experiment. They did. Procedures were then revised by OES to institutionalize the monitoring and alert processes.[6]

The original prediction period ended in 1993, but the interest of the scientific community is still focused on the Parkfield segment. Although the emergency management community saw this experiment as a way to establish a warning system for an imminent earthquake, the scientific community had always viewed it primarily as an effort "to trap a moderate earthquake within a densely instrumented network" (NEPEC Working Group 1994, p. 9), in order to better understand the last stages of the process that leads to an earthquake. For the scientific community, the experimental surveillance of the fault segment continues, although at a somewhat reduced level, in an effort to identify the types of measurable premonitory signals that indicate that an earthquake is about to occur.

The Parkfield experiment gave both the scientific and policy communities an opportunity to consider what the components of a warning system should consist of and how response systems should be developed. Sociological studies conducted during this period evaluated how successful the state had been in communicating earthquake risk and response information to the residents of the four-county area (Mileti, Farhar, and Fitzpatrick 1990; Mileti and Fitzpatrick 1993). These studies yielded advice on how to improve public information campaigns about earthquake hazards, predictions, and protective actions.

The scientific prediction experiment was a "failure" because an earthquake did not occur within the time window specified. But years of cooperation between scientists and the emergency management community forged significant links, at least at the state and federal levels. Unfortunately, as recent interviews with the chief county emergency managers show, the extent to which earthquake prediction response plans were actually incorporated into formal emergency response plans varied greatly among the four at-risk counties. One county had no special plan for responding to an earthquake prediction; another county had a plan, developed in 1988, but did not incorporate it into the county's formal emergency planning document; a third county added a section in its regular disaster response plans on responding to an earthquake prediction, but that was in 1993—the last year of the prediction window. Only one county took the Parkfield prediction seriously enough to conduct a prediction-response exercise and modify its response plan based on the results of the exercise.

The Browning Prediction

In the midst of the Parkfield prediction experiment, another earthquake prediction was made, this time for the New Madrid Fault in the central United States. This prediction differed from the Parkfield experiment in many ways, not the least of which was its repudiation by the scientific community. Nevertheless, the New Madrid Fault had been the site of huge earthquakes in 1811 and 1812, and the prediction of a new event attracted national attention in late 1989 and 1990. This was the first U.S. earthquake prediction outside of California for which NEPEC made a scientific assessment.

Iben Browning, a self-taught climatologist with a Ph.D. in zoology, ran a consulting business that predicted long-term climate trends and their impact on agricultural futures. In October 1989, Browning told attendees of an equipment manufacturing conference that a major earthquake could occur around December 2 or 3, 1990. This prediction attracted the attention of the Missouri Governor's Conference on Agriculture in early December 1989. Two of the region's largest newspapers ran stories on the prediction and also reported (incorrectly) that Browning had successfully predicted the October 1989 Loma Prieta, California, earthquake (Tierney 1994).

Although media attention was intermittent during the early part of 1990, it became increasingly more intense as December approached. By late summer and early fall, major national media stories about the prediction began to appear. While the news stories often pointed out that seismologists still considered it impossible to predict earthquakes, they also continued to give credit to Browning for earlier predictions. At the same time, the director of an earthquake information center at a university in the New Madrid region—a geologist—was quoted frequently in the local and national media as saying that he considered Browning to be highly credible, which created legitimacy for the prediction (Tierney 1994). Subsequent analyses of newspapers in the region found that throughout this period, stories were either neutral about Browning's credibility (Shipman, Fowler, and Shain 1991) or were supportive of his theory (Dearing and Kazmierczak 1991). This "sensational but cautious" approach to the prediction by the media gave it an aura of credibility.

Fueled by increasing media attention, public discussion and concern about the prediction also increased during the late fall. Intense public information-seeking about the meaning of the prediction *and* how to prepare for an earthquake overwhelmed emergency management agencies, the Red Cross, and universities in the region. Prior to this time, very low levels of earthquake preparedness had existed in the New Madrid region. Given this "window of opportunity," state and local emergency management agencies undertook a variety of activities to get information out to the public. Also, to illustrate the extent to which they were prepared to respond to an earthquake, some state emergency management agencies and local jurisdictions conducted earthquake response exercises during this period, some even in the week leading up to December 2. Unfortunately, these activities gave many people (including some local government and school officials) the mistaken impression that the prediction was being taken seriously by scientists, which further stoked public concern.

Fifteen years earlier, when a similar type of pseudoscientific prediction was announced in Southern California by Henry Minturn, the legitimate scientific community had been extremely reluctant to become involved in the issue (Turner et al. 1986), and this same reluctance was on display for the Browning prediction. As early as spring 1990, some of the state geologists in the region—who considered the prediction to be completely without scientific merit—attempted to have NEPEC undertake an evaluation in order to lessen public concern. NEPEC, however, resisted conducting a formal hearing on the prediction because its members mistakenly believed that by evaluating the prediction they would give it more credibility. Informally, the legitimate earth science community had already determined that the theory upon which the prediction was based was not valid, that the evidence Browning used was flimsy, and that Browning himself had no scientific credentials in the earth sciences arena; but it had issued no formal, countervailing statement. Much of the public, meanwhile, was apparently taking the prediction seriously, as indicated by increased information-seeking about protective measures, inquiries about and purchases of earthquake insurance, and the common decision to keep children out of school during the first week of December.[7] Finally, under congressional pressure, NEPEC convened in late fall 1990 and publicly issued a statement to the effect that no evidence existed that an earthquake was any more likely to occur in the New Madrid region in early December than at any other time (USGS 1990a).

This prediction "event" illustrates the complex relationship between a developing science, public understanding, and governmental policy responses. Perhaps most important, the mechanism established to provide legitimate assessments of scientific predictions, NEPEC, did not provide sufficient—or sufficiently timely—guidance to citizens who lived in an area of the country that was not earthquake prone, and who were not familiar with the developing science of earthquake prediction. NEPEC attempted to deal with this prediction in much the same way it dealt with approximately three hundred other less public predictions that had come to its attention since its inception—by not evaluating it because it was deemed unscientific (USGS 1993). Eventually, NEPEC recognized that it needed to respond to the *social*—rather than the scientific—significance of the Browning prediction by conducting a very public evaluation. But by then, much of the damage had already been done.[8]

Changes in Scientific Approaches to Forecasting Earthquakes

The failure of the Parkfield experiment ended optimism about scientific capabilities to provide short-term predictions. In fact, optimism had been declining for several years, as the earth science community investigated other ways to characterize the earthquake hazard for earthquake-threatened areas of the country. With the exception of the Parkfield experiment, by the mid-1980s scientific efforts had begun to shift to long-term "forecasts" (Ellsworth 1986) and "early-warning" systems (FEMA 1986).

Long-Term Forecasts

In the 1985 NEHRP report to Congress, the development of a short-term predictive capability was said to be "more difficult" than anticipated. As an alternative, a "second generation" approach was being taken toward earthquake prediction by closely monitoring localized segments of both the northern and southern San Andreas Fault where "heightened risks" were identified. Over the next few years, the reports to Congress rarely mentioned the term "prediction," except in reference to the Parkfield experiment, but substituted the terms "high, long-term seismic potential" or "heightened probabilities."

These efforts resulted in characterizing various segments of the San Andreas and other fault systems in Southern California and the San Francisco Bay area in terms of their likelihood of generating a certain magnitude earthquake within a given period of time. These forecasts (as they were routinely called) were long-term predictions; that is, they had no lead times but were instead characterized by time windows that started in the present and continued from one to several decades into the future. They were primarily based on calculations of recurrence intervals from historical records or field analyses. The results of these studies were displayed on maps in order to provide visual representations of high-hazard areas with respect to earthquake potential.

Interestingly, in 1990 the USGS took the lead in developing a lengthy supplement for the Sunday newspapers in the San Francisco Bay area to present to the public information on the revised probabilities for local faults (USGS 1990b). The USGS eventually enlisted the assistance of state emergency management officials as well as social scientists who had studied risk and warning communication. The supplement included a lay explanation of the earthquake hazard and the associated probabilities, as well as preparedness guidelines and references to local agencies for additional information. A similar brochure was released in Southern California in 1997.

This approach to forecasting earthquakes has diminished the concerns of local policy makers about the impact that short- and intermediate-term predictions may have on local citizens and economies. Predictions had the cognitive benefit of focusing a lay audience's attention on a specified threat—a place, a time, a magnitude—for which people could imagine likely consequences as well as protective actions. The longer-term forecasts—stating, for example, that there is a 50 percent chance of an earthquake sometime in the next twenty years along a particular fault segment—lack the drama necessary to capture public (and many local politicians') attention. These extremely wide time windows don't convey the same sense of urgency as does a "prediction." While such forecasts can lead to substantial localized efforts to mitigate earthquake risks (Bakun 1995), recent evidence from research conducted by Mileti and his colleagues in the San Francisco Bay Area and by the Disaster Research Center, both in the Bay Area and in Southern California (Nigg et al. 1996), indicates that such broad forecasts are not being used to make substantial improvements in mitigation. The general nature of the forecasts may be insufficiently threatening to mobilize local policy makers to take other than the most rudimentary steps (and usually those required by law) to lessen the vulnerability of their communities (until after an earthquake has occurred).

Early Warning Systems

A second approach currently being pursued by the earth science community is the development of earthquake "early warning systems" (Holden, Lee, and Reichle 1989). Contrary to what the name may imply, an early warning system does *not* function to predict a seismic event. Rather, it functions *after* an earthquake has begun, to warn distant communities that significant ground shaking will begin within seconds. Such a system takes advantage of the fact that an electronic signal transmitted by the warning system travels much faster than the seismic waves that propagate away from the epicenter of the quake. Thus, the farther away the community is from the epicenter, the longer the time between receipt of the transmitted warning and the arrival of the first ground motion.

Mexico developed and implemented a successful early warning system that in 1995 provided seventy-five seconds of notice to residents of Mexico City from an earthquake off the Pacific Coast, over three hundred miles away. Japan and Taiwan also have preliminary systems under development, and the Taiwan system was partially tested in the mid-1990s. Although such a system was first mentioned in the NEHRP report to Congress in 1985 (FEMA 1986), the United States did not devote extensive funding to early warning systems until after the Northridge earthquake. Currently, great efforts are being made to design telemetry systems and upgrade and integrate seismograph networks in Southern California, in order to provide early warning to the Los Angeles basin area of a major earthquake on the San Andreas Fault. To date, however, most effort has focused on the collection, interpretation, and transmission of earth science data—the technical assessment stage of a warning system. Social science research on the dissemination component for such a warning system has only recently begun. Caltech, with funding from FEMA, has commissioned a study to determine what can be done in less than sixty seconds that could save lives and lessen social disruption. Some major policy questions that have not yet been answered are: Who are the likely users of this information? Do they have the capability to use the information effectively? Will the information be transmitted to the general public? If so, for what purpose (what are people expected to do in these seconds)? Given the uncertainty associated with such a warning system, what are some of the problems associated with false alarms?[9] A key policy question is whether spending millions of dollars on the technical development of the warning system is justified by the social benefits expected from such an extremely short "warning period."

Prediction as a Basis for Policy—A Paradox

Scientific approaches to predicting damaging earthquakes in California have contributed to earthquake preparedness despite the failure to achieve a short- and intermediate-term predictive capability. This failure has also led earth scientists to develop alternative ways of providing information that can meet the basic NEHRP mission of reducing earthquake consequences. For example, the earth science community has enhanced the national seismic mapping program to provide each state with earthquake fault maps and some indication of the hazard associated with them. This was not one of the early goals of NEHRP but developed over time as the promise of prediction waned and federal legislators began to expect policy-relevant results from earth science (as opposed to the basic research studies that were funded during the early years of the program).

Public-policy makers have reacted to the promise of prediction capabilities by trying to develop response plans and communicate earthquake threat information more effectively to the general public. However, as the scientific strategies have changed to emphasize both long-term forecasts and instantaneous warnings, it seems that the concerns of public-policy makers have either waned (in the former case) or have yet to develop (in the latter). While we should not expect science to develop in an orderly or linear fashion, rapidly evolving scientific approaches to characterizing and responding to future earthquakes have resulted in reactive, and often short-lived, public policies that do not seem to have had any long-term programmatic effects. In this respect, earthquake prediction has been a disappointment in both science and policy.

On the other hand, the focus on earthquake prediction has had a positive, if indirect, impact on earthquake loss reduction policies, not just in California but in other earthquake-threatened areas across the country. Awareness of the earthquake threat among both the public and policy makers—kept alive in part by the promise of prediction—stimulated progress in reducing social and structural vulnerability to earthquakes. In fact, it was the prospect of predicting earthquakes that resulted in congressional action in 1977 to establish NEHRP, a program that has since contributed to significant reduction of earthquake risk and vulnerability throughout the nation. Another equally important benefit of the early emphasis on prediction was the opportunity for local, regional, and state governments to engage scientists in a discussion of probabilities, uncertainties, and the vagaries of geologic processes, while, at the same time, working with them to develop procedures that provided for quick consultation on potential precursory events and rapid warning notification systems. This close relation between scientists and decision makers has been critically important to the continued development of earthquake hazard mitigation policies, especially in California.

In this context, the Browning prediction is troublesome. In the mid-1980s, social science studies indicated low levels of public awareness of, and governmental preparedness for, an earthquake in the New Madrid Fault zone (Mushkatel and Nigg 1987). Today, however, there is a much wider appreciation of the seismic threat among the general public, and several midwestern states now have seismic elements in their building codes. The pseudoscientific Browning prediction unquestionably contributed to these desirable results.

We are left with a paradox. While earthquake prediction itself was not successful, the policies that resulted from its early, unfulfilled promise were. In considering linkages between scientific prediction and policy initiatives, such nonlinear, serendipitous outcomes should not be ignored. One could argue that because no one can accurately predict when and where an earthquake will occur, policy makers have had to consider and implement policies to actually reduce the vulnerability of the built environment. Yet one would hardly want to base earthquake hazard policies on the expectation that failed science—not to mention pseudoscience—will lead to beneficial societal outcomes. One can easily imagine a scenario in which failed predictions would lead to a backlash against both science and preparedness. Perhaps the wiser course would be for scientists not to predict success at predicting, and for policy makers to respond accordingly.

Notes

1. The "wind" community—those atmospheric scientists, engineers, and social scientists who are concerned with the effects of tornadoes, severe storms, and hurricanes—have been trying to get a similar federal program developed since the early 1980s, but they remain unsuccessful.
2. The four federal agencies identified to implement NEHRP, as specified in the 1980 amendments to the act, were the newly created Federal Emergency Management Agency (as lead agency among the four), the National Science Foundation (NSF), the U.S. Geologic Survey, and the National Bureau of Standards (now the National Institute of Standards and Technology).
3. Although SCEPP originally emphasized prediction, about a year after its founding the penultimate word of its name was changed to "Preparedness."
4. Federal legislation included the Disaster Relief Act of 1974 and the Earthquake Hazards Reduction Act of 1977 and its 1980 amendments.
5. Both the USGS and the State of California invested substantial funding—approximately $1 million each—in instrumenting and monitoring the Parkfield segment of the fault beginning in 1985. NSF sponsored additional, academic research projects in that area.
6. I would like to thank an anonymous reviewer of this chapter for this insight on the process.
7. For a discussion of how Southern California responded to the pseudoscientific prediction by Henry Minturn of an earthquake for December 1975, see Nigg 1982.
8. For an example of a NEPEC evaluation of a scientific prediction involving U.S. scientists in another country, see Olson, Podesta, and Nigg 1989.
9. For example, some electrical and gas utility companies believe that this type of information could allow them to automatically shift loads and switch off service to potentially affected areas; however, any assessment of the usefulness of this very short-term alert system will also have to investigate the

time needed to bring these systems back on line, and the effect of such delay, especially in areas that are not damaged by the event.

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