Geophys. J. Int. (1997) **131**, 425–450

SPECIAL SECTION—ASSESSMENT OF SCHEMES FOR EARTHQUAKE PREDICTION

Earthquake prediction: a critical review

Robert J. Geller

Department of Earth and Planetary Physics, Faculty of Science, Tokyo University, Yayoi 2-11-16, Bunkyo-ku, Tokyo 113, Japan.
E-mail: bob@global.geoph.s.u-tokyo.ac.jp

Accepted 1997 August 15. Received 1997 August 8; in original form 1997 April 24

SUMMARY

Earthquake prediction research has been conducted for over 100 years with no obvious successes. Claims of breakthroughs have failed to withstand scrutiny. Extensive searches have failed to find reliable precursors. Theoretical work suggests that faulting is a non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocentre. Any small earthquake thus has some probability of cascading into a large event. Reliable issuing of alarms of imminent large earthquakes appears to be effectively impossible.

Key word: Earthquake prediction.

'Should a technical issue ever be considered to have real news value, the mass media will provide the publicity. Such instances are relatively rare, and the favored topics tend to be alleged breakthroughs that may perhaps lead to a cure for cancer, or more exact prediction of earthquakes, or greatly improved crop yields. Such stories usually include interviews with, or quotes from, the researchers concerned. The possibility of such exposure is almost irresistibly alluring to scientists.'

—Felix Franks 1981. *Polywater*, MIT Press, pp. 126–127.

1 INTRODUCTION

This paper reviews research aimed at the prediction of imminent future earthquakes. Wood & Gutenberg (1935), Macelwane (1946), Allen (1976) and Kanamori (1996) reserve 'earthquake prediction' for warnings (at most a few days in advance) that would permit measures such as evacuation. As the public and media associate 'prediction' with such alarms, terms such as 'long-term prediction' engender confusion. Nevertheless, some researchers (e.g. Wallace, Davis & McNally 1984; Kisslinger 1989) use 'short-term', 'intermediate-term' and 'long-term' prediction to denote windows of up to a few weeks, a few weeks to a few years, and a few years to a few decades, respectively. Such researchers might think the title of this paper should be 'Short-term earthquake prediction: a critical review'. Longer-term forecasts are reviewed in this issue by Kagan (1997a).

Allen (1976) notes that predictions should be based on a scientific hypothesis, should be accessible and well documented, and should specify: (1) the time window; (2) the spatial window; (3) the magnitude window; (4) the author's level of confidence in the prediction; and (5) the chances of the earthquake's happening anyway, as a random event. The magnitude scale and location data being used to evaluate the prediction must also be specified. Other authorities (Allen *et al.* 1976; Guidelines for Earthquake Predictors 1983; Evison 1984) give basically similar definitions.

2 120 YEARS OF PREDICTION RESEARCH

2.1 Research before 1960

Milne (1880) noted that 'Ever since seismology has been studied one of the chief aims of its students has been to discover some means which would enable them to foretell the coming of an earthquake ....' Milne discussed possible precursors, including weather conditions, animal behaviour, electrical effects, earthquake lights, earth tides, changes in the temperature of hot springs and microearthquakes.

After the Nobi, Japan, earthquake of 1891, the Imperial Earthquake Investigation Committee was founded (Hobbs 1907, pp. 308–310). Its members 'attacked with every resource at their command the various problems bearing on earthquake prediction, such as earth tiltings and earth pulsations, variation in the elements of terrestrial magnetism, variation in underground temperatures, variation in latitude, secular variation in topography, etc., but satisfactory results were not obtained' (Imamura 1937).

Milne (1911a) noted that prediction could secure public support, and hence funding, for seismology:

'What the public imagine they would like to know about an earthquake is the time at which it might occur. If this could be stated, and at the same time something about the character of the expected disturbance in earthquake districts, seismology would be liberally supported.'

Gilbert (1909) discussed prediction in his presidential address to the American Association of Geographers. Reid (1910, p. 31) discussed prospects for prediction:

'As strains always precede the rupture and as the strains are sufficiently great to be easily detected before the rupture occurs, in order to foresee tectonic earthquakes it is merely necessary to devise a method of determining the existence of the strains .... To measure the growth of strains, we should build a line of piers, say a kilometer apart, at right angles to the ... fault .... if the surface becomes strained through an angle of about 1/2000, we should expect a strong shock ....'

Hodgson (1923) and Landsberg (1935) also advocated prediction research. Imamura (1937, p. 346) stated:

'... there are some who declare that the prediction of earthquakes is impossible, but the author does not share in such an idea. Comparing the state of our present knowledge with that of, say, 30 or 40 years ago, it cannot be denied that we are nearer to making practical predictions than we were then. We think that it can at least be said that, though yet very remote, we are steadily advancing toward that desired end.'

However, Macelwane (1946) stated:

'Is it possible, in the present state of scientific knowledge, to predict earthquakes ... ? Unfortunately, no! All reputable seismologists agree that we have no means at the present time of arriving at a reliable forecast of any earthquake anywhere. The problem of earthquake forecasting has been under intensive investigation in California and elsewhere for some forty years; and we seem to be no nearer a solution of the problem than we were in the beginning. In fact the outlook is much less hopeful.'

de Montalk (1934), Wood & Gutenberg (1935), and Richter (1958, pp. 385–387) also expressed pessimistic opinions.

During the period 1910–1960 several geodetic surveys tried to detect premonitory strain (Richter 1958, pp. 191–195). Claims of luminous phenomena associated with earthquakes (Milne 1911b; Terada 1931; Anonymous 1931a, 1932a,b; Aziz 1942), possible or hypothetical geodetic precursors (Anonymous 1912, 1922, 1927, 1931b; Reid 1920; Evans 1923, 1927; Twyman 1935; Sassa & Nishimura 1951; Nishimura & Hosoyama 1953) and precursory anomalous animal behaviour (Anonymous 1933a,b) were also discussed. Geller (1991a) was unaware of the above research when he wrote:

'The empirical approach [to earthquake prediction] depends on the existence of reliably measurable and unambiguously identifiable precursors. There might arguably have been reasons for supposing, in 1962, that such precursors existed, but there no longer is room for such a belief.'

2.2 Prediction proposals after 1960

The 'Blueprint' (Tsuboi, Wadati & Hagiwara 1962), the basis for Japan's prediction program, said:

'... it seems highly probable that we would be able to find some significant correlation between earthquake occurrence and observed phenomena merely by accumulating data for several years.'

An Ad Hoc Committee in the United States (Press *et al.* 1965) proposed a large-scale empirical search for precursors:

'It is possible that some degree of earthquake forecasting can be achieved with imperfect understanding of the physical mechanism (the prediction of weather, tides, and volcanic eruptions, are examples). For this reason a major program of "instrumenting" seismic belts is an essential feature of our recommended program. Absolute stress would be determined and regional and local strains, tilts, microseismicity (i.e., the statistics of the numerous small earthquakes), and gravitational and magnetic fields would be monitored continuously at many locations in the seismic belt. Coherence between variations in these processes would be examined together with possible correlations with the occurrence of larger earthquakes. There is enough experience to indicate that one or more of these techniques could be significant in a prediction scheme.'

Press & Brace (1966) described the proposals of the Ad Hoc Committee:

'... it seems obvious that a major feature of such a program would be the monitoring, with the greatest achievable sensitivity, of all possible indicators foretelling the occurrence of earthquakes. Networks of instruments would be deployed in seismic belts and would be operated continuously over long periods of time in such a way as to provide the greatest possible likelihood that many earthquakes would be "trapped" within the arrays. Although this is essentially an empirical and somewhat wasteful approach, the absence of a confirmed theory for the earthquake mechanism justifies it.'

News articles in *Science* (Walsh 1965; Carter 1966) discussed the report of the Ad Hoc committee.

There was optimism about the time required. The Japanese Blueprint (Tsuboi *et al.* 1962) said:

'Now, when will earthquake prediction become possible and an efficient forewarning service be available? This question cannot be answered now. But if we start the project presented here we should be able to answer the question with sufficient certainty within ten years.'

However, the above question has not yet been answered. K. Mogi, Chairman of Japan's Earthquake Assessment Committee (Section 5.2), said (*Asahi Shinbun* newspaper, 25 February 1994, evening edition, author's translation):

'Earthquake prediction is a 100-year national project. In a small and seismically active country like Japan, there is no place to escape from earthquakes. Even if there are no immediate results, the earthquake prediction programme must not be discontinued.'

A panel of the US National Research Council (Allen *et al.* 1976, p. 3) made the following recommendation:

'*The United States should now make a national commitment to a long-term program aimed at developing a reliable and effective operational earthquake-prediction capability.* Based on an assessment of worldwide observations and findings over the past few years it is the panel's unanimous opinion that the development of an effective earthquake-prediction capability is an achievable goal. In recent years several isolated earthquakes have been successfully predicted by scientific criteria. These results and other studies indicate that with appropriate commitment and level of effort, the routine announcement of reliable predictions may be possible within ten years in well-instrumented areas, although very large earthquakes may present a particularly difficult problem. A truly effective national program will require a significant increase to several times the current annual expenditure for prediction research. If the 10-year research effort is successful, subsequent implementation of the resulting earthquake prediction capability for all seismic areas of the United States and on a continuing basis, will require a comparable national commitment.' (Italics as per original in all quotations in this paper.)

Hanks (1985) said:

'The many accomplishments of the [U.S. National Earthquake Hazards Reduction Program], then, have brought us to the edge of earthquake prediction on short time scales. They clearly point to the next step of intensively focusing on areas specifically identified as candidates for significant earthquakes, with experiments requiring substantial investments in intellect and funding. Until such experiments progress to their logical conclusion, we will not know whether short-term earthquake prediction is feasible or not. In the meantime, there is much to do.'

In contrast, Jordan (1997), the chairman of a committee comparable to that of Allen *et al.* (1976), recently wrote:

'... we still don't know how to answer the question, "Which types of earthquakes, if any, are short-term predictable?" Having said that, we can hardly maintain an optimistic attitude towards the feasibility of deterministic prediction, at least in the short term.'

2.3 Mid-1970s optimism

Alsop & Oliver (1969) wrote:

'Within recent years scientists in several countries, particularly Japan, the Soviet Union, and perhaps to a lesser extent the United States, have increased their efforts to understand the earthquake mechanism with the goals of earthquake prediction and even earthquake prevention or control, among others. At present the situation is very promising.'

Pakiser *et al.* (1969), writing in *Science*, were optimistic about both prediction and control of earthquakes:

'It seems reasonable to hope that short-range prediction of earthquakes (on the order of hours or days) may be achieved through *continuous* monitoring of ground tilt, strain, seismic activity, and possibly fluctuations in the earth's magnetic field ... . Short-range prediction capability cannot be obtained, however, in the absence of accelerating research on earthquake prediction along the general lines [proposed by Press & Brace 1966] ....

'It has been demonstrated that earthquakes can be artificially triggered by fluid injection ..., and also that many earthquakes in California and Nevada occur at depths accessible to the drill. We can soberly conclude from these observations that it may be possible to develop a practical method for artificially dislodging locked sections of a major fault and to induce steady creep or periodic release of accumulating elastic strain energy along the fault to inhibit the natural accumulation of sufficient energy to produce a disastrous earthquake [King 1969].'

Hammond (1971) and Raleigh, Healy & Bredehoeft (1976) also discussed prospects for earthquake control.

The advent of plate tectonics was cited as a reason for optimism about prediction (Healy & Pakiser 1971):

'Our optimism about the possibility of earthquake prediction stems not from the construction of some new instrument or system that will tell us the exact time and place of some large future earthquake, but rather from the startling advances within seismology and related sciences. The increasingly close relation among seismology, rock mechanics, and geology and the tremendous recent impact that the concept of plate tectonics has had on the earth sciences are the real bases for optimism about earthquake prediction.

...

'If the ideas outlined above are basically correct (the evidence supports them), the problem of earthquake prediction in California is nearly solved, even though there may be great technical and engineering difficulties in implementing a useful prediction system.'

Nersesov (1970), discussing work in the Garm region of the (then) Tadzhik SSR, said:

'After we had succeeded in identifying average characteristics of velocity relationships in a volume, we attempted to study the behaviour of velocity relationships in time. It was found that in every case of an earthquake in the 12th or 13th class (M=4.5, 5.25) there occurs in its preparation area an anomalous change in velocity relationships of longitudinal and transverse waves. The law observed in that case was as follows: the stronger the earthquake, the longer the volume persists in an anomalous state ....'

Soviet prediction research is also discussed by Savarensky (1968), Sadovsky *et al.* (1972), Sadovsky & Nersesov (1974), Anonymous (1975a), Dieterich & Brace (1975), Savarenskij & Nersesov (1978), Simpson (1979), Spall (1979, 1980) and Myachkin *et al.* (1986).

Scholz, Sykes & Aggarwal (1973) wrote in *Science* that:

'Earthquake prediction, an old and elusive goal of seismologists and astrologers alike, appears to be on the verge of practical reality as a result of recent advances in the earth and materials sciences.

...

'A variety of effects premonitory to earthquakes such as crustal movements and anomalous changes in such phenomena as tilt, fluid pressure, electrical and magnetic fields, radon emission, the frequency of occurrence of small local earthquakes, and the ratio of the number of small to large shocks have been observed before various earthquakes ... . Vigorous programs to monitor premonitory effects, particularly those in Japan and the U.S.S.R. during the last 5 to 10 years, leave little doubt that such effects are real.'

A news story in *Nature* (Smith 1975a) said:

'The United States Geological Survey claims that "significant progress" was made towards earthquake prediction when scientists at the National Center for Earthquake Research in California managed to anticipate a moderate shock which took place on November 28 last year. This event, which had a magnitude of 5.2, occurred between the San Andreas and Calaveras faults about 16 km north of Hollister, California.

'Prediction was based largely on precursory deformation of the Earth's crust and changes in the magnetic field. Crustal tilting was first observed about 4 weeks before the earthquake at two locations near what was to be the epicentre. But a "dramatic anomaly" in the geomagnetic field in the epicentral region was spotted about 6 weeks ahead. Later analysis of recorded seismic data showed that premonitory variations in seismic wave velocity had also occurred.'

The headline of an article by Press (1975a) declared that:

'Recent technical advances have brought [the] long-sought goal [of earthquake prediction] within reach. With adequate funding several countries, including the U.S., could achieve reliable long-term and short-term forecasts in a decade.'

The peaks of optimism were sessions at the Spring meeting of the American Geophysical Union (AGU) in 1973 (Lubkin 1973; Hammond 1973a) and 1974 (Hammond 1974). Prediction research was reviewed by Kisslinger (1974) in *Physics Today*. Prediction was covered extensively and in a generally optimistic light during the period 1972–1975 in *Nature* (Anonymous 1972a, 1973a,b,c, 1974; Davies 1973, 1974; Smith 1974a,b, 1975a,b,c) and *Science* (Abelson 1973; Hammond 1973a,b, 1974, 1975). Hammond (1975) wrote:

'Earthquake prediction is becoming a scientific reality at a rate that demands serious consideration of operational warning systems and procedures to handle the social consequences of prediction.'

Hamilton (1974) said:

'The ability to predict the time, location and magnitude of seismic events presents earth scientists with an opportunity to help alleviate the ravages of earthquakes. The prediction capability is developing much more rapidly than all but a few scientists believed possible.'

Brace (1975) said:

'... earthquake prediction is now a field with a great deal of scientific momentum, and those involved are optimistic about not only predicting but also controlling earthquakes.'

A cover story in *Time* (1 September 1975) entitled 'Forecast: Earthquake' was also optimistic:

'Recently, in fact, U.S. and Russian seismologists have quietly—and correctly—forecast several other earthquakes. In China, where the understanding of earthquakes has become an important national goal, ten quakes are said to have been accurately predicted in the past ten years. Before two large recent quakes, the government confidently issued public warnings and evacuated vulnerable areas. Buoyed by their rapid progress in forecasting, scientists are already talking about an even more exciting possibility: actually taming the more destructive convulsions of the earth.'

At a public meeting in 1975 (US Geological Survey 1976), R. M. Hamilton, Chief of the Office of Earthquake Studies of the USGS, said:

'The September 1, 1975 issue of *Time* magazine focused national attention on the rapid progress that has been made in recent years toward earthquake prediction. The *Time* cover story accurately reflects the mood of optimism that currently pervades the scientific community. It also highlights the many scientific problems that remain to be solved before, and the many socioeconomic problems that must be dealt with after, earthquake prediction becomes a reality.'

Press (1975b), writing in the *New York Times* newspaper, called for increased funding:

'Despite this extraordinary progress, I believe the U.S. program is insufficiently supported to make prediction a reality within the next decade. With the present level of funding, many potentially important methods cannot be tested. Even now, more data are being accumulated than can be digested, a matter easily rectified if a large computer were provided. The universities and industry, which is where much research talent resides, are insufficiently involved because of a lack of funds. An additional $30 million dollars per year could make prediction within a decade a realistic goal.'

Brune (1974) was pessimistic:

'The general mechanical model for earthquake prediction is consistent with modern concepts. Unfortunately, it contains within it a possibly severe constraint on the accuracy of any prediction scheme: earthquakes represent a critical-limit phenomenon and might be triggered by a wide variety of effects such as atmospheric loading, tidal strains, nearby small and unpredictable earthquakes, unpredictable creep events in the mantle or shallow crust, or hopefully by the episodic and observable increase in tectonic strain.

'In critical-limit phenomena, the accuracy and reliability of predictions depend on the complexity of the system. Repeated stick-slip events along a smooth saw cut in the laboratory, or in a very small and isolated area of the crust, might be quite predictable, whereas in a complex tectonic situation ... with unknown effects of episodic creep at depth or on adjacent fault zones and with a host of different phenomena causing small perturbations in the strain field, the achievable prediction scheme might be quite probabilistic.

'One hope for earthquake prediction is based on finding reliable precursory phenomena. A systematic search for such phenomena associated with large earthquakes is just beginning. Less systematic searches have been carried out for almost 100 years with no reliable result ....

...

'A model at the opposite extreme from the causal precursory model is the probabilistic model in which large earthquakes are triggered off by smaller earthquakes; these in turn are triggered by unobservably small and localized strain changes. This model is suggested by the fact that many large earthquakes appear to be multiple events in which the initial events are small compared with later events (Wyss & Brune 1967). Distant triggering of small fault slips by moderate earthquakes has been suggested for the Borrego Mountain earthquake of 1968 (Allen *et al.* 1968) and the Point Mugu earthquake of 1973 (Ellsworth *et al.* 1973).

'In the case of the Alaska earthquake the initial event in the series had a magnitude of only about 6.6 and occurred at the edge of the subsequent rupture zone at considerable depth. Accurate prediction of the Alaska earthquake would have depended on predicting this moderate event as well as knowing that the main rupture zone was in a state of strain that would allow it to be triggered by this particular event and not by the numerous events that preceded it. ... '

Leary (1997) presents similar arguments. Remote triggering was observed at distances of over 1000 km after the 1992 Landers, California, earthquake (Hill *et al.* 1993).

The mid-1970s optimism was not sustained by further research. Kerr (1978) reported:

'A few years ago, the scientific community was optimistic, even euphoric, in the wake of several successful predictions of earthquakes around the world. Today, that euphoria is gone. The optimism has not given way to pessimism, but, as one administrator puts it, "There's a long, hard road ahead." '

See also Kerr (1979a).

Allen (1982) commented as follows:

'In my opinion, we must face up to the fact that our progress during the past 5 yr in short-term earthquake prediction has not been as rapid as we had envisaged when the program started ... no plethora of precursors has been claimed. Indeed, some of the results have been downright discouraging .... But let us continue to be honest with our funding agencies, Congress, and the public. To some degree, we in the seismological community have been guilty of allowing the public to conclude that short-term earthquake prediction is more imminent than most of us really believe.'

Evernden (1982) said:

'Adopting out of necessity a definition of "earthquake prediction" which stresses short-term warnings (months, weeks, days, and hours), I must conclude that either we are doing the wrong things or such predictions may be impossible.'

See also McNally (1982) and Raleigh (1982).

2.4 Claims of temporal changes in velocity

Semenov (1969), Nersesov (1970), Sadovsky *et al.* (1972), Sadovsky & Nersesov (1974), Aggarwal *et al.* (1973, 1975), Whitcomb, Garmany & Anderson (1973), Wyss & Holcomb (1973), Wyss (1975a), Iizuka (1976) and Wesson *et al.* (1977), among others, claimed that seismic-wave velocities (or related quantities) decreased by 10–20 per cent and then recovered, and that this recovery signalled an impending earthquake. These reports were based on earthquake traveltime data. Data from such studies are shown in Fig. 1. It is hard to see clear evidence of a signal.

Nur (1972), Scholz *et al.* (1973), Whitcomb *et al.* (1973), Anderson & Whitcomb (1975) and Griggs *et al.* (1975) proposed that dilatancy (an increase in volume prior to failure) could explain the above reports. Scholz *et al.* (1973) said:

'The dilatancy responsible for the v_P/v_S anomaly observed to precede earthquakes will by its nature manifest itself in other changes in the source region, many of which may be readily observable. In recent years much effort has been devoted to finding precursors to earthquakes, and many diverse phenomena have been observed.'

Robinson, Wesson & Ellsworth (1974) suggested that 'a sharp increase' of *P*-wave velocity about two months before an $M=5.0$ earthquake was due to dilatancy. However, Lindh, Lockner & Lee (1978) showed that this was an artefact.

Several studies used controlled sources (quarry explosions) rather than earthquakes. Allen & Helmberger (1973) found no significant variations (Fig. 1, lower right). McEvilly & Johnson (1973, 1974) found temporal variations of at most 1 per cent, which could be explained without invoking *in situ* changes. Kanamori & Fuis (1976) found temporal variations of the order of at most 1 per cent. Recent studies (e.g. Leary & Malin 1982; Haase, Shearer & Aster 1995) place even smaller bounds on *in situ* temporal variations.

Aggarwal *et al.* (1975) reported late arrivals (by 0.13 s, corresponding to 0.04 mm on the smoked-paper record) from quarry explosions concurrent with a low in t_s/t_p in earthquake data. However, this may be at the noise threshold.

Whitcomb (1976) reported a velocity anomaly beneath the Transverse Ranges in southern California. This was reported

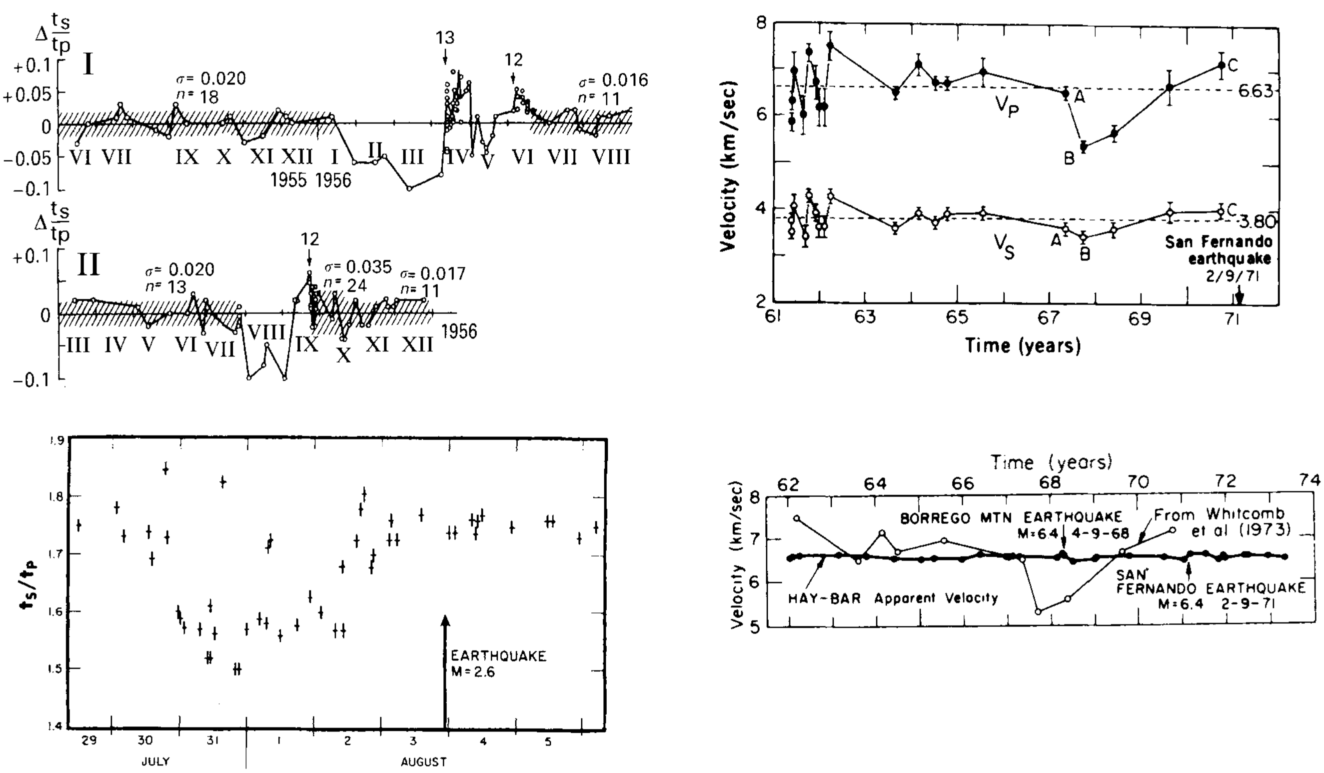

Figure 1. Searches for temporal variations of seismic velocities. All data other than in lower-right panel are for earthquake sources. Upper left: data from the Garm region (Semenov 1969). Lower left: data before and after 1973 August 3 Blue Mountain Lake, New York ($M=2.6$) earthquake (Aggarwal *et al.* 1975). Upper right: data for southern California (Whitcomb *et al.* 1973). Lower right: thick line shows apparent velocity data for controlled sources (quarry explosions) in southern California (Allen & Helmberger 1973); thin line shows *P*-wave data from upper-right figure. The controlled-source data show no notable temporal variation. Copyrighted material reproduced with the permission of the American Geophysical Union (top left, bottom left), American Association for the Advancement of Science (top right) and the School of Earth Sciences, Stanford University (bottom right).

in *Science* (Shapley 1976a; Hammond 1976) as a prediction of an event with $M=5.5$–6.5. No such event occurred. Turner, Nigg & Paz (1986) discussed public reaction.

Reports of 10–20 per cent velocity changes have ceased since about 1980. However, Scholz (1997) suggested that rejection of the dilatancy–diffusion model may have been premature:

'... several tests were made [in California] to detect one of the precursors predicted by the dilatancy–diffusion theory. These tests—which were made on magnitude 5-ish earthquakes and were carried out, in my view, rather desultorily—produced negative results. Though none too conclusive, these results were accepted by consensus as deeming the failure of both the theory and of that particular form of earthquake precursor, neither of which has been seriously investigated since.'

2.5 Prediction research 1962–1997

Many symposia, special issues or sections, etc., have been wholly or partly devoted to prediction or precursors (Box 1). The 1971 Moscow symposium, 'Forerunners of Strong Earthquakes' (Savarensky 1972; Sadovsky *et al.* 1972), had a strong impact. Anonymous (1972b) said:

'The scope of the Soviet program in earthquake prediction research, not previously widely known, was impressive to many attending the symposium.'

A symposium sponsored by the US National Academy of Sciences, 'Earthquake Prediction: the Scientific Challenge' (Knopoff *et al.* 1996), provides a benchmark on current research. The Chairman (Knopoff 1996) said:

'It is a certainty that the problems of societal response and engineering response to earthquake predictions are not going to be solved until the scientific problems can be brought under control. These are no more difficult than they were several decades ago; they are only more clearly defined today. We recognize today that the scientific problems are not simple.'

Reviews (Suzuki 1982; Turcotte 1991) and US national reports (Healy & Pakiser 1971; Healy 1975; Kisslinger & Wyss 1975; Ward 1979; Wyss 1983; Bakun 1987; Agnew & Ellsworth 1991; Aki 1995) provide useful overviews.

3 DO 'PRECURSORS' EXIST?

'It is possible to find the truth without controls, but the process has been demonstrated again and again to be notably inefficient, so that years may be required before it is appreciated that a given treatment is worthless .... If one doubts the necessity for controls, reflect on the following statement: "It has been conclusively demonstrated by hundreds of experiments that the beating of tom-toms will restore the sun after an eclipse." '

—E. B. Wilson, 1952. *An Introduction to Scientific Research*, p. 41.

Thousands of observations (seismological, geodetic, hydrological, geochemical, electromagnetic, animal behaviour and so on) have been claimed as precursors after earthquakes have occurred (e.g. Rikitake 1975, 1976, 1987, 1988; Koizumi

Box 1. Conferences, special issues, etc. wholly or partly on earthquake prediction.
Oliver (1964); Oliver (1966); Rikitake (1968); Alsop & Oliver (1969); Rikitake (1970); Anonymous (1972b), Savarensky (1972); Lubkin (1973), Hammond (1973a); Kovach & Nur (1973); Kisslinger & Rikitake (1974); Rikitake (1974a); Hammond (1974); Wyss (1975b); Smith (1976); Logan (1977), Reasenberg (1978); Lapwood (1977), Suzuki & Kisslinger (1977a,b); Norman (1977); Adams (1977); Spence & Pakiser (1978); Hanks & Kanamori (1979); Vogel (1979); Wyss (1979); UNESCO (1979), Rikitake (1984): King (1980); Simpson (1980), Simpson & Richards (1981); King (1981); Rundle & McNutt (1981); Rikitake (1981a); Hales & Suzuki (1982); McEvilly (1982); Asada (1982) (see review by Kisslinger 1983); UNDRO (1983); Kisslinger (1984), Kisslinger & Rikitake (1985); Shimazaki & Wakita (1986); Shimazaki & Stuart (1984/1985); King (1984, 1984/1985); Berckhemer (1985); Rao (1985); Russ & Johnson (1985); Varotsos & Alexopoulos (1986, p. 410), Tazieff (1992, p. 132); King (1986); Kulhánek (1988); Guha & Patwardhan (1988) (see review by Rikitake 1991); Stuart & Aki (1988); Crampin (1988); Kisslinger, Mikumo & Kanamori (1988); Johnston & Parrot (1989), Berry (1989), Evison (1989); Keilis-Borok (1990); Wyss (1991a); Dragoni & Boschi (1992); Boulanger & Vyskočil (1992); Mikumo *et al.* (1992); Park (1992), Park *et al.* (1993); Johnston & Parrot (1993); Varotsos & Kulhánek (1993); Hayakawa & Fujinawa (1994); Hickman, Sibson & Bruhn (1995); Parrot *et al.* (1995); Stein (1995); Kerr (1995); Masood (1995a), Lighthill (1996); Knopoff *et al.* (1996); Silver & Wakita (1996), Wakita *et al.* (1996); Geller (1996a); Carlowicz (1996); Li & Mervis (1996), IPASD (1997); Gupta (1997); Main (1997), Geller (1997a), this issue; NASDA (1997); Wyss & Dmowska (1997); Monastersky (1997).

1997; also see McEvilly 1976). However, patterns vary greatly from one earthquake to the next, the alleged anomalies are frequently observed at only one point rather than throughout the epicentral region, there are no quantitative definitions of 'anomalies', no quantitative physical mechanism links the alleged precursors to earthquakes, statistical evidence for a correlation is lacking and causes unrelated to earthquakes have not been convincingly excluded (Suzuki 1982; Turcotte 1991; Wyss 1991b; Yoshida & Furuya 1992).[1]

In other fields threshold signals have often erroneously been claimed as important physical effects (e.g. Franks 1981; Langmuir 1989; Anderson 1990; Huizenga 1992; Franklin 1993; Taubes 1993, 1997); this might also be the case for precursor claims.

Some researchers take the existence of precursors as fact. An editorial in *Science* (Abelson 1973) says:

'If we wish to understand and be able to predict the rare, large earthquakes, we should be seeking premonitory signals everywhere that earthquakes have been known to occur.'

Kisslinger (1976) told a US Senate committee:

'Investigations in several countries, Japan, USSR, People's Republic of China, and the United States, have demonstrated that at least some earthquakes are preceded by detectable phenomena that are diagnostic of the impending event. It is this discovery that provides the basis for our confidence that at least some earthquakes in some geological settings are predictable on the basis of readily observed precursors.'

Aki (1980) said:

'I believe it is possible to develop in the next decade a quantitative scale which measures the gradation of concerns about the earthquake occurrence on the basis of observed data on precursory phenomena.

'... [The] conditional probability may be increased further by the discovery of additional precursors, such as uplift, tilt-strain anomaly, water-table change, etc.'

Sykes, Simpson & Richards (1981) said:

'... an overview of large earthquakes in several countries during the past five years does show that a number of forerunning effects have been clearly and consistently observed.'

Raleigh *et al.* (1982) said:

'Reliance on empirically established precursory phenomena will still be necessary until a better formulation of a theoretical model is possible. Both as a means of developing the observational basis for better models and collecting data which will have value as precursory signals, an extensive network for closely monitoring and for analysing strain and seismicity data in real time is imperative.'

After the Armenian earthquake of 7 December 1988, Igor Nersesov was quoted as follows by Markov (1988):

' "We do not have the necessary technical facilities for prompt data processing, which is essential for sufficiently accurate forecasting of earthquakes," says Nersesov. "If we had had such facilities, we could probably have predicted the oncoming catastrophe in Armenia and reduce[d] its toll." '

Chan (1989) reported on a hearing of a US Senate subcommittee held at the 1989 Fall AGU Meeting:

'Testifying on behalf of the seismological community, Don Anderson, AGU president, called for the establishment of a dense seismic research array as a first step in monitoring the San Andreas Fault and other earthquake-prone regions in the U.S. With such an array, many precursory characteristics of large earthquakes that are not presently observed, may be used to better [assess] the hazard potential of a fault zone.'

Ben-Menahem (1995) said:

'What then, must be done to advance the cause of prediction? A major interdisciplinary effort is needed to develop a prediction scheme based on *multi-premonitory* phenomena: it means that the *near field* of a future focal zone must first be identified, and then monitored for electrical, magnetic, acoustic, and thermal precursors simultaneously and *continually*.'

The Balkan Geophysical Society adopted a resolution saying in part (Papanikolaou *et al.* 1997):

'... capabilities to predict earthquakes can be improved when based on observation, study and interpretation of different precursory phenomena. In this respect, the strategy of a multidisciplinary earthquake prediction program is of primary importance at a national and international level.'

Scholz (1997) said:

'Predicting earthquakes is as easy as one-two-three. Step 1: Deploy your precursor detection instruments at the site of the coming earthquake. Step 2: Detect and recognize the precursors. Step 3: Get all your colleagues to agree and then publicly predict the earthquake through approved channels.

...

'The [1995] Kobe earthquake was found retrospectively to have been preceded by a host of precursors, as pointed out by [Silver &

[1] Long-term forecasting of earthquakes is outside the scope of this paper, but the following discussion is added in response to a referee's comment. In two studies involving long-term forecasting more quantitative definitions of possible anomalies were made and data were subjected to statistical testing. The result in each case (Evison & Rhoades 1993; Kossobokov, Healy & Dewey 1997) was that the hypothesis proved not to be statistically significant. Thus these studies made quantitative definitions of phenomena that proved not to be earthquake precursors.

Wakita 1996]. There is no doubt in my mind that many earthquakes are preceded by real precursors, but their causative processes remain murky, mainly because we lack good observations.'

Geochemical and hydrological phenomena were claimed as precursors of the Kobe earthquake (the official name is 'Hyogo-ken-nanbu earthquake', but 'Kobe earthquake' is used throughout this paper) by Tsunogai & Wakita (1995, 1996) and Igarashi *et al.* (1995).

Paul Silver was interviewed by the BBC World Service radio programme 'Science in Action' (14 March 1997). The interview began with a question (not broadcast) asking Silver's opinion of Geller *et al.*'s (1997a) arguments (also see comments by Wyss 1997a and Aceves & Park 1997, and reply by Geller *et al.* 1997b) that earthquakes cannot be predicted. A verbatim transcript follows:

Silver: I would not agree with that. If they're saying that there's something inherent in earthquakes that makes them unpredictable I think that's not correct.

BBC: Paul Silver, a geophysicist at the Carnegie Institution of Washington.

Silver: The argument given in this paper is that they're a very complex phenomenon and you can't really predict from initial conditions. However, we don't need to do that. We just need there to be some sort of signal before an earthquake occurs. And every other kind of natural hazard that we work with, be it hurricanes, volcanic eruptions, floods or even wildfires, these are all very complex, very non-linear, but they're all predictable on the basis of precursory phenomena.

[1 min intervening segment in which Silver did not appear.]

BBC: But Paul Silver, on the other hand, thinks the doubters are being premature. Advances in monitoring technology in the next couple of decades will provide the answers.

Silver: We have not obtained the adequate instrumentation to actually even decide if we can or cannot predict earthquakes. What we need really is a monitoring system to monitor the deformation that occurs generally along plate boundaries. This would be the same as having a weather system to detect hurricanes. Maybe we still have problems with earthquakes, but our children may not have problems with earthquakes.

Some researchers are sceptical about the existence of precursors. Brune (1974) and Allen (1982) are quoted above in Section 2.3 (see also see Brune 1979). Kagan (1994, pp. 161 and 187) made important criticisms of the precursor case-study approach. Suzuki (1982) said:

'... the present state of the art is very chaotic, or at least seems more confusing than in the past. A remarkable variety of earthquake precursors have been reported so far. Some reported precursors seem very strange and open to doubt. Even excluding these ambiguous cases, no general and definite way to successful earthquake prediction is clear.'

Turcotte's (1991) assessment was:

'Presently, there is no evidence that any observable is a systematic precursor to an earthquake.

...

'The empirical approach to earthquake prediction has failed to produce reliable measurements of precursory phenomen[a].'

Lomnitz (1994, p. 268) commented as follows:

'Precursor research has yet to find a useful signal that stands out clearly from the noise. Harold Jeffreys used to say that "if an effect is really there it shouldn't take a statistician to bring it out." He was not a statistician for nothing.'

Kanamori (1996) said:

'Examinations of strain changes just before large earthquakes suggest that consistent detection of such precursory strain changes cannot be expected. Other precursory phenomena such as foreshocks and non-seismological anomalies do not occur consistently either. Thus reliable short-term prediction would be very difficult.'

3.1 IASPEI Subcommission

IASPEI's (International Association of Seismology and Physics of the Earth's Interior) Subcommission on Earthquake Prediction has published guidelines for precursor candidates. The Subcommission's Chairman (Wyss 1991b) states that the main criteria are:

Validation Criteria: (1) The observed anomaly should have a relation to stress, strain or some mechanism leading to earthquakes. (2) The anomaly should be simultaneously observed on more than one instrument, or at more than one site. (3) The amplitude of the anomaly should bear a relation to the distance from the eventual main shock.

Data: There should be a persuasive demonstration that the calibration of the instrument is known, and that the instrument is measuring a tectonic signal.

Detection: Anomaly definitions should be precise.

Association of anomalies with subsequent earthquakes: Rules for associating an anomaly with an earthquake shall be stated precisely. The definition of an anomaly and the association rule should be derived from a data set other than the one for which a precursory anomaly is claimed.

31 precursor nominations were submitted to the Subcommission. None fully satisfied the guidelines, but three were placed on a 'preliminary list of significant earthquake precursors'. Wyss (1991b) explained:

'Placing a precursor, a method, or a case history on this List does not guarantee that the reported anomaly was actually a genuine precursor, that the method works in general or that the case history is without shortcoming. A method is included on the List if the majority of the reviewers and panelists thought it more likely than not that the method may be useful for earthquake prediction. An individual case history is put on the List if the majority thought that it was more likely than not that the claimed anomaly was real and physically related to the mainshock.

...

'The results of this evaluation survey show that earthquake prediction research still has a long way to go to become useful. Only three cases were accepted for the Preliminary List, and all of these with many caveats. In the work by Matsu'ura (1986) only aftershocks are predicted and this has not been done yet in real time. In the correct prediction of the Haicheng earthquake based on fore-shocks reported by Wu *et al.* (1978) many false alarms existed, but the false alarm rate has not been evaluated and no methods exist to recognize fore-shocks in real time. In the case of ground water anomalies (Wakita, Nakamura & Sano 1988) also many questions remain, especially questions concerning the physical mechanism. Thus, at this time, we have not a single method on the List which could be said to be accepted universally and by which earthquakes can be predicted reliably.'

The IASPEI Subcommission's further case studies are summarized by Wyss (1997b). Two additional cases (Bowman 1997; Roeloffs & Quilty 1997) that fail to fully satisfy the guidelines were placed on the preliminary list.

Wyss (1991b) stated that items on the Preliminary List should not be regarded as having been endorsed by either IASPEI or the Subcommission, and that they are not necessarily genuine precursors. However, the Preliminary List is sometimes cited in ways that might lead some readers to infer that an endorsement has been made. Aoki (1996) characterized items on the Preliminary List as 'recognized as meaningful', 'certain precursors', and 'recommended by IASPEI' ('*Yūi to mitomerareta*', '*tashika na zenchō genshō*' and 'IASPEI *suisen*' respectively in the original Japanese). Silver & Wakita (1996) stated:

'Of forty proposed precursors considered by the International Association of Seismology and Physics of the Earth's Interior (IASPEI) subcommission on Earthquake Prediction, only five were judged as significant. Of these two were based ... on hydrogeochemical indicators ....'

3.2 Searches for precursors

Mogi (1984/1985, 1985 pp. 274–284) reported geodetic observations that suggest pre-slip one or two days before the 1944 Tonankai, Japan ($M = 7.9$), earthquake. Thatcher (1981) commented that these data are fragmentary and their relation to the Tonankai earthquake is uncertain. Linde & Sacks (1997) (see also Kerr 1997) discussed the 1944 event.

Some theoretical models (e.g. Stuart 1974, 1979; Dieterich 1978) call for the existence of such pre-slip. However, recent geodetic data, which have a much higher signal-to-noise level than those recorded in 1944, have shown a consistent absence of geodetic precursors (for 1989 Loma Prieta, 1992 Landers, 1994 Northridge, 1994 Shikotan, 1995 Kobe, etc.). For Landers, see Bock *et al.* (1993) and Wyatt, Agnew & Gladwin (1994). Two hypotheses are suggested: (1) Some earthquakes have geodetic precursors, but others do not; (2) there are no geodetic precursors, and the 1944 data were either noise or a signal with no causal relation to the earthquake.

Savage (1996) discussed observations before the Northridge earthquake. Bock (1994) reported anomalous deformation, but this was subsequently found to be an artefact due to instability of the monuments (Johnson & Agnew 1995). Recent GPS observations have shown that 'slow earthquakes', 'silent earthquakes' and accelerated creep are important contributors to the release of seismic moment (e.g. Heki, Miyazaki & Tsuji 1997). As noted by DeMets (1997), this has negative implications for prediction.

It is generally accepted that there is no way to distinguish foreshocks from random small earthquakes (e.g. Jones & Molnar 1979). Retrospective studies show no relationship between foreshock occurrence and the magnitude of the main shock (Abercrombie & Mori 1996). Ogata, Utsu & Katsura (1996) claimed a weak correlation between foreshocks and the subsequent main shock, but their study used some information that became available only after the main shock.

Felt earthquakes sometimes precede large intraplate earthquakes (e.g. Hatzfeld *et al.* 1995; Stiros 1995; Bernard *et al.* 1997). After such events the relative probability of a large earthquake is significantly higher than normal, but the absolute probability is still low (e.g. Kagan & Knopoff 1987; Agnew & Jones 1991). Evison & Rhoades (1993) conducted a statistical test of the hypothesis that main shocks in New Zealand are preceded by precursory swarms; the results were negative. Claims of precursory quiescence were criticized by Richter (1964) and Reasenberg & Matthews (1988). For further discussion see Wyss (1997c); comments by panelists and reviewers (pp. 110–113) immediately follow the body of Wyss's paper. Jones & Hauksson (1997) pointed out that changes in seismicity levels are not necessarily precursors of forthcoming earthquakes.

Crampin (1987), Crampin & Zatsepin (1997) and works cited therein claimed that temporal variations in anisotropy indicate stress build-up. However, Aster, Shearer & Berger (1990) reanalysed some data and argued that there were no clear temporal changes. Crampin *et al.* (1991) commented on this criticism, and Aster, Shearer & Berger (1991) replied.

Many studies claim to have found electromagnetic precursors (Stacey 1963; Warwick, Stoker & Meyer 1982; Gokhberg *et al.* 1982; King 1983; Johnston & Parrot 1989, 1993; Park *et al.* 1993; Hayakawa & Fujinawa 1994; Parrot 1995; Gokhberg, Morgounov & Pokhotelov 1995; Park 1996; Johnston 1997; see also Sections 4.5 and 4.6), but there are several reasons for doubt. One is the absence of simultaneous geodetic or seismological precursors; a second is the absence of coseismic electromagnetic signals of the same type as, but with larger amplitudes than, the alleged precursors; a third is that sources other than earthquakes have not been ruled out; a fourth is the lack of consistency; a fifth is the lack of a quantitative relation between the anomalies and the earthquake source parameters.

Reports of anomalous animal behaviour (e.g. Anonymous 1976; Logan 1977; Reasenberg 1978; Tributsch 1978, 1982; Kerr 1980; Buskirk, Frohlich & Latham 1981; King, Koizumi & Kitagawa 1995) are doubly dubious. They depend not only on distinguishing precursory phenomena from ordinary animal behaviour, but also on human observers who have just undergone a traumatic experience.

3.3 Hydrological and geochemical precursors

Turcotte (1991) commented:

'Without any physical basis for associating water-level and spring-flow changes with stress levels, it is difficult to consider such effects to be credible precursors.

...

'Some of the reports of premonitory emissions of radon come from sites that are tens to hundreds of kilometers away from the subsequent earthquakes. It is extremely difficult to understand how radon can be transported these distances in the required 10 days or less.'

Wakita *et al.* (1980) and Wakita (1981) claim to have observed hydrological and geochemical precursors of the 1978 Izu-Oshima-Kinkai, Japan, earthquake. Wakita *et al.* (1988) said:

'There is another problem. Even though one earthquake has clear precursors, the next earthquake occurring in the same region may have no precursor. An example is the cases of the 1978 Izu-Oshima-kinkai earthquake (M7.0) and the 1980 Izu-Hanto-toho-oki earthquake (M6.7) which occurred in almost the same region about one and a half years apart. Although many obvious precursors were observed for the 1978 Izu-Oshima-kinkai earthquake, practically no meaningful change was observed for the 1980 Izu-Hanto-toho-oki earthquake.'

The absence of anomalies before later events suggests that the observations of Wakita *et al.* (1980) were not causally related to the 1978 earthquake. As pointed out by R. P. Feynman (Goodstein 1993), a hypothesis must be verified by comparison to data other than those used to formulate it. Rhoades & Evison (1989a,b) made the same point.

3.4 Reports of possible geodetic anomalies

Reports of possible geodetic anomalies that were later found to have been artefacts have generated considerable interest and anxiety. Richter (1958, pp. 193, 388) and Geschwind (1997) described one such case.

Perhaps the best-known case occurred in southern California. As an outgrowth of studies of geodetic deformation before and after the 1971 San Fernando, California, earthquake (Castle *et al.* 1974, 1975), Castle, Church &

Elliott (1976) reported an uplift of about 15–25 cm over an area of about 12 000 km^2 in southern California during (approximately) 1960–1975. A reanalysis by Castle (1978) reported 35 cm of uplift. This inferred uplift was usually called either the 'Palmdale Bulge' or the 'Southern California Uplift.' Thatcher (1976, 1979), Savage & Prescott (1979), and Savage *et al.* (1981a,b) discussed the data of Castle and co-workers in relation to other geodetic data.

Frank Press wrote to the Vice President of the United States on 21 January 1976. Excerpts from this letter (see also Press 1976) are given by Shapley (1976a):

'The discovery, which will soon be released publicly, is most disturbing because such uplifts in the past have preceded earthquakes of great destructive power ....

'The effect on Los Angeles of an earthquake in the region of the uplift would be quite disastrous. A structural engineer at U.C.L.A., Professor Martin Duke, has estimated that as many as 40,000 buildings would suffer collapse or serious damage.

'There is no question that the uplift must be taken very seriously even though geophysicists have, as yet, no clear understanding of its origin or significance ....

'The region of the uplift should now be subjected to a most intense scrutiny.... In Japan a geophysical anomaly of this magnitude would trigger an intensive study or a public alert.

...

'Having visited China, I can attest to their technical proficiency in this field of science, and express my concern that because of insufficient resources a similar achievement may not be possible in this country.'

Shapley (1976a) reported that $2.1 million was allocated to the USGS to monitor the uplift. Wyss (1977a) suggested that episodes of rapid uplift were precursors to crustal earthquakes. Wyss (1977b) interpreted the Southern California Uplift as follows:

'The 25-cm uplift in southern California is interpreted as being due to dilatancy of the crust, which started in 1961 along the San Andreas fault and spread laterally during 1964–69. The San Fernando earthquake of 1971 occurred in part of the dilatant volume, and is interpreted as a sideshow of a future repetition of the 1857 San Andreas break, which had a magnitude > 8.'

There was extensive debate over whether the Palmdale Bulge was an artefact (Greathouse 1980; Rundle & McNutt 1981; Kerr 1981a; Stein 1981). Reilinger (1980) and Reilinger & Brown (1981) suggested the possibility of artefacts due to a decline in aquifer levels. Jackson, Lee & Liu (1980, 1981a) (see comment by Castle *et al.* 1981 and reply by Jackson, Lee & Liu 1981b), Jackson, Cheng & Liu (1983) and Strange (1981) (see comment by Castle *et al.* 1983a and reply by Strange 1983) suggested there were significant systematic errors. Holdahl (1982) concluded:

'Vertical motion in the Palmdale region has now been reassessed .... The new results show 7.5 ± 4.0 cm of apparent upward movement at Palmdale. Part or all of the 7.5 cm might be attributable to residual systematic error. The great concern associated with Palmdale, if based on motion calculated from leveling data, does not seem warranted. Castle's original result was strongly influenced by a single level route to Palmdale. Refraction error accumulates rapidly on this route because of the long gentle slope and the location of sightings over railroad ballast where vertical temperature gradients are unusually large .... The rigorous analysis of refraction-corrected leveling data described in this paper supports the approximate computations of Strange (1981) that indicated that what was thought to be uplift at Palmdale was only the appearance of uplift created by different refraction error accumulation in successive surveys. The primary cause of this difference was reduced sight lengths starting in 1964.'

Stein (1987) concluded that the uplift data for Palmdale are 'close enough to measurement uncertainty to be suspect'. There has been much discussion of possible systematic errors in levelling data and how to account for them (Chi *et al.* 1980; Shaw & Smietana 1983; Stein *et al.* 1986, 1989; Craymer & Vaníček 1986, 1989).

Castle and co-workers did not accept the above criticisms (Mark *et al.* 1981; Castle *et al.* 1983a,b; Mark, Gilmore & Castle 1987). Summaries of this group's work are presented by Castle *et al.* (1984) and Castle, Elliott & Gilmore (1987). This group's most recent uplift model is presented by Castle & Gilmore (1992).

A similar scare over a possibly anomalous uplift took place in Kawasaki (20 km from Tokyo) in 1974 (Dambara 1981). The area had been subsiding rapidly since 1950 due to the pumping out of underground water. When this pumping ceased, the water level recovered rapidly, causing an apparent uplift. This was reported extensively as a possible precursor in the media. The Chairman of the Coordinating Committee for Earthquake Prediction had to call a press conference to calm public apprehension (Ohta & Abe 1977; Geographical Survey Institute 1979, p. 45).

3.5 Strategies for precursor evaluation

Much time and effort were wasted evaluating specious claims of a 'fifth force' (e.g. Franklin 1993). Anderson (1992) pointed out that a Bayesian approach would have clarified matters. Because the effect had a low *a priori* probability, which was distributed across the range of unknown parameters, much positive data would have been needed before Bayes theorem supported the existence of a fifth force. The Bayesian approach should also be applied to the evaluation of precursor claims.

Precursor researchers should be required to demonstrate quantitatively that their data are anomalous and are causally related to earthquakes. They should present quantitative physical mechanisms or compelling statistical evidence, preferably both. Precursor researchers should be required to state their claims in the form of objectively testable hypotheses (e.g. Jackson 1996a). Empirical prediction research requires careful attention to experimental protocol and statistical hypothesis testing. Prediction researchers could benefit from experience in fields such as ESP research (Diaconis 1978), where this is also the case.

4 CLAIMS OF 'SUCCESSFUL PREDICTIONS'

4.1 1975 Haicheng, China, earthquake

A swarm of earthquakes, the largest $M = 4.8$, occurred 70 km NE of Haicheng on 22 December 1974 (Raleigh *et al.* 1977). An unsuccessful prediction was issued for the Yinkow area, about 100 km west of Haicheng, at this time (Adams 1976). A prediction of an $M = 5.5$–6.0 event in the first six months of 1975 for a wide area that included Haicheng was issued on 13 January 1975. Based on a swarm (largest event: $M_L = 4.7$, 4 February, 7:51am) that began on 3 February 1975, a general warning was issued at 2pm on 4 February for Yinkow and Haicheng Counties to expect an earthquake within two days.

The $M = 7.3$ Haicheng event occurred at 7:36pm on 4 February 1975. Seismicity before the main shock was discussed by Scholz (1977), Wu *et al.* (1978), Xu *et al.* (1982) and Jones *et al.* (1982). Deng *et al.* (1981) discussed reports of anomalies in ground water and animal behaviour.

Detailed information on what warnings were issued is apparently unavailable in English (e.g. Zhu & Ge 1983; Ma 1990, pp. 4–5). Chu (1976, p. 19) said the Provincial Revolutionary Committee made telephone calls at 10am on 4 February saying there was 'a possibility of [a] strong earthquake in Haicheng Yingkao districts', but the actions taken are not clear. Chu added that a conference for earthquake disaster prevention was held at 2.00pm, at which the instructions of the provincial revolutionary committee were transmitted and duties were assigned, but gave no details.

The claim that the Haicheng earthquake was 'successfully predicted' is widely accepted. Lay & Wallace (1995, p. 493) stated:

'The 1975 Haicheng earthquake (M_s=7.3) ... was the first major earthquake to be predicted. ... The earthquake was very destructive, but almost no one died.'

Hammond (1976) reported in *Science* that 'very few people were killed', and Davies (1975) reported in *Nature* (see also Anonymous 1975b) that there were 'few fatalities'. Savarenskij & Nersesov (1978, p. 83) said:

'... before the severe shock of 4 February 1975 (magnitude over 7), the population was evacuated from buildings in a densely populated area. Despite considerable damage to a number of inhabited localities, the population itself came out unscathed.'

However, Lomnitz (1994, p. 25) stated:

'It has been widely claimed that Haicheng was "evacuated" before the earthquake, though no such claim can actually be found in Chinese sources.'

Quan (1988) stated that there were 1328 deaths and 16 980 injuries due to the Haicheng earthquake. The large disparity between the reports of 1975 and 1988 casts doubt on claims for the Haicheng prediction.

The Cultural Revolution was still taking place in 1975. Raleigh *et al.* (1977) described the atmosphere:

'... earthquake prediction was established and advertised as a national policy of the highest priority. ... Earthquake prediction was not a minor experiment, viewed with a skeptical eye in ruling circles. Indeed, belief in earthquake prediction was made an element of ideological orthodoxy that distinguished the true party liners from right wing deviationists. Repeatedly, we heard disbelief in earthquake prediction attributed to bourgeois class interests. ... And criticism of those who doubt the feasibility of earthquake prediction was linked to everyone's duty to criticize the idealist concepts and revisionist lines of Confucius, Liu Shaoqi, Lin Piao, and, retrospectively, [Deng Xiao-ping].'

A Chinese prediction researcher, Chu (1976), said:

'On 4 February 1975 at 19:36 Peking time, a strong earthquake of M=7.3 shook our nation's Lianoning Province, Haicheng-Yingkao district. Given the forecast of this violent earthquake, however, the Party, the government, the armed forces and the people of the affected province immediately took effective prevention measures under the consolidated leadership of Lianoning Province Committee of the Chinese Communist Party, thus greatly minimizing the damage of this densely populated area. This was the very fruit of our great Proletarian Cultural Revolution and Anti-Lin Piao [Anti-]Confucius movement, as well as the vivid and successful demonstration of the superiority of the socialistic system. It was indeed a great victory of Chairman Mao's revolutionary line.'

Some disasters in China were concealed during the Cultural Revolution. As many as 230 000 people died in the collapse of two dams in southern China in August 1975, but this tragedy was only revealed 20 years later ('China: History warns', *The Economist*, 25 February 1995).

Huebsch (1978) criticized Raleigh *et al.* (1977):

'[Raleigh *et al.* 1977 display] an uncritical and naive attitude toward the alleged accomplishments of Chinese Communist seismology under the guidance of Chairman Mao. The reports of successful predictions would be more convincing had they been noted before, rather than after, the event, and had they been made by visitors fully free to travel and able to converse in the language of the country. The Americans may have received a Potemkin village tour of a type often provided foreign visitors to totalitarian countries.'

AGU's Foreign Secretary (Kisslinger 1978) replied:

'Mr. Huebsch misjudges the perspicacity and sophistication of the American Haicheng Earthquake Study Delegation. The members of the group were carefully selected for their ability to gather and critically evaluate all information that might be provided by their hosts about the successful prediction of the Haicheng earthquake.

...

'On the basis of all reports, including the findings of the group responsible for the *Eos* article and my own observations while in China in 1974, I personally have no doubts whatsoever that the Chinese did successfully predict this earthquake and take actions based on that prediction to reduce losses of life and property. In view of the totally empirical approach of the Chinese, there may well have been a great deal of luck involved in the amazing accuracy of the prediction. This does not reduce the significance of the first real success achieved anywhere in predicting a destructive earthquake.'

At least 240 000 people (the official figure) died in the 1976 Tangshan, China, earthquake, which was not predicted. Norman (1977) said 'more than 600 000' were killed. Spall (1977) quoted reports of 600 000 deaths, and Wallace (1983) quoted reports of 650 000 to 800 000 deaths. Retrospective claims of precursors (e.g. Lomnitz & Lomnitz 1978; Chu *et al.* 1996) were made after the Tangshan earthquake.

A leader in *Nature* immediately after the Tangshan earthquake (Anonymous 1976) commented as follows:

'Animal behaviour as a predictor has now, of course, become an object of popular fascination the world over. For one thing, the jumpiness of cats, dogs and snakes can be understood by a much wider public than can fluctuations in the velocity of elastic waves; for another, it does bring science down to a folksy level at which the good amateur observer is just as valued as the professional. There are few branches of science where this is true today, and it is excellent news that amateur involvement has been given such a good name by the Chinese.

...

'What the Chinese have succeeded in doing, and what this most recent calamity will certainly not dissuade them from continuing, is to raise the consciousness of people to unusual phenomena, even to the extent of encouraging them to file reports. This is a lesson that should not be lost in California, the Soviet Union, Japan, the Middle East, or other places scourged by earthquakes. There are encouraging signs that at least the inhabitants of San Francisco and Los Angeles are prepared to learn from the Chinese experience that the experts need all the help they can get.'

Coe (1971), Bolt (1974), Press (1975c), Press *et al.* (1975), Shapley (1976b), Gu (1981), Anonymous (1982), Russ & Johnson (1985), Chen (1986), Tang (1988), Chen, Chen & Wang (1992), Mei (1992), Zhang & Zhang (1992), Gao & Gao (1995), Hao (1996) and Wu (1997) also discussed prediction research in China. Claims of successful predictions (other than Haicheng) were discussed by Press (1975c), Norman (1977), Li & Mervis (1996) and Li & Kerr (1997), but the details are unclear.

4.2 1978 Oaxaca, Mexico, earthquake

Ohtake, Matumoto & Latham (1977) reported seismic quiescence near Oaxaca, Mexico, as a possible precursor to a large earthquake, but did not predict the occurrence time. Ohtake, Matumoto & Latham (1981) claimed that:

'The rupture zone and type of the 1978 Oaxaca, southern Mexico earthquake ($M_s = 7.7$) were successfully predicted based on the premonitory quiescence of seismic activity and the spatial and temporal relationships of recent large earthquakes.'

See also the news story in *Science* by Kerr (1979b).

Garza & Lomnitz (1979) and Lomnitz (1994, pp. 122–127) suggested that the quiescence reported by Ohtake *et al.* (1977) was an artefact. Whiteside & Habermann (1989) concluded 'that the quiescence in the Oaxaca region between 1975 and 1978 was related to man-made changes in the catalog and was not a precursor to the 1978 mainshock.'

4.3 1978 Izu-Oshima-Kinkai, Japan, earthquake

In January 1978 intense microearthquake activity took place near the Izu Peninsula, Japan. Following 18 felt earthquakes ($M_{max} = 4.9$) in three hours the Japan Meteorological Agency (JMA) issued a statement:

'The present swarm events, which are somewhat larger than typical swarm events, are the largest since events in 1964 that caused a small amount of damage. Because there is a possibility that the present swarm earthquake(s) may cause damage, you might consider taking precautions' (translation by Geller 1991b).

As the above statement makes no mention of the time, place or magnitude of a possible future earthquake, it is not an earthquake prediction. About 90 min after the statement was issued, an $M = 7.0$ earthquake (the Izu-Oshima-Kinkai earthquake, 1978 January 14) occurred nearby. The JMA did not and does not claim a 'successful prediction.'

Hamada (1991) claimed incorrectly that:

'Some earthquakes have actually been successfully predicted. Short-term prediction for the M7.0 Izu-Oshima earthquake in 1978 was issued by the Japan Meteorological Agency 1.5 hours before the event.'

Geller (1991b) presented the above translation to demonstrate that Hamada's claim was false.

The incorrect claim of a 'successful prediction' of the 1978 event was repeated by Roeloffs & Langbein (1994), who stated:

'Earthquake prediction research seemed on the verge of a breakthrough in 1975, when Chinese seismologists successfully alerted Haicheng city of an impending magnitude 7.3 earthquake .... Public warnings were also achieved before ... the 1978 Izu-Oshima, Japan earthquake (N. Nishide, oral communication, 1992).'

The JMA statement referred to a swarm of events with $M \leq 5$. It is inappropriate to claim this as a public warning of an event with $M = 7.0$. Misinformation was further propagated by the Office of Technology Assessment (1995, p. 62) of the US Congress, which stated that 'In Japan public warning was achieved for the 1978 Izu-Oshima earthquake (M7),' citing Roeloffs & Langbein (1994) as an authority.

4.4 1989 Loma Prieta, California, earthquake

Immediately after the Loma Prieta, California, earthquake (1989 October 18, $M = 7.1$) Garwin (1989) reported:

'Twelve hours after last week's earthquake in northern California, the United States Geological Survey (USGS) claimed that it had "forecast" the event in a report issued last year. Californians may find the value of this forecast debatable, but the close resemblance between the earthquake and the event foretold, not just by USGS but by many US seismologists over the past decade, encourages confidence that a practical understanding of earthquakes on the San Andreas Fault is within reach.'

US Geological Survey Staff (1990) claimed that the Loma Prieta, California, earthquake was 'an anticipated event'. However, statistical analyses do not support this claim (Savage 1991, 1992). Harris (1997) reviewed long-term forecasts for this area. 'Successful' long-term forecasts of the Loma Prieta earthquake have been invoked as justification for stepping up efforts to detect precursors. Scholz (1997) said:

'In a USGS open-file report [Lindh 1983] pointed out that the southernmost part of the rupture zone of the 1906 San Francisco earthquake had slipped much less than points to the north, and thus had a high probability of rupturing within the next few decades. [Sykes & Nishenko 1984] further refined this forecast, and I weighed in [Scholz 1985] with further analysis; these subsequent forecasts appeared in refereed journals. I stated that the imminence of this sector (Loma Prieta) was greater than any part of the San Andreas except Parkfield.

'In the last few years before the earthquake occurred, this issue was debated before several forums, and the USGS was urged to instrument the area for detecting precursors. Dissenting opinion within the USGS and organizational inertia prevented any action. Aside from electromagnetic signals picked up by [Fraser-Smith *et al.* 1990, 1993], who had been serendipitiously operating a ULF receiver in the vicinity, no precursors were detected for the Loma Prieta earthquake, for no instruments had been deployed, and a great opportunity was lost.'

However, Thatcher, Marshall & Lisowski (1997) showed that the San Andreas fault near Loma Prieta slipped 2.3–3.1 m in 1906. Thus there was no 'slip deficit'.

The Loma Prieta earthquake did not occur on the San Andreas Fault, and had a significant dip-slip component (Hanks & Krawinkler 1991). Spudich (1996) said:

'Taken together, these results suggest that the [Loma Prieta] earthquake was not the typical shallow strike-slip San Andreas event anticipated by the Working Group on California Earthquake Probabilities (1988). Beroza (1996) points out that the great depth of slip suggests that the earthquake occurred on a fault distinct from the San Andreas fault, and that the San Andreas fault itself may have acted as an obstacle to rupture in this event. He cites the work of Segall & Lisowski (1990), who showed that the movement of Loma Prieta in 1989 was quite different from that in 1906, further distinguishing the 1989 Loma Prieta earthquake from typical San Andreas events.'

As pointed out by Kanamori & Satake (1990), Segall & Lisowski (1990) and Thatcher *et al.* (1997), it seems unreasonable to cite the 1989 Loma Prieta earthquake as having fulfilled forecasts of a right-lateral strike-slip earthquake on the San Andreas Fault.

No convincing precursors of the Loma Prieta earthquake were observed (Johnston, Linde & Gladwin 1990; Johnston 1993). A few 'anomalous phenomena' were claimed (Fraser-Smith *et al.* 1990, 1993; Lisowski *et al.* 1990; Gladwin *et al.* 1991), but no quantitative mechanism links them to the earthquake.

Silver & Valette-Silver (1992) and Silver, Valette-Silver & Kolbek (1993) claimed that variations in the period of eruption of a geyser were precursors. However, the geyser is at an epicentral distance of 177 km. High-quality strain measurements at distances of only several tens of kilometres were uneventful (Johnston 1993, p. C1), and changes in material properties, as indicated by the response to Earth tides, were absent (Linde, Gladwin & Johnston 1992). Silver & Valette-Silver (1992, p. 1367) rejected the possibility that the pre-seismic variations were due to chance coincidence. However, their statistical argument seems flawed, since the parameters were selected retrospectively (see Section 4.7), and there were only three samples.

4.5 VAN

P. Varotsos and co-workers (the 'VAN' group) claim to be able to predict earthquakes in Greece using geoelectrical observations (Tazieff 1992; Varotsos *et al.* 1996a and papers cited therein). However, Stiros (1997) pointed out that VAN's work is not part of national policy and appears unsound from the point of view of tectonophysics. Gruszow *et al.* (1996) showed that some electrical signals claimed as precursors by VAN were artefacts. Varotsos *et al.* (1996b) replied to this criticism. Bernard *et al.* (1997) also conclude that the sources were near the observatory rather than the epicentres, which were at distances of over 100 km. There appears to be no convincing evidence that any of the electrical signals observed by VAN are earthquake precursors.

VAN's 'predictions' are vague and ambiguous (see Geller 1996b for verbatim texts). VAN's 'predictions' never specify the windows, and never state an unambiguous expiration date. Thus VAN are not making earthquake predictions in the first place (Section 1).

VAN's 'successful predictions' are not statistically significant (Kagan & Jackson 1996 and references cited therein). VAN's 'predictions' correlate much better with preceding, rather than subsequent, earthquakes, as they were issued preferentially during periods of heightened seismic activity (Stavrakakis, Drakopoulos & Latoussakis 1990; Mulargia & Gasperini 1992). Simple prediction algorithms using only seismicity data perform at least as well as VAN (Kagan 1996a; Mulargia, Marzocchi & Gasperini 1996a,b). Varotsos *et al.* (1996c) replied to these criticisms.

Greece is the most seismically active country in Europe. VAN (Varotsos *et al.* 1996a) issued 67 'predictions' during the 8.4 yr from February 1987 to June 1995, of which 27 were double 'predictions', giving a total of 94 'predicted' earthquakes. They claim, based on these 94 'predicted earthquakes', to have 'successfully predicted' 10 of 14 earthquakes with $M \geq 5.8$ in Greece during this period (Table 1).

We make a critical reexamination of VAN's claims (see Geller 1996b for details). We use a temporal window of $\Delta T \leq 31$ days, based on VAN's statements giving windows of 'around 22 days' (Varotsos & Lazaridou 1991) and 'of the order of one month' (Dologlou 1993). The spatial window is $\Delta r \leq 100$ km and the magnitude window is $|\Delta M| \leq 0.7$ (Varotsos *et al.* 1996a). When VAN specify a 'predicted epicentral area' rather than a point (for event #14) the epicentre must fall strictly within this area. Ambiguous items are interpreted unfavourably for VAN.

The column 'VAN' in Table 1 gives Varotsos *et al.*'s (1996a) scoring, where plus and minus indicate 'success' and 'failure' respectively. The column 'Crit' gives the results of our critical re-examination, and the column 'Comment' gives the reason. The critical reexamination shows that there was only one 'successful prediction', event #2, rather than the 10 'successes' claimed by VAN. Varotsos *et al.* (1996b) continue to claim events #12–14 as 'successful predictions'.

Table 1. Analysis of VAN's claims of 'successful predictions'.

Event No.	Date DMY	M	'Successes' VAN	Crit	Comment
1	27 02 87	5.9	+	–	Insufficient documentation
2	18 05 88	5.8	+	+	Swarm
3	16 10 88	6.0	+	–	Prediction did not specify magnitude
4	19 03 89	5.8	–	–	missed
5	20 08 89	5.9	–	–	$\Delta r > 100$ km
6	16 06 90	6.0	+	–	$\Delta r > 100$ km
7	21 12 90	5.8	–	–	missed
8	05 03 93	5.8	+	–	$\Delta t > 31$ days
9	13 06 93	5.9	+	–	$\Delta t > 31$ days
10	25 02 94	5.8	–	–	missed
11	16 04 94	5.8	+	–	$\Delta t > 31$ days
12	04 05 95	6.0	+	–	$\lvert\Delta M\rvert > 0.7$
13	13 05 95	6.6	+	–	$\lvert\Delta M\rvert > 0.7$
14	15 06 95	6.1	+	–	epicentre missed
Number of 'successes'			10	1	

4.6 VLF radio waves

'Omega' is a radio navigation system in the 10–15 kHz band. As explained by Michael (1996):

> 'It has been proposed that phase anomalies in the propagation of VLF radio signals broadcast by the U.S. Omega system can be used to predict earthquakes. This idea is currently being championed by A.P. Reutov, a member of the Russian Academy of Sciences, and further work on this topic has been proposed as a joint U.S.-Russian project under the auspices of the Gore-Chernomyrdian Commission's Environmental Working Group.'

Gokhberg *et al.* (1989) (see also Gokhberg *et al.* 1995) claimed that such variations can be used to predict earthquakes. They claimed that more than 250 variations have been observed before earthquakes as small as magnitude 4 at distances of as much as several hundred kilometres from the great-circle path between transmitter and receiver.

A greater correlation between earthquake occurrence and the amplitude and phase variations is obtained than for random Poissonian earthquake occurrence. However, since earthquakes are clustered, such a null hypothesis is inappropriate (Michael 1996, 1997). Michael concluded that the anomalies are probably not earthquake precursors.

4.7 Evaluation of prediction claims

The above examples, especially Section 4.5, show that the windows and 'rules of the game' (criteria for determining success or failure) must be clearly stated as an integral part of predictions. Some general procedural considerations are discussed by Jackson (1996b) and Rhoades & Evison (1996).

Rules for correlating predictions with earthquakes must be stated in advance. If a sharp cut-off ('success' or 'failure') is used, it must be rigidly enforced, but scoring based on smooth likelihood functions (Rhoades & Evison 1996; Kagan & Jackson 1996) is preferable.

The full text of all predictions, not just 'successes', must be accessible and verifiable. Raw data should be made available via the Internet. Workers who refuse to disclose data should be ignored. Empirical methods must be formulated as well-defined algorithms that allow any researcher analysing the same data to issue the same predictions.

Time and effort need not be wasted on evaluating prediction schemes that cannot outperform Kagan's (1996a) 'automatic alarm' strategy. Another possible filter is testing against random predictors (Stark 1996).

Seismicity is characterized by foreshock–main-shock–aftershock clustering (e.g. Kagan & Knopoff 1987). An inappropriate null hypothesis can thus correctly be rejected at a high level of confidence even though the prediction method is ineffective (Michael 1996, 1997; Stark 1997).

Many claims of high levels of statistical significance have a common fallacy: some parameters were chosen *a posteriori*, but the statistical tests were designed for hypotheses whose parameters were fixed *a priori* (see Rhoades & Evison 1989a,b; Matsumura 1993; Kagan & Jackson 1996; Kossobokov *et al.* 1997; Mulargia 1997).

5 THE 'TOKAI EARTHQUAKE'

The 'Tokai' and 'Parkfield' predictions were based on the 'characteristic earthquake' concept. Aki (1989) said:

'We may compare earthquake prediction to the prediction of a person's death. The long-term prediction is comparable to the estimation of life expectancy for a person of a certain age. For this purpose, we must first identify a characteristic earthquake associated with a given fault segment, and determine the statistical distribution of recurrence time of the characteristic earthquake by paleoseismological studies of past earthquakes. The symptoms of death would be easily identified just before the death of a person, but it would be difficult to diagnose it long before the time of death. Thus, the short-term prediction is easier than the intermediate-term prediction.'

Aki (1995) said:

'Once a characteristic earthquake is identified for a given fault segment, it becomes an individual, like a human being, to which life expectancy at a certain age can be evaluated and used for determining the premium for life insurance.'

This simile appears to be at variance with the facts. Davis, Jackson & Kagan (1989) showed that unless other seismicity occurs nearby, the annual probability of an earthquake can decrease with increasing time from the previous earthquake. (Also see Sornette & Knopoff 1997.) Kagan (1996b) presented compelling arguments against the characteristic earthquake model. (Controversy lingers, however; see Wesnousky 1996.)

5.1 Long-term forecast

Mogi (1970) suggested that a large earthquake might occur in the Tokai district; see also Ando (1975), Utsu (1977), Mogi (1981, 1985) and Matsumura (1997). Ishibashi (1977) argued that a large earthquake here was overdue:

'There is reason to fear that the "Suruga Bay earthquake" is imminent. Speaking precisely, the result of long term prediction research is that there is strong reason to fear that precursory phenomena could begin at any time' (author's translation).

The consensus of Japan's earthquake prediction community was summarized by Rikitake (1979):

'Many Japanese seismologists, earthquake engineers, and national and local officials responsible for disaster prevention are quite convinced nowadays that a great earthquake of magnitude 8 or so will hit the Tokai (literally East Sea) area, an area in central Japan between Tokyo and Nagoya, in the near future. The anticipated epicentral region is off the Pacific coast of Shizuoka Prefecture, including Suruga Bay. Should the feared earthquake occur it would certainly destroy one of the most industrial areas in Japan, through which the world-famous Shinkansen (bullet train) runs and where a few nuclear reactors are operating.

'The targeted area was often struck by great earthquakes in historical times such as the 1854 and 1707 earthquakes, both of which had magnitudes estimated at 8.4. The mean return period of recurrence of great earthquakes there is estimated as about 120 years. As more than 120 years have already passed since the last shock, there is reason to believe that an earthquake will recur sooner or later.'

Ishibashi (1981) commented as follows:

'The seismic gap for 126 years on the Suruga trough thrust since 1854 and the considerable amount of strain accumulation in this region estimated from geodetic survey data suggest a fairly high probability of a near-future occurrence of this faulting. And, if the event is a little smaller-scale, it may occur earlier.'

Okada (1984) said:

'It is thought that an interplate earthquake with a magnitude of 8 or more will occur in the Tokai region in the near future and a long-term prediction has already been issued to the general public.'

Ishibashi (1985) issued another long-term forecast:

'Judging from the temporal regularities and considerable amount of strain accumulation on the northwestern coast of Sagami Bay estimated from geodetic survey data, a large earthquake may occur near Odawara during the 1990's or 2000's and the Tokai earthquake in Suruga Bay may follow it in a few years.'

5.2 System for short-term prediction

Ishibashi's warning was reported widely in the Japanese media (Mogi 1985, pp. 270–272; Ashida 1997). Ishibashi called for the establishment of observational networks to detect precursors. Rikitake (1981b, pp. 43–44) criticized Ishibashi's public statements. Powerful politicians took up Ishibashi's call, and legislation was proposed in the Japanese Parliament. While this legislation was pending, the Izu-Oshima-Kinkai earthquake (1978 January 14, $M=7.0$) occurred, causing 25 deaths and significant property damage. In the aftermath, the Large-Scale Earthquake Counter-measures Act (LECA), was passed in June 1978, and took effect in December 1978.

Wakita *et al.* (1980) reported precursory changes in radon concentration before the Izu-Oshima-Kinkai earthquake (see Section 3.3). The *Mainichi Shinbun* newspaper (5 February 1978) reported these observations on page one, under the banner headline 'Epoch making step towards earthquake prediction', with the subheadline 'If the number of observatories is increased prediction is possible'. This publicity facilitated passage of the LECA.

Under the LECA if 'anomalous data' are recorded, an 'Earthquake Assessment Committee' (EAC) will be convened within two hours. Within 30 min the EAC must make a black (alarm) or white (no alarm) recommendation. The former would cause the Prime Minister to issue the alarm, which would shut down all expressways, bullet trains, schools, factories, etc., in an area covering seven prefectures. Tokyo would also be effectively shut down. The procedures for rescinding an unsuccessful alarm have never been publicly discussed. The estimated cost of a prediction is US$7 bn per day; the government is legally immune from demands for compensation (see Aki 1978; Rikitake 1979; Davis & Somerville 1982; Burts *et al.* 1983; Suzuki 1985; Mogi 1985, pp. 299–306).

Once a year (on 1 September, the anniversary of the 1923 Kanto earthquake, which caused 140 000 deaths) a prediction drill is held. The EAC are driven to JMA headquarters in police cars, arriving at about 7am. Mock anomalies are analysed, and a mock prediction ('there is a high risk of a magnitude 8 earthquake [in the Tokai district] within 2 or 3 days') is issued at 9am on national television by the mock Prime Minister. This annual performance helps to create the mistaken impression that the 'Tokai earthquake' is an imminent danger and can be predicted.

A former member (1979–1996) and chairman (1991–1996) of the EAC (Mogi 1986) explains why prediction proponents claim they can predict the 'Tokai earthquake':

'A wide variety of precursory phenomena have been observed, including anomalous crustal movements, anomalous seismic activity, changes in geomagnetism, geoelectric resistivity, and earth potential, and changes in the level, temperature, and chemical components of ground water. In most cases these changes are slight, and the manner in which they appear is complex. This does not mean, however, that they transpire in a completely random manner. Earthquakes have a marked regionality and a tendency to recur in the same region. These facts are particularly favorable for practical earthquake prediction. At this stage no single precursory phenomenon that is a common deciding factor in all cases has been determined. Hence the procedures involved in earthquake prediction are (i) recording a variety of weak signals from the depths of the earth as clearly and exhaustively as possible, (ii) extracting effective data from these signals, and (iii) comprehensively assessing these data and forecasting the occurrence of earthquakes. Developing a dense, highly precise observation network and obtaining effective data on precursory phenomena are prerequisites for achieving these goals.

...

'Since precursory phenomena normally have a marked regional character, the type of phenomena that preceded the Tokai earthquake of 1854 should herald the occurrence of the next one. Unfortunately, there are virtually no reliable data available from 1854. However, the Tonankai earthquake (1944) and the Nankaido earthquake (1946) occurred adjacent to the Tokai region. They could be described as tectonically related to the future Tokai earthquake and thus should provide valuable information .... [In] both of these earthquakes the trough side began to uplift a day or two before they occurred .... Before the Nankaido earthquake, marked anomalies were also reported in the wells and hot springs along the coast. Consequently, if similar phenomena occur before the Tokai earthquake, the changes should be sufficiently marked to be recorded by the present network of highly sensitive observation stations in that region.'

After becoming chairman of the EAC, Mogi pressed for the establishment of a grey ('maybe') verdict (Mogi 1996). This would, for example, call for operating bullet trains at reduced speeds rather than suspending service. Mogi resigned when his proposal was rejected (Normile 1996).

Ishibashi (1977) said that precursors of the 'Tokai earthquake' 'could begin at any time', and Rikitake (1979) said the Tokai earthquake could 'hit in the near future'. These phrases are vague and qualitative. However, from the actions taken by the authorities, it is clear that a timescale of at most a few years was initially envisioned. As 20 years have now passed, it seems reasonable to judge that the long-term forecast of the 'Tokai earthquake' was a failure.

Notwithstanding this scientific failure, the legal and bureaucratic apparatus for predicting the 'Tokai earthquake' remains in effect. Reports in the media continue to imply that the likelihood of an earthquake in the Tokai district is much greater than elsewhere on Japan's Pacific Coast.

5.3 Japan's earthquake prediction program

At present the seventh five-year Earthquake Prediction Plan is underway (April 1994–March 1999) (see Hagiwara & Rikitake 1967; Rikitake 1966, 1972, 1974b, 1986; Kanamori 1970; Asada 1982; Mogi 1981, 1985, 1986, 1992, 1995; Suzuki 1985; Hamada 1992; Hagiwara 1997, pp. 111–140.) The current annual budget is US$147M per year (Normile 1997). There has been discussion of whether the programme should be terminated or overhauled (Geller 1991a,b; Hamada 1991; Swinbanks 1992a,b,c, 1993a,b, 1994a,b, 1995a,b,c, 1997; Normile 1994, 1997; Anonymous 1995).

A government advisory committee recently reported that the prediction programme has not met its goals and has overstated the chances of developing accurate earthquake forecasts (Normile 1997; Swinbanks 1997).

5.4 Public perception

The Science and Technology Agency of Japan periodically conducts 'technology assessment' surveys (Swinbanks 1993c). The respondents are professionals from all fields of science, technology and medicine. The 1971 respondents thought that prediction of earthquakes of magnitude 6 or greater would be possible by 1996. In the 1976 survey the expected date of success receded to 2003, and in 1981 it receded to 2006. The 1986 survey changed the question to cover only prediction of magnitude 7 or greater events a few days in advance; the respondents expected success by 2006. The 1992 respondents expected success by 2010. The 1997 survey results were recently announced (*Asahi Shinbun* newspaper, morning edition, 11 July 1997): prediction is now expected to become possible in 2023.

An opinion poll by Japan's Office of the Prime Minister in September 1995 (Anonymous 1996) revealed that 34.6 per cent of the public thought the 'Tokai earthquake' could be predicted (about half of these respondents thought all $M \geq 7$ events could be predicted); 44.5 per cent thought prediction was impossible; 20.9 per cent didn't know or gave other answers. Polls by Ohta & Abe (1977), Hirose (1985) and Nishida (1989) also found substantial public belief that prediction was possible. A comparable poll in the US (Turner 1982) found 5.4 per cent said earthquakes could be predicted 'quite accurately,' and 36.4 per cent said 'somewhat accurately.'

6 THE 'PARKFIELD EARTHQUAKE'

Bakun & McEvilly (1979, 1984) proposed that characteristic $M = 6$ earthquakes occur on the San Andreas fault at Parkfield, California, at intervals of approximately 22 yr. However, the regularity of Parkfield events was questioned by Toppozada (1985, 1992). Also, a re-examination of geodetic data (Segall & Du 1993) suggested that the 1934 and 1966 Parkfield events may not have been almost identical.

The last $M = 6$ earthquake at Parkfield occurred in 1966. On the basis that there was a 95 per cent probability that 'the next characteristic Parkfield earthquake' would occur by 1993, the USGS and cooperating agencies established the 'Parkfield Earthquake Prediction Experiment' (Bakun & Lindh 1985a,b;

Langbein 1992; Michael & Langbein 1993; Roeloffs & Langbein 1994). As of July 1997, the 'characteristic $M=6$ Parkfield earthquake' had not yet occurred.

The Parkfield prediction was evaluated and approved by the US National Earthquake Prediction Evaluation Council (NEPEC) and other cognizant agencies (Shearer 1985a,b, 1986; Kerr 1985a). The following announcement was issued on 5 April 1985 by the Director of the USGS (Shearer 1985b, pp. 176–177):

'The forecast that an earthquake of magnitude 5.5 to 6 is likely to occur in the Parkfield, Calif., area within the next several years (1985–1993) has been reviewed and accepted by state and federal evaluation panels according to an announcement today (April 5, 1985) by the U.S. Geological Survey.

...

'The California Office of Emergency Services has reviewed the evaluation with local officials and will take coordinated action should the extensive monitoring equipment arrayed throughout the Parkfield region indicate that the anticipated earthquake is imminent.'

Although the 'Parkfield earthquake' has not occurred, there have been several claims of possible precursors. Wyss, Bodin & Habermann (1990a) reported seismic quiescence (also see Stuart 1990) and Wyss, Slater & Burford (1990b) reported a decrease in deformation rate (but see Langbein 1991). Stuart (1991) presented a model to account for these observations. Wyss (1990) reported a change of mean magnitude, Wyss (1991c) reported an increased mean hypocentral depth, and Wyss, Habermann & Bodin (1992) reported seismic quiescence. Other possibly anomalous observations have been reported by Poley *et al.* (1987) (see also Stuart 1987), Roeloffs *et al.* (1989), Langbein, Burford & Slater (1990), Thurber (1996), Gwyther *et al.* (1996) and Linde *et al.* (1996) (also see Segall 1996).

Segall & Harris (1986, 1987) and Harris & Segall (1987) interpreted geodetic data as supporting the hypothesis of an $M=6$ earthquake near Parkfield within five years of 1988. Sung & Jackson (1988) disagreed. See the comment by Segall & Harris (1989) and the reply by Sung & Jackson (1989). Harris & Archuleta (1988) said that the next 'Parkfield earthquake' could be as large as $M=7.2$. Stuart, Archuleta & Lindh (1985) and Stuart & Tullis (1995) presented scenarios for pre-seismic deformation. Miller (1996) posited that the 'non-occurrence' of the 'Parkfield earthquake' was due to faulting during 1982–1985 in the New Idria, Coalinga and Kettleman Hills areas.

The Parkfield experiment has received extensive coverage (Lindh *et al.* 1979; Kerr 1984, 1985a,b, 1986a,b, 1988, 1990a, 1993; Katzoff 1985; Schaefer & Swinbanks 1990; Ellsworth 1993; Grant 1996). *Earthquakes and Volcanoes* (1988, Vol. 20, no. 2, pp. 41–91) published a special issue: 'Parkfield: The prediction ... and the promise'.

A system was established for issuing alarms. The highest category is an A-level alert, which means the estimated probability of an $M=6$ earthquake within the next 72 hr exceeds 37 per cent (Langbein 1993). A-level alerts are issued based on potential foreshocks, aseismic creep or a combination of the two. A-level alerts were issued on 20 October 1992 (Kerr 1992; Finn 1992; Langbein 1992, 1993) and 14 November 1993 (Wuethrich 1993). Both were false alarms.

Savage (1993) said that the basic fallacy of the Bakun & Lindh forecast was that alternatives to the 'characteristic earthquake' hypothesis were not considered. He notes that if an $M=6$ event were to occur today, it would be much better explained by hypotheses other than the characteristic earthquake hypothesis. Savage considered three hypotheses (noting others also were possible): (Q1) the Parkfield earthquakes were randomly drawn from a normal distribution with mean 21.9 yr and standard deviation 7.2 yr; (Q3) the Bakun & Lindh 'characteristic Parkfield earthquake hypothesis'; (Q2) a hypothesis similar to Q3, but including the irregular spacing of the 1922–1934–1966 sequence. Assuming for simplicity that these three hypotheses were mutually exclusive and exhaustive, Savage computed the posterior probabilities for various possible values of the prior probabilities, taking into account the fact that 'the next Parkfield earthquake' had not taken place by 1 January 1992. The calculation most favourable to the Bakun & Lindh hypothesis assigned prior probabilities of 10, 10 and 80 per cent to Q1, Q2 and Q3, respectively; the corresponding posterior probabilities as of 1992.0 were 40, 14 and 46 per cent respectively. Savage (private communication) recomputed the posterior probabilities as of 1997.4 to be 72, 10 and 18 per cent respectively. Thus Baysian reasoning rejects the 'characteristic Parkfield earthquake hypothesis'. Savage notes that if an M=6 event were to occur today, it would be better explained by hypotheses other than the characteristic earthquake hypothesis.

Kagan (1997b) noted the high probability that apparently periodic seismicity (like Parkfield) would randomly occur somewhere in California. He therefore questioned the premise that the Parkfield events were 'characteristic earthquakes'. Lomnitz (1994, pp. 53–54) made similar comments.

A special session, 'Recent Observations at Parkfield', was held at the Spring 1997 meeting of the American Geophysical Union (see Monastersky 1997). The call for papers (*Eos, Trans. Am. Geophys. Un.* 1997, **78**, 30) said:

'The intermediate-term prediction that the next Parkfield earthquake would occur before 1993 has been a failure; however, the Parkfield segment of the San Andreas fault is still unique in that it is the only place on Earth where we know the likely initiation point of a future significant earthquake. Thus, the ongoing monitoring effort at Parkfield should provide unique data on the initiation process.'

6.1 Evaluation of the Parkfield experiment

Bakun & Lindh (1985a) said:

'The next moderate Parkfield earthquake is expected to occur before 1993. The Parkfield prediction experiment is designed to monitor the details of the final stages of the earthquake preparation process; observations and reports of seismicity and aseismic slip associated with the last moderate Parkfield earthquake in 1966 constitute much of the basis of the design of the experiment.'

Board on Earth Sciences (1986) of the National Research Council said:

'Nowhere else in the world is a prediction in effect with a degree of confidence as high as that for Parkfield. Here, on a specific 25-kilometer segment of the San Andreas fault, about half way between Los Angeles and San Francisco, studies during the past decade indicate a 95 percent probability that an earthquake of about magnitude 6 will occur between 1986 and 1993. ... A significant scientific effort is currently underway, supported by both federal and California State funding, to monitor the Parkfield area with instruments, in the hope that it will be possible to predict the earthquake on a still shorter time scale—perhaps hours or days before the event. There are many scientific reasons for optimism that short-term precursors will in fact be observed and that a short-term prediction will be successful. ...

'However , because the current effort is centered on the placement of instruments at or near the ground surface, there is a high possibility that the next Parkfield earthquake will be predicted on an ad-hoc basis without yielding any real understanding of the physics of the fault-rupturing process and without giving us the fundamental scientific knowledge needed if we are to transfer this prediction capability to other faults in other geologic environments. To obtain the additional insight, it is clear that we must measure relevant physical parameters, such as stress, temperature, and fluid pore pressure, to depths several kilometers below the earth's surface, both before and after the earthquake. A truly unique opportunity exists at Parkfield to perform such critical experiments; but the sooner they commence, the greater the assurance that they will precede the earthquake.'

The Economist ('Small earthquake somewhere, next year—perhaps', 1 August 1987) reported:

'Parkfield is geophysics's Waterloo. If the earthquake comes there without warnings of any kind, earthquakes are unpredictable and science is defeated. There will be no excuses left, for never has an ambush been more carefully laid for such an event.'

Bakun (1987) said:

'As a prediction experiment, the principal goal of the Parkfield study is a detailed description of the final stages of the earthquake preparation process; observations at Parkfield should aid in the evaluation of the feasibility of intermediate- and short-term earthquake prediction elsewhere. Furthermore, the detailed history of strain accumulation and release over a complete cycle that is being recorded at Parkfield should provide the basis for testing and refining models for earthquake recurrence on plate boundaries.

'A secondary goal of the experiment is the issuance of a short-term warning by the USGS to the Governor's Office of Emergency Services, the agency responsible for public dissemination of any warning .... It is likely that the prediction experiment and the plans will serve as prototypes and stepping stones for future earthquake prediction efforts in the United States.'

Lindh (1990) commented:

'If we can successfully predict the next Parkfield earthquake, then the techniques developed there can be applied in urban areas of California where an early warning would do the most good. But given what we already know about the likelihood of a forthcoming earthquake that could be even more destructive than the recent Loma Prieta quake, I believe we should begin other prediction projects along the most dangerous segments of the San Andreas—even though we don't know what our chances are of producing a useful warning.'

The Parkfield experiment was evaluated by the NEPEC Working Group (Hager *et al.* 1994). Their report says:

'The relatively narrow window that was stated in the original prediction has led to expectations that the experiment would be over relatively quickly, leading to the misconception that the experiment has now somehow "failed" because the narrow time window has closed.

...

'The general public now perceives the Experiment primarily as a short-term earthquake forecasting project with an inherent expectation to accurately predict an earthquake, while the scientific community views it not only as a short-term prediction experiment but also as an effort to trap a moderate earthquake within a densely instrumented network. It is important to educate the public that there is great value to this monitoring effort even if the prediction effort is unsuccessful.

...

'Parkfield remains the best identified locale to trap an earthquake. The consensus is that the annual probability for the expected "characteristic" event is about 10% per year. At this level, the Working Group concludes that the Experiment should be continued, both for its geophysical and public response benefits.'

Tullis (1994) also advocated the continuation of the Parkfield Earthquake Prediction Experiment.

7 UNCONVENTIONAL METHODS

J. Zschau of the Geo-Research Centre in Potsdam, Germany, claims he can predict large earthquakes by detecting precursory decreases in seismicity using an algorithm he calls 'Seismolap' (see Geller 1997b). Zschau has not yet published on Seismolap in a major refereed journal (cited in Georefs, 1991–96), but has received extensive publicity in the mass media. Reasenberg (1996) applied the 'Seismolap' algorithm to seismicity in California:

'Seismolap appears to be unstable both in these forecasting tests and in the behaviour of the underlying algorithm, whose output is sensitive to the values selected for the free parameters. Seismolap calculations are often based on very small numbers of earthquakes, adding to its instability. And a non-linear filter in the algorithm apparently amplifies these instabilities. The result is that Seismolap tends to generate a large number of extrema and forecasts, some of which, apparently by chance, then become associated with some large earthquakes.'

Wadatsumi (1995) published a popular book detailing 1519 retrospective reports from ordinary citizens of allegedly anomalous phenomena that preceded the Kobe earthquake. Wadatsumi has set up a home page to collect reports of 'anomalous phenomena', and claims he will be able to give at least 24 hours warning before future large earthquakes. He appears frequently on television and in print media.

Y. Kushida, an amateur astronomer, claims that he can predict earthquakes with over 90 per cent accuracy, including events hundreds of kilometres from his observatory, based on 'anomalous FM radio waves'. His claims, which apparently have not been published in a refereed journal, have been widely reported on television and in newspapers. Uyeda & Nagao (1997) described a project that includes Kushida's work.

Earthquake predictions by amateurs are an old story. USGS researchers collected 2500 predictions and found that the success rate did not exceed random chance (Hunter 1976; Hunter & Derr 1978; Anonymous 1978).

8 ROLE OF THE MEDIA

'Since my first attachment to seismology, I have had a horror of predictions and of predictors. Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough .... [Prediction] provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers. The vaporings of such people are from time to time seized upon by the news media, who then encroach on the time of men who are occupied in serious research.'

—C. F. Richter (1977)

8.1 Publicly announced predictions

The Jupiter Effect: Gribben (1971) suggested that earthquakes were correlated with sunspots or planetary alignments. Gribben, by then a member of *Nature*'s editorial staff, published a popular book, *The Jupiter Effect* (Gribben & Plagemann 1974). This book's thesis is (p. 116):

'A remarkable chain of evidence, much of it known for decades but never before linked together, points to 1982 as the year in which the Los Angeles region of the San Andreas fault will be subjected to the most massive earthquake known in the populated regions of the earth in this century. At the end point of this chain, directly causing this disaster, is a rare alignment of the planets in the Solar System.'

Insightful book reviews were published by Kaula (1974), Anderson (1974) and Bolt (1975). Several criticisms (Meeus 1975a,b, 1976; Ip 1976; Hughes 1977) were published, with replies by the authors (Gribben 1975, 1976; Gribben & Plagemann 1975). Los Angeles was not 'subjected to a massive earthquake' in 1982.

North Carolina, 1975–1976: David Stewart, a faculty member of the University of North Carolina, predicted 'a major earthquake in the next few decades or less' in the coastal Wilmington area, near a nuclear reactor (Stewart 1975). Stewart's data (claims of crustal uplift) were shown to be in error. According to Spence *et al.* (1993), Stewart then collaborated with a self-proclaimed psychic, Clarissa Bernhardt, who made 13 specific and general earthquake predictions, one of which (Kerr 1991; Mileti & Fitzpatrick 1993, p. 52) was for an $M=8$ earthquake. According to the *St. Louis Post-Dispatch* newspaper (21 October 1990, 'He Calls it "a Fact"—State's Quake Expert Believes in Psychic Phenomena', reproduced by Spence *et al.* 1993, p. 120) Stewart and Bernhardt publicly predicted an $M=8.0$ event, most likely within three days of 17 January 1976. Widespread public disquiet reportedly occurred; the prediction failed.

Los Angeles, 1976: (see Turner *et al.* 1986, pp. 8, 45–50). Henry Minturn, a self-styled PhD geophysicist, claimed in a local television program on 22 November 1976 to have predicted many earthquakes successfully in Latin America; he forecast a large earthquake in Los Angeles on 20 December. The basis was 'the gravitational pull of the moon on "weak arches" in the earth's crust'. This received extensive coverage, but when Minturn's claim to have a PhD was revealed to be false, the story died out quickly.

Oaxaca, Mexico, 1978: (see Section 4.2; Garza & Lomnitz 1979; Lomnitz 1994, pp. 122–127). A crank letter to the governor of Oaxaca in January 1978 predicted a large earthquake on 23 April 1978. A press conference was called to publicise the long-term forecast by Ohtake *et al.* (1977), and a news story 'Texas U Predicts Big Mexico Quake' (reproduced by Lomnitz 1994, p. 124) was published in the *Mexico City News* newspaper on 10 April 1978. These two predictions were wrongly taken as identical by the public. Considerable public disquiet and economic loss occurred.

Peru, 1981: (see Kerr 1981b,c; Richman 1981a,b; Giesecke 1983; Echevarría, Norton & Norton 1986; Olson, Podesta & Nigg 1989.) Brian Brady, a researcher at the US Bureau of Mines, said that events with $M_W=9.8$ and $M_W=8.8$ would occur at the subduction zone off the coast of Peru in August 1981 and May 1982, respectively. A foreshock with $M_W=7.5$–8 was forecast for June 1981. The scientific rationale for these predictions was given by Brady (1976, pp. 1068–1069). NEPEC issued a statement (reproduced in full by Richman 1981a) rejecting the prediction:

> 'The council regrets that an earthquake prediction based on such speculative and vague evidence has received widespread credence outside the scientific community. We recommend that the prediction not be given serious consideration by the government of Peru.'

When the foreshock failed to occur, Brady retracted his prediction. An official of the USGS had to travel to Lima in June 1981 to reassure the Peruvian people.

Missouri, USA, 1990: (see Kerr 1990b, 1991; Gori 1993; Dalrymple 1991; Spence *et al.* 1993). Iben Browning, a business consultant with a PhD in biology but no background in earth science, predicted that an $M=6.5$–7.5 earthquake would strike New Madrid, Missouri (250 km SE of St. Louis) between December 1 and 5, 1990. Browning's promotional efforts generated a flood of publicity. Due to the panic, public schools were closed on December 3. Browning profited by selling explanatory video tapes at $99 a copy. David Stewart (see above), then Director of the Center for Earthquake Studies at Southeast Missouri State University, said that Browning's prediction was worthy of serious consideration. The media treated this as an authoritative endorsement. Browning claimed to have made a successful prediction of the 1989 October 18 Loma Prieta earthquake. His claim was accepted without investigation by the press, but a transcript of his speech (Spence *et al.* 1993, p. 64) shows that there was no mention of an earthquake occurring in the San Francisco area, or even California. An Ad Hoc Working Group showed that Browning's prediction was without merit (Spence *et al.* 1993, pp. 45–66).

Greece, 1991: (see Drakopoulos & Stavrakakis 1996 and response by Varotsos, Eftaxias & Lazaridou 1996d). A prediction of an $M=5.5$–6.0 event in Thessaloniki was announced on television and in newspapers by P. Varotsos and co-workers. The prediction, which was ultimately a failure, caused considerable unrest.

Central California, 1995: C. G. Sammis predicted an $M=6.0$–6.5 earthquake in central California during 1 February–9 July 1995. The prediction (*Los Angeles Times* newspaper, 29 April 1995, 'USC Geology Chairman Forecasts Quake') failed (follow-up story, 'Quake Prediction Error Can't Shake 2 Scientists' Core Beliefs', 3 August 1995).

Tokyo, 1995: (see Geller 1996c). A 'former JMA employee' (whose routine duties had no connection with seismology) announced in the spring of 1995 that an $M=8.0$ quake would hit Tokyo at 12:37 pm on 9 September 1995. The nominal basis was planetary alignment. No panic resulted, but this groundless prediction was extensively publicised. The JMA received many calls from worried citizens.

8.2 Reports in Nature and Science

VAN's claims (Sections 4.5 and 8.1) were reported in *Nature* (Masood 1995a,b) and *Science* (Kerr 1995). *Science*'s headline, 'Quake prediction tool gains ground', was overly optimistic. The above articles credit VAN with 'successful predictions', although this is presented as a claim by Varotsos rather than as fact. Masood (1995a) reported:

> 'Varotsos says that, using the VAN method, he has correctly predicted the timing, magnitude and location of the three most recent earthquakes in Greece. He has been faxing information on the predicted timing and magnitude of each earthquake to 29 seismological institutes worldwide. [Varotsos asks:] "How many more people will have to die before this method is recognized as being correct." '

Masood (1995b) reported:

> '[Varotsos] says peer review "cannot go on forever" if lives are at risk, just as pharmaceutical companies are allowed to halt trials for AIDS drugs and rush them to market if patients show signs of living longer. "If anyone has doubts about VAN they need to come out with concrete scientific facts. So far I have predicted the last three big earthquakes in Greece, which, statistically, is [*sic*] a one-in-seven million chance of happening. This is no fluke, it is based on good science." '

Kerr (1995) reported:

> 'And the results, Varotsos told *Science*, have been consistently successful. In the past 9 years, he says, 14 earthquakes of magnitude 5.8 or larger have struck Greece, three of which fell outside his network. Of

the remaining 11, 10 were predicted weeks in advance, he says; only one prediction failed, and there were one or two false alarms.'

Neither *Nature* nor *Science* published a book review or article on the Proceedings of the May 1995 London meeting (Lighthill 1996). A special issue of *Geophysical Research Letters*, 'Debate on VAN' (Geller 1996a), also went unreported, as did the study of Gruszow *et al.* (1996).

The above articles presented VAN's claims as controversy rather than fact, but this nuance was lost on the *Los Angeles Times* newspaper, which reported ('Quake Prediction Technique Shows Promise', 4 January 1996):

'The journal *Science* recently reported that over the last nine years, 10 of the 11 earthquakes of magnitude 5.8 or greater that occurred within the area being monitored had been predicted by Greek physicist Panayiotis Varotsos and his team.'

9 IS PREDICTION POSSIBLE?

Lerner-Lam (1997) said:

'Can earthquakes be predicted? This is what society wants to know, yet most of us think this question is not properly posed. But declaring earthquakes to be "unpredictable" does a disservice to the state of our science and, quite frankly, doesn't do the public any good.

...

'The falsification of a particular methodology does not indict an entire field, particularly one in which the set of observations is incomplete. Personally, I am not ready to declare earthquakes inherently unpredictable.'

Observations will always be 'incomplete', but observational techniques have improved dramatically in the past two decades. Digital seismograms are available via the Internet. The Harvard catalogue (Dziewonski, Ekström & Salganik 1996) gives routine CMT solutions for all significant events. Seismic field surveys are made with broad-band digital instruments. Static displacements are accurately measured with GPS or other space-based techniques (e.g. Dixon, Mao & Stein 1996). However, no reliable precursors have yet been reported on the basis of these new data. This is further reason for pessimism about prediction.

9.1 Chaos, SOC and predictability

Chaos—the highly sensitive non-linear dependence of the evolution of physical systems on the initial conditions— places inherent limits on the predictability of many physical phenomena, including earthquakes (e.g. Anderson 1990; Kagan 1994; Main 1996). Even before chaos became a widely used term, seismologists were intuitively familiar with the concept. Richter (1958, pp. 385–386) commented as follows:

'At present there is no possibility of earthquake prediction in the popular sense; that is, no one can justifiably say that an earthquake of consequence will affect a named locality on a specified future date. It is uncertain whether any such prediction will be possible in the foreseeable future; the conditions of the problem are highly complex. One may compare it to the situation of a man who is bending a board across his knee and attempts to determine in advance just where and when the cracks will appear.'

Bak and co-workers introduced the term 'self-organized criticality' (SOC) to describe systems teetering on the edge of instability with no critical length scale (Bak, Tang & Wiesenfeld 1988; Bak 1996). Many systems, including earthquakes, appear to exhibit such instability. The SOC model suggests that any small earthquake has some probability of cascading into a large earthquake. Whether or not this happens depends on unmeasurably fine details throughout a large volume, not just the immediate vicinity of the hypocentre. Critical phenomena in such systems ubiquitously have power-law distributions such as the Gutenberg–Richter law (Kagan 1994; Abercrombie & Brune 1994; Main 1995; Sornette *et al.* 1996; Abercrombie 1996; Kagan 1997c) in seismology.

Theoretical studies using simple models have concluded that whether or not an event grows into a large 'earthquake' depends unpredictably on small variations in elastic properties, fault strength and stored elastic energy (e.g. Otsuka 1972a,b; Vere-Jones 1976; Bak & Tang 1989; Ito & Matsuzaki 1990). Brune (1979) pointed out that if any small earthquake could grow into a large one, prediction would not be possible. Kittl, Díaz & Martínez (1993) used a probabilistic fracture model to argue that deterministic prediction of the origin time and magnitude of an earthquake is impossible. However, Ben-Zion & Rice (1995) presented models in which large earthquakes are quasi-periodic. The above 'earthquake-like' models show how easy it is for a deterministic system to be effectively unpredictable. There is no compelling reason to think these arguments do not also apply to earthquakes.

9.2 Rupture initiation

Vidale (1996) and Beroza (1997) represent the question of the existence and size of the nucleation zone as important for determining whether prediction is possible. Ellsworth & Beroza (1995) and Beroza & Ellsworth (1996) claimed they could identify a 'nucleation phase' in seismograms, but there are no objective criteria. Dodge, Beroza & Ellsworth (1996) claimed to have found evidence of slip localization in foreshock sequences, but only six events were studied.

High-resolution near-field strain and tilt recordings presented by Johnston *et al.* (1987) showed no evidence of pre-seismic strain or tilt perturbations from hours to seconds (or less) before several moderately large earthquakes. Mori & Kanamori (1996) showed that the initial rupture was indistinguishable for earthquakes ranging from $M=0.5$ to $M=5.0$.

Experiments in fracture mechanics (Marder & Fineberg 1996) showed that cracks accelerate in less than a microsecond to a substantial fraction of the speed of sound. There are no compelling reasons for supposing faulting in the Earth to be significantly different, which suggests it is extremely difficult to observe the nucleation process.

10 DISCUSSION

'... the intensity of the conviction that a hypothesis is true has no bearing on whether it is true or not.'

— P. B. Medawar, 1979, *Advice to a Young Scientist*, p. 39

The idea that there must be empirically identifiable precursors before large earthquakes is intuitively appealing, but studies over the last 120 years have failed to support it. Efforts to make longer-term deterministic forecasts, as discussed in this issue by Kagan (1997a), have also been notably unsuccessful. Claims that prediction efforts have failed due to a lack of instrumentation seem unconvincing in view of the great qualitative and quantitative advances in observational networks for seismology and geodesy. Recent results in non-linear dynamics are consistent with the idea that earthquakes are inherently (or effectively) unpredictable due to highly sensitive non-linear dependence on the initial conditions.

We are overdue for a paradigm shift: it appears that the occurrence of individual earthquakes is unpredictable.

ACKNOWLEDGMENTS

I thank the following people (listed alphabetically) for comments and discussion on this paper or earlier related papers, and/or for information and copies of difficult-to-obtain literature: Clarence Allen, Don Anderson, Yehuda Ben-Zion, Greg Beroza, Craig Bina, Phil Campbell, Bob Castle, Bill Ellsworth, Russ Evans, Ruth Harris, Jack Healy, Tom Henyey, Dave Jackson, Malcolm Johnston, Tom Jordan, Yan Kagan, Hiroo Kanamori, Peter Leary, Al Lindh, Ian Main, Tom McEvilly, Andy Michael, Francesco Mulargia, Emile Okal, Paul Reasenberg, David Rhoades, Jim Savage, Bill Spence, Philip Stark, Seth Stein, Stathis Stiros, Joann Stock, Richard Strelitz, Nozomu Takeuchi, Albert Tarantola, Cliff Thurber, Jim Whitcomb, Max Wyss, two anonymous referees and an anonymous editor. I particularly thank those researchers who disagree with my views but nonetheless made constructive criticisms that contributed greatly to the improvement of this manuscript.

REFERENCES

Abelson, P.H., 1973. Observing and predicting earthquakes, *Science*, **180**, 819.

Abercrombie, R.E., 1996. The magnitude-frequency distribution of earthquakes recorded with deep seismometers at Cajon Pass, southern California, *Tectonophysics*, **261**, 1–7.

Abercrombie, R.E. & Brune, J.N., 1994. Evidence for a constant *b*-value above magnitude 0 in the southern San Andreas, San Jacinto and San Miguel fault zones, and at the Long Valley caldera, California, *Geophys. Res. Lett.*, **21**, 1647–1650.

Abercrombie, R.E. & Mori, J., 1996. Occurrence patterns of foreshocks to large earthquakes in the western United States, *Nature*, **381**, 303–307.

Aceves, R.L. & Park, S.K., 1997. Cannot earthquakes be predicted?, *Science*, **278**, 488.

Adams, R.D., 1976. The Haicheng, China, earthquake of 4 February 1975: The first successfully predicted major earthquake, *Earthq. Eng. Struct. Dyn.*, **4**, 423–437.

Adams, R.D., 1977. Earthquake prediction, *Nature*, **269**, 14.

Aggarwal, Y.P., Sykes, L.R., Armbruster, J. & Sbar, M.L., 1973. Premonitory changes in seismic velocities and prediction of earthquakes, *Nature*, **241**, 101–104.

Aggarwal, Y.P., Sykes, L.R., Simpson, D.W. & Richards, P.G., 1975. Spatial and temporal variations in t_s/t_p and in *P* wave residuals at Blue Mountain Lake, New York: Application to earthquake prediction, *J. geophys. Res.*, **80**, 718–732.

Agnew, D.C. & Ellsworth, W.L., 1991. Earthquake prediction and long-term hazard assessment, *Rev. Geophys. Suppl.*, **29**, 877–889.

Agnew, D.C. & Jones, L.M., 1991. Prediction probabilities from foreshocks, *J. geophys. Res.*, **96**, 11 959–11 971.

Aki, K., 1978. Progress in Japanese earthquake prediction research, *Earthq. Info. Bull.*, **10**, 200–203.

Aki, K., 1980. Possibilities of seismology in the 1980's, *Bull. seism. Soc. Am.*, **70**, 1969–1976.

Aki, K., 1989. Ideal probabilistic earthquake prediction, *Tectonophysics*, **169**, 197–198.

Aki, K., 1995. Earthquake prediction, societal implications, *Rev. Geophys. Suppl.*, **33**, 243–247.

Allen, C.R., 1976. Responsibilities in earthquake prediction, *Bull. seism. Soc. Am.*, **66**, 2069–2074.

Allen, C.R., 1982. Earthquake prediction—1982 overview, *Bull. seism. Soc. Am.*, **72**, S331–S335.

Allen, C.R. & Helmberger, D.V., 1973. Search for temporal changes in seismic velocities using large explosions in southern California, in *Proc. Conf. Tectonic Problems of the San Andreas Fault System*, eds Kovach, R.L. & Nur, A., Vol. 13, pp. 436–445, Stanford Univ. Publ. Geol. Sci., Stanford, CA.

Allen, C.R. *et al.*, 1968. The Borrego Mountain, California, earthquake of 9 April 1968: A preliminary report, *Bull. seism. Soc. Am.*, **58**, 1183–1186.

Allen, C.R. (Chairman), Edwards, W., Hall, W.J., Knopoff, L., Raleigh, C.B., Savit, C.H., Toksöz, M.N. & Turner, R.H., 1976. *Predicting Earthquakes: A Scientific and Technical Evaluation—With Implications for Society*, Panel on Earthquake Prediction of the Committee on Seismology, Assembly of Mathematical and Physical Sciences, National Research Council, U.S. National Academy of Sciences, Washington, DC.

Alsop, L.E. & Oliver, J.E. (eds), 1969. Premonitory phenomena associated with several recent earthquakes and related problems, *Eos, Trans. Am. geophys. Un.*, **50**, 376–410.

Anderson, D.L., 1974. The Jupiter effect (book review), *Am. Scientist*, **62**, 721–722.

Anderson, D.L. & Whitcomb, J.H., 1975. Time-dependent seismology, *J. geophys. Res.*, **80**, 1497–1503.

Anderson, P.W., 1990. On the nature of physical laws, *Physics Today*, **43**(12), 9.

Anderson, P.W., 1992. The Reverend Thomas Bayes, needles in haystacks, and the fifth force, *Physics Today*, **45**(1), 9–11.

Ando, M., 1975. Possibility of a major earthquake in the Tokai district, Japan, and its pre-estimated seismotectonic effects, *Tectonophysics*, **25**, 69–85.

Anonymous, 1912. *Nature*, **90**, 340.

Anonymous, 1922. Geological Society, *Nature*, **109**, 361.

Anonymous, 1927. Earthquake prediction in California, *Nature*, **119**, 684.

Anonymous, 1931a. Luminous phenomena accompanying earthquakes, *Nature*, **128**, 155.

Anonymous, 1931b. Active earthquake-faults in Tokyo, *Nature*, **127**, 796.

Anonymous, 1932a. Luminous phenomena accompanying earthquakes, *Nature*, **129**, 27.

Anonymous, 1932b. Luminous phenomena accompanying earthquakes, *Nature*, **130**, 969.

Anonymous, 1933a. Sensitivity of fish to earthquakes, *Nature*, **132**, 817.

Anonymous, 1933b. Birds and earthquakes, *Nature*, **132**, 964.

Anonymous, 1972a. Predicting earthquakes, *Nature*, **237**, 305.

Anonymous, 1972b. Scientific activities of IASPEI during the fifteenth general assembly, *Eos, Trans. Am. geophys. Un.*, **53**, 235–236.

Anonymous, 1973a. Precursory V_P/V_S changes, *Nature*, **243**, 380.

Anonymous, 1973b. Using prediction properly, *Nature*, **245**, 174.

Anonymous, 1973c. No dilatancy, *Nature*, **246**, 332–333.

Anonymous, 1974. New method of predicting earthquakes, *Nature*, **247**, 253.

Anonymous, 1975a. Progress of U.S.–USSR cooperative program in earthquake prediction, *Eos, Trans. Am. geophys. Un.*, **56**, 524.

Anonymous, 1975b. The Chinese dimension, *Nature*, **258**, 277.

Anonymous, 1976. Still a lot to learn from the Chinese, *Nature*, **262**, 431.

Anonymous, 1978. Amateur earthquake predictions, *Eos, Trans. Am. geophys. Un.*, **59**, 963.

Anonymous, 1982. Cooperative seismology studies between the U.S. and the People's Republic of China, *Earthq. Info. Bull.*, **14**, 144–146.

Anonymous, 1995. Japan's seismic tragedy at Kobe, *Nature*, **373**, 269.

Anonymous, 1996. Money doesn't buy quake prediction faith, *Science*, **271**, 915.

Aoki, H., 1996. Critical state of the crust and earthquake precursors, *Kagaku*, **65**, 232–240 (in Japanese).

Asada, T. (ed.), 1982. *Earthquake Prediction Techniques—Their Application in Japan*, University of Tokyo Press, Tokyo.

Ashida, M., 1997. The large-scale earthquake countermeasures act should be repealed immediately, *Ronza*, Feb. 1997, 50–55 (in Japanese).

Aster, R.C., Shearer, P.M. & Berger, J., 1990. Quantitative measurements of shear wave polarizations at the Anza seismic network, southern California: Implications for shear wave splitting and earthquake prediction, *J. geophys. Res.*, **95**, 12 449–12 473.

Aster, R.C., Shearer, P.M. & Berger, J., 1991. Reply, *J. geophys. Res.*, **96**, 6415–6419.

Aziz, A., 1942. Luminous phenomena accompanying the Cyprus earthquake, January 20, 1941, *Nature*, **149**, 640.

Bak, P., 1996. *How Nature Works: the Science of Self-Organized Criticality*, Copernicus, New York, NY.

Bak, P. & Tang, C., 1989, Earthquakes as a self-organized critical phenomenon, *J. geophys. Res.*, **94**, 15 635–15 637.

Bak, P., Tang, C. & Wiesenfeld, K., 1988. Self-organized criticality, *Phys. Rev.*, A, **38**, 364–374.

Bakun, W.H., 1987. Future earthquakes, *Rev. Geophys.*, **25**, 1135–1138.

Bakun, W.H. & Lindh, A.G., 1985a. The Parkfield, California, earthquake prediction experiment, *Science*, **229**, 619–624.

Bakun, W.H. & Lindh, A.G., 1985b. The Parkfield, California, prediction experiment, *Earthq. Predict. Res.*, **3**, 285–304.

Bakun, W.H. & McEvilly, T.V., 1979. Earthquakes near Parkfield, California: Comparing the 1934 and 1966 sequences, *Science*, **205**, 1375–1377.

Bakun, W.H. & McEvilly, T.V., 1984. Recurrence models and Parkfield, California, earthquakes, *J. geophys. Res.*, **89**, 3051–3058.

Ben-Menahem, A., 1995. A concise history of mainstream seismology – origins, legacy, and perspectives, *Bull. seism. Soc. Am.*, **85**, 1202–1225.

Ben-Zion, Y. & Rice, J.R., 1995. Slip patterns and earthquake populations along different classes of faults in elastic solids, *J. geophys. Res.*, **100**, 12 959–12 983.

Berckhemer, H. (ed.), 1985. Special issue: Proceedings of the ESC symposium on earthquake prediction research, *Earthq. Predict. Res.*, **3**, 69–201.

Bernard, P., Pinettes, P., Hatzidimitriou, P.M., Scordilis, E.M., Veis, G. & Paraskevas, M., 1997. From precursors to prediction: A few recent cases from Greece, *Geophys. J. Int.*, **131**, 467–477 (this issue).

Beroza, G., 1996. Rupture history of the earthquake from high-frequency strong-motion data, in *The Loma Prieta, California Earthquake of October 17, 1989—* Main-shock Characteristics, U.S. Geological Survey Professional Paper 1550-A, pp. A9–A32.

Beroza, G., 1997. Earthquake seismology, *Geotimes*, **42**(2), 53–54.

Beroza, G. & Ellsworth, W.L., 1996. Properties of the seismic nucleation phase, **261**, 209–227.

Berry, M.J. (ed.), 1989. Special issue: Earthquake hazard assessment and prediction, *Tectonophysics*, **167**, 81–361.

Board on Earth Sciences, 1986. A Proposed Initiative for Capitalizing on the Parkfield, California, Earthquake Prediction, *Commission on Physical Sciences, Mathematics, and Resources*, National Research Council, National Academy Press, Washington, DC.

Bock, Y., 1994. Crustal deformation and earthquakes, *Geotimes*, **39**(6), 16–18.

Bock, Y. *et al.*, 1993. Detection of crustal deformation from the Landers earthquake sequence using continuous geodetic measurements, *Nature*, **361**, 337–340.

Bolt, B.A., 1974. Earthquake studies in the People's Republic of China, *Eos, Trans. Am. geophys. Un.*, **55**, 108–117.

Bolt, B.A., 1975. Book review of *The Jupiter Effect*, *Physics Today*, **28**(4), 74–75.

Boulanger, Y.D. & Vyskočil, P. (eds), 1992. Special issue on Geodesy—Seismology: Deformations and Prognosis, *Tectonophysics*, **202**, 97–290.

Bowman, J.R., 1997. Case 22: A seismicity precursor to a sequence of M_s 6.3—6.7 midplate earthquakes in Australia, *Pure appl. Geophys.*, **149**, 61–78.

Brace, W.F., 1975. The physical basis for earthquake prediction, *Technology Review*, March/April 1975 issue, 26–29.

Brady, B.T., 1976. Theory of earthquakes — IV. General implications for earthquake prediction, *Pure appl. Geophys.*, **114**, 1031–1082.

Brune, J.N., 1974. Current status of understanding quasi-permanent fields associated with earthquakes, *Eos, Trans. Am. geophys. Un.*, **55**, 820–827.

Brune, J.N., 1979. Implications of earthquake triggering and rupture propagation for earthquake prediction based on premonitory phenomena, *J. geophys. Res.*, **84**, 2195–2198.

Burts, E. *et al.*, 1983. Earthquake prediction and preparedness in Japan, *Earthq. Info. Bull.*, **15**, 142–147.

Buskirk, R.E., Frohlich, C. & Latham, G.V., 1981. Unusual animal behaviour before earthquakes: A review of possible sensory mechanisms, *Rev. Geophys. Space Phys.*, **19**, 247–270.

Carlowicz, M., 1996. Japan, U.S. plan joint earthquake research, *Eos, Trans. Am. geophys. Un.*, **77**, 377–378.

Carter, L.J., 1966. Earthquake prediction: ESSA and USGS vie for leadership, *Science*, **151**, 181–183.

Castle, R.O., 1978. Leveling surveys and the southern California uplift, *Earthq. Info. Bull.*, **10**, 88–92.

Castle, R.O. & Gilmore, T.D., 1992. A revised configuration of the southern California uplift, *Geol. Soc. Am. Bull.*, **104**, 1577–1591.

Castle, R.O., Alt, J.N., Savage, J.C. & Balzars, E.I., 1974. Elevation changes preceding the San Fernando earthquake of February 9, 1971, *Geology*, **2**, 61–66.

Castle, R.O., Church, J.P., Elliott, M.R. & Morrison, N.L., 1975. Vertical crustal movements preceding and accompanying the San Fernando earthquake of February 9, 1971: A summary, *Tectonophysics*, **29**, 127–140.

Castle, R.O., Church, J.P. & Elliott, M.R., 1976. Aseismic uplift in southern California, *Science*, **192**, 251–253.

Castle, R.O., Elliott, M.R., Gilmore, T.D., Mark, R.K., Newman, E.B. & Tinsley, J.C., III, 1981. Aseismic uplift in California, *Science*, **213**, 246–247.

Castle, R.O., Church, J.P., Elliot, M.R., Gilmore, T.D., Mark, R.K., Newman, E.B. & Tinsley, J.C., III, 1983a. Comment on 'The impact of refraction correction on leveling interpretations in southern California,' by William E. Strange, *J. geophys. Res.*, **88**, 2508–2512.

Castle, R.O., Brown, B.W., Jr., Gilmore, T.D., Mark, R.K. & Wilson, R.C., 1983b. An examination of the southern California field test for the systematic accumulation of the optical refraction error in geodetic leveling, *Geophys. Res. Lett.*, **10**, 1081–1084.

Castle, R.O., Elliott, M.R., Church, J.P. & Wood, S.H., 1984. *The Evolution of the Southern California Uplift, 1955 Through 1976*, U.S. Geological Survey Professional Paper 1342, Washington, DC.

Castle, R.O., Elliott, M.R. & Gilmore, T.D., 1987. *An Early-20th Century Uplift in Southern California*, U.S. Geological Survey Professional Paper 1362, Washington, DC.

Chan, W., 1989. Congressional hearing looks at lessons of quake, *AGU Daily in San Francisco*, 5 December 1989, p. 1.

Chen, Y.-T., Chen, Z.-L. & Wang, B.Q., 1992. Seismological studies of earthquake prediction in China: a review, in *Earthquake Prediction – Proceedings of the International School of Solid Earth Geophysics, 5th course*, eds Dragoni, M. & Boschi, E., pp. 71–109, Il Cigno Galileo Galilei, Rome.

Chen, Z.-L., 1986. Earthquake prediction research in China: Status and prospects, *J. Phys. Earth*, **34**, S1-S11.

Chi, S.C., Reilinger, R.E., Brown, L.D. & Oliver, J.E., 1980. Leveling circuits and crustal movement, *J. geophys. Res.*, **85**, 1469–1474.

Chu, F.-M., 1976. An outline of prediction and forecast of Haicheng earthquake of M=7.3, in *Proc. Lectures by the Seismological Delegation of the People's Republic of China*, ed. Muller, P.M., Jet Propulsion Laboratory, Pasadena, CA, Rept SP 43–32, Aug. 1, 1976, pp. 11–19.

Chu, J.J., Gui, X., Dai, J., Marone, C., Spiegelman, M.W., Seeber, L. & Armbruster, J.G., 1996. Geoelectrical signals in China and the earthquake generation process, *J. geophys. Res.*, **101**, 13 869–13 882.

Coe, R.S., 1971. Earthquake prediction program: the People's Republic of China, *Eos, Trans. Am. geophys. Un.*, **52**, 940–943.

Crampin, S., 1987. The basis for earthquake prediction, *Geophys. J. R. astr. Soc.*, **91**, 331–347.

Crampin, S., 1988. Extensive-dilatancy anisotropy: New earthquake prediction tool, *Eos, Trans. Am. geophys. Un.*, **69**, 729.

Crampin, S. & Zatsepin, S.V., 1997. Changes of strain before earthquakes: The possibility of routine monitoring of both long-term and short-term precursors, *J. Phys. Earth*, **45**, 41–66.

Crampin, S., Booth, D.C., Evans, R., Peacock, S. & Fletcher, J.B., 1991. Comment on 'Quantitative measurements of shear wave polarizations at the Anza seismic network, southern California: Implications for shear wave splitting and earthquake prediction,' by Richard C. Aster, Peter M. Shearer, and Jon Berger, *J. geophys. Res.*, **96**, 6403–6414.

Craymer, M.R. & Vaníček, P., 1986. Further analysis of the 1981 southern California field test for leveling refraction, *J. geophys. Res.*, **91**, 9045–9055.

Craymer, M.R. & Vaníček, P., 1989. Comment on 'Saugus-Palmdale, California, field test for refraction error in historical leveling surveys' by R.S. Stein, C.T. Whalen, S.R. Holdahl, W.E. Strange, and W. Thatcher, and Reply to 'Comment on 'Further analysis of the 1981 southern California field test for levelling refraction by M.R. Craymer and P. Vaníček' by R.S. Stein, C.T. Whalen, S.R. Holdahl, W.E. Strange, and W. Thatcher,' *J. geophys. Res.*, **94**, 7667–7672.

Dalrymple, G.B., 1991. Good press for bad science, *Eos, Trans. Am. geophys. Un.*, **72**, 41.

Dambara, T., 1981. Geodesy and earthquake prediction, in *Current Research in Earthquake Prediction I*, pp. 167–220, ed. Rikitake, T., D. Reidel, Dordrecht/CAPJ, Tokyo.

Davies, D., 1973. Predicting earthquakes, *Nature*, **245**, 121–122.

Davies, D., 1974. Quake prediction no bonanza, *Nature*, **249**, 7.

Davies, D., 1975. Earthquake prediction in China, *Nature*, **258**, 286–287.

Davis, J.F. & Somerville, P., 1982. Comparison of earthquake prediction approaches in the Tokai area of Japan and in California, *Bull. seism. Soc. Am.*, **72**, S367–S392.

Davis, P.M., Jackson, D.D. & Kagan, Y.Y., 1989. The longer it has been since the last earthquake, the longer the expected time until the next?, *Bull. seism. Soc. Am.*, **79**, 1439–1456.

DeMets, C., 1997. Afterslip no longer an afterthought, *Nature*, **386**, 549–550.

de Montalk, R.W., 1934. Earthquakes: The futility of predicting them. *Bull. seism. Soc. Am.*, **24**, 100–108.

Deng, Q., Jiang, P., Jones, L.M. & Molnar, P., 1981. A preliminary analysis of reported changes in ground water and anomalous animal behaviour before the 4 February 1975 Haicheng earthquake, in *Earthquake Prediction: An International Review* Simpson, D.W. & Richards, P.G., eds, *Ewing Monograph Series* **4**, pp. 543–565, Am. Geophys. Un., Washington, DC.

Diaconis, P., 1978. Statistical problems in ESP research, *Science*, **201**, 131–136.

Dieterich, J.H., 1978. Preseismic fault slip and earthquake prediction, *J. geophys. Res.*, **83**, 3940–3948.

Dieterich, J.H. & Brace, W.F., 1975. Earthquake-related experimental studies in the USSR, *Eos, Trans. Am. geophys. Un.*, **56**, 221–223.

Dixon, T.H., Mao, A. & Stein, S., 1996. How rigid is the stable interior of the North American plate?, *Geophys. Res. Lett.*, **23**, 3035–3038.

Dodge, D.A., Beroza, G.C. & Ellsworth, W.L., 1996. Detailed observations of California foreshock sequences: Implications for the earthquake initiation process, *J. geophys. Res.*, **101**, 22 371–22 392.

Dologlou, E., 1993. A three year continuous sample of officially documented predictions issued in Greece using the VAN method: 1987–1989, *Tectonophysics*, **224**, 189–202.

Dragoni, M. & Boschi, E. (eds), 1992. *Earthquake Prediction – Proceedings of the International School of Solid Earth Geophysics, 5th course*, Il Cigno Galileo Galilei, Rome.

Drakopoulos, J. & Stavrakakis, G.N., 1996. A false alarm based on electrical activity recorded at a VAN-station in northern Greece in December 1990, *Geophys. Res. Lett.*, **23**, 1355–1358.

Dziewonski, A.M., Ekström, G. & Salganik, M.P., 1996. Centroid-moment tensor solutions for July-September 1995, *Phys. Earth planet. Inter.*, **97**, 3–13.

Echevarría, J.A., Norton, K.A. & Norton, R.D., 1986. The socio-economic consequences of earthquake prediction: A case study in Peru, *Earthq. Pred. Res.*, **4**, 175–195.

Ellsworth, W.L., 1993. Getting beyond numerology, *Nature*, **363**, 206–207.

Ellsworth, W.L. & Beroza, G.C., 1995. Seismic evidence for a nucleation phase, *Science*, **268**, 851–855.

Ellsworth, W.L. *et al.*, 1973. Point Mugu, California, earthquake of 21 February 1973 and its aftershocks, *Science*, **182**, 1127–1129.

Evans, J.W., 1923. Earthquake warnings, *Nature*, **112**, 538.

Evans, J.W., 1927. Earthquake warnings, *Nature*, **120**, 619.

Evernden, J.F., 1982. Earthquake prediction: What we have learned, and what we should do now, *Bull. seism. Soc. Am.*, **72**, S343–S349.

Evison, F.F. (Rapporteur), 1984. Code of practice for earthquake prediction, *IUGG Chronicle*, No. 165, 26–29 (Feb.).

Evison, F. (ed.), 1989. Special section on earthquake hazard and prediction: Time-variable earthquake hazard, *Tectonophysics*, **169**, 154–213.

Evison, F.F. & Rhoades, D.A., 1993. The precursory earthquake swarm in New Zealand: hypothesis tests, *New Zealand J. Geol. Geophys.*, **36**, 51–60 (correction p. 267).

Finn, R., 1992. Rumblings grow about Parkfield in wake of first earthquake prediction, *Nature*, **359**, 761.

Franklin, A., 1993. *The Rise and Fall of the Fifth Force*, Am. Inst. Phys., New York, NY.

Franks, F., 1981. *Polywater*, MIT Press, Cambridge, MA.

Fraser-Smith, A.C., Bernardi, A., McGill, P.R., Ladd, M.E., Heliwell, R.A. & Villard, O.G., Jr., 1990. Low-frequency magnetic field measurements near the epicentre of the M_s 7.1 Loma Prieta earthquake, *Geophys. Res. Lett.*, **17**, 1465–1468.

Fraser-Smith, A.C., Bernardi, A., Heliwell, R.A., McGill, P.R. & Villard, O.G., Jr., 1993. Analysis of low-frequency-electromagnetic-field measurements near the epicentre, in *The Loma Prieta, California, Earthquake of October 17, 1989—Preseismic Observations*, pp. C17–C25, ed. Johnston, M.J.S., U.S. Geological Survey Professional Paper 1550-C, Washington, DC.

Gao, W.-X. & Gao, Q.-H., 1995. Intensifying earthquake prediction in the light of action of international decade for natural disaster reduction, *Earthq. Res. China*, **9**, 211–217.

Garwin, L., 1989. A successful prediction?, *Nature*, **341**, 677.

Garza, T. & Lomnitz, C., 1979. The Oaxaca gap: A case history, *Pure appl. Geophys.*, **117**, 1187–1194.

Geller, R.J., 1991a. Shake-up for earthquake prediction, *Nature*, **352**, 275–276.

Geller, R.J., 1991b. Unpredictable earthquakes, *Nature*, **353**, 612.

Geller, R.J. (ed.), 1996a. Special issue: 'Debate on "VAN"', *Geophys. Res. Lett.*, **23**, 1291–1452.

Geller, R.J., 1996b. VAN: A critical evaluation, in *A Critical Review of VAN*, pp. 155–238, ed. Lighthill, J., World Scientific, Singapore.

Geller, R.J., 1996c. One year after the Kobe earthquake, *Shincho 45*, Feb. 1996 issue, 22–31 (in Japanese).

Geller, R.J., 1997a. Earthquakes: Thinking about the unpredictable, *Eos, Trans. Am. geophys. Un.*, **78**, 63–67.

Geller, R.J., 1997b. Predictable publicity, *Astronomy & Geophysics, J. R. Astr. Soc.*, Feb./March 1997 issue, **38**(1), 16–18 (reprinted 1997, *Seism. Res. Lett.*, **68**, 477–480).

Geller, R.J., Jackson, D.D., Kagan, Y.Y. & Mulargia, F., 1997a. Earthquakes cannot be predicted, *Science*, **275**, 1616–1617.

Geller, R.J., Jackson, D.D., Kagan, Y.Y. & Mulargia, F., 1997b. Cannot earthquakes be predicted?, *Science*, **278**, 488–490.

Geographical Survey Institute, 1979. *Summary of the First 10 Years of the Coordinating Committee for Earthquake Prediction*, Tsukuba (in Japanese).

Geschwind, C.-H., 1997. 1920s prediction reveals some pitfalls of earthquake forecasting, *Eos, Trans. Am. geophys. Un.*, **78**, 401–412.

Giesecke, A.A., 1983. Case history of the Peru prediction for 1980-81, in *Proc. Seminar Earthquake Prediction Case Histories* (Geneva, 12–15 October 1982), pp. 51–75, convened by Office of U.N. Disaster Relief Co-ordinator and UNESCO, UNDRO/83/33. GE.83-03321.

Gilbert, G.K., 1909. Earthquake forecasts, *Science*, **29**, 121–138.

Gladwin, M.T., Gwyther, R.L., Higbie, J.W. & Hart, R.G., 1991. A medium term precursor to the Loma Prieta earthquake?, *Geophys. Res. Lett.*, **18**, 1377–1380.

Gokhberg, M.B., Morgounov, V.A., Yoshino, T. & Tomizawa, I., 1982. Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan, *J. geophys. Res.*, **87**, 7824–7828.

Gokhberg, M.B., Gufeld, I.L., Rozhnoy, A.A., Marenko, V.F., Yampolsky, V.S. & Ponomarev, E.A., 1989. Study of seismic influence on the ionosphere by super long-wave probing of the Earth-ionosphere waveguide, *Phys. Earth planet. Inter.*, **57**, 64–67.

Gokhberg, M.B., Morgounov, V.A. & Pokhotelov, O.A., 1995. *Earthquake Prediction: Seismo-electromagnetic Phenomena*, Gordon & Breach, Amsterdam.

Goodstein, D.L., 1993. Richard P. Feynman, teacher, in *'Most of the Good Stuff.' Memories of Richard Feynman*, pp. 115–124, eds Brown, L.M. & Rigden, J.S., Am. Inst. Phys., New York, NY.

Gori, P.L., 1993. The social dynamics of a false earthquake prediction and the response by the public sector, *Bull. seism. Soc. Am.*, **83**, 963–980.

Grant, L.B., 1996. Uncharacteristic earthquakes on the San Andreas Fault, *Science*, **272**, 826–827.

Greathouse, L., 1980. Palmdale bulge still a puzzle, *Eos, Trans. Am. geophys. Un.*, **61**, 515–516.

Gribben, J., 1971. Relation of sunspot and earthquake activity, *Science*, **173**, 558.

Gribben, J., 1975. Predicting earthquakes, *Physics Today*, **28**(10), 13–15.

Gribben, J., 1976. The author comments, *Physics Today*, **29**(6), 11–13.

Gribben, J.R. & Plagemann, S.H., 1974. *The Jupiter Effect*, MacMillan, London.

Gribben, J. & Plagemann, S., 1975. Response to Meeus, *Icarus*, **26**, 268–269.

Griggs, D.T., Jackson, D.D., Knopoff, L. & Shreve, R.L., 1975. Earthquake prediction: Modeling the anomalous V_P/V_S source region, *Science*, **187**, 537–540.

Gruszow, S., Rossignol, J.C., Tzanis, A. & LeMouël, J.L., 1996. Identification and analysis ofelectromagnetic signals in Greece: the case of the Kozani earthquake VAN prediction, *Geophys. Res. Lett.*, **23**, 2025–2028.

Gu, G.-X., 1981. Strategy of earthquake prediction in China (A personal view), in *Earthquake Prediction: An International Review* eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 667–670, Am. Geophys. Un., Washington, DC.

Guha, S.K. & Patwardhan, A.M. (eds), 1988. *Earthquake Prediction—Present Status*, Proceedings of a symposium held in Pune, India, July 1986, Registrar, University of Poona, Pune, India.

Guidelines for earthquake predictors, 1983. *Bull. seism. Soc. Am.*, **73**, 1955–1956.

Gupta, H.K., 1997. Meeting focuses on catastrophic Asian earthquakes, *Eos, Trans. Am. geophys. Un.*, **78**, 147. (Correction, p.166.)

Gwyther, R.L., Gladwin, M.T., Mee, M. & Hart, R.H.G., 1996. Anomalous shear strain at Parkfield during 1993–94, *Geophys. Res. Lett.*, **23**, 2425–2428.

Haase, J.S., Shearer, P.M. & Aster, R.C., 1995. Constraints on temporal variations in velocity near Anza, California, from analysis of similar event pairs, *Bull. seism. Soc. Am.*, **85**, 194–206.

Hager, B.H. (chair), Cornell, C.A., Medigovich, W.M., Mogi, K., Smith, R.M., Tobin, L.T., Stock, J. & Weldon, R., 1994. Earthquake Research at Parkfield, California, for 1993 and Beyond—Report of the NEPEC [National Earthquake Prediction Evaluation Council] Working Group, *U.S. Geological Survey Circular*, **1116**.

Hagiwara, T., 1997. *Earthquake Prediction and Damage*, Maruzen, Tokyo (in Japanese).

Hagiwara, T. & Rikitake, T., 1967. Japanese program on earthquake prediction, *Science*, **157**, 761–768.

Hales, A.L. & Suzuki, Z. (eds), 1982. Special Issue: Earthquake prediction, *Tectonophysics*, **85**, 1–148.

Hamada, K., 1991. Unpredictable earthquakes, *Nature*, **353**, 611–612.

Hamada, K., 1992. Present state of earthquake prediction system in Japan, in *Earthquake Prediction—Proceedings of the International School of Solid Earth Geophysics, 5th course*, pp. 33–69, eds Dragoni, M. & Boschi, E., Il Cigno Galileo Galilei, Rome.

Hamilton, R.M., 1974. Earthquake prediction and public reaction, *Eos, Trans. Am. geophys. Un.*, **55**, 739–742.

Hammond, A.L., 1971. Earthquake prediction and control, *Science*, **173**, 316.

Hammond, A.L., 1973a. Earthquake predictions: Breakthrough in theoretical insight?, *Science*, **180**, 851–853.

Hammond, A.L., 1973b. Earthquake prediction (II): Prototype instrumental networks, *Science*, **180**, 940–941.

Hammond, A.L., 1974. Dilatancy: Growing acceptance as an earthquake mechanism, *Science*, **184**, 551–552.

Hammond, A.L., 1975. Earthquake prediction: Progress in California, hesitation in Washington, *Science*, **187**, 419–420.

Hammond, A.L., 1976. Earthquakes: An evacuation in China, a warning in California, *Science*, **192**, 538–539.

Hanks, T.C., 1985. *The National Earthquake Hazards Reduction Program—Scientific Status*, U.S. Geological Bulletin 1659.

Hanks, T.C. & Kanamori, H. (eds), 1979. Special section: Fault mechanics and its relation to earthquake prediction, *J. geophys. Res.*, **84**, 2145–2370.

Hanks, T.C. & Krawinkler, H., 1991. The 1989 Loma Prieta earthquake and its effects: Introduction to the special issue, *Bull. seism. Soc. Am.*, **81**, 1415–1423.

Hao, J.-C., 1996. The sixth symposium of the Seismological Society of China held at Zhangjiajie, Hunan Province, China, *Acta seism. Sinica*, **9**, 695–696.

Harris, R.A., 1997. The Loma Prieta, California, Earthquake of October 17, 1989–Forecasts, *U.S. Geological Survey Professional Paper*, **1550-B**, in press.

Harris, R.A. & Segall, P., 1987. Detection of a locked zone at depth on the Parkfield, California, segment of the San Andreas fault, *J. geophys. Res.*, **92**, 7945–7962.

Harris, R.A. & Archuleta, R.J., 1988. Slip budget and potential for a M7 earthquake in Central California, *Geophys. Res. Lett.*, **15**, 1215–1218.

Hatzfeld, D. *et al.*, 1995. The Kozani-Grevena (Greece) earthquake of May 13, 1995, M_s=6.6. Preliminary results of a field multidisciplinary survey, *Seism. Res. Lett.*, **66**(6), 61–70.

Hayakawa, M. & Fujinawa, Y. (eds), 1994. *Electromagnetic Phenomena Related to Earthquake Prediction*, Terrapub, Tokyo.

Healy, J.H. & Pakiser, L.C., 1971. Man-made earthquakes and earthquake prediction, *Eos, Trans. Am. geophys. Un.* (Suppl., U.S. Natl. Rept. 1967–1971, 15th IUGG Genl. Assmbl.), **52**, IUGG 171–IUGG 174.

Healy, J.H., 1975. Recent highlights and future trends in research on earthquake prediction and control, *Rev. Geophys. Space Phys.*, **13**, 361–364; 390–392.

Heki, K., Miyazaki, S. & Tsuji, H., 1997. Silent fault slip following an interplate thrust earthquake at the Japan trench, *Nature*, **386**, 595–598.

Hickman, S., Sibson, R. & Bruhn, R. (eds), 1995. Special section: Mechanical involvement of fluids in faulting, *J. geophys. Res.*, **100**, 12 831–13 132.

Hill, D.P. *et al.*, 1993. Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, **260**, 1617–1623.

Hirose, H., 1985. Earthquake prediction in Japan and the United States, *Intl. J. Mass Emergencies Disasters*, **3**, 51–66.

Hobbs, W.H., 1907. *Earthquakes*, Appleton, New York, NY.

Hodgson, E.A., 1923. A proposed research into the possibilities of earthquake prediction, *Bull. seism. Soc. Am.*, **13**, 100–104.

Holdahl, S.R., 1982. Recomputation of vertical crustal motions near Palmdale, California, 1959–1975, *J. geophys. Res.*, **87**, 9374–9388.

Huebsch, I.O., 1978. Comment, *Eos, Trans. Am. geophys. Un.*, **59**, 2.

Hughes, D.W., 1977. Planetary alignments don't cause earthquakes, *Nature*, **265**, 13.

Huizenga, J.R., 1992. *Cold Fusion: The Scientific Fiasco of the Century*, University of Rochester Press, Rochester, NY.

Hunter, R.N., 1976. Earthquake prediction: Fact and fallacy, *Earthq. Info. Bull.*, **8**(5), 24–25.

Hunter, R.N. & Derr, J.S., 1978. Prediction monitoring and evaluation program: a progress report, *Earthq. Info. Bull.*, **10**, 93–96.

Igarashi, G. *et al.*, 1995. Ground-water radon anomaly before the Kobe earthquake in Japan, *Science*, **269**, 60–61.

Iizuka, S., 1976. Changes in V_P/V_S before the Tokachi-oki earthquake of May 16, 1968 off NE Japan, *Nature*, **260**, 415-417.

Imamura, A., 1937. *Theoretical and Applied Seismology*, Maruzen, Tokyo.

Ip, W.H., 1976. Chinese records on the correlation of heliocentric planetary alignments and earthquakes activities, *Icarus*, **29**, 435–436.

IPSAD, 1997. Abstracts, *United Nations International Conference on Integration of Public Administration and Science of Disasters*, 20–28 Jan. 1979, Beijing, U.N. Global Programme for the Integration of Public Administration and Science of Diasters.

Ishibashi, K., 1977. Re-examination of a great earthquake expected in the Tokai district, central Japan—possibility of the 'Suruga Bay earthquake', *Rep. Coord. Comm. Earthq. Pred.*, **17**, 126–132 (in Japanese).

Ishibashi, K., 1981. Specification of a soon-to-occur seismic faulting in the Tokai District, Central Japan, based upon seismotectonics, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series*, **4**, 297–332, Am. Geophys. Un., Washington, DC.

Ishibashi, K., 1985. Possibility of a large earthquake near Odawara, central Japan, preceding the Tokai earthquake, *Earthq. Predict. Res.*, **3**, 319–344.

Ito, K. & Matsuzaki, M., 1990. Earthquakes as self-organized critical phenomena, *J. geophys. Res.*, **95**, 6853–6860.

Jackson, D.D., 1996a. Hypothesis testing and earthquake prediction, *Proc. Nat. Acad. Sci. USA*, **93**, 3772–3775.

Jackson, D.D., 1996b. Earthquake prediction evaluation standards applied to the VAN method, *Geophys. Res. Lett.*, **23**, 1363–1366.

Jackson, D.D., Lee, W.B. & Liu, C.-C., 1980. Aseismic uplift in southern California: An alternative explanation, *Science*, **210**, 534–536.

Jackson, D.D., Lee, W.B. & Liu, C.C., 1981a. Height dependent errors in southern California leveling, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 457–472, Am. Geophys. Un., Washington, DC.

Jackson, D.D., Lee, W.B. & Liu, C.-C., 1981b. Aseismic uplift in southern California, *Science*, **213**, 247.

Jackson, D.D., Cheng, A. & Liu, C.C., 1983. Tectonic motions and systematic errors in leveling and trilateration data for California, *Tectonophysics*, **97**, 73–83.

Johnson, H.O. & Agnew, D.C., 1995. Monument motion and measurement of crustal velocities, *Geophys. Res. Lett.*, **22**, 2905–2908.

Johnston, M.J.S. (ed.), 1993. *The Loma Prieta, California, Earthquake of October 17, 1989—Preseismic Observations*, U.S. Geological Survey Professional Paper 1550-C, Washington, DC.

Johnston, M.J.S., 1997. Review of electrical and magnetic fields accompanying seismic and volcanic activity, *Surv. Geophys.*, **18**, 441–475.

Johnston, M.J.S. & Parrot, M. (eds), 1989. Special issue: Seismoelectromagnetic effects, *Phys. Earth planet. Inter.*, **57**, 1–177.

Johnston, M.J.S. & Parrot, M. (eds), 1993. Special issue: Seismo-electromagnetic effects, *Phys. Earth planet. Inter.*, **77**, 1–141.

Johnston, M.J.S., Linde, A.T., Gladwin, M.T. & Borcherdt, R.D., 1987. Fault failure with moderate earthquakes, *Tectonophysics*, **144**, 189–206.

Johnston, M.J.S., Linde, A.T. & Gladwin, M.T., 1990. Near-field high resolution strain measurements prior to the October 18, 1989 Loma Prieta M_s 7.1 earthquake, *Geophys. Res. Lett.*, **17,** 1777–1780.
Jones, L.M. & Hauksson, E., 1997. The seismic cycle in southern California: Precursor or response?, *Geophys. Res. Lett.*, **24,** 469–472.
Jones, L.M. & Molnar, P., 1979. Some characteristics of foreshocks and their possible relationship to earthquake prediction and premonitory slip on faults, *J. geophys. Res.*, **84,** 3596–3608.
Jones, L.M., Wang, B.-Q., Xu, S.-X. & Fitch, T.J., 1982. The foreshock sequence of the February 4, 1975 Haicheng earthquake (M = 7.3), *J. geophys. Res.*, **87,** 4575–4584.
Jordan, T.H. 1997. Is the study of earthquakes a basic science?, *Seism. Res. Lett.*, **68,** 259–261.
Kagan, Y.Y., 1994. Observational evidence for earthquakes as a nonlinear dynamic process, *Physica D*, **77,** 160–192.
Kagan, Y.Y., 1996a. VAN earthquake predictions—an attempt at statistical evaluation, *Geophys. Res. Lett.*, **23,** 1315–1318.
Kagan, Y.Y., 1996b. Comment on 'The Gutenberg-Richter or characteristic earthquake distribution, which is it?' by S. G. Wesnousky, *Bull. seism. Soc. Am.*, **86,** 274–285.
Kagan, Y.Y., 1997a. Are earthquakes predictable?, *Geophys. J. Int.*, **131,** 505–525 (this issue).
Kagan, Y.Y., 1997b. Statistical aspects of Parkfield earthquake sequence and Parkfield prediction experiment, *Tectonophysics*, **270,** 207–219.
Kagan, Y.Y., 1997c. Seismic moment-frequency relation for shallow earthquakes: Regional comparison, *J. geophys. Res.*, **102,** 2835–2852.
Kagan, Y.Y. & Jackson, D.D., 1996. Statistical tests of VAN earthquake predictions: Comments and reflections, *Geophys. Res. Lett.*, **23,** 1433–1436.
Kagan, Y. Y. & Knopoff, L., 1987. Statistical short-term earthquake prediction, *Science*, **236,** 1563–1567.
Kanamori, H., 1970. Recent developments in earthquake prediction research in Japan, *Tectonophysics*, **9,** 291–300.
Kanamori, H., 1996. Initiation process of earthquakes and its implications for seismic hazard reduction strategy, *Proc. Nat. Acad. Sci. USA*, **93,** 3726–3731.
Kanamori, H. & Fuis, G., 1976. Variation of P-wave velocity before and after the Galway Lake Earthquake ($M_L = 5.2$) and the Goat Moutain earthquakes ($M_L = 4.7, 4.7$), 1975, in the Mojave Desert, California, *Bull. seism. Soc. Am.*, **66,** 2017–2037.
Kanamori, H. & Satake, K., 1990. Broadband study of the 1989 Loma Prieta earthquake, *Geophys. Res. Lett.*, **17,** 1179–1182.
Katzoff, J.A., 1985. Earthquake watch to be discussed, *Eos, Trans. Am. geophys. Un.*, **66,** 773.
Kaula, W.M., 1974. The next California earthquake (book review), *Science*, **186,** 728–729.
Keilis-Borok, V.I., 1990. Special issue: Intermediate-term earthquake prediction: models, algorithms, world-wide tests, *Phys. Earth planet. Inter.*, **61,** 1–139.
Kerr, R.A., 1978. Earthquakes: prediction proving elusive, *Science*, **200,** 419–421.
Kerr, R.A., 1979a. Prospects for earthquake prediction wane, *Science*, **206,** 542–545.
Kerr, R.A., 1979b. Earthquake prediction: Mexican quake shows one way to look for the big ones, *Science*, **203,** 860–862.
Kerr, R.A., 1980. Quake prediction by animals gaining respect, *Science*, **208,** 695–696.
Kerr, R.A., 1981a. Palmdale bulge doubts now taken seriously, *Science*, **214,** 1331–1333.
Kerr, R.A., 1981b. Prediction of huge Peruvian quakes quashed, *Science*, **211,** 808–809.
Kerr, R.A., 1981c. Earthquake prediction retracted, *Science*, **213,** 527.
Kerr, R.A., 1984. Stalking the next Parkfield earthquake, *Science*, **223,** 36–38.
Kerr, R.A., 1985a. Earthquake forecast endorsed, *Science*, **228,** 311.
Kerr, R.A., 1985b. Prospects for short-term earthquake prediction, *Science*, **227,** 42.
Kerr, R.A., 1986a. Parkfield earthquake looks to be on schedule, *Science*, **231,** 116.
Kerr, R.A., 1986b. Quake prediction under way in earnest, *Science*, **233,** 520.
Kerr, R.A., 1988. Waiting for Parkfield—No precursors recognized, *Science*, **239,** 145–146.
Kerr, R.A., 1990a. Signs of the Parkfield quake?, *Science*, **249,** 1502.
Kerr, R.A., 1990b. Earthquake—or earthquack, *Science*, **250,** 511.
Kerr, R.A., 1991. The lessons of Dr. Browning, *Science*, **253,** 622–623.
Kerr, R.A., 1992. Seismologists issue a no-win earthquake warning, *Science*, **258,** 742–743.
Kerr, R.A., 1993. Parkfield quakes skip a beat, *Science*, **259,** 1120–1122.
Kerr, R.A., 1995. Quake prediction tool gains ground, *Science*, **270,** 911–912.
Kerr, R.A., 1997. Listening to silent earthquakes, *Science*, **276,** 1792–1793.
King, C.-Y., 1969. Seismic efficiency, *J. geophys. Res.*, **74,** 1702–1703.
King, C.-Y. (ed.), 1980. Special section: Geochemical measurements pertinent to earthquake prediction, *J. geophys. Res.*, **85,** 3051–3121.
King, C.-Y. (ed.), 1981. A special collection of reports on earthquake prediction: Hydrologic and geochemical studies, *Geophys. Res. Lett.*, **8,** 421–484.
King, C.-Y., 1983. Electromagnetic emissions before earthquakes, *Nature*, **301,** 377.
King, C.-Y., 1984. Evaluating hydrological and geochemical anomalies, *Nature*, **312,** 501.
King, C.-Y. (ed.), 1984/1985. Special issue: Earthquake hydrology and chemistry, *Pure appl. Geophys.*, **122,** 141–618.
King, C.-Y. (ed.), 1986. Special section: Gas geochemistry of volcanism, earthquakes, resource exploration, and Earth's interior, *J. geophys. Res.*, **91,** 12 157–12 388.
King, C.-Y., Koizumi, N. & Kitagawa, Y., 1995. Hydrogeochemical anomalies and the 1995 Kobe earthquake, *Science*, **269,** 38–39.
Kisslinger, C., 1974. Earthquake prediction, *Physics Today*, **27**(3), 36–42.
Kisslinger, C., 1976. The Earthquake Disaster Mitigation Act, *Eos, Trans. Am. geophys. Un.*, **57,** 437–440.
Kisslinger, C., 1978. Reply, *Eos, Trans. Am. geophys. Un.*, **59,** 2.
Kisslinger, C., 1983. Book review of *Earthquake Prediction Techniques: Their Application in Japan*, edited by T. Asada, *Eos, Trans. Am. geophys. Un.*, **64,** 105–106.
Kisslinger, C., 1984. Practical approaches to earthquake prediction and warning, *Eos, Trans. Am. geophys. Un.*, **65,** 398.
Kisslinger, C., 1989. Portents and predictions, *Nature*, **339,** 337–338.
Kisslinger, C. & Rikitake, T., 1974. U.S.–Japan seminar on earthquake prediction and control, *Eos, Trans. Am. geophys. Un.*, **55,** 9–15.
Kisslinger, C. & Wyss, M., 1975. Earthquake prediction, *Rev. Geophys. Space Phys.*, **13,** 298–300, 316–319.
Kisslinger, C. & Rikitake, T. (eds), 1985. Special issue: Proceedings of symposium on Practical Approaches to Earthquake Prediction and Warning, *Earthq. Predict. Res.*, **3,** 203–685.
Kisslinger, C., Mikumo, T. & Kanamori, H., 1988. U.S.–Japan quake prediction research, *Eos, Trans. Am. geophys. Un.*, **69,** 1672–1674.
Kittl, P., Diaz, G. & Martinez, V., 1993. Principles and the uncertainty principles of the probabilistic strength of materials and their applications to seismology, *ASME Appl. Mech. Rev.*, **46,** S327–S333.
Knopoff, L., 1996. Earthquake prediction—the scientific challenge, *Proc. Nat. Acad. Sci. USA*, **93,** 3719–3720.
Knopoff, L., Aki, K., Allen, C.R., Rice, J.R. & Sykes, L.R. (eds), 1996. *Earthquake Prediction: The Scientific Challenge*, Colloquium Proceedings, *Proc. Nat. Acad. Sci. USA*, **93,** 3719–3837.
Koizumi, N., 1997. Review of geochemical research for earthquake prediction, *Shizen Saigai Kagaku*, **16 (1),** 41–60 (in Japanese).
Kossobokov, V.G., Healy, J.H. & Dewey, J.W., 1997. Testing an earthquake prediction algorithm, *Pure appl. Geophys.*, **149,** 219–232.
Kovach, R.L. & Nur, A. (eds), 1973. *Proc. Conference on Tectonic Problems of the San Andreas Fault System*, Stanford University Publ. Geol. Sci., vol. 13, Stanford, CA.
Kulhánek, O. (ed.), 1988. Special issue: Seismic source physics and earthquake prediction research, *Tectonophysics*, **152,** 165–334.
Landsberg, H., 1935. The problem of earthquake prediction, *Science*, **82,** 37.
Langbein, J., 1991. Earthquake explanations, *Nature*, **349,** 287.
Langbein, J., 1992. The October 1992 Parkfield, California, earthquake prediction, *Earthq. Volc.*, **23,** 160–169.
Langbein, J., 1993. Parkfield: First short-term warning, *Eos, Trans. Am. geophys. Un.*, **74,** 152–153.
Langbein, J.O., Burford, R.O. & Slater, L.E., 1990. Variations in fault slip and strain accumulation at Parkfield, California: Initial results using two-color geodimeter measurements, 1984–1988, *J. geophys. Res.*, **95,** 2533–2552.
Langmuir, I., 1989. Pathological science, *Physics Today*, **42**(10), 36–48.
Lapwood, E.R., 1977. Earthquake prediction, *Nature*, **266,** 220–221.
Lay, T. & Wallace, T.C., 1995. *Modern Global Seismology*, Academic, San Diego, CA.
Leary, P.C., 1997. Rock as a critical-point system and the inherent implausibility of reliable earthquake prediction, *Geophys. J. Int.*, **131,** 451–466 (this issue).
Leary, P.C. & Malin, P., 1982. Millisecond accurate monitoring of seismic traveltimes over 13- and 18-kilometer baselines, *J. geophys. Res.*, **87,** 6919–6930.
Lerner-Lam, A., 1997. Predictable debate, *Seism. Res. Lett.*, **68,** 381–382.
Li, H. & Kerr, R.A., 1997. Warnings precede Chinese temblors, *Science*, **276,** 526.
Li, H. & Mervis, J., 1996. China's campaign to predict quakes, *Science*, **273,** 1484–1486.
Lighthill, J. (ed.), 1996. *A Critical Review of VAN*, World Scientific, Singapore.
Linde, A.T. & Sacks, I.S., 1997. Slow earthquakes, stress redistribution, and fast earthquakes, *Eos, Trans. Am. geophys. Un.* (Spring Mtg. Suppl.), **78,** S214 (abstract).
Linde, A.T., Gladwin, M.T. & Johnston, M.J.S., 1992. The Loma Prieta earthquake, 1989 and earth strain tidal amplitudes: an unsuccessful search for associated changes, *Geophys. Res. Lett.*, **19,** 317–320.
Linde, A.T., Gladwin, M.T., Johnston, M.J.S., Gwyther, R.L. & Bilham, R.G., 1996. A slow earthquake sequence on the San Andreas Fault, *Nature*, **383,** 65–68.
Lindh, A.G., 1983. Preliminary assessment of long-term probabilities for large earthquakes along selected fault segments of the San Andreas Fault system in California, *U.S. Geological Survey, Open-File Report*, **83–63.**
Lindh, A.G., 1990. Earthquake prediction comes of age, *Technology Review*, February/March 1990 issue, 42–51.
Lindh, A.G., Lockner, D.A. & Lee, W.H.K., 1978. Velocity anomalies: alternative explanation, *Bull. seism. Soc. Am.*, **68,** 721–734.
Lindh, A., Evans, P., Harsh, P. & Buhr, G., 1979. The Parkfield prediction experiment, *Earthq. Info. Bull.*, **11,** 209–213.
Lisowski, M., Prescott, W.H., Savage, J.C. & Svarc, J.L., 1990. A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake, *Geophys. Res. Lett.*, **17,** 1211–1214.
Logan, J.M., 1977. Animal behaviour and earthquake prediction, *Nature*, **265,** 404–405.
Lomnitz, C., 1994. *Fundamentals of Earthquake Prediction*, Wiley, New York, NY.
Lomnitz, C. & Lomnitz, L., 1978. Tangshan 1976: A case history in earthquake prediction, *Nature*, **271,** 109–111.
Lubkin, G.B., 1973. Do earthquakes give advance warning signals? *Physics Today*, **26**(7), 17–20.
Ma, Z., *et al.*, (eds), 1990. *Earthquake Prediction: Nine Major Earthquakes in China (1966–1976)*, Springer-Verlag, Berlin.
Macelwane, J.B., 1946. Forecasting earthquakes, *Bull. seism. Soc. Am.*, **36,** 1–4 (reprinted in *Geophys. J. Int.*, **131,** 421–422, this issue).
Main, I.G., 1995. Earthquakes as critical phenomena: implications for probabilistic seismic hazard analysis, *Bull. seism. Soc. Am.*, **85,** 1299–1308.
Main, I.G., 1996. Statistical physics, seismogenesis, and seismic hazard, *Rev. Geophys.*, **34,** 433–462.
Main, I.G., 1997. Long odds on prediction, *Nature*, **385,** 19–20.
Marder, M. & Fineberg, J., 1996. How things break, *Physics Today*, **49**(9), 24–29.
Mark, R.K., Tinsley, J.C., III, Newman, E.B., Gilmore, T.D. & Castle, R.O., 1981. An assessment of the accuracy of the geodetic measurements that define the southern California uplift, *J. geophys. Res.*, **86,** 2783–2808.
Mark, R.K., Gilmore, T.D. & Castle, R.O., 1987. Evidence of suppression of the unequal refraction error in geodetic leveling, *J. geophys. Res.*, **92,** 2767–2790.
Markov, V., 1988. Armenians face up to scenes of total devastation, *Nature*, **336,** 608–609.
Masood, E., 1995a. Greek earthquake stirs controversy over claims for prediction method, *Nature*, **375,** 617.

Masood, E., 1995b. Court charges open split in Greek earthquake experts. *Nature*, **377**, 375.

Matsumura, S., 1993. Overestimates of earthquake prediction efficiency in a 'post-prediction state', *J. Phys. Earth*, **51**, 41–43.

Matsumura, S., 1997. Focal zone of a future Tokai earthquake inferred from the seismicity pattern around the plate interface, *Tectonophysics*, **273**, 271–291.

Matsu'ura, R.S., 1986. Precursory quiescence and recovery of aftershock activities before some large aftershocks, *Bull. Earthq. Res. Inst. Univ. Tokyo*, **61**, 1–65.

McEvilly, T.V., 1976. Book review of *Earthquake Prediction* (by T. Rikitake), *Bull. seism. Soc. Am.*, **66**, 1774.

McEvilly, T.V. (ed.), 1982. Special symposium: Invited papers on earthquake prediction, *Bull. seism. Soc. Am.*, **72**, S331–S392.

McEvilly, T.V. & Johnson, L.R., 1973. Earthquakes of strike-slip type in central California: Evidence on the question of dilatancy, *Science*, **182**, 581–584.

McEvilly, T.V. & Johnson, L.R., 1974. Stability of P and S velocities from central California quarry blasts, *Bull. seism. Soc. Am.*, **64**, 343–353.

McNally, K.C., 1982. Variations in seismicity as a fundamental tool in earthquake prediction, *Bull. seism. Soc. Am.*, **72**, S351–S366.

Medawar, P.B., 1979. *Advice to a Young Scientist*, Harper & Row, New York, NY.

Meeus, J., 1975a. Comments on *The Jupiter Effect*, *Icarus*, **26**, 257–267.

Meeus, J., 1975b. Reply to Gribben and Plagemann, *Icarus*, **26**, 270.

Meeus, J., 1976. Sunspots and earthquakes, *Physics Today*, **29**(6), 11.

Mei, S., 1992. Progress in earthquake prediction in China during the 80's, *J. Earthq. Pred.*, **1**, 43–57.

Michael, A.J., 1996. The evaluation of VLF guided waves as possible earthquake precursors, *U.S. Geological Survey Open-file report*, **96–67**.

Michael, A.J., 1997. Testing prediction methods: Earthquake clustering versus the Poisson model, *Geophys. Res. Lett.*, **24**, 1891–1894.

Michael, A.J. & Langbein, J., 1993. Earthquake prediction lessons from Parkfield experiment, *Eos, Trans. Am. geophys. Un.*, **74**, 145–155.

Mikumo, T., Aki, K., Ohnaka, M., Ruff, L.J. & Spudich, P.K.P. (eds), 1992. Special issue of papers from Intl. Symp. on Earthquake source physics and earthquake precursors, *Tectonophysics*, **211**, 1–344.

Mileti, D.S. & Fitzpatrick, C., 1993. *The Great Earthquake Experiment: Risk Communication and Public Action*, Westview, Boulder, CO.

Miller, S.A., 1996. Fluid-mediated influence of adjacent thrusting on the seismic cycle at Parkfield, *Nature*, **382**, 799–802.

Milne, J., 1880. Seismic science in Japan, *Trans. seism. Soc. Jpn*, **1**, 3–33.

Milne, J., 1911a. The observatory at Messina, *Nature*, **85**, 515–516.

Milne, J., 1911b. Earthquakes and luminous phenomena, *Nature*, **87**, 16.

Mogi, K., 1970. Recent horizontal deformation of the Earth's crust and tectonic activity in Japan (1), *Bull. Earthq. Res. Inst. Univ. Tokyo*, **48**, 413–430.

Mogi, K., 1981. Earthquake prediction program in Japan, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 635–666, Am. Geophys. Un., Washington, DC.

Mogi, K., 1984/1985. Temporal variation of crustal deformation during the days preceding a thrust-type great earthquake—The 1944 Tonankai earthquake of Magnitude 8.1, Japan, *Pure appl. Geophys.*, **122**, 765–780.

Mogi, K., 1985. *Earthquake Prediction*, Academic, Orlando, FL.

Mogi, K., 1986. Recent earthquake prediction research in Japan, *Science*, **233**, 324–330.

Mogi, K., 1992. Earthquake prediction research in Japan, in *Earthquake Prediction—Proceedings of the International School of Solid Earth Geophysics, 5th course*, pp. 11–31, eds Dragoni, M. & Boschi, E., Il Cigno Galileo Galilei, Rome.

Mogi, K., 1995. Earthquake prediction research in Japan, *J. Phys. Earth*, **43**, 533–561.

Mogi, K., 1996. Earthquake policy rests on shaky ground, *Views from Japan*, **1**(9), Foreign Press Center, Tokyo, Oct. 1996 (translation and abridgement of article in *This is Yomiuri*, Oct. 1996).

Monastersky, R., 1997. The overdue quake, *Science News*, **152**, 8–9.

Mori, J. & Kanamori, H., 1996. Initial rupture of earthquakes in the 1995 Ridgecrest, California, earthquake sequence, *Geophys. Res. Lett.*, **23**, 2437–2440.

Mulargia, F., 1997. Retrospective validation of time association, *Geophys. J. Int.*, **131**, 500–504 (this issue).

Mulargia, F. & Gasperini, P., 1992. Evaluating the statistical validity beyond chance of VAN earthquake precursors, *Geophys. J. Int.*, **111**, 32–44.

Mulargia, F., Marzocchi, W. & Gasperini, P., 1996a. Rebuttal to replies I and II by Varotsos *et al.*, *Geophys. Res. Lett.*, **23**, 1339–1340.

Mulargia, F., Marzocchi, W. & Gasperini, P., 1996b. Re-Rebuttal to the reply of Varotsos *et al.*, *Geophys. Res. Lett.*, **23**, 1343–1344.

Myachkin, V.I., Kostrov, B.V., Sobolev, G.A. & Shamina, O.G., 1986. Fundamentals of physics of the earthquake focus forerunners, pp. 1–24, in *Physics of the Earthquake Focus*, ed. Sadovskii, M.A., A.A. Balkema, Rotterdam (Translation of *Fizika Ochaga Zemletryaseniya*, Nauka, Moscow, 1975).

NASDA, 1997. Abstracts, *International Workshop on Seismo Electronics*, 3–5 March 1997, University of Electro-Communications, Tokyo, Japan.

Nersesov, I., 1970. Earthquake prognostication in the Soviet Union, *Bull. New Zealand Soc. Earthq. Eng.*, **3**, 108–119.

Nishida, N., 1989. Public opinion regarding earthquake prediction, *Seism. Soc. Jpn Newsletter*, **1**(1), 58–59 (in Japanese).

Nishimura, E. & Hosoyama, K., 1953. On tilting motion of ground observed before and after the occurrence of an earthquake, *Trans. Am. geophys. Un.*, **34**, 597–599.

Norman, C., 1977. Warning in time, *Nature*, **268**, 684.

Normile, D., 1994. Japan holds firm to shaky science, *Science*, **264**, 1656–1658.

Normile, D., 1996. Chair quits Japan panel in protest, *Science*, **271**, 1799.

Normile, D., 1997. Earthquake prediction: Report slams Japanese program, *Science*, **275**, 1870.

Nur, A., 1972. Dilatancy, pore fluids, and premonitory variations of t_s/t_p traveltimes, *Bull. seism. Soc. Am.*, **62**, 1217–1222.

Office of Technology Assessment, 1995. *Reducing Earthquake Losses*, Report OTA-ETI-623, Sept. 1995, Congress of the United States, Washington, DC.

Ogata, Y., Utsu, T. & Katsura, K., 1996. Statistical discrimination of foreshocks from other earthquake clusters, *Geophys. J. Int.*, **127**, 17–30.

Ohta, H. & Abe, K., 1977. Responses to earthquake prediction in Kawasaki City, Japan, in 1974, *J. Phys. Earth*, **25**, S273–S282.

Ohtake, M., Matumoto, T. & Latham, G.V., 1977. Seismicity gap near Oaxaca, southern Mexico as a probable precursor to a large earthquake, *Pure appl. Geophys.*, **115**, 375–385.

Ohtake, M., Matumoto, T. & Latham, G.V., 1981. Evaluation of the forecast of the 1978, Oaxaca, southern Mexico earthquake based on a precursory seismic quiescence, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 53–61, Am. Geophys. Un., Washington, DC.

Okada, Y., 1984. First results from Japanese network for earthquake prediction, *Nature*, **312**, 500–501.

Oliver, J., 1964. Earthquake prediction, *Science*, **144**, 1364–1365.

Oliver, J., 1966. Earthquake prediction, *Science*, **153**, 1024–1025.

Olson, R.S., Podesta, B. & Nigg, J.M., 1989. *The Politics of Earthquake Prediction*, Princeton University Press, Princeton, NJ.

Otsuka, M., 1972a. A chain-reaction-type source model as a tool to interpret the magnitude-frequency relation of earthquakes, *J. Phys. Earth*, **20**, 35–45.

Otsuka, M., 1972b. A simulation of earthquake recurrence, *Phys. Earth planet. Inter.*, **6**, 311–315.

Pakiser, L.C., Eaton, J.P., Healy, J.H. & Raleigh, C.B., 1969. Earthquake prediction and control, *Science*, **166**, 1467–1474.

Papanikolaou, D. *et al.*, 1997. Roundtable discussion on earthquake prediction; conclusions—recommendations, *Geophysical Newsletter*, No. 18, Hellenic Geophysical Union, Feb. 1997.

Park, S.K., 1992. Workshop on low-frequency electrical precursors to earthquakes, *Eos, Trans. Am. geophys. Un.*, **73**, 491–492.

Park, S.K., 1996. Precursors to earthquakes: Seismoelectromagnetic signals, *Surv. Geophys.*, **17**, 493–516.

Park, S.K., Johnston, M.J.S., Madden, T.R., Morgan, F.D. & Morrison, H.F., 1993. Electromagnetic precursors to earthquakes in the ULF band: a review of observations and mechanisms, *Rev. Geophys.*, **31**, 117–132.

Parrot, M., 1995. Electromagnetic noise due to earthquakes, in *Handbook of Atmospheric Electrodynamics*, vol. II, pp. 95–116, ed. Volland, H., CRC Press, Boca Raton, FL.

Parrot, M., Fraser-Smith, A.C., Molchanov, O.A. & Yoshino, T., 1995. Electromagnetic effects associated with earthquakes and volcanic eruptions, *Eos, Trans. Am. geophys. Un.*, **76**, 223.

Poley, C.M., Lindh, A.G., Bakun, W.H. & Schulz, S.S., 1987. Temporal changes in microseismicity and creep near Parkfield, California, *Nature*, **327**, 134–137.

Press, F., 1975a. Earthquake prediction, *Sci. Am.*, **232**(5), 14–23.

Press, F., 1975b. Earthquake prediction, *Eos, Trans. Am. geophys. Un.*, **56**, 275 (reprinted from *New York Times*).

Press, F., 1975c. Plate tectonics and earthquake prediction: Contrasting approaches in China and the United States, *Bull. Am. Acad. Arts Sci.*, **28**, 14–27.

Press, F., 1976. Haicheng and Los Angeles: A tale of two cities, *Eos, Trans. Am. geophys. Un.*, **57**, 435–436.

Press, F. & Brace, W.F., 1966. Earthquake prediction, *Science*, **152**, 1575–1584.

Press, F. (chairman) *et al.*, 1965. *Earthquake Prediction: A proposal for a ten year program of research*, Ad Hoc Panel on Earthquake Prediction, prepared for Office of Science and Technology, Washington, Sept. 1965.

Press, F. *et al.*, 1975. Earthquake research in China, *Eos, Trans. Am. geophys. Un.*, **56**, 838–881.

Quan, Y.-D., 1988. The Haicheng, Liaoning Province, earthquake of M7.3 of February 4, 1975, in *Earthquake Cases in China (1966–1975)*, pp. 189–210, ed. Zhang, Z.-C., Seismological Press, Beijing (in Chinese).

Raleigh, B., 1982. A strategy for short-term prediction of an earthquake, *Bull. seism. Soc. Am.*, **72**, S337–S342.

Raleigh, C.B., Healy, J.H. & Bredehoeft, J.D., 1976. An experiment in earthquake control at Rangely, Colorado, *Science*, **191**, 1230–1237.

Raleigh, C.B. *et al.*, 1977. Prediction of the Haicheng earthquake, *Eos, Trans. Am. geophys. Un.*, **58**, 236–272.

Raleigh, C.B., Sieh, K., Sykes, L.R. & Anderson, D.L, 1982. Forecasting southern California earthquakes, *Science*, **217**, 1097–1104.

Rao, B.R., 1985. New trends in earthquake prediction, *Eos, Trans. Am. geophys. Un.*, **66**, 796–797.

Reasenberg, P., 1978. Unusual animal behaviour before earthquakes, *Earthq. Info. Bull.*, **10**, 42–50.

Reasenberg, P., 1996. Tests of SEISMOLAP-based methods for earthquake prediction in California , *Eos, Trans. Am. geophys. Un.*, **77**, (Fall Meeting suppl.), F458 (abstract).

Reasenberg P.A. & Matthews, M.V., 1988. Precursory seismic quiescence: a preliminary assessment of the hypothesis, *Pure appl. Geophys.*, **126**, 373–406.

Reid, H.F., 1910. *The California Earthquake of April 18, 1906, vol. II, The Mechanics of the Earthquake*, Rept State Earthquake Investigation Commission, Carnegie Institution of Washington, Washington, DC.

Reid, H.F., 1920. The problems of seismology, *Proc. Nat. Acad. Sci. U.S.*, **6**, 555–561; reprinted in *Trans. Am. Geophys. Un.*, **1**, Reprint and circular series No. 11.

Reilinger, R., 1980. Elevation changes near the San Gabriel fault, southern California, *Geophys. Res. Lett.*, **7**, 1017–1019.

Reilinger, R. & Brown, L., 1981. Neotectonic deformation, near-surface movements and systematic errors in U.S. releveling measurements: implications for earthquake prediction, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 422–440. Am. Geophys. Un., Washington, DC.

Rhoades, D.A. & Evison, F.F., 1989a. On the reliability of precursors, *Phys. Earth planet. Inter.*, **58**, 137–140.
Rhoades, D.A. & Evison, F.F., 1989b. Time-variable factors in earthquake hazard, *Tectonophysics*, **167**, 201–210.
Rhoades, D.A. & Evison, F.F., 1996. The VAN earthquake predictions, *Geophys. Res. Lett.*, **23**, 1371–1374.
Richman, B.T., 1981a. Prediction of Peru quakes rejected, *Eos, Trans Am. geophys. Un.*, **62**, 129.
Richman, B.T., 1981b. Peru earthquake prediction update, *Eos, Trans Am. geophys. Un.*, **62**, 618.
Richter, C.F., 1958. *Elementary Seismology*, W. H. Freeman, San Francisco, CA.
Richter, C.F., 1964. Discussion of paper by V.I. Keylis-Borok and L.N. Malinovskaya, *J. geophys. Res.*, **69**, 3025.
Richter, C.F., 1977. Acceptance of the Medal of the Seismological Society of America, *Bull. seism. Soc. Am.*, **67**, 1244–1247.
Rikitake, T., 1966. A five-year plan for earthquake prediction research in Japan, *Tectonophysics*, **3**, 1–15.
Rikitake, T. (ed.), 1968. Special issue: Earthquake prediction, *Tectonophysics*, **6**, 7–87.
Rikitake, T. (ed.), 1970. Special issue: Earthquake mechanics, *Tectonophysics*, **9**, 97–300.
Rikitake, T., 1972. Problems of predicting earthquakes, *Nature*, **240**, 202–204.
Rikitake, T. (ed.), 1974a. Special issue: Focal processes and the prediction of earthquakes, *Tectonophysics*, **23**, 219–318.
Rikitake, T., 1974b. Japanese national program on earthquake prediction, *Tectonophysics*, **23**, 225–236.
Rikitake, T., 1975. Earthquake precursors, *Bull. seism. Soc. Am.*, **65**, 1133–1162.
Rikitake, T., 1976. *Earthquake Prediction*, Elsevier, Amsterdam.
Rikitake, T., 1979. The large-scale earthquake countermeasures act and the earthquake prediction council in Japan, *Eos, Trans. Am. geophys. Un.*, **60**, 553–555.
Rikitake, T. (ed.), 1981a. *Current Research in Earthquake Prediction I*, D. Reidel, Dordrecht/CAPJ, Tokyo.
Rikitake, T. 1981b. Practical approach to earthquake prediction and warning, in *Current Research in Earthquake Prediction I*, ed. Rikitake, T., pp. 1–80, D. Reidel, Dordrecht/CAPJ, Tokyo.
Rikitake, T. (ed.), 1984. *Earthquake Prediction: Proceedings of the International Symposium on Earthquake Prediction*, Terrapub, Tokyo; Unesco, Paris.
Rikitake, T., 1986. Earthquake prediction in the heart of Japan, *Earthq. Pred. Res.*, **4**, 213–486.
Rikitake, T., 1987. Earthquake precursors in Japan: Precursor time and detectability, *Tectonophysics*, **136**, 265–282.
Rikitake, T., 1988. Earthquake prediction: An empirical approach, *Tectonophysics*, **148**, 195–210.
Rikitake, T., 1991. Book review of *Earthquake Prediction—Present Status*, Guha, S.K. & Patwardhan, A.M. (eds), *Tectonophysics*, **200**, 333–334.
Robinson, R., Wesson, R.L. & Ellsworth, W.L., 1974. Variation of P-wave velocity before the Bear Valley, California, earthquake of 24 February 1972, *Science*, **184**, 1281–1283.
Roeloffs, E. & Langbein, J., 1994. The earthquake prediction experiment at Parkfield, California, *Rev. Geophys.*, **32**, 315–336.
Roeloffs, E. & Quilty, E., 1997. Case 21: Water level and strain changes preceding and following the August 4, 1985 Kettleman Hills, California, earthquake, *Pure appl. Geophys.*, **149**, 21–60.
Roeloffs, E.A., Burford, S.S., Riley, F.S. & Records, A.W., 1989. Hydrologic effects on water level changes associated with episodic fault creep near Parkfield, California, *J. geophys. Res.*, **94**, 12 387–12 402.
Rundle, J.B. & McNutt, M., 1981. Southern California uplift—Is it or isn't it?, *Eos, Trans. Am. geophys. Un.*, **62**, 97.
Russ, D.P. & Johnson, L.E., 1985. Cooperative earthquake research between the United States and the People's Republic of China, *Eos, Trans. Am. geophys. Un.*, **66**, 763–765.
Sadovsky, M.A. & Nersesov, I.L., 1974. Forecasts of earthquakes on the basis of complex [geophysical] features, *Tectonophysics*, **23**, 247–255.
Sadovsky, M.A., Nersesov, I.L., Nigmatullaev, L.A., Latynina, L.A., Lukk, A.A., Semenov, A.N., Simbireva, I.G. & Ulomov, V.I., 1972. The processes preceding strong earthquakes in some regions of middle Asia, *Tectonophysics*, **14**, 295–307.
Sassa, K. & Nishimura, E., 1951. On precursory phenomena forerunning earthquakes, *Trans. Am. Geophys. Un.*, **32**, 1–6.
Savage, J.C., 1991. Criticism of some forecasts of the National Earthquake Prediction Evaluation Council, *Bull. seism. Soc. Am.*, **81**, 862–881.
Savage, J.C., 1992. The uncertainty in earthquake conditional probabilities, *Geophys. Res. Lett.*, **19**, 709–712.
Savage, J.C., 1993. The Parkfield prediction fallacy, *Bull. seism. Soc. Am.*, **83**, 1–6.
Savage, J.C., 1996. No: The L.A. array is not ready for prime time, *Eos, Trans. Am. geophys. Un.*, **77**, 419–427.
Savage, J.C. & Prescott, W.H., 1979. Geodimeter measurements of strain during the southern California uplift, *J. geophys. Res.*, **84**, 171–177.
Savage, J.C., Prescott, W.H., Lisowski, M. & King, N.E., 1981a. Strain on the San Andreas Fault near Palmdale, California: Rapid, aseismic change, *Science*, **211**, 56–58.
Savage, J.C., Prescott, W.H., Losowski, M. & King, N.E., 1981b. Strain accumulation in southern California, 1973–1980, *J. geophys. Res.*, **86**, 6991–7001.
Savarenskij, E.F. & Nersesov, I.L., 1978. Earthquake prediction, in *The Assessment and Mitigation of Earthquake Risk*, pp. 66–90, UNESCO, Paris.
Savarensky, E.F., 1968. On the prediction of earthquakes, *Tectonophysics*, **6**, 17–27.
Savarensky, E.F. (ed.), 1972. Special section: Forerunners of strong earthquakes, *Tectonophysics*, **14**, 177–338.
Schaefer, E. & Swinbanks, D., 1990. Betting on an inexact science, *Nature*, **348**, 273.
Scholz, C.H., 1977. A physical interpretation of the Haicheng earthquake prediction, *Nature*, **267**, 121–124.
Scholz, C.H., 1985. The Black Mountain asperity: Seismic hazard of the southern San Francisco peninsula, California. *Geophys. Res. Lett.*, **12**, 717–719.
Scholz, C.H., 1997. Whatever happened to earthquake prediction, *Geotimes*, **42**(3), 16–19.
Scholz, C.H., Sykes, L.R. & Aggarwal, Y.P., 1973. Earthquake prediction: a physical basis, *Science*, **181**, 803–810.
Segall, P., 1996. Earthquakes: slow down for safety, *Nature*, **383**, 21–22.
Segall, P. & Du, Y., 1993. How similar were the 1934 and 1996 Parkfield earthquakes?, *J. geophys. Res.*, **98**, 4527–4538.
Segall, P. & Harris, R., 1986. Slip deficit on the San Andreas fault at Parkfield, California, as revealed by inversion of geodetic data, *Science*, **233**, 1409–1413.
Segall, P. & Harris, R., 1987. Earthquake deformation cycle on the San Andreas fault near Parkfield, California, *J. geophys. Res.*, **92**, 10 511–10 525.
Segall, P. & Harris, R., 1989. Comment on: 'Geodetic evidence for seismic potential at Parkfield, California' by L.-Y. Sung and D.D. Jackson, *Geophys. Res. Lett.*, **16**, 101–104.
Segall, P. & Lisowski, M., 1990. Surface displacements in the 1906 San Francisco and 1989 Loma Prieta earthquakes, *Science*, **250**, 1241–1244.
Semenov, A.M., 1969. Variations in the travel-time of transverse and longitudinal waves before violent earthquakes, *Izvestia, Acad. Sci. USSR Phys. Solid Earth* (Engl. Transl.), No. 4, 245–248.
Shapley, D., 1976a. Earthquakes: Los Angeles prediction suggests faults in federal policy, *Science*, **192**, 535–537.
Shapley, D., 1976b. Chinese earthquakes: The Maoist approach to seismology, *Science*, **193**, 656–657.
Shaw, R.H. & Smietana, P.J., Jr, 1983. Temperature stratification and refraction errors in geodetic leveling, *J. geophys. Res.*, **88**, 10 485–10 494.
Shearer, C.F., 1985a. Minutes of the National Earthquake Prediction Evaluation Council, November 16–17, 1984, *USGS Open File Report*, **85-201**.
Shearer, C.F., 1985b. Minutes of the National Earthquake Prediction Evaluation Council, March 29-30, 1985, *USGS Open File Report*, **85-507**.
Shearer, C.F., 1986. National Earthquake Prediction Evaluation Council Special Report I. Workshop on special study areas in southern California, San Diego, CA, Feb. 28-Mar. 2 1985, *USGS Open File Rept.*, **86–580.**
Shimazaki, K. & Stuart, W. (eds), 1984/1985. Special issue of papers presented at the earthquake prediction session of the 22nd general assembly of the Intl. Union of Geodesy & Geophysics, Hamburg, Germany, Aug. 1983, *Pure appl. Geophys.*, **122**, 763–997.
Shimazaki, K. & Wakita, H. (eds), 1986. Proceedings of the Japan–China symposium on earthquake prediction, *J. Phys. Earth*, **34**, S1–S291.
Silver, P.G. & Valette-Silver, N.J., 1992. Detection of hydrothermal precursors to large northern California earthquakes, *Science*, **257**, 1363–1368.
Silver, P.G., Valette-Silver, N.J. & Kolbek, O., 1993. Detection of hydrothermal precursors to large northern California earthquakes, in *The Loma Prieta, California, Earthquake of October 17, 1989—Preseismic Observations*, ed. Johnston, M.J.S., U.S. Geological Survey Professional Paper 1550-C, pp. C73–C80, Washington, DC.
Silver, P. & Wakita, H., 1996. A search for earthquake precursors, *Science*, **273**, 77–78.
Simpson, D.W., 1979. Soviet prediction of a major earthquake, *Earthq. Info. Bull.*, **11**, 234–235.
Simpson, D.W., 1980. Earthquake prediction, *Nature*, **286**, 445–446.
Simpson, D.W. & Richards, P.G., eds, 1981. *Earthquake Prediction: An International Review Ewing Monograph Series* **4**, Am. Geophys. Un., Washington, DC.
Smith, P.J., 1974a. Earthquakes predicted, *Nature*, **252**, 9–11.
Smith, P.J., 1974b. Dilatancy, without fluid flow?, *Nature*, **252**, 444.
Smith, P.J., 1975a. Getting closer to prediction, *Nature*, **253**, 593.
Smith, P.J., 1975b. Crack theory developed, *Nature*, **253**, 593–594.
Smith, P.J., 1975c. Successful quake prediction made, *Nature*, **255**, 282.
Smith, P.J., 1976. Radon to predict earthquakes, *Nature*, **261**, 97.
Sornette, D. & Knopoff, L., 1997. The paradox of the expected time until the next earthquake, *Bull. seism. Soc. Am.*, **87**, 789–798.
Sornette, D., Knopoff, L., Kagan, Y.Y. & Vanneste, C., 1996. Rank-ordering statistics of extreme events: Application to the distribution of large earthquakes, *J. geophys. Res.*, **101**, 13 883–13 893.
Spall, H., 1977. An interview with Robert M. Hamilton, *Earthq. Info. Bull.*, **9**(6), 7–9.
Spall, H., 1979. Earthquake research in the Soviet Union, *Earthq. Info. Bull.*, **11**, 22–25.
Spall, H., 1980. Earthquake prediction in the Soviet Union—An interview with I.L. Nersesov, *Earthq. Info. Bull.*, **12**, 60–63.
Spence, W. & Pakiser, L.C., 1978. Conference report: Toward earthquake prediction on the global scale, *Eos, Trans. Am. geophys. Un.*, **59**, 36–42.
Spence, W., Hermann, R.B., Johnston, A.C. & Reagor, G., 1993. Responses to Iben Browning's Prediction of a 1990 New Madrid, Missouri, Earthquake, *U.S. Geological Survey Circular*, **1083**, U.S. Government Printing Office, Washington, DC.
Spudich, P., 1996. Synopsis, in *The Loma Prieta, California Earthquake of October 17, 1989—Main-shock Characteristics*, U.S. Geological Survey Professional Paper 1550-A, pp. A1–A7.
Stacey, F.D., 1963. Seismo-magnetic effect and the possibility of forecasting earthquakes, *Nature*, **200**, 1083–1085.
Stark, P.B., 1996. A few statistical considerations for ascribing statistical significance to earthquake predictions, *Geophys. Res. Lett.*, **23**, 1399–1402.
Stark, P.B., 1997. Earthquake prediction: the null hypothesis, *Geophys. J. Int.*, **131**, 495–499 (this issue).
Stavrakakis, G.N., Drakopoulos, J. & Latoussakis, J., 1990. *Evaluation of the correlation of SES with earthquakes in Greece–time period: 1987–1989*, Publ. no. 1, Natl. Observ. Athens.

Stein, R.S., 1981. Discrimination of tectonic displacement from slope-dependent errors in geodetic leveling from southern California, 1953-1979, in *Earthquake Prediction: An International Review* eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 441–456. Am. Geophys. Un., Washington, DC.

Stein, R.S., 1987. Contemporary plate motions and crustal deformation, *Rev. Geophys.*, **25**, 855–863.

Stein, R.S., 1995. Characteristic or haphazard?, *Nature*, **378**, 443–444.

Stein, R.S., Whalen, C.T., Holdahl, S.R., Strange, W.E. & Thatcher, W., 1986. Saugus-Palmdale, California, field test for refraction error in historical leveling surveys, *J. geophys. Res.*, **91**, 9031–9044.

Stein, R.S., Whalen, C.T., Holdahl, S.R., Strange, W.E. & Thatcher, W., 1989. Reply to 'Comment on "Saugus-Palmdale, California, field test for refraction error in historical leveling surveys" by R.S. Stein, C.T. Whalen, S.R. Holdahl, W. Strange, and W. Thatcher' by Michael R. Craymer and Peter Vaníček and Comment on 'Further analysis of the 1981 southern California field test for leveling refraction' by M.R. Craymer and P. Vaníček, *J. geophys. Res.*, **94**, 7667–7672.

Stewart, D.M., 1975. Is a major earthquake imminent in North Carolina centred near Southport?, Geol. Soc. Am. Southeastern Sect. Mtg., April 9–12, 1975, Memphis, TN, *Geol. Soc. Am. Abstracts with Programs*, 7(4), 540 (abstract).

Stiros, S.C., 1995. Unexpected shock rocks an 'aseismic' area, *Eos, Trans. Am. geophys. Un.*, **76**, 513–519.

Stiros, S.C., 1997. Costs and benefits of earthquake prediction studies in Greece, *Geophys. J. Int.*, **131**, 478–484 (this issue).

Strange, W.E., 1981. The impact of refraction correction on leveling interpretations in southern California, *J. geophys. Res.*, **86**, 2809–2824.

Strange, W.E., 1983. Reply, *J. geophys. Res.*, **88**, 2513–2519.

Stuart, W.D., 1974. Diffusionless dilatancy model for earthquake prediction, *Geophys. Res. Lett.*, **1**, 261–264.

Stuart, W.D., 1979. Strain softening prior to two-dimensional strike slip earthquakes, *J. geophys. Res.*, **84**, 1063–1070.

Stuart, W.D., 1987. Studies of San Andreas fault, *Nature*, **327**, 99–100.

Stuart, W.D., 1990. Parkfield slowing down, *Nature*, **345**, 383–384.

Stuart, W.D., 1991. Seismic quiescence at Parkfield due to detachment faulting, *Nature*, **349**, 58–61.

Stuart, W.D. & Aki, K. (eds), 1988. Special issue of papers presented at the international conference, on Physical and observational basis of intermediate-term earthquake prediction, *Pure appl. Geophys.*, **126**, 175–718.

Stuart, W.D. & Tullis, T.E., 1995. Fault model for preseismic deformation at Parkfield, California, *J. geophys. Res.*, **100**, 24 079–24 099.

Stuart, W.D., Archuleta, R.J. & Lindh, A.G., 1985. Forecast model for moderate earthquakes near Parkfield, California, *J. geophys. Res.*, **90**, 592–604.

Sung, L.-Y. & Jackson, D.D., 1988. Geodetic evidence of the seismic potential at Parkfield, California, *Geophys. Res. Lett.*, **15**, 820–823.

Sung, L.-Y. & Jackson, D.D., 1989. Reply, *Geophys. Res. Lett.*, **15**, 820–823.

Suzuki, Z., 1982. Earthquake prediction, *Ann. Rev. Earth planet. Sci.*, **10**, 235–256.

Suzuki, Z., 1985. The fifth 5-year program for earthquake prediction in Japan, *Earthq. Predict. Res.*, **3**, 207–218.

Suzuki, Z. & Kisslinger, C. (eds), 1977a. U.S.–Japan seminar on earthquake precursors, *Eos, Trans. Am. geophys. Un.*, **58**, 600–603.

Suzuki, Z. & Kisslinger, C. (eds), 1977b. Proceedings of the U.S.–Japan Seminar on Theoretical and Experimental Investigations of Earthquake Precursors, *J. Phys. Earth*, **25**, S1–S296.

Swinbanks, D., 1992a. Trying to shake Japan's faith in forecasts, *Nature*, **356**, 464–465.

Swinbanks, D., 1992b. Without a way to measure their success, Japanese projects are very hard to stop, *Nature*, **357**, 619.

Swinbanks, D., 1992c. Japanese report shows cracks in predicting earthquakes, *Nature*, **358**, 361.

Swinbanks, D., 1993a. Earthquake exposes gaps in seismic network, *Nature*, **364**, 271.

Swinbanks, D., 1993b. Japanese go it alone with earthquake prediction, *Nature*, **364**, 370.

Swinbanks, D., 1993c. Japan disappoints seekers of foresight, *Nature*, **366**, 4.

Swinbanks, D., 1994a. Is Japan throwing good money after bad science?, *Nature*, **367**, 670.

Swinbanks, D., 1994b. Earthquake 'forecasters' face their critics in Japan, *Nature*, **370**, 9.

Swinbanks, D., 1995a. Kobe disaster divides earthquake researchers, *Nature*, **373**, 373.

Swinbanks, D., 1995b. Earthquake prediction 'likely to grow' after new review, *Nature*, **374**, 205.

Swinbanks, D., 1995c. Critics attack hasty review of quake prediction efforts, *Nature*, **374**, 754.

Swinbanks, D., 1997. Quake panel admits prediction is 'difficult', *Nature*, **388**, 4.

Sykes, L.R. & Nishenko, S.P., 1984. Probabilities of occurrence of large plate rupturing earthquakes for the San Andreas, San Jacinto, and Imperial Faults, California, 1983–2003, *J. geophys. Res.*, **89**, 5905–5927.

Sykes, L.R., Simpson, D.W. & Richards, P.G., 1981. Preface to *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. vi–vii, Am. Geophys. Un., Washington, DC.

Tang, X., 1988. *A General History of Earthquake Studies in China*, Science Press, Beijing.

Taubes, G., 1993. *Bad Science*, Random House, New York, NY.

Taubes, G., 1997. The one that got away?, *Science*, **275**, 148–151.

Tazieff, H., 1992. *Earthquake Prediction*, McGraw-Hill, New York, NY.

Terada, T., 1931. On luminous phenomena accompanying earthquakes, *Bull. Earthq. Res. Inst. Tokyo, Imp. Univ.* **9**, 225–255.

Thatcher, W., 1976. Episodic strain accumulation in southern California, *Science*, **194**, 691–695.

Thatcher, W., 1979. Horizontal crustal deformation from historic geodetic measurements in southern California, *J. geophys. Res.*, **84**, 2351–2370.

Thatcher, W., 1981. Crustal deformation studies and earthquake prediction research, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 394–410, Am. Geophys. Un., Washington, DC.

Thatcher, W., Marshall, G. & Lisowski, M., 1997. Resolution of fault slip along the 470-km long rupture of the great 1906 San Francisco earthquake and its implications, *J. geophys. Res.*, **102**, 5353–5367.

Thurber, C.H., 1996. Creep events preceding small to moderate earthquakes on the San Andreas fault, *Nature*, **380**, 425–428.

Toppozada, T.R., 1985. Questioning the regular recurrence of characteristic Parkfield events, *Eos, Trans. Am. geophys. Un.*, **66**, 982 (abstract).

Toppozada, T.R., 1992. Parkfield earthquake history (abstract), *Eos, Trans. Am. geophys. Un.*, **73**, 406.

Tributsch, H., 1978. Do aerosol anomalies precede earthquakes?, *Nature*, **276**, 606–608.

Tributsch, H., 1982. *When the Snakes Awake*, MIT Press, Cambridge, MA.

Tsuboi, C., Wadati, K. & Hagiwara, T., 1962. *Prediction of earthquakes: Progress to date and plans for further development*. Earthquake Prediction Research Group, Tokyo University (English translation).

Tsunogai, U. & Wakita, H., 1995. Precursory chemical changes in ground water: Kobe earthquake, Japan, *Science*, **269**, 61–63.

Tsunogai, U. & Wakita, H., 1996. Anomalous changes in groundwater chemistry— Possible precursors of the 1995 Hyogo-ken Nanbu earthquake, Japan, *J. Phys. Earth*, **44**, 381–390.

Tullis, T.E., 1994. Predicting earthquakes and the mechanics of fault slip, *Geotimes*, **39**(7), 19–21.

Turcotte, D.L., 1991. Earthquake prediction, *Ann. Rev. Earth planet. Sci.*, **19**, 263–281.

Turner, R.H., 1982. Media in crisis: blowing hot and cold, *Bull. seism. Soc. Am.*, **72**, S19–S28.

Turner, R.H., Nigg, J.M. & Paz, D.H., 1986. *Waiting for Disaster*, University of California Press, Berkeley, CA.

Twyman, F., 1935. Prediction of earthquakes, *Nature*, **135**, 1078.

UNDRO, 1983. *Proc. Seminar on Earthquake Prediction Case Histories* (Geneva, 12–15 October 1982), convened by Office of U.N. Disaster Relief Co-ordinator and UNESCO, UNDRO/83/33, GE.83-03321.

UNESCO, 1979. *Report of panel of experts on the scientific, social, and economic aspects of earthquake prediction*, Paris, 9–12 April 1979. Sc-79/COMF.801/2, report issued 11 June 1979.

US Geological Survey, 1976. *Earthquake Prediction—Opportunity to Avert Disaster*, US Geological Survey Circular 729.

US Geological Survey Staff, 1990. The Loma Prieta, California, earthquake: an anticipated event, *Science*, **247**, 286–293.

Utsu, T., 1977. Possibility of a great earthquake in the Tokai district, Japan, *J. Phys. Earth*, **25**, S219–S230.

Uyeda, S. & Nagao, T., 1997. Japanese research on electro-magnetic short-term earthquake prediction, *Seism. Res. Lett.*, **68**, 297 (abstract).

Varotsos, P.A. & Alexopoulos, K.D., 1986. *Thermodynamics of Point Defects and their Relation with Bulk Properties*, North-Holland, Amsterdam.

Varotsos, P. & Kulhánek, O. (eds), 1993. Special issue: Measurements and theoretical models of the earth's electric field variations related to earthquakes, *Tectonophysics*, **224**, 1–288.

Varotsos, P. & Lazaridou, M., 1991. Latest aspects of earthquake prediction Greece based on seismic electric signals, *Tectonophysics*, **188**, 321–347.

Varotsos, P., Lazaridou, M., Eftaxias, K., Antonopoulos, G., Makris, J. & Kopanas, J., 1996a. Short-term earthquake prediction in Greece by seismic electric signals, in *A Critical Review of VAN*, pp. 29–76, ed. Lighthill, J., World Scientific, Singapore.

Varotsos, P. *et al.*, 1996b. Recent earthquake prediction results in Greece based on the observation of seismic electric signals, *Acta Geophysica Polonica*, **44**, 301–327.

Varotsos, P., Sarlis, N., Lazaridou, M. & Bogris, N., 1996c. Statistical evaluation of earthquake prediction results: Comments on the success rate and alarm rate, *Acta Geophysica Polonica*, **44**, 329–347.

Varotsos, P., Eftaxias, K. & Lazaridou, M., 1996d. Reply to 'A false alarm based on electrical activity recorded at a VAN-station in northern Greece in December 1990,' by J. Drakopoulos and G. Stavrakakis, *Geophys. Res. Lett.*, **23**, 1359–1362.

Vere-Jones, D., 1976. A branching model for crack propagation, *Pure appl. Geophys.*, **114**, 711–725.

Vidale, J.E., 1996. Do big and little earthquakes start differently?, *Science*, **271**, 953–954.

Vogel, A. (ed.), 1979. Terrestrial and space techniques in earthquake prediction research, *Proc. Int. Workshop on Monitoring Crustal Dynamics in Earthquake Zones*, Strasbourg, 29 Aug.–5 Sept. 1978, Friedr. Vieweg & Sohn, Braunschweig.

Wadatsumi, K., 1995. *1519 Precursor Testimonies!*, Tokyo Shuppan, Tokyo (in Japanese).

Wakita, H., 1981. Precursory changes in groundwater prior to the 1978 Izu-Oshima-Kinkai earthquake, in *Earthquake Prediction: An International Review*, eds Simpson, D.W. & Richards, P.G., *Ewing Monograph Series* **4**, pp. 527–532, Am. Geophys. Un., Washington, DC.

Wakita, H., Nakamura, Y., Notsu, K., Noguchi, M. & Asada, T., 1980. Radon anomaly: a possible precursor of the 1978 Izu-Oshima-Kinkai earthquake, *Science*, **207**, 882–883.

Wakita, H., Nakamura, Y. & Sano, Y., 1988. Short-term and intermediate-term geochemical precursors, *Pure appl. Geophys.*, **126**, 267–278.

Wakita, H. *et al.* (eds), 1996. Abstracts, *Intl. Symp. on Prediction studies on Earthquake and Volcanic Eruption by Geochemical and Hydrological Methods*, 5–8 March 1996, Tokyo, Japan, Bulletin of Laboratory for Earthquake Chemistry, Faculty of Science, University of Tokyo, No. 7.

Wallace, R.E., 1983. Tangshan, six years later, *Earthq. Info. Bull.*, **15**, 103–107.

Wallace, R.E., Davis, J.F. & McNally, K.C., 1984. Terms for expressing earthquake potential, prediction, and probability, *Bull. seism. Soc. Am.*, **74**, 1819–1825.

Walsh, J., 1965. Earthquake prediction: OST panel recommends 10-year program, *Science*, **150**, 321–323.

Ward, P.L., 1979. Earthquake prediction, *Rev. Geophys. Space Phys.*, **17**, 343–353.

Warwick, J.W., Stoker, C. & Meyer, T.R., 1982. Radio emission associated with rock fracture: Possible application to the great Chilean earthquake of May 22, 1960, *J. geophys. Res.*, **87**, 2851–2859.

Wesnousky, S.G., 1996. Reply to Yan Kagan's comment on 'The Gutenberg-Richter or characteristic earthquake distribution, which is it?', *Bull. seism. Soc. Am.*, **86**, 286–291.

Wesson, R.L., Robinson, R., Bufe, C.G., Ellsworth, W.L., Pfluke, J.H., Steppe, J.A. & Seekins, L.C., 1977. Search for seismic forerunners to earthquakes in central California, *Tectonophysics*, **42**, 111–126.

Whitcomb, J.H., 1976. Time-dependent V_P and V_P/V_S in an area of the Transverse Ranges of southern California (abstract), *Eos, Trans. Am. geophys. Un.*, **57**, 288.

Whitcomb, J.H., Garmany, J.D. & Anderson, D.L., 1973. Earthquake prediction: Variation of seismic velocities before the San [Fernando] earthquake, *Science*, **180**, 632–635.

Whiteside, L. & Habermann, R.E., 1989. The seismic quiescence prior to the 1978 Oaxaca, Mexico earthquake IS NOT a precursor to that earthquake, *Eos, Trans. Am. geophys. Un.*, **70**, 1232 (abstract).

Wilson, E.B., 1952. *An Introduction to Scientific Research*, McGraw-Hill, New York, NY (reprinted by Dover, New York, NY, 1990).

Wood, H.O. & Gutenberg, B., 1935. Earthquake prediction, *Science*, **82**, 219–220.

Working Group on California Earthquake Probabilities, 1988. Probabilities of large earthquakes occurring in California on the San Andreas Fault, *U.S. Geological Survey Open-File Rept*, **88-398**.

Wu, F.T., 1997. The annual earthquake prediction conference in China (National consultative meeting on seismic tendency), *Pure appl. Geophys.*, **149**, 249–264.

Wu, K.T. *et al.*, 1978. Certain characteristics of the Haicheng earthquake ($M=7.3$) sequence, *Chinese Geophys.*, **1**, 289–308.

Wuethrich, B., 1993. Waiting for Parkfield to quake, *Eos, Trans. Am. geophys. Un.*, **74**, 553–554.

Wyatt, F.K., Agnew, D.C. & Gladwin, M., 1994. Continuous measurements of crustal deformation for the 1992 Landers earthquake sequence, *Bull. seism. Soc. Am.*, **84**, 768–779.

Wyss, M., 1975a. Precursors to the Garm earthquake of March 1969, *J. geophys. Res.*, **80**, 2926–2930.

Wyss, M. (ed.), 1975b. Special issue: Earthquake prediction and rock mechanics, *Pure appl. Geophys.*, **113**, 1–330.

Wyss, M., 1977b. The appearance rate of premonitory uplift, *Bull. seism. Soc. Am.*, **67**, 1091–1098.

Wyss, M., 1977c. Interpretation of the southern California uplift in terms of the dilatancy hypothesis, *Nature*, **266**, 805–808.

Wyss, M. (ed.), 1979. Special issue: Earthquake prediction and seismicity patterns, *Pure appl. Geophys.*, **118**, 1079–1315.

Wyss, M., 1983. Earthquake prediction, *Rev. Geophys. Space Phys.*, **21**, 1291–1298.

Wyss, M., 1990. Changes of mean magnitude of Parkfield seismicity: A part of the precursory process?, *Geophys. Res. Lett.*, **17**, 2429–2432.

Wyss, M. (ed.), 1991a. Special issue: earthquake prediction, *Tectonophysics*, **193**, 253–410.

Wyss, M. (ed.), 1991b. *Evaluation of Proposed Earthquake Precursors*, American Geophysical Union, Washington, DC.

Wyss, M., 1991c. Increased mean depth of earthquakes at Parkfield, *Geophys. Res. Lett.*, **18**, 617–620.

Wyss, M. 1997a. Cannot earthquakes be predicted?, *Science*, **278**, 487–488.

Wyss, M., 1997b. Second round of evaluation of proposed earthquake precursors, *Pure appl. Geophys.*, **149**, 3–16.

Wyss, M., 1997c. Case 23: Nomination of precursory seismic quiescence as a significant precursor, *Pure appl. Geophys.*, **149**, 79–113.

Wyss, M. & Brune, J.N., 1967. The Alaska earthquake of 28 March 1964: A complex multiple rupture, *Bull. seism. Soc. Am.*, **57**, 1017–1023.

Wyss, M. & Dmowska, R. (eds), 1997. Special issue: Earthquake prediction—state of the art, *Pure appl. Geophys.*, **149**, 1–264.

Wyss, M. & Holcomb, D.J., 1973. Earthquake prediction based on station residuals, *Nature*, **245**, 139–140.

Wyss, M., Bodin, P. & Habermann, R.E., 1990a. Seismic quiescence at Parkfield: an independent indication of an imminent earthquake, *Nature*, **345**, 426–428.

Wyss, M., Slater, L. & Burford, R.O., 1990b. Decrease in deformation rate as a possible precursor to the next Parkfield earthquake, *Nature*, **345**, 428–432.

Wyss, M., Habermann, R.E. & Bodin, P., 1992. Seismic quiescence: a test of the hypothesis and a precursor to the next Parkfield, California, earthquake, *Geophys. J. Int.*, **110**, 518–536.

Xu, S.-X., Wang, B.-Q., Jones, L.M., Ma, X.-F. & Shen, P.-W., 1982. The foreshock sequence of Haicheng earthquake and earthquake swarm—the use of foreshock sequences in earthquake prediction, *Tectonophysics*, **85**, 91–105.

Yoshida, A. & Furuya, I., 1992. Case study on earthquake precursory phenomena, *Zisin*, **45**, 71–82 (in Japanese).

Zhang, G. & Zhang, Z., 1992. The study of multidisciplinary earthquake prediction in China, *J. Earthq. Pred.*, **1**, 71–85.

Zhu, F.-M. & We, G., 1983. Prediction of the Haicheng earthquake and measures taken for disaster prevention, in *Proc. Seminar on Earthquake Prediction Case Histories* (Geneva, 12–15 October 1982), pp. 1–18, convened by Office of U.N. Disaster Relief Co-ordinator and UNESCO, UNDRO/83/33, GE.83-03321.