PERSPECTIVE

Earthquakes Cannot Be Predicted

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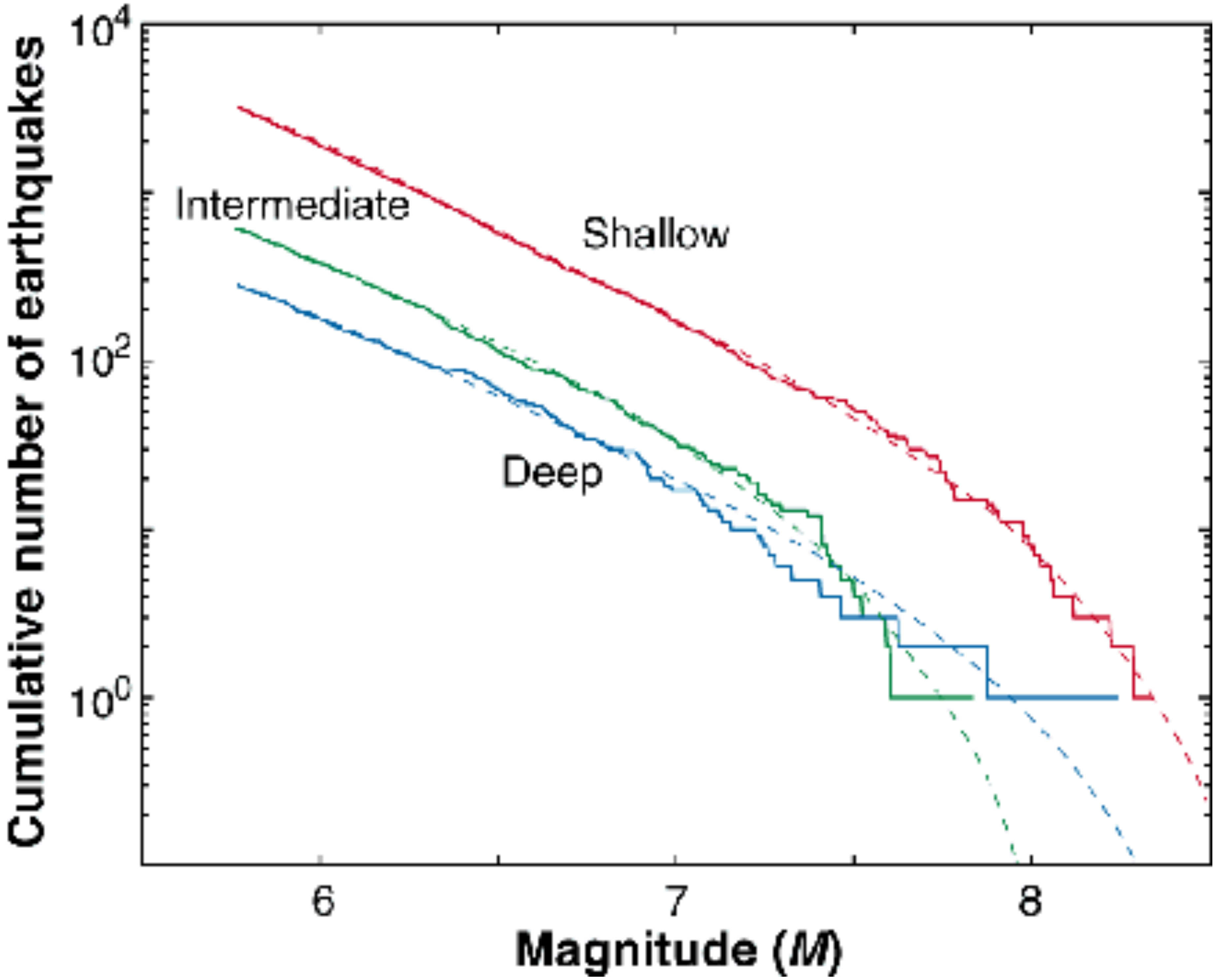
Earthquake prediction [HN5–7] is usually defined as the specification of the time, location, and magnitude [HN8–9] of a future earthquake within stated limits. Prediction would have to be reliable (few false alarms and few failures) and accurate (small ranges of uncertainty in space, time, and magnitude) to justify the cost of response. Previous Perspectives in*Science* may have given a favorable impression of prediction research, and the news media and some optimistic scientists encourage the belief that earthquakes can be predicted (1). Recent research suggests to us that this belief is incorrect.

An earthquake results from sudden slip on a geological fault. [HN10] Such fracture and failure [HN11–13] problems are notoriously intractable. The heterogeneous state of the Earth and the inaccessibility of the fault zone to direct measurement impose further difficulties. Except during a brief period in the 1970s (2), the leading seismological authorities of each era have generally concluded that earthquake prediction is not feasible (3). Richter [HN14–15], developer of the eponymous magnitude scale, commented as follows in 1977: "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" (4). This comment still holds true.

For large earthquakes to be predictable, they would have to be unusual events resulting from specific physical states. However, the consensus of a recent meeting [HN5] (5) was that the Earth is in a state of self-organized criticality [HN16] where any small earthquake has some probability of cascading into a large event. This view is supported by the observation that the distribution of earthquake size (see figure) is invariant [HN17] with respect to scale for all but the largest earthquakes. Such scale invariance is ubiquitous in self-organized critical systems (6). Whether any particular small earthquake grows into a large earthquake depends on a myriad of fine details of physical conditions throughout a large volume, not just in the immediate vicinity of the fault (7). This highly sensitive nonlinear dependence of earthquake rupture on unknown initial conditions severely limits predictability (8,9). The prediction of individual large earthquakes would require the unlikely capability of knowing all of these details with great accuracy. Furthermore, no quantitative theory for analyzing these data to issue predictions exists at present. Thus, the consensus of the meeting was that individual earthquakes are probably inherently unpredictable.



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Critical quakes.

Number of earthquakes from 1 January 1977 to 30 June 1996 in the Harvard catalog [HN27] (24) with magnitude greater than*M* for shallow (0 to 70 km), intermediate (71 to 300 km), and deep (301 to 700 km) earthquakes. Dotted lines are power-law curves modified by an exponential taper for the largest magnitudes [equation 3 of (8)]. Analyses of smaller earthquakes show that self-similarity extends to magnitudes as small as zero (25). Such power-law curves are characteristic of systems in a state of self-organized criticality.

Empirical earthquake prediction would require the existence of observable and identifiable precursors [HN18] that would allow alarms to be issued with high reliability and accuracy. There are strong reasons to doubt that such precursors exist (10). Thousands of observations of allegedly anomalous phenomena (seismological, geodetic, hydrological, geochemical, electromagnetic, animal behavior, and so forth) have been claimed as earthquake precursors, but in general, the phenomena were claimed as precursors only after the earthquakes occurred. The pattern of alleged precursors tends to vary greatly from one earthquake to the next, and the alleged anomalies are frequently observed at only one point, rather than throughout the epicentral region. There are no objective definitions of "anomalies," no quantitative physical mechanism links the alleged precursors to earthquakes, statistical evidence for a correlation is lacking, and natural or artificial causes unrelated to earthquakes have not been compellingly excluded (11). In other fields threshold signals have often been erroneously claimed as important physical effects (12); most if not all "precursors" are probably misinterpreted as well. Unfortunately, each new claim brings a new set of proposed conditions, so that hypothesis testing, which is what separates speculation from science, is nearly impossible.

Chinese seismologists claimed that the 4 February 1975 Haicheng (magnitude = 7.3) earthquake was successfully predicted and that "very few people were killed" (13). However, an official publication in 1988 (14) states there were 1328 deaths and 16,980 injured. This disparity casts doubt on claims [HN19] for the Haicheng prediction. China's Cultural Revolution was still taking place in 1975. An American delegation's report (15) captures the remarkable atmosphere: "Earthquake prediction was not a minor experiment.... Indeed, belief in earthquake prediction was made an element of ideological orthodoxy that distinguished the true party liners from right wing deviationists." The possibility that political pressures caused inaccuracies in claims for the Haicheng prediction cannot be excluded. An intense swarm of microearthquakes, many of which were large enough to be felt by local residents, began over 24 hours before the main shock (15). These microearthquakes might well have induced some spontaneous evacuation. At least 240,000 people died in the 1976 Tangshan, China, earthquake, which was not predicted.

Varotsos [HN20] and co-workers claim to be able to predict earthquakes in Greece on the basis of geoelectrical observations (16), but our analyses show their claims to be without merit (17,18). Some of the geoelectrical signals are artifacts of industrial origin (19), and there is no compelling evidence linking any of the geoelectrical signals to earthquakes. Controversy lingers primarily because Varotsos's claims have not been stated as unambiguous and objectively testable hypotheses (20).

Is prediction inherently impossible or just fiendishly difficult? In practice, it doesn't matter. Scientifically, the question can be addressed using a Bayesian approach [HN21] (21). Each failed attempt at prediction lowers the a priori probability for the next attempt. The current probability of successful prediction is extremely low, as the obvious ideas have been tried and rejected for over 100 years (17). Systematically observing subtle phenomena, formulating hypotheses, and testing them thoroughly against future earthquakes would require immense effort over many decades, with no guarantee of success. It thus seems unwise to invest heavily in monitoring possible precursors.

Seismology can, however, contribute to earthquake hazard mitigation. [HN22–25] Statistical estimates of the seismicity expected in a general region on a time scale of 30 to 100 years (22) [as opposed to "long-term predictions" of specific earthquakes on particular faults within a few years (23)] and statistical estimates of the expected strong ground motion are important data for designing earthquake-resistant structures. Rapid determination of source parameters (such as location and magnitude) can facilitate relief efforts after large earthquakes. Warnings of tsunamis **[HN26]** (seismic sea waves) produced by earthquakes also contribute significantly to public safety. These are areas where earthquake research can greatly benefit the public.

HyperNotes Related Resources on the World Wide Web

The **SeismoSurfing Index** provides comprehensive links to seismological resources on the Internet.

The **National Earthquake Information Center** of the **U. S. Geological Survey** provides **a near real-time bulletin** of global earthquake activity and **global earthquake maps**. USGS also has an **"Earthquake Information from USGS"** page primarily dealing with Northern California, but also data on the **Parkfield study** and a general discussion on the **use of foreshocks to estimate the odds of larger events in the future**.

The **Incorporated Research Institutions for Seismology** is a university research consortium dedicated to exploring Earth's interior through the collection and distribution of seismographic data.

The British Geological Survey's **Web page** has an **Earthquake FAQ** that answers many common questions.

The **Seismological Society of America**, the **Earthquake Engineering Research Institute**, and the**International Association of Seismology and Physics of the Earth's Interior** all maintain home pages on the Web.

The **Earthquake Research Institute, University of Tokyo**, has information about seismic activity and their **Earthquake Prediction Research Center**.

Glossaries of seismological terms are available at the **California Institute of Technology**, and **the National Earthquake Information Center**. Excerpts from the book: **A Parent's Guide to Earthquakes** by Lucy Jones of the USGS are also available.

1. **Robert Geller's Home Page** describes his research interests.

2. **David Jackson's Home Page** summarizes his research interests and lists his publications.

3. **Yan Kagan's Home Page** summarizes his research interests and lists his publications.

4. F. Mulargia can be reached via the **Department of Physics' Home Page** at the Universita di Bologna, Italy.

5. The**Royal Astronomical Society** and its affiliated **Joint Association for Geophysics** held a discussion meeting in November 1996 on **Assessment of schemes for earthquake prediction**.

6. The**US National Academy of Sciences** held a symposium (attendance and presentation by invitation only) on earthquake prediction in February 1995, for which abstracts are available. The introduction **Earthquake prediction: The scientific challenge** was given by L. Knopoff.

7. K. Aki gave a review of **earthquake prediction** in *Reviews of Geophysics*, vol. 33, 1995, as part of the *U.S. National Report to International Union of Geodesy and Geophysics 1991–1994*.

8. The **USGS Cascades Volcano Observatory** offers **definitions and descriptions** of Magnitude, Intensity, and the Modified Mercalli Scale.

9. **Michigan Technological University, Department of Geological Engineering and Sciences**, presents an **Earthquake Magnitude Scale and Classes Chart** as part of UPSeis, a new program created to teach young people about Earth.

10. The fundamentals of faulting are reviewed in **Earthquake ABCs** at the **Southern California Earthquake Data Center**.

11. The **Landers Earthquake** page has links to **MPEG movies of the rupture** and **animations of the aftershocks**. Related pages about the **Northridge** earthquake and **the faults of Southern California** are also available.

12. M. Willemse **(Stanford University, Department of Geological and Environmental Sciences)** provides links to **images** of fracture patterns, strike-slip faults, and normal faults.

13. K. M. Cruikshank **(Geology Department, Portland State University)** has a **comprehensive bibliography** on faulting.

14. A description of the **Richter scale** is provided by **NORSAR**, a geophysics research institution supported by the **Research Council of Norway**.

15. The online pages of the science radio series **Earth and Sky** has information on **Charles Richter** and the magnitude scale he developed.

16. **The Santa Fe Institute** presents a discussion of **Self-Organized Criticality** that includes applications to sandpiles and document delivery over the Web.

17. **R. Devaney** of the Boston University Math Department has a Web page about chaos and fractals, including a discussion of **self-similarity and scale invariance**.

18. At the November meeting of the **Royal Society**, I. Main discussed the **difficulties of defining precursory phenomena**.

19. The official position of the government of the People's Republic of China on **recent prediction research** is outlined in the *China Science and Techology Newsletter* (The State Science and Technology Commission). See also the review by **Aki** on prediction claims (earlier hypernote).

20. A **special issue** of *Geophysical Research Letters* (27 May 1996) edited by R. J. Geller contains reports by Varotsos and his collaborators, along with reports critical of his methods.

21. **A brief definition and a simple example** of using Bayes' Theorem is presented in the **Statistics for Engineers** course at the **Faculty of Engineering, University of Wollogong**, Australia.

22. A **lecture** on the hazards of earthquakes is offered by the **Department of Earth Sciences & The Institute of Tectonics**, University of California, Santa Cruz.

23. **A guide to international building codes** that are designed to mitigate earthquake damage is provided by the **National Center for Earthquake Engineering Research** of **SUNY Buffalo**.

24. The **Western States Seismic Policy Council** has images of the aftermath of **the 1995 Kobe earthquake** among others.

25. The **US Geological Survey's Homepage for Earthquakes** points to a variety of hazard topics, such as the **National Seismic Hazard Mapping Project**.

26. The Japanese word **tsunami** is written as two characters meaning “harbor wave.” The **Tsunami Web site** is an online information resource about these **great waves**.

27. The **Harvard Centroid-Moment Tensor (CMT) database** is a catalog of large earthquakes maintained by the **Harvard Seismology group**. A **query page** for the CMT database is available at the Earthquake Research Institute, University of Tokyo.

Supplementary Discussion from References 1, 10 and 23:

Discussion from note 1:

Belief in earthquake prediction is widespread, as indicated by the following. (i) An opinion poll by

Japan's Office of the Prime Minister in September 1995, which revealed that 34.6% of the public thought the "Tokai earthquake" (a magnitude M = 8 earthquake near Shizuoka, about 150 km west of Tokyo, which since 1976 has been claimed by some researchers and government agencies to be imminent) could be predicted (about half of these respondents thought all earthquakes with M ≥ 7 could be predicted); 44.5 % thought prediction was impossible; 20.9% didn't know or gave other answers. (ii) A newspaper article with the title "Scientists Upbeat on Earthquake Prediction" (Los Angeles Times, 22 December 1996, p. A3). (iii) See R. A. Kerr, *Science*, **253**, 622 (1991); W. Spence et al., U. S. Geol. Surv. Circ. 1083 (1993) **click here for additional information about the Spence Report**; and R. J. Geller, Astron. Geophys. 38, 16 (Feb/Mar 1997) for information on many other pro-prediction items in the mass media. (iv) After the 17 January 1994 Northridge, California, event, rumors of the prediction of an even larger earthquake were so prevalent that the California Institute of Technology (Caltech) had to issue the following statement: "Earthquake Prediction Rumors Are False. In response to rumors about imminent major quakes, Caltech seismologists are saying that earthquakes cannot be predicted. Aftershocks will continue. However, the rumor of the prediction of a major earthquake is false. Caltech cannot release predictions since it is impossible to predict earthquakes." And finally, (v) there have been several news articles in *Science* that discuss earthquake prediction. We think these stories accord too much emphasis to the views of pro-prediction researchers; however, as negative views are also reported, the stories could arguably be characterized as accurate. Unfortunately, the headlines and sub-headlines are sometimes much more pro-prediction than warranted by the contents of the stories. For example, a Research News story on the Greek "VAN" group [R.A. Kerr, *Science*, **270**, 911 (1995)] was headlined "Quake Prediction Tool Gains Ground," and the sub-headline of a story on earthquake prediction in China [H. Li and J.D. Mervis, *Science*, **273**, 1484 (1995)] was "A vast, 30-year effort to monitor the earthquakes that regularly shake China has led to unprecedented—and controversial—success in predicting them." In our view the former story does not show any "ground being gained," and the latter story presents no evidence of "unprecedented success." Readers are encouraged to judge for themselves.

Discussion from note 10:

A group of prediction researchers established validation criteria (including a precise definition of the anomaly, an explicit statement of the signal-to-noise ratio, detection at more than one station, and full disclosure of both negative and positive results) and invited nominations of precursor candidates. Only 31 nominations were submitted; none of these fully satisfied the validation criteria. As these nominations were presumably the cream of the crop, the fact that not one fully met the validation criteria is strong empirical evidence against the existence of the type of precursors required for prediction. (Three of the 31 precursor nominations were placed on a "preliminary list of significant earthquake precursors," despite failure to fully meet the validation criteria: One lacked a clear definition of what constitutes an "anomaly" and a comprehensive statistical evaluation; a second was not supported by a quantitative analysis, and the number of false alarms and missed events was not evaluated; and a third was seen for one event at only one station, and there was no quantitative definition of what constituted an anomaly.) Further evaluations of precursor case studies by the above group of prediction researchers are presented by M. Wyss, Ed., Pure Appl. Geophys. 149, 3 (1997).

Discussion from note 23:

Long term predictions were issued in 1976 for the Tokai region in Japan [the initial publications were all in Japanese; see K. Ishibashi in, Earthquake Prediction: An International Review, D. W. Simpson and P. G. Richards, Eds. (Ewing Monograph Series, Am. Geophys. Union, Washington, DC, 1981), pp. 297–332, for a discussion in English and references] and in 1985 for the Parkfield region in California [W. H. Bakun and A. G. Lindh, *Science* **229**, 619 (1985)]; both predictions have failed, as no large earthquakes have occurred. In contrast, severely damaging earthquakes in California [Loma Prieta in 1989 (see below), Landers in 1992, Northridge in 1994] and Japan (Okushiri Island in 1993, and Kobe in 1995) occurred on faults for which long-term predictions had not been issued. J.C. Savage [*Bull. Seismol. Soc. Am.* **83**, 1 (1993)] discusses and criticizes the "Parkfield prediction fallacy." Y. Y. Kagan [*Tectonophys.* **270**, 207 (1997)] questions the claim that quasi-periodic "characteristic earthquakes" regularly occur at Parkfield. After the 1989 Loma Prieta earthquake there was a claim that a relatively general long term seismicity forecast—as opposed to a long term prediction for the particular fault that ruptured—had been successful [U.S. Geological Survey Staff, *Science* 247, 286 (1990)]. But this claim proved controversial [R. A. Kerr, ibid. 249, 860 (1990)], and a statistical analysis strongly argues against this claim [J. C. Savage, *Geophys. Res. Lett.* **19**, 709 (1992)].

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2.↵ There was intense optimism about prediction in the early to mid-1970s [C. H. Scholz, L. R. Sykes, Y. P. Aggarwal, *Science* **181**, 803 (1973); F. Press, *Sci. Am.* **232**, 14 (May 1975); "Forecast: Earthquake," *Time* **106**, 38 (1 September 1975)], but this optimism was soon recognized to be unwarranted [R. A. Kerr, *Science* **200**, 419 (1978); C. R. Allen, *Bull. Seismol. Soc. Am.* **72**, S331 (1982)]. The fundamental flaw was that the prediction scenarios were not stated as testable hypotheses. Google Scholar

3.↵ H. O. Wood, B. Gutenberg, *Science* **82**, 219 (1935); FindText @ Notre Dame FREE Full Text Google Scholar J. B. Macelwane, *Bull. Seismol. Soc. Am.* **36**, 1 (1946); FindText @ Notre Dame FREE Full Text Google Scholar C. F. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), pp. 385–387. Google Scholar

4.↵ C. F. Richter, *Bull. Seismol. Soc. Am.* **67**, 1244 (1977). FindText @ Notre Dame Google Scholar

5.↵ *Assessment of Schemes for Earthquake Prediction*, meeting held 7-8 November 1996, London. See meeting reports by I. Main [*Nature* **385**, 19 (1997)] and R. J. Geller [*Eos* **78**, 63 (1997)]. Google Scholar

6.↵ P. Bak, *How Nature Works: The Science of Self-Organized Criticality* (Copernicus, New York, 1996). **Publisher's Synopsis of the book and order form:**. Google Scholar

7.↵ M. Otsuka, *Phys. Earth Planet. Inter.* **6**, 311 (1972); FindText @ Notre Dame Google Scholar J. Brune, *J. Geophys. Res.* **84**, 2195 (1979); FindText @ Notre Dame Google Scholar P. Bak, C. Tang, *ibid.* **94**, 15635 (1989); FindText @ Notre Dame Google Scholar J. Mori, H. Kanamori, *Geophys. Res. Lett.* **23**, 2437 (1996). FindText @ Notre Dame CrossRef Web of Science Google Scholar

8.↵ Y. Y. Kagan, *Physica D* **77**, 160 (1994). FindText @ Notre Dame CrossRef Google Scholar

9.↵ I. Main, *Rev. Geophys.* **34**, 433 (1996). FindText @ Notre Dame Google Scholar

10.↵ See M. Wyss, Ed., *Evaluation of Proposed Earthquake Precursors* (American Geophysical Union, Washington, DC, 1991). Supplementary discussion and supporting citations are available at **[SUPPL. B]**. Google Scholar

11.↵ D. L. Turcotte, *Annu. Rev. Earth Planet. Sci.* **19**, 263 (1991). FindText @ Notre Dame CrossRef Web of Science Google Scholar

12.↵ I. Langmuir, *Phys. Today* **42**, 36 (October 1989); FindText @ Notre Dame Google Scholar P. W. Anderson, *ibid.* **43**, 9 (December 1990); FindText @ Notre Dame Google Scholar G. Taubes, *Science* **275**, 148 (1997). FindText @ Notre Dame FREE Full Text Google Scholar

13.↵ At the time, A. L. Hammond [*Science* **192**, 538 (1976)] stated "…very few people were killed, although more than 1 million live near the epicenter, because the earthquake was predicted and the population evacuated—the first known instance of a major quake successfully predicted and disaster prevented or mitigated on such a scale," and D. Davies [*Nature* **258**, 286 (1975)] stated "There was enormous damage—a town of 100,000 is being completely rebuilt—but few fatalities.". Google Scholar

14.↵ Y.-D. Quan The Haicheng, Liaoning Province, Earthquake of M7.3 of 4 February 1975 *Earthquake Cases in China* Z.-C. Zhang State Seismological Bureau Publication in Chinese, Seismological Press Beijing 189 210 1988; Google Scholar In some cases, disasters in China during the Cultural Revolution were concealed. 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*, 30 (25 February 1995)].

15.↵ C. B. Raleigh *et al.*, *Eos* **58**, 236 (1977); FindText @ Notre Dame Google Scholar see also R. D. Adams, *Earthquake Eng. Struct. Dyn.* **4**, 423 (1976). FindText @ Notre Dame Google Scholar

16.↵ P. Varotsos *et al.*, in *A Critical Review of VAN*, J. Lighthill, Ed. (World Scientific, Singapore, 1996), pp. 29-76 **Here** you can read a one-page synopsis of Lighthill's book, including ordering information. Google Scholar

17.↵ R. J. Geller, *ibid.* 155-238. Google Scholar

18.↵ F. Mulargia, P. Gasperini, *Geophys. J. Int.* **111**, 32 (1992); FindText @ Notre Dame Abstract/FREE Full Text Google Scholar Y. Y. Kagan, D. D. Jackson,*Geophys. Res. Lett*. **23**, 1433 (1996). FindText @ Notre Dame CrossRef Web of Science Google Scholar

19.↵ S. Gruszow *et al.*, *ibid.* 2025. This **page** provides the Table of Contents for the Special Issue of Geophysical Research Letters, Volume 23, Number 11, 1996. Google Scholar

20.↵ "Debate on Evaluation of the VAN Method," *ibid.*, p. 1291. This **page** provides the Table of Contents for the Special Issue of Geophysical Research Letters, Volume 23, Number 11, 1996. Google Scholar

21.↵ P. W. Anderson, *Phys. Today* **45**, 9 (January 1992). FindText @ Notre Dame Google Scholar

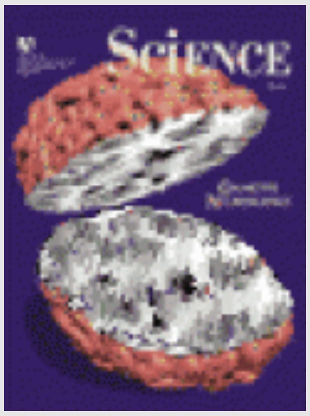
22.↵ Y. Y. Kagan, D. D. Jackson, *J. Geophys. Res.* **99**, 13685 (1994); FindText @ Notre Dame Google Scholar D. D. Jackson *et al.*, *Bull. Seismol. Soc. Am.* **85**, 379 (1995); FindText @ Notre Dame Abstract/FREE Full Text Google Scholar I. Main, *ibid.*, p. 1299. Google Scholar

23.↵ Y. Y. Kagan, D. D. Jackson, *J. Geophys. Res.* **100**, 3943 (1995); FindText @ Notre Dame Google Scholar F. Mulargia, P. Gasperini, [*Geophys. J. Int.* **120**, 453 (1995)] and Y. Y. Kagan, [*Bull. Seismol. Soc. Am.* **86**, 274 (1996)] FindText @ Notre Dame CrossRef Google Scholar question the models invoked to justify long-term predictions. Supplementary discussion and supporting citations are available at **[SUPPL. C]**

24.↵ A. M. Dziewonski, G. Ekström, M. P. Salganik, *Phys. Earth Planet Inter.* **97**, 3 (1996). FindText @ Notre Dame Google Scholar

25. R. E. Abercrombie, *Tectonophysics* **261**, 1 (1996); FindText @ Notre Dame CrossRef Web of Science Google Scholar —— and J. N. Brune, *Geophys. Res. Lett.* **21**, 1647 (1994). FindText @ Notre Dame CrossRef Web of Science Google Scholar

26. We thank S. Stein for valuable comments. Google Scholar



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