



Review article

A systematic compilation of earthquake precursors

Robert D. Cicerone^{a,*}, John E. Ebel^b, James Britton^{b,c}^a Department of Earth Sciences, Bridgewater State College, Bridgewater, MA 02325, USA^b Weston Observatory, Department of Geology and Geophysics, Boston College, 381 Concord Road, Weston, MA 02493-1340, USA^c Weston Geophysical Corporation, 181 Bedford Street, Suite 1, Lexington, MA 02420, USA

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ABSTRACT

A survey of published scientific literature was undertaken to identify and catalog observed earthquake precursors. The earthquake precursors selected for analysis included electric and magnetic fields, gas emissions, groundwater level changes, temperature changes, surface deformations, and seismicity. For each of these precursors, the published scientific literature was searched to document the statistics of each reported earthquake precursor (spatial extent, time, duration, amplitude, signal/noise ratio), to analyze dependence of the observable for each precursor on earthquake magnitude, and to explore proposed physical models to explain each earthquake precursor. Some general characteristics were observed for these precursory phenomena. First, the largest amplitude precursory anomalies tend to occur before the largest magnitude earthquakes. Also, the number of precursory anomalies tends to increase the closer in time to the occurrence of the earthquake. Finally, the precursory anomalies tend to occur close to the eventual epicenter of the earthquake. In general, the physical models indicate that all of the precursory phenomena are related to deformation that occurs near the fault prior to the main earthquake. While the models provide plausible physical explanations for the precursors, there are many free parameters in the models that are poorly resolved.

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* Corresponding author. Tel.: +1 508 531 2713; fax: +1 508 531 1785.

E-mail address: rcicerone@bridgew.edu (R.D. Cicerone).

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1. Introduction

One of the more elusive goals in seismology is short-term earthquake prediction. By the mid 1970s, seismologists were confident that short-term earthquake prediction would be achieved within a short period of time. This confidence came about in part as the result of the first successful prediction of a large earthquake, the 1975 M7.4 Haicheng earthquake in China. Because of this prediction, an alert was issued within the 24-hour period prior to the main shock, probably preventing a larger number of casualties than the 1328 deaths that actually occurred from this event. However, the failure to predict another devastating earthquake 18 months later, the 1976 M7.8 Tangshan earthquake, was a major setback to the earthquake prediction effort. Casualties from this earthquake numbered in the hundreds of thousands. A summary of these events, as well as other successes and failures in earthquake prediction, is given by Lomnitz (1994).

One area that may hold promise in advancing the science of short-term earthquake prediction is the study of earthquake precursors. In fact, short-term predictions are typically based on observations of these types of phenomena. The term *earthquake precursor* is used to describe a wide variety of physical phenomena that reportedly precede at least some earthquakes. These phenomena include induced electric and magnetic fields, groundwater level changes, gas emissions, temperature changes, surface deformations, and anomalous seismicity patterns. While each of these phenomena has been observed prior to certain earthquakes, such observations have been serendipitous in nature. For example, anomalous magnetic fields were recorded prior to the 1989 Loma Prieta earthquake in California by a magnetometer installed to monitor electromagnetic noise produced by electric trains. Fortuitously, this magnetometer was located within 7 km of the epicenter of the Loma Prieta earthquake (Fraser-Smith et al., 1990). The magnetometer detected two precursory magnetic fields, the first approximately 2 weeks prior to the main shock and the second approximately 3 h before the main shock.

More recently, attempts have been made to monitor various precursory phenomena as part of an overall earthquake prediction effort. The Parkfield, CA experiment (Bakun and Lindh, 1985) is one such experiment. A wide array of geophysical instruments was installed along a segment of the San Andreas Fault in central California (the so-called Parkfield segment) in 1981. These instruments included magnetometers, water level monitors, creepmeters, and strainmeters and were designed to record a wide variety of precursory phenomena. Based on magnitude 6+ earthquakes on the San Andreas Fault at Parkfield from 1857 to 1966, the United States Geological Survey (USGS) issued an official prediction of a M6 earthquake along this segment in 1985, to occur with 95% probability before the end of 1993 (Working Group on California Earthquake Probabilities, 1988). This earthquake did not occur until late 2004, and no precursory phenomena of significance were observed. A preliminary report on this earthquake and its lack of precursors is given by Langbein et al. (2005).

The purpose of this study was to carry out a survey of published scientific literature to identify and catalog observed earthquake precursors that have been published. In this work we identified several types of earthquake precursors and searched the published scientific literature to carry out the following tasks:

- Document the statistics of each reported earthquake precursor (spatial extent, time, duration, amplitude, signal/noise ratio)
- Analyze the dependence of the observable for each precursor on earthquake magnitude

- Explore proposed physical models to explain each earthquake precursor

This report summarizes the results of this research and presents recommendation for follow-up research. With an eye toward future earthquake prediction research, the potential of observing the reported earthquake precursors from a space-based remote-sensing platform is assessed.

2. Selection of earthquake precursors

Two major criteria were used to select the earthquake precursors for this study. The first criterion used for the selection of the earthquake precursory observables was the reported existence of credible scientific evidence for anomalies in the observables prior to at least some earthquakes. As noted above, the successful measurement of some anomalous phenomenon prior to an earthquake usually depends on the luck of having a good scientific experiment operating in an area before, during and after an earthquake. In many cases there have been anecdotal reports of unusual phenomena before earthquakes (e.g., unusual groundwater level changes or unusual animal behavior), but these have not been documented scientifically in a quantitative way. In order to best summarize the behavior of precursory phenomena of interest, we sought out those studies from the published scientific literature that report observations of earthquake precursors that were observed in credible, controlled, calibrated experiments.

The second criterion for the selection of the earthquake precursors is that there are accepted physical models to explain the existence of the precursor. For example, it only makes sense to look for changes in the local electric or magnetic field near an earthquake epicenter if there is some physical or chemical reason why the time prior to the initiation of an earthquake rupture should be accompanied by those field changes. In some cases, there are multiple, competing models to explain the existence of a reported earthquake precursor. We used these competing models as evidence that there is some physical model to explain the precursor, even if there is no current scientific agreement about which model is best.

The earthquake precursors selected for analysis in this study were

- *Electric and magnetic fields* — localized changes in magnetic and electric fields (including changes in ULF, VLF, ELF and RF fields). There is the uncontested observation of a localized strong ULF field change that took place in the area of the 1989 Loma Prieta, California earthquake (magnitude 7.1) during the hours prior to the main shock. A weaker field change was observed about 2 weeks before the main shock.
- *Gas emissions* — there is a great deal of interest in the emissions of various gases from the earth prior to earthquakes. The most well-known experiments have focused on radon gas, but some experiments have measured changes in the emission of other gases from the earth.
- *Water level changes* — wells have been reported to change levels or water quality in the hours, days or weeks prior to a number of earthquakes. In fact, well-water level changes is one of the most commonly reported earthquake precursors.
- *Temperature changes* — there have been some reports of surface temperature changes prior to earthquakes. These may involve changes in the circulation patterns of groundwater bringing water of different temperature to the surface.
- *Surface deformations* — there have been reports that changes in ground elevations over distances of tens of kilometers have preceded

some strong earthquakes. The number of permanent, high quality GPS sites to monitor permanent ground deformations is increasing in earthquake-prone areas, but broadscale remote sensing of surface elevations and especially elevation changes could yield important new clues for predicting earthquakes.

- *Seismicity* – this is already well covered by surface-based seismic instrumentation. However, some high-frequency (acoustic emission) energy and very low frequency seismic motions not detected by conventional seismographs may provide important precursory information. For example, [Ihmle and Jordan \(1994\)](#) have shown that some earthquakes exhibit low frequency precursory signals prior to the higher frequency main rupture.

3. Method of data analysis

For each of the earthquake precursors defined in the previous section, two different research tasks were conducted. The first was to carry out a survey of the scientific literature to find studies documenting anomalous changes in one or more of the selected precursors prior to the occurrence of an earthquake. From these studies, several types of information about the anomalous precursory signal were sought. These included the length of time before the earthquake when the precursor initiated, the duration of the precursor, the amplitude of the precursory signal, the signal-to-noise ratio of the anomalous relative to normal background noise, and the distance from the observation point to the earthquake. In addition, some basic source information was collected for each earthquake, including the date, time, location and magnitude of the earthquake. For each type of precursor, the observational information from the literature survey was collected and analyzed to find the statistical properties of the initiation and duration of the precursors, the strength of the precursory signal, and the relation of the precursory signal properties to the magnitude of the earthquake and the distance from the observation point to the source.

The second research task was to survey the scientific literature for studies proposing physical models to explain each of the precursors. Each physical model was evaluated to see if it predicted pre-earthquake anomalies consistent with the observations collected in the first research task. The goal of this aspect of the research was to find realistic physical models of the precursory earthquake signals that can be used to estimate the strength and character of anomalous pre-earthquake signals for each of the earthquake precursors. In particular, this aspect of the analysis is necessary to determine the importance of such earthquake source properties as magnitude, seismic moment, focal mechanism, depth, and stress drop in generating precursory signals.

4. Summary of the earthquake precursors: observations and models

This section presents a summary of the data collected for each of the precursors analyzed in this study. The reported observations for each precursor for each earthquake are summarized in tables. Discussions of the observations are given in each subsection here. Also described in each subsection are the results of the search for the physical models to explain the earthquake precursor observations. Those models are explored to determine their consistency with the reported precursor observations.

4.1. Electric and magnetic field observations

Anomalous electric and magnetic field prior to earthquakes have been detected by both ground-based and satellite-based instruments. In fact, this is the one earthquake precursor for which satellite-based observations have been reported in the literature. Those satellite observations come from two different studies. The first is a Russian study of an earthquake on March 19, 1979, where [Larkina et al. \(1989\)](#) reported that the Intercosmos 19 satellite detected changes in the ionospheric ELF and VLF emissions at 800 Hz and 4650 Hz from 8 h before

to 3 h after each earthquake in their data set. The anomalously large amplitudes at these two frequencies were detected within 2° latitude and 60° longitude of the eventual epicenter of the earthquake.

The second satellite-based EM study of precursory earthquake emissions was reported by [Serebryakova et al. \(1992\)](#). In that study ELF/VLF signals from the COSMOS-1809 satellite were analyzed to look for signals associated with aftershocks of the 1988 earthquake in Armenia. [Serebryakova et al. \(1992\)](#) found that EM radiation at frequencies below 450 Hz was observed during 12 of the 13 orbital passes of the satellite within 6° of longitude of the aftershock epicenter. The anomalously strong emissions were not observed at the latitude of the epicenters of earthquakes but rather 4° to 10° south of those epicenters. The emissions were observed up to a few hours before strong aftershocks took place in the epicentral region. [Serebryakova et al. \(1992\)](#) report that similar anomalous radiation was detected in this same area by the AUREOL-3 satellite.

Finally, [Parrot \(1994\)](#) described a statistical study of ELF/VLF emissions recorded by the AUREOL-3 satellite in the vicinity of the epicenters of 325 earthquakes of $M_s > 5$ from 1981–1983. In order to maximize the strength of the signals analyzed, [Parrot \(1994\)](#) averaged the data over time, thus sacrificing the time resolution in his study. He reported that the EM signal strength is at a maximum within 10° of longitude of the earthquake epicenters and that these signals are observed at all latitudes. The temporal averaging of the data precluded determining whether the anomalous signals occurred prior to, coincident with, or subsequent to the earthquakes that were analyzed.

There are some important ground-based observations that support the idea that the earth can generate anomalous electric and magnetic signals prior to the occurrences of earthquakes. The most important is that of [Fraser-Smith et al. \(1990\)](#) who, quite by accident, detected a strong ULF magnetic field change near the epicenter of the 17 October 1989 M_s 7.1 Loma Prieta, California earthquake. A low frequency (0.5–2.0 Hz), low amplitude increase in the background ULF field strength began being recorded about a month before the earthquake by an instrument placed at Corralitos (7 km from the eventual epicenter) to monitor ULF background noise for purposes not related to seismology. About 2 weeks before the earthquake, the background ULF signal detected by the instrument increased noticeably. Finally, within a few hours of the earthquake there was an exceptionally great increase in the signal amplitude at frequencies of 0.01 to 0.5 Hz, which grew continuously until the occurrence of the earthquake (and power was lost to the instrument). Atmospheric disturbances as the cause of the anomalous signals were ruled out, and it appears likely that the signals observed were generated by magnetic field changes in the earth below the instrument. Curiously, an ELF/VLF instrument operating about 52 km away on the Stanford U. campus detected no anomalous signals during this same time period.

Also supporting the idea that earthquakes are associated with magnetic and electric field changes in the rock is a study by [Kopytenko et al. \(1993\)](#) who reported unusual ULF signals at a ground-based observatory within 200 km of the epicenter of the 1988 Armenia earthquake. They reported that anomalous ULF emissions were detected several hours before the Armenia main shock and some of its strong aftershocks. This is the same aftershock sequence analyzed by [Serebryakova et al. \(1992\)](#).

As is clear from the discussion here and the results summarized in [Table 1](#), there are still many uncertainties in the observations of possible precursory EM emissions associated with strong earthquakes. Some satellite frequency bands seem to see anomalous signals, while others do not. One study reports the signals at a wide range of latitudes and a narrow range of longitudes, while another sees the opposite pattern. However, all of the data, including the best ground-based observations, show that precursory signals can be observed within several hours of a coming earthquake and that those signals seem to be strongest near the coming epicenter. The Loma Prieta observations suggest that signal-to-noise ratios of anomalous ULF

Table 1

Reported precursory electric and magnetic fields associated with earthquakes.

| Earthquake | Magnitude | Date | Type of emission | Before (b)/during (d)/after (a)? | Frequency range | Signal level | Background level | SNR | Distance from epicenter (km) | Instrumentation | Reference |
|----------------------------------|-----------|----------------|----------------------------------|----------------------------------|------------------------------|--|-------------------------------------|------|------------------------------|--|--------------------------------|
| Chile | 9.5 | 5/22/1960 | Radio | b (6 days) | 18 MHz | 2.56×10^{-6} W/Hz | | | Worldwide | radio astronomy receiver | Warwick et al., 1982 |
| Worldwide (13 events) | 5.7–8.3 | 1964–1973 | Geomagnetic | b (<1 h) | | | | | | | Gogatchivili, 1984 |
| San Andreas Fault, California | 3.9 | 6/22/1973 | Electrical resistivity variation | b (2 months) | DC | 10% increase | | | 4 km | Dipole–dipole array | Mazzella and Morrison, 1974 |
| Hollister, California | 5.2 | 11/28/1974 | ULF magnetic | b (7 weeks–several months) | | 0.9–1.5 nT | | | 11 km | Array of 7 proton-precession magnetometers | Smith and Johnston, 1976 |
| Haicheng, China | 7.3 | 2/4/1976 | Electric | b (12 h) | | –150 mV | | | 20 km | | Savage, 1977 |
| Tangshan, China | 7.8 | 7/28/1976 | Resistivity | b (2–3 years) | | 3–5% decrease | | | ≤150 km | | Zhao and Qian, 1994 |
| Tangshan, China | 7.8 | 7/28/1976 | Self potential | b (3 months) | | 3 mV/km increase | | | ≤120 km | | Zhao and Qian, 1994 |
| Sungpan–Pingwu, China (3 events) | 7.2 | 8/16/1976 | Telluric currents | b (1 month) | | 20–50 μ A | | | ≤200 km | | Wallace and Teng, 1980 |
| | 6.8 | 8/22/1976 | | | | | | | | | |
| | 7.2 | 8/23/1976 | | | | | | | | | |
| Worldwide (8 events) | 5.0–6.1 | 1979–1980 | VLF EM | b (26–183 min) | 0.1–16 kHz | | | | 700–14,100 km | Interkosmos–19 satellite | Larkina et al., 1984 |
| Kyoto, Japan | 7.0 | 3/31/1980 | VLF electric | b (1/2 h) | 81 kHz | +15 dB | | | 250 km | Electric antenna | Gokhberg et al., 1982 |
| Tokyo, Japan | 5.3 | 9/25/1980 | VLF electric | b (1 h) | 81 kHz | +15–20 dB | | | 55 km | Electric antenna | Gokhberg et al., 1982 |
| Tokyo, Japan | 5.0 | 1/28/1981 | VLF electric | b (3/4 h) | 81 kHz | +12 dB | | | 50 km | Electric antenna | Gokhberg et al., 1982 |
| Greece (47 events) | 3.4–6.8 | 1983 | Electric | b | | 0.2–15.6 mV | | | 10–160 km | | Varotsos and Alexopoulos, 1984 |
| Japan (26 events) | 5.0–6.6 | 1985–1990 | VLF electric | b (up to 2 days) | 82 kHz | | | | 2–895 km | Loop antennas | Yoshino et al., 1993 |
| Kalamata, Greece | 6.2 | 9/13/1986 | Electric | b (3–5 days) | | 10s mV | | | 200 km | | Gershenson and Gokhberg, 1993 |
| Spitak, Armenia | 6.9 Ms | 12/7/1988 | ULF magnetic | b (4 h), a | 0.01–1 Hz | 0.2 nT | 0.02 nT | 10 | 128 km | 3-axis high-sensitivity magnetometers | Molchanov et al., 1992 |
| Spitak, Armenia | 6.9 Ms | 12/7/1988 | ULF magnetic | b (4 h), a | 0.005–1 Hz | 0.1–0.2 nT | 0.03 nT | 6.67 | 120 km and 200 km | | Kopytenko et al., 1993 |
| Ito, Japan (earthquake swarm) | ≤5.5 | June–July 1989 | ELF/VLF electric | b (4–6 h) | 1–9 kHz | ~10 mV | | | 200 km | Borehole electrodes | Fujinawa and Takahashi, 1990 |
| Loma Prieta, California | 7.1 Ms | 11/19/1989 | ELF/VLF EM | b (3 h), d | 0.01 Hz | 5–60 nT Hz ^{−1/2} | ~1 nT Hz ^{−1/2} | | 52 km | Ground-based magnetometers | Fraser-Smith et al., 1990 |
| Loma Prieta, California | 7.1 Ms | 11/18/1989 | ULF magnetic | b (3 h), a | 0.01 Hz | 4–5 nT | | | 7 km | | Molchanov et al., 1992 |
| Loma Prieta, California | 7.1 Ms | 11/18/1989 | ULF magnetic | a | 0.01–10 Hz | 1 nT | | | 7.3 km | Proton magnetometers | Mueller and Johnston, 1990 |
| Armenia region | | 1989 | ELF/VLF EM | b (3 h) | 140 Hz | 10 m γ | | | 6 in. long, 2–4 in latitude | COSMOS-1809 satellite | Serebryakova et al., 1992 |
| Armenia region | | 1990 | ELF/VLF EM | b (3 h) | 450 Hz | 3 m γ | | | 6 in long, 2–4 in latitude | COSMOS-1809 satellite | Serebryakova et al., 1992 |
| Worldwide (325 eq's) | Ms>5 | | ELF/VLF EM | b (0–4 h) | 140 Hz | 3.28E–5 γ Hz ^{−1/2} | 1.53E–5 γ Hz ^{−1/2} | 2.14 | Δ long<10 | ARCAD-3 aboard AUREOL-3 satellite | Parrot, 1994 |
| Worldwide (325 eq's) | Ms>5 | | ELF/VLF EM | b (0–4 h) | 800 Hz | 9.08E–5 γ Hz ^{−1/2} | 1.57E–5 γ Hz ^{−1/2} | 5.78 | Δ long<10 | ARCAD-3 aboard AUREOL-3 satellite | Parrot, 1994 |
| Worldwide (325 eq's) | M>5.5 | | LF radio wave | | | 10 ² –10 ³ V m ^{−1} | | | 60 in long, 2 in latitude | Interkosmos-19 satellite | Parrot, 1994 |
| Upland, California | 4.7 | 4/17/1990 | ELF magnetic | b (1 day) | 3.0–4.0 Hz | –40 dB | –46.8 dB | | 160 km | Vertical magnetic sensor | Dea et al., 1993 |
| Western Iran | 7.5 | 6/20/1990 | Ionospheric (radio wave) | b (16 days) | 0–8 kHz, 10–14 kHz, F region | | | | 250–2000 km | Interkosmos-24 satellite | Shalimov and Gokhberg, 1998 |

| | | | | | | | | | | |
|--------------------------------|--------------------------|-------------------|--|-------------------------------|------------------------------------|---|--------------------------------|--------------------------------------|--|---|
| Watsonville, California | 4.3 | 3/23/1991 | ELF magnetic | b (data averaged over 2 days) | 3.0–4.0 Hz | –43 dB | –47.6 dB | 600 km | North–south magnetic sensor | Dea et al., 1993 |
| Watsonville, California | 4.3 | 3/23/1991 | ELF magnetic | b (data averaged over 2 days) | 3.0–4.0 Hz | –44 dB | –46.8 dB | 600 km | Vertical magnetic sensor | Dea et al., 1993 |
| Coalinga, California | 4.0 | 1/15/1992 | ELF magnetic | b (data averaged over 2 days) | 3.0–4.0 Hz | –50 dB | –57 dB | 400 km | Vertical magnetic sensor | Dea et al., 1993 |
| Central Italy | 3.0–4.3 | 1991–1994 | LF radio waves | b (6–10 days) | 216 kHz | –21 to –22 db (atmospheric) – 7 to –5 db (ground) | | <100 km | | Bella et al., 1998 |
| Hokkaido, Japan | 7.8 | 7/12/1993 | foF ₂ ionospheric | b (3 days) | | | | 290 km, 780 km, 1280 km (3 stations) | | Ondoh, 1998 |
| Guam | Ms 7.1 | 8/8/1993 | ULF magnetic | b (1 month) | 0.02–0.05 Hz | 0.1 nT | | 65 km | 3-axis ring–core-type fluxgate magnetometer | Hayakawa et al., 1996; Hayakawa et al., 1999 Yépez et al., 1995 |
| Mexico (Pacific Coast) | $M \geq 6.0$ (4 events) | 1993–1994 | ULF electric | | 0–0.125 Hz | | | < 200 km | | |
| Hokkaido–Toho–Oki, Japan | M_w 8.1 | 10/4/1994 | VLF electric | b (20 min) | 1–9 kHz | 1.34 mV | | > 1000 km | Borehole antenna | Fujinawa and Takahashi, 1998 |
| Taiwan | $M \geq 6.0$ (14 events) | 1994–1999 | ULF magnetic | b (1–6 days) | | | | <400 km | IPS-42 ionosonde | Liu et al., 2000 |
| Hyogo-ken Nanbu (Kobe), Japan | 7.2 | 1/17/1995 | DC geopotential, ELF magnetic, VLF radio, MF–HF, VHF FM-wave | b (up to 7 days) | 223 z, 1–20 kHz, 163 kHz, 77.1 MHz | | | ≥ 100 km | | Enomoto et al., 1998 |
| Hyogo-ken Nanbu (Kobe), Japan | 7.2 | 1/17/1995 | VLF radio | b (2 days) | 10.2 kHz | | | 70 km | | Molchanov et al., 1998 |
| Hyogo-ken Nanbu (Kobe), Japan | 7.2 | 1/17/1995 | Electric | b (1 h) | 22.2 MHz | 0.2 W signal power | | 77 km | Phase-switched interferometer with two horizontally-polarized antennas | Maeda and Tokimasa, 1996 |
| Kozani-Grevena, Greece | 6.6 | 5/13/1995 | VHF electromagnetic | b (20 h) | E: 41 and 5 MHz M: 3 & 10 kHz | ~300 mV above background | | $\Delta lat, \Delta long < 3$ | Electric dipole antennas, magnetic loop antennas | Eftaxias et al., 2002 |
| Kozani-Grevena, Greece | 6.6 | 5/13/1995 | Electric, magnetic | b (2 weeks) | | 10–60 mV/km, 0.4 nT | | 70 m, 200 km | | Bernard et al., 1997 |
| Biak, Indonesia | 8.2 | 2/17/1996 | UHF magnetic | b (1–1.5 months) | 5–30 mHz | 0.2–0.3 nT | | ≤ 1200 km | Fluxgate magnetometers | |
| Chiba-ken Toko-oki, Japan | 6.2 | 9/11/1996 | VHF electric | b (3 days) | | | | 320, 430 km | Vertical-dipole ground electrodes | Enomoto et al., 1997 |
| Akita-ken Nairiku-Nanbu, Japan | 5.9 | 8/11/1996 | VHF electric | b (6 days) | | | | <100 km | Vertical-dipole ground electrodes | Enomoto et al., 1997 |
| Vrancea, Romania | M (3.9 (19 events)) | 1997–1998 | ULF electromagnetic | b (1–12 days) | 3 kHz | | $\sim 15 \text{ pT Hz}^{-1/2}$ | 100 km | 3-axis fluxgate magnetometers, non-polarizable electric sensors | Enescu et al., 1999 |
| Umbria–Marche, Italy | 5.5 | 3/26/1998 | LF radio | b (1.5 months) | 0.006 Hz | 6–8 dB increase | | 818 km | Radio wave vertical antenna | Biagi et al., 2001 |
| San Juan Bautista, California | MW 5.1 | 8/12/1998 | UHF magnetic | b (2 h) | 0.01–10 Hz | 0.02 nT | | 3 km | 3-component magnetic field inductor coils | Karakelian et al., 2002 |
| Athens, Greece | 5.9 | 9/7/1999 | VHF electromagnetic | b (12–17 h) | E: 41 and 5 MHz M: 3 and 10 kHz | (300 mV above background) | 6 | $\Delta lat, \Delta long < 3$ | Electric dipole antennas, magnetic loop antennas | Eftaxias et al., 2001a,b |
| Chi-Chi, Taiwan | 7.7 | 9/20/1999 | ULF magnetic | b (1, 3, 4 days) 3 signals | | | | < 400 km | IPS-42 ionosonde | Liu et al., 2000 |
| Chi-Chi, Taiwan | M_w 7.6 | 9/20/1999 | foF ₂ ionospheric | b (3–4 days) | | | | 120 km | IPS-42 ionosonde | Chuo et al., 2002 |
| Chia-Yii, Taiwan | M_w 6.4 | 10/22/1999 | foF ₂ ionospheric | b (1–3 days) | | | | 179 km | IPS-42 ionosonde | Chuo et al., 2002 |
| Japan | M (4.8 (29 events)) | 9/4/2001–4/8/2003 | VHF electromagnetic | b (up to 5 days) | | | | $\Delta lat \Delta long < 4$ | Two 5-element Yagi antennas | Fujiwara et al., 2004 |

fields associated with coming earthquakes can be quite strong (up to 60). The three satellite-based studies described above report signal-to-noise ratios up to 10. Thus, EM radiation significantly above the background noise prior to at least some earthquakes may be observable from space in carefully designed experiments.

4.2. Electric and magnetic field models

Several physical models have been proposed to explain the observed electromagnetic precursors associated with earthquakes. These models can be classified into two main categories, which can be related to the frequency of the resultant electromagnetic precursor. The first class of models attempts to explain the observation of magnetic fields in the ULF range. The second class of models relates to electric fields observed at higher frequency, principally in the ELF/VLF range, but also extending to the LF and HF frequency bands.

4.3. ULF magnetic fields

For ULF magnetic fields, there have been three mechanisms proposed to explain the generation of these precursory signals. The first of these mechanisms is the magnetohydrodynamic (MHD) effect (e.g., Draganov et al., 1991). For this mechanism, the flow of an electrically conducting fluid in the presence of a magnetic field generates a secondary induced field. The MHD equation is derived from Maxwell's equations and is given by

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{v} \times \mathbf{B} + \frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma}, \quad (1)$$

where μ_0 is the permeability of free space, σ is the conductivity, \mathbf{v} is the fluid velocity, and \mathbf{B} is the magnetic field. The first term on the right is the convection of the magnetic field caused by the resistance to flux changes in the conductive loop. The second term represents the diffusion of the magnetic field caused by ohmic dissipation.

From the two terms on the right-hand side of the MHD equation, a magnetic Reynolds number R_m , analogous to the hydrodynamic Reynolds number, can be defined. The Reynolds number defines the relative importance of the convective and diffusive terms. Using dimensional analysis,

$$R_m = \frac{|\nabla \times \mathbf{v} \times \mathbf{B}|}{|\lambda \nabla^2 \mathbf{B}|} = \mu_0 \sigma v \ell, \quad (2)$$

where $\lambda = 1/\mu_0 \sigma$ and ℓ is the characteristic length of the source. Then the induced magnetic field \mathbf{B}_i is given by

$$\mathbf{B}_i = R_m \mathbf{B}. \quad (3)$$

The second mechanism proposed for the generation of precursory ULF magnetic fields is the piezomagnetic effect (e.g., Sasai, 1991). For this mechanism, a secondary magnetic field is induced due to a change in magnetization in ferromagnetic rocks in response to an applied stress. For an isotropic material, the change in magnetization ΔM_i due to the piezomagnetic effect is given by

$$\Delta M_i = \left(-\frac{1}{2} \tau_{kk} \delta_{ij} + \frac{3}{2} \tau_{ij} \right) \beta M_j, \quad (4)$$

where β is the stress sensitivity, τ is the stress tensor, and δ_{ij} is the Kronecker delta. If the material is linear elastic and obeys Hooke's law, the constitutive relation can be written as

$$\tau_{ij} = \lambda \delta_{ij} \nabla \cdot \mathbf{u} + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad (5)$$

where λ and μ are the Lamé constants and \mathbf{u} is the displacement vector. Substituting this constitutive law into the equation for

the change in magnetization leads to a difference equation that can be numerically integrated to determine the magnetic field at the surface resulting from piezomagnetic effects.

The third mechanism proposed to explain the generation of ULF magnetic fields is the electrokinetic effect (Nourbehecht, 1963; Fitterman, 1978, 1979). The electrokinetic effect results from the flow of electric currents in the earth in the presence of an electrified interface at solid–liquid boundaries. These electric currents in turn produce magnetic fields. The current density and fluid velocity are coupled processes defined by

$$\mathbf{j} = -\sigma \nabla E - \frac{\varepsilon \zeta}{\eta} \nabla P, \quad (6)$$

and

$$\mathbf{v} = -\frac{\varepsilon \zeta}{\eta} \nabla E - \frac{k}{\eta} \nabla P, \quad (7)$$

where \mathbf{j} is the current density, \mathbf{v} is the fluid velocity, E is the streaming potential, ε is the dielectric constant, ζ is the zeta potential (a measure of the initial potential at the electrified interface), σ is the fluid conductivity, η is the dynamic viscosity, k is the permeability, and P is the fluid pressure. The magnetic field \mathbf{B} is induced by the flow of electric current and is given by the Biot–Savart law

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int \int \frac{\nabla' \times \mathbf{j}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV, \quad (8)$$

where μ_0 is the permeability of free space.

Fenoglio et al. (1994a,b; 1995) analyzed the relative contribution of these three mechanisms applied to the ULF magnetic field signals observed prior to the 17 October 1989 Loma Prieta earthquake (Fraser-Smith et al., 1990). The analysis focused on two major increases in the magnetic field prior to the earthquake, the first having a magnitude of 2.0 nT occurring on 5 October 1989 and the second of magnitude 6.7 nT occurring just 3 h prior to the earthquake.

The results of these studies indicate that the MHD effect has a negligible contribution to the ULF magnetic signal, due to the rapid attenuation of the magnetic field strength, which decays as $1/r^3$. The piezomagnetic effect contributes an induced magnetic field of at most 10^{-2} nT, approximately two orders of magnitude less than the observed signals. The electrokinetic effect appears to be the most significant, contributing an induced magnetic field of about 5–10 nT, of about the same order as the observed fields prior to the earthquake.

In contrast, Draganov et al. (1991) attributed the observed precursory ULF magnetic fields as being the result of magnetohydrodynamic effects. However, as pointed out by Fenoglio et al. (1995), the Draganov analysis used certain model parameters that were unrealistic. These include a value for the permeability k of 10^{12} m^2 , a value which is approximately two orders of magnitude higher than would be expected for the rocks in the earthquake source region, and a pressure field of $4 \times 10^{10} \text{ Pa}$, well above the lithostatic pressure at that depth (about 10^8 Pa).

4.4. ELF/VLF/LF/HF electric fields

As mentioned above, there have been several reports in the literature of anomalous electric fields in the ELF/VLF frequency ranges and higher. The mechanisms proposed for the generation of these fields include contact electrification, separation electrification, and piezoelectrification (Ogawa et al., 1985) and atmospheric electricity generated by the emission of radon gas from the earth (Pierce, 1976).

Ogawa et al. (1985) examined the electric field generated from granite samples that were struck with a hammer or fractured by bending. They attributed the generation of the electric field to two possible mechanisms: contact (or separation) electrification or piezoelectrification. These mechanisms create a dipole moment due to separation

Table 2
Reported precursory gas emissions associated with earthquakes.

| Area (notes) | Country | Date | z [km] | Gas | δa [%] | Background level [cpm] | Signal level [cpm] | M | D [km] | d [days] | δt [days] | References |
|-------------------------------------|---------|------------|--------|---|----------------|------------------------|--------------------|------------------------------|---------|----------|-------------------|----------------------------|
| Southern (a) | Iceland | 7/3/1978 | | Rn | + | 380 | Not given | 2.7 | 14 | 22 | 25 | Hauksson and Goddard, 1981 |
| Iceland | Iceland | 8/28/1978 | | Rn | + | 60 | Not given | 3.4 | 5 | 17 | 30 | Hauksson and Goddard, 1981 |
| Seismic | Iceland | 8/28/1978 | | Rn | + | 280 | Not given | 3.4 | 21 | 17 | 27 | Hauksson and Goddard, 1981 |
| Seismic | Iceland | 11/19/1978 | | Rn | – | 80 | Not given | 4.3 | 16 | 18 | 10 | Hauksson and Goddard, 1981 |
| Seismic | Iceland | 6/29/1979 | | Rn | + | 40 | Not given | 1.9 | 9 | 19 | 25 | Hauksson and Goddard, 1981 |
| Seismic | Iceland | 9/5/1979 | | Rn | + | 40 | Not given | 2.8 | 8 | 17 | 20 | Hauksson and Goddard, 1981 |
| Seismic | Iceland | 9/5/1979 | | Rn | + | 100 | Not given | 2.8 | 5 | 33 | 33 | Hauksson and Goddard, 1981 |
| Tjörnes Fature Zone | Iceland | 12/15/1979 | | Rn | + | 100 | Not given | 4.1 | 56 | 50 | 50 | Hauksson and Goddard, 1981 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Cu | + | | 0.91 ± 0.37 ppb | 6.28 (2 σ = 2.54) | 5.8 | 100 | 1 week | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Zn | + | | 26 ± 23 ppb | 381 ppb (2 σ = 134) | 5.8 | 100 | 2 weeks | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Mn | + | | 1.25 ± 0.35 ppb | 6.76 ppb (2 σ = 2.91) | 5.8 | 100 | 5 weeks | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Cr | + | | 2.8 ± 2.2 ppb | 34 ppb (2 σ = 16) | 5.8 | 100 | 10 weeks | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Fe | + | | 2.8 ± 2.2 ppb | 28 (2 σ = 14.8) | 5.8 | 100 | 10 weeks | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | Na/Ca | + | | | 5.8 | 100 | | | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | B, Ca, K, Li, Mo, Na, Rb, S, Si, Sr Cl, SO ₄ | + | 12–19% | | 5.8 | 100 | | | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | $\delta^{18}\text{O}$ | – | 1.0 ± 0.1% | | 5.8 | 100 | | | Claesson et al., 2004 |
| Tjörnes Fature Zone | Iceland | 9/16/2002 | | δD | – | 9 ± 1% | | 5.8 | 100 | | | Claesson et al., 2004 |
| San Andreas fault | USA | 3/17/1976 | 9 | Rn | + | 120 | Not given | 4.3 | 25 | 60 | 25 | King, 1978; King, 1980 |
| San Andreas fault | USA | 1/19/1977 | 6 | Rn | + | 500 | Not given | 4 | 47 | 90 | 25 | King, 1978; King, 1980 |
| San Andreas fault | USA | 12/15/1977 | 11 | Rn | + | 400 | Not given | 4 | 45 | 15 | 30 | King, 1980 |
| San Andreas fault | USA | 8/29/1978 | 6 | Rn | + | 200 | Not given | 4.2 | 75 | 240 | 90 | King, 1980 |
| South California | USA | 9/24/1977 | 15 | Rn | + | 44 | Not given | 2.9 | 21 | 1 | 5 | Shapiro et al., 1980 |
| South California | USA | 12/20/1977 | 6 | Rn | + | 40 | Not given | 2.8 | 12 | 10 | 24 | Shapiro et al., 1980 |
| Malibu | USA | 1/1/1979 | ? | Rn | | 4 spikes | Not given | 4.6 | 54 | 4 spikes | | Shapiro et al., 1980 |
| Coalinga fault (b) | USA | 6/7/1909 | | H ₂ | + | 800 | Not given | 5.2 to 6.7 | 40–120 | | | Sato et al., 1986 |
| Kettleman Hill | USA | 4/8/1985 | | Rn | + | 100 | Not given | 5.6 | 300 | 10 | 7 | Teng and Sun, 1986 |
| Raquette Lake | USA | | | Rn | | | Not given | 3.9 | 14 | | | Fleischer, 1981 |
| Blue Mountain Lake | USA | | | Rn | | | Not given | 1.5 | 1 | | | Fleischer, 1981 |
| Pearlblossom | USA | 11/22/1976 | | Rn | + | 36 | Not given | 3.5 | 25 | 31 | | Hauksson, 1981 |
| Jocasse | USA | 2/23/1977 | | Rn | – | 50 | Not given | 2.3 | 1 | 14 | | Hauksson, 1981 |
| Pasadena | USA | 9/24/1977 | | Rn | + | 62 | Not given | 2.9 | 21 | 3 | 5 | Shapiro et al., 1980 |
| Pasadena | USA | 12/20/1977 | | Rn | + | 25 | Not given | 2.8 | 12 | 9 | | Shapiro et al., 1980 |
| Malibu | USA | 1/1/1979 | | Rn | + | 72 | Not given | 4.7 | 54 | 42 | | Shapiro et al., 1980 |
| Malibu | USA | 1/1/1979 | | Rn | + | 225 | Not given | 4.7 | 20 | 82 | | Hauksson, 1981 |
| Big Bear | USA | 6/28/1979 | | Rn | + | 310 | Not given | 5 | 85 | 12 | | Hauksson, 1981 |
| Big Bear | USA | 6/28/1979 | | Rn | + | 72 | Not given | 5 | 31 | 45 | | Hauksson, 1981 |
| Imperial Valley | USA | 10/15/1979 | | Rn | + | 400 | Not given | 6.6 | 335 | 116 | | Hauksson, 1981 |
| Imperial Valley | USA | 10/15/1979 | | Rn | + | 200 | Not given | 6.6 | 310 | 95 | | Hauksson, 1981 |
| Imperial Valley | USA | 10/15/1979 | | Rn | + | 72 | Not given | 6.6 | 265 | 145 | | Hauksson, 1981 |
| Imperial Valley | USA | 10/15/1979 | | Rn | + | 64 | Not given | 6.6 | 260 | 2 | | Hauksson, 1981 |
| Imperial Valley | USA | 10/15/1979 | | Rn | | | Not given | 6.6 | 300 | | | Fleischer, 1981 |
| Caruthersville, Missouri | USA | 6/??/1979 | | Rn | + | 375 | not given | 3.9 | nd | 33 | 60 | Steele, 1981 |
| Caruthersville, Missouri | USA | 8/??/1981 | | Rn | + | 340–504 | | 4.0 | 40 | 5 months | 2–7 months | Steele, 1984 |
| Central Arkansas (earthquake swarm) | USA | 1/??/1982 | | Rn | – | | | 4.0–4.5 | 160 | 1 year | 1 year | Steele, 1984 |
| SW Illinois | USA | 5/15/1983 | | Rn | + | 483 | | 4.2 | 120–320 | 2 months | | Steele, 1984 |
| New Madrid Seismic Zone | USA | 1/28/1983 | | Rn | + | 400 | | 3.5 | 50 | 2 months | | Steele, 1984 |
| Big Bear, California | USA | 6/30/1979 | | Rn | + | 60 | Not given | 4.8 | 30 | 150 | 120 | Chung, 1985 |
| | USA | | | He | + | 65 | Not given | 4.8 | 30 | 150 | 120 | Chung, 1985 |
| Alandale, California | USA | 6/??/1983 | | Rn | + | 1200 | not given | 3.7 | 13 | 3 | 15 | Shapiro et al., 1985 |

(continued on next page)

Table 2 (continued)

| Area (notes) | Country | Date | z [km] | Gas | δa [%] | Background level [cpm] | Signal level [cpm] | M | D [km] | d [days] | δt [days] | References |
|----------------------------------|----------|------------|--------|---------------------|----------------|------------------------|--------------------|------------|----------|------------|-------------------|-----------------------------------|
| San Andreas, California | USA | 10/13/1979 | | Rn | + | 400 | Not given | 3.4 | 40 | 0.5 | 0.2 | King, 1985 |
| | USA | 12/22/1979 | | Rn | + | 800 | Not given | 3.3 | 20 | 1 | 0.5 | King, 1985 |
| Loma Prieta, California | USA | 10/17/1989 | | He | + | 4 | Not given | 7.1 | 60 | | 1 | Reimer, 1990 |
| Coyote Lake, California | USA | 8/6/1979 | | He | — | | Not given | 5.9 | 65 | | 21 | Reimer, 1990 |
| Mt Diablo, California | USA | 1/24/1980 | | He | — | | Not given | 5.5 | 155 | | 35 | Reimer, 1990 |
| Salinas, California | USA | 4/13/1980 | | He | — | | Not given | 4.9 | 35 | | 28 | Reimer, 1990 |
| Livermore, California | USA | 8/24/1980 | | He | + | | Not given | 4.1 | 120 | | | Reimer, 1990 |
| San Juan Bautista, California | USA | 1/7/1981 | | He | — | | Not given | 4.5 | 45 | | 10 | Reimer, 1990 |
| San Juan Bautista, California | USA | 4/13/1980 | | D | — | 7% | | 4.8 | | | 1 month | O'Neil and King, 1980 |
| Hollister, California (5 events) | USA | 1979–1980 | | He | — | | | ≥ 4.0 | | | 5–6 weeks | Reimer, 1980 |
| Big Bear, California (swarm) (c) | USA | July 1979 | | Rn | + | 72 | | 4.8 | | | 60 \pm 15 | Craig, 1980 |
| Big Bear, California (swarm) (c) | USA | July 1979 | | He | + | 72 | | 4.8 | | | 60 \pm 15 | Craig, 1980 |
| Big Bear, California (swarm) (c) | USA | July 1979 | | CH ₄ | + | 60 | | 4.8 | | | 60 \pm 15 | Craig, 1980 |
| Big Bear, California (swarm) (c) | USA | July 1979 | | Ar | + | 25 | | 4.8 | | | 60 \pm 15 | Craig, 1980 |
| Big Bear, California (swarm) (c) | USA | July 1979 | | N ₂ | + | 17 | | 4.8 | | | 60 \pm 15 | Craig, 1980 |
| Sand Point, Alaska | USA | 2/14/1983 | | Rn | + | 6–40 times background | | 6.3 | 180 | | 6 weeks | Fleischer and Mogro-Campero, 1985 |
| Mexico | Mexico | 9/19/1985 | | Rn | + | 200 | Not given | 8.1 | 260 | nd | nd | Segovia et al., 1989 |
| Reventador (d) | Ecuador | 3/6/1987 | 14 | Rn | | | Not given | 6.9 | 367 | | 50 | Flores Humanante et al., 1990 |
| | Ecuador | | | | + | 230 | Not given | 6.9 | 377 | | 15–50 | Flores Humanante et al., 1990 |
| | Ecuador | | | | + | 400 | Not given | 6.9 | 339 | | 15–35 | Flores Humanante et al., 1990 |
| | Ecuador | | | | + | 100 | Not given | 6.9 | 388 | | 50 | Flores Humanante et al., 1990 |
| | Ecuador | | | | + | 100 | Not given | 6.9 | 183 | | 15–40 | Flores Humanante et al., 1990 |
| | Ecuador | | | | + | 300 | Not given | 6.9 | 350 | | 15–40 | Flores Humanante et al., 1990 |
| Ligurian Sea | France | 5/1/1986 | | Rn | + | 100 | Not given | 3.9 | 56 | 5 | 3 | Borchiellini et al., 1991 |
| Western Nagano | Japan | 9/14/1984 | | N ₂ /Ar | — | | Not given | 6.8 | 50 | 230 | 120 | Sugisaki and Sugiura, 1985, 1986 |
| | Japan | | | He/Ar | — | | Not given | 6.8 | 50 | 230 | 120 | Sugisaki and Sugiura, 1985, 1986 |
| | Japan | | | CH ₄ /Ar | — | | Not given | 6.8 | 50 | 230 | 120 | Sugisaki and Sugiura, 1985, 1986 |
| Western Nagano | Japan | 9/14/1984 | | H ₂ | — | | Not given | 6.8 | 50 | 120 | 50 | Sugisaki and Sugiura, 1985, 1986 |
| | Japan | | | H ₂ | + | 2000 | Not given | 6.8 | 70 | | 15 | Sugisaki and Sugiura, 1985, 1986 |
| | Japan | 8/6/1982 | | H ₂ | — | | Not given | 3.8 | 8.6 | | 70 | Sugisaki and Sugiura, 1985, 1986 |
| Byakko | Japan | 9/24/1990 | | He/Ar | + | | Not given | 6.6 | 280 | 0.1 | co-seismic | Nagamine and Sugisaki, 1991a |
| | Japan | 10/16/1990 | | He/Ar | + | | Not given | 4.2 | 31 | 0.15 | co-seismic | Nagamine and Sugisaki, 1991a |
| | Japan | 5/11/1991 | | He/Ar | + | | Not given | 3.9 | 35 | 0.25 | co-seismic | Nagamine and Sugisaki, 1991a |
| Chiba-Ken-Okii | Japan | 6/1/1990 | | Rn | — | 3 | Not given | 6 | 200 | 1 | | Wakita et al., 1989 |
| Nagoya | Japan | 4/3/1977 | | He/Ar | + | | Not given | 4.1 | 100 | 60 | 60 | Sugisaki, 1978 |
| | Japan | 8/6/1977 | | He/Ar | + | | Not given | 4.3 | 15 | 60 | 50 | Sugisaki, 1978 |
| | Japan | 8/15/1977 | | He/Ar | + | | Not given | 4.3 | 45 | 75 | 50 | Sugisaki, 1978 |
| | Japan | 1/14/1978 | | He/Ar | + | | Not given | 7 | 216 | 130 | 120 | Sugisaki, 1978 |
| Izu-Oshima | Japan | 1/14/1978 | | Rn | + | 7 | Not given | 6.8 | 25 | 230 | | Wakita et al., 1988 |
| Izu-Oshima | Japan | 1/14/1978 | | Rn | — | 8 | Not given | 6.8 | 25 | 7 | | Wakita et al., 1988 |
| ? | Japan | 5/26/1983 | | H ₂ | + | 100,000 | Not given | 7.7 | 480 | ? | ? | Satake et al., 1985 |
| Matsuyama area | Japan | 12/10/1982 | | CH ₄ /Ar | + | 120 | Not given | 4.9 | 50 | 120 | 100 | Kawabe, 1984 |
| Subducted zone | Japan | 3/6/1984 | | Rn | | | Not given | 7.9 | 1000 | 2 | 9 | Igarashi and Wakita, 1990 |
| | Japan | 2/6/1987 | | Rn | | | Not given | 6.7 | 130 | 4 | 3 | Igarashi and Wakita, 1990 |
| Kobe (e) | Japan | 1/17/1995 | | Rn | + | 200 | Not given | 7.2 | 30 | 90 | 75 | Igarashi et al., 1995 |
| | Japan | 1/17/1995 | | Rn | + | 1000 | Not given | 7.2 | 30 | 3 | 10 | Igarashi et al., 1995 |
| Pohai Bay | PR China | 6/18/1969 | | Rn | + | 60 | Not given | 7.4 | 170 | 170 | | Hauksson, 1981 |
| Ningshin | PR China | 8/5/1971 | | Rn | + | 200 | Not given | 4.3 | 42 | 40 | | Hauksson, 1981 |
| Hsingtang | PR China | 6/6/1974 | | Rn | + | 290 | Not given | 4.9 | 18 | 16 | | Hauksson, 1981 |
| Haicheng | PR China | 2/4/1975 | | Rn | + | 38 | Not given | 7.3 | 50 | 270 | | Hauksson, 1981 |
| Haicheng | PR China | 2/4/1975 | | Rn | + | 17 | Not given | 7.3 | 50 | 50 | | Hauksson, 1981 |
| Haicheng | PR China | 2/4/1975 | | Rn | — | 43 | Not given | 7.3 | 140 | 66 | | Hauksson, 1981 |
| Haicheng | PR China | 2/4/1975 | | Rn | + | 20 | Not given | 7.3 | 140 | 8 | | Hauksson, 1981 |
| Haicheng | PR China | 2/4/1975 | | Rn | | | Not given | 7.3 | 26 | | | Fleischer, 1980 |
| | PR China | | | | | | Not given | | 14 | | | Fleischer, 1981 |
| Liaoyang | PR China | | | | | | Not given | 4.8 | 32 | | | Fleischer, 1981 |

| | | | | | | | | | | | | |
|----------------|----------|------------|-------------------|---|------|-----------|-----------|-----|------|------|-----|---------------------------|
| Tangshan | PR China | 6/27/1976 | Rn | + | 15 | Not given | Not given | 7.8 | 50 | 970 | | Hauksson, 1981 |
| Tangshan | PR China | 6/27/1976 | Rn | + | 50 | Not given | Not given | 7.8 | 100 | 15 | | Hauksson, 1981 |
| Tangshan | PR China | 6/27/1976 | Rn | — | 40 | Not given | Not given | 7.8 | 130 | 1370 | | Hauksson, 1981 |
| Tangshan | PR China | 6/27/1976 | Rn | + | 27 | Not given | Not given | 7.8 | 130 | 162 | | Hauksson, 1981 |
| Tangshan | PR China | 6/27/1976 | Rn | | | Not given | Not given | 7.8 | 1800 | | | Fleischer, 1981 |
| Chienan | PR China | 3/7/1977 | Rn | + | 70 | Not given | Not given | 6 | 200 | 3 | 1 | Teng, 1980 |
| Sabteh | PR China | 4/8/1972 | Rn | + | 55 | Not given | Not given | 5.2 | 70 | 12 | | Teng, 1980 |
| Takung | PR China | 9/27/1972 | Rn | + | 34 | Not given | Not given | 5.8 | 54 | 12 | | Teng, 1980 |
| Luhuo | PR China | 2/6/1973 | Rn | + | 120 | Not given | Not given | 7.9 | 200 | 9 | | Wakita et al., 1988 |
| Yiliang | PR China | 4/22/1973 | Rn | + | 41 | Not given | Not given | 5.2 | 340 | 14 | | Teng, 1980 |
| Songpan | PR China | 5/8/1973 | Rn | + | 40 | Not given | Not given | 5.2 | 345 | 14 | | Hauksson, 1981 |
| Mapien | PR China | 6/29/1973 | Rn | + | 89 | Not given | Not given | 5.5 | 200 | 9 | | Wakita et al., 1988 |
| Lungling | PR China | 5/29/1976 | Rn | + | 20 | Not given | Not given | 7.5 | 20 | 510 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 15 | Not given | Not given | 7.5 | 190 | 425 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 8 | Not given | Not given | 7.5 | 210 | 160 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 12 | Not given | Not given | 7.5 | 215 | 130 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 7 | Not given | Not given | 7.5 | 360 | 75 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 20 | Not given | Not given | 7.5 | 420 | 290 | | Hauksson, 1981 |
| Lungling | PR China | 5/29/1976 | Rn | + | 200 | Not given | Not given | 7.5 | 450 | 12 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 29 | Not given | Not given | 7.2 | 40 | 480 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 11 | Not given | Not given | 7.2 | 100 | 420 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 20 | Not given | Not given | 7.2 | 100 | 190 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 70 | Not given | Not given | 7.2 | 320 | 1 | | Teng, 1980 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | — | 12 | Not given | Not given | 7.2 | 320 | 200 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 90 | Not given | Not given | 7.2 | 340 | 48 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | — | 60 | Not given | Not given | 7.2 | 340 | 160 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 55 | Not given | Not given | 7.2 | 390 | 160 | | Hauksson, 1981 |
| Songpan-Pingwu | PR China | 8/16/1976 | Rn | + | 110 | Not given | Not given | 7.2 | 560 | 34 | | Hauksson, 1981 |
| Fengzhen | PR China | ??/??/81 | H ₂ | + | 1000 | Not given | Not given | 5.8 | 285 | 15 | 7 | Shi and Cai, 1986 |
| Tangshan | PR China | 7/27/1976 | Rn | + | 50 | Not given | Not given | 7.8 | 460 | 8 | 10 | Shi and Cai, 1986 |
| Ninghe | PR China | 11/15/1976 | H ₂ | + | 900 | Not given | Not given | 6.9 | nd | 12 | 8 | Jiang et al., 1981 |
| Songpan | PR China | 8/16/1976 | Rn | + | 100 | Not given | Not given | 7.2 | 350 | 1.5 | 10 | Jiang and Li, 1981 |
| Haicheng | PR China | 1975 | F— | | | | | 7.4 | | | | Liang, 1980 |
| Tangshan | PR China | 1976 | F— | | | | | 7.8 | | | | Liang, 1980 |
| Songpan-Pingwu | PR China | 1976 | F— | | | | | 7.9 | | | | Liang, 1980 |
| Ninghe | PR China | 1977 | F— | | | | | 6.5 | | | | Liang, 1980 |
| Taschkent | Ex-USSR | 4/26/1966 | Rn | + | 20 | Not given | Not given | 5.3 | 5 | 400 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 3/24/1967 | Rn | + | 100 | Not given | Not given | 4 | 5 | 11 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 6/20/1967 | Rn | + | 23 | Not given | Not given | 3.5 | 5 | 3 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 7/22/1967 | Rn | + | 20 | Not given | Not given | 3.5 | 5 | 3 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 11/9/1967 | Rn | + | 23 | Not given | Not given | 3 | 5 | 8 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 11/17/1967 | Rn | + | 23 | Not given | Not given | 3.3 | 5 | 7 | | Hauksson, 1981 |
| Taschkent | Ex-USSR | 12/17/1967 | Rn | + | 23 | Not given | Not given | 3 | 5 | 4 | | Hauksson, 1981 |
| Uzbekistan | Ex-USSR | 2/13/1973 | Rn | + | 47 | Not given | Not given | 4.7 | 130 | 5 | | Hauksson, 1981 |
| Markansu | Ex-USSR | 8/11/1974 | Rn | + | 100 | Not given | Not given | 7.3 | 530 | 100 | | Hauksson, 1981 |
| Tien Shan | Ex-USSR | 2/12/1975 | Rn | + | 10 | Not given | Not given | 5.3 | 100 | 110 | | Hauksson, 1981 |
| Gazli | Ex-USSR | 5/17/1976 | Rn | + | 220 | Not given | Not given | 7.3 | 470 | 4 | | Hauksson, 1981 |
| Gazli | Ex-USSR | 5/17/1976 | Rn | + | 25 | Not given | Not given | 7.3 | 550 | 90 | | Hauksson, 1981 |
| Gazli | Ex-USSR | | Rn | | | not given | Not given | 7 | 700 | | | Fleischer, 1981 |
| Gazli | Ex-USSR | 5/17/1976 | Rn | | | Not given | Not given | 7.3 | 400 | | | Fleischer, 1981 |
| Isfarin-Batnen | Ex-USSR | 1/31/1977 | Rn | — | 30 | Not given | Not given | 6.6 | 190 | 60 | | Hauksson, Fleischer, 1981 |
| Isfarin-Batnen | Ex-USSR | 1/31/1977 | Rn | — | 20 | Not given | Not given | 6.6 | 200 | 125 | | Hauksson, 1981 |
| Alma-Ata | Ex-USSR | 3/24/1978 | Rn | + | 32 | Not given | Not given | 7.1 | 65 | 50 | | Hauksson, 1981 |
| Zaalai | Ex-USSR | 11/1/1978 | Rn | — | 30 | Not given | Not given | 6.7 | 270 | 470 | | Hauksson, 1981 |
| Zaalai | Ex-USSR | 11/1/1978 | Rn | — | 40 | Not given | Not given | 6.7 | 300 | 470 | | Hauksson, 1981 |
| Zaalai | Ex-USSR | 11/1/1978 | Rn | + | 20 | Not given | Not given | 6.7 | 150 | 75 | | Hauksson, 1981 |
| Zaalai | Ex-USSR | 11/1/1978 | Rn | — | 20 | Not given | Not given | 6.7 | 150 | 70 | | Hauksson, 1981 |
| Iran | Ex-USSR | 9/16/1978 | H ₂ S | + | 170 | Not given | Not given | ? | nd | 2 | 25 | Barsukov et al., 1985 |
| Duchambe | Ex-USSR | 9/29/1981 | Hg _{gas} | + | 400 | Not given | Not given | ? | 20 | | 1.2 | Varshal et al., 1985 |

(continued on next page)

Table 2 (continued)

| Area (notes) | Country | Date | z [km] | Gas | δa [%] | Background level [cpm] | Signal level [cpm] | M | D [km] | d [days] | δt [days] | References |
|-----------------------|---------|------------|--------|--|----------------|-----------------------------|--------------------|-----------|--------|----------|-------------------|--|
| Paravani, Caucasus | Ex-USSR | 5/13/1986 | | | + | 9000 | Not given | Not given | ? | | 0.8 | Varshal et al., 1985 |
| Spitak, Caucasus | USSR | 12/7/1988 | | | | | | 5.6 | | | | Bella et al., 1995a,b |
| Kamchatka Peninsula | Russia | 3/2/1992 | 34 | Na ⁺ , Ca ²⁺ , HCO ₃ , SO ₄ ²⁻ | + | Exceeds 3 σ level | | 6.9 | 100 | | 35 | Bella et al., 1995a,b Biagi et al., 2000a,b |
| | | | | Ca ²⁺ | + | | | | | | | |
| | | | | HCO ₃ ⁻ | — | | | | | | | |
| | | | | SO ₄ ²⁻ | + | | | | | | | |
| Kamchatka Peninsula | Russia | 11/13/1993 | 56 | Na ⁺ , Ca ²⁺ , HCO ₃ , SO ₄ ²⁻ | + | Exceeds 3 σ level | | | 152 | | 6–80 | Biagi et al., 2000a,b |
| | | | | Ca ²⁺ | + | | | | | | | |
| | | | | HCO ₃ ⁻ | — | | | | | | | |
| | | | | SO ₄ ²⁻ | + | | | | | | | |
| Kamchatka Peninsula | Russia | 1/1/1996 | 10 | Na ⁺ , Ca ²⁺ , HCO ₃ , SO ₄ ²⁻ | + | Exceeds 3 σ level | | | 96 | | 107 | Biagi et al., 2000a,b |
| | | | | Ca ²⁺ | + | | | | | | | |
| | | | | HCO ₃ ⁻ | — | | | | | | | |
| | | | | SO ₄ ²⁻ | + | | | | | | | |
| Kamchatka Peninsula | Russia | 6/21/1996 | 1 | Na ⁺ , Ca ²⁺ , HCO ₃ , SO ₄ ²⁻ | + | Exceeds 3 σ level | | | 228 | | 72 | Biagi et al., 2000a,b |
| | | | | Ca ²⁺ | + | | | | | | | |
| | | | | HCO ₃ ⁻ | — | | | | | | | |
| | | | | SO ₄ ²⁻ | + | | | | | | | |
| Kamchatka Peninsula | Russia | 12/5/1997 | 10 | Ar | + | Exceeds 3 σ level | | | 366 | | 6–80 | Biagi et al., 2000a,b |
| | | | | N ₂ | + | | | | | | | |
| Irpinia | Italy | 11/23/1980 | | Rn | + | 25 | Not given | Not given | 6.5 | 220 | 150 | Allegrì et al., 1983 |
| Irpinia | Italy | 11/23/1980 | | Rn | + | 170 | Not given | Not given | 6.5 | 200 | 180 | Allegrì et al., 1983 |
| Northern Taiwan | Taiwan | 10/18/1980 | 8.2 | Rn | nd | | Not given | Not given | 5.8 | 39 | nd | Liu et al., 1985 |
| | Taiwan | 5/14/1981 | 8.2 | Rn | nd | | Not given | Not given | 5.2 | 23 | nd | Liu et al., 1985 |
| | Taiwan | 6/21/1981 | 8.4 | Rn | nd | | Not given | Not given | 4.6 | 14 | nd | Liu et al., 1985 |
| | Taiwan | 7/18/1981 | 6.7 | Rn | nd | | Not given | Not given | 5 | 37 | nd | Liu et al., 1985 |
| | Taiwan | 10/31/1982 | 9.8 | Rn | nd | | Not given | Not given | 5.3 | 45 | nd | Liu et al., 1985 |
| | Taiwan | 11/??/1982 | | Rn | + | 3–4 times background | | 4.1 | 60 | | 2 weeks | Liu et al., 1983 |
| Uttarkashi (f) | India | 10/20/1991 | | Rn | + | 200 | Not given | Not given | 7 | 450 | 7 | Virk and Baljinder, 1994 |
| | India | | | | + | 300 | Not given | Not given | 7 | 270 | 7 | Virk and Baljinder, 1994 |
| | India | | | | + | 180 | Not given | Not given | 7 | 330 | 7 | Virk and Baljinder, 1994 |
| Himachal Pradesh (g) | India | 4/9/1992 | | Rn | + | 195 | Not given | Not given | 2.2 | 166 | | Virk and Baljinder, 1995 |
| | India | 5/23/1995 | | Rn | + | 165 | Not given | Not given | 2.7 | 105 | | Virk and Baljinder, 1995 |
| | India | 1/12/1993 | | Rn | + | 153 | Not given | Not given | 4.4 | 440 | | Virk and Baljinder, 1995 |
| | India | 1/12/1993 | | Rn | + | 183 | Not given | Not given | 4.4 | 440 | | Virk and Baljinder, 1995 |
| | India | 7/21/1992 | | Rn | + | 250 | Not given | Not given | 3.6 | 265 | | Virk and Baljinder, 1995 |
| | India | 8/5/1993 | | Rn | + | 242 | Not given | Not given | 3.7 | 325 | | Virk and Baljinder, 1995 |
| | India | 8/5/1993 | | Rn | + | 227 | Not given | Not given | 3.7 | 325 | | Virk and Baljinder, 1995 |
| Maheshwaram | India | 4/17/2002 | | Rn | + | 100 | Not given | Not given | <1 | 30 | <1 | Reddy et al., 2004 |
| Chamoli (groundwater) | India | 3/29/1999 | | Rn | + | 69.66 Bq/l | 56.69 Bq/l | Not given | 6.8 | | | Virk et al., 2001 |
| Chamoli (soil gas) | India | 3/29/1999 | | Rn | + | 46.63 Bq/l | 24.31 Bq/l | Not given | 6.8 | | | Virk et al., 2001 |
| Chamoli | India | 3/29/1999 | | He | + | 5.6 ppm | 5.1 ppm | Not given | 6.8 | | | Virk et al., 2001 |

| | | | | | | | | | | | | | |
|---------------------------|-------------|---------------------------------------|-----|-------------------------------|------------|----------|-------------|-------------|--------|-----|-----|----------|---|
| Chiba-ken Toho-oki | Japan | Jan 1991 | | | background | | | | | | | | |
| | | 6/1/1990 | 59 | Rn | — | 5 | 2350 | 2225 | 6 | 200 | 2 | 2 | Wakita et al., 1991 |
| Fukushima | Japan | Jan 1987 | | Rn | — | 2 | 2025 | 1975 | 6.6 | 260 | 0 | 0 | Igarashi et al., 1990 |
| Fukushima | Japan | Feb 1987 | | Rn | — | 11 | 2025 | 1800 | 6.7 | 130 | 0 | 0 | Igarashi et al., 1990 |
| Fukushima | Japan | Apr 1987 | | Rn | — | 9 | 2000 | 1825 | 6.6 | 110 | 0 | 0 | Igarashi et al., 1990 |
| Kobe | Japan | 1/17/1995 | 14 | Cl [−] | + | 10 | 13.85 ppm | 15.3 ppm | 7.2 | 20 | 4 | | Tsunogai & Wakita, 1995; Tsunogai & Wakita, 1996 |
| Kobe | Japan | 1/17/1995 | | Rn | — | 5 | 3100 | 2950 | 7.2 | 260 | | | Ohno & Wakita, 1996 |
| Western Nagano prefecture | Japan | 9/14/1984 | | Rn | + | | | | | 65 | | 2 weeks | Ui et al., 1988 |
| Eastern Pyrenees | France | 2/18/1996 | 7.7 | Cl [−] | + | 36 | 0.272 mml/l | 0.369 mml/l | 5.2 | 29 | 5 | 10 to 13 | Toutain et al., 1997 |
| Hyogo-Ken Nambu Zisin | Japan | Sep 1984 | | He/Ar | — | 25 | 0.112*** | 0.084*** | 6.9 | 50 | | | Sugisaki et al., 1996 |
| Hyogo-Ken Nambu Zisin | Japan | Sep 1984 | | N ₂ /Ar | — | 10 | 126*** | 113*** | 6.9 | 50 | | | Sugisaki et al., 1996 |
| Hyogo-Ken Nambu Zisin | Japan | Sep 1984 | | CH ₄ /Ar | — | 32 | 22*** | 15*** | 6.9 | 50 | | | Sugisaki et al., 1996 |
| Hyogo-Ken Nambu Zisin | Japan | Jan 1995 | | He/Ar | — | 4 | 0.113*** | 0.109*** | 7.2 | 220 | 3 h | 15 min | Sugisaki et al., 1996 |
| Izu-Oshima-kinkai | Japan | 1/14/1978 | 7.0 | Rn | + | 15% | | | 7.0 | 25 | | 5 | Wakita et al., 1980 |
| Hyogo-Ken Nambu Zisin | Japan | Jan 1995 | | N ₂ /Ar | — | 2 | 132*** | 130*** | 7.2 | 220 | 3 h | 15 min | Sugisaki et al., 1996 |
| Hyogo-Ken Nambu Zisin | Japan | Jan 1995 | | CH ₄ /Ar | — | 6 | 21.8*** | 20.6*** | 7.2 | 220 | 3 h | 15 min | Sugisaki et al., 1996 |
| Mindoro | Philippines | 11/14/1994 | | Rn | + | 600 | Not given | Not given | 7.1 | 48 | 7 | 22 | Richon et al., 2003 |
| Perpignan | France | 1996 | | HCO ₃ [−] | + | 135 mg/L | 80–110 mg/l | | 5.2 | 100 | | | Perez, 1996 |
| Perpignan | France | 1996 | | Ca ²⁺ | + | 45 mg/l | 20–30 mg/l | | 5.2 | 100 | | | Perez, 1996 |
| Perpignan | France | 1996 | | Cl [−] | + | 75 mg/l | 35 mg/l | | 5.2 | 100 | | | Perez, 1996 |
| Galicia | Spain | 2 events, 11/29/1995 12/24/1995 | | Cl [−] | + | 26 mg/l | 24 mg/l | | 4.64.6 | 90 | | | Redondo et al., 1996 |
| Galicia | Spain | 2 events, 11/29/1995 12/24/1995 | | Br [−] | + | | | | 4.6 | 90 | | | Redondo et al., 1996 |
| Galicia | Spain | 2 events, 11/29/1995 12/24/1995 | | δD | + | | | | 4.6 | 90 | | | Redondo et al., 1996 |

Note: The data through the earthquakes at Himachal Pradesh have been adapted from a table by Toutain and Baubron (1999).

Legend:

z = epicentral depth.

δa = deviation.

M = magnitude.

D = epicentral distance.

d = duration.

δt = days before event.

+, gas emission increase.

−, gas emission decrease.

*** unitless (ratio).

a Values from Hauksson (1981). This author does not supply time lag values.

b Hydrogen values from Sato et al. (1986). H₂ displays a very complex pattern probably linked to a sudden increase in seismicity (11 events of magnitude 5.2 to 6.7 within 6 months).

c The Big Bear earthquake swarm occurred on June 29 and 30. The main shock was $M = 4.8$ and was considered as the total event.

d Time lags vary at some sites which have several probes. No duration of anomalies is shown because of the track-etch method used.

Values of deviation of signal at each site are from one of the several probes. Values at one site (epicentral distance of 350 km) are either positive or negative, depending on the probe (Flores Humanante et al., 1990).

e According to data by Igarashi et al. (1995), we can assume the existence of two precursors, one lasting about 3 months and the other being a spike-like one occurring 7 days before the onset.

f Magnitudes were indicated to be 6.5 (Mb) and 7.0 (MS).

g Only anomalies above 1a have been selected. Graphical data are not enough precise to estimate values of duration and time lags of claimed anomalies.

Note: These notes are from the original table compiled by Toutain and Baubron (1999).

of positively and negatively charged particles, and an electric field is generated. In the rock samples, the near field E_s is related to the dipole moment p by

$$E_s = \frac{1}{4\pi\epsilon_0} \frac{p}{r^3}, \quad (9)$$

where r is the distance between the dipole and the antenna and ϵ_0 is the permittivity of free space. For earthquakes, Ogawa et al. (1985) propose that the electric fields actually generated are the induced field E_i in the VLF frequency range and the radiation field E_r for the LF frequency range. These fields are related to the dipole moment by

$$E_i = \frac{1}{4\pi\epsilon_0} \frac{\dot{p}}{cr^2}, \quad (10)$$

and

$$E_r = \frac{1}{4\pi\epsilon_0} \frac{\ddot{p}}{c^2r}, \quad (11)$$

where c is the velocity of light and the dots represent derivatives with respect to time.

Pierce (1976) presented a model that relates changes in atmospheric electricity to the emission of radon gas from the earth. The radon gas alters certain parameters that affect atmospheric electricity, including fair-weather conductivity near the ground and the electric field (i.e., potential gradient). Specifically, the model predicts that the conductivity near the ground would increase by about 50%, while the electric field would decrease by about 30%.

4.5. Gas emission observations

In the late 1960s and early 1970s reports primarily from Russia and China indicated that concentrations of radon gas in the earth apparently changed prior to the occurrences of nearby earthquakes (Lomnitz, 1994). This stimulated a number of experiments in other parts of the world to monitor underground radon with time and to look for radon changes associated with earthquakes. Since radon is a radioactive gas, it is easy and relatively inexpensive to monitor instrumentally, and its short half-life (3.8 days) means that short-term changes in the radon concentrations in the earth can be monitored with very good time resolution. While other gases have also been looked at as possible earthquake precursors, the bulk of the experiments reported in the scientific literature have focused on radon.

In our literature survey, we found reports of 159 observations of changes in gas emissions from 107 earthquakes. Of these, there were 125 radon observations from 86 earthquakes, 7 observations of hydrogen gas from 7 earthquakes, 7 observations of helium gas from 7 earthquakes, 10 observations of helium/argon gas ratios from 10 earthquakes, 4 observations of methane/argon ratios from 4 earthquakes, 3 observations of nitrogen/argon ratios from 3 earthquakes, 2 observations of chlorine ions from 2 earthquakes, and 1 observation of mercury gas from 1 earthquake. There are also reports of possible changes in the emission of other gases, such as carbon monoxide and carbon dioxide, from the earth associated with earthquakes, but no specific measurements were reported in the papers we surveyed.

Table 2 contains the complete listing of gas emission anomalies found in our literature search along with estimates of the initiation time, strength and duration of the gas anomalies. Because the preponderance of data is concerned with radon gas changes, we summarize those results here.

There is a very wide range of earthquake magnitudes for which anomalous radon precursors have been reported. In the dataset in Table 2 the smallest earthquake magnitude is 1.5 and the largest is 7.9. Most of the observations are for earthquakes greater than magnitude 4.0. Radon gas changes up to 1200% relative to background radon concentration levels are reported in Table 2 although most of the changes are between 20% and 200%, with the most common reported change between 50% and 100% (Fig. 1). In Table 2, 83% of the observations reported that radon levels increased prior to the earthquake relative to the background radon levels.

In Fig. 2 the times of initiation of the radon anomalies and the durations of the radon anomalies are shown. Most of the radon anomalies began within 30 days of the earthquake, and most lasted less than 200 days. In some cases in Table 3 the radon anomaly initiated and terminated before the earthquake (δt greater than d in the Table 3), while in other cases the radon anomaly continued after the time of the earthquake (δt less than d in the Table 3). Thus, there does not appear to be any diagnostic behavior of either the beginning or the end of a radon anomaly that gives a consistent clue about when an earthquake is to happen. The best that can be said is that most of the time the earthquake takes places within a month of the time that an increase in radon gas is observed.

Fig. 3 shows the dependence of the magnitude of the reported radon anomalies on distance of the observation site to the earthquake epicenter and on the magnitude of the event. The greatest anomalies are reported closest to the epicenters of the coming earthquakes, suggesting that the

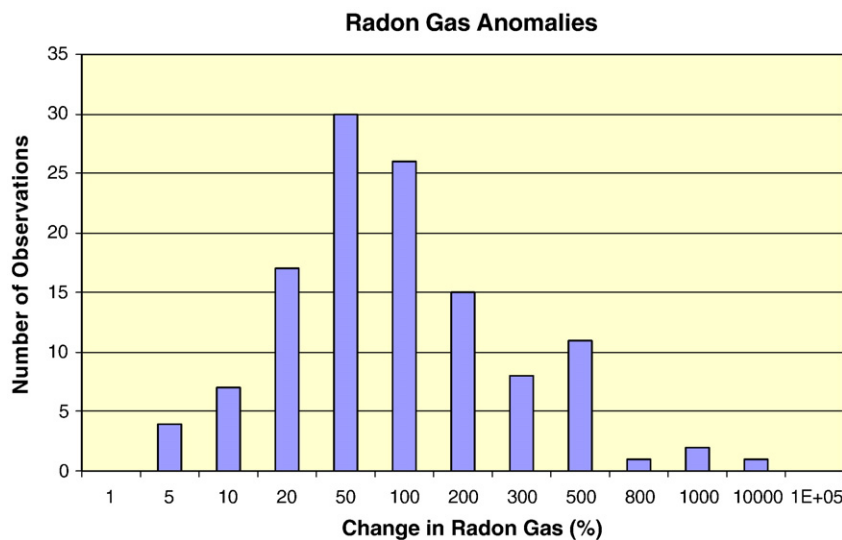


Fig. 1. Distribution of reported maximum changes in radon gas concentrations in the earth (in percent relative to the background radon levels) prior to earthquakes. Most of the changes are between 20% and 200%. The vertical axis represents the number of observations for each data range.

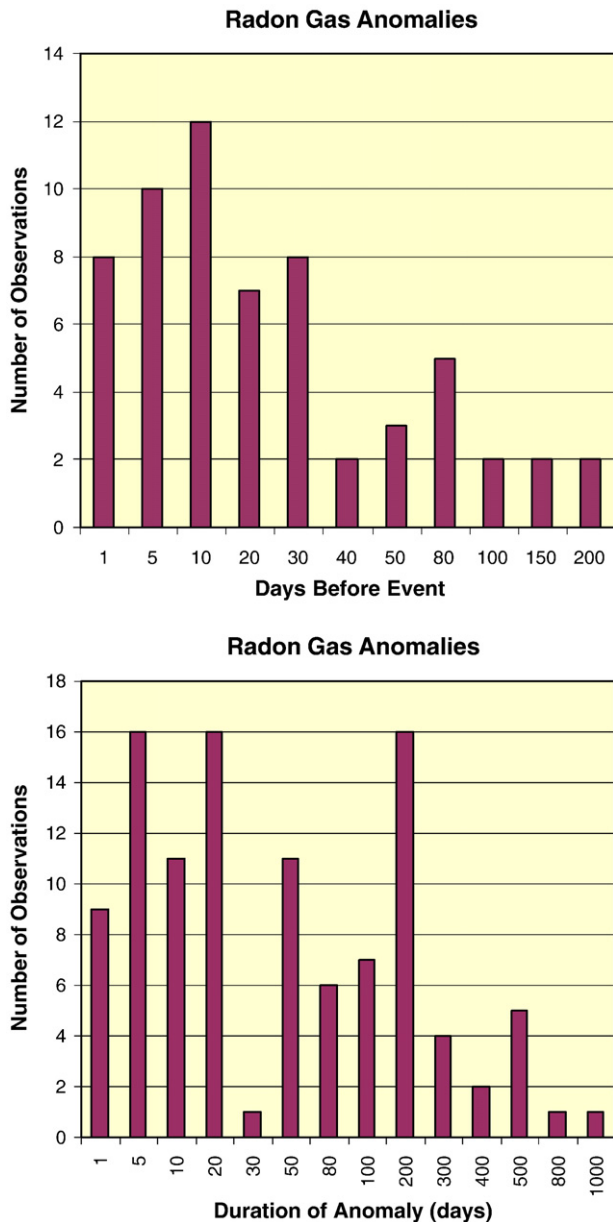


Fig. 2. Distribution of reported times of initiation of the radon anomaly prior to the earthquake (top) and of the durations of the radon anomaly (bottom). Most of the radon anomalies began within 30 days of the earthquake and lasted less than 200 days.

radon anomalies are associated with some physical processes in or near the earthquake fault zone. On the other hand, the amplitude of the radon anomaly does not seem to depend on the magnitude of the coming earthquake. This appears to indicate that whatever causes the anomalous radon emissions does not control the size of the earthquake. The significant amount of scatter in the data precludes the determination of any useful regression curves of radon anomaly as a function of either distance or magnitude. On the other hand, curves that represent the possible extremal values from the data in Table 3 are plotted in Fig. 3, and the corresponding equations, for these lines are summarized in Table 4. These curves are intended to place a possible upper bound on the expected anomaly radon values as a function of magnitude and distance as determined by the data collected in this study.

Fig. 4 analyzes the dependence of magnitude of the coming even with the start time of the radon anomaly relative to the time of the earthquake and with the duration of the anomaly. Greater times between the start of the anomaly and the earthquake as well as longer durations of the radon anomalies appear to be associated with larger

event magnitudes. Thus, in an earthquake prediction scheme, the longer the duration of a radon anomaly, the larger the earthquake that might be expected. Again, line segments representing possible extremal values of the data as a function of magnitude are plotted in Fig. 4.

The paucity of data for the other types of gases in Table 2 precludes analyses similar to those of Figs. 1–4. However, some general statements can be made about the observational data for these other gases. First, for the other gases the distribution of reported anomaly amplitudes, time durations, time of initiation before the event, and distance to the epicenter appear in all cases to be similar to the observations for radon gas. The amplitudes of the anomalies seem to vary from gas to gas, with the largest reported increase being 100,000% for an observation of H_2 prior to an earthquake. This would seem to suggest that other gases besides radon may give higher amplitude gas emissions prior to earthquakes if they were widely monitored. Finally, while radon tends to increase in emission before earthquakes, this appears to be true of some but not all of the gases in Table 2. Of these other gases for which data were collected, H_2 (6 of 7 observations), He/Ar (7 of 10 observations) and Cl^- (2 of 2 observations) show gas increases before the earthquakes, while He (4 of 7 observations), CH_4/Ar (3 of 4 observations) and N_2/Ar (3 of 3 observations) report gas decreases before the earthquakes.

4.6. Gas emission models

Thomas (1988) provides a summary of physical processes proposed to explain geochemical precursors, including gas emissions, to earthquakes. Although many different models have been proposed in the literature to account for the various observed geochemical precursors, most can be associated with one of the following mechanisms:

- Physical and/or chemical release by ultrasonic vibration (UV model);
- Chemical release due to pressure sensitive solubility (PSS model);
- Physical release by pore collapse (PC model);
- Chemical release by increased loss or reaction with freshly created rock surfaces (IRSA model);
- Physical mixing due to aquifer breaching and/or fluid mixing (AB/FM model).

These mechanisms are briefly described below. Readers are referred to the review paper of Thomas (1988) for the original references.

4.7. Ultrasonic vibration model

This model proposes that loosely-bound constituents in subsurface rocks can be released by ultrasonic vibration. Laboratory studies have indicated that rocks react more readily with water when ultrasonic vibration is applied. Field studies have also shown that geochemical anomalies can be generated in response to a subsurface explosive discharge, similar to those commonly used in seismic exploration.

Critics of this model contend that the relatively high frequencies necessary to release chemical species from subsurface rocks are either too weak or completely absent in the frequency spectrum of earthquakes. In addition, geochemical anomalies associated with explosions are typically much smaller than those associated with earthquakes. Also, these explosion-induced anomalies occur some time after the explosion itself, indicating that some other mechanism may be generating these anomalies.

4.8. Pressure sensitive solubility model

This model proposes that increases in dissolved chemical species in groundwater are caused by increases in fluid pressure due to precursory stress changes. This mechanism is unlikely to contribute significantly to the generation of geochemical anomalies, because the required stress changes are on the order of tens to hundreds of bars. Even though stress changes of this order are common in earthquakes,

Table 3

Reported precursory groundwater level changes associated with earthquakes.

| <i>Earthquakes with reported groundwater precursors</i> | | | | | | | | |
|---|------|--|--------|--------------------------|------------|---------|--|-------|
| Earthquake | Mag. | Date | D [km] | A [m] | T [day] | t [day] | Reference | Notes |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 10 | −1.300 | 180.0 | 7.0 | Mil'kis, 1984 | * |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 10 | −0.800 | 60.0 | 45.0 | Mil'kis, 1984 | * |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 90 | −0.400 | 225.0 | 40.0 | Mil'kis, 1984 | * |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 90 | −0.600 | 225.0 | 40.0 | Mil'kis, 1984 | * |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 90 | −0.400 | 225.0 | 40.0 | Mil'kis, 1984 | * |
| Turkmenia, former U.S.S.R. | 7.3 | 10/5/1948 | 90 | +/- 0.5 | 150.0 | 70.0 | Mil'kis, 1984 | * |
| Uzbekistan, former U.S.S.R. | 7.3 | 5/17/1976 | 200 | −2.000 | 1.0 | 0.5 | Ishankulov and Kalugin, 1976 | * |
| Uzbekistan, former U.S.S.R. | 7.3 | 5/17/1976 | 530 | −16.000 | 300.0 | 40.0 | Mil'kis and Voronin, 1983 | * |
| Tadzhikistan, former U.S.S.R. | 6.3 | 1/31/1977 | 210 | 1.000 | 135.0 | — | Sultankhodzaev and Chernov, 1978 | * |
| Turkmenia, former U.S.S.R. | 4.5 | 3/25/1977 | 120 | −0.080 | 60.0 | 25.0 | Zhukov et al., 1978 | * |
| Tadzhikistan, former U.S.S.R. | 5.0 | 12/6/1977 | 25 | 2.000 | 150.0 | — | Sultankhodzaev and Chernov, 1978 | * |
| Kirgizia, former U.S.S.R. | 6.6 | 3/25/1978 | 300 | −0.500 | 35.0 | 20.0 | Orolbaev, 1984 | * |
| Kirgizia, former U.S.S.R. | 6.6 | 3/25/1978 | 140 | −0.200 | 14.0 | 10.0 | Orolbaev, 1984 | * |
| Kirgizia, former U.S.S.R. | 6.8 | 11/2/1978 | 140 | −0.800 | 3.0 | 1.0 | Mavlyanov and Sultankhodzaev, 1981 | * |
| Uzbekistan, former U.S.S.R. | 5.1 | 12/11/1980 | 150 | −0.110 | 40.0 | 30.0 | Kissin et al., 1984a | * |
| Uzbekistan, former U.S.S.R. | 5.1 | 12/11/1980 | 150 | −0.005 | 5.0 | 5.0 | Kissin et al., 1984a | * |
| Uzbekistan, former U.S.S.R. | 5.1 | 12/11/1980 | 160 | −0.030 | 1.0 | 0.5 | Kissin et al., 1984a | * |
| Kazakhstan, former U.S.S.R. | 5.3 | 12/31/1982 | 95 | 0.130 | 2.0 | — | Ospanov and Mizev, 1985 | * |
| Tadzhikistan, former U.S.S.R. | 5.9 | 12/26/1984 | 100 | 8.100 | 3.0 | — | Sultankhodzaev et al., 1986 | * |
| Kuril Islands, former U.S.S.R. | 7.5 | 3/22/1978 | 270 | −0.030 | 7.0 | 2.5 | Monakhov, 1981 | * |
| Kuril Islands, former U.S.S.R. | 7.0 | 6/21/1978 | 450 | −0.045 | 6.0 | 3.0 | Monakhov et al., 1980 | * |
| Kuril Islands, former U.S.S.R. | 5.2 | 10/11/1978 | 90 | −0.070 | 6.0 | 2.0 | Monakhov et al., 1980 | * |
| Kuril Islands, former U.S.S.R. | 5.6 | 12/2/1978 | 440 | −0.090 | 9.0 | 2.0 | Monakhov et al., 1979 | * |
| Kuril Islands, former U.S.S.R. | 5.4 | 2/25/1979 | 95 | −0.040 | 5.0 | 1.5 | Monakhov, 1981 | * |
| Kuril Islands, former U.S.S.R. | 6.3 | 2/15/1980 | 170 | −0.030 | 6.0 | 2.0 | Monakhov, 1981 | * |
| Baykal area, former U.S.S.R. | 5.0 | 10/2/1980 | 25 | −0.300 | 60.0 | — | Golenetskii et al., 1982 | * |
| Lutt Plateau, Iran | 6.7 | 1/16/1979 | 400 | −0.350 | 21.0 | 14.0 | Mil'kis & Voronin, 1983 | * |
| Hindu Kush, Afghanistan | 6.6 | 5/2/1981 | 450 | 0.015 | 4.0 | 3.0 | Kissin et al., 1984b | * |
| Singhai, China | 6.8 | 3/24/1971 | 20 | −0.300 | 20.0 | 7.0 | Wang et al., 1984a | * |
| Singhai, China | 6.8 | 3/24/1971 | — | −0.410 | 30.0 | 1.0 | Hamilton, 1975 | * |
| Liaoning, China | 7.3 | 2/4/1975 | 40 | −0.100 | 8.0 | 5.0 | Raleigh et al., 1977 | * |
| Liaoning, China | 7.3 | 2/4/1975 | 145 | −0.030 | 4.0 | 2.0 | Raleigh et al., 1977 | * |
| Hebei, China | 7.8 | 7/28/1976 | 5 | −15.000 | 2640.0 | 5.0 | Wang et al., 1984b | * |
| Hebei, China | 7.8 | 11/15/1976 | 30 | −13.000 | 1090.0 | 5.0 | Wang et al., 1984b | * |
| Hebei, China | 6.9 | 11/15/1976 | 100 | −3.000 | 100.0 | 30.0 | Alimova and Zubkov, 1983 | * |
| Liaoning, China | 5.6 | 11/27/1977 | 20 | −0.500 | 1.2 | — | Wang et al., 1984a | * |
| Liaoning, China | 5.6 | 11/27/1977 | 20 | −0.580 | — | 0.4 | Cai and Shi, 1980 | * |
| near Izu Peninsula, Japan | 7.0 | 1/14/1978 | 35 | +/- 2.0 | 288.5 | 30.0 | Alimova and Zubkov, 1983 | * |
| Izu Peninsula, Japan | 6.6 | 6/29/1980 | 30 | 0.480 | 40.0 | 15.0 | Yamaguchi, 1980 | * |
| California, U.S.A. | 5.0 | 2/24/1972 | — | −0.050 | 25.0 | 10.0 | Kovach et al., 1975 | * |
| California, U.S.A. | 4.7 | 4/9/1972 | — | −0.100 | 40.0 | 15.0 | Kovach et al., 1975 | * |
| San Jacinto, California, U.S.A. | 5.5 | 2/25/1980 | 35 | 0.450 | 3.7 | 3.4 | Merfield and Lamar, 1981 | * |
| Kettleman Hills, California, U.S.A (2 wells) | 6.1 | 8/4/1985 | 35 | + 3.0 cm, + 3.8 cm | — | 3 | Roeloffs and Quilty, 1997 | |
| Taiwan | 6.3 | 12/29/1984 | — | 0.050 | 0.0 | 0.0 | Yu and Mitchell, 1988 | |
| Taiwan | 6.3 | 6/12/1985 | — | 0.030 | 0.0 | 0.1 | Yu and Mitchell, 1988 | |
| Taiwan | 6.2 | 1/16/1986 | — | 0.240 | 0.0 | 0.0 | Yu and Mitchell, 1988 | |
| Izu–Oshima–kinkai, Japan | 7.0 | 1/14/1978 | 30 | −0.300 | 0.0 | — | Wakita, 1984 | |
| southwest Japan | 6.6 | 3/18/1987 | 226 | 0.2 ml/s | 15 min | 0 | Kawabe et al., 1988 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | 0.040 | 2.0 | 1.5 | Igarashi et al., 1992 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | 0.034 | 2.0 | 1.5 | Igarashi et al., 1992 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | −0.100 | 1.0 | 0.5 | Igarashi et al., 1992 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | 0.200 | 0.0 | — | Igarashi et al., 1992 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | −0.038 | 0.0 | — | Igarashi et al., 1992 | |
| Tokyo Bay, Japan | 5.9 | 2/2/1992 | 90–110 | 0.010 | 0.0 | 1.0 | Igarashi et al., 1992 | |
| Hokkaido, Japan | 8.1 | 10/4/1994 | 1260 | −50 cm | — | 10 | Igarashi et al., 1996 | |
| Sanriku, Japan | 7.8 | 12/28/1994 | 800 | −50 cm | — | 10 | Igarashi et al., 1996 | |
| Izu Peninsula, Japan (6 swarms, >1000 events/day) | ≥2.5 | 9/1995–10/1995, 10/1996, 3/1997, 4/1998–5/1998, 5/2002, 6/2002 | 30 | 0.0024 m/h | <1 day | <1 | Koizumi et al., 1999, Koizumi et al., 2004 | |
| Tono Mine, Japan | 6.1 | 9/24/1990 | 510 | 0.5 | 5 days | 0 | King et al., 2000 | |
| Tono Mine, Japan | 7.2 | 10/4/1994 | 220 | 0.5 | 10 days | 0 | King et al., 2000 | |
| Tono Mine, Japan | 7.5 | 12/28/1994 | 800 | 0.5 | 10 days | 0 | King et al., 2000 | |
| Tono Mine, Japan | 8.1 | 1/17/1995 | 1260 | 0.5 | 30 days | 0 | King et al., 2000 | |
| Tono Mine, Japan | 6.6 | 9/5/1996 | 290 | 0.2 | 5 days | 0 | King et al., 2000 | |
| Tono Mine, Japan | 5.8 | 3/16/1997 | 50 | 2 | 6 months | 0 | King et al., 2000 | |
| Koyna–Warna, western India | 4.4 | 4/25/1997 | 3 | + 3 cm, + 7 cm (2 wells) | 23 days | 23 | Chadha et al., 2003 | |
| Koyna–Warna, western India | 4.3 | 2/11/1998 | 12 | + 5 cm | 3 days | 3 | Chadha et al., 2003 | |
| Koyna–Warna, western India | 4.7 | 4/6/2000 | 24 | + 2.5 cm | 28 days | 28 | Chadha et al., 2003 | |
| Koyna–Warna, western India | 5.2 | 9/5/2000 | 12–20 | − (0.4–8) cm (7 wells) | 24–28 days | 24–28 | Chadha et al., 2003 | |
| Thessaloniki, Greece | 4.8 | 10/20/1988 | 33–46 | 5–10 cm | 5 days | 5 | Asteriadis and Livieratos, 1989 | |

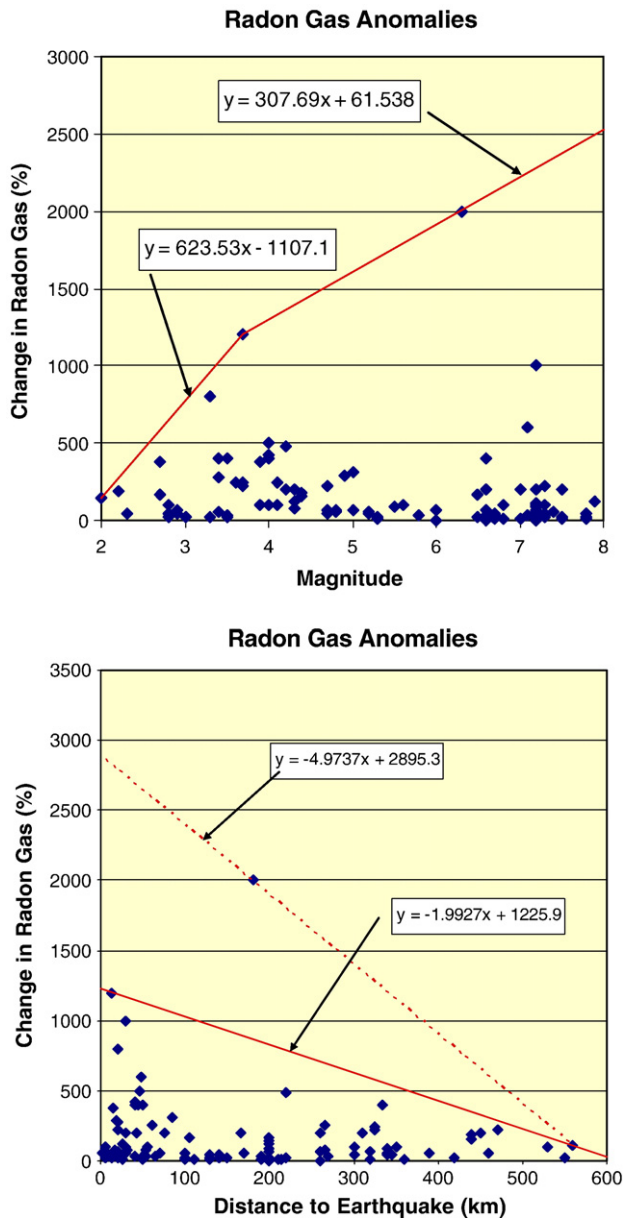


Fig. 3. Distribution of reported changes in radon gas concentrations with distance to the earthquake (top) with event magnitude (bottom). The greatest anomalies are reported closest to the epicenters, but no dependence on magnitude is seen. Curves representing the possible extremal values of the data sets are also shown. On the bottom figure, two different extremal lines are shown, where the solid line ignores the one extreme data point at about 180 km epicentral distance.

there is little evidence that these stress changes are transferred to the fluid phase in the rocks.

4.9. Pore collapse model

This model suggests that, as stresses in the earth increase prior to an earthquake, the pore volume in the rocks collapses, thereby releasing chemical species into the groundwater, generating a geochemical

anomaly. Decreases in rock pore volume have been demonstrated in a number of laboratory and field studies.

The importance of the pore collapse model to the study of earthquake precursors is not well established. Laboratory studies indicate that volume losses in rocks tend to occur at relatively low stress levels and tend to be small. In fact, high stresses in porous rocks result in an increase in pore volume for most rocks. Also, decrease in pore volume is an irreversible process and would not account for the repeated and cyclic nature of precursory geochemical precursors.

4.10. Increased reactive surface area model

For this model, it is proposed that microfracturing prior to major earthquakes leads to increases in ion and gas concentrations in the groundwater. The fracturing process has two effects. The first is that it allows trapped gases to escape from the rock matrix. The second is that it produces fresh silicate surfaces, which are believed to increase the rate of reaction with groundwater.

Laboratory studies indicate that microfracturing and the associated dilatancy can increase the porosity of rocks appreciably, from 20% up to as much as 400%. Reaction with fresh rock surfaces has been shown to significantly increase ions in groundwater. Also, laboratory studies have indicated that the release of gases, most notably radon, can increase substantially at the stress levels associated with microfracturing (Holub and Brady, 1981). Field studies have indicated a correlation with increased radon concentrations in groundwater and regional stress and deformation changes.

The major uncertainty associated with this model is the fact that laboratory studies have indicated that rock dilatancy and the associated increases in pore volume only become important in rocks near the failure strength. This would indicate that the mechanism should be confined to a small volume of rock close to the fault. This is in conflict with the observations of geochemical precursors at significant distances from seismogenic faults. However, it has been argued that this model does not consider the importance of stress corrosion cracking and subcritical crack growth, which can occur at relatively low stress levels and high moisture content.

4.11. Aquifer breaching/fluid mixing model

This model can be used to account for anomalous changes in groundwater geochemistry as the result of mixing of chemical species from two distinct aquifer systems. The advantage of this model is that it can account for both increases and decreases in chemical species and gas concentrations, as well as the concurrent temperature changes that often accompany these geochemical precursors.

The mechanism of fluid mixing is believed to be due to precursory fracturing of hydrologic barriers that separate the individual aquifer systems. A similar mechanism has been proposed by Byerlee (1993) to explain the compartmentalization of high-pressure fluid regions in the vicinity of faults. This mechanism was cited by Fenoglio et al. (1994a,b; 1995) to support their conclusion that the electrokinetic mechanism is the process by which transient ULF magnetic field precursors were generated prior to the Loma Prieta earthquake.

4.12. Groundwater level change observations

Changes in groundwater level changes prior to earthquakes have been reported back to early historic times (Martinelli, 2000). This is

Notes to Table 3:

*Compiled by Kissin and Grinevsky, 1990.

D = epicentral distance.

A = amplitude (+, groundwater rise; −, groundwater drop).

T = time (period of time from the beginning of the precursor to the earthquake origin time).

t = extremum time (period of time from the onset of a precursor extremum to the earthquake origin time).

Table 4
Summary of equations for extremal value curves.

| Figure number | Type of anomaly | Physical quantity (y vs. x) | Equation |
|---------------|--------------------|--|------------------------------|
| 3 | Radon gas | Change in radon gas vs. magnitude | $y = 307.69x + 61.538$ |
| 3 | Radon gas | Change in radon gas vs. magnitude | $y = 623.53x - 1107.1$ |
| 3 | Radon gas | Change in radon gas vs. distance to earthquake | $y = -4.9737x + 2895.3$ |
| 3 | Radon gas | Change in radon gas vs. distance to earthquake | $y = -1.9927x + 1225.9$ |
| 4 | Radon gas | Anomaly duration vs. magnitude | $y = 359.72x - 1005.8$ |
| 4 | Radon gas | Anomaly duration vs. magnitude | $y = 135.59x - 71.186$ |
| 4 | Radon gas | Days before event vs. magnitude | $y = 42.857x - 85.714$ |
| 7 | Water level change | Water level change vs. distance to earthquake | $y = -0.9867\ln(x) + 7.5439$ |
| 7 | Water level change | Water level change vs. distance to earthquake | $y = 0.9867\ln(x) - 7.5439$ |
| 7 | Water level change | Water level anomaly vs. magnitude | $y = 4.2632x - 17.053$ |
| 7 | Water level change | Water level anomaly vs. magnitude | $y = -4.2632x + 17.053$ |
| 8 | Water level change | Time of anomaly maximum before event vs. magnitude | $y = 16.207x - 48.31$ |
| 8 | Water level change | Time of anomaly maximum before event vs. magnitude | $y = 57.5x - 230$ |
| 8 | Water level change | Start of anomaly before event vs. magnitude | $y = 69.25x - 196.25$ |
| 8 | Water level change | Start of anomaly before event vs. magnitude | $y = 150x - 600$ |

not surprising, because water is essential to human life and the use of wells to provide water for human settlements has been important going back to the beginning of human civilization. Any unusual changes in groundwater levels, particularly dug wells that either drop significantly in level or even go dry, would be noted and be a cause for concern. Unfortunately, most such reports are anecdotal rather than of a careful scientific measurement, and so they would not be reflected in the database accumulated in this study.

The groundwater change observations are summarized in Table 3. There are 52 observations from 32 earthquakes, with the earthquake magnitudes ranging up to 7.8. Most of the reports come from within 200 km of the epicenter of the earthquake, with the greatest distance for an observation being 530 km.

Fig. 5 shows the distribution of the maximum water level changes reported prior to the earthquakes in Table 3. While the maximum changes ranged from a 15 m drop in water level to an 8 m rise, most of the changes were less than 1 m. In 72% of the cases, the groundwater level was observed to drop before the earthquake. Fig. 6 indicates that most of the changes in groundwater levels began within about a year of the coming earthquake, but some much earlier than that. However, generally the greatest change in groundwater level was observed within about 40 days of the coming earthquake.

Fig. 7 shows the dependence of the amplitude of the groundwater level change with distance to the earthquake epicenter and with magnitude of the coming earthquake. Fig. 8 illustrates the start time of the groundwater anomaly and the time of the greatest anomaly as a function of the magnitude of the coming earthquake. While there are not as many data points as for the radon data, the tendencies in these two figures are very similar to those seen in the radon dataset. The greatest anomalies tend to be observed closest to the event epicenters, and the start times and the times of the greatest anomalies tend to increase with the magnitude of the coming earthquake. Also, there is a hint in Fig. 7 that the greatest groundwater level changes may be associated with the largest magnitude events. As for the gas emission data, the significant amount of scatter in the groundwater data precludes the determination of any useful regression curves as a function of either distance or magnitude. Here also curves that represent the possible extremal values from the data are plotted in Figs. 7 and 8, and the corresponding equations for these lines are summarized in Table 4.

In many ways, many of the characteristics of the groundwater change precursors documented in this study, such as the time of the initiation of the anomalies, the time of the greatest anomaly, and the dependence of the amplitude of the anomaly on magnitude and epicentral distance, seem to parallel the same characteristics in the radon gas anomalies. This is probably because both phenomena are associated with changes in rock permeability and perhaps porosity during the days, weeks and perhaps months before an earthquake rupture initiates.

4.13. Groundwater level change models

Changes in groundwater levels have been observed before certain earthquakes and are believed to be in response to volumetric strain in the earth's crust. However, in order to determine the groundwater level changes are directly related to crustal strain, nontectonic causes of water level changes must be considered. These include barometric pressure changes, tidal effects, rainfall, and extraction of groundwater and other fluids such as oil and gas. A summary of evaluating groundwater level changes as earthquake precursors is given by Roeloffs (1988).

The largest precursory water level changes are observed in confined aquifers (Roeloffs and Quilty, 1997). For these aquifers, the change in reservoir fluid pressure Δp is related to the incremental change in volumetric strain Δe by (Rice and Cleary, 1976)

$$\Delta p = -(2GB/3)[(1 + \nu_u)/(1 - 2\nu_u)]\Delta e, \quad (12)$$

where G is the shear modulus, B is Skempton's coefficient, and ν_u is the undrained Poisson's ratio. The change in water level Δh is related to Δp by

$$\Delta h = \frac{\Delta p}{\rho g}, \quad (13)$$

where ρ is the fluid density and g is the gravitational acceleration. For typical values of $G = 3$ GPa, $B = 0.8$, and $\nu_u = 0.3$, the water level change would be 52 cm per 10^{-6} strain (Roeloffs, 1988), with a rise in water level corresponding to compressive strain and a drop in water level corresponding to dilatational strain.

For unconfined aquifers, the water level change is given by

$$\Delta h = -(H/n)\Delta e, \quad (14)$$

where H is the saturation thickness of the aquifer and n is the porosity. For a 100 m saturated aquifer with 2% porosity, the expected change in water level is 0.5 cm per 10^{-6} strain (Roeloffs, 1988), significantly less than that for a confined aquifer.

As mentioned above, water level changes due to nontectonic origin can occur and must be accounted for in order to accurately determine the amount of water level change due to crustal strain. Barometric pressure changes can contribute to changes in water levels in a groundwater aquifer. An increase in barometric pressure Δb compresses the aquifer, causing the pressure in the aquifer to increase by

$$\Delta p = (b/3)[(1 + \nu_u)/(1 - \nu_u)]\Delta b. \quad (15)$$

In an open well, however, the increase in barometric pressure causes a downward force on the fluid surface, counteracting the effect

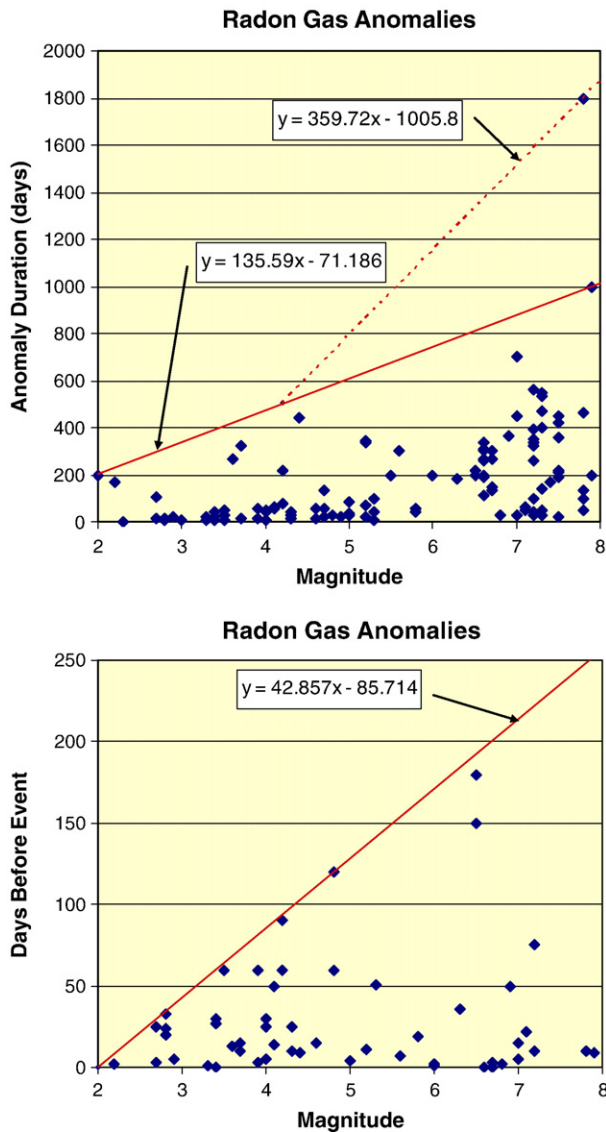


Fig. 4. Distribution of the initiation times (top) and durations (bottom) of the radon anomalies with event magnitude. The greatest initiation times and anomaly durations are associated with the largest earthquakes. Curves representing the possible extremal values of the data sets are also shown. On the top figure, the solid extremal line ignores the one extreme data point at about magnitude 8, while the combination of the solid and dashed extremal lines include this data point.

of the increase in the reservoir fluid pressure. The net effect is a decrease in water level given by

$$\Delta h = -(1/\rho g)[1 - (B/3)(1 + \nu_u)(1 - \nu_u)]\Delta b. \quad (16)$$

This relation predicts a decrease of 0.52 cm in water level per 1 mbar of pressure change (Roeloffs, 1988).

Another important effect that causes changes in water levels is the earth's tidal response. The change in water level due to the earth's tidal response is given by

$$\Delta h = -\frac{K\Delta e}{n\rho g}, \quad (17)$$

where Δe is now the volumetric strain induced in the earth by the tidal response and K is the bulk modulus of water (Bredehoeft, 1967). This relation assumes the compressibility of the individual rock grains is negligible compared to the compressibility of the reservoir, and it is not valid for low porosities. This relation can be used with a porosity

vs. depth relation to determine the sensitivity to the tidal response as a function of depth.

Roeloffs (1988) discusses the effect of rainfall on groundwater level changes. Rainfall acts to recharge the aquifer by providing a transient source of fluid into the reservoir. Similar effects can also be considered when fluids are withdrawn from aquifers.

The effects of rainfall are often delayed by some period of time, depending on the thickness and permeability of the overburden, and the distance between the rainfall source. This time delay can be as long as several months. In addition, a threshold amount of rainfall may be required before reservoir recharge is initiated.

4.14. Ground temperature change observations

There have been relatively few reported observations of temperature changes in the earth prior to earthquakes. This is probably due to a lack of experiments to look for such an effect. The thermal

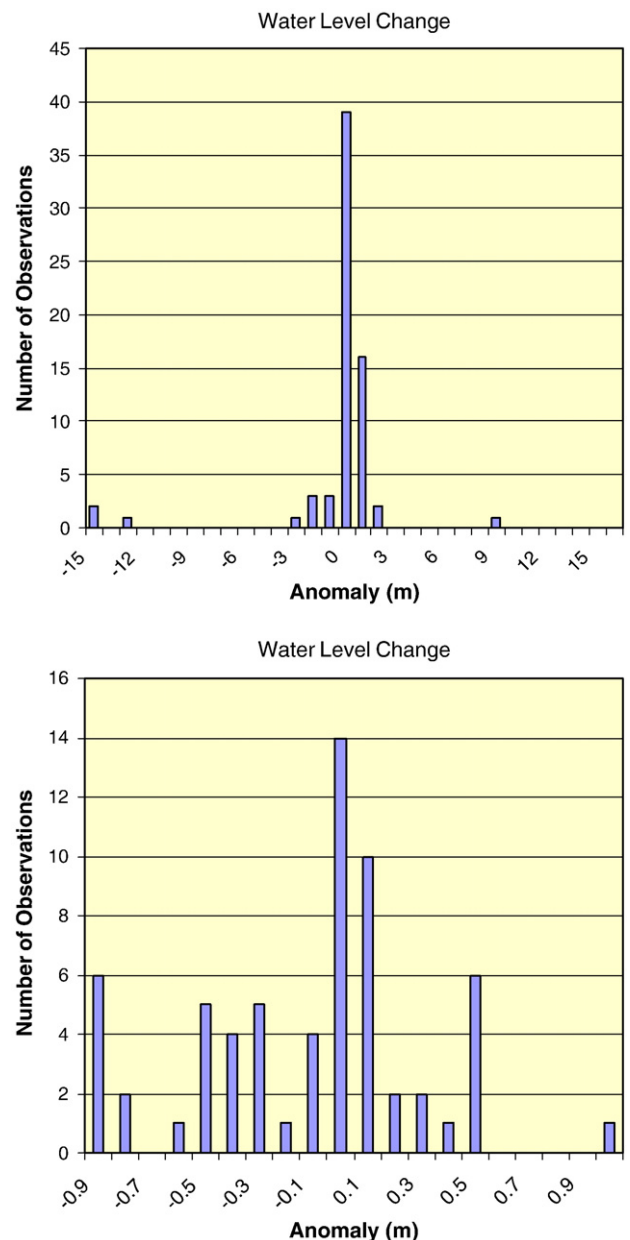


Fig. 5. Distribution of reported maximum changes in groundwater level prior to earthquakes. The top plot shows all the observations, while the bottom plot shows the observations of water level changes between -1 m and $+1$ m.

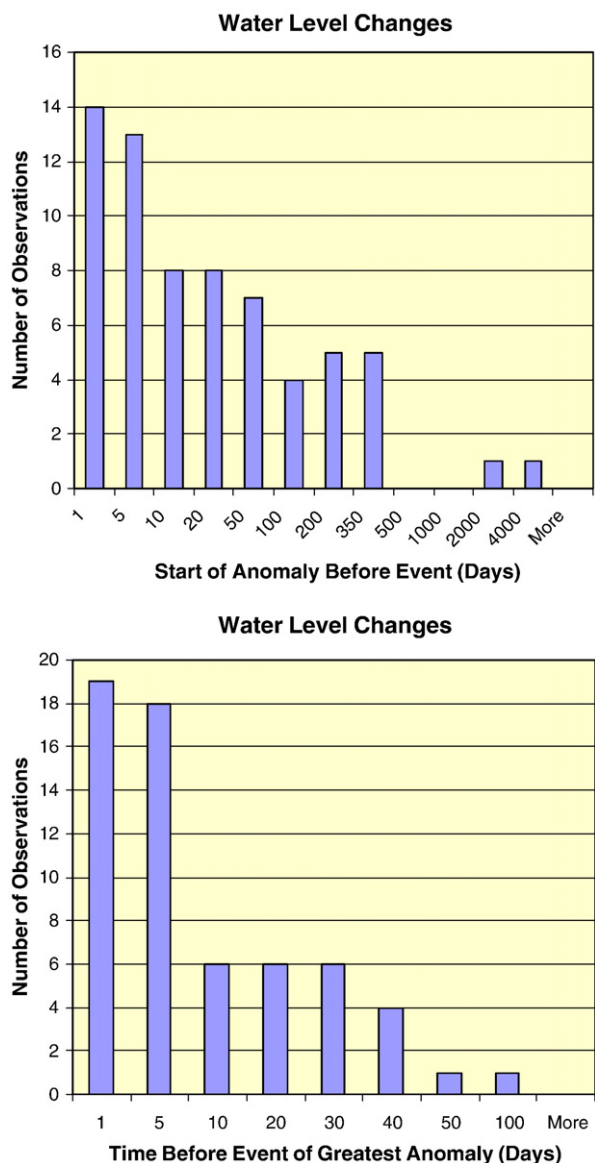


Fig. 6. Distribution of reported times of initiation of the groundwater anomaly prior to the earthquake (top) and of the times of the greatest groundwater change (bottom).

conductivity of rock is quite low, and it takes many years for a significant temperature change to diffuse just a few meters in rocks. Thus, from a theoretical point of view, one would not expect to observe thermal anomalies in rocks prior to earthquakes.

On the other hand, as documented above the flow of groundwater and gases through the rocks and soils might be altered during some time period before an earthquake occurs in a region. Particularly in areas of active tectonics and volcanics, such alterations of the flow of water in the earth before an earthquake might sometimes allow that water to come into contact with hotter rock bodies at depth and raise the temperatures of near-surface groundwaters. In some cases, the alterations in the rock pore structure at depth before an earthquake might cut off a flow of geothermally warmed water to the surface, leading to a cooling of near-surface water temperatures. Of these two possible scenarios for precursory temperature changes, the former would be easier to observe since the rock and soil around the cooler water would remain at a warmer temperature for a long period of time due to the poor thermal conductivity of the rock and soil.

The temperature change dataset assembled in this study consisted of 15 observations from 12 earthquakes ranging in magnitude from 2.3 to 7.0 (Table 5). Of the 15 observations, 10 reports came from

measurements taken at hot springs in volcanic areas. Most of the observations were taken within 50 km of the epicenters of the coming earthquakes, although the greatest reported epicentral distance for an anomaly was 470 km. In all cases an increase in ground temperature was reported, with the largest change being 6 °C and most of the changes being <1 °C. Five of the temperature changes in groundwater were reported to have been coseismic, i.e., having occurred at the time of the earthquake, while 5 were reported to take place within the 10 days prior to the earthquake. The rest of the observations did not report the time at which the temperature change was reported.

All of these reported changes in temperature associated with earthquakes were from Greece and Japan. Both are areas of active plate subduction with active volcanoes and numerous geothermal features. It is not known if there might be temperature changes in the groundwater of non-geothermal areas prior to earthquakes, as there

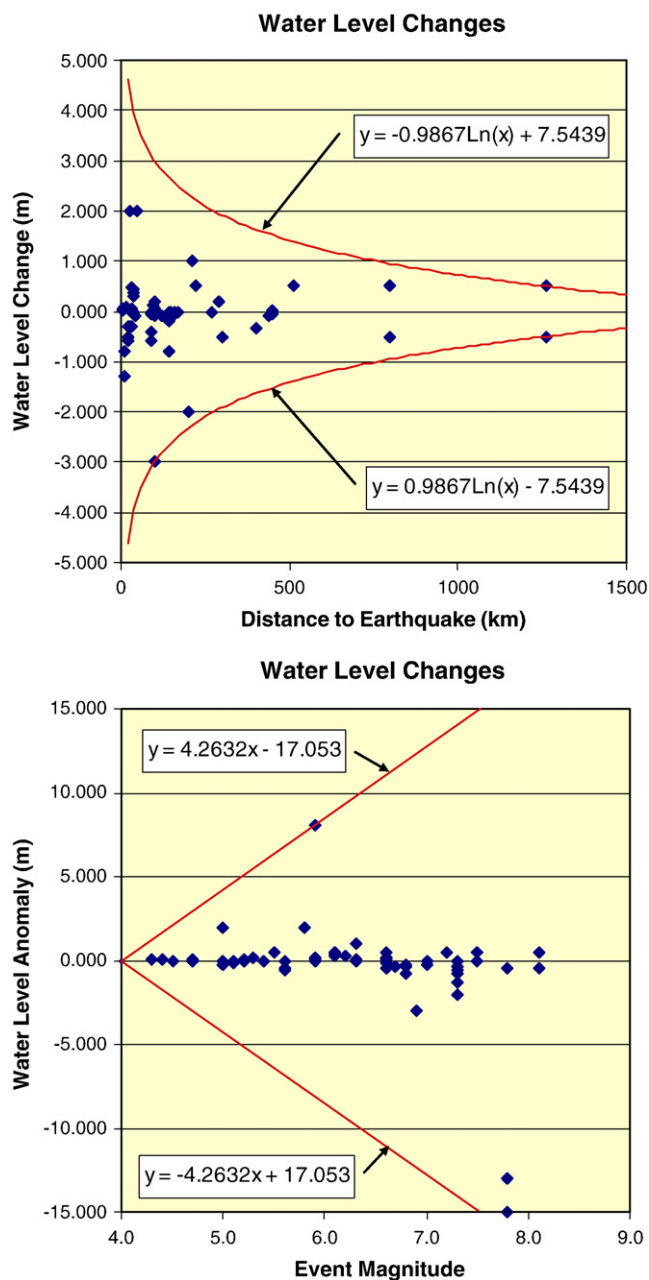


Fig. 7. Distribution of reported changes in maximum groundwater level with distance to the earthquake (top) with event magnitude (bottom). The greatest anomalies are reported closest to the epicenters and perhaps for the largest earthquakes. Curves representing the possible extremal values of the data sets are also shown.

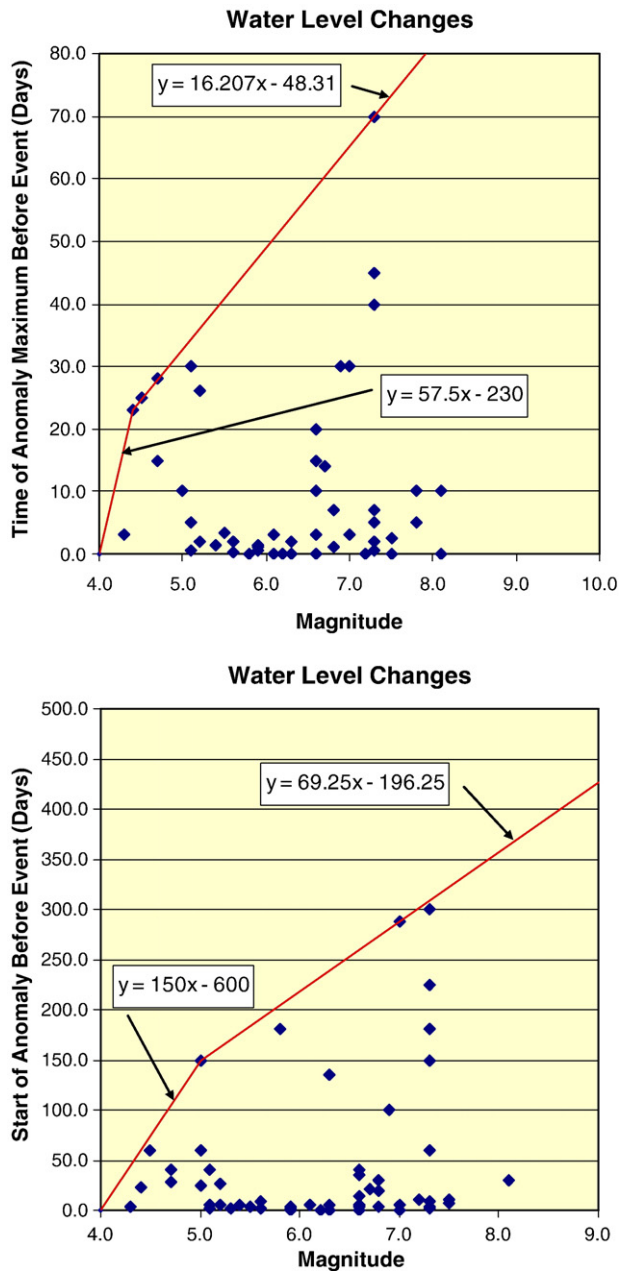


Fig. 8. Distribution of the times of the greatest groundwater level changes (top) and of the start time of the groundwater changes (bottom) with event magnitude. The greatest groundwater level changes and start times are associated with the largest earthquakes. Piecewise linear curves representing the possible extremal values of the data sets are also shown.

have been no reported studies. However, it is possible that such would not be the case. The San Andreas Fault has no geothermal anomaly associated with it (e.g., [Lachenbruch and Sass, 1992](#)), an unexpected observation because shear strain heating from the multitude major earthquakes on that fault over geologic time was thought to have led to an increase in heat flow and rock temperatures in the vicinity of that fault. This observation could mean that temperature changes may not take place prior to earthquakes in non-volcanic or geothermal areas.

4.15. Ground temperature change models

Precursory temperature anomalies are usually associated with changes in groundwater levels and with geochemical anomalies,

although frictional heating on fault surfaces could contribute to ground temperature changes. Because rocks have a relatively low thermal conductivity, any such temperature-related changes that may occur at depth in the earth would take a long time to reach the surface. Therefore such a temperature anomaly is expected to be relatively small.

Temperature anomalies associated with groundwater level changes could be significant, however. Heat generated at depth within the earth would be more efficiently transported to the surface by the convective flow of groundwater than by thermal conduction through the rock itself. Should pre-earthquake dilatancy be a significant pre-earthquake effect, the opening of new pores and the widening of old pore as the rock becomes dilatant may allow groundwater and gases trapped in the rock to circulate through deeper, and therefore warmer, rock. Near the surface of the earth, geothermal gradients can be 1.5 °C–3.5 °C per 100 m, except at geothermal areas and volcanoes where they can be much higher. Thus, if the groundwater is suddenly allowed to circulate through rock that is 200 m deeper than before the dilatancy began, then the surface groundwater may increase in temperature by several degrees. The amount of temperature increase that would be observed at the surface would be controlled by the depth to which the groundwater would circulate, the temperatures at the new depths where the water is circulating, the speed at which the deep groundwater would come to the surface, and the ratio of the volumes of the deep and shallow groundwaters.

4.16. Surface deformation observations

There has been a longstanding interest in looking for surface deformations (uplifts, downdrops, tilts, strains, strain rate changes, etc.) prior to earthquakes ([Rikitake, 1976](#)). Many crustal earthquakes of M6 and greater have been associated with deformations at the surface of the earth, and in some cases there is evidence that there were deformations that were precursory to the occurrences of the earthquakes ([Rikitake, 1976](#); [Lomnitz, 1994](#)). Unfortunately, until very recently, documenting such changes has been very difficult. Surface leveling and laser-ranging geodetic measurements were the most accurate way to document ground deformations over regions that are tens of kilometers in dimension. However, such measurements are time consuming and expensive to make, and the feasible time between individual measurements is months to years. Modern GPS and satellite-based SAR interferometry measurements are now available to produce geodetic position changes with individual measurements separated by minutes to days. However, these new technologies have yet to capture surface deformations precursory to strong earthquakes.

The sparse ground-deformation dataset compiled in this study ([Table 6](#)) reflects the formerly difficult nature of making such measurements prior to earthquakes and the lack of successful precursory measurements using the new technologies. We compiled a dataset of 12 tilt observations from 9 earthquakes, 5 strain observations from 2 earthquakes, and 3 strain rate change observations from 1 earthquake. The earthquakes ranged in magnitude from 3.0 to 7.1. Most of the measurements were made at epicentral distances of less than 100 km, although the measurements range as far as 400 km from the epicenter in one case. The reported deformations took place months to days before the earthquakes, and the larger amplitude strains and tilts seem to be associated with the larger earthquakes.

4.17. Surface deformation models

Models to predict surface deformation in the vicinity of a fault involve the ability to model the behavior of the fault itself. These models can indicate what type of surface deformations can occur and

Table 5
Reported precursory temperature changes associated with earthquakes.

| Earthquakes with reported temperature–variation precursors | | | | | | | | | |
|--|------|------------|---------------------------|--------------------------------|-----------------------------|---------------------------|---|---|--|
| Earthquake | Mag. | Date | Precursor time | Anomaly (°C) ^a | Ambient temp before eq (°C) | Dist. from epicenter [km] | Ref. | Notes | |
| Thessaloniki, Greece | 4.8 | 10/20/1998 | 2 days | 0.2 | 16.6 | 33 | Asteriadis and Livieratos, 1989 | From well data | |
| Thessaloniki, Greece | 4.8 | 10/20/1998 | 5 days | 0.7 | 15.5 | 41 | Asteriadis and Livieratos, 1989 | From well data | |
| Thessaloniki, Greece | 4.8 | 10/20/1998 | Coseismic | 0.7 | 17.6 | 41 | Asteriadis and Livieratos, 1989 | From well data | |
| Thessaloniki, Greece | 4.8 | 10/20/1998 | Coseismic | 0.5 | 19.8 | 41 | Asteriadis and Livieratos, 1989 | From well data | |
| Bay of Patras, Greece | 5.4 | 7/14/1993 | 12 h | 6 | 17 | 1.5 | Soter, 1999 | From sea bed (20 m below surface, 10 m above sea bed, 650 m from shore) | |
| Kawazu, Japan | 5.4 | 1976 | Not reported ^b | 0.3 | 60 | 28 | Mogi et al., 1989 | From hot springs data | |
| Izu–Oshima–Kinkai, Japan | 7 | 1978 | 10 days | 1.3 | 59.5 | 31 | Mogi et al., 1989 | From hot springs data | |
| Miyagi–Ken–Oki, Japan | 7.4 | 1978 | Not reported ^b | 0.6 | 60 | 470 | Mogi et al., 1989 | From hot springs data | |
| Ito–Oki, Japan | 5.4 | 1978 | Not reported ^b | 1.2 | 59.8 | 16 | Mogi et al., 1989 | From hot springs data | |
| Ito–Oki (swarm), Japan | 3.8 | 1979 | Not reported ^b | 0.5 | 59.3 | 10 | Mogi et al., 1989 | From hot springs data | |
| Izu–Hanto–Toho–Oki, Japan | 6.7 | 1980 | 3 days | 1.75 | 59 | 16 | Mogi et al., 1989 | From hot springs data | |
| Ito–Oki, Japan | 3.7 | 1981 | Not reported ^b | 0.5 | 59.5 | 11 | Mogi et al., 1989 | From hot springs data | |
| Sagami Bay, Japan | 5.7 | Aug–82 | Coseismic | 1 | 59.7 | 46 | Mogi et al., 1989 | From hot springs data | |
| Ito–Oki, Japan | 2.3 | Jul–82 | Coseismic | 0.7 | 59.4 | 6 | Mogi et al., 1989 | From hot springs data | |
| Ibaraki–Ken–Oki, Japan | 7 | Jul–82 | Coseismic | 0.6 | 59 | 290 | Mogi et al., 1989 | From hot springs data | |
| Datong, China | 6.1 | 10/18/1989 | 2 days | 2–4 avg., 5–6 max. | 10 | £ 200 | Qiang et al., 1997 | Thermal infrared satellite (Meteosat) | |
| Oroville, California | 5.8 | 8/1/1975 | 1 day | > 100 min | 50 min | < 200 | Valette–Silver and Silver, 1991; Valette–Silver and Silver, 1992 | Old Faithful Geyser, Calistoga, California (eruption interval data) | |
| Morgan Hill, California | 6.1 | 4/24/1984 | 1 day | 25 and 50 min (bimodal signal) | 40 min | < 200 | Silver and Valette–Silver, 1992 | Old Faithful Geyser, Calistoga, California (eruption interval data) | |
| Loma Prieta, California | 7.1 | 10/18/1989 | 60 h | 172 min | 90 ± 2 min | 180 | Silver et al., 1990; Valette–Silver and Silver, 1991; Silver and Valette–Silver, 1992 | Old Faithful Geyser, Calistoga, California (eruption interval data) | |

^a Positive, unless otherwise indicated.^b It is inferred from the paper that these precursors are on the order of a couple months, but it is not clearly stated.

whether or not these deformations are likely to be detected with the available surface instruments.

Fault models attempt to specify the mechanical behavior along the faults. This mechanical behavior is modeled using a constitutive relationship that defines the rate- and state-dependent behavior of friction along the fault surface. Dieterich (1972; 1978; 1979) defined such a law and Ruina (1983) later modified it. The steady-state coefficient of friction μ_{ss} is given by

$$\mu_{ss}(V) = \mu^* + (a - b) \ln(V/V^*), \quad (18)$$

where V is the slip velocity, V^* is an arbitrary reference velocity such that $\mu_{ss}(V^*) = \mu^*$, and a and b are constitutive parameters. The parameter a is a measure of the magnitude of the instantaneous change in the coefficient of friction as the velocity changes, and b is a measure of the decay in the coefficient of friction at the new velocity. The decay of the coefficient of friction is exponential with decay constant D_c , called the characteristic decay distance.

An alternative form of the constitutive relation for the fault is given by Tse and Rice (1986). This form uses shear stress instead of the coefficient of friction and is given by

$$\tau_{ss}(V) = \tau^* + \sigma_n(a - b) \ln(V/V^*), \quad (19)$$

where τ_{ss} is the steady-state shear stress, σ_n is the normal stress, and $t^* = t_{ss}(V^*)$.

Lorenzetti and Tullis (1989) used the Tse and Rice (1986) model to study crustal strike-slip earthquakes and to calculate displacement, velocity, strain, and strain rate distributions associated with these earthquakes. Their results indicate that strain rates are the most readily detectable signals, because the magnitudes of these signals are larger than the detectability thresholds of strains by current instrumentation due to the presence of noise that cannot yet be removed from the data.

4.18. Precursory seismicity observations

This precursor is well studied by ground-based seismic instruments, but it is included here for two reasons. First, because many of the earth's strong earthquakes are preceded within hours, days or weeks by smaller earthquakes called foreshocks, this premonitory seismic activity may well be related in some way to the non-seismic precursors described above. Second, in principle, satellite-based detection of seismic ground motions is possible, and in the future there may be interest in developing such a technology to complement surface-based observations.

No formal table of foreshock observations was compiled for this study, as the list would be very extensive but not particularly informative for the purposes of this paper. However, we present here some summary statistics of earthquake foreshock activity from published analyses.

The most important summaries of foreshocks on a global basis were published by Jones and Molnar (1976) and Reasenberg (1999). The former study reported on $M > 7.0$ earthquakes from 1950 to 1973 and showed that 44% of these strong earthquakes had a least one foreshock ($M > 4.5$) within 40 days of the main shock. The latter study analyzed $M > 6.0$ earthquakes from 1977 to 1996 and showed that 13.2% had a least one foreshock ($M > 5.0$) with 10 days and 75 km of the main shock. It is likely that many earthquakes have smaller foreshocks than those reported in these studies, and so these results probably represent a lower bound on global foreshock rates before strong earthquakes. However, no statistical work to document the rates of smaller magnitude foreshocks has been done due to uneven earthquake detection worldwide.

One significant point of these foreshock studies is that most foreshocks seem to take place during the same time period (within

Table 6
Reported measured precursory ground deformations associated with earthquakes.

| Earthquakes with reported ground-deformation precursors | | | | | | | | |
|---|-------------------------|---------|---|----------------|--|-----------------------------|--------------------------------|-------|
| Area | Date | M | Type | D [km] | Anomaly | Time before event | References | Notes |
| San Andreas Fault, California | 7/73 to 3/7 (28 events) | 2.5–4.3 | Tilt | <30 km | 2×10^{-6} (tilt direction often changes prior to earthquakes) | Typically 1 month | Johnston and Mortensen, 1974 | |
| Kalapana, Hawaii | 11/29/1975 | 7.2 | Strain | | 3.5×10^{-4} | 5 months | Wyss et al., 1981 | |
| Friuli, Italy | 5/6/1976 | 6.5 | Tilt | 15 | 200 sec | 3 years | Dragoni et al., 1985 | |
| Friuli, Italy | 9/15/1976 | 6.5 | Tilt | 15 | 200 sec | 3 years | Dragoni et al., 1985 | |
| Izu–Oshima, Japan | 1/14/1978 | 7.0 | Compressional strain change S of epicenter | | 2.5×10^{-6} | 6 weeks | Linde and Suyehiro, 1983 | |
| Izu–Oshima, Japan | 1/14/1978 | 7.0 | Compressional strain change NE of epicenter | | 4×10^{-5} | days | Linde and Suyehiro, 1983 | |
| Homestead Valley, California | 1/21/1979 | 3.1 | Pre-seismic creep | 32 | – 100 mm | 40 h | Leary and Malin, 1984 | |
| Homestead Valley, California | 2/17/1979 | 2.0 | Pre-seismic creep | 8 | + 100 mm | 5 days | Leary and Malin, 1984 | |
| Homestead Valley, California | 3/9/1979 | 2.4 | Pre-seismic creep | 24 | – 200 mm | 2 days | Leary and Malin, 1984 | |
| Homestead Valley, California | 3/15/1979 | 5.1 | Pre-seismic creep | 150 | – 100 mm | 20 h | Leary and Malin, 1984 | |
| Lytle Creek, California | 10/19/1979 | 4.1 | Stress transient | 15 | 0.14 MPa | 2–4 weeks | Clark, 1981 | |
| Irpinia, Italy | 11/23/1980 | 6.5 | Tilt | 250 | 1.5×10^{-5} radians | 2 months | Allegri et al., 1983 | |
| Irpinia, Italy | 11/23/1980 | 6.5 | Tilt | 250 | 2×10^{-5} radians | 6 months | Allegri et al., 1983 | |
| Kamchatka Gulf | 8/17/1983 | 6.9 | Leveling | 100 | 2.4 mm/day | 2 days | Fedotov et al., 1992 | |
| Friuli region, Italy | 2/1/1988 | 4.1 | Tilt | 1.8 | 1.5×10^{-5} radians | 2 months | Dal Moro and Zadro, 1999 | |
| Friuli region, Italy | 10/5/1991 | 3.9 | Strain | 2.9 | 9×10^{-7} | 9 days | Dal Moro and Zadro, 1999 | |
| Spitak, Armenia | 12/7/1988 | 6.9 | Strain | 100 | 3×10^{-7} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Tilt | 100 | 1×10^{-7} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Strain | 125 | 1×10^{-8} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Strain | 300 | 1.5×10^{-6} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Tilt | 300 | 2×10^{-5} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Strain | 400 | 9×10^{-7} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Spitak, Armenia | 12/7/1988 | 6.9 | Tilt | 400 | 1×10^{-7} | 0–8 days | Neresov and Latynina, 1992 | 1, 2 |
| Loma Prieta, California | 10/17/1989 | 7.1 | Strain rate change | 31 | From – 10.8 to – 18.9 ± 5.0 mm/yr | 1.3 years | Lisowski et al., 1990 | |
| Loma Prieta, California | 10/17/1989 | 7.1 | Strain rate change | 31 | From 6.6 ± 1.1 to 2.0 ± 5.0 mm/yr | 1.3 years | Lisowski et al., 1990 | |
| Loma Prieta, California | 10/17/1989 | 7.1 | Strain rate change | 43 | From – 8.7 ± 1.5 to – 23.8 ± 7.1 mm/yr | 1.3 years | Lisowski et al., 1990 | |
| Loma Prieta, California | 10/17/1989 | 7.1 | Creep retardation | 0–80 (6 sites) | From 10.3 to 6.8 mm/yr | July 1987 to September 1989 | Breckenridge and Burford, 1990 | |
| Central Appenines, Italy | 4/3/1991 | 3.3 | Tilt | 7.6 | 1.34×10^{-7} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 7/13/1991 | 3.7 | Tilt | 35.8 | 6×10^{-9} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 5/5/1992 | 3 | Tilt | 11.5 | 1.4×10^{-8} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 8/25/1992 | 3.9 | Tilt | 23.1 | 3.8×10^{-8} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 8/27/1992 | 3.1 | Tilt | 9.1 | 3.9×10^{-8} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 10/24/1992 | 3.7 | Tilt | 27.7 | 1.1×10^{-8} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 10/24/1992 | 3.5 | Tilt | 27.7 | 6×10^{-9} | months | Bella et al., 1995a,b | 3 |
| Central Appenines, Italy | 7/16/1993 | 3.5 | Tilt | 28 | 6×10^{-9} | months | Bella et al., 1995a,b | 3 |
| Hollister, California | 11/28/1974 | 5.2 | Tilt | 11.2 | 7×10^{-6} radians | 30 days | Mortensen and Johnston, 1976 | |
| Briones Hills, California | 1/8/1977 | 4.3 | Tilt | 5.5 | 2×10^{-6} radians | 1 month | Jones et al., 1977 | |
| Calaveras Fault, California | 8/29/1978 | 4.2 | Tilt | 6.0 | 8.6×10^{-6} radians | 63 h | Iwatsubo and Mortensen, 1979 | |
| Calaveras Fault, California | 8/29/1978 | 3.9 | Tilt | 4.5 | 8.6×10^{-6} radians | 63 h | Iwatsubo and Mortensen, 1979 | |
| Calaveras Fault, California | 9/5/1978 | 2.5 | Tilt | | | | Iwatsubo and Mortensen, 1979 | |
| Niigata, Japan | 6/16/1964 | 7.5 | Vertical crustal movement | 30 | 5 cm | 5 years (1959–1964) | Fujii and Nakane, 1997 | |
| Japan Sea | 5/26/1983 | 7.7 | Strain (about 100 events) | 90 | 1×10^{-8} to 3×10^{-8} (typically 3 h duration) | 5 months | Linde et al., 1988 | |
| Joshua Tree, California | 4/23/1992 | 6.1 | Fault normal extension | | 30 ± 3 mm | 3/8/1992–3/9/1992 | Shifflett and Witbaard, 1996 | |
| Landers, California | 6/28/1992 | 7.3 | Fault normal extension | | 30 ± 3 mm 24 ± 6 mm | 6/7/1992–6/8/1992 6/6/1992 | Shifflett and Witbaard, 1996 | |
| Landers, California | 6/28/1992 | 7.3 | Horizontal slip (dextral) | | 20 ± 9 mm 24 ± 6 mm | 6/6/1992 | Shifflett and Witbaard, 1996 | |
| Big Bear, California | 6/28/1992 | 6.2 | Fault normal extension | | 30 ± 3 mm 24 ± 6 mm | 6/7/1992–6/8/1992 6/6/1992 | Shifflett and Witbaard, 1996 | |
| Big Bear, California | 6/28/1992 | 6.2 | Horizontal slip (dextral) | | 20 ± 9 mm 24 ± 6 mm | 6/6/1992 | Shifflett and Witbaard, 1996 | |
| Tonankai, Japan | 12/7/1944 | 8.1 | Uplift | | 4 mm | 1 day | Mogi, 1985 | |
| Tonankai, Japan | 12/7/1944 | 8.1 | Tilt | | 1×10^{-5} sec | 1 day | Mogi, 1985 | |

¹These values are approximate, as they were read off a figure.

²The background signal (i.e., tidal strain) levels are not available from this report.

³The exact precursor times are not provided.

about 30 days of the main shock) when the most frequently reported non-seismic precursors (i.e., radon anomalies, groundwater level changes, EM emissions) seem to take place. Thus, it is possible that there are some physical links in the generation mechanisms of all of these precursors.

4.19. Precursory seismicity models

Scholz (1990) argued that foreshock activity is probably a manifestation of the nucleation process that ultimately results in the main earthquake. He noted that foreshocks tend to occur in the immediate vicinity of the hypocenter of the later main shock, they increase in frequency of occurrence as the time of the main shock is approached, and they are typically much smaller in magnitude than the main shock. Dilatancy may explain short-term quiescences just prior to the main shock in some foreshock sequences. The models for precursory crustal deformation, described earlier, also can be applied to explain foreshock sequences since rapid crustal deformations may be associated with some seismic energy release. The individuality of foreshock sequences from one earthquake to another may mean that foreshocks are not an intrinsic part of the nucleation process on a fault but rather are part of that nuclear process (Scholz, 1990).

5. Discussion of the observations and models of earthquake precursors

The data and analyses described in the previous sections can be combined to make some general statements about the characteristics of anomalous precursors that may precede earthquakes. From the observational data, it appears that the largest amplitude anomalies tend to occur before the largest magnitude earthquakes. This seems most clear for the groundwater level and the gas emission datasets, while there are insufficient data to generalize this argument for the other precursors looked at in this study. Nevertheless, such a characteristic is implicit in the physical models describing all of the precursors. A second common characteristic for all of the precursors is that the strongest anomalies seem to occur within about 1 month of the coming earthquake, and the closer in time to the occurrence of the earthquake, the larger the number of precursor types that might be observed. The observations of increasing EM anomalies and foreshock activity in the hours just prior to many earthquakes suggest that this might be a critical preparatory time in a fault region just before an earthquake occurs.

For all of the precursor types researched here, it appears that most of the anomalies tend to be observed within a couple hundred kilometers of the coming earthquake epicenter. This is consistent with the scaling relationships of fault length and earthquake magnitude. Large earthquakes move large volumes of rock in the earth. For example, the average fault lengths for earthquakes of magnitude 5, 6, 7 and 8 are approximately 5 km, 15 km, 40 km, and 100 km, respectively. Thus, most precursory earthquake anomalies seem to be observed in or near the region in the earth where the largest deformations are experienced in the eventual earthquake. There are some important implications of the size of the area around an earthquake epicenter where precursory phenomena might be observed. First, if an anomaly suggesting a coming earthquake is observed, the area on the earth in which that earthquake might take place is relatively limited, giving some spatial resolution for earthquake predictions. Second, it is currently not known how large a surface area on the earth may emit an EM anomaly, show a radon anomaly, or experience a groundwater change prior to an earthquake.

The models for the various earthquake precursors analyzed in this study also have some important common features. The most important common feature is that the earthquake precursory anomalies are thought to be driven by rapid and probably non-linear strain and strain changes within the earth in the rock near or in the

fault zone at the region of the eventual earthquake rupture. Non-linear stress–strain and dilatant behavior prior to rock fracture has long been observed in laboratory experiments when small pieces of rock (a few cm on a side) are fractured (Scholz, 1990). The rapid deformations just prior to fracture combined with changes in the groundwater and gas flow in the earth due changes in porosity and permeability in the rock volume that fractures in the earthquake can generate, in one way or another, all of the earthquake precursors studied here (e.g., Press and Siever, 1978; Lomnitz, 1994). It is not known how well the small-scale laboratory experiments may apply to the large-scale rupture processes that take place within the earth. Also, there are many free parameters that are poorly known in the models discussed in the previous section of this report. Nevertheless, the laboratory experiments and theoretical models do provide some plausible physical explanations for the observed earthquake precursory data.

Regarding individual precursors, some comments should be made about the observational data. The EM observations compiled in this study give a somewhat confused picture about exactly what kinds of precursory signals might be seen before earthquakes. The frequency content of the observed anomalous signals compiled in our work seems to vary considerably from study to study. One study indicates that the anomalous precursory signals are confined in latitude but observed at a wide range of longitudes, while another study show confinement of the anomalous signals over a narrow longitude band but at essentially all latitudes. Much still probably must be learned about precursory EM signals and earthquakes. We point out that there was one surface-based observation of a strong ionospheric signal at about 4–5 MHz recorded at Boulder, Colorado that started about 2 h before the great Alaskan earthquake of 1964 (Davies and Baker, 1965). This earthquake (M9.2) was the second largest earthquake known since earthquake recording began in the late 1800s. Thus, as with the 1989 Loma Prieta ULF observation, there are some provocative observations that suggest that the earth may well radiate EM energy at perhaps many different frequencies prior to the initiation of a strong earthquake.

The paucity of studies of temperature change data prior to earthquakes is most consistent with the lack of interest in this topic by most earthquake scientists. There have been very few experiments to look for such a phenomenon. Furthermore, the lack of a heat flow anomaly at the San Andreas Fault may mean that San Andreas earthquakes are not accompanied by precursory temperature changes. Even so, in volcanic areas that are also prone to strong earthquakes, changes in the flow of groundwater and gas emission may be accompanied by anomalous changes in the temperature of the surface groundwater and gas emissions. This could be a target for future space-based research. It could also have application in the search for the imminence of major volcanic eruptions.

Surface deformations precursory to earthquakes are of interest to seismologists. In part this is because laboratory and theoretical rock deformation studies prior to fracture, especially the observation of dilatancy in rocks just prior to their fracture, indicate that in many cases surface deformations might be observed. As noted above it has been very expensive, laborious and time consuming to make surface deformation observations in the past. The advent of relatively inexpensive continuous GPS observations and of methods to measure ground deformations using satellite-based synthetic aperture radar interferometry (IN-SAR) are rapidly changing the way that surface deformations will be observed for scientific studies. For example, the Plate Boundary Observatory (PBO) is a major effort by the NSF to fund a very large number of continuous, permanent GPS stations in the western U.S. The purpose of the PBO is to monitor real-time deformation of the western plate boundary of North America (Silver, 1998). Thus, in the future many of the past constraints limiting surface deformation studies in earthquake-prone areas are likely to be eliminated.

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