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Earthquake-induced Groundwater and Gas Changes

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Abstract—Active faults are commonly associated with spatially anomalously high concentrations of soil gases such as carbon dioxide and Rn, suggesting that they are crustal discontinuities with a relatively high vertical permeability through which crustal and subcrustal gases may preferably escape towards the earth's surface. Many earthquake-related hydrologic and geochemical temporal changes have been recorded, mostly along active faults especially at fault intersections, since the 1960s. The reality of such changes is gradually ascertained and their features well delineated and fairly understood. Some coseismic changes recorded in "near field" are rather consistent with poroelastic dislocation models of earthquake sources, whereas others are attributable to near-surface permeability enhancement. In addition, coseismic (and postseismic) changes were recorded for many moderate to large earthquakes at certain relatively few "sensitive sites" at epicentral distances too large (larger for larger earthquakes, up to 1000 km or more for magnitude 8) to be explained by the poroelastic models. They are probably triggered by seismic shaking. The sensitivity of different sites can be greatly different, even when separated only by meters. The sensitive sites are usually located on or near active faults, especially their intersections and bends, and characterized by some near-critical hydrologic or geochemical condition (e.g., permeability that can be greatly increased by a relatively small seismic shaking or stress increase). Coseismic changes recorded for different earthquakes at a sensitive site are usually similar, regardless of the earthquakes' location and focal mechanism. The sensitivity of a sensitive site may change with time. Also pre-earthquake changes were observed hours to years before some destructive earthquakes at certain sensitive sites, some at large epicentral distances, although these changes are relatively few and less certain. Both long-distance coseismic and preseismic changes call for more realistic models than simple elastic dislocation for explanation. Such models should take into consideration the heterogeneity of the crust where stress is concentrated at certain weak points (sensitive sites) along active faults such that the stress condition is near a critical level prior to the occurrence of the corresponding earthquakes. To explain the preseismic changes, the models should also assume a broad-scaled episodically increasing strain field.

1. Introduction

Groundwater and gas changes (other than seismic oscillation), such as in water level, color, and smell in wells, have been observed since ancient times in many seismic regions. A systematic search for such changes to uncover earthquake-related, and especially pre-earthquake, changes with scientific instruments did not begin, however, until the 1960s. Earlier results, obtained before 1980 mainly in China,

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Japan, the former Soviet Union, and the United States, were reviewed by KING (1986), THOMAS (1988), MA, *et al.* (1990), IGARASHI and WAKITA (1995), and ROLOEFFS (1988, 1996), among others. This paper gives a brief review of more recent results.

2. Earlier Results

Hydrologic and geochemical parameters studied include water level/pressure, temperature, electric conductivity at wells, and flow rate at springs, concentration of various ions and dissolved gases, and components of soil gas in shallow holes. Earthquake-related changes were reportedly observed before and after many destructive earthquakes, especially at certain relatively few "sensitive" sites. The sensitive sites were usually found to be situated along active faults, especially at intersections of faults, and may be at unexpectedly large epicentral distances (many source dimensions, or hundreds of km, away for large events). This pattern was difficult to understand by many seismologists, who were accustomed to using simple dislocation models of earthquake sources that assume a homogeneous and linearly elastic medium. Because of this difficulty as well as the poor quality of some studies which sometimes failed to take proper account of background noises caused by such environmental variables as rainfall, barometric pressure, temperature, and earth tide, many geophysicists dismissed the earthquake relatedness of such changes (e.g., GELLER, 1997). Nevertheless, as pointed out by KING (1986) and MA *et al.* (1990), the difficulty may be partly due to unrealistic modeling of earthquakes occurring in an inhomogeneous and non-elastic crust by such simple dislocations. They suggested that if the crustal heterogeneity and a large-scale, episodically increasing tectonic stress field are taken into consideration, the observed features can be reasonably understood. This suggestion is confirmed by recent observations, as reviewed below.

In a related group of studies, many active faults, including some buried ones, were found to show spatial anomalies, such as higher concentration of various terrestrial gases (radon, helium, hydrogen, mercury vapor, carbon dioxide, isotope ratios, etc.) in groundwater and soil air (e.g., IRWIN and BARNES, 1980; KING, 1986; MA *et al.*, 1990).

3. Recent Observations

Observations of earthquake-related groundwater and gas changes were made more carefully since 1980, many by using continuously-recording instruments of better sensitivity and reliability and by giving proper consideration to background noise, such as changes caused by rainfall, barometric-pressure variation, and solid-earth tide. The results, however, still show largely the same characteristic features as observed earlier: (1) Sensitivity of monitoring sites, even only meters apart, can be greatly different; (2) at near-field sites, some recorded earthquake-related changes are approximately consistent with poroelastic dislocation models of earthquakes; (3) however, "far-field" co- and postseismic changes recorded for many moderate and large earthquakes at some "sensitive sites" are too large (up to about 1000 km or more for magnitude 8) to be explained by the poroelastic models. Being recorded at larger distances for larger earthquakes, they are probably triggered by seismic shaking; (4) the recorded premonitory changes are relatively few and uncertain; (5) sensitive sites are usually located on or near active faults and characterized by some near-critical hydrologic or geochemical condition (e.g., permeability that can be greatly changed by a slight shaking or stress change); (6) the earthquake-related changes recorded for different earthquakes at a sensitive site are usually similar, regardless of the earthquake's location and focal mechanism; and (7) the sensitivity may change with time as the crustal stress changes (e.g., SILVER and VALLETTE-SILVER, 1992; ZHANG, 1994; ROELOFFS, 1988, 1996; WAKITA, 1996; TOUTAIN and BAUBRON, 1999; KING *et al.*, 1999, 2000; KING and IGARASHI, 2002; MONTGOMERY and MANGA, 2003).

A notable example of the long-distance seismic-wave triggering effect of large earthquakes is the observation of numerous earthquakes triggered by the 7.3 earthquake at Landers, California, in 1992. Many earthquakes were triggered minutes to hours later in geothermal and volcanic areas across the western United States at distances of up to 1250 km, about 10 fault lengths, from the Landers epicenter (HILL *et al.*, 1993). No significant earthquakes were triggered, however, in the nearby San Andreas Fault segments outside the aftershock area. Such a long-distance triggering phenomena cannot be explained by the small static stress changes of the earthquake expected from elastic-dislocation models, but can be attributed to seismic-wave-triggered fluid movement in and near some nearly critically loaded faults in the triggered area. Indeed, various hydrologic phenomena, including gas bubbling, increased spring discharge, and groundwater-level changes, were observed after the earthquake in many of such areas (ROELOFFS, 1996). Since Landers earthquake, numerous additional moderate-to-large earthquakes have been found to have dynamically triggered distant earthquakes and volcanic eruptions (HILL *et al.*, 2002); one such example is the Hector Mine earthquake, which was followed by an abrupt increase in seismicity at distances of 110–270 km at sites within the Salton Trough to the south (GOMBERG, *et al.*, 2001). It is the observation of such long-distance triggering of events that has helped to remove some geophysicists' skepticism about the possibility of far-field hydrologic and geochemical (as well as some other kinds of) anomalies (including precursors), and to demonstrate the inadequacy of the simple elastic dislocation models in explaining anomaly occurrences.

Another example of earthquake-related changes in crustal-fluid movement is provided by the study of eruption-interval changes at a nearly periodic geyser located in proximity to the San Andreas Fault north of San Francisco, California (SILVER and VALLETTE-SILVER, 1992). Co- and preseismic changes were detected for three earthquakes (including the magnitude 6.9 Loma Prieta event in 1989) at epicentral distances of 100–200 km. Such changes may possibly be due to permeability changes caused by seismic shaking and an episodically increasing stress field, respectively.

In Parkfield, where an earthquake-prediction experiment that includes a water-level study at a dozen wells has been in progress for about two decades, steplike coseimic water-level drops were recorded at four wells at the time of the magnitude 5.8 Kettleman Hills earthquake in 1985 approximately 35 km away (ROELOFFS and QUILTY, 1997). Such coseismic changes are of the correct sign and roughly the expected size from the poroelastic dislocation model, based on the well's strain sensitivity as inferred from earth tidal response (QUILTY and ROELOFFS, 1997; see also WAKITA, 1975). This is in contrast to coseismic changes at long distances near active faults recorded elsewhere (larger changes than expected and may be of a different sign, see IGARASHI and WAKITA, 1991 and KING *et al.*, 1999). A detailed study of the Kettleman Hills data also shows small water-level changes beginning three days before the earthquake in two of the wells. In addition, there is a shallow well at which coseismic water-level rises were observed at the time of three local and five distant earthquakes with different azimuth and focal mechanisms (as distant as 730 km for a magnitude 7 event) (ROELOFFS, 1998). These rises, like those observed by the above-mentioned other authors, cannot be explained by poroelastic response to coseismic static strain changes. No pre-earthquake changes were observed by Roeloffs at this well.

In Japan, coseismic water-level drops were recorded at two wells monitored by the Geological Survey of Japan in Shizuoka prefecture in response to earthquakes up to 740 km away; some of the larger changes were also preceded by smaller preearthquake changes (e.g., MATSUMOTO, 1992). Similar coseismic and sometimes pre-earthquake changes have been observed in groundwater temperature and discharge also (e.g., MOGI, *et al.*, 1989; FUJIMORI *et al.*, 1995). The University of Tokyo has maintained a network of about a dozen continuously monitored hydrologic and geochemical stations along the nearby Pacific Coast since 1978 (WAKITA, 1996). One of the stations in Izu Peninsula recorded a clear radon-concentration change before the nearby Izu-Oshima-Kinkai earthquake in 1978. Similar preseismic changes in groundwater level, temperature and strain were observed at three other sites, all at epicentral distances of 25–50 km beginning a month before the event. Also, over the years, only two of the stations (one for radon and one for water level) have been found to be sensitive to distant earthquakes (such as a magnitude 8.1 event 1200 km away). The sensitivity was found to vary with time (WAKITA, 1996), probably due to local stress or permeability variation.

Many co- and preseismic changes in groundwater level/discharge, geochemistry, radon concentration in groundwater and atmosphere, and strain were observed at locations up to 220 km away from the magnitude 7.2 Kobe earthquake in 1995, in spite of the fact that the earthquake occurred beyond the Japanese intensive-study area of Tokai (e.g., SATO, *et al.*, 2000). Most of the preseismic changes were recorded within the ultimate aftershock zone beginning three months before the event (IGARASHI *et al.*, 1995; KING *et al.*, 1995; TSUNOGAI and WAKITA, 1995; YASUOKA and SHINOGI, 1995; SUGISAKI *et al.*, 1996). In a questionnaire survey conducted shortly after the earthquake, KOIZUMI *et al.*, (1996) found postearthquake water level/discharge changes at many sites (among many more sites without such changes) at epicentral distances up to about 300 km. The distribution pattern of these changes cannot be explained satisfactorily by volume strain changes derived from dislocation models of the earthquake but may be caused by permeability enhancement (SATO *et al.*, 2000). Also FUJIMORI *et al.* (1995) observed coseismic seep discharge increases at the Rokko-Takao site near Kobe in response to earthquakes up to several hundred km away; they also observed a gradual discharge increase over a two-month period preceding the Kobe earthquake, which ruptured to within 20 km of the discharge point and produced a coseismic discharge increase of more than one order of magnitude.

KING *et al.* (1999) studied water-level data continuously recorded over a period of ten years at a closely clustered set of 16 wells within 400 m of a fault in Tono, central Japan. They observed co- and postseismic changes for many moderate local and distant earthquakes (longer distance for larger earthquakes up to more than 1000 km, at locations where the calculated coseismic strain is as low as a few 10^{-8}). They found that the changes recorded at wells on different sides of the fault show very different features. The difference is attributable to a seismically induced permeability increase of the normally impermeable fault-gouge zone, which had been sustaining a considerable hydraulic gradient across the fault. One of the wells showed coseismic changes for more than 20 local and distant earthquakes, including a magnitude 8 event about 1200 km away. All the coseismic changes (water-level drops) and subsequent recoveries have similar shapes, irrespective of the location and focal mechanism of the earthquakes. This well is located on the higher-groundwater-pressure side of the fault. The high sensitivity is attributable to this well's tapping a high-permeability aquifer connected to one of the high-permeability fracture zones that bracket the impermeable fault-gouge zone. Such a structure is observable in an underground tunnel through the fault zone, and is commonly observed elsewhere (see EVANS *et al.*, 1997). Because of the large hydraulic gradient across the gouge zone, a relatively small seismic shaking (or tectonic stress increase) may have introduced some quickly healable fissures in the gouge zone and resulted in a significant but temporary permeability increase which allowed water seepage across the fault and thus caused the observed changes. Water-level at this well was also found to have shown pre-earthquake drops for several earthquakes. Some of the pre-earthquake drops were later found to be due to human activities (e.g., drilling of holes by other people across the fault, resulting in a cross-fault water flow), however one of them, beginning about six months before a magnitude 5.8 local earthquake (the largest near the well since 1983) 50 km away in 1997 may be truly premonitory in nature (KING *et al.*, 2000). The sensitivity of the well showed a temporary decrease during a one-year period after the earthquake, similar to what was observed by WAKITA (1996), presumably due to a temporary relaxation of local stress to a subcritical level, as a result of the magnitude 5.8 earthquake.

Earthquake-related permeability increase is also invoked to explain post-earthquake (including the magnitude 7.1 Loma Prieta event in 1989) flow rate increases and water-chemistry changes observed at some springs and streams in California (KING *et al.*, 1994; ROJSTACZER and WOLF, 1992; ROJSTACZER *et al.*, 1995) as well as at many springs near the epicenter of the1995 Kobe earthquake in Japan (SATO *et al.*, 2000). Some changes that began before certain local earthquakes may be premonitory in nature (KING *et al.*, 1994). Coseismic excess stream flows were observed also for several other earthquakes, including the magnitude 7.5 Hebgen Lake event in 1959 and the magnitude 7.3 Borah Peak event in 1983 (MUIR-WOOD and KING, 1993). The changes in the latter case, however, were attributed to the expulsion of water from the depth due to elastic compression.

In Taiwan, coseismic water-level changes of up to 11.1 m were recorded at 157 of 179 monitored wells located in an alluvial fan 2 to 50 km from the seismogenic fault of the magnitude 7.3 Chi-Chi earthquake (the largest in about 100 years) in 1999 (CHIA *et al.*, 2001). LEE *et al.* (2002) found that the polarities of most of the observed (near field) water-level and some river-discharge changes are in good agreement with those of the static volumetric strain calculated from a well-constrained dislocation model of the seismogenic fault.

Since the mid-1960s, China has established an extensive network of earthquake-related hydrologic and geochemical monitoring stations in areas of earthquake risk, especially along major active faults. The network covers large areas of the China mainland with 330 hydrogeochemical and 250 groundwater-level monitoring stations (ZHANG and LI, 1994). Various effective observation measures have been adopted to obtain reliable continuous data. Studies of possible earthquake precursors and their mechanisms towards earthquake prediction have been carried out from various approaches, both in the field and in the laboratory. The resultant data showed the usefulness of monitoring such parameters as ^{222}Rn, H_2, He, CO_2, H_2S, total gas, Hg^0, F^-, Cl^-, water level, conductivity, temperature and flow (ZHANG, 1994). Since 1966, numerous strong earthquakes of magnitude 7 or above have occurred in the monitoring areas of China: Bohai, 7.4, 1969; Haicheng, 7.3, 1975; Longlin, 7.4, 1976; Tangshan, 7.8, 1976; Songpan, 7.2, 1976; Langcan, 7.6, 1988; Gonghe, 7.0, 1990; and Mongliang, 7.3, 1995. Valuable raw data and practical experience have been accumulated. Many earthquake-related anomalies were recorded; those observed in epicentral areas (near field) were found to have different characteristics from those recorded at large distances (far field). The anomalies in near field are closely related to the process of earthquake preparation, whereas those in the far field are due to stress concentration along active faults, especially at their intersections and bends, under the action of regional stress field. Many spike-like anomalies were observed, and are thought to be useful for predicting earthquake time, whereas the spatial and temporal extent of anomalies are thought to be useful for earthquake magnitude. Some recent studies also found that radon-concentration changes in escaped gases from groundwater showed better correlation with solid-earth tides than in dissolved gases and were more sensitive to earthquake occurrences (SHI and ZHANG, 1995; ZHANG and ZHANG, 1996). These findings are similar to observations by WOLLENBERG (1985) in California that groundwater radon at certain sites may respond to minute crustal stress changes, with amplitudes comparable to tidal amplitude (about 0.001 MPa).

A series of publications (8 volumes so far), entitled Earthquake Cases in China, have been published in China, summarizing more than 2000 earthquake-related changes recorded prior to about 200 earthquakes of magnitude 5 and above during 1966–99 (ZHANG *et al.*, 1988–2000; CHEN *et al.*, 2002–03). About 30% of these changes are hydrologic and geochemical. These data are the result of some systematic and standardized studies and are of particular importance to understanding the seismogenic processes in future studies. However, they are currently reported only in Chinese, as are many co- and post-earthquake changes.

In the Koyna-Warna region in western India where reservoir-triggered earthquakes have been studied for four decades, CHADHA *et al.* (2003) recorded four cases of coseismic and some preseismic water-level changes of several centimeters at a network of wells, for earthquakes of magnitude of 4.3–5.2 at epicentral distances up to 24 km during 1997–2000.

Recent geochemical studies at certain volcanic-hydrothermal systems in the Central American graben detected some earthquake-related CO_2-efflux changes (SALAZAR *et al.*, 2002). Continuous monitoring of CO_2 flux in volcanic areas, where deeply penetrating faults abound, can be easily done and could be useful because CO_2, being a major volcanic gas that has low solubility in silicate melts, can readily migrate to the surface and be influenced by earthquake-related stress changes (SILVER and WAKITA, 1996; PEREZ and HERNANDEZ, 2005).

Many gas-geochemical surveys were conducted across active faults worldwide. Most of the results show fault-related spatial anomalies of such soil air components as CO_2, He, H_2, Hg^0, and ^{222}Rn, suggesting that active faults are crustal discontinuities with a higher vertical permeability than surrounding rocks, thus providing preferential pathways for crustal and subcrustal gases to escape towards the surface (e.g., IRWIN and BARNES, 1980; SUGISAKI *et al.*, 1983; ZHANG *et al.*, 1988; KLUSMAN, 1993; KING *et al.*, 1996). Based on measurements of ^{222}Rn, CO_2, and O_2 in soil air, KING *et al.* (1996) attributed the ^{222}Rn anomalies observed along several fault segments in California to an upward flow of soil air in the high vertical-permeability fracture zones of the faults. LEWICKI and BRANTLEY (2000) found similar fault-related CO_2 flux anomalies along 12 of 16 San Andreas fault-crossing transects at five sites in Parkfield. Based on carbon-isotope data, they concluded the measured CO_2 to be of biogenic origin, and not deeply derived. Geochemical studies of deeper fluids in wells and springs along the San Andreas in central and south-central California by KENNEDY *et al.* (1997) exhibited high $^3He/^4He$ ratios, suggesting mantle origin of the fluids, which may contribute to the fault-weakening high-fluid pressures at seismogenic depths; they estimated an upward flow rate of about 1 to 10 mm/year, which may be too small to significantly affect the soil-air movement.

4. Mechanisms for Earthquake-related Hydrologic and Geochemical Changes

The earth's crust contains numerous pores and fractures filled with water, gas and other fluids that have different chemical compositions at different places. When the crust is deformed in the tectonic process of earthquake generation, certain transient movements (fissure opening, fault creep, etc.) may be induced in the crust (BERNARD, 2001), and fluids in the fault and other weak zones may be forced to migrate to different locations and thus cause the observed hydrologic and geochemical changes at these locations.

Several inter-related mechanisms were proposed to explain the hydrologic and geochemical changes in the epicenter area and at the distant sensitive sites: Dilatancy due to the increasing number and size of microcracks; increased upward flow of deep-seated fluids to the monitored aquifers or shallow holes; squeezing of gas-rich pore fluids out of the rock matrix into the aquifers; mixing of water from other aquifers through tectonically created fissures in the intervening barriers (permeability enhancement); increased rock/water interactions; and increased gas emanation from newly created crack surfaces in the rock to the pore fluids (e.g., NUR, 1974; KING, 1986; THOMAS, 1988; MUIR-WOOD and KING, 1993; KING and MINISSALE, 1994; ROJSTACZER *et al.*, 1995). For ^{222}Rn, which has a short half-life of 3.8 days, the anomalous changes are likely dependent on corresponding changes of some carrier gases, such as CO_2. KING (1986) demonstrated how an upward flow of soil air could perturb the subsurface ^{222}Rn profile to cause the anomalies that he had observed. The ^{222}Rn pulses observed in China and elsewhere may be caused by the release of pockets of relatively high or low soil air. For a brief review of the origin and migration of fluids in the crust, see KING and IGARASHI (2002).

Some of the explanations were tested by laboratory studies of audio and ultrasonic vibrations and pressure solution of crushed rock samples , and by field studies of underground explosions, large-scale hydraulic fracturing, and groundwater pumping (e.g., BRACE and ORANGE, 1968; GIARDINI *et al.*, 1976; HONDA *et al.*, 1982; KITA *et al.*, 1982; KING, 1986; KING and LUO, 1990; ZHANG, 1994). Most of the laboratory studies involve the pre-failure phenomena of the volume increase of the specimen and stable sliding along a plane of weakness. When a rock specimen is subjected to increasing uniaxial or triaxial compression, it commonly begins to display nonelastic volume increase (dilatancy) due to the occurrence of micro-cracks at a stress level somewhat below the failure level. The same phenomena may presumably occur in the crust, but to date has not been observed directly.

However, a 'self-organized critical state' (BAK and TANG, 1989), including dilatancy and other related phenomena (permeability increase, acoustic emission, etc.), may possibly have occurred only at the hypocenter and to lesser degrees at some relatively few widely scattered sensitive sites, where the local stress had reached certain subcritical level before the corresponding earthquake; and thus it is hard to detect. To account for such a possibility, one needs to invoke imhomogeneity of the crust, and in the case of pre-earthquake changes a broad-scaled and episodically increasing stress field (KING, 1986; MA *et al.*, 1990). Such a field also may be evidenced by common observation of multiple earthquake occurrences within a short-time interval over a broad region. Under such a condition, strain may concentrate along some faults and weak zones, especially at their intersections and bends, where voids and fluids abound and the stress is near a critical level, thus causing local dilatancy and related hydrologic and geochemical (as well as electric, magnetic, and animal behavior) anomalies at/near the time of the earthquakes. This scenario may explain the observation that the sensitivity of a sensitive site may change with time, because the sensitivity depends on how close the pre-earthquake local stress is to the critical level. The same scenario may also explain volcanic unrest and eruptions triggered by earthquakes over surprisingly long distances (HILL *et al.*, 2002).

5. Discussion and Conclusions

Hydrologic and geochemical parameters, like other geophysical parameters, have been studied extensively during the past several decades, mainly in search of possible premonitory changes useful for earthquake prediction. Nevertheless, relatively few significant precursors have been recorded and the results are still inconclusive. The enormous complexity of the challenge has not been met by a matching amount of funding and manpower. Not knowing where the next destructive earthquakes are going to strike, it has been extremely difficult to deploy a sufficient number of reliable instruments at appropriate locations long enough to record sufficient background data and to catch a significant number of possibly true precursors. To date few significant earthquakes have occurred in several areas of intensive global studies at anticipated times. Maintaining monitoring efforts over long periods of time is difficult because of some inevitable problems, such as funding uncertainty, personnel change, and instrument failure. Other difficulties arise from the inaccessibility of earthquake sources, inhomogeneity of the crust (and the resultant problem of sensitive vs. insensitive sites), and the lack of realistic models that can allow for the imhomogeneity.

In spite of the above-mentioned difficulties, recent studies have shown credible premonitory changes as well as many co- and postseismic changes, some at previously unexpectedly extended epicentral distances. Although the long-distance changes were recorded only at relatively few sensitive sites, their reality can no longer be denied. This phenomenon calls for more realistic models for explanation. The sensitive sites are usually located at structurally weak zones, characterized by certain near-critical stress conditions where some local property, such as permeability, can be greatly changed by seismic shaking and possibly by a small stress increment. Permeability in a fault zone may be enhanced by such processes as faulting, fracturing, microcracking, and brecciation, and reduced by such processes as gouge formation, microcrack healing, hydrothermal cementation of fractures, and solution precipitation (HICKMAN *et al.*, 1995; PARRY, 1998; MORROW *et al*, 2001). The sensitivity of a sensitive site may change with time, depending on how close the pre-earthquake stress is to the critical level for new fissure production.

Because of the current lack of sufficient data to meet the enormous challenge, it seems too early to conclude at this time whether earthquakes are predictable or not in general terms, as GELLER (1997) did. To overcome the above-mentioned difficulties, a prediction effort should: adopt a multistage, multisite, multidisciplinary approach; use sensitive telemetered instruments of good long-term stability and time resolution; deploy them at a sufficient number of sensitive locations long enough to recognize normal background noise and to catch enough target earthquakes; develop sufficiently realistic geophysical and geochemical models for the heterogeneous crust; and use appropriate statistical methods and relevant environmental monitoring for objective data analysis.

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