

Review

Previous, Current, and Future Trends in Research into Earthquake Precursors in Geofluids

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Abstract: Hazard reduction policies include seismic hazard maps based on probabilistic evaluations and the evaluation of geophysical parameters continuously recorded by instrumental networks. Over the past 25 centuries, a large amount of information about earthquake precursory phenomena has been recorded by scholars, scientific institutions, and civil defense agencies. In particular, hydrogeologic measurements and geochemical analyses have been performed in geofluids in search of possible and reliable earthquake precursors. Controlled experimental areas have been set up to investigate physical and chemical mechanisms originating possible preseismic precursory signals. The main test sites for such research are located in China, Iceland, Japan, the Russian Federation, Taiwan, and the USA. The present state of the art about the most relevant scientific achievements has been described. Future research trends and possible development paths have been identified and allow for possible improvements in policies oriented to seismic hazard reduction by geofluid monitoring.

Keywords: earthquake precursors; earthquake forecasting; groundwater monitoring; geofluids; seismic hazard

1. Introduction

Civil defense authorities of all over the world need to forecast earthquakes. For these purposes, most utilized methods are based on probability evaluations. These evaluations are carried out by the exploitation of data stored in seismic catalogues. Calculations may describe the chances that an earthquake of a certain magnitude will occur during a time window in a particular area, assuming the annual rate is relatively constant. These evaluations are usually represented in seismic hazard maps and are utilized in building codes (e.g., [1]). Improved knowledge of future seismic activity may come from research projects on earthquake forecasting. Earthquake forecasting is based on the understanding of physical laws that relate to the measurement of those physical or chemical parameters believed to be precursors to the occurrence of seismic events. A “precursor” is defined as a quantitatively measurable change in an environmental parameter that occurs prior to mainshocks, and that is thought to be linked to the preparation process for this mainshock [2]. Seismic hazard evaluations have improved their quality during time, are subjected to periodic updating, and, to date, have turned out to be a reliable tool for building codes and land planning. Earthquake prediction research based on parameters believed to be precursors of earthquakes is still controversial and still appear to be premature for the practical purposes demanded by governmental standards [3]. Despite these limitations, part of the scientific community argue that possible improvements to probabilistic seismic hazard evaluations

may come from the information coming from present-day research into the possible geophysical and geochemical earthquake precursors. Although not funded like other routine activities in the field of seismology, some recent projects on earthquake precursors have produced interesting data recognized by the whole scientific community. In recent years, an extensive literature of review papers has advised the scientific community as to the present state of the art. For instance, Johnston and Linde [4] reviewed data about crustal strain, which includes possible precursory behavior; King and Igarashi [5] reviewed reliable data about possible earthquake precursors detected in geofluids; Johnston [6] reported some possible electric and electromagnetic phenomena detected prior to significant seismic events; and Paudel and coworkers [7] reviewed previous chemical data about possible precursory signals recorded in geofluids and proposed new parameters. Uyeda and coworkers [8] reported on electric and electromagnetic signals detected before earthquakes in different countries and commented on recent trends in research activities, Ismail-Zadeh and Kossobokov [9] reported on the possible use of seismic catalogues for intermediate-term earthquake forecasting, and Chadha [10] reviewed the generation mechanisms of possible precursory signals in geofluids. Current recent trends in earthquake precursors have also been summarized in special issues of scientific journals like in [11] and [12–15] among others, or in special volumes collecting contributions by various authors like in [16] and in [17]. The empirical approach to the problem of earthquake prediction is the attempt to establish phenomenological laws that have led, during historical times, many scholars and researchers to suggest specific relationships between precursors and earthquakes. These studies reached the scientific dignity of present-day studies about a century ago through the activities of researchers like Bendandi in Italy who utilized astronomical parameters in 1931 [18], Lorenzini in Italy who utilized physical and chemical groundwater data in 1898 [19], Imamura in Japan who utilized chemical groundwater data in 1947 [20], Rikitake in Japan who utilized water flow rate data in 1947 [21], Milne in Japan who utilized electromagnetic emissions in 1890 [22], Tanakadate and Nagaoka in Japan who utilized electromagnetic emissions in 1893 [23], Bertelli and de Rossi in Italy who monitored crustal deformations in the period 1878–1887 [24–26], and Galitzin who promoted the interdisciplinary approach of earthquake precursors studies in 1911 [27], while microgravity variations were utilized together with other geophysical and geochemical parameters during the first earthquake prediction experience in 1975 by Chen and coworkers [28]. The purpose of the present work was to attempt to identify possible future research trends about earthquake precursors in geofluids after a review of historical, contemporary, and ongoing research activities. In fact, the observations of physical and chemical variations in geofluids as possible parameters capable of contributing to earthquake forecasting started about 2500 years ago (e.g., [29]) and are still being carried out (see also [30–32]).

2. 600. B.C–1500 A.D.: The First Observations of Geofluid Variations before Earthquakes: The “Theory of Winds”

Earthquake prediction studies started in the Mediterranean region. They spread to Central Europe, Euro-Asian Continent, and the Far East in ways and times similar to those found in the past of earthquake theories and seismic instruments [33]. There are a variety of examples of earthquake forecasts in ancient literature, but the author of the forecast often only adopted guesswork or speculation to make general disaster forecasts. It was only in a few cases that it was possible to establish a causal relationship between a phenomenon described as “precursory” and an earthquake. An early example worthy of note is that of Pherecydes of Syros (600–550 B.C.), who is believed to have been a Pythagorean teacher. Cicero describes the situation in his “De divinatione.” Pherecydes, who expected an earthquake when he saw that the water from the well, which was normally filled, had vanished before the earthquake [34]. During the same time, Anaximander of Miletus (610–546 B.C.) [35] warned the Spartans to be careful because an earthquake was looming. The earthquake occurred a few days later, but there is no information available on the forecasting methods [36]. There are nine volcanoes in the Aegean Sea, and five of them erupted in historical times [37,38].

Thus, the study of macroscopic natural phenomena may have had an influence on the theories of ancient Greek philosophers. Recent work into changes in water levels in aquifers prior to earthquakes shows that Pherecydes had identified a trend that still appears to play a useful role in earthquake prediction [39]. Throughout the Middle Ages, thinkers and academics turned their attention to studying the cause of earthquakes rather than attempting to predict them. In accordance with the metaphysical and religious attitudes of the time, scholars turned their attention to other phenomena, such as different kinds of disasters, miracles, etc., which followed and seemed to be related to earthquakes. The prevailing philosophy in the Middle Ages was that of Aristotle and his philosophy of the subterranean stream.

The first critique of Aristotle's theories came from Georg Bauer (known as Agricola, 1494–1555), who refused to accept the Aristotelian seismology of signs predicting earthquakes and believed in the unpredictability of earthquakes [35].

3. The Period 1500–1800: The Diffusion of Greek Theories

The observation of natural phenomena became quite important in the Renaissance, and a new mentality could be found in natural philosophy. A.J. Buoni, a doctor from Ferrara, refers to the bubbling of gas and the muddying of water in wells before and after the quake of Ferrara in 1570.

This piece of evidence is documented in his treatise “Del terremoto (On the Earthquake)” by Buoni [40], which contains a great deal of observational and historical detail, including a reference to Nicolò Cardano's observation of similar phenomena. Scientific theories became more common in the 16th and 17th centuries, partly as a result of the printed word, the availability of data, and the rejection of the Aristotelian earthquake theory. The 17th century saw a significant exchange of scientific knowledge between the Jesuit fathers and China, and Father Matteo Ricci's voyage there for scholarly and research purposes was of particular importance. He developed good diplomatic relations with the Chinese authorities and “initiated” cultural exchanges. He called his successor Father Nicola Longobardo, whose name was modified by the Chinese to Long Huamin. Longobardo came from Caltagirone, Sicily. He arrived in Beijing in 1597, where he died in 1655. His dissertation on The Analysis of Earthquakes was published in 1626 [33,41]. It points out the precursors he was aware of, such as anomalous gas bubbling from the earth, clouding of water in wells, and the taste of water changing before the earthquakes. Such anomalies are now known to be hydrological and geochemical macroscopic variations in geofluids [42,43] likely related to earthquakes. He also listed the frequency of unusually high tides, which are now considered indications of potential crustal deformations. Father Longobardo ascribes the appearance of precursor phenomena to subterranean gas pressure and also considers particular meteorological situations and the appearance of some cloud formations to be seismic forerunners, emphasizing the importance of the work of Aristotle, particularly the *Meteorologica* [35]. A further historical document printed in China in 1663, defined as the Longde County Annals [33] cited by [43], records the existence of macroscopic precursor phenomena almost accurately as described by Longobardo in 1626. This aspect may be interpreted as suggesting the role of Greek thinking in Chinese culture.

4. The Period 1800–1920: The First Observatories for Earthquake Precursors

The 19th century saw the scientific contributions of many outstanding scholars, such as Robert Mallet (1810–1881), Michele Stefano de Rossi (1834–1898), Timoteo Bertelli (1826–1905), Giuseppe Mercalli (1850–1914), and John Milne (1850–1913). These scholars identified many phenomena presumed to be earthquake precursors. Their scientific contribution included several geophysical parameters that have been studied in recent times in the advanced fields of geomagnetism, gravimetry, and findings about slow deformations in the earth's crust, hydrology, and applied geochemistry. In particular, between 1870 and 1888, Michele Stefano De Rossi and Timoteo Bertelli [24,25] handled the first instrumental network consisting of 20 “tromometers” (instruments based on the pendulum principle) capable of measuring slow crustal deformation movements in Italy, and a possible precursor

of an M 5.2 seismic event was found near Florence [26]. At about the same time, similar research was performed in Japan, comprising a cluster of observatories to record, amongst other parameters, electromagnetic emissions [22,23]. The founding of the Japanese Seismological Society after the Yokohama earthquake in 1880 was of particular significance. Following the 1891 Nobi earthquake, the Imperial Earthquake Investigation Committee was established to study seismic and volcanic phenomena. The need for a comprehensive approach to earthquake prediction studies was highlighted first of all by the Russian prince Borisovich Galitzin (Saint Petersburg, 1862-Saint Petersburg, 1916). Prince Borisovich Galitzin designed the first electromagnetic seismograph. In 1911, at a conference held in London, he was elected president of the International Seismology Association, which in 1951 became the International Seismology and Physics Association of the Earth Interior. During the meeting, he spoke, among other topics, on the precursor changes detected in the physical and chemical parameters of the thermal waters of Borjomi (currently in Georgia) [44]. In the same year, a list of parameters useful, in principle, for earthquake prediction was released. The list also contains numerous non-seismic parameters and is still utilized in many research projects around the world, using modern monitoring techniques as well. In 1911, B.B. Galitzin drew up a detailed earthquake prediction research program [27] involving:

- The study of the frequency and magnitude of seismic events and of the features of seismic oscillations;
- The study of the propagation rate of seismic waves to evaluate the state of tension in seismically active areas;
- Geodetic measurements aimed at discovering slow deformations in the earth crust;
- Gravimetric measurements; and
- The study of the condition of springs and wells, and study of the composition of the gases in the earth crust.

Galitzin's attention to the behavior of fluids in the earth crust was due to his work on the seismicity of the Caucasian area; however, his work was definitely influenced by the impressive relationship he had with many European geophysicists. He had been to Italy and shared ideas with local scholars. In Europe, a large number of historical sources like [25,45] and [46] have shown an interest in the behavior of earth fluids linked to the prediction of seismic events. In particular, Michele Stefano De Rossi reported he had simultaneously observed crustal deformation phenomena and significant variations in the flow rate and temperature of geofluids offshore from the Ischia Island (Italy) M = 5.8 earthquake of 1883 [47] and his findings had almost certainly been read by B.B. Galitzin. All the countries that developed research projects with the purpose of reaching a routine capability to issue, at least potentially, alarms for impending earthquakes have set up monitoring networks managed by institutions and research agencies belonging to the state and not directly run by the universities. In order of importance, the most relevant networks are seismometric, geophysics, and geochemical, or hydrological. In the following sections, an outline is given of the most relevant experiences.

5. Research Starting in the Modern Ages

5.1. The Former Soviet Union and the Russian Federation

The Aschabad earthquake in 1948 stimulated systematic work into earthquake precursors in the Soviet Union [48,49]. In the Garm region of Tajikistan, a test area was set up in 1949: Fundamental work was carried out there to predict earthquakes. G.A. Gamburtsev initiated a new research program on precursors in 1953. It was primarily carried out in Uzbekistan after the Tashkent earthquake of 1966. Semenov and his colleagues in the Tajikistan Test Area found in 1969 that the compression wave velocity (V_p) diminished prior to some local earthquakes [50]. This phenomenon was later recognized as a consequence of the so-called dilatation-identified [51–53] precursor signals in radon detected in groundwater prior to a significant seismic event in the Tashkent region in 1966. The research team led

by A.N. Sultankhodjaev carried out further work into geochemical precursors in geothermal fluids in wells of Uzbekistan and obtained important results [54]. Considering the quality as well as the number of papers, it can be argued that most of the research carried out in many countries on geochemical and geophysical earthquake precursors was certainly encouraged and influenced by the groundbreaking research carried out in Central Asia in the past half century [55–57]. The geochemical approach has achieved, generally speaking, important results in the former Soviet Union. These characteristics are not always visible in other countries, where the seismological approach seems to prevail. Previously, these peculiarities were highlighted by [58–62]. Observational wells networks (0.2–2.9 km depth range) or thermal springs created by approximately 600 sampling points (1 sampling site per 10,000 km² and higher density in test site areas: The so-called “polygons”) were used in Tajikistan, Uzbekistan, Kazakhstan, the Caucasus, and Kamchatka between 1970 and 1990. Various scholars, such as [54,63–65], have stated that some local severe seismic events were preceded, some hours or days before, by precursor changes in the water level and by changes in geochemical parameters, such as helium. The authors of [66] reported on a significant number of seismic events in Kamchatka preceded by variations in the physical and chemical parameters of groundwaters monitored in spring sources and in wells. Probably the experience of Kamchatka is the most comprehensive of all in the former Soviet Union and is currently the most effective in the study of geochemical and hydrologic earthquake precursors. Monitored data are also published at the web site <http://www.emsd.ru/lgi/result>.

5.2. China

In 1956, Fu Chengyi formulated a research project regarding earthquake prediction that started in 1966 after the Xingtai earthquake [43]. The main guidelines of the Chinese research program were similar to those of the USSR. The local peculiarity is the particular attention paid to the empirical observation of a number of natural phenomena, including some of a macroscopic kind, such as animal behavior and meteorological phenomena that were believed to be earthquake precursors. The prediction of the seismic event of Haicheng in 1975 ([28,67] and references therein), and the subsequent successful warning to the population was obtained by observations of geophysical and geochemical parameters, including radon. Despite the failures in predicting some of the later seismic events, the Haicheng forecasting spawned the Chinese scientific institutions devoted to the study of earthquakes. Automatic instrumental measurements of a variety of parameters, using advanced technology [68] were carried out. At present the Chinese monitoring network for the monitoring of earthquake precursors include GPS stations, magnetotelluric stations [69,70], and microgravimetric stations [71,72]. In particular, a network for groundwaters and gas monitoring was also set up in China. The network consists of over 600 thermal springs and wells (depth range 0.1–2.0 km). The authors of [73–75] reviewed the most relevant characteristics of the Chinese monitoring network devoted to geofluids. Direct inspections by the author in 2018 and 2019 confirmed that each monitoring site includes the monitoring of the water level, temperature, basic chemical components, and gases like carbon dioxide, hydrogen, and helium. Precursory variations in the water level were observed before some strong earthquakes, and tectonic-related geophysical and geochemical variations are widely studied to better understand possible fluid phenomena related to geodynamic processes [76–79].

5.3. USA

In California, Whitcomb and coworkers [80] replicated some of Semenov’s groundbreaking experiments in 1969 [50] on velocity fluctuations of compression waves (Vp) preceding earthquakes, while [81] reported on crustal deformation prior to earthquakes in California. The observed anomalies were considered as caused by dilatancy [82], but some errors in forecasting seismic events in California in the same years provoked a pessimistic reaction. Skepticism regarding the potential risks resulting from apparent false or missing warnings before earthquakes greatly restricted work on earthquake precursors in the United States in the subsequent decade [83,84], but new studies began in California in the Parkfield region in 1985. The Parkfield test site, in California, was instrumental in detecting

precursor phenomena [85]. A cluster of 12 wells was organized and water level data were registered and correlated with other geophysical and geochemical indicators, such as radon and hydrogen [86]. It can be viewed, as a comprehensive approach, as a revival of the geophysical observatory network's operational tradition during the 19th century in Europe. Following a precursor variation reported in the water level in 1985 [87,88], some local earthquakes were not accompanied by precursor signals in controlled wells, leading to less interest in geofluids, and monitoring activities at the sea level shifted towards the Plate Boundary Observatory project on the west coast of the USA [88]. The interest of the Plate Boundary Project is not related to earthquake precursors but to crustal deformative processes in general. Monitoring wells in the frame of Plate Boundary Observatory are characterized by a depth in the 50–100 m range. This depth is significantly shallower when compared to experiences carried out in other countries. No warm spring sources are monitored in the same project frame. The latter details led us to deduce that geofluid monitoring oriented to earthquake precursors research is currently characterized by a relatively low profile. Evelyn Roeloffs, in charge of geofluid monitoring during the previous Parkfield experiment on earthquake precursors, recently reported that one of the most effective ways of predicting an earthquake is operational earthquake forecasting (OEF) based on the occurrence of seismic activity of various kinds that raises the short-term probability that additional earthquakes, including damaging earthquakes, could occur in hours or up to a few days [89].

5.4. Japan

The first studies on seismic precursor parameters in geofluids have appeared in Japan in the 1940s and 1950s [90–92]. Japan's interest in earthquake prediction rose following the publication of a detailed study by Tsuboi and coworkers [93], usually referred to as the “blueprint”. The “blueprint” defined the guidelines of the earthquake prediction research activity initiative in Japan.

The initiative began a few years later, giving preference to the monitoring of crustal motions, the observation of seismic activity, geomagnetic recording, and research lab rock mechanics [94]. Recently, promising results have been obtained in the field of electrical and electromagnetic parameters [8,95], whereas little attention has been paid to fluid monitoring in the early stages of the Japanese program. Intense work in this area started in the late 1970s with the establishment of the Earthquake Chemistry Laboratory at the Faculty of Sciences of the University of Tokyo (now Geochemical Research Center), where promising scientific results were achieved [42]. Some failings regarding earthquake prediction in Japan have led local government to disregard the word ‘prediction’ in recent documents, and the apparent decline in the importance of short-term prediction has been blamed by Uyeda [96]. The comprehensive approach to research has, moreover, been confirmed. Many research teams have reported hydrological and geochemical data in the single spring sources or in the small wells networks in Japan, and important precursor phenomena have been detected [97]. The Geological Survey of Japan, along with the National Institute of Advanced Industrial Science and Technology, has recently established a network of about 50 deep wells (0.6 km depth). The network started a monitoring activity in the area of Nankai, Tonankai, and Tokai [97–99], because of a possible expected local strong earthquake. All recorded data are available online at the web site: https://gbank.gsj.jp/wellweb/GSJ_E/index.shtml.

5.5. Turkey

Significant results have been obtained in Turkey in recent decades, in which the Turkish and German research institutes have carried out a joint earthquake prediction project. The main feature of this joint project was its multi-parameter approach, which included the simultaneous detection and study of numerous precursors. This concept also goes back to the working style of the 19th century geophysical observatories. The findings obtained so far have proved the suitability of this method and have been widely supported by the scientific community. In the period 1984–1989, groundwater levels (six monitoring stations) and radon activity (five monitoring stations) were measured along with other geophysical parameters in Turkey [100]. The lack of powerful earthquakes during the

observation period hindered the final findings, but major technological and operational improvements have been made in groundwater monitoring and data analysis techniques, as [101–103] reported precursory variations in geofluid in wells and in selected springs in Turkey in 2006. Inan and coworkers led the deployment of several radon monitoring stations in soils and some wells in 2007, but no definitive results were obtained in the following years [104,105]. The long-term government earthquake plan [106] did not consider the previous encouraging results obtained in geofluid monitoring and paid attention to seismic monitoring and some further geophysical parameters.

5.6. Iceland

The first research into earthquake prediction started in Iceland in the period 1975–1980 [107] with an intense radon monitoring in local geofluids. In the period 1986–2006, the Icelandic government promoted international cooperation in the field of earthquake prediction led by Ragnar Stefansson [108], which led to significant results in particular in the southern part of the island. A strong multidisciplinary approach characterized the research carried out in Iceland, and valuable results were achieved in the field of geochemistry [109,110].

5.7. Taiwan

The first earthquake prediction research program in Taiwan started in 1979 [111]. The program included the study of changes in microseismicity, the study of crustal deformations, the monitoring of microgravity, the monitoring of the magnetic field, and the sampling and analysis of geothermal waters to monitor possible radon changes in five selected hot springs. Precursory water-level fluctuations before the 1999 Mw 7.6 Taiwan earthquake [112–114] identified in 2017 precursory signals in noble gases and in the chemical composition of thermal waters. The monitoring network devoted to geofluids is at present composed of 11 sites equipped with automatic instrumentation. Taiwan is actively cooperating with Japan, the USA, and China in all the fields of earthquake precursors, and the government plan includes the enhancement of these research activities.

6. Why Monitor Geofluids?

Hydrogeological and geochemical analyses are performed in geofluids with the purpose to increase information useful for earthquake prediction studies. Experimental sites have provided the opportunity to better understand the physical origin of reported pre-seismic anomalies. The main experimental sites are currently located in Japan (areas of Nankai, Tonankai, and Tokai) [98,99], China (provinces of Sichuan, Yunnan, Singjiang, and the capital area of Beijing) [73–75,79] the Russian Federation (Kamchatka) [66], Iceland (southern part of the island) [108–110], and Taiwan [113,114]. The studied parameters usually involve water level, water temperature, electrical conductivity, water-dissolved anions and cations, CO₂, CH₄, radon, and helium. Possible geochemical and hydrogeological precursors have been found in many sensitive sites hours to months prior to certain significant earthquakes [5,114]. Sensitive locations are generally found along active faults, in thermal springs, or in deep wells that reach confined reservoirs [115,116] capable of acting as natural strain meters [117,118] (Figure 1).

Groundwaters, hydrocarbons and gases, are around ubiquitous fluids that fill deep-seated rock formations where porosity values permit the accumulation or the diffusion and circulation of geofluids [119]. Formation waters usually fill sedimentary rock formations that are often associated to hydrocarbons, while meteorological generated groundwater may fill all kinds of rocks. Formation waters are very old and characterized by ages similar to hydrocarbons, while meteoric water ages vary from 1 to 100,000 years. Young groundwaters (1–100 years old) are typically located in phreatic aquifers and connected to present hydrological cycles, whereas confined groundwaters and geothermal systems host relatively old groundwaters (100–100,000 years old) affected by a low circulation velocity and scarcely related to current hydrological cycles. Geothermal systems may be affected by faults capable of inducing the expulsion of geofluids by thermal springs and allowing carbon dioxide emissions. Carbon dioxide is primarily caused by thermometamorphic reactions in the crust [120] or by degassing

of the mantle in volcanic systems. Geochemical phenomena found prior to earthquakes include stable water isotopes [121], dissolved ions, dissolved gases, and soil gas [5,115]. The most relevant gases related to Earth's degassing activities are CH₄ and CO₂ [119], which are known to be responsible for water–gas–rock interaction reactions capable of causing chemical fluctuations in groundwater chemistry. A large part of the geochemical changes in the chemical composition of groundwater have also been attributed to aquifer mixing processes, in particular when geofluids are subjected to temperature variations. Possible precursory variations found in radon, helium, and hydrogen in soil gases were induced by CO₂ or CH₄ carrier gas flow rate fluctuations. Hydrological and geochemical precursor generation processes have been reviewed by [5,39,66,98,115]. It seems that many of the geochemical anomalies found prior to seismic events are due to deep geofluid pressure changes generated by crustal deformation because fluid pressure is proportional to stress and volumetric strain. The stress–stress interaction for the isotropic linearly elastic porous material was investigated, among other authors, by Rice and Cleary in 1976 [122] and by Roeloffs in 1996 [123].

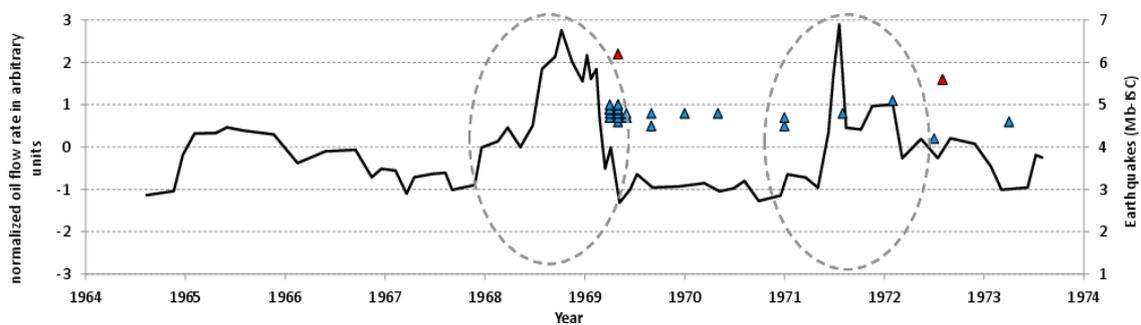


Figure 1. Oil flow rate variations in a 10-year time series recorded in the Sinai area in a 3-km-deep well before two Mb > 5.5 earthquakes (red triangles) occurred within a radius of 150 km from the well. Blue triangles indicate 4 < Mb < 5 seismic events (after [116] redrawn and modified). Crustal deformations preceding shocks induced an increase in spontaneous oil flow from a deep hydrocarbon well. The authors considered the observed evidence to be “not conclusive”, but similar phenomena were observed in geofluids in the following decades [28]. These phenomena may affect groundwaters and thermal waters since confined geofluids may act as natural strain meters.

In particular, the stress tensor σ_{kk} , the volumetric strain ϵ_{kk} , and the fluid pressure p under undrained conditions can be described as:

$$92 p = -B \epsilon_{kk} / 3, \quad (1)$$

$$93 p = -2GB(1 + \nu_u) \epsilon_{kk} / 3(1 + \nu_u), \quad (2)$$

where G is the shear modulus, B is the Skempton coefficient, and ν_u is the Poisson ratio in undrained conditions. As a result, fluid pressure change is directly proportional to stress and volumetric strain. Therefore, deep groundwaters can be used as natural strain meters due to the low compressibility of water [124]. Furthermore, large reservoirs can be monitored by wide-scale networks. In order to further restrict the candidate region affected by anomalous signals, experiments have been made to better identify areas affected by the highest intensity signals in the water level [112,125–128]. Review articles explicitly or implicitly argue that the deformation mechanism causes observed fluid anomalies. Most of the works refer to “a posteriori” recognized precursor signals, while official warnings were given prior to the Haicheng shock of 1975 [129] and the Pamir earthquake of 1978 [63], but the precise date and location of the coming shocks were not properly defined. In 2006, Roeloffs evaluated data on deformation processes prior to earthquakes. In at least 10 earthquakes, an aseismic deformation characterized by time durations of 10 min to 15 years was found [130]. Not all seismic events appear to be accompanied by observable crustal strain in the epicentral region and this may reflect the absence of fluid-related precursors found in many situations. As water is scarcely compressible [124], the water

level can be considered a natural sensitive (10^{-7} – 10^{-8}) strain meter useful to record the deformation of the crust in the region of the occurring seismic event. Signal properties of the recorded anomaly could be determined as in the case of the last generation recording network managed in the Tokai region [131]. Water is not completely compressible while gases are compressible, therefore radon data, compared to data from strain meters, cannot give unequivocal results [132]. Calculation of the stress tensor from a gas like radon is an unresolved challenge. Nevertheless, data from radon or helium can also be used to semi-quantitatively track tectonic activity in faulted zones. Radon originates in the upper crust and can fluctuate due to crack opening or to changes in the speed of carrier gases, such as CO_2 or CH_4 , and to possible changes in rock permeability. Helium has two isotopes: Helium 4 and helium 3. The most abundant is helium 4, which originally comes from the crust by the decay of radon. Helium is characterized by a high fugacity value [132], thus it is widely utilized in studies related to tectonics and to faults. In principle, helium may change due to possible crustal permeability changes induced by crustal deformations and has been utilized for earthquake precursor research [133]. The less abundant helium 3 originates from the mantle and may provide highly important knowledge of deep geophysical and geochemical processes [134]. The use of $3\text{He}/4\text{He}$ for earthquake precursor research was proposed in 1979 by Mamyrin and coworkers [135] and interesting results were achieved by [136–138]. The International Association for Seismology and Physics of the Earth's Interior Sub-Commission Earthquake Prediction analyzed available anomalies of various precursors and included radon and water levels in the list of potentially significant precursors in 1991 and 1997 [2,139].

7. Possible Experimental Applications

Earthquakes often follow the path of a defined direction being generated by huge-scale crustal deformations [140]. Indirect and direct observational evidence of the influence of regional strain on precursor geofluid anomalies was reported by [112,126,141–143]. Motions of deforming fronts can activate earthquakes and can be characterized by speeds of between 10 and 100 km/year. Such processes are related to the rheological stratification of the lithosphere [144] and play a key role in the medium- and long-term prediction of earthquakes. Monitoring of groundwaters by networks of wells can lead to a better knowledge of the considered parameters for earthquake prediction research. The presence of a large amount of hot springs, of CO_2 emissions, and of boreholes in zones affected by a relatively high number of large earthquakes will make it feasible to set up recording network systems in the near future. The most appropriate techniques comprise instruments for the water level, temperature, electrical conductivity, and gases like CO_2 , CH_4 , helium, hydrogen, and radon in defined wells or in warm springs.

Agnew [145] and Kumpel [146] evaluated the available observational data and pointed out that the limiting factor of standard wells utilized as stress monitors is due to the fact that fluid flow phenomena still lack sufficient control regarding a potential inhomogeneity of the reservoir and the flow pattern. To further regulate the observational conditions and minimize problems caused by local geological conditions, Swolfs and Walsh [147] proposed to experiment on a kind of “artificial-confined aquifer” putting a liquid-filled pressurized container in a hollow bored in a geological formation. Local shock precursors have been observed, highlighting the need for sophisticated networks to continuously record crustal deformations. The benefit of a natural aquifer, if properly selected, is the size-dependent efficiency that cannot be accomplished by manmade equipment. Developments in electronic equipment and information technology have improved control techniques. Automatic recording was used by [148], which detected possible tectonic-induced phenomena in Turkey's confined groundwaters consistent with local crustal deformations. Their observation and recording have shown that transient anomalies in confined reservoirs usually last from some hours up to some days. The possible presence of short-term transient anomalies has been demonstrated in the Parkfield well network [149] and by other authors in different geological situations. Short-term possible precursory anomalies in gas emissions or in groundwaters can be detected by automatic recording. During the last 20 years, possible precursory

anomalies related to geofluids have been reported in China, Greece, Italy, Spain, Slovenia, Turkey, Israel, Germany, Czech Republic, Taiwan, Kamchatka, Mexico, France, India, Iceland, Bulgaria, Afghanistan, Iran, and Israel. Available data were evaluated by [30,31,118,150–155] in review papers. No fully conclusive results have been achieved by the above-listed scientists, because the number of false alarms or missing alarms is fairly high for practical purposes, possibly due to an insufficient instrument density, or to ineffective site selection, or to the elusiveness of the result, because of the very small variation in pore pressure near the earthquake depth, probably <0.1 MPa [3]. Furthermore, [39,123] demonstrated that groundwater-level variations observed before earthquakes are generated by elastic strain due to pre-seismic deformation. Thus, they cannot be larger than coseismic water-level variations. The authors of [156] underlined that any earthquake precursors in geofluids could be detected with great difficulty at a distance exceeding approximately 100 km from the epicentral area due to the lack of crustal strain at long distances [157].

A large part of the identified geochemical and hydrological anomalies published in the referenced review articles were found in places affected by relatively high (>65 mW/m²) heat flow [158,159], which indicate the presence of hydrothermal circuits where shallow earthquakes similar to volcanic seismic events may occur. The observed short-term pre-seismic fluctuations may have been caused by fluid-kinetic-based processes that are characteristic of volcanic regions. In volcanic environments, fluid kinetic is able to induce or to favor seismicity, while fluids have a subordinate role in the induction of plate tectonic earthquakes. The brittle–ductile transition in geothermal regions can migrate to shallower depths [160], increasing the consequences of crustal deformation attributable to the highly effective deformation of ductile geological formations caused by temperatures >300 °C [161]. Therefore, mechanisms linked to dilatancy are usually not invoked to describe earthquake-related phenomena in volcanic areas. Possible precursory hydrological and geochemical phenomena have frequently been reported in volcanic areas, and the monitoring of geofluids is currently part of civil defense surveillance activities oriented to volcanic eruption risk mitigation.

Thus, the reported short-term hydrological and geochemical seismic precursors may have been generated in geothermal areas, the seismicity of which is similar to that observed in volcanic regions. Such regions are typically influenced by the significant presence of CO₂-dominated geofluids. Such features may explain the relatively promising results achieved in Japan, central Asia, and China as well as the scarce results achieved in seismically active low heat flow regions. Volcanic fluid monitoring is, in this sense, at the scientific level of maturity, while earthquake geofluid precursor monitoring is still at an early stage. No conclusive findings have yet been obtained in the short-term monitoring of earthquake precursors, because earthquake precursors are not observable for all seismic events and because of the fairly high number of missing warnings. Geochemical and hydrogeological monitoring could help to better identify the time and place of earthquakes forecasted by various different approaches (e.g., [162,163]) since the presence of potential short-term precursor signals could not be ruled out if the monitored reservoir is directly linked to a deep geothermal environment. It is the case of hot springs and of deep boreholes, which should be regarded as most relevant monitoring locations. The data collected, while incomplete, appear to support more intense research of this kind oriented to risk reduction in the upcoming future.

7.1. Indirect Geochemical Monitoring of Geofluids by Satellite Techniques

Several results of research published over the last 30 years on earthquake forerunners have been obtained using satellite technologies (e.g., [164–168]). The authors observed anomalous transient signals in thermal infrared (TIR) radiation both in time and space emitted by the Earth and likely due to the emission of underground geofluids caused by crustal deformation during the pre-earthquake stages. The authors of [169] indicated that irregularities could be generated by ionization phenomena due to radon emissions from the earth. The authors of [170] and [171] stated that the contribution of radon to potential anomalies is insignificant, whereas [172] indicated that the release of greenhouse gases, such as CH₄ and CO₂, may be efficient in producing the observed anomalies. The authors

of [173] reported that increased infrared emissions may also be attributable to electrical charges due to minerals during stress. Electron density fluctuations in the ionosphere before significant earthquakes were also detected by [174] via satellite techniques. These signals are probably due to charge motions in rocks under stress due to crustal deformations processes [175,176]. Crustal deformation may be accompanied by fluid expulsion when available; thus, the way has been paved for a new research field of fluid monitoring. Ground-based and satellite-based joint measurements will probably better explain the observed phenomena.

7.2. Indirect Geophysical Monitoring of Geofluids by Ambient Seismic Noise

Several authors (e.g., [177–179]) proposed in recent times the monitoring of geofluids located in the crust by utilizing ambient seismic noise. This method can also be utilized in areas where no spring sources or gas emissions are present and, in principle, could allow measurement of the transient strains of deep reservoirs. The explorable depth may reach some kilometers and is undoubtedly higher when compared to the one monitored by a borehole in groundwaters. If the instrumental array is relatively economical, a wide diffusion of these methods at least in test site areas is possible.

7.3. Indirect Geophysical Monitoring of Geofluids by B-Value

High fluid pressure at depth can play a significant role in triggering earthquakes by reducing the fault strength and potentially controlling the nucleation, and the occurrence of earthquake ruptures [180]. On a global scale, it is known that CO₂ discharges are associated to seismically active zones, in particular in extensional areas. The authors of [181,182] recognized a role in geofluids in earthquake generation and triggering. The authors of [183] reported that pressurized geofluids might strongly influence the b-value's possible fluctuations before earthquakes. The authors of [184] and references therein reviewed places in the world where the b-value's possible precursory fluctuations were previously observed in the period 1970–2008. The majority of the considered places are located in extensional areas characterized by abundant geofluid occurrence. Possible variations in the b-value over time might be related to pore pressure variations at depth driven by geofluids influenced by crustal deformation processes. The authors of [185] described the role of pore fluids in the generation of part of seismic precursors to shear fracture. Possible precursory variations in the b-value could be considered as an indication of fluctuations in geofluids in selected areas. Based on these findings, very encouraging results have been obtained in China by [186]. Thus, seismometric monitoring of the b-value could be considered as a proxy of geofluid monitoring in particular geological environments.

7.4. New Parameters and New Indirect Monitoring Techniques of Geofluids

Several research studies published over the past 30 years on earthquake precursors have been carried out utilizing satellite techniques capable of identifying deep originated possible gas emissions [172,187]. Further possible pore pressure fluctuations are presently monitored utilizing magnetotelluric stations [69,70]. Other authors suggested monitoring geofluids located in the crust by utilizing ambient seismic noise [177–179], while the significance of the b-value could be better investigated in the upcoming future [182,188] in selected geological contexts. Crustal deformation processes may be accompanied by fluid expulsion when available. Thus, the mentioned methods have opened new research fields in fluid monitoring based on the indirect recording of possible pore pressure fluctuations when wells or spring sources are not available. The cost of the equipment for such kinds of monitoring activities is coming down in time, thus allowing universities or research centers to launch independent research projects without the need for large-scale infrastructures. The contemporary diffusion of personal electronic devices capable of monitoring, in principle, various environmental parameters could allow for future developments in this kind of research.

7.5. Forecastable and Unforecastable Seismic Events

After the pioneering publications by Ulomov and Mavashev [53], the first three decades of geochemical and fluid monitoring were characterized by an empirical approach. The immediate correlation between a possible fluid-related anomaly and a forthcoming seismic event was followed as a research task in many cases. Experience, new technologies, and more accurate data processing procedures evidenced serious difficulties in constraining the time and location of a possible forthcoming seismic event. A better understanding of physical mechanisms capable of generating possible hydrological anomalies prior to earthquakes slowly induced a more complete interpretation of recorded data [39,123]. To date, all the experimental data obtained in fluid monitoring do not clearly indicate that the observed anomaly is generated by the hypocentral volume of a forthcoming earthquake. Crustal deformations, when detectable, are regional large-scale processes. Thus, eventual geochemical or fluid-related anomalies can generally be attributed to an extensive process that could generate intense seismic events or a variety of low magnitude events. Recent data indicate that fluid-related anomalies could be interpreted as an indicator of the stress field evolution over time rather than signals generated by a hypothetical focal volume of a forthcoming seismic event. A significant part of CO₂, CH₄, and water reservoirs are located in the first 2–5 km of the crust while most seismic events occur at a depth of 10–30 km.

Thus, large-scale deformation processes, if they are able to reach the Earth's surface, may easily affect fluid reservoirs while it is really hard to believe in an active role of a single forthcoming seismic source. Furthermore, a recent review by Martinelli and Dadomo of all available data concerning possible earthquake precursors recorded in geofluids evidenced that about only extensional tectonic regimes located in relatively high heat flow areas (Figure 2) may host these phenomena [189].

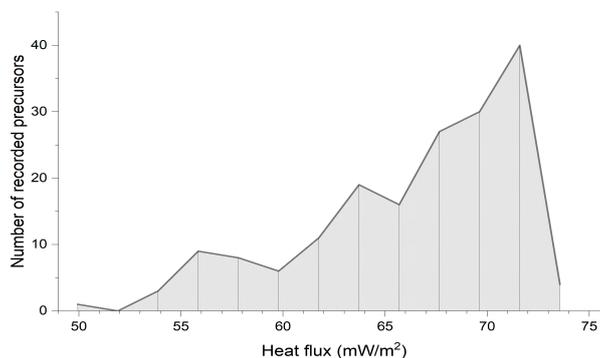


Figure 2. Number of recorded precursors in geofluids and heat flux. A great part of them have been recorded in areas characterized by relatively high heat flux (after [189], modified).

This finding implies that, in principle, all earthquakes occurring in compressional tectonic regimes cannot be forecasted by geofluid monitoring. Different patterns of occurrence of earthquakes seem to affect compressional and extensional areas [188,190]. Thus, different monitoring strategies will probably be adopted in the upcoming future for research oriented to earthquake forecasting.

8. Conclusions

The occurrence of migration phenomena in crustal deformation fronts induces a need to continuously control crustal topography and crustal masses influenced by strain induced by stress variations. Deep wells and thermal springs in confined reservoirs may be considered as highly sensitive natural instruments capable of detecting strain variations. Water level, electrical conductivity, and temperature may be monitored by automatic equipment in the most tectonically active regions of the world and may provide important contributions to earthquake forecasting studies in both the short and medium term. Gaseous monitoring of carrier gases and of noble gases, in identified degassing areas affected by high heat flow, could also be carried out jointly. Instrumental networks should be

strengthened with respect to past groundbreaking experiences and defined by at least one observation point (thermal spring or borehole or gas emission) per 500 km² as in the finest monitored areas of China, Japan, Kamchatka, Iceland, and Taiwan. Geofluid monitoring networks should be embedded in existing GPS, tiltmeter, and strain meter networks and satellite-based monitoring activities. Data interpretation should be comprehensive and take account of all geophysical and geochemical monitored parameters. Many examples of scientific research into earthquake prediction allow us to trace paths of future investigations in this topic. Research on earthquake prediction has never achieved results that are so convincing as to assert itself over other methodologies for an approach to the question of defense against earthquakes. A paradigm shift is needed to learn from the most relevant results obtained in the aforementioned test site areas. Thus, future trends in research oriented to the monitoring of possible geofluid precursors include:

- (1) New monitoring satellite-based techniques capable of evidencing possible fluctuations in gaseous emissions;
- (2) New ground-based monitoring networks in geofluids in areas characterized by relatively high heat flow areas;
- (3) Indirect monitoring techniques of geofluids by b-value monitoring;
- (4) Indirect monitoring techniques of geofluids by ambient noise monitoring; and
- (5) Indirect monitoring techniques of geofluids by magnetotelluric techniques.

The inclusion of geophysical parameters like electric and electromagnetic parameters, minor seismicity monitoring, gravimetric monitoring, and improvements in the monitoring of crustal deformative processes will accompany upcoming research in geofluids from the geophysical side.

To date, hazard maps are still preferred by governmental authorities as a first approximation tool to mitigate earthquake risks [191], while operational earthquake forecasting (OEF) utilizing seismic data catalogues [192–195] is experienced in new test sites areas. Jordan and Jones have underlined that “Data other than seismicity have been considered in earthquake forecasting (e.g., geodetic measurements and geoelectrical signals), but so far, studies of nonseismic precursors have not quantified short-term probability gain, and they therefore cannot be incorporated into operational forecasting methodologies” [196].

Research in earthquake precursors, in particular in geofluids, for the next decades will bring to fruition the efforts to forecast earthquakes utilizing earthquakes catalogues but will not be able to completely replace them as long as the probability gain remains incalculable.

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