Chapter 13
Hydrologic Precursors

Abstract Predicting earthquakes is a long-desired goal. The main challenge is to identify precursory signals that reliably predict the impending earthquake. Since hydrological and hydrogeochemical properties and processes can be very sensitive to minute strains, the hope is that measurements from hydrological systems might record precursory rock deformation that would otherwise be undetectable. Of the many hundreds of studies, we review a subset to illustrate how signals can be challenging to interpret and highlight questions raised by observations—examples come from China, Japan, Taiwan, India, the USA, Russia, France, Italy and Iceland. All are retrospective studies. Some signals seem to have no other explanation than being precursory, however, rarely is enough data available to undertake a thorough analysis. Some hydrological precursors might be recording deformation events that are slower than traditional earthquakes (and hence usually harder to detect). Long times series of data are critical for both identifying putative precursors and assessing their origin and reliability.

13.1 Introduction

Earthquake prediction is an enduring goal. The key challenge is to recognize precursory signals that would foretell the occurrence of earthquakes and hence allow a warning to be issued. For this reason, the search for precursors to earthquakes has a long history. Despite early optimism (Scholtz et al. 1973), we are not yet able to predict earthquakes—a successful prediction being defined here as some combination of time, location and magnitude within some stated and useful limits.

There are, however, mechanical reasons for anticipating precursors. Laboratory studies of rock deformation show that beyond the elastic limit, shearing of consolidated rock creates microcracks that open and hence increase the rock volume (e.g., Brace et al. 1966). At still higher deviatoric stresses, microcracks merge and localize to form a shear zone, leading to eventual large-scale rupture (e.g., Lockner and Beeler 2002). There are several ways in which the mechanical changes leading up to rupture can be manifest in hydrological measurements. First, the increase in surface

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area produced by microcracks can release gases trapped in pores (e.g., radon) or change the ionic concentration and hence electrical conductivity of groundwater. Such possible changes provide the motivation for seeking and interpreting changes in gas concentration, hydrogeochemistry, or electrical conductivity. Second, microcracks can change hydrogeologic properties such as permeability as well as pore pressure. Such changes, in turn, can cause a redistribution of fluids and fluid pressure and hence may be detected from changes in water level in wells or changes in spring and stream discharge.

As reviewed in previous chapters, hydrogeologic systems can greatly magnify minute tectonic and seismic strains, as recorded by changes in pore pressure and water level in wells. For example, the change in pore pressure p under undrained conditions is given by (see also Eq. 3.25)

$$p = -K_u B \varepsilon_{kk} \tag{13.1}$$

where K_u is the undrained bulk modulus and B is Skempton's coefficient. A volumetric strain ε_{kk} as small as 10^{-8} can be expected to produce (detectable) water changes of 2 cm for reasonable choices of $B = 1$ and $K_u = 20$ GPa (Wang 2000). It is in part because of the potential sensitivity of hydrogeological systems that much of the search for precursors has focused on hydrological measurements. In addition, hydrological measurements can be made with relative ease (compared with electromagnetic and seismic surveys) and can be recorded continuously.

The hydrogeochemical basis for searching for precursors is similar. The gas composition of springs, for example, can respond to (small) tidal strains (e.g., Sugisaki 1981), hence any preseismic strain might be amplified in hydrogeochemical changes. Radon concentration changes are among the most commonly reported and discussed hydrogeochemical precursors (e.g., King 1980; Wakita et al. 1988; Virk and Singh 1993; Richon et al. 2003; Oh and Kim 2015; Fu et al. 2017; Papachristodoulou et al. 2020) and geochemical recorder of small strains (e.g., Trique et al. 1999; Kawabata et al. 2020)—this is not unreasonable given that radon accumulates over time in micropores, and can be released by small structural changes in rocks and pore connectivity. Small strains may also permit mixing between reservoirs by breaching barriers, or may expose fresh mineral surfaces which in turn permit water–rock interaction (e.g., Thomas 1988). In a manner similar to hydrological recovery after co-seismic hydrological changes (stream flow, water level in wells), water geochemistry also exhibits a postseismic recovery if disturbed by the earthquake (e.g., Claesson et al. 2007).

The elastic properties of rocks, and hence the velocities of seismic waves, are highly sensitive to the opening and closing of microcracks and to the changes in their degree of saturation (e.g., O'Connell and Budiansky 1974). Laboratory measurements confirm that precursory changes in wave speed occur for the full spectrum of fault failure, from slow events to normal earthquakes (Scuderi et al. 2016). Seismologists have carried out various experiments to test the microcrack hypothesis and produced a series of controversial results over the past 50 years. The first published works of such tests were carried out by Kondratenko and Nersesov (1962) for earthquakes in the Tadjikistan region and by Semenov (1969) for earthquakes near Garm, both in the former Soviet Union. These reports were initially met with skepticism by seismologists in Japan and the United States (Bolt and Wang 1975). Nevertheless, the work was sufficiently suggestive to motivate other seismologists to set out independent experiments to examine the claims. The first U.S. experiments along these lines, using quite small earthquakes in the Adirondacks in New York, also detected reductions in the Vp/Vs ratio in three cases (Aggarwal et al. 1973). After the 1971 San Fernando earthquake (magnitude 6.5), Whitcomb et al. (1973) concluded that there had been a precursory decrease in the Vp/Vs ratio lasting about 30 months and a subsequent return to normal, which was followed quickly by the earthquake. On the other hand, McEvilly and Johnson (1974) used travel times between quarry blasts in central California along the San Andreas fault, with known position and origin time, and the University of California seismic network; their study indicated that the recorded fluctuations in travel times for the years 1961–1973 could be accounted for simply by reading errors and changes of shot location in the quarry. They concluded that there were no detectable premonitory travel-time changes prior to 17 earthquakes in the region with magnitudes between 4.5 and 5.4. Later work in the region (Robinson et al. 1974) showed, however, that positive P residuals were detectable before the 1972 M5.1 Bear Valley earthquake (magnitude 5.1). Wang (1974) interpreted these conflicting observations in terms of laboratory evidence that seismic velocities in stressed rocks are significantly affected by the relative orientation between seismic waves and microcracks; thus the conflicting observations in different field experiments may be partly explained by different relationships between the seismic ray path and the free surface in the source region, which controls the direction of stress-induced crustal microcracks. Niu et al. (2008) conducted an active source cross-well experiment at the San Andreas Fault Observatory at Depth (SAFOD) drill site and studied the shear wave travel time along a fixed pathway for three small earthquakes ($M \leq 3$) over a period of 2 months. They show excursions in the travel time before two of these earthquakes, but no excursion before the third. In summary, there is a physical basis for expecting precursors, precursors are seen in the lab, yet earthquake prediction outside the lab remains elusive.

13.2 What is a Precursor?

We begin by defining a "precursor" as a change in a measured quantity that occurs prior to an earthquake that does not originate from any process other than those that lead to the earthquake. Reported hydrological examples include changes in water pressure, streamflow, and water geochemistry and turbidity.

A useful precursor is one that also predicts the time, location and size of the forthcoming earthquake. To our knowledge, no paper has claimed to make these three predictions based on reported hydrological anomalies, noting that the peer review process may be slow compared to the warning time offered by precursory signals.

13.3 Identifying Precursors

Definitive and consistent evidence for hydrological and hydrogeochemical precursors has remained elusive to the extent that there is no consensus on the significance and origin of reported precursors. Earthquake prediction is not currently operational. Difficulties include that, until recently, most reported changes were not corrected for the fluctuations in temperature, barometric pressure, earth tides, and other environmental factors, so that some changes taken to be earthquake-related may in fact be "noise" (e.g., Hartmann and Levy 2005). One common feature of reports is that changes are recorded at some sites but not at other nearby sites (e.g., Biagi et al. 2000). Moreover, instrument failures and personnel/program changes often do not allow persistent and consistent monitoring over long periods of time (King et al. 1994)—a necessary condition for obtaining reliable precursory data. Distinguishing a precursor from a response to a previous earthquake creates additional and unavoidable ambiguity.

Roeloffs (1988) lists the ideal, and arguably necessary, criteria and complementary data for establishing that some signal is in fact precursory. We reproduce (sometimes paraphrased or modified slightly) her list below and then comment of some of these criteria. As noted by Roeloffs (1988), poor documentation is the major impediment to using and interpreting water level data.

(1) Depth of well
(2) Rainfall over at least one year
(3) Record of barometric pressure recorded at least once every three hours
(4) Information about pumping and injection at wells in the vicinity
(5) The entire observation record should be presented
(6) Measurement technique (e.g., pressure transducer, float)
(7) Sampling interval; this should be short enough to reliably distinguish between anomalies before and after the earthquake (Sugisaki 1978)
(8) Response to earth tides
(9) Co-seismic and post seismic response to the earthquake
(10) Earthquake magnitude, azimuth, distance, depth and focal mechanism
(11) Time, location and magnitude of any foreshocks
(12) Raw water level data (unprocessed)
(13) Description of other wells in the area that did not document the anomaly.

Roeloffs (1988) also points out that site geology, in particular the proximity to fault zones, and whether the aquifer is confined, are useful for interpreting any

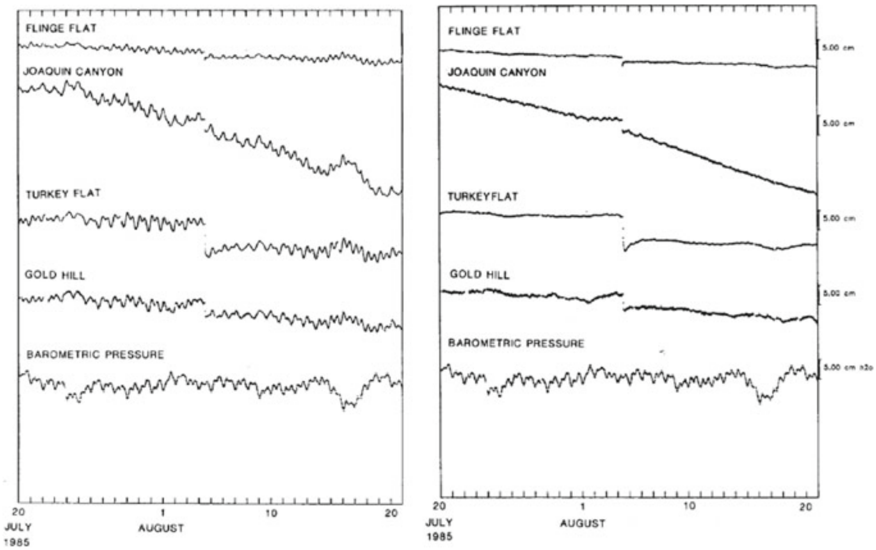

Fig. 13.1 Raw water level measurements (left) at 4 wells located near Parkfield, California. The coseismic response to the August 4 1985 M 6.1 Kettleman Hill, California earthquake can be clearly seen in the raw water level records. The earthquake was located 30–40 km from these wells. On the right is the same data with the effects of earth tides and barometric pressure removed. The coseismic response remains clear. Now, two proposed precursory signals can be seen, a gradual preseismic increase in Joaquin Canyon and Gold Hill (from Roeloffs and Quilty 1997)

signals. For gas or hydrogeochemical anomalies, multiple measurements of ions and gases are helpful in identifying the origin and reliability of the anomaly (Sugisaki and Sugiura 1985).

The importance of removing signals that arise from tides and barometric pressure variations is highlighted in Fig. 13.1 in which raw water level records are compared with records in which the effects of tides and barometric pressure changes are removed. The coseismic water level response becomes much clearer. In addition, two pre-seismic anomalous changes become apparent (discussed in more detail later).

Notwithstanding these difficulties, progress has been made in the past decade. For example, intensive and continued observations of various kinds of precursory hydrological and hydrogeochemical changes have been made in Japan during the past half century (Wakita 1996), providing a long time series of observations. Records are now routinely corrected to remove the noise introduced by fluctuations in temperature, barometric pressure, earth tides, and other factors (Igarashi and Wakita 1995). Tools are readily available to remove the effects of earth tides and barometric pressure variations (e.g., BAYTAP-G). The importance of these corrections should be clear from all the raw records presented in this chapter. Other signal processing techniques can be helpful. For example, high- and low-pass filtering has been applied to the time series of raw hydrogeochemical data in Kamchatka, Russia, to remove long- and short-period changes unrelated to earthquake processes (Kingsley et al. 2001).

Effort has also been made to address the statistical significance of possible precursors. Statistical, rather than deterministic, procedures have been introduced (Maeda and Yoshida 1990) to assess the conditional probability of future seismic events. Multi-component, hydrochemistry analysis was applied to groundwater samples in Iceland before and after a major earthquake to enhance the possibility of detecting possible precursors (Claesson et al. 2004). Highlighting the importance of long time series, Claesson et al. (2007) extended the time series of geochemical measurements after this and subsequent earthquakes and found that the statistical significance of previously identified anomalies could not be verified.

13.4 Examples

There are hundreds of reports of possible earthquake precursors. Here we review and discuss only selected studies to (1) illustrate the range of types of measurements that have been made, (2) highlight the challenges with identifying precursors, and (3) identify some of the key questions raised by reported precursor identifications. In all but one of the examples that we discuss, the hydrological changes are identified retrospectively as being premonitory to the earthquake.

Reviews of reported hydrologic precursors include Roeloffs (1988) and Hartmann and Levy (2005). Hydrogeochemical precursor reviews include Hauksson (1981), Thomas (1988), Toutain and Baubron (1999), Woith (2015), and Martinelli and Dadomo (2018).

13.4.1 China: Haicheng, 1975 and Tangshan, 1976

The most celebrated and first (indeed only, as far as we know) prediction of a large earthquake was the 1975 magnitude 7.3 Haicheng earthquake in China. Based in part on hundreds of hydrological anomalies, a prediction of an imminent earthquake was made. Evacuations and preparations in Haicheng, with a population of about 1 million, contributed in part to the modest number of casualties, just over 2000. The prediction correctly identified the location, though not the precise time, of the event, and the magnitude was underestimated (Wang et al. 2006).

One and a half years later, the 1976 M 7.8 Tangshan earthquake occurred without the issuance of a prediction. Figure 13.2 shows the distribution of anomalies and time histories of radon concentration, groundwater level, land level and electrical resistivity in the region around Tangshan before and after the earthquake (Ma et al. 1990). The fact that no prediction was issued, despite the abundance of potentially precursory anomalies, highlights the difficulty in making predictions. Casualties from this earthquake exceeded 240,000.

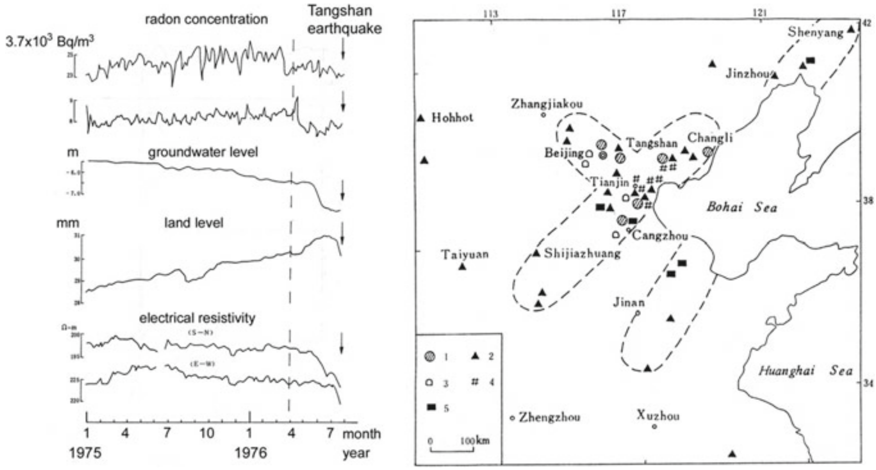

Fig. 13.2 Left: Some of the possibly precursory changes to the M7.8 Tangshan earthquake, China. The arrow shows the time of the earthquake. Right: Location of various precursory anomalies: resistivity (1), radon (2), land level (3), groundwater level (4), anomalies in oil wells (5) (from Ma et al. 1990)

13.4.2 Kobe, Japan, 1995

Following the 1995 M 7.2 Kobe earthquake several papers reported precursory changes in the concentrations of radon, chlorine, and sulfate ions in groundwater (e.g., Tsunogai and Wakita 1995; Igarashi et al. 1995) and in groundwater level (King et al. 1995). The hydrogeochemical changes could be identified by analyzing bottled spring water (Tsunogai and Wakita 1995). Figure 13.3 shows a gradual increase in chloride concentration that begins 7 months before the earthquake. The initiation of these changes coincides with a “drastic” increase in strain measured 5 km away from the well (Tsunogai and Wakita 1995). This coincidence supports a broader tectonic origin of the pre-earthquake changes. However, whether the deformation responsible for hydrogeochemical changes and strain is connected to the later Kobe earthquake is difficult to evaluate. Given the length of the proposed precursory signal, a longer time series of measurements would be useful for establishing the uniqueness of the recorded changes.

13.4.3 Nankaido, Japan, 1946

A few days prior to the 1946 M 8.3 Nankaido earthquake in Japan, water levels in some wells reportedly fell by more than 1 m and some wells went dry (Sato 1982). Linde and Sacks (2002) show that the pre-seismic deformation (observations reviewed in Roeloffs 2006) can be explained by aseismic slip along the subduction

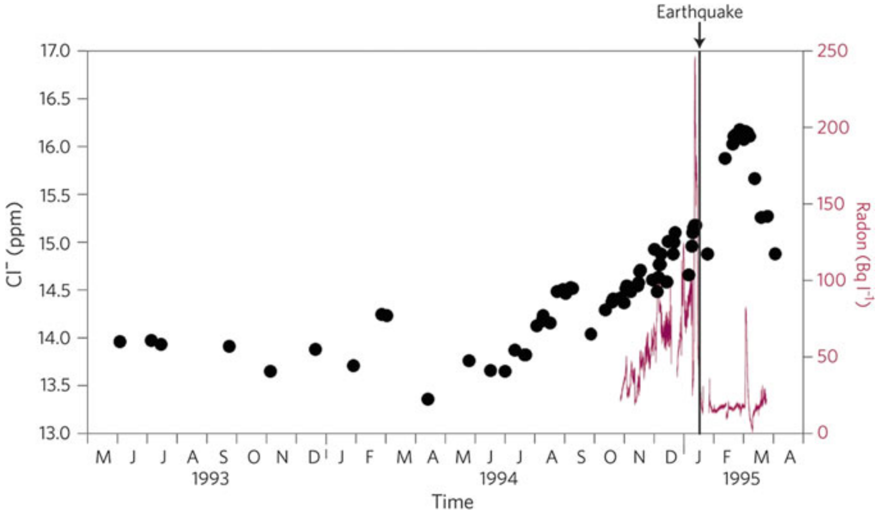

Fig. 13.3 Change in chloride and radon concentration in bottled groundwater 20 km from the epicenter of the 1995 M7.2 Kobe earthquake, Japan. Time of the earthquake is shown by the vertical line. Data from Tsunogai and Wakita (1995) and Igarashi et al. (1995) (from Ingebritsen and Manga 2014)

interface. This area is now intensively monitored with 1200 continuous GPS stations. This data (Ozawa et al. 2002) along with leveling and tide-gauge data document other aseismic slip events (importantly, not followed by large earthquakes) in the region. Multiple and large aseismic events highlight the caution that a correlation of strain and hydrologic changes does not necessarily reflect deformation leading directly to a major earthquake, but possibly document events that may remain purely aseismic.

The 1946 event was preceded by the 1944 M 8.2 Tonankai event, creating some ambiguity about whether the reported changes are responses or premonitory. Measured hydrological changes can lag behind tectonic strains (e.g., Ben-Zion et al. 1990) because of the time required for pore pressure diffusion.

13.4.4 Oxygen Isotope Precursors to the 2016 Tottori Earthquake, Japan

The magnitude 6.6 Tottori earthquake, Japan, occurred on October 21, 2016. It was a shallow strike-slip earthquake. Onda et al. (2018), following the analysis done after the Kobe earthquake (Sect. 13.4.2), analyzed commercially bottled water extracted from a 240 m deep aquifer. The well is only ~5 km from the fault that ruptured. Water isotopes show annual modulation. When this signal is removed (Fig. 13.4), Onda et al. (2018) identify an anomaly in oxygen isotopes prior to the earthquake that is not seen in hydrogen isotopes. Oxygen isotope changes not accompanied

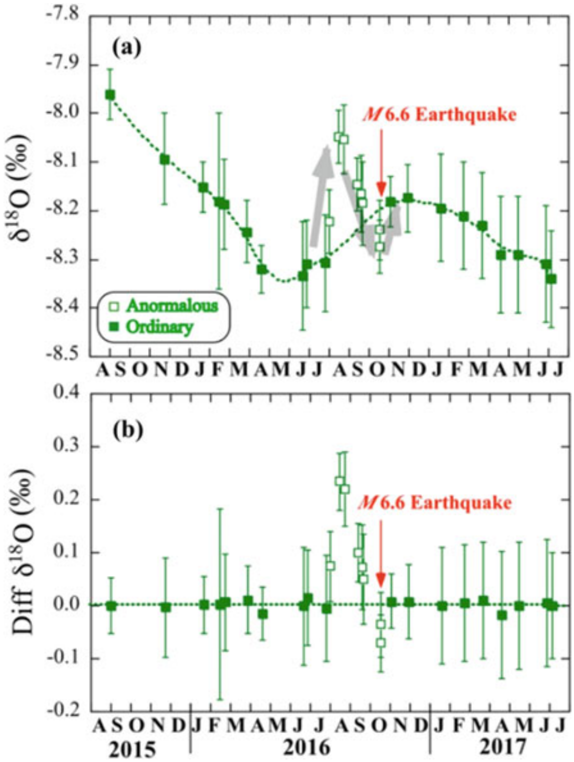

Fig. 13.4 Variations on oxygen isotopes from bottled waters collected before and after the magnitude 6.6 Tottori earthquake in Japan. Panel a shows raw data and panel b removed the assumed seasonal variations. Open symbols show the inferred anomalous data. The red arrow shows the time of the earthquake (from Onda et al. 2018)

by changes in hydrogen isotopes are most easily explained by increasing water–rock interaction. Here this would be the release of water that experienced more extensive reaction with rocks than the bulk of the water in the sampled aquifer. Onda et al. (2018) performed rock crushing experiments to quantify the expected changes in water isotopes, and inferred a plausible 10^{-7} volumetric strain, though there is no geodetic data documenting that such strains did in fact occur. Missing in this analysis are complementary data of water pressure and temperature—if fluids are being released from precursory volumetric strains, pore pressure and temperature may increase (though in Chap. 9 we showed that the velocity required to affect solute composition is lower than that requires to change pore pressure and still lower than that required to change temperature). This study highlights the value of an archive of data from regular water sampling.

13.4.5 Kettleman Hills, California, 1985

Three days before the 1985 M 6.1 Kettleman Hill, California earthquake, Roeloffs and Quilty (1997) found a gradual, anomalous rise in water level of about 3 cm in

2 of 4 wells in the nearby Parkfield area. These changes are shown in Fig. 13.1. Barometric pressure changes and rainfall cannot explain these changes. One of these two wells exhibited several similar changes that were not followed by earthquakes. In the second, however, the documented increase was unique during the 5 year monitoring period. Figure 13.1 shows that the sign of these possible precursory changes is opposite to the coseismic change implying that they are not caused by accelerating pre-seismic slip.

This observation was included in the IASPEI Preliminary List of Significant Precursors (Wyss and Booth 1997). Nevertheless, important questions remain. What caused the anomalies? Why are they not recorded everywhere?

13.4.6 Chi-Chi, Taiwan, 1999

Abundant monitoring data in Taiwan provided a host of opportunities to look for precursors to the September 21, 2009 magnitude 7.7 Chi-Chi earthquake. Chen et al. (2015) report anomalous decreases in water level across the Choshuichi alluvial fan for approximately 100–200 days prior to the earthquake (Fig. 13.5). Using the network of monitoring wells, they show that this pattern is widespread and is at least qualitatively consistent with geodetic measurements of strain. It is not immediately clear that the anomalies are unique given that the time series is limited to only a few times longer than the duration of the anomaly. The time leading up to the earthquake was also marked by a late onset of the rainy season which would have contributed to lower water levels, though the magnitude of the changes seems too large to be due solely to a reduction in recharge.

Another reported possible precursor to the Chi-Chi earthquake is a change in the spectral characteristics of water level fluctuations in some wells in the month preceding the earthquake compared with those 2 and 3 months before the earthquake (Gau et al. 2007). This is not a compelling comparison as the amount and character of precipitation also changed (Fig. 13.5). As discussed in Sect. 9.3 and Roeloffs (1988), the full range of relevant environmental factors must be considered. Given the long-term memory and variability of hydrogeological systems, time series analysis should be undertaken for more than three months to assess the reliability of the analysis techniques in isolating seasonal effects, long term trends, and irregular variations. A longer analysis could also identify the uniqueness of the reported precursory change—an essential attribute of any precursor.

King and Chia (2018) report a large and rapid increase in streamflow 4 days before the earthquake. A nearby well showed an anomalous rise two days before the earthquake and a 4 cm drop three hours before the earthquake. They attribute these changes to pre-earthquake shallow slow slip events that created fractures enabling fluid migration. The authors do not report any independent geodetic data that confirm the inferred slow slip. The explanation does make a testable (in principle) prediction that there should be permeability changes.

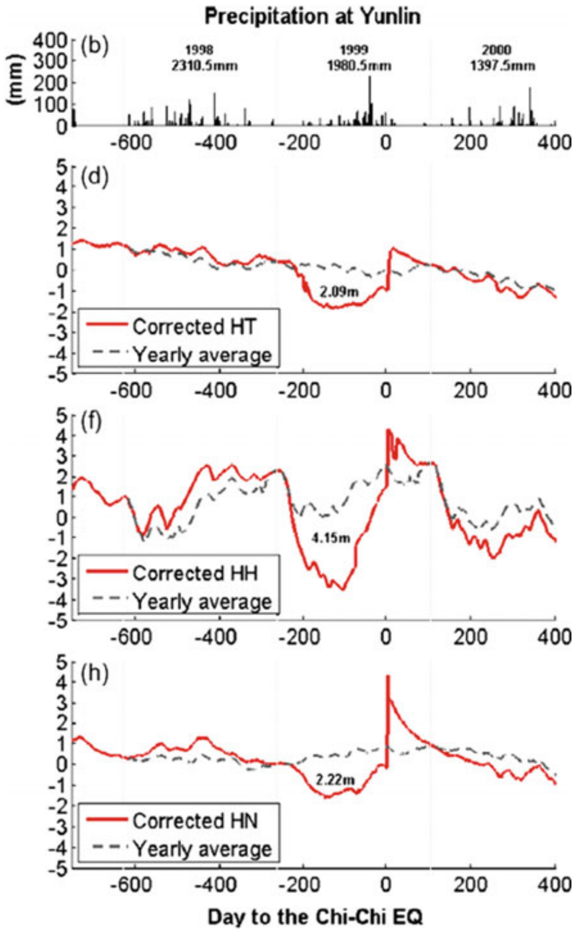

Fig. 13.5 Water level corrected for atmospheric pressure variations compared to the mean daily value where 0 is the day of the Chi-Chi earthquake. The yearly average is that from 1998 to 2000. It is not clear why those averages are not periodic (from Chen et al. 2015)

Song et al. (2006) analyzed the composition of water at hot and artesian springs in Taiwan. Large, reversible anomalies in Cl^- or SO_4^{2-} were identified over a few year period. At the hot springs, a couple anomalies precede earthquakes; however, anomalies do not exist before all earthquakes, and there is no correlation between the intensity of the shaking and the occurrence of precursory anomalies. Moreover, some anomalies are not followed by earthquakes. The artesian springs document postseismic changes, but these do not occur for all earthquakes and the occurrence of a response does not seem to be correlated with the intensity of shaking. Despite these severe limitations, Song et al. (2006) nevertheless claim that these springs are possibly ideal sites for recording precursors.

Some of the reported hydrologic "precursors" to the Chi-Chi earthquake are interesting as cautionary tales. One example of a "precursor" was claimed shortly after the earthquake. The earthquake occurred at 1:47 a.m., 21 September, local time. 59 of the 157 monitoring wells that showed stepwise changes in groundwater level reported

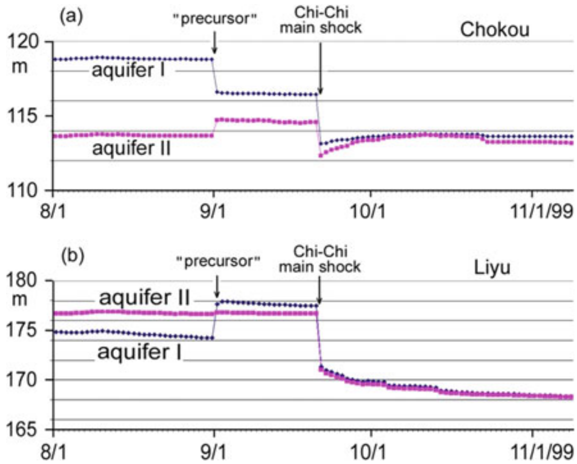

Fig. 13.6 Incorrectly identified groundwater level precursors to the 1999 M 7.3 Chi-Chi earthquake in Taiwan. The step a few weeks before the Chi-Chi earthquake is due to readjustment of the water level monitoring system

times of these change between the hour of 11 p.m., 20 September 20, and 1 a.m., 21 September. In other words, these records showed stepwise changes in groundwater level about 1 to 3 h before the earthquake. If true and repeated for other earthquakes, these would be ideal precursors. Careful examination and verification of the clock of the recording instruments in the field and inspection of the information management process (Chia et al. 2000), however, necessitated a readjustment of the time-axis of the entire groundwater-level records. After corrections were made, all the "precursors" turned out to be co-seismic responses. A second example of misidentified precursors is illustrated in Fig. 13.6. The stepwise changes in groundwater level in four wells two weeks before the Chi-Chi earthquake could be mistaken as "precursory". These changes, however, turn out to be a result of readjustment of the recording instruments (Y. Chia, personal communication). Both examples highlight the importance of (1) using a common time-base for the hydrologic and seismic records, and (2) documenting all instrumental changes as part of the hydrologic records.

13.4.7 Kamchatka

Long term hydrogeochemical records are available in Kamchatka, an area with many large earthquakes. Biagi et al. (2006) illustrate a clear postseismic response in a spring following a M 7.1 earthquake about 100 km away—Fig. 13.7 shows this response. Biagi et al. (2006) also show that following this earthquake the spectral characteristics of the hydrogeochemical variations change, with an increase in short period variability. Biagi et al. (2006), expanding on Biagi et al. (2000), further claim that variations in other components, in particular H_2 and CO_2, are precursory—their amplitude fluctuations decrease after the earthquake. We offer an alternative explanation for these changes and instead propose that they too are postseismic

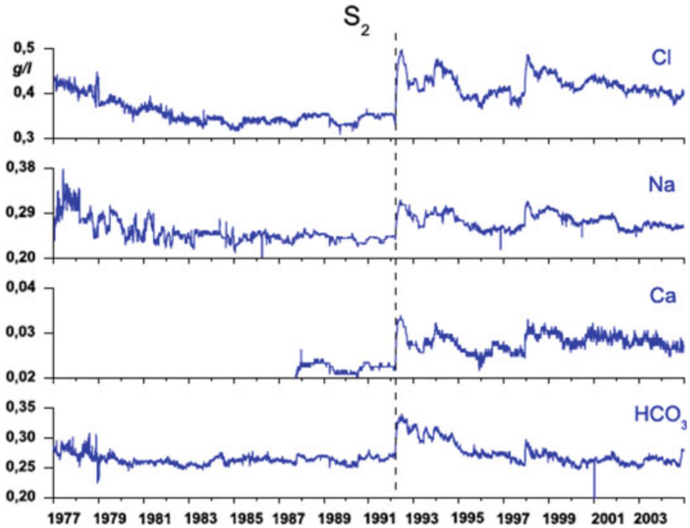

Fig. 13.7 Change in water composition at a spring in Kamchatka. Water is sampled every 3 days. The time of a M 7.1 earthquake about 100 km distant is shown by the vertical dashed line. There is a clear postseismic response (from Biagi et al. 2006)

changes—the earthquake-created changes in hydraulic connectivity that lead to the changes shown in Fig. 13.7 are also responsible for the character changes in H_2 and CO_2.

With a long record of hydrogeochemical monitoring and many earthquakes, Kamchatka offers an opportunity to test approaches to identifying precursors. Kingsley et al. (2001) identified as precursory, any signals that exceed 3 standard deviations of the mean and that are seen at the same time (within 7 days) in at least 2 measurements. With this criterion, they identify 8 precursors (anomalies within 158 days of the earthquake) and 3 failures (anomalies not followed by earthquakes) for a time period with 5 large (magnitudes between 6.9 and 7.3) earthquakes. With a more restrictive criterion that anomalies are confined to ion data alone, Biagi et al. (2001) identify 3 anomalies, all of which are followed by earthquakes (the three closest large earthquakes to the wells). Examining their data (Fig. 2 in Biagi et al. 2001), however, shows that there are correlated anomalies slightly smaller than 3 standard deviations that are not followed by earthquakes. Moreover, as the 5 large earthquakes occurred within less than a 5 year period, and correlated anomalies (greater than 3 sigma) occur every year or so, we thus expect that roughly half of identified precursory anomalies would fall within the 158 day time window simply by chance. Once again, we are left with several questions: what caused these anomalies? why are some wells (apparently) more sensitive? What is the statistical significance of the anomalies?

13.4.8 Pyrenees, France, 1996

Toutain et al. (1997) analyzed the composition of bottled and dated spring water, as done following the 1995 Kobe earthquake (Tsunogai and Wakita 1996), to document the pre- and postseismic response of groundwater to a M 5.2 earthquake in the French Pyrenees. The spring is located 29 km from the epicenter. As shown in Fig. 13.8, about 5 days before the earthquake, the chloride concentration increased by about 40%, an increase much larger than the standard deviation of pre-seismic values (at least over the 200 days analyzed). The high chloride values persisted for about another 5 days

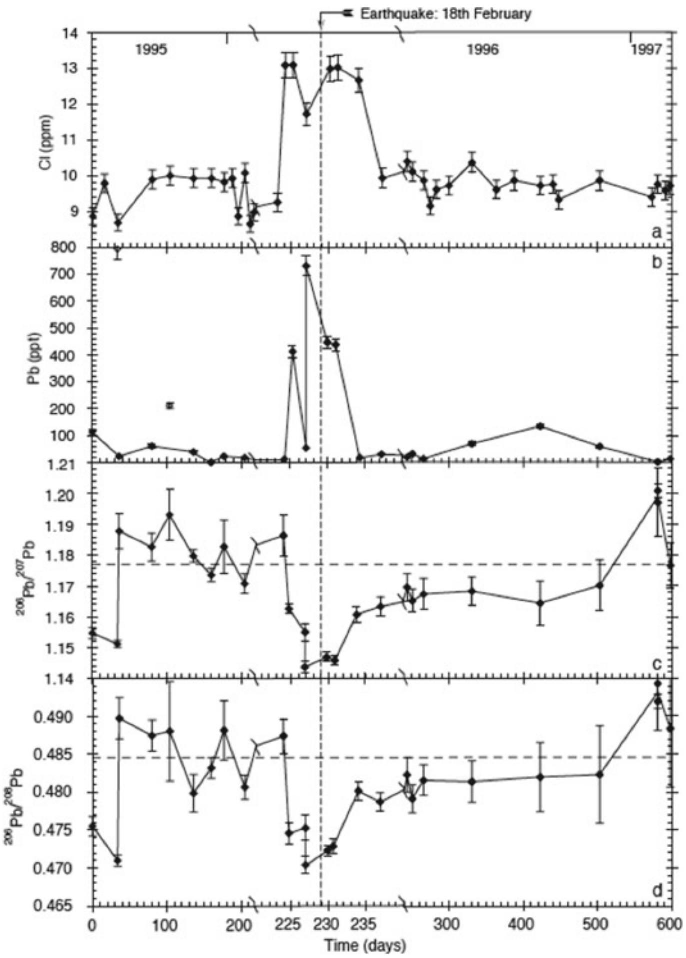

Fig. 13.8 Chloride and lead anomalies identified a posteriori from bottled waters. The time of a M 5.2 earthquake is shown by the vertical dashed line. The spring is located 29 km from the epicenter (from Poitrasson et al. 1999)

and then returned to "normal". Poitrasson et al. (1999) documented a lead anomaly in the same waters, also shown in Fig. 13.8. The lead anomaly has a shorter duration and is more than 10 times background values. The lead isotope changes suggest an anthropogenic source.

Toutain et al. (1997) propose that a small amount of chloride-rich water was injected into the aquifer feeding the springs—measured changes reflect mixing of previously isolated waters. The lead anomaly is not consistent with the possible sources for the chloride anomaly (Poitrasson et al. 1999), implying a third source of water. It is not clear why the start and end of the documented changes are so abrupt because dispersion should lead to more gradual changes, especially during the post-seismic period.

13.4.9 Reservoir Induced Seismicity, Koyna, India

Chadha et al. (2003) report on an experiment to search for precursors to the reservoir-induced earthquakes near the Koyna and Warna reservoirs, India. The project involved drilling 19 wells for monitoring purposes. In addition to coseismic water level changes, Chadha et al. (2003) identify small, centimeter-scale, changes in water levels over periods of days to many days before earthquakes with magnitudes between 4.3 and 5.2 and within distances of 24 km.

Figure 13.9 shows an example of two of the premonitory changes, including the raw data and barometric pressure. The coseimic signal and possible precursory anomalies are dwarfed by the response to tides and barometric pressure. After removing effects of tides and barometric pressure changes, a coseismic and post-seismic response become clear. This study does not address the uniqueness of the proposed precursor anomalies. Inspection of Fig. 13.9 and other figures in this paper shows that similar anomalies occur and are not followed by earthquakes. Other questions remain about these purported precursors: Why don't all wells record the same anomalies? Why is the time duration of the anomalies different from earthquake-to-earthquake?

Complementary hydrogeochemical and water level measurements have now been made at 15 wells for >12 years, beginning in 2005 (Reddy et al. 2017). No precursory signals are seen before earthquakes with magnitude <5. There are long term trends in water chemistry along with annual variations in water level—with no clear or repeatable patterns of changes before or after earthquakes.

13.4.10 Calistoga Geyser, California

As discussed in Chap. 11, geyers can be especially sensitive to small earthquake-generated strains. Silver and Vallette-Silver (1992) analyzed 18 years of eruptions at the Old Faithful, Calistoga, California geyser. During this period, they documented

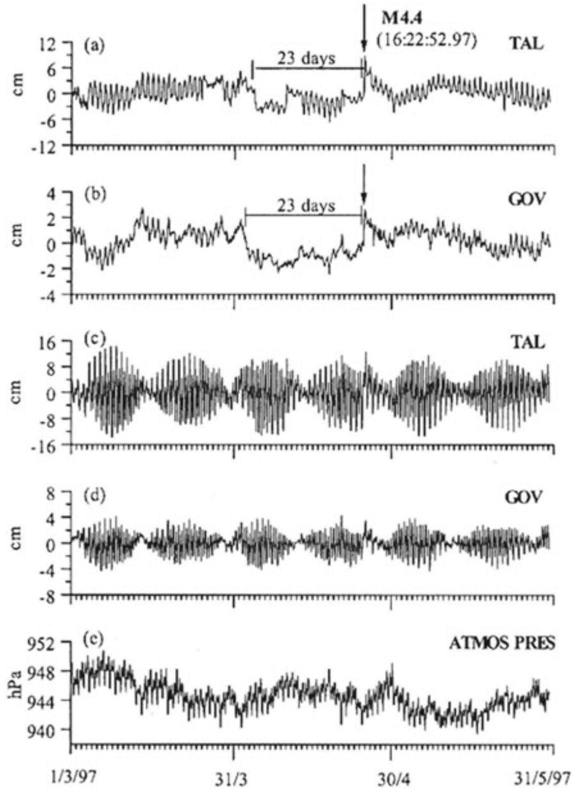

Fig. 13.9 Water level in two wells (TAL and GOV) over a 5 months period. **a**, **b** Show water level after removing tides and barometric pressure effects (shown in e). **c**, **d** Show raw water level records. The time of a M 4.4 earthquake that occurred 3 km from the wells is shown with the arrow. Chadha et al. (2003) claim that the 23 day period before this event is a precursory anomaly (from Chadha et al. 2003)

three clear responses to regional earthquakes, as manifested in changes in the interval between eruption (IBE, the most common measure, as discussed in Chap. 11, of geyser response) or the distribution of IBE. Two earthquakes caused an increase in IBE. The third caused a change in the mode of eruption, from a single IBE to multiple IBEs. These three earthquakes are consistent with a magnitude-distance threshold similar to other hydrological responses (Fig. 14.4).

Silver and Vallette-Silver (1992) also propose that there are precursory changes in IBE that begin days before these three regional earthquakes. The data in this paper, however, clearly show many features similar to the proposed precursory changes that were not followed by earthquakes. We believe that the statistical analysis in this paper significantly underestimates the number of times the IBE changes character, by perhaps 1–2 orders of magnitude, over the monitored period.

13.4.11 Iceland, 2012–2013

Four to six months before a magnitude 5.6 earthquake in Iceland, there were hydrogen isotope and major ion changes (Fig. 13.10) in a 100 m deep artesian well (Skelton et al. 2014). Continued monitoring documented large hydrogeochemical responses to the earthquake (Fig. 9.2; Skelton et al. 2019). There are several abrupt changes in oxygen isotopes over the several year period with data (Fig. 13.10b), which suggests that permeable paths switch over time (Fig. 9.10). No water pressure data are available to quantify permeability changes. Statistical tests of the hydrogen isotope and Na concentration data show that excursions prior to the earthquake are not random, leading Skelton et al. (2014) to conclude that the changes are probable precursors. They, however, "make no claim of being able to predict earthquakes" and instead highlight that groundwater chemistry is a "promising target for future earthquake prediction studies".

Iceland hosts abundant seismic and volcanic activity. Magma movement in the subsurface and volcanic eruptions create earthquakes, deform the crust and hence can change permeability, and discharge gases and aqueous fluids. In fact, eruption precursors at volcanoes are widespread and play a role in forecasting volcanic eruptions (National Academies of Sciences, Engineering, and Medicine 2017). An alternative interpretation of the hydrogeochemical data is thus that both the geochemical changes and the earthquakes are responses to magma movement (Ingebritsen and Manga 2014).

13.4.12 Central Italy Seismic Sequence, 2016

Several magnitude 6 earthquakes occurred in the central Apennines, Italy in 2016. A few months before the seismic swarm, there were anomalous changes in trace element concentrations, specifically As, V and Fe, in springs (Fig. 13.11). There were also large hydrogeochemical and water level responses to the earthquakes (and no unambiguous water level precursors). Barberio et al. (2017) attribute the geochemical changes to an influx of deep hydrothermal fluids or fluids mobilized from deep organic-rich units and hence that the changes are recording permeability changes. Those same permeability changes could redistribute pore pressure and hence promote seismicity. These inferences would certainly benefit from co-located pore pressure measurements at depth along with a longer time series to decipher annual variations and long-term trends. Since the earthquakes are between 57 and 96 km away from the springs, the inferred connections must reflect regional changes in strain.

Water pressure and electrical conductivity are also monitored at high frequency (50 Hz) in boreholes around the deep underground Gran Sasso laboratory in central Italy. Five days, and perhaps as long as 40 days, before the 24 August 2016 magnitude 6 Amatrice event, De Luca et al. (2018) document significant changes in the kurtosis and skewness of pressure fluctuations. They also document large pressure changes

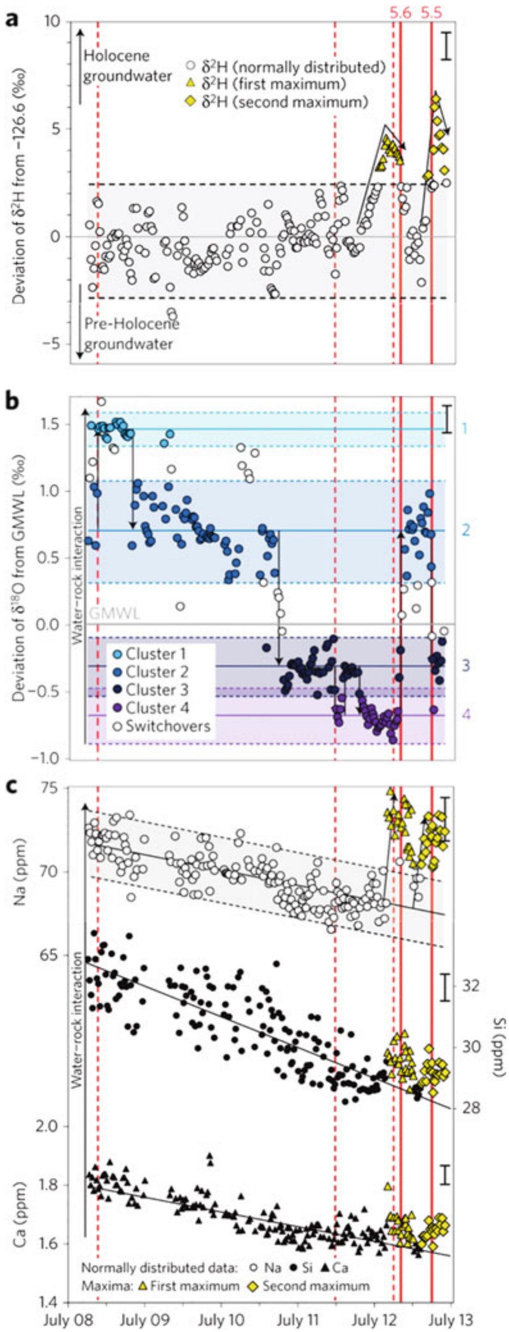

Fig. 13.10 Changes in **a** hydrogen isotopes, **b** oxygen isotopes, **c** major ions in a 100 m deep artesian well in Iceland with the time of earthquakes shown with vertical lines (dashed lines are events with magnitudes less than 5). The water is hot (73–76 °C) and alkaline (from Skelton et al. 2019)

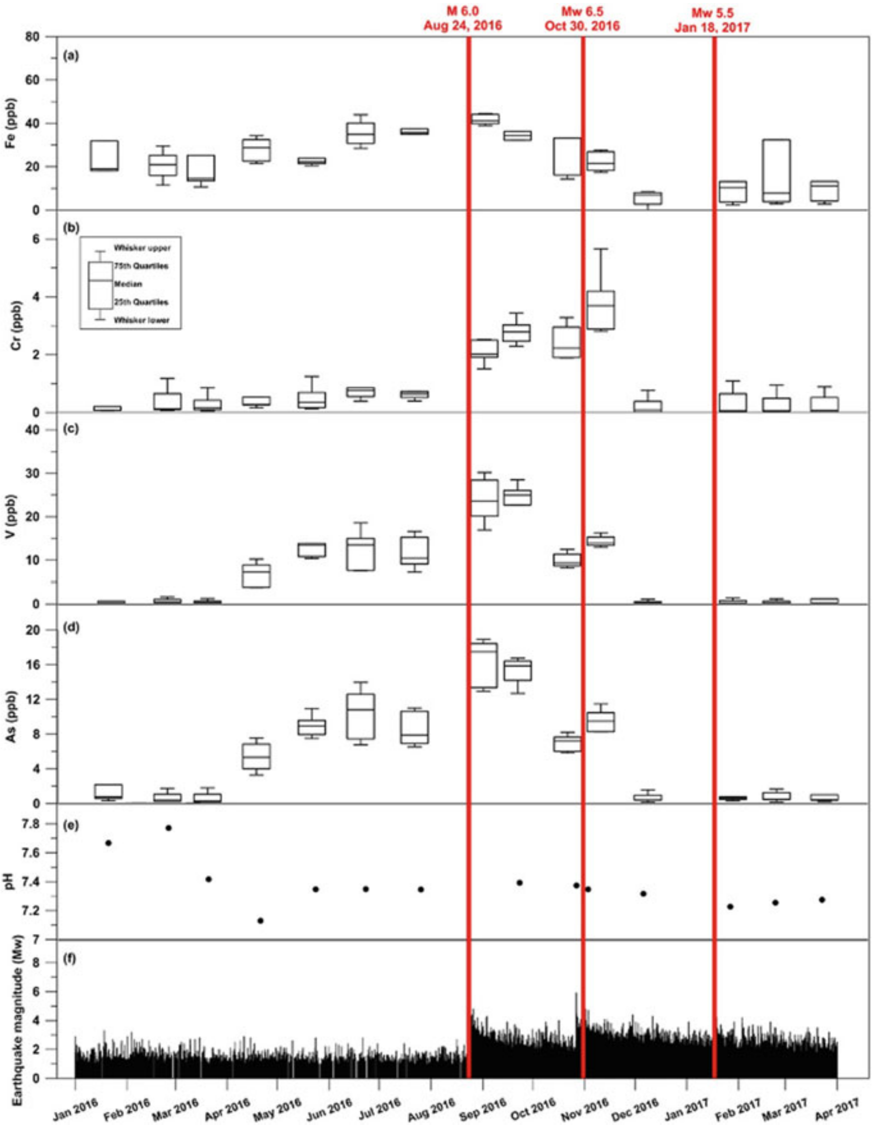

Fig. 13.11 Water chemistry at the Sulmona test site springs, Italy (panels a–e) and seismicity (panel f). Times of regional earthquakes are shown with vertical red lines. Panel b explains the meaning of the plotted symbols (from Barberio et al. (2017))

after the earthquake. They attribute precursory changes to microfracturing that leads to high frequency pressure changes and upflow of gases. If De Luca et al. (2018) have indeed documented a precursor, their results suggest that very high frequency sampling might be needed to identify the precursory signals.

13.4.13 Precursory Changes in Spring Temperature

In Chap. 8 we discussed the co- and post-seismic changes in temperature of a well on the Izu Penisula, Japan (Mogi et al. 1989). At this well, rapid increases in temperature of 1–2 °C typically accompany regional earthquakes. Following earthquakes, temperature decreases approximately linearly. Also of note is a correlation of temperature changes with tides and barometric pressure, with magnitudes up to 0.5 °C. Mogi et al. (1989) attributed these trends to be the result of unblocking, followed by gradual resealing, of fractures.

For a small number of earthquakes, as many as 5, there are abnormal changes in temperature, defined as changes that are not coseismic, do not follow the linear trend of decreasing temperature, and do not appear to be related to tides or weather. Mogi et al. (1989) referred to such abnormal changes as precursory. The changes occur between 3 days and 10 months before regional earthquakes. In one case, the precursory changes are coincident with a regional earthquake swarm.

As with other claimed precursors, there is no obvious predictive feature—the abnormal signals differ in form, timing, and do not always occur. Figs. 7 and 9 in Mogi et al. (1989) also show abnormal changes not followed by earthquakes.

One possible explanation for the abnormal changes is that they are in fact responses to tectonic events—the "precursory" response coincident with a regional earthquake swarm being an example. There is a wide range of earthquake phenomena, particularly in subduction zone settings, in which slip does not only generate regular earthquakes (Beroza and Ide 2011). These events differ in the duration of the slip event, which can range from seconds for very-low frequency earthquakes (e.g., Ito et al. 2005), to hours for slow earthquakes (e.g., Linde et al. 1996) to days for slow-slip events (e.g., Hirose and Obara 2005) to many months for silent earthquakes (e.g., Dragert et al. 2001; Ozawa et al. 2002; Kostoglodov et al. 2003). Such events are common in Japan and other subduction zones (Ide et al. 2007), but also occur along strike-slip faults such as the San Andreas in California (e.g., Linde et al. 1996) and at volcanoes (e.g., Segall et al. 2006).

If the "precursory" changes reported by Mogi et al. (1989) are in fact responses to slower slip events than regular earthquakes, it suggests the changes are more sensitive to the magnitude of strain rather than dynamic strains. At the same time, this also implies that "precursors" are not useful for forecasting as not all slow earthquakes are followed by regular (and damaging) earthquakes.

13.5 Outlook

There are several restrospective reports of hydrological changes preceding earthquakes that appear to have no other obvious explanation. In few cases, however, do criteria meet those needed for critical evaluation—those listed in Sect. 13.2 and Roeloffs (1988). To identify these changes as precursory in a useful way also requires a criterion for distinguishing them from non-precursors before the actual earthquake occurs. Given the lack of success in using hydrological and hydrogeochemical anomalies to predict earthquakes (including all three desired features: size, location and date) it is not surprising that earthquake prediction is not the focus of modern seismology. Some readers may be surprised by our skepticism about some reported precursors and our critical assessment of the observations and data analysis. However, extraordinary claims require extraordinary proof (if not at least attention to, and documentation of, details); the ability to predict earthquakes certainly qualifies as an "extraordinary claim".

Hydrological precursors to earthquakes, if they exist, can be thought of as being a subset of a broad range of transient phenomena that includes silent and slow earthquakes, transient creep, episodic tremor and slip, and seismic swarms. Such transient phenomena occur more often and provide more measurement opportunities. Consequently, their study may prove insightful about earthquake initiation and the types and origins of possible hydrological phenomena that can be mistaken as precursors to normal earthquakes.

Multiparametric monitoring is particularly important both for identifying spurious anomalies and understanding the origin of hydrological changes. Combined deformation and water level measurements have proven useful to understand the spatiotemporal relationship between transient hydrological changes and deformation (e.g., Ben-Zion et al. 1990) and to support the identification of hydrological precursors (Roeloffs and Quilty 1997). Long-term and multi-parameter monitoring requires investment and patience, but both are probably required to assess whether there are precursors and to establish the statistical significance of signals. Woith (2015) reviewed more than 100 studies that report radon precursors and found a negative correlation between the number of anomalies and the length of the time series analyzed. Woith (2015) concluded that tectonic anomalies probably exist but may be indistinguishable from non-tectonic anomalies. Advances in machine learning may help tease out signals that are otherwise challenging to recognize (e.g., Rouet-Leduc et al. 2017; Asim et al. 2018).

The now widespread use of ambient noise to monitor temporal changes in seismic velocity is opening up new opportunities for documenting changes in elastic properties, including responses to earthquakes (e.g., Brenguier et al. 2008; Nakata and Snieder 2011; Gassenmeier et al. 2016; Nimiya et al. 2017), creep (e.g., Hillers et al. 2019), healing of faults (e.g., Pei et al. 2019), and long term trends that may be recording an evolving stress state (e.g., Ikeda and Tsuji 2018; Taira et al.

2018). Connecting such monitoring to hydrological and hydrogeochemical data may prove especially useful for interpreting anomalies and identifying reliable precursory signals.

Although we may still be far from achieving a complete understanding of the underlying mechanisms of the various earthquake-related anomalies that are reported in the literature, there remain significant monitoring efforts. A negative result, such as the absence of clear precursory signals at the multiparametric and densely monitored Parkfield, California site (Bakun et al. 2005), may frustrate the effort to predict earthquakes, but provides important and useful constraints on models of rupture initiation and other tectonic processes that lead up to earthquakes. There still remains a physical basis for expecting precursory signals, and lab experiments confirm that that expectation holds in the lab.

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