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RESEARCH PAPER

Advances in research on earthquake fluids hydrogeology in China: a review

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Abstract Monitoring of subsurface fluid (underground fluid) is an important part of efforts for earthquake prediction in China. The nationwide network, which monitors groundwater level, water temperature, and radon and mercury in groundwater, has been constructed in the last decades. Large amounts of abnormal fluid changes before and after major earthquakes have been recorded, providing precious data for research in earthquake sciences. Many studies have been done in earthquake fluid hydrogeology in order to probe the nature of the earthquake. Much progress in earthquake fluid hydrogeology has been made in the last decades. The paper provides a review of the advances in research on earthquake fluid hydrogeology over the last 40 years in China. It deals with the following five aspects: (1) an introduction to the development history of monitoring networks construction; (2) cases of different subsurface fluid changes recorded before some major earthquakes which occurred in the last decades; (3) characteristics of subsurface fluid changes following major earthquakes; (4) mechanism of subsurface fluid changes before and following earthquakes; (5) application of earthquake fluids in the hydrogeology field.

Keywords Earthquake · Subsurface fluid · Monitoring well networks · Co-seismic · Precursor

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1 Introduction

China is one of the countries in the world prone to suffer from the serious hazards of major earthquakes. During the twentieth century, many disastrous quakes of over magnitude 7 have occurred in China, such as the 1933 Diexi M_s7.5, 1966 Xingtai M_s7.2, 1975 Haicheng M_s7.3, 1976 Tangshan M_s7.8, 1976 Songpan-Pingwu M_s7.2, 2008 Wenchuan M_s8.0, and 2010 Yushu M_s7.1 events. These shocks have caused a great number of casualties and enormous economic losses. Therefore, earthquake monitoring and studies including investigations into source mechanisms and earthquake prediction have drawn much attention in the earth sciences.

Subsurface fluids (underground fluid), which are widely present in the crust, are some of the most active components that are very sensitive to minor variations of stress or strain in the crust. Through monitoring and studies of these fluids, much information on crustal activity can be extracted to provide evidence for understanding the process of the generation and the occurrence of earthquakes. Such scientific practices include a series of efforts, such as the establishment of large-scale monitoring well networks, studies of subsurface fluids prior to earthquakes and their regularities, research on co-seismic responses of fluids and their mechanisms, and exploration into the application of these dynamic tools in hydrogeology.

After the 1966 Xingtai $M_s7.2$ earthquake, China began to construct groundwater-monitoring networks to detect earthquake precursors. For more than 40 years, the country has had a professional monitoring system of subsurface fluids, which is one of the largest earthquake subsurface fluid monitoring networks in the world. Abundant data and case studies on prediction and insights into earthquake precursors and co-seismic responses of subsurface fluids have been accumulated. To summarize these efforts, observation results, and lessons, and to identify problems and shortages of monitoring networks of this size, is of great importance in the determination of the direction of future development and enhancement of this area of research.

2 Construction of subsurface fluid monitoring well networks

The relationship between the occurrence of an earthquake and groundwater anomalies was known 4,000 years ago, but not until the 1960s did the scientific practice of earthquake forecasting based on monitoring of dynamic groundwater using modern technology begin (Wang et al. 2003; Gao et al. 2004; Che and Yu 2006; Wang and Shen 2010). In more than 40 years, the construction of subsurface fluid monitoring networks experienced four major stages: a creation stage, a development stage, an enhancement stage, and an overall modernization stage.

The creation stage refers the period from 1966 to 1978. In 1966, the first monitoring network was constructed in Hebei Province, which consisted of 913 wells with manual monitoring. The first regional network equipped with instruments to monitor groundwater levels was established in the regions of Beijing and Tianjin in the next year. Since 1968, hydrogeochemical monitoring has operated in Hebei Province, Beijing, and Tianjin. Subsequently, this network was tested by several large earthquakes such as the 1975 Haicheng $M_s7.3$, 1976 Longling $M_s7.3$, and 1976 Songpan $M_s7.2$ events, when the contribution to the efforts of earthquake prediction was confirmed (Yue 2005; Zhang et al. 2005).

The development stage consisted of the period spanning 1979–1989. Based on previous practices, new networks with deep wells were constructed along the major faults all over the country. By 1986, 260 automatically operated wells around mainland China were used predominantly for water level monitoring.

Meanwhile, 68 basic stations, 110 regional stations, and 152 local stations were picked to form a nationwide monitoring network of hydrogeochemistry that mainly performed radon (Rn) measurements. In addition, temperature sensors with high resolution (0.0001 °C) were successfully developed. It was widely applied in earthquake monitoring after reliable water temperature precursors in the Gengma-Lanchang earthquake were recorded (Wang et al. 2003).

The enhancement stage, from 1991 to 2000, was characterized by local adjustment and optimization to networks and stations of subsurface fluid monitoring, development of digital technologies, and normalization of network operation.

Groundwater level and hydrogeochemsitry monitoring networks, which were previously constructed separately, were integrated into a subsurface fluids monitoring network. The stations were classified into national, regional, and local levels. The most prominent advancement during this period was the widespread development and testing of digital technology. New digitalized instruments were created to measure 6 water-quality components, including: water level, Rn content, and dissolved He, H, and CO_2. These greatly improve the ability of subsurface fluid monitoring. To promote the level of network management, a set of scientific criteria have been proposed, and systematic evaluation methods have been established, such as technical specifications of observations on groundwater chemistry (1985), groundwater level (1989), groundwater temperature (1992), and technical specifications of digital monitoring (2001, 2012), etc.

Since 2000, digital monitoring technology has been widely used. A network center (China Earthquake Networks Center) that manages the operation of the monitoring stations and data collection was established. Daily monitoring data from national and some regional wells are transmitted to the network center daily. And data in other wells are collected by the provincial earthquake administrations.

Based on previous work, further digitalization reform was conducted on existing monitoring stations, and many new digitalized stations was constructed. The sampling rate changed from 1 h to 1 min. In addition, several professional arrays were built in Xichang, Sichuan Province, and Tianzhu, Gansu province. In addition, groundwater-level monitoring associated with the reservoir-induced seismicity in the Three Gorges area and in the Jinshajiang river was constructed (Che et al. 2002; Yu et al. 2012).

So far, China has a total of 670 subsurface fluid monitoring stations. Among them, 437 stations are used to monitor groundwater level, 296 stations measure groundwater temperature, 284 stations make Rn measurements, 86 stations mercury (Hg) measurements, and more than 100 stations monitor soil gas, and dozens of springs monitor dissolved gas (Fig. 1).

3 Subsurface fluid anomalies as seismic precursors

Subsurface fluid anomalies refer to the variations with respect to background dynamic signals. A dynamic change

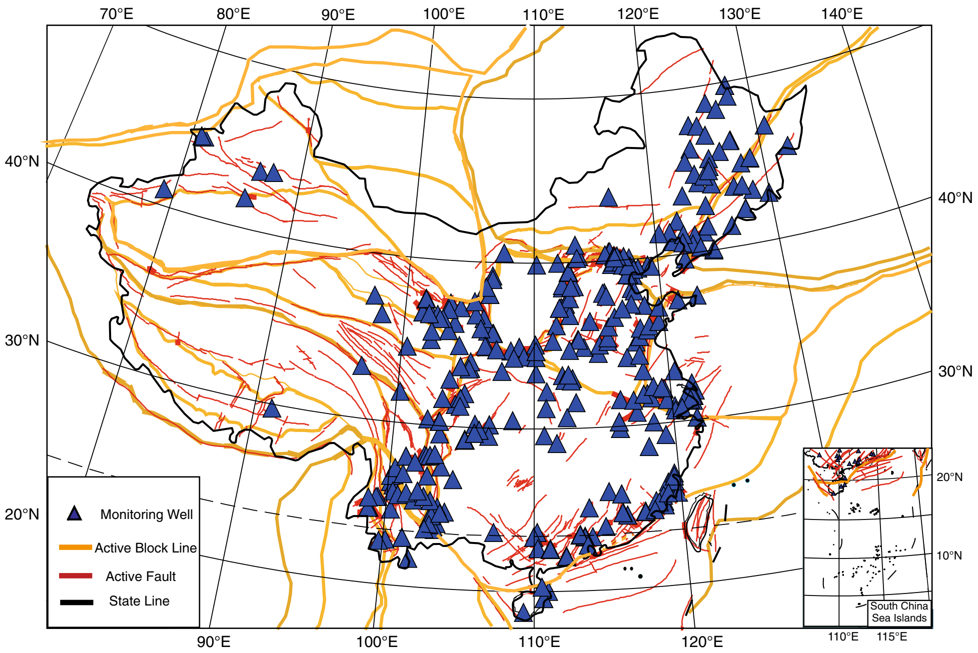

Fig. 1 Distribution of the earthquake fluid monitoring network in China

in subsurface fluids, which is considered to be very different from the background state and associated with an earthquake, is defined as a precursory anomaly. Such anomalies include abnormal variations of water level, water temperature, flow rate (quantity), and chemical components (Roeloffs 1988). But some subsurface fluid anomalies, caused by other external force such as rainfall, load of surface water, passing of trains, landslides, etc., have also been recorded in the monitoring network (Wang et al. 1988; Che and Yu 2006). It is important in the earthquake prediction study to distinguish these anomalies from those caused by earthquakes. Some typical anomalies recorded by the monitoring well networks are illustrated by examples below.

3.1 Precursory anomalies of groundwater level

3.1.1 Decline-type anomaly

The decline-type anomaly refers to a decline in groundwater level that deviates considerably from the background value before an earthquake. In some cases, such declines are followed by rapid rises just before (or after) the earthquakes. In general, earthquakes occur when the water level is at the lowest or just beginning to rise. This kind of anomaly is one of the most common changes observed in groundwater.

Table 1 lists the typical anomalous decline in groundwater level prior to several major earthquakes (Zhong 1978; Wang et al. 1988, 1990; Shi and Cai 1980; Huang et al. 1982; Lan et al. 1992; Zhu et al. 1998, 2010; Liu et al. 2011a; Che et al. 2011).

From Table 1, the time of the beginning of the anomalies varied from several years to 1 day. Most of the anomalies began several months before the earthquakes and lasted until the earthquakes happened. The anomaly amplitude ranged from several centimeters to as high as 10 m.

3.1.2 Rise-type anomaly

In addition to decline-type anomalies of water level before earthquakes, rise-type anomalies have also been observed in some wells. They are characterized by an abnormal rise of water level that deviates from the background, turning to water level decline before the quake (or when the quake occurs or immediately after the quake). This kind of anomaly is opposite to the decline-type anomaly, and has also proven to be a common occurrence prior to previous earthquakes. Table 2 lists the typical rise anomalies in groundwater level prior to several earthquakes (Shi and Cai 1980; Su et al. 1984; Wan et al. 1993).

In Table 2, the epicentral distance of anomaly wells ranged from 590 to 11 km, and the time of beginning of the anomalies varied from 2 months to several minutes prior to the quakes. The rise-type anomaly can be visible when earthquakes are impending.

Table 1 Typical decline anomalies in groundwater level prior to earthquakes

Earthquake	Epicentral distance (km)	Anomaly well	Anomalous before the quake (day)	Anomaly in groundwater level
Haicheng $M_s7.3$	165	3 Wells in Fuxian	64	Dropped about 10 m
	10	Well in Yingkou	60	Dropped about 1.5 m
Tangshan $M_s7.8$	44	Luannan well	1	Dropped 5 cm
	12	Tangshan well	60	Accelerated dropping in water level, 2–3 times faster than normal trend
	60	Supply wells	120	Dropped as much as 2–3 times than background
Datong-Yanggao $M_s6.1$	150	Wanxian well	3	Dropped 13 cm
	210	Xiongxian well	3	Dropped 8 cm
	56	Zhenchuan well	1	Abruptly dropped 39.2 cm
	280	Jin7-1	30	Dropped 60 cm
	410	Jin10-1	120	Dropped 70 cm
Zhangbei $M_s6.1$	220	Tatyuan	120	Dropped 47.5 cm
Wenchuan $M_s8.0$	114	Qionglai	150	Stopped artesian 5 months prior to the quake, and recovered artesian after the quake
	157	Pujiang	1.5 year	Began declining in 2006, declined to the lowest in the end of 2007
	200	Groundwater in Longnan	10	Water level, taste, color changes

Table 2 Typical rise anomalies in groundwater level prior to earthquakes

Earthquake	Epicentral distance (km)	Anomaly well	Time before quake (day)	Anomaly in groundwater level
Tangshan $M_s7.8$	12	Yue42 well	3 h	Blowout suddenly from a depth of 10 m
	23	Sannvhe well	10 min	Blowout 0.7 m above the ground surface suddenly
	11	Louzhuangzi well	4–6 min	Water was ejected from a depth of 5 m
Heze $M_s5.9$		17 Wells	6	Water level rose
Vietnam $M_s7.1$	590	Dian06 well	31	Water level rose by 18 cm
	450	Dian11 well	40	Water level rose by 19 cm
Yanyuan $M_s5.4$	80	Chuan03	60	Water level rose 2.7 times faster than the normal trend
Gengma-Lanchuang	166	Simao Dian17	10	Totally rose 4 cm
	198	Fengqing	2	Abruptly rose
	140	Dian08	17	Rose 3 cm under the trend of decline
	235	Dian2-5	15	Abruptly rose about 19.5 cm
	340	Qujiang	27	ROSE 12.8 cm

3.2 Precursory anomaly of groundwater temperature

Due to technological progress, high-accuracy measurements of groundwater temperature began much later than that of water level. Nevertheless, more than 30 years of observations have recorded many precursory data of groundwater temperature. Anomalies of water temperature can also classified into rise and decline types, most consisting of sudden changes, and then returning to background value at times of impending earthquakes or after their occurrence. Typical cases are listed in Table 3 (Wan et al. 1993; Li and Tao 1985; Che and Yu 2006; Wang 1995; Yao et al. 1997; Chen and Yao 1999; Zhu et al. 1998).

As can be seen in Table 3, the temperature anomalies occur as far as several hundred kilometers from the epicenters and begin at half a year before the earthquakes. The anomaly amplitude varied from 0.0013 to 3 °C. Gradual and abrupt changes of rise and drop can be observed. The anomalies lasted for several days before the earthquakes (or following the earthquakes).

3.3 Precursory hydrogeochemistry anomalies

In addition to the aforementioned precursory anomalies of water level and temperature, other anomalies of hydrogeochemistry are also observed before earthquakes, such as variations in Rn, Hg, and CO_2 content, ion composition, and ^{3}He/^{4}He. Usually these anomalies are characterized by high values before quakes, and the shocks occur when these abnormal values come down or just begin to descend.

An M_s7.4 event took place in the Bohai area on 18 July 1969. In early 1969, the Rn content in water of the Yachang well in Tianjin rose from 25.9×10^3 to 48.1×10^3 Bq/m^3, and such anomalies lasted for half a year or more (Wang et al. 1988). Before the event, high-value anomalies of water Rn were present for about half a month in the Ninghe well and Tanggu well of Tianjin and in the Shahe well and Wali well of Beijing, and they declined when the Bohai quake occurred (Zhang et al. 1986). In addition, similar high values were recorded before the event at other wells of Beijing and Tianjin, accompanied with big synchronous changes of electric conductivity of the water ions fluorine and nitrite (Zhang et al. 1988).

Similar anomalies of varied size were observed before the Haicheng M_s7.3 event of 4 February 1975, at 10 sites measuring Rn 200 km from the epicenter. Increases in Rn content also appeared prior to the 1976 Tangshan quake (Zhang et al. 1986). It was reported that, 3–5 days before the Songpan-Pingwu M_s7.2 quake on 16 August 1976, abnormal changes of chemical compositions of groundwater occurred near the Longmenshan fault zone, 10 or 200 km from the epicenter (Shi and Cai 1980).

Likely associated with the M_s6.2 quake in the southern Yellow Sea on 21 May 1984, an anomaly of hydrochemistry was recorded in a well at the Huishan pesticide factory of Wuxi city, Jiangsu Province, 190 km from the epicenter. Usually, this well has a background chlorine concentration of 5 mg/L, with normal fluctuation of 5 mg/L. From 20 April 1984, the concentration began to rise, and culminated on 21 May at 85 mg/L. It recovered to normal background concentration after the seismic event (Wang et al. 1988).

In response to the Datong-Yanggao M_s6.1 of 19 October 1989, the volume fraction of dissolved H_2 in the Xiaotangshan well of Beijing went up considerably after September. It rose to 0.00015 mL/L before the earthquake, almost 8 times higher than the background level. Then, it fluctuated at high values until mid-December 1989 after the quake. Additionally, similar variations also occurred to water hydrogen in the Huailai well, and in the well at the Guanghua dye factory of Beijing (Chen 1990).

4 Co-seismic response of groundwater

In a generalized sense, anomalies of groundwater following earthquakes include pre-seismic (precursor) signals, co-seismic responses, and post-seismic effects. The co-seismic response refers to instantaneous or short-term responses of groundwater to a seismic event (Wang and Shen 2010). It includes various phenomena such as the appearance of new springs or disappearance of old springs, mud-volcanic activity, soil liquefaction, water and sand blowout, changes of water temperature and level, and variations of water chemical composition. Studies on these phenomena are of great importance for understanding earthquake mechanisms and interactions between earthquakes and groundwater.

4.1 Oscillation of water level caused by earthquakes

Since Blanchard and Byerly (1935) discovered oscillation responses of well-water level to large, remote earthquakes, many studies on such phenomena have been made by

Table 3 Typical rise anomaly in groundwater temperature prior to earthquakes

Earthquake	Epicentral distance (km)	Anomaly well	Time before quake (day)	Anomaly in groundwater temperature
Tangshan M_s7.8	190	Xiongxian	7	Dropped 3 °C
Ninghe M_s6.4		Tangshang	20	Drop of large amplitude
Daofu M_s6.9	110	Maoya	47	Abruptly rose 7.4 °C
Gengma-Lanchang	350	Dayao	Half a year	Rose 0.25 °C
	370	Jiangchuan	Half a year	Rose 0.04 °C
Zaisang M_s7.3	500	Xin04	60	Dropped 0.2 °C
	430	Kazakhstan spring	75	Abruptly rose in April, then gradually rose
Zhangbei M_s6.1	100	Sanmafang	42	Abruptly dropped 0.01 °C
	210	Tayuan	14	Rose 0.0013 °C
	150	Wulinying	1	Rose 0.004 °C
	230	Taipingzhuang	25	Distortion anomalies in earth tide from 1997.12.13 to 1998.1.8

foreign scientists. With the establishment of the groundwater observational networks, Chinese researchers have also observed these response signals and performed relevant research (Chen and Liu 2006).

4.1.1 *Features of seismic waves recorded by water level*

Wang et al. (1983) analyzed the characteristics of water-level oscillation caused by major earthquakes of the 1970s recorded by the Beijing–Tianjin–Tangshan network and surrounding wells. They found that oscillation of water level in wells mainly respond to shallow and remote quakes in certain azimuths (Wang et al. 1983). Using a self-designed instrument, Liu et al. (1986a) successfully recognized P- and S-waves from records of water level changes, which seem more robust in the records of distant events than in those of near quakes.

4.1.2 *Frequency characteristics of seismic waves recorded by well water*

Quantitative analysis of water oscillation related with earthquakes recorded by the Wali well of Beijing suggests that the maximum peak period is about 20 s (Liu et al. 1986b, 1989). In slug tests and seismic-response records from five wells, Zhang et al. (2000) found that the water level will change more in response to seismic waves if the monitoring well has an inherent frequency close to 20 s and has large permeability. Yin et al. (2009) calculated the amplitude and times of water level changes in the Tangshan well caused by the 2008 Wenchuan M_S8.0 event and its major aftershock, made comparisons with seismic waves recorded by neighboring stations, and concluded that the maximum amplitude of the water-level oscillation appeared in the period between S-waves and Rayleigh waves.

4.2 Step-change of groundwater level caused by earthquakes

In addition to oscillation of water level, step-changes of water level are also observed in some wells in response to earthquakes. Since the 1970s, researchers began to study co-seismic step-change of water level, focusing on its mechanisms, influence factors, and implications.

4.2.1 *Mechanism and influence factors of water level step-change*

After the 1976 Tangshan earthquake, considerable step-changes of water level were recorded at the Tangshan hydrological station well, the Lulong well, and other wells in Tianjin. Wang et al. (1988) suggested that these variations were attributed to change of pore pressure due to a stress-step regime imposed on the aquifer medium. Upon studying the step-response data of the Three Gorges network to the 2008 Wenchuan earthquake, Liu et al. (2009) suggested that the differences in the characters of these responses depend on the tectonic setting of the wells, the transmissibility of the aquifers, and the hydrogeological types of groundwater.

4.2.2 *Application of study on co-seismic step-change of water level*

Firstly, inferring stress and strain by step-change: with water level step-change data associated with the earthquakes at Akita, Japan, Heze, Shandong and Datong-Yanggao, Shanxi, Zhang et al. (1991, 1999b, 1994) inferred adjustment of the regional stress fields produced by these quakes, and offered a new approach for exploring dynamic regional stress fields. Based on the co-seismic step-change of water level in 5 wells after the Wenchuan event, Shi et al. (2012) estimated volumetric strain variation in local aquifers. Secondly, application to earthquake prediction: Li (1995) analyzed co-seismic step-change of water level in two wells of Sichuan associated with the Taiwan Straits M_S7.6 quake, and proposed that such anomalies are related to major earthquakes in a newly active region. With this perspective, Huang et al. (2004) studied the Taiwan Chichi event and suggested that the area with co-seismic step-change anomalies may imply elevated earthquake risk.

4.3 Co-seismic water temperature variations

Since Fu (1989) first observed the co-seismic water temperature response by temperature sensors, many co-seismic water temperature changes have been studied in the last decades. The representative examples are outlined as follows.

Sun and Liu (2007) used water temperature of the Benxi artesian well to study its co-seismic response to the Sumatra event, analyzed the relationship between water level change and water temperature variation, and constructed a physical model for interpretation with mixed groundwater from varied layers. By means of finite element modeling, Shi et al. (2007) studied the responses of water temperature in the Tangshan well to several quakes, and concluded that the diffusion effect by vertical oscillation of well water is responsible for co-seismic change of water temperature. From the study of co-seismic response of water temperature in the digitalized Tayuan well of Beijing to earthquakes during 2000–2005, Yang et al. (2007) noted that each response was a decline first, and a rising afterwards, and its amplitude is well correlated with the magnitude and distance of the event. Thus, they suggest that the change of water temperature in this well can be attributed to upwelling of warm water from depth and the falling of cold water at upper levels. Che et al. (2008) made a systematic review of observations and research on groundwater temperature in China, and concluded that the geothermal gradient, thermal convection, heat conduction, and thermal diffusion should be taken into consideration for mechanisms of micro-dynamic changes in water temperature. In addition, some new phenomena such as tidal response in water temperature change (Zhang et al. 2007; Yang 2012) and different co-seismic water temperature responses at multiple depths in one well have also been observed (such as in Chuan03 well), and these new phenomena need to be studied further.

5 Mechanisms of precursory anomalies and co-seismic response

5.1 Precursory anomalies of subsurface fluids

Today, more than 40 years have passed since the initiation of studies on mechanisms of precursory anomalies from monitoring of subsurface fluids. Various hypothesis and models have been proposed by Chinese researchers.

The gestation model of major earthquakes: by combining the gestation model of major earthquakes with changes observed in groundwater before events, Guo et al. (1974) suggest that relative motion between neighboring crustal blocks can cause a stress change in the crust. This causes aquifers to be compressed or extended, leading to a variation in water flow, and even changes in the chemical composition of groundwater. They also discussed the possibility of water upwelling from depth to the surface.

Field-zone-source model: This model was proposed by Che et al. (1994) upon the study of the large Tangshan earthquake. It claims that long-lasting horizontal compression causes gestation of seismic events as the source, accompanied by non-uniform and discontinuous upwelling of mantle material from depth to form anomalous zones, thus generating a precursor field of groundwater.

The hypothesis of a hard layer in the middle crust and fluid triggering was proposed by Che et al. (2000a), who supposed that two active systems of fluids are present in the crust, between which is a hard layer in the middle crust where stress builds up to generate earthquakes. They further infer that this layer would enter a micro-fracture-dilation (dilatancy) stage, and nucleation as stress at some location reaches yield strength. Within the dilated seismic source, fluids are transported from the lower system by vacuum pumping, thus shear stress increases and the source ruptures to ultimately produce earthquakes.

The relationship between fluid in the crust and seismic activity: Che et al. (2000a) argued that large amounts of medium and small earthquakes always occur in the area with strong heat fluid activities, while major earthquakes occur in the area with weak heat fluid activities. And they also found that the distribution of seismogenetic layer of medium–small seismic activities have good agreement with the bottom boundary of circulation depth of hot springs in the Yan-Huai basin. Furthermore, they also found that the major earthquakes occur at moderate depth of the top surface of the layer with high electric conductivity and low velocity (Che et al. 1998, 2000b).

Composite model of source, field, and outside: This model was proposed by Wang et al. (2002) and states that dynamic change is caused by rainfall and other factors, and, consequently, additional stress is generated to the rocks in the crust, changing the rocks' strength and promoting or inducing tectonic activity. These changes are derived or are accompanied by various anomalies of deformation, crustal stress, hydrochemistry, and so forth.

The studies above focused on the interpretation of precursory anomalies of groundwater. Some fundamental understanding has also been achieved in the mechanisms of hydrogeochemical precursors, such as the finding that: (1) accumulation, enhancement, and release of tectonic stress is the dynamic source for generation of hydro-geochemical precursors (Wang et al. 1984); (2) deformation of crustal rock and its secondary effects are the direct cause of these precursors (Zhang et al. 2005); and (3) rock deformation and its secondary effects lead to migration and redistribution of water and gas in media, as well as various chemical elements in the crust, thus changing compositions of water and gas chemistry (Liu 1996). In addition, Chinese researchers have used field explosions and laboratory simulations to study the mechanisms of hydro-geochemical precursors (Zhang et al. 1988).

5.2 Mechanisms of co-seismic response of subsurface fluids

The co-seismic response is one of the focused topics in earthquake research in recent years. Various interpretations of the mechanisms have been suggested, such as deformation or failure of aquifers caused by dynamic stress (seismic wave) or static stress (fault slip), including aquifer consolidation, upwelling of deep hot fluids, removal of a temporary blockage in a fracture, and regional strain change, which spawn variations in groundwater level (pore pressure) (Wang 2001; Brodsky et al. 2003; Jónsson et al. 2003; Roeloffs et al. 2003; Manga and Wang 2007).

5.2.1 *Change of aquifer parameters by seismic waves*

In the study of the step-change response of the Zhouzhi well to the Wenchuan event, Lai et al. (2011) thought that this phenomenon was caused by a combination of effective stress changes and the barriers being removed in the flow channel due to seismic waves. This was also confirmed by Shi et al. (2013a), who studied the co-seismic response in the Three Georges area and found that the co-seismic water level changes were closely related to aquifer parameter changes. From the co-seismic water level changes in 17 wells of the Sichuan and Chongqing areas, Shi et al. (2013a) pointed out that static stress is the primary reason for co-seismic change of water level when the epicenter distance is less than 300 km, while dynamic stress dominated when the epicenter distance exceeds 300 km.

5.2.2 *Theory of poroelasticity*

In their study of co-seismic responses of water level in the wells of the intermediate field with similar well–epicenter distances to the Wenchuan quake, Zhang and Huang (2011) concluded that, when this distance equals or is less than one and half times the fault-rupture length, these response changes can be explained by the poroelastic theory. When this distance is greater than this length, these changes are likely produced by propagation of seismic waves. Using the poroelastic theory, in conjunction with tidal effects, Liu et al. (2011b) studied phase differences between aquifer water level and tidal force in relation to transmissivity, and suggested that the change of water level is associated with variations in transmissivity.

5.2.3 *Effects of geological structure and well-borehole properties*

With the analysis of co-seismic responses of the Jinshajiang network to the Tohoku $M_s9.0$ earthquake, Yu et al. (2012) proposed that the response of water level mainly depends on the height of the water column in the well, and the duration time of water oscillation is determined by the transmissibility coefficient of the well–aquifer system. From the co-seismic response of the Three Gorges network to the Wencuan earthquake, Liu et al. (2009) found that the strikes of faults and the presence of different groundwater types impose significant effects on the pattern of co-seismic response and post-seismic recovery of water levels.

6 Application of earthquake fluids to hydrogeology

The application of subsurface fluids to hydrogeology focuses on recording micro-dynamic effects (barometric and solid tidal effects, among others), and calculation of aquifer parameters in terms of the co-seismic response.

As early as the 1960s, the tidal effect of groundwater was used to infer aquifer parameters. Bredehoeft (1967) derived the method for the inversion of an aquifer's specific storage coefficient in terms of the response of well water level to the earth-tide. Using responses of earth-tide and air pressure to well holes, Rhoads and Robinson (1979) derived a formula for the calculation of the porosity and specific storage coefficient. In light of Cooper et al.'s (1965) work on response of well water level to seismic waves, Hsieh et al. (1987) proposed a method to invert an aquifer's transmissivity by using the phase lag of the tidal effect. Based on a model of tidal response with a single plane crack, Bower (1983) derived the relationships between diurnal and semi-diurnal waves in well-tide, openness, and azimuth (strike, dip) of the crack, and inverted the crack occurrence in terms of well-tidal parameters.

6.1 Calculation of aquifer parameters using micro-dynamic water level of wells

Since the 1980s, Chinese researchers have begun to calculate aquifer parameters. Du (1988) compared the methods for the inversion of aquifer parameters from earth-tide and barometric effects proposed by former researchers, and further developed them. Zhang et al. (1989) studied the relationship between the effects of earth-tide and barometric effects and aquifer parameters, and discussed the factors influencing the barometric effect and the tidal coefficient. Zheng and Liu (1990) used Venedikov's harmonic analysis method to calculate the amplitude ratio and phase shift of the water-tide with respect to the volumetric strain earth-tide, and derived an aquifer's permeability from this phase shift. Shi et al. (2013b) calculated the transmissivity and specific storage evolutions before and after the Wenchuan earthquake by the tidal response.

6.2 Estimating rock elastic parameters from micro-dynamic of groundwater level

With the analysis of 2 years of monitoring data of water level and barometric data in three wells, Liu and Zheng (1985) derived the formulas for the calculation of volume compression modulus Ea, vertical compression modulus Ev, and average aquifer porosity. Tian et al. (1987) derived relevant formulas for aquifer porosity, effective water volume, and rock-elastic modulus, and applied it to the Long06 well. On the basis of the relationship between water level and tidal strain, poroelastic theory, and assuming undrained conditions, Zhang et al. (2009) suggested a method for the calculation of the Skempton coefficient. Using Hsieh's model, Liao et al. (2011) inferred permeability and Skempton coefficients of the aquifer.

The co-seismic response of well water level can be used to calculate parameters of aquifer and rock properties, as well as to invert the aquifer's parameters. Through research of responses of well water level to seismic waves and slug tests, Zhang et al. (1990, 1999a) proposed a simple approach for calculation of transmissibility coefficients of aquifer. Taking the data of the Chanping seismic station as an example, Yan et al. (2008) calculated the response coefficient of water waves to volume strain in an aquifer, and gave a method for estimating the Skempton coefficient B.

7 Concluding remarks

At present, China has established one of the largest earthquake monitoring networks in the world, which include various observation subjects and some special arrays. On the basis of the high quality of data recorded from the networks, significant progress in various aspects has been achieved, especially in the efforts to use subsurface fluids in earthquake prediction, and several successful cases are acknowledged. For example, for the successful prediction of Haicheng earthquake, a large number of fluid anomalies had been observed before the event; researchers had suggested that a 5.0–5.5 earthquake would occur on the boundary of Shanxi and Heibei Province before the 1998 Zhangbei $M_s6.2$ earthquake based on the hydrogeochemistry anomalies (Che and Liu 2008). And they have begun to consider the joint effect of crust stress and crust strength (which may relate to the heat fluid activities in the deep crust) on earthquake prediction (Che 2002). Many interpretations of the mechanisms of fluids precursors have been suggested, which are of great significance for understanding the generation and occurrence processes of earthquakes.

It should be noted, however, that some difficulties still remain for us in further understanding the role of fluids in earthquakes. First, more dense monitoring wells with high quality data are needed. Although we have many monitoring wells over the country, the density is low and they are distributed unevenly. For example, many monitoring wells in Sichuan province are concentrated in the Xichang area, while the wells distributed along the Longmenshan fault before the Wenchuan earthquake were sparse. This may make it difficult to capture some important precursor signals before earthquakes. Second, continuous monitoring and high quality data are needed. With background noise and interference from human activities and meteorological effects, it is difficult to distinguish precursors and interference. What is more, instrument failures and personnel/program changes often destroy the persistent and consistent monitoring for long periods of time which lower the reliabillity of the data. Third, the quantitative physical mechanisms linking the abnormal changes in fluids to earthquakes are still poorly understood. The current earthquake predictions are mostly made through experience. No clear and identifying standard is available to make sure if the abnormal changes in fluid are earthquake precursors. More studies on the physical mechanisms of precursor fluid anomalies are needed.

Furthermore, some gaps or shortages exist compared with our international peers.

First, further combination with other disciplines is required. In fact, the research into earthquake subsurface fluids comes from the integration of hydrogeology, geophysics, and other subjects. The development of this interdisciplinary approach relies on the introduction of new ideas and methods from other disciplines in order to advance in a systematic fashion. Second, during the last 10 or more years, most work has focused on water level and temperature, while less attention has been paid to hydrogeochemistry, such as the research of Rn, Hg, ions, and isotopes, as well as their application to earthquake prediction. Third, in the aspect of co-seismic responses of subsurface fluids, despite many descriptions of relevant phenomena, relatively few studies have been made on their mechanisms, and thus few real creative ideas and methods have been developed.Fourth, subsurface fluids contain abundant geophysical information, and how to extract this valuable information from observational data to serve in the development of other subjects is a problem for future research.

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