Pure appl. geophys. 163 (2006) 675–691
0033–4553/06/040675–17
DOI 10.1007/s00024-006-0046-x

Pure and Applied Geophysics

Hydrogeochemical Anomalies in the Springs of the Chiayi Area in West-central Taiwan as Possible Precursors to Earthquakes

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Abstract—Water samples from both hot and artesian springs in Kuantzeling in west-central Taiwan have been collected on a regular basis from July 15, 1999 to the end of August 2001 to measure cation and anion concentrations as a tool to detect major earthquake precursors. The data identify chloride and sulfate ion anomalies few days prior to major quakes and lasting a few days afterward. These anomalies are characterized by increases in Cl^- concentrations from 34.9% to 41.2% and 71.5% to 138.1% as well as increases in SO_4^{2-} concentrations from 232.7% to 276.8% and 100.0% to 155.1% above the means in both hot and artesian springs. The occurrence of these anomalies is probably explained first as stress/strain-induced pressure changes in the subsurface water systems which then generate precursory limited geochemical discharges at the levels of subsurface reservoirs. Therefore, finally leading to the mixing of previously separated subsurface water bodies occurs. This suggests that the hot and artesian springs in the Kuantzeling area are possible ideal sites for recording strain changes serving well as earthquake precursors.

Key words: Chloride ion, sulfate ion, hot and artesian springs, anomaly, earthquake precursor, Taiwan.

1. Introduction

On account of highly active seismicity and a major destructive earthquake of magnitude $M_L = 7.3$ which occurred in a densely-populated area in Taiwan on 21 September, 1999, a large-scale research program to monitor active faults and identify earthquake precursors was jointly initiated by the Central Geological Survey, MOEA-ROC and the Institute of Geosciences, National Taiwan University. In one subprogram, weekly measurements of cation and anion concentrations are made in both hot and artesian springs in Taiwan to establish background concentrations and to identify geochemical earthquake-related anomalies. The

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purpose of this subprogram is to evaluate potential sites at which regular monitoring systems should be set up in the future.

The destructive Chi-Chi earthquake with magnitude $M_L = 7.3$ occurred in west-central Taiwan, causing a total of about 80–90 km in length of surface ruptures along the Chelungpu fault, with the largest measured vertical offsets reaching as far as 5–8 m (CHEN *et al.*, 2001). The epicenter of the earthquake was located about 15 km east of the surface trace of the thrust fault at 120.82°E and 23.85°N and had a hypocenter depth of about 12 km (CHUNG and SHIN, 1999; MA *et al.*, 1999; KAO and CHEN, 2000), near the town of Chi-Chi in Nantou County in west-central Taiwan (Fig. 1). This earthquake became one of the largest inland events in the past century, causing the death of about 2,400, injuring another 10,000 and destroying more than 100,000 buildings. Numerous aftershocks, including one event of $M_L = 6.8$, were distributed around the main shock in a large area of central Taiwan (KAO and CHEN, 2000). Following the Chi-Chi earthquake, another large quake with magnitude $M_L = 6.4$ struck the Chiayi area on October 22, 1999 in west-central Taiwan. The epicenter, 2.5 km northwest of Chiayi City was located at 120.40°E and 23.51°N and had a hypocenter depth of about 12.1 km (Fig. 1) (CWB, 1999).

One important goal of geoscientists has long been the detection of valuable short-term precursors of earthquakes, and, indeed, many types of precursors, including chemical and hydrological changes in subsurface fluids prior to large earthquakes. Among these, gases involved in hydrothermal processes (Rn, He, CO_2, CH_4, H_2, Ar and N_2) and water chemistry (Cl^-, F^-, NO_3^- and SO_4^{2-}) are the most unambiguous precursors (HAUKSSON, 1981; KING, 1986; SUGISAKI *et al.*, 1996; TSUNOGAI and WAKITA, 1995, 1996; TOUTAIN *et al.*, 1997; SONG *et al.*, 2005). These geochemical and hydrologic anomalies are generally related to changes in groundwater circulating systems because of earthquake generation (THOMAS, 1988; SUGISAKI *et al.*, 1996; KING *et al.*, 1999). Thus, geochemical anomalies observed in groundwater have provided useful information for earthquake prediction in seismic countries (e.g., KOIZUMI *et al.*, 1985; BARSUKOV *et al.*, 1984/1985; GUIRU *et al.*, 1984/1985). Meanwhile, preceding the major 1995 Kobe earthquake ($M_L = 7.2$) and the 1996 Pyrenean earthquake ($M_L = 5.2$) (TSUNOGAI and WAKITA, 1995, 1996; TOUTAIN *et al.*, 1997), anomalies of ions in commercialized bottled groundwater and spring water, respectively, have been recently detected.

This paper contributes to this field by presenting the results of a two-year study investigating hydrochemical changes in hot springs by collecting water samples from both hot and artesian springs in response to earthquakes in the Chiayi area of west-central Taiwan. Furthermore, the possible mechanisms inducing the chemical changes in the respective subsurface water systems are discussed.

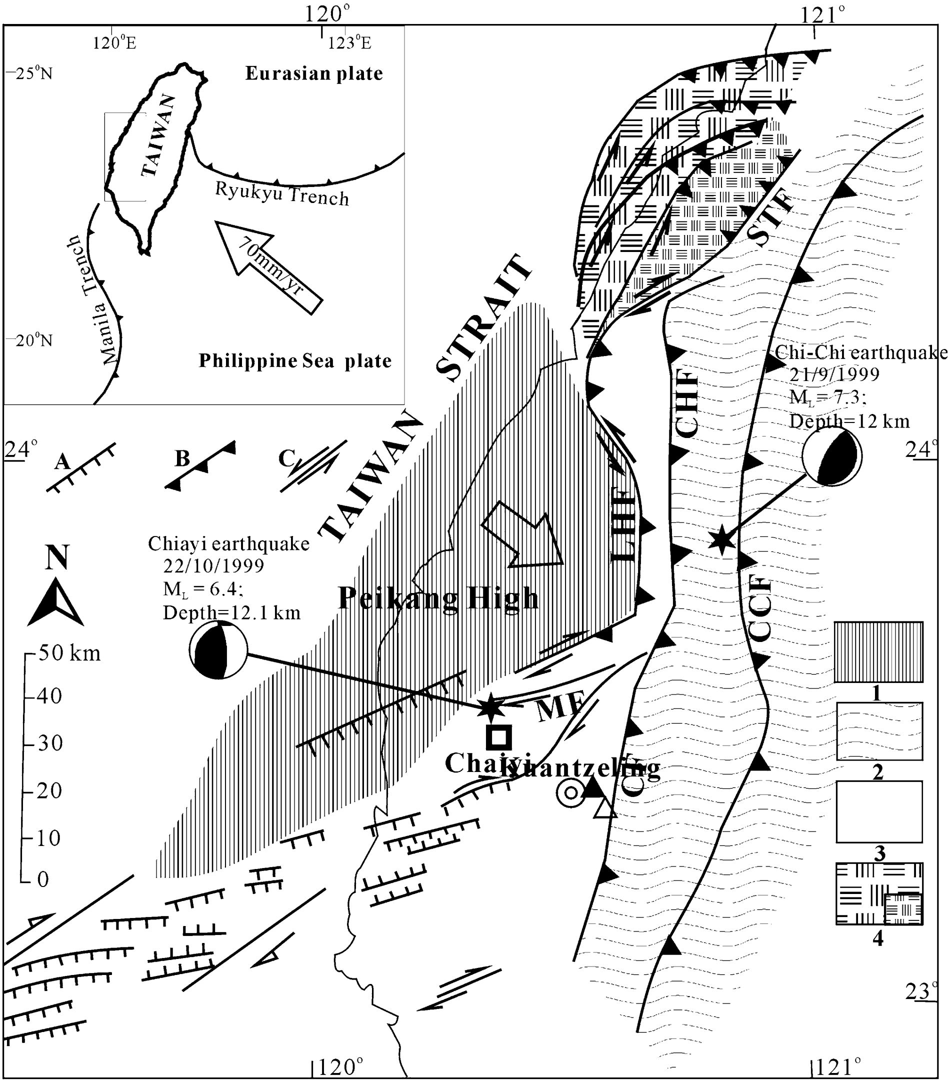

Figure 1
Regional structural sketch map of west-central Taiwan with the locations of the September 21 and October 22, 1999 earthquake epicenters and focal mechanisms. The legend in the lower right-hand corner indicates: 1: Pre-Tertiary basement; 2: Early Pleistocene tectonic belt; 3: Late Pleistocene tectonic belt; and 4: Escape blocks. The legend in the middle on the left-hand side indicates: A: Normal fault; B: Thrust fault; and C: Strike-slip fault. Shown on the map are: CCF: Chaochou-Chuchih fault; CF: Chukou fault; CHF: Chelungpu fault; LHF: Linnei-Hsinchu fault; MF: Meishan fault; and STF: Shihtan-Tuntzechiao fault (modified from BIQ, 1990; YANG *et al.*, 1994). Inset map shows the tectonics in the vicinity of Taiwan (modified from HO, 1986). Soild triangle: hot spring; open triangle: artesian spring.

2. Sites and Geological Background

Taiwan is located within the complexity of the oblique collision zone of the Eurasian continental plate and the Philippine Sea plate (Fig. 1). Presently, the Philippine Sea plate is moving WNW at about 70 mm per year (SENO and MARUYAMA, 1984), and it is believed the mountain-building process is still in progress (TSAI *et al.*, 1981; YU and CHEN, 1994; YU *et al.*, 1999). A dominant collision zone frequently inducing folding and fault thrusting, i.e., the Chelungpu thrust fault, may exist in west-central Taiwan. At the latitude of southern Taiwan, the Philippine Sea plate is riding up over the continental shelf of the South China Sea. Such active movements over the last 5 million years have been creating the island of Taiwan (HO, 1986; TENG, 1987, 1990), and more recently, rapid crustal movements and widely distributed active structures have induced at least tens of large earthquakes with magnitudes over 7.0 in the last few hundred years (YU *et al.*, 1997, 1999; CHANG *et al.*, 1998; CHENG *et al.*, 1999).

The Chiayi area is located in west-central Taiwan, and its pre-Tertiary basement high, called the Peikang High, is below. This Peikang High is an indentation block controlling the structures and seismic activities around the Chiayi area during the orogeny of Taiwan (Fig. 1) (LU, 1994; LU and MALAVIEILLE, 1994). The curvilinear active Chukou fault thrusts westward onto the Peikang High, with its northward extension connecting the Chelungpu thrust fault (Fig. 1) (BIQ, 1990; LU, 1994). South of the Peikang High there is a large transtension zone (BIQ, 1990; YANG *et al.*, 1994), while in the middle, an active strike-slip fault, the Meishan fault, cuts through on the southern edge of the Peikang High (BIQ, 1990; LIN *et al.*, 2000). Thus, earthquake epicenters in this area, one of the most highly active seismic areas of western Taiwan, distribute in a semicircular formation around the High (SHIN and CHANG, 1992). The epicenters of the September 21, 1999 Chi-Chi earthquake and the October 22, 1999 Chiayi earthquake are located about 35 km to the north and about 2.5 km to the northwest, respectively (Fig. 1).

The village of Kuantzeling is located in the southeastern part of the Chiayi area and is well-known for its hot spring spas. It is in the western foothills of Taiwan, where a passive margin shallow marine clastic sequence of the late Tertiary age crops out. Fossilferrous, fine-grained and little metamorphosed, the strata have been deformed by folding and faulting. The outpouring of hot spring waters is located on the axis of the Kuantzeling anticline, and a thrust fault, the Liuchungchi fault, cuts through it (HSU and WEY, 1983). The local geological structure, heat flow, silica geothermometry and Tritium data indicate that the hot springs may have come from a deep old water reservoir, over 2 km in depth rising along the fault fracture zone (CHEN *et al.*, 2001). The temperature and pH value of the Kuantzeling hot springs are 79°C and 8.1, respectively. According to historical records, the perturbations of the hot spring system, i.e., the bursts of steam and increased outpouring, occurred a few days prior to, during and a few days after the 1964 Paiho earthquake, one of the most devastating earthquakes on Taiwan in the last hundred years, with magnitude 6.3 (CHENG *et al.*, 1999) and its epicenter near the Kuantzeling area. Here, therefore, our attention was focused on the hot and artesian springs in this area, and the cations and anions in the water samples were regularly analyzed.

3. Sampling and Analysis

From July 15 to September 19, 1999 and for a period of about two months before the Chi-Chi earthquake, students from a local high school for a national science competition collected 9 samples from the Kuantzeling hot springs at different time intervals. Twenty days after the earthquake, the present researchers joined in and intensely collected one hot spring sample per day during two months and then decreased the sampling interval to one sample every three days and subsequently to one a week until the end of July 2001. Thus, a total of over 200 samples of hot spring water were collected for analyses. Meanwhile, one sample was also collected from the beginning of January 2000 to December 2000 every three days from an artesian spring located about 1 km southwest of the Kuantzeling hot springs. Later the sampling intervals decreased to one per week until the end of August 2001 for a total of about 170 samples of artesian spring water for analyses.

Dissolved anions and cations in both sets of samples were measured with an ion chromatographer (IC, Type Dionex DX-100) and an inductively coupled plasma-atomic emission spectrometer (ICP-AES, Type Jobin-Yvon JY-38plus), respectively. A sample from the same spring was measured after each sample analysis in order to enhance the precision of the measurements. Analytical uncertainties in the absolute concentrations were less than 3% for all of the anions and less than 5% for all of the cations. This study also analyzed the oxygen and hydrogen isotopes of the Kuantzeling hot springs from September 1999 to September 2000 using a Finnigan Delta Plus-Mass Spectrometer with precisions of about 0.1‰ for the oxygen isotopes and 1‰ for the hydrogen isotopes.

4. Results and Discussions

1. Temporal Variations in the Chemical Compositions

The temporal variations in the Cl^- and SO_4^{2-} concentrations of the water samples from the Kuantzeling hot springs from July 1999 to July 2001 are shown in Figs 2A and 2B, respectively. Chloride ion is the major anion in the hot springs and its average concentration reaches 2201 ppm, whereas that of the sulfate ion is about 33.6 ppm. Generally, the concentrations of chloride of in samples are almost constant, except on a few dates, but this is unlike those of sulfates, which are more

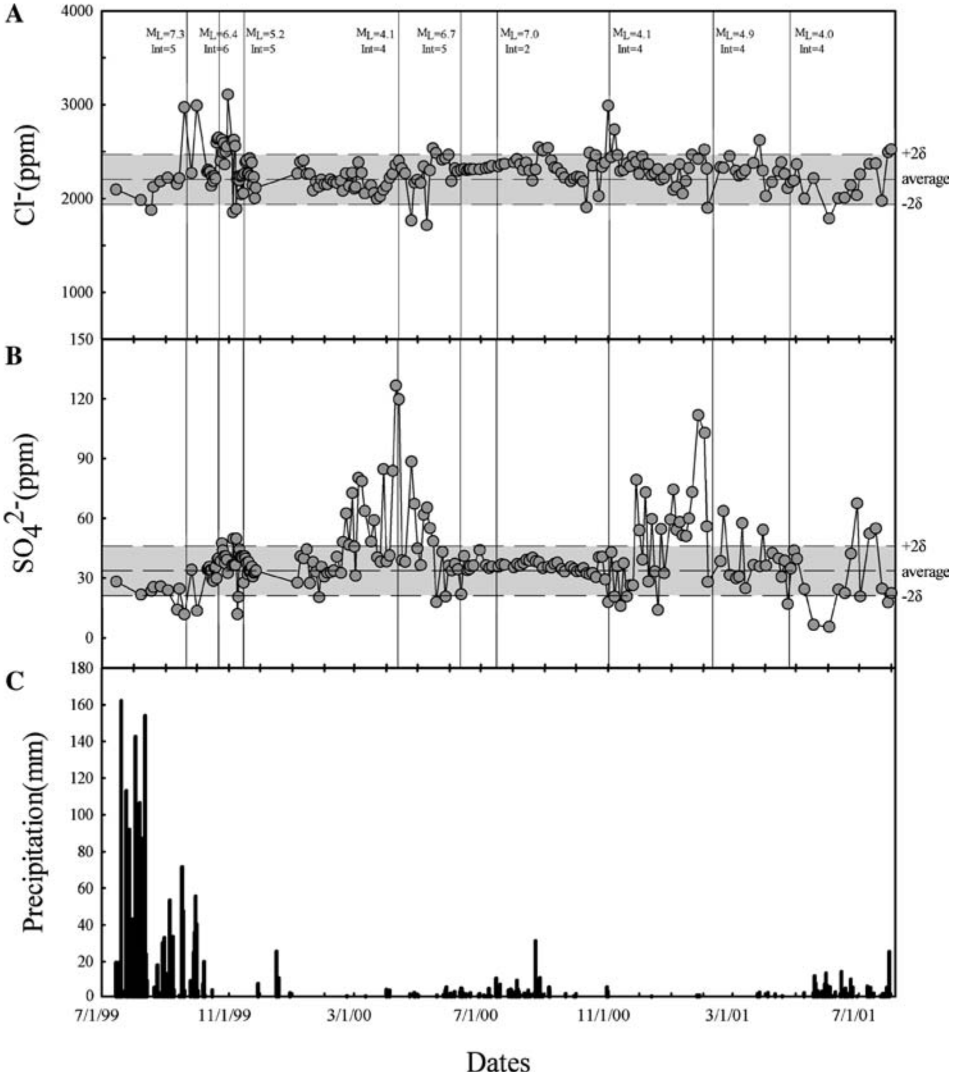

Figure 2

Temporal variations in (A) Cl^- and (B) SO_4^{2-} concentrations in the Kuantzeling hot springs. The average concentration (solid lines) and 2σ variation range (dashed lines) are also shown. The vertical lines represent the earthquakes with magnitudes and intensities greater than 4 that occurred in this area. (C) Daily amounts of precipitation obtained at the Kuantzeling area (Data from Central Weather Bureau of Taiwan).

fluctuant in two periods, i.e., from March 2000 to June 2000 and from December 2000 to February 2001. Two-sigma relative standard deviations (2σ) were calculated for those samples and are 12.0% (Cl^-) and 36.9% (SO_4^{2-}). We have considered the 2σ domains as representative of spring water background values, which may have resulted from water-rock interactions in the deep circulations of the hot spring reservoirs, sampling heterogeneity and analytical uncertainties. Except for the chloride and sulfate ions, all of the cations and anions vary within the 2σ domains during the entire sampling period. Figure 2A shows that the Cl^- concentrations increased abruptly on September 19, October 1, October 31, 1999 and November 1, 2000, reaching their maximum values of 2970 ppm, 2988 ppm, 3107 ppm and 2987 ppm, which are, respectively, about 34.9%, 35.8%, 41.2% and 35.7% above the mean value. It is important to note that these variations are very sudden. The sulfate contents during the same period seem to show no variations, but they do show high fluctuations from March to June 2000 and December 2000 to February 2001, when the respective concentrations reached their peaks at 126.6 ppm and 111.8 ppm, or about 276.8% and 232.7% above the mean. Figures 3A and 3B show the temporal variations in the hydrogen and oxygen isotopic ratios of the water samples from the Kuantzeling hot springs from September 1999 to September 2000, respectively. The $\delta^{18}O$ and δD ratios of all samples remain fairly constant during the sampling period, firmly indicating that the hot spring waters have come from a stable homogeneous subsurface water body.

The temporal variations in the Cl^- and SO_4^{2-} concentrations of the water samples from the Kuantzeling artesian spring from January 2000 to August 2001 are shown in Figures 4A and 4B, respectively. The sulfate ion with an average concentration of about 25.4 ppm is the major anion in the spring waters, if we compare with an average of about 2.70 ppm for the chloride ion. The chloride and sulfate concentrations of all samples are fairly constant during the sampling period. Two-sigma relative standard deviations (2σ) were calculated for those samples and are 30.4% (Cl^-) and 17.9% ($SO_4{}^{2-}$). These 2σ domains can be assumed as representative of the spring water background values. They may be attributed to annual fluctuations in groundwater chemistry, which are themselves mainly as a result of rainfall and other superficial phenomena, such as heterogeneity in the sampling and analytical uncertainties (TOUTAIN *et al.*, 1997). Except for the chloride and sulfate ions, all cations and anions vary within the 2σ domains during the entire sampling period. Figure 4A shows that the Cl^- concentrations increase sharply on April 12, June 13 and July 16, 2000 reaching their maximum values (6.43 ppm), (5.55 ppm) and (4.63 ppm), which are, respectively, about 138.1%, 105.6% and 71.5% above the mean value. Again, of significance is these variations are very abrupt. Except for July 15, 2000 when little change is found, the variations in the sulfate content (Fig. 4B) are the same as those for chloride, with concentrations reaching their maximum values of 50.8 ppm and 64.8 ppm, which are, respectively, about 100.0% and 155.1% above the mean value.

2. Mechanism for the Chemical Changes

Changes in the chemical compositions of hot and artesian springs have previously been attributed to several factors. Different compositions of groundwater recharge,

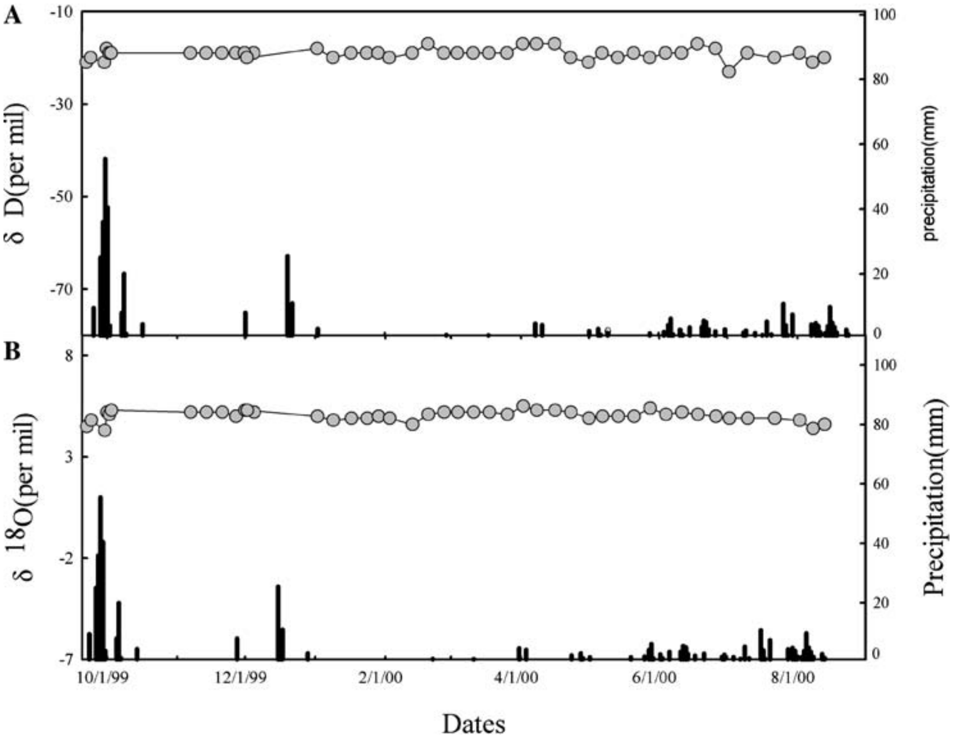

Figure 3
Temporal variations in (A) δD and (B) δ^{18}O in the Kuantzeling hot springs. Heavy bars are daily amounts of precipitation obtained at the Kuantzeling area (Data from Central Weather Bureau of Taiwan).

petrologic and mineralogical compositions of subsurface rocks, water-rock interactions (DOMENICO and SCHWARTZ, 1990; LANGMUIR, 1997), mixing of different water compositions and artificial pollutants, etc. To evaluate which mechanisms are responsible for the observed chemical changes, two facts must be kept in mind. Firstly, chloride ion is considered chemically stable, and the concentration level is high enough to measure reliably. The second, in contrast to the chloride ion, sulfate is not so stable in groundwater conditions and can be affected by sulfide mineral oxidation, precipitation-dissolution of gypsum in an unsaturated zone, dissolution of anhydrite or gypsum or redox reactions in a saturated zone (DOMENICO and SCHWARTZ, 1990). Such reactions, however, are not quick enough to cause such abrupt changes in SO_4^{2-} concentrations in a stable subsurface water system. Among all those factors that are capable of causing the observed temporal variations in both Cl^- and SO_4^{2-} concentrations in a short duration (Figs. 2 and 4), mixing of different water compositions (KING *et al.*, 1981; THOMAS, 1988) and artificial pollutants are the only two factors that cannot be ruled out.

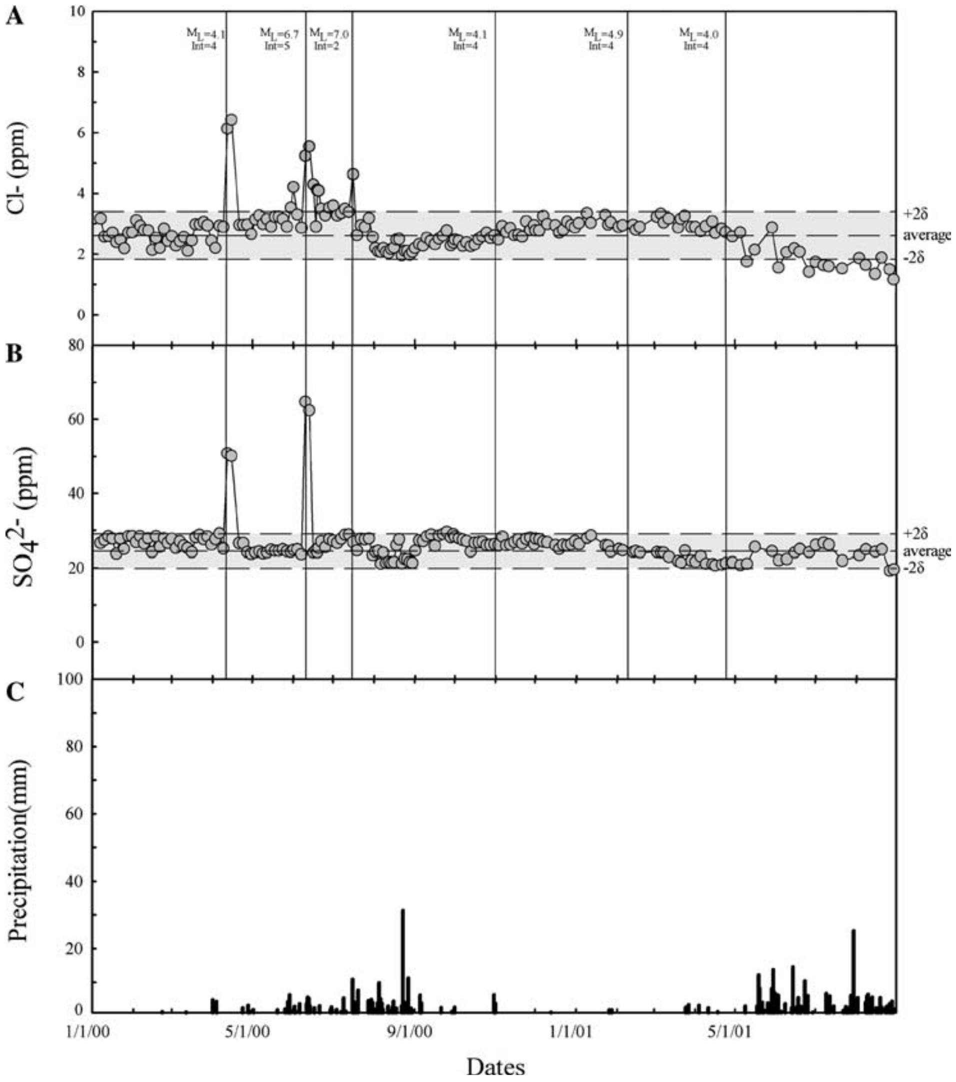

Figure 4

Temporal variations in (A) Cl^- and (B) SO_4^{2-} concentrations in the Kuantzeling artesian springs. The average concentration (solid lines) and 2σ variation range (dashed lines) are also shown. The vertical lines represent the earthquakes with magnitudes and intensities greater than 4 occurred in this area. (C) Daily amounts of precipitation obtained at the Kuantzeling area (Data from Central Weather Bureau of Taiwan).

Kuantzeling is located in an industry-free, sparsely populated mountainous area. Accordingly, pollutant solutes require media, i.e., meteoric water, in order to be transported down into the groundwater system. However, no correlated relationships among the anomalies of the ions in the temporal variations and daily amounts of precipitation are found during the sampling period (Figs. 2 and 4), highly suggesting that the observed temporal variations in the Cl^- and SO_4^{2-} concentrations are not, in fact, induced by recent meteoric water flowing down into the circulation system of the subsurface water system. Meanwhile, the analysis results of Tritium (^3H) concentration in the hot springs are less than 0.2 ($TU < 0.2$) (CHEN *et al.*, 2004), and almost no variations in the oxygen and hydrogen isotopic ratios are found (Fig. 3). This again strongly supports the notion that no recent meteoric water flows down into the circulation system of the hot spring waters. Given these lines of evidence, the abrupt change in the temporal variations of Cl^- and $SO_4{}^{2-}$ concentrations cannot be attributed to artifact pollutants. It follows then that the most probable factor controlling the temporal chemical variations in the hot and artesian springs of the Chiayi area is the mixing of water bodies with different compositions.

Several mechanisms can bring about the mixing of different water compositions in a subsurface water body, and these include the mixing of meteoric and formation waters, groundwater and brines or pore waters, and the mixing of different aquifers or reservoirs with different chemical compositions (DOMENICO and SCHWARTZ, 1990). Among these, the formers may change chemical compositions gradually and eventually lead to complete changes or at least changes that last a long period, while the mixing of different aquifers or reservoirs with different chemical compositions can quickly occur and the chemical changes can disappear in a short duration. What is particularly salient is that Figures 2 and 4 clearly illustrate that such chemical changes are abrupt and that the dates correlate well with the occurrence of earthquakes, near the hot and artesian springs. Thus, it is reasonable to attribute the mechanism of the rapid temporal chemical variations in the hot and artesian springs in the Chiayi area to the mixing of different aquifers or reservoirs. It may be equally justifiable to make the claim that the mechanism of the rapid temporal chemical variations may have been induced by an earthquake. Such an interpretation is strongly supported by the observation of the large 1.0- to 11.1-m changes in the groundwater levels induced by the Chi-Chi earthquake on 21 September 1999, as recorded at 157 out of 179 monitoring wells in the Choshui River alluvial fan, which is located about 10–20 km northwest of the Chiayi area (CHIA *et al.*, 2001).

Two different earthquake-induced mechanisms for the mixing of different water systems of different compositions have been proposed in previous studies. The first involves permeability enhancement due to a breaking in the crust (KING *et al.*, 1981; THOMAS, 1988; ROJSTACZER and WOLF, 1992; Rojstaczer *et al.*, 1995; KING *et al.*, 1999), while the second encompasses the changing of pressure in aquifer systems because of elastic compression (MUIR-WOOD and KING, 1993; TOUTAIN *et al.*, 1997), before and after a major earthquake. The former necessitates cracking water barriers, i.e., fault gauge zones or aquicludes and, subsequently, inducing the mixing of initially isolated aquifers. Chemical changes induced by such a mechanism, however, would require large-scale mixing processes (TSUNOGAI and WAKITA, 1996) and would not be compatible with short-term reversible anomalies, such as those observed in the

Table 1

The Cl^- *and* SO_4^{2-} *concentrations (ppm) of the Kuantzeling hot spring*

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
7/15/1999	2093	28.1	11/8/1999	2200	11.8	2/19/2000	2132	46.6
8/8/1999	1983	21.7	11/9/1999	2233	20.5	2/22/2000	2272	72.8
8/18/1999	1875	23.5	11/10/1999	2193	44.5	2/25/2000	2102	45.7
8/20/1999	2123	25.4	11/11/1999	2237	40.3	2/28/2000	2123	31.1
8/27/1999	2178	25.8	11/12/1999	2043	41.0	3/1/2000	2385	80.3
9/3/1999	2219	23.7	11/13/1999	2242	40.5	3/2/2000	2272	78.6
9/12/1999	2153	14.1	11/14/1999	2054	27.5	3/5/2000	2055	63.6
9/14/1999	2215	24.7	11/15/1999	2263	41.0	3/8/2000	2141	48.2
9/19/1999	2970	11.7	11/16/1999	2388	39.9	3/11/2000	2057	59.0
9/26/1999	2268	34.1	11/17/1999	2406	37.7	3/17/2000	1994	40.3
10/1/1999	2988	13.5	11/18/1999	2260	31.9	3/20/2000	2022	38.1
10/11/1999	2284	34.4	11/19/1999	2259	38.0	3/23/2000	2089	84.6
10/12/1999	2306	34.6	11/20/1999	2425	33.1	3/26/2000	2133	38.3
10/13/1999	2287	35.5	11/21/1999	2237	33.2	3/29/2000	2220	41.3
10/14/1999	2285	33.9	11/22/1999	2382	35.6	4/1/2000	2258	83.8
10/15/1999	2136	33.8	11/23/1999	2145	30.7	4/4/2000	2359	126.6
10/16/1999	2234	29.3	11/24/1999	2226	32.5	4/7/2000	2398	119.7
10/17/1999	2184	28.3	11/25/1999	2000	32.9	4/10/2000	2320	38.8
10/18/1999	2236	34.8	11/26/1999	2112	33.7	4/13/2000	2266	38.1
10/19/1999	2211	35.4	11/27/1999	2263	27.5	4/16/2000	1764	88.4
10/20/1999	2593	29.8	1/6/2000	2388	41.0	4/19/2000	2168	67.2
10/21/1999	2635	39.4	1/9/2000	2406	39.9	4/25/2000	2196	44.8
10/22/1999	2646	39.9	1/12/2000	2260	44.5	4/28/2000	2164	36.5
10/24/1999	2399	38.6	1/15/2000	2259	27.4	5/1/2000	2340	61.7
10/25/1999	2627	47.4	1/18/2000	2085	38.0	5/4/2000	1714	65.3
10/26/1999	2489	43.8	1/21/2000	2177	33.1	5/7/2000	2299	55.0
10/27/1999	2585	40.8	1/24/2000	2123	20.3	5/10/2000	2534	48.6
10/28/1999	2361	37.5	1/27/2000	2200	35.6	5/13/2000	2485	17.9
10/29/1999	2497	40.9	1/29/2000	2150	30.7	5/16/2000	2413	43.0
10/30/1999	2553	39.1	2/1/2000	2150	32.5	5/19/2000	2426	20.6
10/31/1999	3107	32.4	2/4/2000	2204	32.9	5/25/2000	2464	36.1
11/4/1999	2617	36.5	2/7/2000	2177	33.7	5/28/2000	2183	33.8
11/5/1999	1851	49.6	2/10/2000	2166	40.6	5/31/2000	2317	37.0
11/6/1999	2623	36.5	2/13/2000	2188	32.5	6/3/2000	2290	34.3
11/7/1999	2558	36.4	2/17/2000	2080	48.1	6/6/2000	2306	21.8
6/9/2000	1886	49.7	10/20/2000	2334	40.7	3/4/2001	2243	30.6
6/12/2000	2299	33.9	10/23/2000	2266	62.4	3/7/2001	2262	57.6
6/15/2000	2306	34.5	10/26/2000	2380	29.3	3/10/2001	2314	41.0
6/18/2000	2313	36.0	10/29/2000	2987	18.0	3/13/2001	2300	24.7
6/20/2000	2311	36.3	11/1/2000	2437	42.9	3/21/2001	2376	36.6
6/21/2000	2312	44.1	11/4/2000	2734	20.7	3/27/2001	2620	35.7
6/24/2000	2321	36.5	11/7/2000	2461	35.7	3/30/2001	2295	54.2
6/30/2000	2329	34.9	11/10/2000	2291	15.9	4/2/2001	2022	36.1
7/6/2000	2345	35.7	11/13/2000	2304	37.4	4/8/2001	2173	42.4
7/9/2000	2339	35.5	11/16/2000	2373	20.7	4/14/2001	2289	39.9
7/12/2000	2361	36.9	11/19/2000	2342	26.2	4/17/2001	2385	30.5
7/18/2000	2366	36.5	11/22/2000	2444	26.2	4/20/2001	2259	38.6
7/21/2000	2386	35.3	11/25/2000	2388	79.3	4/23/2001	2108	16.9

Table 1

(Contd.)

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
7/24/2000	2418	36.9	11/28/2000	2259	53.9	4/26/2001	2171	34.8
8/2/2000	2365	36.2	12/1/2000	2449	39.2	4/29/2001	2189	43.8
8/5/2000	2305	37.5	12/4/2000	2361	73.0	5/2/2001	2363	39.6
8/8/2000	2382	39.1	12/7/2000	2365	28.2	5/9/2001	1997	24.4
8/11/2000	2299	38.7	12/10/2000	2249	59.6	5/18/2001	2216	6.5
8/14/2000	2188	40.3	12/13/2000	2269	33.3	6/2/2001	1786	5.4
8/17/2000	2307	38.3	12/16/2000	2310	14.0	6/11/2001	2001	24.2
8/20/2000	2542	37.9	12/19/2000	2196	54.5	6/17/2001	2006	22.4
8/23/2000	2508	34.9	12/22/2000	2219	32.3	6/23/2001	2140	42.2
8/26/2000	2538	35.6	12/25/2000	2310	59.3	6/29/2001	2034	67.5
8/30/2000	2406	35.2	12/31/2000	2091	74.4	7/2/2001	2256	20.7
9/4/2000	2329	37.2	1/3/2001	2123	54.1	7/11/2001	2367	52.3
9/7/2000	2320	37.7	1/6/2001	2365	58.1	7/17/2001	2372	54.9
9/10/2000	2267	34.4	1/9/2001	2051	51.4	7/23/2001	1974	24.6
9/13/2000	2222	33.3	1/12/2001	2184	50.9	7/29/2001	2491	17.7
9/17/2000	2182	35.5	1/15/2001	2323	59.9	8/1/2001	2522	22.4
9/20/2000	2212	34.4	1/18/2001	2466	73.1			
9/26/2000	2231	33.4	1/21/2001	2421	111.8			
9/29/2000	2225	33.7	1/27/2001	2518	102.9			
10/2/2000	2178	34.9	2/2/2001	2319	55.9			
10/5/2000	1904	32.3	2/4/2001	1900	28.0			
10/8/2000	2486	31.8	2/5/2001	2331	38.4			
10/11/2000	2346	32.4	2/17/2001	2324	63.6			
10/14/2000	2460	30.4	2/20/2001	2451	31.5			
10/17/2000	2023	40.4	2/26/2001	2297	29.9			

Kuantzeling hot and artesian springs, where the chloride and sulfate contents returned to pre-seismic levels within a few days after the onset of the anomaly. The latter mechanism, on the other hand, is induced by elastic compression on aquifers, which generates pressure variations among them, enough to generate reversible changes in hydraulic levels (MUIR-WOOD and KING, 1993) and, therefore, lead to subsequent limited geochemical discharge effects (THOMAS, 1988). It is clear that a limited mixing of aquifers with different compositions, not unlike that in the case of the rapid geochemical changes in the Kuantzeling hot and artesian springs (Figs. 2 and 4), is the most likely model for the generation of the drastic ion concentration changes. Aside from this, the mechanism is supported by the significant changes in groundwater levels induced by the Chi-Chi earthquake (CHIA *et al.*, 2001). It is highly expected, therefore, that the chloride- and sulfate-rich spring waters were introduced into the Kuantzeling subsurface water systems. Although it is difficult to precisely identify the water introduced in the subsurface system, a hot spring with high chloride and sulfate concentrations, located nearby the Kuantzeling hot springs (KU, 2001) is a potential source.

Table 2

The Cl^- *and* SO_4^{2-} *concentrations (ppm) of the Kuantzelingartesian spring*

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
1/7/2000	3.17	26.6	4/24/2000	2.96	26.6	7/31/2000	2.57	23.4
1/10/2000	2.58	27.4	4/27/2000	2.97	24.2	8/2/2000	2.20	24.3
1/13/2000	2.60	28.4	4/30/2000	2.66	23.7	8/4/2000	2.09	24.6
1/16/2000	2.71	27.8	5/3/2000	3.14	24.1	8/6/2000	2.08	21.1
1/19/2000	2.40	23.8	5/6/2000	3.27	24.4	8/8/2000	2.20	24.1
1/22/2000	2.48	27.8	5/9/2000	2.99	23.9	8/10/2000	2.07	21.4
1/25/2000	2.19	25.0	5/12/2000	3.15	24.1	8/12/2000	2.03	21.5
1/28/2000	2.71	28.4	5/15/2000	2.91	24.9	8/14/2000	2.17	21.3
1/31/2000	2.72	28.4	5/18/2000	3.23	24.5	8/16/2000	2.21	21.6
2/3/2000	3.11	26.9	5/21/2000	3.23	24.6	8/18/2000	2.48	26.0
2/6/2000	2.94	28.4	5/24/2000	3.15	24.9	8/20/2000	2.50	27.6
2/9/2000	2.79	26.5	5/27/2000	2.91	24.4	8/22/2000	1.96	21.2
2/12/2000	2.78	27.9	5/30/2000	3.52	24.2	8/24/2000	2.11	22.4
2/15/2000	2.14	24.2	6/1/2000	4.21	24.8	8/26/2000	2.11	22.2
2/18/2000	2.54	28.3	6/4/2000	3.30	25.0	8/28/2000	1.98	21.6
2/21/2000	2.20	25.6	6/7/2000	2.87	23.7	8/30/2000	2.08	21.3
2/24/2000	2.84	27.8	6/10/2000	5.24	64.8	9/1/2000	2.20	24.6
2/27/2000	2.44	26.6	6/13/2000	5.55	62.4	9/4/2000	2.33	27.3
3/1/2000	2.60	27.7	6/16/2000	4.29	24.1	9/7/2000	2.28	27.1
3/4/2000	2.28	25.2	6/18/2000	2.91	24.7	9/10/2000	2.54	28.3
3/7/2000	2.43	27.0	6/19/2000	4.12	24.1	9/13/2000	2.44	28.8
3/10/2000	2.57	25.8	6/20/2000	4.09	25.2	9/16/2000	2.33	25.8
3/13/2000	2.11	25.2	6/22/2000	3.48	27.0	9/19/2000	2.51	28.6
3/16/2000	2.46	24.2	6/25/2000	3.27	25.5	9/22/2000	2.61	28.9
3/19/2000	2.98	28.1	6/28/2000	3.53	27.6	9/25/2000	2.78	29.5
3/22/2000	2.98	28.8	7/1/2000	3.59	27.2	9/28/2000	2.29	28.1
3/25/2000	3.05	27.7	7/4/2000	3.27	26.6	9/30/2000	2.38	28.9
3/28/2000	2.95	28.3	7/7/2000	3.35	27.7	10/1/2000	2.48	28.2
3/31/2000	2.44	26.2	7/10/2000	3.48	28.8	10/4/2000	2.45	27.8
4/3/2000	2.20	27.6	7/13/2000	3.38	28.8	10/7/2000	2.27	27.5
4/6/2000	2.93	29.2	7/16/2000	4.63	26.9	10/10/2000	2.39	27.0
4/9/2000	2.90	25.1	7/19/2000	2.62	24.6	10/13/2000	2.26	24.3
4/12/2000	6.14	50.8	7/22/2000	2.95	27.7	10/16/2000	2.32	26.7
4/15/2000	6.43	50.1	7/25/2000	2.90	27.5	10/19/2000	2.50	26.7
4/21/2000	2.96	26.6	7/28/2000	3.18	27.8	10/22/2000	2.59	26.9
10/25/2000	2.71	26.0	2/5/2001	2.95	24.7	7/7/2001	1.63	26.6
10/28/2000	2.53	26.0	2/13/2001	2.96	24.2	7/11/2001	1.60	26.2
10/31/2000	2.63	26.3	2/15/2001	2.80	24.5	7/21/2001	1.53	21.9
11/3/2000	2.49	26.0	2/18/2001	2.90	24.1	8/3/2001	1.87	23.4
11/6/2000	2.92	28.2	3/3/2001	3.23	24.2	8/8/2001	1.65	24.9
11/9/2000	2.73	25.9	3/6/2001	3.33	24.1	8/15/2001	1.34	24.4
11/12/2000	2.86	26.2	3/8/2001	3.04	24.1	8/20/2001	1.89	24.9
11/15/2000	2.62	26.9	3/12/2001	3.17	23.0	8/26/2001	1.50	19.2
11/18/2000	2.64	27.4	3/19/2001	2.88	21.8	8/29/2001	1.16	19.6
11/21/2000	2.58	26.5	3/21/2001	3.16	21.4			
11/24/2000	3.08	27.7	3/24/2001	3.26	24.6			
11/27/2000	2.79	28.0	3/29/2001	2.90	21.9			
11/30/2000	2.95	26.3	4/1/2001	2.90	21.6			

Table 2

(Contd.)

Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}	Date	Cl^-	SO_4^{2-}
12/1/2000	2.78	27.8	4/5/2001	2.76	23.1			
12/4/2000	2.78	27.5	4/9/2001	2.92	21.1			
12/7/2000	3.25	26.9	4/14/2001	3.07	21.0			
12/10/2000	2.99	26.8	4/16/2001	2.70	20.7			
12/16/2000	2.95	26.0	4/21/2001	2.84	20.9			
12/19/2000	2.71	25.0	4/24/2001	2.73	21.3			
12/22/2000	2.80	26.1	4/29/2001	2.59	21.5			
12/25/2000	3.06	25.9	5/5/2001	2.72	20.8			
12/28/2000	2.95	26.3	5/10/2001	1.76	21.1			
12/31/2000	2.88	27.1	5/16/2001	2.15	25.6			
1/3/2001	3.02	26.3	5/29/2001	2.88	24.5			
1/9/2001	3.35	28.0	6/3/2001	1.56	22.0			
1/12/2001	3.03	28.6	6/9/2001	2.06	22.3			
1/23/2001	3.29	26.0	6/15/2001	2.19	24.1			
1/25/2001	2.97	25.8	6/19/2001	2.08	25.1			
1/27/2001	3.05	24.4	6/26/2001	1.41	24.1			
2/2/2001	2.90	25.0	7/1/2001	1.74	26.1			

The Cl^- and $SO_4{}^{2-}$, especially the $SO_4{}^{2-}$ variations, which responded to the earthquakes in the Kuantzeling hot and artesian springs, seem to be so different. The variations in the hot springs were more fluctuant and lasted longer than those in the artesian springs (Figs. 2 and 4). This may have been a result of the different depths of the aquifers or reservoirs. In other words, the shallower the artesian springs are, the faster are the responses from the earthquake-induced stresses.

Although the chemical anomalies that occurred in the Kuantzeling hot and artesian springs can be explained by the earthquakes, there still remain several open questions like why some earthquakes do not cause chemical anomalies in the same subsurface water systems (Figs. 2 and 4). The answer surely must lie in the fact that such anomalies are likely related to the unknown characteristics of some subsurface structures and water systems, the complexities of the processes of earthquake-induced stresses on the crust and aquifers or reservoirs, the wide-ranging chemical compositions of subsurface waters, varying water-rock interactions, and so on. Obviously, more data from geochemical monitoring and further investigations into earthquake precursors are required to enhance our understanding vis-à-vis the origin of earthquakes in the future.

5. *Conclusions*

Located in an orogenic belt with highly active seismicity, Taiwan has often been struck by major devastating earthquakes, which have caused huge numbers of fatalities and casualties as well as the destruction of countless buildings. Nonetheless, in spite of this, it has given rise to numerous opportunities to investigate the potentially hydrological geochemical precursors of the earthquakes. Here, short-term, reversible precursory geochemical anomalies have been recorded in hot and artesian springs prior and subsequent to the major earthquakes occurred September 1999 in the Kuantzeling area of west-central Taiwan. The anomalies were sharp sudden increases in chloride and sulfate ions. These are interpreted here as stress/strain-induced pressure changes in the subsurface water system, followed by limited precursory geochemical discharges generated by limited changes in the levels of the subsurface reservoirs, finally leading to the mixing of previously isolated subsurface water bodies. This strongly suggests that both the hot and artesian springs in the Kuantzeling area may be ideal sites for recording strain changes and that therefore, they should serve well in earthquake precursor research.

Acknowledgements

The authors appreciate the assistance of Mr. Yu, W.Y. for the field samplings and partial IC and ICP-AES analyses. This research was supported by the Central Geological Survey, Ministry of Economic Affairs and partly by the National Science Council, Republic of China under grants NSC 89-2116-M-002-046.

REFERENCES

BARSUKOV, V.L., VARSHAL, G.M., and ZAMOKINA, N.S. (1984/1985), *Recent results of hydrogeochemical studies for earthquake prediction in the USSR*, Pure Appl. Geophys. *122*, 143–156.

BIQ, C. (1990), *Another Coastal Range on Taiwan*, Ti-Chih *12*, 1–14 (in Chinese).

CENTRAL WEATHER BUREAU (CWB) (Taiwan) (1999), *CWB earthquake report*, http:// www.cwb.gov.tw.

CHANG, H.C., LIN, C.W., CHEN, M.M., and LU, S.T. (1998), *An Introduction to the Active Faults of Taiwan: Explanatory Text for the Active Fault of Taiwan, Scale 1:500,000*, Spec. Publ. Central Geol. Survey, Taiwan *10*, 103 pp. (in Chinese with English abstract).

CHEN, C.H., LIU, T.K., SONG, S.R., YANG, T.Y., and LEE, C.Y. (2004), *Environmental geochemistry with respect to the fault activity during 2000–2002 in Chiayi–Tainan and Hsinchu-Miaoli Area, Western Taiwan*, Bull. Centl. Geol. Survey *17*, 129–174 (in Chinese).

CHEN, Y.G., CHEN, W.S., LEE, J.C., LEE, Y.H., LEE, C.T., CHANG, H.C., and LO, C.H. (2001), *Surface rupture of the 1999 Chi-Chi earthquake yields insights on the active tectonics of central Taiwan*, Bull. Seismol. Soc. Amer. *91*, 977–985.

CHENG, S.N., YEH, Y.T., HSU, M.T., and SHIN, T.C., *Photo Album of Ten Disastrous Earthquakes in Taiwan* (CWB, Taiwan, 1999).

CHIA, Y.-P., WANG, Y.S., CHIU, J.J., and LIU, C.W. (2001), *Changes of groundwater level due to 1999 Chi-Chi earthquake in the Choushui River alluvial fan in Taiwan*, Bull. Seismol. Soc. Am. *91*, 1062–1068.

CHUNG, J.K. and SHIN, T.C. (1999), *Implication of the rupture process from the displacement distribution of strong ground motions recorded during the 21 September 1999 Chi-Chi Taiwan earthquake*, Terr. Atmos. Oceanic Sci. *10*, 777–786.

DOMENICO, P.A. and SCHWARTZ, F.W., *Physical and Chemical Hydrogeology* (John Wiley and Sons, Singapore, 1990).

GUIRU, L., FONGLIANG, W., JIHUA, W., and PEIREN, Z. (1984/1985), *Preliminary results of seismogeochemical research in China*, Pure Appl. Geophys. *122*, 218–230.

HAUKSSON, E. (1981), *Radon content of groundwater as an earthquake precursor: Evaluation of worldwide data and physical basis*, J. Geophys. Res. *86*, 9397–9410.

HO, C.S. (1986), *An introduction to the Geology of Taiwan: Explanatory Text of the Geologic Map of Taiwan*, Cent. Geol. Survey, Taiwan, 163 pp.

HSU, C.Y. and WEY, S.K. (1983), *Structural geology in the Chiayi foothills, Taiwan,* Petroleum Geol. Taiwan *19*, 17–28.

KAO, H. and CHEN, W.P. (2000), *The Chi-Chi earthquake sequence: Active out-of-sequence thrust faulting in Taiwan*, Science *288*, 2346–2349.

KING, C.Y. (1986), *Gas geochemistry applied to earthquake prediction. An overview*, J. Geophys. Res. *91*, 12,269–12,281.

KING, C.Y., AZUMA, S., IGARASHI, G., OHNO, M., SAITO, H., and WAKITA, H. (1999), *Earthquake-related water-level changes at 16 closely clustered wells in Tono, central Japan*, J. Geophys. Res. *104*, 13,073–13,082.

KING, C.Y., EVANS, W.C., PRESSER, T., and HUSK, R. (1981), *Anomalous chemical changes in well waters and possible relation to earthquakes,* Geophys. Res. Lett. *8*, 425–428.

KOIZUMI, N., YOSHIOKA, R., and KISHIMOTO, Y. (1985), *Earthquake prediction by means of change of chemical composition in mineral spring water*, Geophys. Res. Lett. *12*, 510–513.

LANGMUIR, D., *Aqueous Environmental Geochemistry* (Prentice-Hall, New Jersey 1997).

LIN, C.W., CHANG, H.C., LU, S.T., SHIH, T.S., and HUANG, W.C. (2000), *An Introduction to the Active Faults of Taiwan, second edition: Explanatory Text of the Active Fault Map of Taiwan, Scale: 500,000*, Special Publication of Central Geological Survey, 13, 122 pp. (in Chinese with English abstract).

LU, C.Y. (1994), *Neotectonics in the foreland thrust belt of Taiwan*, Petroleum Geol. Taiwan *29*, 1–26.

LU, C.Y. and MALAVIELLE, J. (1994), *Oblique convergence, indentation and rotation tectonics in the Taiwan mountain belt: Insights from experimental modeling*, Earth Planet. Sci. Lett. *121*, 477–494.

MA, K.F., LEE, C.T., TSAI, Y.B., SHIN, T.C., and Mori, J. (1999), *The Chi-Chi Taiwan earthquake: Large surface displacement on an island thrust fault,* EOS, *80*, 605–611.

MUIR-WOOD, R. and KING, G.C.P. (1993), *Hydrological signatures of earthquake strain,* J. Geophys. Res. *98*, 22,035–22,068.

ROJSTACZER, S. and WOLF, S. (1992), *Permeability changes associated with large earthquakes: an example from Loma Prieta, California,* Geology *20*, 211–214.

ROJSTACZER, S., WOLF, S., and MICHEL, R. (1995), *Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes,* Nature *373*, 237–239.

SENO, T. and MARUYAMA, S. (1984), *Paleogeographic reconstruction and origin of the Philippine Sea*, Tectonophys. *102*, 53–84.

SHIN, T. and CHANG, Z. (1992), *Earthquakes in 1992*, Rep. Metro. *38*, 218–232.

SONG, S.R., CHEN, Y.L., LIU, C.M., KU, W.Y., CHEN, H.F., LIU, Y.J., KUO, L.W., YANG, T.F., CHEN, C.H., LIU, T.K., LEE, M. (2005), *Hydrochemical changes in spring waters in Taiwan: Implications for evaluating sites for earthquake precursory monitoring*, Terr. Atmos. Oceanic Sci. *16*, 745–762.

SUGISAKI, R., ITO, K., NAGAMINE, K., and KAWABE, I. (1996), *Gas geochemical changes at mineral springs associated with the 1995 southern Hyogo earthquake ($M = 7.2$), Japan*, Earth Planet. Sci. Lett. *139*, 239–249.

TENG, L.S. (1987), *Stratigraphic records of the late Cenozoic Penglai Orogeny of Taiwan*, Acta Geologica Taiwanica *25*, 205–224.

TENG, L.S. (1990), *Geotectonic evolution of late Cenozoic arc-continent collision in Taiwan*, Tectonophys. *183*, 57–76.

THOMAS, D. (1988), *Geochemical precursors to seismic activity*, Pure Appl. Geophys. *126*, 241–265.

TOUTAIN, J.P., MUNOZ, M., POITRASSON, F., and LIENARD, A.C. (1997), *Springwater chloride ion anomaly prior to a $M_L = 5.2$ Pyrenean earthquake,* Earth Planet. Sci. Lett. *149*, 113–119.

TSAI, Y.B., LIAW, Z.S., LEE, T.Q., LIN, M.T., and YEH, Z.H. (1981), *Seismological evidence of an active plate boundary in the Taiwan area*, Mem. Geol. Soc. China *4*, 143–154.

TSUNOGAI, U. and WAKITA, H. (1995), *Precursory chemical changes in ground water: Kobe earthquake, Japan,* Science *269*, 61–63.

TSUNOGAI, U. and WAKITA, H. (1996), *Anomalous change in groundwater chemistry- possible precursors of the 1995 Hyogo-ken Nanbu Earthquake, Japan,* J. Phys. Earth *44*, 381–390.

YANG, K.M., CHI, W.R., WU, J.C., and TING, H.H. (1994), *Tectonic evolution and mechanisms for the formations of Neogene extensional basins in southwestern Taiwan: Implications for hydrocarbon exploration*, Extended abstract of Ann. Meeting, Geol. Soc. China, 392–395.

YU, S.B. and CHEN, H.Y. (1994), *Global positioning system measurement of crustal deformation in the Taiwan arc-continent collision zone*, Terr. Atmos. Oceanic Sci. *5*, 477–498.

YU, S.B., CHEN, H.Y., and KUO, L.C. (1997), *Velocity fields of GPS stations in the Taiwan area*, Tectonophys. *274*, 41–59.

YU, S.B., KUO, L.C., PUNONGBAYAN, R.S., and RAMOS, E.G. (1999), *GPS observations of crystal deformation in the Taiwan-Luzon region*, Geophys. Res. Lett. *26*, 923–926.

(Received: January 30, 2003, revised: November 28, 2005, accepted: November 30, 2005)