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# The influence of seismotectonics on precursory changes in groundwater composition for the 1995 Kobe earthquake, Japan

Jens Hartmann · Jason K. Levy

**Abstract** It is shown that temporal variation in hydrochemistry may be attributed, in part, to continuous seismotectonic activity occurring before the onset of the 1995 “Kobe” earthquake, Japan, challenging the “one earthquake–one signal” hypothesis with respect to potential precursory signals to this devastating event. A possible continuous seismotectonic influence on chloride and sulphate ion-concentration is evaluated with aggregate earthquake-information by transforming a multivariate earthquake time series (including coordinates and magnitude) into a one-dimensional time series (considering geometric relationships between earthquakes and the well-site). A piecewise analysis of ion-concentration and seismotectonic-activity time series compares trends and change points between the two time series: a positive correlation (before the proposed onset of the preparation stage) is followed by a negative correlation (during the proposed preparation stage) which, in turn, is succeeded by a positive correlation (after the heaviest aftershock sequences). This suggests that seismotectonic processes occurring before the Kobe earthquake dynamically influenced aquifer characteristics, leading to temporal variations in the hydrochemical time series. Accordingly, a dynamic change in the mixing ratios of waters with different hydrochemical characteristics is proposed as a mechanism for explaining observed variation. The research can be extended by considering vectors in the stress field that lead to changes in the aquifer-well system.

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**Résumé** D’après les observations, des fluctuations hydrochimiques temporaires peuvent être partiellement imputées à une activité sismotectonique permanente précédant le début du train d’ondes du séisme de Kobe (Japon) en 1995. Ceci remet en cause l’hypothèse “un séisme – un signal”, concernant les signaux précurseurs potentiels de cet événement dévastateur. Une potentielle influence sismotectonique continue sur les concentrations en ions chlorure et sulfate est estimée par recouplement des informations sismiques, en transformant les séries temporelles multivariées (incluant les coordonnées et la magnitude) en une série temporelle unidimensionnelle (en prenant en compte les relations géométriques entre les séismes et l’emplacement du puits). Une analyse par morceaux des séries temporelles des compositions ioniques et de l’activité sismique compare les tendances et les points d’inflexion entre les deux séries : une corrélation positive (précédant l’amorce des précurseurs) est suivie d’une corrélation négative (synchrone des précurseurs), précédant elle-même au final une corrélation positive (après les répliques les plus intenses). Ceci suggère que les processus sismotectoniques précédant le séisme de Kobe ont influencé dynamiquement les caractéristiques de l’aquifère, causant des variations dans les séries hydrochimiques temporelles. Suivant le même raisonnement, un mécanisme proposé pour expliquer les variations observées implique un changement dynamique dans les proportions de mélange des eaux selon les différents paramètres hydrochimiques. La recherche peut être étendue en prenant en compte les vecteurs du champ de contraintes qui génèrent les changements dans le système puits-aquifère.

**Resumen** Se muestra que la variación temporal en hidroquímica puede atribuirse en parte a la continua actividad sismotectónica que ocurrió antes del inicio del terremoto de 1995 en Kobe, Japón, lo que desafía la hipótesis “un terremoto-una señal” en relación con las señales precursoras potenciales para este evento devastador. Se evalúa una posible influencia sismotectónica continua en la composición de la concentración de iones sulfato y cloruro con información agregada de terremotos mediante la transformación de series de tiempo multivariadas de terremotos (incluyendo coordenadas y magnitud) a series de tiempo en una dimensión (considerando relaciones geométricas entre terremotos y el sitio del

pozo). Un análisis por partes de las concentraciones de iones y series de tiempo de actividad sismotectónica compara tendencias y puntos de cambio entre las dos series de tiempo: una correlación positiva (antes del inicio propuesto de la etapa de preparación) es seguido por una correlación negativa (durante la etapa de preparación propuesta) la cual, a su vez, es continuada por una correlación positiva (después de las fuertes secuencias de réplicas). Esto sugiere que los procesos sismotectónicos que ocurrieron antes del terremoto de Kobe influyeron dinámicamente en las características de los acuíferos, ocasionando variaciones temporales en las series de tiempo hidroquímicas. Por lo tanto, se propone que un cambio dinámico en las relaciones de mezcla de las aguas con las diferentes características hidroquímicas es un mecanismo que explica la variación observada. La investigación puede extenderse tomando en consideración los vectores del campo de esfuerzos que pueden conducir a cambios en el sistema pozo-acuífero.

**Keywords** Hydrochemistry · Tectonics · Kobe · Time series · Earthquake

## Introduction

Many geochemical precursory signals to single earthquakes have been reported in previous decades, as summarized by Hauksson (1981), Toutain and Baubron (1999), Hartmann and Levy (2005) and others. However, previous research has focused on analyzing possible relations between a recognized anomaly in hydrogeological (or geochemical) time series and a recognized single significant earthquake event. Moreover, scientific controversy regarding the existence of precursory signals (Geller 1997) has led to the need for additional precursor research in order to provide additional empirical evidence that earthquake prediction is, in fact, possible. For this reason, more data and more hydrogeochemical and geophysical parameters must be tested to show that there is an “extremely small possibility that the precursors detected occurred randomly and are unrelated to the earthquakes” (Biagi 1999).

Seismotectonic processes have been shown to significantly contribute to the observed variation of hydrogeological (and hydrochemical) time series (e.g. Bolognesi 1997; Biagi et al. 2000; Hartmann et al. 2005). Changes to the mixing ratios of waters of different hydrochemical characteristics constitute the most frequently considered mechanism for the generation of these hydrochemical signals (e.g. Bolognesi 1997). Earthquake-related hydrogeochemical signals can be observed up to several hundred kilometres away from the hypocenter (e.g. Igarashi and Wakita 1990; Zongjin 1990; Bella et al. 1998).

Multiple earthquake related signals have been observed in some long-term monitoring stations (e.g. Igarashi and Wakita 1990; Zongjin 1990; Bella et al. 1998), indicating the possibility of a long-term seismotectonic influence on the variation of a monitoring time series. Even small

earthquakes ( $M < 3$ , with  $M$  as moment magnitude) may contribute to a detectable response in a hydrochemical groundwater time series (Bolognesi 1997) and aseismic tectonic activity in fault systems may temporarily affect permeability (Wakita et al. 1980). Mechanisms leading to pre- and postseismic signals such as permeability changes and alterations to the mixing ratios of hydrochemically different waters, are discussed in Montgomery and Manga (2003), Hamza (2001), Heinicke and Koch (2000) and Bolognesi (1997).

## Analysis of earthquake related signals

Toutain et al. (1997) present a distinct, nearly binary, earthquake-related signal in response to seismotectonically induced aquifer changes. This binary response results in a sharp increase of chloride ion concentrations that return to previous levels several days after the reported earthquake. Such an observation is normally interpreted as a “one earthquake—one signal” event (either postseismic, preseismic or coseismic, depending on whether the signal starts after, before or at the same time as the referenced earthquake). In seismotectonically active regions, it is often difficult to ascertain whether a proposed time-series signal is related to a single earthquake event (occurring either before or after the signal). Shapiro et al. (1980) present a signal in a seismotectonically active region, which may be related to a seismic event before or after the identified signal, thereby illustrating the difficulties in determining whether a signal is pre- or postseismic.

Hauksson (1981), Toutain and Baubron (1999) and Hartmann and Levy (2005) provide an overview of proposed earthquake-related precursory signals, analysing the relationships among signal attributes such as earthquake magnitude, epicentral distance, precursory time or signal duration. They show that the potential maximum of both the epicentral distance and the signal duration can be described as a function of magnitude. Montgomery and Manga (2003) identify similar findings for hydrological coseismic and postseismic signals related to single earthquakes.

These insights indicate a possible interconnection among (1) the released seismic energy, (2) the geometric relationship between the hypocentral area and the monitoring site and (3) the time between the two considered events. However, there is an absence of standardized analysis techniques and algorithms for investigating the preliminary variation of signals before the onset of the related major earthquakes in relation to the available seismotectonic information. Developing such techniques may prove valuable for uncovering processes related to signal creation. Accordingly, an analysis technique is herein proposed and discussed in order to investigate the link between temporal variations in a hydrochemical time series and calculated functions of earthquake activities. In particular, aggregate earthquake information is used to provide insights into the existence and complexity of empirical precursors by analysing the relationship between

temporal variations in a hydrochemical time series and seismic activity. The Kobe (Hyogo-ken) earthquake, Japan, is used as a case study to investigate the influence of seismotectonic activity on changes in groundwater composition before the devastating seismic event of 17 January 1995. The case study location is shown in Fig. 1. Finally, the extent to which seismotectonic processes influence the temporal hydrochemical variation in the composition of the well water is investigated, strengthening the argument that seismotectonics can dynamically influence permeabilities or other aquifer characteristics (Muir Wood 1994; Stephenson et al. 1994).

### The 1995 Kobe earthquake and the detected hydrochemical signal

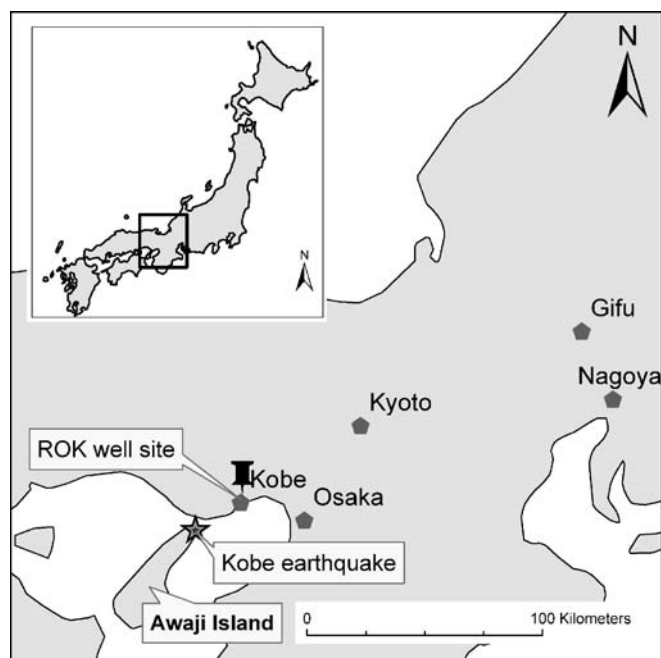
Japan is located at the intersection of three tectonic plates: the Eurasian, the Philippine and the Pacific plates. Most seismotectonic activity in Japan is related directly or indirectly to the subduction of the Pacific and the Philippine plates. Kobe is located in the active Awaji-Rokko Fault System (Kanaori and Kawakami 1996), north of the easternmost left-stepping bend of the dextral median tectonic line, MTL (Itoh et al. 2000).

An earthquake with magnitude  $M=7.2$  struck Kobe and surrounding regions at 5:46 am on 17 January 1995, (Fig. 1; Kanaori and Kawakami 1996), leading to more than 5,500 deaths. The earthquake's quadrant-type focal mechanism (with a maximum compression axis in an east-west direction) caused a distinct 9-km rupture along

the pre-existing Nojima fault, in the northeast of Awaji Island. After this earthquake, Tsunogai and Wakita (1995) analysed previously bottled groundwater from two wells in the Rokko Mountains. Beginning in August 1994, chloride and sulphate ion concentrations gradually increased leading to statistically significant extrema (Johansen et al. 1996). The highest pre-earthquake concentration levels were recorded on 13 January, 4 days before the major earthquake (Tsunogai and Wakita 1995, 1996; Silver and Wakita 1996).

The ion concentrations in the water samples taken after the earthquake event continued to increase for approximately 4 weeks, followed by a decrease. The increasing trend in dissolved ion concentrations before the earthquake event has been interpreted as a potential earthquake precursory signal to the single referenced earthquake. Additional potential precursory signals and phenomena associated with the Kobe earthquake event have been reported from a number of monitoring sites in the earthquake vicinity (Sato et al. 1995; King et al. 1995; Igarashi et al. 1995).

This report presents results of an investigation into whether the observed variation in chloride and sulphate concentrations before the Kobe earthquake is related to seismotectonic processes before this event. Tsunogai and Wakita (1996) conclude that the chloride variation in the analysed ROK wells (located in the Rokko Mountains) is likely to be the result of the mixing of normally separated fluids induced by a breaking of barriers. Tsunogai and Wakita (1996) state that this is related to processes resulting in the single major earthquake under consideration.



**Fig. 1** The monitoring station discussed (ROK well 1 and 2) is located in the granitic mountains rising behind the city of Kobe (Osaka Bay) and 20 km east of the main earthquake event, which occurred on the northeast side of Awaji Island, Japan (marked by a star)

### The study site

Tsunogai and Wakita (1996) used commercially bottled water from the ROK-site for hydrochemical analysis. The bottled water is a mixture of waters from two 100-m-deep wells, mixed in a fixed ratio of 60:40. The stability of the ratio was confirmed by further analysis. These two wells, separated by a distance of 50 m, are located 20 km east of the epicentre of the Kobe earthquake in the granitic Rokko Mountains behind the coastline of Kobe. Table 1 gives an overview of the hydrochemical composition of both well waters and the variation of the analysed parameters. Only the time series of well 1 shows a significant variation. The variation of the second well is very low, as illustrated by the extrema in Table 1. It is unclear if the detected changes in hydrochemical composition are the result of groundwater composition changes in the sampled aquifer(s) or the result of alterations to the mixing ratios of genetically different waters in the well itself. The authors are unaware of any other research that provides additional insights on this issue.

Between 25 July 1990 and 4 April 1995, chemical analyses were performed on 79 samples. Further analysis (using additional samples from the two wells separately before the major earthquake event), confirmed that the variation in the chemical composition of the bottled water

**Table 1** Chemical characteristics of the two ROK wells (Tsunogai and Wakita 1996)

	Valid N	Mean	Median	Minimum	Maximum	10-Percentile	90-Percentile	SD
Well 1								
Cl <sup>-</sup>	19	18.5	19.3	16.4	19.4	16.5	19.4	1.1
SO <sub>4</sub> <sup>2-</sup>	19	26.7	28.8	20.0	29.5	21.3	29.4	3.4
Si	15	10.6	10.2	9.7	12.6	9.9	12.2	0.9
Mg <sup>2+</sup>	15	5.2	5.2	5.0	5.6	5.1	5.4	0.1
Ca <sup>2+</sup>	15	30.4	31.2	28.1	32.0	28.2	31.8	1.6
Sr <sup>2+</sup>	15	121.7	125.6	109.6	129.3	111.7	128.5	6.9
Ba <sup>2+</sup>	15	13.4	14.1	9.3	16.9	10.6	16.2	2.1
Na <sup>+</sup>	15	16.2	16.2	15.6	17.1	15.7	16.7	0.4
Well 2								
Cl <sup>-</sup>	19	13.9	14.0	13.5	14.1	13.7	14.1	0.1
SO <sub>4</sub> <sup>2-</sup>	19	14.6	14.8	14.1	14.9	14.3	14.9	0.2
Si	15	14.8	14.8	14.0	15.2	14.5	15.1	0.3
Mg <sup>2+</sup>	15	4.7	4.7	4.6	4.9	4.6	4.9	0.1
Ca <sup>2+</sup>	15	22.9	22.9	22.0	23.5	22.3	23.3	0.4
Sr <sup>2+</sup>	15	89.5	89.8	86.2	92.2	87.0	91.6	1.7
Ba <sup>2+</sup>	15	8.6	8.6	6.6	10.6	7.6	10.6	1.1
Na <sup>+</sup>	15	14.5	14.4	14.0	15.0	14.1	14.7	0.3

The additional samples were taken from each well between October 1995 and April 1996. Values are given in ppm (parts per million), with the exception of Sr and Ba (*ppb* parts per billion). *SD* standard deviation

was caused by only one of the wells (well 1). After the Kobe earthquake, additional samples were taken from both wells because the disaster disrupted the distribution of bottled water (Tsunogai and Wakita 1996). The chemical composition of the second well was stable throughout the observation period. The uncertainties in the absolute ion-concentrations were less than 5% for individual ions and repeated sampling reduced measurement errors. For example, chloride measurement errors were reduced to less than 0.3%.

Tsunogai and Wakita (1996) identified a strong correlation between the chloride and sulphate parameters (correlation coefficient  $r=0.94$ ); Kuroda et al. (1981) found a similar correlation in the Rokko Mountains. Kusaka et al. (1982, in Tsunogai and Wakita 1996) note that, from deeper to shallower groundwater, an increase in chloride and sulphate is accompanied by a decline in silica and sodium. This is consistent with a negative correlation (correlation coefficient  $r=-0.71$ ) between chloride and silica in the sampled water (Tsunogai and Wakita 1996) and suggests the mixing of two end members (probably shallower and deeper groundwater) in well 1 (Table 1). However, Tsunogai and Wakita (1996) note that it is implausible to assume that pressure changes were responsible for hydrological changes in the aquifer. Instead, they propose that a possible fracture of barriers between aquifers with different chemical signatures might be responsible for the chloride concentration increase before the Kobe earthquake. On the other hand, related changes in permeability due to the earthquake preparation process may account for changes in the groundwater mixing process of the identified end members (Johansen et al. 1996). It is also possible that the observed variation is caused by mixing processes related to the well settings. Such a mechanism has been repeatedly demonstrated at other sites (e.g. Bolognesi 1997; Bella et al. 1998; Hartmann et al. 2005). The presence of local and absolute extrema in the chloride

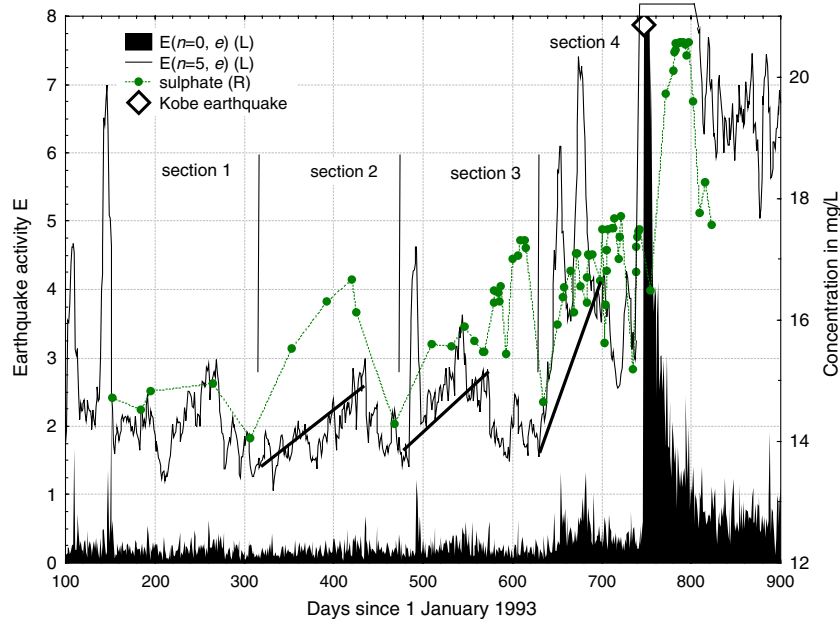
time series (Johansen et al. 1996) suggests the occurrence of mixing ratio changes over time, giving rise to the question of whether the mixing ratios are affected by a dynamic process.

## Methodology

Temporal variations in the chloride and sulphate ion concentrations (Figs. 2 and 3) can be interpreted as a typical earthquake related signal, displaying a significant increase in ion concentrations before the onset of the considered major earthquake, leaving previous confidence intervals. Hartmann and Levy (2005) summarize this category of signals. The identification of continuous seismotectonic influences on geochemical time series can be problematic if the only available information is anticipated to be related to a single (major) earthquake. A methodology is put forth to address this problem which incorporates the findings of previous studies (Hauksson 1981; Toutain and Baubron 1999; Montgomery and Manga 2003; and Hartmann and Levy 2005) and uses relationships among the following three fundamental categories of variables:

1. Released seismotectonic energy represented by a function of magnitude
2. Geometrical relationships between seismotectonic activity and the monitoring site
3. Time

Aggregation functions of observed seismotectonic activity are defined and compared with identified sections in the measured hydrochemical time series in order to investigate whether, before the occurrence of the Kobe earthquake event, variation in the hydrochemical time series is related to variation in seismotectonic activity. This comparison is valid since a change in



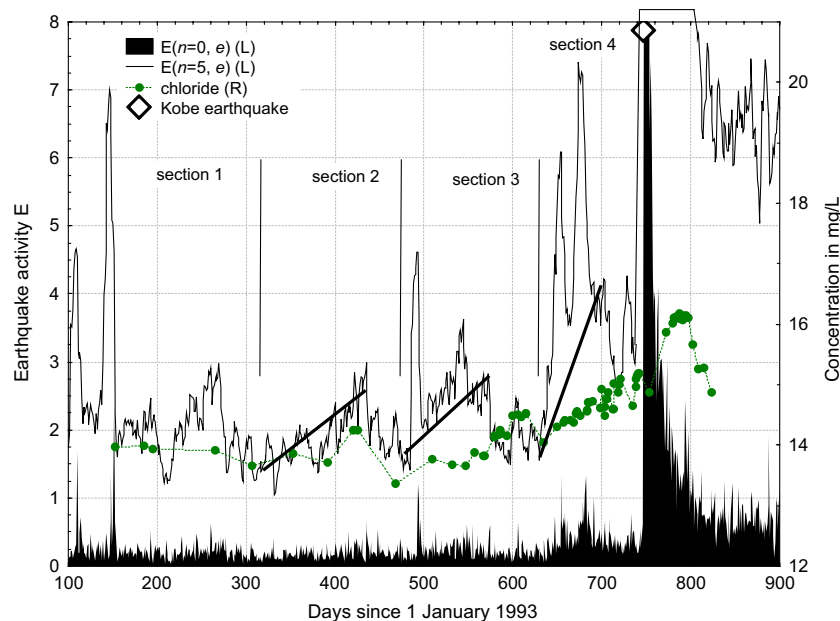
**Fig. 2** Comparison of  $E(n=0$  and  $n=5$ ,  $e=10^M/D_{epi}^2$ ) representing factor 1 and sulphate concentrations gained from the water samples taken from the ROK wells (see Tables 2 and 3);  $E(n, e)$  is the sum

of all  $e$  parameters within a given time interval ( $n$  days). The Kobe earthquake occurred on day 747. The letters  $L$  and  $R$  refer to the left and right axes in the figure

the mixing ratio of waters of different genesis in aquifers (or wells) may cause changes to a well's (or a spring's) water chemistry composition, which are often related to seismotectonic processes (Bolognesi 1997; Hartmann et al. 2005; Hartmann 2005a). Two major difficulties arise when analysing the relationship between an earthquake time series and a monitoring time series. First, the earthquake time series is not a univariate, but at least a four-dimensional time series (energy and three spatial

coordinates of the location). Moreover, geometrical relationships between the observed seismic event and the monitoring site are different for each earthquake. Second, the temporal occurrence of earthquakes is neither equidistant nor synchronous with the water sampling time.

To overcome these difficulties, a time-series transformation is proposed: univariate functions of earthquake activities,  $E$ , with equidistant time steps (according to



**Fig. 3** Comparison of  $E(n=0$  and  $n=5$ ,  $e=10^M/D_{epi}^2$ ) representing factor 1 with the chloride concentrations gained from the water samples taken from the ROK wells. The Kobe earthquake occurred on day 747. The letters  $L$  and  $R$  in the labels refer to the left and right axes in the figure

**Table 2** Different  $e$ -parameter definitions were used based on physical and geometrical considerations and the following variables

1. $e=M$	2. $e=10^M$	3. $e=M/D_{\text{hypo}}$	4. $e=M/D_{\text{hypo}}^3$
5. $e=10^M/D_{\text{hypo}}$	6. $e=10^M/D_{\text{hypo}_2}^3$	7. $e=M/D_{\text{epi}}$	8. $e=M/D_{\text{epi}}^2$
9. $e=10^M/D_{\text{epi}}$	10. $e=10^M/D_{\text{epi}_2}$	11. $e=1/\text{depth}$	12. $e=1/\exp(\text{depth})$
13. $e=M/\text{depth}$	14. $e=10^M/\text{depth}$	15. $e=10^M/\text{depth}^3$	16. $e=\varepsilon_{\text{dobro}}=10^{(1.3Ma^{8.19})}/D_{\text{epi}}^3$

Moment magnitude ( $M$ ), epicentral and hypocentral distance ( $D_{\text{epi}}$  and  $D_{\text{hypo}}$ ) and the depth of the earthquake event (depth).

Parameter 16 is calculated according to the epsilon parameter of Dobrovolsky et al. (1979) and estimates the released stress attributed to a single earthquake

groundwater sampling times) are defined, transforming the seismic observations according to the following two steps (Hartmann et al. 2005).

### Step 1

Transformation of the earthquake time series into a univariate time series. The multivariate earthquake time series is transformed into a univariate time series. Each earthquake is expressed as a single parameter “ $e$ ”. Based on previous research (Toutain and Baubron 1999; Montgomery and Manga 2003; Hartmann and Levy 2005),  $e$  is composed of an energy component of the earthquake and/or a component expressing the geometrical ratio of the relationship between the earthquake and the monitoring station, e.g.  $e=M/D_{\text{epi}}$  (with  $M$  as magnitude and  $D_{\text{epi}}$  as the epicentral distance). It is important to note that as  $D_{\text{epi}}$  increases, the influence of the earthquake decreases. In addition, the parameter  $\varepsilon$  (which estimates the stress release attributed to a single earthquake) is calculated (Dobrovolsky et al. 1979) because it is frequently used for analysing seismotectonic influence on hydrogeological time series (e.g. Bella et al. 1998). The sixteen  $e$ -transformations used in this study (Table 2) represent the most fundamental relationships between the energetic component of an earthquake and/or the geometrical relationship between earthquake location and monitoring site.

### Step 2

Synchronisation of the earthquake and monitoring time series. An earthquake activity function,  $E(n, e)$ , is calculated.  $E(n, e)$  is the sum of all  $e$ -parameters that occur within  $n$  days before and after the sampling time  $t_k$ .

$$E_t = \sum_{t-n}^{t+n} e_i \quad (1)$$

In other words,  $E(n, e)$  represents the sum of all  $e$ -parameters within a considered time interval. For example,  $n=0$  represents the sum of all  $e$ -parameters on day  $t$  while  $n=5$  represents the sum of all  $e$ -parameters within the time interval of  $t-5$  days to  $t+5$  days.

Factor analysis (Bortz 1993), or other conventional linear approaches (Hartmann 2005a,b; Hartmann et al. 2005), can be used to group  $E(n, e)$  variables on “independent, hidden” factors (according to the underlying

ing correlation matrix) since  $E(n, e)$  values depend on the spatial-temporal earthquake distribution (Hartmann et al. 2005). Resulting groups are not necessarily based on the similarity of  $e$ -transformations because transformations are highly non-linear and, most importantly, earthquakes are not equally distributed in time and space. To reduce the number of  $E(n, e)$  values required for comparison with the hydrochemistry, a factor analysis with orthogonal varimax rotation (Bortz 1993) is performed, yielding a factor loading index number. This index number not only provides insights into the strength with which a variable fits the extracted factor (Table 3), but also helps to interpret similarities among variables. Bortz (1993) notes that when the factor loading index number exceeds 0.707, more than half of the variance in the variables can be explained by an extracted factor.

If an  $E(n, e)$  yields a high correlation on an extracted factor, then both the  $E(n, e)$  and this extracted factor will have a similar time series. Even if the  $e$  parameters are defined differently, the energetical–geometrical pattern of seismic events may lead to similar  $E(n, e)$  patterns resulting in high correlations (Hartmann 2005b). This helps to limit the number of  $E(n, e)$  under consideration for further analysis.

The long-term increase in chloride concentration during the proposed preparation stage is non-linear, with significant extrema (Johansen et al. 1996) as confirmed by

**Table 3** Factor analysis with varimax rotation of the earthquake activities  $E$  with  $n=0$ 

$e=$	Factor 1	Factor 2
$M$	0.86	0.40
$\varepsilon_{\text{dobro}}$	0.97	0.09
$10^M$	0.97	0.11
$M/D_{\text{hypo}_3}$	0.95	0.15
$M/D_{\text{hypo}_2}$	0.96	0.13
$10^M/D_{\text{hypo}_3}$	0.98	0.09
$10^M/D_{\text{hypo}_2}$	0.98	0.09
$M/D_{\text{epi}_2}$	0.96	0.15
$M/D_{\text{epi}}$	0.96	0.15
$10^M/D_{\text{epi}_2}$	0.98	0.09
$10^M/D_{\text{epi}}$	0.98	0.09
$1/\text{depth}$	0.61	0.75
$1/\exp(\text{depth})$	-0.09	0.92
$M/\text{depth}$	0.62	0.75
$10^M/\text{depth}$	0.95	0.23
$10^M/\text{depth}^3$	0.00	0.81
Variance	11.76	2.98
Proportional to total variance	0.74	0.19

Two factors were extracted, representing 93% of the total observed variance

the presence of systemic shifts or significant changes in the time series of neighbouring monitoring stations (King et al. 1995). Based on previous work from Johansen et al. (1996) and King et al. (1995), the chloride time series is divided into relevant sections in order to compare the behaviour of the chloride and the  $E(n, e)$  time series. Two methods were selected for this comparison: (1) a direct comparison of both time series and (2) a correlation analysis of  $E(n, e)$ -values and hydrochemistry using previously defined time-series sections and well-water sampling times.

## Analysis

$E(n, e)$  for  $n=0$  and  $n=5$  were calculated using earthquakes with magnitude greater than 2 within a distance of 500 km from the ROK-site using data provided in the earthquake catalogue of the Meteorological Institute of Japan (MIJ). The factor analysis of the calculated  $E(n, e)$  for  $n=0$  results in two factors (Table 3). The scree-test (Bortz 1993) was used to determine the number of significant factors (eigenvalue of the matrix  $<1$  as exclusion criteria). The factors are assumed to be independent because the varimax rotation does not change the angle between extracted factors and preserves factors orthogonal to each other. The two extracted factors in Table 3 explain 93% of the total variance within the calculated  $E(n, e)$ . Each of the sixteen variations of the  $e$ -parameter shows a strong correlation with one of the two extracted factors. For this discussion, the high correlations on the extracted factors enable the use of only two representative  $E(n, e)$ . The extracted factors represent the region's earthquake activity during the time period under consideration and may not be representative for the analysis of other time periods. Chloride and sulphate were chosen for analysis because all values were present, whereas silica (and other analysed variables) contained missing values).

Johansen et al. (1996) analysed the shape of the chloride time series in Fig. 3 by comparing it with other earthquake related signals; they identified significant extrema in the chloride time series by using a fitted function of log-periodic modulations around a leading power law. The most significant minima coincided with two phenomena: the global minimum of the chloride time series around day 480 (April 1994) and a strong local minimum around day 635 (October 1994), which coincided with systemic shifts in water temperature and pressure in neighbouring monitoring stations (King et al. 1995).

Four pre-Kobe-earthquake sections are defined based on local and global minima in the chloride concentration time series. Tsunogai and Wakita (1995) suggest that the global minimum occurs at the beginning of the earthquake precursory stage (reflecting the preparation stage of the Kobe earthquake). At this minimum, the chloride time series is divided into two parts (before and after day 480). The first part is further broken into two sections (section 1 and 2) based on a dividing point in the chloride-and

sulphate time series around day 307. Taking into account the strong local minimum at day 635 (which coincides with systemic shifts in neighbouring monitoring stations), the second section of the time series is divided into two additional parts (section 3 and section 4). It follows that four sections can be identified, demarked by vertical lines in Figs. 2 and 3: (1) days 0–307, (2) days 307–480, (3) days 480–635 and (4) days 635–738.

## Results

Figures 2 and 3 compare the temporal variation in the time series of the sulphate and chloride ion concentrations with the temporal variation in the time series of  $E(n=0, e=10^M/D_{\text{epi}}^2)$  and  $E(n=5, e=10^M/D_{\text{epi}}^2)$ , representing factor 1 of the earthquake activities in Table 3. The Kobe earthquake was observed on day 747 of the analysed time-period (day 1 corresponds to 1 January 1993). In sections 2, 3 and 4, the time series of both the ion concentrations and  $E(n=5, e=10^M/D_{\text{epi}}^2)$  show similar trend characteristics: an increase followed by a decrease. A time lag exists between the decrease of  $E(n=5, e=10^M/D_{\text{epi}}^2)$  and the corresponding decrease of the ion concentrations in sections 3 and 4 of the time series. Insufficient hydrochemical data is present in section 1 to characterize the behaviour of the ion concentration time series.

The most significant increase in  $E(n=5, e=10^M/D_{\text{epi}}^2)$  representing factor 1 occurs in section 4, the time period immediately before the Kobe earthquake (days 635–738). The associated ion concentration increase in section 3 has been interpreted, together with section 4, as part of a possible precursory signal (Tsunogai and Wakita 1996).

Figure 4 shows  $E[n=5, e=1/\exp(\text{depth})]$  representing factor 2 in Table 3, along with the time series of the chloride and sulphate ion concentrations. In this case, no clear periodic relationship between seismotectonic activity and hydrochemical variation can be identified. This suggests that seismotectonic processes related to factor 2 have no influence (or at best a minor influence) on the behaviour of the hydrochemical time series during the analysed period.

Figure 5 shows the correlations and their trends between  $E(n=5, e=10^M/D_{\text{epi}}^2)$  at well water sampling times and the chloride concentration time series for four sections. For both sections 1 and 2, the regression correlation coefficients are  $r=0.29$ . For sections 3, 4, and the section after the Kobe earthquake, the regression correlation coefficients are  $r=-0.71$ ,  $r=-0.62$  and  $r=0.88$ , respectively.

A double trend change is evident: in particular, a positive correlation in the pre-precursory period is followed by a negative correlation (in sections 3 and 4) of the supposed preparation-stage period and a positive correlation (in the “after Kobe earthquake” section), giving rise to the two correlation patterns shown in Fig. 5. The associated correlation coefficient for the entire data set is  $r=0.87$ . This indicates a strong positive correlation between  $E(n, e=10^M/D_{\text{epi}}^2)$  and the chloride ion concentration. In the correlation analysis, five

outlying samples coinciding with the extreme aftershock sequence (immediately after the Kobe earthquake) were removed ( $E > 20$ , up to 158), leading to the distinct trends shown in Fig. 6. The system leaves temporarily normal patterns, as indicated by the strong correlation of the remaining cases.

## Discussion

### Discussion of earlier work

Tsunogai and Wakita (1995, 1996) classify the increasing trend in the chloride and sulphate concentrations (starting at the beginning of section 3 on day 480), as a possible precursor to the Kobe earthquake; they also found that other factors had no influence on the composition of the well water. However, similarities in the behaviour of the ion concentration time series and the  $E(n=5, e=10^M/D_{\text{epi}}^2)$  time series suggest the possibility that long-term seismotectonic processes dynamically influence the proposed mixing process of ion concentrations in the well water.

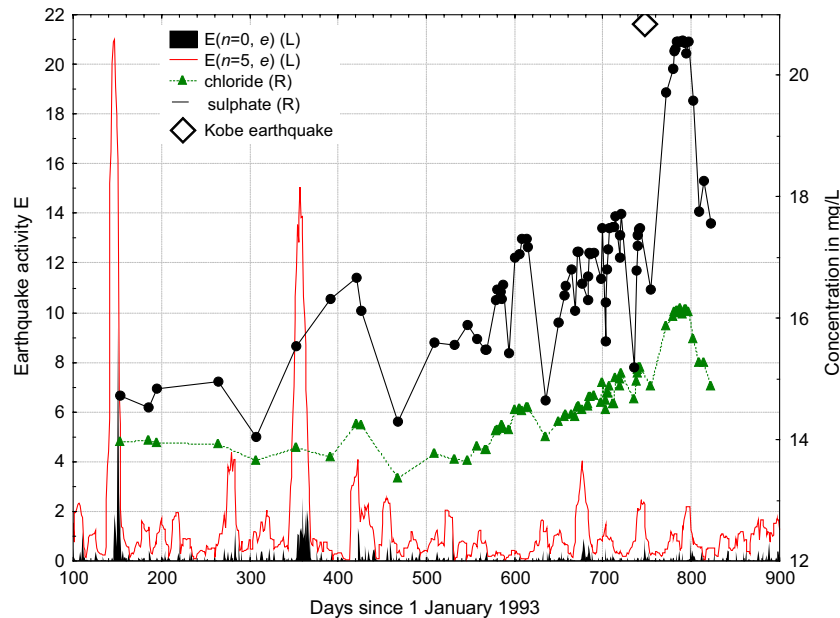
By considering local geological conditions, Tsunogai and Wakita (1995, 1996) note that changes in observed groundwater chemistry might reflect processes in the shallow crust, thereby changing permeability in the stratum before and after the considered major earthquake. Furthermore, Tsunogai and Wakita (1996) argue that the increasing ion concentration trends (beginning several months before the earthquake) may reflect the preparation stage of the main earthquake rupture. They suggest that this increase in ion concentrations can be explained by a breaking of the barriers between aquifers (separated before the Kobe earth-

quake). The possibility that the signal was caused by well-water mixing processes has, to the knowledge of the authors, not been previously discussed. Finally, there is insufficient information for determining the exact mechanism responsible for the observed changes to ion concentrations.

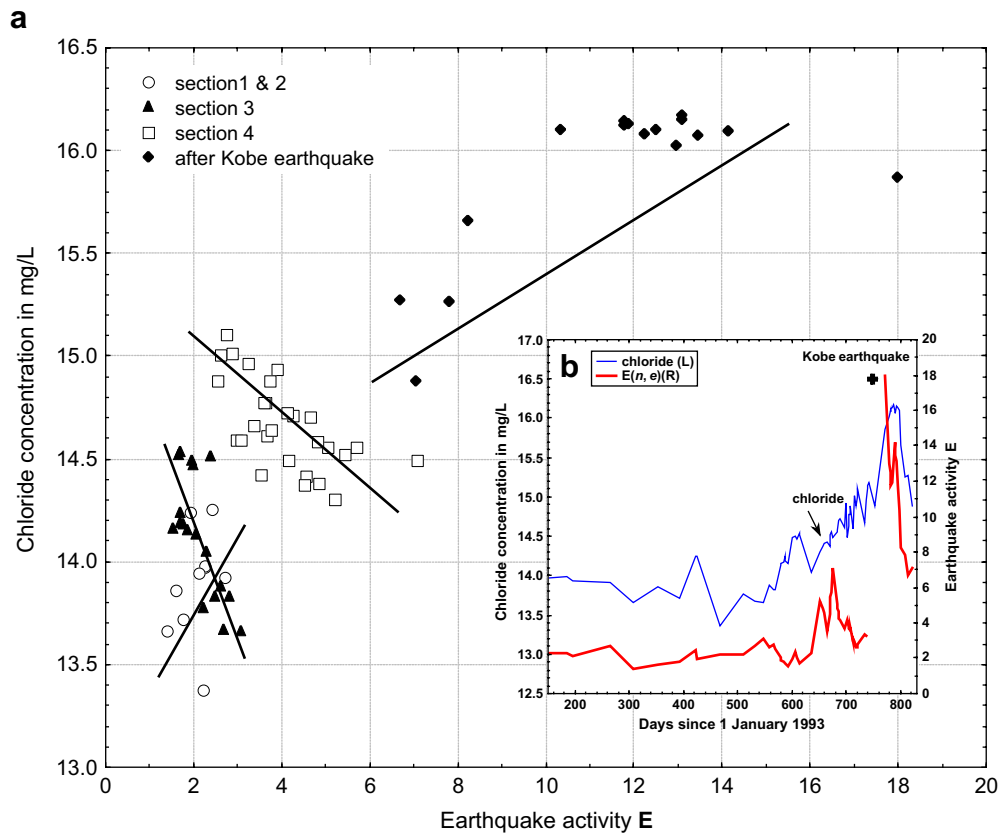
### Discussion of the results

Chloride and sulphate ion concentrations positively correlate with an increase of calculated  $E(n=5, e=10^M/D_{\text{epi}}^2)$  at the beginning of sections 2, 3 and 4 (Figs. 2 and 3). In sections 3 and 4, the decrease in the ion concentration time series exhibits a time lag with respect to the decrease in the  $E(n, e)$  time series, resulting in the observed negative correlation for both sections. This may be attributed in part to a sub-optimal selection of the  $e$ -transformation and earthquake events, in addition to uncertainties associated with the mechanism responsible for mixing waters with different chemical compositions in the aquifer or well.

Comparing the behaviour of these time series provides insights into the unknown proposed mixing mechanism of the two identified end members. In particular, higher values of  $E(n=5, e=10^M/D_{\text{epi}}^2)$  correlate with an increase in chloride and sulphate concentrations at the beginning of sections 2, 3 and 4, indicating that the ratio of one end member is increased. When  $E(n=5, e=10^M/D_{\text{epi}}^2)$  decreases, the increasing trend in ion concentrations in sections 3 and 4 (the proposed preparation stage) continues for a significant length of time. Moreover, in both sections 3 and 4,  $E(n=5, e=10^M/D_{\text{epi}}^2)$  are higher than in section 2 (considering the aggregation time  $n=5$ ). After the major earthquake event, the start of the decrease in chloride concentration is



**Fig. 4** Comparison of  $E[n=0$  and  $5, e=1/\exp(\text{depth})]$  representing factor 2 and the chloride and sulphate concentrations gained from the water samples taken from the ROK wells. The Kobe earthquake occurred on day 747. The letters  $L$  and  $R$  refer to the left and right axes in the figure



**Fig. 5 a** Scatterplot of  $E(n=5, e=10^M/D_{\text{epi}}^2)$  and chloride concentration showing the relevant sections for trend analysis. A double trend change from a positive in the proposed pre-precursory stage of the Kobe earthquake to a negative trend during the

precursory stage (sections 3 and 4) and back to a positive trend after the Kobe earthquake can be observed. **b** Time series courses of ion concentration and earthquake activity during the observation period

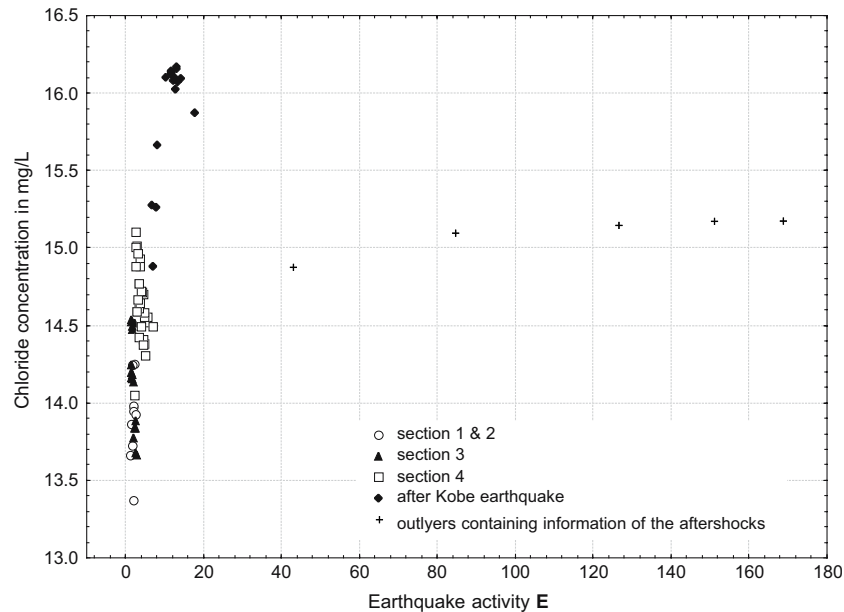
delayed when compared to the change point in earthquake activity  $E$ .

In section 2, the increasing trend in  $E(n, e)$  continues longer than the chloride concentration trend. However, the  $E(n, e)$  peaks are lower than in sections 3 and 4 and after the Kobe earthquake. Insufficient data exists in section 1 for a separate analysis. The negative correlation between chloride ion concentration and  $E(n=5, e=10^M/D_{\text{epi}}^2)$  in sections 3 and 4 is partly caused by the decoupling of the increasing trends.

The data provide at least four occurrences which suggest that the previously proposed mechanism, a breaking of barriers, is insufficient for explaining the decreasing ion concentration trends after periods of increased earthquake activity. Accordingly, it is proposed that seismotectonic activity dynamically alters the strain–stress field, thereby influencing the aquifer–well system and hence the mixing ratio of waters. This provides an alternative hypothesis to the suggestion that processes related to a single seismic event are responsible for the temporal variation in the ion concentration time series (Tsunogai and Wakita 1996); in this interpretation, the presence of other seismotectonic activity is excluded. However, variation in earthquake activity before the Kobe earthquake may be related to its preparation stage (Johansen et al. 1996).

It is observed that strong local minima in  $E(n, e)$  demark the start of longer lasting increasing trends. On the other hand, a decoupling of trends is observed. Three possibilities are put forth to account for these observations: (1) the mixing mechanism is partly inert due to a decrease in earthquake activity, (2) the increase in seismotectonic activity influences the mixing process in a way that endures even after a period of strong earthquake activity, (3) the calculated  $E(n, e)$  fails to sufficiently capture the trend changes in the mixing ratio time series.

The proposed method provides a new perspective for examining the relationships between the temporal variation in ion concentrations before the onset of major earthquakes (and regional earthquake activity). The reported 10-fold coseismic increase in the discharge level in a neighbouring observation well (Tsunogai and Wakita 1996) provides further evidence that seismotectonics may dynamically affect aquifer conditions in the study region. Other signals possibly related to the Kobe earthquake have been reported for hydrogeological (groundwater discharge), gas-geochemical (radon), and geophysical (crustal strain) monitoring time series (Tsunogai and Wakita 1996; Silver and Wakita 1996; Igarashi et al. 1995), indicating a change in permeability, pore pressure, or other aquifer conditions.



**Fig. 6** Scatterplot of  $E(n=5, e=10^M/D_{epi}^2)$  and chloride concentration including five points coinciding with highly increased earthquake activity values ( $E > 20$ ) containing information from the aftershock period directly after the main event. Only the five

observations, directly after the Kobe earthquake, left clearly normal patterns, coinciding with extraordinarily strong calculated earthquake activities  $E$

The results also suggest that aquifer conditions in the region were altered significantly before the major earthquake event. When taken together with the trend analysis for the analysed sections, they also provide two important pieces of evidence for supporting the hypothesis that seismotectonics dynamically influence the aquifer system. First, the correlation analysis includes data from before the previously supposed barrier break. Second, ion concentrations decrease after the onset of increased seismotectonic activity. In addition, the preparation stage of the Kobe earthquake may have influenced the aquifer system before the previously proposed break of barriers around day 480, causing a significant high variance in earthquake activity before this time.

### **The relevance for further research**

The proposed analysis algorithm can be used to test whether groundwater-monitoring sites are sensitive to seismotectonic activity and to analyse proposed earthquake precursory signals. This research presents a serious challenge to the one earthquake–one signal paradigm. Accordingly, the development of more sophisticated methods for the analysis of supposed earthquake precursors and their underlying mechanisms is encouraged. The methodology herein proposed and described can be easily adapted by modifying  $e$ -parameter definitions, selecting different earthquake events and including knowledge of regional tectonic settings. The additional detection of systemic shifts or signals in monitoring time series from sites, close to the ROK well site, suggests that future

earthquake-precursor research should combine a variety of techniques for the identification of earthquake precursors. In Japan, groundwater-monitoring networks are established with the purpose of identifying earthquake precursors (Oki and Hiraga 1988). These kinds of networks might be a suitable backbone for future research on the characteristics of earthquake-related signals using aggregated earthquake information.

Bernard (2001) proposes that future research should focus on transients (such as fluid instabilities and episodic fault creep) because previously identified supposed precursors occur infrequently. The analysis technique put forth in this report is expected to aid in the search for trend changes in the relationship between groundwater composition and  $E(n, e)$ . Alternatively, representative functions of strain tensors can be used.

Molchan (1997) notes that earthquake prediction also involves decision making, i.e. defining which of the several possible types of alerts should be declared. An optimal earthquake prediction strategy should take into account all relevant information sources in order to better support earthquake decision making. The proposed analysis algorithm can provide additional information about the relationship between hydrochemical time series and seismotectonic activity, thereby enhancing earthquake-prediction decision support. However, a reliable earthquake alert system requires the verification of station stability and sensitivity (a monitoring site must be demonstrably sensitive to seismotectonics). Finally, mechanisms must be understood in sufficient detail in order to detect earthquake-related signals.

## Conclusions

Functions of aggregated earthquake information were compared with hydrochemical groundwater changes in order to investigate proposed earthquake precursory signals. The suggested earthquake activity concept shows that the time series of potential precursory signals can be partly correlated with seismotectonic activity before a major earthquake takes place. The use of aggregation functions provides additional insights about the relationship between the hydrochemical time series and seismotectonic activity beyond information gleaned from the traditional one earthquake–one signal analysis. The method introduced is also suitable as a decision-making tool if a monitoring site is sensitive to seismotectonics; a positively identified monitoring site can be included in an earthquake prediction and mitigation network.

Previous work has interpreted the presented temporal variation in ion concentrations as a precursory signal to the Kobe earthquake. The current work established a strong correlation between calculated earthquake activity  $E(n, e)$  and the ion concentration time series for distinguished sections, based on minima in the ion concentration curves. It follows that  $E(n, e)$  variations before the Kobe earthquake may be interpreted as part of a precursor to a major earthquake, indicating the preparation stage of the Kobe earthquake. The temporal variation in the ion concentrations can also be interpreted as a long-term effect due to changed aquifer–well conditions (responsible for altering the mixing ratios of waters with different hydrochemical signatures) because of variations in seismotectonic activity.

The  $E(n, e)$  definition of earthquake activity used in this study constitutes an aggregate function of seismic activity. It is recommended that future work extend the  $E(n, e)$  concept by considering vectors in the stress field that result in changes to the aquifer (or well) environment. This, in turn, may help identify detailed mechanisms leading to differences in the mixing ratios of waters with different hydrochemical signatures, providing insights into the search for earthquake precursors.

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