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7 authors, including:


Simon Kingsley
The University of Sheffield


P. F. Biagi
Università degli Studi di Bari Aldo Moro


Vito Capozzi
Università degli studi di Foggia


E. I. Gordeev
Institute Of Volcanology And Seismology

Pergamon

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Hydrogeochemical Precursors of Strong Earthquakes: A Realistic Possibility in Kamchatka

S. P. Kingsley[1], P. F. Biagi[2], R. Piccolo[2], V. Capozzi[3], A. Ermini[4], Y. M. Khatkevich[5] and E. I. Gordeev[5]

[1]Sheffield Centre for Earth Observation Science, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, United Kingdom
[2]Department of Physics, University of Bari, Via Amendola, 173 - 70126 Bari, Italy
[3]Medicin Faculty and National Institute of Condensed Matter, University of Foggia, Via L. Pinto-71100 Foggia, Italy
[4]Department of Physics and Energy Science and Technology, University of Roma "Tor Vergata", Via di Tor Vergata - 00133 Rome, Italy
[5]Experimental and Methodical Seismological Department, Geophysical Service Russian Academy of Science, Pijp Av. 9, Petropavlovsk-Kamchatsky 683006, Russia

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Abstract. The Kamchatka peninsula, located in the far East of Russia, is characterised by frequent and strong seismic activity (magnitudes up to 8.6). For many years, samples for hydrogeochemical analyses have been collected with a mean sampling frequency of three days in the form of the pH values and of the most common ions and gases in the groundwater of some deep wells and springs in the south area of the Kamchatka peninsula, where the capital city Petropavlovsk is located. In the last ten years, five earthquakes with M>6.5 have occurred at distances of less than 250 km from the measurement sites. In order to reveal any possible precursors of these earthquakes, the hydrogeochemical data collected from three wells have been analysed. We have identified 12 anomalies with 8 of them being possible successes and 4 failures as earthquake precursors and we have obtained a probability of 67% that any given hydrogeochemical anomaly is an earthquake precursor. One of the results obtained indicates that the possibility of observing precursors in the hydrogeochemical parameters of a well seems to be related to the location of an earthquake with respect to the well. Recently, this behaviour was confirmed when we observed a clear co-post seismic effect in only one well after an earthquake on December 5, 1997, which was about 400 km distant and very strong (M=7.7). © 2001 Elsevier Science Ltd. All rights reserved

1 Introduction

In the last decade five earthquakes with magnitudes greater than 6.5 have occurred in the south area of the Kamchatka peninsula (Russia), within a circle of radius 300 km centred on the capital city Petropavlovsk. Some key parameters of these earthquakes are listed in Table1 and the location of the epicentres is indicated in the map of Fig.1.

Correspondence to: Pier Francesco Biagi

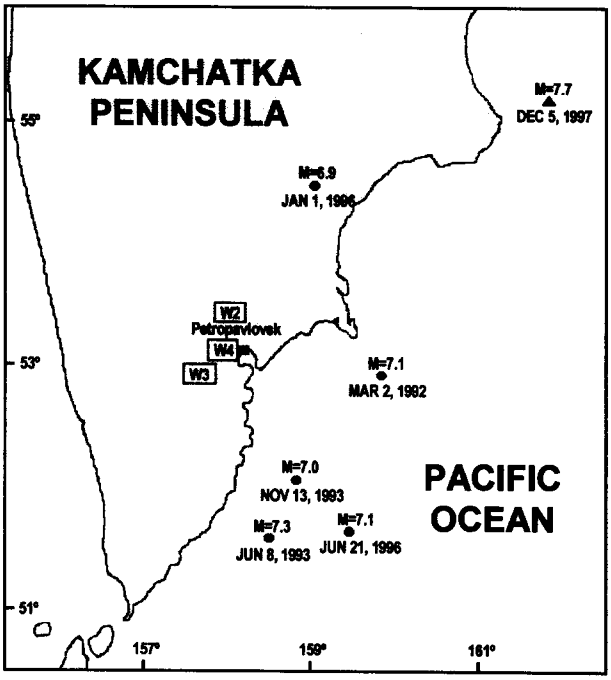

Fig. 1. Map showing the epicentres of the five strongest earthquakes that occurred within 300 km of Petropavlovsk city in the last ten years. The wells W_2, W_3 and W_4 where the hydrogeochemical data are collected are also shown. The triangle at the top-right margin of the map represents a very strong earthquake at a distance of about 400 km from the wells.

Generally, in these circumstances, the presence of precursors in different hydrogeochemical parameters has been reported (Wakita, 1978; Allegri et al., 1983; Barsukov et al., 1984/85; Roeloffs, 1988; Wakita et al., 1988; Areshidze et al., 1992; Bella et al., 1995; King et al., 1995; Takahashi and Sano, 1995; Biagi et al., 1999; Kingsley et al., 1999). The Geophysical Service of Kamchatka has been collecting data concerning the ion content (Na^+, Ca^{++}, Cl^-, HCO_3^-, SO_4^{--}), the gas content (total, Ar, He, N_2,

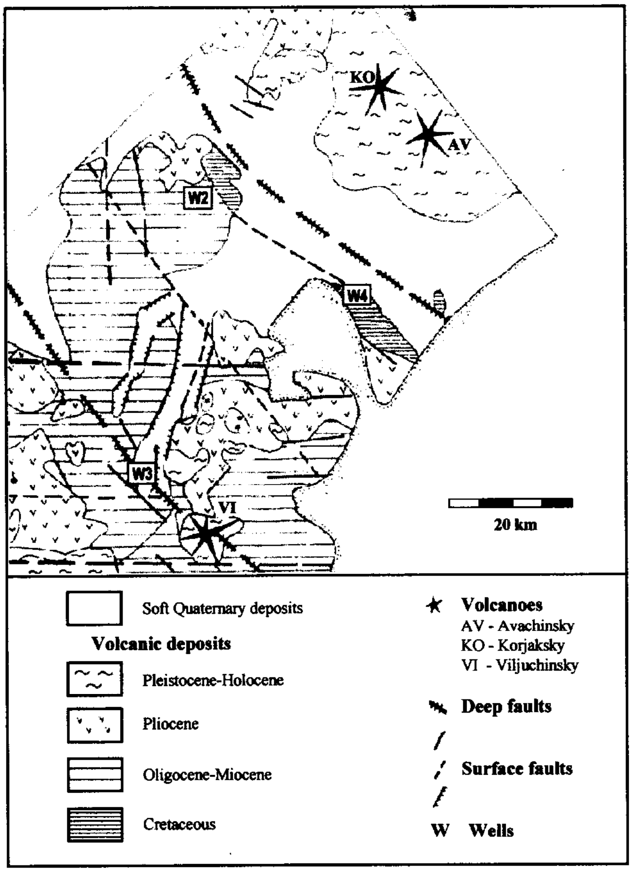

Fig. 2. Schematic geologic map of the area where the wells are located.

CO_2 and CH_4), the pH value and the flow rate in water samples of two springs and several wells in Kamchatka since 1977. The content of dissolved gases after thermovacuum degassing is measured by means of gas chromatography; the Na^+ and Ca^{++} concentration is measured by flame emission spectrometry; the Cl^-, HCO_3^-, and SO_4^{--} concentration by titration methods; the pH value by pH-meter. The accuracy of the measurements ranges from 2% to 10%. The dissolved ions and gases listed above are recorded at each site only if the value of the content is over the sensitivity of the measurement method. For this paper, we have selected three deep wells, in order to analyse the relationship between the hydrogeochemical anomalies in these wells and the strongest seismic activity that occurred in their area. All of them are located at a maximum distance of 40 km from Petropavlovsk and are labelled as W_2, W_3, and W_4 in Fig.1. The distances of the three wells from the five earthquakes mentioned above are indicated in Table1. In Fig.2, a schematic geological map of the area where the wells are located is shown. The main geological formations are caused by volcanic activity that continues today, as testified by the existence of the volcanoes Avachinsky, Koryaksky and Viljiuchinsky, the first two ones active at present. Table2 shows the date of drilling of each well, its depth and the present water temperature, and whether or not the water is flowing. At W_2 and W_3 the measurements started in January 1988; at W_4 in January 1992.

2 Results

In order to investigate this possibility of precursors, we analysed the hydrogeochemical data. First, we carried out a spectral analysis on the hydrogeochemical data. Generally, the signals showed harmonics with periods around 365 days and longer components connected with slow effects that are not relevant to this study, and so we applied a high-pass filter to the hydrogeochemical raw trends to remove them. Then, in order to reduce the short-term effects of the variations due to a single measurement, we applied a low pass FFT filter to these filtered trends with a smoothing window of ten days. Finally, we calculated the standard deviation σ over the entire sample for each final data set.

Having filtered the hydrogeochemical data we began a study of the time series to try and identify possible premonitory signals. At first we considered each signal over the 3σ level to be an irregularity and we assumed the existence of irregularities appearing simultaneously on two parameters or more at each well to be an anomaly. We considered a temporal window of 7 days as the maximum shift allowed for this simultaneity of the irregularities. The window of 7 days was chosen because of the three day frequency of the original observations and the possibility that a shift of two successive measurements might occur before the appearance of hydrogeochemical irregularities. At this point a problem arose concerning how to find a suitable rule for choosing the time interval between an anomaly and the subsequent earthquake. This is a very critical factor: if this time interval is too large then every anomaly will become a precursor and, on the contrary, if

DATE (mm,dd,yy)	MAGNITUDE	DISTANCE (km)			FOCAL DEPTH (km)
		W_2	W_3	W_4	
03 02 92	7.1	117	129	95	32
06 08 93	7.3	247	185	247	40
11 13 93	7.0	168	118	162	50
01 01 96	6.9	96	152	81	10
06 21 96	7.1	246	202	235	2

Table 1. Key parameters of the five earthquakes considered in this study.

WELL	ZONE	DRILLING	DEPTH (m)	WATER TEMP. (°C)	CHARACTER
W_2	Morosnaya	1983	600	15	flowing water
W_3	Paratunka	1971	1208	23	nonflowing water
W_4	Petropavlosk	1986-1988	2542	7	nonflowing water

Table 2. Some parameters of the three wells considered in this study.

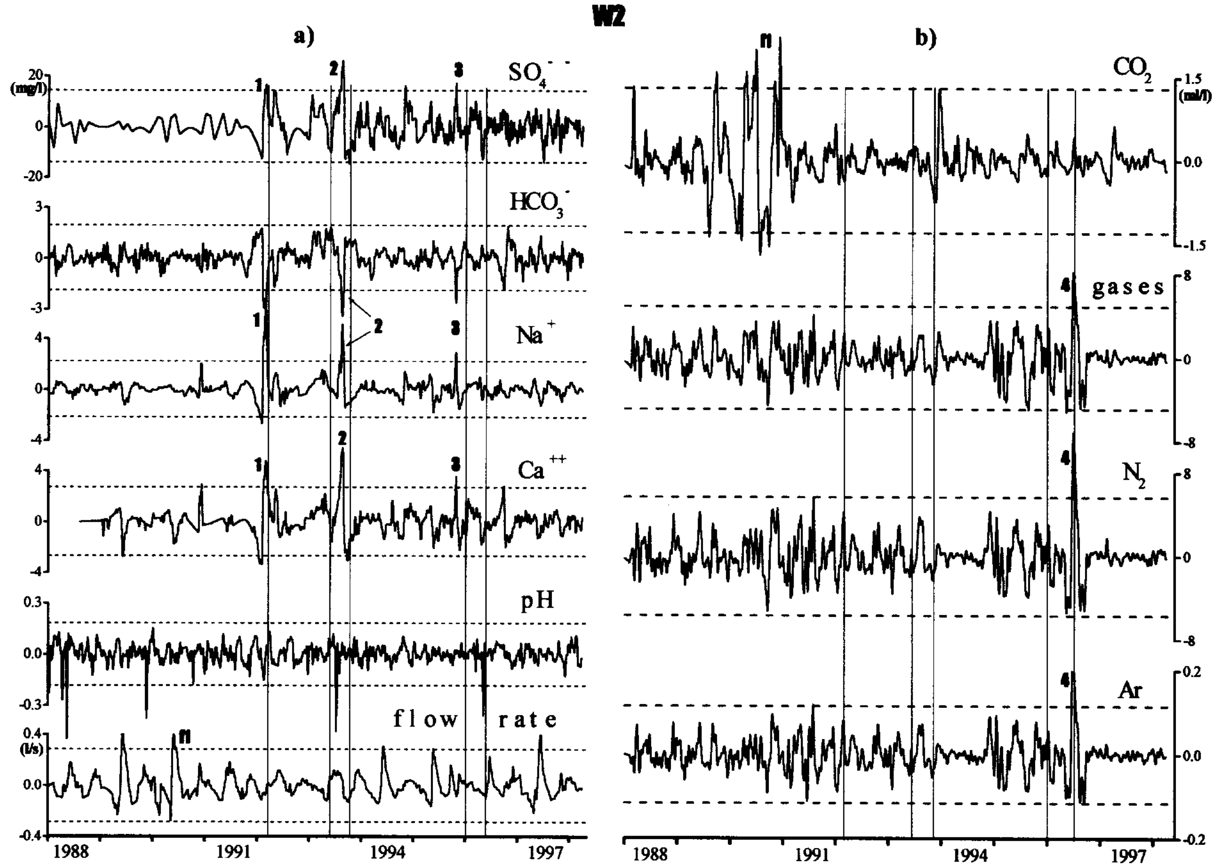

Fig. 3. a) Filtered and smoothed time-series of ions content and of pH and flow rate at W_2 from 1 Jan, 1988 to 31 Mar, 1998. **b)** Filtered and smoothed time-series of gases at W_2 from 1 Jan, 1988 to 31 Mar, 1998. In the plots **f1** represents a failure and 1-4 the successes; the horizontal dashed lines represent the 3σ level. The vertical lines represent the occurrence of the five earthquakes of Fig.1.

the time interval is too small then the probability of an anomaly being considered as a precursor will tend to zero.

In this paper we investigate the so-called intermediate-term precursor. The following empirical formula relating the time interval T (days) between a hydrogeochemical anomaly, the subsequent earthquake of magnitude M and the epicentral distance R (km) has been proposed by Sultankhodzhayev et al. (1980):

$$\log RT = 0.63M \pm 0.15 \quad (1)$$

From the data reported in Table1, we obtained a maximum T value of 349 days, but for our choice we must take into account the time intervals between the earthquakes mentioned in Sect.1. The minimum time interval between two successive earthquakes is 158 days (between the June 1993 and the November 1993 earthquakes). If we select a time interval between a hydrogeochemical anomaly and the subsequent earthquake greater than 158 days then the rule for associating an anomaly with an earthquake will not be unambiguous. In order to avoid this problem we have chosen a window of 158 days as the maximum allowable for our data set.

The results of this analysis are presented in Figs.3, 4, and 5, where the successes (precursors) are indicated by numbers **1**,..... ,**8** and the failures by **f1**,...., **f4.**

The anomalies (precursors or failures) that have been identified at the three wells have a duration ranging from 11 to 60 days. We have not found any significant differences in the duration, the shape or in the amplitude between the precursors and the failures, and so we are unable to identify any discriminating criterion.

When deciding whether anomalies should be included with the precursors or failures, the results do not change if the time interval between an anomaly and the subsequent earthquake is chosen to be 97 days (97 days is the longest time interval for the precursors presented here), instead of using the 158 day window, we fixed. However the results change dramatically if a lower value is assumed. For example, if an interval of 60 days is chosen as the time between the onset of an anomaly and the occurrence of the subsequent earthquake we obtain 4 precursors and 8 failures and with a time interval of 6 days (7 days is the shortest time interval of our precursors) no precursors would exists.

3 Discussion

According to the criteria that we presented in Sect.2, we

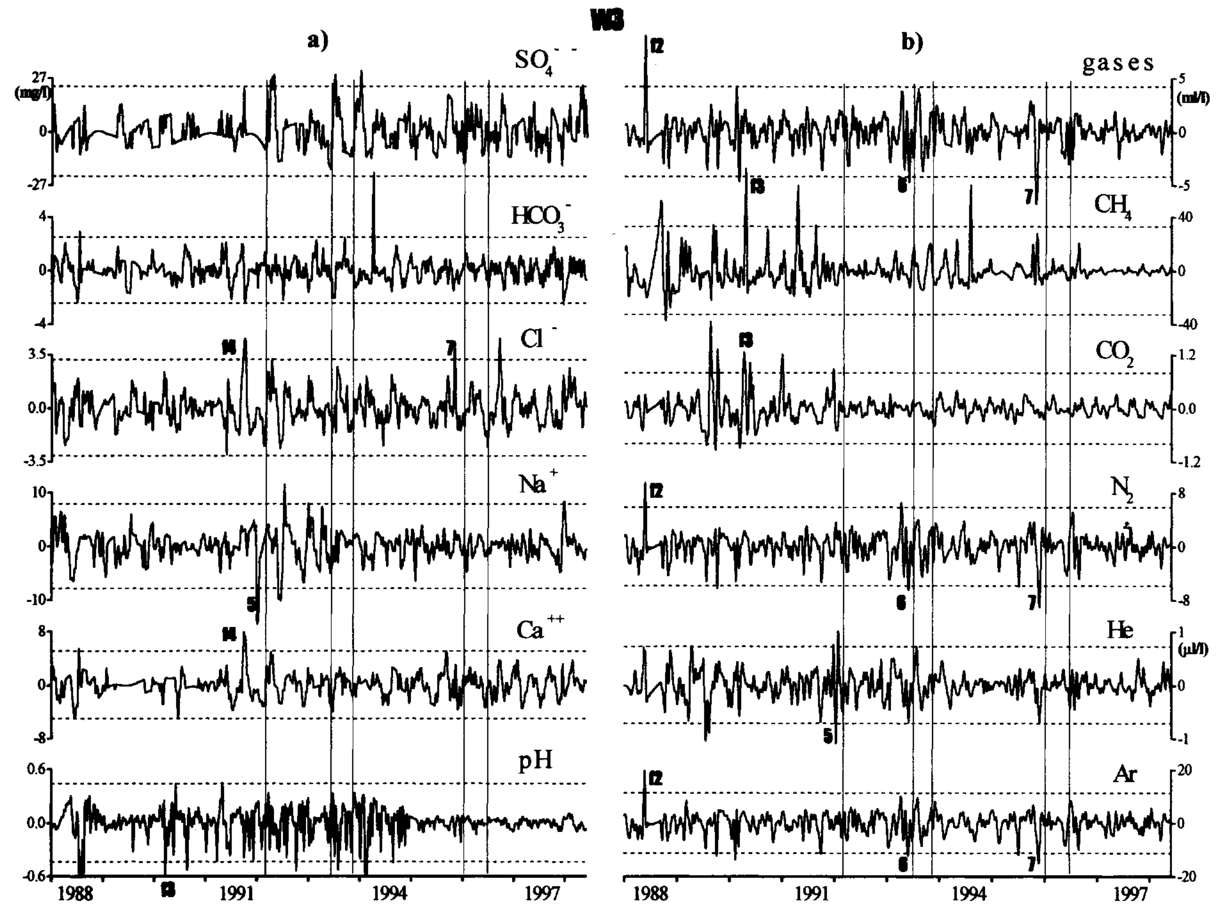

Fig. 4. a) Filtered and smoothed time-series of ions content and of pH at W_3 from 1 Jan, 1988 to 31 Mar, 1998. **b)** Filtered and smoothed time-series of gases content at W_3 from 1 Jan, 1988 to 31 Mar, 1998. In the plots f2-f4 represent failures and 5-7 the successes; the horizontal dashed lines represent the 3σ level. The vertical lines represent the occurrence of the five earthquakes of Fig.1.

identified 12 anomalies of which 8 could be considered precursors, and 4 seem to be failures. At W_2 we have 5 anomalies with 1 failure and 4 successes; at W_3 we have 6 anomalies with 3 failures and 3 successes; at W_4 we have only 1 anomaly and it is a success. The failures must either be random variations in the parameters measured or due to various effects that we were not able to identify, such as some local meteorological process, the settlement of water-bearing strata after drilling, the slow tectonic re-adjustment processes and variations in the hydrological cycle. Certainly there was nothing in the characteristics of the failures that enabled us to develop a discriminating criterion for distinguishing them from the precursors. In this sense, it is hard to ignore these failures.

At this stage we can say that in our data sets there is a 67% probability that any one hydrogeochemical anomaly is an earthquake precursor. Out of the five earthquakes considered large enough to produce precursors we found precursors in all cases.

Consider the delay from the onset of the precursor to the occurrence of the following earthquake, i.e. the precursory time. The values in days we obtained are 7, 20, 53, 58, 72, 74, 95, 97. The probability that the earthquake takes place in the time interval 7-20 days after the precursor onset is 25%, in the time interval 7-58 days is 50%, in the time interval 7-74 days is 75% and 88% is in the time interval 7-97 days.

We can calculate the probability that our precursors occur randomly, are unrelated to earthquake activity and that our results have occurred by chance. With a 158 day window before each of five earthquakes in a ten year period, there is a 22% probability that any day chosen at random will fall into a window. The probability that 8 out of 12 events chosen at random will fall into these windows is given by the cumulative binomial distribution function and is 0.1 percent in this case. There is thus only an extremely small possibility that the precursors are unrelated to the subsequent earthquake and it is much more likely they are real premonitory signals.

We propose a possible explanation for the existence of our precursors and of their presence or absence. In hypothesising on the existence of a stress/strain transmission process, modifications of the hydrogeochemicals of water in a well may be produced by: 1) The flow into the well of waters with different chemistries, perhaps as a consequence of pumping or

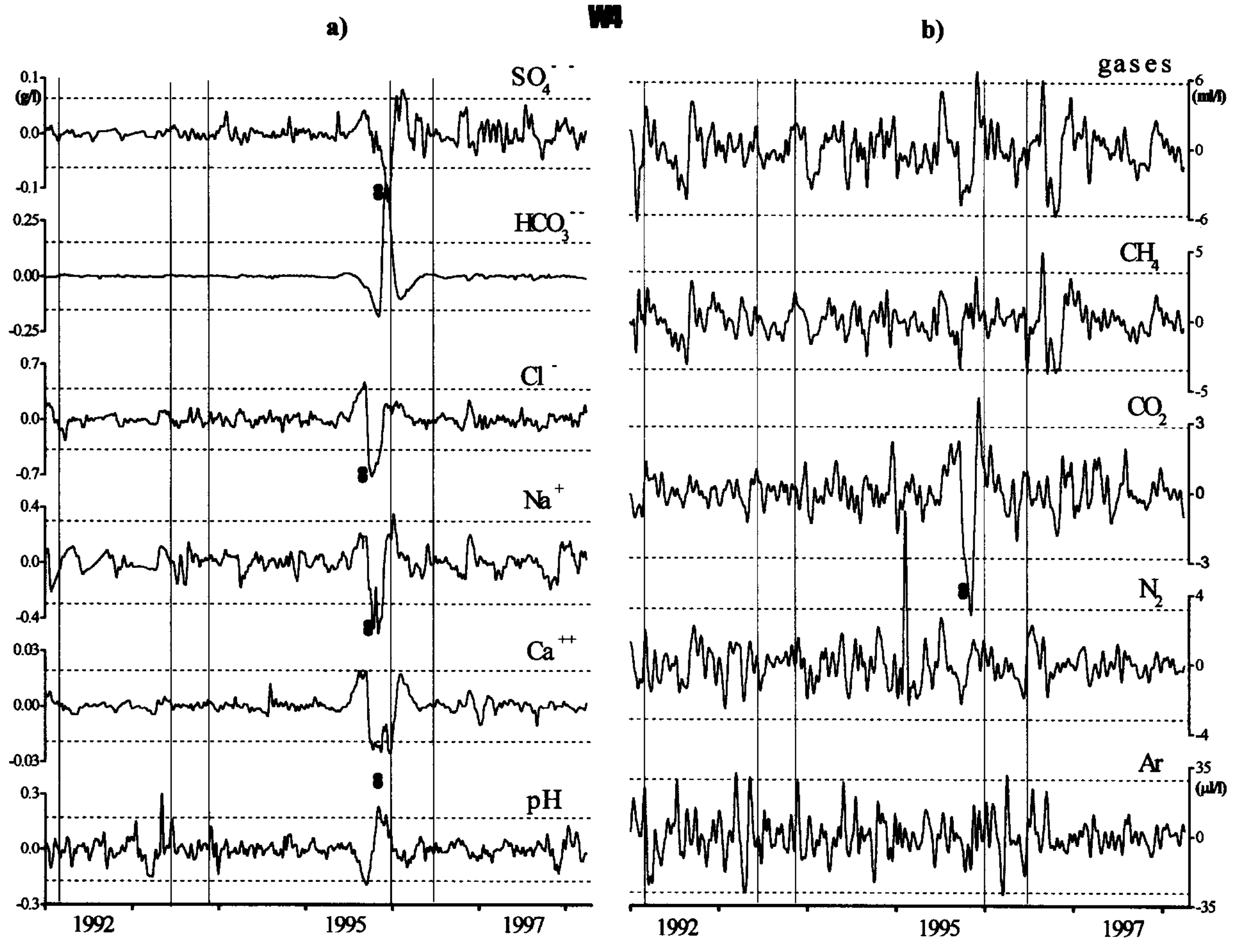

Fig. 5. a) Filtered and smoothed time-series of ions content and of pH at W_4 from 1 Jan, 1992 to 31 Mar, 1998. **b)** Filtered and smoothed time-series of gases content at W_4 from 1 Jan, 1992 to 31 Mar, 1998. In the plots **8** represents a success; the horizontal dashed lines represent the 3σ level. The vertical lines represent the occurrence of the five earthquakes of Fig.1.

mixing of the output from different water-bearing strata, created by the induced stress/strain in the well zone (Barsukov et al.; 1984/85). 2) The circulation of the groundwater into new zones belonging to the water-bearing stratum connected with the well as a consequence of the intensification of the microfracturing processes and/or changes in existing cracks produced by the induced stress/strain (Barsukov et al.1984/85; Areshidze et al. 1992; Bella et al., 1995).

In either case, the modification of hydrogeochemicals at a particular well could be related to the direction of the incoming stress and thus a possible response of the well variable with direction should be considered. In this regard, on Dec 5, 1997 an earthquake with magnitude M = 7.7 took place NE of Kamchatka at about 400 km from the wells (Fig.1). According to our criteria we did not observed any premonitory anomaly in hydrogeochemical data, but a very clear co-post seismic effect appeared only in W_4 (Fig.6), that is the well that showed a preseismic effect only on the occasion of the Jan 1, 1996 earthquake , the stress of which was coming from the same direction. This could be a further confirmation of the directionality of the stress.

Finally, the following rules can be generated: 1) At each well, hydrogeochemical precursors can appear before some earthquakes and not appear before others, even if all these earthquakes are potential precursors sources. 2) At each well, hydrogeochemical precursors may be different in nature (i.e. an increase or decrease) and can appear in different parameter sets, for each earthquake considered a potential precursors sources. 3) It is always possible that earthquakes not producing hydrogeochemical precursors in a well network can exist, even if they are large enough to be potential precursors sources.

4 Conclusions

We have analysed the hydrogeochemical data collected over several years at three wells located in Kamchatka and related the anomalies at each well to the earthquakes with magnitude greater than 6.5 that occurred within a distance of 250 km from the wells. We chose 158 days for the maximum temporal interval between an anomaly and the subsequent earthquake. Using this framework we identified

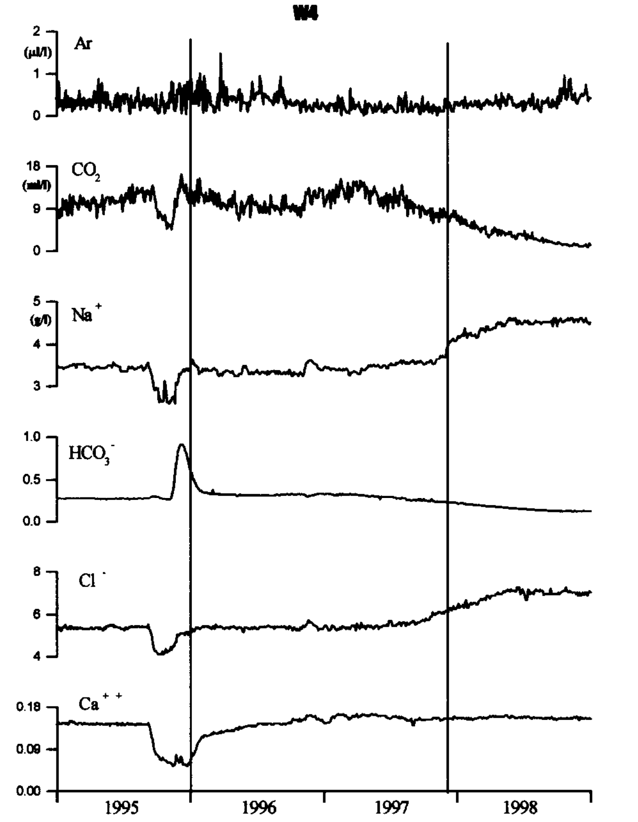

Fig. 6. Raw time series of some ions and gases content at W_4 from 1 Jan, 1995 to 31 Dec, 1998. The vertical lines represent the occurrence of the Jan 1, 1996 and Dec 5, 1997 earthquakes.

a 67% probability that any one hydrogeochemical anomaly is an earthquake precursor. Finally, it seems that the possibility of observing precursors in the hydrogeochemicals of a well changes as a function of the location of the earthquakes. Of course the previous results change if different earthquakes are selected and/or if a different value for the maximum temporal interval between an anomaly and the subsequent earthquake is assumed. Different choices could imply that either no precursor exists or a precursor always exists. At present these choices are arbitrary. The choices made in this paper were based on past world-wide results, on data processing experience and on the time re-occurrence of the earthquakes; these seemed to be the only reasonable criteria.

References.

Allegri, L., Bella, F., Biagi, P.F., Della Monica, G., Ermini, A., Improta, S. and Sgrigna, V., Radon and tilt anomalies detected before the Irpinia (South Italy) earthquake of November 23, 1980 at great distances from the epicenter. *Geophys.Res.Lett. 10*, 269-272, 1983.

Areshidze, G., Bella, F., Biagi, P. F., Caputo, M., Chkuaseli, V., Della Monica, G., Ermini, A., Manjgaladze, P., Melikadze, G., Sgrigna, V., Slavina, L., and Zilpimiani, D., Anomalies in geophysical and geochemical parameters revealed on the occasion of the Paravani (M=5.6) and Spitak (M=6.9) earthquakes (Caucasus). *Tectonophysics, 202*, 23-41, 1992.

Barsukov, V.L., Varshal, G.M., and Zamokina, N.S., Recent results of hydrogeochemical studies for earthquake prediction in USSR. *Pure Appl. Geophys. 122*, 143-156, 1984/85.

Bella, F., Biagi, P.F., Caputo, M., Cozzi, E., Della Monica, E., Ermini, A., Plastino, W., Sgrigna, V., and Zilpimiani, D., Helium content in thermal waters in the Caucasus from 1985 to 1991 and correlations with the seismic activity. *Tectonophysics, 246*, 263-278, 1995.

Biagi, P.F., Bella, F., Cozzi, E., Ermini, A., Martinelli, G., Khatkevich, Y.M., Gordeev, E.I., and Zilpimiani, D., Groundwater Helium content related to the Spitak (Armenia) and Karymsky (Russia) earthquakes. *Il Nuovo Cimento C, 22*, 399-405, 1999.

King, Chi-Yu, Koizumi, N., and Kitagawa, Y., Hydrogeochemical anomalies and the 1995 Kobe earthquake. *Science, 269*, 38-39, 1995.

Kingsley, S.P., Anderson, C.W., Biagi, P.F., Derlien, P.J., Ermini, A., Gordeev, E.I., Khatkevich, Y.M., Analysis of Argon concentration anomalies in underground water in Kamchatka (Russia). *Il Nuovo Cimento C, 22*, 407-413, 1999.

Roeloffs, E.A., Hydrologic precursors to earthquakes: A review. *Pure App. Geophys., 126*, 177-209, 1988.

Sultankhodzhayev, A.N., Latipov, S.U., Zakirov, T.Z., Zigan, F.G., et al., Dependence of hydrogeoseismological anomalies on the energy and epicentral distance of earthquakes. *Dokl. AN Uzb. SSR, 5*, 57-59, 1980.

Takahashi, M., and Sano, Y., Ground-water radon anomaly before the Kobe earthquake in Japan. *Science, 269*, 60-61, 1995.

Wakita, H., Earthquake prediction and geochemical studies in China. *Chin. Geophys. 1*, 443-457, 1978.

Wakita, H., Nakamura, Y., and Sano, Y., Short-term and intermediate-term geochemical precursors. *Pure Appl. Geophys. 126*, 267-278, 1988.