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Hydrogeochemical precursors of strong earthquakes in Kamchatka: further analysis

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Abstract. For many years, ion and gas content data have been collected from the groundwater of three deep wells in the southern area of the Kamchatka peninsula, Russia. In the last ten years, five earthquakes with $M > 6.5$ have occurred within 250 km of the wells. In a previous study, we investigated the possibility that the hydrogeochemical time series contained precursors. The technique used was to assume that each signal with an amplitude of three times the standard deviation is an irregularity and we then defined anomalies as irregularities occurring simultaneously in the data for more than one parameter at each well. Using this method, we identified 11 anomalies with 8 of them being possible successes and 3 being failures as earthquake precursors. Precursors were obtained for all five earthquakes that we considered. In this paper, we allow for the cross-correlation found between the gas data sets and in some cases, between the ion data sets. No cross-correlation has been found between gas and ion content data. Any correlation undermines the idea that an anomaly might be identified from irregularities appearing simultaneously on different parameters at each site. To refine the technique, we re-examine the hydrogeochemical data and define as anomalies those irregularities occurring simultaneously only in the data of two or more uncorrelated parameters. We then restricted the analysis to the cases of just the gas content data and the ion content data. In the first case, we found 6 successes and 2 failures, and in the second case, we found only 3 successes. In the first case, the precursors appear only for three of the five earthquakes we considered, and in the second case, only for two, but these are the earthquakes nearest to the wells. Interestingly, it shows that when a strict set of rules for defining an anomaly is used, the method produces only successes and when less restrictive rules are used, earthquakes further from the well are implicated, but at the cost of false alarms being introduced.

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1 Introduction

The Kamchatka peninsula is located in the far east of Russia and is characterised by frequent and strong seismic activity (with magnitudes up to 8.6). For many years, the Geophysical Service of Kamchatka has been collecting hydrogeochemical parameters in the form 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. The mean sampling frequency was three days and some analyses of the data collected have been reported in the literature (Khatkevich, 1994; Kopylova et al., 1994; Bella et al., 1998; Kingsley et al., 1999). In the last ten years, five earthquakes with $M > 6.5$ have occurred at distances of less than 250 km from Petropavlovsk. Some key parameters of these earthquakes are listed in Table 1 and the location of the epicentres is indicated in the map of Fig. 1. In order to investigate whether any of these earthquakes had precursors, the hydrogeochemical data collected from three wells (labelled as W_2, W_3, and W_4 in Fig. 1) have been analysed in a previous study (Kingsley et al., in press). The distances of the three wells from the five earthquakes mentioned above are indicated in Table 1. In Table 1, we indicated in the column labelled W_m the distance of the five epicentres from the point located at the centre of the well network. Here, we present a further analysis of the hydrogeochemical data.

2 Results

In the previous study (Kingsley et al., in press), continuous data sets having one value per day were derived from the raw

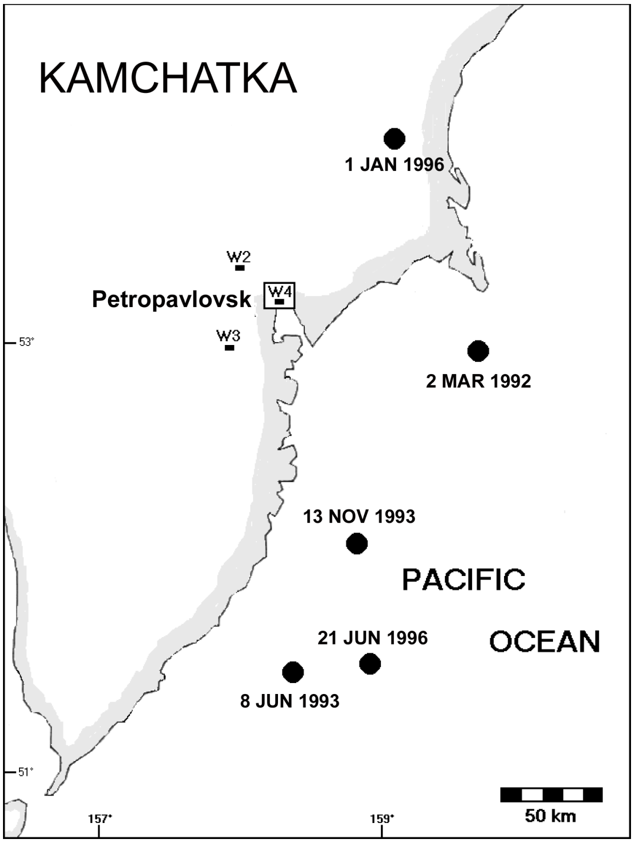

Fig. 1. Map showing the location of the five strongest earthquakes (full circle) which occurred within a radius of 250 km from Petropavlovsk city during the period January 1988–March 1998. The three wells where the hydrogeochemicals are collected are indicated as W_2, W_3 and W_4.

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

Date	Magnitude	Focal depth (km)	Distance (km)			
			W_2	W_3	W_4	W_m
2 Mar 1992	7.1	32	117	129	95	114
8 Jun 1993	7.3	40	247	185	247	226
13 Nov 1993	7.0	50	168	118	162	150
1 Jan 1996	6.9	10	96	152	81	110
21 Jun 1996	7.1	2	246	202	235	228

data by linear interpolation. A high-pass filter was then applied to the hydrogeochemical raw data plots in order to remove longer components connected to slow temporal effects. The data also contain effectively noise created by short-term effects associated with variations due to a single measurement and these were removed by applying a low pass FFT with a smoothing window of ten days. Finally, we calculated the standard deviation σ over the entire sample for each data set. In our analysis, we considered each signal over the 3σ level to be an irregularity worthy of further investigation, and we assumed the existence of irregularities appearing simultaneously on two parameters or more at each well to be an anomaly. With a low mean sampling frequency of three days, it is necessary to define what is meant by simultaneous and we have taken a temporal window of 7 days as the maximum time difference allowed. The motivating force behind the adoption of this data analysis strategy comes from IASPEI (International Association of Seismology and Physics of the Earth's Interior), whose Subcommission on earthquake prediction published guidelines in 1991 for potential precursor candidates (Wyss, 1991; Wyss and Booth, 1997). One of the main criteria is that the definition of an anomaly should be clearly fixed and the anomaly should be simultaneously observed on more than one instrument, or at more than one site. With the technique developed so far, the next problem is to decide how long the temporal window should be for a hydrogeochemical anomaly to be considered as a precursor associated with a subsequent earthquake. Clearly, a very long window allows for almost any anomaly to be claimed as a precursor and very short windows preclude any precursors. We have chosen a window of 158 days for this maximum time interval for reasons explained in detail in Kingsley et al. (in press) and connected to the time interval between earthquakes. The results of this analysis are presented in Figs. 2, 3, and 4, where the successes (precursors) are indicated by numbers 1 through 8 and the failures by f1, f2, f3. Out of the five earthquakes considered large enough to produce precursors, we found precursors in all five cases. The largest premonitory time we found in this analysis was 92 days.

At this point, possible cross-correlations between the gas and ion data sets were considered. Any such correlation could undermine the IASPEI criterion, which requires independence between observations that are being claimed as simultaneous thus indicating an anomaly. To investigate the possible cross-correlation effects in our data, coefficients were obtained using the Statgraphic Software packet and the results are listed in Tables 2, 3 and 4. From these tables it can be seen that values greater than 0.5 exist at W_2 both between some ions and between some gases, whereas at W_3 and W_4, values over 0.5 only exist between some gases. There are no wells where a cross-correlation appears between gas and ion content data.

In order to take into account possible correlations in the data, we re-examined our data and defined anomalies to be those irregularities that occurred simultaneously only in the data of two or more uncorrelated parameters. In this context, uncorrelated parameters were taken to mean those characterised by cross-correlation coefficients less than 0.5 and using this rule, at W_2 (Fig. 2, Table 2), anomaly 4 is eliminated and at W_3 (Fig. 3, Table 3), anomalies f1 and 6 are eliminated. We are left with precursors remaining for only three of the five earthquakes considered; these are 13 November 1993, 2 March 1992 and 1 January 1996. In an attemp to stay within the spirit of the IASPEI guidelines as well as the definitions, we restricted the analysis even further and defined anomalies as only those irregularities occurring si-

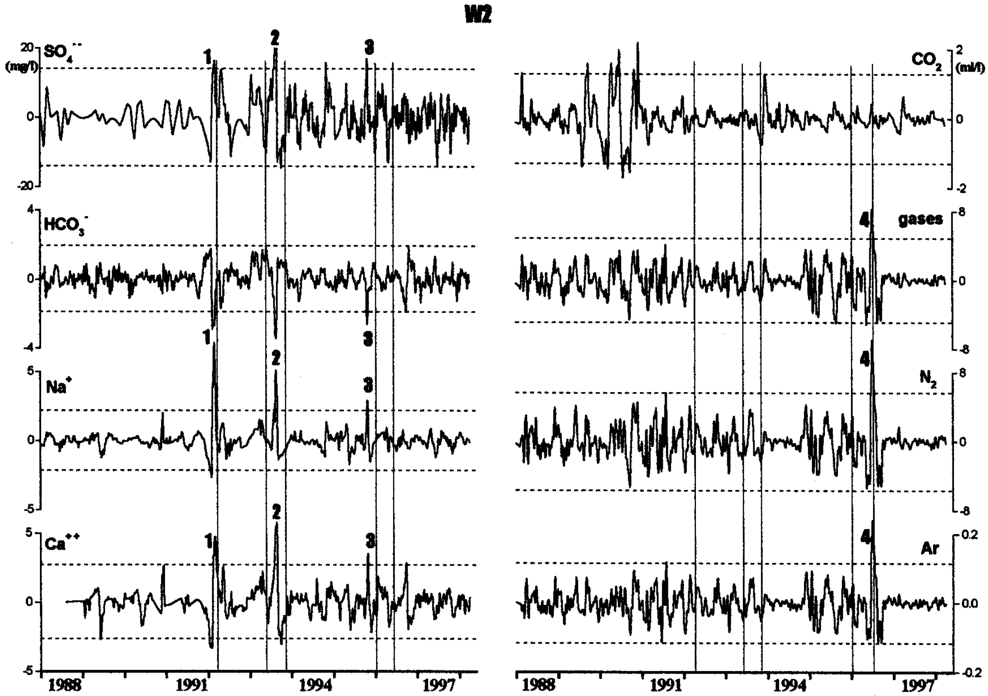

Fig. 2. Filtered and smoothed time-series of ion and gas content at W_2 from 1 January 1988 to 31 March 1998. In the plots, 1–4 represent the successes; the horizontal dotted lines represent the 3σ level. The vertical lines represent the occurrence of the five earthquakes of Fig. 1.

Table 2. Cross-correlation coefficients at W_2

Ca^{++}	Na^{+}	HCO_3^-	SO_4^{--}	
0.65	0.60	0.46	1	SO_4^{--}
−0.61	−0.60	1	0.46	HCO_3^-
0.80	1	−0.60	0.60	Na^{+}
1	0.80	−0.61	0.65	Ca^{++}

Ar	N_2	Total	CO_2	
0.25	0.59	0.44	1	CO_2
0.93	0.94	1	0.44	Total
0.97	1	0.94	0.59	N_2
1	0.97	0.93	0.25	Ar

Ca^{++}	Na^{+}	HCO_3^-	SO_4^{--}	
−0.07	0.08	0.1	0.01	CO_2
0.07	0.11	−0.09	0.21	Total
0.13	0.15	0.13	0.22	N_2
0.12	0.16	0.14	0.24	Ar

multaneously in the gas content and ion content data. In this framework, at W_2 (Fig. 2), no anomalies remain; at W_3 (Fig. 3), only anomalies 5 and 7 are left and at W_4 (Fig. 4), the anomaly 8 remains. The end result of this rigorous process is that only three anomalies remain and they are all successes. These precursors are related to only two of the five earthquakes and these are the ones that occurred on 2 March 1992 and 1 January 1996. Finally, the largest premonitory time we found in this analysis was 76 days.

3 Discussion

In the previous study (Kingsley et al., in press), 11 anomalies were identified using gas and ion data sets and of these, 8 could be considered precursors, and 3 seemed to be failures. At that stage, we could say that examination of our data sets indicated that there was a 73% probability that any one hydrogeochemical anomaly was an earthquake precursor. At W_2, we had 4 anomalies and 4 successes; at W_3, we had 6 anomalies but with 3 failures and 3 successes; at W_4, we had just 1 anomaly which was a success. Out of the five earthquakes considered large enough to produce precursors, we found precursors in all cases. This seemed like an good result but given the IASPEI recommendations and our concern over possible cross-correlations in the data, it was considered timely to revisit the data and re-analyse it. In the initial analysis using uncorrelated parameters, we identify 8 anomalies of which 6 could be considered precursors, and 2 seem to be failures. With the current analysis, we can claim that in our data sets, there is a 75% probability that any one hydrogeochemical anomaly is an earthquake precursor. At W_2, we have 3 anomalies, all of which are successes; at W_3, we have 4 anomalies with 2 failures and 2 successes and at W_4, we have only 1 anomaly which is a success. Out of the five earthquakes considered large enough to produce precursors, the precursors appear in only three cases: these are the

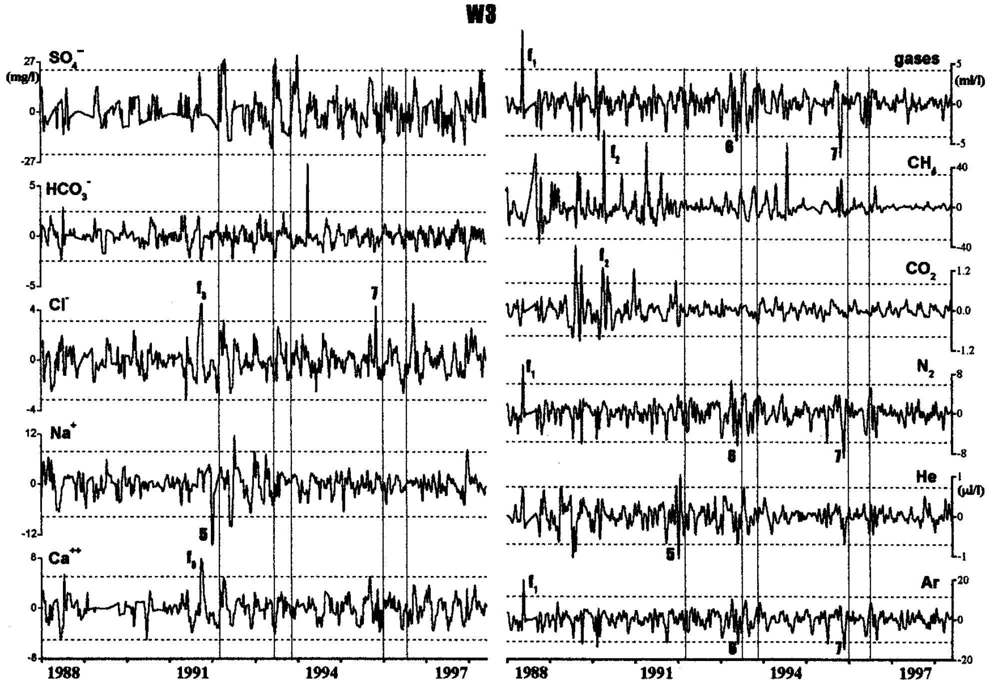

Fig. 3. Filtered and smoothed time-series of ion and gas content at W_3 from 1 January 1988 to 31 March 1998. In the plots, f1–f3 represent the failures and 5–7 represent the successes; the horizontal dotted lines represent the 3σ level and the vertical lines the occurrence of the five earthquakes of Fig. 1.

Table 3. Cross-correlation coefficients at W_3

Cl^-	Ca^{++}	Na^+	HCO_3^-	SO_4^{--}		
0.29	0.21	0.12	0.05	1	SO_4^{--}	
−0.12	0.15	−0.12	1	0.05	HCO_3^-	
0.23	0.26	1	−0.12	0.12	Na^+	
0.47	1	0.26	0.15	0.21	Ca^{++}	
1	0.47	0.23	−0.12	0.29	Cl^-	

N_2	He	Ar	CH_4	CO_2	Total	
0.63	0.33	0.60	−0.04	0.20	1	Total
0.11	−0.20	0.14	0.08	1	0.20	CO_2
0.04	0.06	0.15	1	0.08	−0.04	CH_4
0.93	0.32	1	0.15	0.14	0.60	Ar
0.34	1	0.32	0.06	−0.20	0.33	He
1	0.34	0.93	0.04	0.11	0.63	N_2

Cl^-	Ca^{++}	Na^+	HCO_3^-	SO_4^{--}	
−0.15	−0.15	0.11	0.12	0.13	Total
0.13	0.12	−0.10	0.10	0.11	CO_2
0.10	0.15	0.10	0.09	0.07	CH_4
−0.12	−0.10	−0.15	−0.03	0.15	Ar
−0.12	−0.12	−0.15	0.09	0.24	He
−015	−0.08	−0.18	−0.05	0.16	N_2

13 November 1993 earthquake, the 2 March 1992 and the 1 January 1996 earthquakes. Examination of Table 1 reveals that the three earthquakes identified are those nearest to the wells (mean distance ≤ 150 km).

In the more detailed analysis (gas and ion content data), we identify 3 anomalies and they are all successes. Therfore, the probability that any one hydrogeochemical anomaly is an earthquake precursor appears to be 100%. At W_2, we do not have an anomaly; at W_3 and W_4, we have 2 successes and 1 success, respectively. These successes are related only to two of the five earthquakes we considered, i.e. the 2 March 1992 earthquake and the 1 January 1996 earthquake. Looking at Table 1, it is possible to see that these earthquakes are the nearest to the wells (mean distance < 115 km).

The largest premonitory time decreases from 92 days in the analysis of the previous study (Kingsley et al., in press) to 76 days in the present, more detailed analysis (gas and ion content data). The results presented here indicate that the use of a more restrictive criteria for defining the anomalies decreases the probability of failures as earthquake precursors from 27% to 25% down to 0% but at same time, it reduces the "sensitive" distance from the measurement sites of the forthcoming earthquake from 228 km to 114 km (Table 1) and it reduces the largest premonitory time from 92 days to 76 days. Therefore, a strict set of rules for defining an anomaly (analogous to a high threshold in detection theory) produces only successes. However, when the threshold is lowered, earthquakes further from the well are implicated but also failures are introduced, as might be expected from

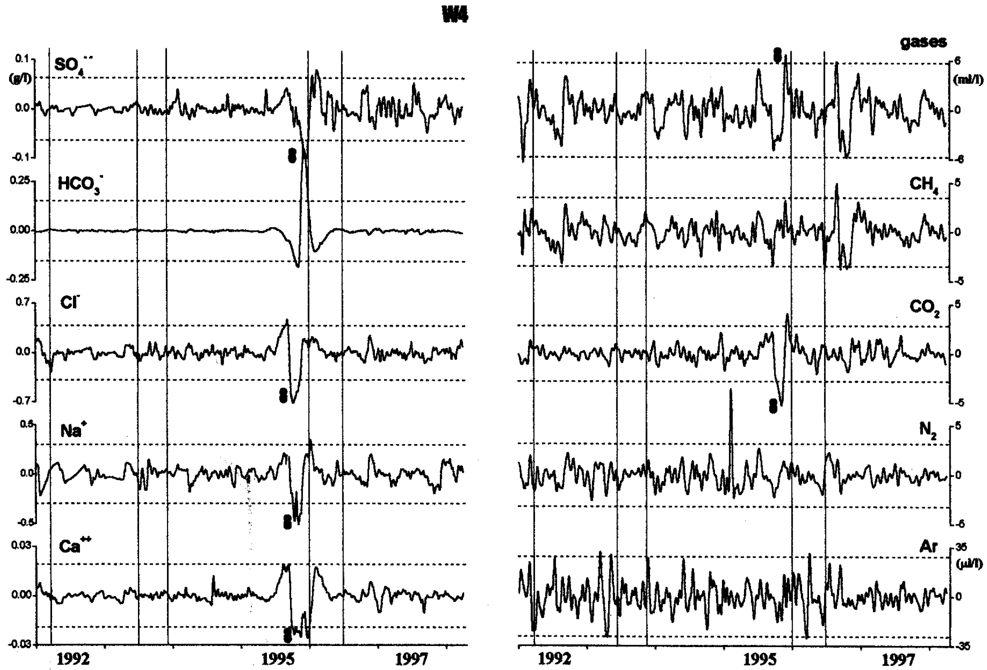

Fig. 4. Filtered and smoothed time-series of ion and gas content at W_4 from 1 January 1992 to 31 March 1998. In the plots 8, represents a success; the horizontal dotted lines represent the 3σ level. The vertical lines represent the occurrence of the five earthquakes of Fig. 1.

Table 4. Cross-correlation coefficients at W_4

Cl^-	Ca^{++}	Na^+	HCO_3^-	SO_4^{--}	
0.08	0.07	0.04	0.06	1	SO_4^{--}
0.05	0.08	0.07	1	0.06	HCO_3^-
0.18	0.09	1	0.07	0.04	Na^+
0.05	1	0.09	0.08	0.07	Ca^{++}
1	0.05	0.18	0.05	0.08	Cl^-
N_2	Ar	CH_4	CO_2	Total	
0.34	0.12	0.52	0.23	1	Total
0.22	0.05	0.28	1	0.23	CO_2
0.33	−0.10	1	0.28	0.52	CH_4
0.21	1	−0.10	0.05	0.12	Ar
1	0.21	0.33	0.22	0.34	N_2
Cl^-	Ca^{++}	Na^+	HCO_3^-	SO_4^{--}	
0.08	0.04	0.11	−0.05	0.04	Total
0.12	0.06	0.18	0.03	0.03	CO_2
0.03	0.04	0.05	−0.07	0.03	CH_4
0.06	0.06	0.05	−0.04	−0.06	Ar
0.07	0.08	0.05	−0.08	−0.05	N_2

detection theory. The failures might either be random variations in the parameters measured or real effects, but due to some local meteorological or geostructural process. Such local processes are very difficult to identify.

4 Conclusions

Previously, using rules for defining the anomalies that were not too restrictive, we identified possible precursors in the data, but some failures as well. We have shown that there was a small possibility that the precursors we revealed were unrelated to the subsequent earthquake. Here, we have used a stricter set of rules for defining an anomaly and have shown that it is possible to develop a data processing method that has only successes and furthermore, these successes turn out to be related to the nearest earthquakes and the premonitory time is shorter. This is an important result because if the anomalies were unrelated to the earthquakes, then the statistics should not change in such a convenient way. Therefore we believe that we have much stronger evidence that the precursors revealed were real premonitory signals.

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