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Abstract. For many years flow-rate, temperature, ions and gases content data have been collected from a natural spring located in the Koryakskiy volcano area (Kamchatka, Russia). We have investigated the correlations between the hydrogeochemical data and the areal seismicity represented by the k_s values (k_s is a function of magnitude and hypocentral distance) of the earthquakes. At first we smoothed the raw hydrogeochemical data using a semi-triangle weight function. Then we compared the trends of each smoothed hydrogeochemical parameter with the k_s trend using a running cross-correlation function with a maximum lag of ± 30 days and the main result was that, sometimes, we found $0.7-0.4$ cross-correlation coefficients with no lag for flow rate and with $+(10-15)$ days lags for some ion and gas contents. The correlation is positive, i.e. flow rate and ion and gas contents increase when k_s increases. This phenomenology could be explained by an underground water pumping produced by some earthquake. We advance the hypothesis that this pumping could be the response of the viscoelastic underground medium of the Koryakskiy volcano to seismic waves. So, sometimes, the supply of elastic energy of the earthquakes may provide the trigger to a catastrophic nucleation of bubbles of this material producing a new melt with a lower density which will tend to expand and cause a pressure increase. This pressure produces a more intensive circulation of underground water and an anomalous increase of the flow rate and subsequently anomalous increases in groundwater ions and gases content.

1 Introduction

The Kamchatka peninsula is an active margin where the Pacific plate subducts beneath the North American and Eurasia plate. More than 100 volcanoes exist and many of them are active. The relative plate motion changes from underthrusting of the Pacific plate at the Kuril-Kamchatka arc to strike slip motion along the Aleutin arc at the junction of the Kamchatka and Aleutian trench. The majority of earthquakes occur in a zone located offshore $60-100$ km south-east of the Pacific coast of the peninsula (Fig. 1a) with focal depths up to 650 km; the direction of the maximum extension of their isoseismals is parallel to the east coast of the peninsula (Fedotov et al., 1985; Gorbatov et al., 1997). In this zone, earthquakes with magnitudes up to 8.6 take place; the strongest one in the last few decades ($M = 8.5$) happened on 4 November 1952. Earthquakes also occur in the continental part of Kamchatka, but with a frequency much less than in the subduction zone. Basically these continental earthquakes are related to volcanic activity, their magnitude rarely exceeds 6.0 and their focal depth is not more than 50 km (Gordeev et al., 1998).

The Russian team in the Geochemical Laboratory of the Geophysical Service of Kamchatka measured the pH value, the flow rate and temperature, the ions (Na, Ca, Cl, HCO_3, SO_4) and gases content (total, CO_2, Ar, He, N_2, CH_4) in water samples collected from a natural spring located at a distance of about 40 km from the capital city Petropavlovsk. The location of the spring is indicated in Fig. 1. In Fig. 1b, a schematic geological map of the area around Petropavlovsk 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 Viljuchinsky, the first two ones active at present. Generally a sampling frequency of three days has been used for the hydrogeochemical measurements although sometimes a frequency of six days and rarely of one day has been used. At the spring the measurements of flow rate, temperature and ions content started in January 1977; the measurements of gases content in June 1984. Figure 2 shows an example of the data collected.

At the purpose to take into consideration the seismic ac-

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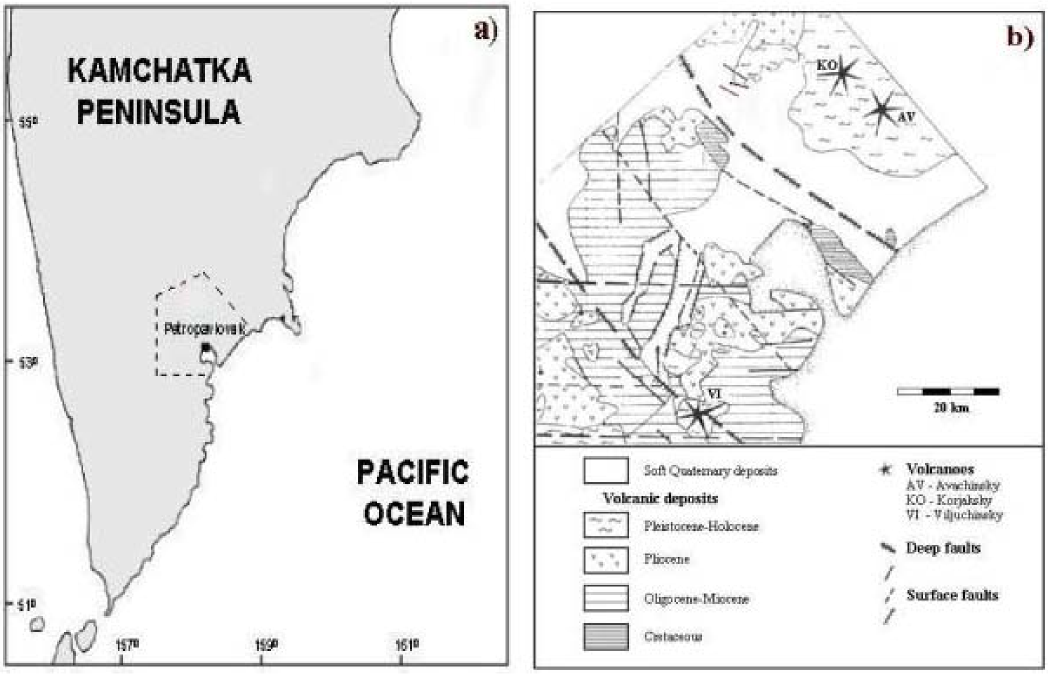

Fig. 1. **(a)** Map showing the south part of Kamchatka peninsula. **(b)** Schematic geologic map of the area around the capital city Petropavlosk. The location of the spring where the hydrogeochemical data are collected is indicated by a black circle.

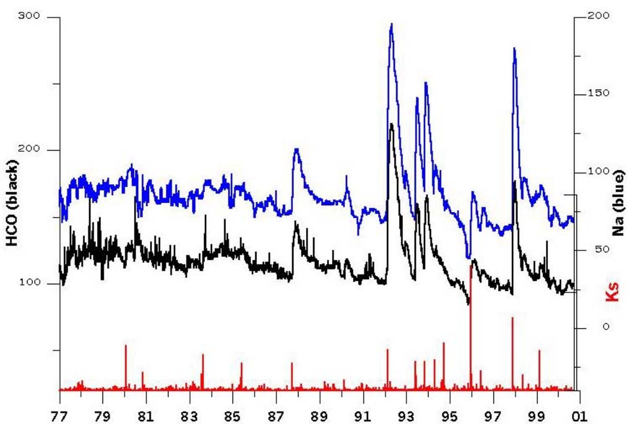

Fig. 2. HCO_3 and Na ion content in the spring together with k_s values from January 1977 to September 2001. The ions contents are in mg/l.

tivity we used k_s (Molchanov et al., 2002) values:

$$K_s = 10^{0.75\,M-1} * \left(1 + R * 10^{-M/2}\right)^{-2.5} * R^{-1}, \qquad (1)$$

where M is the magnitude and R the hypocentral distance. This parameter is a good indictor of the seismic activity occurring in a circle of radius 300–400 km around the measurement site. The k_s trend we obtained using the data of seismic catalog of Kamchatkian network is reported at the bottom of Fig. 2. From Fig. 2 some increase in the k_s trend appears in the period 1992–1999 respect to the previous time interval. Such an increase recalls the fact that the seismic activity in the area is characterized by an alternation of quiet time intervals and intervals when very strong earthquakes occur. So, in the period 1977–1991 only earthquakes with magnitude 6.0 or less occurred, whereas several events with $M \geq 6.5$ took place later.

2 Analysis

We considered the relative difference between the raw and smoothed hydrogeochemical data using the formula:

$$s(n) = [x(n) - X]/X$$
$$\left(X = \sum p_j x_j \quad j \text{ from } n - 2k \text{ to } n\right), \qquad (2)$$

where n is the day number, x the raw datum, X the smoothed datum, k the window width (15 days) and p the semi-triangle weight function. We named the s data as relative deviation values. Some example of relative deviation trend together with k_s trend is shown in Figs. 3 and 4. Figures 3 and 4 reveal that some parameter [Na, Q_a (flow rate)] seems to be related to seismic activity. On the contrary some other one (T) does not show any relation.

At the purpose to precise the previous correspondence, we compared the s trend of each hydrogeochemical parameter with the k_s trend using a running cross-correlation function with a maximum lag of ±30 days. Some result of this analysis is shown in Figs. 5 and 6. The main results is that significant (0.4−0.7) cross-correlation values appear with no lag for flow rate and with $+10 - 15$ days lags for some ion (Na, Cl, HCO_3) and gas (CH_4) content. The time interval

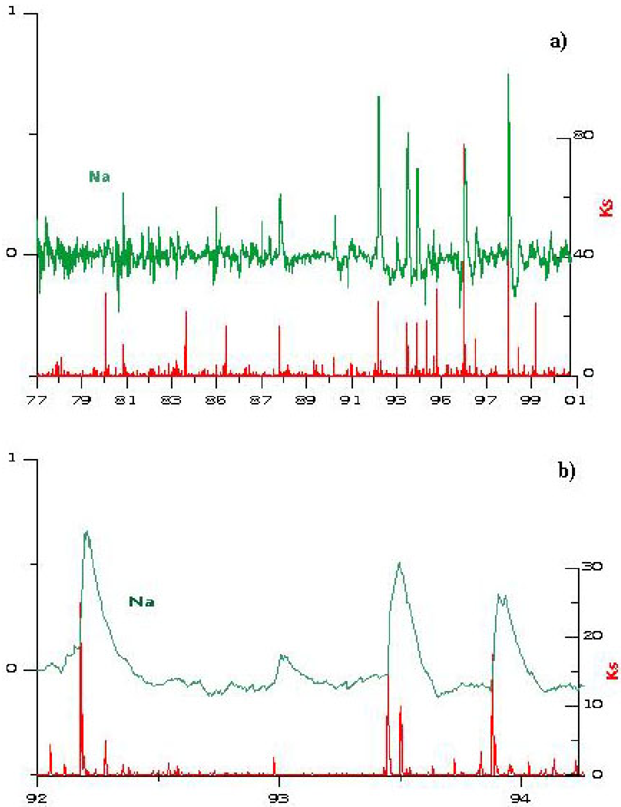

Fig. 3. **(a)** Relative deviation trend of Na ion content together with k_s values from January 1977 to September 2001. **(b)** A part of the trends of Fig. 3a in expanded scale.

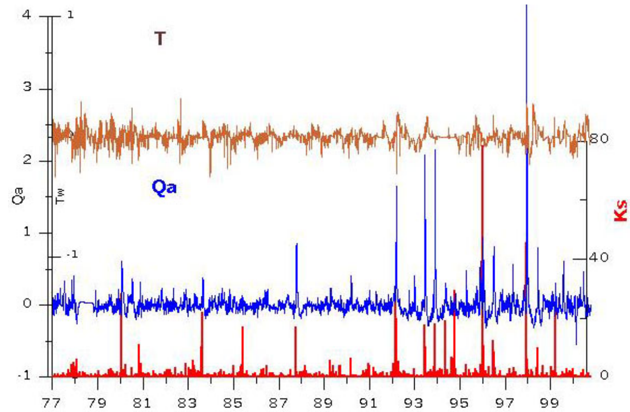

Fig. 4. Relative deviation trend of flow rate (Q_a) and water temperature together with k_s values from January 1977 to September 2001.

in which this phenomenology appears clearly is the interval 1992−1999. The correlation is positive one, i.e. flow rate and ion/gas contents increase when k_s increases.

3 Discussion

In the past the hyd Discussionrogeochemical data collected at artificial wells located in southern Kamchatka were analysed and possible precursors of earthquakes were proposed (Biagi et al., 1999; Biagi et al., 2000a, b, c; Biagi et al., 2001; Kingsley et al., 2001). The phenomenology we described in Sect. 2 is unique of its kind and it is different from the results previously obtained for the wells in Kamchatka. Such a difference must be related to the location of the natural spring and to its water peculiarities. Let us assume that such a water is characterized by an underground deep circulation in the zone where the viscoelastic underground medium beneath the Koryaksky volcano is present. The absence of preseismic effects on the hydrogechemical data seems to indicate that this material is always able to absorb stress variations connected with the preseismic phase. This suggestion seems to be realistic because preseismic stress variations generally are transmitted by very long period waves (Bella et al., 1990) and those media with viscoelastic properties cannot be crossed by such waves (Bilham and Beavan, 1979; Bella et al., 1986). On the contrary these media are not able to absorb the short period waves produced by earthquakes. So, the co-postseismic effects revealed at the spring in Kamchatka can be interpreted as a response of the magma chamber of the volcano to seismic waves on the occasion of some earthquake, mainly those largest and nearest to volcano. A mechanism able to produce the phenomenology we presented might be as follows. Let us consider a supersaturated magma chamber in which there is no abundance of Fe-Ti oxides to permit the exsolution of water. In this case, the melt is in a state of chemical disequilibrium and the supply of elastic energy by some earthquake may provide the trigger to the catastrophic nucleation of bubbles that restores the equilibrium with the exsolution of the excess water. The nucleation and growth of bubbles within the magma chamber produces a new melt with a lower density which will tend to expand and cause a pressure increase on the chamber wall (Scandone, 1996). This pressure produces a more intensive circulation of underground water and an anomalous increase of the flow rate at the spring happens. At the beginning the more surface water pours out and no change in its chemical composition appears. Subsequently, due to the emission of the deepest water, anomalous increases in some ion and gas content of the water is revealed. Finally, a gradual return of the perturbed groundwater system to the initial conditions happens and the water parameters at the spring get back to normality.

4 Conclusions

We presented co-postseismic effects in flow rate and some ion/gas contents revealed in a spring located in the Koryakskiy volcano area. At the purpose to justify this phenomenology we proposed a pumping effect of the magma chamber on the surrounding underground water produced by the seismic waves on the occasion of some earthquake. Of course, more results are needed to confirm the proposed model, but the

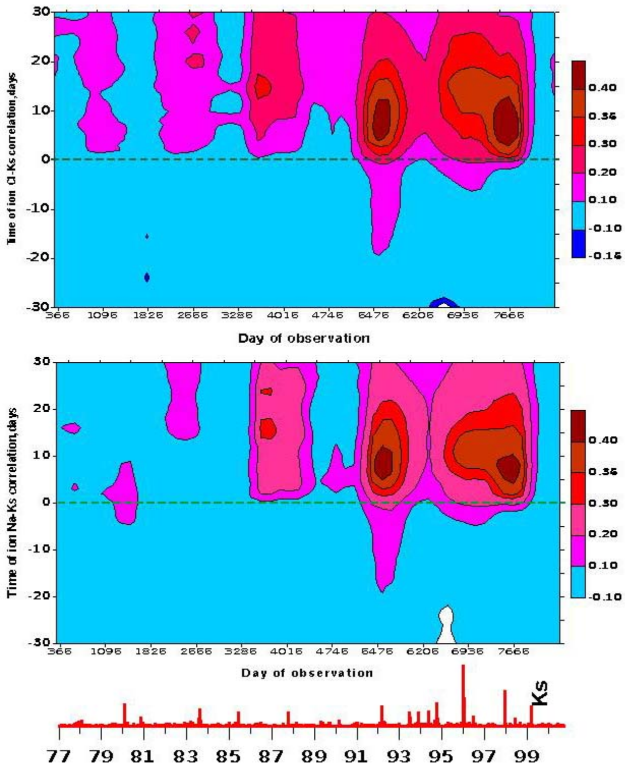

Fig. 5. Running cross-correlation Cl ion content-K_s (top) and Na ion content-K_s (bottom) with a maximum lag of ±30 days. The running window is half a year. The different colors represent the values of the cross-correlation coefficient. The relative chromatic scale is indicated on the right.

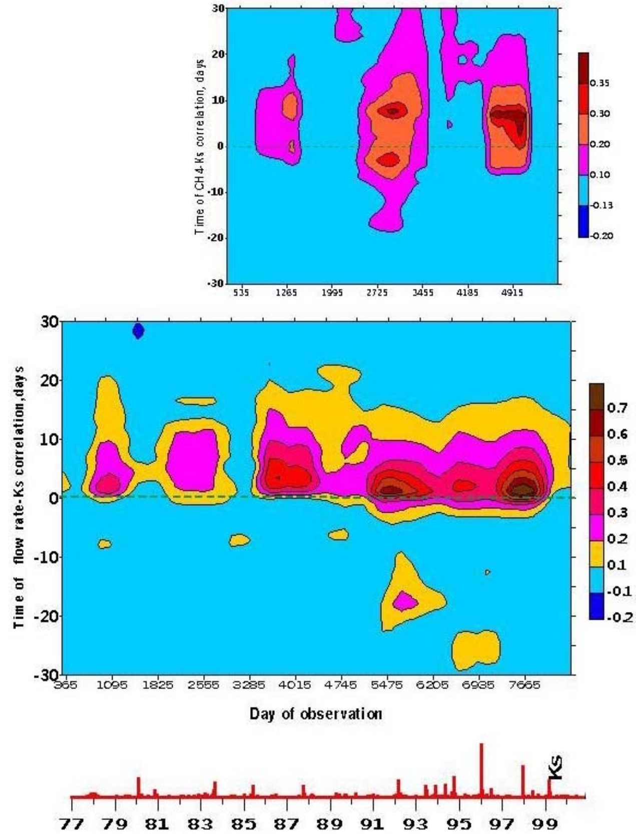

Fig. 6. Running cross-correlation CH_4 gas content-K_s (top) and flow rate-K_s (bottom) with a maximum lag of ±30 days. The running window is half a year. The different colors represent the values of the cross-correlation coefficient. The relative chromatic scale is indicated on the right.

past history of the Koryakskiy volcano seems indicative of the model. In fact phreatic activity was revealed (Melekestsev, 1996) as a consequence of the activity of the nearby Avacha volcano and of a strong earthquake and this phenomenology is indicative of an ease of volcanic gases escape from the reservoir which comes into contact with the surrounding hydrothermal system.

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