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Seismo-geochemical anomalies of He/Ar ratio of gas bubbles at Hoshina spa near Matsushiro, Nagano Prefecture, central Japan

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ABSTRACT

Continual monitoring data of gas bubbles at Hoshina spa near Matsushiro, Nagano Prefecture, central Japan, showed three coseismic anomalies in the period from 1989 to 1994. The respective anomalies were associated with three nearby earthquakes with M=3-4 and focal distances less than 10 km. They are characterized commonly by sudden decreases of He/Ar ratio and sluggish recoveries of the ratio over more than one month. These seismo-geochemical anomalies can be interpreted as the result of decreased pore pressures in the reservoir filled with deep groundwater with a high concentration of He relative to shallow groundwater. The decreases of pore pressure could be caused by crustal stress/strain changes accompanied by the respective nearby earthquakes, but possibly not by the ground motion due to seimic waves. The gas monitoring results at Hoshina spa suggest that the behavior of subsurface gases is sensitive to the change in crustal stress/strain conditions.

INTRODUCTION

It has been known for centuries that a variety of apparently strange phenomena were observed at groundwater wells and mineral or hot springs immediately before and after many large earthquakes. These phenomena include changes of various subsurface fluids such as groundwater, mineral or hot spring water, gas associated with subsurface water and soil gas (King, 1986 and references therein). The subsurface fluids may be affected by crustal stress/strain changes relating to earthquakes. Information on the changes of subsurface gas and water qualities and the factors causing such changes is prerequisite in order to utilize the geochemical anomalies for earthquake prediction study. For this purpose, continual and precise monitoring of geochemical species is primarily important. In our laboratory, we have monitored compositions of mineral spring gases at several sites in central Japan by using an automated gas chromatogragh system for more than ten years (Sugisaki, 1985; Nagamine, 1987). During our studies, the sensitivity and reliability of the monitoring system have been improved (Nagamine, 1990 and 1994). At Byakko spa, another monitoring site in Mizunami, Gifu Pref., conspicuous changes in the spring gas composition were observed prior to two

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large inland earthquakes with M>6, namely, the 1984 Western Nagano Prefecture earthquake (Sugisaki and Sugiura, 1985) and the 1995 Southern Hyogo Prefecture earthquake (Sugisaki et al., 1996; Ito et al., 1996). Several coseismic anomalies were also recorded at Byakko spa, when earthquakes with M=4-5 occurred within about 50 km (Nagamine and Sugisaki, 1991b; Nagamine, 1994; Ito et al., 1994).

The spring gas composition at Hoshina spa near Matsushiro, Nagano Pref., has also been monitored similarly since 1989. Coseismic drops of He/Ar ratio have been recorded for the earthquakes with 3<M<4 at short focal distances less than 10 km. In this paper the unique seismo-geochemical anomalies of gas bubble composition at Hoashina spa are reported.

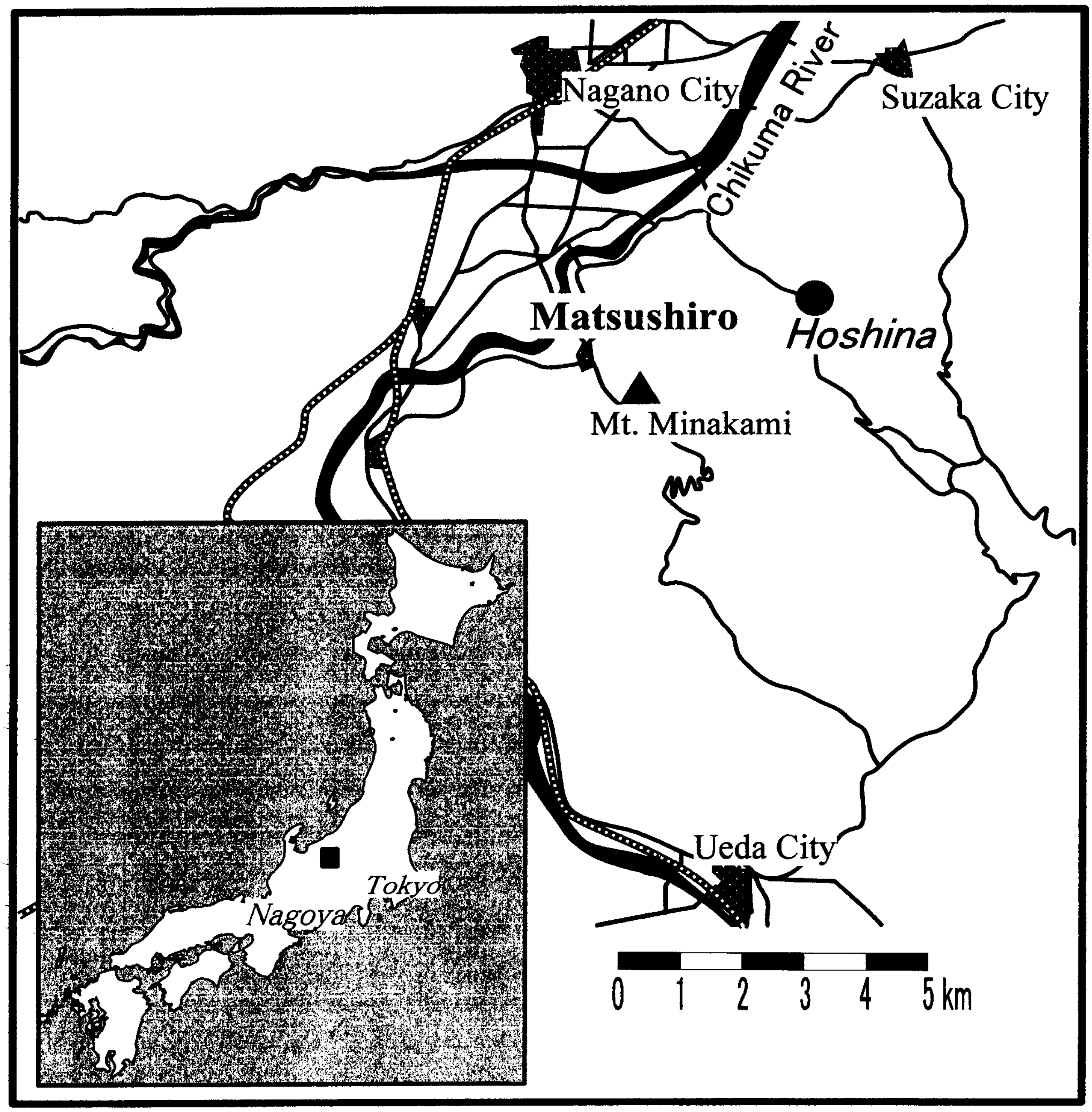

Fig. 1. Location map for the Hoshina spa as a gas monitoring station for seismo-geochemical study.

EXPERIMENTAL

Hoshina spa is located in the south-eastern suburb of Nagano city (Fig. 1). Matushiro, which is famous for "Matsushiro earthquake swarm" in the middle of 1960 (Scholz, 1990), is also very close to Hoshina spa. Spring water of 30°C is issuing constantly from a borehole drilled into the bedrock of Tertiary volcanic rocks to a depth of 160 m. Numerous small gas bubbles are associated with issuing spring water because of dissolved gases supersaturating in the water at ground surface. The average composition of such gas bubbles is N_2 (98%), Ar (1%), CH_4 (0.02%) and He (0.02%). Gas bubbles are separated into a "gas collection box" with a funnel placed upside down inside of the tank of issuing spring water. An automatic gas sampler for gas chromatographic analysis pumps a gas sample from the gas collection box, and injects 2 ml of it into a gas chromatograph with an interval of 3 hours. A standard gas in a cylinder is also analyzed twice a day for calibration.

Figure 2 shows a schematic illustration of the hardware configuration of the geochemical monitoring system at Hoshina. A personal computer controls the gas chromatograph for gas bubble analysis, and records the analytical data at the monitoring site. The computer also transmits the data to our laboratory via public telephone line (Nagamine et al., 1989). An Ohkura 802TDH gas chromatograph with a thermal

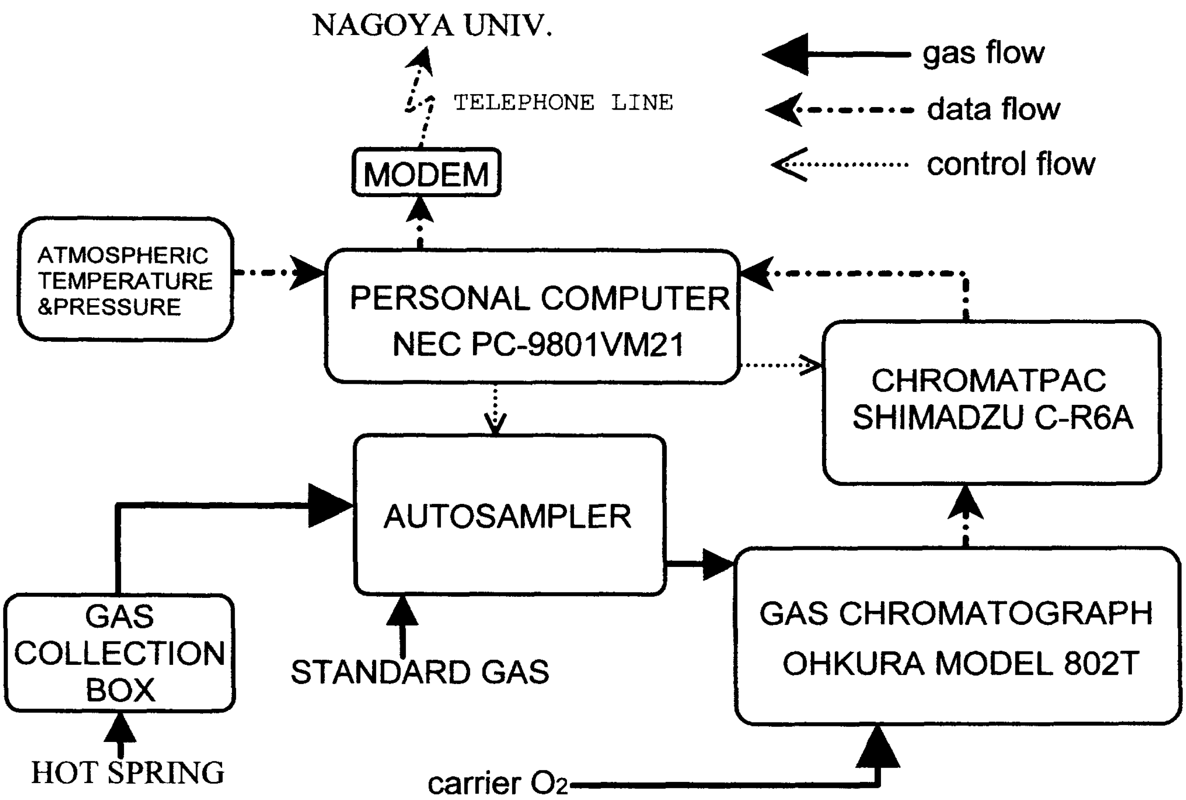

Fig. 2. A schematic illustration of the hardware configuration of the geochemical monitoring system at Hoshina spa. A personal computer controls the gas chromatographic analysis of gas bubbles, recording the analytical data, and transferring the data to our laboratory via public telephone line.

conductivity detector (TCD) has been used for analyzing He, H_2, Ar, N_2 and CH_4 in the gas bubbles, although quatitative analysis of H_2 is impossible because of its low concentration level less than a few ppm. Detailed description of the automated gas monitoring system is given elsewhere (Nagamine and Sugisaki, 1991a).

RESULTS

Figure 3 shows the monitored He/Ar ratio of gas bubbles at Hoshina spa from 1989 to 1994, in which daily average values of individual analyses of He/Ar ratio are plotted. The periods with no data points mean that the monitoring system was in trouble. The monitored values of He/Ar ratio between August, 1990 and November, 1993 are apparently lower and more fluctuating than those in the other periods. In the period, an earlier type of gas chromatographic monitoring system (Nagamine, 1987) has been used. We suspect that a small amount of air possibly through somewhere of the pipe line and its joints between the gas collection box and the auto sampler was mixed with every gas sample when it was pumped into the autosampler. Although we could not be aware of where the air contamination occurred, such air contamination was not recognized before July, 1990 and after December, 1993, judging from the monitoring results of He/Ar ratio.

Apart from the air contamination, two remarkable changes of He/Ar ratio are seen in 1990 and 1994. They show quite similar changing patterns with each other, in which sudden decreases of He/Ar ratio and slow subsequent recoveries of the gas ratio over more than one month are commonly recognized. Figure 4a and c are enlarged plots of data for the two periods, in which all the data obtained in every three hours are shown. The respective decreases of He/Ar ratio occurred quite rapidly within a day, and then the He/Ar ratio recovered very slowly for prolong times more than one month. Two felt earthquakes occurred exactly when the respective sudden decreases of He/Ar ratio started as is indicated in Fig. 4. The focal distances of the two seimic

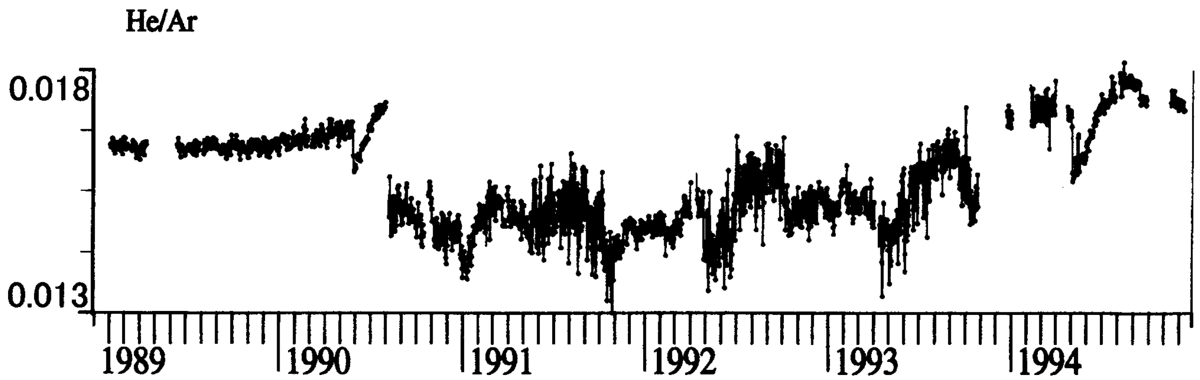

Fig. 3. Plots of daily averages of He/Ar ratio of gas bubbles issuing from Hoshina spa in our monitoring period. No plotted data mean that the monitoring system was in trouble in the periods. We suspect that a small amount of air was mixed with every gas sample when it was pumped into the autosampler in the period from August, 1990 and November, 1993 (see text).

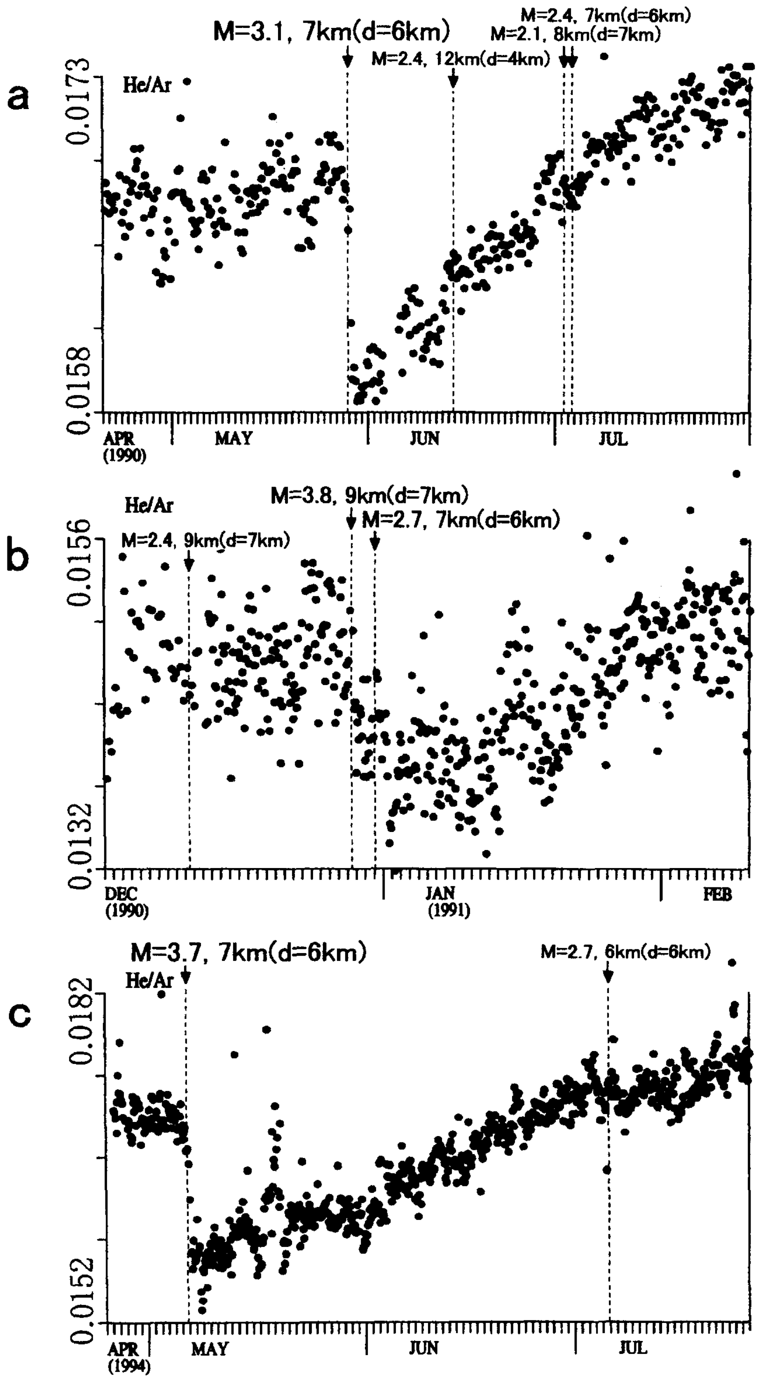

Fig. 4. Enlarged plots of He/Ar data showing anomalous changes. All the data obtained in every three hours are shown for the three different periods of a, b and c. Vertical lines indicate occurrence times of felt earthquakes at Nagano city and/or Matsushiro (Table 1). The He/Ar anomalies correspond to respective nearby earthquakes.

events are within 10 km, therefore the sudden decreases of He/Ar ratio were caused by the respective nearby earthquakes. As shown in Fig. 4b, a similar anomaly of He/Ar ratio was recorded in late December 1990 – January 1991, although gas samples in this period are suspected to have been contaminated with small amounts of air and resulted in more fluctuating data of He/Ar ratio than in the cases of Figs. 4a and c.

Two earthquakes with M=3.8 and 2.7 occurred very close to Hoshina spa in late December 1990. Possibly this sudden drop of He/Ar ratio was a seismo-geochemical anomaly caused by the event with M=3.8 like the cases of Fig. 4a and c.

In Figs. 4a and c, occurrences of other seismic events felt at Nagano city and/or Matsushiro (Table 1) are also indicated. No obvious drops of He/Ar ratio or other types of anomalous changes can be recognized for such smaller events. It appears that some specific earthquakes with the larger magnitudes at the smaller distances can cause coseismic decreases of He/Ar ratio at Hoshina spa.

Table 1. Felt earthquakes at Nagano and Matsushiro occurring in observation period.

year	month	day	latitude	longitude	Focal depth	Magnitude	Seismic intensity		Focal distance
			(N)	(E)	(km)		Nagano	Matsushiro	(km)
1989	11	1	39°50'	143°04'	0	7.1	1		555
1989	11	11	36°31'	138°07'	6	2.4		1	16
1990	2	20	34°42'	139°19'	17	6.5	1		229
1990	2	22	36°35'	138°12'	6	1.8		1	10
1990	3	2	36°36'	138°18'	6	2.7	1	2	7
1990	3	13	36°32'	138°20'	8	1.5		1	11
1990	5	2	36°36'	138°18'	6	2.6		1	6
1990	5	11	36°35'	138°15'	7	2.2		1	8
1990	5	28	36°35'	138°15'	6	3.1	1	2	7
1990	6	14	36°30'	138°12'	4	2.4		2	12
1990	7	2	36°35'	138°15'	7	2.1		2	8
1990	7	3	36°35'	138°15'	6	2.2		1	7
1990	10	11	36°35'	138°16'	7	2.9	1	2	8
1990	10	21	36°36'	138°16'	7	1.6		1	8
1990	10	25	36°31'	138°21'	7	2.9		1	12
1990	10	25	36°35'	138°19'	5	2.5		2	6
1990	11	26	36°35'	138°14'	2	1.7		1	5
1990	11	29	36°36'	138°16'	6	2.6		2	6
1990	12	10	36°37'	138°19'	7	2.4		1	9
1990	12	28	36°36'	138°21'	7	3.8	2	2	9
1990	12	31	36°35'	138°20'	6	2.7		1	7
1991	4	9	36°35'	138°14'	5	1.7		1	7
1991	11	12	36°35'	138°22'	9	2.6		1	11
1992	2	7	36°35'	138°16'	6	2.9	1	2	6
1992	3	3	36°32'	138°11'	7	2.2		1	13
1992	7	1	36°26'	138°03'	6	3.5		1	27
1992	8	5	35°54'	138°04'	11	4.3		1	78
1993	2	7	37°39'	137°18'	25	6.6	3	1	150
1993	6	9	37°41'	137°23'	21	5.1	1		148
1994	5	6	36°35'	138°19'	6	3.7	2	2	7
1994	7	5	36°35'	138°17'	6	2.7	1		6
1994	10	4	43°22'	147°40'	30	8.1	1		1105
1994	11	28	36°32'	138°08'	11	2.6	1	1	14
1994	12	26	36°36'	138°16'	6	2.5	1		6
1994	12	28	40°27'	143°43'	0	7.5	1		641

Figure 5 shows the concentrations of He, Ar and CH_4 in gas bubbles for the same period of Fig. 4c. The changing pattern of He concentration is quite similar to that of He/Ar ratio of Fig. 4c. The coseismic drop of He/Ar ratio is due to the decrease of the He concentration. The concentration of CH_4 also shows a step-like decrease at the time of the earthquake. The N_2 concentration did not show any detectable changes, since the gas bubbles are almost totally composed of N_2.

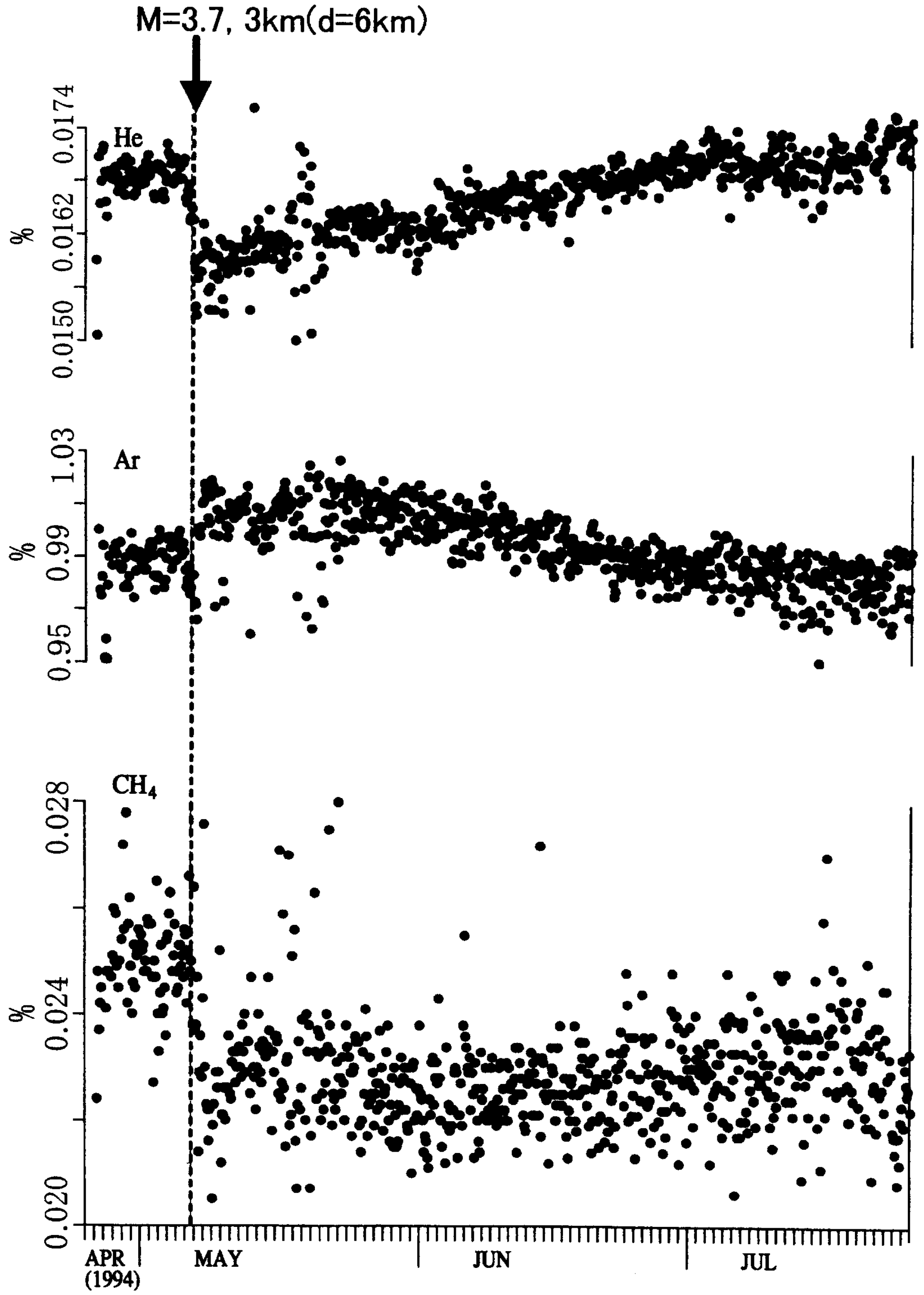

Fig. 5. Variations of He, Ar and CH_4 concentrations in Hoshina spa gas bubbles in the same period as in Fig. 4c. The anomalous change in He/Ar ratio is due to the change of He concentration. The CH_4 concentration also shows a coseismic decrease.

DISCUSSION

Remarkable coseismic changes of He/Ar ratio were observed for the two earthquakes in the immediate neighborhood of Hoshina spa (Fig. 4). Table 1 lists the seismic parameters including JMA seismic intensities for the earthquakes felt at Nagano city and/or Matsushiro in our observation period of Fig. 3. They are selected from JMA seismic data. Comparison of seismic intensity data for the felt earthquakes with our gas monitoring results of Fig. 4 suggests that seismic events at far distant places do not cause anomalous changes of He/Ar ratio even if accelerations of seismic ground motions due to such quakes are large enough at Hoshina. It is less likely that ground motions due to seismic waves cause the anomalies of He/Ar ratio at Hoshima spa.

Our gas monitoring at Byakko spa revealed coseismic changes of He/Ar ratio (Nagamine and Sugisaki, 1991a; Nagamine, 1994; Ito et al., 1994). However, the coseismic anomalies of He/Ar ratio at Byakko are all spike-like increases within several hours. The occurrence of such a spike-like increase of He/Ar ratio at Byakko is roughly correlated with the seismic intensity for each earthquake at Byakko. The situations are totally different between Byakko and Hoshina.

In search for a possible mechanism of He/Ar anomalies at Hoshina, the earthquakes assigned to the He/Ar anomalies in Fig. 4 are compared with the other seismic events in their plots on the magnitude vs. focal distance diagram (Fig. 6). Seismic events with M>1 and focal distances <100 km have been selected from JMA seismic data base for the period of our monitoring at Hoshina. In the plot of Fig. 6, the three earthquakes accompanying the He/Ar anomalies in Figs. 4 a,b and c are clustered and readily distinguished from the other seismic events. The three events are characterized by short focal distances less than 10 km and relatively larger magnitude values greater than 3. The dotted line shown in Fig. 6 is a tentative empirical threshold for the earthquakes accompanying gas anomalies of He/Ar ratio at Hoshina spa. The plots of Fig. 6 and irrelevant seismic ground motions mentioned before imply that the coseismic changes of He/Ar ratio at Hoshina spa could be caused by changes of crustal stress/strain condition associated with the respective nearby earthquakes.

Wakita et al. (1978) postulated the existence of "Helium spots" characterized by the mantle helium with high $^3He/^4He$ ratio in the Matsushiro area. Because of high He fluxes originated from deep mantle and radiogenic He of the crustal origin, the He concentration in deep groundwater beneath the Matushiro area including Hoshina spa could be higher than that in shallow groundwater in the same area. It may be reasonable to assume that the spring water at Hoshina spa is a mixture of He-rich deep groundwater and He-poor shallow one. If the mixing ratio of deep water relative to shallow one decreases at the time of a certain nearby earthquake, the observed decreases of He concentration and He/Ar ratio will be explained. The occurrence of the nearby earthquake possibly accompanies changes in crustal stress/strain conditions for groundwater reservoirs. In general, such changes give rise to a more significant effect for deep grounwater reservoir than for the shallow one, since porosity and water permeability in deep reservoir are much smaller than those in shallow water reservoir. A reduction of pore pressure of deep groundwater reservoir relative to that of shallow one leads to a decreased mixing ratio of deep water enriched in He and

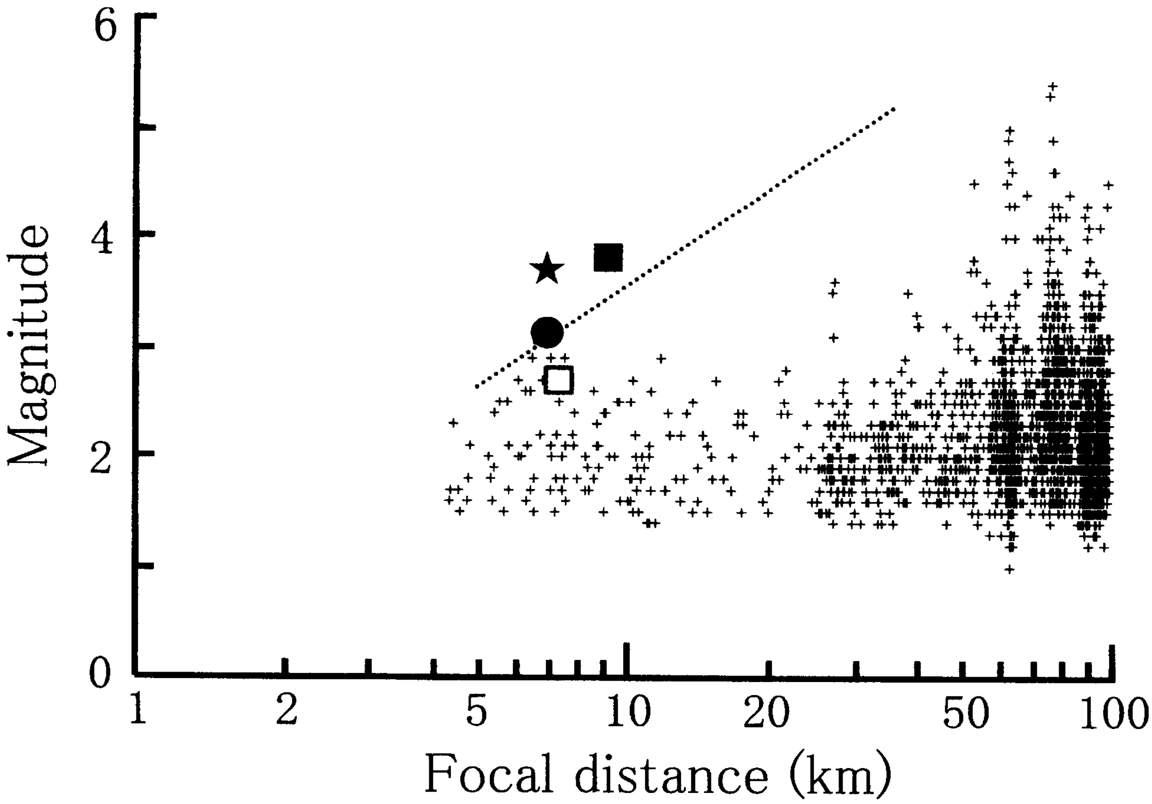

Fig. 6. Magnitude vs. focal distance plots for seismic events for the period of our monitoring at Hoshina spa. Seismic events with M>1 and epicentral distances <100 km have been selected from the JMA seismic data base. The filled circle (May 28, 1990), filled square (December 28, 1990), and filled star (May 6, 1994) are the nearby earthquakes corresponding to the gas anomalies of He/Ar ratio. The open square is the event on December 30, 1990 just after the event of filled square (December 28, 1990). The plus symbols represent the other seismic events occurred in the period of our monitoring at Hoshina spa. The dotted line is a tentative empirical threshold for the earthquakes accompanying gas anomalies of He/Ar ratio at Hoshina spa.

possibly in CH_4. The pore pressure decreases when the compressional volumetric strain of pores of the deep groundwater reservoir is reduced without the change of effective water permeability of the reservoir. If the connectivity of water flow pores in deep groundwater reservoir is reduced without the effective pore volume, namely, a reduction of water permeability, a decreased mixing ratio of deep water relative to the shallow one is also expected. Although it is difficult to infer the details of coseismic gas anomalies by our monitoring results, the observed changes in the He/Ar ratio and He concentration of gas bubbles at Hoshina spa are important as one type of coseismic gas anomalies associated with rather small earthquakes in the immediate neighbor of the mineral spring.

CONCLUSIONS

Continual monitoring data of gas bubbles at Hoshina spa near Matsushiro by an automated gas chromatographic system, revealed three coseismic anomalies in the period from 1989 to 1994. These anomalies were associated with nearby earthquakes with M=3-4 and focal distances less than 10 km. At the time of each event, He/Ar ratio of gas bubbles sharply decreased and subsequently recovered quite slowly for more than one month. The seismo-geochemical anomalies can be interpreted as the result of decreased pore pressure and/or effective water permeability in the reservoir for deep groundwater with high helium concentration relative to shallow groundwater. The decreases of pore pressure and/or water permeability could be caused by crustal stress/strain changes accompanied by the respective nearby earthquakes, but possibly not by the ground motions due to seismic waves. The gas monitoring results at Hoshina spa are examples suggesting that the behavior of subsurface gases is sensitive to the change in crustal stress/strain conditions induced by earthquakes.

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