J. Earth Planet. Sci. Nagoya Univ., Vol. 45, 1 to 15, 1998

Seismo-geochemical observation at a deep bore-hole well of Nagashima spa in the Yoro-Ise Bay fault zone, central Japan

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(Received October 14, 1998 / Accepted November 20, 1998)

ABSTRACT

A new station for seismo-geochemical observation has been installed at a 1,500 m bore-hole well of Nagashima spa in a southwestern suburb of Nagoya, central Japan. The well is located in the Yoro-Ise Bay active fault zone. Gas bubbles are separating from groundwater being pumped constantly at the well. In November 1997, we started automated monitoring of H_2, He, Ar, N_2, CH_4 and Rn in the gas bubbles by using a gas chromatograph and an α scintillation Rn monitor. Even in a short monitoring period less than one year, similar preseismic increases in the H_2 concentration have been recorded for nearby microearthquakes (M = 1.6, 1.9, 2.0 and 2.6) and small and moderately large events (M = 3.8 and 5.4) within the focal distance of 25 km. All the six events occurred in parallel with the Yoro fault several kilometers apart in the west. In particular, three microearthquakes before the M = 5.4 event and the moderately large event itself accompanied conspicuous H_2 anomalies. Preseimic increases in the H_2 concentration up to 100% during a few to several weeks were followed by spike-like increases of H_2 concentration of 10–100% immediately after the respective four shocks. No comparable anomalies were seen in the gas species other than H_2. The preseismic increases in groundwater H_2 are plausibly geochemical diagnostics of the stress corrosion process preceding earthquakes. The preseismic H_2 anomalies for the two events (M = 3.8 and 1.9) after the M = 5.4 shock were less conspicuous than those for the other four events. The background-level of H_2 concentration also decreased significantly after the M = 5.4 event. The subsurface H_2 behavior may have reflected the stress condition in the Yoro fault zone altered by the M = 5.4 earthquake.

INTRODUCTION

There have been reported seismo-geochemical anomalies of several gas components including Rn, He, H_2 and CH_4 in groundwater and soil gas in active fault zones of U.S.A., Russia, China and Japan (King, 1986 and references therein). Automated monitoring of multi-gas components rather than a single component is favorable to studying groundwater gas behavior related to seismic activities. In late October 1997, we installed a new multi-gas component monitoring system equipped with an automated gas chromatograph and an α

scintillation Rn detector at a pumping groundwater well of Nagashima spa, a southwestern suburb of Nagoya, central Japan (Fig. 1).

The Nagashima well is 1,500 m deep and located in the Yoro-Ise Bay active fault zone. The Yoro fault is one of the major active faults in the vicinity of Nagoya (Fig. 1). Surface geology, compilation of drilled cores data and seismic reflection data (Toda et al., 1997 and references therein) indicate that the cumulative vertical displacement of the Yoro fault reaches at least about 2 km since the late Pliocene. The eastern block of the Yoro fault has subsided and tilted in the west. This allowed to form a thick tilted sedimentary basin of the Pliocene and Quaternary. A densely populated area centered by Nagoya City is now expanding to the west across the Yoro fault. If a large earthquake with M = 7 occurs along the fault, it gives rise to a serious disaster as exemplified by the tragedies of the 1976 Tangshan earthquake in China and the 1995 Kobe earthquake in Japan. The preseismic geochemical anomalies of the Tangshan

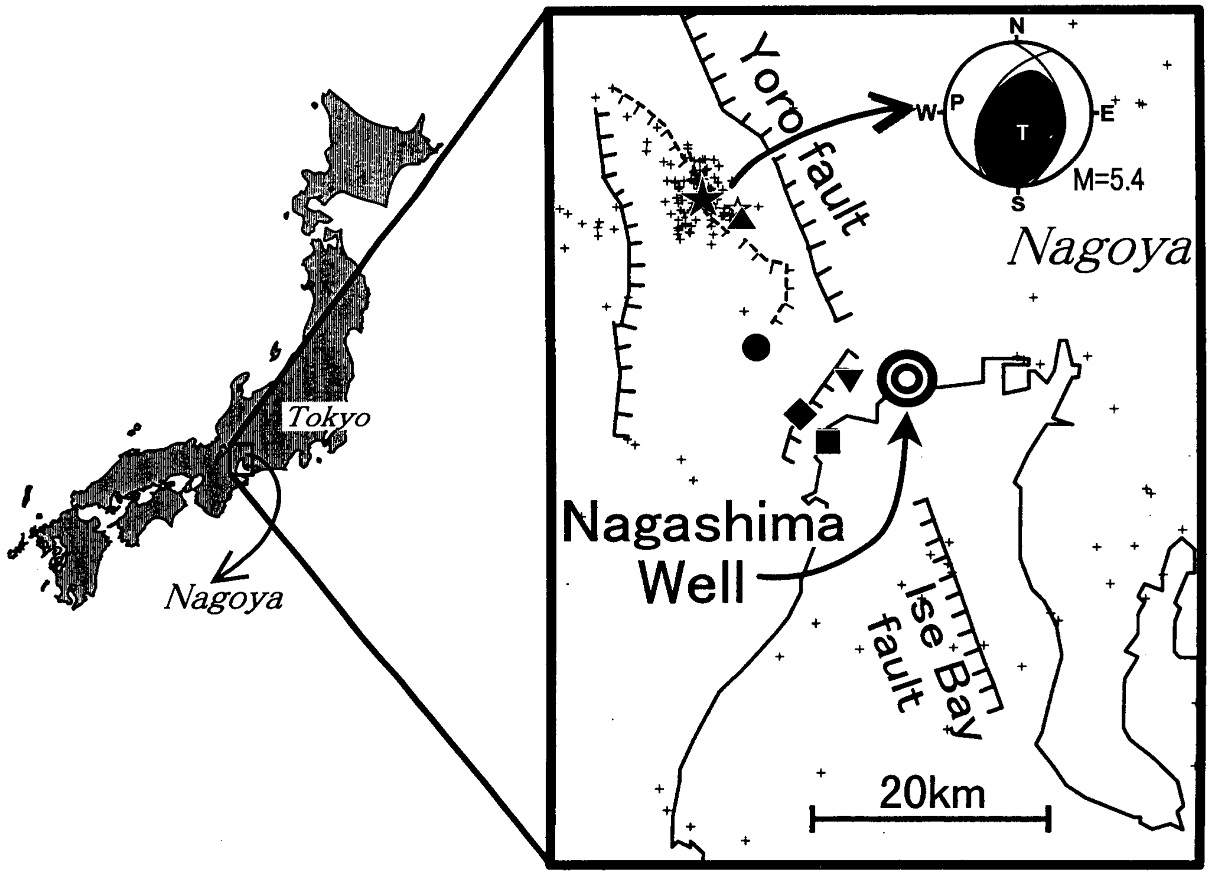

Fig. 1. The Yoro-Ise Bay fault system and the location of Nagashima well for monitoring He, H_2, Ar, N_2, CH_4 and Rn concentrations in gas bubbles separating from pumped groundwater. Filled symbols indicate the epicenters of earthquakes (M = 1.6–5.4) which are assigned to the H_2 anomalies (see Fig. 4). The open star is the epicenter of a fore shock of the M = 5.4 earthquake (the filled star). Small plus symbols indicate the epicenters of seismic events which are unrelated with the H_2 anomalies. The focal mechanism for the M = 5.4 event by JMA is the dip-slip reverse, which coincides with the field observation of reverse faulting on the Yoro fault.

and Kobe earthquakes have reported (Shi and Cai, 1986; Igarashi et al., 1995; Tsunogai and Wakita, 1995; Sugisaki et al., 1996), but the anomalies were identified after the respective disasters.

If the correlation between preseismic gas anomalies and large earthquakes reported so far is essential, even smaller seismic events may accompany similar gas anomalies. However, little attention has been paid to this point. Simultaneous monitoring of different gas species may elucidate subsurface gas behaviors associated with small earthquakes in an active fault zone even in a relatively short period. The smaller earthquakes occur the more frequently than larger ones. This is one of our motivations for monitoring groundwater gas components at the Nagashima well located in the Yoro-Ise Bay active fault zone.

MONITORING WELL

The Nagashima well was drilled in 1963 to a depth of 1,500 m. The well is cased to a strainer at the bottom. The $NaHCO_3$-type groundwater at 55°C is being pumped at an approximately constant rate (3,000 m^3/day) by a pump submerged at depth of 50 m. It is being sent to a storage tank and delivered to a nearby amusement center. The strainer level at depth of 1,500 m corresponds to the basal gravel layer of the Tokai group (Adachi and Kuwabara, 1980). The groundwater contains gas bubbles composed mainly of N_2 (54%), CH_4 (45%) and Ar (1%). We analyzed groundwater from the well to compare chemically it with seawater (Table 1). The groundwater has rather low concentrations of soluble constituents. For example, its chloride concentration is only 20 ppm. Although the well is drilled in a coastal area (Fig. 1), it shows no trace of seawater in the chemical constituents of its groundwater, suggesting the recharge of the groundwater in mountain regions.

GAS MONITORING SYSTEM AT NAGASHIMA

A small fraction of pumped ground water with gas bubbles is introduced into the gas collection unit of our gas monitoring system at a rate of about 1,000 ml/min. Gas bubbles are separated from water in the gas collection unit as shown in Fig. 2. The relatively high humidity in the collected gas is reduced by an electric cooler and then the gas continuously flows to the vent through the gas analysis unit at a flow rate of about 30 ml/min. An α scintillation Rn monitor (Pylon® Model AB5 with a Model 300A Lucas cell) counts Rn activity in the continuous mode for one-hour intervals. In every three hours, the gas of 2 ml is injected into a gas chromatograph (Ohkura model 802 TDH) by an automatic gas sampler (Ohkura model R4013), and He, H_2, Ar, N_2 and CH_4 are analyzed with the carrier gas of O_2. Standard gas in a cylinder with a similar composition to the sample is also analyzed twice a day for calibration. A digital integrator (Shimazu C-R3A) is used to record the peak areas on all the gas chromatograms. The automated gas chromatograph system is similar to

Table 1. Dissolved constituents of the groundwater from Nagashima well, and its comparison with seawater.

	Nagashima groundwater*	Seawater†
pH	8.28	≈ 8.1
K^+ (mg/kg)	1.47	399
Na^+ (mg/kg)	111	10,733
NH_4^+ (mg/kg)	0.64	–
Ca^{2+} (mg/kg)	3.53	412
Mg^{2+} (mg/kg)	0.22	1,294
Fe^{2+} + Fe^{3+} (mg/kg)	0.05	0.002
Al^{3+} (mg/kg)	0.06	0.0005
Mn^{2+} (mg/kg)	0.1	0.0002
Cl^- (mg/kg)	20.2	19,344
F^- (mg/kg)	0.4	1.3
SO_4^{2-} (mg/kg)	0.43	2,712
HCO_3^- (mg/kg)	–	142

* Chemical analyses were made by ion chromatography and ICP-AES in our laboratory. The pH value was measured by a pH meter.
† Cited from Chester (1990).

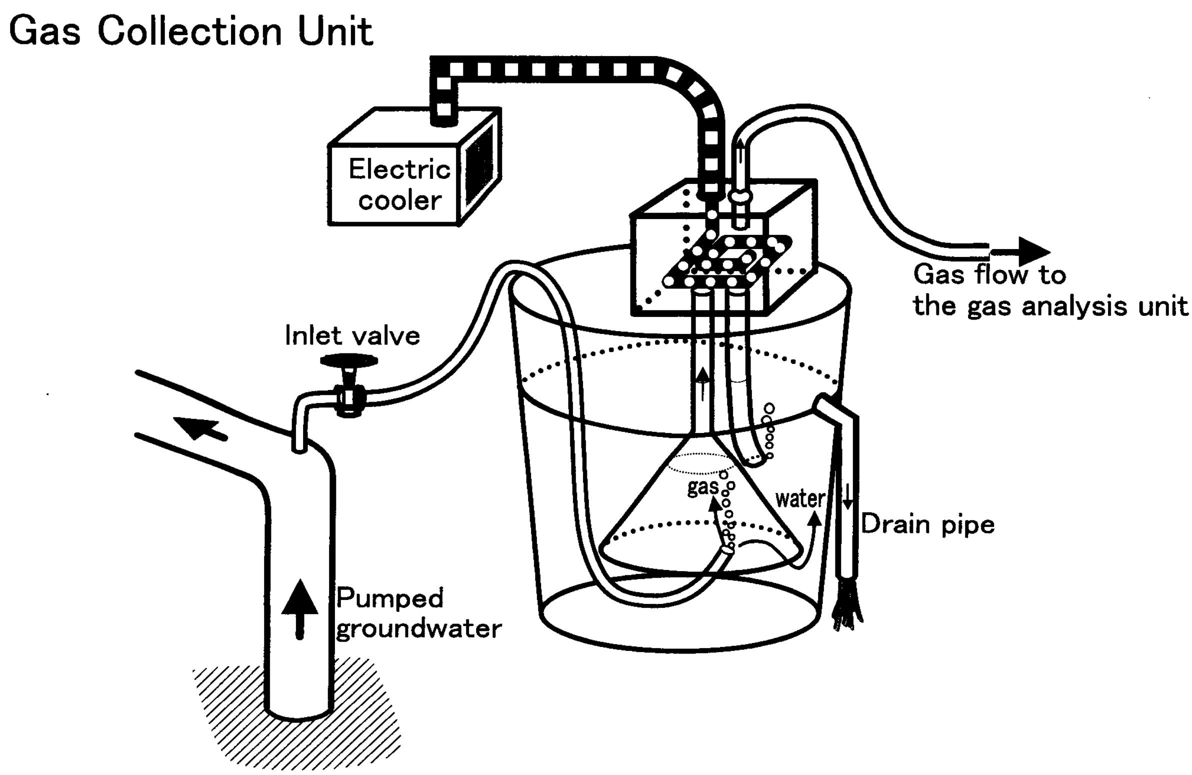

Fig. 2. A schematic diagram to illustrate the gas collection unit of our monitoring system at Nagashima.

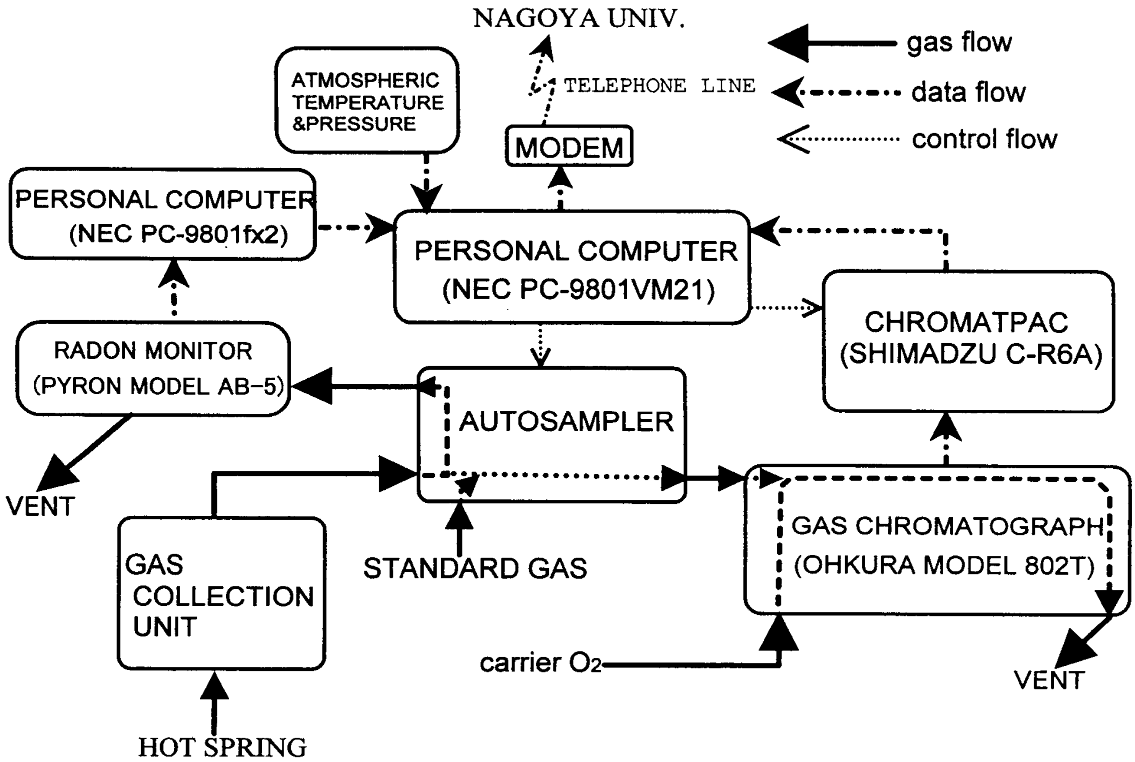

Fig. 3. A block diagram to illustrate of the automatic gas monitoring system at Nagashima.

that reported elsewhere (Nagamine, 1994). Observation data by this system are sent to our laboratory via public telephone line once a day in midnight. Two personal computers control all the procedures for gas analyses and data transmission (Fig. 3).

The water flow to our monitoring system is controlled only by an inlet valve for introducing groundwater into the gas collection unit (Fig. 2). Therefore water and gas flows into the monitoring system are not precisely constant. The gas flow fluctuations do not affect the gas chromatographic analyses. The fluctuating gas flow rate, however, might influence Rn counting data as well as fluctuating air temperature and pressure. The gas flow rate is normally about 30 ml/min, therefore the residence times of sample gas in the gas collection box shown in Fig. 2 and the Lucus cell of Rn detector are about 30 and 10 minutes, respectively. These residence times are much shorter than the half-life of Rn of 3.82 days, and the decay correction due to these residence times is less than 1%. If the gas flow rate decreases to 3 and 1.5 ml/min, the decay correction amounts to 5 and 10%, respectively. Hence, unless the gas flow rate is decreased to one-tenth of the normal value or less, gas flow fluctuations little influence Rn counts. The observed daily fluctuations of Rn data are about 3%, which are mainly due to the fluctuations of air temperature.

Our gas monitoring system was set up at the Nagashima well in late October, 1997. After three weeks for checking installation errors, the system has been providing good data for the composition of gas bubbles until now except for short periods of troubles. One serious trouble occurred in the gas collection unit in early January, 1998. A tube connecting the plastic box with the funnel (Fig. 2) was slightly too long to fix the funnel tightly in water. The tube was bent and twisted because the polyethylene funnel placed in water gradually moved upward in the water due to its buoyancy. The gas therefore did not flow into the gas analysis. This trouble was removed by making the tube shorter. It was also a good opportunity for us to evaluate the memory effect of our gas monitoring system. During the repair, the gas in the plastic box was mixed with the atmospheric air and then flowed into the analytical system after the repair. It was just a spike-like change in the sample gas composition. We monitored in three-hour intervals how quickly the gas composition became normal. The memory effect disappeared within three to six hours. Hence we infer that compositional changes of gas bubbles lasting at least for several hours can be recorded by our gas monitoring system.

RESULTS AND DISCUSSION

Observed results from Nov. 1997 to July 1998 are shown in Fig. 4. We present gas chromatographic analyses in terms of the concentration ratios of respective components to Ar, because the normalization to the Ar concentration eliminates the fluctuations due to ambient temperature and pressure changes on our gas analyses, and because the Ar concentration is fairly constant (1%) like the concentrations of major components of N_2 and CH_4. The Rn data are presented in Fig. 4 without any kinds of corrections. A part of the observation data of Fig. 4 has been reported briefly in Ito et al. (1998).

(1) Large and sharp changes in H_2/Ar ratio

The H_2/Ar ratio sometimes showed sharp and large changes more than 100% (Fig. 4). In contrast, the He/Ar, N_2/Ar and CH_4/Ar ratios have been fairly constant within their fluctuations of only 3–4%. The overall variation of Rn activity is slightly larger than those of the He/Ar, N_2/Ar and CH_4/Ar ratios, but it is much smaller than the variation of H_2/Ar ratio. As mentioned above, the Rn activity is influenced by the change in gas flow rate, but the H_2/Ar, He/Ar, N_2/Ar and CH_4/Ar ratios are not. The gas flow rate itself depends on both the gas/water ratio and the water flow rate of groundwater introduced into our monitoring system.

The water and gas flow rates are not monitored automatically but measured manually only at irregular intervals of a few months when we visited the monitoring site for maintenance. The meaning of observed changes of Rn activity is ambiguous, because the Rn data are not corrected for the fluctuations in gas flow rate. However, there is no ambiguity about the anomalous changes of H_2/Ar ratio. They have been caused by the changes in H_2 concentration in gas bubbles, because the Ar concentration is approximately constant, and because they are not affected by the change of gas flow rate. Hydrogen gas shows the largest and sharpest changes among the gas components being monitored.

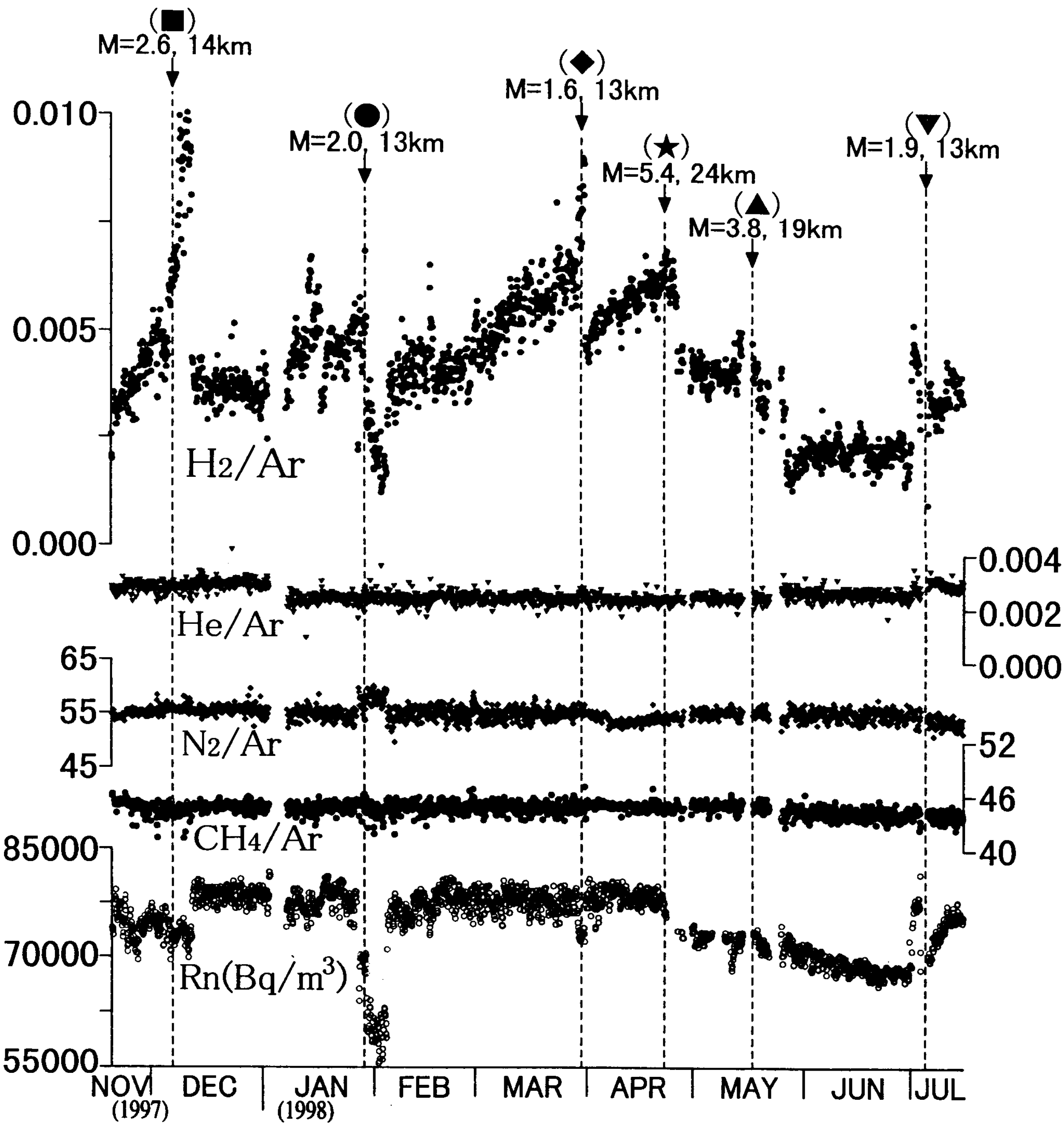

Fig. 4. Observed concentration ratios of H_2/Ar, He/Ar, N_2/Ar and CH_4/Ar and Rn activity of gas bubbles of pumped groundwater from the Nagashima well for the period from Nov. 1997 to July 1998. Arrows indicate the earthquakes assigned to the H_2 anomalies (see text). Their magnitudes and focal distances are also shown. The parenthesized symbols for the respective earthquakes are also used in Figs. 1 and 5.

On April 22, 1998, a moderately large earthquake (M = 5.4) occurred in the Yoro fault zone. The focal mechanism of the shock is the dip-slip reverse type, which coincides with the field observation of reverse faulting on the Yoro fault (Fig. 1). There can be seen a relatively large peak in the H_2/Ar ratio at the time of occurrence of the M = 5.4 event (Fig. 4). We have examined the possible correlation between the H_2 anomalies and nearby earthquakes including microearthquakes with M < 3 as below.

(2) Seismic events correlated with H_2 anomalies

In search for nearby seismic events correlated with the H_2 anomalies, we have utilized the seismic database by NIED (National Institute for Earth Science and Disaster Prevention). The NIED seismic network has the highest density of seismic observation sites in this area. The automatically processed seismic data by NIED, however, are not yet available for a period from January 1 to February 9, 1998. We complemented them with the seismic data by Research Center for Seismology and Volcanology, Nagoya University (RCSV-NU). The seismic events recorded by NIED and RCSV-NU from November 20, 1997 to July 15, 1998 have been considered.

As a result, we found that most of the large H_2 anomalies coincide with occurrences of shallow seismic events within the focal distance of 25 km from the monitoring well. They are four nearest microearthquakes (M < 3), a small event (M = 3.8) and a moderately large event (M = 5.4) as shown in Fig. 4.

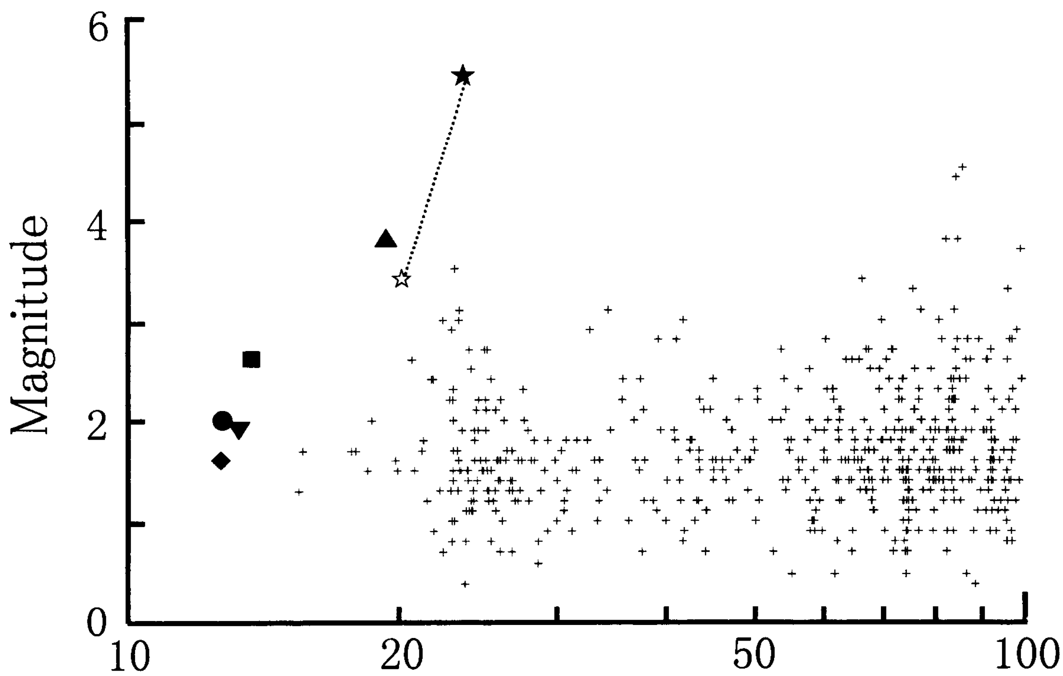

Fig. 5. The magnitude vs. focal distance plots for seismic events recorded by NISD and RCSV-NU networks from November 20, 1997 to July 15, 1998. The six earthquakes we assigned to the H_2 anomalies are easily distinguished from many other events. The six earthquakes with M = 1.6–5.4 occurred in parallel with the Yoro fault several kilometers apart in the west. The M = 3.4 event at 19 km (open star) is a fore shock of the M = 5.4 event (filled star). We assigned only the main shock to the H_2 anomaly in late April 1998, although the fore shock occurred 29 hours before the main shock.

Table 2. Seismic parameters for the earthquakes assigned to observed hydrogen anomalies at the Nagashima well.

Date and Time (JST)	Long. (°E)	Lat. (°N)	Depth (km)	Magnitude	Epicentral distance (km)	Focal distance (km)	Data source*
97/12/07, 1:08	34.99	136.67	10.9	2.6	8.4	13.8	NIED
98/ 1/29, 8:09	35.06	136.60	1.4	2.0	12.7	12.8	NU
98/ 3/30, 11:36	35.01	136.64	8.8	1.6	9.2	12.7	NIED
98/ 4/22, 20:32	35.17	136.56	4.5	5.4	21.6	23.7	NU
98/ 5/17, 12:59	35.15	136.59	2.8	3.8	19.2	19.4	NIED
98/ 7/ 5, 3:26	35.03	136.69	12.4	1.9	4.9	13.3	NIED

* NIED and NU mean the seismic data by National Institute for Earth Science and Disaster Prevention and Research Center for Seismology and Volcanology, Nagoya University, respectively.

They were selected in the NIED and RCSV-NU seismic data judging from their occurrence times, magnitudes and focal distances. The magnitude vs. focal distance plots for seismic events considered here are shown in Fig. 5, in which the six seismic events assigned to the H_2 anomalies are easily distinguished from many other events. All the epicenters of earthquakes correlated with the H_2 anomalies are located in parallel with the Yoro fault several kilometers in the west (Fig. 1). Table 2 summarizes the seismic parameters for the six event. For an apparent peak of H_2/Ar ratio in the middle of January 1998 (Fig. 4), we could not find any nearby event correlated with it at least from the RCSV-NU seismic data. We will re-examine small events for the period, when the final compilation of NIED seismic data will be published.

(3) Origin of H_2 anomalies

Seismo-geochemical anomalies of groundwater H_2 before and after large earthquakes have been previously reported from Japan and China (Sugisaki and Sugiura, 1986; Jiang and Li, 1981; Shi and Cai., 1986). Sato et al. (1986) reported the continuous monitoring of H_2 by the fuel cell H_2 sensor in soil gas along the San Andreas and Calaveras faults, central California. They concluded that soil gas H_2 anomalies were correlated with creep events and several nearby earthquakes with $M \geq 5$. Our monitoring at Nagashima for recent eight months revealed that even microearthquakes with $M < 3$ accompany quite large preseismic H_2 anomalies as does the moderate event with $M = 5.4$ in the same fault zoned. The preseismic increases in H_2 concentration are much conspicuous than those in other gas parameters.

Two hypotheses have been proposed in order to explain the selective increases of H_2 related to seismic activity (Ito et al., 1998). One is the reaction of H_2O with ≡Si· radical on freshly formed rock surfaces (Schrader et al., 1969; Wakita et al., 1980; Kita et al., 1982; Sugisaki et al., 1983);

$$\equiv\text{Si-O-Si}\equiv \;\rightarrow\; \equiv\text{Si}\cdot(\text{unstable}) + \equiv\text{Si-O}\cdot(\text{stable}),$$

$$\equiv\text{Si}\cdot + H_2O \;\rightarrow\; \equiv\text{SiOH} + (1/2)H_2. \qquad (1)$$

This reaction becomes unlikely at a temperature higher than 200°C, because both ≡Si· and ≡Si-O· radicals are unstable to form ≡SiOH;

$$\equiv\text{Si}\cdot \; + \; \equiv\text{Si-O}\cdot \; + \; H_2O \; \rightarrow \; 2[\equiv\text{SiOH}]. \qquad (2)$$

The reaction (1) is only possible in the crust shallower than 7–8 km when a normal geothermal gradient (20–30°C/km) is assumed. The other hypothesis is the hydration reaction of mafic silicates to produce magnetite and H_2 like serpentinization (Sato et al., 1986);

$$3FeO \text{ (in mafic silicates)} \; + \; H_2O \; = \; Fe_3O_4 \; + \; H_2. \qquad (3)$$

It is postulated that H_2 produced by (3) is released episodically to the earth's surface due to crustal deformation leading to seismic events.

We prefer the reaction (1) to the latter hypothesis from the two reasons: Firstly, no serpentinite is found around the monitoring well or along the Yoro fault. Nor mafic rocks like basalts occur extensively in this area. Only a small body of Permian basalt outcrops in the western block of the northern Yoro fault. Secondly, the reactions of (1) and (2) are based on crushing and pulverizing experiments of quartz and other silicate minerals or rocks (Schrader et al., 1969; Kita et al., 1982; Sugisaki et al., 1983). Nevertheless they are quite analogous to the stress-corrosion reaction for the subcritical crack growth (Atkinson, 1984; Freiman, 1984; Dove, 1995) as noted in Wakita (1994).

In Fig. 4, the increased H_2/Ar ratio dropped rather quickly without showing prolonged post-seismic tailings in most cases. Hence we infer that the reaction (1) occurred in the immediate vicinity of the monitoring well. The earthquakes assigned to the H_2 anomalies (Fig. 4) have focal depths of 8–15 km except for one event at 1.5 km. Hence the reaction (1) is unlikely in their source areas. We believe that aseismic deformations prior to earthquakes in shallower parts of active faults accompanied the reaction (1).

(4) Preseismic increases in groundwater H_2 and stress-corrosion process preceding earthquakes

Among recent physical interpretations for earthquake precursors, the nucleation models of earthquakes are important (Scholz, 1990; Ohnaka, 1992). Both crack and friction models predict quasi-static to quasi-dynamic growth of crack or slip displacement to a certain critical size prior to an onset of unstable dynamic rupture. The nucleation process is explained by the subcritical crack growth by the stress-corrosion mechanism or the slip-weakening friction constitution. Not only the main rupture but also the nucleation may be accompanied by H_2 production in the fault zone, because they involve the mechanochemical reaction (1).

We interpret that selective and preseismic increases of groundwater H_2 are geochemical diagnostics of the stress corrosion process preceding earthquakes (Ito et al., 1998). When the earthquake preparation process initiates in an active fault zone under shear stress, asperities and frictionally contacting surfaces of pre-existing fault planes enhance aseismic slips or microfracturings due to stress corrosion. This results in H_2 production by mechanochemical reaction of fractured rock surface with water. When such pre-existing fault planes are conduits for groundwater in the vicinity of the pumping well, the H_2 anomaly is seen in the well water. Dynamic disturbances of frictional contacts of fracture surfaces by propagating seismic waves may also account for co- and post-seismic increases of H_2.

In the physical models for nucleation process preceding earthquake rupture (Ohnaka, 1992; Matsu'ura, et al., 1992), it is expected that the nucleation initiates at a weak portion within the final rupture zone, and that geophysical precursors associated with the nucleation process are spatially limited within the segment to be ruptured finally (Ohnaka, 1992). By contrast, the conspicuous H_2 increases in the groundwater in the Yoro fault zone reported here suggest that the geochemical signals of the final stage of earthquake preparation process are seen even in the segments outside the final rupture zone. The groundwater H_2 anomalies (Sugisaki and Sugiura; 1986; Jiang and Li, 1981; Shi and Cai., 1986) were recorded at distances of 50 km and more from the epicenters of earthquakes with M = 5.8–6.8. It seems interesting that conspicuous preseismic anomalies of H_2 are not limited within the final rupture zone.

(5) Long-term variation in H_2/Ar ratio and the occurrence of M = 5.4 event

Apart from short-term variations of H_2/Ar ratio, the ratio shows a broad peak in March to April 1998 (Fig. 4). This apparently coincides with the occurrence of the M = 5.4 event in April 22, 1998. The observed H_2/Ar ratio showed a saw-like variation pattern in the period from February to April 1998. The two sharp peaks exactly coincide with the occurrences of M = 1.6 and 5.4 events, respectively. The H_2/Ar ratio immediately after the M = 1.6 event decreased to 0.0045. This lowered H_2/Ar ratio, however, is still slightly higher than its background level (≈0.003) when the monotonous increase of H_2/Ar ratio had begun to appear. Indeed the H_2/Ar ratio decreased to the background level immediately after the M = 5.4 event. Therefore, it is likely that the obvious increase in H_2/Ar ratio before the M = 1.6 event is the preseimic increases for the M = 1.6 and M = 5.4 events overlapping each other. We infer that the preseismic increase in H_2 for the M = 5.4 event had continued for about two months. This may be a reason for the broad peak recognized in March to April 1998.

Another reason is that the background level of H_2/Ar ratio further decreased to 0.002 about one month after the M = 5.4 event. The shapes of anomalous H_2/Ar peaks also appear to be different between the periods before and after the M = 5.4 event (Fig. 4). Preceding the four earlier earthquakes, the H_2/Ar ratio increased rather monotonously, and then it further showed spike-like increases up to 100% immediately after the shocks. Although the spike-like increases for the three microearthquakes at 12–13 km were larger than that for the M = 5.4 event, the increased values of H_2/Ar ratio rapidly dropped within several days after the four respective events. However, the shapes of anomalous H_2/Ar peaks for the two events later than the M = 5.4 event are not quite obvious, because monotonous increases preceding earthquakes are apparently lacking. This contrast in the subsurface H_2 behavior may have originated from the temporal decrease in shear stress in the Yoro fault zone after the occurrence of the moderately large event with M = 5.4.

(6) Changes in Rn activity correlated with nearby earthquakes

An obvious drop of the Rn activity from 77,000 to 60,000 Bq/m^3 is seen in late January to early February 1998 (Fig. 4). This drop appears to coincide with the M = 2.0 event. The N_2/Ar ratio also shows a small broad peak. In this case, we found that both water and gas flow rates were less than one-tenth of the normal values in early February 1998. In order to make the flow rates normal, we have re-adjusted the inlet valve for introducing groundwater into the gas collection unit, and then the Rn activity immediately recovered to a normal level of 77,000 Bq/m^3. At the time of the nearby M = 1.6 event in late March 1998, the Rn activity also showed a small coseismic decrease.

Another obvious drop of Rn activity is seen in the period from late April to late June 1998 (Fig. 4). The Rn activity began to decrease just after the M = 5.4 earthquake. In middle July 1998, the decreased Rn activity recovered to the normal level of 77,000 Bq/m^3, even though we did not make any adjustment of the inlet valve. A spike-like increase in Rn activity was recorded just before the Rn activity had begun to recover. A similar sharp peak is also seen in the H_2/Ar ratio. On July 5, 1998, a microearthquake with M = 1.9 occurred at an epicentral distance of 3 km from the well (Fig. 4). The seismic event is very close to the well, although its focal distance is 13 km. A samll break can also be seen in the variation of He/Ar ratio at the time of this closest microearthquake.

Most of the nearby earthquakes assigned to the H_2 anomalies are also correlated with the observed changes in Rn activity. However, the Rn changes seen in Fig. 4 do not necessarily mean the changes in Rn activity in gas bubbles as mentioned above. If the gas flow rate decreases to 5% of the normal rate without any change of Rn activity in the gas bubbles, the apparent Rn activity decreases by 10% because we are calculating the activity without correction for changes in the gas flow rate. The observed changes in Rn data shown in Fig. 4 are drops in the apparent Rn activity except for the case of M = 1.9 event in July 1998. We sometimes found that both water and gas flow rates have decreased after nearby seismic events. These observations may imply that the observed co- and post-seismic changes in Rn activity have been caused mostly by the changes in hydraulic parameters rather than those in the Rn concentration in the gas bubbles. Continuous monitoring of gas and water flow rates are necessary for correct interpretations of the observed changes in our Rn data.

CONCLUSIONS

We have set up a new seismo-geochemical monitoring station at a pumping bore-hole well 1,500 m deep in Nagashima spa near Nagoya. This well is located in the active fault zone of Yoro-Ise Bay fault system. In November 1997, we started an automated monitoring of H_2, He, Ar, N_2, CH_4 and Rn in gas bubbles separating from the groundwater by using a gas chromatograph and an α scintillation Rn monitor.

The observation data from Nov. 1997 to July 1998 provided interesting results. Among the six gas species, only the H_2 concentration showed large and similar changes up to 100% for four nearest microearthquakes (M = 1.6, 1.9, 2.0, and 2.6), a small event (M = 3.8) and a moderately large event (M = 5.4) within the focal distance of 25 km. Their epicenters are located in parallel with the Yoro fault several km in the west. Most of the H_2 anomalies are composed of steady preseismic increases of 50–100% for a few to several weeks and spike-like increases of up to 10–100% just after the shocks. The remarkably large H_2 anomalies are unique.

We interpret that the preseismic H_2 anomalies are geochemical signals of earthquake preparation process due to stress corrosion. When the earthquake preparation process initiates in the active fault zone under shear stress, asperities and frictionally contacting surfaces of pre-existing fault planes enhance aseismic slips or microfracturings due to stress corrosion. This accompanies H_2 production by mechanochemical reaction of fractured rock surface with water. In particular, when the pre-existing fault planes are conduits for ground water to the pumping well, H_2 anomaly is seen in the well water.

On April 22, 1998, a moderately large earthquake (M = 5.4) with the dip-slip reverse type occurred in the Yoro fault zone. We suggested that the occurrence of the shock had altered the subsurface H_2 behavior slightly. The H_2 anomalies for the earthquakes in the period until the shock exhibited obvious preseismic increases and the background-level of H_2/Ar ratio was about 0.003. But those anomalies for two earthquakes after the M = 5.4 shock were not quite obvious and the background-level of H_2/Ar ratio temporally decreased to 0.002.

Our observation data at Nagashima well are quite interesting for the study of subsurface gas behaviors in earthquake preparation process for frequently occurring small earthquakes with $M < 3$. It is important to monitor different subsurface gas components simultaneously at a deep groundwater well located in an active fault zone.

ACKNOWLEDGMENTS

We are deeply grateful to Nagashima Spa Land Company for kind permission to install our monitoring system in the well facility owned by the company. We also thank N. Fujii and T. Ohida of Research Center for Seismology and Volcanology, Nagoya University for their information as to microseismic activity around our monitoring site.

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