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Preseismic groundwater gas anomalies at Nagashima spa near Nagoya for the M=5.7 earthquake (Oct. 31, 2000) in southern Mie Prefecture, Japan: An episodic subsurface process related to the 2001 Tokai silent earthquake

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ABSTRACT

Groundwater gas anomalies were observed at the 1,500 m deep Nagashima spa well near Nagoya for the M=5.7 earthquake (Oct. 31, 2000) in southern Mie Prefecture, Japan. In spite of the very long focal distance of 98 km, H_2/Ar, He/Ar, N_2/Ar, and CH_4/Ar ratios of groundwater gas bubbles significantly changed not only at the time of the shock but also 3 days before it. Water temperature indicated a sharp coseismic increase. The earthquake was a dip-slip reverse event occurred approximately beneath the plate boundary in the eastern part of Kii Peninsula at 44 km depth. The gas anomalies are strikingly different from the previous ones at the same well, which were restricted to those in H_2/Ar ratio for nearby events with M=1.6–5.4 within 25 km. The apparently "long-distance" nature of the groundwater gas anomalies may suggest a coherent subsurface deformation over a roughly 100 km × 100 km area. In view of the size and occurrence timing, we speculate that such a subsurface episode may possibly be related to the onset of unsteady crustal displacements of the 2001 Tokai silent earthquake revealed by the nationwide GPS observation system.

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INTRODUCTION

A seismo-geochemical monitoring station was installed at a 1,500 m well of Nagashima spa in a southwestern suburb of Nagoya, central Japan in November 1997 (Fig. 1). Gas bubbles were separating from groundwater being pumped from the bottom of the well at an approximately constant rate (3,000 m^3/day). The gas bubbles contained N_2 (54%), CH_4 (45%), Ar (1%), He (30 ppm), and H_2 (25 ppm). The constituent gases were determined by an automated gas chromatographic system in every three hours, and the gas analyses were sent to our laboratory via public telephone line once a day in midnight, together with the records as to water temperature and air pressure and temperature (Ito *et al.*, 1998).

The owner company of Nagashima spa facility changed the way of pumping groundwater from the approximately steady pumping to unsteady one in early 2002. After that time, the gas analyses begun to show large temporal variations due to the unsteady pumping activity. In early 2003, an accident of flooding of groundwater occurred inside of the housing for our monitoring system. The system was suffered from a fatal damage, and we had to cease the gas bubble monitoring (Kawabe, 2008). In this paper, we will present the automated chemical analyses of gas bubbles and water temperature data for groundwater pumped steadily before early 2002.

Our observation results at Nagashima well from late 1997 to middle 1999 have revealed an interesting fact as to seismo-geochemical gas anomalies: Only the H_2/Ar ratio in groundwater gas anomalously increased prior to nearby earthquakes with M=1.6–5.4 and with focal distances less than 25 km, while the other gas ratios of He/Ar, N_2/Ar and CH_4/Ar did not show significant changes (Ito *et al.*, 1998 and 1999;

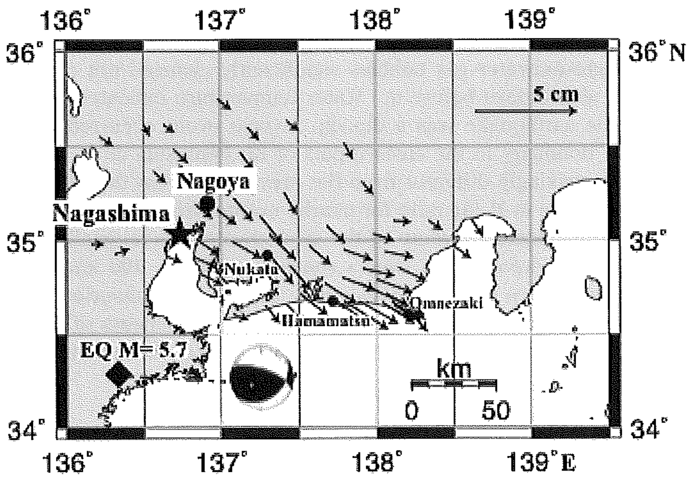

Fig. 1 The location of Nagashima groundwater well (filled star) and the epicenter of the M=5.7 earthquake on Oct. 31, 2000 in southern Mie Prefecture (filled diamond). The seismic data are after JMA. Here are also shown geographical locations of GPS sites of Nukata, Hamamatu, and Omaezaki, where unsteady southeastward displacements have been reported by GSI. Each arrow indicates the unsteady crustal displacement at the site for the period from January 2001 to June 2002 (Ozawa *et al.*, 2002).

Mori *et al.*, 2000). Two types of the anomalies of H_2/Ar ratio were distinguished: one is the spike-like increase and the other is the ramp-function like increase (Mori *et al.*, 2000; Kawabe, 2008). The spike-like increases of H_2/Ar anomalies appeared at least several days before respective nearby events with M<4, but the ramp-function like increase was observed only for the M=5.4 earthquake on the Yoro fault in 22 km northwest of the monitoring well. The monotonous increase had continued for 1.5 months before the nearby event with M=5.4. Possible mechanisms for the anomalies of H_2/Ar at Nagashima well have been discussed elsewhere (Ito *et al.*, 1998 and 1999; Mori *et al.*, 2000; Kawabe, 2008).

On October 31, 2000, a M=5.7 earthquake with a dip-slip reverse mechanism occurred in southern Mie prefecture, and remarkably large gas anomalies not only of H_2/Ar ratio but also of He/Ar, N_2/Ar and CH_4/Ar were observed at Nagashima well for the event. We perceived unusual simultaneous changes in H_2/Ar, He /Ar, N_2/Ar and CH_4/A ratios a few days before the shock, and expected an earthquake to occur somewhere very close to the well in an immediate future. The earthquake actually occurred on Oct. 31 and conspicuous coseismic changes were observed at the well. However, it did occur at a remote location with a focal distance of 98 km beneath the eastern part of Kii Peninsula but not in a neighbor of the well (Fig. 1). Indeed this distance value is too large to be compatible with an empirical threshold relationship characterized by magnitude and focal distance for previous events with anomalies of H_2/Ar ratio at the same well (Fig. 4). No significant seismic activities were recorded in the neighbor of the well within 25 km in this period. Except the M=5.7 event itself, there are no observation data comparable to the unusual groundwater gas behavior at Nagashima well.

On July 25, 2001, which was nine months later than our observation of the unusual seismo-geochemical anomalies at Nagashima spa, Geographical Survey Institute (GSI) of Japan first announced that GPS Earth Observation Network (GEONET) was detecting unsteady crustal displacements over the Tokai region from Omaezaki to Nagoya (Fig. 1). According to the announcement, the unsteady displacements directing southeastward reached about 1 cm during March to June, 2001, and the displacement rates appeared accelerating in respective GPS stations in the region (Fig. 1). Ozawa *et al.* (2002) reported the occurrence of a crustal deformation in the Tokai region became evident from the beginning of 2001 in the GPS time series data. Ohta *et al.* (2004) re-examined the interplate coupling in terms of back slip rate at the Nankai-Suruga Trough beneath the Tokai region, and showed a maximum forward slip rate of 3 cm/yr for the period from January 2001 to December 2002. Miyazaki *et al.* (2006) also reported the spatial and temporal distributions of stress and slip rate of the Tokai silent earthquake on the basis of the inversion of GEONET GPS data from 2000 to 2003, and they showed that the maximum slip rate exceeded 10 cm/y.

The crustal movement in the western part of Tokai region revealed by GEONET may be an important clue to understand significant groundwater gas anomalies observed at Nagashima well for the M=5.7 earthquake in the eastern part of Kii Peninsula on October 31, 2000. The aim of this paper is to describe our observations of the seismo-geochemical anomalies at Nagashima deep well, and to discuss its possible relation to the 2001 Tokai silent earthquake revealed by GEONET GPS observation.

RESULTS AND DISCUSSION

1) Groundwater gas anomalies for the M=5.7 earthquake on Oct. 31, 2000

The method and previous results of continual monitoring of groundwater gas bubbles at the 1,500 m deep Nagashima well have outlined briefly as above. More detailed reports have been published by Ito *et al.* (1998 and 1999) and Mori *et al.* (2000). Although the monitoring system had been in trouble for several months in 2000, the automated gas chromatographic monitoring system was re-set up on Oct. 10, 2000. The Rn monitoring unit originally installed was still in trouble. Figure 2 shows the gas chromatographic observation results for one month period from Oct. 10 to Nov. 10, 2000, together with those for water temperature monitoring. The occurrence timing of the M=5.7 earthquake in southern Mie Prefecture (JST AM 1: 42, Oct. 31, 2000) is also indicated in Fig. 2.

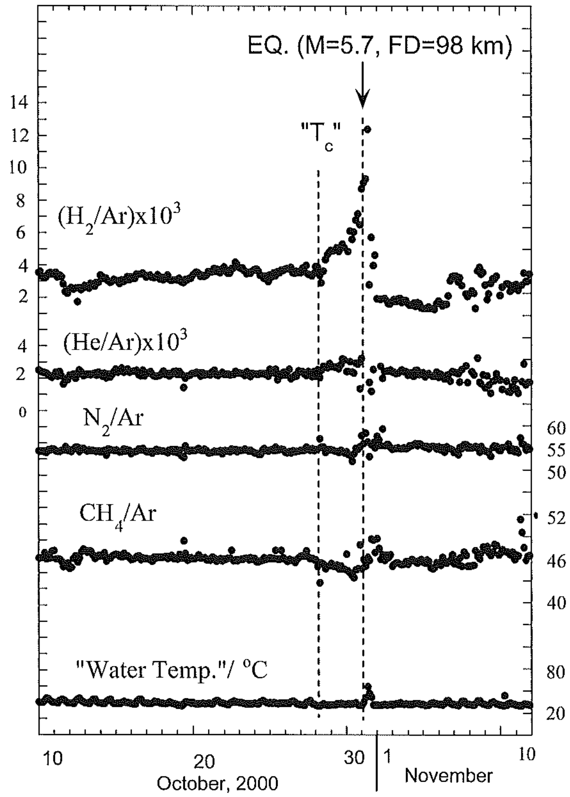

Fig. 2 Observed results of groundwater gas composition and water temperature at Nagashima well for the period from Oct. 10 to Nov. 10, 2000. The occurrence timing of the M=5.7 earthquake on Oct. 31, 2000 in southern Mie Prefecture at a focal distance of 98 km from the well is also indicated. "T_c" shows the timing (Oct. 28) when the preseimic increasing trend of H_2/Ar ratio became much larger than before and the other gas ratios began to change. The data for water temperature are actually those for the temperature of outer surface of polyvinyl tube for sampling continuously a small fraction of pumped groundwater into our gas monitoring system (see text and explanation for Fig. 3).

The water temperature data shown in Fig. 2 are not exactly for the temperature of pumped groundwater but for the temperature of outer surface of polyvinyl tube introducing a small fraction of pumped groundwater with gas bubbles into our gas monitoring system. Although the groundwater flow in the tube was not controlled precisely, the rate was roughly adjusted to be about 1,000 ml/min. The gas concentration ratios like H_2/Ar, He/Ar, N_2/Ar and CH_4/Ar cannot be affected by the fluctuations in water flow rate. Normally the water temperature pumped to the surface is quite constant at about 55°C, but the surface temperature of sampling tube is fluctuating at around 35°C affected by the variations of air temperature and water flow rate in the tube. Cyclic variations of "water temperature" seen in Fig. 2 are caused by daily variations of air temperature. The original data of "water temperature" have been corrected for the response to changing ambient air temperature (Fig. 3) by using the following equation:

$$T_W'(t) = T_W(t) - a\,[T_A(t) - b]\ , \qquad (1)$$

where $T_W'(t)$ and $T_W(t)$ denote the corrected and original "water temperatures" at the

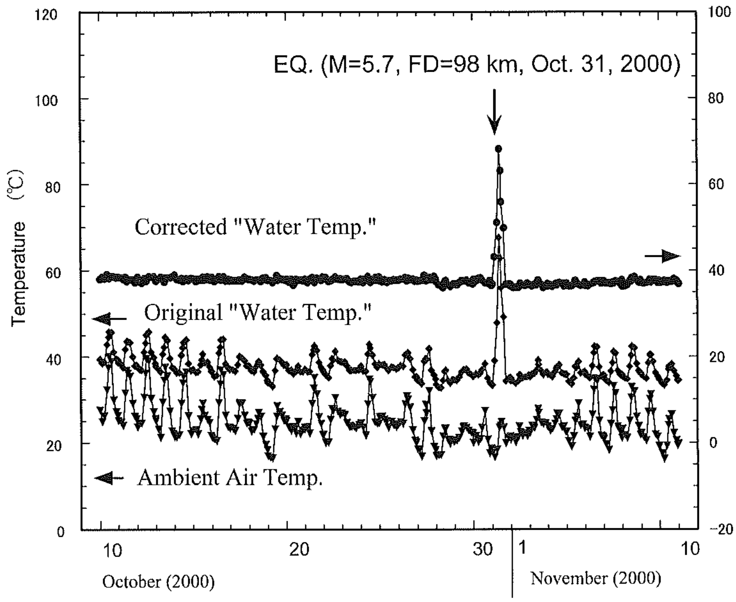

Fig. 3 The records of air temperature (Lower), "water temperature" (Middle) and corrected "water temperature" (Upper). "Water temperature" is not exactly the temperature of pumped groundwater but for the temperature of outer surface of polyvinyl tube introducing a small fraction of pumped groundwater with gas bubbles into our gas monitoring system continuously. The surface temperature of sampling tube is affected by changing air temperature, and is fluctuating at around 35°C, though the temperature of groundwater pumped to the surface is normally quite constant at about 55°C. The response of "water temperature" to changing air temperature can be removed by using Eq. (1) in the text. The corrected "water temperature" is an index of the temperature of pumped groundwater and its flow rate in the sampling tube, and it reveals a sharp spike-like increase immediately after the event on Oct. 31, 2000.

time of t, respectively. $T_A(t)$ is the ambient air temperature. The constant “a” is 0.50, which is estimated from the amplitude ratio of daily variations of $T_w(t)$ to those of $T_A(t)$. The constant “b” is the average value of $T_A(t)$ for the period. This correction reveals a sharp spike-like increase of “water temperature” just after the shock.

About two hours before the shock (AM 0: 00, Oct. 31, 2000), the “water temperature” was 33°C, but after the shock, it increased to 39°C (AM 3:00), to 47°C (AM 6:00) and then to the maximum of 67°C (AM 9:00). Seventeen hours after the shock, the “water temperature” decreased to the background values. The spike-like increase of the indirectly measured water temperature suggests a more immediate increase in the temperature of pumped groundwater itself. We infer not only the temperature increase of pumped groundwater by about 15°C but also a significant increase of water flow in the sampling tube probably due to a similar spike-like increase of the water pressure in the bore-hole just after the shock.

In contrast to the water temperature anomaly, H_2/Ar and He/Ar ratios of groundwater gas bubbles showed fairly large preseismic increases of about 150% and 40%, respectively, for a few days before the shock. Even the N_2/Ar and CH_4/Ar ratios, which are less likely to change because N_2 and CH_4 are major constituents, indicated preseimic decreases up to several % (Fig. 2). Such simultaneous preseismic anomalies in the four gas ratios could not be observed even in the case of the M=5.4 earthquake (April 28, 1998) on the Yoro fault at a focal distance of 24 km, in which only the H_2/Ar ratio showed a ramp-function like preseimic anomaly (Ito *et al.* 1998 and 1999; Mori *et al.*, 2000; Kawabe, 2008). The characteristics of groundwater gas anomalies for the event on Oct. 31, 2000 are strikingly different from those observed previously at the same well. We could perceive some unusual situation which might be followed by a large earthquake possibly in a neighbor of the monitoring well at least a few days before the shock. The total variations of H_2/Ar and He/Ar ratios before and after the shock are 400% and 80%, respectively. Those of the N_2/Ar and CH_4/Ar ratios are approximately 10%. The H_2/Ar anomaly was indeed the most conspicuous. Since the middle of October, the H_2/Ar ratio began to show a steadily increasing trend which continued for more than one week, but three days before the shock, the increasing rate began to accelerate. This change in increasing rate of H_2/Ar ratio was almost coherent with the increase of He/Ar ratio and the subtle decreases of N_2/Ar and CH_4/Ar ratios. At this moment, which is indicated as “T_c” in Fig. 2, we anticipated that this situation might be a critical phase for earthquake occurrence at a location closer to the well.

2) Apparently “long-distant” nature of groundwater gas anomalies

The source mechanism of the M=5.7 earthquake is a dip-slip reverse one (Fig. 1), which is similar to those of mega-thrusting earthquakes recurring historically along the Nannkai Trough. The epicenter is close to the Kumano-nada coast in central to southern Mie Prefecture, and its focal depth is 44 km. This was a dip-slip reverse event occurred approximately on the plate boundary between the Pacific and continental plates beneath the eastern part of Kii Peninsula. Figure 4 shows the magnitude vs. focal distance plots for the seismic events with M≥1.5 and focal distance ≤ 150 km in the period from Oct. 10 through Nov. 10, 2000. They are selected from the seismic

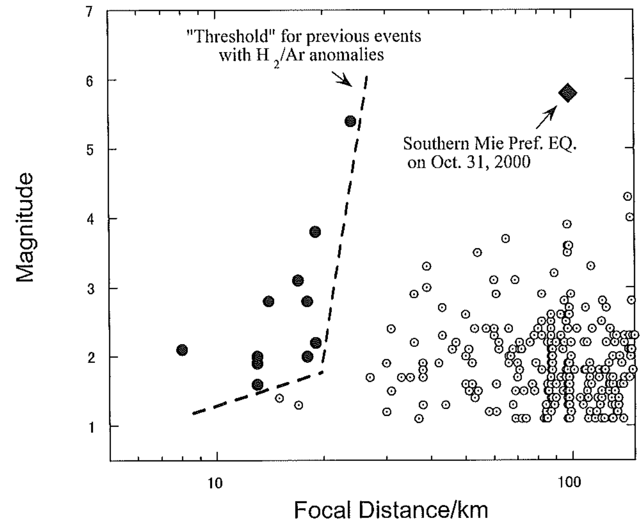

Fig. 4 Magnitude vs. focal distance plots for the seismic events with M≥1.5 and focal distance ≤ 150 km in the period from Oct. 10 through Nov. 10, 2000. They are selected from the seismic records by Research Center of Seismology and Volcanology, Nagoya University (RCSV-NU). The large filled diamond is the moderately large earthquake in southern Mie Prefecture on Oct. 31. Its magnitude value by RCSV-NU is 5.8, which is slightly larger than the JMA value of 5.7. The seismic events other than the moderately large one are plotted by open circles. Filled circles are the previous seismic events assigned to groundwater anomalies of H_2/Ar ratio at Nagashima well by Ito *et al.* (1998 and 1999) and Mori *et al.* (2000). The dashed line is an empirical threshold relation for the previous events with preseimic anomalies of H_2/Ar ratio at Nagashima well.

records by Research Center of Seismology and Volcanology, Nagoya University (RCSV-NU). The large filled diamond is the moderately large earthquake in central Mie Prefecture on Oct. 31, and its magnitude value by RCSV-NU is 5.8, which is slightly larger than the JMA value of 5.7. The events other than the moderately large one are plotted by small open circles in Fig. 4. Filled circles are the seismic events assigned to previous groundwater anomalies of H_2/Ar ratio by Ito *et al.* (1998 and 1999) and Mori *et al.* (2000). There were no nearby seismic events comparable to the previous ones which accompanied the anomalies of the H_2/Ar ratio. The groundwater gas anomalies observed for the event on Oct. 31, 2000 were so significant, but it was a rather remote event with a focal distant of 98 km from the observation well.

It is unacceptable to consider that the preseimic groundwater gas anomalies at Nagashima well directly relate to the source process of the M=5.7 earthquake itself, because the source size of the discrete event is too small to explain the focal distance of 98 km. One possible explanation for the apparently "long-distance" nature of groundwater gas anomalies is to assume an episodic crustal deformation over a wide region with a dimension in the order of 100 km × 100 km which can cover both the source area of the M=5.7 shock and Nagashima spa near Nagoya. The episodic crustal process is assumed to have prepared the dip-slip reverse event beneath the eastern part of Kii Peninsula and induced coherently the unusual hydro-geochemical aquifer condition beneath Nagashima spa well in the Yoro-Ise Bay fault system near Nagoya. We were unable to find any observation data that might support the interpretation until the time of an announcement by the GSI. On July 25, 2001, GSI made the first announcement as to the unsteady crustal displacements in the Omaezaki-Nagoya region detected by GEONET. This might be the anticipated episodic large-scale subsurface process to have produced the seismo-geochemical anomalies at Nagashima well for the distant M=5.7 shock on the plate boundary on Oct. 31, 2000.

3) Gas anomalies at Nagashima and the onset of unsteady crustal slips of the 2001 Tokai silent earthquake

According to the first announcement by GSI (http://www.gsi.go.jp/), unsteady southwestward displacements up to about 1 cm were found over the Tokai region including Omaezaki and Nagoya areas for the period from March to June, 2001. The unsteady displacements became significant in March, 2001, and they appeared to accelerate in the end of 2001 (Ozawa *et al.*, 2002; Miyazaki *et al.*, 2006). Eventually the unsteady displacements in the western part of Tokai region was not the pre-slip leading to a large earthquake but a silent earthquake, namely, the 2001 Tokai silent earthquake. The moment of the silent earthquake increased rapidly for 2000 to 2005, and had grown to the event with $M_w > 7.0$ (GSI, 2008). We would like to pay our attention to the following three points:

i) The onset of unsteady crustal displacements is temporally in accordance with the groundwater gas anomalies at Nagashima well for the M=5.7 earthquake in southern Mie Prefecture on Oct. 31, 2000. The time series data of horizontal displacement vectors at GPS sites, for example, Nukata in central Aich Pref. and Hamamatsu in Shizuoka Pref., indicate that the unsteady displacements had already started in middle to late 2000.

ii) The focal mechanism of the M=5.7 earthquake in southern Mie Prefecture on Oct. 31, 2000 is a dip-slip reverse one with an almost horizontal compression axis in the north-south direction at 44 km depth. This appears to be compatible with the southeastward unsteady crustal displacements at the surface in the western part of Tokai region.

iii) Nagashima well and the epicenter of the M=5.7 earthquake are located in the north-western and western borders of the segment of Tokai region displacing southeastward, and the distance between the two locations seems to match the characteristic size of segment slipping unsteadily southwestward (Fig. 1).

In view of the points above, we speculate that a subsurface episodic process suggested by the seismo-geochemical anomalies at Nagashima well in late October, 2000, may possibly be related to the onset of unsteady crustal displacements in Omaezaki-Nagoya region by the 2001 Tokai silent earthquake revealed by GEONET.

Slow slip events after large earthquakes (Kawasaki *et al.*, 1995; Heki *et al.*, 1997) and silent slips without accompanying seismic events (Hirose et al, 1999; Dragert *et al.*, 2001) have been reported from Japanese and Cascadia subduction zones by means of continuous GPS observations. The aseismic slips in the Bungo Channel reported by Hirose at al. (1999) are seen over an 80 km × 150 km area, and those by Dragert *et al.* (2001) distribute over a 50 km × 300 km area in Cascadia subduction zone.

For the 2001 Tokai Silent earthquake, Miyazaki *et al.* (2006) considered a fault plane of 190 km × 190 km. It seems important to make a careful examination of continual hydro-geochemical monitoring at deep groundwater wells in reference to the crustal displacements revealed by GPS observations.

4) "Long-distance" effect of precursory hydro-geochemical anomalies

The "long-distance" characteristics of precursory anomalies in hydro-geochemical phenomena for mega-thrusting earthquakes can be acceptable because of large scale faulting with dimensions of 100 km × 100 km (Kawabe, 1991). However, similar "long-distance" effects of preseimic hydro-geochemical anomalies for earthquakes with M<6 (King, 1986) are apparently perplexing as well as those for large inland earthquakes: Sugisaki *et al.* (1996) and Ito *et al.* (1996) reported that preseismic mineral spring gas anomalies for the 1995 Kobe earthquake (M=7.2) were observed at Byakko Spa, Mizunami, Gifu Prefecture with the epicentral distance of 220 km. Such puzzles in seismo-geochemical observations might be solved, if it is directly or indirectly verified that crustal displacements in seismogenic processes occur over unexpectedly wide areas by means of the large and dense GPS array like GEONET.

As to the observed long-range correlations in seismicity, Bowman *et al.* (1998) put forward the concept that seismicity prior to a large earthquake can be understood in terms of the statistical physics of a critical phase transition. In their model, the cumulative seismic strain release (Benioff strain) increases as a power law time to failure before the final event. Using the seismicity data along the San Andreas fault system since 1950, they showed that all the events on the San Andreas fault greater than magnitude 6.5 were preceded by an identifiable region of accelerating seismicity which follows a power law time to failure. Such regions with correlated seismicity are described by the critical region radius (R), and this radius appears to be proportional to the linear size (L) of mainshock rupture. Bowman *et al.* (1998) argued that R can be ten times larger than L or more. The critical earthquake concept by Bowman *et al.* (1998) may also provide an interesting suggestion to understand the "long-distance" characteristics of precursory anomalies in hydro-geochemical phenomena as we reported here.

The 2001 Tokai silent earthquake revealed by the dense GPS array of GEONET is indicating that the crustal block shown in Fig. 1 gives rise to aseismic slips on a wide area of approximately 190 km × 190 km in the subduction zone of the arc-trench system. The Nagashima spa is located in the active fault zone of Yoro-Isewan Fault system in central Japan (Ito *et al.*, 1998; Kawabe 2008). The hydro-geochemical system is developing along the active fault zone, and this may be a part of the complex hierarchical fracture system which is fairly sensitive to the aseismic slip and stress change on the plate boundary. In this respect, the "long-distance" effect of hydro-geochemical precursors might be akin to the long-range correlations in seismicity explained by the critical earthquake concept (Bowman *et al.*, 1998).

CONCLUSIONS

Distinct groundwater gas anomalies have been recorded at the 1,500 m deep Nagashima well near Nagoya, when the M=5.7 earthquake occurred on Oct. 31, 2000, in southern Mie Prefecture, Japan. Our conclusions concerning the seismo-geochemical anomalies are as follows:

1) Despite the focal distance of 98 km, H_2/Ar, He/Ar, N_2/Ar and CH_4/Ar ratios of groundwater gas bubbles showed anomalous changes not only at the time of the shock but also at least 3 days before it. The maximum changes in H_2/Ar and He/Ar ratios reached 400% and 80%, respectively. Even the N_2/Ar and CH_4/Ar ratios showed anomalies up to 10%. Water temperature indicated a spike-like increase just after the shock.

2) The M=5.7 earthquake is characterized a dip-slip reverse mechanism similar to those of mega-thrusting earthquakes recurring along the Nankai Trough. The focal location and source mechanism suggest that the event occurred approximately on the plate boundary beneath the eastern part of Kii Peninsula.

3) The hydro-geochemical anomalies for this event are strikingly different from those observed at the same well previously. All the previous preseismic gas anomalies were observed only in the H_2/Ar ratio for the inland earthquakes with M=1.6–5.4 at small focal distances less than 25 km.

4) The apparently "long-distance" nature of preseimic groundwater gas anomalies for the M=5.7 earthquake on Oct. 31, 2000, may suggest a coherent crustal deformation over a wide region with a dimension in the order of 100 km × 100 km. We speculate that such a subsurface episodic event may be related with the onset of unsteady crustal displacements in Omaezaki-Nagoya region (the 2001 Tokai silent earthquake) revealed by GEONET of the nationwide GPS observation.

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