地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 80 (2005) pp. 105-131

Deep Groundwater Discharge and Ground Surface Phenomena

Tameshige Tsukuda[1),*], Keinosuke Gotoh[2)] and Osamu Sato[3)]

[1)] Earthquake Research Institute, University of Tokyo
[2)] Division of Environmental System Science, Department of Systems Science, Graduate School of Science and Technology, Nagasaki University
[3)] Research Center for Hazards in Snowy Areas, Niigata Univerisity[†]

Abstract

Stress changes associated with crustal deformations may induce migration of fluid within the crust. It is hypothetically expected that a volume of pore water, being suddenly pressured in response to an elevated stress level in some seismogenic zone, will tend to intrude up into a crack network, and incidentally emerge at the ground surface. Groundwater changes in temperature and concentrations of chemical constituents should be observed at the spot where the upwelling fluid comes out. This paper reports the following 4 transient events recently found in Japan as evidence of the near surface discharge of hot and pressured water of a deep origin: 1) Frequent rises in well water temperature were observed at Iwakuni,Yamaguchi Prefecture, southwest Japan. The largest rise occurred just before the 2001 Geiyo earthquake of M 6.7, which indicated a possible precursor for the shock. A chemical analysis of ion concentrations of the hot water suggested that the temperature anomalies arise from contamination by intruding external deep water; 2) Gushing of groundwater at the sea bottom was considered to have occurred at the Akashi Strait 2 days before the 1995 Kobe earthquake of M 7.3, based on an interpretation of the appearance of brownish-black seawater found by the captain of a passenger boat; 3) Upwelling of deep hot groundwater was occurred at Inagawa Town, Hyogo Prefecture, southwest Japan, which was associated with the 1995 Kobe earthquake. The well water temperature rose 3-4℃ at the time of the shock, and decayed with a time constant of 1-2 years; 4) Heating of ground rocks by upwelling hot water intruding into the fracture zone of an active fault, which is considered to be a precursor for the April 1, 1995 Niigata-ken Hokubu earthquake of M 5.5, was confirmed by a LANDSAT infrared image in the northern Niigata area, central Japan, on a summer night in 1994. All of the above transient phenomena can be reasonably understood in the light of the hypothesis of pressured hot water upwelling from deep underground in response to crustal movements around seismically active regions.

Key words: pore water, groundwater, water temperature, remote sensing

1. Introduction

It is quite likely that pore water in the crust may sensitively respond to the deformation and stress state of the medium. Deformations with stress changes in rock systems may create new microcracks, or act to expand the area and/or volume of preexisting microcracks. Opened or expanded cracks provide paths for the fluids, i.e, pore water and such gasses as Rn, CO_2 and H_2, to flow. Stress changes in the rock medium partially cause pressure changes in the pore water. High pressures would possibly drive water upward through a crack network, when a vent-like path occurs in the network. It is probable that we would observe at some ground spots anomalous discharging phenomena of upwelling water from deep underground.

* e-mail: tsukuda@eri.u-tokyo.ac.jp (Yayoi 1-1-1, Bunkyo-ku, Tokyo, 113-0032, Japan)
† Now retired. Present address: Sunshine-Aoyama 318, Urayama 2-1-66, Niigata-shi 950-2001, Japan

Oki *et al.* (1992) considered that geopressured water in sedimentary basins is one of the candidates for upwelling water. They pointed out that some landslides were accompanied by water of deep origin, as suggested by a study on the concentration of ions by Sato (1981, 1982), and took this phenomena to be a consequence of deep water discharging at the ground surface. Further, they presented a seismogenic model in which geopressure-type water drives and triggers earthquake activity. Water of a deep origin is characterized by high temperature and high ion concentrations. Where deep water is discharging, we might have some traces of such water. Xu *et al.* (1998) took measurements of temperarure and electric conductivity of water at snow-melting wells along main roads distributed in Niigata Prefecture, central Japan, and found regions with well water having high temperatures and high conductivities. High conductivity implies a high concentration of ions. They regarded the anomalous regions as fracture zones or potentially active fault zones, providing paths for upwelling water.

The achievement of Xu *et al.* (1998) should be highly evaluated in the following two points: finding evidence of discharges of deep water and lineating the distribution of discharge sites. Their study described the stationary state of discharged deep water. Our next point of interest is to clarify the time-dependent characteristics of this problem. The purpose of this paper is to present the transient properties of the discharge process of deep pressured water.

This paper deals with such phenomena as: 1) sudden rises of water temperature at Iwakuni City, Yamaguchi Prefecture, southwest Japan, 2) a sea water anomaly at Akashi Strait, near Kobe City in Kinki District, southwest Japan, 3) a sudden rise and long-term decay of water temperature at Inagawa Town, Hyogo Prefecture in Kinki District, and 4) remote-sensing disclosure of heating of the ground surface in northern Niigata Prefecture, central Japan (Fig. 1). The last case is based on a method of infrared satellite observations similar to that developed by Tronin (1996) and Tronin *et al.* (2002).

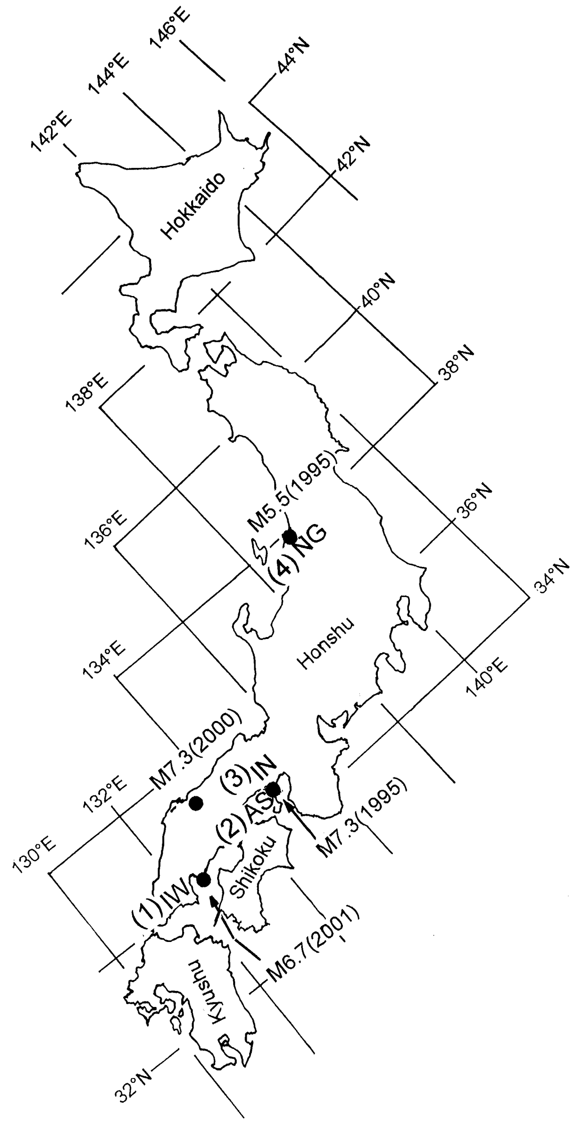


Fig. 1. Map showing the locations of 4 sites where a deep water discharge at the ground surface took place. (1) IW: Iwakuni City, Yamaguchi Prefecture, Chugoku District; (2) AS: Akashi Strait, near Kobe City, Hyogo Prefecture, Kinki District; (3) IN: Inagawa Town, Hyogo Prefecture, Kinki District; (4) NG: northern Niigata Prefecture region, central Honshu. The earthquake epicenters associated with the above discharge phenomena are also plotted with their magnitudes. The magnitudes are new values revised by Japan Meteorological Agency, which were announced on September 25, 2003. The previous values for the 1995 Kobe earthquake and the 2001 Geiyo earthquake were 7.2 and 6.4, respectively. Those for the 1995 Northern Niigata earthquake of M 5.5 and the 2000 Western Tottori earthquake of M 7.3 did not change.

2. Hot water intrusion into a shallow groundwater reservoir

First, we relate a peculiar phenomenon at a shallow well in Iwakuni City, Yamaguchi Prefecture, Chugoku District, southwest Japan (Figs. 1, 2) (Tsukuda, 2002). Mr. Tadao Horimoto, a carpenter, who

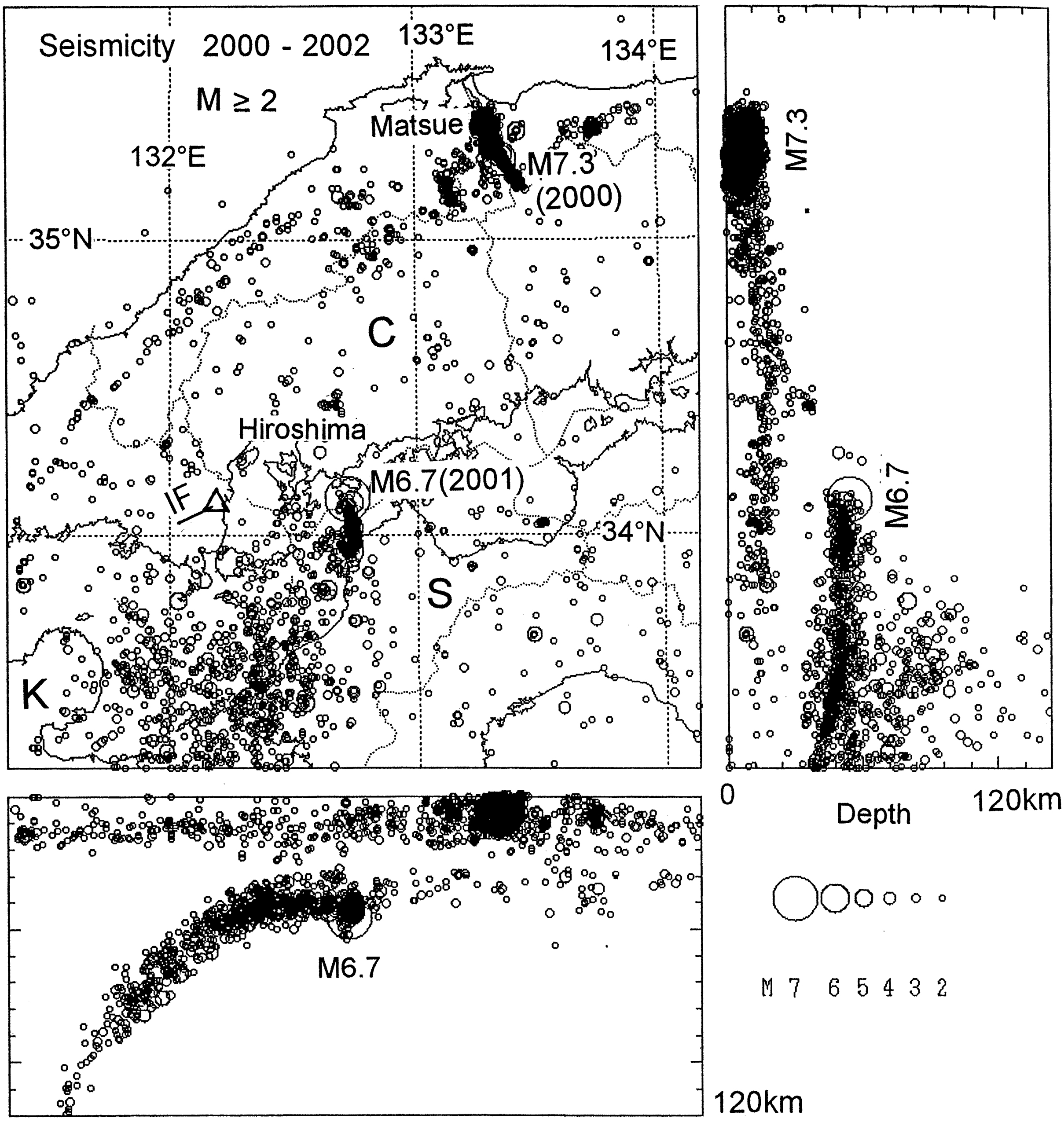


Fig. 2. Site map of the Iwakuni event with seismicity around. The open triangle indicates the location of Iwakuni, Yamaguchi Prefecture, in Chugoku District. IF indicates Iwakuni fault, which is an active fault running toward the site, after Research Group for Active Faults of Japan (1991). C, K, and S denote Chugoku District in Honshu, Kyushu Island, and Shikoku Island, respectively. The seismicity data are from Hiroshima Earthquake Observatory, Earthquake Research Institute, University of Tokyo (January, 2000〜December, 2002; M≥2; focal depth ≤120 km). Epicenters and depths are plotted on the plane in the same scale in the horizontal and vertical directions. The October 6, 2000 Tottori-ken Seibu (Western Tottori Prefecture) earthquake of M 7.3 and the March 24, 2001 Geiyo earthquake of M 6.7 are described with their aftershock hypocenters.

had been taking water daily from his own well instead of city water, found an anomalous high water temperature at the well in the evening of October 6, 2000, several hours after the occurrence of the 2000 Tottori-ken Seibu earthquake (Western Tottori earthquake) (M 7.3) whose epicentral distance was 163 km. It is important to note that hot water from the faucet (See Fig. 3) came out for a short time, usually several tens of seconds, returning to normal cool water soon, and that this anomaly occurred

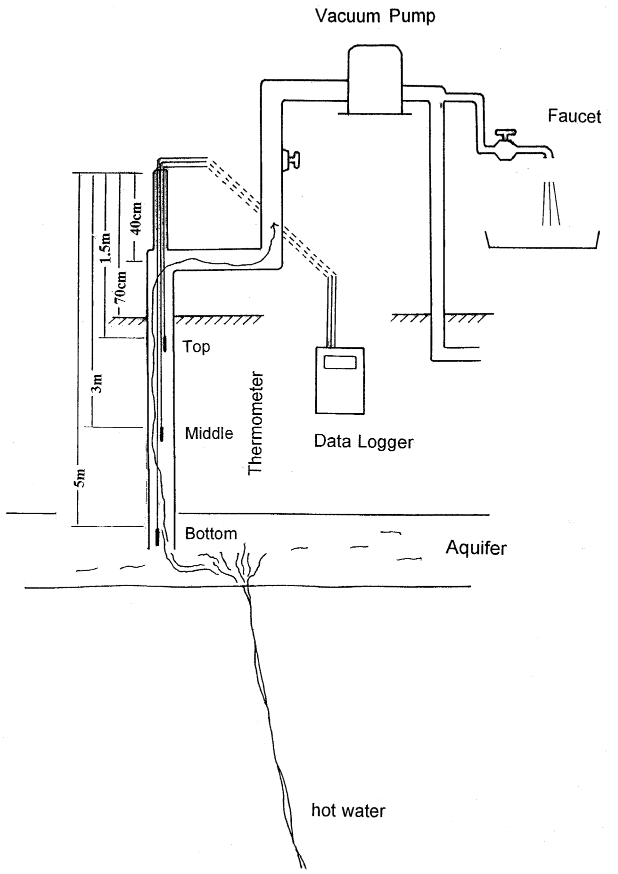


Fig. 3. The well system at Iwakuni. 3 sets of thermometers were set inside the pipe of the well. Hot water intermittently intruded into the pipe from below.

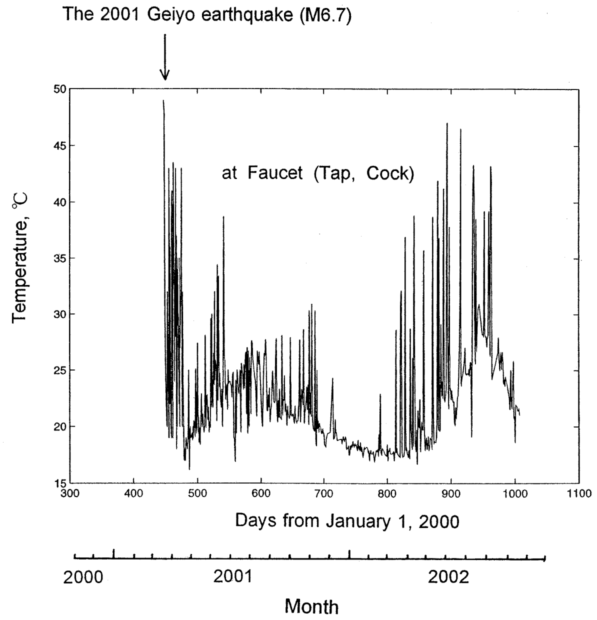


Fig. 4. Water temperature variations. The temperature was measured manually at the faucet (tap or cock) (See Fig. 3). Measurements were made at the faucet of the well system, mostly in the early morning around 06 : 30 local time, recording data every 10 seconds during 2 minutes of water-drainage. The maximum value for each temperature measurement is adopted in the graph. The occurrence time of the Geiyo earthquake is indicated by an arrow. The Western Tottori earthquake occurred 279 days from January 1, 2000.

intermittently. Prior to March of the following year, the temperature rises tended to increase. He, therefore, decided to measure the temperature using both alcohol and mercury thermometers at the faucet, starting in the early morning of March 23, 2001. On the first day of measurement, he recorded 49℃.

He also meassured a high temperature of 48℃ in the following morning. This time the water became cloudy like diluted milk for several minutes. This was the first disturbance since the initiation of anomalous temperature rises. It was probably due to a sudden increase of CO_2 concentration leaving sol particles of $CaCO_3$. It was in the afternoon 15: 27 (JST) on the same day, March 24, that the 2001 Geiyo earthquake (M 6.7) occurred in the region near Hiroshima City, the epicentral distance being 49 km, and the depth 69 km. This hot and cloudy water was recognized about 9 hours before the M 6.7 shock.

The structure of the well is drawn in Fig. 3. The well pipe reaches about 5 m below the ground surface into sand and gravel layers. The basement rock is Cretaceous granite according to a geological map (Yamaguchi Prefectural Government, 1976). According to recent drilling 1.5m from the well, the depth of the basement is more than 10 m. Water is supplied for the daily use by the family of Mr. Horimoto by pumping it through conduit pipes (Fig. 3). On April 23, 2001, we set up a thermometer at the bottom of the well, and then 2 other sets of thermometers in the conduit of the well on June 27, 2001. The thermometer sensors were located at depths of 1.5 m, 3 m, and 5 m from the top of the pipe (Fig. 3). Data were stored in digital data loggers with a sampling interval of 10 min. Besides these automated instrument measurements, Mr. Horimoto has taken manual measurements at the faucet at least once a day. Regular manual measuremensts have been conducted early in the morning at 06 : 30 local time.

Figure 4 shows the record of the maximum wa-

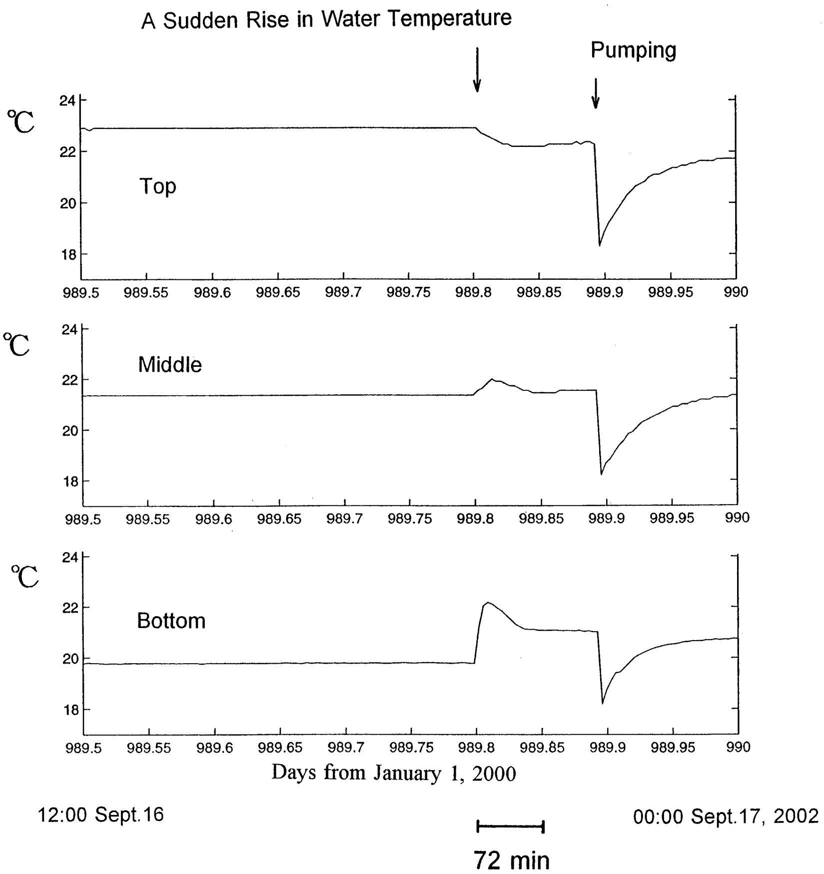


Fig. 5. Sudden rise of water temperature in the well at Iwakuni on September 16, 2002. The data are from 3 thermometers set in the well at different depths as shown in Fig. 3. Pumping disturbances in the morning are also recorded.

ter temperature at the faucet, plotting the value for each measurement almost everyday. The high activity of hot water seemed to be gradually decreasing until around the beginning of 2002, about a year after the 2001 Geiyo earthquake. After that, revival activity was registered during the period from March to August in 2002. We took instrument measurements in the well during this period. It was, however, difficult to grasp the rise of water temperature inside the well corresponding to the anomalouly high temperature at the faucet. Notwithstanding, when extremely high temperatures exceeding 40 degrees were found at the faucet in the morning, the instrument-measured temperatures in the well during the night before had remained nearly constant, indicating a stable temperature structure within the conduit of the well. During ordinary days and nights, the temperature changes greatly, probably because of irregular movements of water due to thermal convection in the well pipe. Fluctuations of water temperature in the well are so severe that we cannot detect small temporal changes. On the contrary, it is considered that the hot water occupied the top of the conduit, and consequently convection might have been surpressed, when the hot water intruded into the conduit of the well. Hence, the temperature data was nearly constant during the night. However, a sudden temperature rise due to the intrusion of hot water was detected in the early morning of September 16, 2002 (Fig. 5), due to small fluctuations of temperature, because the well had no longer been used for daily water for about a month.

No longer obtaining a transient time function as shown in Fig. 5 for the very active period from March to August, 2002, Fig. 6 shows an outline of temperature variations, where we take an average for each day, removing artificial daily disturbances. The temperature component T_p of seasonal variations at the depth of 1.5 m in the pipe is approximately represented as

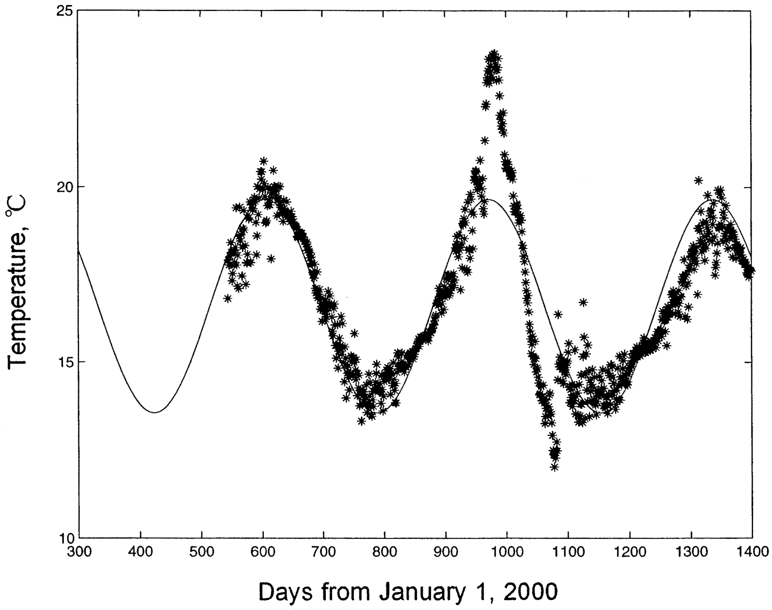


Fig. 6. One-day average of the water temperature obtained by continuous measurements at an interval of 10 min. The data were plotted at 24 : 00 everyday. The temperature was measured at a depth of 1.5 m from the head of the pipe (See Fig. 3). The sinusoidal time function given in Eq. (1) is fitted to describe the annual change of expected ordinary water.

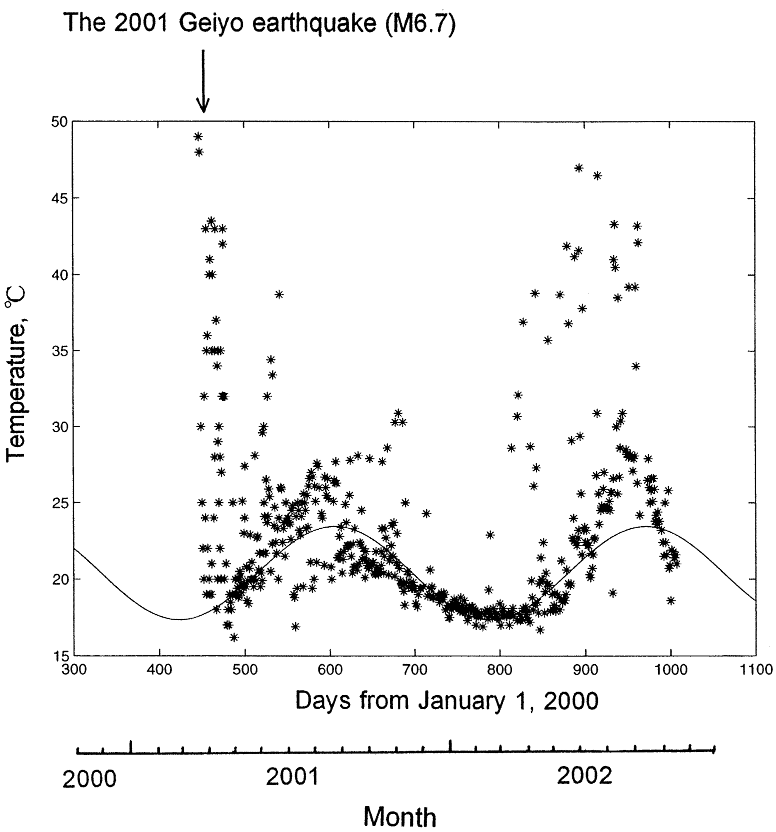


Fig. 7. Water temperature variation. The temperature had been measured manually at the faucet (tap or cock) (Same as Fig. 4). A sinusoidal time function given in Eq. (2) is fitted to describe an annual change of the expected ordinary water.

Table 1. Temporal changes of chemical composition during the period from February to September 2002. EC* : Electric conductivity measured at the faucet of the well (Fig. 3). The electric equivalency for HCO_3^- is derived from alkalinity.

M	D	Temp. (°C)	EC* (mS/m)	EC (mS/m)	pH	HCO_3^- (meq/L)	Cl^- (mg/L) (meq/L)	NO_3^- (mg/L) (meq/L)	SO_4^{2-} (mg/L) (meq/L)	Mg^{2+} (mg/L) (meq/L)	Ca^{2+} (mg/L) (meq/L)	Na^+ (mg/L) (meq/L)	K^+ (mg/L) (meq/L)
2	3	18.2	15.70	12.36	6.39		8.4	7.3	9.4	1.7	11.4	9.1	3.1
							0.237	0.118	0.196	0.140	0.569	0.396	0.079
2	7	18.2	14.04	12.81	6.47		8.6	7.6	10.2	1.8	12.3	9.1	3.2
							0.243	0.123	0.212	1.261	0.614	0.396	0.082
2	24	18.0	10.60	12.82	6.52		8.7	7.4	12.9	1.8	12.3	9.4	3.2
							0.245	0.119	0.269	0.148	0.614	0.409	0.082
4	10	18.2	12.93	12.94	6.55		8.8	7.1	10.9	1.6	11.1	9.4	3.0
							0.248	0.115	0.227	0.132	0.554	0.409	0.077
4	15	17.2	8.57	11.86	6.57		8.8	7.4	10.1	1.7	11.1	9.4	3.0
							0.248	0.119	0.210	0.140	0.554	0.409	0.077
4	25	17.8	9.47	12.29	6.56		9.1	7.6	11.5	1.7	11.3	9.7	3.0
							0.257	0.123	0.239	0.140	0.564	0.422	0.077
5	4	20.4	14.12	13.15	6.57		9.3	8.7	12.8	1.8	12.1	10.6	3.1
							0.262	0.140	0.267	0.148	0.604	0.461	0.079
5	11	19.0	12.65	12.06	6.62		8.7	8.3	9.5	1.7	11.3	9.4	3.0
							0.245	0.134	0.198	0.140	0.564	0.409	0.077
5	22	21.2	18.17	16.93	6.59		10.2	9.6	28.8	2.2	15.0	15.1	3.5
							0.288	0.155	0.600	0.181	0.749	0.657	0.090
6	3	29.1	14.51	13.74	6.65		8.5	9.6	14.9	1.9	12.6	11.9	3.3
							0.240	0.155	0.310	0.156	0.629	0.518	0.084
6	7	41.2	12.79	13.90	6.62		9.1	10.5	14.1	1.9	12.6	11.9	3.3
							0.257	0.169	0.294	0.156	0.629	0.518	0.084
6	15	21.6	15.71	14.65	6.60		9.0	10.1	19.2	1.9	12.4	13.8	3.4
							0.254	0.163	0.400	0.156	0.619	0.600	0.087
6	17	23.2	18.31	16.93	6.63		9.7	10.5	26.6	2.2	14.6	15.8	3.6
							0.274	0.169	0.554	0.181	0.729	0.687	0.092
7	4	46.5	19.72	15.69	6.55		9.9	11.0	20.6	1.9	12.3	15.3	3.4
						0.664	0.279	0.177	0.429	0.156	0.614	0.666	0.087
7	13	24.6	16.31	16.15	6.54		9.8	12.4	23.6	2.0	13.1	16.4	3.6
						0.647	0.276	0.200	0.491	0.165	0.654	0.713	0.092
7	23	41.0	19.14	15.85	6.60		9.8	10.7	20.2	2.1	13.7	15.6	3.6
						0.693	0.276	0.173	0.421	0.173	0.684	0.679	0.092
7	24	43.3	21.20	18.14	6.59		10.4	11.3	30.3	2.4	16.1	19.0	3.9
						0.703	0.293	0.182	0.631	0.197	0.803	0.826	0.100
7	25	40.5	19.93	18.40	6.60		10.4	11.5	31.7	2.2	14.4	17.2	3.6
						0.705	0.293	0.185	0.660	0.179	0.718	0.749	0.093
8	10	39.2	17.03	14.15	6.74		9.6	11.4	11.9	2.0	12.8	11.3	3.4
						0.722	0.271	0.184	0.248	0.165	0.639	0.492	0.087
8	18	34.0	16.03	13.94	6.67		9.7	12.2	11.7	2.0	12.7	11.3	3.5
						0.731	0.274	0.197	0.244	0.165	0.634	0.492	0.090
8	20	43.2	16.22	14.16	6.73		9.7	10.7	13.1	2.0	12.8	11.3	3.4
						0.699	0.274	0.173	0.273	0.165	0.639	0.492	0.087
8	21	42.1	15.61	13.17	6.78		9.7	11.2	12.3	2.0	12.8	11.1	3.4
						0.703	0.274	0.181	0.256	0.165	0.639	0.483	0.087
9	2	26.0	15.13	13.60	6.79		10.0	5.9	10.9	2.1	13.4	10.4	3.4
						0.784	0.282	0.095	0.227	0.173	0.452	0.452	0.087

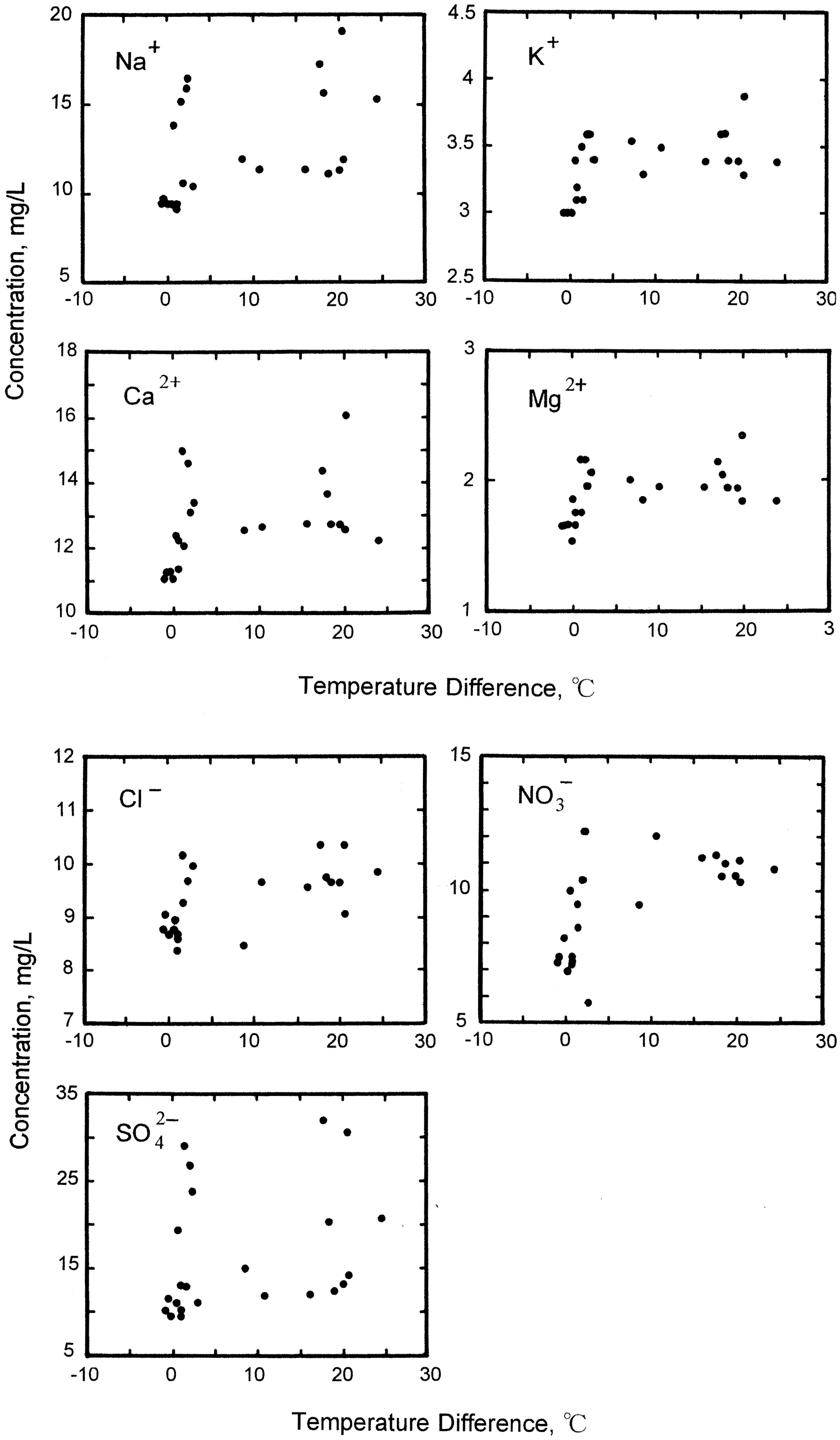


Fig. 8. Ion concentration versus temperature difference at the faucet for the well water. Top: for cation. Bottom: for anion. Data are from Table 1. The temperature difference is calculated with reference to the annual change of expected ordinary water, which is represented by Eq. (2).

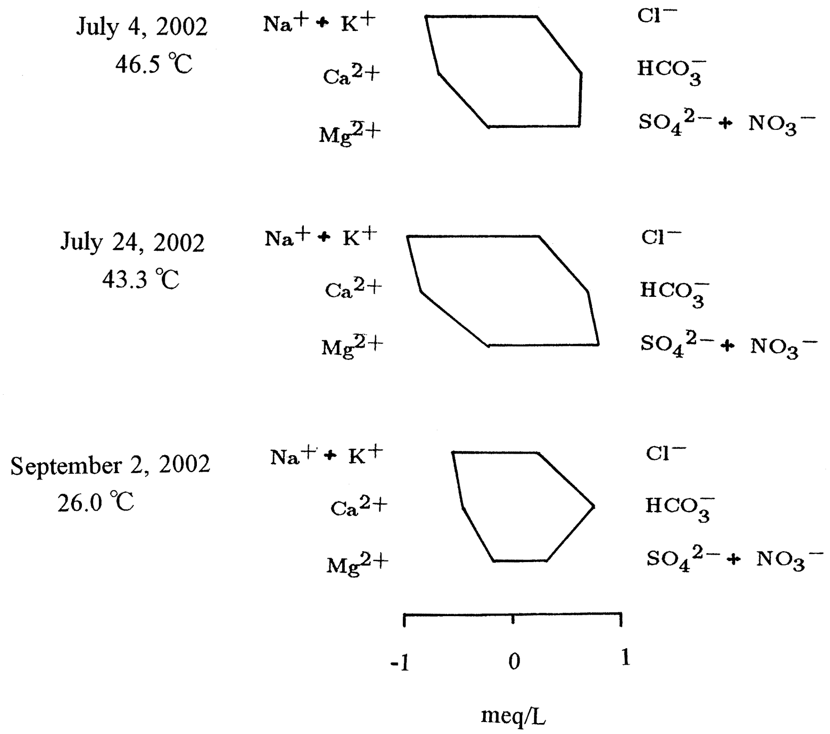


Fig. 9. Hexadiagrams for well water at the faucet. The top and middle diagrams show water highly contaminated with $Na^{+}+K^{+}$ and $SO_4^{2-}+NO_3^{-}$ with high temperature values at the faucet. Data are from Table 1.

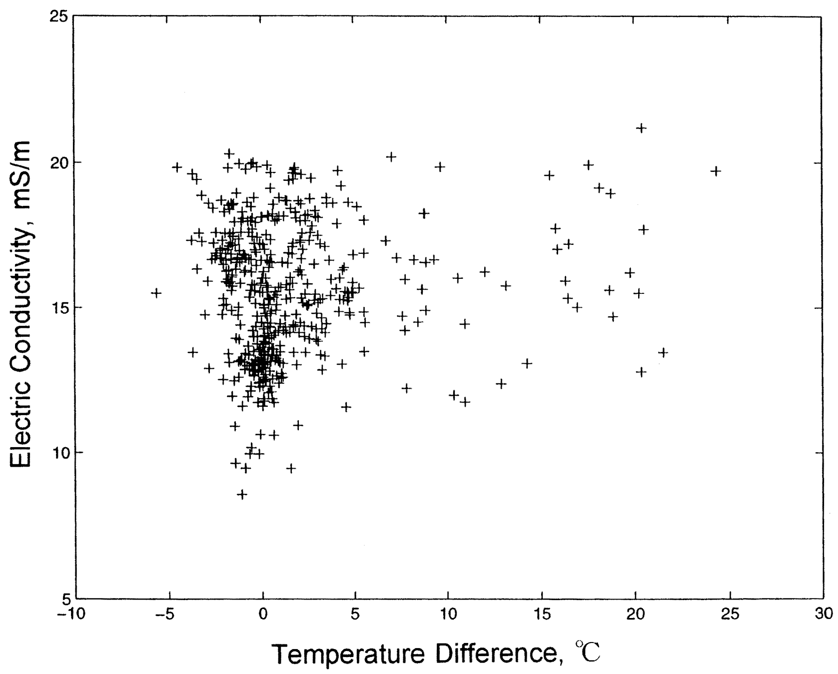


Fig. 10. Electric conductivity versus temperature difference for well water. Measurements were made at the faucet of the well mostly in early morning around 06 : 30 local time, recording data in every 10 seconds during 2 minutes of water-drainage. The maximum value for each conductivity and temperature measurement is adopted in the graph.

$$T_p = a\sin(2\pi(t-t_0/t_p)) + b, \quad (1)$$

where t is time elapsed from January 1, 2000, $t_0 = 880.0$ days, $t_p = 365.24$ days, $a = 3.05$℃, and $b = 16.6$℃. Observing the temperatures in the pipe in Fig. 6, we recognize an elevation of temperature, up to 4 degrees more than the ordinary seasonal trend given by Eq. (1), corresponding to the anomalously high temperatures recorded at the faucet.

The concentration of ions was studied using water samples obtained during the revival of activity from March to August in 2002. Table 1 shows the results of the chemical analysis. To confirm that the concentrations have some relationship with the rise of the water temperature, we estimated beforehand an effective increase of the temperature. The seasonal variation of the temperature at the faucet is assumed to take the same form of function as (1) with constant c as given as

$$T_f = T_p + c. \quad (2)$$

By fitting the above function to the data in Fig. 7, we get $c = 3.8$℃. The temperature difference with reference to T_f will be used for the temperature anomaly, or the effective increase of temperature. Fig. 8 shows the ion concentrations versus temperature differences for water at the faucet. Concentrations of Na^+ and SO_4^{2-} increased particularly by a maximum of 2 times when the temperature difference was positive. It should be noted that it is very difficult to sample the highly contaminated water at the faucet because of dilution by a large amount of ordinary water. Hence, the values for ion concentrations in high-temperature water is scattered. The hexadiagrams for both highly and slightly contaminated waters certify the intrusion of water of a deep origin with high concentrations of $Na^+ + K^+$ and $SO_4^{2-} + NO_3^-$ in the hot water (Fig. 9). Electric conductivity measurements were also conducted together with temperature measurements by Mr. Horimoto. The graph in Fig. 10 indicates an tendency of a somewhat normal correlation between temperature difference and conductivity, although the values are severely scattered.

Around the city of Iwakuni, the site of this anomalous water, no hot springs are known, although there are some cold mineral water sources which are used for bathing after heating up the water. The well site is located in the granite zone in the surface geology, which is adjacent to the Paleozoic Ryoke metamorphic formation (Yamaguchi Prefectural Government, 1976). In Quaternary geology, it should be noted that the well is located at the eastern end of the Iwakuni fault (IF in Fig. 2), one of the active faults around the site. The path of the pressured hot water is considered to be created in the fractured region along this fault. If this is the case, there is a possibility that the anomaly at this site would have a close relation to the activity of the fault; we have to bear in mind that there is a possiblity of a destructive earthquake in near future in this region, in addition to the precursory phenomenon for the 2001 Geiyo earthquake.

3. A jet of groundwater discharged at the sea bottom

The second narrative refers to an anomalous sea phenomenon, which might be a significant precursor for the 1995 Hyogo-ken Nanbu earthquake of M 7.3 (Kobe earthquake). At about 10 : 30 on January 15, about 2 days (43 hours) prior to the quake, the captain of the passenger boat, No. 5 Fuki, Nishi-Awaji Lines, navigating the Seto Inland Sea in the Akashi strait from the Akashi port, near Kobe City, toward Toshima port, Hokudan Town (Now Awaji City), Awaji Island, found his boat just crossing a black or brownish tidal eddy. The size was estimated to be 30–50 m in diameter compared to the size of the boat, which was 30 m. The place was well located by the nearby mark No. 1 fairway buoy. The captain was looking at the buoy left of the boat as it crossed the spot. This was only 4.8 km from the epicenter of the 1995 Kobe earthquake (Figs. 11, 12).

About one hour later, the captain of the next boat passing the spot noticed brownish water, but it had spread out. This event with concentrated brownish black water occurred just around the time when the No. 5 Fuki boat arrived at the No. 1 fairway buoy area.

This sea event is quite different from such ordinary sea phenomena as the reddish brown tide caused by the propagation of plankton. First, the latter, which occurs frequently, merely produces a thin film on the sea surface, and is easily separated into 2 colored domains by the boat crossing it. Secondly, the brownish black color cannot be made by such planktons. The likely candidate for the black

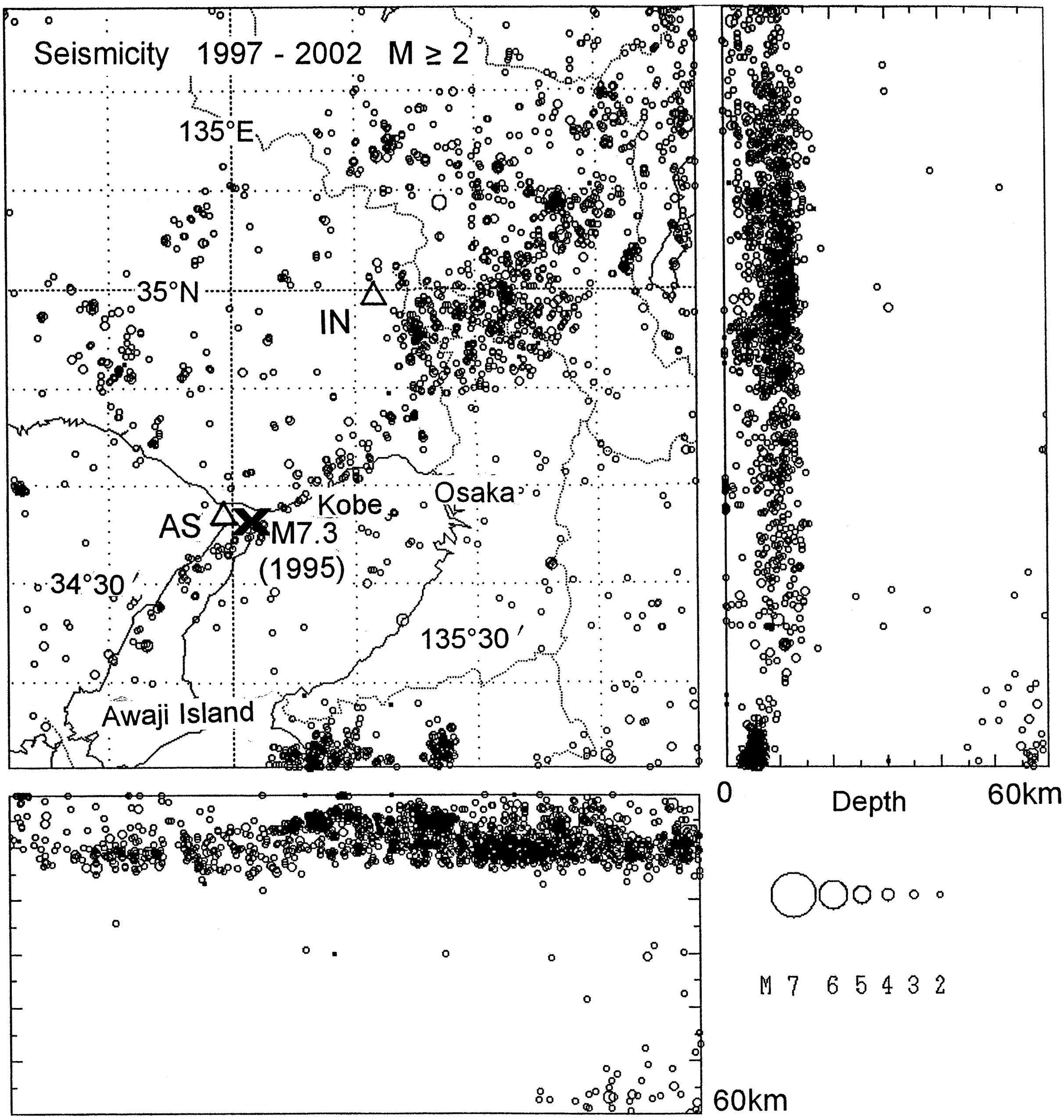


Fig. 11. Recent seismicity in Kinki District in southwestern Japan. Data are selected as after 1997 when the national dense seismic network was established in this region. Hypocentral data are from the Wakayama Earthquake Observatory, Earthquake Research Institute, University of Tokyo. Hypocenters were determined using data from not only its own stations but also stations attached to Kyoto University and Japan Meteorological Agency. The sites are indicated by open triangles: AS and IN denote Akashi strait and Inagawa Town, respectively. X indicates the epicenter of the January 17, 1995 Hyogo-ken Nanbu earthquake (the Kobe earthquake) of M 7.3.

material is sludge sedimented on the sea bottom. Sludge at a depth of 50–100 m (Fig. 13) must have surfaced within a limitted sea area. The interpretation of this phenomenon is that a jet of water sent the sludge 50–100 m up from the sea bottom (Fig. 13). This might be highly pressurized water with a lower density than the seawater.

It is difficult to imagine that the sludge might be due to human activity. The impact of dropping objects onto the seafloor might cause a mud cloud just above the floor. However, how was the cloud able to rise to the sea surface without any driving

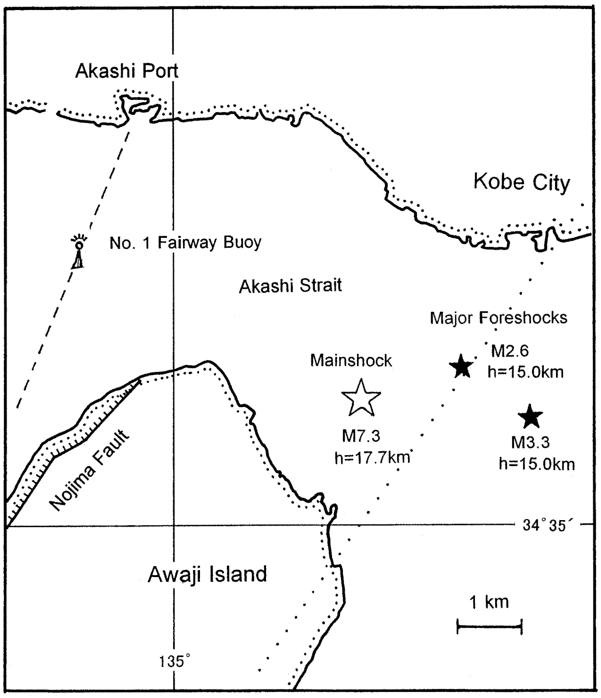


Fig. 12. Map showing area around the Akashi strait. The sea anomaly was found at the No. 1 fairway buoy. The broken line is the course of the passenger boat connecting Akashi port and Awaji Island. The epicenter of the Kobe earthquake and its major foreshocks are shown with their magnitudes and focal depths. Their hypocenter data are based on Katao *et al.* (1997). The dotted line shows the trace for the deepest end of the seismic fault of the Kobe earthquake estimated by Yoshida *et al.* (1996).

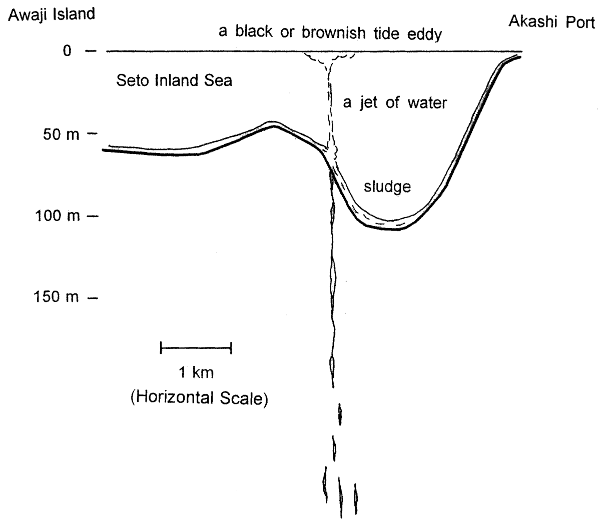


Fig. 13. Cross-section of the topography of the sea bottom along the course of the passenger boat, which crossed the black tide eddy area at 10 : 30 on January 15, about 43 hours before the Kobe earthquake. The hydrographic data is after Japan Coast Guard (2002). The tide eddy and the hypothetical fracture system are drawn for illustration. The spatial scale is not in accord with that of the topography.

mechanism and produce the black-brownish sea over an area more than 30 m in diameter ? The Akashi Strait Bridge, the longest spanning suspension bridge in the world, had been under construction when the Kobe earthquake took place. It might have been the most powerful artificial source of this problem. However, it was not the source: the bridge is located about 4 km from the No. 1 fairway buoy, and at that time, the construction of the foundation completed, and moreover work was suspended on the day the phenomenon was found because it was a holiday.

This water discharge phenomenon might be thought to be a precursory signal indicating a highly pressured state around the hypocentral region before the large earthquake. Deep pressured water rose up to the sea bottom from the highly stressed domain beneath the Akashi strait region. It is difficult to speculate the origin of the pressured water. First, the spot is far from the initiation point of the rupture of the Kobe earthquake. Moreover, it is not on a line of extention from the Nojima fault, the earthquake fault of the Kobe earthquake. Yoshida *et al.* (1997) concluded that the seismic fault generated by the Kobe earthquake consists of 2 major faults branching at the site around the epicenter; the northeastern part is nearly vertical and southwestern part is dipping southeastward. Both faults have a common root running roughly along the dotted line in Fig. 12 at a depth of 15–18 km. The fault of the northeastern part is vertical and that of the southwestern part is inclined with a surface break at the Nojima fault (Fig. 12). Foreshocks occurred in the evening of the day before the Kobe earthquake at around the mainshock hypocenter. If the water discharging spot had been located close to the Nojima fault, one of plausible models for the origin of the pressured water would be that it is located around the mainshock hypocenter, and the water migrated up through the Nojima fault system. However, this is not the case. This problem remains unsolved at present.

4. Upwelling of deep hot groundwater

At the time of the 1995 Hyogo-ken Nanbu earthquake of M 7.3 (Kobe earthquake), an artesian flowing well indicated an anomaly; water flooded over the spring-fed pond and the temperature rose 3–4℃. The site was located 51 km northeast of the epicenter of the Kobe earthquake as indicated in Fig. 11, and a schematic view of the well system is given in Fig. 14. The 30-m well was drilled into the granite bedrock. The water was cloudy like thick milk at that time, which remained for more than half a day and less than one day, leaving no sign of sedimentation in the pond and the surrounding ground. The mechanism for this is considered to be an anomalous increase of CO_2 concentration leaving sol particles of $CaCO_3$ similar to the Iwakuni case in Section **3.** Mr. Masao Tanaka, the owner of the well, noticed this anomaly and took a temperature measurement with an alcohol thermometer, confirming a slightly high temperature of 18℃ compared to normal value of 14℃.

We started monitoring the temperature in the well about 3 weeks after the earthquake. Initially, we used an analog recording system with a thermocouple sensor (Hereafter, we call this observation system instrument No. 1). The temperature values were read from the analog chart with a precision of 0.1–0.2℃. This observation system was succeeded by a digital recording system with the same sensor. The depth of the sensor in the well was 11.5 m. Besides, a Pt resistance thermometer was set at a depth of 26.9 m to take parallel measurements (Hereafter, we call this additional observation system instrument No. 2). All digital systems were set to acquire data with a sampling rate of 10 min.

To obtain the long-term trend of the temperature of the well water, a reduction process is required, because the recorded water temperature values were somewhat influenced by air temperature variations. This is a causal effect of environmental temperature on the electric circuit of the data aquisition system. Consequently, the annual seasonal change of water temperature is up to about 0.4 degree p-p according to the first thermometer (instrument No. 1), and 0.16 degree p-p according to the second type (No. 2). To reduce the effect, we take a running mean over one year. Then, the apparent seasonal change due to the fluctuations noted above was considered to have been removed. Furthermore, we made a correction for instrumental and environmental conditions between No. 1 and No. 2 instruments: We compared the daily averaging temperature data from the 2 instruments during the year. Removing daily and seasonal variations, we confirmed that the temperature values for the No. 1 instrument are as much as 0.018 degree higher than the No. 2.

A long-term trend of the water temperature is shown in Figs. 15 and 16. It was found that the temperature had gradually decreased following an exponential time function. First, using the semi-logarithmic curve of the combined temperature data from instruments No. 1 and No. 2, the time constant τ was determined to be 500 days for the empirical equation. This value is the midpoint between 400 and 600, which are the lower and higher limits of fitting. The trend of the temperature decay curve is approximated in the form:

$$T = a\mathrm{e}^{-(t-t_0)/\tau} + T_0, \tag{3}$$

where t is time elapsed from January 17, 1995, $t_0 =$ 295.0 days, $\tau = 500.0$ days, $a = 0.36$℃, and $T_0 = 14.26$℃.

The water temperature became almost constant around 3 years after the Kobe earthquake. Recent precise measurements of temperature with a resolution of 1 m℃ show the temporal change over a year is less than 0.01℃. From this fact, we can conclude that the higher temperature was transient.

The time constant of decay in (3) is so large that some crustal movements must be involved. The model for the water flow is given in Section **6**. A large volume of hot water must have been supplied into the ordinary cold water. According to (3), the temperature at the time of the Kobe earthquake was 14.9 degrees. The 3–4 degree rise just after the M 7.3 shock might indicate an initial transient phenomenon.

It is reasonable to consider that rain water was heated by external water originating from deep underground. Taking acount of the following parameter values as temperature difference ΔT, flow rate of the well v_r, and heat capacity of water c_p, the heat absorbed by water flowing out at the well for an extremely long time is represented by

$$c_p v_r \Delta T \int_0^{\infty} \mathrm{e}^{-t/\tau} \mathrm{d}t = c_p v_r \tau \Delta T. \tag{4}$$

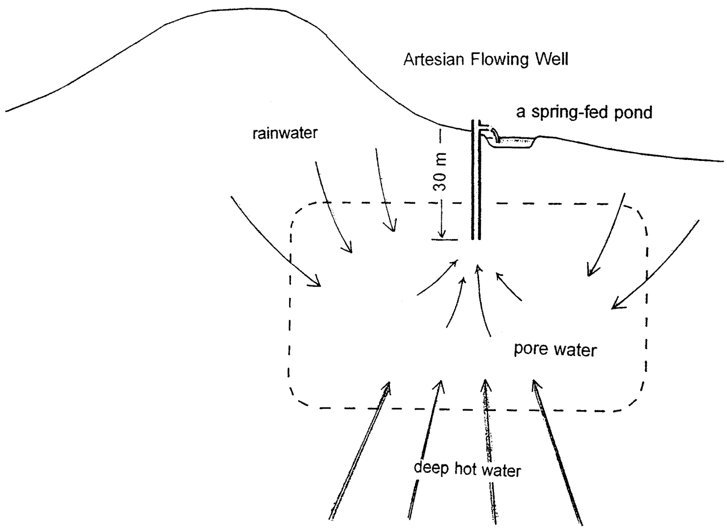


Fig. 14. Schematic view of the artesian well at Inagawa, Hyogo Prefecture. The reservoir of the pore water is assumed. The rain water circulates through this reservoir. Deep hot water enters from below to carry the heat and cause the rise of shallow water temperature.

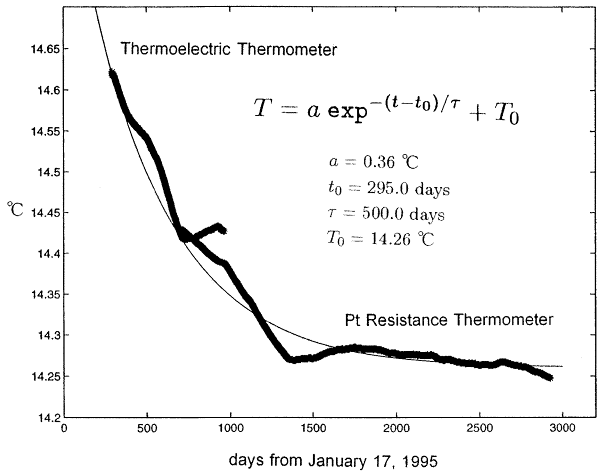


Fig. 15. Running mean water temperature at Inagawa over one year. The time constant τ is determined by the method explained in Fig. 16. The temperature values for instrument No. 2 are raised by 0.02℃ to adjust to those of instrument No. 1 (See text).

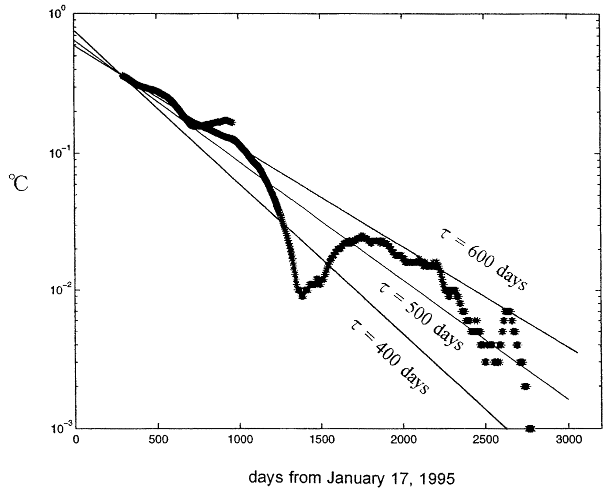


Fig. 16. Semi-logarithmic graph for the running mean water temperature at Inagawa. The time constant is determined by fitting a straight line to the curve. The temperature values for instrument No. 2 are raised by 0.02℃ to adjust to those of instrument No. 1, similar to Fig. 15.

To estimate the total heat capacity supplied by the hot water over 8 years, we apply (4) to the data: $\Delta T = 14.90-14.26 = 0.64$℃, $v_r = 9.0$ l/min, $\tau = 500.0$ days and $c_p = 4.18\times10^3$ J/l・degree. Then, a heat energy of 1.8×10^{10} J had been input to the artisian well over 8 years.

In addition to the heat estimated above, we have to examine the temperature rise of 3-4 degrees at the time of the earthquake. We assume that the initial process was another transient event, and the time constant was quite short at around half a day. Assuming the rate of flow at that time was constant with a value twice the normal flow, we estimate the heat consumed for the initial event. We adopt $\Delta T =$ 3.5℃, $v_r = 18.0$ l/min, and $\tau = 0.5$ days. The supplied heat amounts to 1.9×10^8 J. This heat energy is comparable to the seismic wave energy released by an M

2.3 earthquake, as calculated by the empirical formula of Gutenberg and Richter (1956). The heating caused by ground vibration due to the M 7.3 Kobe earthquake could not be the main source. One of the authors undertook an interview study around the severely damaged area just after the quake, and received no report of temperature rises of water pushing out from the ground even in the region of liquefaction.

The most effective frictional heat is generated by a seismic fault. Taking account of the low conductivity of heat of rocks, the source would be located very close to the anomaly event site. There is an example of an evaluation of heat production by faulting: Kanamori *et al.* (1998) made an analysis of worldwide ground velocity records for the deep-focused Bolivian large Earthquake, which was M_W 8.3 with fault size well constrained, and calculated efficiency, i.e., radiated wave energy / the total potential-energy. The efficiency of the deep large earthquake was as small as 0.036. In this case, the heat producted was extremely large. On the other hand, we have no definite estimate of efficiency for shallow earthquakes, due to the complexity of records of observed waveforms. Here, we assume that heating energy is comparable to the radiated wave energy of the earthquake which we are concerned. However, no such shocks of M 2 level were found close to the well site. The region around Inagawa is relatively aseismic compared to the seismic regions adjacent to it as shown in Fig. 11, and there were no registered shocks just before and after the 1995 Kobe earthquake.

We have no doubt that the above heat was sourced deep underground. However, it is not certain whether the heat was transported only at the time of the Kobe earthquake or if it had continued for a long period of up to several years. Either way, the capacity of the reservoir of hot water would be considerably large rather than a small-scale vent-type water passage system. Fig. 14 is an image of the reservoir and the water circulation system. On ordinary days, rain water circulates through the rock system beneath the site forming a reservoir of pore water. The M 7.3 earthquake brought a supply of hot water from deep underground.

5. Heating ground rocks in a lineament zone

If upwelling and discharge of hot water takes place over a wide area, the rocks around the ground surface will be heated by the hot water, and accordingly some high-temperature zones on the ground surface will be detected corresponding to the upwelling zone of hot water. This temperature pattern on the map could be obtained through satellite infrared images. Gotoh *et al.* (1999) attempted this for a seismically active region in central Japan. Fig. 17 shows the results of their study as described below in detail.

Thermal measurement of the earth's surface is based on Stefan-Boltzmann law and Wien's displacement law for a black body. The absolute temperature T in Kelvin of the body surface is given by

$$T = 2897.8/\lambda_{max}, \tag{5}$$

where λ_{max} is the wavelength in μm for the maximum intensity of the radidated electromagnetic waves. Strictly, the Earth is a grey body, and has an overall reduced emissivity in comparison to a black body. As the emissivity is practically constant over all wavelengths, we approximately regard the Earth to be a black body. Minimal absorption of infrared radiation by the atmosphere is observed over the ranges 3〜5μm and 8〜13μm (e.g. Tronin, 1999). The latter range corresponds to the temperature range of −5.2〜89.0℃. This range almost covers the ground surface temperature on the Earth.

We used data from the LANDSAT satellite because of its high resolution for infrared band observations. This satellite orbits the Earth with a 99 -minute period. The same place is visited every 16 days. Over Japan, it moves from north to south during the day at around 10 : 00 (local time)and from south to north at night at around 21 : 00 (local time). We selected night-time data for No. 6 band (10.40–12.50μm) infrared obtained by the Thematic Mapper (TM) sensor. In this specification, the resolution is 120 m for one dot on the image.

To monitor the ground surface temperature, observations with clouds and snow cover should be avoided. An opportunity to get the ideal data for our purpose was confirmed to occur only about once a year for the target area of this paper, the Niigata Prefecture region, central Japan.

Figure 17 is a LANDSAT 5 image showing the earth surface temperature distribution on August 10, 1994 over the area of northern Niigata Prefecture (Fig. 1). We can notice a lineament hot zone 10–20 km long and several kilometers wide. The area is about 1 degree higher in temperature than the surrounding area. The absolute temperature is around 23℃. This value is somewhat higher than the ordinary state of the ground in Niigata region as found by repeated observations (Fig. 18). This hot zone lies along the Tsukioka fault system (Research Group for Active Faults of Japan, 1991). The fault zone is located along the border between the eastern mountainous region and the alluvial plain region toward the west. The fault zone is located over basement rocks with Cretaceous granite (Niigata Prefectural Government, 1977). Because there are hot springs around the fault, it is reasonable for a hot zone to be formed there. The above mentioned heating may occur frequently. The image in 1984 also has the same hot zone lineament along the Tsukioka fault (indicated by T in Fig. 18 (a)). In this case, the temperature was as low as 17℃ and similar regions with relatively high temperatures were found. It is quite probable that the Tsukioka fault zone is frequently active with hot water upwelling. It was also confirmed that, when we

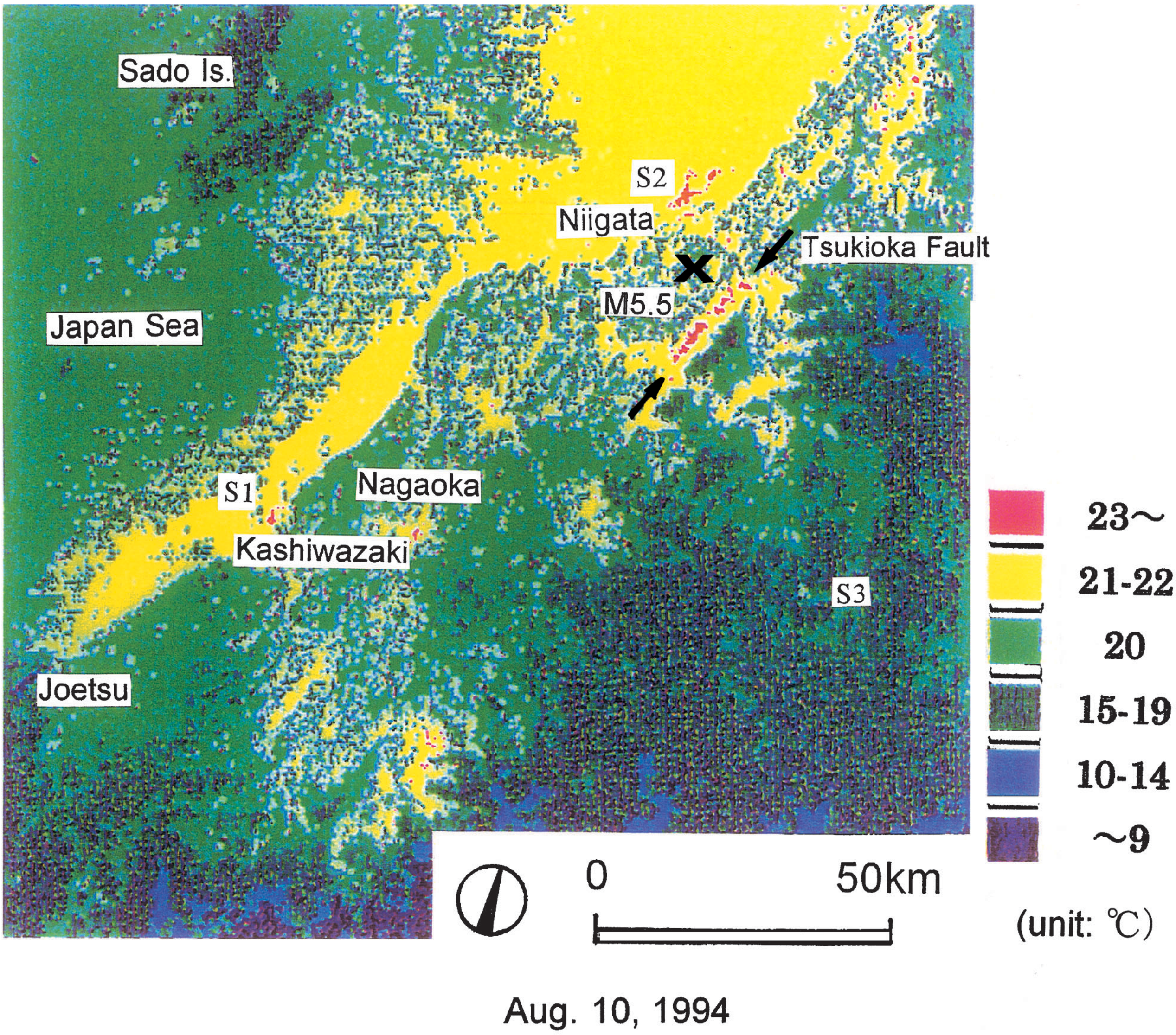
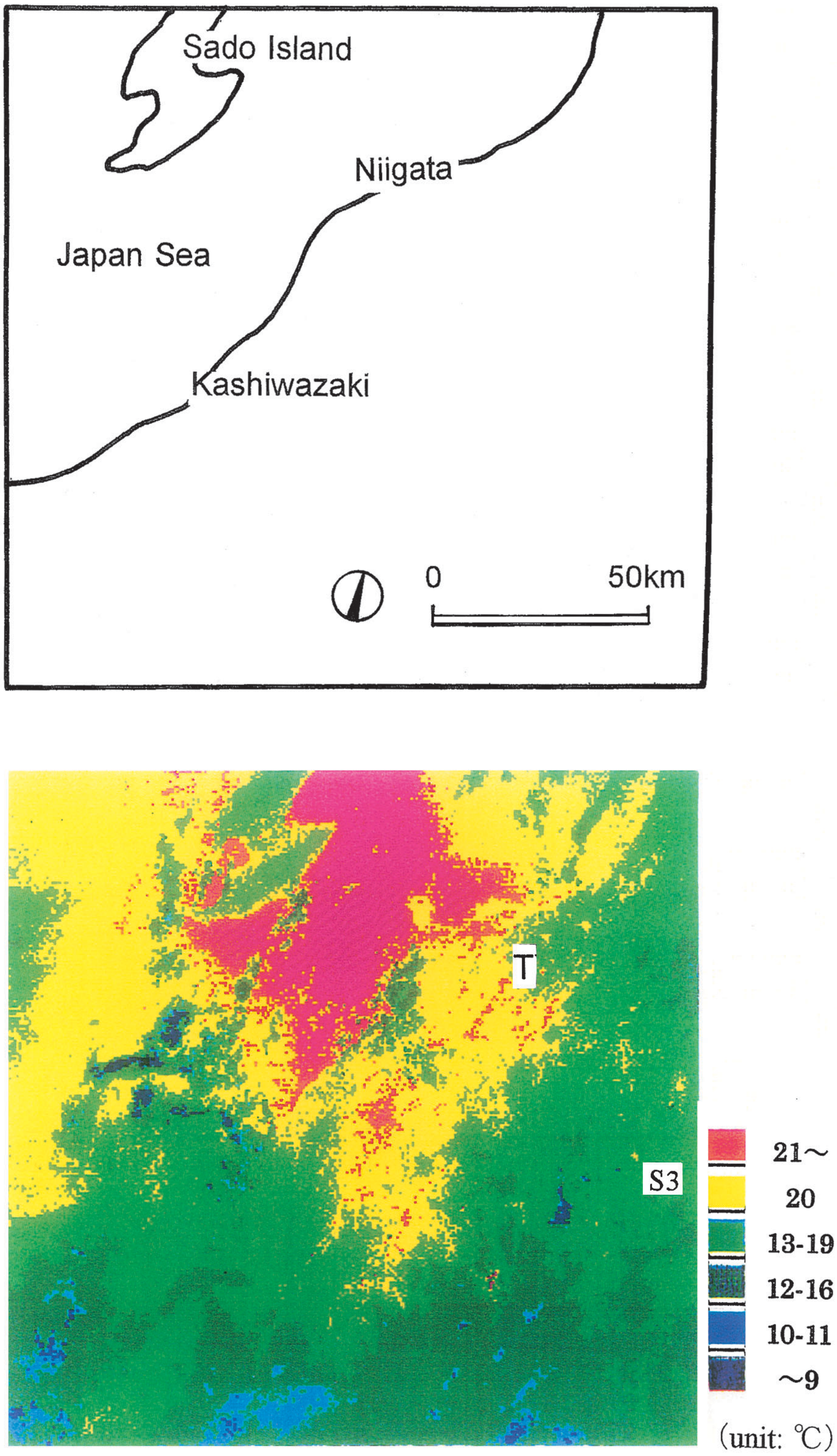


Fig. 17. LANDSAT infrared thermal image of the Niigata region at around 21 : 00 on August 10, 1994. S1, S2 and S3 indicate spots off Kashiwazaki, off Niigata and Lake Numazawa, respectively. X indicates the epicenter of the 1995 Niigata-ken Hokubu earthquake (Northern Niigata earthquake) of M 5.5. The lineament of the hot zone close to the M 5.5 shock is located along the Tsukioka fault (indicated by arrows) (Research Group for Active Faults of Japan, 1991).



(a) Aug.14, 1984

Fig. 18. Night-time LANDSAT infrared thermal images for the period from 1984 to 1995. The top of the figure shows a map indicating the area range of the satellite images below. The dates of the images are (a) Aug.14, 1984; (b) July 16, 1985; (c) May 19, 1987; (d) Oct. 2, 1990; (e) May 14, 1991; (f) Aug. 10, 1994; (g) Aug. 29, 1995. S1, S2 and S3 indicate spots off Kashiwazaki, off Niigata and Lake Numazawa, respectively. In (a), T denotes the Tsukioka fault (See Fig. 17).

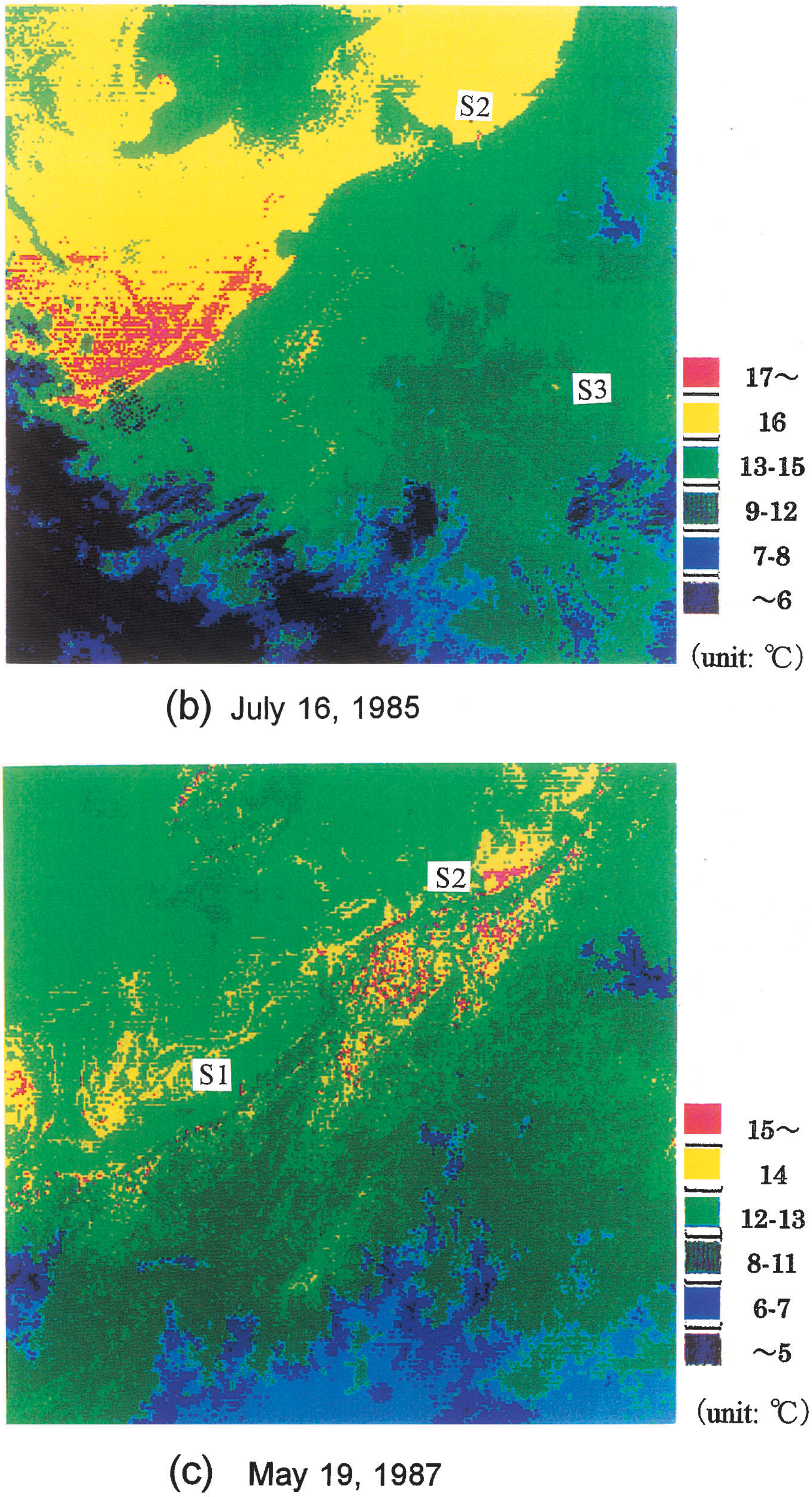
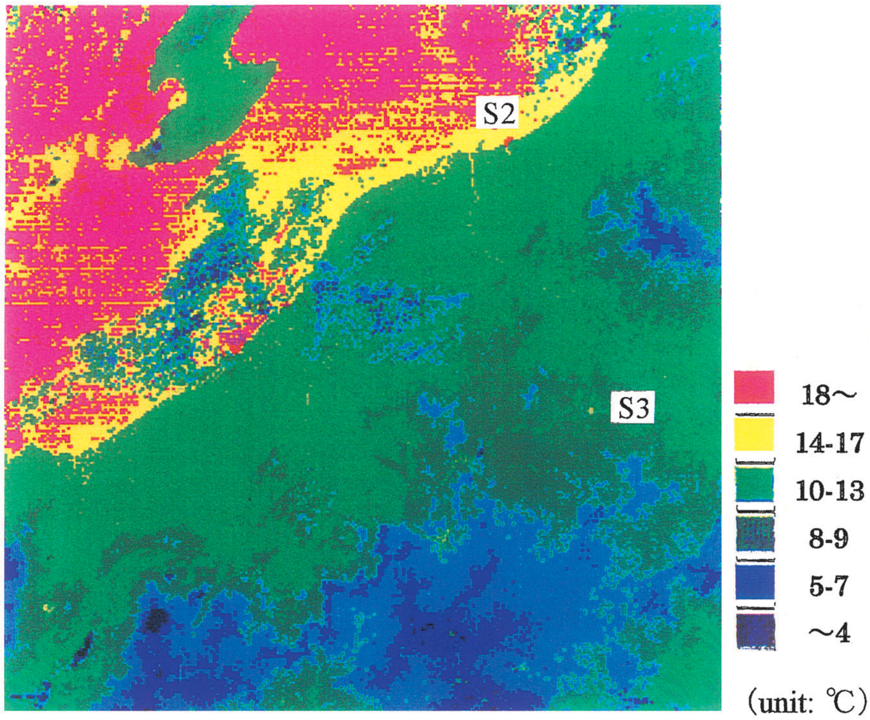
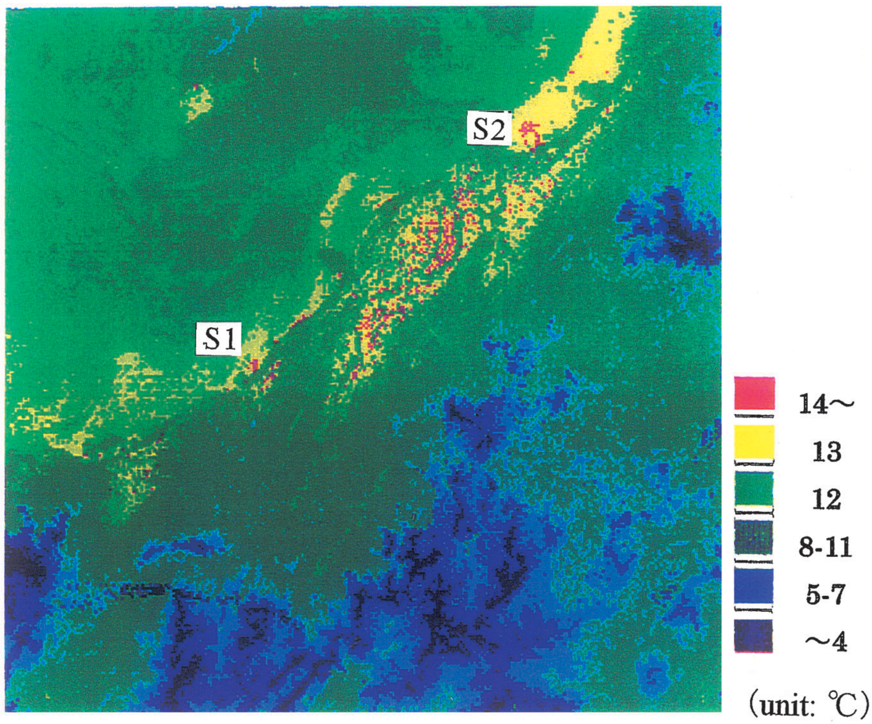


Fig. 18. (continued).

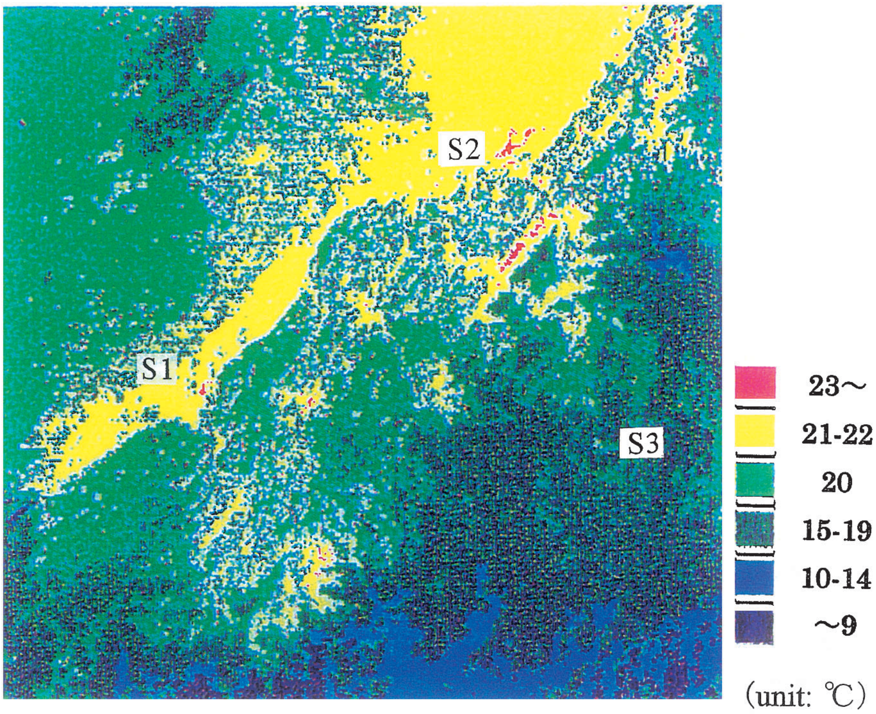


(d) Oct. 2, 1990

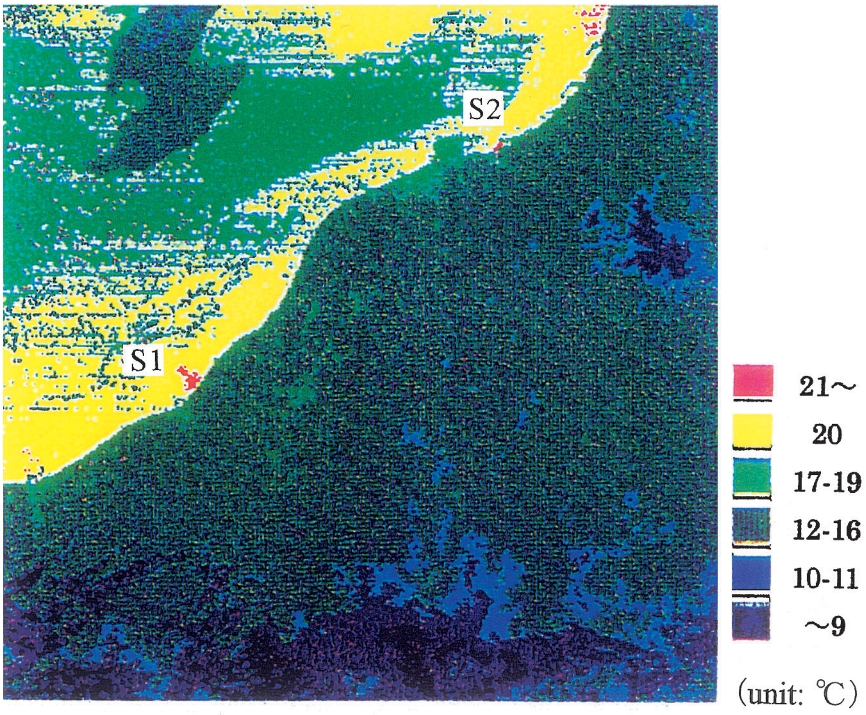


(e) May 14, 1991

Fig. 18. (continued).



(f) Aug. 10, 1994



(g) Aug. 29, 1995

Fig. 18. (continued).

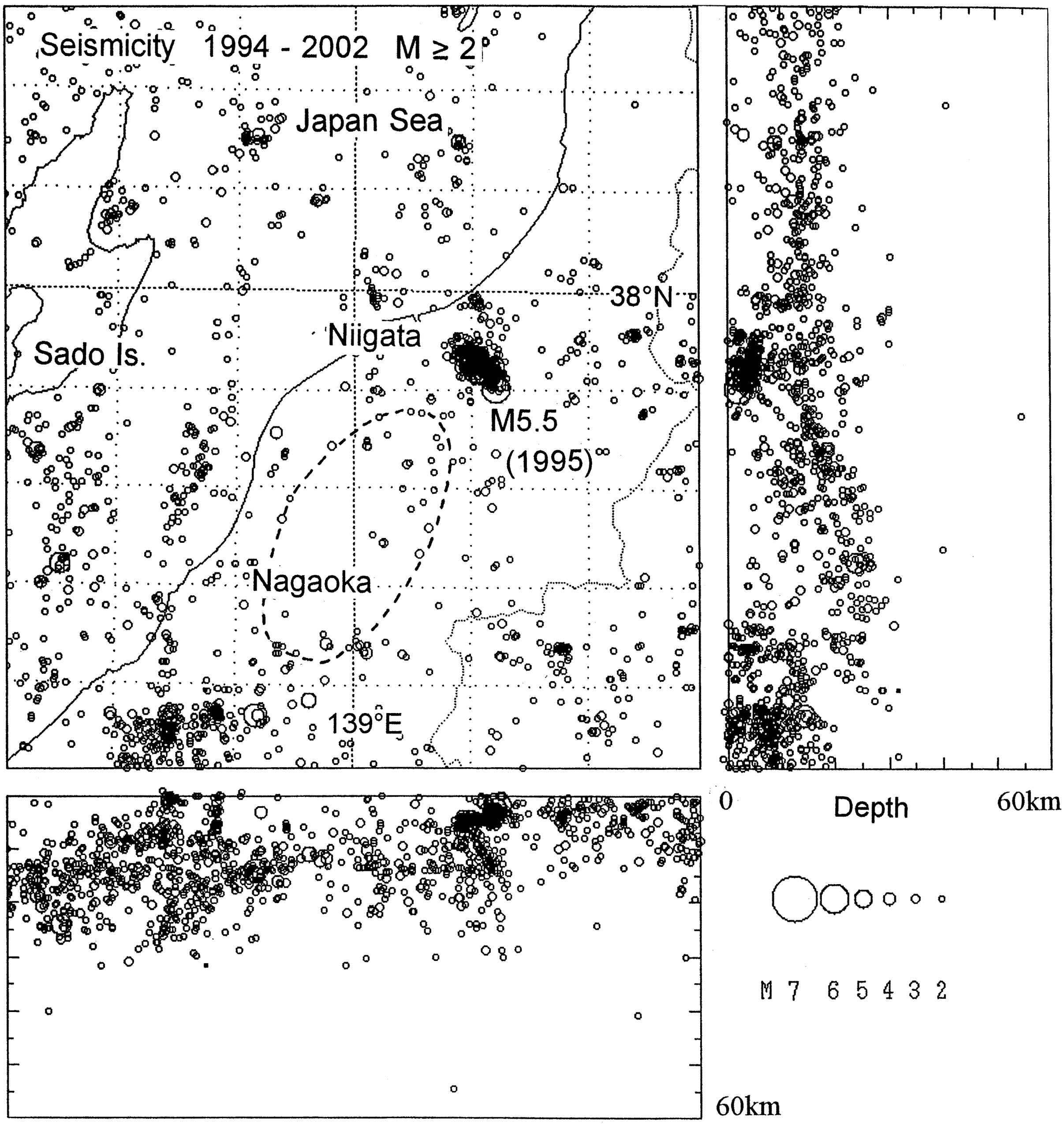


Fig. 19. Map showing seismicity in Niigata region. Data are from Earthquake Research Institute, University of Tokyo. Very shallow hypocenters of the April 1, 1995 Niigata-ken Hokubu (Northen Niigata Prefecture) earthquake of M5.5, the precursory earthquake swarm and aftershocks are shown. The seismic gap for the source area of an expected future large earthquake is shown by a dotted curve based on Tsukuda (1995).

carefully inspected the paper by Tronin *et al.* (2002), a relatively hot lineament zone was found around the Tsukioka fault zone in the NOAA satellite image (Fig. 8 in their paper) in December 1996. However, the above two cases of 1984 and 1996 are not as clear as the 1994 image, which provided us with a predominant lineament image at the Tsukioka fault zone. Consequently, no other remarkable hot zone like that found in the 1994 image is seen in the other images in Fig. 18. In particular, a comparison of the images in 1994 and 1995 ((f) and (g) in Fig. 18) makes this clear. Both images were taken in the same season (summer) with similar conditions in the sea area (Japan Sea), and the land area shows a clear contrast between them: one with a clear hot zone and the other with no such noticeable hot zone.

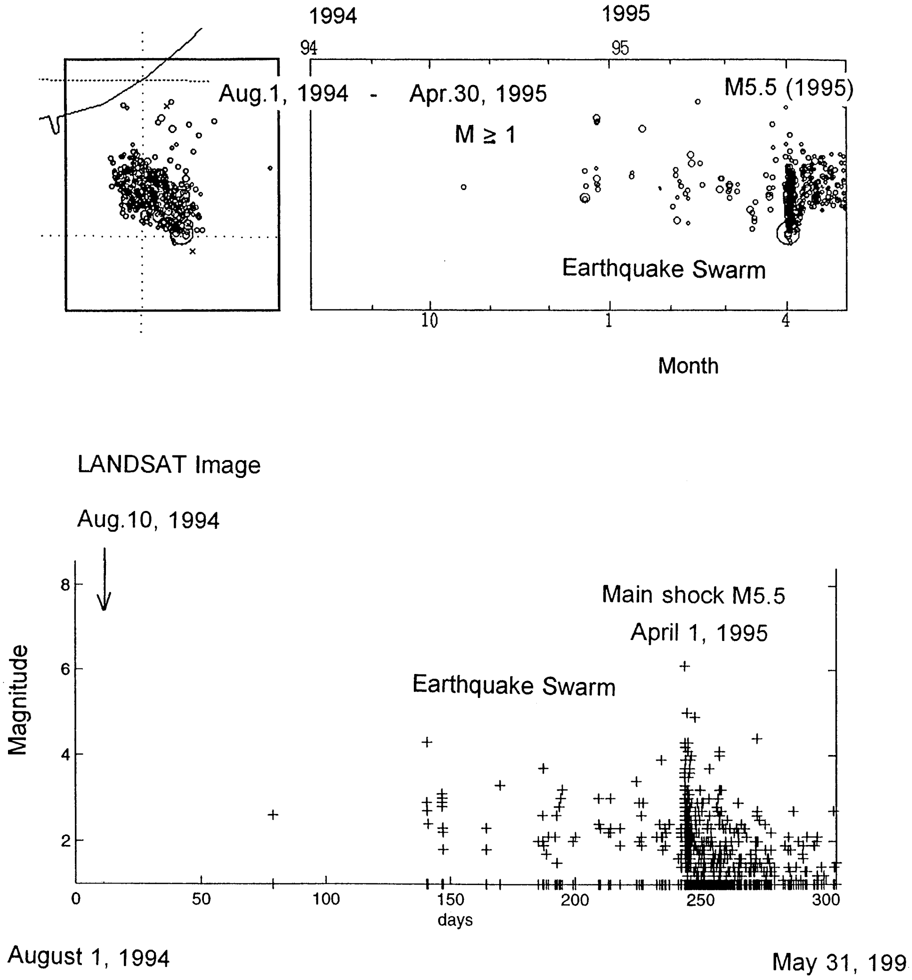


Fig. 20. Time sequence of the earthquake swarm, the M 5.5 shock and its aftershocks.

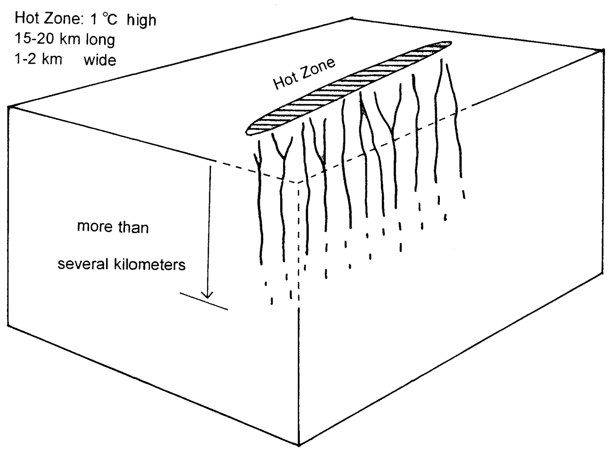


Fig. 21. Model for heating ground rocks with the intrusion of hot water from the deep crust.

It might be useful for confirming the sensitivity of the LANDSAT image to note some distinctive spots in the image picture. We first notice two hot spots on the sea near the coasts of both Kashiwazaki City and Niigata City (spots S1 and S2 in Figs. 17 and 18). These are the sites of electric power stations: a nuclear power station at Kariwa, close to Kashiwazaki City and a thermal power station at Niigata City. The steam turbine system at both stations uses seawater for cooling the condensing unit of the system. The hot seawater released raises the water temperature. Another marked spot noted as S3 in Figs. 17 and 18 is located at the crater lake of a Quaternary volcano, i.e., Numazawa Lake, in Fukushima Prefecture. Although the absolute temperature is not so high at the lake, it clearly marks a hot spot in a relatively low temperature region. The above 3 spots are frequently observed, and we can regard them as an indicator of the high sensitivity of the satellite observations. S1 and S2 are seen clearly on both images, (f) and (g) in Fig. 18. This again gives proof that the 2 images were taken under almost the same environmental conditions.

The 1995 Niigata-ken Hokubu (Northern Niigata) earthquake of M 5.5 occurred on April 1, 1995 in the alluvial plain region about 5 km from the Tsukioka fault, the high-temperature lineament zone (Fig. 17). Before this destructive earthquake, swarm activity had taken place in the same region as the source area of the major shock (Figs. 19, 20). It started around October in 1994 and became highly active in December of the same year, and lasted until just before the major shock of April 1, 1995. The maximum magnitude recorded before the M 5.5 shock was M 4.3; eleven shocks were greater than or equal to 3 in magnitude. The M 5.5 shock was accompanied by many aftershocks: the maximum shock of M 5.0 and 47 shocks with magnitudes greater than or equal to 3. A detailed study of the aftershocks based on nearby temporary observations revealed that the hypocenters were very shallow at a depth of around 5 km (Sakai *et al.,* 1995).

The temporary heating of the ground surface possibly arose from intermittent heat transfer by water. Either process whereby new paths for upwelling of hot water were created or the rates of upwelling at the preexisting hot springs were increased, or both, might have occurred. Schematic illustration of this heating model is given in Fig. 21. It is considered that the series of phenomena mentioned above are due to a temporarily raised stress level around the Northern Niigata region. Thermal activity preceded the seismicity.

6. Model for intrusion and diffusion of upwelling hot water

The pressured water comes up from deep underground, intrudes into the reservoir just beneath the ground surface, and leaves the reservoir, diffusing into the near surface medium. The simplest model of this process is given in Fig. 22. The source of the deep water is located at some depth. The excess pressure P_0 there is given. The reservoir has a capacity C for receiving deep water, and the pressure increment for the intruded water in the reservoir is defined as P. The water intrudes through pipes with resistance R_1, diffuses through other pipes with resistance R_2. Actually, the pipes are composed of a lot of small cracks, which are described in the figure by two kinds of pipe representing them. The amount of heat Q supplied from deep underground into the reservoir is

$$Q=CP. \qquad (6)$$

The heat changes with time t in the following equations:

$$P_0-P=R_1\frac{dQ}{dt} \qquad (7)$$

for intrusion, and

$$-P=R_2\frac{dQ}{dt} \qquad (8)$$

for diffusion. Assuming P_0 is such a step function,

$$P_0=\begin{cases}0 & t<0\\ a & t\geq 0,\end{cases} \qquad (9)$$

we get the following solutions:

$$P=a(1-\mathrm{e}^{-t/\tau_1}) \qquad (10)$$

for Eq. (7), and

$$P=b\mathrm{e}^{-t/\tau_2} \qquad (11)$$

for Eq. (8), where b, τ_1, and τ_2 are constants, and $\tau_1=R_1C$, and $\tau_2=R_2C$.

The increment T of the water temperature for the reservoir should be

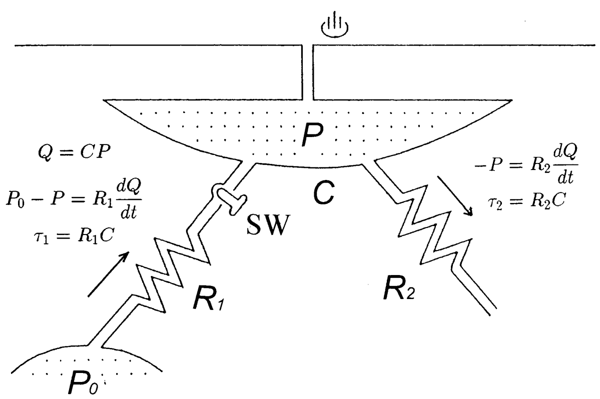


Fig. 22. Conceptual model of the reservoir, intrusion path, and diffusion path for the upwelling hot deep water. P, P_0, C, R_1, and R_2 are pressure at the reservoir, pressure at the hot water source, capacity of the reservoir, resistance of the path for upwelling, and resistance of the path for diffusion, respectively. SW denotes the switch for the intrusion path to be active to initiate the circulation of water flow.

$$T = Q/C_h, \tag{12}$$

where C_h is the heat capacity of the water. From Eqs. (6) and (12), T is in proportion to P. Then, Eqs. (10) and (11) can be rewritten as

$$T = T_1(1 - e^{-t/\tau_1}), \tag{13}$$

$$T = T_2 e^{-t/\tau_2}, \tag{14}$$

respectively, where T_1 and T_2 are constants.

In this paper, we deal with no whole time function for the process of water temperature rise. The record at Inagawa in Section **4** shows a decay curve of the final stage of the process. Recently, Tsukuda and Kamikubo (2004, 2005) found a temporal change of water temperature with a height of 10–25℃ and obtained the time function of the whole process, in Tokai region, central Japan. The time constants for τ_1 and τ_2 are 1–2 days and 2–4.5 days, respectively. In Section **4**, the time constant τ_2 in Eq. (14) was 500 days. This means that either the capacity of the reservoir or the resistance of the pipe for diffusion, or both, should be fairly large compared to those of the Tokai region.

7. Discussion

Here, we examine previous studies concerning the upwelling discharge hypothesis for deep water. Overpressures generated by the overburden of the subsiding sedimentary basins, or geopressures, have been confirmed in oil and gas fields (e.g., Bebout *et al.,* 1977; Hart *et al.,* 1995; Robert *et al.,* 1996). The excess of pressure against hydrostatic state should drive pore water upward for discharge at the ground surface. Oki *et al.* (1992) presented a model to explain seismic activity in the geopressured region in the light of upwelling water. Their model was based on the following facts:

1) Thick sedimentary layer system, where oil or natural gas resources are abundant, is highly stressed by tectonic force, and the lithospheric stresses are also high. Under such circumstances, geopressured pore water originates within the crust. The high-pressure water has been revealed by drilling at petroleum plants. Oki *et al.* (1992) took an example for this from Shiroishi (1970) in Niigata region.

2) Hot water discharge is noticed even at high altitudes in some hot spring regions. To lineate the spatial distribution of the hot zone where a hot water discharge occurs, Xu and Oki (1998) and Xu *et al.* (1998) conducted temperature measurements at snow-melting wells in the Niigata region. They found a steady state nature for the discharge of deep water without distinction for altitude of the ground.

3) Regarding chemical composition, Sato (1981, 1982) studied water under the near surface at landslide areas. A Na-Cl type water was found as the surface water. Such water originates from deep underground, because Na rich water cannot be attributed to interactions with surface rocks.

4) Highly pressurized water within the crust may drive the fracturing of rocks, generating earthquakes as discussed fully for the Matsushiro earthquake swarm, in central Japan, which was initiated in 1965 (Nakamura, 1971; Mogi, 1988).

The above model extends to areas other than the sedimental zone. The discharge events shown in this paper took place in regions covered mostly with granitic rocks at the surface. Generally, pore water in the deep crust are pressurized when stresses increase within the crust. Furthermore, the discharge of deep water at or near the ground surface is promoted as stresses increase in the crust. This implies that the deep water discharge carries a signal for the stress state in the crust. Regrettably, we have not suceeded in estimating the depth of the source of the deep water. A future study should involve an isotope analysis of water and gasses to identify the origin of the water.

The objective of this paper is to present some examples of episodic and transient aspect of such discharge events. Some are closely related to preparations for large earthquake generation. These will be linked to the study of precursors for large earthquakes as a key element of earthquake prediction studies. In the future, outcomes from this kind of study will be accumulated, and detailed chracteristics of these precursors will be clarified. We believe that this paper marks the first step in research on precursory phenomena that involve anomalies in groundwater coming from deep sources. The events presented in this paper are summarized in Fig. 23. The Iwakuni and Akashi Strait events are considered to be very local discharges of deep water with a unique vent for the path of water. The Inagawa event may require hot pore water reservoir with a considerable volume, rather than a small vent for the

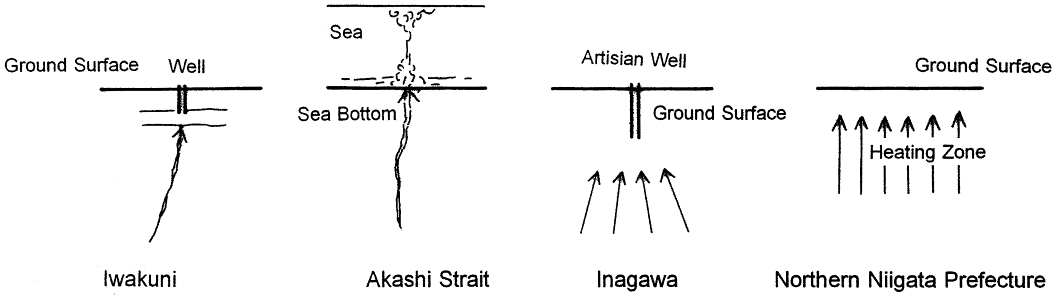


Fig. 23. Summary of four cases of deep groundwater discharge.

passage of deep water as in Iwakuni or Akashi strait. The Niigata event is characterized by a zonal discharge of deep hot water. It is likely that the source of the hot water is at high temperature close to boiling point in free air or higher. If this is the case, the depth of the source would be more than several kilometers as illustrated in Fig. 21. This study marks the starting point for clarifying the anomalous discharging of deep water by deploying such fundamental methods and techniques as continuous measurements of water temperature, repeated measurements of temperature and electric conductivity of water, repeated water sampling, and observations of infrared radiation by LANDSAT satellite with fine-resolution images.

The problem of identifying the source of the hot water seems to be beyond our ability today. The second issue is to identify where the water paths are generated. In the Niigata region, the hot lineament zone corresponds to an active fault. The well in Iwakuni is also located at the end of an active fault. The water expulsion at the sea bottom at Akashi Strait took place close to the northeast extension of the Nojima fault, which slipped right laterally associated with the 1995 Kobe earthquake. These examples indicate that the paths seem to be selected close to preexisting fracture zones in the crust. However, the Inagawa event should be considered differently. There were no nearby faults. Moreover, the microseismicity around the site is very low compared to the eastern seismic zone as shown in Fig. 11.

Finally, we should mention the background of the present study with the intention of promoting these kinds of studies that explore ground surface phenomena as disclosed in this paper. The Akashi-strait event and the Inagawa event were discovered by one of the authors during field research just after the 1995 Kobe earthquake. His first summarized report on the research was on luminous phenomena (Tsukuda, 1997). The present paper applies other results of his research. The Iwakuni event was brought to us via communications with one of the observatories attached to the Earthquake Research Insitute, University of Tokyo, the Hiroshima Earthquake Observatory (Tsukuda, 2002). Assuming such anomalous phenomena as those presented in this paper frequently occur in many places, we could get more information from communications with local people, and, in addition, it might be a good idea to undertake simple observations at many preexisting wells. Along this line, we have already started experiments for obtaining new data at wells where anomalous high water temperatures had been previously reported.

8. Conclusion

This paper presents the following phenomena providing evidence of the near surface discharge of deep water originating at a depth of more than several kilometers:

1) A small mass of deep hot water frequently intruded into a shallow groundwater reservoir at Iwakuni, Yamaguchi Prefecture, southwest Japan, which might be a possible precursor for the 2001 Geiyo earthquake of M 6.7. High temperatures have been frequently observed from manual measurements at the exit of the well water supply system since October 6, 2000, on the same day as the 2000 Tottori-ken Seibu earthquake of M 7.3 occurred. The temperature increased to 49℃ one day before the 2001 Geiyo earthquake, and 48℃ in the morning of the day of the shock, about 9 hours before the occurrence. Continuous observations detected an impulsive rise of temperature in the well, indicating the

intermittent intrusion of hot water. The results of a chemical analysis of ion concentrations substantiate speculation about the intrusion of external deep water.

2) Expulsion of groundwater was considered to have occurred at the Akashi Strait, near Kobe City, southwest Japan, which was about 2 days (43 hours) before the 1995 Hyogo-ken Nanbu earthquake of M 7.3 (the Kobe earthquake), based on reports on the appearance of brownish-black seawater by the captain of a passenger boat in regular service crossing the strait. This is also considered to be due to a pressurized deep groundwater discharge at the sea bottom, which is possibly one of the precursory phenomena of the large M 7.3 earthquake.

3) Upwelling of deep hot groundwater at the time of the 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake), was confirmed by long-term observations of temperature at a flowing well at Inagawa Town, Hyogo Prefecture, Kinki District, southwest Japan, which is located 51 km northeast of the epicenter of the shock. The report by the owner of the well, stating that heated water flooded the pond, which was cloudy like milk shortly after the quake. 25 days after the quake, continuous observations of groundwater temperature started. Data over a period of more than 8 years shows a decrease of temperature over 2–3 years with a time constant of about 1.5 years and a stationary trend after that period. The heat source is considered to be deep underground water, which had been stored within the rock system beneath the site.

4) Heating of ground rocks by upwelling deep hot water intruding into the fracture zone of an active fault related to the 1995 Niigata-ken Hokubu earthquake of M 5.5. A LANDSAT infrared image presented a temporary lineament distribution of high temperatures on the ground in the northern Niigata area, central Japan, in the summer of 1994. An earthquake swarm then began in October of that year, and the M 5.5 shock occurred on April.1, 1995.

Acknowledgements

The authors are indebted to many persons who brought valuable information to us. Among them, Mr. Masao Tanaka at Inagawa Town in Hyogo Prefecture, Mr. Saburo Tanaka, Mr. Haruo Tsutsumi, and Mr. Shigeru Ido in Awaji Island in Hyogo Prefecture, Mr. Sadao Kawakami at Sasakami Village (Now Agano City) in Niigata Prefecture, and Tadao Horimoto at Iwakuni City in Yamaguchi Prefecture should in particular be acknowledged. Thanks are extended to Mr. Katsumi Miura for technical support, Mr. Naoto Togashi for assistance of the chemical analysis, Mr. Koji Yanagi for processing satellite images, and Profs. Kosyun Yamaoka and Teruyuki Kato for reviewing the manuscript and giving valuable suggestions. Part of this study was conducted under the project of Earthquake Research Institute, University of Tokyo: Prediction Study on Inland Large Earthquakes.

References

Bebout, D.G., R.G. Loucks and A.R. Gregory, 1977, Texas geothermal prospect slated to begin operations at Martin Ranch, *Oil and Gas Journal,* **41**: 184–188.

Gotoh, K., K. Yanagi and T. Tsukuda, 1999, Satellite ground temperature measurements around the Niigata plain in central Japan, *Bulletin of the Study of Natural Disaster, Report of Western District of Japan,* **23**: 167–170 (in Japanese).

Gutenberg, B. and C.F. Richter, 1956, Magnitude and energy of earthquakes, *Annali. di Geofisica,* **9**: 1–15.

Japan Coast Gard, 2002, Hydrographic Chart W131.

Hart, B.S., P.B. Flemings and A. Deshpande, 1995, Porosity and pressure: Role of compaction disequilibrium in the development of geopressures in a Gulf Coast Pleistocene basin, *Geology,* **23**: 45–48.

Kanamori, H., D.L. Anderson and T.H. Heaton, 1998, Frictional melting during the rupture of the 1994 Bolivian Earthquake, *Science,* **279**, 839–842.

Katao, H., N. Maeda, Y. Hiramatsu, Y. Iio and S. Nakao, 1997, Detailed mapping of focal mechanisms in/around the 1995 Hyogo-ken Nanbu earthquake rupture zone, *J. Phys. Earth,* **45**: 105–119.

Mogi, K., 1988, The mechanism of the occurrence of the Matsushiro earthquake swarm in central Japan and in relation to the 1964 Niigata earthquake, *Tectonophys.,* **159**: 109–119.

Nakamura, K., 1971, A hypothesis on mechanism of the Matsushiro earthquake swarm, *Kagaku Asahi,* **10**: 127–133 (in Japanese).

Niigata Prefectural Government, 1977, Geological Map of Niigata Prefecture.

Oki, Y., O. Sato and S. Aoki, 1992, The earthquake and landslide generated by the geopressured hydrothermal system in the Northern Fossa Magna Region, *Earth Monthly,* **5**: 121–125 (in Japanese).

Research Group for Active Faults of Japan, 1991, Active faults of Japan, University of Tokyo Press, 438 pp (in Japanese).

Roberts, S.J. and J.A. Nunn, 1996, Expulsion of abnormally pressured fluids along faults, *J. Geophys. Res.,* **101**: 28231–28252.

Sakai, S., S. Hashimoto, M. Kobayashi, K. Sakai, T. Haneda,

T. Urabe and S. Tsukada, 1995, Aftershock distribution of the 1995 Niigata-ken Hokubu earthquake, *Earth Monthly,* **17**: 779–783 (in Japanese).

Sato, O., 1981, The chemical composition of ground water in landslide areas 1 The Mushigane and Takakura areas in Niigata Prefecture, *Ann. Rep. Saigai-ken, Niigata Univ.,* **No. 3**: 47–58 (in Japanese with English abstract).

Sato, O., 1982, The chemical composition of ground water in landslide areas 2 The Nigorisawa and Kamibaba areas in Niigata Prefecture, *Ann. Rep. Saigai-ken, Niigata Univ.,* **No. 4**: 77–85 (in Japanese with English abstract).

Shiroishi, K., 1972, Troubles in drilling in the Niigata oil field, *Journal of the Petroleum Technology Society of Japan,* **37**, 338–339 (in Japanese).

Tronin, A.A., 1996, Satellite thermal survey — a new tool for the study of seismoactive regions, *Int. J. Remote Sensing,* **17**, No. 8: 1439–1455.

Tronin, A.A., 1999, Satellite Survey Application for Earthquake Prediction, Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes, Ed. M. Hayakawa, *TERRAPUB,* 717–746.

Tronin, A.A., M. Hayakawa and O.A. Molchanov, 2002, Thermal IR satellite data application for earthquake research in Japan and China, *Journal of Geodynamics,* **33**: 519–534.

Tsukuda, T., 1995, On the possibility of a forthcoming large earthquake in Niigata Plain region, *Earth Monthly,* **17**: 789–796 (in Japanese).

Tsukuda, T., 1997, Sizes and some features of luminous sources associated with the 1995 Hyogo-ken Nanbu earthquake, *J. Phys. Earth,* **45**: 73–82.

Tsukuda, T., 2002, Precursory phenomena for the 2000 Tottori-ken Seibu Earthquake and the 2001 Geiyo Earthquake, *Earth Monthly,* **S38**: 228–238 (in Japanese).

Tsukuda T. and H. Kamikubo, 2004, Deep groundwater discharge and ground surface phenomena — Repeated anomalous water temperature rises at wells in the Tokai and Kanto areas —, *PROGRAMME and ABSTRACTS, THE SEISMOLOGICAL SOCIETY OF JAPAN,* A40 (in Japannese).

Tsukuda T. and H. Kamikubo, 2005, Deep groundwater discharge and ground surface phenomena — Sudden water temperature rises at a shallow well in the Tokai area —, *PROGRAMME and ABSTRACTS, THE SEISMOLOGICAL SOCIETY OF JAPAN,* A007 (in Japanese).

Yamaguchi Prefectural Government, 1976, Geological Map of Yamaguchi Prefecture.

Yoshida, S., K. Koketsu, B. Shibazaki, T. Sagiya, T. Kato and Y.Yoshida, 1996, Joint inversion of near- and far-field waveforms and geodetic data for the rupture process of the 1995 Kobe earthquake, *J. Phys. Earth,* **44**: 437–454.

Xu, H. and Y. Oki, 1998, Personal communication.

Xu, H., Y. Oki and T. Ito, 1998, The 1995 Northern Niigata Earthquake with special attention to a geopressured hydrothermal system, *The Island Arc,* **7**: 647–659.

(Received July 8, 2005)
(Accepted March 20, 2006)