as temperature, atmospheric pressure, or rainfall. The temperature of the ground water is very stable and its variation was less than 0.2°C during the observation period. The response of radon concentration to atmospheric pressure is also negligible (9). There was no heavy rainfall from the summer of 1994 to the spring of 1995 (*10*).

A fault has been recognized in the subsurface about 500 m west of the observation well. The fault was identified in layers deeper than about 8 m from the surface. It is not certain whether this fault ruptured during the earthquake. However, the anomalous increase in radon concentration near the fault may suggest that there was some strain around this fault. Because it is difficult to explain such a large radon increase by mixing of ground water, it may reflect formation of microcracks in the aquifer system. The sudden radon decrease 1 week before the earthquake may be attributable to some sealing of microcracks. Convergence of strain along the forthcoming earthquake fault might have caused strain release at places off the fault line before its rupture.

Since the earthquake, the radon concentration has been rather stable at a low level. However, some irregular variations have been observed, which we interpret as an indication that the strain release by the main shock was not complete and that some accumulation and release of strain have still continued in the region.

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8. The radon monitoring system consists of a radon detection chamber, a 256-channel high-speed analog-to-digital converter (AD), and a personal computer. Ground water is continuously introduced into a detection chamber with a flow rate of about 1 liter/min. Radon dissolved in ground water is degassed to the gas phase in the chamber. A container of electrostatic collector is mounted just above the interface between the gas and liquid phases in the chamber. The container is equipped with an α-particle detector of a PIN photodiode (Hamamatsu Photonics K. K.) with a surface area of 1 cm^2. Because a static voltage of −120 V is applied between the PIN photodiode and the bottom of the container, positive ions in the gas phase are collected on the surface of the PIN photodiode. The α particles emitted mainly by the decays of ^{214}Po and ^{218}Po (daughters of ^{222}Rn) are detected as electric currents through the PIN photodiode. The electric currents are amplified and then digitized with the AD converter, which is controlled by a Z80 microcomputer system. The data of the α-particle counting are transmitted to a personal computer once per hour and stored in a floppy disk.
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10. Since 21 October 1994, we have monitored radon concentration at a shallower well, 4 m deep, drilled about 1 m from the 17-m-deep well. The shallower well taps the shallowest major aquifer in the region, whose radon concentration is expected to be influenced more easily by rainfall, but there was no notable radon change related to rainfall during the observation period. Above all, the shallower well did not show radon increase before the Kobe earthquake. The anomalous radon increase was detected only at the 17-m-deep well, which taps the second-shallowest major aquifer.

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Precursory Chemical Changes in Ground Water: Kobe Earthquake, Japan

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Chloride (Cl^-) and sulfate (SO_4^{2-}) ion concentrations of ground water issuing from two wells located near the epicenter of the Kobe earthquake in Japan fluctuated before the disastrous magnitude 7.2 event on 17 January 1995. The samples measured were pumped ground water packed in bottles and distributed in the domestic market as drinking water from 1993 to April 1995. Analytical results demonstrate that Cl^- and SO_4^{2-} concentrations increased steadily from August 1994 to just before the earthquake. Water sampled after the earthquake showed much higher Cl^- and SO_4^{2-} concentrations. The precursory changes in chemical composition may reflect the preparation stage of a large earthquake.

A destructive magnitude (M) 7.2 earthquake (*1*) occurred at 05:46 on 17 January 1995 (Japanese standard time) in the Kansai district near Kobe, Japan (Fig. 1). The focal mechanism of the earthquake was a quadrant type with the maximum compression axis in an east-west direction. A distinct 9-km rupture appeared along the preexisting right lateral Nojima fault, which strikes northeast in Awaji Island. Maximum displacement was about 1.7 m horizontally and about 1.3 m vertically (*2*). The distribution of the aftershock area coincided well with the earthquake fault region (*3*).

A striking feature of the earthquake was the variation in ground-water flow. After the earthquake, increased ground-water discharge was observed in many parts of the aftershock region. Increases were seen in river flow, reservoir levels, and water temperature. In addition, Kyoto University reported an unusual increase in the discharge rate of ground water in a tunnel of the Rokko-Takao Station for crustal movement observation that began more than 2 months before the main shock (*3*). The rate increased by about 7% from early November 1994 and suddenly by 1000% after the earthquake, even though this period is typically a season of low precipitation and the total rainfall in 1994 was low. Here we report geochemical evidence of precursory ground-water changes observed near the epicentral region, recorded in commercial bottled drinking water.

Many chemical and hydrological changes are reported to have occurred before past large earthquakes. One of the best examples is a sudden hot-spring eruption observed several months before the 1923 Great Kanto earthquake (M 7.9) in the epicentral region (*4*). Geochemical monitoring of ground water may provide useful information for earthquake prediction.

Shortly after the Kobe earthquake, we started collecting ground-water samples from Kobe in order to investigate possible changes in ground water. We collected commercial bottled water with as many different bottling dates as possible. The granitic Rokko mountains rising behind Kobe City are known to produce high-quality mineral water mainly used in the brewing of Sake and as drinking water. One of the water sources is at the ROK site, located about 20 km east of the epicenter (Fig. 1). Ground water pumped from two 100-m-deep wells is passed through a microfilter (0.2 μm), sealed in polyethylene terephthalate bottles, and distributed on the market. The chemical composition of the ground water is bicarbonate [~70 parts per million (ppm)], chloride (~14 ppm), sulfate (~14 ppm), nitrate (~10 ppm), calcium (~24 ppm), and sodium (~15 ppm). This bottled water has the merit of providing samples with known dates.

We collected a total of 72 water bottles, including 59 bottles with different dates

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ranging from 5 June 1993 to 13 January 1995. The longest storage period before analysis was 580 days. In addition, we collected 11 sets of duplicate water samples with the same date to examine the homogeneity of same-day water. Dissolved Cl^- and SO_4^{2-} in samples were measured with an ion chromatograph. Chloride and sulfate are major anions in water samples and are relatively stable during storage compared with other anions, cations, and dissolved gas components. We measured the same running standard after each sample analysis to enhance the precision of the measurement. The precision is estimated to be less than 0.3% by repeated measurement of the same sample, and the accuracy is estimated to be about 3% on the basis of standard sample measurements. The dispersion of Cl^- concentration in the 11 sample sets is 0.2% on average and 0.8% at maximum. This implies that heterogeneity from differences in the bottling process and storage environment is small, less than 1% of Cl^- concentration.

From June 1993 to July 1994, Cl^- concentrations of water samples were almost constant (Fig. 2) at 13.9 ppm with a 1σ variation of 1.6%. This value may be regarded as the background Cl^- level of the ground water. Judging from the distribution of background data, annual changes, including rainfall (precipitation is about four times greater during summer than during winter), seem to be negligible. This indicates that precipitation variation may not result in Cl^- concentration variation. Beginning in August 1994, however, the Cl^- concentration gradually increased, with some fluctuations, and reached the highest preearthquake level on 13 January, 4 days before the earthquake (the 13 January sample was the nearest sample to the earthquake available). The Cl^- concentration was about 10% higher than the average background value.

In the wake of the disaster and disruption of normal life in the city, the distribution of bottled water was interrupted and the pumping rate of the ROK wells changed after the earthquake. Water samples with 17 different dates (from 25 January to 4 April 1995) were separately taken from two wells. The average Cl^- concentrations of water from two wells are plotted in Fig. 2. The Cl^- concentration reached the highest level at the end of February and began to decrease in the middle of March 1995.

The observed temporal Cl^- variations cannot be attributed to storage conditions, including dissolution or absorption processes or evaporation of water in the bottle. The Cl^- ion is chemically stable, and the concentration is also sufficiently high. Evaporation of water from the bottle is difficult to assume. The observed Cl^- variations are highly likely to reflect actual changes in ground-water composition at the ROK site.

Judging from the linear relation between Cl^- and SO_4^{2-} (Fig. 3), changes in the SO_4^{2-} concentration resemble those of Cl^- . The observed dispersion may reflect the chemical reactivity of SO_4^{2-} in biogenic and abiogenic processes mainly in the stratum.

Chemical changes observed before the earthquake can be attributed to the introduction of ground water enriched in Cl^- and SO_4^{2-} to the artesian layer of the ROK wells. There is no principal source of Cl^- and SO_4^{2-} in shallow strata beneath the Kobe area, which is mainly composed of granitic rocks. High concentrations of Cl^- and SO_4^{2-} are common features of ground water issuing through the fracture zone near the Rokko mountains (5, 6). The observed rise in concentration after the earthquake is consistent with a 10-fold increase in the discharge rate of ground water at the Rokko-Takao Station (3). Such changes of groundwater flow may occur by a change either in regional tectonic stress or in permeability resulting from microcrack formation in rocks before and after the earthquake.

The observed ground-water anomaly was corroborated by some other observations. A striking similarity with our chemical results is found at the data of a multicomponent borehole strainmeter (7, 8), installed at the Rokko-Takao Station and operated by Kyoto University. The observatory is about 5 km

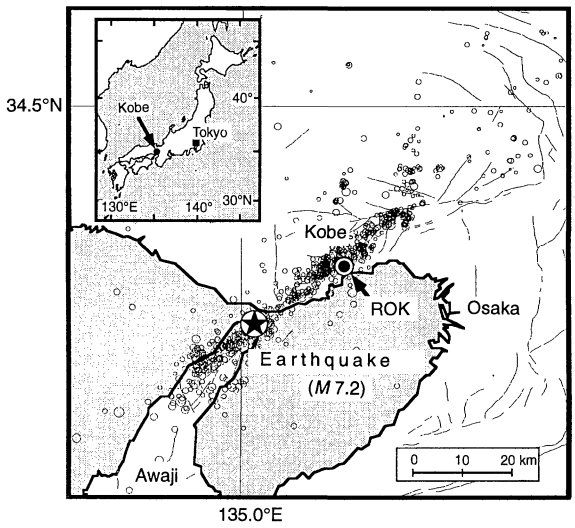

Fig. 1. Location of the ROK well relative to the epicenter of the 1995 Hyogoken-Nanbu (Kobe) earthquake and active fault systems (*10*). [The original map including the main shock and aftershocks is courtesy of Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University.]

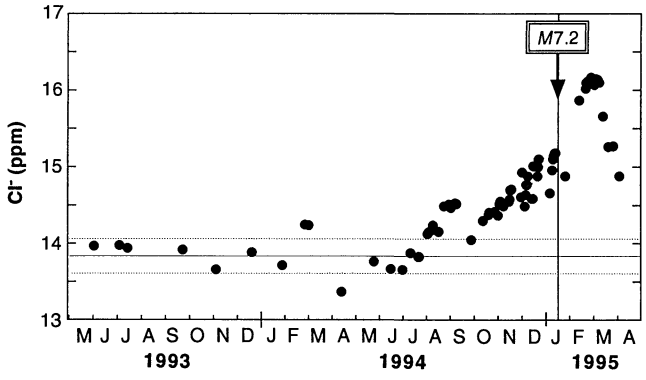

Fig. 2. Temporal variation of the Cl^- concentration in ground water before and after the Kobe earthquake at the ROK site. The average Cl^- concentration (solid line) and 1σ variation range (dashed line) during the background period (June 1993 to July 1994) are also shown.

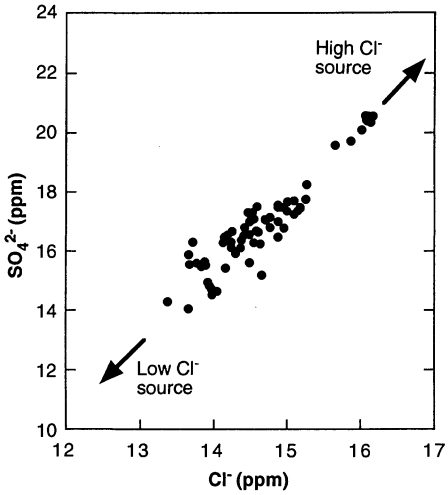

Fig. 3. Correlation between the Cl^- and SO_4^{2-} concentrations of ground water at the ROK site. The correlation coefficient is 0.94.

from the ROK site at a depth of 240 m in Rokko granite, which contains many active faults. A drastic change in both the N99°E (ST1) and N21°W (ST3) components started in August 1994 and reached an extension of 6.2 and 2.8 μstrain (a part per million deformation), respectively. The coseismic strain step direction is consistent with strain and stress fields of the region, showing N71°W compression (−7.1 μstrain) and N19°E extension (3.4 μstrain) (3).

Another piece of supporting evidence is the continuous record of radon concentration in ground water at a well about 10 km east of ROK, where the radon concentration gradually increased from the beginning of the measurement in October 1994 until its peak on 8 January 1995. It returned suddenly to the previous low level just before the main shock (9). These results indicate that ground-water observations can provide useful information on the earthquake formation process and clues for predicting inland earthquakes.

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Dissecting Amazonian Biodiversity

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Biogeographical and biodiversity studies in lowland Amazonian rain forests typically refer to observed or postulated distribution barriers such as past unfavorable climates, mountains, rivers, and river floodplains that divide the uniform tierra firme (noninundated) forest. Present-day ecological heterogeneity within tierra firme has hardly been discussed in this context, although edaphic differences are known to affect species distribution patterns in both inundated areas and tierra firme. Quantification of landscape heterogeneity in Peruvian lowland Amazonia (500,000 kilometers squared), based on field studies and satellite image analysis, shows that Peruvian Amazonia is considerably more heterogeneous than previously reported. These observations have implications for the research, management, and conservation of Amazonian biodiversity.

Amazonian lowland rain forests are celebrated for their high α-diversity or species richness within habitats (*1–4*), whereas γ- or regional diversity reported by floristic checklists (*5*) is surprisingly low. The recognition of only a few vegetation types (*6*) and the limited interest in β- or between-habitats diversity (*1*, *2*, *4*, *7*, *8*) have contributed to a general impression of wide-scale homogeneity. We surveyed the extent of habitat heterogeneity at different spatial scales in the tropical lowland rain forests of Peruvian Amazonia; the terms "habitat" and "biotope" are here used for units that seem reasonably uniform at the scale of observation without implying that they are homogeneous at more detailed scales.

Species distribution patterns of Pteridophytes and Melastomataceae were studied in tierra firme along continuous transects at the local (10 to 10^3 m) and landscape (10^3 to 10^5 m) levels. At the local scale (Fig. 1), habitat differences correlated sometimes with canopy openings but more often and more clearly with topography. Within each transect in the field (0.25 to 0.65 ha), many species showed a distinct preference for either the moister valleys or the drier hills. Spatially separate, recurring species associations were hence found, with the greatest local diversity generally being found in the valleys. At the landscape level (Fig. 2), each transect represented a different biotope, as shown by the leveling-off of the species-area curves and the low percentage of species shared among transects (Fig. 2, B and C). Tree data collected along six of the transects (0.16 ha per site, minimum stem diameter 2.5 cm) showed the same floristic relationships (Fig. 2D); the correlation between the similarity matrices based on Pteridophytes and Melastomataceae on the one hand, and on trees on the other, was 0.91 (Mantel test) (*9*). The observed floristic patterns could not be explained by geographical distances or geomorphology, but they correlated with topsoil properties (Fig. 2E). This suggests that the overall patterns in species composition are to a large extent edaphically controlled and therefore to some degree predictable.

The color patterns visible in satellite images are determined by the physical properties of the vegetation and soil and can therefore be used to identify different vegetation formations. Patterns shown by satellite imagery in the area we selected for detailed floristic studies were not especially pronounced as compared with patterns found elsewhere in Peruvian Amazonia (Fig. 3), but they nevertheless proved to reflect significant floristic differences. The transect on white sand soil (number 2) was expected to be floristically distinct, because the forest has a characteristic structure (*6*), but the differences among the structurally more similar forests of the other sites could only be anticipated because of their dissimilar spectral reflectances in satellite images (Landsat MSS and TM) (*10*) (Fig. 2). Also in other parts of Peruvian Amazonia, visual analysis of satellite images revealed numerous structurally and floristically distinct biotopes within the vegetation types already known. We have verified these patterns by field analysis throughout our study area (Fig. 3B); our most distant study sites were about 1200 km apart. Structural characteristics of the vegetation were documented along 2000 km of river, and during low-altitude flights over 4000 km of forest (*10–12*). Quantitative floristic data were obtained at 16 sites in tierra firme (46 square plots totaling 2.1 ha, 8 transects totaling 7.8 km) (*2*, *13*) and along 8 river systems in inundated areas (17 transects totaling 6.5 km) (*11*, *14*). No evidence of

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