polar motion (1). As an initial check to determine whether earthquakes have a discernible effect on the motion of the pole at the time of the earthquake, we plotted the times of all earthquakes of magnitude 7.0 (Richter scale) or larger that occurred in 1984 (7). The magnitudes of the earthquakes (Table 1) were calculated from surface-wave measurements. No significant changes in the motion of the pole are seen near the time of these quakes. Only the first earthquake in Table 1 was as large as magnitude 7.5, and it occurred in the middle of one of the smoothest parts of the pole path (Fig. 1). If earthquakes of this magnitude do not produce effects discernible with the subdecimeter accuracy of these determinations, then it seems unlikely that such effects would be found in the older, optically determined series whose accuracy is an order of magnitude poorer (8). Continued monitoring of the pole position with subdecimeter accuracy should eventually produce a series that overlaps a sufficient number of large earthquakes so that we can definitively characterize the relations of such quakes to the motions of the pole.

The smooth changes in the motion of the pole have a character similar to the atmosphere-dominated variations in the length of day; for example, there are broad, flat extrema with sharp peaks in winter and summer (5). There is considerable disagreement on the question of whether meteorological excitation is sufficient to cause the observed polar motion. Barnes and coworkers (9) have argued that most of the polar motion can be explained in terms of meteorological effects, whereas Wahr (10) has claimed that meteorological effects are too small to excite all the observed polar motions. Resolution of the question of the excitation of the pole will depend on continued high-accuracy monitoring of the pole position coupled with improved atmosphere sensing.

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25 April 1985; accepted 26 July 1985

Geochemical Indicator of Tectonic Stress Resulting in an Earthquake in Central Japan, 1984

Abstract. *Conspicuous changes in gas composition were observed at a fumarole and a mineral spring just before the occurrence of an inland earthquake (magnitude, 6.8) in central Japan in September 1984; the fumarole and spring were 9 and 50 kilometers, respectively, from the earthquake's epicenter. Deep-seated fluids emitted as a result of the compressional stress of the earth tide had been observed previously at this mineral spring and at a lava lake in Hawaii. By analogy, the gas anomaly observed before the earthquake in Japan probably resulted from deep-seated fluids being squeezed to the surface by the tectonic stress that caused the earthquake.*

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An inland earthquake (magnitude, 6.8; focal depth, 3.8 km), called the western Nagano prefecture earthquake, occurred in central Japan on 14 September 1984 (Fig. 1). Although this earthquake occurred in a sparsely populated, mountainous region, it resulted in 29 deaths. Five years earlier, on 28 October 1979, the Ontake volcano (Fig. 1) suddenly began to erupt on its southwestern flank near the summit, forming several new craters. Up to that time, the volcano had been believed to be dormant, and any precursory signs for the eruption such as seismic activity had not been observed, although weak geothermal activities had been detected around it.

The craters formed from the Ontake eruption were 9 km northwest of the epicenter of the Nagano prefecture earthquake. We have been analyzing volcanic gases from one of these craters at least once a year since the Ontake eruption and, for the purpose of predicting earthquakes, have been testing subsurface gases at several locations in central Japan. Gas bubbles from mineral springs have been analyzed four times a day by means of gas chromatography at our field laboratories (1). When we started the project, an earthquake of the magnitude experienced in 1984 had never occurred in this region. Our observations revealed a conspicuous gas anomaly at a fumarole and a mineral spring (epicentral distance, 9 and 50 km, respectively) just before the event. Because this anomaly probably occurred as a result of stress changes that gave rise to the earthquake, it can be considered a precursor event.

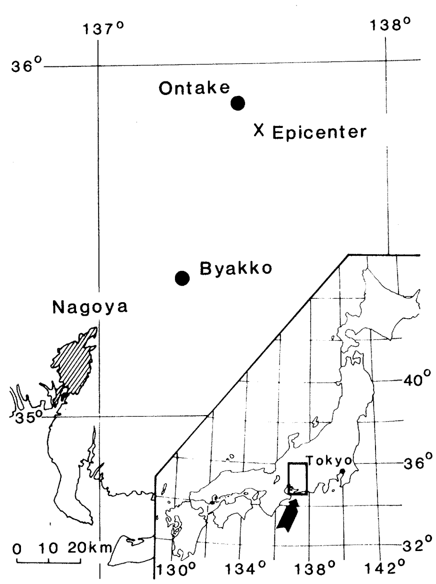

Fig. 1. Location and index maps showing observation sites (Byakko Spa and the Ontake volcano) and the epicenter of the western Nagano prefecture earthquake, 1984.

The He : Ar and CH_4 : Ar ratios as well as H_2 concentrations in subsurface gases have been proposed as useful geochemical indicators for earthquake prediction (2–5). Figure 2 shows the variation of these parameters in bubble gases from the mineral spring at Byakko (Fig. 1), the monitoring station nearest to the epicenter. Both He : Ar and CH_4 : Ar ratios had been increasing with small fluctuations until March 1984 and dropped abruptly in July 1984. They showed a minimum value at the beginning of August 1984. About 40 days later, the earthquake occurred.

At Byakko, Sugisaki (3) had previously observed a regular, cyclic variation in the He : Ar ratio that was caused by the earth tide. The gas analyzed at this station was characterized by a high He : Ar ratio and was dissolved in deep-seated waters of the mineral spring, which were then squeezed out of fissures under the tidal compression. Subsequent observations showed that the CH_4 : Ar ratio fluctuated synchronously with the He : Ar ratio (3). If deep-seated gases are similarly squeezed out by stresses preceding an earthquake (3), then the temporal varia-

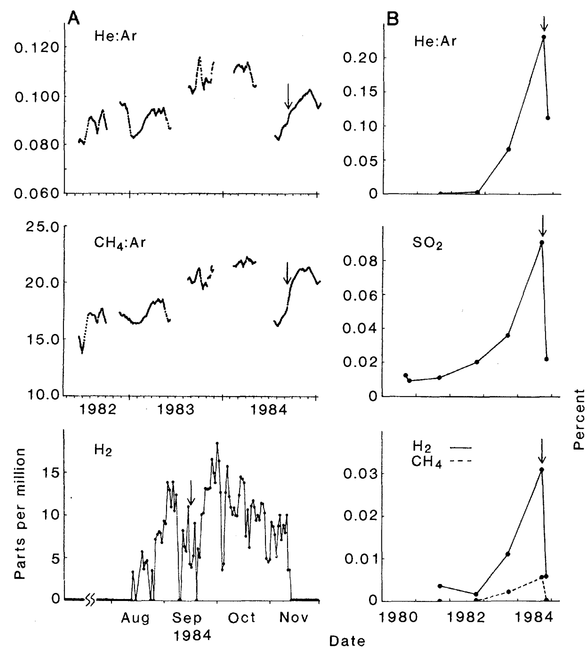

Fig. 2. Temporal variation of gas quality in bubbles at (A) the mineral spring at Byakko and (B) the fumarole on Ontake. Arrows indicate the occurrence time of the earthquake. Mineral spring gases were analyzed automatically and by gas chromatography (*1*). H_2 was detected by the integrator only during this period. The mineral spring gases were measured four times a day, and the average of the four measurements was considered the value for the day. The original data sequence was smoothed by 15-term moving averages according to the standard statistical method. When the data gap exceeded 5 days, the moving average was cut off at each end of the data sequence (the long data gaps after 1982 and the lack of extensive sequential data before 1981 were due to equipment failure). Although measurements at Byakko started in 1979, CH_4 was not detected before 1981 because of the limits of the chromatograph. The volcanic gases were collected once every summer except for 1984. Volcanic gases were analyzed by gas chromatography for H_2, He, CH_4, and Ar content (*1*) and were chemically analyzed for SO_2 content (*13*) (H_2, CH_4, He, and Ar concentrations were not determined for 1980 because of equipment failure; SO_2 concentrations were determined from condensed volcanic gas). Errors in determinations of volcanic gas composition were at most 10 percent, so that the temporal increase can be considered anomalous.

tion of tectonic stresses operating at Byakko can be represented by the curve in Fig. 2. There have been alternative hypotheses pertaining to processes at the focal region (*6*). One of these hypotheses, represented by a dilatancy model in which extensive pore-fluid diffusion is not important, asserts that an earthquake occurs after a stress drop; that is, the main earthquake occurs at considerably lower stress than the maximum stress prior to the event (*7*). The behavior of the He : Ar and CH_4 : Ar ratios at Byakko may reflect such a process.

Emission of H_2 was also detected at Byakko (Fig. 2). For almost 5 years before the earthquake, H_2 had not been detected in subsurface gases by our gas chromatograph, which had a determination limit of about 3 parts per million. H_2 began to appear in bubbles on 12 August 1984 and reached a peak on 4 September 1984. The main shock occurred 10 days later. H_2 emission continued during the period of aftershocks, and the concentration of H_2 showed another peak on 28 September. After 10 November, H_2 emission disappeared as the aftershocks diminished. Measurements made at another monitoring station (a mineral spring at Yuya) showed that the periods of increased H_2 emission coincided with occurrences of nearby earthquake swarms (*4*). Because active faults associated with historical earthquakes usually expel large amounts of H_2 (*8*), this evidence, together with the results of laboratory experiments (*8*), implies that H_2 was produced by the reaction between ground water and rock fractured during seismic activity (*4*). Thus H_2 has a unique origin with respect to the other gases considered here. H_2 began to appear in bubbles at Byakko when the ratios of He : Ar and CH_4 : Ar were minimum, so that its emission seems to have an important bearing on short-term earthquake prediction.

Because the earthquake occurred close to the fumarole on Ontake, the premonitory change in gas composition, if present there, would be expected to be pronounced. Concentrations of SO_2, H_2, CH_4, HCl, and HF and the He : Ar ratio gradually increased after the 1979 Ontake eruption (Fig. 2). The concentrations of these gases increased sharply on 7 September 1984, 1 week before the Nagano earthquake, and dropped sharply 50 days later. These gases are characteristic of high-temperature volcanic emissions; therefore this observation indicates that the rate of discharge of deep-seated gas was enhanced before the event.

More than 60 years ago, Jagger (*9*) observed fluctuations in the level of Halemaumau lava lake in Kilauea, Hawaii. Using theoretical arguments, Shimozuru (*10*) concluded that the observed semidiurnal tides of the lava lake had been caused by the squeezing out and draining back of magma through the conduit as a result of a volume change of the magma reservoir due to the earth tide. The observation by Jagger and the interpretation by Shimozuru for the level fluctuations in the lava lake at Hawaii are essentially the same as those for the compositional fluctuations of gas bubbles at Byakko, because the tidal process is responsible for both phenomena. By analogy, we suggest that the strain near the focal region of the Nagano prefecture earthquake enhanced the discharge rate of deep volcanic gases. However, the temporal relation between the compositional change of gases and the occurrence of the event was not accurately determined because of the long intervals between measurements.

Monitoring of seismic activity and crustal deformation at many sites in central Japan did not reveal premonitory phenomena for the earthquake (*11, 12*). The geochemical observations, however, monitored the behavior of pore fluids under changes of pore pressure to gauge strains on the crust. Because the deep fluid is collected from a large region under the ground into a vent such as the fumarole and the mineral spring, geochemical changes in fluids at such vents may be clear premonitory signals. Although our results may not be applicable in all geologic settings, networks of telemetered gas monitors at suitable stations may be useful for predicting the location, magnitude, and time of a possible earthquake.

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14. We thank T. Ooida, F. Yamazaki, K. Yamamoto, K. Taki, and A. Kamijo for technical assistance.

8 April 1985; accepted 25 June 1985