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Earthquake Effect on the Geological Environment

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Background

The islands of Japan are located in the Circum-Pacific Seismic Zone, an area with one of the highest earthquake occurrence rates in the world. This situation provides the opportunity to study the change of geological environment due to earthquake motion, if such changes occur. The Kamaishi *In Situ* Test Site is a very practical place to collect 3-dimensional geological data because of its existing gallery of shafts and drifts and other infrastructure.

This short report briefly provides the up-to-date results gained over the last 9-years through monitoring earthquake motion and analysis of the expected effects.

Objectives

The objectives of the study at the Kamaishi Site were as follows:

- To characterize the change of acceleration amplitude with depth caused by earthquakes
- To understand the relationship between earthquakes and changes in the deep geological environment such as water pressure, groundwater chemistry and rock mass strain in the crystalline rock

Methodology

The observation apparatus installed at various locations are shown in Figure 1. Acceleration caused by earthquakes (K-1 - K-4), changes in water pressure (KWP-1 - 3) and rock-mass strain data have been measured simultaneously (Figure 2).

1) Location of seismometers
Seven seismometers have been installed (*see* Figure 1).

K-1 : ground surface (el. 865 m drift)
K-7 : ground surface (el. 725 m drift)
K-5 : underground, about 150 m below the surface (el. 725 m drift)
K-2 / K-3 / K-4 :underground, about 300 m below the surface (el. 550 m drift)
K-6 : underground, about 700 m below the surface (el. 250 m drift)

Sampling points K-1 / K-5 / K-2 / K-6 form a vertical array from the surface to a depth of 700 m. Sampling points K-2 / K-3 / K-4 provide a horizontal array, which in conjunction with the vertical array, was used to monitor changes in the geological environment.

2) Groundwater monitoring
Changes in water pressure, discharge rate of inflow and groundwater chemistry have been measured for 6 years between 1992 to 1997.

- Water pressure: Three boreholes (KWP-1 / KWP-2 / KWP-3; *see* Figure 1) have been used to identify the exact changes of water pressure in the deep geological environment caused by earthquakes.
- Total volume of groundwater inflow: The total volume of groundwater inflow had been measured at KO-10.
- Groundwater chemistry: Groundwater chemistry of inflow at the drift wall at KO-10 were also analyzed for physical-chemical characteristics (electric conductivity and pH) and groundwater composition (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, SiO_2).

3) Strain of rock mass
A crystal pipe extensometer was installed at the end of the el. 550 m NE drift in order to measure the change of rock mass strain.

Results and Discussion

1) Seismometry
A series of 344 earthquakes were monitored at or near the ground surface between February 1990 to March 1998. Among these, 73 earthquakes were registered at the deepest seismometer (K-6, about -700m from the surface).

The largest earthquake, named "Eastward offshore of Hokkaido Earthquake", occurred at 22:23 on October 4, 1996 and was a magnitude 8.1. The maximum acceleration was 36.94 gal at the ground surface K-1 E-W. The maximum detected acceleration was 57.14 gal (K-1, N-S) for the earthquake named "North coast of Iwate Earthquake" which had a magnitude of 4.4 and occurred at 9:37 on June 5, 1996.

Measurements made during 64 of these earthquakes confirmed that the acceleration amplitude is greatly reduced with measurements were recorded by all four seismometers in the vertical array, K-1 (surface), K-5 (-150m), K-2 (-300m) and K-6 (-700m). The N-S and Z (vertical) component of amplitude was reduced in between 1/2 - 1/4, and the E-W ingredient was reduced to between 1/2 - 1/3 of the maximum amplitude (Figure 3) (Shimizu *et al.*, 1996).

2) Influence for groundwater
Water pressure measurements have been conducted within three boreholes named KWP-1, 2, 3 (end of the el. 550 m NW drift, *see* Figure 1).

Water pressure changes were recorded for 27 earthquakes (Figure 4). The biggest change was -0.35 kgf/cm^2 at KWP-2 for the "Sanriku-Haruka Earthquake" (at 21:19 on December 28, 1994, M7.5). Most changes were, however, less than 0.1 kgf/cm^2. The magnitude of water pressure change caused earthquakes usually is smaller than the changes that occur due to rainfall in this area. Also it was shown that the change of water pressure that occurred during earthquakes usually returned to the same general trend existing before the earthquake within a period of several weeks after the earthquake (Shimizu *et al.*, 1996; Ishimaru *et al.*, 1996; Ishimaru and Shimizu, 1997) (Figure 5).

There is no clear correlation between changes in water pressure and the level of maximum acceleration amplitude. On the other hand, the possible correlation between quantity of theoretical strain (Dobrovolsky *et al.*, 1979; Okada, 1995) and changes in water pressure was briefly identified (Figure 6). The water pressure changes for three boreholes - before / after earthquake are shown in Figure 4 (Shimizu *et al.*, 1996; Ishimaru *et al.*, 1996; Ishimaru and Shimizu, 1997).

The discharge of inflow water from the drift roof at KO-10 was measured, however there were no observable changes associated with earthquakes during the observation period.

The electric conductivity and groundwater pH were monitored at KO-10, along with chemical composition before and after earthquakes using the Auto Continuous Water Sampler (ACWS) system. No change of electric conductivity or pH from before to after earthquakes was recognized during the entire monitoring period. The ACWS functioned properly, providing groundwater composition for four of 14 cases. The results suggested the possibility that there is a change in SO_4^{2-} and HCO_3^- during a short period of several hours after each earthquake (Figure 7) (Shimizu *et al.*, 1996).

3) Rock mass strain
The extensometer can detect the strain of rock mass on to the order of 10^{-8} to 10^{-9} degrees. This level of accuracy has been shown by detecting earthquakes that occurred a long distance from Japan, for example at the Fiji Islands, Chile and Peru.

The extensometer is also capable of detecting the dynamic strain of the rock mass. In the case of the "Offshore Miyagi Earthquake" (October 11, 1997, M5.1), which by the way changed the water pressure, the remaining strain of about 2.5×10^{-9} degrees was recorded following the earthquake (Figure 8).

Concluding Remarks

The reduction characteristic of ground motion caused by earthquakes of underground was confirmed in San-Andreas Fault area. And it could be understood that this phenomenon not only happened in Kamaishi, but in general. The water pressure changes caused by earthquakes also happened generally, but it could not be made clear enough that the basic process that causes the water pressure to change as a result of earthquakes. For the understanding of this phenomenon, the shorter step observation data set (less than 1 second) of water pressure is needed. It is epoch-making to observe earthquake, water pressure and rock mass strain simultaneously.

Acknowledgment

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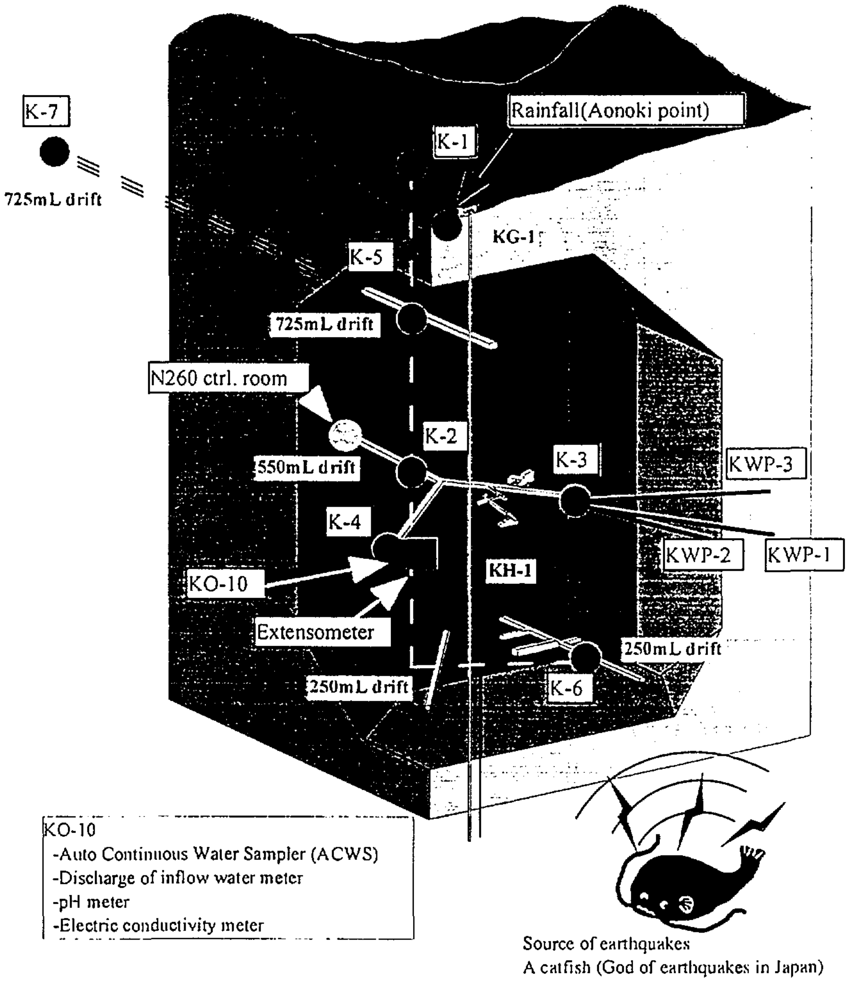

Figure 1 The location of observation machineries at Kamaishi mine

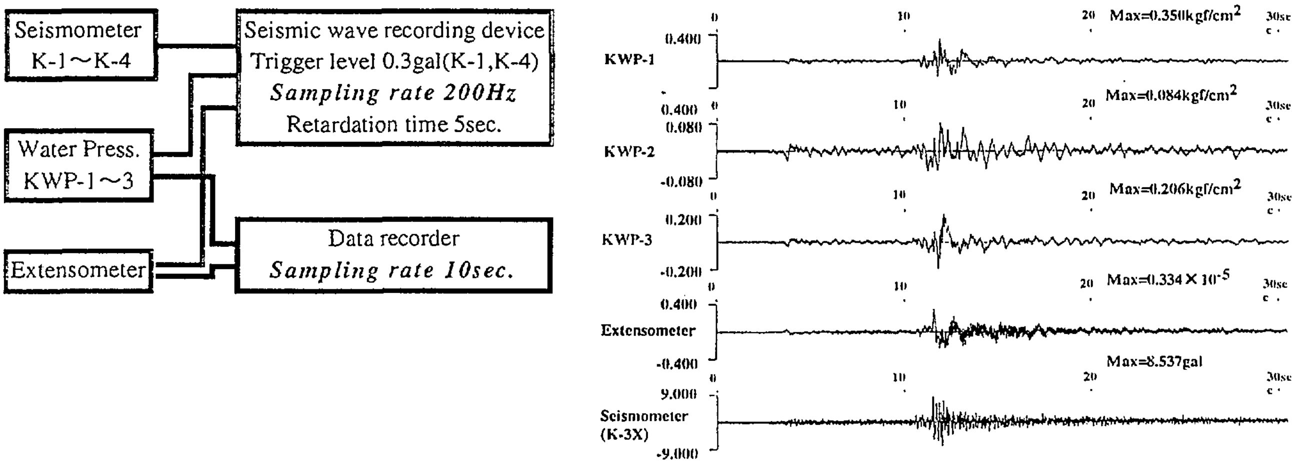

Figure 2 Data recording system of seismic wave, water pressure and rock strain and the example that were recorded with seismic wave recording device

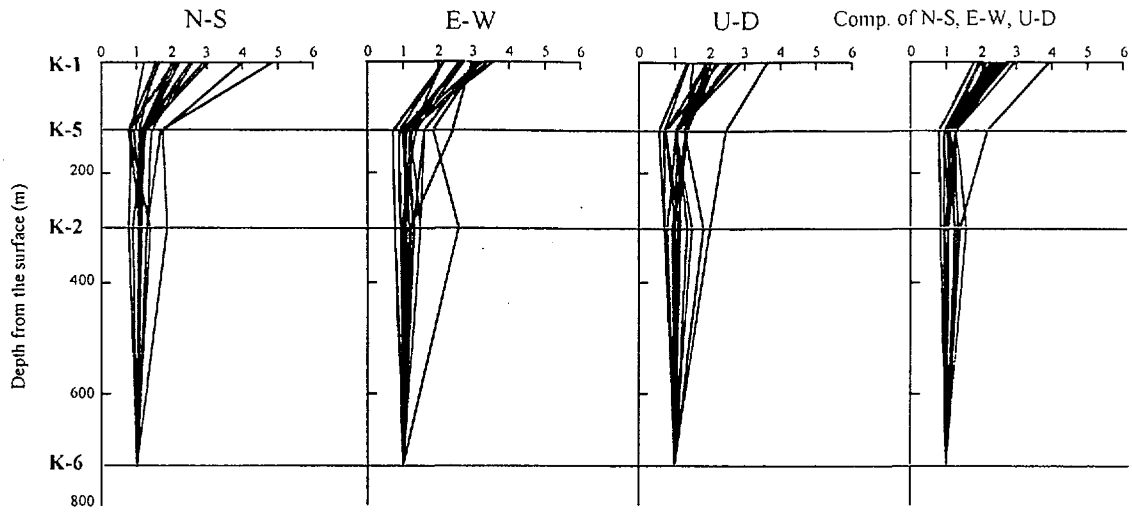

Figure 3 Reduction profile of the amplitude of maximum accelaration
Maximum amplitude of K-6 calculate as 1

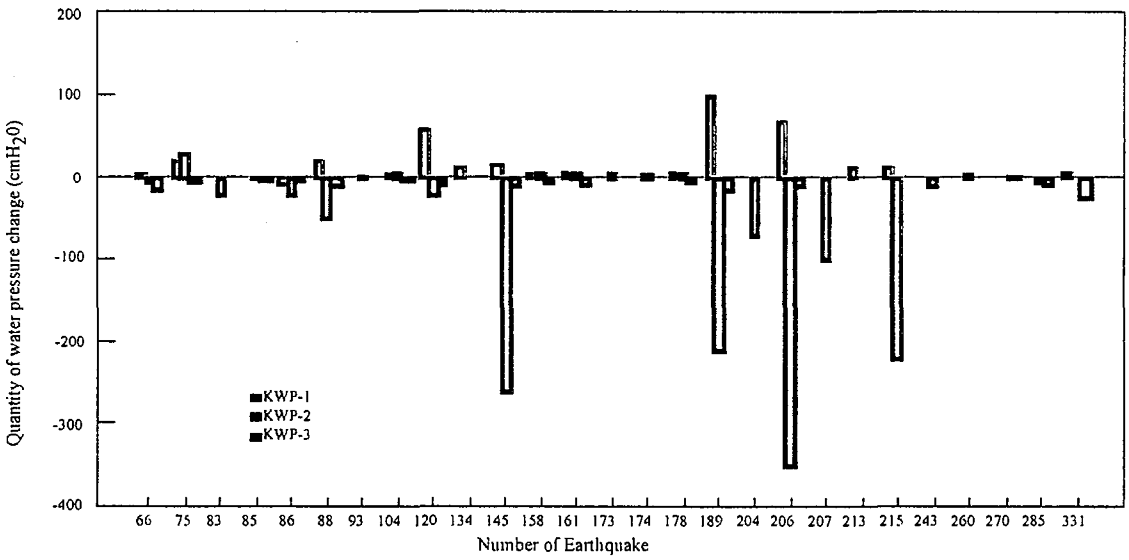

Figure 4 The earthquakes related to the water pressure change at the Kamaishi site

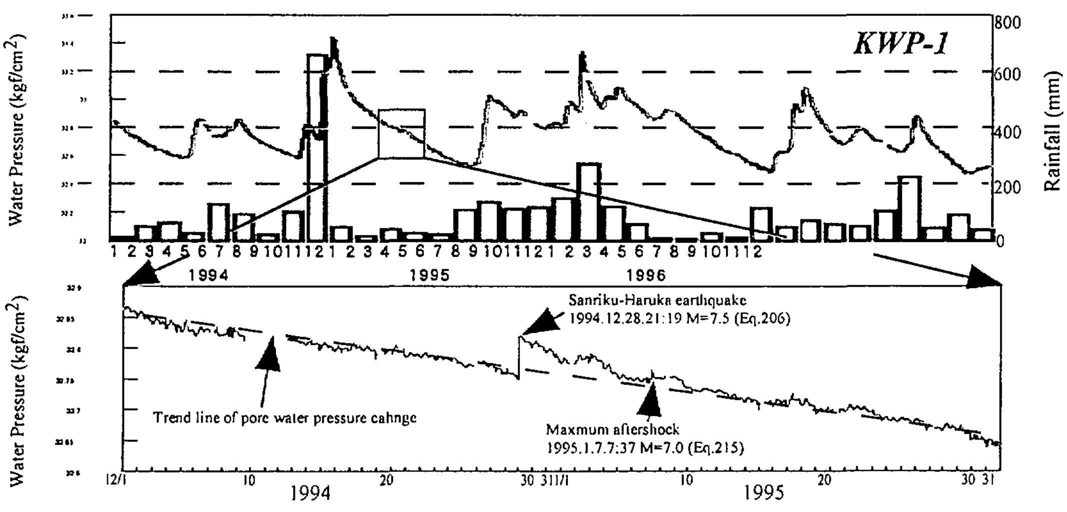

Figure 5 Changes of water pressure (KWP-1) due to Sanriku-Haruka earthquake in 1994

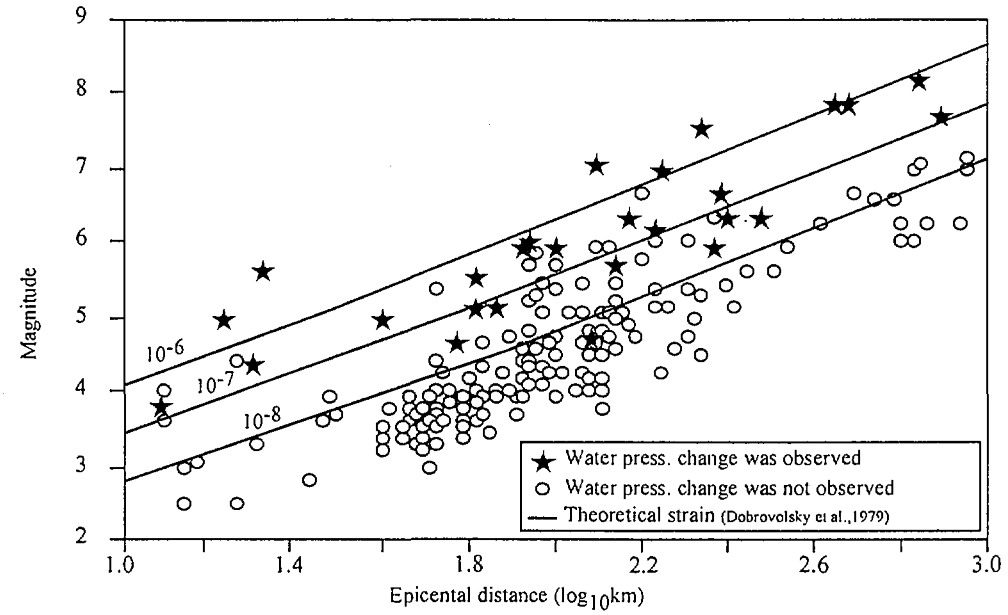

Figure 6 The relationship between epicental distance - magnitude - theoretical strain

Change of water pressure can be seen by the earthquake which has more than10^{-8} of theoretical strain.

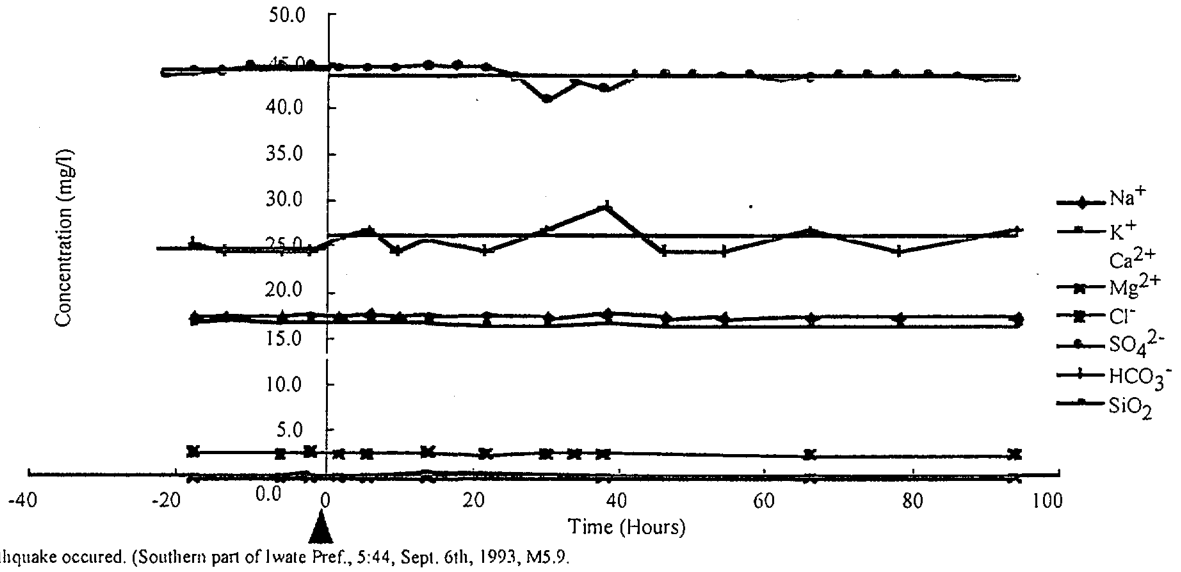

Figure 7 Changes of the groundwater composition (KO-10, *see* Figure 1) after the earthquake (1995, M5.9)

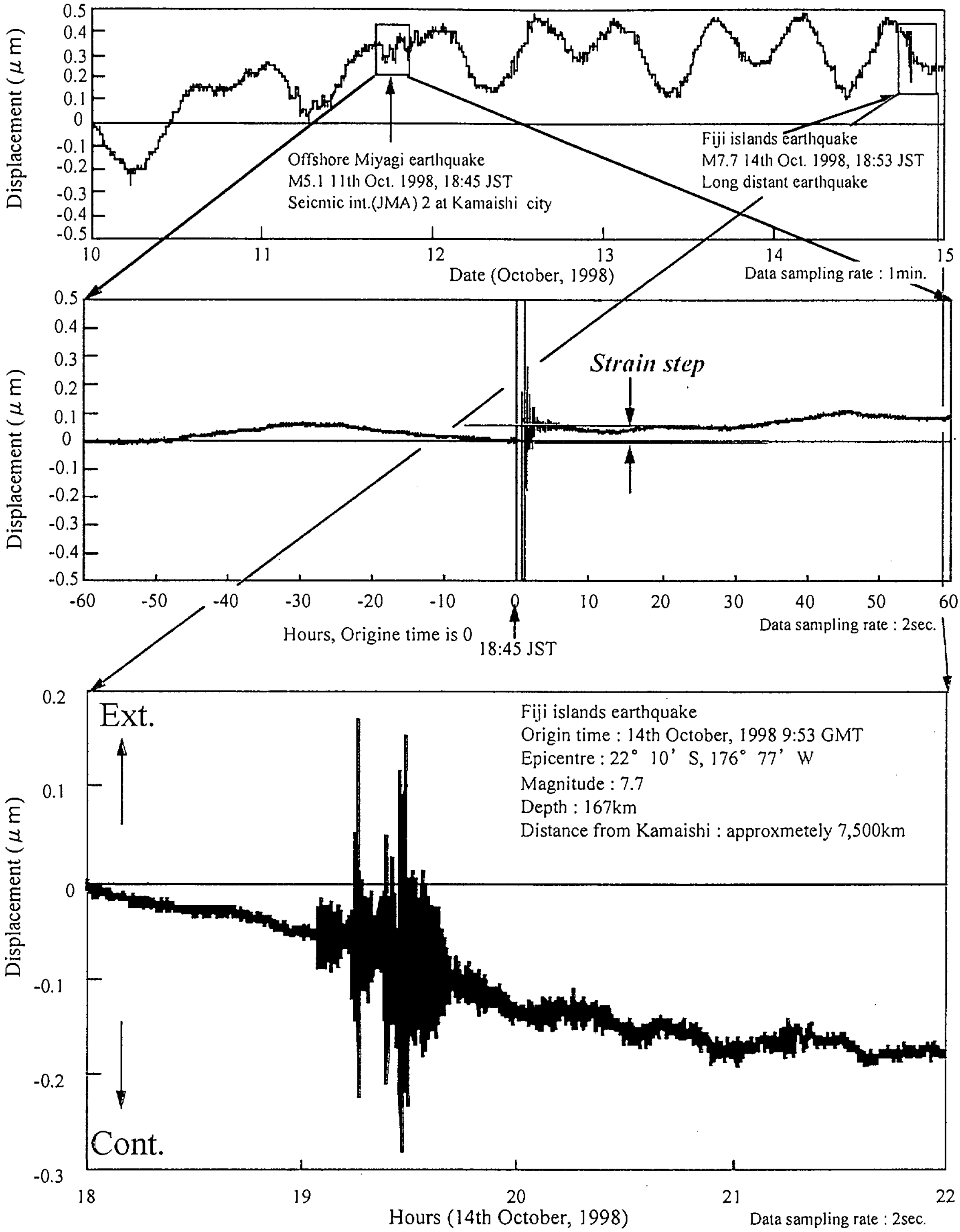

Figure 8 An example of strain change

The accuracy of extensometer installed in Kamaishi site is quite sensitive (detect strain up to the order of 10^{-8} to10^{-9}) to be able to detect the effects of the long distant earthquake such as Fiji Islands Earthquake. Extensometer was also able to record the dynamic strain. When the pore water pressure changed by the Offshore of Miyagi earthquake (11 October 1997, M5.1), the remaining strain of about 2.5×10^{-9} degree was observed after the earthquake.