Stepwise Variations of Strain Observed by Two Strainmeters Installed in Nearby Boreholes in a Fracture Zone

by

Sumio Yoshikawa, Takeshi Koizumi and Itsuo Furuya

Meteorological Research Institute, Tsukuba, Ibaraki, 305 Japan

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Abstract

Stepwise variations of strain (hereafter called the strain step) were observed by a couple of borehole strainmeters installed 30 meters apart in a fracture zone of the southern Fossa Magna. Strain changes for a year after the installation carried at December, 1986—January, 1987 were apparent expansion indicating the cooling of grout and the relaxation of stress concentrated around the strainmeter. For two years after the installation the number of the strain steps decreased gradually. No clear relationships are seen between the occurrence of strain steps and the environmental conditions such as the rainfall, the atmospheric pressure, the groundwater temperature, and the groundwater level. The strain steps that occurred in the two boreholes are independent, which means that the spatial extent of the phenomenon is less than the distance between the strainmeters. The amplitude-frequency relationship for the strain steps is analogous to those of fracture processes such as earthquakes and acoustic emission in rocks. The decrease in the number of strain steps with time is represented by a formula similar to Ohmori's for the aftershock sequences of earthquakes. A laboratory experiment showed that the frequency of strain step occurrence depends on the stress levels in the surrounding media. Consequently it is inferred that the strain steps observed by our strainmeters are caused by local fracturing processes around the boreholes, the number of which indicates relaxation of the initial stress induced by the installation of the strainmeters.

1. Introduction

Sacks-Evertson borehole strainmeters (Sacks *et al.*, 1971) have been used since 1976 in the Japan Meteorological Agency's (JMA) routine observation. They have contributed to monitoring the strain changes associated with seismic and volcanic events in the Tokai and the southern Kanto district of Japan (e.g., Suyehiro, 1987). We started our strain measurement in 1987 using two identical strainmeters of

this type. Our observation site is located in a fracture zone of the Fossa Magna (Fig. 1), one of the largest tectonic lines in Japan. In such a fracture zone the ground surrounding an observation site does not always act as a perfect elastic body and the output from a strainmeter sometimes shows stepwise changes at irregular intervals (Yoshikawa, 1987).

In this observation we aimed to observe these stepwise strain changes in detail, which are called 'strain steps' in this paper. These strain changes have been frequently observed at the JMA stations equipped with the same type

Fig. 1 Location of Yui, the volumetric strainmeter station, which is in a fracture zone of the Fossa Magna, one of the largest tectonic lines in Japan.

strainmeter and the relationship between the strain steps and the seismic and volcanic activities in the adjacent areas has been often pointed out (e.g., Sawada *et al.*, 1984). However, the sources of the strain steps have never been sufficiently discussed. To disclose the sources of the strain steps, fundamental characteristics of the strain steps and the behavior of the strainmeters should be investigated from various points of view together with the simultaneous measurement of environmental conditions such as the atmospheric pressure, the rainfall, the groundwater temperature, the groundwater level, *etc.*

We show in the following the behaviors of strainmeters and the characteristics of strain steps according to our observation, and discuss the physical meaning of the strain steps. The results of the laboratory experiments with the strainmeters are also discussed.

2. Method

The site of observation is located at Yui, about 140 km southwest of Tokyo, as shown in

Fig. 1. The site is in the fracture zone of the southern Fossa Magna. Figure 2 shows the general geological setting adjacent to the observation site. The fracture zone belongs to the Iriyama Fault System with a reverse dip-slip component inclined to the west, having a strike from north to south, with a length of 10km (The Research Group for Active Faults, 1991). The Kambara gravel bed of the Quaternary spreads on the east side of the fault. The ground around the observation site is mainly composed of sandy mudstone on the west side of the fault, where the Hamaishidake formation of the last Tertiary is widely distributed. A couple of strainmeters of identical make are installed at a depth of 50 meters in different boreholes which are 30 meters apart. Such close emplacement will help us to find out whether the strain changes occur locally or not. Figure 3 shows a schematical cross section of strainmeters in the boreholes. The conditions of the ground around the two boreholes are almost the same but differ in gravel content and the level of groundwater. For observations of level and temperature of groundwater a

Fig. 2 Map of the area adjacent to Yui station. The fracture zone belongs to the Iriyama fault system. To the west of the fault spreads sandy mudstone of Hamaishidake formation, and to the east the Kambara gravel bed is dominant. Insert shows a detailed map around the observation site, which shows an echelon type fault array.

strainer is made near the level of groundwater layer in each of the two wells.

The strainmeters used in this measurement are of the same type as that used in the JMA (e.g., Suyehiro, 1978). Installation of the sensor unit, which is the underground part of the strainmeter, was done in the same way as in the JMA stations (Nihei *et al.*, 1987). The body of the strain sensor, which contains silicon oil, is a cylinder made of a thin stainless steel of 3mm thick, 114mm in outer diameter, and approximately 3.8 meters long (see Fig. 16). The deformation of the cylinder caused by the stress changes of the ground is transformed into the level change of the silicon oil. The displacement of the elastic bellows due to the level change of the silicon oil is detected by the 'differential transformer', the equipment for transforming displacement into electric output.

As a result, the output of the strainmeter is proportional to the total volume change of the inside of the cylinder (Sacks *et al.*, 1971). The strainmeter has an automatic valve opening mechanism as a fail-safe device, which operates when the displacement of the bellows exceeds a certain threshold level (e.g., Suyehiro, 1978).

The sensor unit is fixed by the expansive grout to make a tight contact with the ground. The grout generates an appreciable amount of heat by chemical reaction when it hardens. The thermal expansion of the oil is as large as $10^{-3}/^{\circ}\text{C}$, which greatly affects the output of the strainmeter. To study the behavior of the strain sensor in the setting process, we started the observation immediately after the installation.

The strainmeters have dual output of the long-period (LP) and the short-period (SP)

Fig. 3 Vertical section of the volumetric strain-meter observation wells. Sensors of the strainmeters were installed at a depth of 50 meters and fixed by the expansive grout (mortar) to make the contact tight with the ground.

components. The LP component is the output filtered through periods longer than ten seconds, and the SP component is the output filtered through periods from ten seconds to hours. In general, changes in the crustal strain contain the effects of the atmospheric pressure, the rainfall, and the level and temperature of the groundwater. These environmental data are simultaneously obtained with the output of the strainmeter every minute.

3. Strain changes observed in the Long-Period component

Changes in strain immediately after installation

The strain changes recorded immediately after the installation are shown in Fig. 4. For the LP component of each strainmeter, the strain shows a large contraction over 10^{-4} , and then changes to expansion within a half day. Though we did not measure the temperature inside the strain sensors at this stage, it is not to

be doubted that the thermal expansion of the silicon oil due to the heat generated in the expansive grout caused the apparent contraction. For several hours after the installation, the hardening grout is not strong enough to maintain the stress in itself. Most of the contraction is not of mechanical origin but is the effect of heating. The change from contraction to expansion is observed on the completion of heat generation. Many spikes in the SP component with the same amplitude, 2.2×10^{-6} , are due to automatic valve opening, the frequency of which is proportional to the apparent strain rate.

Changes in strain during one year after installation

Figure 5 shows the strain records in the period from February to December in 1987. Both LP components show large expansion until early May when the rates of expansion ceases. Similar behavior was observed at the JMA Ohshima strainmeter station, where the observation of strain and borehole bottom temperature started a month after the installation and large expansion was observed from the beginning (Nihei *et al.*, 1987). In the early stage of the operation of the strainmeter, two effects are dominant in the strain changes. One is the apparent expansion associated with cooling of the grout and the silicon oil, as pointed out by Nihei *et al.* (1987). The other is the relaxation of the stress that is concentrated around the boreholes during the drilling and of the internal stress that remained in the grout (Sacks *et al.*, 1971).

Response to the atmospheric pressure

The variations of LP components ceased in a half year after the beginning of the observation. The responses of the Yui strainmeters to the atmospheric pressure is investigated for the period from April to July in 1987. The raw data are filtered through the band from thirty to eighty hours to eliminate the effect of the daily changes and long-term trends. The correlation between the output of LP components and the atmospheric pressure is appreciably low when the strain steps frequently occur. The average

Fig. 4 Strain records after the installation of both strainmeters. 'I' indicates the installation of each strainmeter. 'A' indicates an artificial change, and the other spikes, the amplitudes of which become equally -2.2×10^{-6} , show the changes associated with automatic valve openings. DC offsets in the LP component records associated with valve openings are corrected.

values of the atmospheric pressure coefficients (the rate of the strain change to the atmospheric pressure change) are $1.9 \times 10^{-8}/\text{mb}$ and $2.5 \times 10^{-8}/\text{mb}$ for No.1 and No.2 strainmeter, respectively, with the correlation coefficient larger than 0.95. These values are somewhat larger than those obtained for the 31 strainmeter stations of the Tokai and the southern Kanto district (Hikawa *et al.*, 1983). As pointed out by

Furuya and Hikawa (1983) and Yoshikawa (1987), the ground is relatively soft at the sites where the atmospheric pressure coefficient is large. The Yui observation site is in the fracture zone and the depth of the strain sensor is as shallow as fifty meters. The values of the atmospheric pressure coefficients reflect the low stiffness of the ground.

Fig. 5 Records of strain, atmospheric pressure and rainfall from February to December in 1987. The impulsive changes seen in early September was caused by a power breakdown.

Relation to groundwater and rainfall

Figure 6 shows the records of strain, groundwater level and groundwater temperature together with the atmospheric pressure and the rainfall for about one year from November 1987. The stable water level in No.1 well is due to the overflow of water from its top. The water level in No.2 well changes slowly within

the range of five millimeters. There is no clear response to the atmospheric pressure. Some correspondences between water level and rainfall are seen.

No remarkable changes in the water temperature can be seen except for a daily change in No.1 well, but a variation not larger than 0.02°C occurs in No.2 well. Many tempera-

Fig. 6 Records of strain, groundwater temperature, and groundwater level, in each well for one year from November 1987. The atmospheric pressure and rainfall are also shown below.

ture spikes are seen in No.2 well in early 1988. The times of occurrence of these spikes and their durations are different from those of the strain steps. The relations of these spikes to the water level and to the rainfall are not clear. Mechanical or electrical malfunction cannot be eliminated as a possible cause. The origins of these phenomena are not known at present and

further observation is necessary for their elucidation. The correlation is very weak between the changes in strain and groundwater temperature.

When the rain falls, contractive changes of the same amount are observed simultaneously in both of strainmeters. The temporal change in strain is related to the rate of precipitation.

These strain changes are different from the strain steps shown below and are easily distinguished from them.

4. Strain steps

The stepwise strain changes began to appear several hours after the installation. As shown in Fig. 5, such strain step has an impulsive shape in the SP component. The amplitudes of these pulses are mostly in the range from 10^{-8} to 10^{-7} on the SP record and their polarities are negative, *i.e.*, contractive in the volumetric strain. Figure 7 shows the variations of LP- and SP-components for the first forty-eight hours of every three weeks. As the trend in the LP record becomes stationary, the number of the strain steps decrease gradually. The total number of their occurrences exceeds one thousand for two years in a strainmeter. We analyze the strain steps here by reading the profiles of such features as duration, maximum amplitude, rise time, *etc.* The SP record is used for the analysis, since those quantities are hard to read with accuracy on the LP record which includes long-term trends.

Shape of strain step

Figure 8 shows three typical patterns of the strain step. Type A is characterized by a fast onset and a quick relaxation, type B by a slow onset and a slow relaxation, and type C by a successive occurrence of type A's or type B's. As seen in Fig. 7, the events of type C were frequently observed just after the installation of the strainmeter. To see the characteristics of the strain steps except for type C's, we first examine their relaxation times. The relaxation time is defined here as the duration from the onset to the completion of an event, which is normalized by the maximum amplitude of the strain step. Figure 9 shows the histograms of the relaxation time for the events which occurred from February, 1987 to December, 1988. There is no clear boundary which separates type A from type B. We set here $0.3 \text{ hours}/10^{-8}$ as the boundary value. In this figure, for example, if the maximum amplitude of the strain step is equal to 10^{-8} on the SP record, most of the strain steps complete within an hour and the mode value of the relaxation time for No.1 is about 0.2 to 0.3 hours, whereas that for No.2 is about 0.4 hours. The ratios of

Fig. 7 Records of the strain in the early stage of installation of the strainmeters for the first forty-eight hours of every three weeks. Numerals indicate the number of weeks that have elapsed after the installation of No. 1 and No. 2 strainmeters.

Fig. 8 Typical patterns of the strain steps. Left and right show LP- and SP-output, respectively.

Fig. 9 Distribution of relaxation time of strain steps observed by No. 1 and No. 2 strainmeters. Abscissa is the relaxation time normalized by amplitude.

Fig. 10 Distribution of rise time of strain steps observed by No. 1 and No. 2 strainmeters.

type A's to type B's are different between No.1 and No.2 strainmeters. Figure 10 shows the distribution of the rise time, which is defined here as the interval from the onset of the event to the time when the peak amplitude is reached. The dynamic characteristics of the strain step can be measured in terms of the rise time. In the figure, the mode value of the rise time of No.1 is 1-2 minutes and that of No.2 is 3-4 minutes. These rise times indicate that the strain step is a slow event as compared to the other fracture phenomena like earthquakes, rock bursts, *etc.* (e.g., Iio, 1986). The meaning of occurrence of this slow event will be considered in the discussion below (§ 6).

As shown above, the shapes of the strain steps differ between the couple of strainmeters. The question arises whether this difference is instrumental or phenomenal. Figure 11 shows the strain step recorded at the time of the earthquake that occurred off the East coast of Chiba Prefecture in December, 1987, the epicentral distance of which is about 220km. We see a clear difference in the forms of strain step observed by the two strainmeters for the same event. That is, the amplitude of the strain step

Fig. 11 Records of strain at the time of the earthquake off the East coast of Chiba Prefecture in December, 1987.

in No.1 is four times larger than that in No.2 and the forms of the strain steps in No.1 and No.2 belong to type A and type B, respectively. Hence the strain steps having different shapes in the two strainmeters can be ascribed to the difference of instrumental characteristics. Since the electrical and mechanical characteristics of these strainmeters are the same, the difference is certainly in the states of the surrounding media and/or in the coupling conditions between the sensors and the ground.

Sizes of phenomena

There are few strain steps observed simultaneously by the two strainmeters. The number of cases where simultaneous steps (within a minute) are observed is less than 1 percent of the total number of steps observed by the two strainmeters. Thus the spatial extent and the location of the sources for the strain step are mostly within the distance between the wells or the strainmeters, *i.e.*, 30m.

Figure 12 shows the amplitude-frequency

Fig. 12 Amplitude-frequency distribution of the strain steps observed by the borehole strainmeters at Yui. Open circles show the data on No. 1 and solid circles on No. 2, respectively.

distribution of the steps obtained from the SP component record (Yoshikawa *et al.*, 1988). The frequencies decrease monotonically with increase of the amplitudes of the strain steps for the two strainmeters. This tendency is similar to those for earthquake activity and acoustic emissions in rocks (e.g., Mogi, 1962a). The amplitude-frequency distribution is usually expressed by Ishimoto-Iida's relationship, $n(a)da = ka^{-m}da$, where $n(a)da$ is the number of events with recorded amplitudes of a to $a+da$, and k and m are the parameters (Ishimoto and Iida, 1939). When the number of events counted cumulatively, the relation can be represented as

$$N(a) = k / (m-1) \cdot a^{-(m-1)},$$

where $N(a)$ is the cumulative number and m is related to the b value by $b = m - 1$. In Fig. 12, the trend (the b value) of these plots for the linear portion is about 2 for both strainmeters.

Changes in frequency

The strain steps initially occurred frequently, then less frequently, and subsequently occurred only sporadically. Figure 13 shows the number of strain steps which occurred in

Fig. 13 Changes in the number of strain steps averaged for every one third of a month observed by the strainmeters at Yui. At the bottom is shown that of the earthquakes within 50km of the observation site with magnitudes equal to or larger than 3.0.

the period from February, 1987 to December, 1988. The changes in the number of strain steps do not correspond to the seismic activity in this region shown at the bottom of the figure. Figure 14 shows the number of strain steps in a logarithmic scale versus the logarithm of each lapse time (t) from the installation of the strain sensor. We see linear trends clearly in the plots for both strainmeters. The frequency of the strain steps, $n(t)$ at time t , can be represented by the modified Ohmori's formula (e.g. Utsu, 1957) as $n(t) = A/(t+c)^p$, where A , c , and p are parameters, in the same way as the aftershock sequences of earthquakes. It should be noted here that the linear trends (p value) are almost the same for both strainmeters. Mogi (1962b) suggested that the 'p' parameter in the earthquake aftershock sequences reflects the mechanical structure in the seismic region. If an analogy holds between the strain steps and the earthquake activity, this means that the surrounding media of the strainmeters have nearly the same mechanical structure.

Fig. 14 Changes in the daily number of the strain steps observed by the volumetric strainmeters at Yui. Numerals in the figure indicate values of the 'p' parameter in the modified Ohmori's formula.

5. Indoor experiment

In order to understand the occurrence of the strain steps more clearly, we refer to the results of the laboratory experiments (Yoshikawa and Koizumi, 1988). Figure 15 shows the whole experimental system, in which there is a loading frame for compression of a medium containing a miniature strain sensor. The loading frame is a box with the inner dimensions of $30\text{cm} \times 30\text{cm} \times 30\text{cm}$, which is filled with various granular materials as the matrix media. As the frame is compressed horizontally through a steel plate from the outside, the output from the strain sensor, the displacement of the plate, and the external load are measured. The strain sensor is shown in the right part of Fig. 16. The semi-conductor strain gauges are stuck to the inside wall of the hollow brass cylinder to measure the strain. The volumetric strainmeter in the borehole measures the whole volumetric change of the cylinder, but the experimental strain sensor is for the measurement of linear strain at a small

portion of the cylinder wall.

We could observe similar strain steps by the experimental strain sensor. In many cases, the strain step occurs in releasing the accumulated strain. Figure 17 shows the effect of the external stress on the occurrence of the strain steps. The strain steps occur more frequently as the horizontal and/or the vertical stress levels become higher. The steps occur more frequently when gravel is used as the media. The grain size of the gravel is less than five millimeters. It is relatively coarse and heterogeneous in contrast to the sand whose grain size is less than one millimeter. The more heterogeneous the structure of the medium is, the more strain steps occur. We see a linear frequency and amplitude relationship which can be represented by the Ishimoto-Iida's equation, as shown in Fig. 18. The b values are in the range from 1.8 to 2.2 in the experiment, which

Fig. 15 Schematic view of the experimental apparatus. The strain sensor is embedded in a box filled with various granular materials, such as sand and gravel. The sensor is compressed by the medium through a steel plate. Deformation of the media is measured by displacement of the plate. Output from these sensors was converted to digitals every second.

Fig. 16 Comparison of the strain sensors. The left one is the Sacks-Evertson type, and the right one is that used in the present experiment.

Fig. 17 Influences of stress level and grain size on occurrence of strain steps. Amplitudes of these traces are strain rates per second, which correspond to high frequency components in the strain records. Abscissa is the displacement of the plate in the loading frame, showing deformation of the medium. Numerals in the center show weight of the load on the medium, with an area of $30\text{cm} \times 30\text{cm}$ and a depth of 30cm .

Fig. 18 Amplitude-frequency distribution of strain steps observed in the laboratory experiment.

are close to the values obtained by the in situ strainmeters of Yui (Yoshikawa *et al.*, 1988). This statistical nature suggests that the strain steps occurring in the field and those recorded in the experiment have a common physical background.

6. Discussion

The results obtained from the analyses of the strain steps indicate that most of the strain steps observed by our strainmeters occur in very local regions around the strain sensor. Supposing that the source of the strain step is a fracture near the strain sensor, we can roughly estimate the dislocation and the radiated energy. There can be tensile and shear type fracture modes. In either case the released

energy (E) is proportional to $(\Delta u)^2$, when the dislocation is Δu . For simplicity, the details of the coupling conditions and the mechanical states around the strain sensors are neglected. The dislocation (Δu) can be estimated from

$$\Delta u = L\Delta\epsilon,$$

where L is the typical source size and $\Delta\epsilon$ is the magnitude of the strain step. If we assume L to be 10 meters ($10^7\mu\text{m}$) and that $\Delta\epsilon$ is 10^{-7} , Δu is $1\mu\text{m}$. Generally it is difficult to measure such a small displacement at a long distance by a seismometer, since the ground noise is usually greater than $1\mu\text{m}$. The released energy (E) can be represented as

$$E = k (\Delta\epsilon)^2 V,$$

where k is the elastic constant of the medium and V is the typical source volume. Substituting $k = 10^{12} \text{ dyn/cm}^2$, $\Delta\epsilon = 10^{-7}$ and $V = 10^9 \text{ cm}^3$ into the equation, we obtain the energy released by a strain step as

$$E \approx 10^7 \text{ (erg)}.$$

If this quantity is reduced to the earthquake magnitude (M) in Richter's scale,

$$M = (\log E - 11.8)/1.5 = -3.2.$$

The predominant period of an ordinary earthquake with the same energy is several milliseconds (Iio, 1986). As stated above, the typical rise time of the strain step is a few minutes, that is 100000 times longer than that of the corresponding earthquake. The rupture velocity (v) is estimated from the typical size of the source (L) and the typical rise time (T). Substituting $T = 100 \text{ sec}$ and $L = 10\text{m}$ into the equation $v = L/T$, we obtain 10 cm/sec as the rupture velocity. The strain step is quite a slow phenomenon. According to our observation by the seismometer with 4.5Hz characteristic frequency of velocity type, no event corresponding to the strain step could be detected, even when it was located in the neighborhood of the strain sensor. The low energy and the long period of the phenomenon are perhaps responsible for this.

Our laboratory experiment showed that the strain steps occur more frequently with the

increase of the applied stress. The strain steps occur when the stress is released by the sudden slips on the grain boundary of the medium or on the boundary of the grain and the strain sensor in the manner of frictional sliding or stick-slip. In the field an appreciable stress is concentrated by the installation of strainmeters. This initial stress remains in the ground and in the grout. The coupling between the sensor and the grout or the ground changes and the microcracks develop on the boundaries between them, since the rates of contraction and the elastic moduli are different among these materials. On these microcracks a shear dislocation can occur in the same way as in the laboratory experiment, which can be considered as the source of the strain step. The strainmeters installed at Yui are embedded in a heterogeneous medium in a fracture zone. In such a locality, the occurrence of a strain step can be accelerated by interaction with the ground.

The decrease in the number of strain steps is represented by the modified Ohmori's formula for aftershock sequences. The temporal change in the number of strain steps reflects the relaxation of the stress initially induced around the strain sensor. Another possibility cannot be denied that the microfracturing activity decreases even under a constant stress level, which is called a 'delayed fracture' (Mogi, 1962a). That is, the decrease in number does not always indicate stress reduction over a wide area but sometimes shows a process of stress-redistribution on a local scale. However, it is, at least, certain that the local stress around the sensor relaxes with time.

7. Summary

Strain changes for a year after the installation of the strainmeter indicate apparent expansion associated with the cooling of the grout and the relaxation of the stress concentrated around the borehole. For the period from February, 1987 to December, 1988, our observation on the strain steps are summarized as follows:

- 1) No clear relationships are seen between the

occurrence of the strain steps and the environmental conditions such as the rainfall, the atmospheric pressure, the groundwater temperature, and the groundwater level.

2) Spatial extent and distribution of strain step sources are within the order of the distance of the sensors, which means that the scale of the phenomenon is less than the distance between the strainmeters.

3) Amplitude-frequency relation holds in a way analogous to earthquakes and acoustic emissions in rocks.

4) Temporal changes of the occurrence of frequency of the strain step follow the modified Ohmori's formula on aftershock sequences of large earthquakes.

5) A laboratory experiment shows that the occurrence frequency of the strain steps are influenced by the stress levels in the surrounding media.

From these results, we conclude that the strain steps are caused by local fracturing processes around the boreholes where the initial stress had been induced by the installation of the strain sensors. The decrease in the frequency of the strain steps indicates relaxation of the initial stress caused around the sensors.

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近接距離に設置した2台の埋込式歪計で観測された歪ステップ

吉川澄夫・小泉岳司・古屋逸夫

南部フォッサマグナの破砕帯中に30 mの間隔で設置した2台の埋込式体積歪計による観測に基づいて歪ステップの調査を行った。設置直後から約1年間の長期的な歪変化は概してモルタルの冷却化による見かけの膨張と周囲の応力集中の緩和を示した。この間、歪ステップの発生頻度は徐々に減少した。歪ステップの発生と降雨、気圧変化、地下水位、そして地下水温のような環境条件との間に明瞭な関連性はない。2台の体積歪計で見られる歪ステップには相関がなく、その現象の規模は2本の体積歪計の設置間隔よりも小さいことが判る。歪ステップの振幅別頻度分布は地震や岩石のアコースティックエミッションで見られるものと類似しており、破壊過程が関与していることを示唆する。歪ステップの発生数の時間変化は余震系列と同様改良大森公式によって表現できる。室内実験では歪ステップの発生頻度が歪センサー周辺の媒質内の応力レベルに依存することが判った。以上の事から、体積歪計で観測される歪ステップはボアホール周辺の破壊過程で生じていると考えられ、その発生の推移は体積歪計の設置によって生じた初期応力の緩和過程を反映していると考えられる。