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55. *Occurrence of Micro-fracturing Shocks during Rock Deformation with a Special Reference to Activity of Earthquake Swarms.*

By Shozaburo NAGUMO,
Earthquake Research Institute
and
Kazuo HOSHINO,
Geological Survey of Japan.*

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1. Introduction

When one tries to relate genesis of earthquake swarm to any kinematical process, one must know the relation between occurrence of earthquake shocks and deformation of media.

In the pervious paper[1] which treats kinematics of earthquake swarms, it is assumed that the occurrence of small shocks in earthquake swarms is caused by plastic deformation of the media, and that the frequency of occurrence is proportional to the time rate of plastic deformation. In order to examine this assumption, a laboratory experiment was planned for rock deformation and failure. Namely, occurrence of micro-fracturing shock was observed simultaneously with stress$\sim$strain curve during tri-axial rock deformation test.

The occurrence of micro-fracturing shock has been studied by several investigators. Kishinouye[2] and Mogi[3] have reported strong correlation between the number of shocks and strain of the media. The research group for foundation bed rock in the Central Research Institute[4] has reported that micro-fracturing sound occurs from the early stage of deformations in the in-situ rock failure test at a foundation bed rock of large archdam. Sasaki et al.[5] has reported the stress dependency of

* Present address, Japan Petroleum Development Cooperation.

1) S. NAGUMO, *Bull. Earthq. Res. Inst.*, **44** (1966), 1623-1664.

2) F. KISHINOUYE, *Zisin* (i), **6** (1934), 25-31; *Bull. Earthq. Res. Inst.*, **15** (1937), 785-827.

3) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 125-173.

4) Central Research Institute of Electric Power Industry, Technical Laboratory, *Report, Civil engineering* 64004, (1964).

5) K. SASAKI et al., *The first interior symposium on rock mechanics* (1964), 78-87.

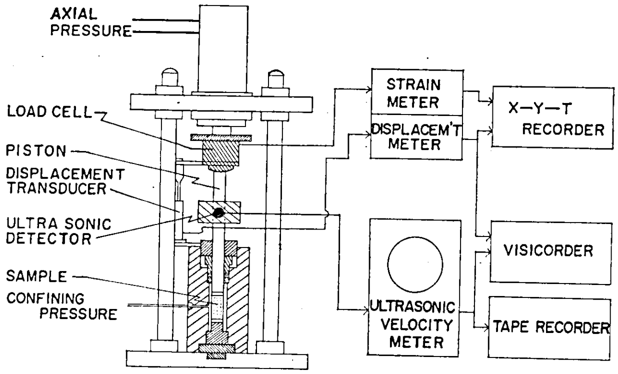

Fig. 1. Block diagram of instrument set up.

micro-fracturing shock. In order to advance these findings, special interest has been placed upon towards the strain dependency of micro-fracturing in our experiment.

Through experiment it has been found that the aspect of micro-fracturing occurrence is far more full of variety than hitherto expected. The occurrence of micro-fracturing shocks seems to depend upon the operational procedure—speed of loading. Even though the experiments are not as yet completed, since the results obtained so far are very interesting and suggestive for continuing further study of this kind of problem and also for understanding the activities of earthquake swarms, the data and tentative interpretations will be reported in this paper.

2. Experimental apparatus and rock specimen

In Fig. 1 is shown the block diagram of the experiment set up, which is a combination of the tri-axial high pressure rock deformation apparatus[6] and equipment for observation of micro-fracturing sound. The latter apparatus consists of ultra-sonic velocity measurement apparatus[7] and several recorders, such as magnetic tape recorder, visicorder. The ultrasonic receiver is a disc type barium-titanate transducer (30 mm in diameter, natural frequency 1MC/S), and is attached to the loading piston of the rock testing machine. The output of the amplifier in the ultrasonic velocity measurement apparatus is fed to the visicorder and magnetic FM tape recorder.

6) H. KOIDE and K. HOSHINO, "Development of Microfractures in Experimentally Deformed Rocks (Preliminary Report), *Zisin* (ii), **20** (1967), 85-97.

7) S. NAGUMO, *Bull. Geol. Survey of Japan*, **8** (1957), 517.

Frequency responses of the amplifier and the tape recorder are flat from 10KC/S to 2MC/S, and from 0 to 16KC/S respectively.

Rock specimen used in this experiment is taken from Kimyosan tuff in Matsushiro, Nagano prefecture.[8] The density, and elastic wave volocity of the sample is shown in Table 1.[9]

Table 1. Data of rock specimen.

rock	density		porosity	grain density	wave velocity	
	dry	wet			dry	wet
pyro-clastic tuff	2.37gr/cm^3	2.45gr/cm^3	7.76%	2.57gr/cm^3	4.50km/sec	4.36 km/sec

Rock specimen is cylinder type (19.5 mm in diameter, 39.0 mm in length), shielded with annealed copper jacket (0.02 mm in thickness), placed in the high pressure vessel. In the experiment, confining pressure is applied first, then axial compressional load is applied. The confining pressures are 500 bars for specimen VI-N9, and 1000 bars for VI-N8. The compressional load is manually controlled by hand pump so as to prevent the high sensitive observation system from any mechanical and electrical noises due to driving of motor. The stress$\sim$strain curve is recorded through load-cell and displacement meter by a X-Y-T pen-recorder. The output of displacement meter is fed in parallel to the visicorder, where micro-fracturing shocks are recorded simultaneously.

3. Experimental result

First let us describe the experimental result obtained under nearly constant loading speed. The confining pressure is held at 500 bars. The compressive load is applied so that the strain increases linearly with time. The strain rate is controlled at about 5×10^{-5} strain/sec before yield point and 1.7×10^{-4} strain/sec after yielding. Since the manual control of loading speed is adopted, we suffered from a few fluctuations of loading rate. In Fig. 2 are shown the curves of a cumulative number of micro-fracturing shocks (dotted line) and the strain (solid line) as a function of time.

8) K. HOSHINO and S. NAGUMO, "Experimental deformation of the rocks of Matsushiro Area (Report 1)," *Notes of Cooperative Research for Disaster Prevention*, No. 5 (1967), 41-47.

9) The measurement was made by Mr. Kazuo INAMI, Geological Survey of Japan.

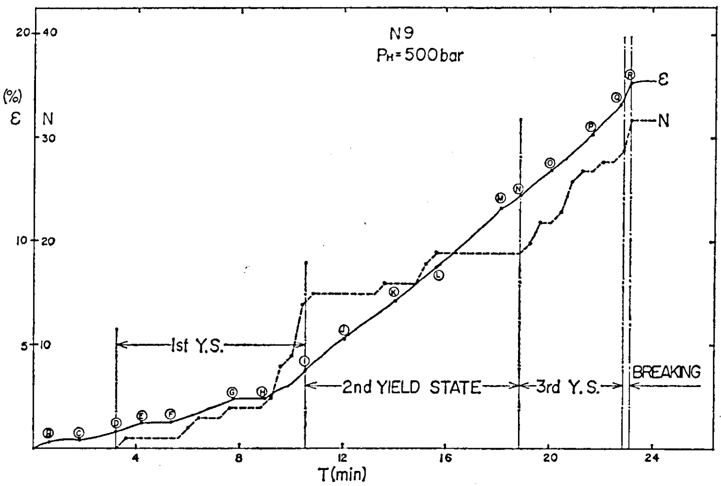

Fig. 2. The total strain ε (%) (solid line) and the cumulative number N of micro-fracturing shocks (dotted line) are plotted as a function of time. The confining pressure is 500 bar.

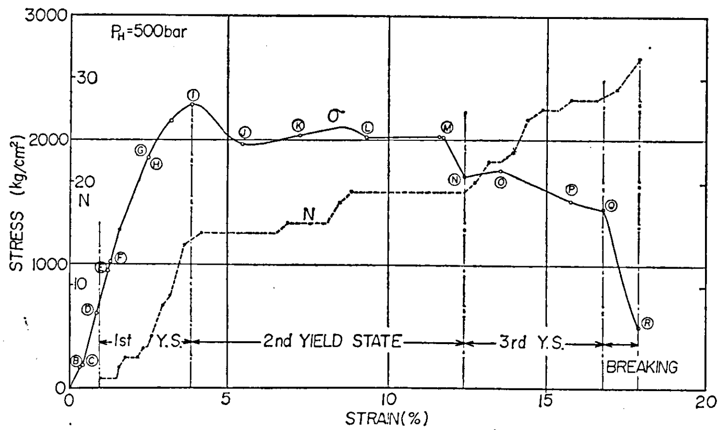

Fig. 3. The solid line presents stress~strain curve, and the dotted line presents cumulative shock number~strain curve. The confining pressure is 500 bar.

In the figure, the following characteristics will be noticed. (1) The micro-fracturing shocks occur from the early stage of deformation (from Ⓔ to Ⓗ) even before yield point. (2) The numbers of micro-fracturing shocks sharply increase at the stage from Ⓗ to Ⓘ. (3) Even though the strain increases very much at the stage from Ⓙ to Ⓝ, the increase of micro-fracturing shocks is small. (4) At the later stage from Ⓝ, the number of micro-fracturing shocks increases again.

As seen in the above characteristics, the occurrence of micro-fracturing shock which corresponds to strain increase is not simple, but seems to have several states. In order to examine the linear relation between the number of micro-fracturing shocks and strain, and the relation of deformation modes to the occurrence of micro-fracturing shock, both the stress∼strain curve and the cumulative number of micro-fracturing shocks are plotted in the same figure. In Fig. 3, the solid line represents stress∼strain curve, and the dotted line respresents shock number∼strain curve. The samll fluctuations on the stress∼strain curve are due to manual control of compressive load. On this representation, one can notice the following characteristics.

There seem to be three states in the process of micro-fracturing shock occurrence. The first state is from Ⓓ to Ⓘ in the stress∼strain curve of Fig. 3, and is characterized by an almost linear relation between strain and cumulative number of shocks. The second state is from Ⓘ to Ⓝ in the stress∼strain curve, and is characterized by little occurrence of micro-fracturing shocks for the development of strain. The third state is from Ⓝ to Ⓠ in the stress∼strain curve, and is characterized by another production of micro-fracturing shocks with increase of strain.

The linear relationship between the number of micro-fracturing shocks and strain seems to exist in the first and third states of deformation. As seen in the stress∼strain curve, the first state seems to correspond to the process of deformation which begins from the appearance of slight plastic deformations and continues to the state of ultimate strength, one of the macro-fracturing. The second state seems to follow the so-called yield point and to correspond to a state of quasi-stationary creep where external stress is being held nearly constant. The third state may correspond to the state of so-called strain-softening where external stress decreases with strain increase. In such manner, the production of micro-fracturing shocks relates closely to the progress of deformation.

Since the production of micro-fracture is an indication of plastic deformation, the classification of three states for micro-fracturing occurrence will correspond to the conditions of plastic deformation or yielding. Therefore, let us classify each state as yield state.

Next, let us describe the experimental result obtained under stepwise loading test. The confining pressure is held at 1000 bars. The compressive load is kept constant for several minutes at various stages of deformation.

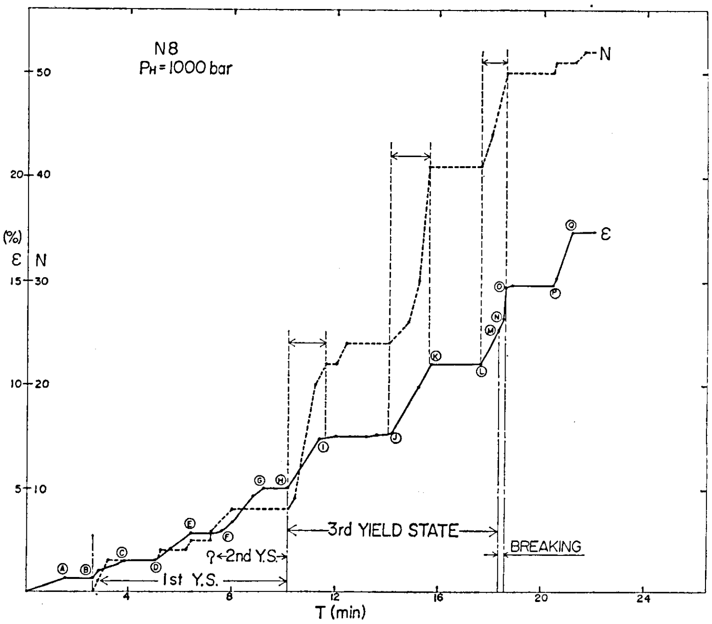

Fig. 4. The total strain $\varepsilon(\%)$ (solid line) and the cumulative number N of micro-fracturing shock (dotted line) are plotted as a function of time. The confining pressure is 1000 bar.

In Fig. 4 are shown the curves of a cumulative number of micro-fracturing shocks (dotted line) and strain (solid line) as a function of time. In Fig. 5 are shown stress$\sim$strain curve (solid line) and cumulative shock number$\sim$strain curve (dotted line). As seen in these figures, in the early stage of deformation (from Ⓑ to Ⓗ in the stress$\sim$strain curve), the occurrence of micro-fracturing shocks is not always proportional to the strain. In the later stage, however, one can clearly see the state where micro-fracturing shocks occur with development of strain and cease at the cassation of strain increase. The former appear from Ⓗ to Ⓘ, from Ⓙ to Ⓚ, and from Ⓛ to Ⓝ, the latter appears from Ⓘ to Ⓙ, from Ⓚ to Ⓛ, in Fig. 4. These states correspond to the states of general yielding in the stress$\sim$strain curve of Fig. 5.

In the range from Ⓗ to Ⓢ in Fig. 5, where creep phenomena are present, one can see an almost linear relationship between the number of micro-fracturing shocks and strain. The proportional constant seems to depend upon the strain rate. The effect of strain rate, however, should be studied further by a more elaborate experimental procedure.

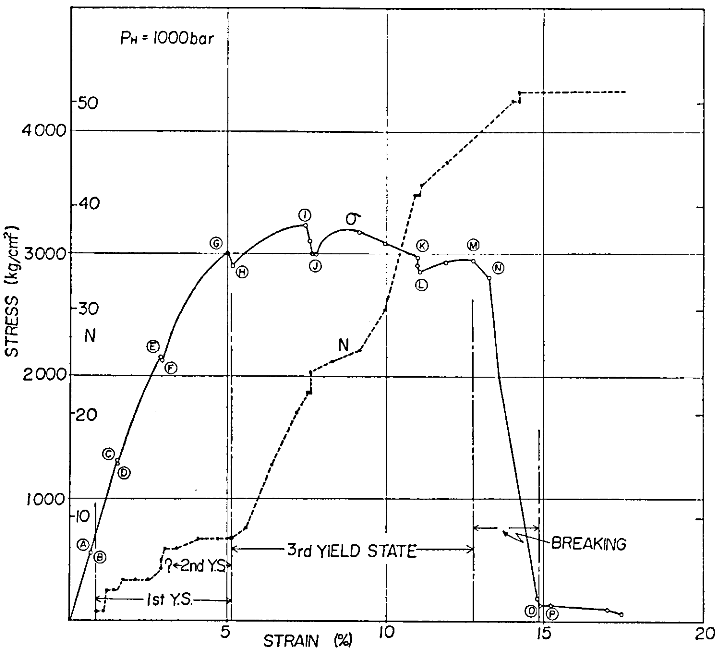

Fig. 5. The solid line presents stress～strain curve, and the dotted line presents cumulative shock number～strain curve. The confining pressure is 1000 bar.

The process from Ⓗ to Ⓝ would be regarded as corresponding to the third yield state.

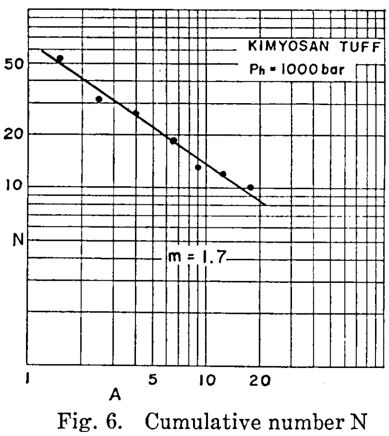

Fig. 6. Cumulative number N of small shocks as a function of amplitude A.

The second yield state, which appears evidently in the experiment under 500 bars confining pressure, is not well separated in this case of 1000 bars confining pressure. As seen in Fig. 5, the micro-fracturing shocks begin to occur from Ⓑ, and increase with strain. A slight proportionality between the number of shocks and strain is seen in the range from Ⓑ to Ⓓ. From Ⓓ to Ⓗ, however, the linearity is very poor, and one can clearly notice the state where micro-fracturing shocks do not occur with strain increase (a part of from Ⓓ to Ⓔ, and Ⓕ to Ⓖ in Fig. 4).

Therefore, it may be concluded that the state from Ⓓ to Ⓗ is the one where both the first yield state and the second yield state co-exist.

As regards larger shocks, these occurred at the state of ultimate strength and the final break. After the final break, no micro-fracturing shock is observed unless it is loaded again.

In Fig. 6 is shown the cumulative number of micro-fracturing shocks as a function of amplitude. From this graph, the coefficient of Ishimoto-Iida is obtained as $m=1.7$.

The above experimental results are summarized as follows:

(1) The occurrence of micro-fracturing shocks has been observed in the early stage of deformation even before the macroscopic yield point.

(2) There seems to be three states for the occurrence of micro-fracturing shocks in the development of deformation.

(3) The first yield state is the one which appears in the early stage of deformation with the commencement of plastic deformation.

(4) The second yield state is a kind of flow state which is characterized by the development of deformation without micro-fracturing shock. This state will follow or co-exist with the first yield state.

(5) The third state is the one which appears in a state of creep after the second state. The occurrence of micro-fracturing shock is caused by the fast increase of strain.

(6) An almost linear relationship is observed between the number of micro-fracturing shocks and strain both in the first and third states.

(7) The difference of the second and the third yield states seems to depend upon the loading rate. Fast loading rate is likely to cause the third state.

(8) No micro-fracturing shock is observed after the final break so long as no additional loading is made.

(9) Ishimoto-Iida's coefficient for the micro-fracturing shock is obtained as $m=1.7$.

4. Interpretation

As described above, the aspects of the occurrence of micro-fracturing shock during deformation under high confining pressure are very complex. They seem to be changed according to such experimental conditions as loading rate, confining pressure and temperature. It would be natural to suppose that the aspects may differ in different kinds of rocks. Therefore, it is very difficult to derive a definite interpretation of the process from the above limited experimental results. However, by the aid of the concept of dislocation theory in crystal, it was found that there may be some systematic properties among such complex behaviour. Even though it is very tentative and speculative, some interpretations will be presented in the following for the classification of the process of deformation and for the main mechanism which controls each process.

Micro-fracturing shock and dislocation. First let us review the relations between micro-fracturing shock, dislocation and plastic strain. According to the theory of dislocation,[10] the increment of plastic strain $\Delta\epsilon$ for a time interval Δt is caused by the migration of dislocations. The incremental plastic strain rate $\Delta\epsilon/\Delta t$ relates to the density ρ and velocity v of mobile dislocation in a form

$$\Delta\epsilon = b\cdot\rho\cdot v\cdot\Delta t, \tag{1}$$

were b is Burgers vector. From this relation it will be evident that, if one makes any forced plastic strain $\Delta\epsilon/\Delta t$, it should be accompanied with the necessary amount of ρ and v. According to Stroh,[11] when dislocations are produced and are mobile, they will pile up around some obstacles and produce stress accumulation around it. When the amount of stress exceeds a certain critical value of the media, a micro-crack is produced at the obstacle. The newly formed micro-crack is finite in length, and absorbs piled up dislocations within the crack by releasing a part of surrounding accumulated strain. The production of such micro-cracks will be thought to correspond to the micro-fracturing shocks in our experiment.

Therefore, it can be said that so long as production and migration of dislocations are present production of micro-cracks is inevitably accompanied. Whenever any forced deformation is given and any forced plastic strain is produced, the accompanying dislocations are produced, migrate, pile up, and finally result in the formation of micro-cracks radiating micro-fracturing shocks.

It will be also understood from the equation (1) that the production of micro-cracks is controlled by the mutual relations among plastic strain rate $\Delta\epsilon/\Delta t$, mobile dislocation density ρ, and dislocation velocity v.

The first yield state. Johnston and Gilman[12] have found in a plastic deformation of crystal LiF that there is a linear relationship

10) A. H. Cottrell, *Dislocations and Plastic Flow in Crystals* (Oxford, 1953), p. 18.
11) A. N. Stroh, *Proc. Roy. Soc. A*, **223** (1954), 404.
12) W. G. Johnston and J. J. Gilman, *Jour. Appl. Phys.*, **30** (1959), 129.

between dislocation density ρ and plastic strain ϵ,

$$\rho = 10^9 \epsilon \tag{2}$$

in the early stage of plastic deformation of crystals. This state, where production of dislocation is proportional to plastic strain, will be regarded as corresponding to the first yield state of our experiment. The co-existing of plastic deformation with elastic deformation in this state will be seen in the slight non-linear curving of stress-strain curve in Figs. 3 and 5.

The second yield state. It is known[13] that dislocation velocity increases with stress in a form of

$$v = v_0 e^{-D/\sigma} \tag{3}$$

where σ is stress, D activation constant and v_0 terminal dislocation velocity. This relation means that dislocation velocity builds up with stress and has a large value around the yield point. Therefore, when the dislocation velocity increases and almost all parts of forced plastic strain is provided by the migration of such high speed mobile dislocations, the given forced deformation will not need any production of new dislocations for its development. This will mean that, under such conditions, plastic deformation proceeds without production of new micro-fracture. In another words, deformation proceeds as flow. This state will be regarded as corresponding to the second yield state.

The co-existing of the second yield state with the first state, which is seen in Fig. 6, may be due to the ductile nature of the specimen under the condition of higher confining pressure of 1000 bars.

The third yield state. Even under the state of high speed dislocation velocity in macroscopic yielding region, the new production of dislocation will be needed for a given forced deformation if given forced plastic strain is so fast that it cannot be fully provided with the movement of dislocation only. Since successive production of dislocation is likely to produce micro-cracks, such a condition will be regarded as corresponding to the third yield state. Since plastic strain is provided by the product of density and velocity of dislocations, as seen in the equation (1), the new production of dislocation depends upon the balance of speed of plastic strain and velocity of dislocation. Therefore it will be reasonable to suppose that the production of micro-fracturing shock

13) *loc. cit.*, 12).

depends upon such experimental operation as strain rate of loading. The difference of the second and the third states may depend upon the strain rate control.

The occurrence of micro-fracturing shock in the second state, which is seen between Ⓚ and Ⓛ in Figs. 2 and 3, may be caused by a small increase of strain rate due to the increase of loading stress.

The above interpretations are tentative ones based upon very preliminary experimental data. Further experiments with more refined control for many other kinds of rocks will be necessary to ascertain these interpretations.

From a microscopic study of thin sections of rock specimen taken from various states of deformation, one of the authors[14)] has observed the production of micro-cracks in the first yield state and the opening of micro-cracks in the second yield state. The opening of micro-cracks will be nothing but the indication of flow, that is to say, the progress of plastic deformation without production of new cracks. The linear relationship between number of cracks and strain has also been observed. These microscopic observations on a rock specimen are very consistant with our interpretations.

5. Relation to earthquake swarms

The next problem is to compare there experimental results to the activity of earthquake swarm. Since there may be much differences in the process and mechanism of deformation between such an experimental process in the rock specimen and the actual process of earthquake swarm in the earth's crust, the correspondence will not be self-evident. It will be very interesting to examine to which state the earthquake swarm corresponds and to what extent the linear relation exists between the number of shocks and the deformation of the curst.

The data are taken from Shōwa-Shinzan and Matsushiro earthquake swarm. In Fig. 7 is plotted the number of small earthquakes observed at Toya as a function of the amount of upheaval at the Bench Mark 12(B) which lies at the eastern foot of the Shōwa-Shinzan during the period of eruption and the birth of lava-dome in 1944~1945. These data are taken from the paper by Minakami et al[15)]. The period from

14) *loc. cit.*, 6).

15) T. Minakami, T. Ishikawa and K. Yagi, *Bull. Volcanologique*, **2** (1951), 45-157, Table 2 and 10(b).

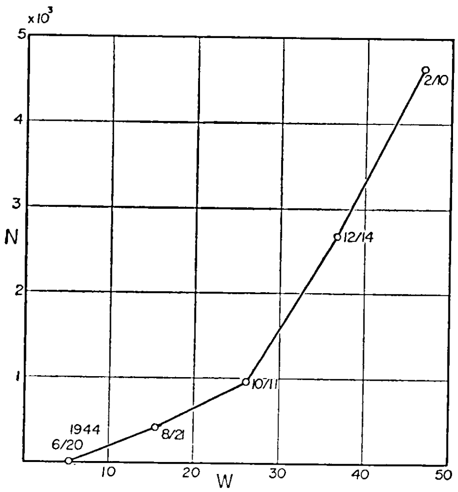

Fig. 7. The cumulative number N of earthquakes observed at Toya as a function of the upheaval W(m) of the Bench Mark 12, which lies at the eastern foot of the Shōwa-Shinzan, during the period of eruption and the birth of the lava-dome of the Shōwa-Shinzan in 1944~1945. Data are read from the paper by Minakami et al.[15]

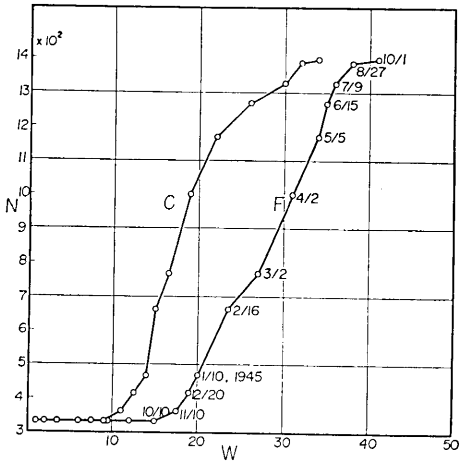

Fig. 8. The cumulative number N of earthquakes observed at Muroran as a function of the upheaval W of the new lava-dome (F), and the roof mountain (C) of the Shōwa-Shinzan, during the period of birth and development of lava-dome of Shōwa-Shinzan in 1944~1945. Data are read from the paper by Kizawa.[16]

June 20th 1944 to October 11th 1944 corresponds to the stage of paraxysmal eruption. The period later that date corresponds to the brith and formation of lava-dome. It is seen that linear relation exists for each stage.

Kizawa[16] has reported the existence of the strong correlation between the monthly number of earthquakes observed at Sapporo and the monthly upheaval of the lava-dome of the Shōwa-Shinzan. In order to examine the linear relation, the data in Kizawa's paper are plotted in Fig. 8. The number of earthquakes observed at Muroran is plotted as a function of the upheaval of the Shōwa-Shinzan. The amount of upheaval is read from the Mimatsu diagram. (F) is the upheaval at the centre of the lava-dome, and (C) is the one at the edge of the roof mountain. At Muroran, whose epicentral distance is about 25 km, the increase of earthquakes is registered only from the end of October, namely in the stage of birth and development of the new lava-dome. An almost linear relation is seen in curve (F), but is not so clear in

16) I. KIZAWA, *Papers in Meteorology and Geophysics*, **8** (1957), 150-169.

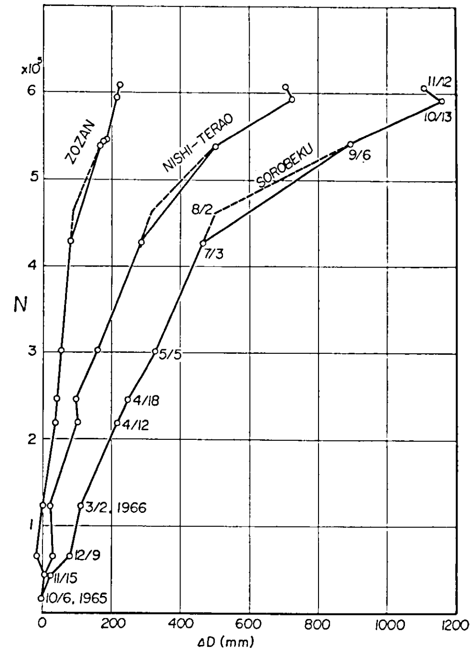

Fig. 9. The cumulative number N of small shocks at Matsushiro (JMA) as a function of the horizontal elongation or contraction ΔD(mm) which are observed by electro-optical measurement by Kasahara et al.,[18] during the period from October 6, 1965 to November 12, 1966.

curve (C).

In the Matsushiro earthquake swarm, a strong correlation between the curstal deformation and the activity of earthquake swarm has been reported by Hagiwara and Yamada[17], Kasahara et al.[18], and Tsubokawa et al.[19]

In order to examine the correlation, the cumulative number of small skocks, reported by JMA, is plotted as a function of horizontal elongation or contraction observed by Kasahara et al.[18] by the electro-optical geodetic measurement in Fig. 9. One can see there an almost linear proportionality between the cummulative number of small shocks and horizontal strain. Since the measurement was made at a discrete time interval, the dotted line represents the change of horizontal distance under the assumption that the trend of the crustal deformation of the second stage of swarm activity continued without change till the commencement of the third stage of swarm activity on August 2nd. These characteristics are in accord with our experimental results shown in

17) T. HAGIWARA and J. YAMADA, Read at the Monthly Meeting of Earthquake Research Institute, December 27, 1966.

18) K. KASAHARA et al., *Bull. Earthq. Res. Inst.*, **45** (1967), 225-239.

19) I. TSUBOKAWA et al., *Bull. Earthq. Res. Inst.*, **45** (1967), 265-288.

Figs. 3 and 5. However, the proportional constant seems to have changed since August 3rd in 1966 in the thrid stage of its swarm activity. The state of the earth's crust in the period before August 2nd, 1966, may be regarded as corresponding to the first yield state of rock deformation test. In the period later than that date, the increase of horizontal strain is far greater than the increase in the number of earthquakes. This may be an indication of the second yield state of rock deformation, that is, the state of flow. Some changes might have taken place in the state of deformation of the earth's crust from that date in Matsushiro area.

From the above examples, it will be concluded that the assumption which is used in the previous paper for relating the deformation of media to the occurrence of micro-shocks is valid for practical application.

6. Summary and Conclusions

In connection with the kinematical process of earthquake genesis, a laboratory experiment was performed for the purpose of examining the relation between occurrence of micro-fracturing shocks and rock deformation. The micro-fracturing shocks were observed during the tri-axial rock deformation test of which confining pressures are 500 bars and 1000 bars. The rock specimen is pyroclastic tuff sampled in Matsushiro where the earthquake swarms are active.

The main experimental results obtained are as follows:

(1) The occurrence of micro-fracturing shocks has been observed in the early stage of deformation even before the macroscopic yield point.

(2) It seems that there are three states for the occurrence of micro-fracturing shocks in the development of rock deformation.

(3) The first yield state of micro-fracturing occurrence is the one which appears in the early stage of deformation with the commencement of plastic deformation.

(4) The second yield state is a kind of flow state which is characterized by the development of deformation without micro-fracturing shocks.

(5) The third yield state is the one which appears after the second state in a state of creep. The occurrence of micro-fracturing shock in this state is caused by the fast increase of strain.

(6) An almost linear relationship is observed between the number of micro-fracturing shocks and strain of deformation both in the first and the third states.

(7) The differences of the second and the third yield states seem to depend upon the loading rate. A fast loading rate is likely to cause the third state.

(8) No micro-fracturing shocks is observed after the final break so long as no additional loading is made.

(9) The Ishimoto-Iida's coefficient for the micro-fracturing shock is obtained as m=1.7.

The tentative interpretations are made for the above experimental results from the view point of dislocation theory. By assuming that the occurrence of micro-fracturing shocks corresponds to the increase of dislocation density, and by using a relation among plastic strain rate $\Delta\epsilon/\Delta t$, dislocation density ρ, dislocation velocity v, $\Delta\epsilon=b\cdot\rho\cdot v\cdot\Delta t$, rather systematic, but tentative, interpretations are obtained for the various aspects of micro-fracturing shock occurrence.

(10) The linear relationship between the number of micro-fracturing shocks and the strain will be based upon the linear relationship between dislocation density and plastic strain.

(11) The first yield state of micro-fracturing shock is considered as corresponding to the state of very low dislocation velocity where the production of dislocation is needed for the development of plastic strain.

(12) The second and third yield states of micro-fracturing are considered as corresponding to the state of higher dislocation velocity beyond yield point. In the second state, it is thought that the given plastic deformation is fully provided with the migration of dislocations, and consequently there is no need of new production of dislocations or micro-cracks for the development of deformation.

(13) The third yield state will appear when the given plastic strain is so fast that it is not fully provided with the migration of dislocations only, the increase of dislocation density being needed for the development of the strain.

Comparing these results with the activities of earthquake swarms, the following correspondence is obtained:

(14) In the earthquake swarm of Shōwa-Shinzan in 1944~1945, an almost linear relation is observed between the upheaval and the cumulative number of small shocks. The proportional constant varies with the stage of activity.

(15) The relationship between the horizontal strain observed by electro-optical geodetic measurement and the total number of small earthquakes observed by JMA in the Matsushiro earthquake swarm is very

similar to the one obtained in this experiment.

(16) Since August 3rd 1966, the state of deformation at Matsushiro seems to have changed, and it may be considered that a part of the crust might come into the second yield state, that is, the flow state.

(17) From the above examples, it will be concluded that the assumption which is used in the previous paper for relating the deformation of media to the occurrence of micro-shocks is valid for practical application.

Acknowledgement

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55. 岩石の変形に伴う微小破壊音の発生
—特に地震群活動との関連—

地震研究所 南 雲 昭 三 郎
地質調査所 星 野 一 男*

地震発生の動力学過程を考えようとする際には媒質の変形と地震の発生との間に関して，何らかの関係を知らねばならない．前論文において筆者の一人は，微小地震の発生は媒質内の転位の発生に由来するとの考えの下に，クラックの発生頻度は媒質の塑性変形の進行速度に比例するという転位論で知られている関係が地殻媒質においても成り立つものと仮定した．この仮定は実験的に又験震的に吟味されねばならない事柄である．今回松代産岩石（奇妙山凝灰岩）について三軸変形破壊試験を行いその際発生する微小破壊音を同時に測定し，変形と微小破壊音との関係を調べてみた．封圧は 500 bar, 1000 bar で行った．実験結果は非常に複雑であり，荷重速度等の実験操作に依存するようであり，実験は未だ完了していないが，この種の実験を更に進めるに際して非常に興味ある二三の結果と漸定的解釈が得られたのでとりあえず報告する．

主なる実験結果は次の通りである．

(1) 微小破壊音の発生は巨視的な降伏点以前，変形の初期の段階から既に発生していることが観測された．

(2) 岩石変形の発達に伴う微小破壊の発生過程には 3 つの状態が存在するようである．

(3) 微小破壊音発生の第 1 塑性状態は，変形の初期において塑性変形の開始と共に出現する状態である．

(4) 第 2 塑性状態は一種の流動の段階で，微小破壊音の発生なしに変形の発達する状態で特徴づけられる．

(5) 第 3 塑性状態は第 2 塑性状態以後クリープの状態において現われるもので，微小破壊音の発生は塑性歪の急速な進行によっておこされる．

(6) 微小破壊音の数と歪との間にほぼ直線的な関係が成り立つことが，第 1，第 3 状態において観測された．しかしその比例係数は必ずしも一致しない．

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* 現在 石油開発公団．

(7) 第2塑性状態と第3塑性状態との差は加荷重速度に依存する．急速な加荷重は第3状態を生じ易い．

(8) 最終破壊以後は荷重を増加せしめない限り，微小破壊音の発生は観測されなかった．

(9) 微小破壊音の石本一飯田の係数は $m=1.7$ という値が得られた．

微小破壊音の発生は微小クラックの突然の生成に外ならず，微小クラックの生成は，転位論によれば，転位の発生・移動・集積によって起され，転位の移動は塑性変形の進行に外ならないことが知られている．従って微小クラックの発生は転位密度の増加に対応するものと仮定すると，微小破壊音発生の様子は，塑性歪進行速度 $\Delta\varepsilon/\Delta t$，転位密度 ρ，転位の移動速度 v との相互関係，$\Delta\varepsilon=b\cdot\rho\cdot v\cdot\Delta t$，によって系統的に説明されそうである．この様な観点から今回の実験データについて次のような漸定的な解釈を行った．

(10) 微小破壊音の発生数と塑性変形歪との直線的関係は転位密度と塑性歪との直線的関係に基づくものであろう．

(11) 微小破壊音発生の第1塑性状態は転位速度の非常に遅い状態で，塑性歪の進行に対して転位の発生が必要とされている状態に対応するものと考えられる．

(12) 微小破壊音発生の第2，第3塑性状態は，降伏点以後における転位速度の速い状態に対応するものと考えられる．第2塑性状態においては与えられた塑性歪は転位の移動ですべてまかなわれるので，変形の発達に対して転位の発生・微小クラックの発生というものを必要としないと考えられる．

(13) 第3塑性状態は与えられる塑性歪の進行が速やかで，転位の転位速度だけでは充分まかなわれきれず，転位密度の増加が必要とされる状態に表われるものと考えられる．

以上の実験結果と地震群活動との関連を調べてみた所次のような結果を得た．

(14) 昭和新山の例では水準測量で観測された降起量と地震の累積回数との間にほぼ比例関係がみられるが，活動の段階が変わるとその比例係数も変わる．

(15) 松代地震群の例では，光波測量で観測された水平距離の伸びと微小地震の総回数との間には比例関係が認められ，実験結果と非常に類似している．

(16) 松代においては，1966 年 8 月 30 日以降の第3活動期において，変形状態に何らかの変化が生じたようである．地殻の一部が第2塑性状態（流動状態）に入ったのかも知れない．

(17) 以上の例から前論文で用いた媒質の変形と微小破壊とを結びつける仮定は妥当なものであると結論される．