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On the Flow and Fracture of Igneous Rocks

and

On the Deformation and Fracture of Granite under High Confining Pressure

By

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ABSTRACT

1. The stress-strain relations of some igneous rocks for longitudinal and lateral direction were observed. The curves of the longitudinal strain versus stress were approximately linear up to the moment of rupture, but the strain in the lateral direction showed the abrupt increase in the fracture range.

2. It was found that such abrupt increase of the lateral strain was closely related with the flow. The longitudinal creep during the moderate period was almost recovered by the removal of the load, but in the lateral direction, large amount of residual strain was observed after the removal of the load.

3. The empirical formulae of creep for granite were given as follows,

$$S=A_0+A_1e^{-\alpha_1t}+A_2e^{-\alpha_2t}+A_3e^{-\alpha_3t}+B\log t+Ct,$$

for the longitudinal direction, and

$$S=A+B\log t+Ct,$$

for the lateral direction, respectively. In the former equation, the reciprocals of α_1, α_2 and α_3 denote the retardation times. The later equation concurs with the formula given by Griggs and others.

1. If we consider the problems of the occurrence of the earthquake, it seems to be very important to study the rupture mechanism of rocks constituting the earth's crust in the deep place. However, the rocks which exist in the deeper part of the crust must be different from the ones found at the surface of the earth. Moreover, they are under high pressure and high temperature.

In spite of the above circumstances, it may give us some clue of the interpretation of the rupture phenomena in the crust to study the mechanism of fracture of rocks in ordinary states. The experiments reported here were carried out under an atmospheric pressure and room temperature. In these experiments the simple compressional force was applied to the specimens.

The strain was measured by the strain gauge of the electric resistance type. The strain gauge of this type has high sensitivity and considerable accuracy. Besides, it has a very convenient characteristics such as the any desired strain component can be measured easily. The difficulties caused by the unstability of the indication, which we always encounter in the treatment of the electric instruments during the long period observation, were avoided sufficiently by the use of the unbonded type of strain gauge.

2. It has been reported in many papers that the stress-strain relations in the loading direction for silicate rocks were approximately linear up to the moment of rupture. It may be said that the rocks are the quite elastic and brittle material. It is well known, however, that the rocks are the very porous material, and because of its porous structure, they have the considerably lower value of Poisson's ratio at the incipience of loading than that of the other materials[1]. Then, it may be expected at the rupture stage, that the porous structure will considerably affect to the rupture mechanism for the rocks.

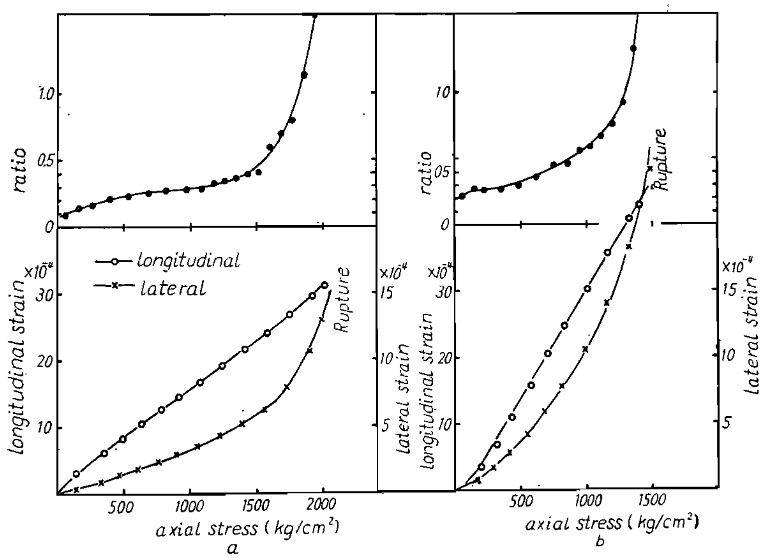

Fig. 1. Stress-strain curves and variation of Poisson's ratio with stress, (a) Aokiko-Nagano quartz monzonite, (b) Yakuno-Kyoto olivine basalt.

According to the above consideration, the measurements of stress-strain relations of the several sorts of igneous rocks both in the longitudinal and in the lateral directions were carried out up to the rupture point, and the ratio of the lateral to the longitudinal strain was calculated. The rock specimens used for these experiments are 30 mm. in diameter and 60 mm. long.

The longitudinal strain of each specimen varied almost linearly with stress up to the rupture as above mentioned. As shown in Fig. 1, however, it was found that the rate of increase of the lateral strain increased gradually with stress, and in the fracture range the increase of the lateral strain becomes much larger than the longitudinal one. At the first stage, the Poisson's ratio gives the less value compared with the other materials, and with the increasing load it reaches at the ordinaly value, about 0.3. When the rock specimen begins to show the aspect of failure, the ratio increases beyond 0.5, and finally it shows the extraordinaly high value at the rupture stage. This suggests the effect of volume expansion in the fracture or the plastic stage, which was found by P. W. Bridgman in his volumetric tests[2]. It is supposed that this effect involves in itself the fundamental meaning for the rupture mechanism of rocks.

3. When the stress-strain relation was observed in the fracture range, it was clearly indicated that all the abrupt increase of lateral strain was not produced instantaneously at the moment of loading, but the flow strain after loading had the close connection with such abrupt increase of strain. Then it may be interesting to observe the amount of flow along the lateral direction compared with the one along the longitudinal direction during the moderate period at the fracture stage.

To avoid the reasonable suspicion on the barrel shape deformation of the specimen, the lateral strain was measured at the ending portion of them. The other conditions were kept the same as the previous experiments. As an example, the results of strain-time relations for a Kitashirakawa biotite granite under various stresses are shown in Fig. 2, where (a) denotes the longitudinal direction and (b) the lateral direction. The results of the others were almost the same as the above. The normal strength of this granite is 1400 kg/cm^2, then it will be seen that the lateral flow is hardly perceptible below the stress of one third of the normal strength. Beyond the stress of a half of the normal strength, however, the lateral flow becomes larger than that of the longitudinal one, and it surpasses the later

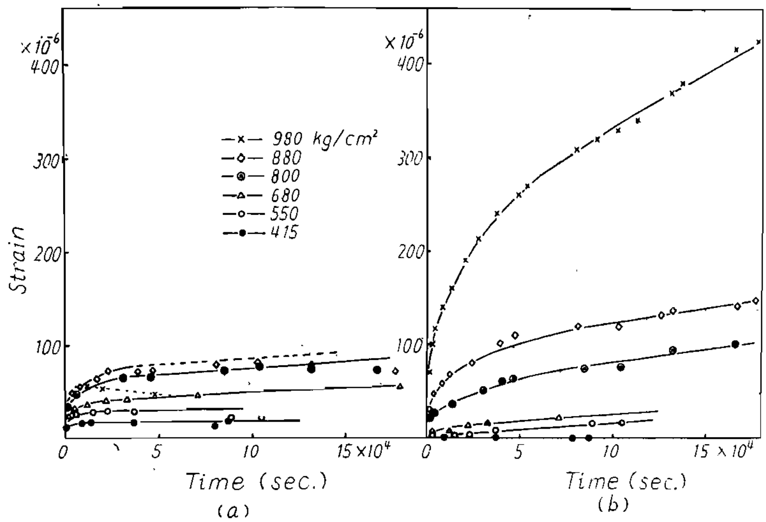

Fig. 2. Strain-time curves for Kitashirakawa biotite granite under various loads, (a), longitudinal direction, (b) lateral direction.

by far in the fracture range, in which the microscopic failure will rapidly occur.

Thus the deformation process of rocks can be divided into three stages, that is, the first stage in which the pores are closed, the second stage in which the material behaves almost perfectly elastic, and the final and fracture stage in which the lateral strain shows a distinctive increase.

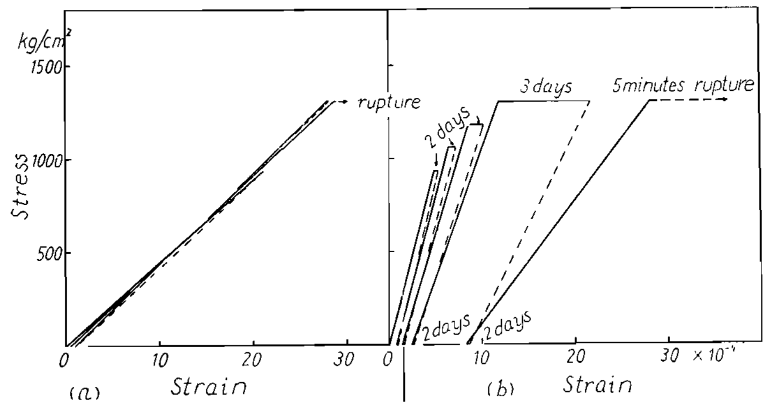

Fig. 3. Stress-strain relations, which involve the flow and recovery, for Kitashira biotite granite, (a) longitudinal direction, (b) lateral direction.

In these observations, the elastic recovery was measured after each test. Fig. 3 shows the stress-strain-time relation given from the successive test for flow and recovery. In the longitudinal direction, the strain caused by the creep almost returned, but the lateral creep strain scarcely returned at the removal of the load. Then the large amount of permanent set, the amount of which will be closely related with the duration of loading, was observed in the lateral direction. It may be said that the rocks have the unusual properties, elastic in the direction of compression and plastic in the direction transverse to it.

4. Many measurements have been reported on the creep of rocks, and the experimental equation of the results has been given in the form of

$$S=A+B\log t+Ct,$$

where S denotes the flow strain, t the time and A, B, C the constants.

In this section, the experimental formula of the creep for granite is estimated. The specimens used in this experiments are Shodoshima biotite granite, 30 mm. in diameter and 60 mm. long. The measurements were done in two stages, the one was in the short period 1 to 10^2 second, and the other was in the long period 10^2 to 10^6 seconds. The creep of long period was measured by the unbonded-type strain gauge. This sensitivity is a quarter of 10^{-6} in the axial direction and 10^{-6} in the transverse direction. The error of the observed value was within 3×10^{-6}, during the all period of the observation. The change of the room temperature, by which the

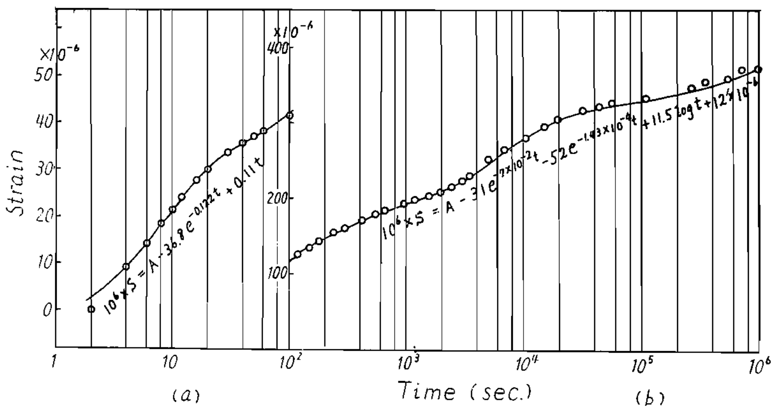

Fig. 4. Creep curves of longitudinal direction for biotite granite, (a) short period test for Kitashirakawa granite under load of 945 kg/cm², (b) long period test for Shodoshima granite under load of 1170 kg/cm².

observed values are materially affected, was kept within $\pm 0.2^{\circ}C$ in the axial direction and $\pm 0.5^{\circ}C$ in the transverse direction. The results are described separately in two directions.

In Fig. 4(a) and (b) show the creep curves for the longitudinal direction in two periods plotted on semilogarithmic papers, respectively. The empirical formulae derived from these two curves are

$$S = A + A'e^{-\alpha t} + Ct,$$
$$S = A_0 + A_1 e^{-\alpha_1 t} + A_2 e^{-\alpha_2 t} + B \log t + Ct.$$

Let us assume that the term Ct of the former equation can be replaced by the second and later terms of the later equation, as it was determined in the short period 1 to 10^2 seconds. Then the full equation can be described in the form

$$S = A_0 + A_1 e^{-\alpha_1 t} + A_2 e^{-\alpha_2 t} + A_3 e^{-\alpha_3 t} + B \log t + Ct$$

putting together, where the reciprocals of α_1, α_2, α_3 express the retardation times of Kelvin's model of the order of 10, 10^2, 10^4 seconds respectively.

The results of lateral direction in short and long periods are shown in Fig. 5. These formulae are

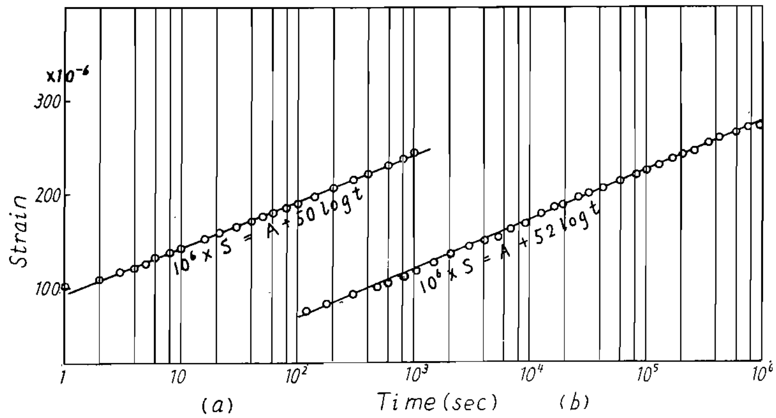

Fig. 5. Creep curves of lateral direction for Shōdoshima biotite granite under load of 1170 kg/cm², (a) short period test, (b) long period test.

$$S = A + B \log t,$$
$$S = A + B \log t + Ct,$$

respectively. Putting together, the empirical formula of the creep for the direction perpendicular to the applied force is given as follows

$$S = A + B \log t + Ct.$$

This formula entirely coincides with the formula given by Griggs and others[3]. The formula for the longitudinal direction, does not concur with theirs, but has the different expression with the lateral one. While the curves shown in Fig. 5 are approximately linear, the ones in Fig. 4 somewhat indicate the unduration.

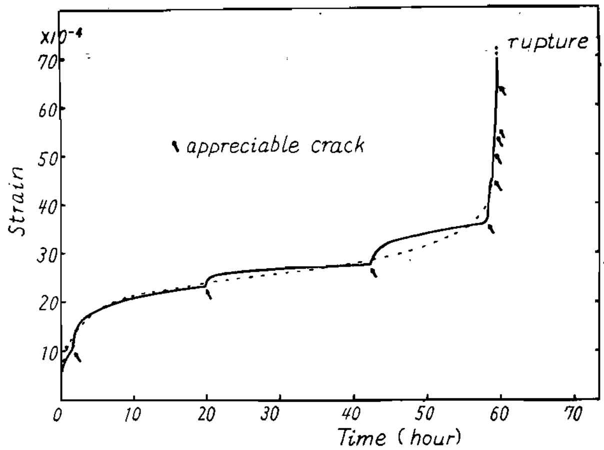

Fig. 6. Creep and rupture for Shodoshima biotite granite, observed in lateral direction. Solid line denotes the observed value, and the dotted line denotes the normal creep curve.

An example of rupture caused by creep is shown in Fig. 6. This curve has the same three stages as the metals and other materials have. However, it was observed that the deformation did not continue smoothly, but the appreciable cracks occurred in succession on the way of creep, and finally reached to rupture with continual crack.

ACKNOWLEDGEMENT

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