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The science reports of the Tohoku University. Fifth series, Tohoku geophysical journal 33 3-4 241-250 1990-12

URL http://hdl.handle.net/10097/45333
Fault Development in Oshima Granite under Triaxial Compression Inferred from Hypocenter Distribution and Focal Mechanism of Acoustic Emission

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(Received March 5, 1990)

Abstract: During a triaxial cyclic loading experiment of Oshima granite at a confining pressure of 40 MPa, we found a clear precursory localization of acoustic emission hypocenters around a part of the main fault plane. The localized zone first formed in the lower part of the sample, and then extended upward gradually along the main fault. Finally a brittle fracture occurred when the front of the localized zone reached the central portion of the sample. The localized zone was not a simple planar zone, but consisted of several clusters of events aligned in directions parallel or conjugate to the main fault, suggesting that a set of small shear faults developed in the localized zone. Using P-wave first motions, the focal mechanism solutions were calculated assuming a source model of an axial tensile crack coupled with a shear crack. Events belonging to the most active cluster, which was located on one of the macroscopic faults, included large shear components having focal mechanisms similar to that of a normal fault parallel to the macroscopic fault. This suggests that linking of axial crack array with shear crack almost parallel to a macroscopic fracture plane is a plausible mechanism of fault development.

1. Introduction

Under triaxial compression, a rock sample fractures typically with shear faults at 20–30° with respect to the maximum compression axis (Paterson, 1978). Planar localization of microfractures coinciding well with a part of the macroscopic fault is sometimes observed prior to the ultimate fracture (Spetzler et al., 1977; Lockner and Byerlee, 1980; Granryd et al., 1983; Kurita et al., 1983). For understanding how the microfractures develop and lead to the formation of the macroscopic fault in rock, it is very important to elucidate the fracturing process of microcracks, such as nucleation, growth and coalescence of microcracks, in the localized zone.

During a triaxial creep experiment of Westerly granite, Lockner and Byerlee (1980) found that the AE (acoustic emission) hypocenters began to concentrate around a part of the ultimate fracture plane at the onset of the tertiary creep. The concentrated zone spread along the fracture plane with the progress of deformation. However, a detailed picture of the structure of concentrated zone did not emerge, mainly because of the limitation of their experimental system. The multichannel AE data acquisition system they employed was designed to pick up the time when the signal amplitude exceeded a
preset threshold level, and not for recording the waveforms (Byerlee and Lockner, 1977). Therefore, P arrival times measured by such systems do not have enough accuracy for precise location of AE hypocenters, and it is important to correctly pick up the P onsets on the basis of the waveform data (Sondergerd and Estey, 1981; Nishizawa et al., 1984/85). The recording of waveforms is also indispensable to determine the focal mechanism of AE events.

Recently we have constructed a data acquisition and processing system which enables us to digitally record AE waveforms simultaneously at more than twenty observation points and to locate the hypocenter automatically (Satoh et al., 1987). In this paper, we report the results of AE activity in Oshima granite subjected to cyclic loading under triaxial compression. Prior to the ultimate fracture, we found that AE hypocenters were localized around a part of the main fault plane. Focal mechanisms of some of these events were also examined. We are discussing the microprocess of fault development in rock by comparing the geometry of the macroscopic faults with the space-time distribution of AE hypocenters and the AE focal mechanisms.

2. Experiment

A right circular cylinder (50 mm in diameter and 100 mm long) of medium grained granite (Oshima granite) was cyclically loaded with progressively increasing peak differential stresses at a confining pressure of 40 MPa. Figure 1 shows the differential stress as a function of time. The peak stresses were 310, 410, 510 and 535 MPa for cycles-I, -II, -III and -IV, respectively. In each loading cycle, the stress was held constant at its peak for about 20 minutes. At about 110 seconds after the stress reached
the peak value of cycle-IV, the sample fractured in a brittle manner. The final fracture planes comprised mainly two steeply inclined shear faults shown in the AE hypocenter map for cycle-IV in Fig. 2. We call the larger fault the main fault and the smaller one the sub-fault. The main fault went through the sample from the bottom to the top at an angle of about 15° with respect to the maximum compression axis. The sub-fault was formed in the lower part of the sample with its orientation conjugate to the main fault.

The AE measurement was performed using a detector network of twenty longitudinal type piezoelectric transducers of 2 MHz resonant frequency. The AE signals from the transducers were digitized using transient recorders, and then transferred to a minicomputer where they were stored on a hard disk. Each transient recorder was set for 20 MHz digitization rate and 1024 words data length for this experiment.

In order to measure P-wave velocity of the sample, elastic waves were intermittently emitted from two of the twenty transducers by successively pulsing them with a pulse generator. One of them was located at the central portion on the radial surface, and the other in a steel end-piece attached to the top end of the sample. The waveforms were recorded using the system for the AE measurement. The P-wave velocities in directions parallel and perpendicular to the maximum compression axis were calculated from these records. The velocity data obtained were utilized for the AE hypocenter determination.

After the experiment, the AE waveform data were processed for the automatic hypocenter determination. P-wave first arrival time was picked up by an algorithm developed by Yokota et al. (1981). On the basis of AIC (Akaike information criterion) (Akaike, 1974), the algorithm identifies the statistically best point dividing a time series into two stationary parts; the background noise and the signal. The AE hypocenters were determined by basically the same technique used for locating earthquake hypocenters. In order to estimate the accuracy of the automatic AE hypocenter determination, we applied this technique to the waveforms radiated from the source transducer which was mounted on the radial surface for velocity measurements. The source transducer was located with an accuracy of ±2 mm.

Full details of the AE data acquisition and automatic hypocenter location system have been described in Satoh et al. (1987).

3. Results

3.1. Hypocenter Distribution

We were able to determine hypocenters of more than two thousand AE events during the experiment, and these are distributed in numbers as 393, 545, 693 and 415 during cycles-I to -IV. Figure 2 shows hypocenter distributions together with the Cartesian coordinate system used in this study. The origin of the coordinate axes is taken as the center of the sample. The surface traces of the final fracture planes are superposed on the x-z projection of the data of cycle-IV (Fig. 2(IV)). During the first two loading cycles, a cluster of AE hypocenters was observed at a bottom corner of the sample (Fig.
Fig. 2 Orthographic projection showing spatial distribution of AE hypocenters during each loading cycle. Cartesian coordinate system used in this study is also shown. The origin of the coordinate axes is the center of the sample. Solid and dashed lines in the x-z projection for cycle-IV (Fig. 2(IV)) denote surface traces of the ultimate fracture planes appearing on the front and opposite sides of the sample, respectively.

2(I)(II). Since this cluster appeared from the earlier stage of the experiment, it was probably due to a macroscopic heterogeneity included originally in the sample. If we neglect this cluster, the hypocenter distribution during these two cycles seems to be random. During cycle-III, the cluster disappeared and a weak concentration of the AE hypocenters around the main fault plane can be identified in the lower part of the sample (Fig. 2(III)). During cycle-IV, the AE hypocenters concentrated much stronger and formed a planar distribution pattern around the main fault plane in the lower half of the sample, while the AE activity was very low in the upper half (Fig. 2(IV)).

It is interesting to examine the AE activity during cycle-IV more closely. Figure 3 is a space–time plot of the hypocenters during cycle-IV. The localized zone first formed in the lower part of the sample, and then extended upward gradually along the main fault. Finally, the ultimate fracture occurred when the front end of the localized zone reached the central portion of the sample. Figure 2 (IV) shows that the AE hypocenters did not concentrate preferentially on the ultimate fracture planes. The localized zone seems to have a width of about 10 mm. Figure 4 shows the x-z projections of the hypocenters occurring within every 10 mm interval along the y axis during cycle-IV. The AE hypocenters did not show a simple planar distribution pattern, but formed a number of clusters in which the hypocenters aligned in the directions parallel or conju-
Fig. 3  Space-time plot of AE hypocenters during cycle IV. The origin of the time axis is the beginning of the cycle.

Fig. 4  Sliced x-z projections showing the AE hypocenter distribution during cycle IV. Intervals along the y axis are a) $y \leq -15$ mm, b) $-15$ mm $< y \leq -5$ mm, c) $-5$ mm $< y \leq 5$ mm, d) $5$ mm $< y \leq 15$ mm and e) $15$ mm $< y$. Approximate locations of the macroscopic fracture planes are also drawn for reference. The detailed discussion is given in the text on the focal mechanism solutions of events belonging to the cluster indicated by an arrow in Fig. 4(c).

3.2. Focal Mechanism

P-wave first motion directions were picked up from the events that occurred inside $\pm 40$ mm along the z axis, because the events located near the top and the bottom end of the sample did not give good coverages of the polarity distributions on the focal
hémisphère. Hence the events belonging to the cluster observed for the first two loading cycles were excluded from the focal mechanism study. Reliable data of P-wave first motion polarity at more than fourteen transducers could be obtained for a total number of 215 AE events throughout the experiment. Typical examples of the polarity distribution are shown in Fig. 5. Seventy-seven AE events showed the distributions with compressional first motions at all transducers (Fig. 5(C)). Thirty-three events satisfied quadrant type focal mechanism solutions (Fig. 5(Q)). The other 105 events showed the distributions with both compressional and dilatational first arrivals, but could not be

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\(^{1}) Distribution with compressional first motions at all transducers
\(^{2}) Quadrant distribution
\(^{3}) Other than type-C and -Q
fitted by any double couple focal mechanism solution. For simplicity, we call these three types of polarity distribution type-C, -Q and -X, respectively. For most of the type-X events, the compression was dominant and the dilatation was projected on a relatively small area of the focal hemisphere (Fig. 5(X-1)-(X-3)). A wide variety of the distribution pattern was observed, ranging from the distribution with only one dilatational datum (Fig. 5(X-1)) to that nearly identical to a quadrant type one (Fig. 5(X-3)). The number of events of each type is listed in Table 1. The type-Q events mostly occurred during the last two loading cycles, suggesting that shear fracture became dominant with the progress of deformation.

The above results agree well with the results of a triaxial compression test of Oshima granite by Satoh et al. (1990). They have demonstrated that a composite crack model consisting of an axial tensile crack coupled with a shear crack, which is similar to the model originally proposed by Brace et al. (1966), explains well the observed polarity distributions. Focal mechanism solutions of the type-X events were calculated

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<td>X</td>
<td>59 70</td>
<td>-157 17</td>
<td>-148 63</td>
<td>6 30</td>
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1) Source location (mm).
2) Number of compressional and dilatational first motions.
3) Type: Type of polarity distribution pattern.
4) Trend and plunge of the principal stress axes of shear component (deg.). Trend is measured counterclockwise from the x axis. Plunge is measured downward from the x-y plane.
5) Dip direction and dip angle of the nodal planes of shear component (deg.). Dip direction is measured counterclockwise from the x axis. Dip angle is measured downward from the x-y plane.
Fig. 6 Distribution of principal stress axes of shear components for events belonging to the cluster on the sub-fault marked with the arrow in Fig. 4(c). Asterisks denote principal stress axes expected theoretically for a normal fault whose plane is parallel to the sub-fault (180° in dip direction and 70° in dip angle). Open and solid symbols denote the P- and T-axes, respectively.

assuming the model of Satoh et al. (1990). The model could fit the polarity distributions for eighty-three type-X events with no inconsistent data, and for nineteen type-X events with one inconsistent datum.

Focal mechanism solutions of events belonging to a cluster will provide us important information on micromechanics of fault development in rock by comparing them with geometry of the cluster and/or that of the macroscopic fracture plane on which the cluster is located. We examined the focal mechanism solutions for events belonging to the cluster pointed out with an arrow in Fig. 4(c). This cluster is located on the sub-fault, which dips toward the negative direction of the x axis at a dip angle of about 70°. The polarity distributions were obtained for sixteen events. The source location, first motion polarity data, the type of polarity distribution pattern and the source parameters of shear components are listed in Table 2. Two events were found classified as type-Q, while the other fourteen events showed the type-X distributions. However, the number of dilatational first motions were comparable to that of the compressional ones for most of the events, indicating that they included large shear components. Figure 6 shows the distribution of the principal stress axes of the shear components. The shear components had similar focal mechanisms to that expected from a normal fault whose plane is parallel to the sub-fault. The dip angles of the nodal planes almost parallel to the sub-fault (nodal plane 1 in Table 2) ranged from 45° to 80°.

4. Summary and Discussion

A remarkable concentration of AE hypocenters around a part of the main fault plane was found prior to the ultimate fracture of Oshima granite. It must be noted that the planar localization of microfracture prior to the ultimate fracture, as reported earlier by Spetzler et al. (1977), Lockner and Byerlee (1980), Granryd et al. (1983) and Kurita et al. (1983) and by this study, is not always observed in laboratory fracture experiments. Hirata et al. (1987) have found from a triaxial creep test of Oshima granite that the spatial distributions of AE hypocenters have fractal structures, and that the fractal dimension decreases with the progress of creep. This means that AE events tend to
cluster with evolution of rock fracture. In their experiment, however, the localization is a volumetric one rather than a planar one even during the tertiary creep stage. From SEM (scanning electron microscope) observations of microcracks in Westerly granite samples deformed triaxially up to various stages of deformation, Wong (1982) revealed that it is not until post-failure stage that the localization of microcracks becomes evident. In our experiment, the region where the precursory localization first formed was close to the cluster activity that was observed during the first two loading cycles. This suggests that the presence of the pre-existing macroscopic heterogeneity that caused the cluster activity during cycles-I and -II might have influenced the appearance of precursory localization. It is necessary to confirm whether the results of the present experiment represent some general features of precursory localization of microfractures or they depend largely on location, size, shape, etc. of the pre-existing macroscopic heterogeneity in rocks.

From the space-time distribution of AE hypocenters (Fig. 3), we could follow the evolution of the precursory localization; the localized zone began to form in the lower part of the sample, and then extended upward slowly resulting in brittle fracture which occurred when the front of the localized zone reached the central portion of the sample. The AE events did not show a simple planar distribution pattern, but formed a number of clusters in which the events aligned in the directions parallel or conjugate to the main fault (Fig. 4). This suggests that a system of small shear faults developed in the localized zone.

The focal mechanism solutions of the events that belonged to the cluster on the sub-fault indicate that these events included large shear components, and that the shear components had focal mechanisms similar to that expected from a normal fault whose plane was parallel to the sub-fault (Fig. 6). The SEM observations by Wong (1982) found that a localized zone of deformation in post-failure stage is comprised of a number of almost coplanar shear cracks at dip angles of 45-75°. He concluded that a fault is formed by coalescence of axial crack arrays and networks with the inclined shear cracks. If we assume that the nodal plane subparallel to the sub-fault corresponds to the crack plane, the range of dip angle (45-80°) is consistent with the microcrack observations by Wong (1982). Shear linking of axial crack array is one of the most plausible mechanisms of fault development.

Acknowledgments: We thank T. Hirata for his assistance during the experiment and discussion. We also thank A. Cho and M.V.M.S. Rao for reviewing the manuscript.

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