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Takashi Satoh
Geological Survey Of Japan

Shivakumar Karekal
National Institute of Rock Mechanics, skarekal@uow.edu.au

Osamu Nishizawa
Geological Survey Of Japan

K Kusunose
Geological Survey Of Japan

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Abstract

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Keywords

triaxial, under, amphibolite, plane, fracture, ultimate, along, microfractures, development, creep, localization, precursory

Disciplines

Engineering | Science and Technology Studies

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Precursory localization and development of microfractures along the ultimate fracture plane in amphibolite under triaxial creep

Takashi Satoh[1], Karekal Shivakumar[2], Osamu Nishizawa[1], and Kinichiro Kusunose[1]

Abstract. In a triaxial creep experiment in amphibolite, we clearly found a precursory localization and development of microfractures along the final fracture plane using an AE (acoustic emission) source location technique. The precursory localization of AE hypocenters first nucleated near a pre-existing macroscopic defect and then extended gradually along the final fracture plane prior to failure. On the other hand, no significant precursory localization of AE hypocenters on the final fracture plane before failure has been reported in rock samples free of pre-existing macroscopic defects. This difference in AE occurrence patterns before failure could be explained by the difference in the degree of damage in the portion of the rock surrounding the localization zone when it nucleates.

Introduction

Using loading apparatuses that can deform a brittle rock sample quasi-statically throughout its entire fracture process, *Wong* [1982] and *Lockner et al.* [1991] found that localization of microfractures on the macroscopic fracture plane usually occurs at almost the same time that the peak differential stress is attained. It is expected from their results that, if we deform a brittle rock sample with a conventional loading machine, few indications of fault nucleation can be detected, because the sample fractures violently in a fraction of a second when the differential stress reaches the strength of the sample. However, several authors have reported precursory localization of microfractures around the final macroscopic fault by using holographic interferometry [e.g., *Spetzler et al.*, 1977] and AE (acoustic emission) source location [e.g., *Lockner and Byerlee*, 1980] techniques.

Development of microfractures in space and time is of primary importance for understanding the fault formation process in rock. In order to see the microfracturing process, AE source location has a major advantage in that it can detect the three-dimensional distribution of microfractures, while holographic interferometry can only detect deformation on the sample surface. Among a number of rock fracture experiments under various loading conditions that we have completed [e.g., *Satoh et al.*, 1986, 1990; *Lei et al.*, 1992], we have only twice found clear evidence of precursory localization of AE hypocenters around the final macroscopic fault plane: once in granite in a triaxial cyclic loading experiment [*Satoh et al.*, 1990], and more recently in amphibolite in a triaxial creep experiment. In this paper, we discuss which case such precursory localization of microfractures is sometimes observed on the basis of the experimental results of the amphibolite creep experiment. We also discuss microfracturing that occurred during formation of a macroscopic fracture plane by means of AE focal mechanism.

[1]Geological Survey of Japan, Tsukuba, Japan.
[2]National Institute of Rock Mechanics, Kolar Gold Fields, India.

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Experiment

A fine grained amphibolite sample was collected from the 700 m depth level of the Champion Reefs Mine, Kolar Gold Fields, India. A right circular cylinder 50 mm in diameter and 100 mm in length was precisely prepared. The sample contained a healed vertical joint about 1 mm in mean aperture dividing it into two equal halves.

AE waveforms were detected using 16 longitudinal type piezoelectric transducers; 14 on the sample side surface and 2 in the end-pieces attached to the top and bottom ends of the sample. Six cross-type metal foil strain gauges 5 mm in length were bonded along the sample mid-plane at 60° intervals to measure axial and circumferential strains.

The sample was subjected to a constant differential stress of 570 MPa at a confining pressure of 30 MPa, which is about 85 % of the short-term fracture strength. Figure 1 shows the observed strains as functions of differential stress for the loading stage and of time for the creep stage. The ultimate fracture occurred in a violent manner about 114 minutes after the beginning of creep, and the macroscopic fracture plane was formed as shown in Figure 2. The fracture plane was oriented at about 20° with respect to the maximum compression axis, a typical orientation for triaxial compression [*Paterson*, 1978].

Results

Figure 2 shows the temporal change of the AE hypocenter distribution during the creep stage. Hypocenters

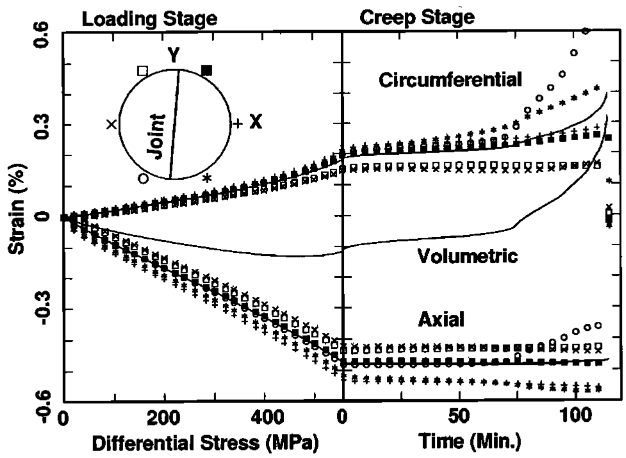

Figure 1. Strains as functions of differential stress during the loading stage (left) and of time during the creep stage (right). The solid lines indicate the average strains. Symbols indicate positions of the strain gauges.

are plotted for the events which were located with a probability error smaller than 2 mm. The time intervals are selected so that we can see the temporal change of the distribution pattern clearly.

During the first 60 minutes after the beginning of creep, most AE events were concentrated on a linear segment, located along the intersection of the pre-existing joint and the final fracture plane (Figure 2(a)). A composite focal mechanism for the events in this linear cluster is shown in Figure 3(a). Neither of the two nodal planes of the focal mechanism solution coincide with the pre-existing joint. Instead, one of the nodal planes (C in Figure 3(a)) is roughly parallel to the AE cluster and perpendicular to the pre-existing vertical joint. From this focal mechanism solution, we can speculate that these AE events resulted from normal faulting on a thin linear crease that forms a small jog on the pre-existing joint surface. Thus, the reproducibility of these experimental results is not expected. In spite of this, the results provide us important information about the failure process of rock samples containing pre-existing macroscopic defects.

The linear AE cluster shown in Figure 2(a) remained active until fracture (Figure 2(b)-(e)). However, during the second interval, AE activity in the region where the linear cluster intersected the sample surface began to broaden (Figure 2(b)), and it continued to extend along the circumferential surface on the final fracture plane (Figure 2(c)-(e)). From the average volumetric strain (Figure 1), it appears that tertiary creep started at about 70 minutes. However, the local strains were very uneven. Two strain gauges close to the place where the precursory AE activity nucleated (o and * in Figure

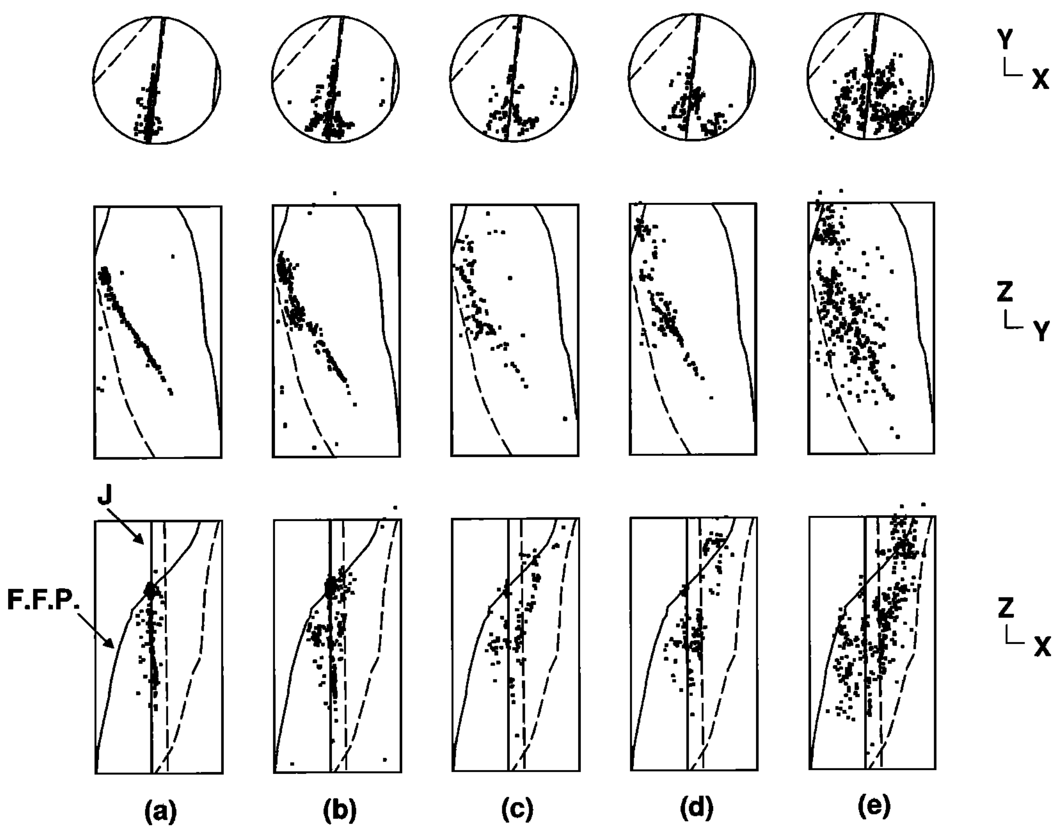

Figure 2. Orthographic projection showing the spatial distribution of AE hypocenters during (a) 0-60, (b) 60-100, (c) 100-110, (d) 110-113, and (e) 113-114 minutes from the beginning of creep. Surface traces of the final fracture plane (F.F.P.) and the pre-existing joint (J), which appeared on the front and rear sides of the sample, are drawn by solid and dashed lines, respectively.

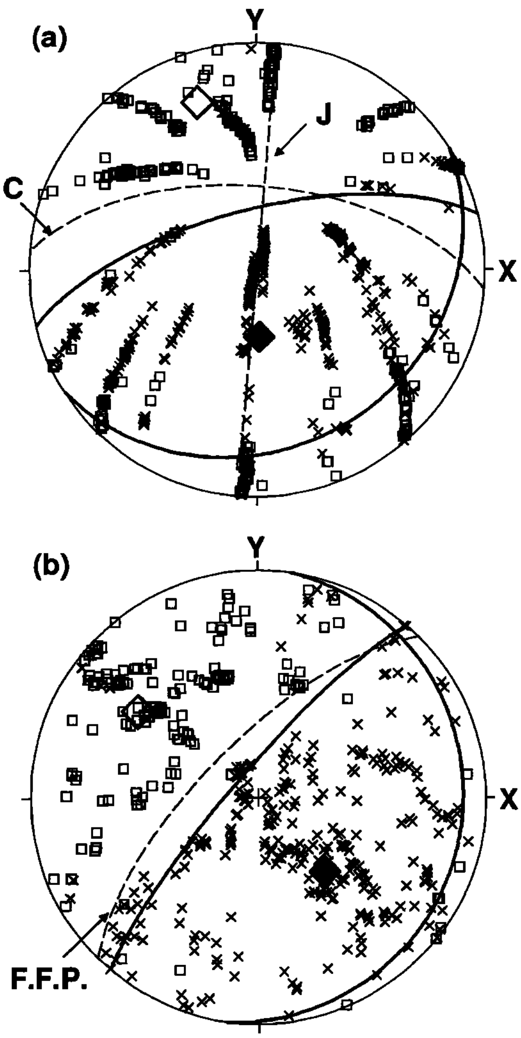

Figure 3. Composite polarity distribution of P-wave first motions and its best-fit, quadrant type focal mechanism solution. Squares and crosses denote compressional and dilatational first motions, respectively. Thick solid lines indicate nodal planes of the focal mechanism solution. Solid and open diamonds represent the P- and T-axes, respectively. The data are plotted on a lower focal hemisphere by equal area projection. (a) events belonging to the linear cluster shown in Figure 2(a). Dashed line marked by J indicates the pre-existing vertical joint, and that marked by C, the plane parallel to the alignment of the AE cluster and perpendicular to the pre-existing joint. (b) events plotted in Figure 2(e) except for the events belonging to the linear cluster. Dashed line marked by F.F.P. indicates the final fracture plane.

1) showed remarkable accelerations in circumferential strain.

From the x-z projections of the hypocenter distribution in Figure 2, we can see that the AE activity diminished after the front of the precursory events passed (Figure 2(b)-(e)). Most events that occurred behind the front were those belonging to the linear AE cluster. A similar distribution pattern of AE hypocenters was found during the post-failure stage in a Westerly granite triaxial compression experiment conducted by *Lockner et al.* [1991]. They concluded that these AE events occurred in the process zone ahead of the slowly expanding macroscopic fracture plane. Their interpretation supports the idea that the distribution pattern of the AE hypocenters found in Figure 2(b)-(e) resulted from quasi-static growth of the final fracture plane prior to failure. Figure 3(b) shows a composite distribution of the first motion polarities for the events plotted in Figure 2(e), except for the events belonging to the linear cluster. The distribution can be well fit by a quadrant type focal mechanism solution whose steeper nodal plane is almost coincident with the macroscopic fracture plane.

Discussion

The focal mechanism solution shown in Figure 3(b) is the first solution for the events which occurred in the process zone, and provides us with a very important clue to the fault formation process in rock. It is noted that this focal mechanism is apparently different from that for the linear cluster (Figure 3(a)). This suggests that the events which occurred in the process zone were not greatly affected by the existence of the pre-existing joint, but represents some general feature of microfracturing in the process zone. It has been reported that shear type AE events become dominant approaching final fracture in fine grained andesite [*Satoh et al.*, 1986] and in medium grained granite [*Satoh et al.*, 1990; *Lei et al.*, 1992]. They interpreted that these events occurred by crack-crack interaction (connection of cracks by sliding). The focal mechanism solution shown in Figure 3(b) indicates that, in the process zone ahead of the macroscopic fault, crack-crack interaction was the dominant process of microfracturing. This result is consistent with recent theoretical and experimental studies on fault nucleation and growth process in rock [e.g., *Reches and Lockner*, 1994; *Moore and Lockner*, 1995]. In order to understand the crack-crack interaction occurring in the process zone, it is very important to know which nodal plane corresponds to the shear crack. From a microscopic observation of Westerly granite samples, *Moore and Lockner* [1995] suggest that linking cracks with a shear crack at a small angle to the maximum compression axis occurs just in front of the macroscopic fault. *Kranz* [1979] found, from scanning electron microscope observations of an uniaxially stressed Barre granite, an example of *en echelon* linkage by shear cracks whose planes are almost perpendicular to the maximum compression axis. Thus, at present, we can not reject the either of the two possibilities.

A failure process similar to that presented here was observed in the granite cyclic loading experiment reported by *Satoh et al.* [1990] . A cluster of AE hypocenters appeared in an early stage of the experiment. *Satoh et al.* [1990] interpreted this cluster to be due to a pre-existing macroscopic defect. The precursory localization of AE activity nucleated near this early cluster and extended gradually along the final fracture plane, followed by the ultimate failure. In both experiments, the precursory nucleation and development of a macroscopic fracture plane was induced by a pre-existing macroscopic defect probably due to stress concentration around it. AE clustering from early stage of loading on the eventual fracture plane was also observed in triaxial compression experiments on sandstone conducted by *Lockner et al.* [1992]. *Lockner* [1993] and *Lockner et al.* [1992] attributed these early AE clusters to the presence of a pre-existing weak zone. Our experimental results support their interpretation. On the other hand, no significant precursory localization of AE hypocenters on the final fracture plane has been reported when we deformed rock samples free of pre-existing macroscopic defects. *Lockner et al.* [1991] were able to follow quasi-statically the entire fracture process of a brittle granite sample by controlling the axial load so as to maintain a constant AE occurrence rate. They found from AE source locations that fault nucleation occurred at the sample surface soon after the peak stress was attained, and that the fault plane grew across the sample, accompanied by a gradual drop in axial load. If we deform a similar rock sample with a conventional loading apparatus, we would expect to detect little precursory localization of AE hypocenters because the fracture process after the peak stress would occur violently in a fraction of a second. This difference in the AE occurrence pattern before failure could be explained by a difference in the degree of damage in the region surrounding the fault zone when it nucleates.

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T.Satoh, O.Nishizawa and K. Kusunose, Geological Survey of Japan, 1-1-3, Higashi, Tsukuba, Ibaraki, 305 Japan (e-mail: satoh@gsj.go.jp)

K. Shivakumar, National Institute of Rock Mechanics, Kolar Golds Fields, Karnataka, 563-117 India

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