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# The Effect of Velocity Anisotropy on AE Source Locations in a Very Large Granite Sample

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**Abstract**

Hypocenters of 110 AE (acoustic emission) events were determined in an octagonal prismatic sample of Inada granite under uniaxial compression assuming two kinds of velocity distributions. Compressional wave velocities used in this computation were measured in the same Inada granite as previous ones under uniaxial compression. Comparing AE hypocenters determined assuming a uniform velocity with ones determined assuming velocity anisotropy with axial symmetry, it is clear that the latter distribution corresponds to the final fracture surface better than the former one. And it is clear that it is possible to trace the process of fracture in a rock sample using the space-time distribution of the latter AE hypocenters. However, the fact that the correspondence between the latter AE hypocenters and the final fracture surface is not very good suggests that the velocity distribution may be locally inhomogeneous in the sample.

## 1. Introduction

It is well known that the elastic wave velocity of rocks initially isotropic becomes anisotropic upon application of nonhydrostatic stress (e.g. Tocher, 1957; Nur and Simmons, 1969: Gupta, 1973; Bonner, 1974; Fujii and Hamano, 1977; Lockner et al., 1977; Soga et al., 1978). Therefore it is considered that the anisotropy of elastic wave velocity (VA) could not be caused by preferred orientation of minerals composing the rock, but by closure of pre-existing cracks or by preferred orientation of stress-induced cracks in the rock.

On the other hand, it is necessary to determine the locations of these cracks to investigate the physical process of fracture of rocks. Mogi (1968) discussed the relation between the two dimensional distribution of acoustic emission (AE) hypocenters and the final fracture in various rocks subjected to bending stress. Although several studies on AE hypocenters in three-dimensional cases have been done recently under nonhydrostatic stress (.e.g. Scholz, 1968; Lockner and Byerlee, 1977; Nishizawa et al., 1981; Sondergeld and Estey, 1981), all of these studies, except for Nishizawa et al. (1981), do not take VA into account on the determination of AE hypocenters. Nishizawa et al. (1981) have determined AE hypocenters assuming that VA was symmetric with respect to the load axis.

Thus we have measured the compressional wave velocities in four directions as described later on granite samples under uniaxial compression, and we have determined AE hypocenters on a very large granite sample under uniaxial compression with two kinds of velocity distribution using previous results. One kind of velocity distribution is a uniform distribution in a sample, the other is an anisotropic one with axial symmetry. In this paper we will investigate the influence of VA on the locations of determined AE hypocenters and discuss two kinds of AE hypocenters, comparing them with the location of the final fracture surface.

## 2. Experimental methods

### 2.1 *Velocity measurement*

A dry rock sample of Inada granite was used. The rectangular prismatic sample having a size of $3.1\times3.1\times9.5$ cm was prepared. Opposing faces were ground parallel to within $\pm0.005$ cm. The characteristic constants of the sample are given in Table 1. The original sample was almost isotropic within the limits of experimental error. This experiment was performed under uniaxial compression using a 50t uniaxial press. The mean stress rate was about 3.5 bars/sec which corresponded to about $6.4\times10^{-6}$/sec in strain rate.

In this experiment, for detecting VA, compressional wave (P wave) velocities were measured in four different directions whose angles with regard to the load axis ($\theta$) were 6°, 30°, 60° and 90°, respectively, as shown in Fig. 1(a). The block diagram of the measurement system is shown in Fig. 1(b). For the velocity measurement by the pulse transmission method (Birch, 1960), five PZT of compressional mode with a resonant frequency of 5 MHz were cemented to the upper end-piece and the sample with epoxy.

The velocity measurement system is as follows: Signals generated at the pulse generator (PG) are received at each sensor and amplified and, after

Table 1. Characteristic constants of the granite sample

| | | |
|---|---|---|
| mean grain size | 1.5 mm | |
| density | 2.65±0.02 g/cc | |
| porosity | 0.6±0.1% | |
| $P$ wave velocity (initial) | 4.43±0.13 km/sec | |
| compressional strength | 1.8±0.1 Kbar | |
| tensile strength | 170±20 bar | (after Maeda, 1981) |
| $Q_\alpha$ value | 300 | (after Kanema, 1977) |

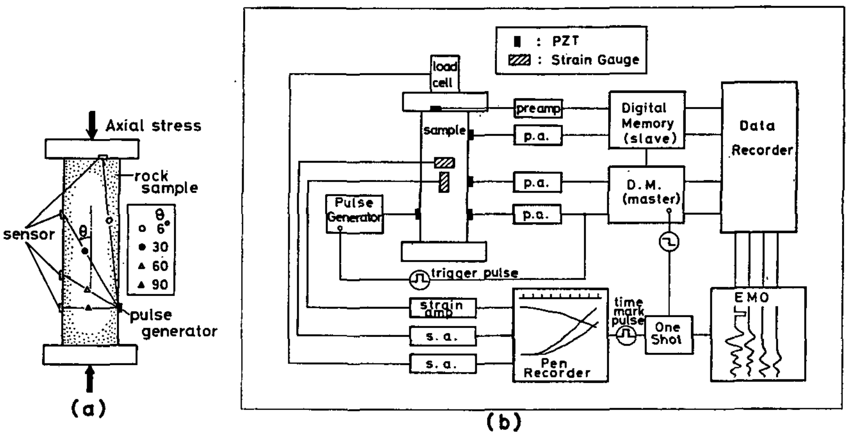


Fig. 1. Sensor arrangement (a) and block diagram of the velocity measurement system (b).

A/D conversion, they are memorized in a RAM temporarily. For detecting the origin time, trigger pulses generated at the PG, which are synchronized with the signals generated at the PG, are also memorized in a RAM temporarily, after A/D conversion. When the RAM is filled, the data are read out and are sent to a magnetic tape recorder (MT). The recorded data are reproduced on an electromagnetic oscillograph (EMO). P wave travel times are read from these reproduced records. By using this measurement system, about 50 data on velocity were obtained during the experiment.

On the other hand, the axial load was measured by a load cell and the strain was measured by two strain gauges attached to the sample.

### 2.2 *Experimental method for monitoring AE*

The rock sample used was the same Inada granite as in the previous experiment. The octagonal prismatic sample having a size of 32×32×80 cm was prepared. Thin lead plates were attached to both ends of the sample. The loading machine was a 2,500 t uniaxial press which had already been reported in detail by Maeda (1979a). The axial load was measured by a specially designed stress cell (Maeda, 1979b). The mean stress rate was 4.9 bars/min which corresponded to about $1.5 \times 10^{-7}$/sec in strain rate. The strain was measured by four strain gauges attached to the central part of the sample as shown in Fig. 2. For detecting AE, five PZT of compressional mode with a resonant frequency of 5 MHz were cemented to the sample with epoxy as shown in Fig. 2. This measurement system has already been described in detail by Maeda (1979c). The AE data were classified in five groups according to the passage of experiment. The data with good S/N ratios were selected out of a large number of data reproduced on an EMO in each group.

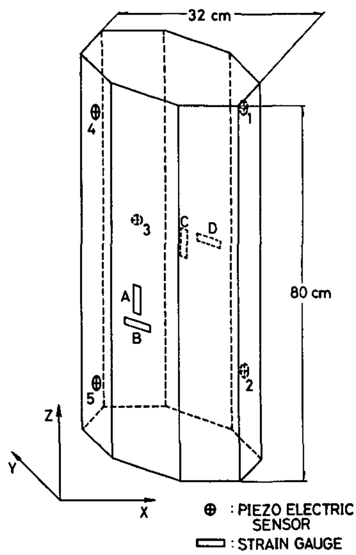


Fig. 2. PZT and strain gauges arrangement of a very large sample for monitoring AE.

## 3. Results and discussion

The volumetric strain, which is calculated from the axial strain and the lateral strain, and the relative velocities normalized to initial velocity are plotted as a function of axial stress in Fig. 3. Symbols used in this figure correspond to ones defined in each direction as shown in Fig. 1. The effect of axial stress on P wave velocities observed in our experiment (Fig. 3) is about the same as that observed in previous experiments (e.g., Tocher, 1957; Nur and Simmons, 1969; Fujii and Hamano, 1977). The experimental results on velocity may be summarized as follows; P wave velocities in each direction, more or less, increase with volume reduction of the sample and then decrease with its volume expansion. The rate of velocity increase and that of decrease depend on propagation direction ($\theta$). The dependence of velocity on $\theta$, which is the same as that observed by Nur and Simmons (1969), could be expressed here as a function of $\cos 2\theta$ under a given axial stress.

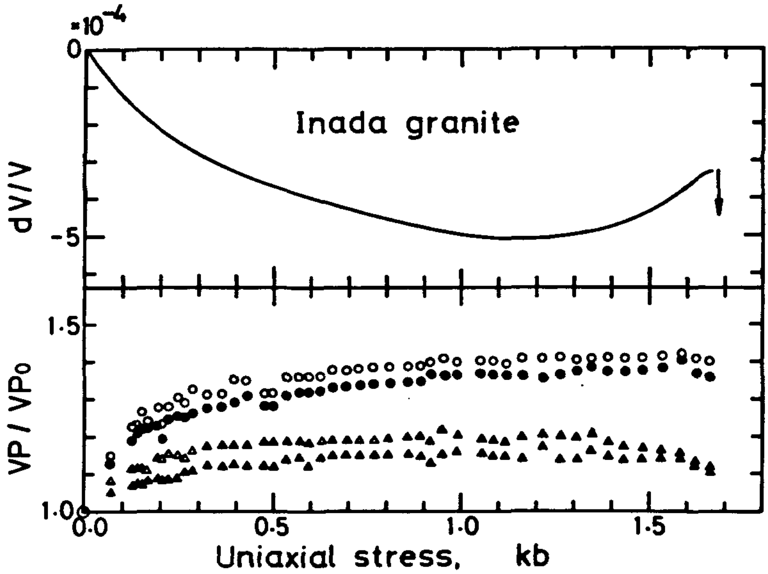


Fig. 3. Variations of volumetric strain and P wave velocities in four directions versus axial stress.

Hypocentral locations of AE were determined by the weighted least square method assuming two kinds of velocity distributions. One of the velocity distributions was uniform distribution in a sample, the other was an anisotropic one, which was axially symmetric with respect to the load axis. In the latter case, velocities along the ray paths from AE events to each receiver were given by the previous results on velocity. In this computation, P wave arrival times only were used, and the weights were determined according to the clearness for the onsets. The errors for reading the arrival times were within 1 $\mu$sec, and the computational errors for AE hypocenters were within $\pm 1$ cm.

AE hypocentral distribution of 110 events for uniform velocity distribution is shown in Fig. 4, and for the anisotropic one with axial symmetry in Fig. 5. In these figures, the projection on XY plane, on XZ plane and on YZ plane of AE hypocenters are shown. The location of the final fracture surface, which was observed after experiment, is also shown in these figures by heavy lines. The following become clear after the investigation on comparing two kinds of AE hypocentral distributions.

(1) AE event clustering is more evident for an anisotropic case than for a uniform case.

(2) VA makes AE hypocenters located in the central part of the sample for uniform case move almost parallel to Y axis, and ones located in the upper part move upward.

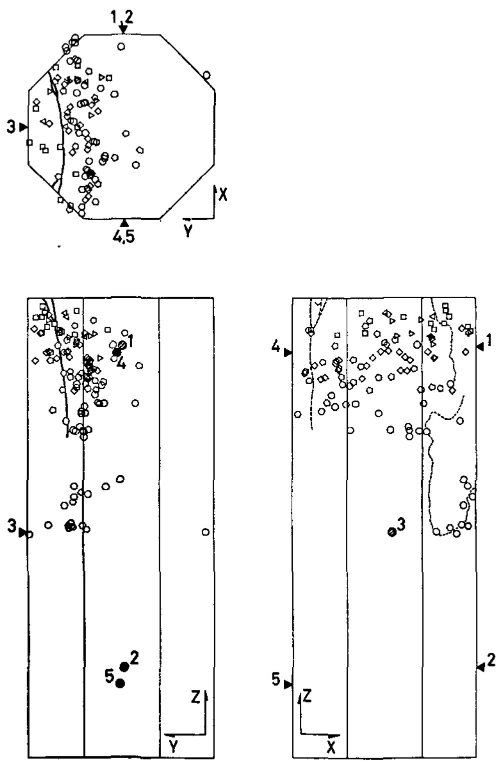


Fig. 4. AE hypocentral distribution calculated with a uniform velocity distribution. Bold and broken lines are the traces of cracks appearing on the sample surface.

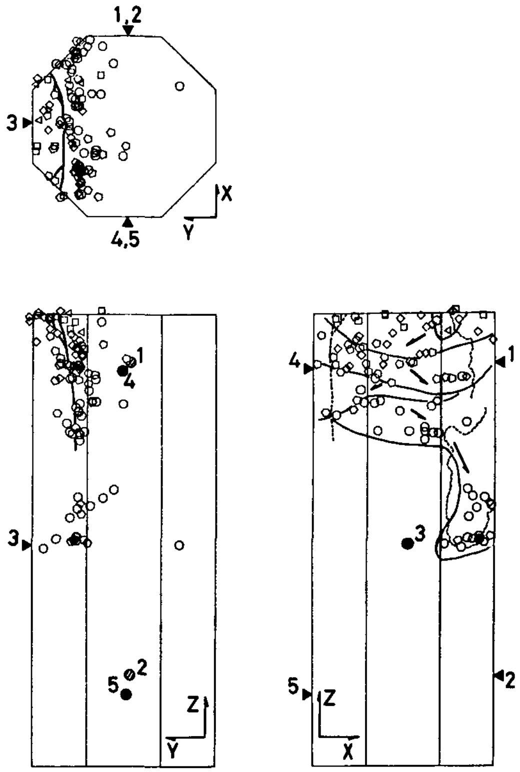


Fig. 5. AE hypocentral distribution calculated with an anisotropic velocity distribution. Bold lines in the projection on XZ plane show the front of fault at each stage of compression.

Although AE hypocentral distribution for a uniform case would not correspond well to the location of the final fracture surface, for an anisotropic case it would correspond relatively well, however not well enough to estimate the location of the final fracture surface. With these facts, the assumption that velocity distribution is anisotropic with axial symmetry is not well sustained. We suggest that the velocity distribution may be unexpectedly inhomogeneous locally in the sample.

The axial and lateral strains are plotted as a function of axial stress in Fig. 6. We see in Fig. 6 that both strains (A, B gauges in Fig. 2), which were measured at about the central part of the sample, show the elastic behavior. On the other hand, since a large number of AE occured and the fracture surface was formed at the upper part of the sample, strains at this vicinity should show the anelastic behavior. Really strain at C gauge shows the anelastic behavior. This fact also suggests that the sample becomes inhomogeneous locally. Maximum axial stress is 550 bars, that corresponds to the axial stress of about 30% of the ultimate strength. It can be considered that the formation of fracture surface at such a low stress level is due to the inhomogeneous loading.

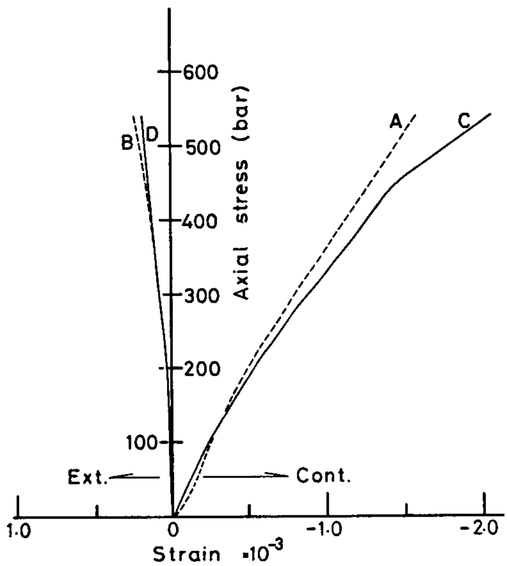


Fig. 6. Stress-strain relations. Symbols A to D attached to lines correspond to ones shown in Fig. 2.

The process of AE occurence with time is shown schematically in the projection on XZ plane in Fig. 5. We see here that the region of AE occurence migrates downward accompanied with the lateral migration. We conclude that it is necessary to take VA into account to determine, with accuracy, the locations of AE hypocenters, and that it is possible to trace the process of fracture in a rock sample using AE hypocenters determined in such a way. It may be necessary to take account of factors like a station correction in seismology to determine the location of AE hypocenters with a higher degree of accuracy.

## 4. Conclusion

We determined the hypocentral locations of AE observed in the fracture experiment of Inada granite under uniaxial compression. It is clear that, if VA is taken into account in this computation, the absolute accuracy of the results is improved when compared with that of results computed assuming a uniform velocity distribution. AE hypocenters determined assuming anisotropic velocity distribution are useful tools to trace the process of fracture in a rock. However, one should note that velocity inhomogeneity other than anisotropy with axial symmetry exists locally in the sample.

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