Broadband P waves transmitting through fracturing Westerly granite before and after the peak stress under a triaxial compressive condition

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We analyzed temporal changes in the velocity and amplitude of P waves transmitted through a granite sample during a triaxial compression test, with the goal of monitoring the fault formation process associated with open and shear cracking. We used newly developed transducer assemblies for the broadband recording, and we continued to record transmitting waves even after the peak stress occurred. For transmitting P waves with paths parallel to the maximum compressive axis, we found that both the first wave amplitude and the velocity decreased after dilatancy started, and they kept decreasing even after the peak stress. In addition, the large nonlinear decrease in amplitude was associated with a rapid decrease in differential stress, whereas the rate of decrease in velocity remained almost constant. Thus, before the rapid decrease of differential stress, when both the amplitude and the velocity gradually decreased, open cracking was indicated to be dominant. Thereafter, shear cracking was indicated to become dominant in synchronization with the rapid decrease in differential stress. It is suggested that a main fault started to grow around the sample surface and then progressed into the sample interior; this corresponded to the rapid stress decrease. This fault acts as a strong scatterer for P waves that are parallel to the maximum compressive axis.

Key words: Broadband recording, fracturing Westerly granite, triaxial compression test, post-peak stress, transmitting P wave, amplitude change, velocity change, fault formation process.

1. Introduction

When a low differential stress is applied to a rock mass, some of the open cracks that were contained by static pressure close, so that the crack density decreases. As the differential stress increases, new cracks are generated and dilatancy appears. The decrease and increase of open cracks associated with loading and the elastic deformation of the mineral grains result in a volumetric change and a change in the elastic properties of the medium, such as V_P (the P wave velocity) and V_S (the S wave velocity). In these cases, we can use a transmitting wave to monitor the fracturing rock interior. For example, Lockner *et al*. (1977) recorded transmitting waves with paths that were perpendicular to the maximum compressive axis under a triaxial condition. They found that V_P, V_S, and the first wave amplitude rapidly decreased just before the fracture strength was reached. Yukutake (1989) recorded transmitting waves along 20 separate paths that were perpendicular or oblique to the maximum compressive axis and used them to compute a velocity tomography. They reported that V_P started to decrease only around a prospective fault plane just before the compressive strength value was reached.

To image a fracture growth in more detail, it is essential to investigate the characteristics of the transmitting wave even after the peak stress level occurs. Lockner *et al*. (1992) and Kawakata *et al*. (1999) both developed systems that can control the fracture process even after peak stress, and they imaged the quasi-static fracture growth using acoustic emission (AE) activities and X-ray computed tomography (CT) images, respectively. Nevertheless, there have been few studies that investigated the temporal changes in wave velocity and amplitude after peak stress occurs. Using the AE feedback technique by Lockner *et al*. (1992), Thompson *et al*. (2006) measured the velocity of transmitting waves through a rock sample after peak stress, while recording AE. However, since they were mainly interested in AE characteristics, they had a long interval between velocity samples, making it difficult to discern the detailed velocity change in their experiments.

Also, only narrowband transducers were used in many previous studies to obtain wave data (including those of Lockner *et al*., 1977, 1992; Thompson *et al*., 2006). If narrowband transducers are used both to radiate the transmitting waves and to record them, then the recorded data only include the influence of cracks whose sizes correspond to the resonant frequency of the transducers. Sellers *et al*. (2003) carried out a broadband AE recording in a uniaxial compression test and proposed a scaling for the AE. A new transducer assembly was developed by Kawakata *et al*. (in preparation) to apply broadband transducers under triaxial conditions.

In this study, we used broadband transducers to investigate temporal changes in the velocity and amplitude of transmitting *P* waves through a triaxially compressed granite sample even after the peak stress occurred. We used a wave path parallel to the maximum compressive axis; this differs from many previous studies which used perpendicular paths (e.g., Lockner *et al*., 1977; Yukutake, 1989). A parallel path of a *P* wave should be less sensitive than a perpendicular path to any open cracks that are parallel to the maximum compressive axis that is dominant in a dilatancy phase. Thus, if there are phases where other types of cracking are dominant, it would be more likely to appear on the records of a parallel path rather than a perpendicular path.

2. Experiment and Data

Our experimental procedures were the same as those of Kawakata *et al*. (1999), with the exception of the confining pressure. We prepared a cylindrical sample of intact Westerly granite that was 50 mm in diameter and 100 mm long. A confining pressure of 80 MPa was maintained under a dry condition at an ambient temperature. Figure 1 shows the stress-strain relationships for this experiment. The sample was loaded at a constant circumferential displacement rate, and it was unloaded when it experienced a stress decrease of ~10 MPa after having reached peak stress. The recovered sample has a fault trace of ~70 mm on its surface (Photo 1).

Figure 2 shows a schematic image of the broadband recording system developed by Kawakata *et al*. (in preparation). *P*-wave type piezoelectric transducers (Olympus-NDT corporation V103RM) with a sensitivity higher than 50% over a frequency range around 600–1600 kHz were attached inside the upper and lower "end pieces" (Fig. 2). We repeatedly applied 50-V pulses with a duration of 1/80 s to the upper transducer every 1/40 s, and at the lower transducer we recorded the transmitting waves resulting from rising portion of the pulses, for 2 ms at 100 MS/s.

The elastic waves were originally recorded without stacking to maintain their temporal resolution (Fig. 3(a)), and were posteriorly stacked 100 times to improve the *S*/*N* ratio (Fig. 3(b)). The cross-correlations between the original

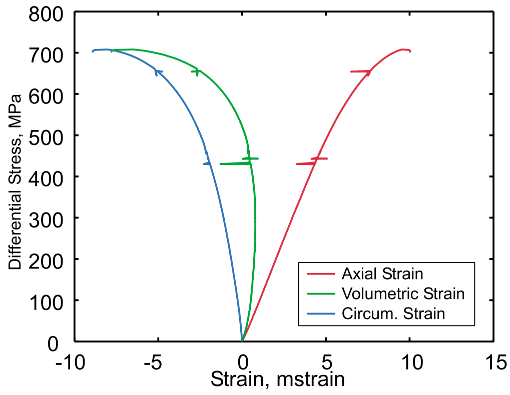

Fig. 1. Stress-strain relationships in the experiment. The red, green, and blue curves show axial strain, volumetric strain, and circumferential strain, respectively.

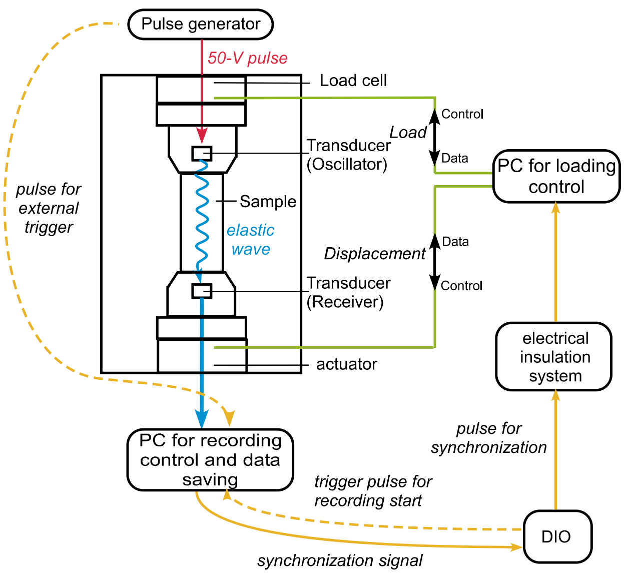

Fig. 2. A schematic image of the recording system for broadband elastic waves.

waveforms and the stacked waveforms were so high (≥0.9) that the stacked waveforms could be considered to be identical to the original waveforms. The spectra of stacked waves appeared flat in the frequency range 200–1000 kHz (Fig. 3(c)). Thus, we analyzed 100-times stacked waveforms without any corrections to transducer properties.

Photo 1. A photograph of the sample recovered after unloading. A fault trace and a fault edge are visible on the sample surface.

3. Analysis and Results

We estimated the *P* wave arrival time using the AR model with the AIC (Kitagawa, 1993). We defined the peak-to-peak amplitude of the first cycle as the first wave amplitude. We refer to the *P* wave velocity and the first wave amplitude at the start of the loading as V_0 and A_0, respectively. Under a confining pressure of 80 MPa, V_0 was 5952 m/s. Typical waveforms around the *P* wave onsets shown in Fig. 4 indicate temporal changes both in the *P* wave velocity and in the first wave amplitude.

Figure 5 shows the temporal changes in the differential stress, the *P* wave velocity, and the first wave amplitude, where the time of origin was set to be the time the loading started. The *P* wave velocity increased about 3.5% of V_0

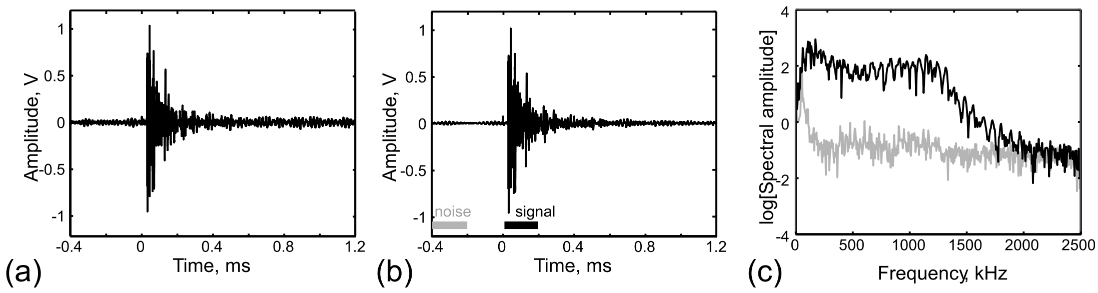

Fig. 3. (a) A typical transmitting waveform of the original recording (2279 s). Bimodal periodic noise has contaminated the waveform. (b) A stacked waveform (100 times) of (a). (c) Spectral amplitudes of the signal (black) and noise (gray) for the stacked waveform. Time windows for the spectra are indicated with black and gray thick lines in (b).

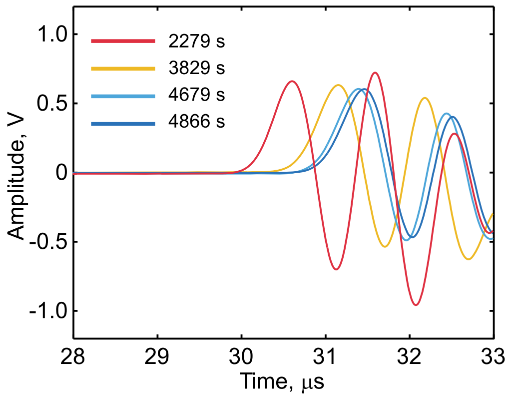

Fig. 4. Typical waveforms around the *P* wave onsets. The recorded time of each waveform is indicated by an arrow in the same color as the waveform in Fig. 5(c-1).

until dilatancy started, and then decreased 4.5% at an almost constant rate of 0.0016%/s (Fig. 5(b-1)). After the peak stress, the *P* wave velocity kept decreasing at a similar rate down to ∼5900 m/s; this velocity is ∼1.0% slower than V_0 (Fig. 5(b-2)).

The first wave amplitude increased about 4% of A_0 until dilatancy started. Sudden decreases in differential stress, together with the sounds that corresponded to small fractures, occurred around 2129 s and 3366 s after the loading started, but the differential stress recovered quickly. At the small fracture around 2129 s, the first wave amplitude suddenly decreased about 10%. After that, it decreased 20% at an almost constant rate of 0.0072%/s (Fig. 5(c-1)). Except for the sudden decrease in the first wave amplitude around 2129 s, the temporal changes in the amplitude were smooth. The decrease in the first wave amplitude continued after the peak stress at an almost constant rate of 0.0058%/s. The rate of decrease then drastically grew to 0.0238%/s (Fig. 5(c-2)) in synchronization with the rapid decrease in differential stress (Fig. 5(a-2)), while the rate of decrease in *P* wave velocity held constant. The first wave amplitude should have corresponded to the differential stress change.

4. Discussion

For *P* waves with paths parallel to the maximum compressive axis, both their velocity and their first wave amplitude decreased before the peak stress occurred (Fig. 5). The decrease in the parallel *P* wave velocity (4.5% following their increment before dilatancy) was much lower than the decrease in the perpendicular *P* wave velocity (20–30% found by Lockner *et al.*, 1977). The velocity of parallel *P* waves was inferred to be less sensitive than that of perpendicular *P* waves to dilatancy which related to the open cracks that are parallel to the maximum compressive axis.

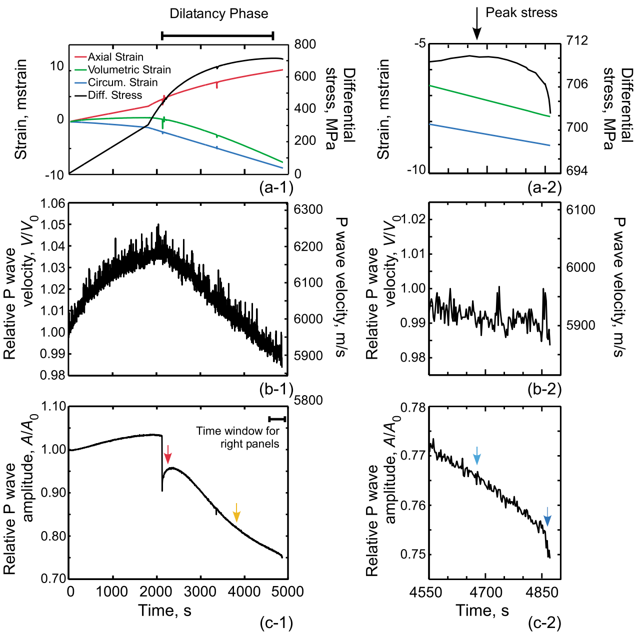

Fig. 5. (a) The temporal changes in differential stress and strains, (b) the *P* wave velocity, and (c) the first wave amplitude. The left panels show the time series of whole loading and the right panels show the enlarged time series around the peak stress.

After the peak stress, the rate of decrease in the first wave amplitude drastically grew in synchronization with the rapid decrease in differential stress, while the rate of decrease in velocity remained almost constant (Fig. 5(b-2), (c-2)). Considering that the sample was loaded at a constant circumferential strain rate, the constant rate of decrease in *P* wave velocity indicated that the *P* wave velocity corresponded to a circumferential strain after dilatancy started. The circumferential strain is related to the porosity resulting from open cracking parallel or subparallel to the maximum compressive axis. The drastic growth of the rate of decrease in the first wave amplitude implies the increase of scatterers other than open cracks, such as shear cracks, and/or the decrease in specific stiffness due to shear faulting (Pyrak-Nolte *et al.*, 1990). We tried to apply the model of Pyrak-Nolte *et al.* (1990) with an incident angle of 60°, but the synthetic waveform shows a clear decrease in velocity rather than the first wave amplitude. This might be because the infinite fault plane is assumed in their model, whereas the developing fault in our experiment was finite and small.

The connection of open cracks resulting into shear cracks should become dominant after the peak stress. This is consistent with a conceptual model by Reches and Lockner (1994) that was proposed from stress computations. Using AE mechanisms, Lei *et al.* (2000) showed that the shear cracking became dominant in a quasi-static fault growth phase; however, the quasi-static fault growth was allowed to occur under the condition of constant stress (creep) loading in their experiments. From quasi-sequential X-ray CT images, Kawakata *et al.* (1999) suggested a sequence of a main fault formation process. At first, cracks open parallel to the maximum compressive axis concentrated near some parts of the sample surface. Then, some of these connect and spread into the sample interior, becoming fault planes. After some time, only one of these fault planes maintains two-dimensional growth after the peak stress. Finally, when in-plane growth of the fault completes at another fault or at the surface of the sample, the rate of decrease in the differential stress increases. Moore and Lockner (1995) also indicated similar features of crack connection after the peak stress through observation of thin sections and AE results by Lockner *et al.* (1992). Based on this idea, the drastic amplitude decrease after the peak stress indicated the rapid growth of a main fault. This is consistent with the surface observation of our recovered sample, in which in-plane fault growth was indicated to be completed at the sample surface (Photo 1), and resistance to in-plane fault slip drastically decreased just before unloading.

We also found that the amplitude of P waves transmitting through a fault was more sensitive than the velocity to a change in the heterogeneity, for the path parallel to the maximum compressive axis. This is likely due to the amplitude being influenced by the attenuation of any frequency in the sensitive range, while only the fastest wave component in the sensitive range affects the velocity, especially in broadband recordings.

Broadband monitoring of transmitting S waves under a triaxial condition with the same configuration of this study, together with the monitoring of P/S waves along perpendicular paths, will enable us to image a fault growth in more detail.

5. Conclusions

We recorded transmitting P waves with paths parallel to the maximum compressive axis, during a triaxial compression test within an intact Westerly granite sample. Broadband recording was continued even after the peak stress level occurred, and we studied the temporal changes in the velocity and the amplitude of transmitting P waves. Together with the rapid decrease in stress after the peak stress, the first wave amplitude drastically decreased, while the rate of decrease in velocity remained almost constant. This is consistent with the understanding of the fault formation process, in which it occurs in the period after the peak stress. First, open cracks subparallel to the maximum compressive axis increase. Next, these cracks connect to form fault planes, and shear cracking becomes dominant. Then, after the peak stress occurs, a fault plane rapidly grows into the sample interior.

It is more beneficial to monitor the fault process in rock samples using the amplitude of transmitting P waves parallel to the maximum compressive axis than using their velocity.

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