Anisotropies of Electrical Conductivities and P Wave Velocities of Cataclasites and Mylonites under Ambient Conditions: Laboratory Measurements of Hatagawa Fault Zone Samples

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Abstract

I conducted measurements at ambient conditions of the electrical conductivities and P wave velocities of mylonite and cataclasite samples collected at the Hatagawa fault zone, which is a large exhumed fault in northeastern Japan. Foliations and lineations were clearly observed in the mylonite samples, but no planar or linear fabric was seen on the cataclasite samples. There was little difference in the conductivities at 1Hz of samples in dry condition. In wet condition, on the other hand, the conductivities of all samples increased by more than one order of magnitude and the conductivities along the three orientations of mylonite were significantly different from each other; the conductivity perpendicular to the foliation is lower by about one order of magnitude. The P wave velocities of the mylonite samples showed anisotropy in both the dry and wet conditions; the velocity perpendicular to the foliation was slowest. The extent of the anisotropy appeared to be small in the wet condition. These results indicate that the distribution and connectivity of cracks in mylonite is anisotropic and that water, which has higher conductivity and lower velocity than the rock matrix, occupies the cracks along the foliation.

Key words : Electrical conductivity, P wave velocity, Anisotropy, Mylonite, Cataclasite

1. Introduction

Recent electromagnetic survey studies have revealed the electrical conductivity structure in the deeper regions of faults (Iio *et al.*, 2000; Ogawa *et al.*, 2001). There seems to be a high-conductivity region around the focal area. The high conductivity may be related to the existence of water in the rocks, which affects the strength and activity of the fault; i.e., earthquake activity. At the same time, the electromagnetic responses indicate a two-dimensional structure of the long period response (Ogawa *et al.*, 2001). Rocks at the focal zone of a fault are expected to be subjected to hard deformation and/or fracturing with alteration. These fault-related rocks, such as mylonite and cataclasite, have characteristic fabrics related to shear deformation. Some experimental studies on the electrical conductivity and P wave velocity of fault-related rocks (Jones and Nur, 1984; Kern and Wenk, 1990; Siegesmund *et al.*, 1991; Matsuzawa *et al.*, 1995) have shown that these rocks seem to have anisotropic physical properties due to oriented microcracks and preferred orientation of minerals.

Mylonite and cataclasite samples were collected from the Hatagawa fault zone in northeastern Japan. The Hatagawa fault zone is regarded as a major exhumed fault. At the surface, mylonite and cataclasite can be observed now that were produced from host rocks in the focal depth region in the past. Under ambient conditions, I conducted measurements of the electrical conductivities and P wave velocities of these fault-related rocks collected from the fault zone, mainly concentrating on the anisotropic features. The experimental results obtained in this study show anisotropy related to anisotropic crack distribution.

The experimental data obtained for my samples can be directly applied to the interpretation of geophysical survey data with the aim of exploring the structure of fault seismic source regions.

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2. Samples

Mylonite and cataclasite samples were collected from the Hatagawa fault zone (**Fig. 1**). The Hatagawa fault zone is a NNW-SSE trending major inactive fault zone exposed at the eastern margin of the Abukuma mountains in northeastern Japan. It is composed of cataclasite zones, surrounding mylonite zones, and local small shear zones. It seems to be an exhumed ancient seismogenic zone produced in the brittle-plastic zone of the crust (Shigematsu, 1999; Takagi *et al.*, 2000; Fujimoto *et al.*, 2001; Tomita *et al.*, 2001).

Fig. 2 shows the microscopic structures of two mylonite samples and one cataclasite sample under cross-polarized microscopy. One mylonite sample, MY61712, shows strong deformation and a two-dimensional structure featuring foliation (XY plane) and lineation (XZ plane). It is characterized by extreme elongation of quartz. The other mylonite sample, MY61701, has the same type of structure but the deformation is weak. The cataclasite sample, UC6161A, has an ultra-cataclastic structure and no obvious features of foliation or lineation. Details of the mineralogical and chemical compositions are described in Tomita *et al.* (2001) and Fujimoto *et al.* (2001).

Mylonite and cataclasite samples were cut into three cylindrical pieces along three orientations relative to the plane of foliation and lineation: the Z ⊥ foliation plane, X//Lineation line, Y ⊥ X, and Z (**Fig. 3**). The radius was about 20mm and the length was 5mm or 10 to 20mm. The former samples were used for electrical conductivity measurements and the latter for P wave velocity measurements. All of the samples were dried in an electric oven at 120°C for several hours. They were then measured in the dry condition. After that, the samples were fully humidified by distilled water in a vacuum chamber and then

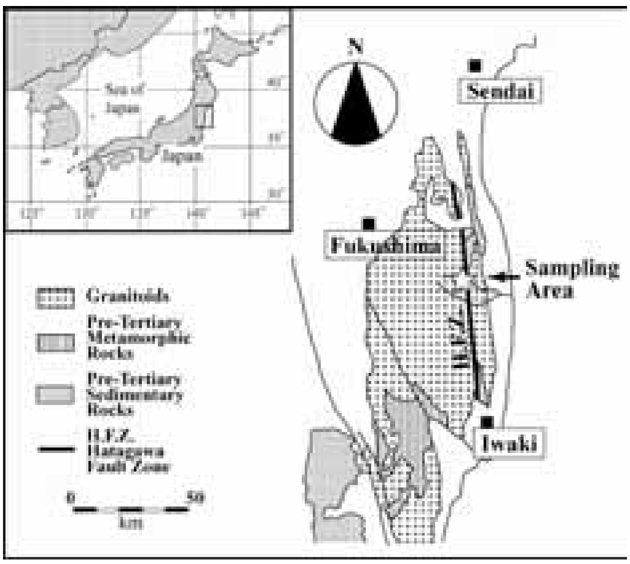

Fig. 1 Location map of the Hatagawa fault zone and the sampling area (modified from Shigematsu, 1999).

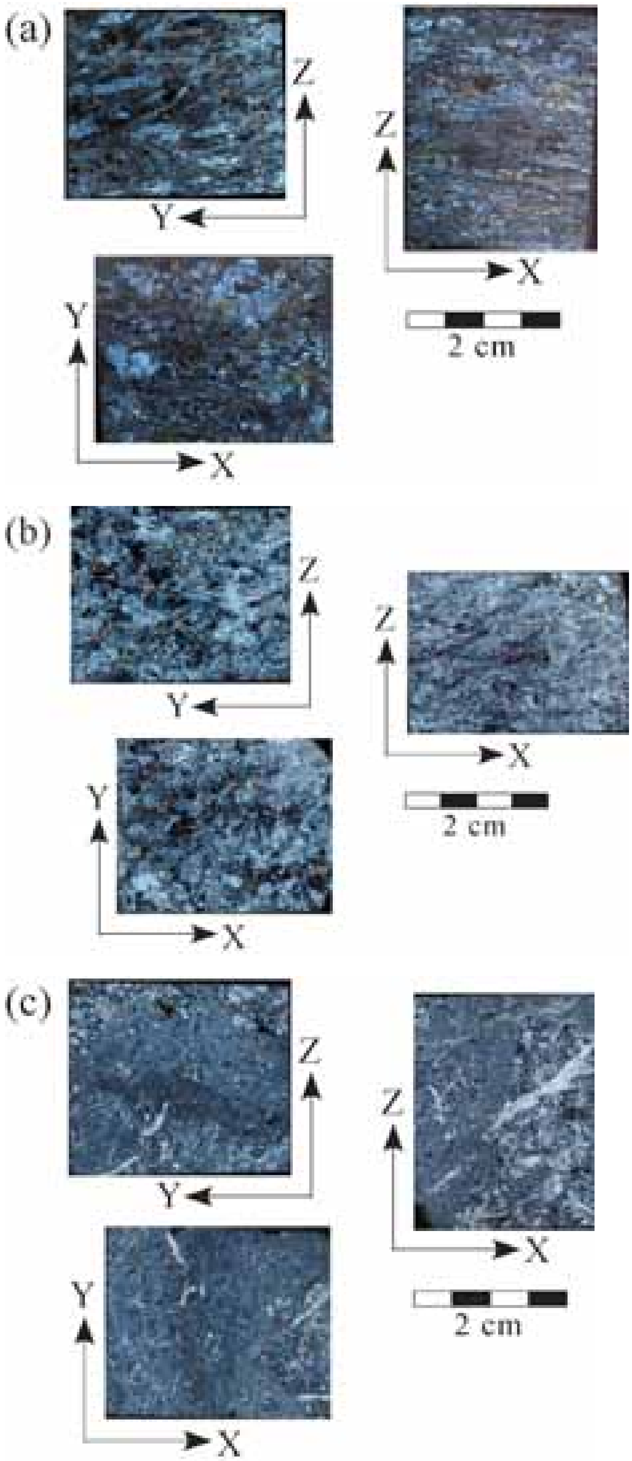

Fig. 2 Photomicrographs of samples studied, observed in thin sections: (a) strongly deformed mylonite (MY61712), (b) weakly deformed mylonite (MY61701), and (c) cataclasite (UC6161A).

measured in the wet condition.

The weight, length, and radius of the samples were measured by direct reading balance and micrometer, respectively. The porosities of the samples were no greater than 1%.

3. Experiments

3. 1 Electrical conductivity measurements

The AC impedance of the samples was measured with a frequency response analyzer (FRA) and a potentiostat (**Fig. 4**). The FRA emits a single sine wave signal to a sample. The potentiostat maintains a constant potential and measures a low-level current passing through a reference resistance that is automatically controlled. The FRA correlates the signal of the sample with that of the reference resistance. Then the amplitude ratio and phase shift of the two signals are obtained . As the reference resistance is known, the impedance, i.e., resistance, and phase angle are determined. Since the signal emitted to the sample is composed of a single sine wave and the FRA stacks the response signals, noise buried in the signal is effectively eliminated. In addition, the potentiostat can measure a microcurrent. As a result, the measurement system is basically robust to electrical noise around the sample under severe conditions and is able to measure up to $10^9 \Omega$.

Circular electrodes were attached to a sample using highly conductive adhesive tape and mechanically connected to the lead wires of the potentiostat. The resistivity of the adhesive tape and the contact resistance due to the mechanical connection were considered to be negligible in the conductivity measurements of the samples.

3. 2 Elastic wave measurement

The P wave velocity was calculated from the travel time of the ultrasonic P wave traveling through a sample and the length of the sample. A block diagram of the measurement setup is shown in **Fig. 5**. Two piezooscillators were attached to the end surfaces with silicon grease to maintain tight contact. Two waveforms were compared: that when the piezooscillators were stuck together and that when the piezooscillators sandwiched the sample. The difference between the rise times of the waveforms was the travel time. The waveform sampling interval was 80nsec. A micrometer measured the lengths of the samples within an accuracy of 0.01mm.

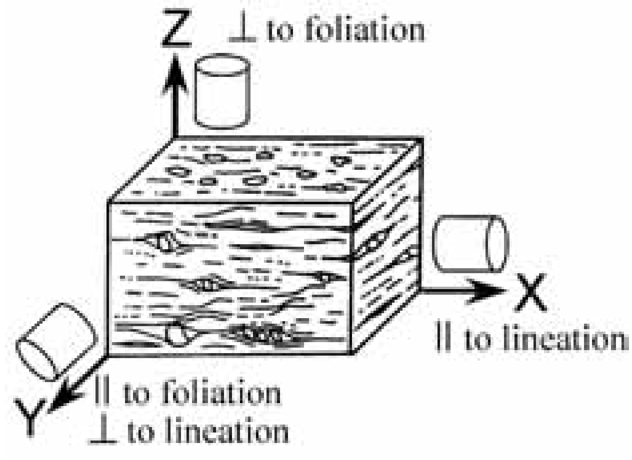

Fig. 3 Orientations for cutting of sample X, Y, Z with respect to the foliation and lineation (modified from Matsuzawa *et al*., 1995).

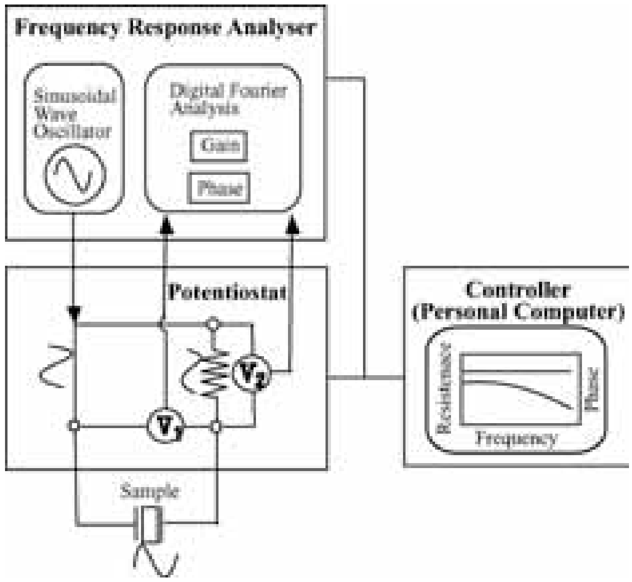

Fig. 4 Block diagram of the electrical conductivity measurement setup.

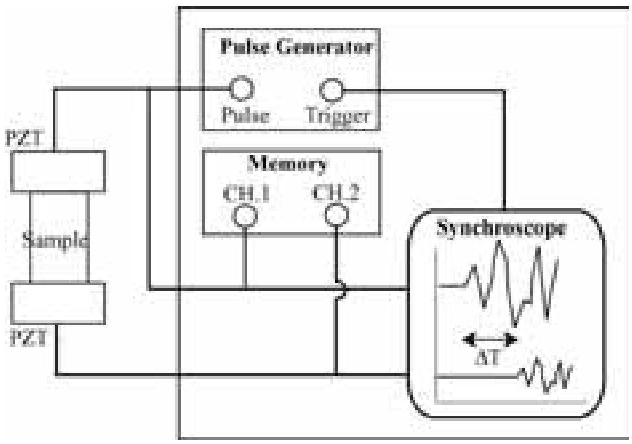

Fig. 5 Block diagram of the P wave velocity measurement setup.

4. Results

4. 1 Electrical conductivity measurements

The results of the electrical conductivity measurements are shown in **Fig. 6**. The frequency of the sinusoidal signal was 1Hz. The conductivities along three orientations were measured for the mylonite and cataclasite samples. In the case of both samples, the conductivities in the wet condition were greater by more than one order of magnitude than those in the dry condition. The conductivities in the dry condition were lower than the conductivity of pure distilled water at 20°C; i.e., $5-10^{-6}$ 1/Ωm. The conductivities in the wet condition were higher than or equal to that of pure distilled water. As the water filtered in the sample may have been contaminated by some electrolyte, the conductivity of distilled water is probably higher than the standard value.

The electrical conductivity of the cataclasite sample was equivalent to that of the mylonite sample in the dry condition. In the wet condition, the conductivities of the three orientations of the mylonite sample differed from each other within one order of magnitude, although there was little difference between each orientation in the dry condition.

4. 2 P wave velocity measurements

Fig. 7 shows the results of the P wave velocity measurements for the mylonite and cataclasite samples. All of the samples with one exception had faster P wave velocities in the wet condition than in the dry condition by 0.1-0.2km/sec. Although the cataclasite and weakly deformed mylonite samples showed little difference within the margins of error among the X, Y, and Z orientations, the strongly deformed mylonite appears to have a significant anisotropic velocity difference. The differences among the three orientations appear to be larger in the dry condition.

The P wave velocity of the cataclasite samples was significantly slower than that of the mylonite samples. Tentative measurements of density and porosity did not show significant differences between the mylonite and cataclasite samples. The difference in P wave velocities may be caused by variance in the chemical or mineral compositions.

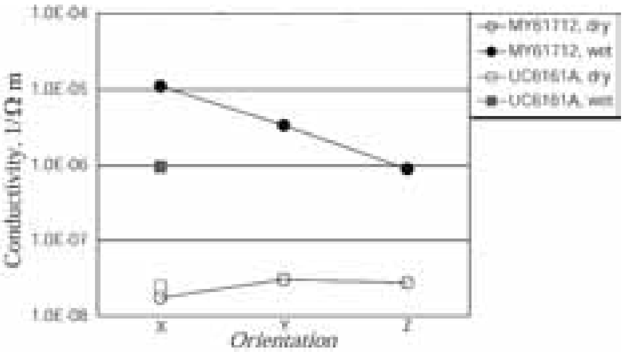

Fig. 6 Results of the electrical conductivity measurements with a 1Hz sinusoidal signal. MY61712 is a strongly deformed mylonite sample and UC6161A is a cataclasite sample. The horizontal axis represents the three orientations of conductivities defined as shown in **Fig. 3**. Weakly deformed mylonite (MY61701) and two orientations of cataclasite (UC6161A) were not measured. Closed and open symbols show the results for the wet and dry conditions, respectively.

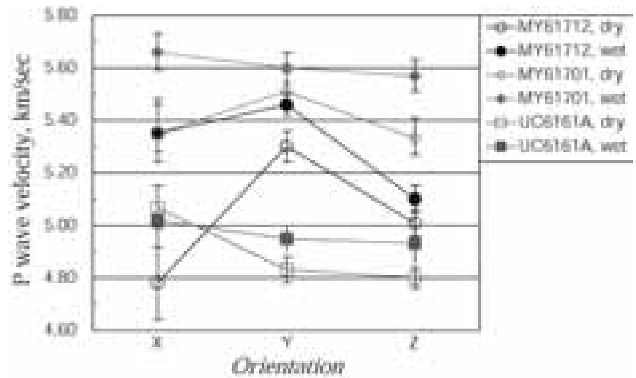

Fig. 7 Results of the P wave velocity measurements. MY61712, MY61701, and UC6161A are strongly deformed mylonite, weakly deformed mylonite, and cataclasite samples, respectively. The horizontal axis represents the three orientations of conductivities defined as shown in **Fig. 3**. Closed and open symbols show the results for the wet and dry conditions, respectively.

5. Discussion

Both the electrical conductivity and P wave velocity depend on the orientation relative to the foliation and lineation in the case of a strongly deformed mylonite sample. The same types of anisotropies have been reported for mylonite from the Hatagawa fault zone (Matsuzawa *et al.*, 1995) and amphibolite and gneiss of KTB drilled core (Lastovickova *et al.*, 1993; Rauen and Lastovickova, 1995; Rauen and Soffel, 1995). In the case of weakly deformed mylonite and cataclasite samples, however, the dependence on orientation appears to be weak or nonexistent. The anisotropy is significant in the wet condition for electrical conductivity, but in contrast it appears to be weak for P wave velocity. The water infiltrates into small cracks in the wet condition. In the dry condition, observations of original samples and thin sections suggest that flat cracks can be expected to distribute in the preferred orientation; the flat planes are parallel to the foliation. This preferred distribution of cracks seems to bring about the anisotropy of electrical conductivity and P wave velocity (Kern and Wenk, 1990; Matsuzawa *et al.*, 1995). The difference in electrical conductivity between the rock matrix and water is larger than the difference between the rock matrix and air occupying the cracks in the dry condition. On the contrary, the difference in P wave velocity between the rock matrix and water is smaller than that between the rock matrix and air. It is therefore reasonable in the present experimental results that anisotropy is clear in the wet condition for electrical conductivity, while the P wave velocity shows clear anisotropy in the dry condition.

Anisotropic distributions of flat cracks are expected to exist in shallow regions of a fault fracture zone. Anisotropic distribution of electrical conductivity and seismic wave velocity may be detected by field electromagnetic and seismic surveys. At the higher pressures found in an earthquake source region, cracks are closed. Nevertheless, the preferred orientations of minerals arranged in relation to the foliation and lineation will remain and the characteristics of anisotropy may be detected in electromagnetic and seismic surveys (Kern and Wenk, 1990; Lastovickova *et al.*, 1993; Rauen and Lastovickova, 1995; Rauen and Soffel, 1995; Matsuzawa *et al.*, 1995).

6. Conclusions

The electrical conductivities and P wave velocities of mylonite and cataclasite samples were measured under ambient dry and wet conditions. Anisotropy was obvious for a strongly deformed mylonite sample due to the anisotropic distribution of microcracks. A weakly deformed mylonite sample and cataclasite samples had weak or no obvious features of anisotropy within the margins of measurement error. At relatively shallow depths, cracks are insufficiently closed and anisotropic distribution of the electrical conductivity and P wave velocity may be detected. At greater depths, cracks are closed but anisotropy due to the preferred orientation of minerals may be observed.

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カタクレーサイトとマイロナイトの常温常圧下での電気伝導度とP 波速度の異方性：畑川断層帯の試料を用いた室内実験

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要　旨

畑川破砕帯（東北日本に位置する，大規模な露出断層）において採取した断層深部岩石であるカタクレーサイト，マイロナイト試料の常温常圧下での電気伝導度およびP 波速度測定を行なった．マイロナイト試料にはカタクレーサイト試料には見られない面構造と線構造が顕著であった．1Hz の電気伝導度は，乾燥状態ではすべての試料で同様な値になった．一方，湿潤状態では，すべての試料で乾燥躁状態より 1 桁以上，値が大きくなるとともに，マイロナイト試料では方位によって値に違いが見られた．つまり，面構造に平行な方向の電気伝導度はそれに垂直な方向に比べて, 1 桁だけ値が大きくなった. P 波速度ではマイロナイト試料で乾燥状態, 湿潤状態ともに異方性が見られた. つまり，面構造に垂直な方向の P 波速度が一番小さかった．P 波速度で両状態を比べると，湿潤状態のほうが，異方性の度合いが小さかった．これらの結果から，マイロナイト試料では亀裂が異方的に分布し，面構造に沿って水（周囲の固体部分より電気伝導度の値が大きく，P 波速度の値が小さい）で充填されていることを示している．

キーワード：電気伝導度，P 波速度，異方性，マイロナイト，カタクレーサイト