Effects of pressure on pore characteristics and permeability of porous rocks as estimated from seismic wave velocities in cores from TCDP Hole-A

Keigo Kitamura,1,* Miki Takahashi,2 Kazuo Mizoguchi,3,† Koji Masuda,2 Hisao Ito4 and Sheng-Rong Song5

1Institute of Geology and Geoinformation, National Institute of Advanced Industrial Science and Technology (AIST), Japan. E-mail: keigo@rite.or.jp
2Active Fault and Earthquake Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Japan
3National Research Institute for Earth Science and Disaster Prevention (NIED), Japan
4Center for Deep Earth Exploration (CDEX), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan
5Department of Geology, National Taiwan University, Taipei, Taiwan

Accepted 2010 June 7. Received 2010 June 7; in original form 2009 June 15

SUMMARY
Changes in \( V_p/V_s \) (Poisson’s ratio) around a fault are related to changes in the fluid transport properties of rocks, which play a significant role in seismogenic processes. Here we report a notable relationship between \( V_p/V_s \) and the permeability of porous fault-related rocks (Chelungpu fault, Taiwan) by direct and simultaneous measurement of elastic wave velocities (\( V_p \) and \( V_s \)) and permeability under increasing effective confining pressure (\( P_{\text{eff}} \)) up to 25 MPa. \( V_p \) and \( V_s \) for all samples increased with \( P_{\text{eff}} \) in the range up to 20 MPa, then were nearly constant as \( P_{\text{eff}} \) increased to 25 MPa. Most silty sandstones with large proportions of fine-grained material showed positive correlations between \( V_p/V_s \) and permeability with rising pressure. On the other hand, well-sorted sandstones showed only slight changes in permeability with respect to \( V_p/V_s \) with rising pressure. We infer that grain size distributions, in particular the amount of silt- and clay-size grains, are responsible for the change in permeability with pressure as small particles clog pore networks with increasing \( P_{\text{eff}} \), causing the decrease in permeability. These findings may be useful to explain changes in permeability and pore pressure in the deep crust.

Key words: Microstructures; Permeability and porosity; Fracture and flow; Acoustic properties.

1 INTRODUCTION
Seismic tomographic studies of the lower crust and upper mantle have shown that anomalous zones of low seismic velocity with high Poisson’s ratio can exist in seismogenic regions (e.g. Zhao et al. 1996). Zhao & Mizuno (1999) suggested that these anomalies indicate the presence of water. Zhang et al. (2009) inferred the existence of water in seismogenic regions of the San Andreas fault by monitoring of \( V_p, V_s \) and \( V_p/V_s \). If water indeed plays a significant role in earthquake events, it is important to understand how water behaves and moves about earthquake faults within the deep crust.

Nur (1974) and Chen & Talwani (2001) suggested that migration of water could induce earthquakes. This type of induction is now regarded as a typical earthquake source process. Changes of stress in and around a deep fault zone can generate changes in permeability by varying the pore connectivity in the surrounding rocks. These permeability changes can induce fluid movements within the fault zone that can lead to changes in pore pressure, which in turn can cause earthquakes. Husen & Kissling (2001) documented post-seismic fluid flow in the Antofagasta earthquake region around the Chilean subduction zone and inferred a relatively high permeability of the lower crust based on the time evolution of the \( V_p/V_s \) ratio. Clearly, the permeability of fault zones is an important parameter in understanding seismogenic processes and the timing of earthquake recurrence (Scholz 2002; Wibberley & Shimamoto 2005). But the relationships between permeability and other physical parameters of rocks are not well understood.

However, it has been established that permeability and elastic wave velocities are closely related to pore structure and connectivity in rocks (e.g. Gueguen & Palscuzas 1994). Consequently, it is expected that there is also a relationship between the seismic velocities, \( V_p \) and \( V_s \), and rock permeability. Such a relationship suggests a way of estimating permeability in seismogenic zones where water movement is important. In this study, we explored the relationships between permeability and elastic wave velocities by simultaneously...
measuring both parameters in rock samples from a borehole near a fault zone.

2 EXPERIMENT

2.1 Rocks

In the aftermath of the 1999 Chi-Chi earthquake, two boreholes that intersected the Chelungpu fault at a depth of about 1100 m (see Hirono et al. 2006; Kano et al. 2006; Ma et al. 2006) were drilled under the auspices of the Taiwan Chelungpu Fault Drilling Project (TCDP). Drilled cores were recovered from the fault zone and the surrounding basement rocks (Fig. 1).

We selected 18 specimens sampled from depths between 482 and 1316 m of TCDP Hole-A (Table 1). The samples were divided into two groups depending on their volume ratios of large (>60 μm) and small (<60 μm) sand grains, as measured by point counting under the microscope. Eight of these samples contained more than 60 per cent large grains and were classed as sandstone; the other 10 were classified as silty sandstones (Fig. 2 and Table 1).

Fig. 3 shows the cumulative grain size distributions of the silty sandstone and sandstone samples. The cumulative numbers increased rapidly (50–60 per cent) in sandstones with grain diameters of 40–160 μm (1.6–2.2 on a log scale), showing them to be better sorted than the silty sandstones. In Fig. 3, there are two types of distribution in the sandstone group, with samples TCDP-2, 4, 5, 6 and 7 displaying better grain sorting than samples TCDP-8, 17 and 18. These two groups are referred to as Type-A and Type-B sandstones, respectively. Photomicrographs of Type-A and Type-B sandstone and silty sandstone (Fig. 4) illustrate the difference in grain distribution between sandstone and silty sandstone. The difference between Type-A and Type-B sandstone is not as clear, but different grain size categories are more equally distributed in Type-A than in Type-B sandstones.

Differences in porosity proved suitable to evaluate the possible effects of pore structure on both elastic wave velocity and permeability, given that pore volume changes appreciably under confining pressure. We did not measure the pore volume drained from the specimen because the monitoring system for pore volume change had poor accuracy. Instead, we measured porosity using a mercury injection porosimeter (Automated mercury porosimeter IV 9520, Micrometrics) and ASTM (The American Society for Testing and Materials) standard methods. We obtained pore volumes by increasing the pressure from 9 to 400 MPa, corresponding to a range of pore throat size from about 20 to about 80 μm. Integration of the distribution histograms yielded the total porosity of the specimens.

Fig. 5 shows differences of pore size distribution among Type-A sandstone, Type-B sandstone and silty sandstone. Type-B sandstone...
Table 1. Corrected depth and rock type of samples.

| Sample Number | Depth (m) | Rock type     | Porosity* (φ ≥ 60) | Silt (120 < φ ≤ 240) | Fine sand (120 < φ ≤ 240) | Medium sand (120 < φ ≤ 240) | Coarse sand (φ ≤ 240) |
|---------------|-----------|---------------|---------------------|-----------------------|---------------------------|-----------------------------|------------------------|
| TCDP-1        | 738.4     | Silty sandstone | 4.40                | 48.7                  | 41.0                      | 10.1                        | 0.2                    |
| TCDP-2        | 1209.4    | Sandstone      | 6.69                | 32.5                  | 50.2                      | 17.3                        | 0.0                    |
| TCDP-3        | 975.1     | Silty sandstone | 3.66                | 53.3                  | 31.8                      | 9.7                         | 5.1                    |
| TCDP-4        | 1043.8    | Sandstone      | 14.09               | 22.4                  | 50.1                      | 24.8                        | 2.8                    |
| TCDP-5        | 1023.7    | Sandstone      | 2.50                | 23.2                  | 55.9                      | 20.3                        | 0.6                    |
| TCDP-6        | 1121.8    | Sandstone      | 4.15                | 36.4                  | 43.8                      | 18.8                        | 1.0                    |
| TCDP-7        | 999.9     | Sandstone      | 17.34               | 17.0                  | 37.7                      | 41.8                        | 3.6                    |
| TCDP-8        | 640.2     | Sandstone      | 8.92                | 28.0                  | 21.7                      | 47.2                        | 3.2                    |
| TCDP-9        | 1056.2    | Silty sandstone| 2.24                | 43.6                  | 50.6                      | 5.8                         | 0.0                    |
| TCDP-10       | 1246.8    | Silty sandstone| 3.98                | 57.2                  | 41.4                      | 1.4                         | 0.0                    |
| TCDP-11       | 1082.1    | Silty sandstone| 4.69                | 40.2                  | 41.7                      | 17.9                        | 0.2                    |
| TCDP-12       | 1276.6    | Silty sandstone| 5.33                | 45.6                  | 42.8                      | 11.4                        | 0.2                    |
| TCDP-13       | 926.6     | Silty sandstone| 3.69                | 44.9                  | 37.3                      | 17.6                        | 0.2                    |
| TCDP-14       | 885.6     | Silty sandstone| 3.57                | 55.8                  | 39.8                      | 4.4                         | 0.0                    |
| TCDP-15       | 832.1     | Silty sandstone| 3.64                | 62.2                  | 36.9                      | 0.8                         | 0.2                    |
| TCDP-16       | 482.4     | Silty sandstone| 4.00                | 40.8                  | 44.8                      | 13.8                        | 0.6                    |
| TCDP-17       | 679.6     | Sandstone      | 4.35                | 38.7                  | 26.9                      | 32.3                        | 2.0                    |
| TCDP-18       | 1316.2    | Sandstone      | 3.77                | 33.6                  | 23.7                      | 41.7                        | 1.1                    |

*Porosity was measured by using mercury porosimeter after experiments.

φ: grain diameter (μm).

Figure 2. Modal composition of grain size distribution. Sample locations are given in Fig. 1 and Table 1.
Effect of pore pressure change on porous rocks

had a bimodal distribution while Type-A sandstone and silty sandstone had unimodal distributions.

2.2 Measurements

Seismic velocity measurements were obtained using a gas-medium, high-pressure and high-temperature deformation apparatus at AIST, Japan (Masuda et al. 2002). This apparatus produces confining and pore pressures of up to 200 MPa. Argon gas and distilled water were used as confining and pore pressure media, respectively.

We measured seismic velocities under conditions up to 200 MPa and 200 °C in the presence of pore fluids using a new method developed in our laboratory (Kitamura et al. 2006). In this study, we employed an improved piston assembly for elastic wave velocity measurements (Fig. 6). Lithium niobate transducers (3.3 MHz resonance frequency) were embedded on the upper surface of the lower piston, using three transducers for P waves and two orthogonally polarized transducers for S waves.

The specimens were cylinders 20 mm in both length and diameter. The elastic wave pulse was generated by applying an electrical pulse (3.3 MHz single-shot pulse, ±20 V) to the transducers. The signal was reflected at the interface between the specimen and the tungsten carbide buffer rods. Transmitted P and S waves were reflected from both end surfaces of each specimen and buffer rods, R1 and R2. The differences in arrival times between the two reflected waves, T1 and T2, were used to determine traveltimes (Fig. 7a). The received waves were stacked up to 1000 times and then bandpass filtered (2–5 MHz). We calibrated this system using single crystal quartz. Fig. 7(b) shows P and S waveforms from this calibration. The first arrival time T1 of reflected waves from R1 was calculated by using Vp and Vs of the buffer rods and the piston length. The arrival time T2 of reflected waves from R2 was determined by manual picks as illustrated in Fig. 7(c), a detail of waveforms of P waves around time T1. This diagram shows two events (E2 and E3) after E1, a group of reflected waves from R1. Because E3 is more similar to E1 than to E2, we determined that E3 represents reflected waves from R2. The calibration velocities of quartz were $V_p = 6.01$ and $V_s = 3.94$ km s$^{-1}$, which have errors of 1 and 4 per cent, respectively, from a previous study (Anderson et al. 1968; Table 2).

At the same time as our velocity measurements, we also determined permeability by an oscillation technique (e.g. Kranz et al. 1990; Fischer 1992; Fischer & Paterson 1992; Faulkner & Rutter 2000; Takahashi 2003). In this method, sinusoidal pressure waves on the upstream side of the specimen give rise to downstream pressure waves with amplitude attenuation $R$ (0 ≤ $R$ ≤ 1) and phase retardation $\delta$ > 0, as illustrated in Fig. 8. These two parameters, $R$ and $\delta$, yield both the permeability $k$ (m$^2$) and the storage capacity $\beta$ (M Pa$^{-1}$) of a specimen. Errors in the measured permeability depend on the measurement conditions, especially the frequency of the pore pressure wave. We used a constant oscillation amplitude of 0.5 MPa for all experiments with frequencies between 0.1 and 10 Hz.

The permeability and $V_p$ and $V_s$ in our rock specimens were measured under effective pressures from 10–30 MPa, where the effective pressure ($P_{eff}$) was determined as a first approximation from $P_c$–$P_p$ with $P_c$ and $P_p$ being the confining pressure and the pore pressure, respectively.

All experiments were performed at room temperature with an initial confining pressure of 30 MPa and pore pressure of 20 MPa applied and held constant for 1 h. The confining pressure was kept constant throughout all measurements. During the holding period, the permeability was monitored every 10 min. At the end of the holding period, twice the permeability was measured before and after the P- and S-wave velocity measured. Each error of the permeability measured by the oscillation method tends to depend on the frequency of pore pressure sinusoidal change. At the oscillation method, we should adapt the appropriate frequency to get the permeability value with higher accuracy. However, if the case for higher permeability, the system for the pore pressure control cannot always

Figure 3. Cumulative grain size distributions as a function of grain diameter in samples of (a) silty sandstone and (b) sandstone.
Permeability and velocity measurements were repeated while the pore pressure was decreased progressively from 20 MPa in steps of 5 MPa or 1.5 MPa. The permeability was monitored every 10 min during each 20-min holding time, and velocities and representative permeabilities were determined during each step in pressure. Finally, velocities and permeability were measured at zero pore pressure for 20 min.

3 RESULTS

3.1 \( V_p \) and \( V_s \) as functions of effective pressure

Fig. 9 illustrates the increasing \( P \)-wave velocity with increasing effective pressure \( P_{\text{eff}} \) (sample TCDP-1). Fig. 10 and Table 3 show...
Effect of pore pressure change on porous rocks

Figure 6. Schematic illustration of the apparatus used for elastic wave velocity measurements. Confining pressure and pore pressure are controlled independently by servocontrolled systems.

Table 2. Results of calibration by using single quartz.

|          | V_p  | V_s  |
|----------|------|------|
| This study | 6.01 | 3.94 |
| Reference* | 6.05 | 4.09 |
| Error (per cent) | 0.73 | 3.74 |

*Anderson et al. (1968).

V_p and V_s as functions of the effective pressure (P_eff). In all cases, V_p and V_s increased with increasing P_eff in the range up to 20 MPa and remained nearly constant above 20 MPa. V_p ranged from 3.1 to 3.9 km s^{-1}, and V_s ranged from 1.5 to 2.4 km s^{-1}. The V_p and V_s values in the sandstone samples were generally smaller than those in the silty sandstones. No differences were apparent between Type-A and Type-B sandstones.

Under low P_eff (<20 MPa), V_p and V_s increased rapidly with pressure as a result of closure of narrow cracks. At pressures above 20 MPa, V_p and V_s showed only gradual changes caused by deformation of pores and partial closure of some cracks. Voids and cracks in rock close fully only at pressures above 200 MPa.
3.3 Elastic wave velocity versus permeability

Both $V_p$ and $V_s$ and permeability were strongly affected by $P_{\text{eff}}$. The relationships between permeability and $V_p$ and $V_s$ (Fig. 12) indicate a rough correlation between the velocity and rock grain size. That is, silty sandstones and Type-B sandstones generally had high velocities and low permeability, whereas the high permeability of Type-A sandstones was coupled with pronounced changes in velocities.

Higher values of $V_p$ and $V_s$ and lower permeabilities corresponded to higher $P_{\text{eff}}$ ranges, which suggest that the elastic and transport properties of these rocks are related through some microstructural changes. Obvious effects were produced by changes in pore condition, such as pore volume and the number of open cracks. Hence, $V_p$ and $V_s$ may provide some clues that allow pore conditions to be estimated.

4 DISCUSSION

4.1 Relationships between porosity and $V_p$, $V_s$, $V_p/V_s$ and permeability

Fig. 13 shows the relationships between porosity and $V_p$, $V_s$, $V_p/V_s$ and permeability. The data in Fig. 13(a) indicate negative correlations between porosity $\phi$ and velocity at $P_{\text{eff}} = 30$ MPa ($V_p = 3.82 - 0.013 \phi$, $V_s = 2.25 - 0.007 \phi$). These relationships can be explained by empirical formulae like Wyllie’s or Han’s laws (see Gueguen & Palciauskas 1994; Mavko et al. 2009). The data in Fig. 13(b) showing the relationship between $V_p/V_s$ and porosity (also at $P_{\text{eff}} = 30$ MPa) can be divided into two groups: the silty sandstones and Type-B sandstones show no correlation with porosity, whereas the Type-A sandstones have a positive correlation with porosity. Fig. 13(c) shows a positive correlation between porosity and permeability (at $P_{\text{eff}} = 25$ MPa). The porosities of silty sandstones range from 2 to 5 per cent, whereas those of Type-A sandstones range more widely from 2 to 17 per cent.

These figures show that the silty sandstones are characterized by a high $V_p$ and low permeability and the sandstones are characterized by a low $V_p$ and high permeability. Type-A sandstones have a large porosity range that produces a variable response to any increase in $P_{\text{eff}}$. These differences can be explained by percolation theory (Gueguen & Dienes 1989). There are two types of flow regimes: the...
percolative regime and the connected regime (Gueguen & Schubnel 2003). It is considered that the high-porosity group of rocks (over 5 per cent) is in the connected regime and the low-porosity group is in the percolative regime. Generally, percolation has a strong relationship with crack density in crack evolution modelling (Benson et al. 2006). The thin aperture flow passes have an important role in permeability change.

4.2 $V_p/V_s$ versus permeability

$V_p/V_s$ (or Poisson’s ratio: $\nu$) is sensitive to both crack shapes and to the presence of fluid in pores and cracks. The relation between $V_p/V_s$ and $\nu$ is given by $\nu = [(V_p/V_s)^2 - 2]/2[(V_p/V_s)^2 - 1]$. Hence, the relationship between permeability and $V_p/V_s$ provides useful insight into deep crustal fluid movements, given that $V_p/V_s$ can be determined from seismic observations.

Fig. 14 shows the relationships between $V_p/V_s$ and permeability in our samples with increasing $P_{eff}$. Silty sandstones (Fig. 14a) show permeability changes of one to two orders of magnitude, whereas their $V_p/V_s$ values are in the relatively narrow range of 1.65–1.85. For most samples, permeability and $V_p/V_s$ show a negative correlation, except in TCDP-1, which yielded a small variation in permeability with a large change in $V_p/V_s$.

Sandstones showed two types of response. Type-A sandstones showed moderate changes in $V_p/V_s$ with pressure, similar to the silty sandstones (except for TCDP-2, which showed a large variation in the range 1.65–2.05), but small changes in permeability. Among Type-B sandstones, samples TCDP-17 and 18 had small changes in $V_p/V_s$ but appreciable changes in permeability, and sample TCDP-8 showed moderate changes in both parameters. Hereafter, we refer to these two sandstone groups within Type-A and Type-B as the uncorrelated group and correlated group, respectively.

The results indicate that the relationship between permeability and $V_p/V_s$ is strongly controlled by the lithology of sandstones. Type-A and Type-B sandstones differ in their volumetric content of very fine sand (Fig. 2) and in their degree of grain sorting (Fig. 3). In a sandstone containing a large proportion of silt, the permeability decreases with increasing $P_{eff}$. When the grains of a sandstone are sorted such that the dominant grain size is in the range 150–300 μm, permeability changes only slightly with increasing $P_{eff}$. However, when sand grains are poorly sorted, permeability is affected more readily by $P_{eff}$.

Fortin et al. (2007) documented a relationship between $V_p/V_s$ and aspect ratio. Benson et al. (2006) found that the aspect ratio of cracks directly controls the evolution of crack permeability. These findings may provide insight into the relationship between $V_p/V_s$ and permeability of porous sandstone and silty sandstone.

4.3 Mechanisms affecting the correlation between permeability and $V_p/V_s$

Fig. 15 is a schematic diagram showing the changes in pore connectivity, porosity and saturation with increasing $P_{eff}$. As $P_{eff}$ increases, pores and cracks are compressed and gradually close. During this process the cross-sections of fluid channels decrease. The resulting changes in pore connectivity can lead to the formation of isolated pores and non-saturated pores. Both play important roles in reducing permeability.

The silty sandstones and correlated group of sandstones contain many silt-sized particles that occupy the spaces between the larger sand particles; thus, they have large numbers of isolated and non-saturated pores under the initial experimental conditions (Fig. 15a-1). When $P_{eff}$ increases, the grains become more closely packed and create a new generation of isolated and non-saturated pores (Fig. 15a-2). Pore connectivity is reduced as finer grains clog narrowing pore throats. Hence, these sandstones show large changes in permeability at higher confining pressures.

Fig. 15(b) illustrates the internal structure of the uncorrelated group sandstones. Initially, these rocks have small numbers of isolated and non-saturated pores (Fig. 15b-1) and abundant,
Table 3. Results of $V_p$, $V_s$ and permeability measurements.

|        | TCDP-1 | TCDP-2 | TCDP-3 | TCDP-4 | TCDP-5 | TCDP-6 | TCDP-7 | TCDP-8 | TCDP-9 | TCDP-10 | TCDP-11 | TCDP-12 | TCDP-13 | TCDP-14 | TCDP-15 | TCDP-16 | TCDP-17 | TCDP-18 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $V_p$ (km s$^{-1}$) $P_{efl} = 10$ MPa | 3.42 | 3.18 | 3.15 | 3.21 | 3.19 | 3.28 | 3.30 | 3.29 | 3.13 | 3.19 | 3.17 | 3.17 | 3.17 | 3.31 | 3.21 | 3.20 | 3.26 | 3.15 | 3.16 |
|       | 3.66 | 3.40 | 3.57 | 3.48 | 3.58 | 3.40 | 3.35 | 3.39 | 3.55 | 3.67 | 3.26 | 3.26 | 3.47 | 3.56 | 3.48 | 3.39 | 3.40 | 3.41 |
|       | 3.73 | 3.66 | 3.85 | 3.69 | 3.80 | 3.75 | 3.53 | 3.62 | 3.75 | 3.77 | 3.86 | 3.68 | 3.82 | 3.69 | 3.70 | 3.73 | 3.74 |
|       | 3.87 | 3.67 | 3.85 | 3.69 | 3.80 | 3.76 | 3.56 | 3.69 | 3.74 | 3.77 | 3.88 | 3.68 | 3.83 | 3.69 | 3.74 | 3.71 | 3.74 | 3.72 |
|       | 3.89 | 3.68 | 3.88 | 3.70 | 3.82 | 3.78 | 3.59 | 3.68 | 3.74 | 3.80 | 3.85 | 3.70 | 3.83 | 3.73 | 3.75 | 3.72 | 3.73 | 3.74 |
| $V_s$ (km s$^{-1}$) $P_{efl} = 10$ MPa | 1.83 | 1.54 | 1.83 | 1.72 | 1.83 | 1.87 | 1.87 | 1.80 | 1.74 | 1.75 | 1.75 | 1.74 | 1.82 | 1.76 | 1.76 | 1.78 | 1.77 | 1.69 |
|       | 2.04 | 1.86 | 2.06 | 1.83 | 1.98 | 1.90 | 1.99 | 1.90 | 2.06 | 1.84 | 1.81 | 1.80 | 2.02 | 1.99 | 1.94 | 1.95 | 2.00 | 1.89 |
|       | 2.22 | 2.11 | 2.30 | 2.12 | 2.28 | 2.35 | 2.12 | 2.11 | 2.27 | 2.14 | 2.21 | 2.10 | 2.24 | 2.05 | 2.20 | 2.17 | 2.14 | 2.14 |
|       | 2.33 | 2.21 | 2.32 | 2.18 | 2.28 | 2.32 | 2.14 | 2.17 | 2.22 | 2.17 | 2.20 | 2.07 | 2.29 | 2.10 | 2.19 | 2.16 | 2.17 | 2.13 |
|       | 2.35 | 2.21 | 2.30 | 2.22 | 2.34 | 2.36 | 2.14 | 2.21 | 2.26 | 2.15 | 2.28 | 2.20 | 2.28 | 2.10 | 2.21 | 2.20 | 2.18 | 2.14 |
| $V_p/V_s$ $P_{efl} = 10$ MPa | 1.87 | 2.06 | 1.72 | 1.87 | 1.75 | 1.76 | 1.77 | 1.83 | 1.80 | 1.82 | 1.81 | 1.82 | 1.82 | 1.82 | 1.81 | 1.83 | 1.78 | 1.87 |
|       | 1.79 | 1.83 | 1.73 | 1.98 | 1.80 | 1.78 | 1.68 | 1.78 | 1.99 | 1.98 | 1.80 | 1.81 | 1.81 | 1.72 | 1.79 | 1.79 | 1.74 | 1.80 |
|       | 1.68 | 1.73 | 1.67 | 1.67 | 1.59 | 1.66 | 1.72 | 1.65 | 1.76 | 1.75 | 1.75 | 1.71 | 1.80 | 1.70 | 1.71 | 1.74 | 1.75 |
|       | 1.66 | 1.66 | 1.66 | 1.69 | 1.66 | 1.62 | 1.67 | 1.70 | 1.68 | 1.74 | 1.76 | 1.77 | 1.67 | 1.76 | 1.71 | 1.72 | 1.72 | 1.75 |
|       | 1.66 | 1.67 | 1.69 | 1.67 | 1.63 | 1.60 | 1.70 | 1.72 | 1.65 | 1.77 | 1.74 | 1.78 | 1.68 | 1.78 | 1.70 | 1.71 | 1.74 | 1.72 |
| Permeability (m$^2$) $P_{efl} = 10$ MPa | 3.69E-16 | 1.51E-13 | 2.60E-15 | 1.61E-14 | 1.62E-15 | 1.91E-15 | 1.02E-14 | 2.98E-16 | 1.83E-15 | 1.16E-15 | 1.12E-14 | 4.74E-15 | 9.71E-16 | 7.26E-16 | 3.91E-15 | 2.27E-15 | 2.06E-14 |
|       | 2.77E-16 | 6.52E-14 | 1.79E-15 | 1.49E-14 | 1.14E-15 | 1.32E-15 | 8.38E-15 | 5.40E-15 | 1.81E-16 | 7.18E-16 | 8.67E-16 | 3.69E-15 | 3.18E-15 | 7.22E-16 | 4.43E-16 | 2.92E-15 | 1.08E-15 | 7.00E-15 |
|       | 2.23E-16 | 2.94E-14 | 4.03E-16 | 1.28E-14 | 9.98E-16 | 9.60E-16 | 7.83E-15 | 4.33E-15 | 1.19E-16 | 3.40E-16 | 4.69E-16 | 4.94E-16 | 7.08E-16 | 6.51E-16 | 1.82E-16 | 5.77E-16 | 6.15E-16 | 1.46E-15 |
|       | 1.80E-16 | 1.33E-14 | 1.66E-16 | 1.14E-14 | 8.24E-16 | 7.15E-16 | 7.82E-15 | 2.92E-15 | 8.64E-17 | 1.35E-16 | 2.63E-16 | 2.46E-16 | 3.71E-16 | 5.52E-16 | 7.52E-17 | 3.35E-16 | 2.09E-16 | 5.97E-16 |
well-sorted grains. They have a more homogeneous structure and allow for less random movements of particles than the correlated group sandstones. Increases in \( P_{\text{eff}} \) produce fewer new isolated pores and less clogging of fluid paths (Fig. 15b-2), thus the permeabilities of these rocks decrease only slightly.

A study by Takahashi et al. (2007) demonstrated the importance of clay content in determining permeability. They found that the packing structure of fault gouge is strongly controlled by its clay content. Gouge with high clay content showed a compact packing structure with low permeability. Both our study and that of Takahashi et al. (2007) are consistent with grain size distribution being the essential factor in determining permeability change under conditions of high \( P_{\text{eff}} \).

The proportion of silt-sized particles is an indicator of the crude density of a sample, which is an important factor in estimating changes in elastic wave velocities and permeability with increasing \( P_{\text{eff}} \). On the other hand, the content of very fine sand, which inhabits pore spaces, accounts for the differences between the correlated and uncorrelated sandstone groups.

### 4.4 Effects of clay content on \( V_p/V_s \) changes under increasing confining pressure

The empirical relationship between \( V_p \) and \( V_s \) in a sandstone was described by Mavko et al. (2009) as

\[
V_s = a \times V_p - b. \tag{1}
\]

This equation can be recast as

\[
\frac{V_p}{V_s} = \frac{1}{a} + \left(\frac{b}{a}\right) \left(\frac{1}{V_s}\right). \tag{2}
\]

The coefficients \( a \) and \( b \) depend on clay content: \( a = 0.754, b = 0.657 \) for a clay content of less than 25 per cent, and \( a = 0.842, b = 1.099 \) for a clay content of more than 25 per cent. These give \( 1/V_s \) as 0.871 and 1.305, respectively. Mudrock has a \( 1/V_s \) value of 1.360, which is notably higher than clay-rich sandstones. These results indicate that clay contents enhance changes in \( V_p/V_s \) under confining pressures.

\( V_s \) increases with increases in confining pressure, which decreases the second term of eq. (2) and causes \( V_p/V_s \) to decrease with increases in confining pressure, as shown in Fig. 14. The scatter seen in \( V_p/V_s \) in Fig. 13(b) may be explained by the pronounced sensitivity of \( (1/V_s) \) to silt content in the silty sandstones, where the ratio of silt to sand varies between samples.

Clay content also exercises important control on permeability with increasing \( P_{\text{eff}} \). Our experimental results indicate a positive correlation between permeability and \( V_p/V_s \) (or \( \nu \)) for the correlated
Figure 13. The relationship between porosity and (a) elastic wave velocities, (b) $V_p/V_s$ and (c) permeability. Effective pressure $P_{\text{eff}} = 30$ MPa in (a) and (b) and 25 MPa in (c).

4.5 Mechanism of water supply to a fault zone in the deep crust

The deep Chelungpu fault zone is composed of alternating layers of silty or Type B sandstone and Type-A sandstone (Fig. 1). In this formation, the silty and Type-B sandstone layers act as aquifers or aquicludes, depending on the pore pressure $P_p$ (Fig. 15a). On the other hand, Type-A sandstones serve as aquifers regardless of $P_p$ (Fig. 15b). Under high $P_p$, the whole formation is entirely saturated by water. With decreasing $P_p$, the silty sandstone layer becomes impermeable and provides a barrier to flow, confining high-pressure water in Type-A sandstones.

Water contained in the formation can become localized in the fault zone by channelling and subsequent restriction of water flow within the surrounding rock layers. Changes in the distribution and pressure of the contained water can be accounted for by such a mechanism. Zhao et al. (1996) reported a low $V_p$, low $V_s$ and high $\nu$ anomaly at the hypocentre of the Kobe earthquake. Their results were similar to those we found among the correlated group rocks. When the pore pressure in these rocks increased, the effective confining pressure decreased, which in turn decreased the Poisson’s ratio and increased permeability. If these conditions applied in the deep crust, water could then move into the fault zone where it would decrease the strength of the fault.

Formation water is now considered an important contributor to the seismogenic process. Zhao et al. (1996) proposed three sources for formation water: dehydration of hydrous minerals, trapped fluid in pore spaces and meteoric water. Dehydration of hydrous minerals is an important source of deep formation water but requires conditions in excess of 500 MPa and 500 °C. Consequently, water in a shallow fault zone cannot be derived from the dehydration of hydrous minerals.
Effect of pore pressure change on porous rocks

5 CONCLUSIONS

We measured the seismic velocities and permeabilities of porous rocks with changing pore pressure (or effective pressure). The sample rocks came from between 482 and 1316 m depth in TCDP Hole-A, drilled near the Chelungpu fault that was responsible for the Chi-Chi earthquake in 1999.

We found relationships between seismic velocity and permeability for some of the porous rocks. In the silty sandstones and in sandstones with a large proportion of fine grains, we found correlations between changes in their permeability and changes in $V_p/V_s$. We suggest that this relationship is controlled by the clay content and the degree of grain sorting. A plausible mechanism involves alterations in pore structures under elevated effective confining pressures as the pore throats become clogged by fine sand or silt grains. Consequently, sandstones consisting of well-sorted grains show the same changes in $V_p/V_s$ with confining pressure, but only small changes in permeability.

Figure 14. Relationship of permeability and $V_p/V_s$ for (a) silty sandstone and (b) sandstone under confining pressure of 30 MPa and temperature of 25 °C.

Figure 15. Schematic diagrams of changes in pore structures with increasing effective pressure. (a) Correlated group. (b) Uncorrelated group.

© 2010 The Authors, GJI, 182, 1148–1160
Journal compilation © 2010 RAS
Well logs indicate that there are alternating layers of silty sandstone and well-sorted sandstone around some fault zones. The sandstone layers can serve as aquifers when the permeability of the surrounding silty sandstone layers is reduced. However, the permeability of the silty sandstone layers varies depending on pore pressure. When pore pressure increases, the permeability of the silty sandstone increases, accompanied by an increase in $V_p/V_s$ and a decrease in Poisson’s ratio. This allows water to permeate the fault zone. Consequently, the strength of the fault, as related to the water content in the fault zone, may be controlled by the water supply from the surrounding area.

ACKNOWLEDGMENTS

Financial support provided by Prof. Jiro Mori of Kyoto University was particularly helpful in collecting the TCDP Hole-A core samples (Japanese Society for the Promotion of Science, 16253003). Dr. Yasuo Yabe of Tohoku University helped with sample collection in Taiwan. We are grateful to Dr. Osamu Nishizawa of AIST for helpful discussions and comments regarding this paper. We thank the editor of Geophysics Journal International (Dr. Saskia Goes) and two reviewers (Dr. Sergei Stanchits and Dr. Alexandre Schubnel) for helpful comments that greatly improved the manuscript.

REFERENCES

Anderson, O.L., Schreiber, E., Liebermann, R.C. & Soga, N., 1968. Some elastic constant data on minerals relevant to geophysics, Rev. Geophys., 6, 491–524.

Benson, P., Schubnel, A., Vinciguerra, S., Trovato, C., Meredith, P. & Young, R.P., 2006. Modeling the permeability evolution of microcracked rocks from elastic wave velocity inversion at elevated isotropic pressure, J. geophys. Res., 111, B04202, doi:10.1029/2005JB003710.

Chen, L. & Talwani, P., 2001. Mechanism of initial seismicity following impoundment of the Monticello Reservoir, South Carolina, Bull. seism. Soc. Am., 91, 1582–1594.

Christensen, N.I., 1974. Compressional wave velocities in possible mantle rock to pressure of 30 kilobars, J. geophys. Res., 79, 407–412.

Faulkner, D.R. & Rutter, E.H., 2000. Comparisons of water and argon permeability in natural clay-bearing fault gouge under high pressure at 20°C, J. geophys. Res., 105, 16415–16426.

Fischer, G.J., 1992. The determination of permeability and storage capacity: pore pressure oscillation method, in Fault Mechanics and Transport Properties of Rocks, pp. 187–211, ed. Evans, B and Wong, T.-F., Academic, San Diego, California.

Fischer, G.J. & Paterson, M.S., 1992. Measurement of permeability and storage capacity in rocks during deformation at high temperature and pressure, in Fault Mechanics and Transport Properties of Rocks, pp. 213–252, eds Evans, B and Wong, T.-F., Academic, San Diego, California.

Fortin, J., Gueguen, Y. & Schubnel, A., 2007. Effects of pore collapse and grain crushing on ultrasonic velocities and $V_p/V_s$, J. geophys. Res., 112, B08207, doi:10.1029/2005JB004005.

Gueguen, Y. & Dienes, J., 1989. Transport properties of rocks from statistics and percolation, Math. Geol., 21, 1–13.

Gueguen, Y. & Palciauskas, V., 1994. Introduction to the Physics of Rocks, Princeton University Press, Princeton.

Gueguen, Y. & Schubnel, A., 2003. Elastic wave velocities and permeability of cracked rocks, Tectonophysics, 370, 163–176.

Hirono, T. et al., 2006. Evidence of frictional melting from disk-shaped black material, discovered within the Taiwan Chelungpu fault system, Geophys. Res. Lett., 33, L19311, doi:10.1029/2006GL027329.

Husen, S. & Kissling, E., 2001. Postseismic fluid flow after the large subduction earthquake of Antofagasta, Chile, Geology, 29, 847–850.

Kano, Y., Mori, J., Fujiro, R., Ito, H., Yanagidani, T., Nakao, S. & Ma, K.-F., 2006. Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, Geophys. Res. Lett., 33, L14306, doi:10.1029/2006GL026733.

Kitamura, K., Masuda, K., Takahashi, M. & Nishizawa, O., 2006. The influence of pore fluids on seismic wave velocities under high temperature and high pressure conditions: development of a new technique with gas apparatus at AIST, Japan, Earth Planets Space, 58, 1515–1518.

Kranz, R.L., Saltzman, J.S. & Blacic, J.D., 1990. Hydraulic diffusivity measurements on laboratory rock samples using an oscillating pore pressure method, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 27, 345–352.

Ma, K-F. et al., 2006. Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project, Nature, 444, doi:10.1038/nature05253.

Masuda, K., Fujimoto, K. & Arai, T., 2002. A new gas-medium, high-pressure and high-temperature deformation apparatus at AIST, Japan, Earth Planets Space, 54, 1091–1094.

Mavko, G., Mukerji, T. & Dvorkin, J., 2009. The Rock Physics Handbook, 2nd edn, Cambridge University Press, New York.

Nur, A., 1974. Matsushiro, Japan, earthquake swarm: confirmation of the dilatancy-fluid diffusion model, Geology, 2, 217–221.

Scholz, C.H., 2002. The Mechanics of Earthquakes and Faulting, 2nd edn, Cambridge University Press, New York.

Takahashi, M., 2003. Permeability change during experimental fault smearing, J. geophys. Res., 108(B5), doi:10.1029/2002JB001984.

Takahashi, M., Mizoguchi, K., Kitamura, K. & Masuda, K., 2007. Effects of clay content on the frictional strength and fluid transport property of faults, J. geophys. Res., 112, B08206, doi:10.1029/2006JB004678.

Wang, C., Chang, C. & Yen, H., 2000. An interpretation of the 1999 Chi-Chi earthquake in Taiwan based on the thin-skinned thrust model. Terrestrial Atmospheric Oceanic Sci., 11, 603–630.

Wibberley, C.A.J. & Shimamoto, T., 2005. Earthquake slip weakening and asperities explained by thermal pressurization, Nature, 436, 689–692.

Wong, T-F., David, C. & Menendez, B., 2004. Mechanical compaction, in Mechanics of Fluid-Saturated Rocks, pp. 55–114, eds Gueguen, Y. and Bouteca, M., Elsevier, Amsterdam.

Wulf, A.-M. & Burkhardt, H., 1997. Mechanisms affecting ultrasonic wave propagation in fluid-containing sandstone under high hydrostatic pressure, J. geophys. Res., 102, 3043–3050.

Zhang, H., Thurber, C. & Bedrosian, P., 2009. Joint inversion for $V_p$ and $V_p/V_s$ at SAFOD, Parkfield, California, Geochem. Geophys. Geosyst., 10, Q11002, doi:10.1029/2009GC002709.

Zhao, D., Kanamori, H. & Negishi, H., 1996. Tomography of the source area of the 1995 Kobe earthquake: evidence for fluids at the hypocenter? Science, 274, 1891–1894.

Zhao, D. & Mizuno, T., 1999. Crack density and saturation rate in the 1995 Kobe earthquake region, Geophys. Res. Lett., 26, 3213–3216.

© 2010 The Authors, GJI, 182, 1148–1160
Journal compilation © 2010 RAS