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Project Title:
Permeability and Strength of Core Samples from the Taiwan Chelungpu-fault Drilling Project - Hydromechanical constraints on earthquake rupture: Collaborative research (SBU & WHOI)

Principal Investigators:
Teng-fong Wong
Department of Geosciences, Stony Brook University
Teng-fong.wong@stonybrook.edu

Wen-lu Zhu
*Department of Geology and Geophysics, WHOI
*Now at: Department of Geology, University of Maryland, College Park,
wzhu@geol.umd.edu

Objectives:
In January 2004 the Taiwan Chelungpu-fault Drilling Project (TCDP) was initiated to drill two vertical holes into the northern portion of the Chelungpu fault that ruptured during the M_w7.6 Chi-Chi earthquake in 1999. Core samples from hole A to a depth of 2 km are now available for scientific studies related to earthquake physics. While the overall objectives of TCDP and SAFOD are very similar, the Chelungpu and San Andreas fault systems are associated with very different tectonic settings, styles of faulting and earthquake cycles. This is a proposal to undertake a study of TCDP core samples in parallel with current efforts to study SAFOD samples that can potentially lead to synergistic understanding of some important questions on earthquake mechanics that remain unresolved. Inversion of geodetic data for the fault geometry and coseismic displacement is sensitive to elastic heterogeneity and anisotropy. Detailed seismological and geodetic measurements indicate that the Chi-Chi earthquake may involve dynamic weakening, which is sensitive to the permeability and storage properties. Hydromechanical tests will be conducted on TCDP core samples with the objective of placing constraints on some of these fault models and proposed weakening mechanisms. The experimental efforts at Stony Brook and Woods Hole will be coordinated with David Lockner's laboratory at USGS Menlo Park, who will also involve a graduate student from Stony Brook in his experiments.

Results:

This is a collaborative research project led by the Stony Brook University.

A suite of experiments have been completed in the Stony Brook laboratory on TCDP cores retrieved from a depth range of 587-1248m. We also conducted a few experiments at nominal dry condition with argon as pore fluid using a Paterson rig at MIT. The petrographic properties of these core samples are shown in Table 1.

Table 1. Compilation of Samples.

Depth (m)	588	785	837	850	1248
Sample name	T588	T785	T837	T850	T1248
Rock type	Sandstone	Siltstone	Shaly siltstone	Sandstone	Shaly siltstone
Density (g/cm3)	2.14	2.52	2.59	2.20	2.59
Porosity (%)	15.9-18.7	6.6	3.5-4.5	18.6	4
Grain size (μm)	200	~30	5-50	200	30
Composition	Quartz, feldspar, clay	Quartz, clay, feldspar, pyrite	Quartz, clay (illite, chlorite), feldspar	Quartz, feldspar, calcite, clay	Quartz, feldspar, clay (illite, chlorite), rutile
Mechanical tests	2		7 (at both dry and saturated conditions)		
Permeability tests I. distilled water	1	1	6	1	1
Permeability tests II. argon			4		

To understand the anisotropic hydromechanical behaviors of the drillcores, cylindrical samples were cored in 3 orthogonal directions (with the axial axis of a sample being parallel, perpendicular, and 45° in respect to sedimentary beddings). Two different sample sizes are used: 18.4 mm (diameter) x 38.1 mm (length) (for water-saturated experiments conducted at Stony Brook University), and 10 mm x 20 mm for tests with argon as pore fluid (using a Pateson rig at MIT).

For water saturated experiments, a wide range permeameter was used to measure permeability. The permeameter is designed so that either the steady flow or pulse transient technique can be used for relatively permeable and tight samples, respectively. The technique can also be switched during a test if significant permeability changes occur in response to the application of stress. In recent years, this system has been extensively used for characterizing the permeability of fault cores (Seront et al., 1998) as well as tight and permeable sandstones under triaxial compression and extension conditions (Zhu and Wong, 1997; Zhu et al., 2002). Pore volume change is monitored in parallel with the permeability measurement. Care is taken to ensure that in addition to the permeability, its pressure sensitivity as well as the hydraulic diffusivity can be measured accurately for

input into theoretical models for the generation and maintenance of pore pressure excess in a fault zone. A representative data set is shown in Figure 1.

We also conducted a few experiments with argon as pore fluid, using a Paterson rig at MIT. Oscillating flow method was used to measure permeability in this case. A constant temperature and pore pressure, the servo-controlled motor drives the volumometer piston and generates a sinusoidal oscillation of fluid pressure in the upstream reservoir, which results pressure variations in downstream reservoir. Using this method, permeability and storage capacity can be calculated simultaneously. Porosity variations can be inferred from the recorded volumometer data. Using this method, permeability can be measured continuously during both hydrostatic and triaxial loading conditions. Figure 2 shows a typical set of data using this method.

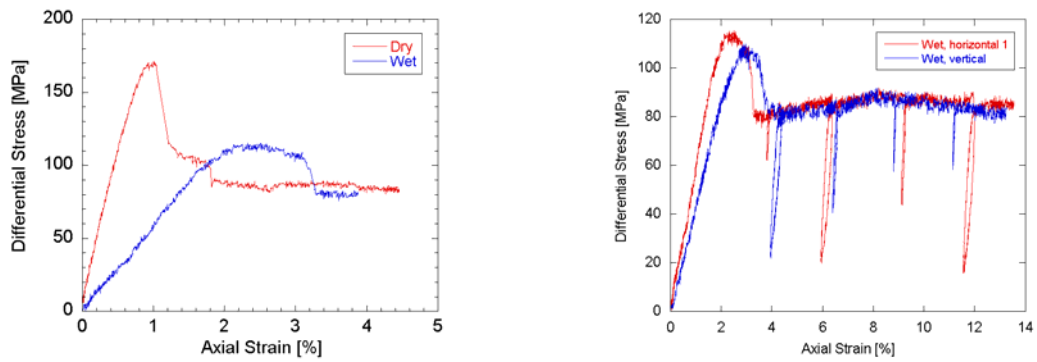
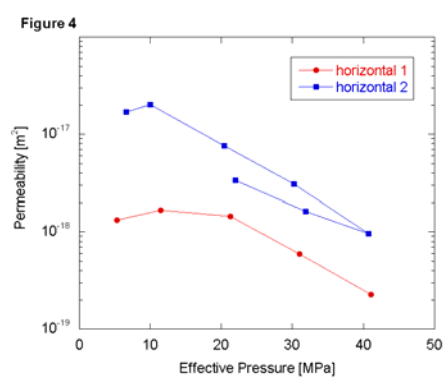


Figure 1a) Mechanical data for two TCDP shaly sandstone samples cored in the horizontal direction, deformed at an effective pressure of 20 MPa. Note that the sample saturated with water was significantly weaker and more compliant. **1b)** Mechanical data for two saturated samples cored in two orthogonal directions deformed at confining pressure of 30 MPa and pore pressure of 10 MPa. The vertical sample was weaker and more compliant.



<u>Figure 1c)</u> Permeability of two TCDP samples as a function of effective pressure. Note permeability contrast up to an order of magnitude between the samples cored in two orthogonal directions, a manifestation of the bedding acting as a flow barrier. Both samples were cored horizontally, with the less permeable sample aligned relative to the bedding as shown in Figure 3a, whereas the more permeable sample was cored horizontally such that the bedding was aligned axially along the flow direction.

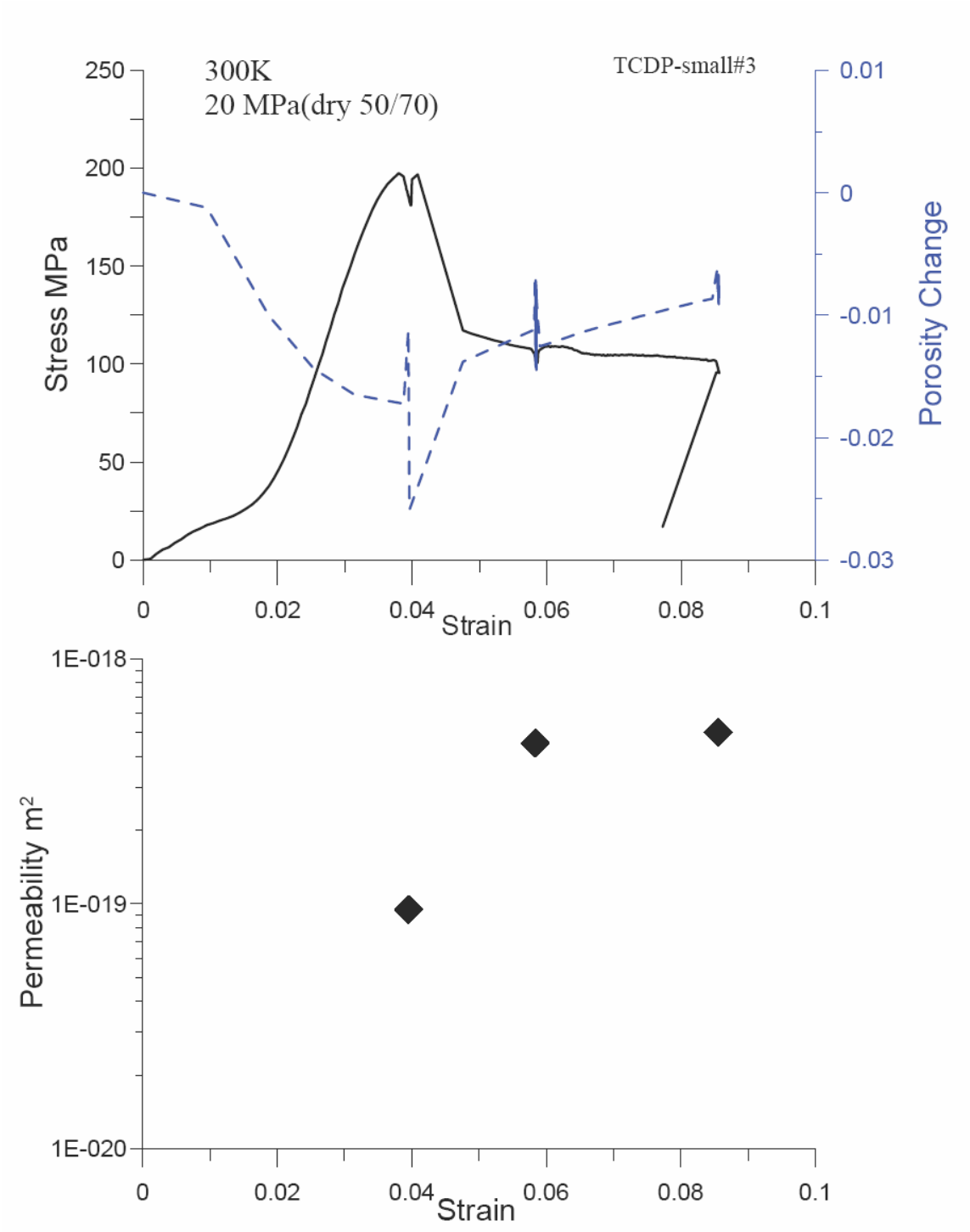


Figure 2. Mecanical behavior and permeability data of a TCDP sample deformed at 20 MPa at a strain rate of 10^{-5}/s.

Several conclusions can be drawn from the data. [1] The shaly sandstone samples are associated with beddings that dip preferentially at ~30°. The principal stresses for the samples cored horizontally simulated those in a thrust faulting regime, and the failure

mode in these samples was characterized by almost planar shear faults that were aligned along the dip of the bedding, demonstrating that bedding anisotropy has dominant control over the style of faulting. [2] Interconnected porosities were determined to be 4-5%. Possibly due to their high clay content our samples were mechanically weak, with strengths only ~ 1/2 of those of a clean quartz arenite such as Tennessee sandstone (with 6% porosity). However, the frictional strengths are quite normal, in that the friction coefficient of a fractured sample under wet condition is comparable to Byerlee's law. [3] The shaly sandstone shows significant water weakening, and dilatancy observed prior to brittle failure was relatively small. Presence of water resulted in ~30% reduction in the strengths of the saturated samples relative to the corresponding dry samples cored in either directions. If further experiments confirm these trends, the data would provide important hydromechanical constraints and impact our analysis of the tectonics and development of pore pressure excess, as well as borehole breakout and inference of the stress states. [4] While elastic moduli of the saturated samples are comparable to those inferred from seismic data, they are sensitively dependent on bedding and presence of water. Although elastic heterogeneity was considered to be very important in the inversion of geodetic data for resolving details of the fault geometry (Johnson and Segall, 2004), elastic anisotropy and its implication seem not to have been analyzed. [5] The permeability was relatively low, with values in the range of 10^{-17}-10^{-19} m^2 at effective pressures of 5-40 MPa. Permeability for flow perpendicular to bedding was lower than that parallel to bedding by one order of magnitude. Such permeability anisotropy seems not to be considered in fault models on thermal pressurization.

TCDP encounters a thrust fault system that recently experienced a major earthquake with very large slip displacement. Because the 1999 Chi-Chi event is probably the earthquake with the most extensive instrumental data over a broad frequency band (Shin and Teng, 2001), the spatio-temporal heterogeneity of rupture characteristics along the Chelunpu fault has been documented in great detail (BSSA special issue, Teng et al., 2001). Specific to such an earthquake with large slip displacement, dynamic weakening mechanisms including thermal pressurization, melting and elastohydroynamic lubrication have been postulated (e.g. Kanamori and Heaton, 2000). Systematic laboratory measurements on the TCDP core samples thus provide an unusual opportunity to characterize the hydromechanical and constitutive properties that are critical in validating these models.