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Wonn Soh  JAMSTEC
Mark Zoback  Stanford Univ.
Steve Hickman  USGS
Bill Ellsworth  USGS

http://www.icdp-online.de/sites/chelungpu/news/news.html
Chelungpu Fault

1999 年9月21日
Chi-Chi, Taiwan, Earthquake
Mw 7.6
Bei-Fung Bridge near Fung-Yan city
Chelungpu fault:

shallow dipping thrust fault

slip at shallow depth

>Drilling the Chelungpu fault:

Undersatnd physics of faulting

North  South
Fengyuan (North well): high water content

Nantou (South well): pseudotachylite
Structural Mapping by the Shallow Reflection Seismic Method

淺層反射震測預測井況
TCDP: Understand physics of faulting

Why Drill at Chelungpu Fault

• Clear Scientific Target:
• Achievable Drilling Target:
• Well Defined Fault Plane:
• International Interests:
Northern portion of the Chelungpu fault

車籠埔斷層北段
Dakeng Seismic Section

Profile C: TaKungHsi

Surface Rupture

YouKoShan Gravel

ChihShui Shale

ChoLin

Grf
Structural Cross Section across the Proposed Drilling Site
Scientific Objectives

- Understand Dynamic Faulting Process

- Estimate Levels of Absolute Stress

- Identify Physical Characteristics of an Asperity
What is an Asperity?

- Area of large slip during an earthquake (large stress drop)

- Area of high stress before the earthquake

- Locked area of the fault prior to the earthquake

Opportunity to actually see an Asperity
Tasks

- Retrieve and analyze physical sample of the fault (Core Measurement)
- Make geophysical and geological characterizations of the site (geophysical imaging, pore pressure, permeability lithostratigraphy, sedimentary facies)
- Measure static stress levels (Logging, Hydro-fracture)
- Measure residual temperatures from earthquake
- Continue geophysical monitoring (Seismometers, thermometer, pore pressure)
## Lists of Scientific Targets (I)

### a) Identify and characterize the fault zone

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scientific Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation Fabrics</td>
<td>Factors control the localization of slip and strain; Microstructures and deformation mechanisms within fault zone and protolith</td>
</tr>
<tr>
<td>Mineralogy and petrology of fault and wall rocks (XRD, XRF, AFM, etc.)</td>
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</tr>
<tr>
<td>Experimental studies and modeling</td>
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</tr>
<tr>
<td>Seismic velocities (Vp and Vs)</td>
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</tr>
<tr>
<td>Temperature (ESR, OM, T-logging, etc.)</td>
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</tr>
<tr>
<td>Thermochronology</td>
<td></td>
</tr>
</tbody>
</table>
### Lists of Scientific Targets (II)

**b) Physical and Chemical properties of the fault (weak or strong fault)**

<table>
<thead>
<tr>
<th>parameters</th>
<th>Scientific Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid pressure</td>
<td>1. Vertical and lateral distribution of fluid pressure regimes</td>
</tr>
<tr>
<td></td>
<td>2. Time-dependence of fluid pressure within the fault zone</td>
</tr>
<tr>
<td></td>
<td>3. The extent of vertical and lateral fluid migration after a large earthquake</td>
</tr>
<tr>
<td>Permeability, Porosity</td>
<td>Permeability and porosity structure within fault zone (thermal pressurization)</td>
</tr>
<tr>
<td>Fluid chemistry</td>
<td>The origin and composition of fault zone fluids</td>
</tr>
</tbody>
</table>
Lists of Scientific Targets (III)

**c) Mechanical Properties**

<table>
<thead>
<tr>
<th>parameters</th>
<th>Scientific Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poroelastic properties, Storage capacity, Biot coefficient, Skempton coefficient</td>
<td>Physical and mechanical properties of fault-zone material and country rock</td>
</tr>
<tr>
<td>Fault Roughness (Coefficient of friction)</td>
<td>Fault roughness can reach the value in the range of $10^{-3}$ - $10^{-4}$.</td>
</tr>
</tbody>
</table>
### Lists of Scientific Targets (IV)

#### d) Strain and stress State

<table>
<thead>
<tr>
<th>parameters</th>
<th>Scientific Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress state</td>
<td>Stress tensor vary in the vicinity of the fault zone</td>
</tr>
<tr>
<td>Borehole strain measurements</td>
<td>Strain accumulation occur within the fault zone over different time scale</td>
</tr>
</tbody>
</table>

#### e) Microbiology in the deep biosphere

<table>
<thead>
<tr>
<th>parameters</th>
<th>Scientific Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microbiology data</td>
<td>Collect new microbiology data across a range of lithologic conditions</td>
</tr>
</tbody>
</table>
ENERGY BUDGET

Total Earthquake Energy = Fracture Energy + Radiated Energy + Frictional Heat

Radiated Energy: Seismic data
Fracture Energy: Dc determination
(Seismic dynamic modeling, Laboratory)
Frictional Heat: Temperature
Chelungpu Fault Drilling Project

- Obtain samples of fault with large displacement
- Measure temperatures change across fault
Logging Plan
TCDP Drilling Time Table

Hole A

5/3-5/5 開鑽 2
800-1300m Logging#2
ICDP Schlumberger
5/6-5/15 下套管
0-1300m casing
5/16-7/24 取岩心
1300-2000m coring
6/1

8/1

0-800m no coring
700m/70day=10.0m/day

7/25-7/27 開鑽 3
1300-2000m Logging#3
ICDP Schlumberger
7/28-8/3 清洗3周
1300-2000m filling
8/4-8/10 移動支架
total: 220days(166 drill days)

12/1

12/31

800m/26day=30.7m/day

8/8-9/17 下套管
10days
8/9-9/7 升4
0-800m Logging#4 CPC
9/18-10/21 開始取岩心
34days
800-900m no coring
900-1300m coring
9/6-9/7 升4
0-800m Logging#4 CPC
10/22-10/24 800-1300m Logging#5 CPC
10/25-10/30 前期準備
6days
400m/34day=11.7m/day

11/1-11/20 前期
20days
1000-1200m branching
200m/20day=10.0m/day

11/21-12/30 下套管
10days
12/1-12/27 檢查
total: 119days(80 drill days)

12/1

12/31

Hole B

8/11-9/5 開鑽 start drilling
0-800m no coring
26days

8/8-9/17 下套管
10days

800m/26day=30.7m/day

Total: 220 days (166 drill days)
## Fault Zone Drilling Projects

<table>
<thead>
<tr>
<th>Science Goals</th>
<th>Target Site</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nojima</strong></td>
<td>Nojima fault</td>
<td>Hirabayshi (0.7, 1.8 km) 1996</td>
</tr>
<tr>
<td>Fault zone properties</td>
<td>1995 Kobe Eq.</td>
<td>Ogura (0.5, 0.8, 1.8 km) 1996</td>
</tr>
<tr>
<td>Healing, Water injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SAFOD</strong></td>
<td>San Andreas fault</td>
<td>Pilot hole (2 km) 2003</td>
</tr>
<tr>
<td>Repeating Earthquakes</td>
<td>Parkfield</td>
<td>Main hole (4 km) 2004</td>
</tr>
<tr>
<td>Physical properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NantroSeis</strong></td>
<td>Off-shore</td>
<td>3 km hole 2007 ?</td>
</tr>
<tr>
<td>Splay faults</td>
<td>Nankai Trough</td>
<td>5 km hole</td>
</tr>
<tr>
<td>Accretionary prism</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Corinth</strong></td>
<td>Gulf of Corinth</td>
<td>?</td>
</tr>
<tr>
<td>Fluids in faulting</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TCDP</strong></td>
<td>Chelungpu Fault</td>
<td>2 holes (2, 1.3 km) 2004</td>
</tr>
<tr>
<td>Dynamics of large slip Friction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asperity</td>
<td>1999 Chi-Chi Eq.</td>
<td></td>
</tr>
</tbody>
</table>
Goals

- Understand Dynamic Faulting Process
- Estimate Levels of Absolute Stress
- Identify Physical Characteristics of an Asperity
Thank You!
Drilling Schedule

• 12/15/2003: Start
• 01/10/2004: start drilling
• 02/07/2004: 500m (start coring)
• 03/04/2004: 800m, logging#1
• 05/03/2004: 1300m, logging#2
• 07/25/2004: 2000m, logging#3
• 08/11/2004: Start Hole B
• 09/06/2004: 800m (no coring), logging#4
• 10/22/2004: 1300m, logging#5
大坑深度剖面 TaKung Depth Profile
Structural Cross Section across the Proposed Drilling Site
Sites of two boreholes into the Chelungpu fault
Magnified view of temperature logging results

Northern (Fengyuan) Well

-200
-250
-300
-350
-400

Drilling Depth (m)

26.6
27
27.4

Temperature (°C)

N-MFZ-1 fracture zone

Positive thermal anomaly

7 mm slip zone

Southern (Naotou) Well

-50
-100
-150
-200

Drilling Depth (m)

24
25
26

Temperature (°C)

Apparent Geothermal gradient

S-MFZ fracture zone

Positive thermal anomaly

2 m Ultracataclasite zone

S-LFZ fracture zone

?
Forward Modeling of Temperature Rise at North and South Sites

\[ \mu = 0.1-0.2 \]

\[ \mu = 0.7-1.0 \]
Frictional Heat Produced by Earthquake

- Use $\mu = 0.2$ in North for asperity
  $\mu = 0.8$ in South

- Use (lithostatic-pore) pressure as normal pressure

$=>$ Frictional heat of $1.0 \times 10^{17}$ joules
Asperity

Rest of Fault

Radiated Energy

Frictional Heat

0 bars 2 meters

0 bars 8 meters

100 bars

70 bars

0 bars

320 bars

310 bars
Chelungpu Fault Drilling Project

- Obtain samples of fault with large displacement
- Measure temperatures change across fault
反射震測 Reflection Seismics
Pcs : ChinShui Shale

Mkc : KueiChuLin Fm.

Mnc : NanChuang Fm.
Electric Resistivity

ChinShui Shale

Gravel?

地電剖面

地電阻影像剖面法 RIP

大地電磁法 MT