Macroscopic to Microscopic of Earthquake Dynamics
從巨觀到微觀看地震動力

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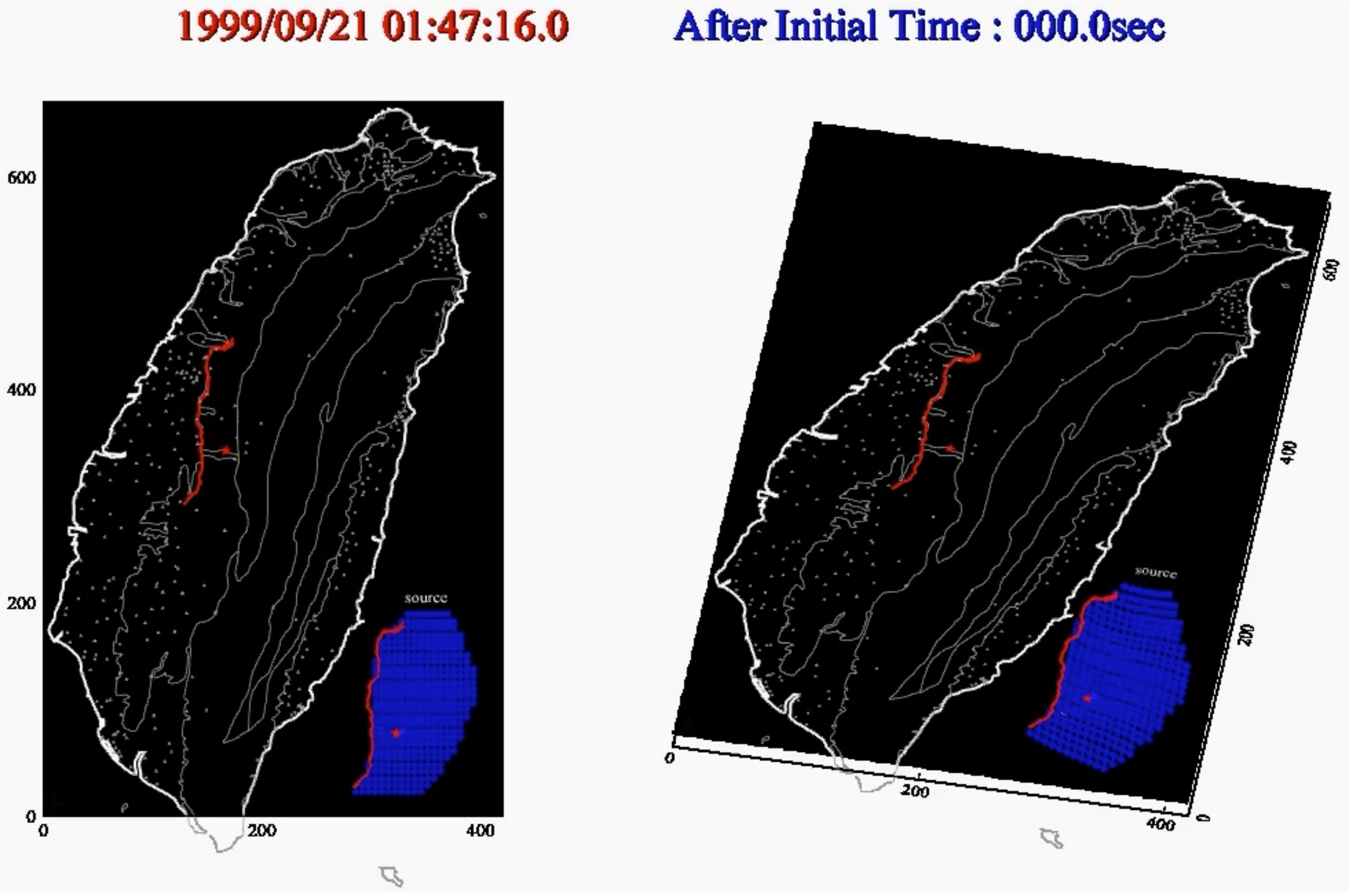
中央大學 地球科學系

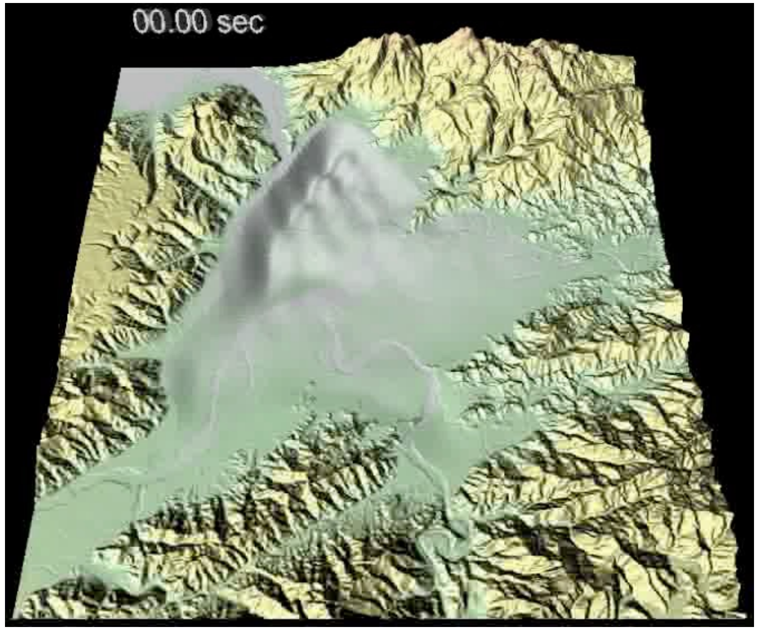
- 集集地震情境模擬 （動畫)：了解地振動特質與災損關係

地震預警技術開發

三維斷層到三維空間地震動模擬



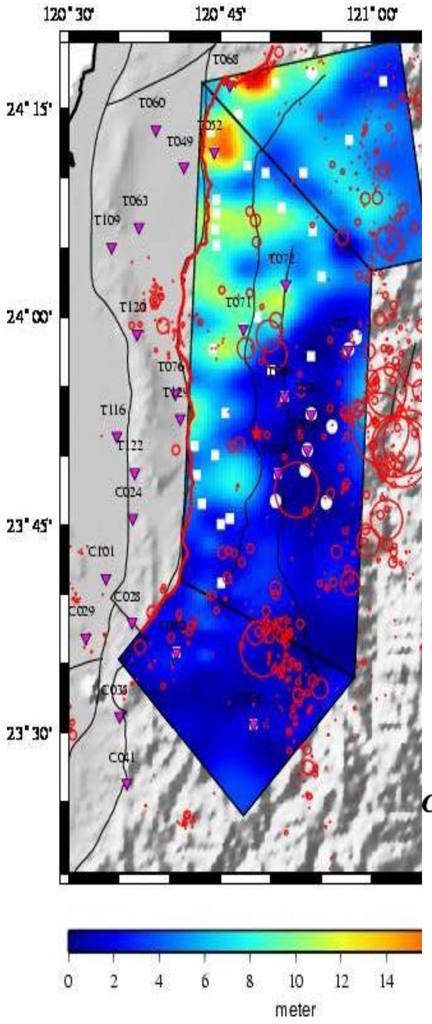
大台北地區
台北盆地 （盆地效應）

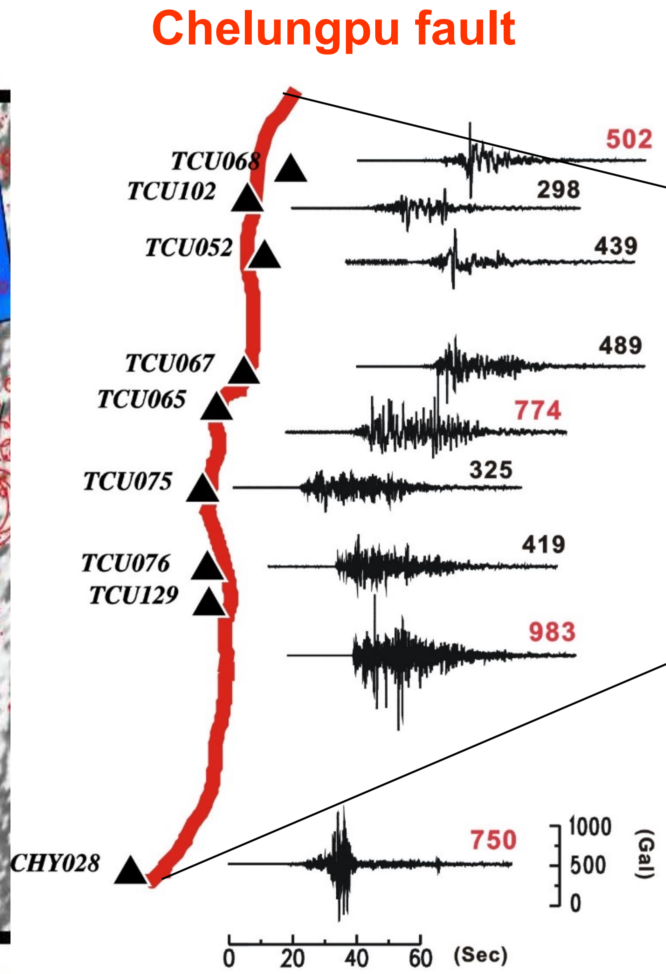


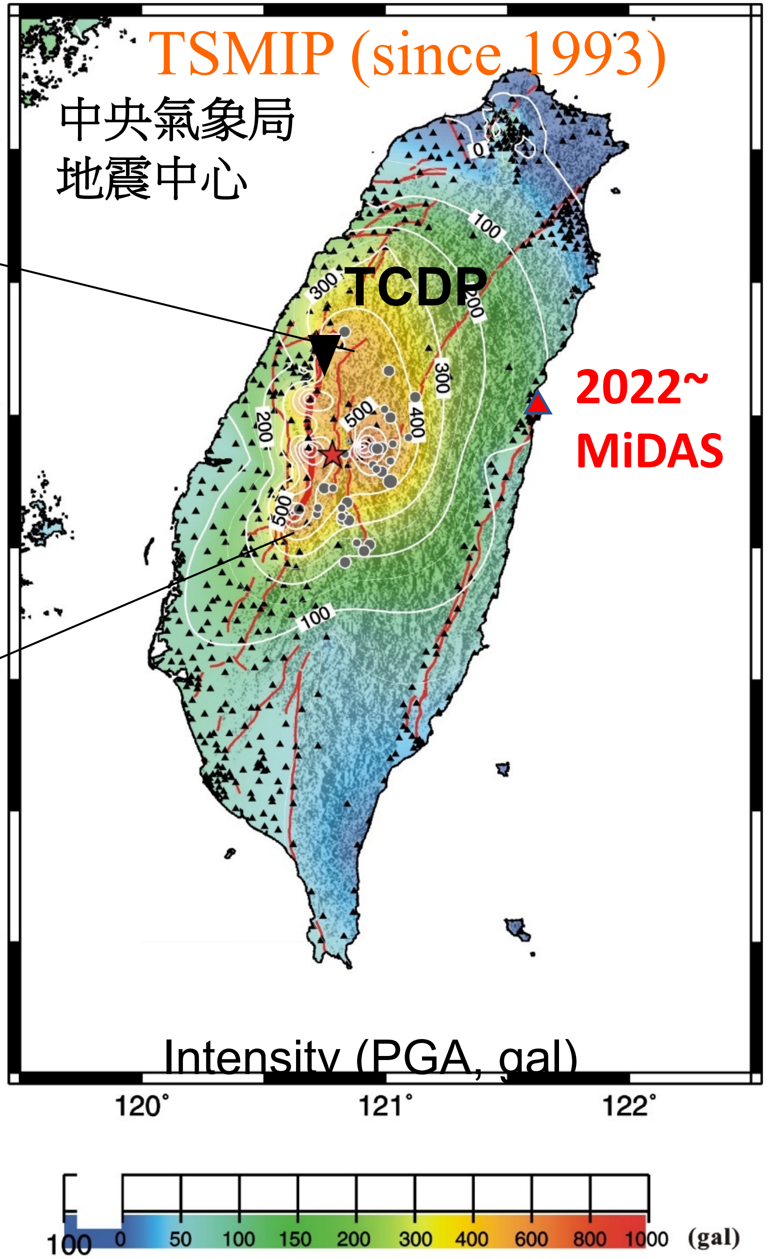
Lee et al., 2005

中研院地球所
李憲忠

1999 Chi-Chi (Mw7.6) Earthquake



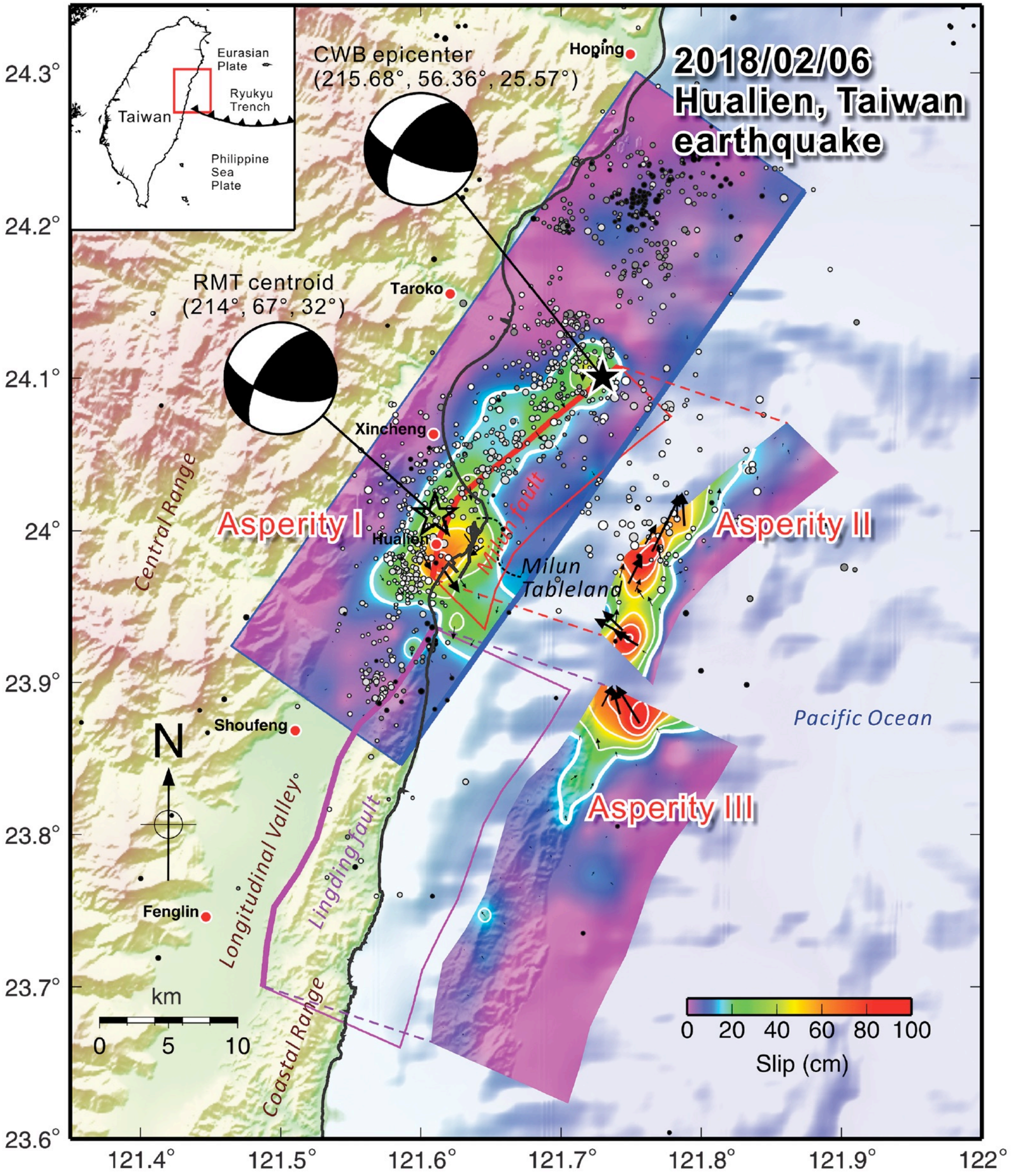




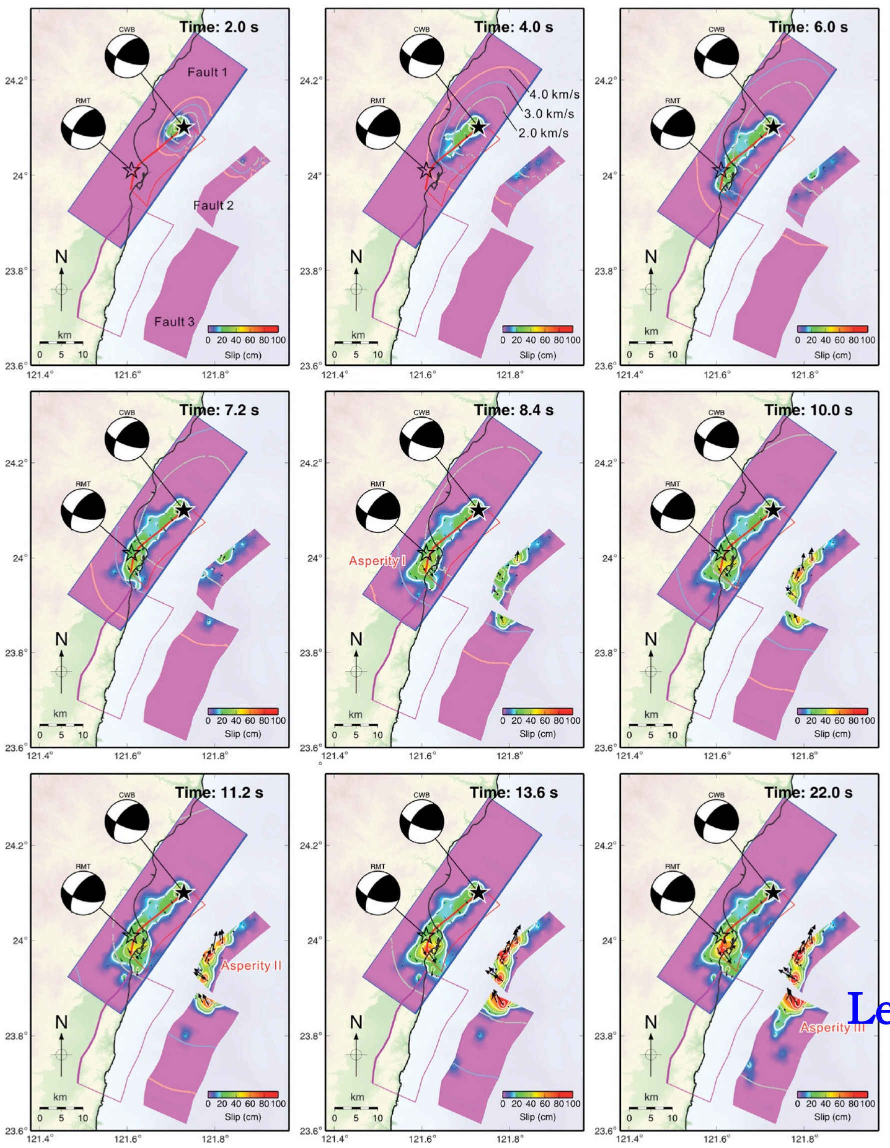
Temporal-spatial slip distribution from seismic waveform inversion

2018 0206 Hualiean Earthquake, ruptured Milun fault

Rupture three fault segments

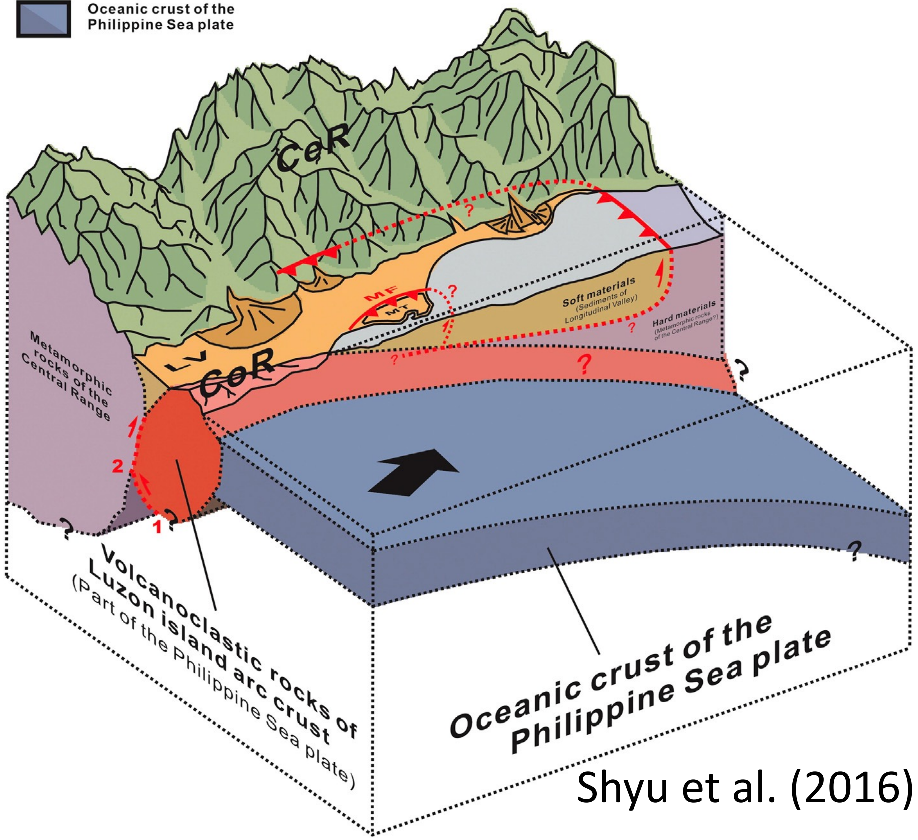


SRL Early Edition

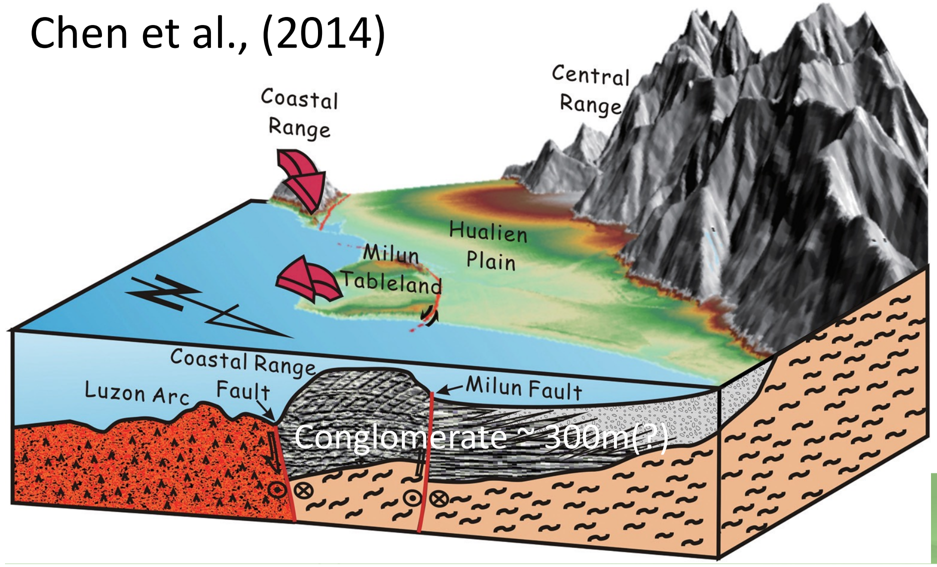


Lee et al., (2019)

Schematic tectonic structure near Milun fault
- Subducting Slab (potential megathrust event)
- Longitudinal Valley Fault (LF)
- Central Range Fault



Shyu et al. (2016)

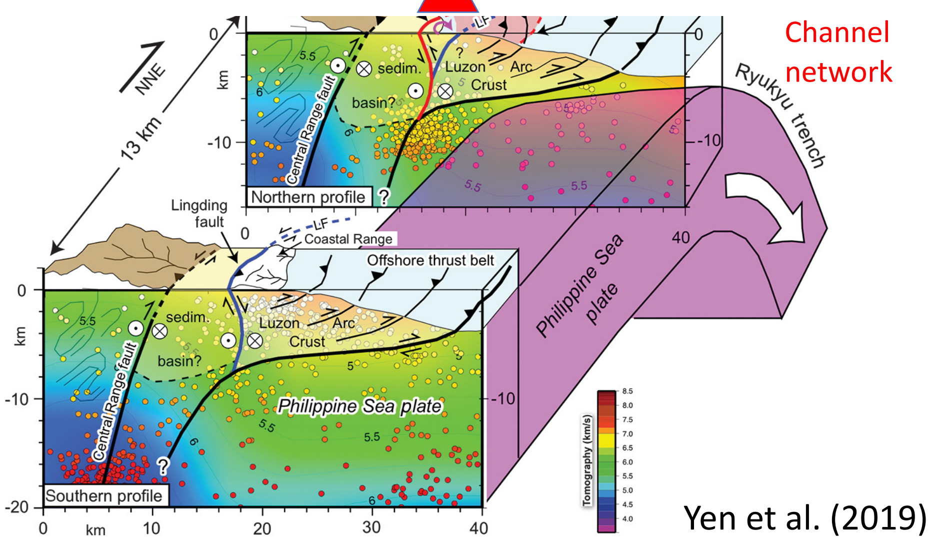


Chen et al., (2014)

Milun Fault
(~75 dipping strike-slip fault)

MiDAS 2021~

Channel network



Yen et al. (2019)

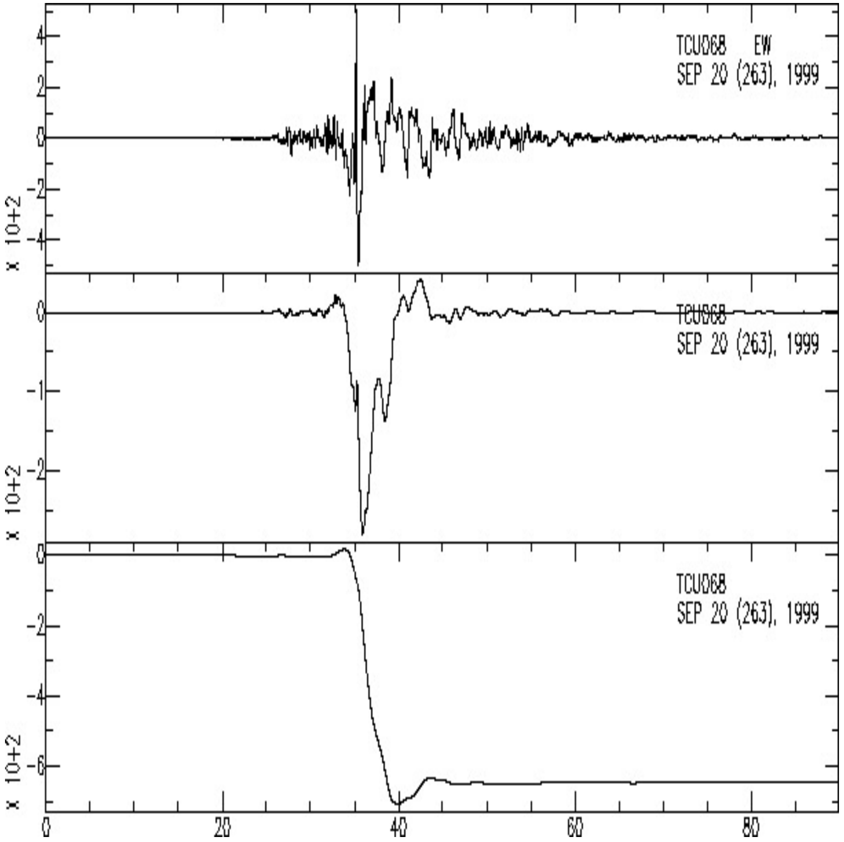
▲ **Figure 6.** Structural interpretation of faults involved in seismogenic deformation during the 6 February Hualien earthquake (focal mechanism in cross-section view), overlain on regional color tomography and seismicity (profile locations in Fig. 1, inset; seismicity from Central Weather Bureau, 1990–2015). Discordant vertical displacements on the Milun and Lingding faults indicate that they are separate strands of a regional fault network that accommodates oblique left-lateral convergence between Eurasian crust (Central Range), Luzon arc crust in a large offshore thrust belt, and oceanic crust of the Philippine Sea plate. Northward subduction of the Philippine Sea plate into the Ryukyu trench flexes the plate downward, causing subsidence and reduction of topography in the northern Coastal Range. See Discussion section.

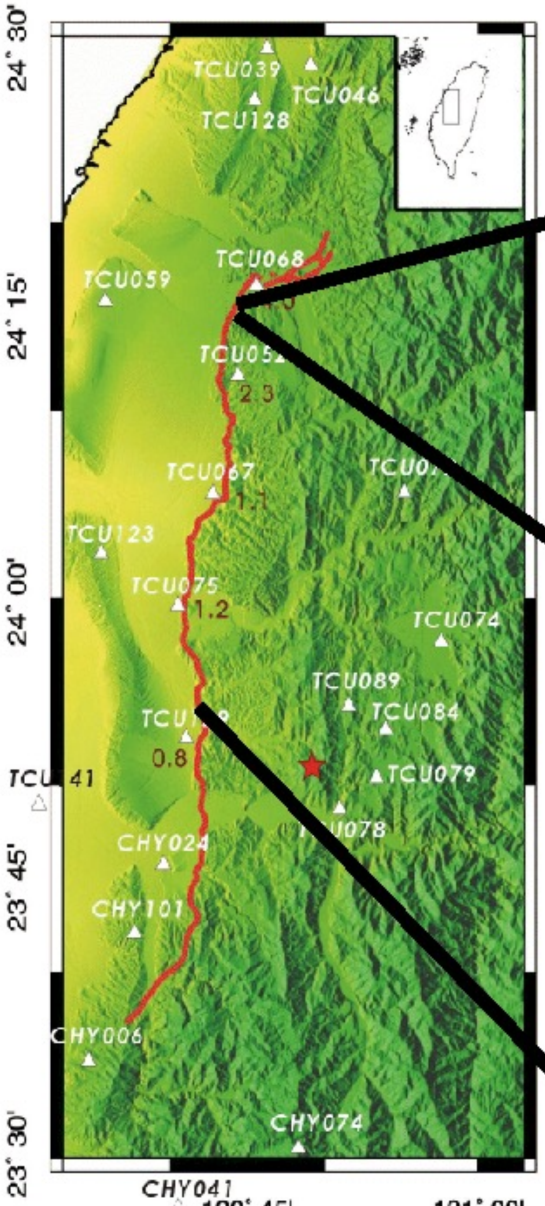
- **How earthquake was initiated and terminated?**
- **What mechanism to cause the damages?**
- **Can we predict the ground motion in amplitude and period to reduce the impact?**

Damaging junior high school during the 1999 Chi-Chi earthquake

Large velocity pulse observed in the 1999 Mw7.6 earthquake

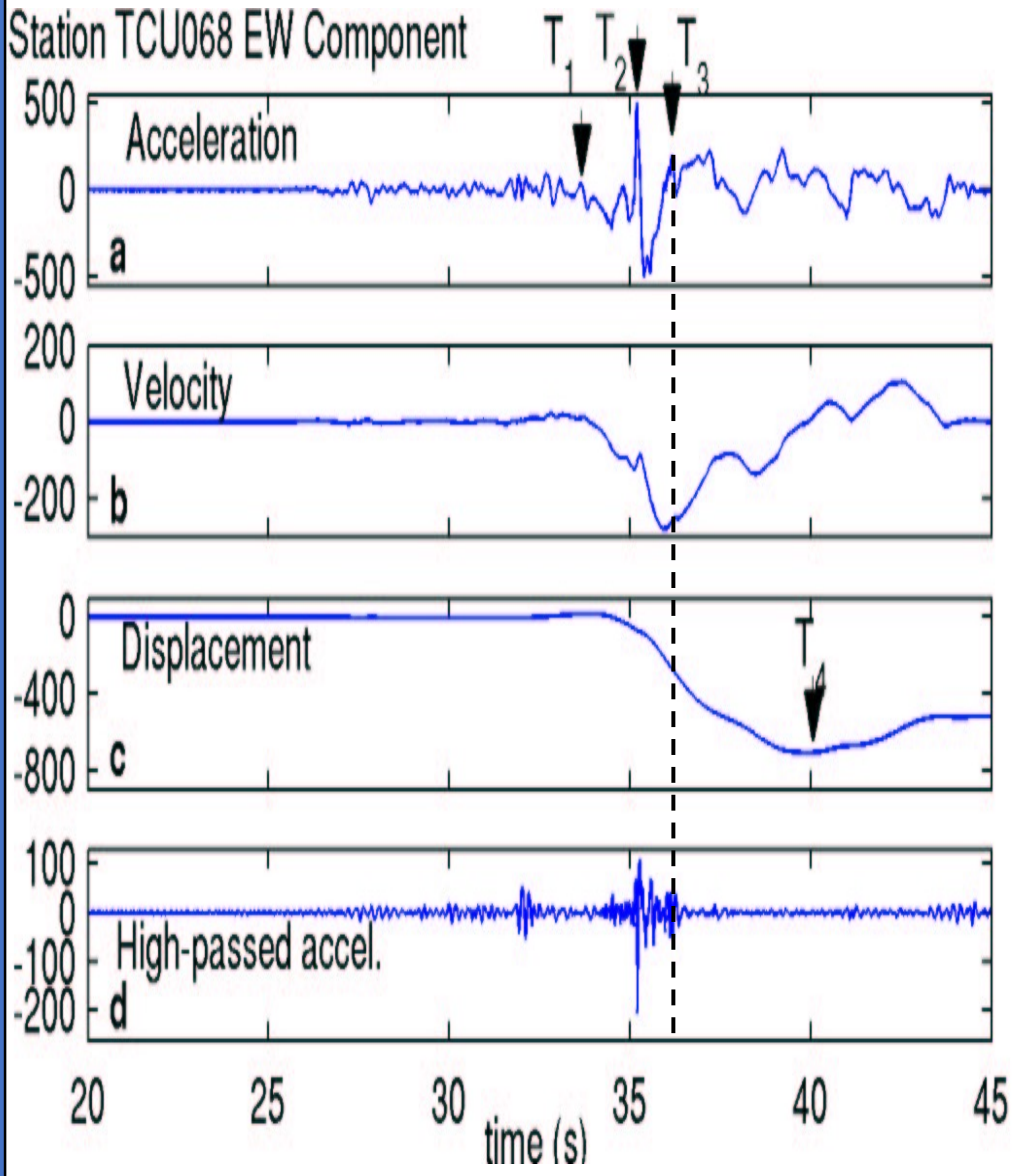
TCU068



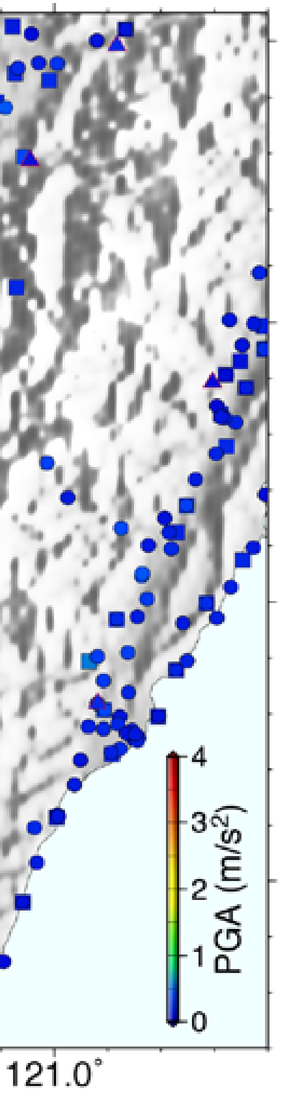


Evidence for fault lubrication Ma et al. (2003)

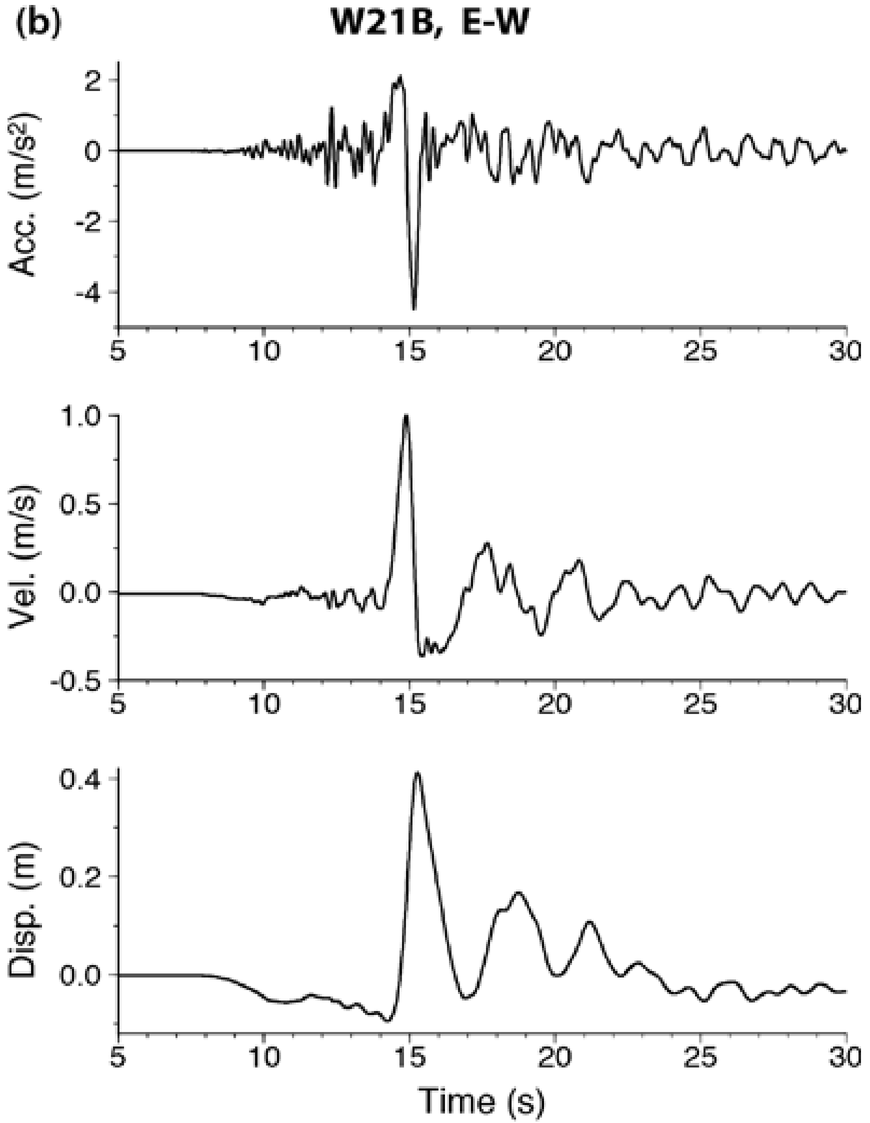
•Start at T1
•Impulsive acc. waveform between T2 (max.) and T3 (small)
•T3: max. velocity
•Continue slip until T4
=>Widening of the fault gap and reduction of asperity collision (displacement increase yields large lubrication pressure)
* Change of frequency contains after T3



Large velocity pulses are now commonly observed with and without static offset

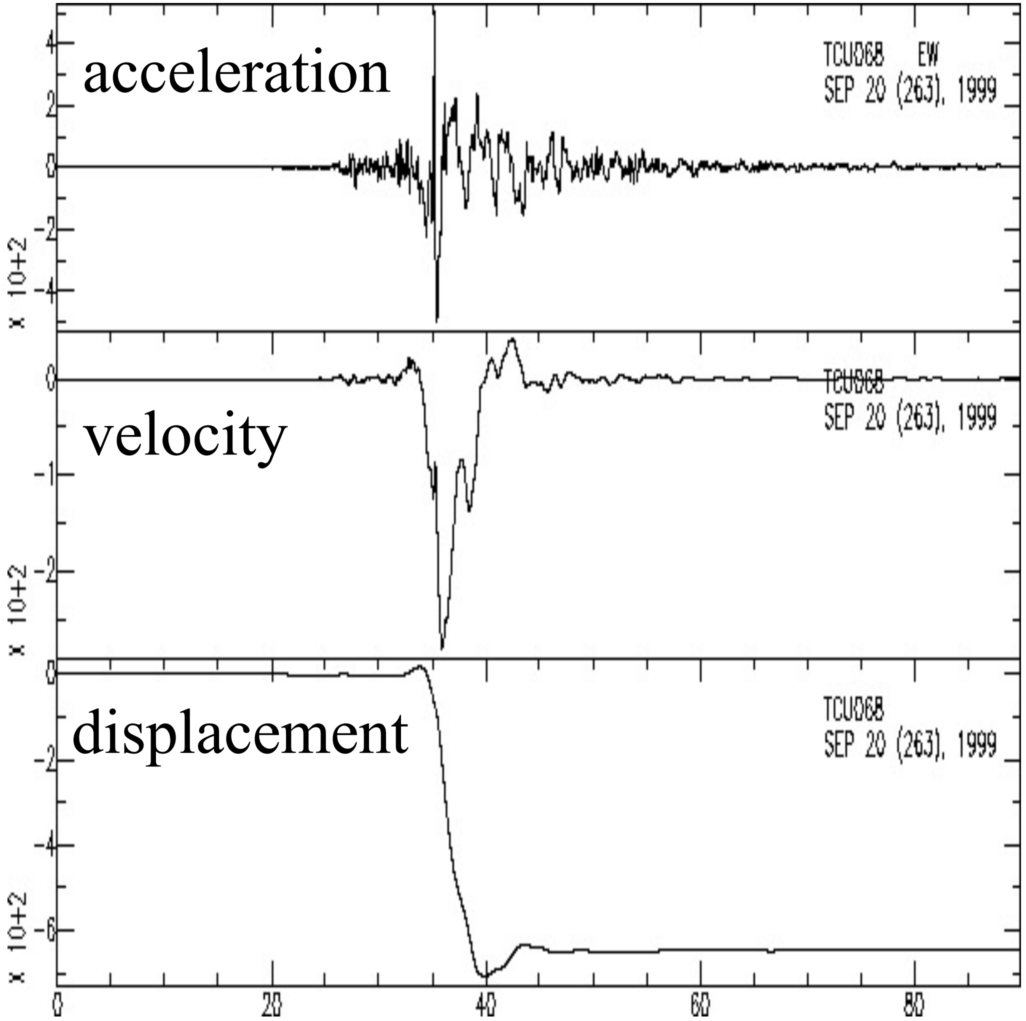


Mw6.4 Meinong earthquake

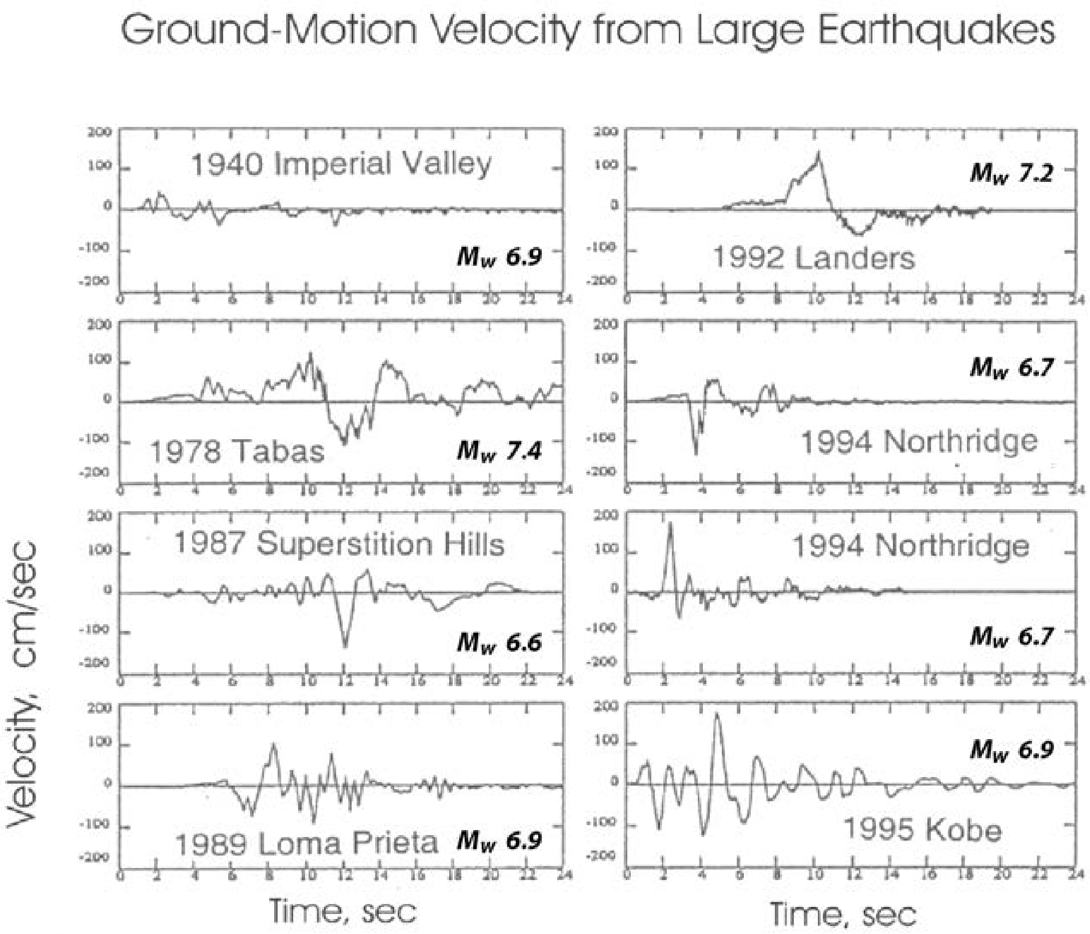


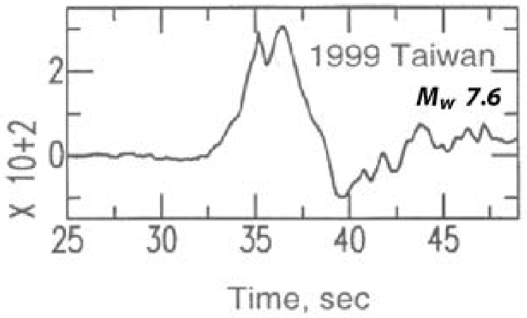
Mw7.6 Chi-Chi earthquake

Station TCU068

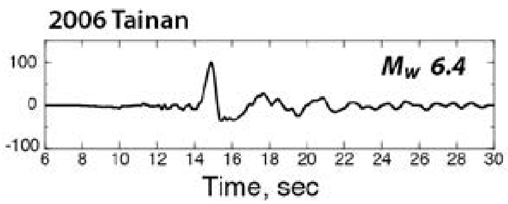


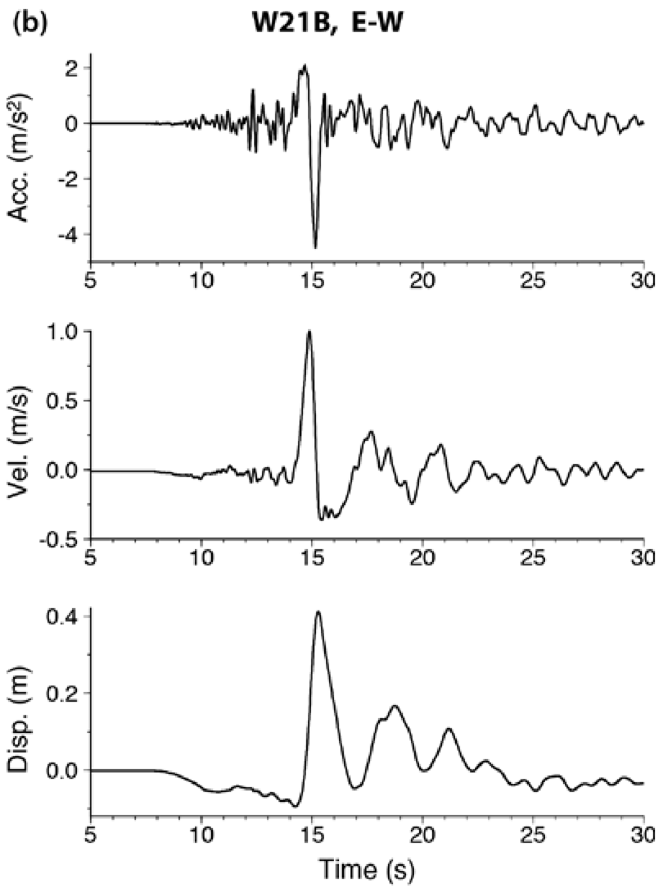
Any PGV scaling relationship to Asperity Distance, and Period to Magnitudes ?





20160206

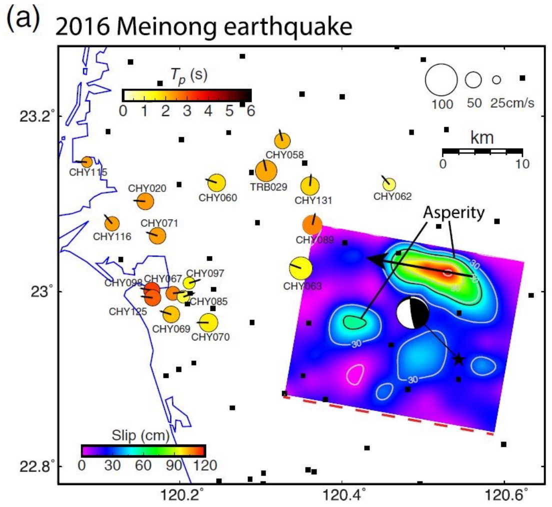


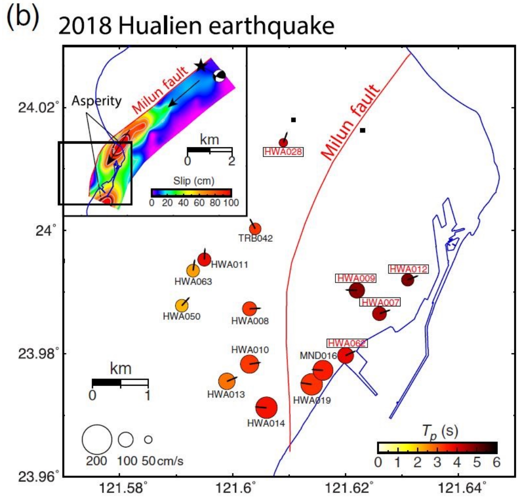


*20180206 Hualiean earthquake, W028 ;

* 20220918 Mw7.0 Chihshan earthquake

Strong-velocity pulses without the static-offset effect and finite-fault slip distributions of the five moderate earthquakes. The color in circles represent the pules period, Tp.

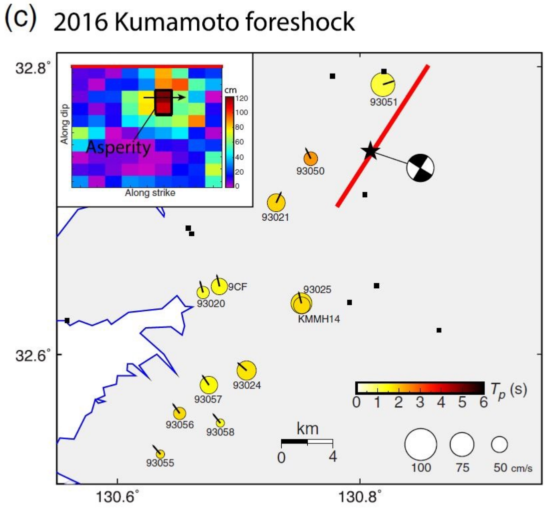


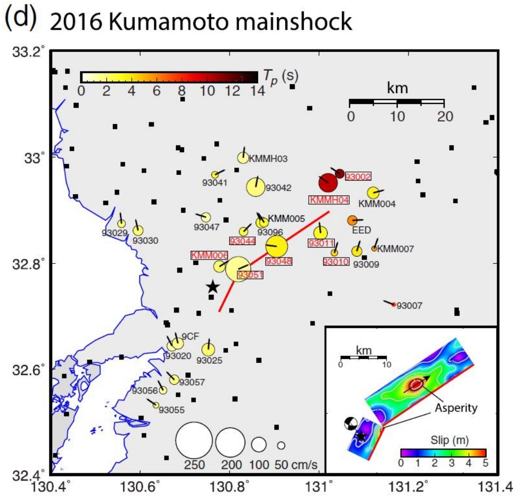


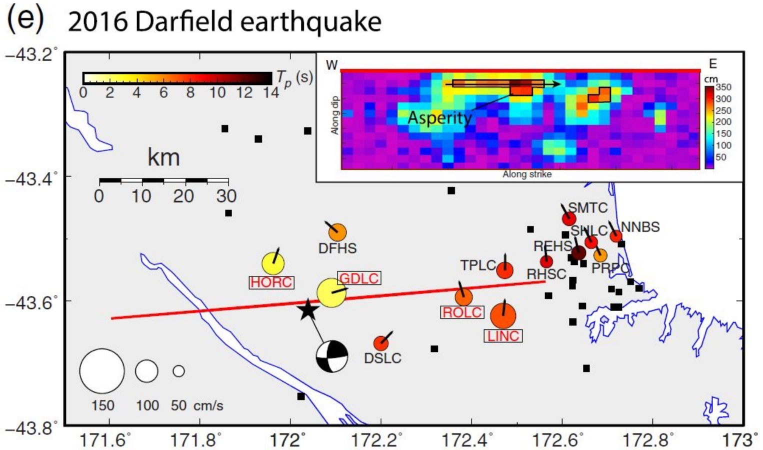
Finite-fault models, Lee et al. (2016; 2019)

The identified asperity and the rupture direction of slip distribution.

Squares represent the station without pulses. The stations names with frame of which represent the pulses that are impacted upon the static offset.



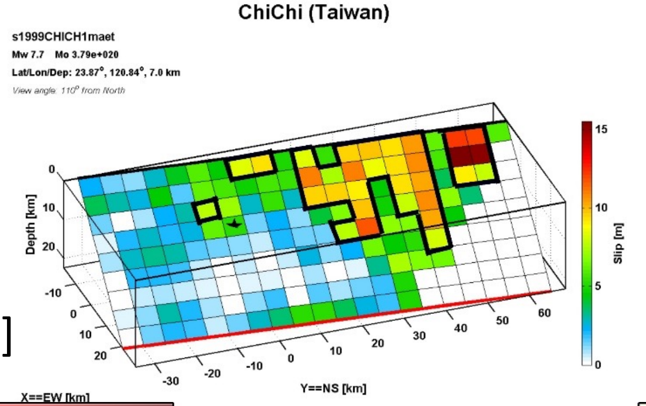




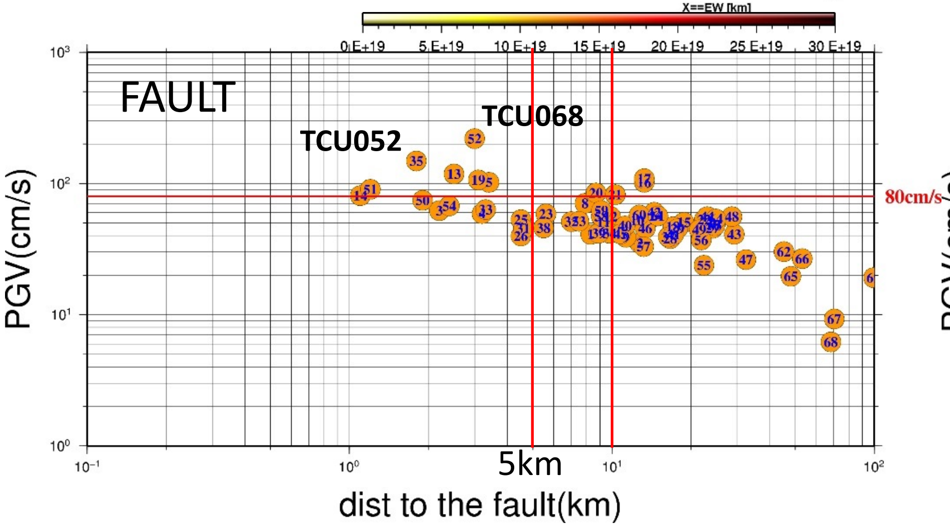
Kobayashi *et al.* (2017), Asano and Iwata (2016), Hayes (NEIC, Darfield 2010

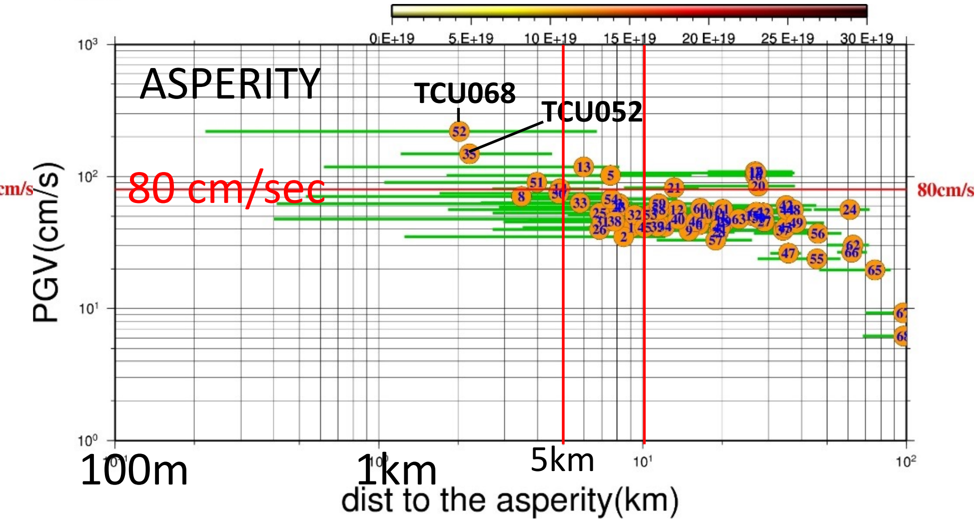
1999 ChiChi (Taiwan)
20 slip models

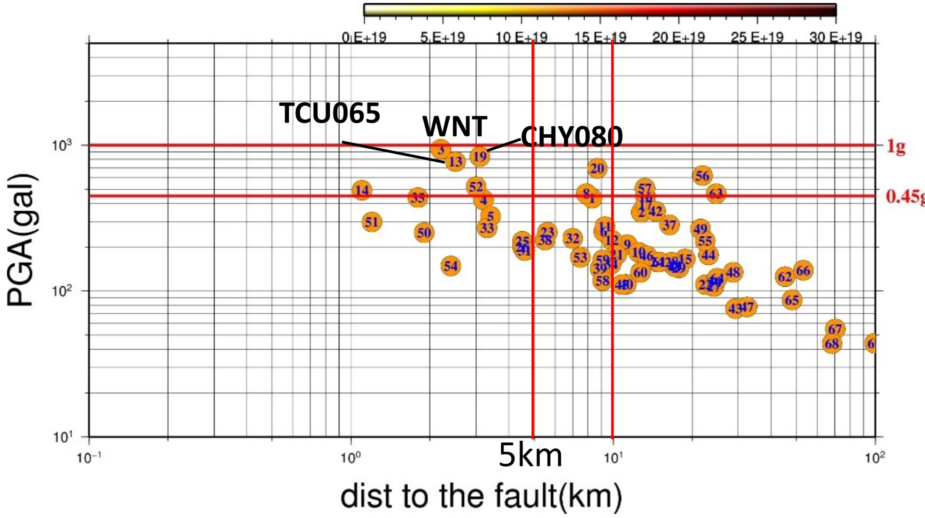
[e.g. Ma et al., 2001]

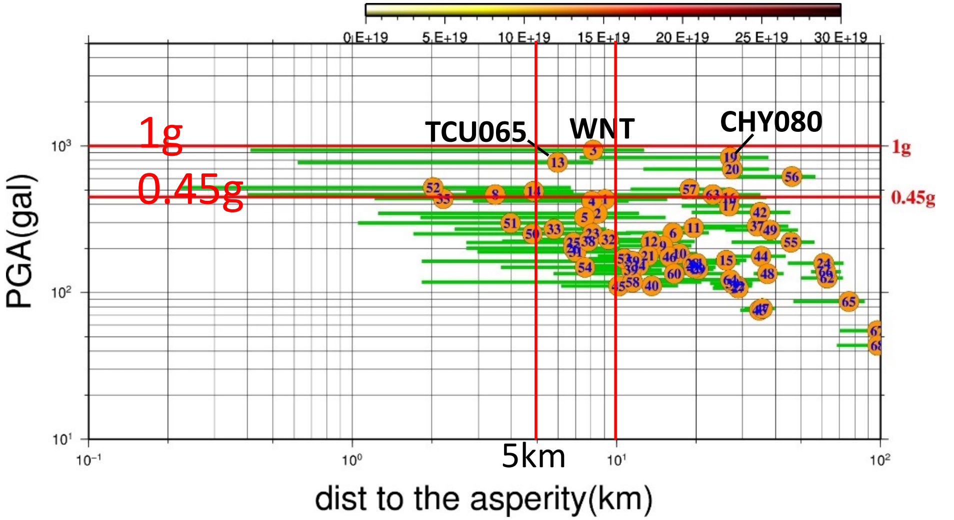


Asperity: D>1.5Dav

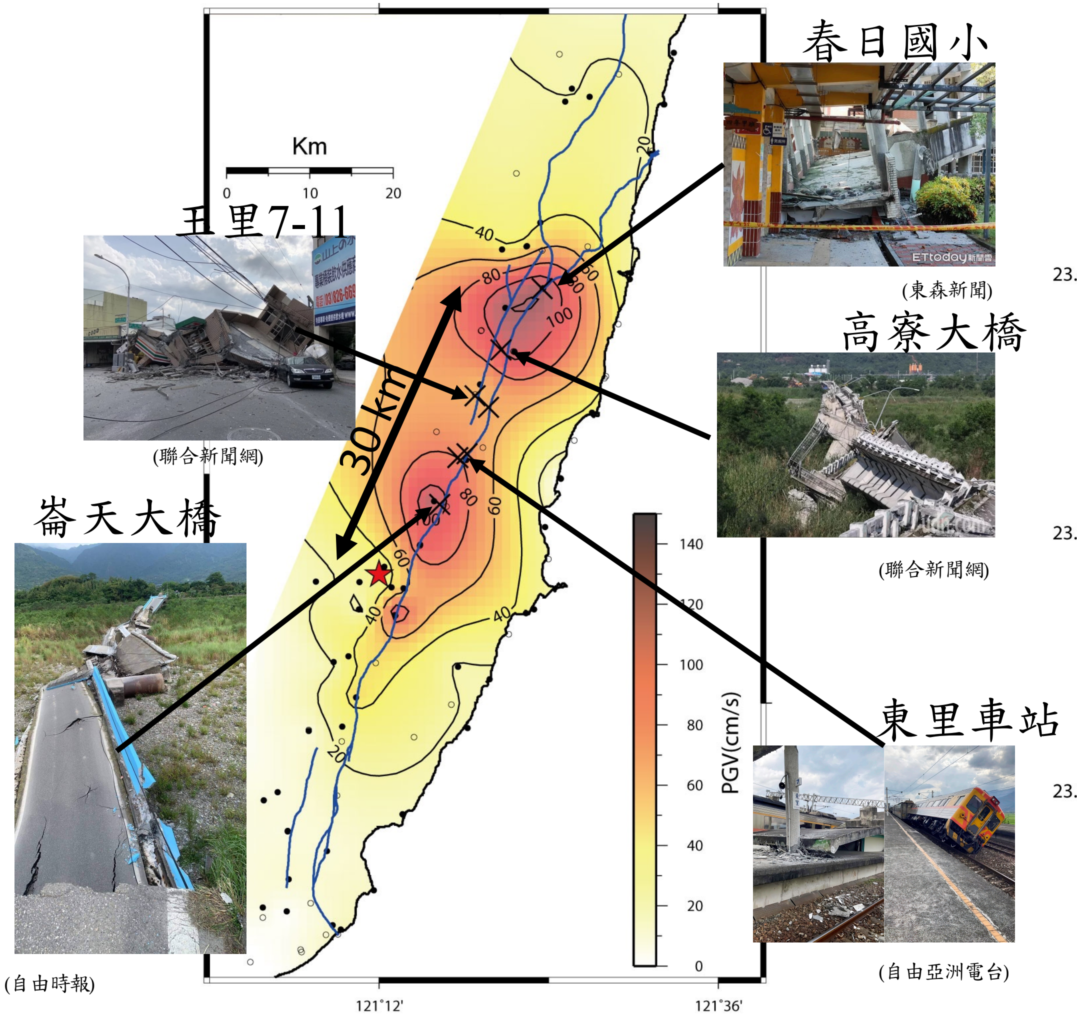






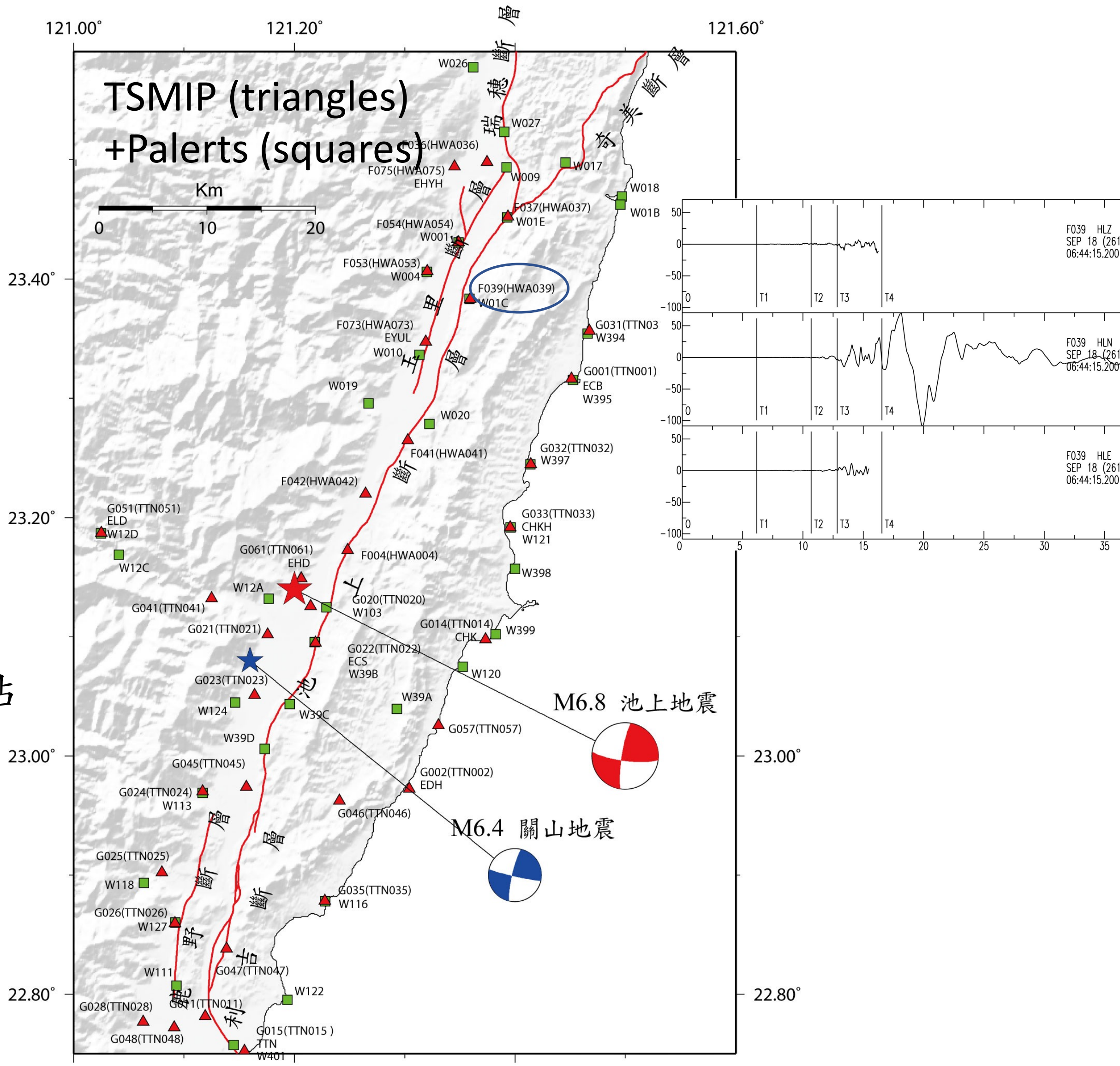


20220918 Mw7.0 Chihshan earthquake



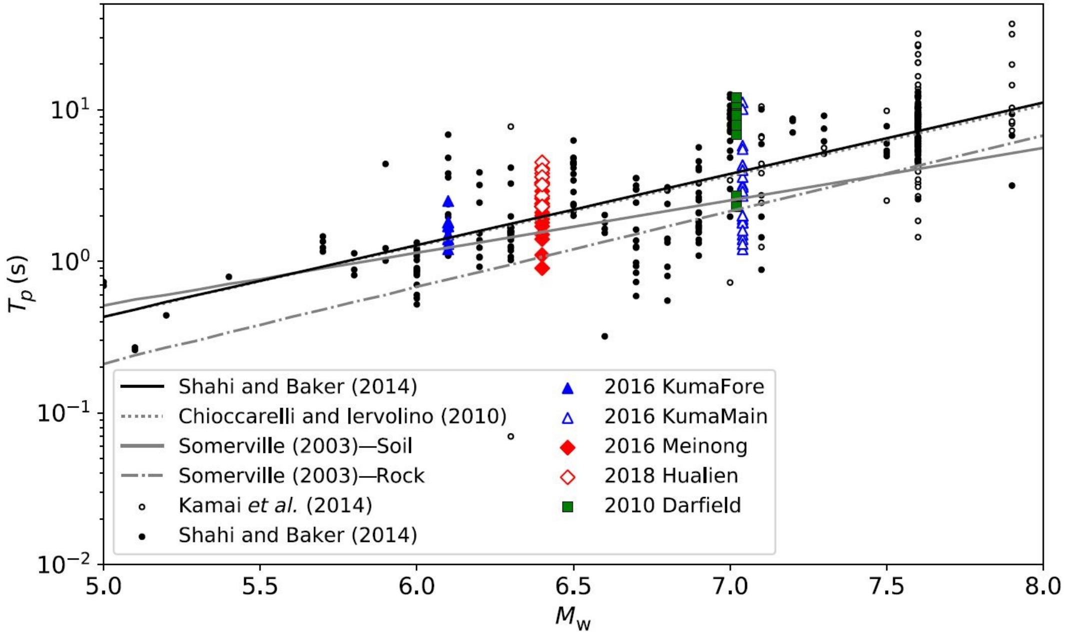
(災害位置來源：中央地質調查所)

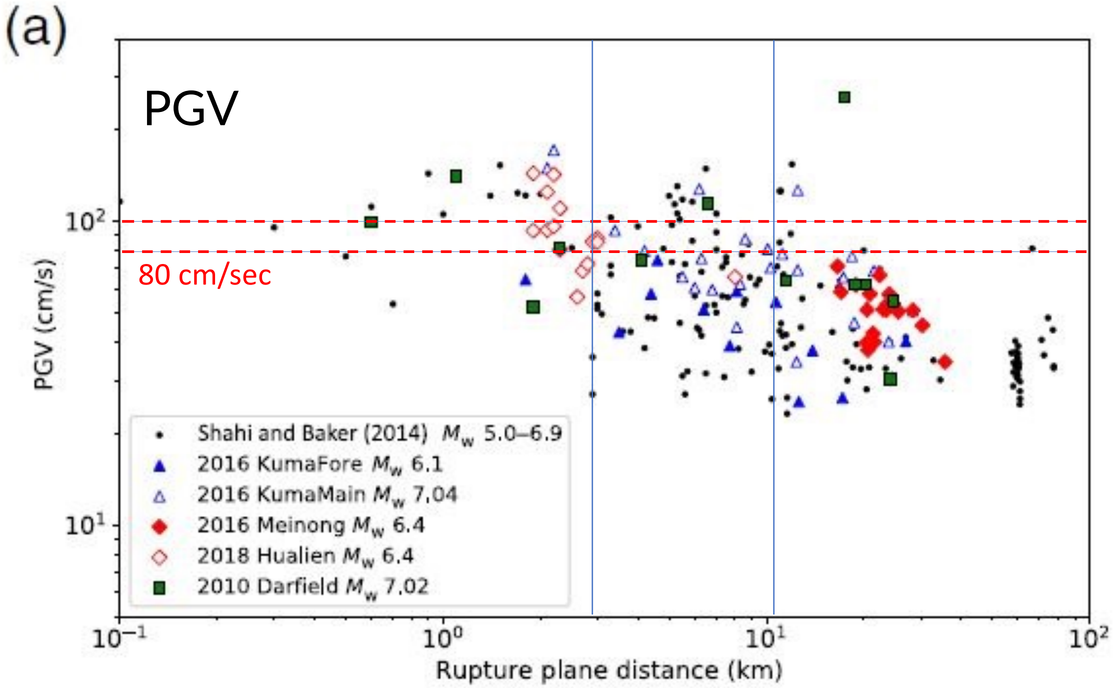
PGV distribution



Lin et al. (2022)

Within- and Between-Event Variabilities of Strong-Velocity Pulses of Moderate Earthquakes within Dense Seismic Arrays, Yen, M.-H., S. von Specht, Y.-Y. Lin, F. Cotton, and K.-F. Ma (BSSA, 2021).





Pulse periods are highly variable from one earthquake to another of similar magnitude (between-event variability) or even for various records of a single earthquake (within-event variability).

PGV > 100 cm/sec, R<3km
PGV > 80cm/sec, R<10km

***Building code 2022; Near-fault building code**

Challenges & Current Practices

*** Multiple-Faults**

- Identification of the Multiple-fault ruptures (Fault System),
- Distribution of the slip rates among the multiple-faults

  SOLUTION?

  - GNSS, Geodetic Model? Quality and Quantity
- Dynamic Modeling

*** Ground Motion Prediction Equation**

- Site Response (Vs30?)
- Near-fault ground motion, large velocity pulse

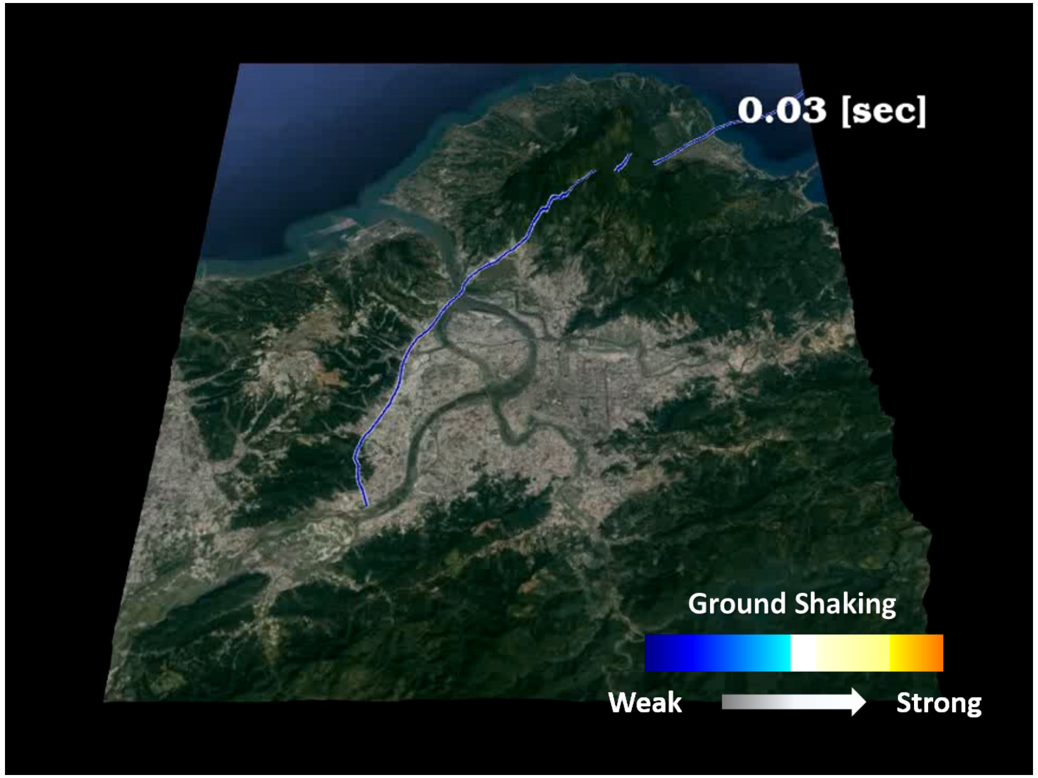
  Practical SOLUTION - 2022 Building Code https://www.cpami.gov.tw/filesys/file/chinese/publication/law/law2/111061501.pdf

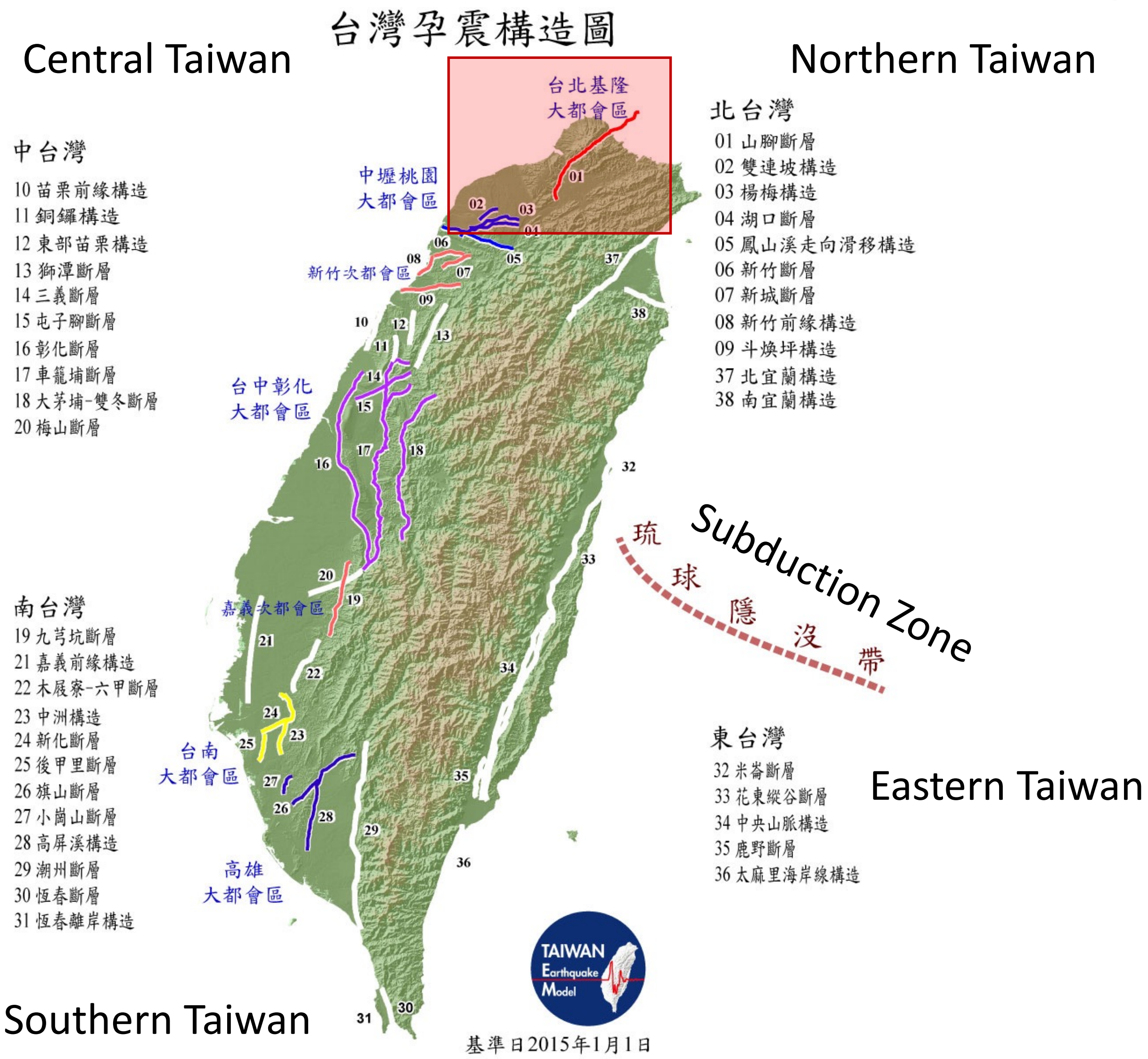
  - New codes for near-fault; 0-2km, 2-5km, 5-9km, 8-12km, 12-14km

  - Strengthen Soft Story Buildings

- Earthquake Scenarios, Annual September Earthquake Drill

Taipei Metropolitan earthquake scenario for disaster prevention and risk management





RESIST-Resilient societies through smart-city technology: Assessing earthquake risk (Taiwan, Japan, US, New Zealand)

與相關合作夥伴合作、
共同創造、推廣及教
育民眾實現韌性社會

Educate the public, with cooperation of associated partners

以情境為基礎的地震
危害分析和風險評估

Scenario-based earthquake hazard and risk assessments

建構開放和
脆弱性曲線

Transparent fragility curves

高密度地震地表震動
資料彙整

Large-scale earthquake ground-shaking data collection

建築內地震陣列和
建築物健康監控

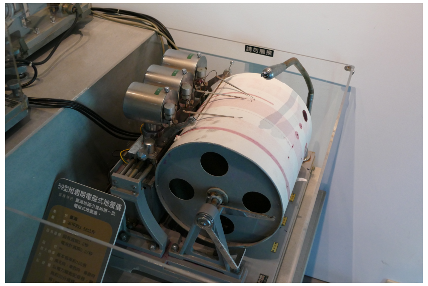
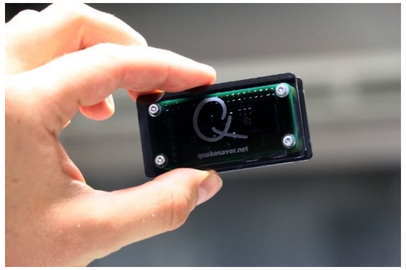
Building seismic array & building-health monitoring

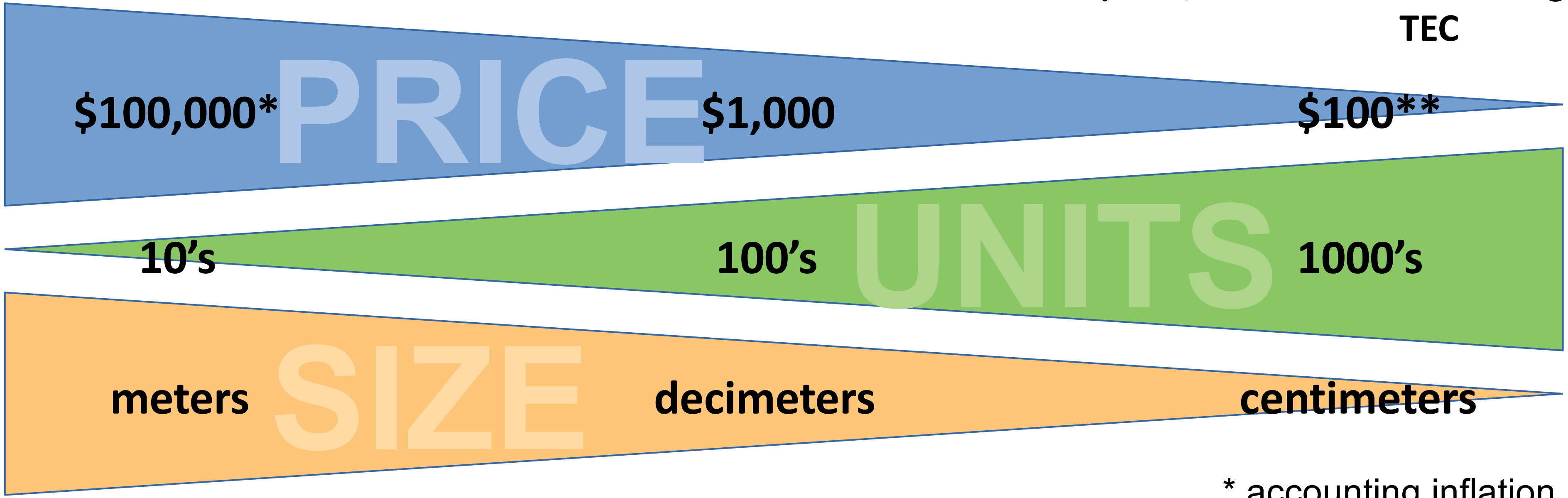
開放街景模塊中的
暴露模型

Exposure model from "Open Street" modules

Assessing earthquake risk in ultra-high resolution

RESIST: *advancement of instruments*

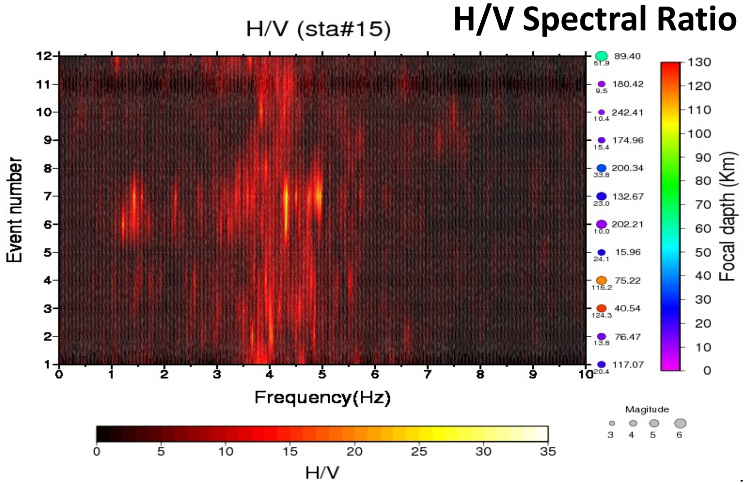
1960s	***1990s***	***2020s***
		
		(QSIS, Quake Structure Integrity Sensor) **TEC**



* accounting inflation
** target cost

H/V Spectral Ratio during earthquakes

- Resonance frequency of the structure can be measured quantitatively through the H/V spectral method
- MEMS sensor is suitable for extracting the building response in a tectonically active region

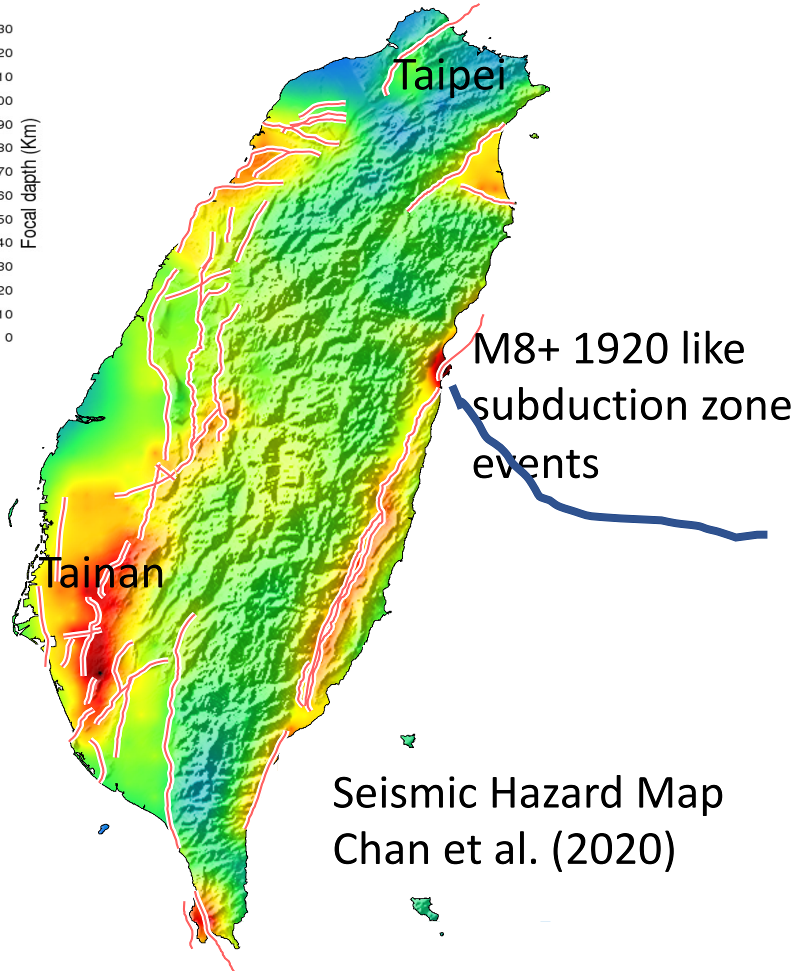


(provided by WT Liang)

For more data from more buildings

⇒ from ground to buildings

⇒ hazard and risk mitigation



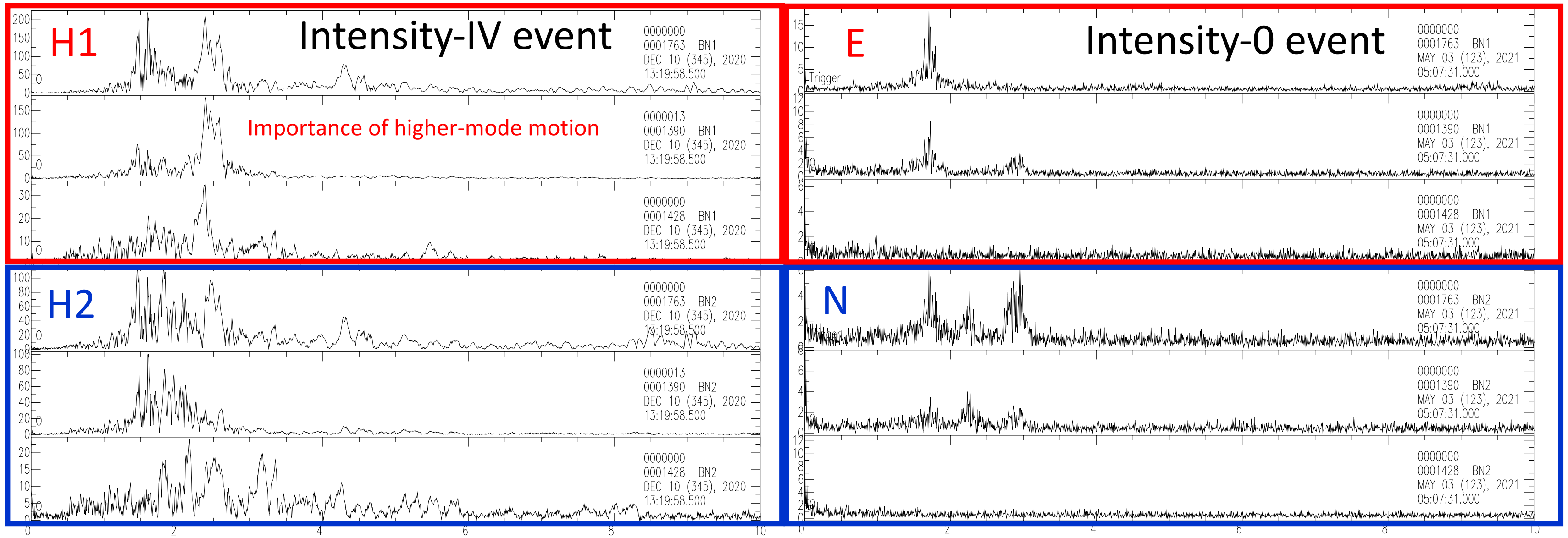
* Impact of subduction zone earthquakes to Taipei Metropolitan. (long-period motion to high-rise buildings)

* Impact of regional large earthquake to high risk Tainan Metropolitan

TAIWAN, Examples on performance of low-cost sensor building array from recent two earthquakes, M_L6.6, and M_L6.4 for the site of Intensity IV and Intensity 0, respectively.

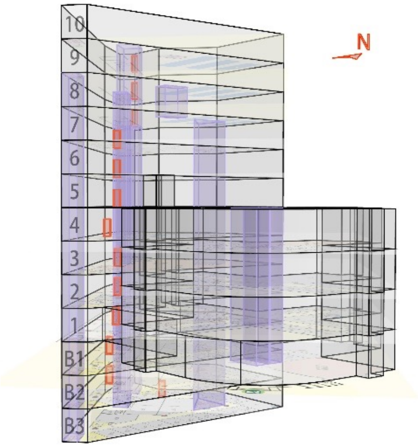
Amplification from floors

11F
7F
B1F
11F
7F
B1F

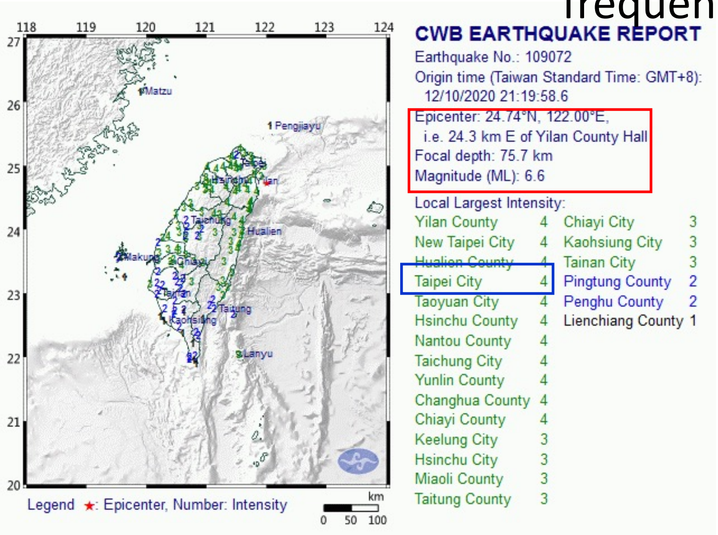


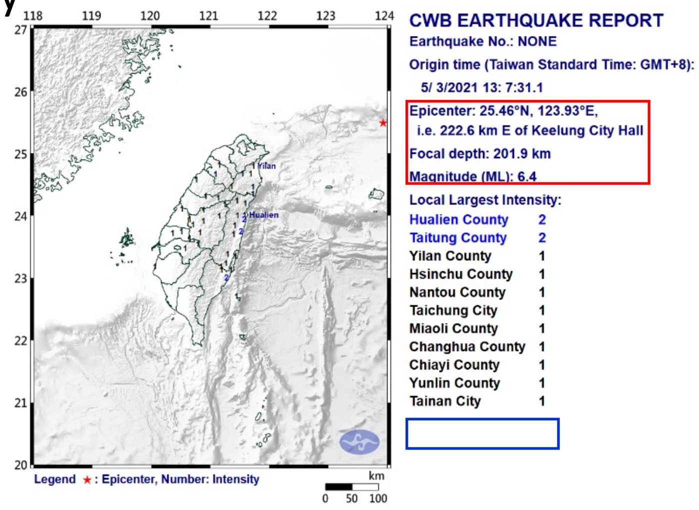
Spectra plots

frequency   frequency



low-cost sensor building array
@Institute of Physics, Academia Sinica





For building responses of different building types.
-sites, building types, magnitudes, azimuthal dependence.

MACROSCOPIC

*** Multiple-Faults**

- Identification of the Multiple-fault ruptures (Fault System),
- **Dynamic Modeling**

*** Ground Motion Prediction Equation**

- Site Response
- Near-fault ground motion, large velocity pulse

Practical SOLUTION - 2022 Building Code https://www.cpami.gov.tw/filesys/file/chinese/publication/law/law2/111061501.pdf

- New codes for near-fault; 0-2km, 2-5km, 5-9km, 8-12km, 12-14km

- Strengthen Soft Story Buildings

- Earthquake Scenarios, Annual September Earthquake Drill (Ground shaking to building shaking)

***Societal impact:**

Assessing earthquake risk in ultra-high resolution, Small Sensors (QSIS, Quake Structure Integration Sensor)

MICROSCOPIC

*** Modeling earthquakes with high resolution (Earthquake Physics, Fault Zone Dynamics)**

- Sensing the fault zone at depth from TCDP to MiDAS

TCDP, Taiwan Chelungpu-fault Drilling Project,

MiDAS, Milun fault Drilling and All-inclusive Sensing, using borehole optical fiber)

Taiwan Chelungpu-fault Drilling Project (2004-2005)

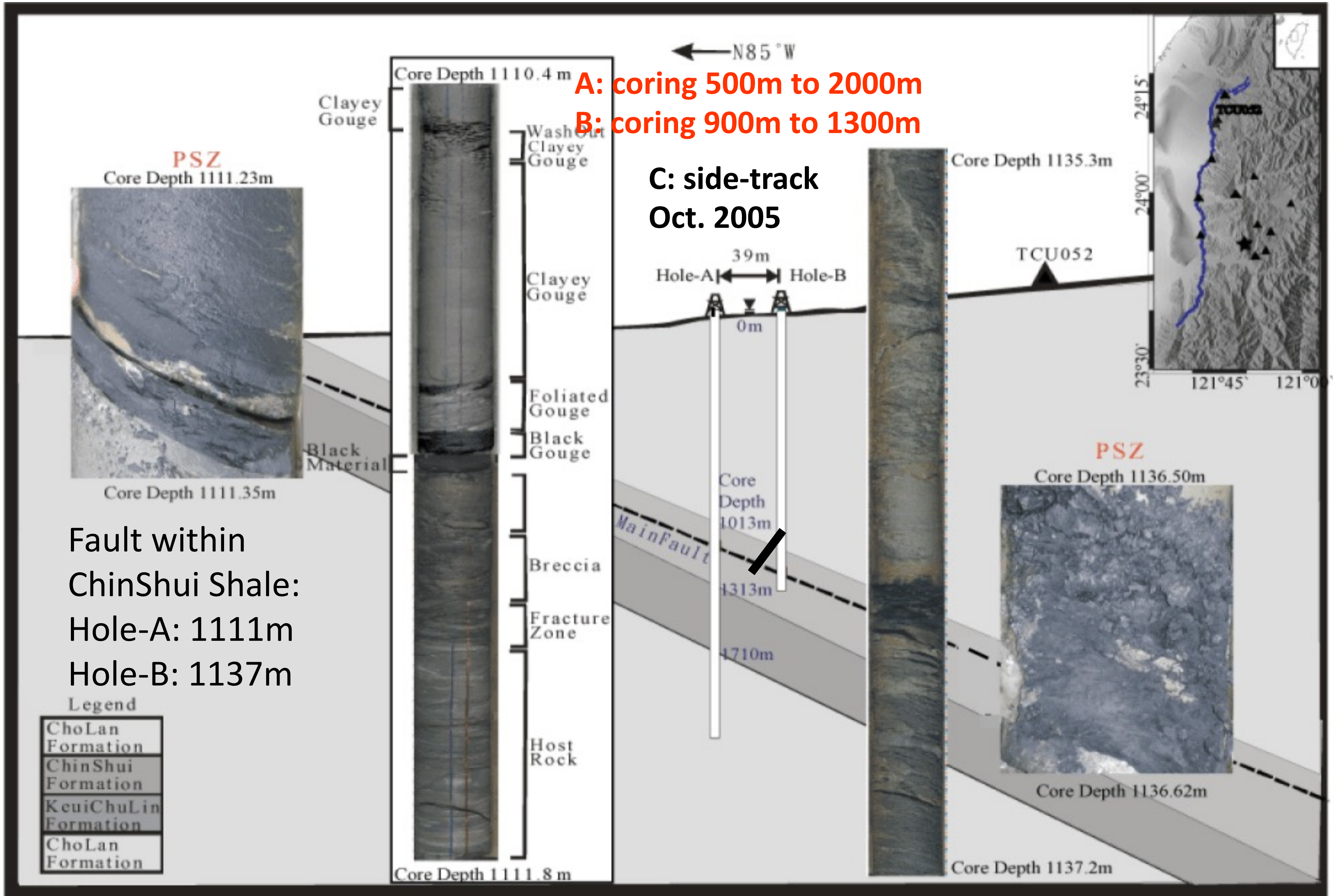
- **Core retrieval from drilling (~99.5%)**
- Biological Analysis (randomly)
- Gas measurements
- Non-destructive Thermo-parameters measurement
- Core Description (on-site geologists)
- Geophysical Logging
- FMI &DSI logging (Hole-A)
- FMI logging and LOT (Hole-B)

After Drilling

- Temperature measurement (Hole-A, September 2005)
- **Temperature measurement (North Shallow Hole, 2002)**
- Hydraulic Pumping Test (Nov., 2005)
- **Installation of 7-level Borehole Seismometers (June, 2006)**
- In-Situ cross hole experiments, Fluid Injection Test (FIT) (Nov., 2006~April, 2007)

A Review of the 1999 Chi-Chi, Taiwan, Earthquake from Modeling, Drilling, and Monitoring with the Taiwan Chelungpu-Fault Drilling Project
Ma K.-F. (2021) doi.org/10.1007/978-981-15-6210-5_4

TCDP: hole-A, and hole-B Drilling Schedule



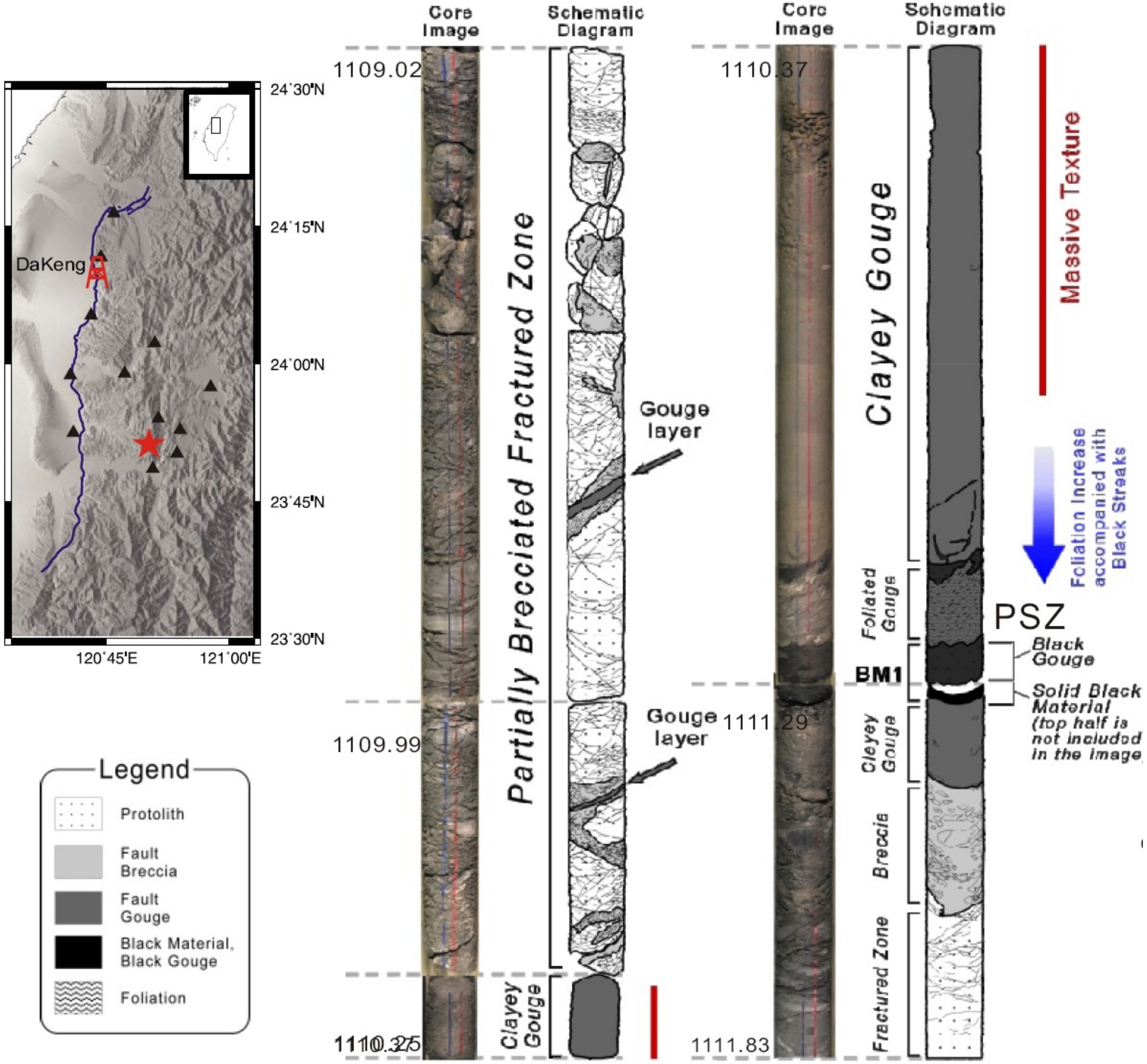
A: coring 500m to 2000m

B: coring 900m to 1300m

C: side-track
Oct. 2005

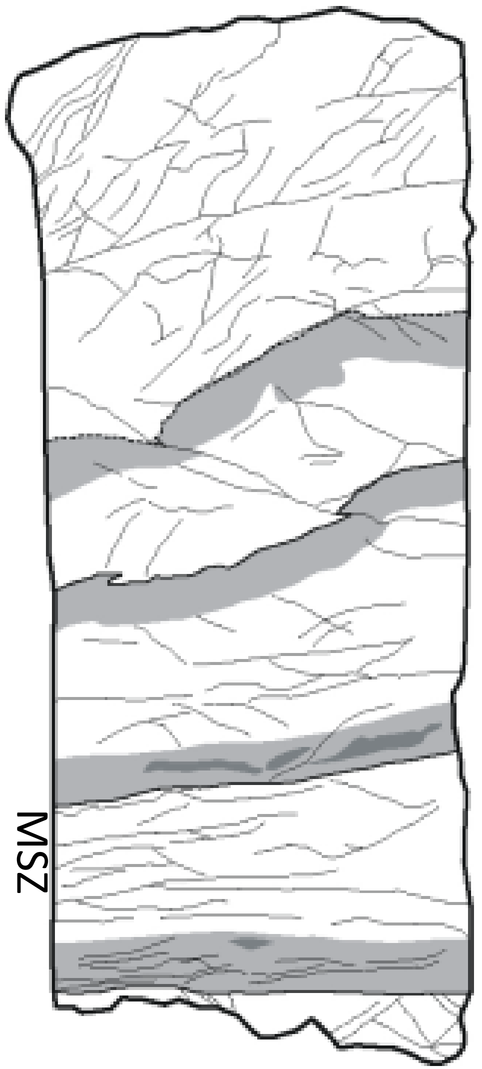
Fault within
ChinShui Shale:
Hole-A: 1111m
Hole-B: 1137m

FZ1111: Identification of the Primary Slip Zone



Split and Polished PSZ from Hole-C

PSZ **(Ma, Tanaka et al., Nature, Nov. 2006)**



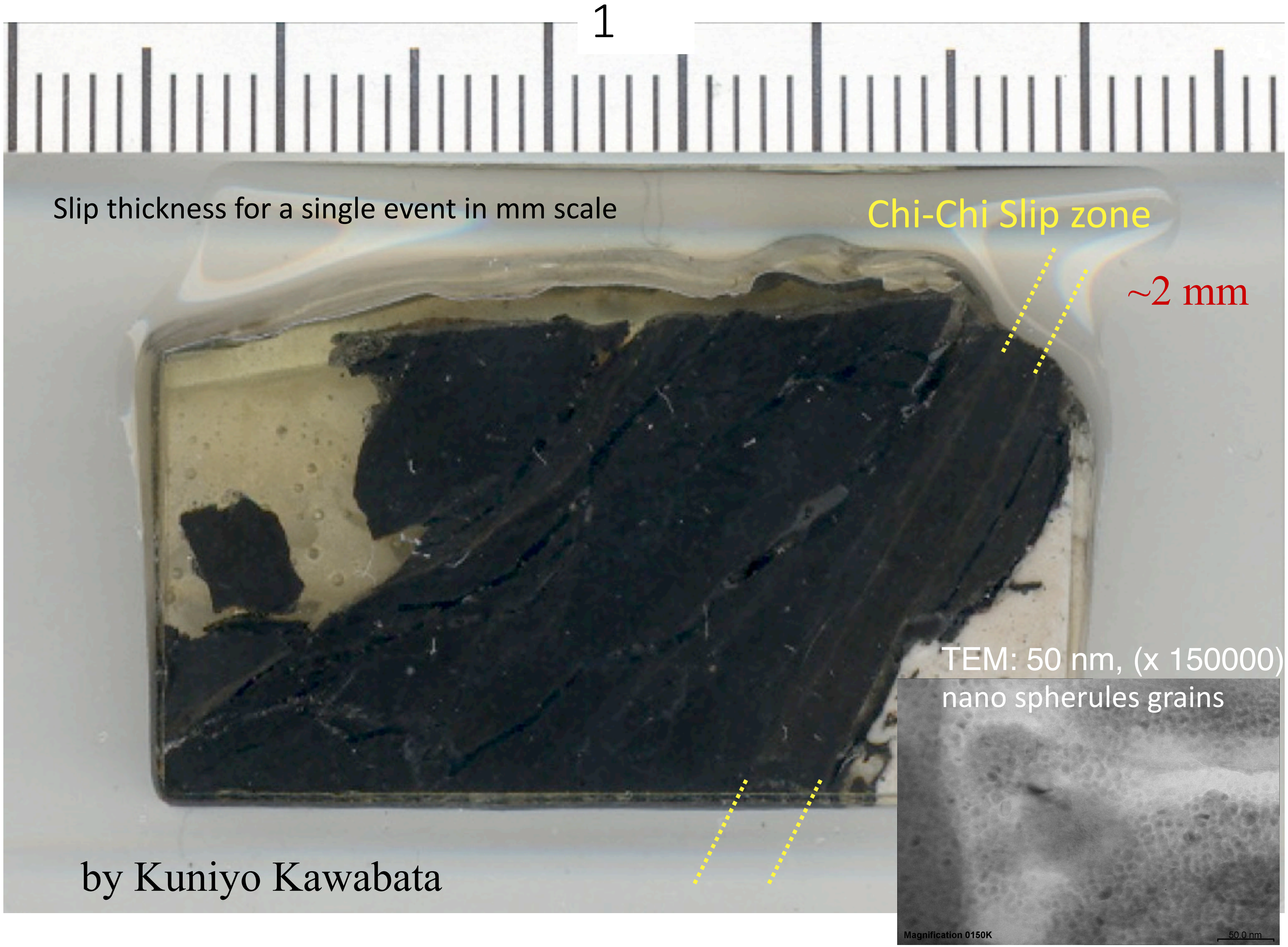
-PSZ was formed in layers from repeating earthquakes

-5mm very fine grain sub-layer in the bottom of each layer

- The bottom layer was least deformed

=>**Major Slip Zone (MSZ)** for the Chi-Chi earthquake

-Slip thickness of about 5 mm for a single event

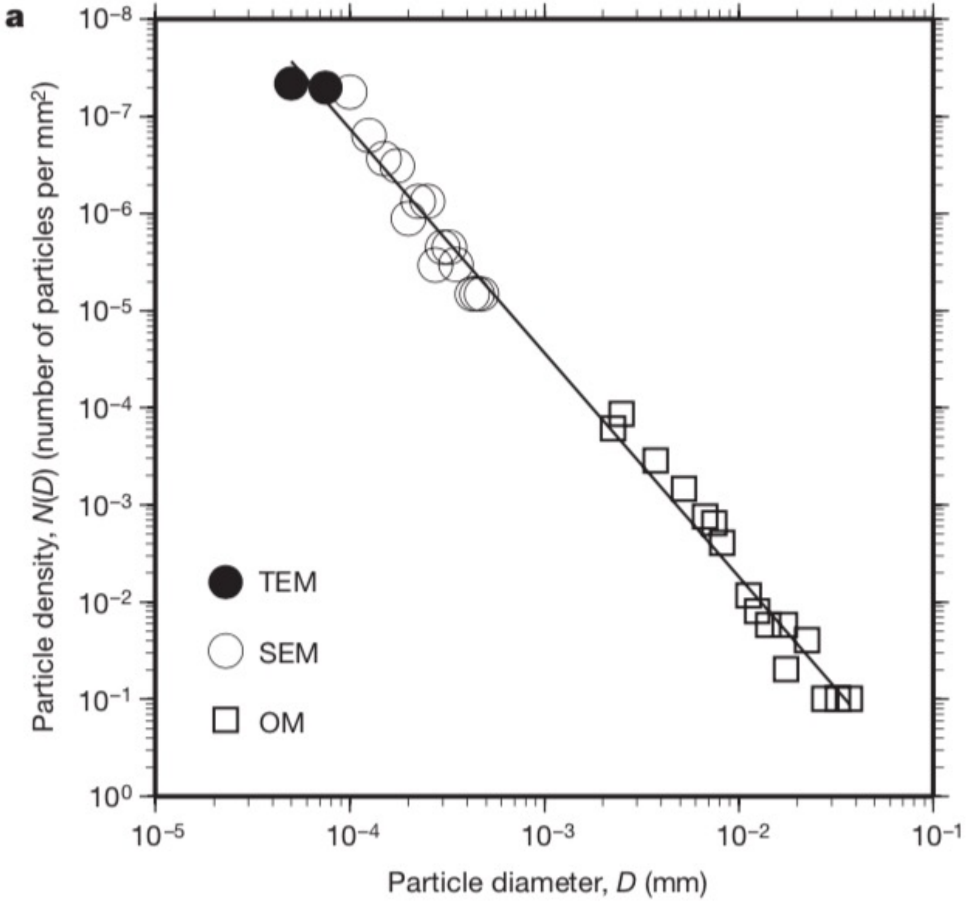

1
Slip thickness for a single event in mm scale
Chi-Chi Slip zone
~2 mm
TEM: 50 nm, (x 150000)
nano spherules grains
Magnification 0150K
50.0 nm
by Kuniyo Kawabata

Examination of the historical slip zone

- Behavior of the Historical Events (studies from LW Kuo's group)
  - Fracture Energy of each slip zone
  - Comparison of the Chemical Composition in each slip zone=>
    whether possible to retrieve the dynamic behavior of faulting of the historical events
  - Possible examination on the pressure solution (Kuniyo Watabata),
    and the healing process

Grain size distribution

TEM images of Major Slip Zone



b

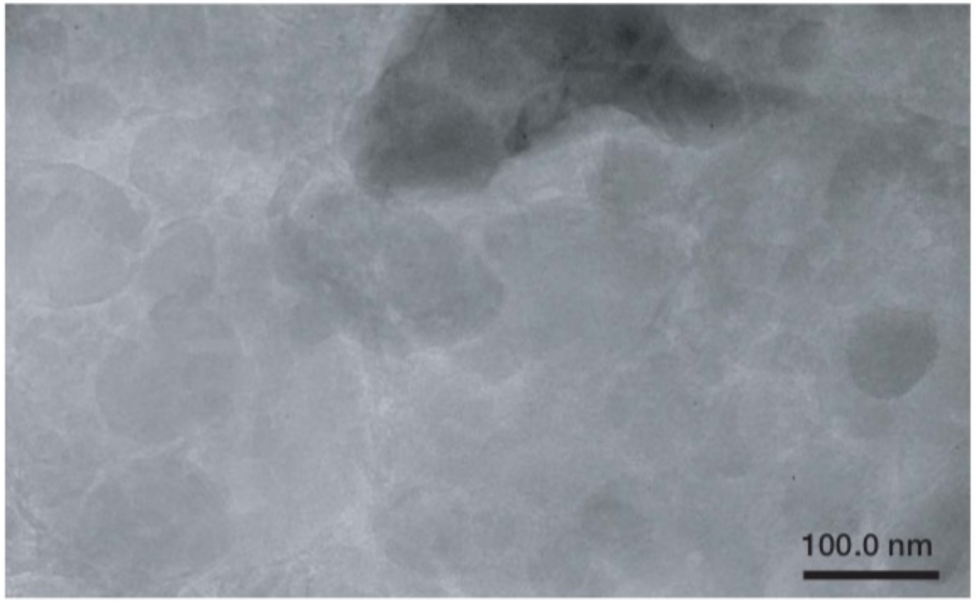
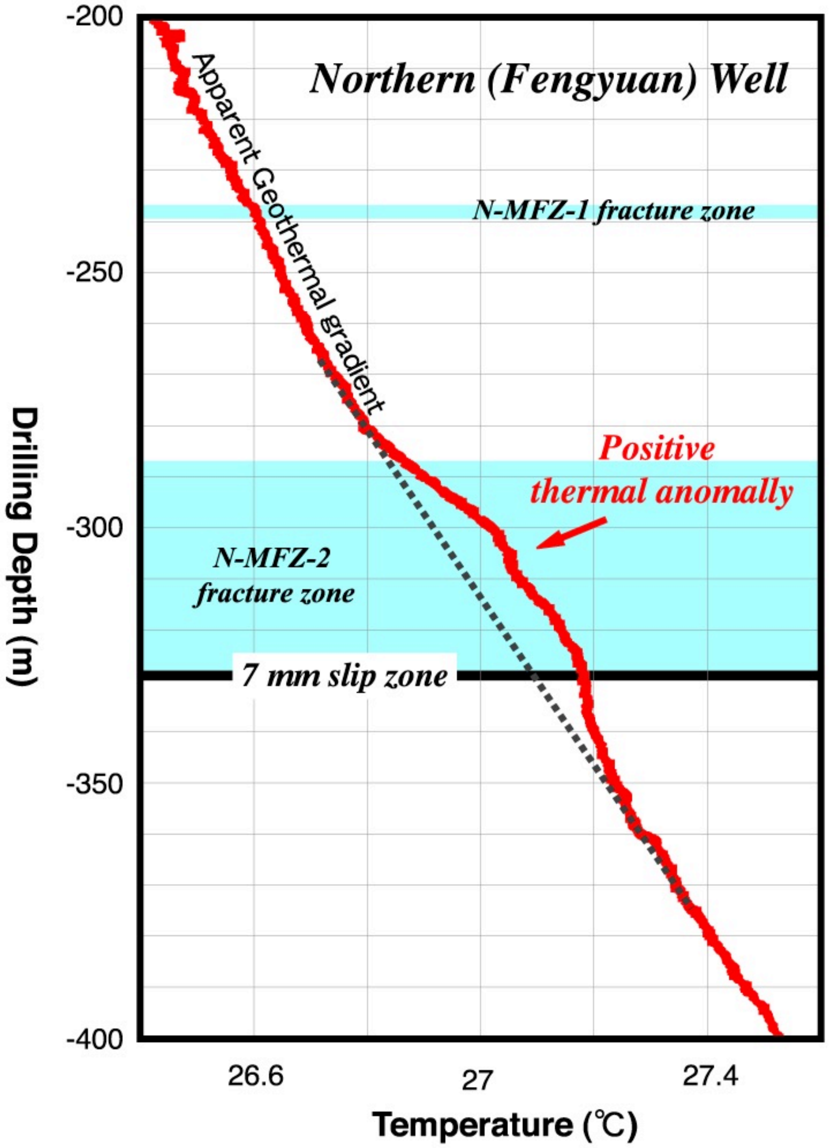


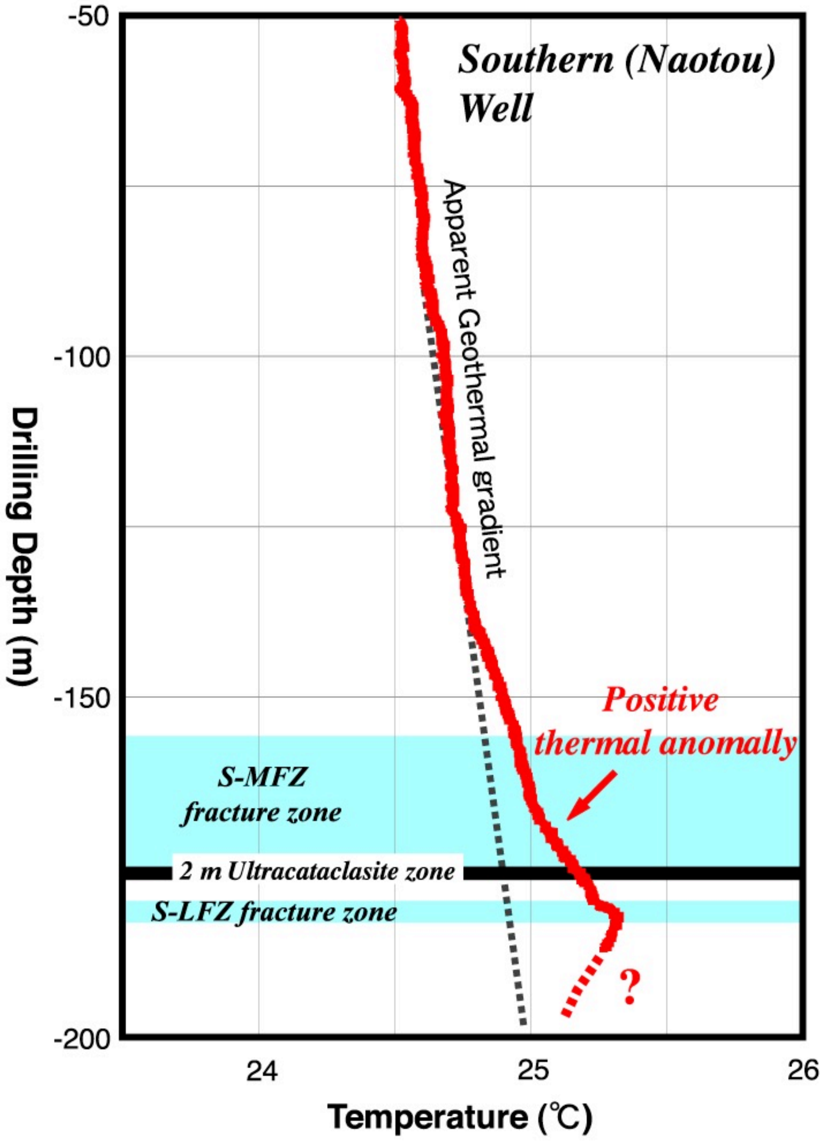
Figure 2 | Particle size in the major slip zone. a, Distribution of the particle size, $N(D)$ as a function of particle diameter (D) in millimetres. The $N(D)$ is the number of grains per mm^2 for a class of grain size. The measurements are imaged from TEM (solid circles), SEM (circles), and optical (square). The regression of the particle size distribution follows the power law $N(D)=aD^{-b}$, where a is 0.0045 and b is 2.3. **b**, TEM image; scale, 100 nm.

Ma et al. (Nature, 2006)

Spherical nanograins, Heating during rapid slip
(increasing the temperature to hundreds degree in few sec.)

Magnified view of temperature logging results for Chi-Chi Earthquake (residual heat from rupture)

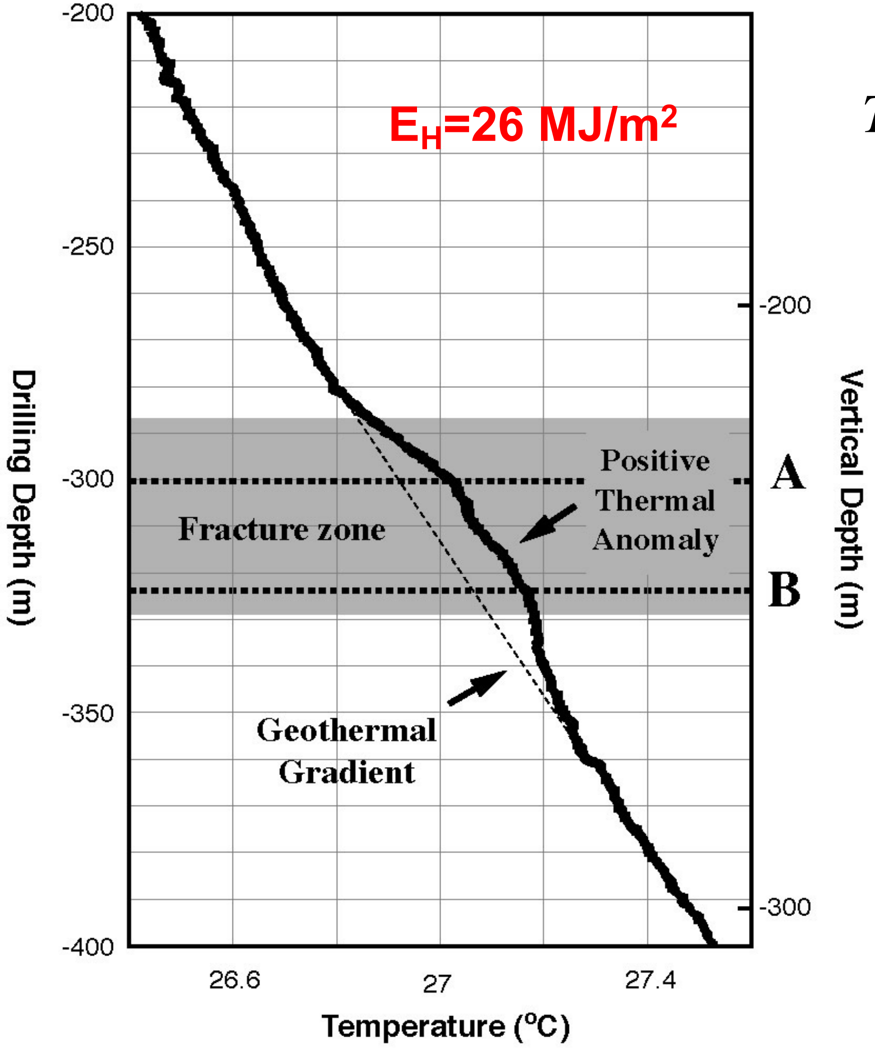




Tanaka et al. (2006, GRL)

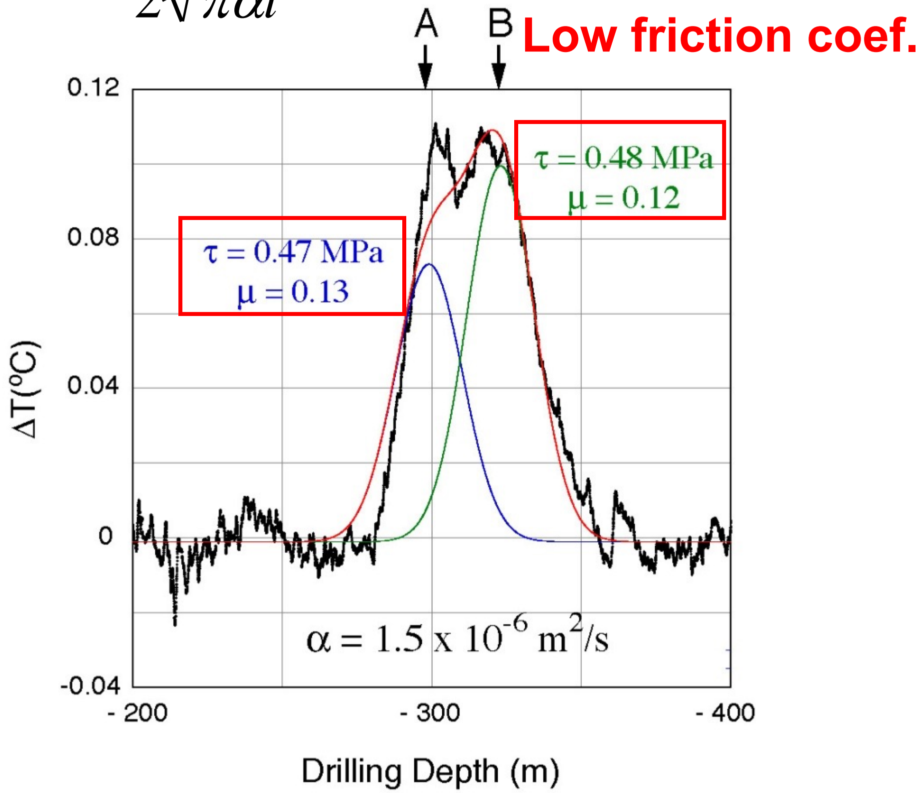
Friction Heat Calculations
(shallow drilling at North)

First direct measurement for Friction Heat



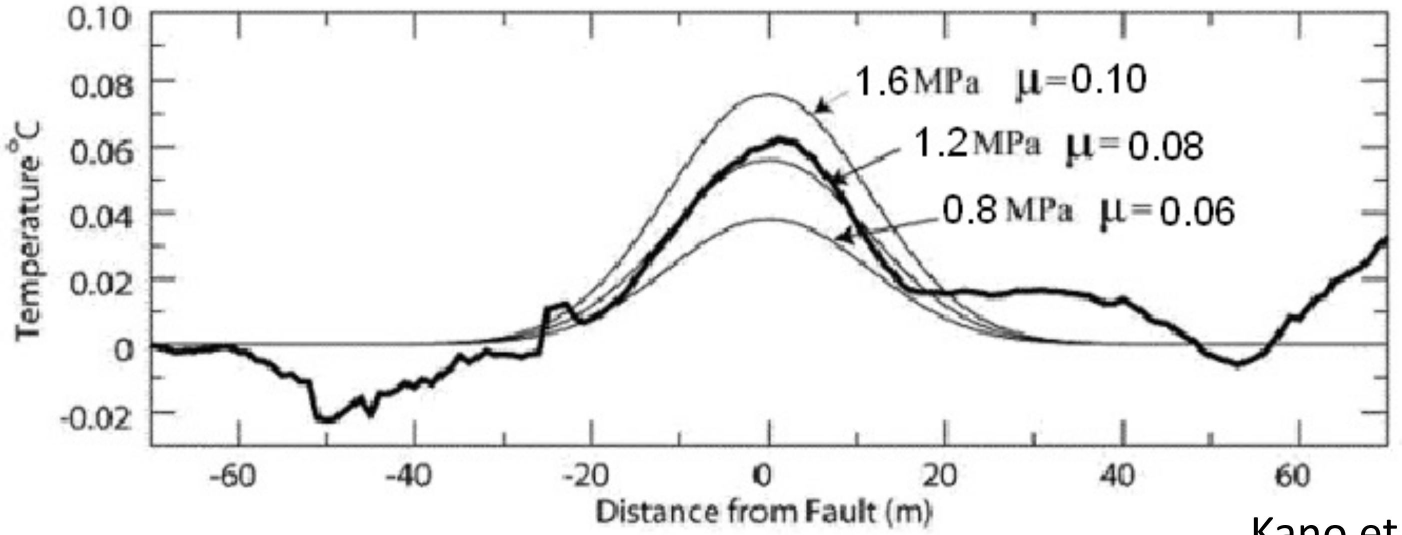
$$T(x,t) = \frac{S}{2\sqrt{\pi \alpha t}} e^{-x^2/4\alpha t}$$

$$S = \frac{\tau \cdot D}{c \cdot \rho}$$



Tanaka et al., (2006a)

Temperature measurements 6 years later



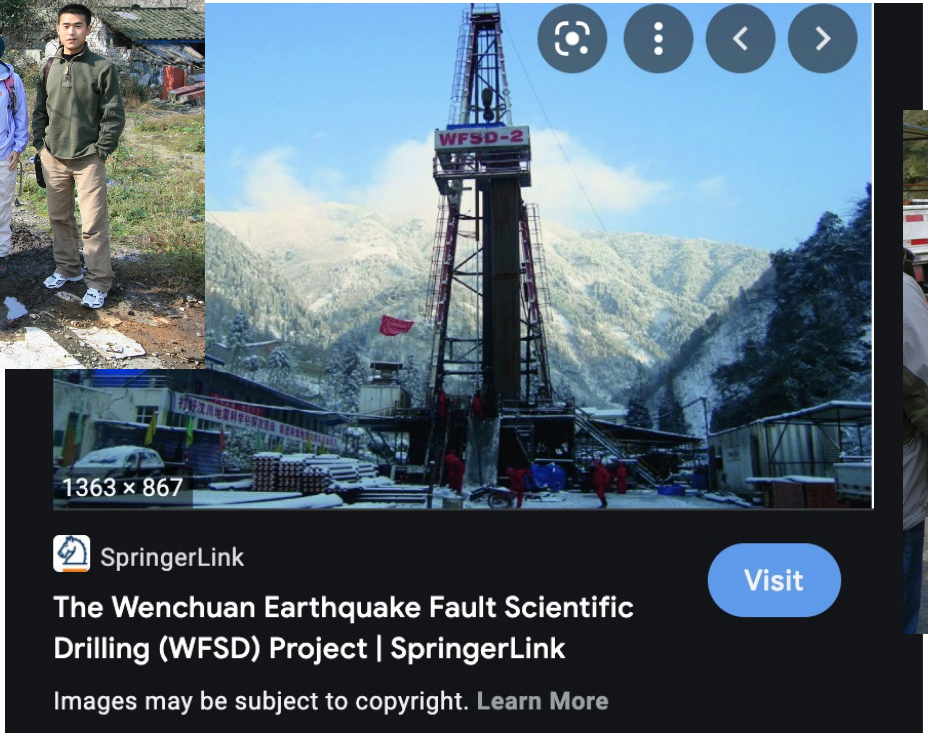
Kano et al., 2006

Provisional Answer:
Friction in nature is even less than the lab

All the small frictional coefficients of about less than 0.1
From TCDP, WSFD, and JFAST

The Wenchuan Earthquake Fault Scientific Drilling (WFSD) Project

- https://link.springer.com/chapter/10.1007/978-981-13-8015-0_3 by Xu and Li



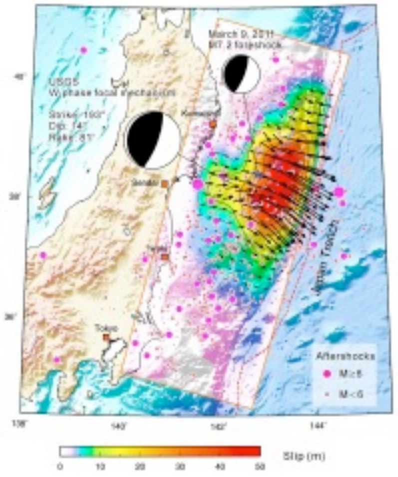
Fluid and temperature measurements

2008-2010~

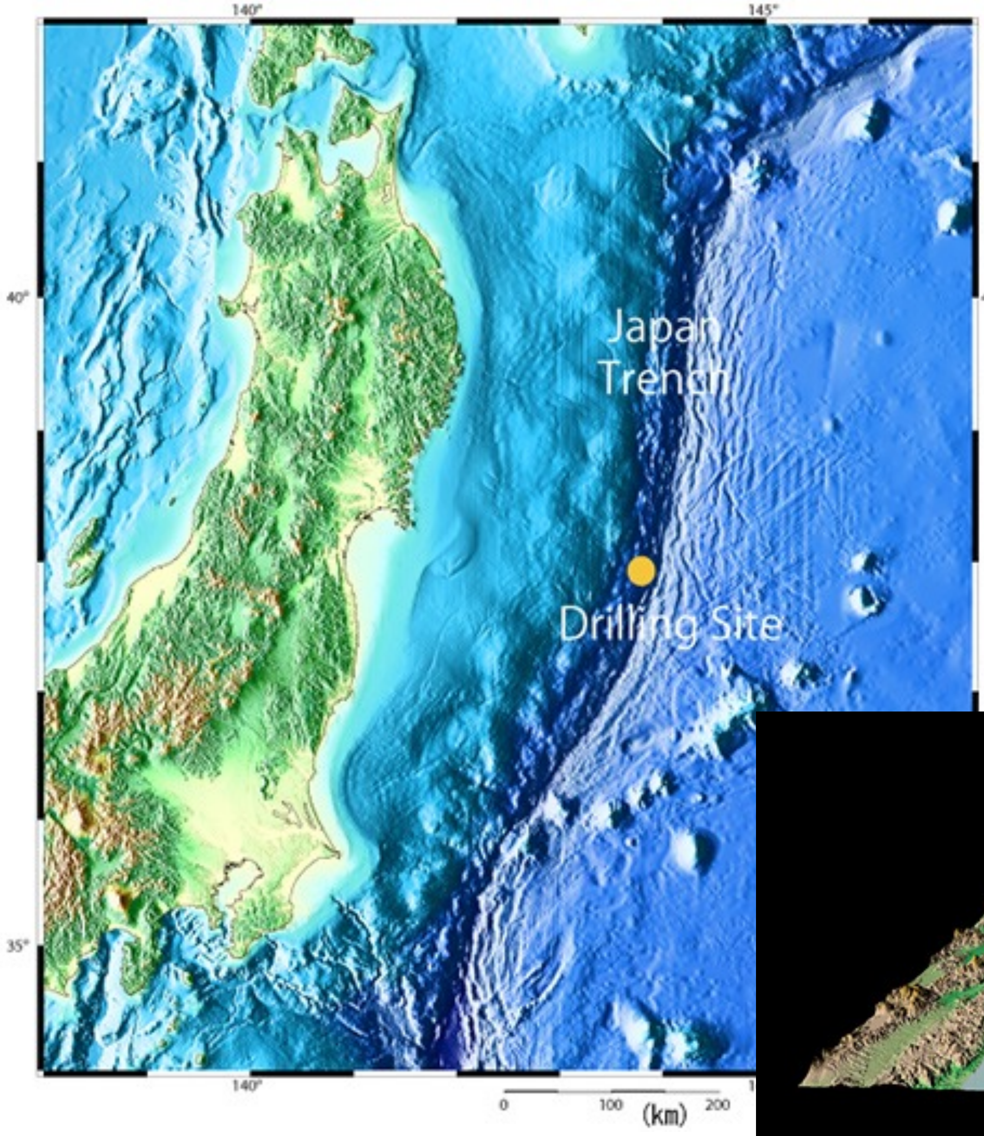
EXP.343 Please feel free to get IODP Expedition 343 logo for print sticker or T-shirt!

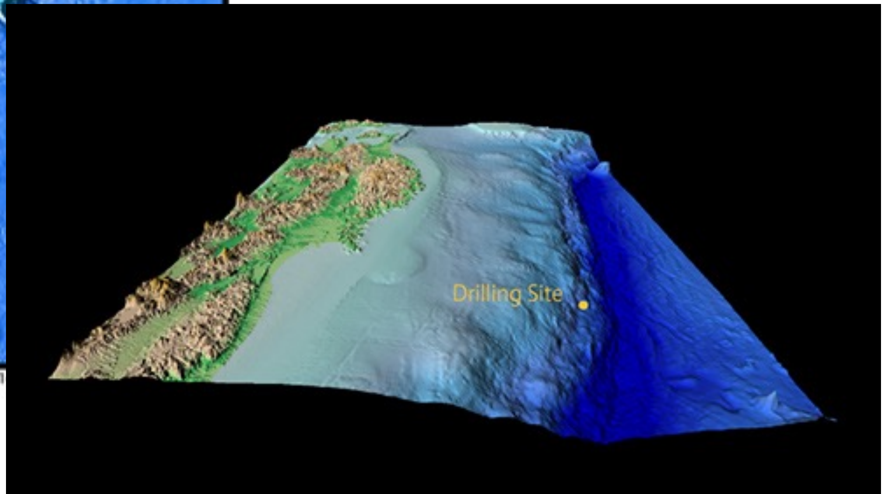
Chikyu J-FAST,

https://www.jamstec.go.jp/chikyu/e/exp343/science.html

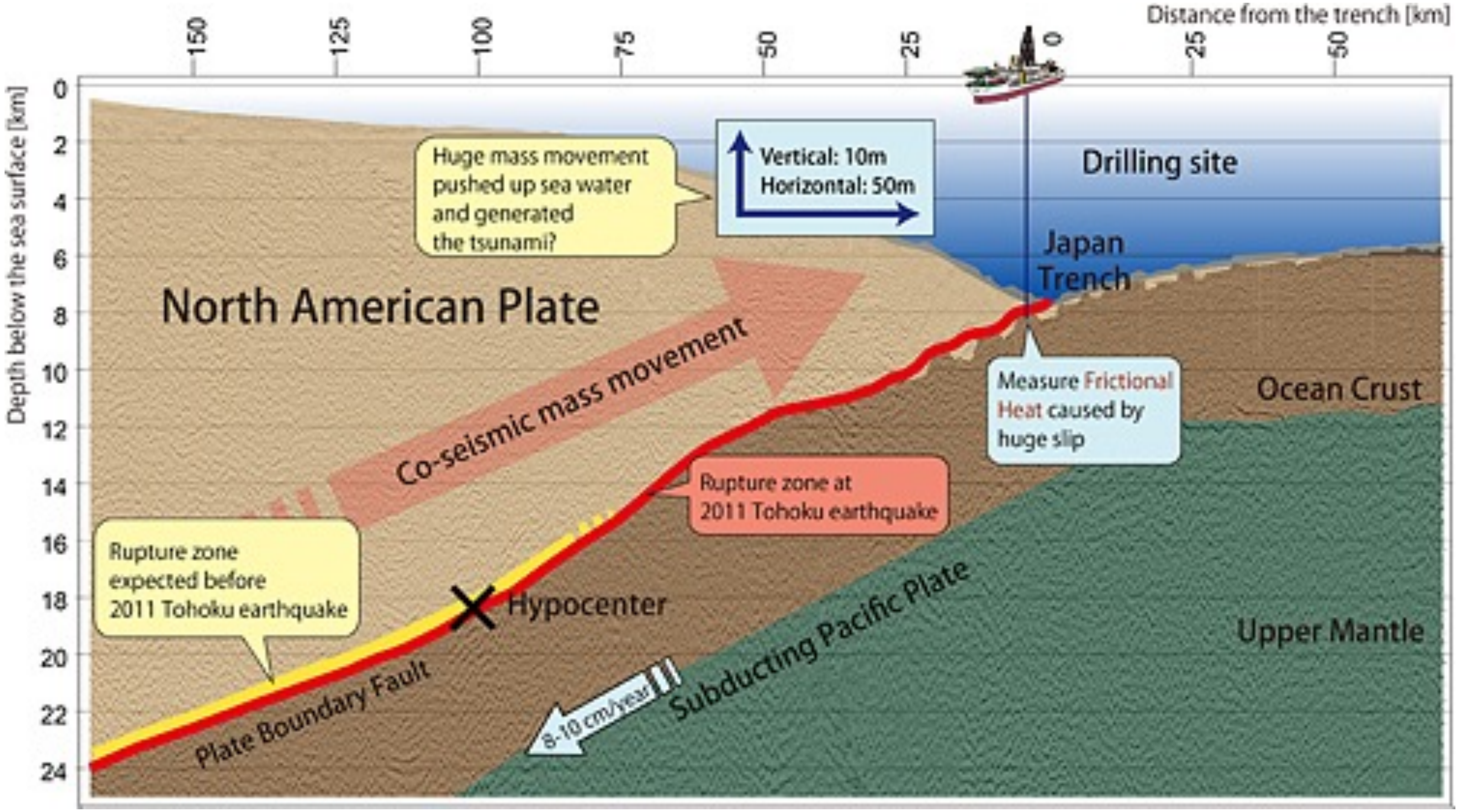

March 9, 2011
USGS
Aftershocks
Slip (m)

From SJ Lee


140°
145°
40°
35°
Japan Trench
Drilling Site
0
100
200
(km)

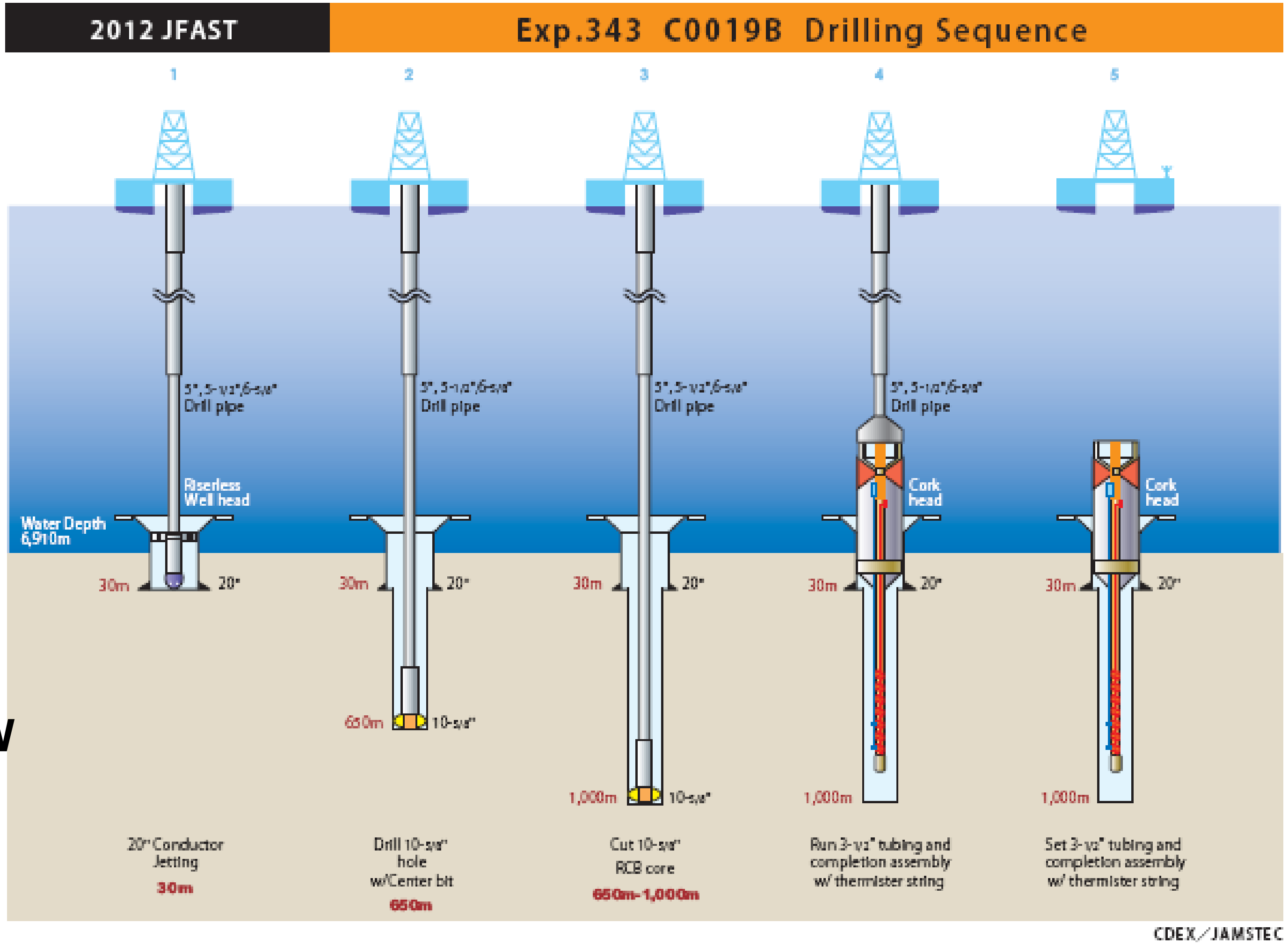

Drilling Site

Conceptual image of sub-seafloor structure at the drill site



J-FAST Pore-pressure/ Temperature Observatory

(unresolved challenges, fluid/heating/penetrating the slip zone)



TD: MBSW 825m

SCIENTIFIC OBJECTIVE

TCDP
Taiwan Chelungpu-fault Drilling Project

(2004-2005)

- Core a continuous profile through a large-displacement rupture at a depth where elastic strain energy was stored and released.
- Sample the material in the high-speed slip zone
- Determine the physical conditions (stress, pore pressure, temperature) within the fault zone.

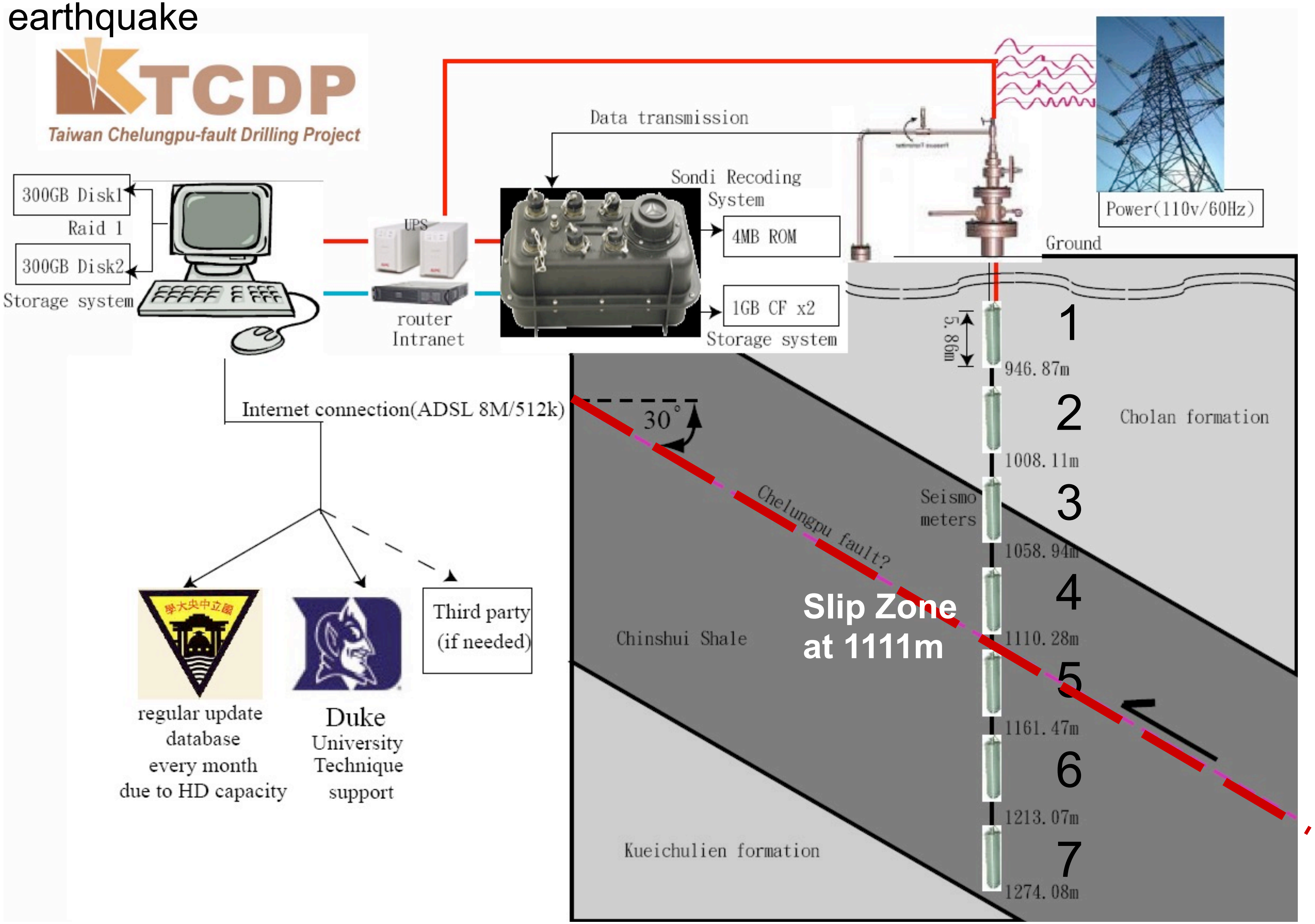
MiDAS 花蓮臺灣

(2021-2022)

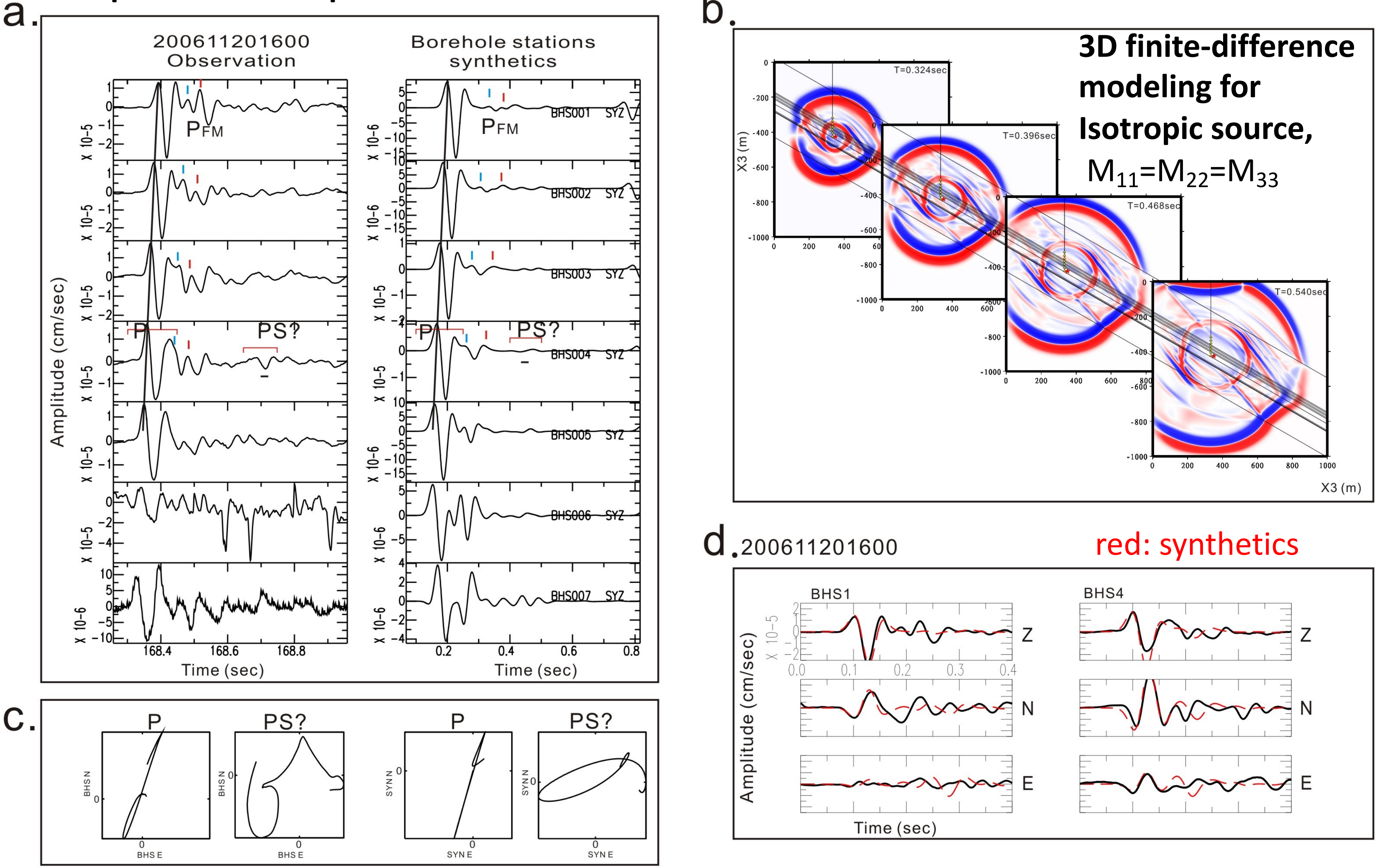
- Mapping the seismogenic system (subduction zone, offshore-inland fault structure, etc.)
- Sample the material in the frequent rupture slip zone

  (limited budget with uncertainties on the depth of conglomerate)
- Determine the physical conditions (stress, pore pressure, temperature) within the fault zone.
- Earthquake physics- Energy budget
- Role of fluid
- Precursors (?)

TCDP BHS (June, 2006): **Borehole Observatory** 15m Slip Zone of the 1999 Chi-Chi, Taiwan, earthquake



Isotropic Events: Isotropic mechanism resulted from a natural hydraulic fracturing within a complete stress drop crust

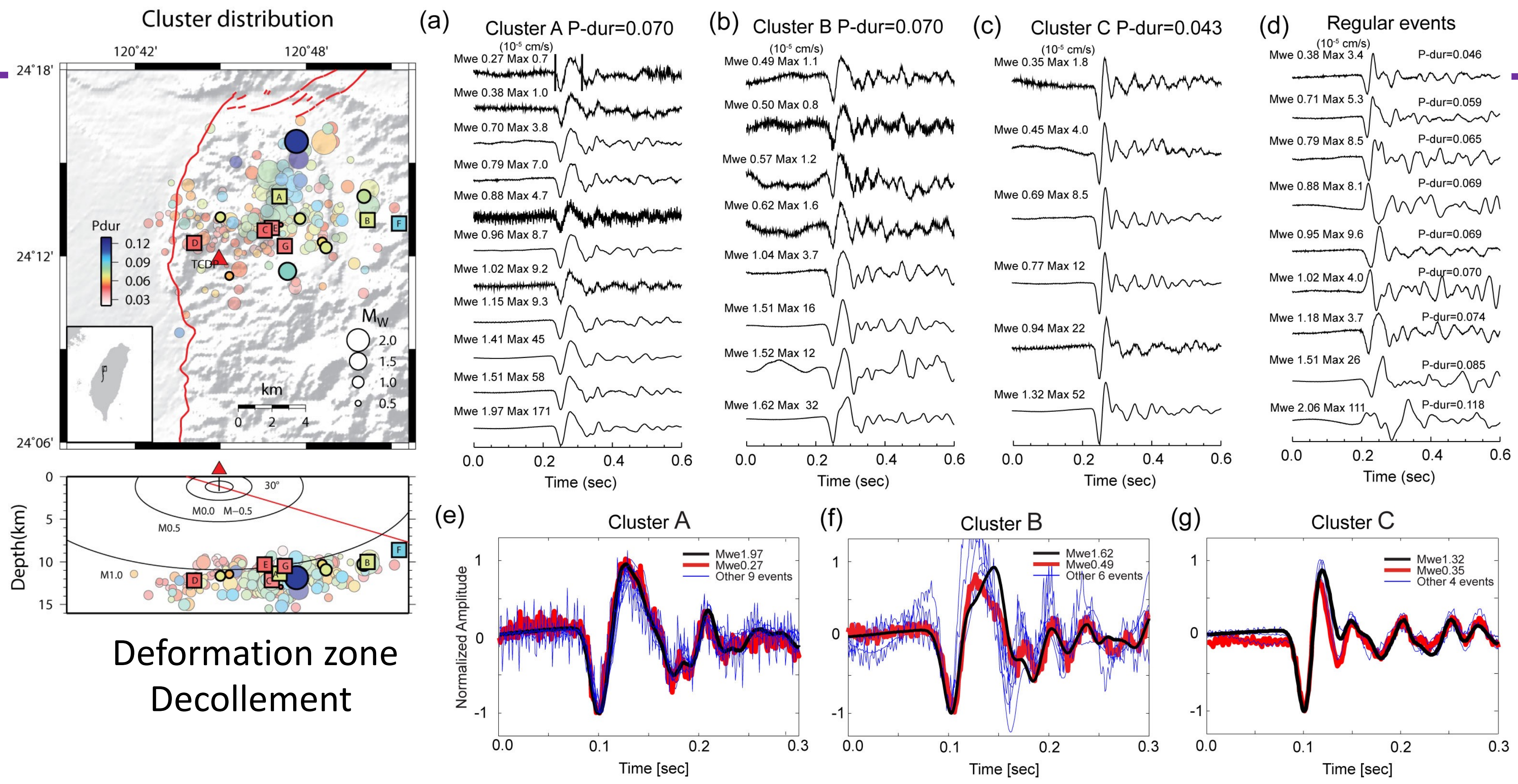


Observation - Particle Motions - Synthetics

Ma et al. (Science, 2012)

Figure 3

Constant source duration event clusters along the decollement



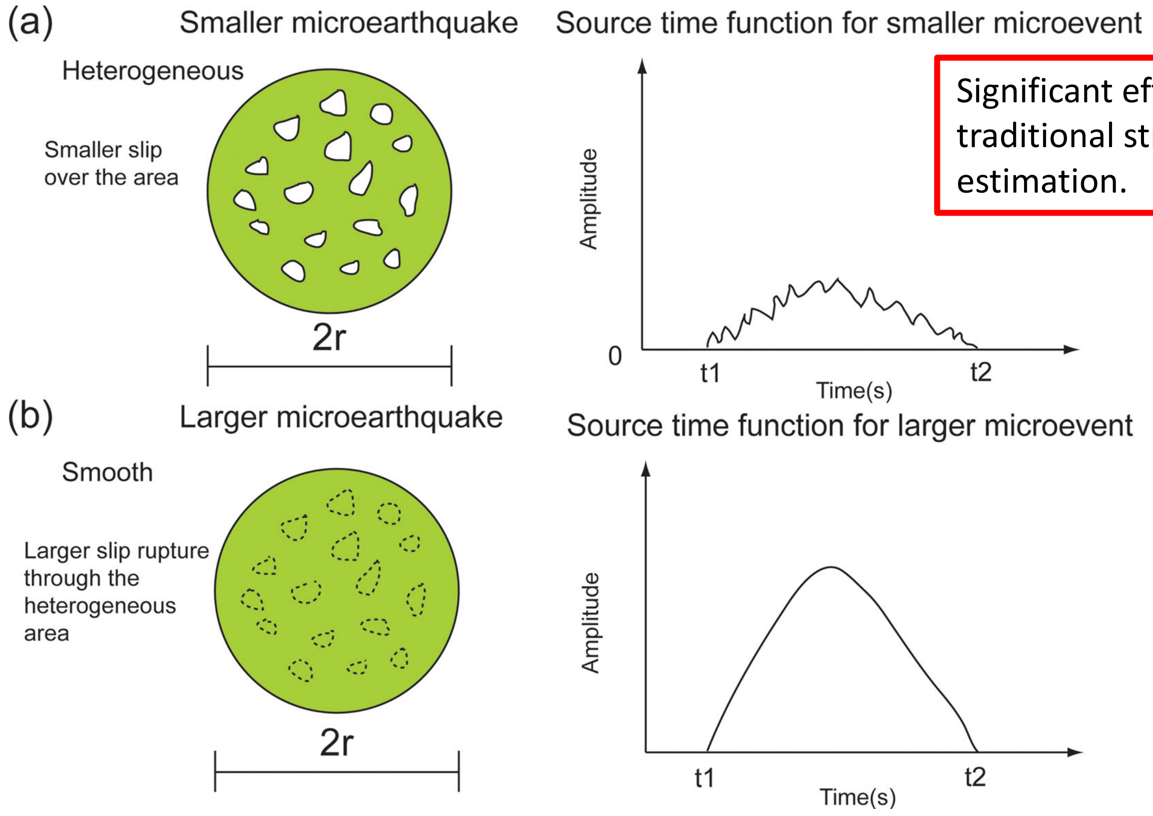
M0.27-M1.95 with the same source duration

Evidence for non-self-similarity of microearthquakes recorded at a Taiwan borehole seismometer array, Lin et al. (2016)

Hints to earthquake nucleation process, and formation of a new frontal fault from fluid?

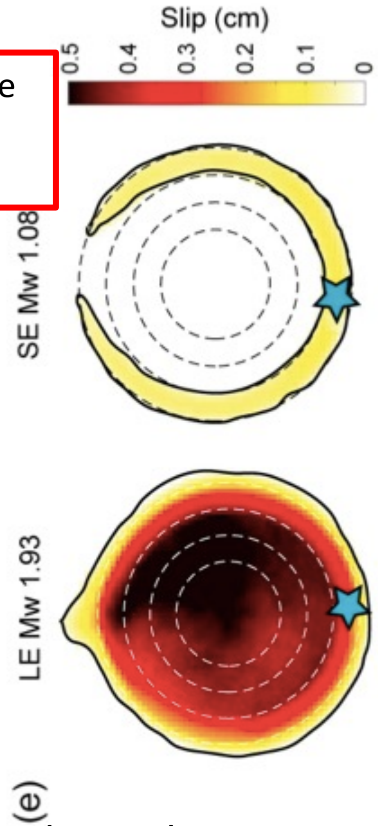
Event duration controlled by the size of the patch and event magnitude determined by how much of the patch area has been ruptured.

Conceptual model (Lin et al., GJI, 2016)



Significant effect to the traditional stress drop estimation.

Dynamic modeling from Lin and Lapusta (GRL, 2018)



Small

Large

Similar features were observed for **low-frequency earthquakes** beneath southern Vancouver Island in Canada (Bostock et al., 2015).

2004 TCDP => 2021 MiDAS

- **Earthquake Energy Budget**

  -seismic dynamic modeling (Ma et al., 2006)

  -fault gouge: surface fracture energy (Ma, et al., 2006)

  -temperature measurement

  (Tanaka et al., 2006a, 2006b, Kano et al., 2007, Kuo et al., 2011)

  - nano spherules grains (e.g., Kuo et al.,2014, Kuo et al., 2015)

- **Faulting Dynamics**

  -existence of fluid (Ishikawa et al, 2008)

  -fault zone permeability (Doan et al., 2006, Murakami et al., 2008)

  -long-term borehole seismometers (e.g. Lin et al., 2012, Ma et al., 2012)

- **Status of Stress**

  -earthquake focal mechanisms (thrust→ strike-slip) (Ma et al., 2005)

  -geophysical logs, FMI, DSI (rotation of the stress axis) (Wu et al., 2007, Lin et al., 2007, Hung et al., 2008)

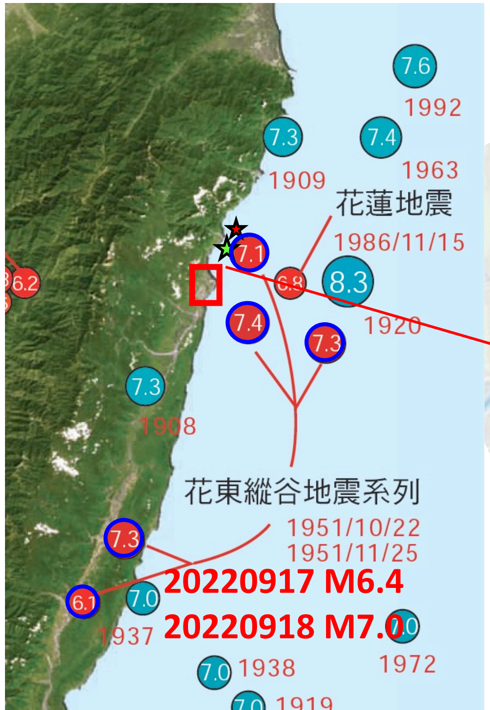
- **Core Description, Geochemistry/Geophysics and Others**

  (Song et al., 2008, Kuo et al., 2019, 2020.. ,Hirono et al., 2006, 2007…)

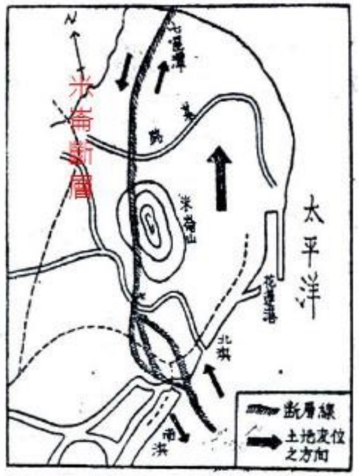
Milun fault Drilling and All-inclusive Sensing (MiDAS), 2021~

- The Milun fault has a special geographical location as it's **short recurrence interval** (~70 years, TEM), inland and near the **boundary of the subducting plat**
which with high-potential for **mega-earthquakes.**

- A **three-dimensional cross-fault borehole observatory with optical fiber fo DAS and DTS** provides the key observations to address the frontier questions fo earthquake nucleation, energy budget, fault zone dynamics, and precursors.

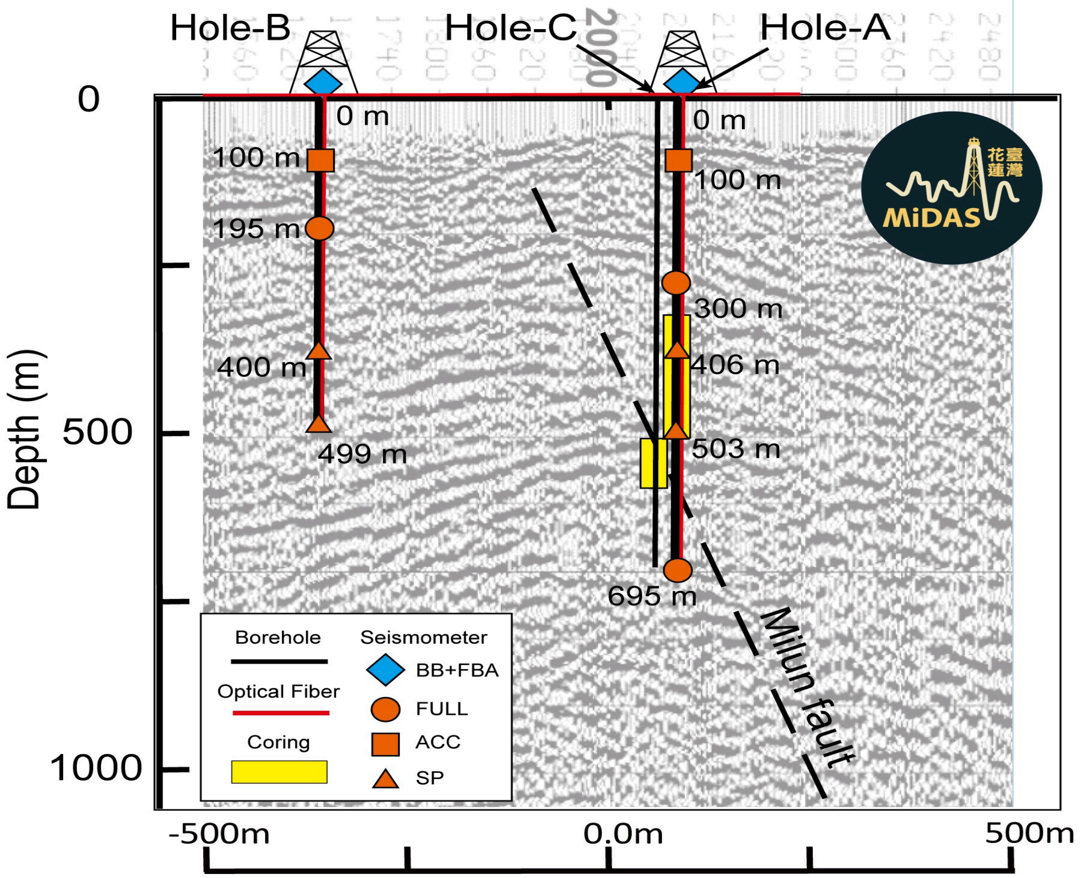


1951
Milun fault rupture



1951

Crossing fault downhole optical fiber
Probing the fault zone with high spatial resolution



Spatial resolution ~4m

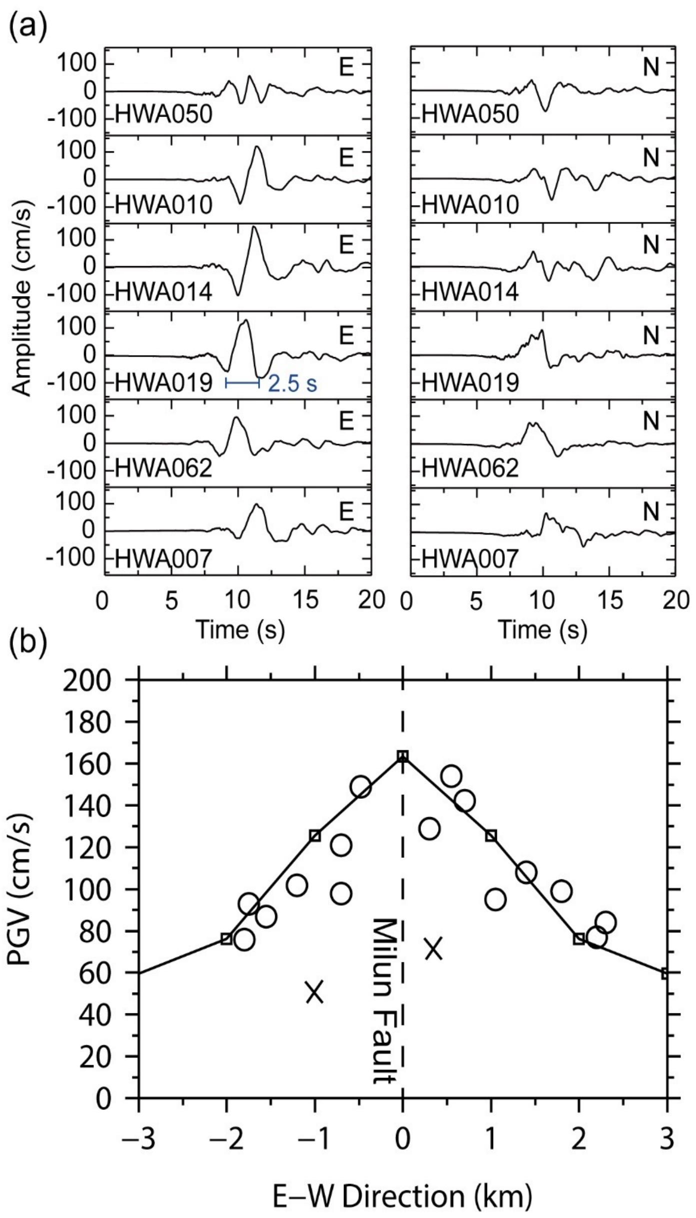
20220918 repeating rupture segment of 19511125

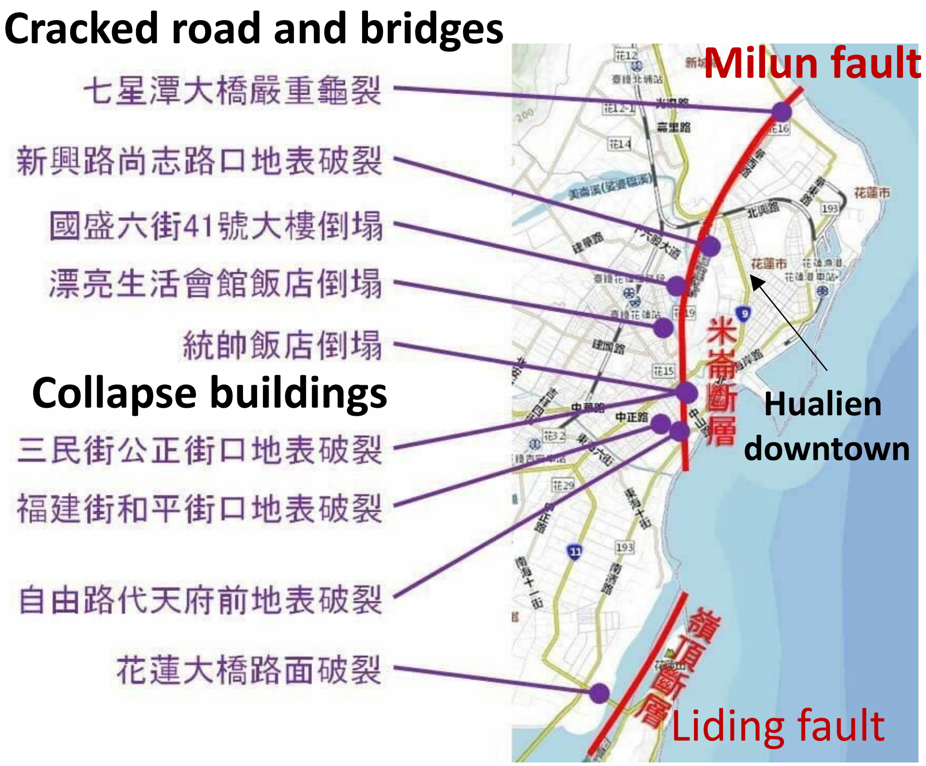
Earthquake hazard and risk- Engineering Seismology (near-fault long-period motion)

Recorded PGV along the Milun Fault near Hualien city

Pulse-like velocity motion (killer pulse) was generated by the slip patch on Milun Fault.

(Lin et al., 2020; Yen et al., 2021, submitted)



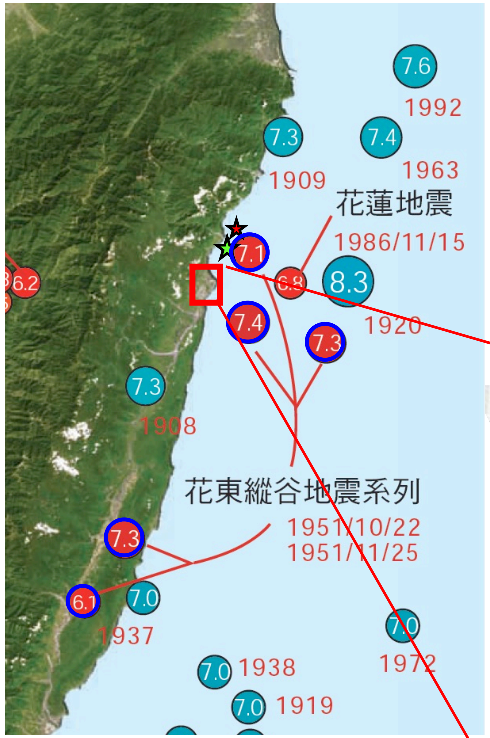


(from Dr. Lin (NTU)

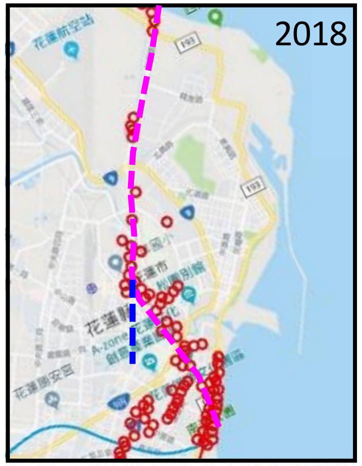
Data from Central Weather Bureau (CWB), http://www.cwb.gov.tw and P-Alert network

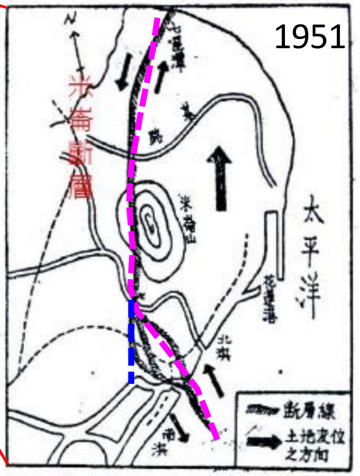
2018 and **1951**

Ruptured similar zone along **Milun fault**



米崙斷層





1951 Oct.-Nov. Hualien-Taidong Earthquakes

發震時間	緯度 (°N)	經度 (°E)	震源深度 (km)	地震規模 (ML)
1951/10/22 05:34	23.875	121.725	4.0	7.3
1951/10/22 11:29	24.075	121.725	1.0	7.1
1951/10/22 13:43	23.825	121.950	18.0	7.1
1951/11/25 02:47	23.100	121.225	16.0	6.1
1951/11/25 02:50	23.275	121.350	36.0	7.3

火車站前

明禮國小

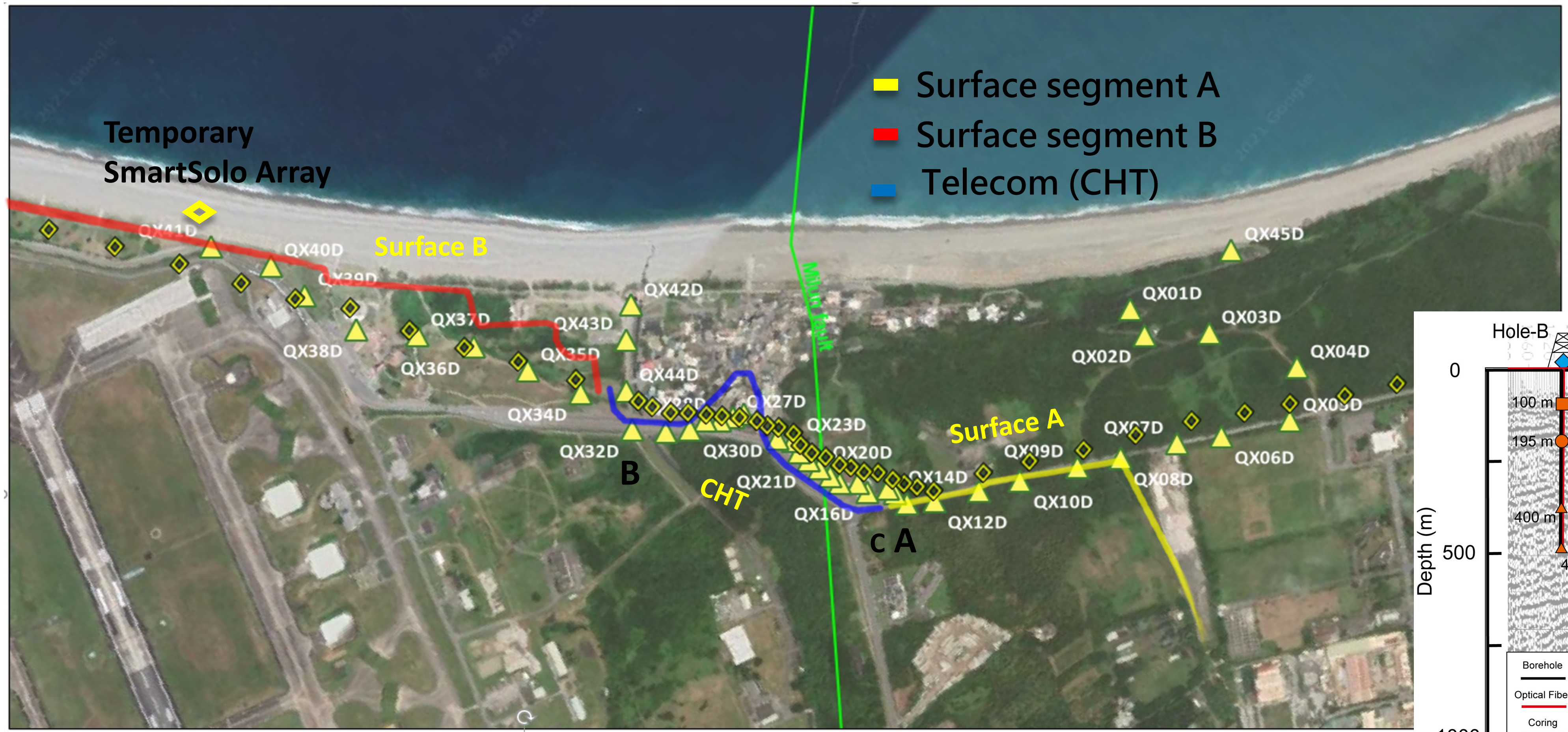
中正路

中華路

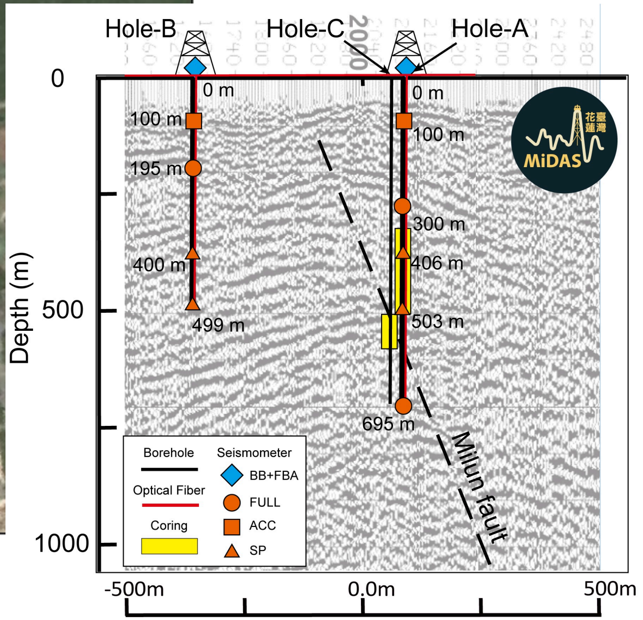
22nd Oct., 1951 M7+ earthquake sequence

Milun fault Drilling and All-inclusive Sensing (DAS & DTS) crossing fault holes: 700m Hole-A, footwall 500m Hole-B

Crossing fault three-dimensional optical fiber configuration (HoleA, 0-700m-0, Surface A (forth-345m-back), Telecom (1052m), HoleB, 0-500m-0, Surface B(forth-1128m-back)

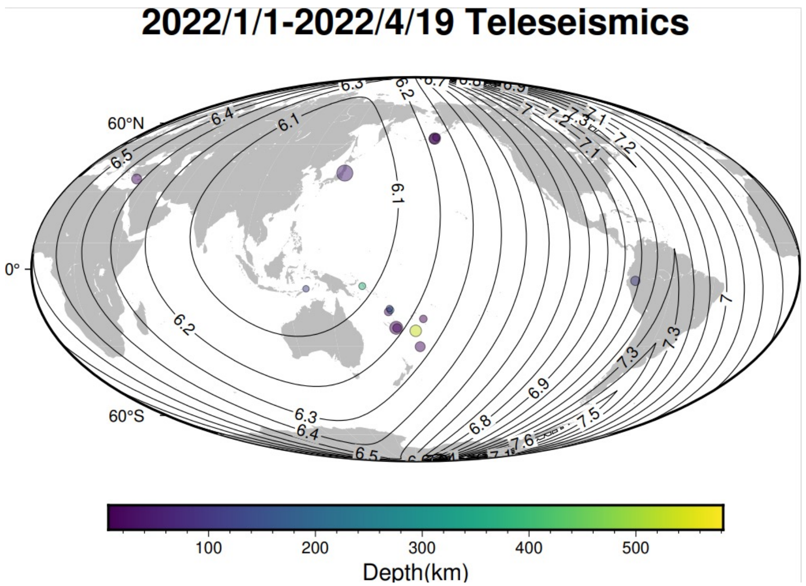


Hole-A, Hole-B Borehole Seismometer



https://www.elab.earth.sinica.edu.tw/midas-metadata

Fault Zone Amplification
Teleseismic Earthquakes

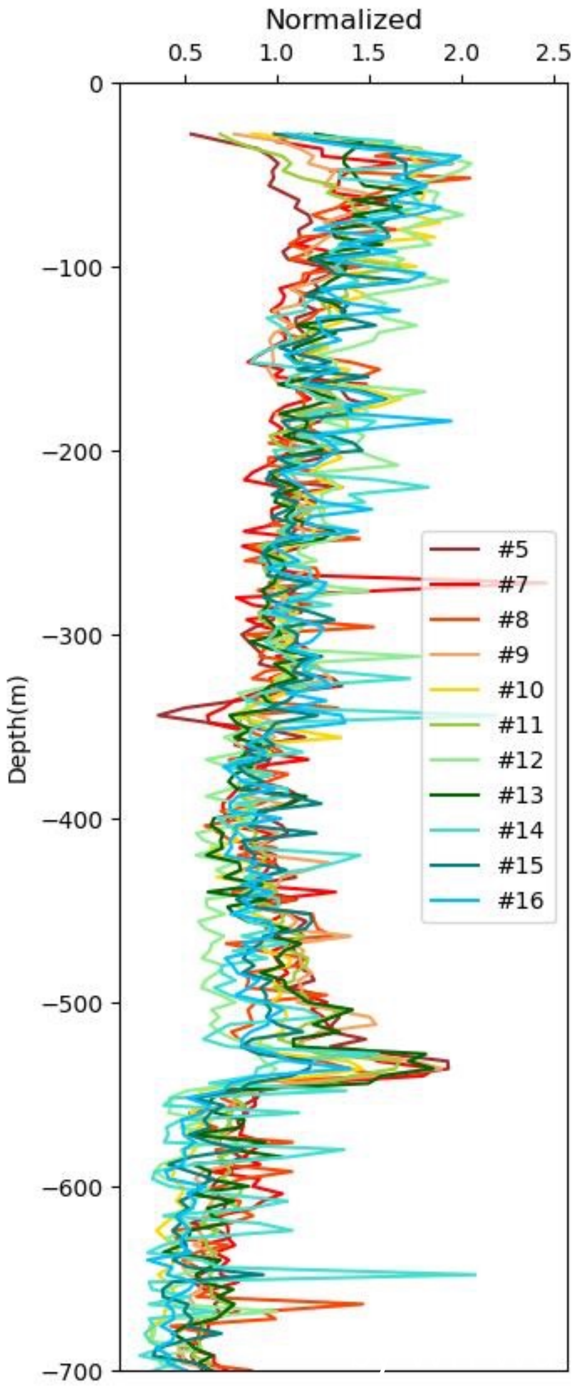


Recording capability
for **teleseismic** events

Fault Zone Amplification
from teleseismic events

⇒ **Hints on Dynamic Triggering ?**

⇒ **Global Triggered Seismicity after mega-earthquakes (e.g. 2004 M9.3 Sumatra, 2011 M9.0 Tohoku)**



Band pass 0.05-1.5Hz

Still see similar features seen in local earthquakes despite the thin fault zone of 20m.

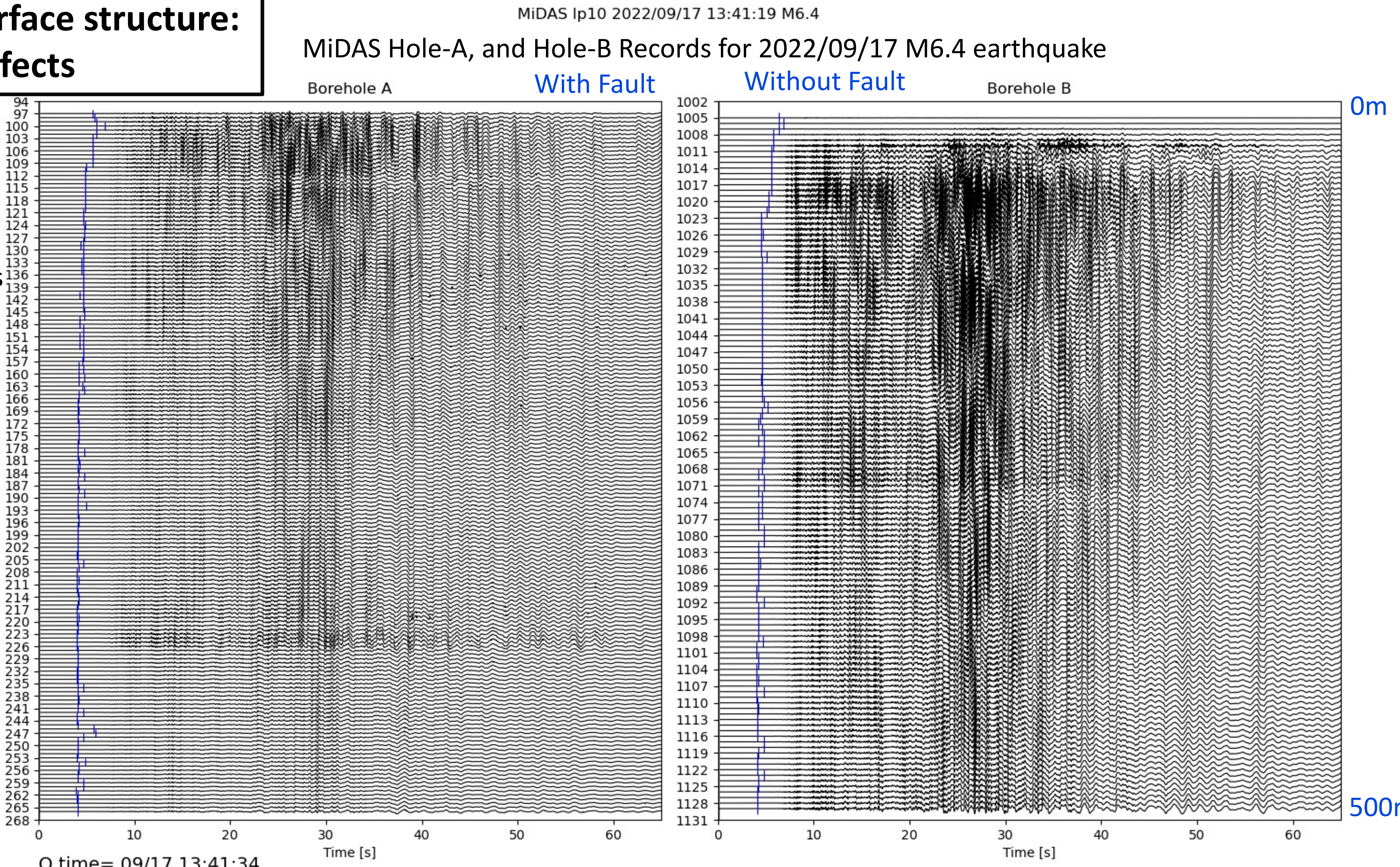
Fault Zone Amplification
520-540m

- Narrow fault zone ~ 20m
- Amplitude decay from surface to depth~200m
- Asymmetric feature crossing fault zone
- Amplitudes larger in hanging-wall than footwall (Hanging-wall effect)

Amplification due to strong velocity/ material contrast within/outside the fault zone?)

Numerical Modeling

Subsurface structure: Site effects



Busy Waveforms from subsurface structure

Fault Zone

Consistent waveforms

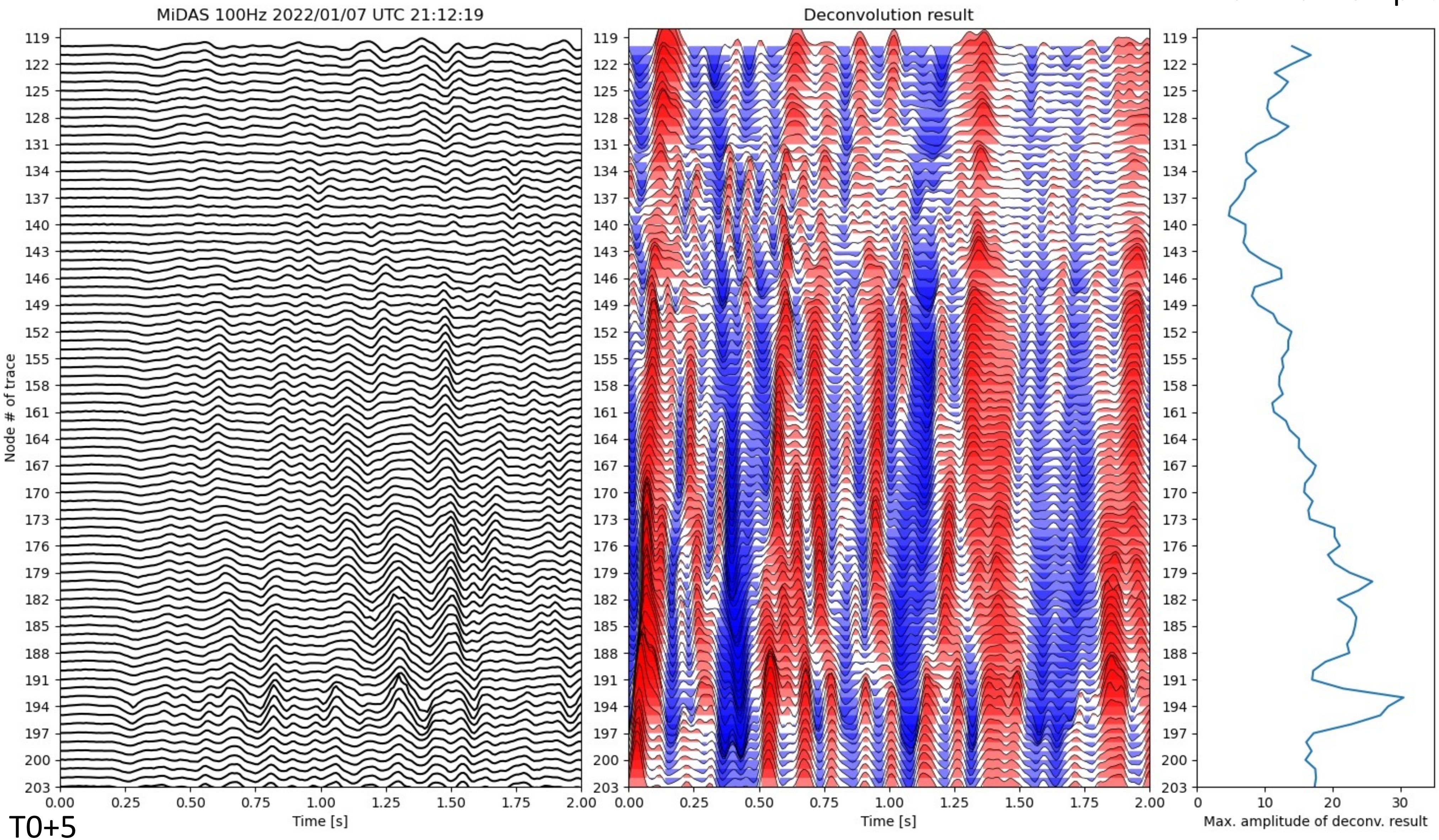
700m

Site Deconvolution to #235 (bottom)

Maximum amplitudes

2022/01/07
21:12:19.96

M4.7



T0+5

plot_amp_ScalingConstant=3*10**(-4)

CONCLUSIONS
2004 TCDP => 2021 MiDAS
(Macroscopic to Microscopic)

* **Earthquake Kinematics to Earthquake Scenario**
    - Style of Faulting, Rupture Initiation
    - Multiple segment ruptures,
    - Triggering seismicity

* **Faulting Dynamics**
    - long-term in-situ crossing fault borehole observatory:
    Optical Fiber Sensing of DAS/DTS, and borehole seismic array,
    (e.g. Lin et al., 2012, Ma et al., 2012)
    - roles of nano spherules grains (e.g., Kuo et al.,2014, Kuo et al., 2015), and fluid
    - temperature measurement, possible capture of the Friction heat?

* **Status of Stress (Healing and Reloading?)**
    - earthquake focal mechanisms (thrust→ strike-slip) (Ma et al., 2005)
    - rotation of the stress axis

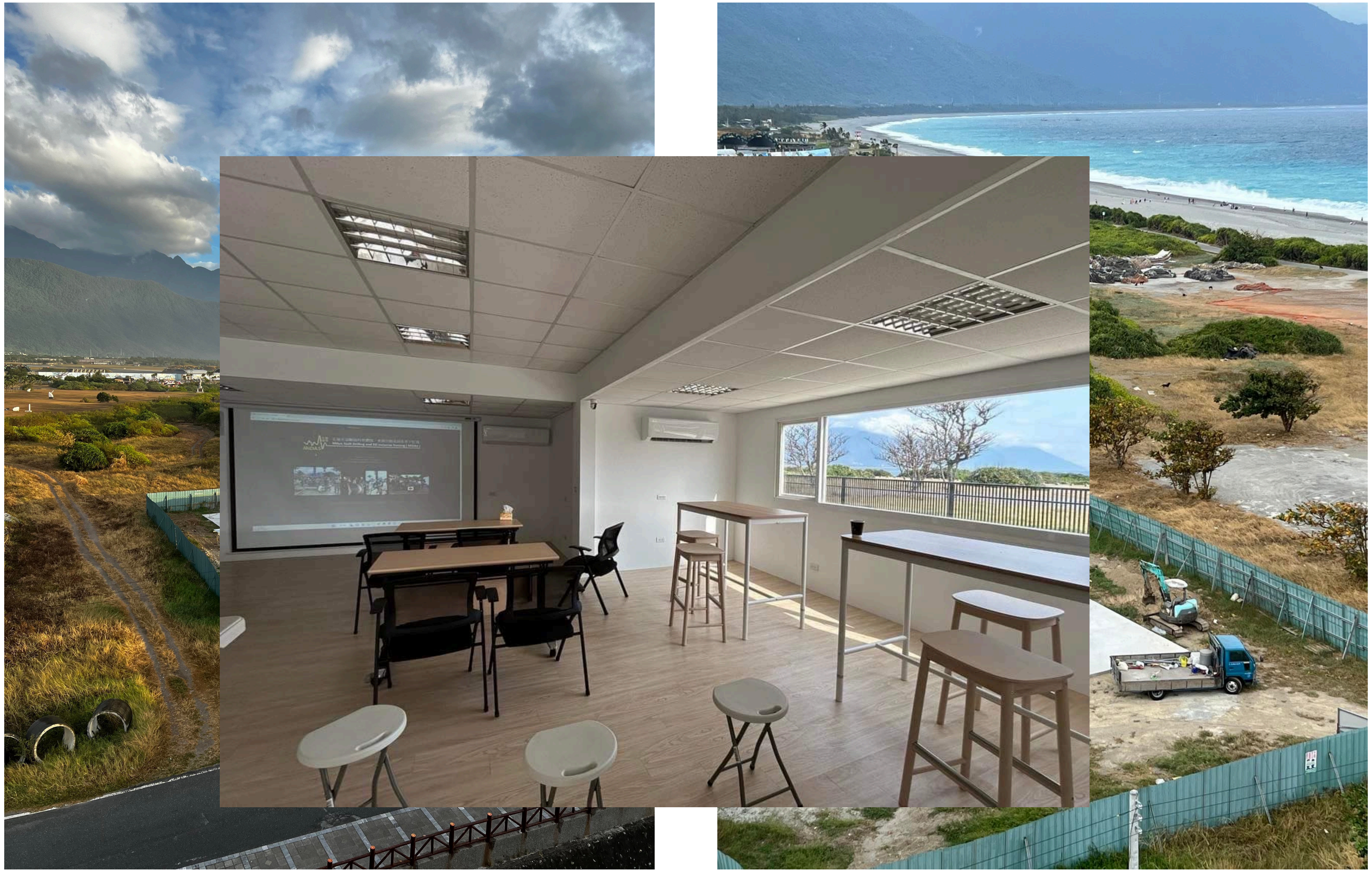
Core Description, Geochemistry/Geophysics and Others

From Macroscopic to Microscopic
TOWARD HIGH RESOLUTION
Earthquake kinematics and dynamics modellings

THANK YOU

@MiDAS site

From Macroscopic to Microscopic
TOWARD HIGH RESOLUTION
Earthquake kinematics and dynamics modellings



THANK YOU

@MiDAS site

E-DREaM NCU

Milun fault **D**rilling and **A**ll-inclusive **S**ensing
MiDAS project