強地動預估與模擬：
從震源破裂到三維波傳

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地震動特徵專題講座之一- 地震動模擬技術應用之現況與展望

2018.08.28 (二) 國震中心R101會議室

報告內容

一、簡介

二、地震波數值模擬

震源、路徑、場址

三、地震波數值模擬案例

過去 - 1935年 新竹-台中地震

現在 - 2016年 美濃地震

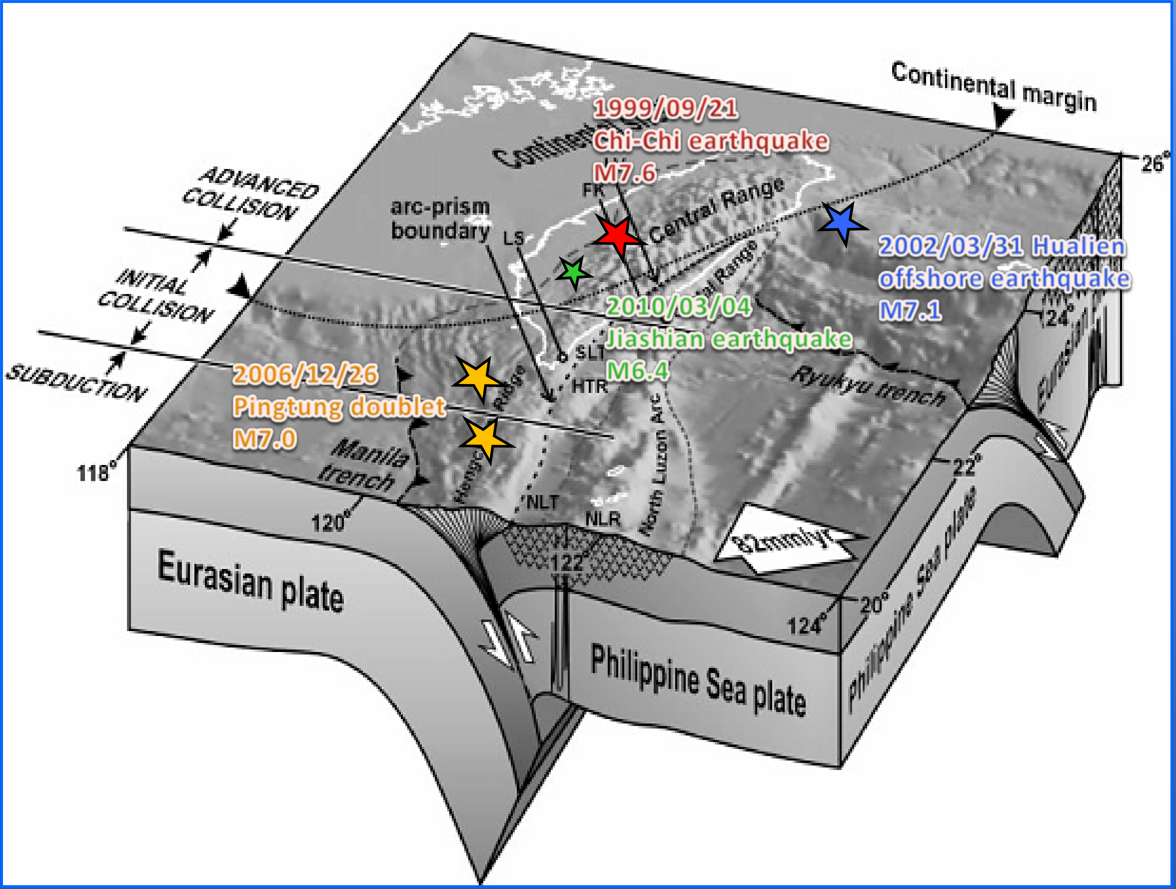
未來 - 琉球隱沒帶地震

四、台灣數值地震模型

伍、總結

一、簡介

- Taiwan is formed by a collision between the Philippine Sea plate and the Eurasian continental margin.
- In the last 20 years, numerous large hazardous earthquakes had caused remarkable damages with considerable casualties.
- It is therefore an important scientific mission to understand the hazardous earthquakes by using high resolution, advanced numerical simulation techniques.

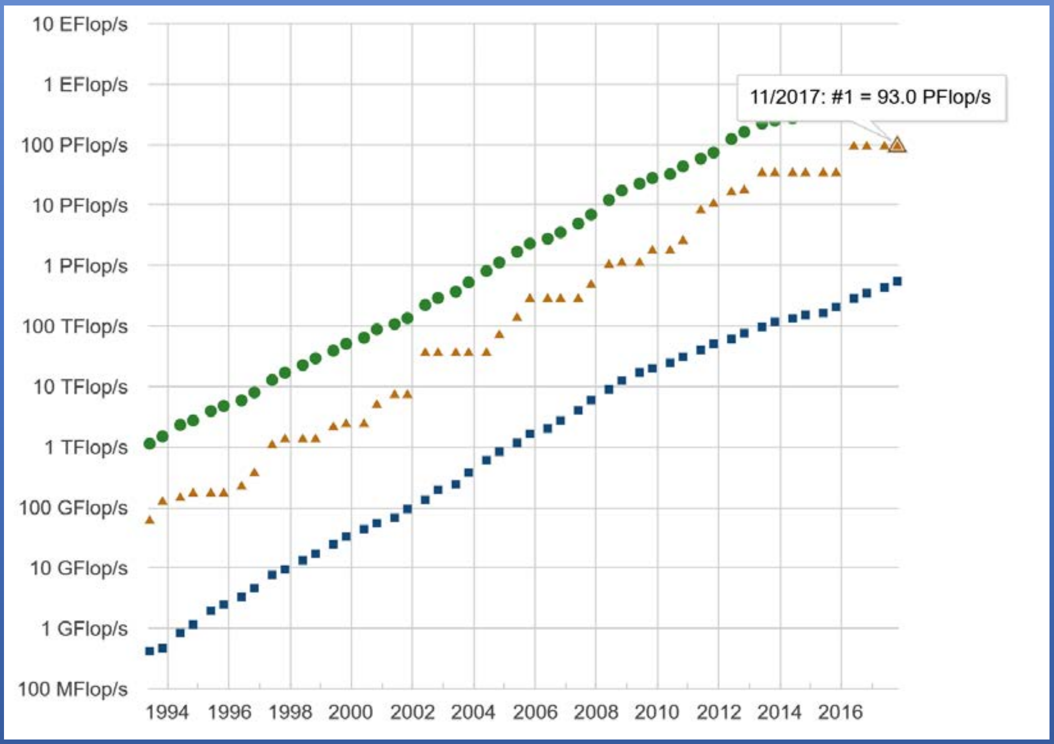


Block diagram showing arc-continent collision and tectonic setting of Taiwan (by CHANG,2001)

高效能計算

Performance development of Top 500

Performance



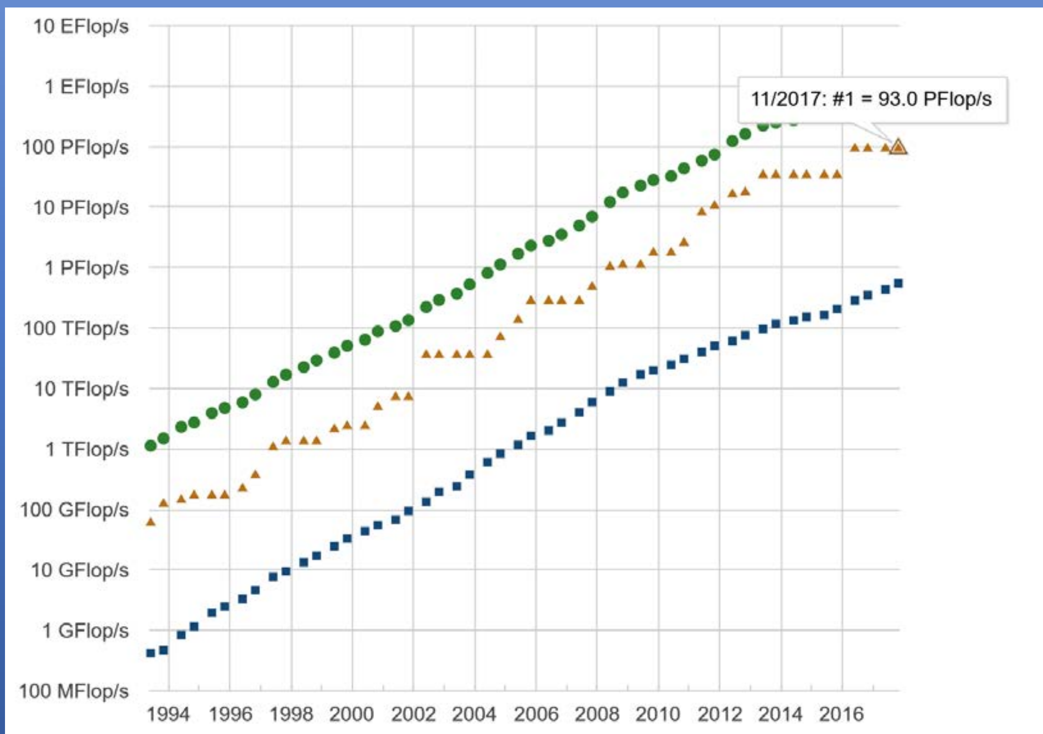
Time (year)

2016-2017 #1: Sunway TaihuLight (神威-太湖之光)

Site:	National Supercomputing Center in Wuxi
Manufacturer:	NRCPC
Cores:	10,649,600
Memory:	1,310,720 GB
Processor:	Sunway SW26010 260C 1.45GHz
Interconnect:	Sunway
Performance	
Linpack Performance (Rmax)	93,014.6 TFlop/s
Theoretical Peak (Rpeak)	125,436 TFlop/s

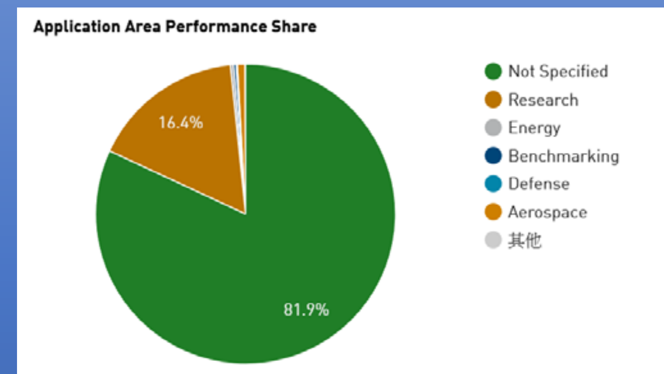
高效能計算

Performance development of Top 500



Performance

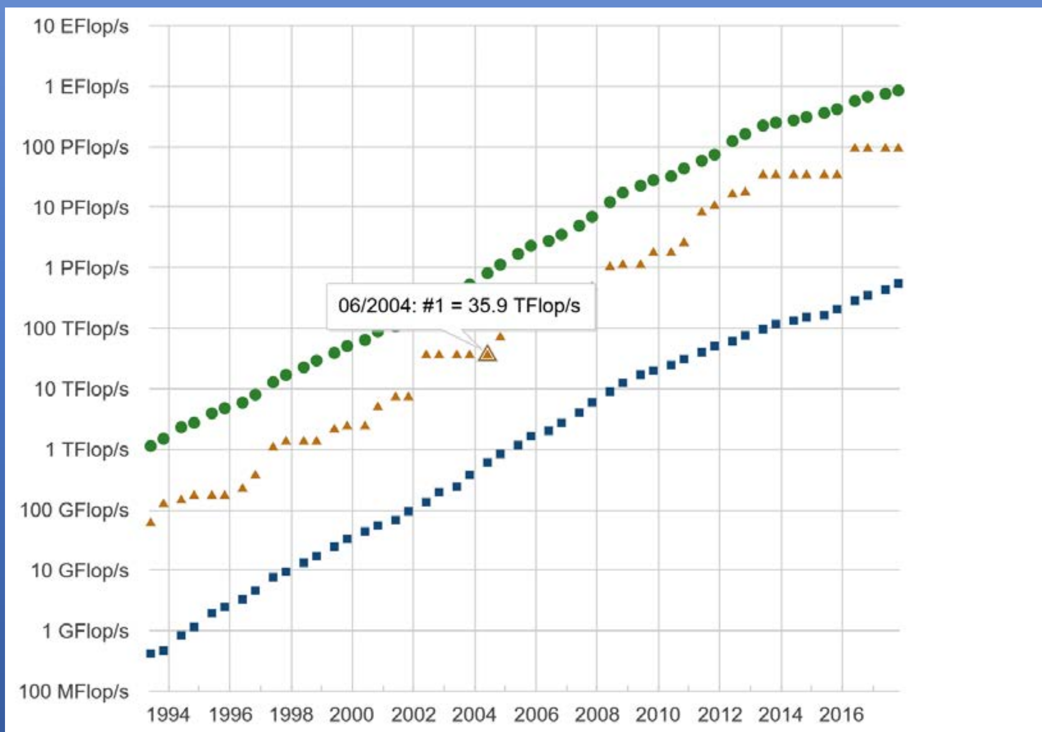
Time (year)



Application Area	Count	System Share (%)	Rmax (GFlops)	Rpeak (GFlops)	Cores
Not Specified	478	95.6	613,068,057	953,033,090	34,596,574
Research	14	2.8	123,105,793	164,503,585	12,807,444
Energy	3	0.6	2,613,329	3,156,903	142,568
Benchmarking	2	0.4	2,017,459	2,470,761	75,904
Defense	1	0.2	1,050,000	1,254,550	138,368
Aerospace	1	0.2	5,951,550	7,107,149	241,108
Weather and Climate Research	1	0.2	565,700	715,981	77,824

高效能計算

Performance development of Top 500



Performance

Time (year)

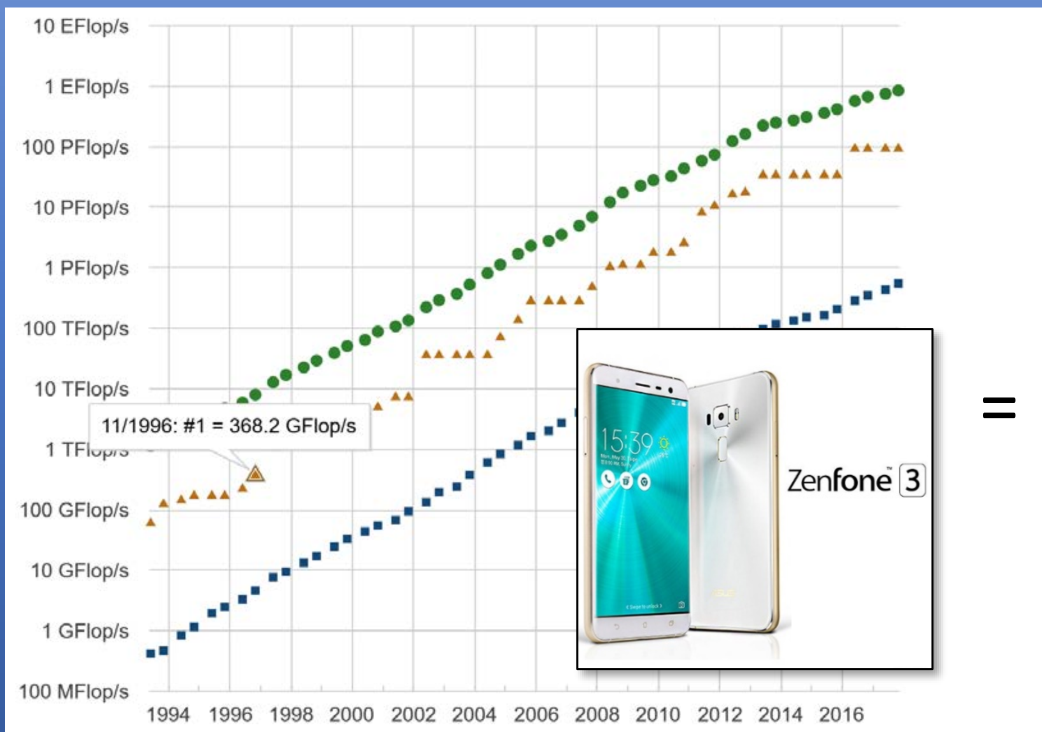
2002-2004 #1: Earth Simulator

Site:	Japan Agency for Marine-Earth Science and Technology
System URL:	http://www.es.jamstec.go.jp/esc/eng/ES/index.html
Manufacturer:	NEC
Cores:	5,120
Memory:	
Processor:	NEC 1GHz
Interconnect:	Multi-stage crossbar
Performance	
Linpack Performance (Rmax)	35.86 TFlop/s
Theoretical Peak (Rpeak)	40.96 TFlop/s

高效能計算

Performance development of Top 500

Performance



Time (year)

=

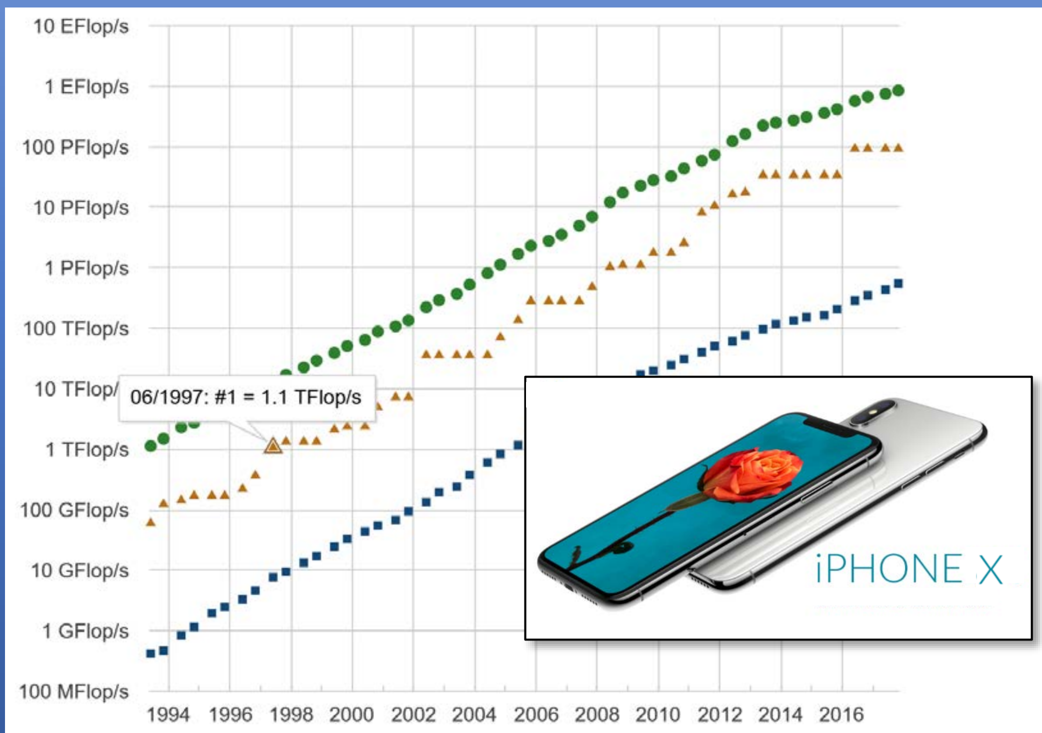
1996 #1: CP-PACS/2048

Site:	Center for Computational Sciences, University of Tsukuba
Manufacturer:	Hitachi/Tsukuba
Cores:	2,048
Memory:	
Processor:	HARP-1E 150MHz
Interconnect:	Hyper crossbar
Performance	
Linpack Performance (Rmax)	0.3682 TFlop/s
Theoretical Peak (Rpeak)	0.6144 TFlop/s

高效能計算

Performance development of Top 500

Performance



Time (year)

=

1997 #1: ASCI/Red

Site:	Sandia National Laboratories
System URL:	http://www.sandia.gov/ASCI/Red/
Manufacturer:	Intel
Cores:	7,264
Memory:	
Processor:	Pentium Pro 200MHz
Interconnect:	Proprietary
Performance	
Linpack Performance (Rmax)	1.068 TFlop/s
Theoretical Peak (Rpeak)	1.453 TFlop/s

高效能計算

Performance development of Top 500

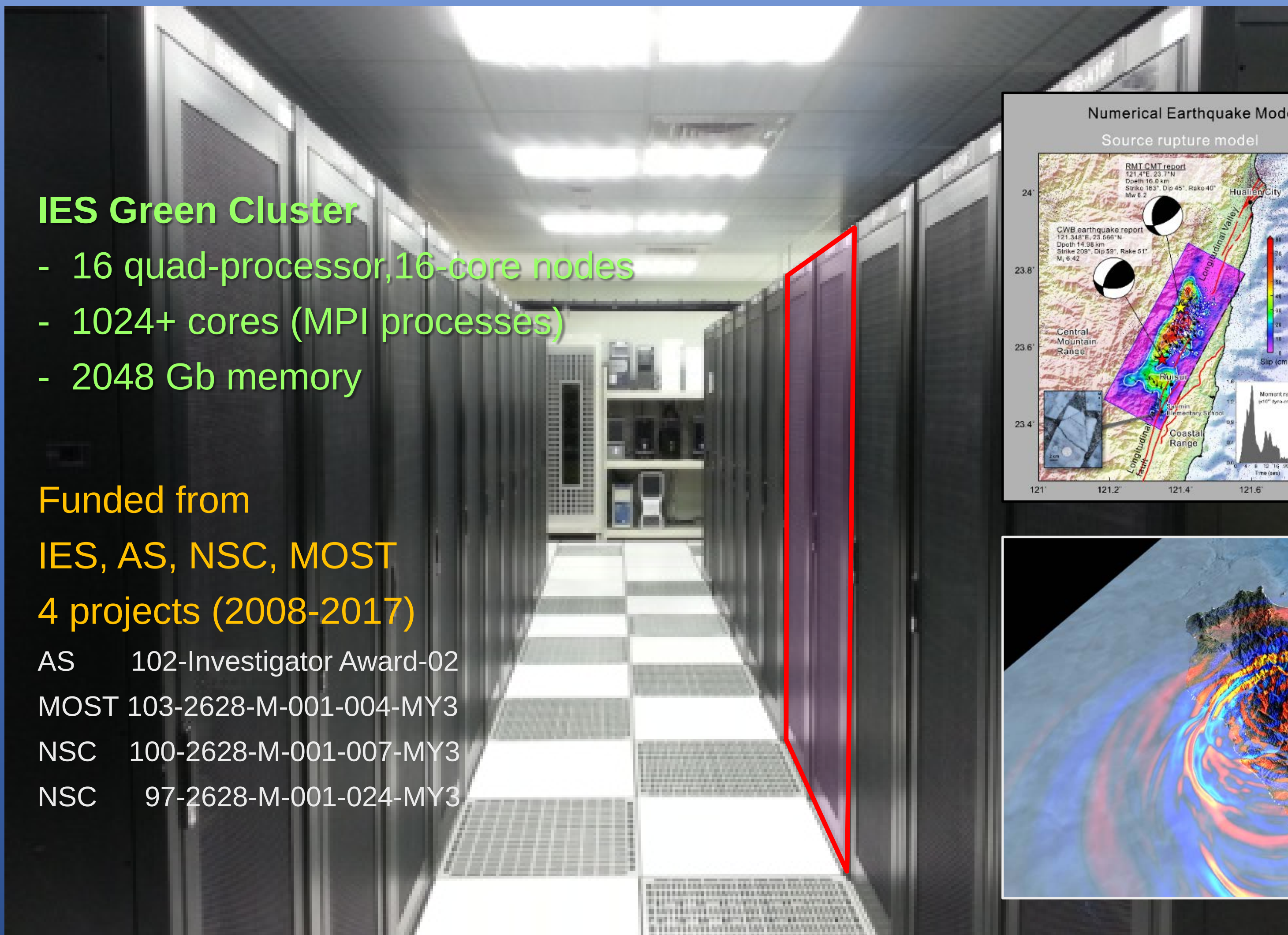
Performance

Time (year)

=

2002-2004 #1: Earth Simulator

中研院地球所 Green Cluster



IES Green Cluster

- 16 quad-processor,16-core nodes
- 1024+ cores (MPI processes)
- 2048 Gb memory

Funded from

IES, AS, NSC, MOST

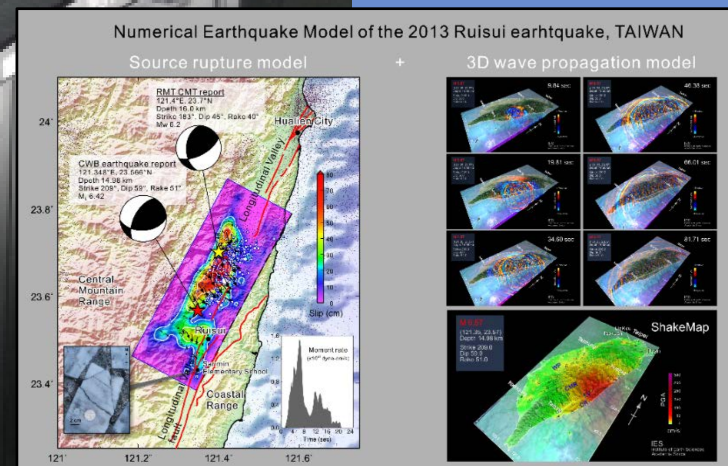
4 projects (2008-2017)

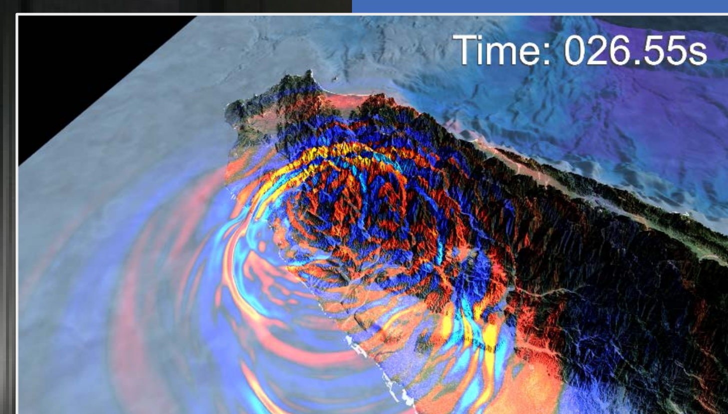
AS 102-Investigator Award-02

MOST 103-2628-M-001-004-MY3

NSC 100-2628-M-001-007-MY3

NSC 97-2628-M-001-024-MY3





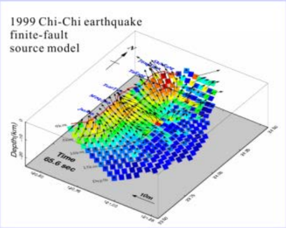
二、地震波數值模擬

震源、路徑、場址

Earthquake simulation - Source, Path and Site

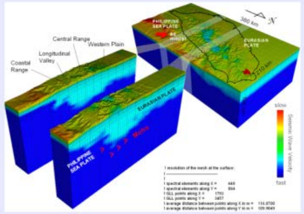
Numerical source model

- Point source parameters for earthquake M <6
- Finite-fault model for earthquake M≧6
- Kinetic and dynamic analyses



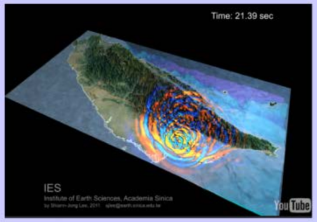
Numerical structure model

- Large-scale model
- Local velocity model
- Realistic topography
- Moho, plate boundaries
- Basin
- Sedimentary plain
… etc.



Numerical earthquake simulation

- ShakeMovie
- ShakeMap
- Synthetic waveforms
- Visualization



Near real-time simulation & visualization
http://www.earth.sinica.edu.tw/~sjlee/rcs/index.htm

Source

- M<6: Point source parameters
- M>6: Finite-fault source model
- Fault and seismogenic zone
- Kinetic and dynamic analyses

Path and site

- Large-scale velocity model
- Local velocity model
- Surface topography
- Moho, plate boundary
- Basin, sedimentary plain, … etc.

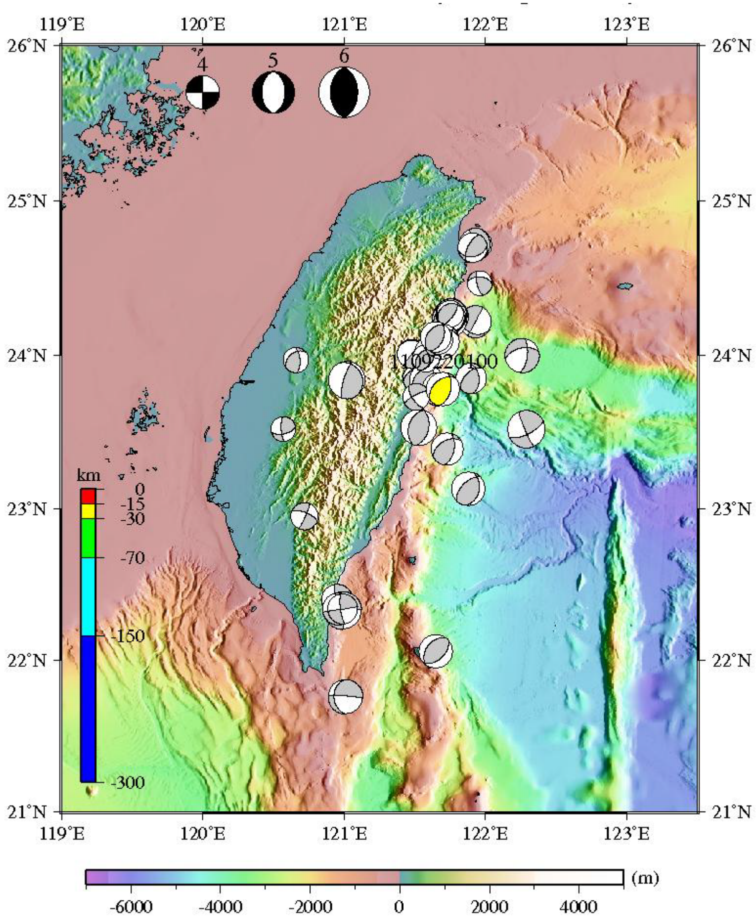
Earthquake Simulation

- ShakeMovie: 3D wave propagation
- ShakeMap: PGA, PGV, Intensity map
- Synthetic waveforms
- Visualization

A. Source representation

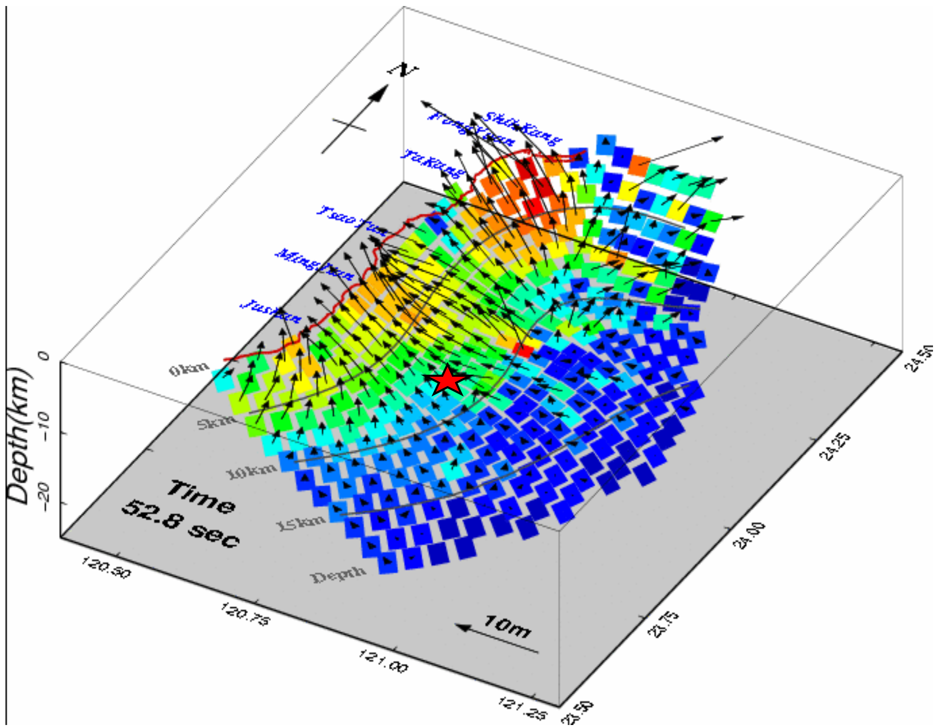
M < 6.0: Point source

Broadband array in Taiwan for seismology:
http://bats.earth.sinica.edu.tw



M > 6.0: Finite-fault source model

1999 Chi-Chi earthquake (Mw7.6) source model

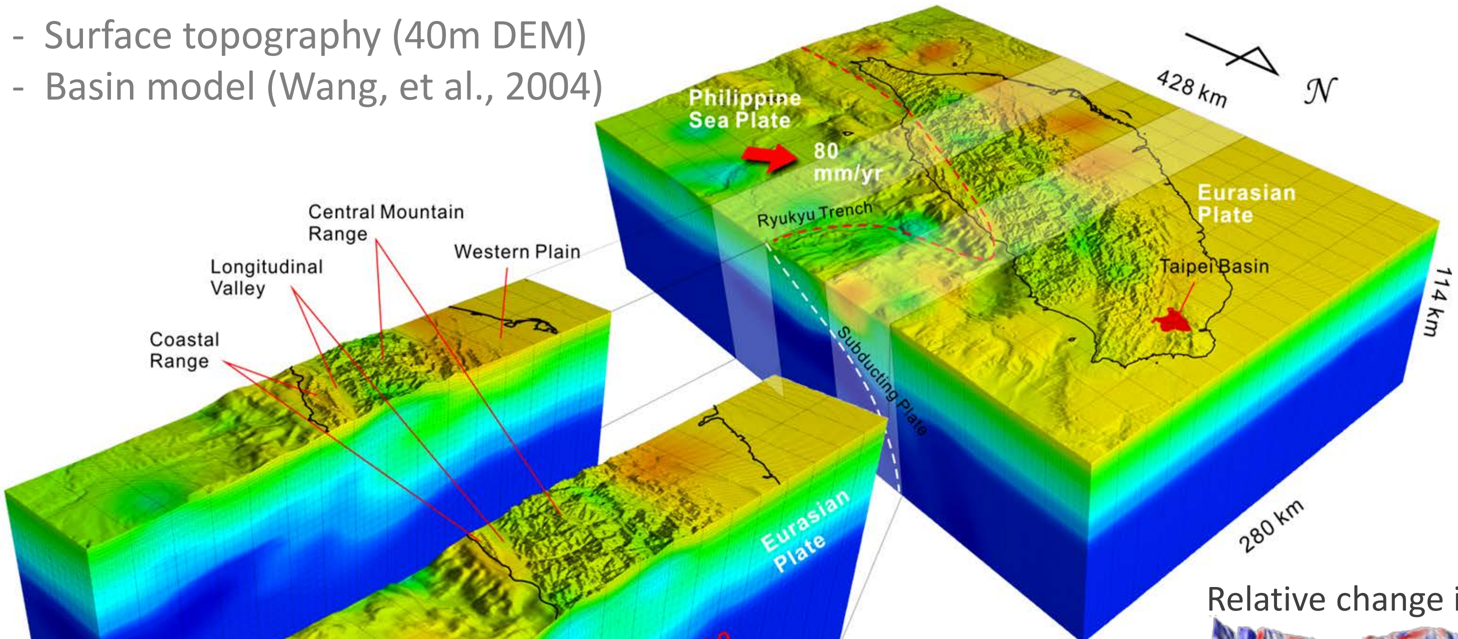
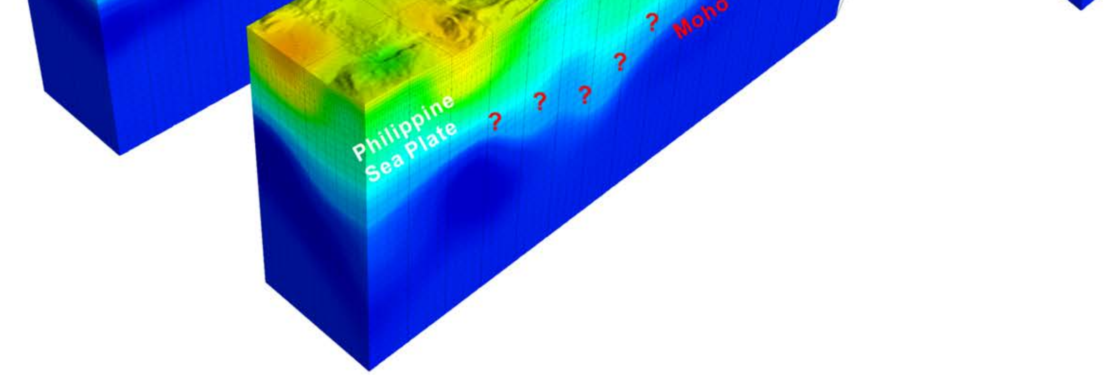


Lee et al. 2006

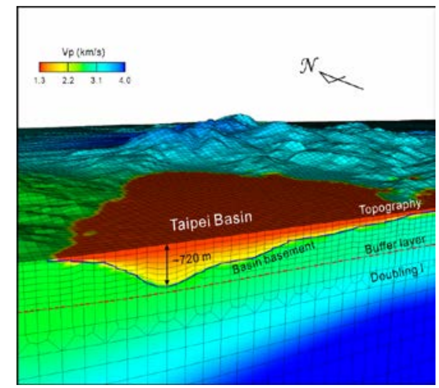
B. Path & Site: Numerical velocity model

Spectral-element method mesh model

- Large scale velocity model (Kuo-Chen et al., 2012)
- Local structure model
- Surface topography (40m DEM)
- Basin model (Wang, et al., 2004)

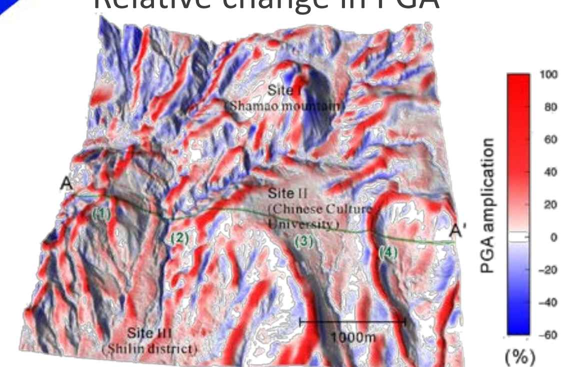



Mesh implementation for the Taipei basin



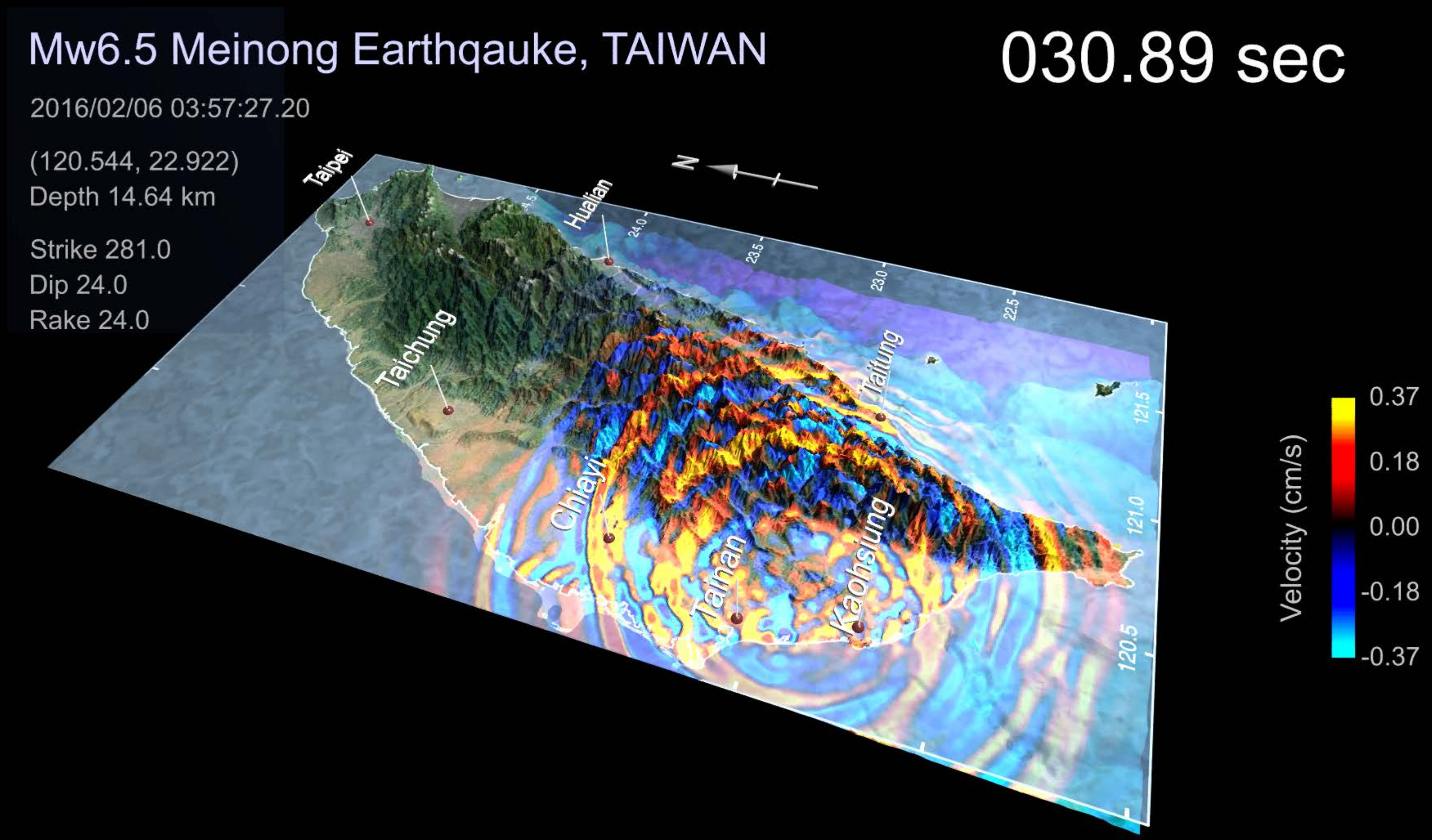
Lee et al., 2008

Relative change in PGA



Lee et al., 2009

C. Realistic ground motion simulation



三、地震波數值模擬案例

現在 - 2016年 美濃地震

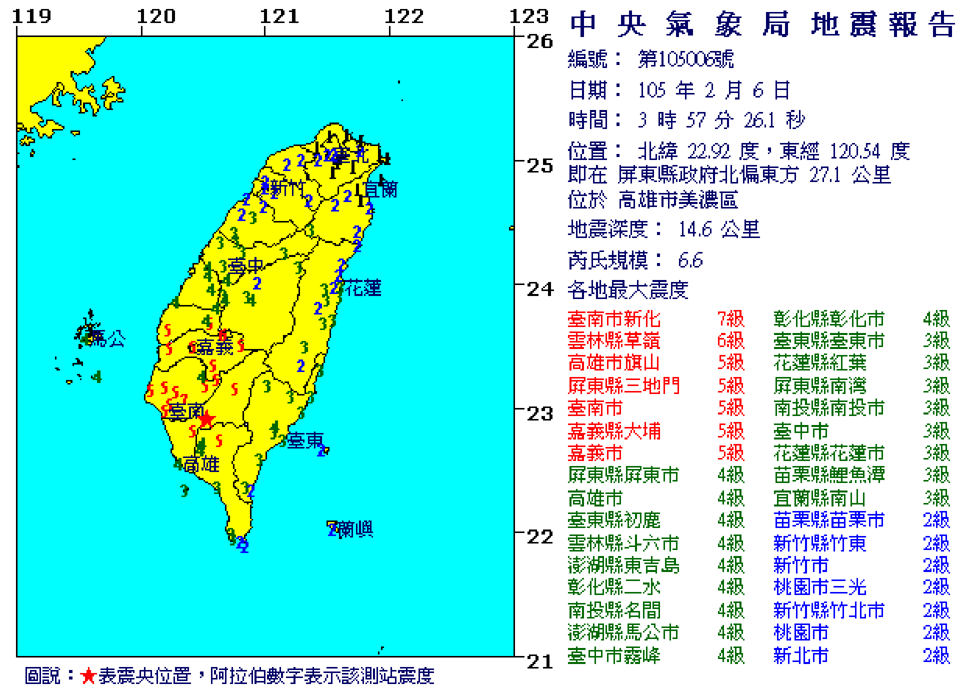
過去 - 1935年 新竹-台中地震

未來 - 琉球隱末帶地震

Recent earthquake

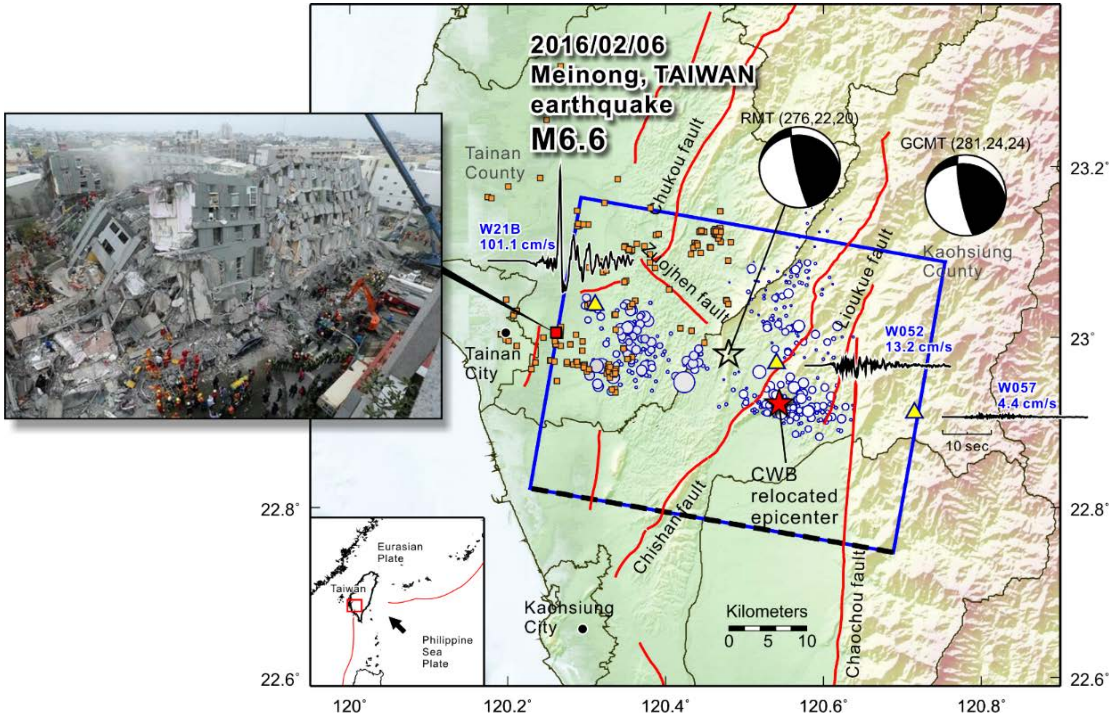
2016 Meinong earthquake M6.6

2016 Meinong earthquake (M6.6)




6.4南台大震
華視
CTS
HD
2016/02
台南善化民宅
二樓變一樓
"維冠"整棟塌 路面像在跳躍
19:42:49
南台強震
離震央最近 旗山美濃多處民宅屋瓦掉落

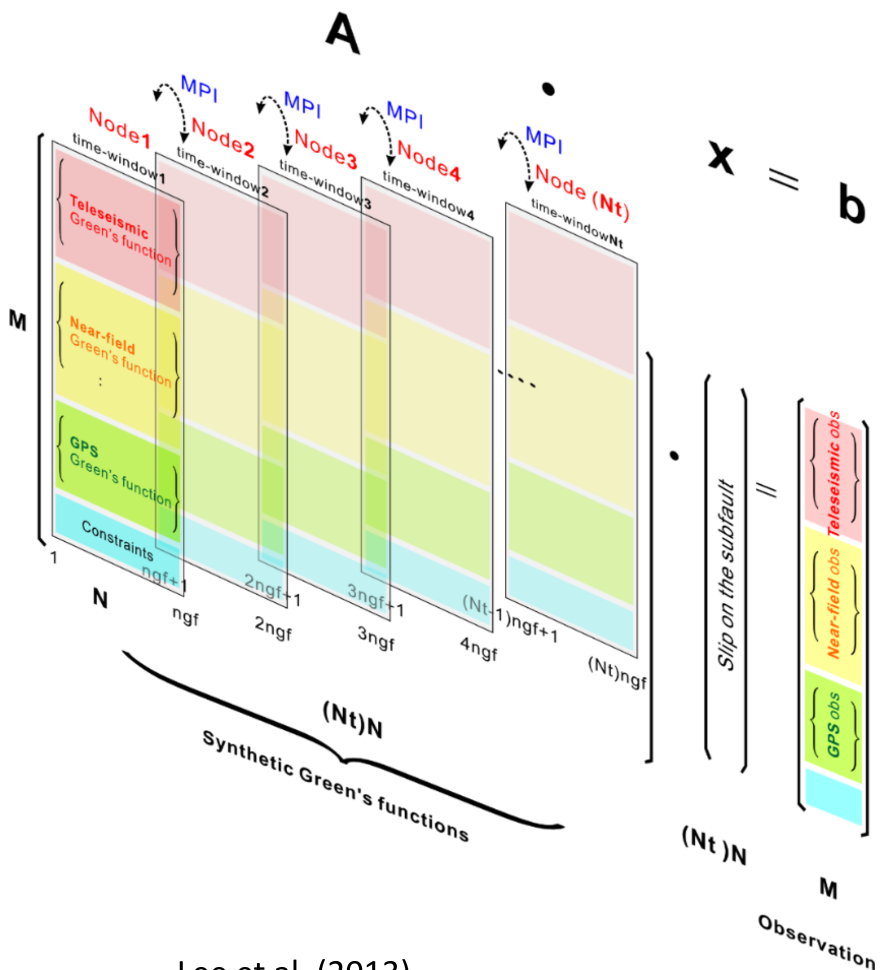
Joint source inversion



Data

- Teleseismic body wave (GSN)
- Local seismic data (CWB RTD, BATS, Palert)
- GPS coseismic displacement (CWB)

Joint source inversion



Lee et al. (2013)

Data

- Teleseismic body wave (GSN)
- Local seismic data (CWB RTD, BATS, Palert)
- GPS coseismic displacement (CWB)

Method: Parallel NNLS

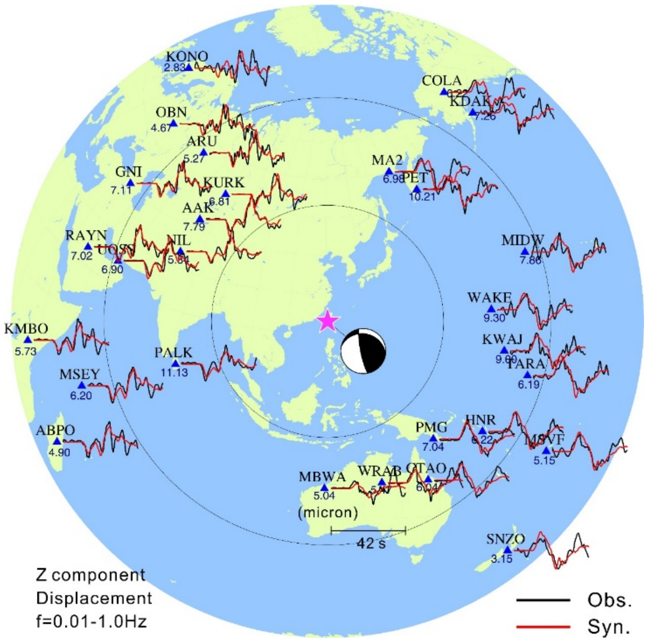
- Multiple-time window (48 time window)
- Time window overlap 0.2s
- Max. rupture velocity 3.5 km/s
- Smooth in time & space
- Damping at fault edge
- Misfit: $(Ax-b)^2/b^2$

Green's functions

- Teleseismic: Kikuchi and Kanamori (1982)
- Local: 3D SEM (Komatitsch and Tromp, 2004)
- GPS: analytic expressions of Okada (1985)

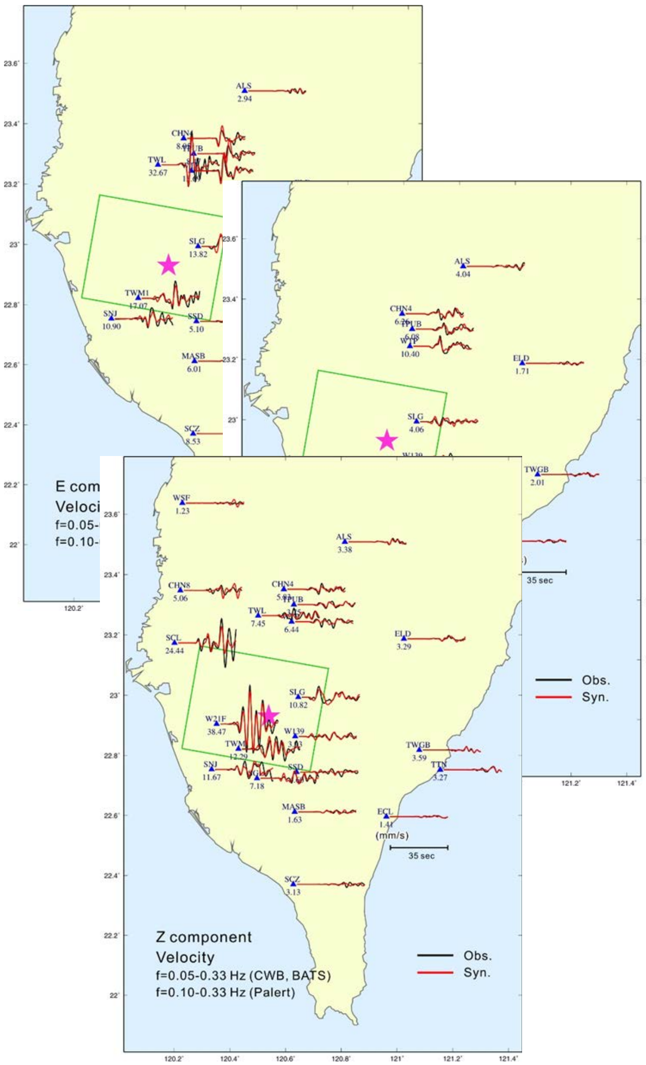
Data fitting

Teleseismic



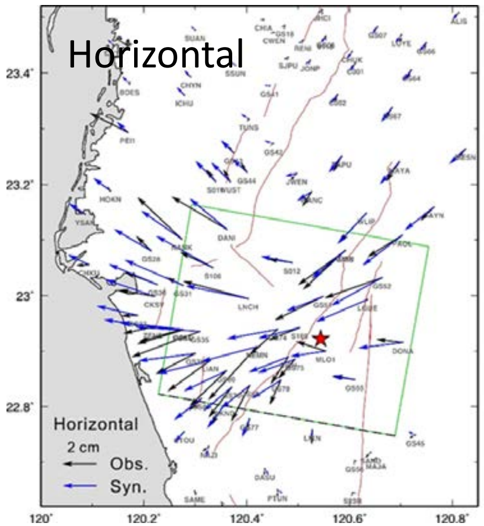
Misfit:0.21

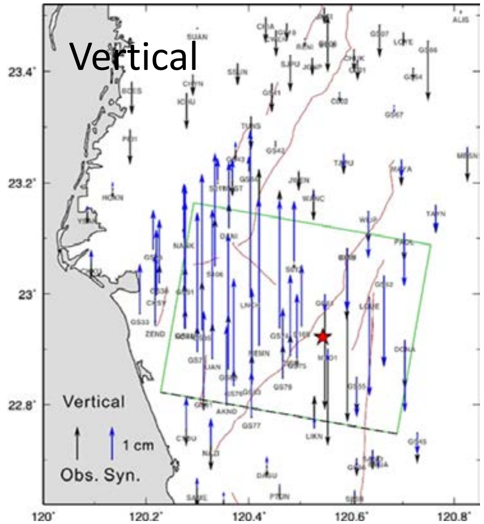
Local



Misfit: 0.40

GPS

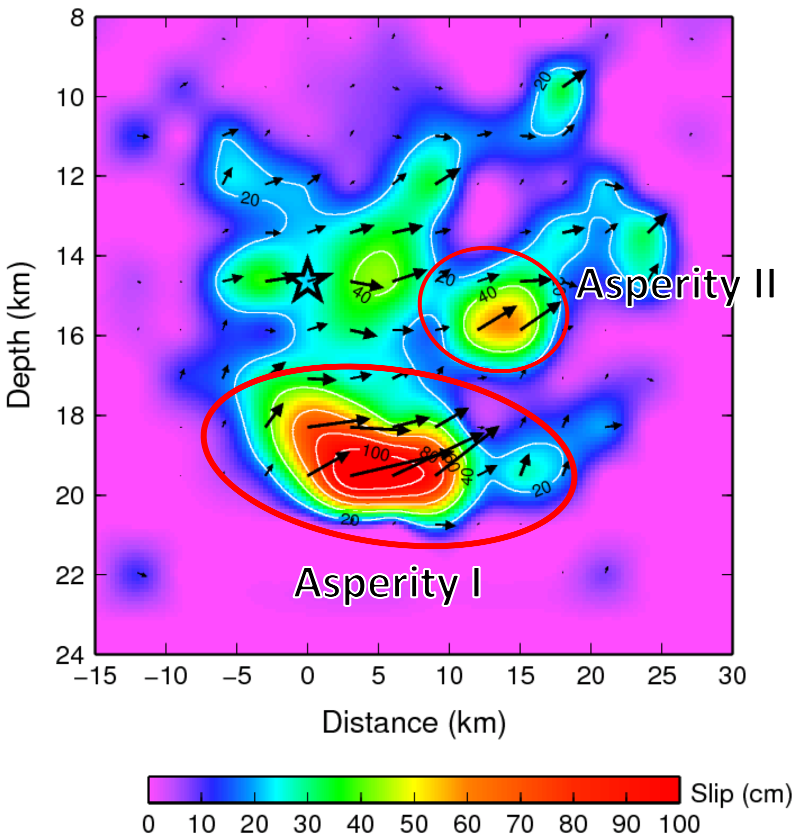




Misfit:0.38

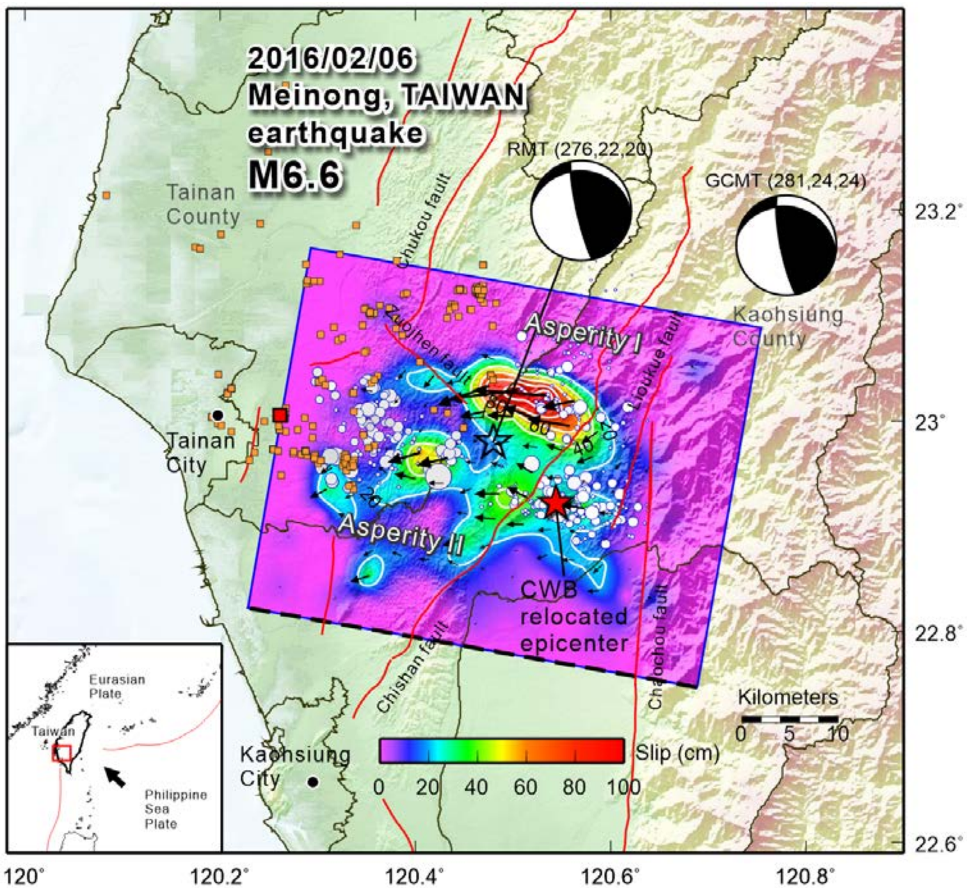
Slip distribution

Slip on the fault plane



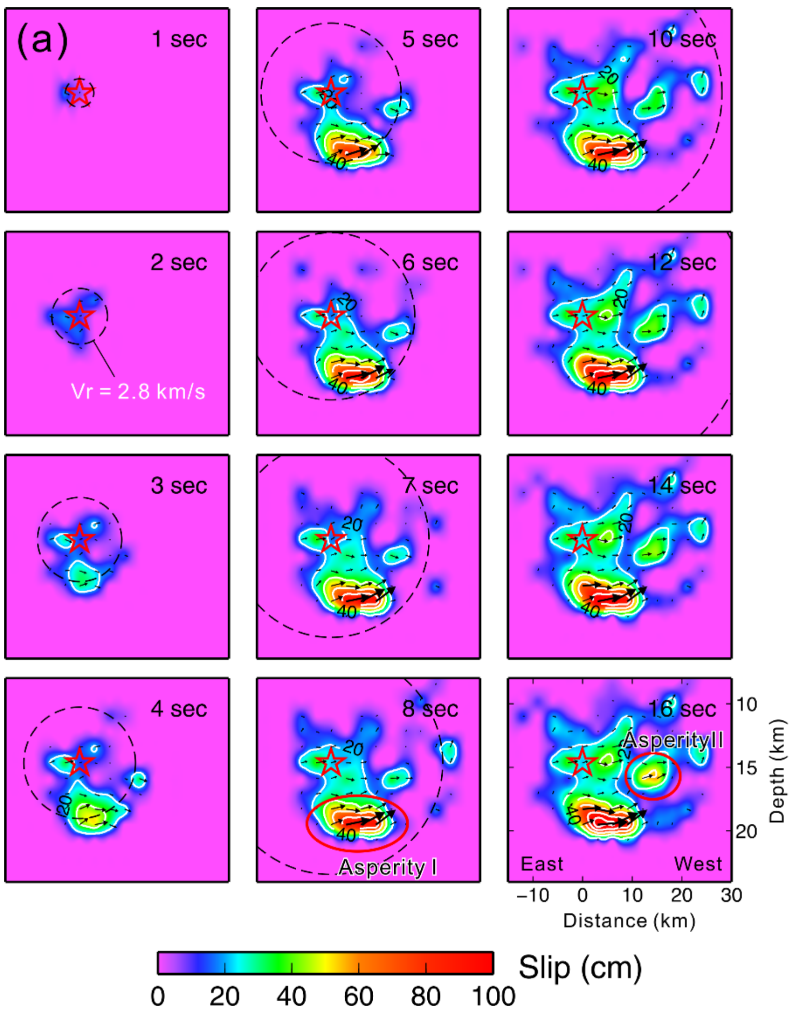

```
Slip area (km**2):    630.0
Average slip (cm):    29.17
Maximum slip (cm):    120.2
Stress drop (MPa):   0.4786
```

Slip projected to the surface

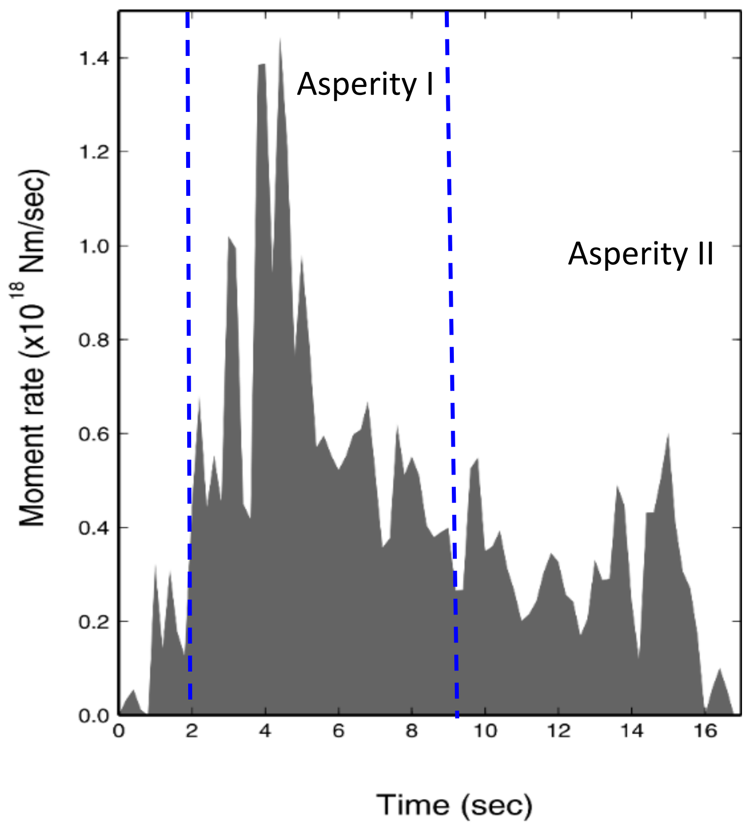


Rupture process

Accumulated slip



Source time function

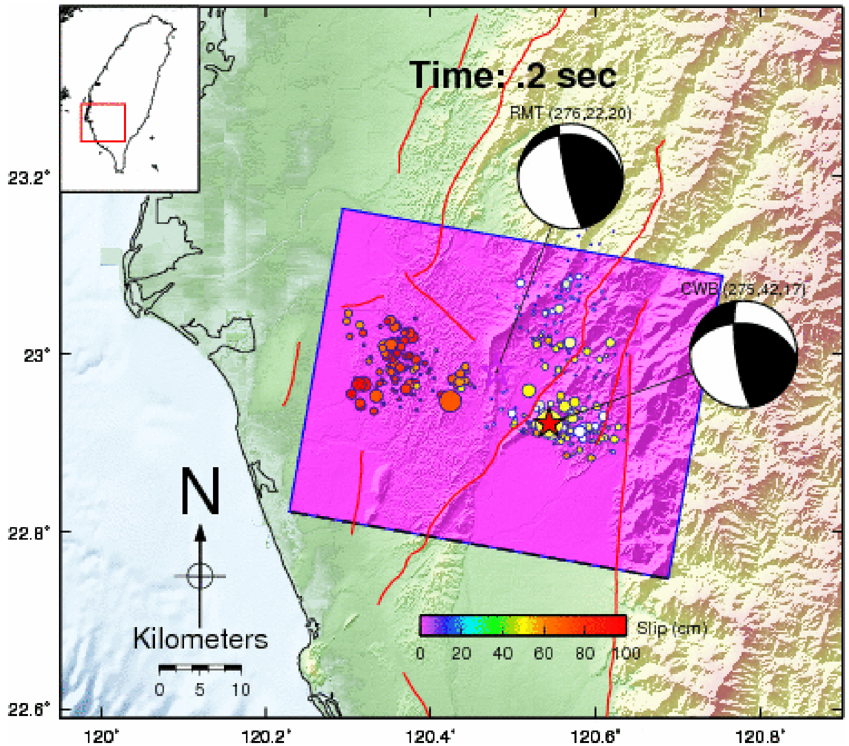


Total moment

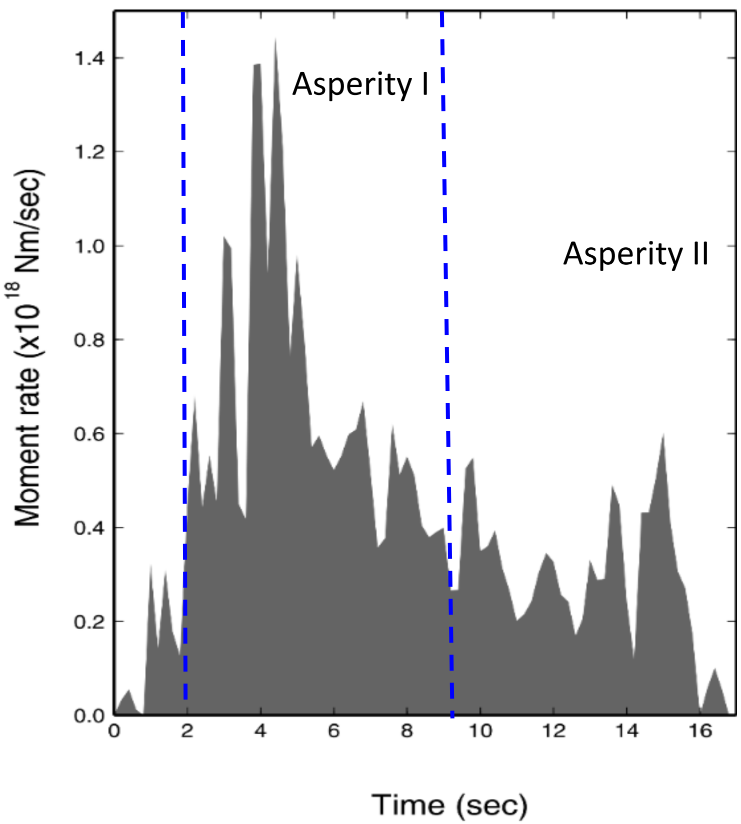
7.53×10^{18} Nm ~ M_w 6.52

Rupture process

Accumulated slip



Source time function



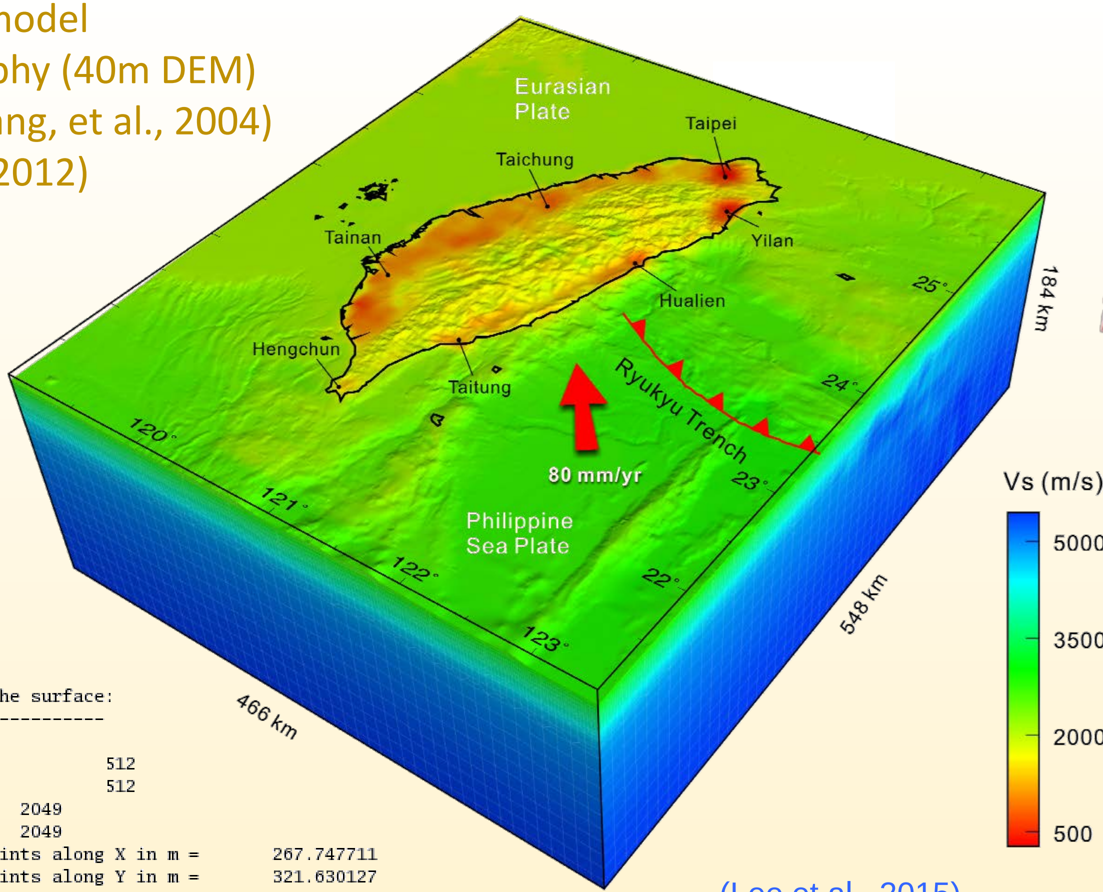
Total moment

7.53×10^{18} Nm ~ M_w 6.52

Spectral-element method mesh model

SEM mesh model

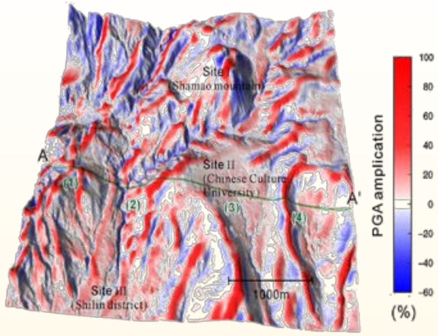
- Large scale velocity model (Huang et al., 2014)
- Local structure model
- Surface topography (40m DEM)
- Basin model (Wang, et al., 2004)
- Vs30 (Kuo et al, 2012)




```
! resolution of the mesh at the surface:
! -----------------------------------
!
! spectral elements along X =          512
! spectral elements along Y =          512
! GLL points along X =          2049
! GLL points along Y =          2049
! average distance between points along X in m =       267.747711
! average distance between points along Y in m =       321.630127
!
```

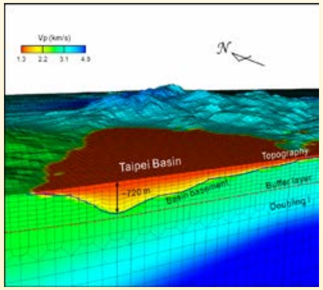
(Lee et al., 2015)

Topography effect



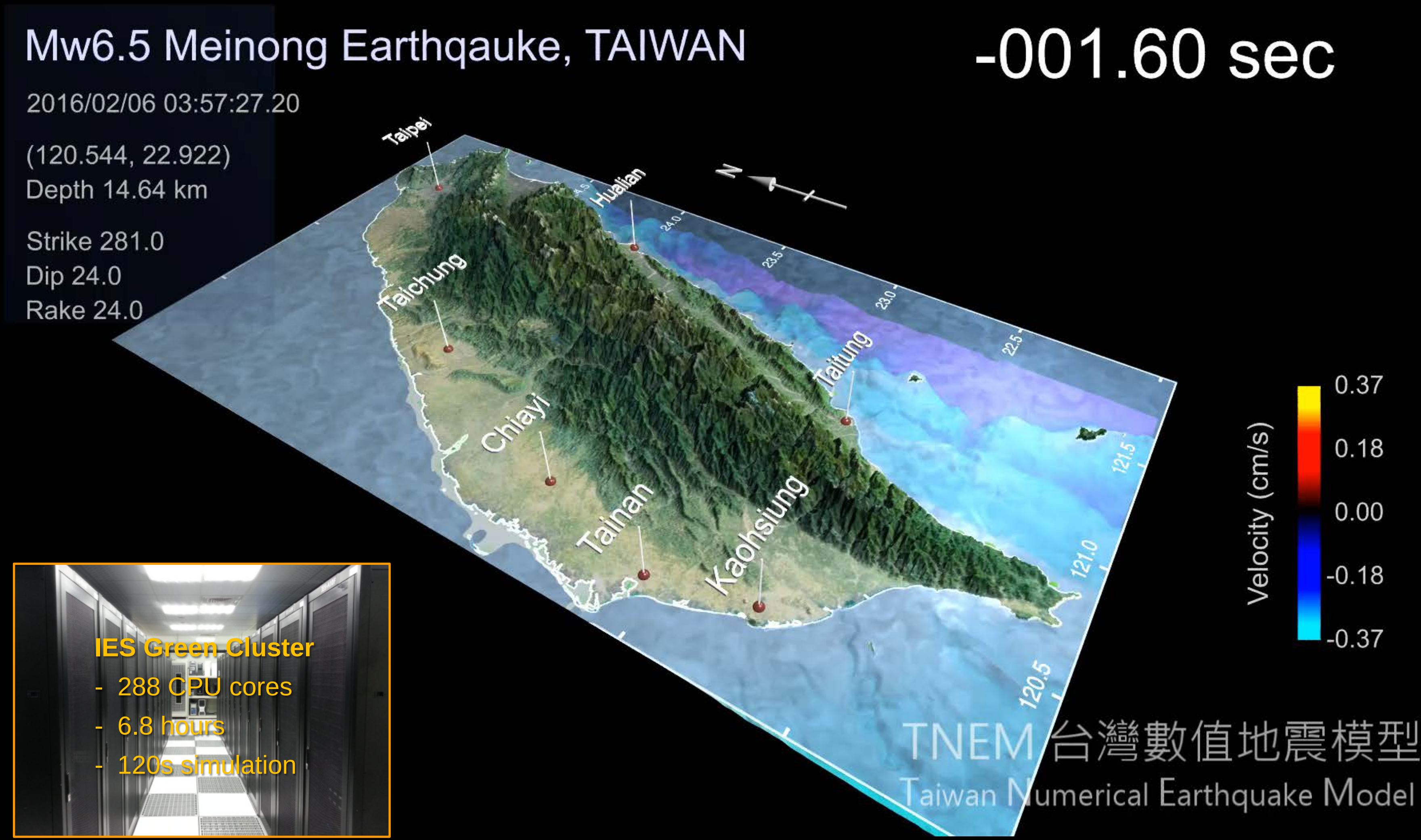
Lee et al., 2009

Mesh implementation for the Taipei basin



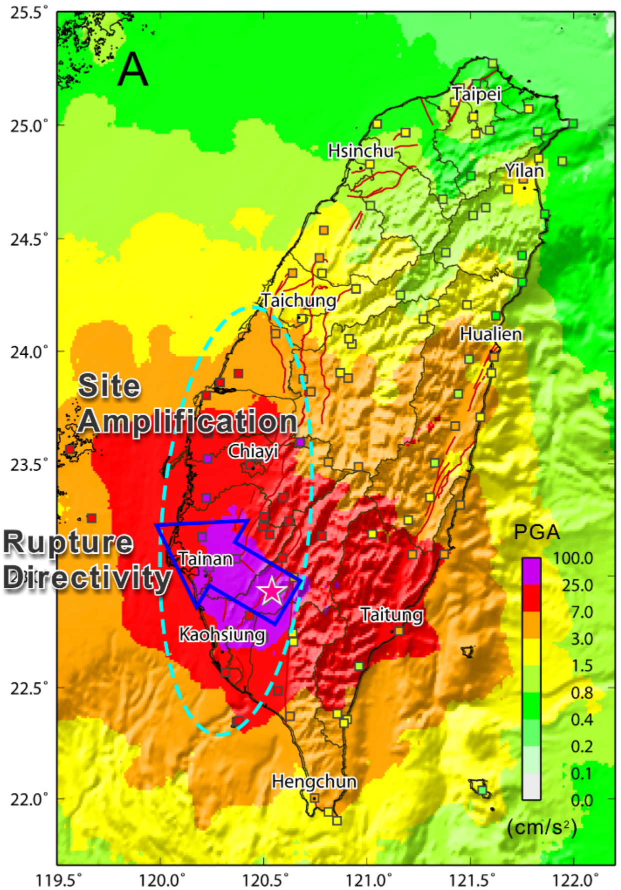
Lee et al., 2008

Realistic ground motion simulation



ShakeMap

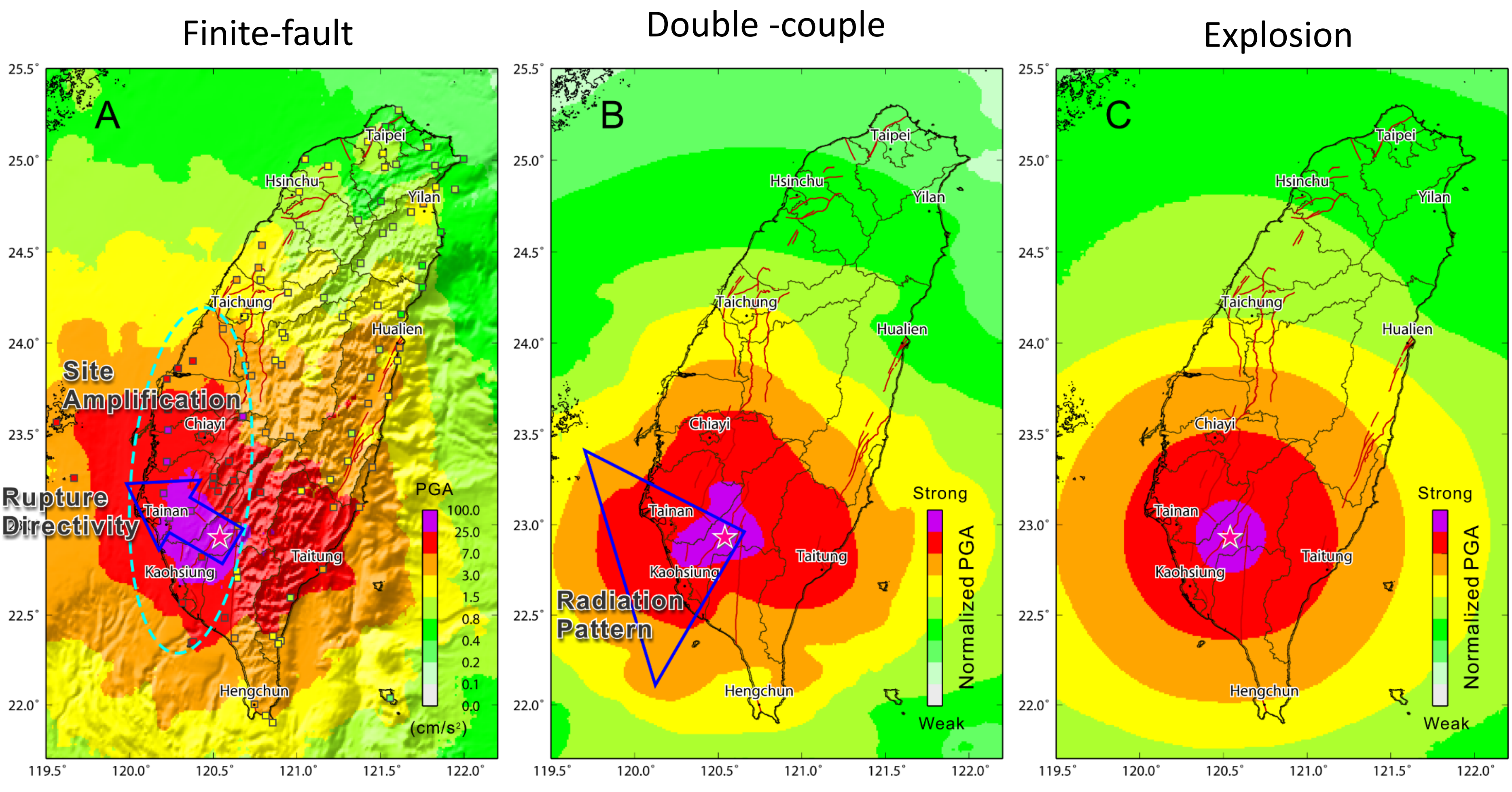
Finite-fault



Frequency 0.625 Hz

The colored squares in (A) indicate the norm of PGA observations which were compiled from the CWB 24-bit Seismic Monitoring Network. The observations were low-pass filtered using a corner frequency of 0.625 Hz to compare with the simulated ShakeMap determined by a frequency of ≤0.625 Hz.

ShakeMap



Frequency 0.625 Hz

Summary of Meinong earthquake

- Joint source inversion result indicates that the rupture area is about $25 \times 25 km^2$ and the maximum slip is 120 cm.
- The rupture was complex. At least two asperities are found on the fault plane.
- At the first 8 seconds, Asperity I was developed in the down-dip area below the hypocenter and propagated toward northwest. The second asperity was found at the shallow part after 9 second.
- The source time function shows several peaks that has a total duration of about 16 seconds. The moment magnitude is Mw6.5.
- 3D wave propagation simulation result indicates that the strong ground shaking observed in Tainan could be caused by three factors: (a) rupture directivity, (b) source radiation and (c) site effect.

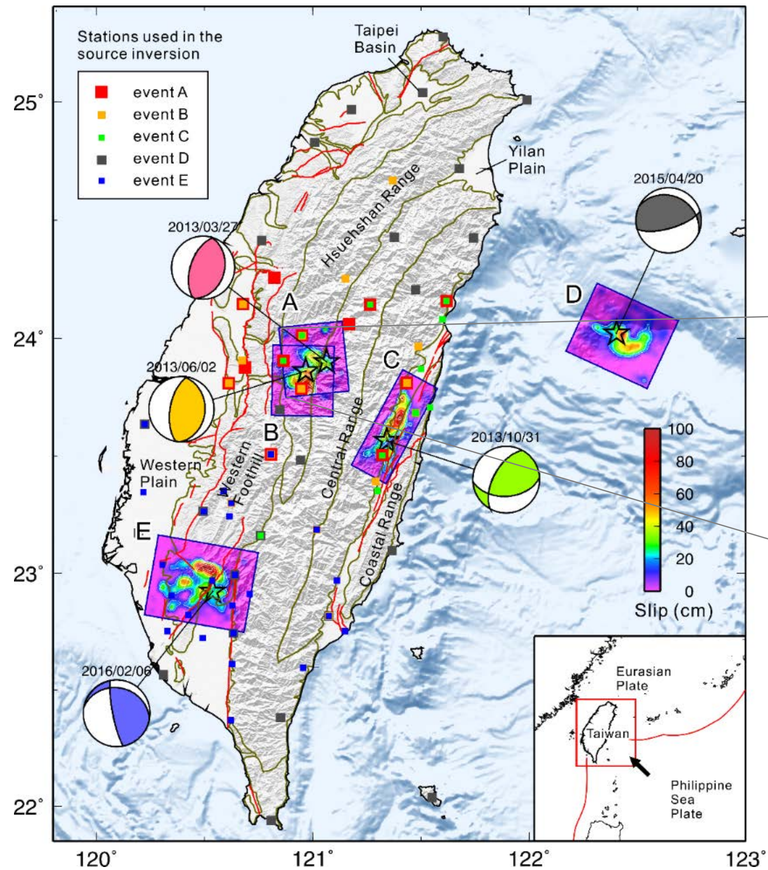
Reference

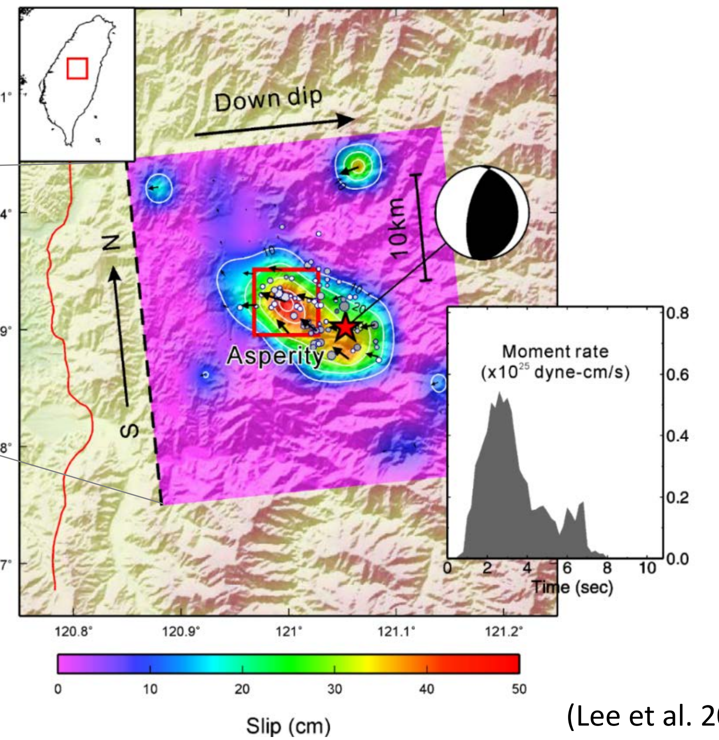
Lee, S. J.*, T. Y. Yeh, and Y. Y. Lin, 2016. Anomalously large ground motion in the 2016 ML 6.6 Meinong, Taiwan, earthquake: A synergy effect of source rupture and site amplification, Seismol. Res. Lett., doi: 10.1785/0220160082.

Lessons learned

Source Parameters of Five Recent Moderate Earthquakes Occurred in Taiwan (2013–2016)

Events	Earthquake Date (yyyy/mm/dd)	Magnitude (M_L)	Epicenter (Longitude, Latitude)	Depth (km)	Strike, Dip, Rake (°)	Maximum Slip (cm)	Number of Asperity	ΔDistance (km)*	Stress Drop (MPa)	Frequency Band (Hz)
A	2013/03/27 Nantou earthquake I	6.2	121.05 °E, 23.90 °N	19.4	355, 25, 75	48.7	1	6.69	2.16	0.05–0.2
B	2013/06/02 Nantou earthquake II	6.5	120.97 °E, 23.86 °N	14.5	2, 29, 83	106.7	1	9.54	2.95	0.05–0.2
C	2013/10/31 Ruisui earthquake	6.4	121.35 °E, 23.57 °N	15.0	209, 59, 51	102	2	12.0	3.90	0.05–0.2
D	2015/04/20 Eastern offshore earthquake	6.4	122.44 °E, 24.02 °N	30.6	295, 26, 128	82.3	2	3.15	2.48	0.02–0.1
E	2016/02/06 Meinong earthquake	6.6	120.54 °E, 22.92 °N	14.6	281, 24, 24	120.2	2	12.37	2.49	0.05–0.33





(Lee et al. 2015a)

Lessons learned

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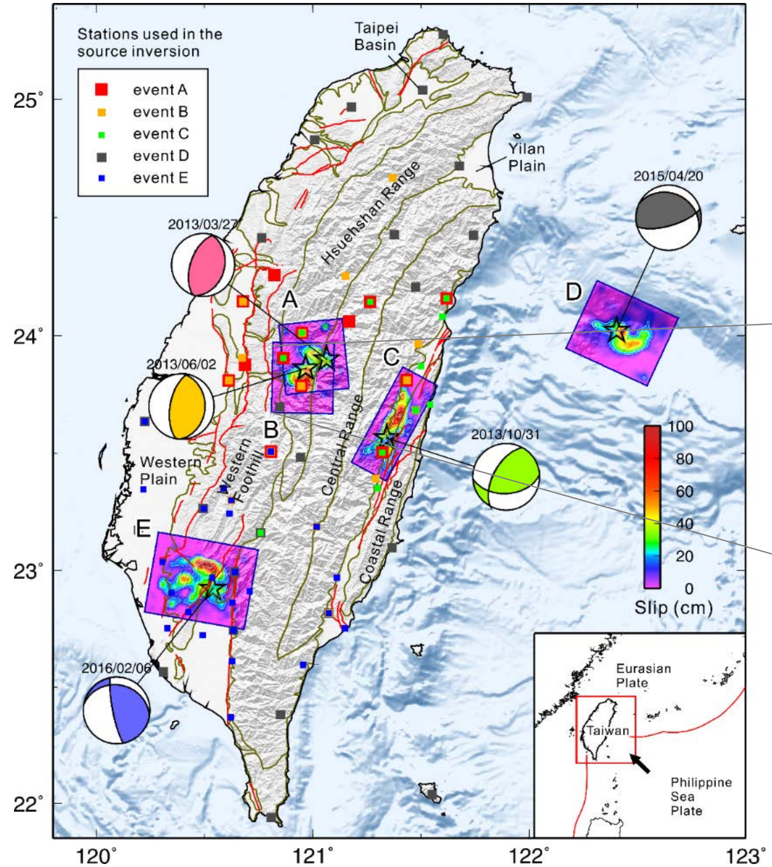
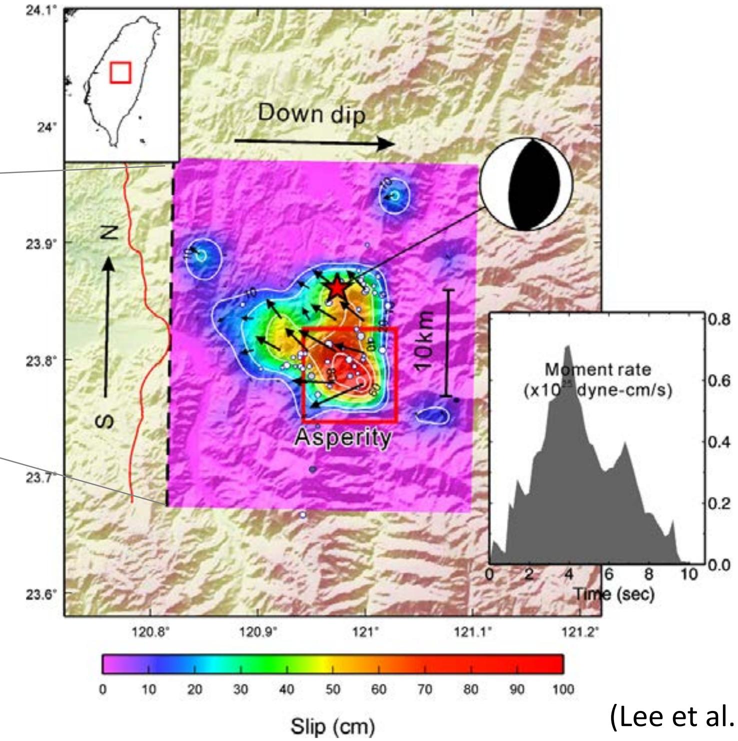
D	2015/04/20 Eastern offshore earthquake	6.4	122.44 °E, 24.02 °N	30.6	295, 26, 128	82.3	2	3.15	2.48	0.02–0.1
E	2016/02/06 Meinong earthquake	6.6	120.54 °E, 22.92 °N	14.6	281, 24, 24	120.2	2	12.37	2.49	0.05–0.33





(Lee et al. 2015a)

Lessons learned

Source Parameters of Five Recent Moderate Earthquakes Occurred in Taiwan (2013–2016)

Events	Earthquake Date (yyyy/mm/dd)	Magnitude (M_L)	Epicenter (Longitude, Latitude)	Depth (km)	Strike, Dip, Rake (°)	Maximum Slip (cm)	Number of Asperity	ΔDistance (km)*	Stress Drop (MPa)	Frequency Band (Hz)
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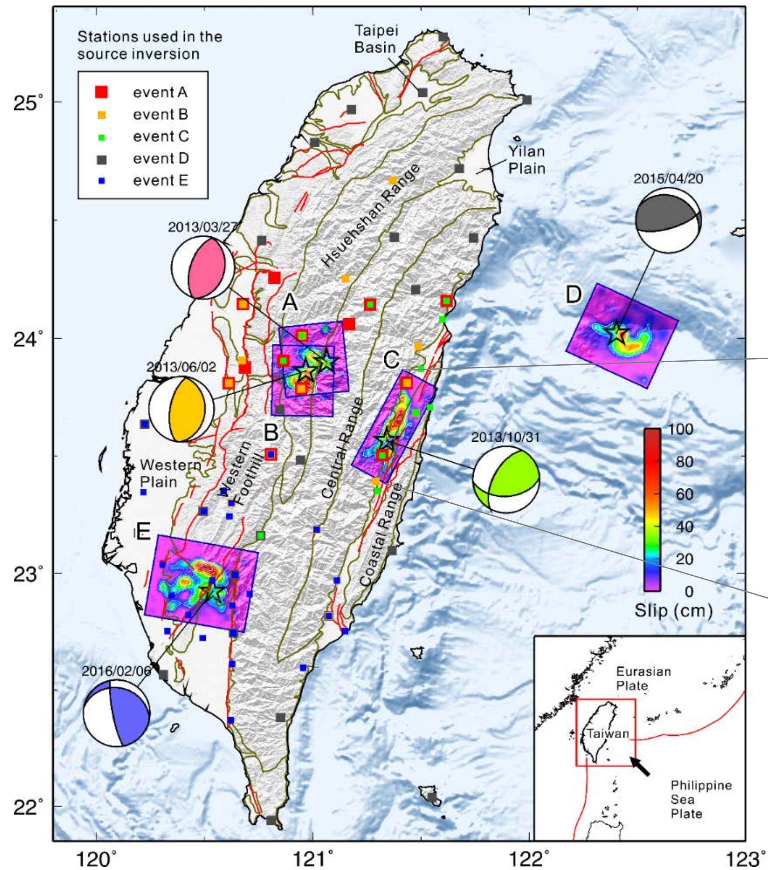

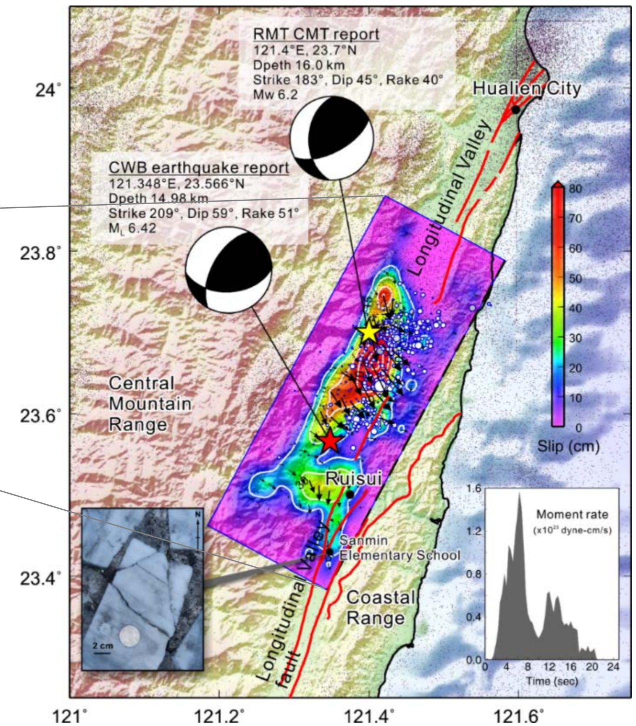

(Lee et al. 2014)

Lessons learned

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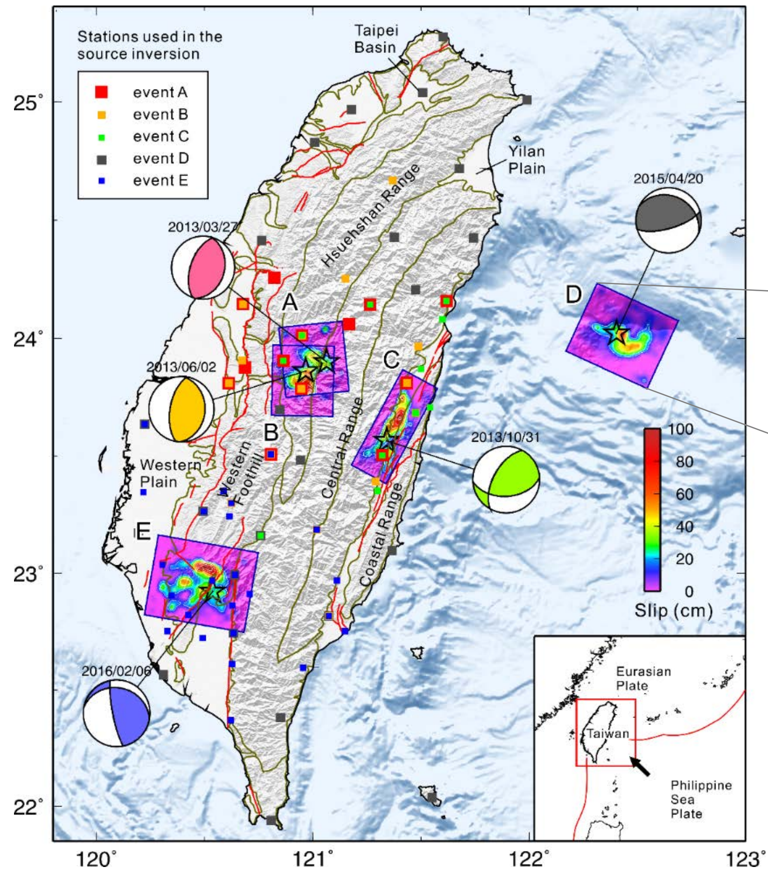

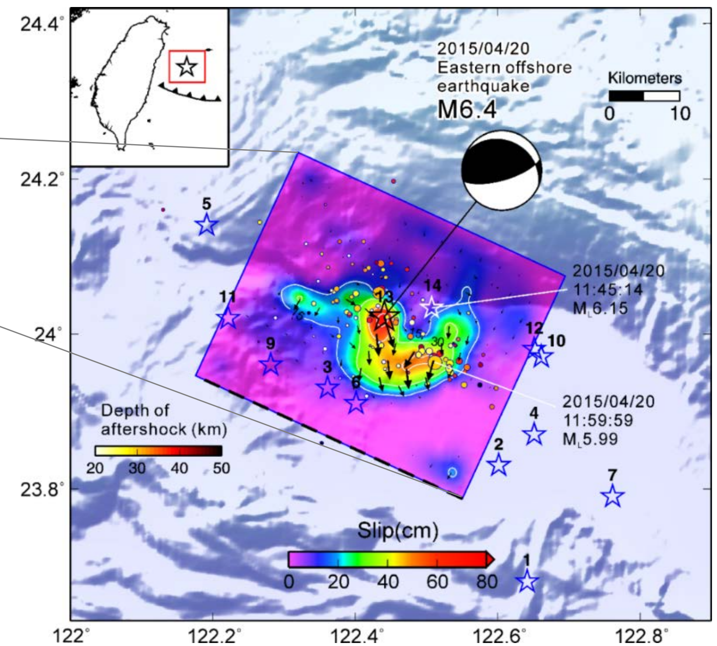

(Lee et al. 2015b)

Lessons learned

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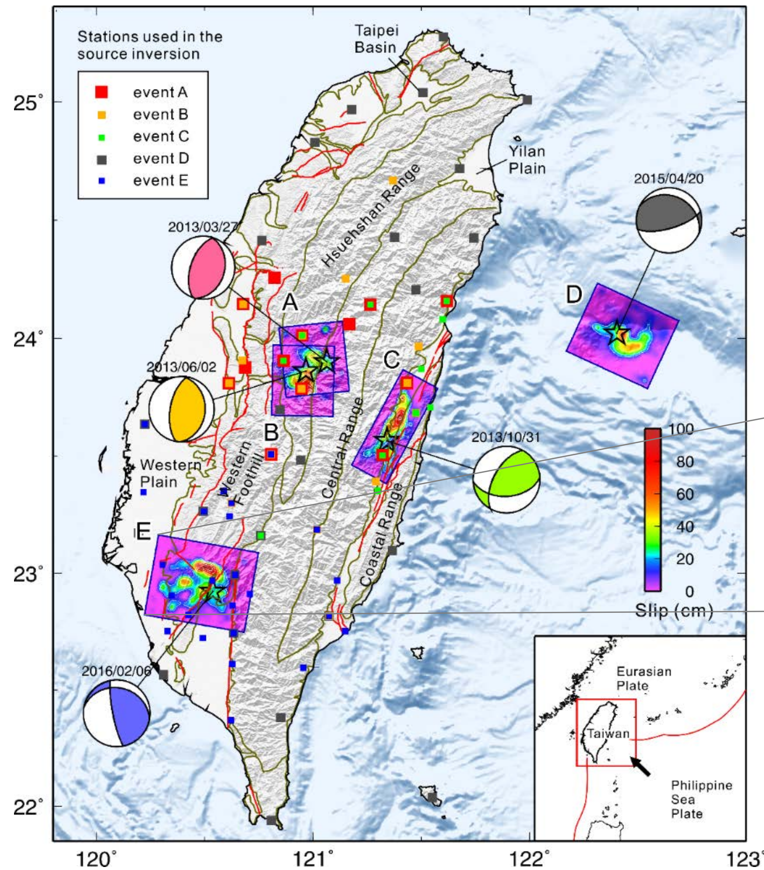
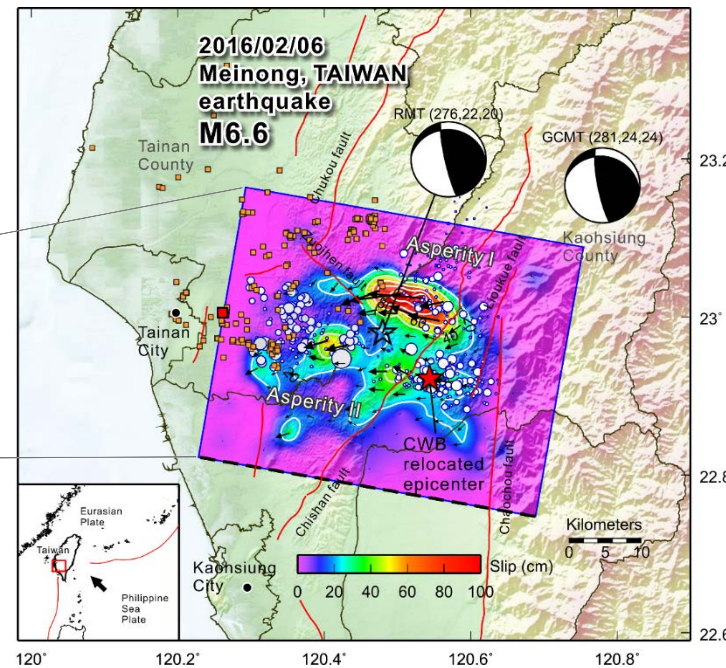
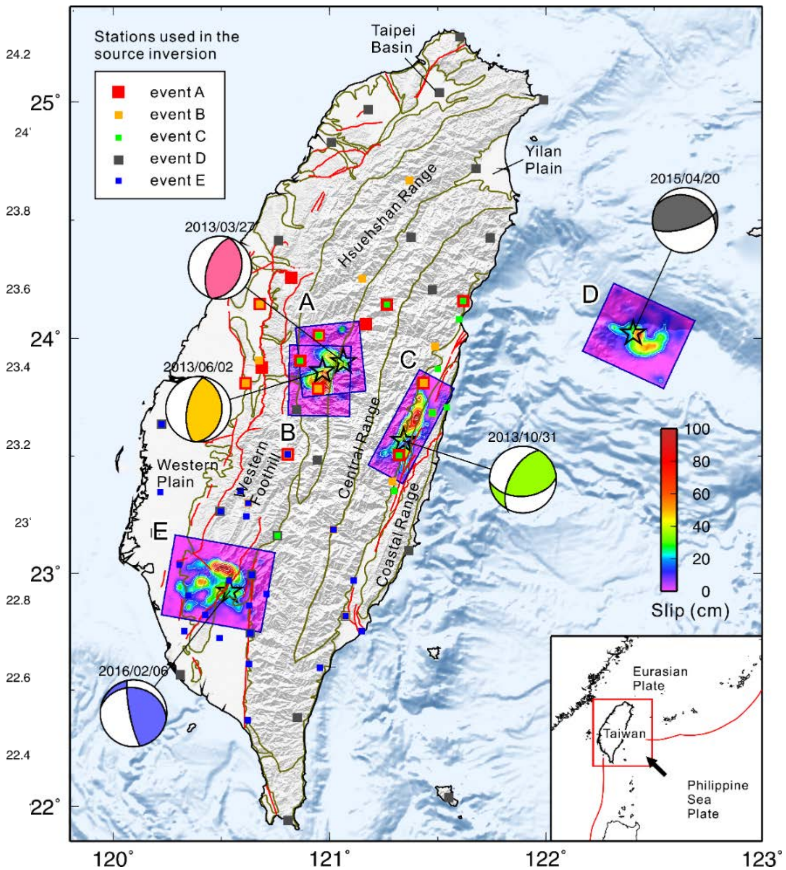




(Lee et al. 2016)

Lessons learned



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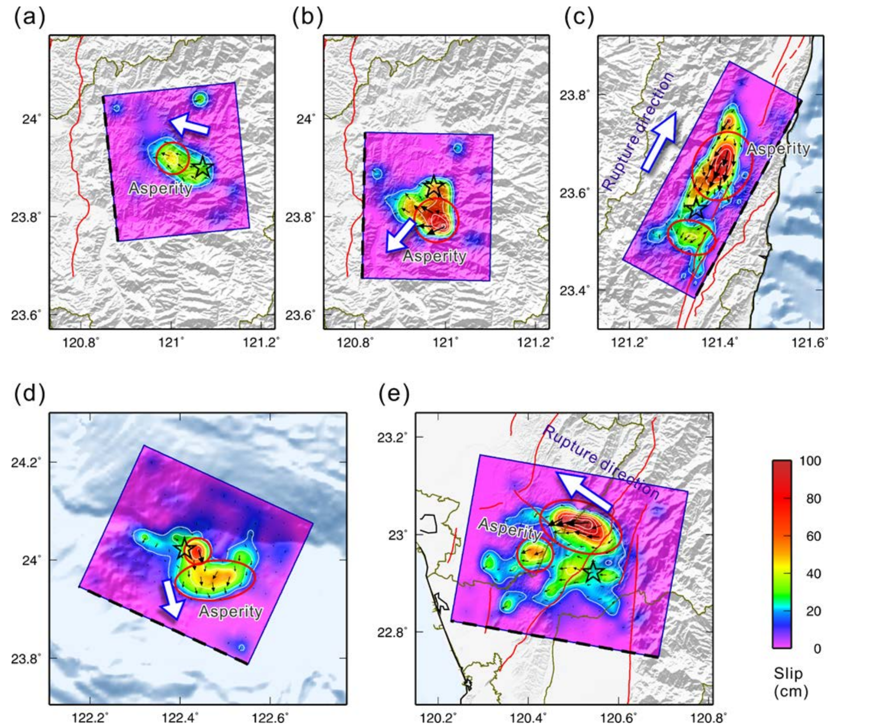
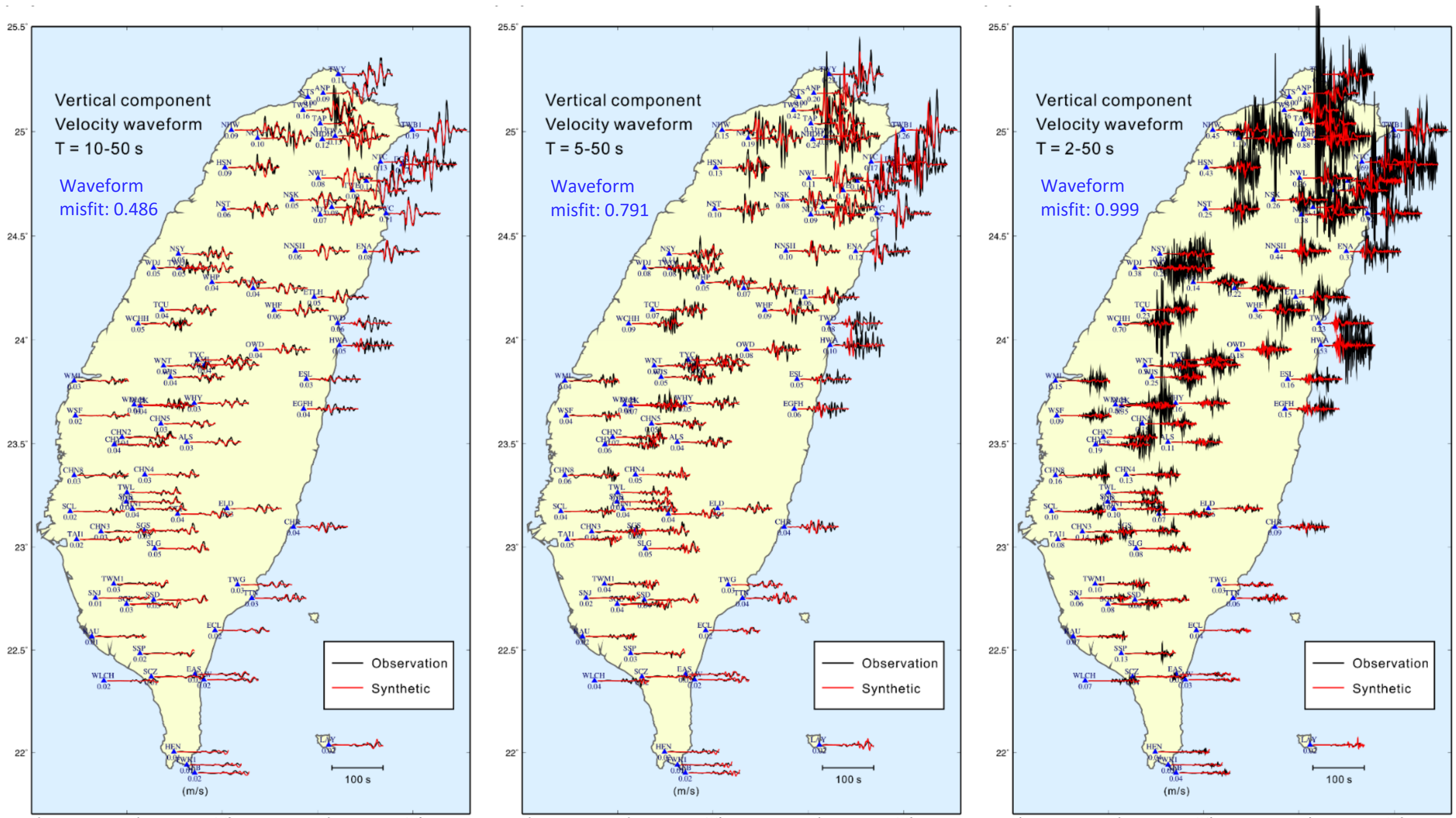


(Lee, 2017)

Lessons learned

2015/04/20 M6.4

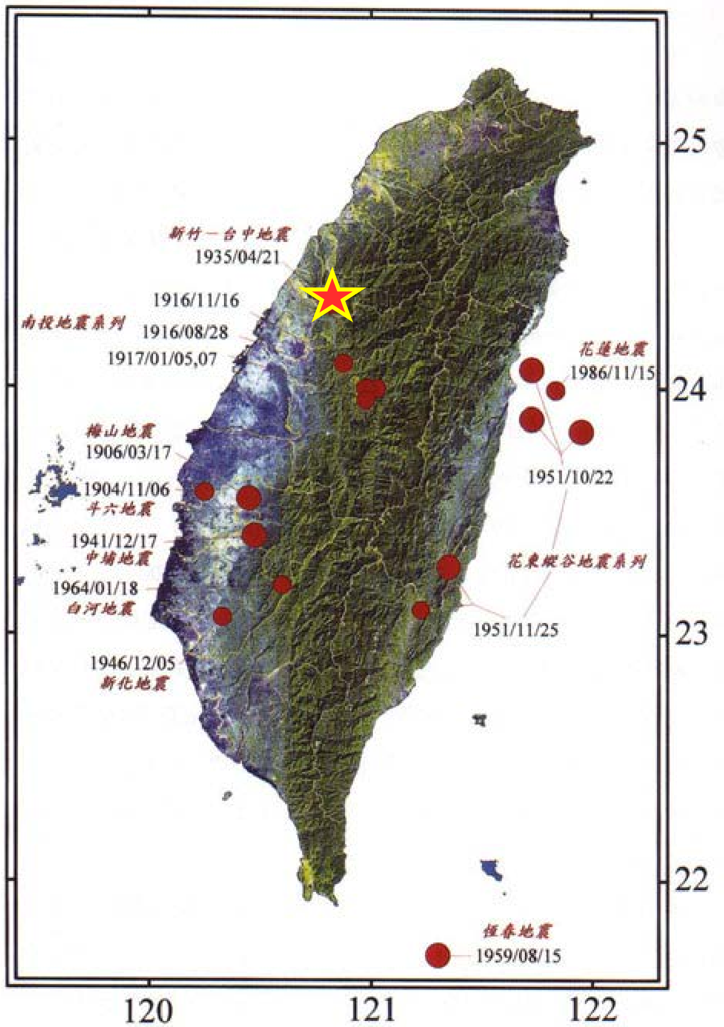
(Lee, 2017)



Historical earthquake

1935 Hsinchu-Taichung earthquake M7.1

1935 Hsinchu-Taichung earthquake



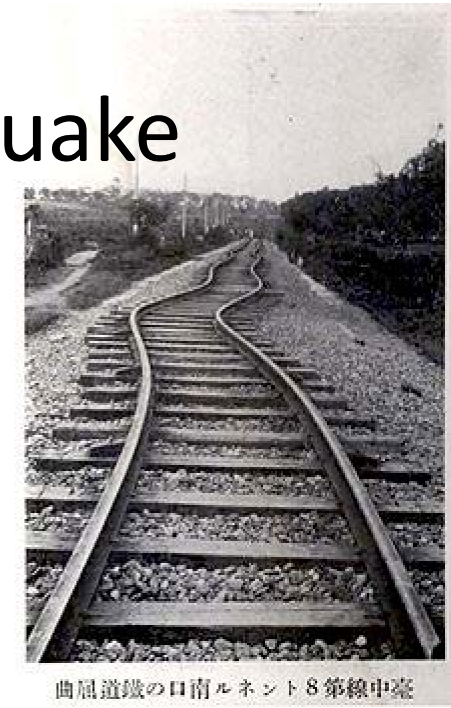
編號	地震名稱	發震時間 (120°E)	震央位置		震源深度 (公里)	地震規模 (M_L)
			北緯(N)	東經(E)		
1	斗六地震	1904/11/06 04:25	23.575	120.250	7.0	6.1
2	梅山地震	1906/03/17 06:43	23.550	120.450	6.0	7.1
3	南投地震系列	1916/08/28 15:27	24.000	121.025	45.0	6.8
		1916/11/15 06:31	24.100	120.875	3.0	6.2
		1917/01/05 00:55	24.000	120.975	很淺	6.2
		1917/01/07 02:08	23.950	120.975	很淺	5.5
4	新竹一台中地震	1935/04/21 06:02	24.350	120.817	5.0	7.1
5	中埔地震	1941/12/17 03:19	23.400	120.475	12.0	7.1
6	新化地震	1946/12/05 06:47	23.070	120.330	5.0	6.1
7	花東縱谷地震系列	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
8	恆春地震	1959/08/15 16:57	21.700	121.300	20.0	7.1
9	白河地震	1964/01/18 20:04	23.200	120.600	18.0	6.3
10	花蓮地震	1986/11/15 05:20	23.992	121.833	15.0	6.8

本圖表採自台灣十大災害地震圖集（鄭世楠等人著，1999）

1935 Hsinchu-Taichung earthquake

州	郡/市	死亡人數	受傷人數
新竹州	新竹市	4	19
	新竹郡	-	5
	中壢郡	-	3
	竹東郡	14	150
	竹南郡	328	1208
	苗栗郡	794	2555
	大湖郡	229	656
	合計	1369	4596
台中州	台中市	20	40
	大屯郡	-	2
	東勢郡	28	250
	豐原郡	1494	5913
	大甲郡	386	1206
	彰化郡	-	5
	合計	1910	7380
總計		3279	11976

地震後的街景



台中線第8隧道口外的鐵道扭曲

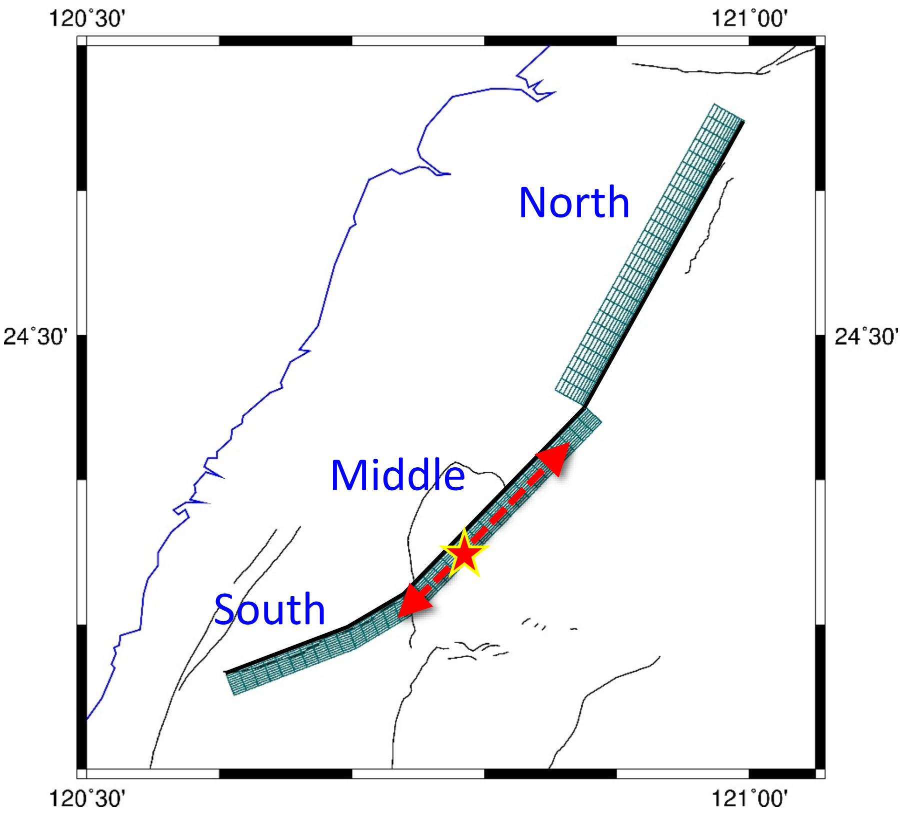
龍騰斷橋（魚藤坪斷橋）現今的模樣就是因為這場地震造成的

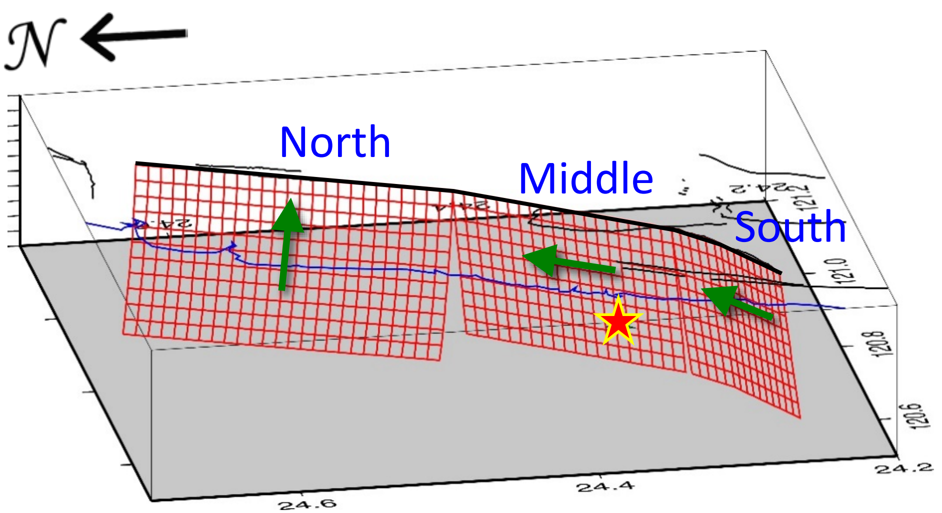
山線鐵路第8號隧道嚴重受損，
屯仔腳地震斷層穿越此隧道

Source rupture model

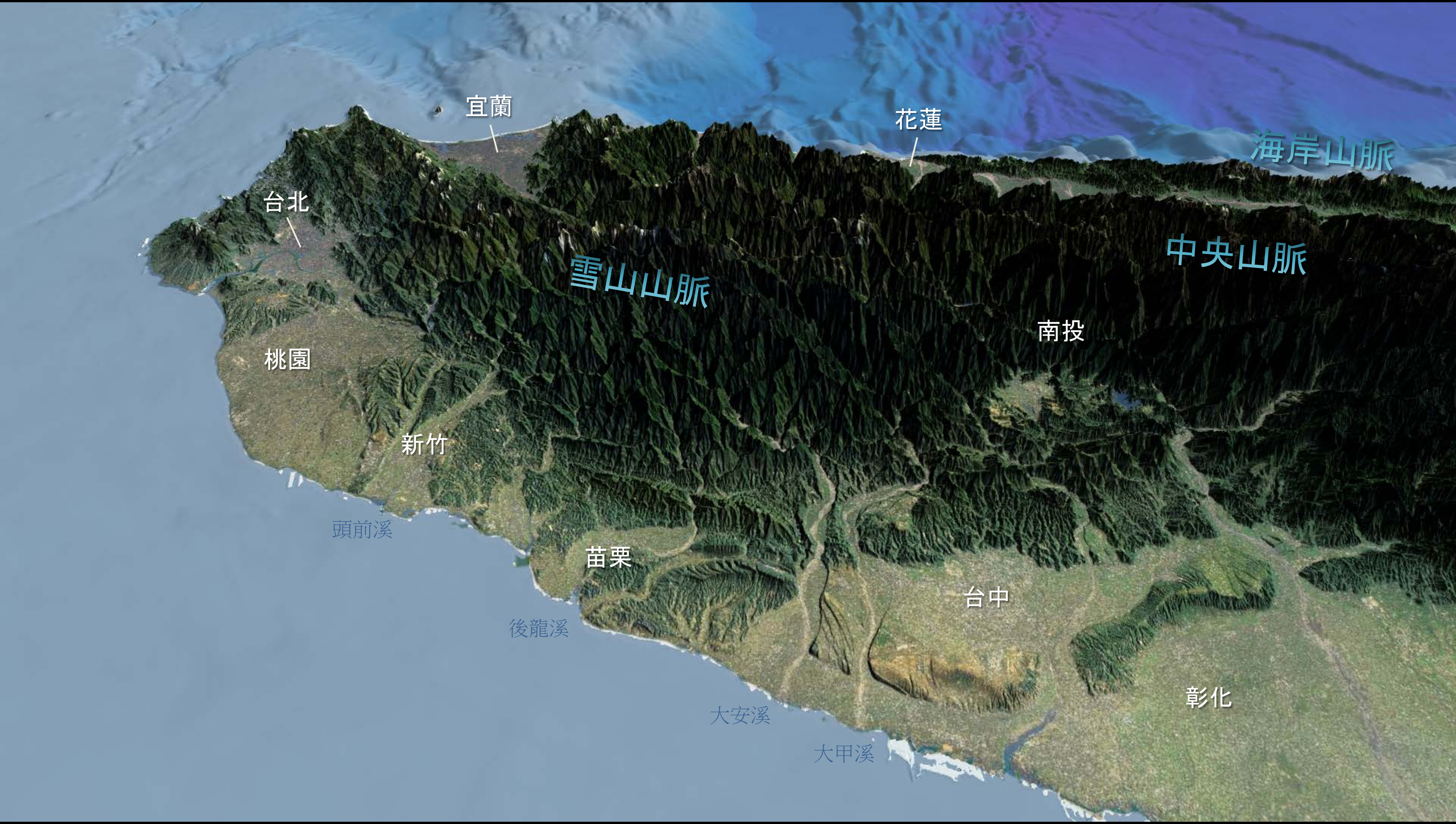
	Shihtan fault (Northern segment)	Blind fault (Middle segment)	Tuntzuchiao fault (Southern Segment)
Strike	N30°E	N45°E	N70°E-N60°E
Dip	85°W-70°W	80°E	80°E
rake	90°	180°	180°

Source parameters	
Lon.	120.79°
Lat.	24.35°
Depth	7.4 km
Avg. Slip	134 cm

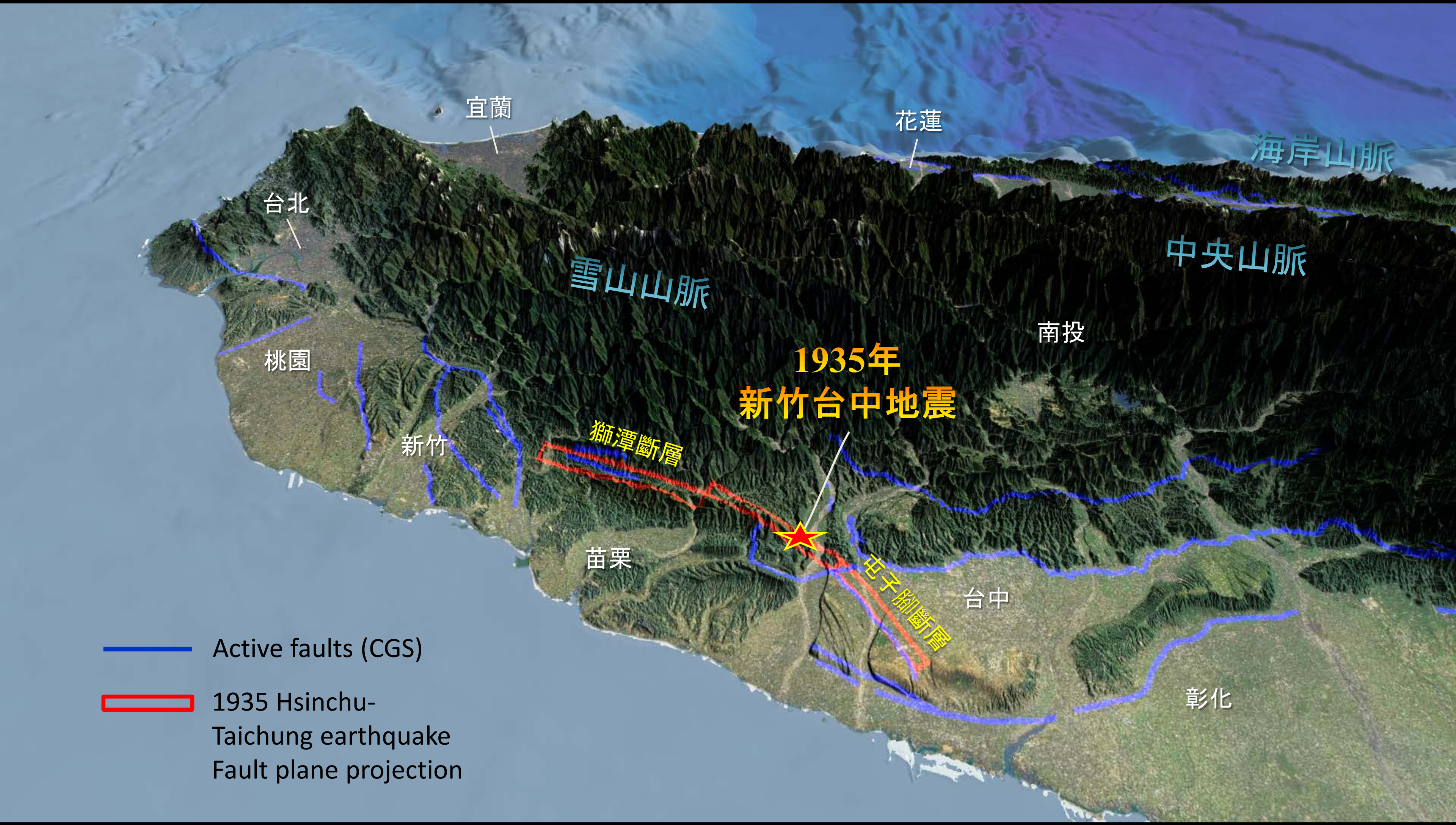


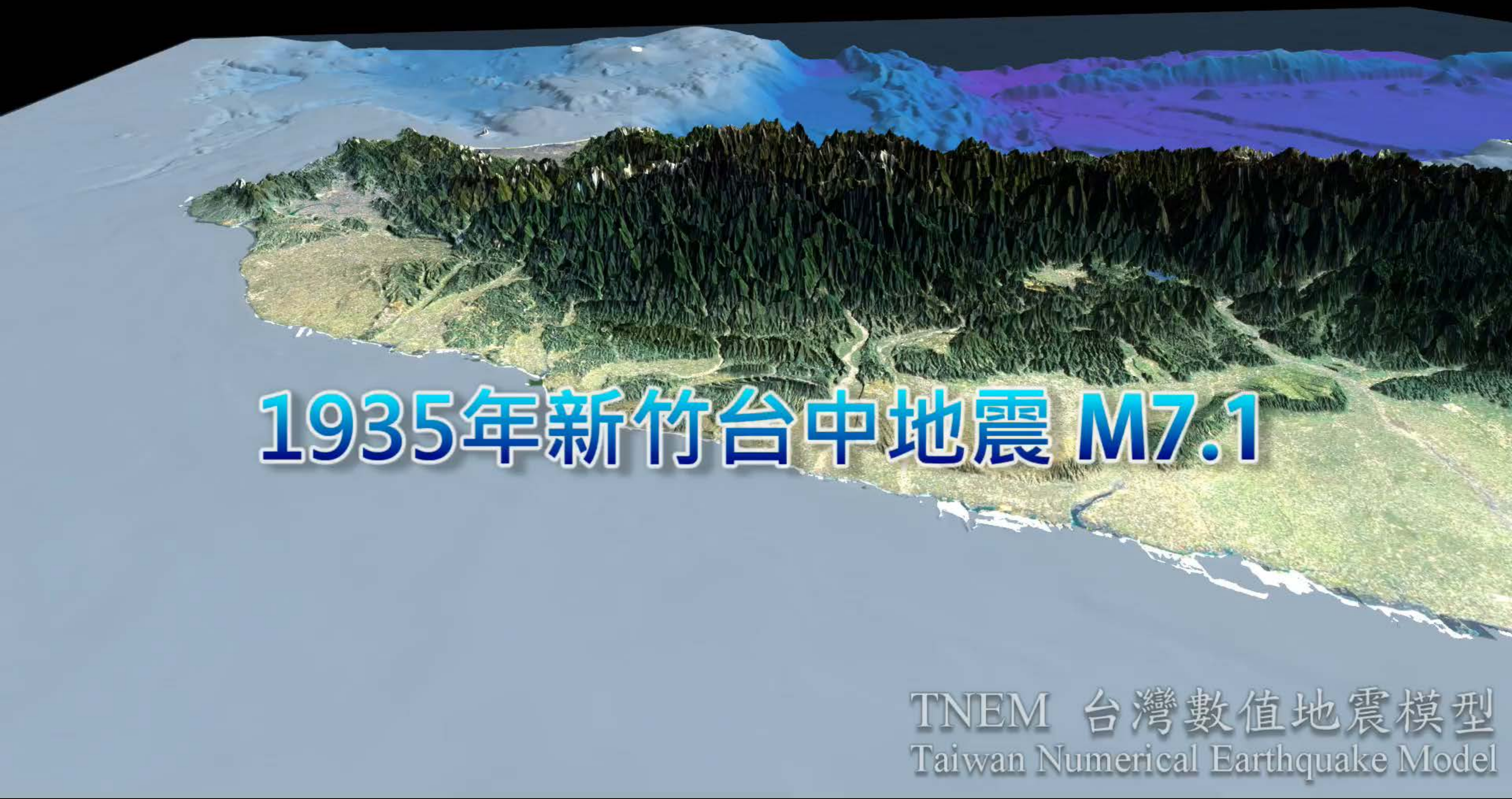


Source rupture model



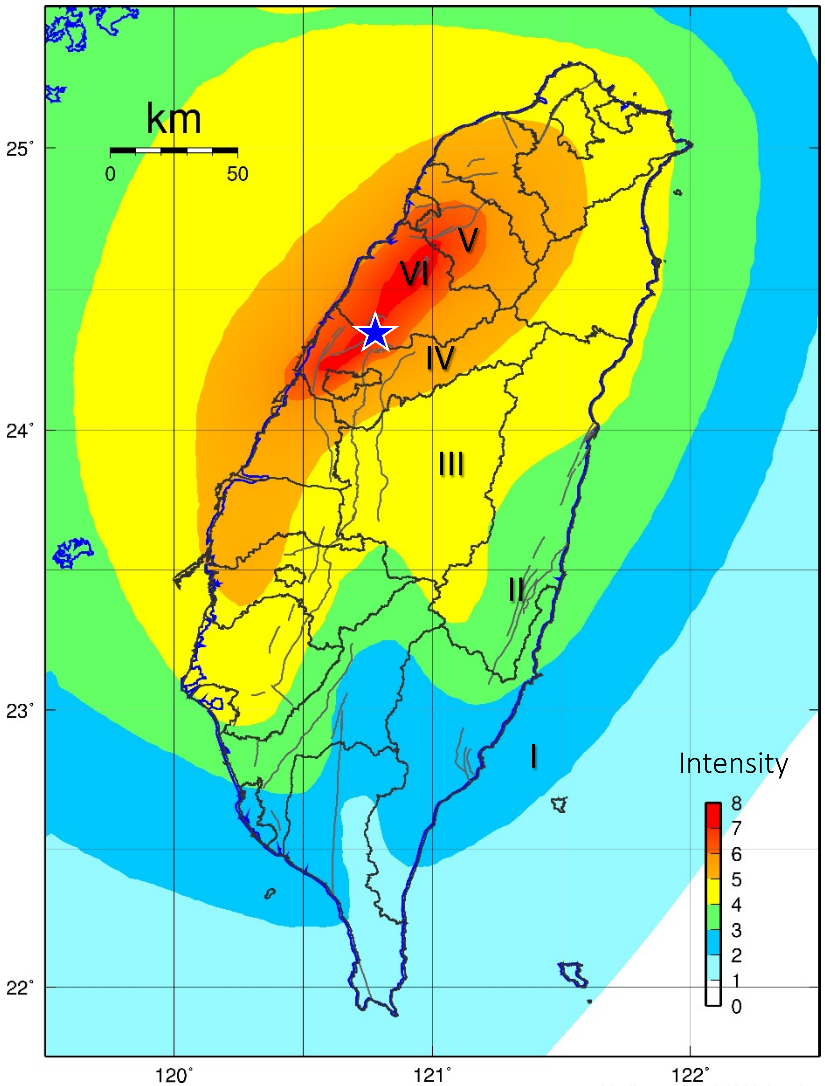
Source rupture model




1935年新竹台中地震 M7.1
TNEM 台灣數值地震模型
Taiwan Numerical Earthquake Model

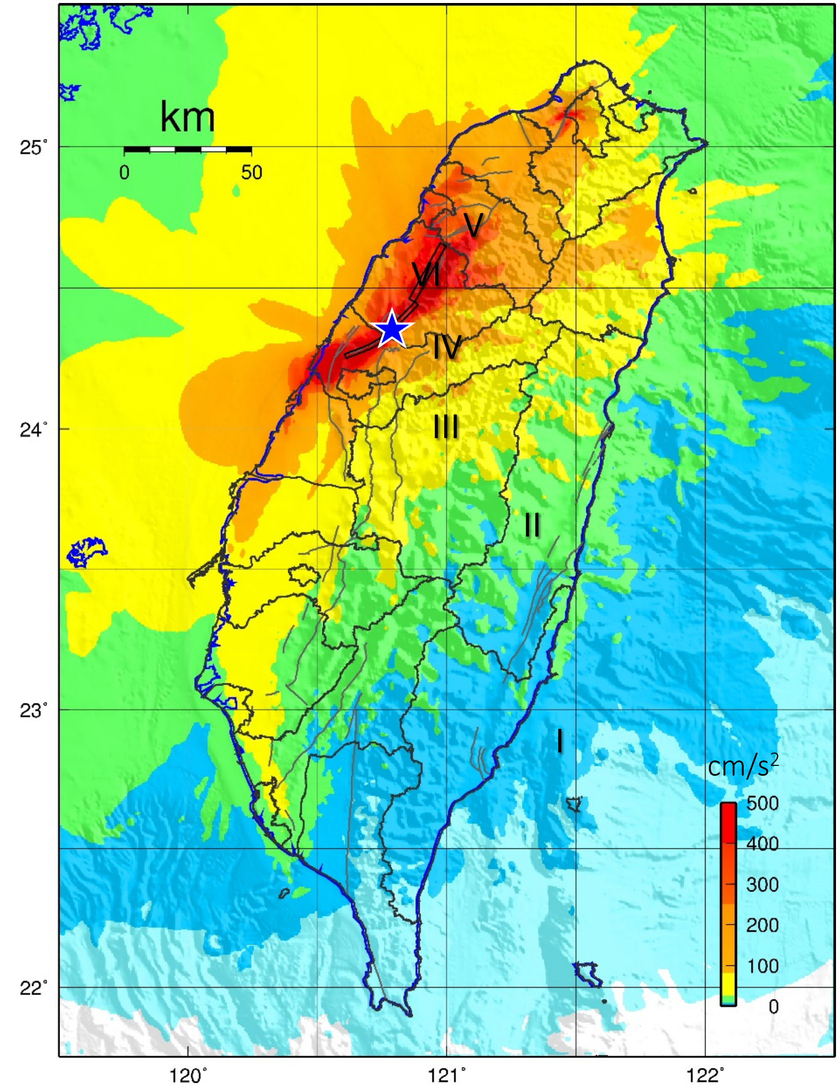
Intensity Map vs. ShakeMap

Historical Intensity Map



1935年4月21日新竹—台中地震等震度分佈圖(根據台北觀測所(1936)資料重繪)。 (鄭世楠教授提供)

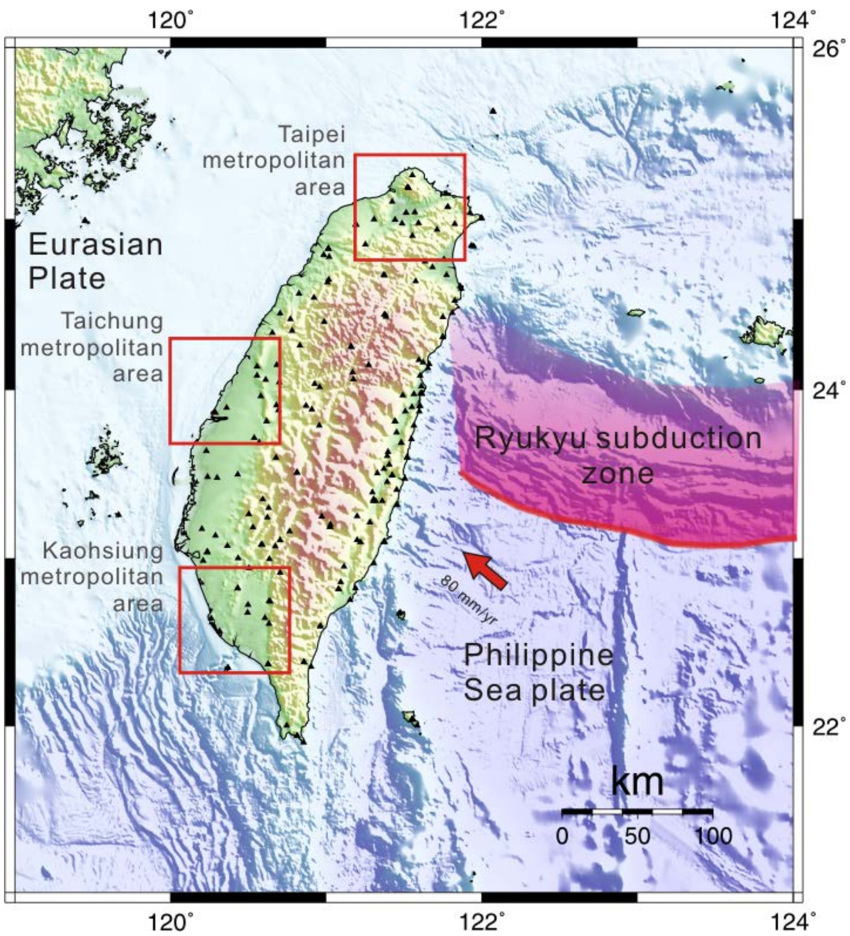
PGA distribution (ShakeMap)



Scenario earthquake

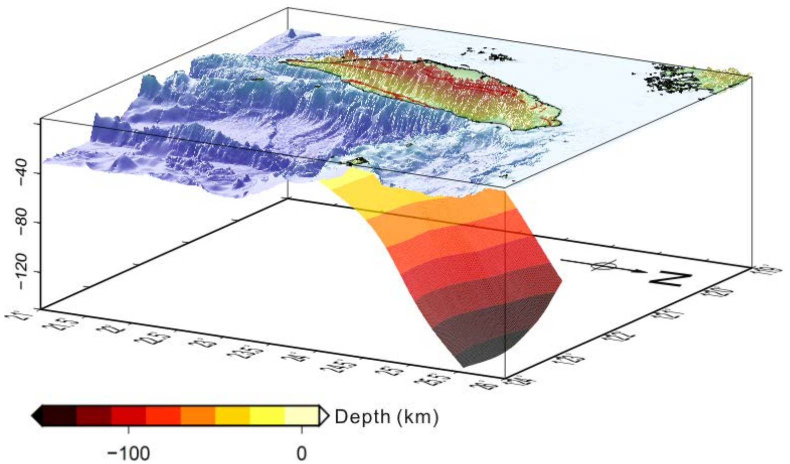
Ryukyu subduction zone earthquake M8.0+

Southernmost Ryukyu Subduction Zone

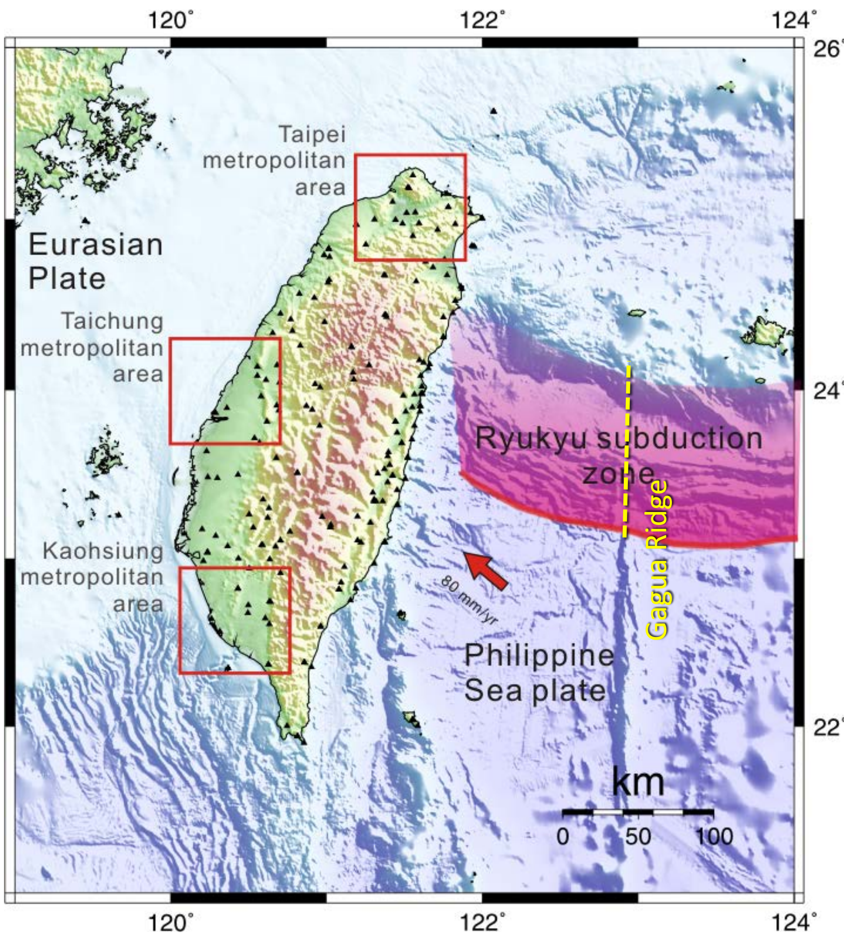


The potential for a very large earthquake near Taiwan.

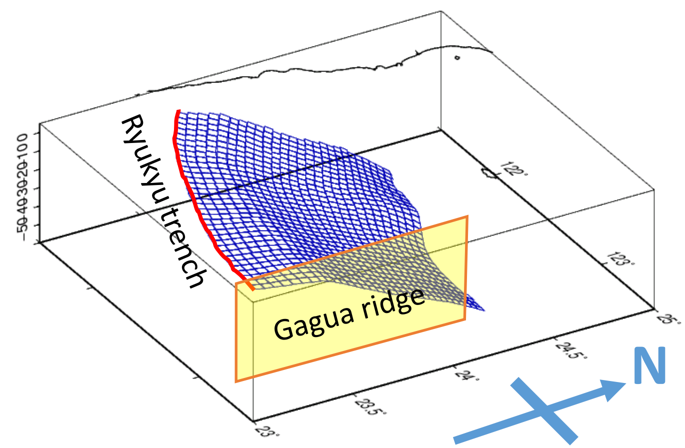
- ✓ Ryukyu subduction zone
- ✓ Manila subduction zone



Southernmost Ryukyu Subduction Zone

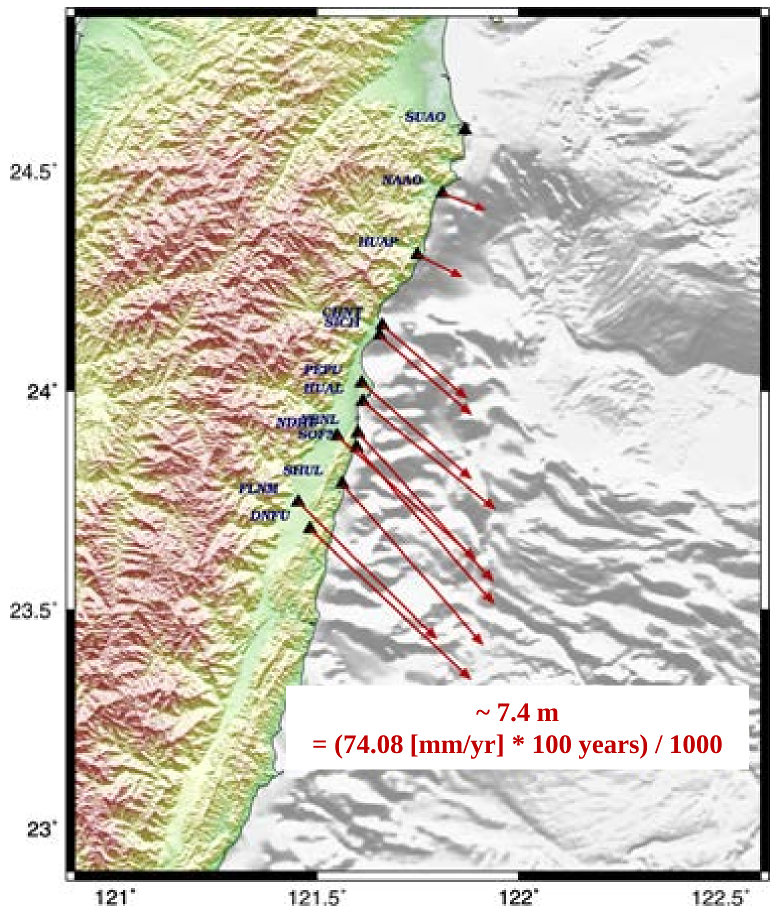


Fault plane setting
- Subfault size: 2.5x2.5 km^2
- Total subfault: 3612
- Average strike 285.1°
- Average dip: 35.6°



Slip distribution: CGPS inversion

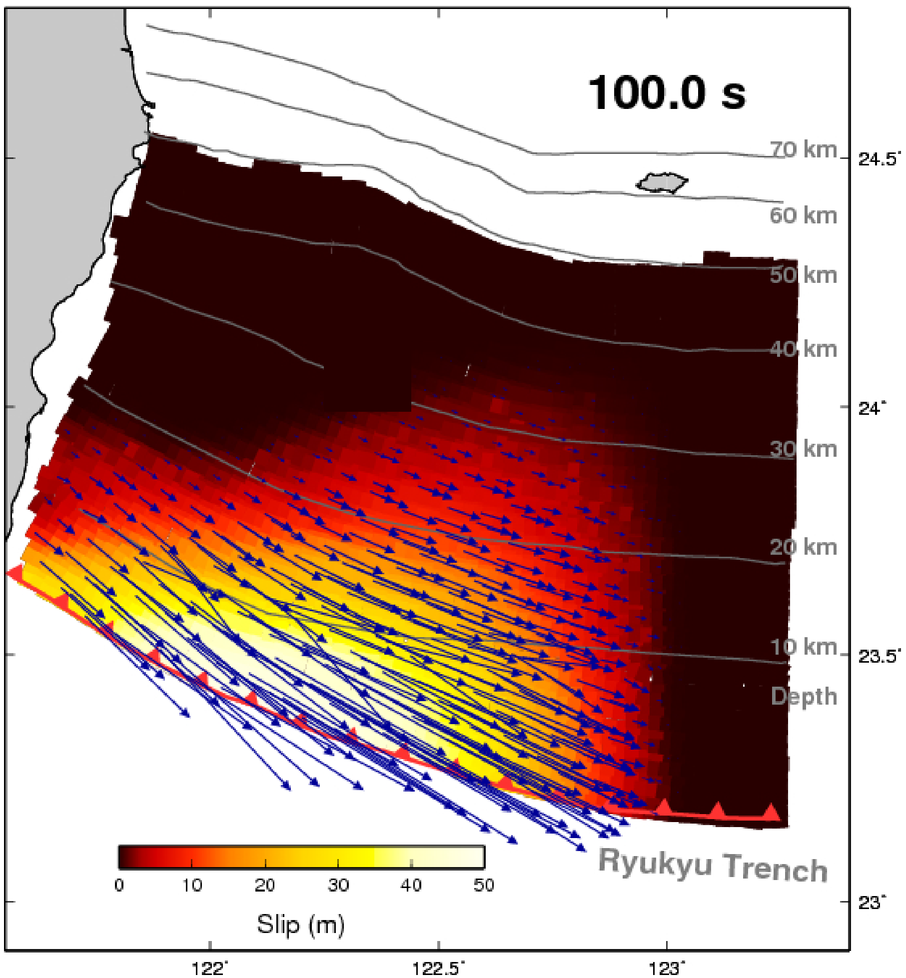
CGPS data



Hsu et al., 2012

- We use the CGPS data spanning the time period from 2005 to 2010 to infer the slip-deficit rate on the southernmost Ryukyu subduction zone.

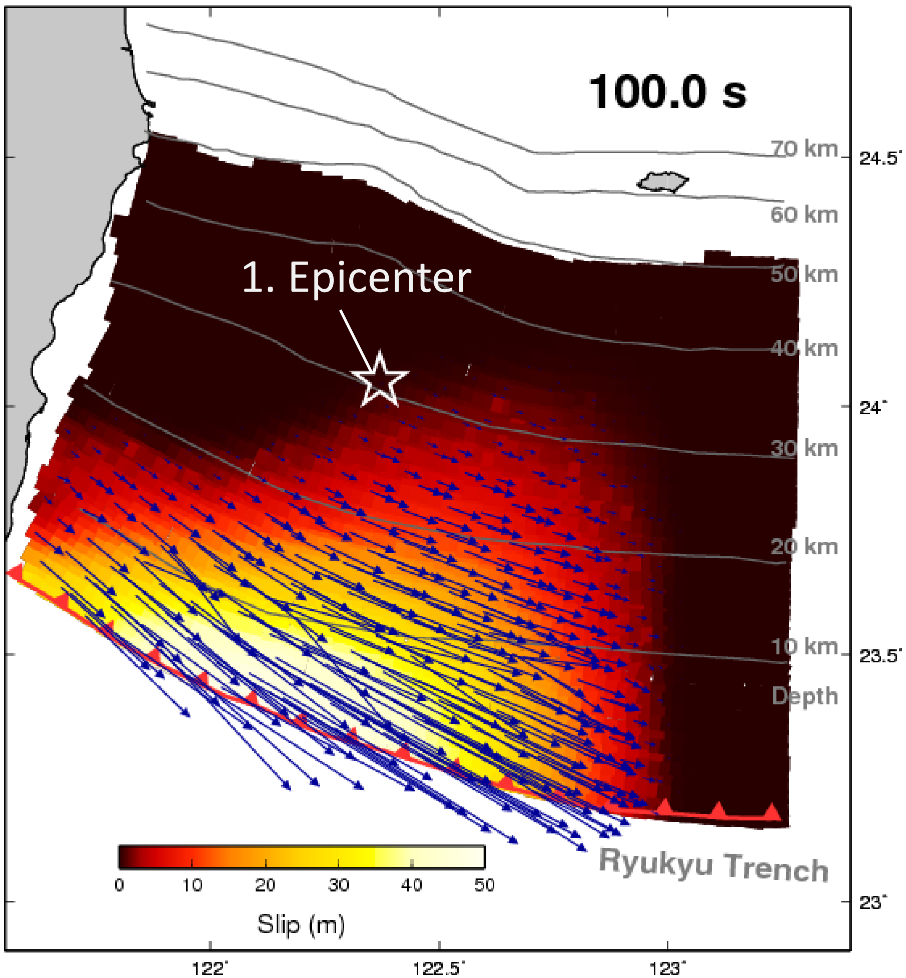
Slip distribution: CGPS inversion



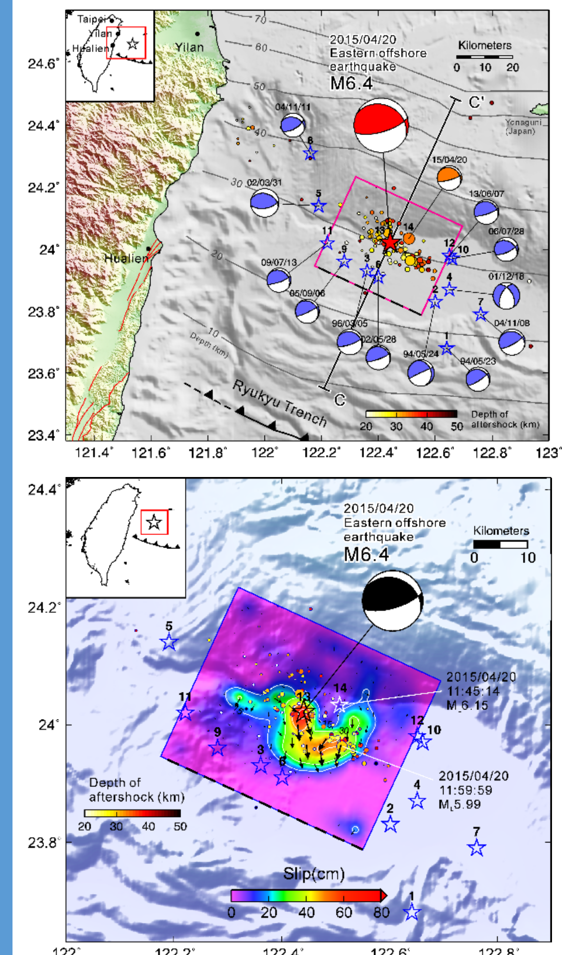
- We use the CGPS data spanning the time period from 2005 to 2010 to infer the slip-deficit rate on the southernmost Ryukyu subduction zone.
- Inversion result shows a large amount of slip occurs in the shallow subduction zone along the trench.
- The slip is predominated by right-lateral thrust movement with a maximum slip > 30 m.
- The total moment is about 4.4×10^{21} Nm, equivalent to M8.4 earthquake.

Rupture process

Accumulated slip



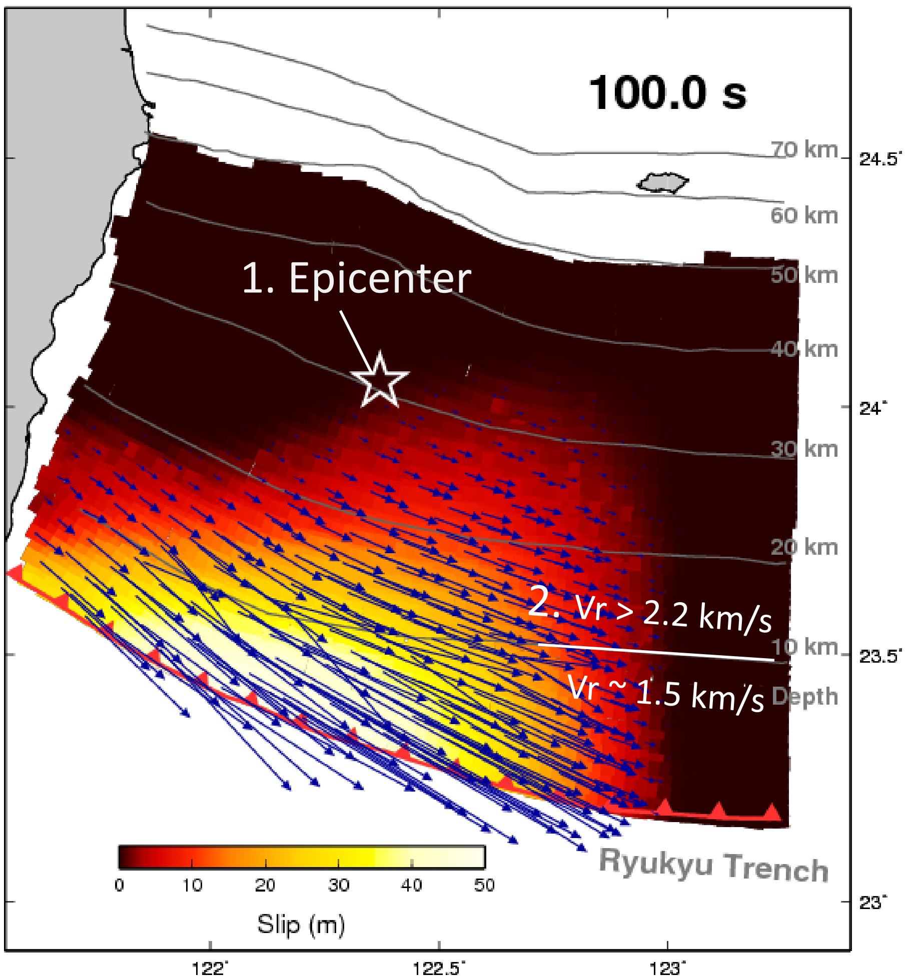
Hypothesis I



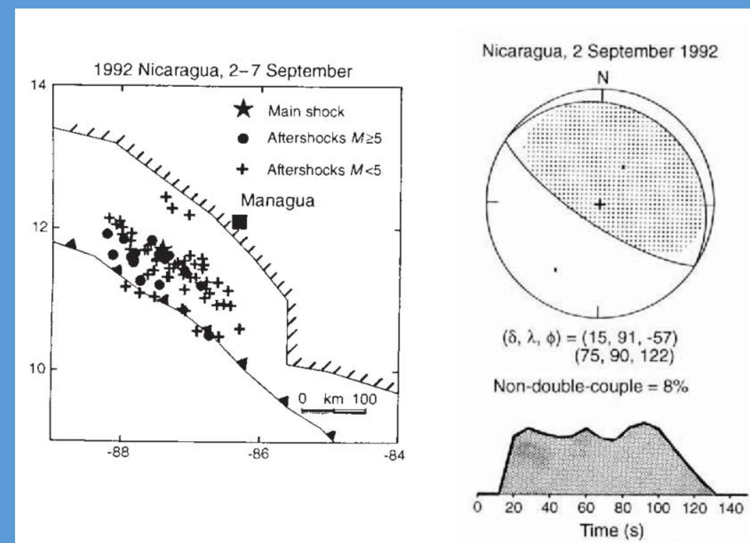
Lee, 2015

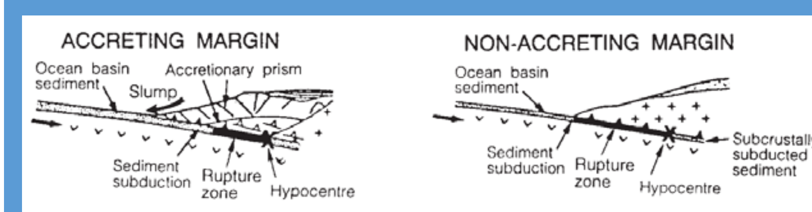
Rupture process

Accumulated slip



Hypothesis II

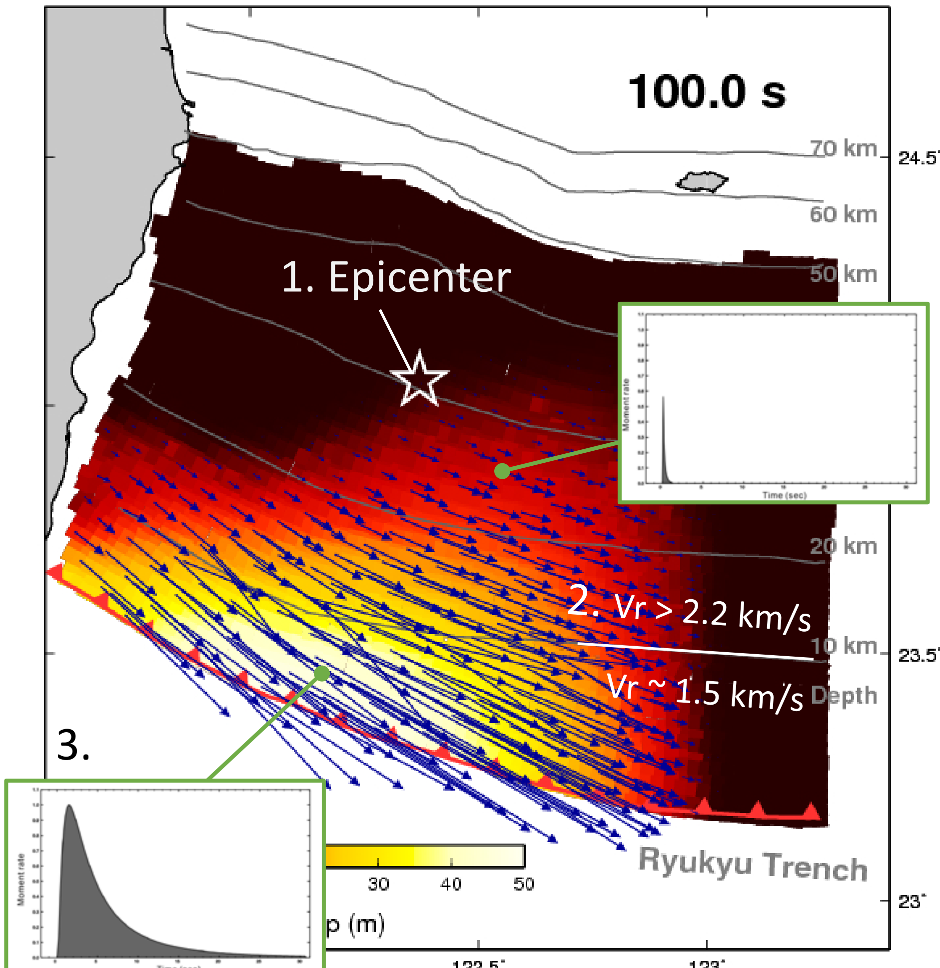




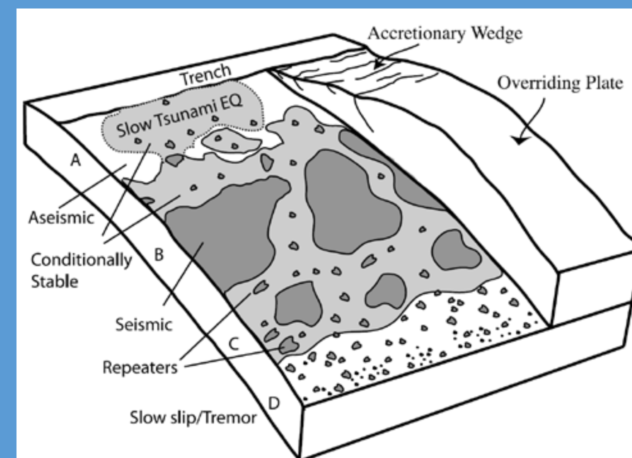
Kanamori and Kikuchi, 1993

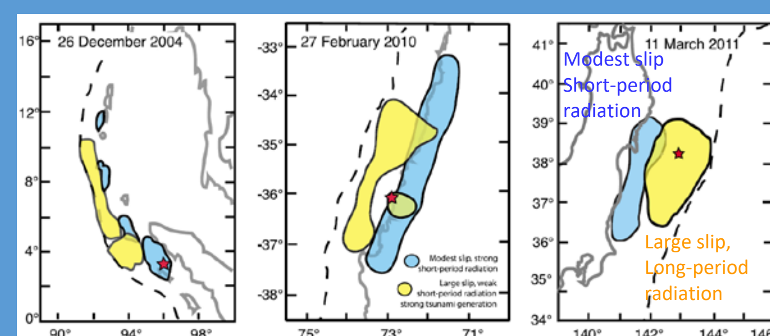
Rupture process

Accumulated slip



Hypothesis III

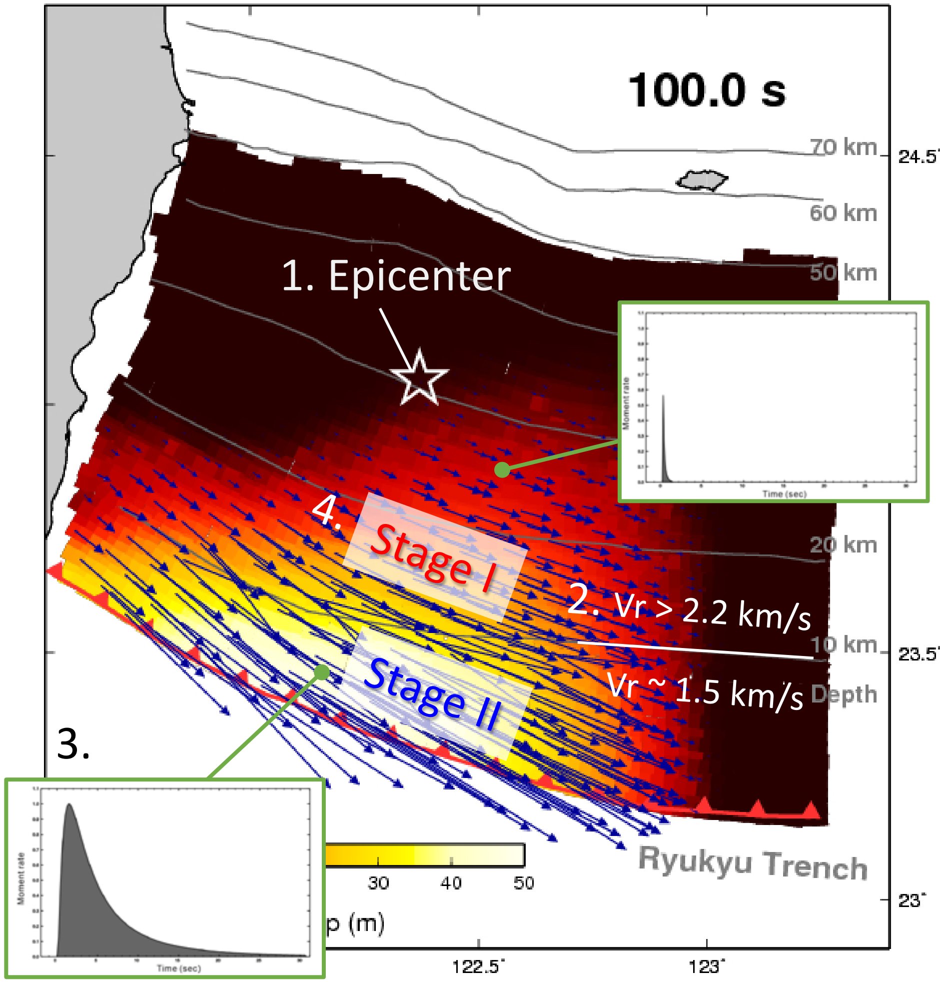




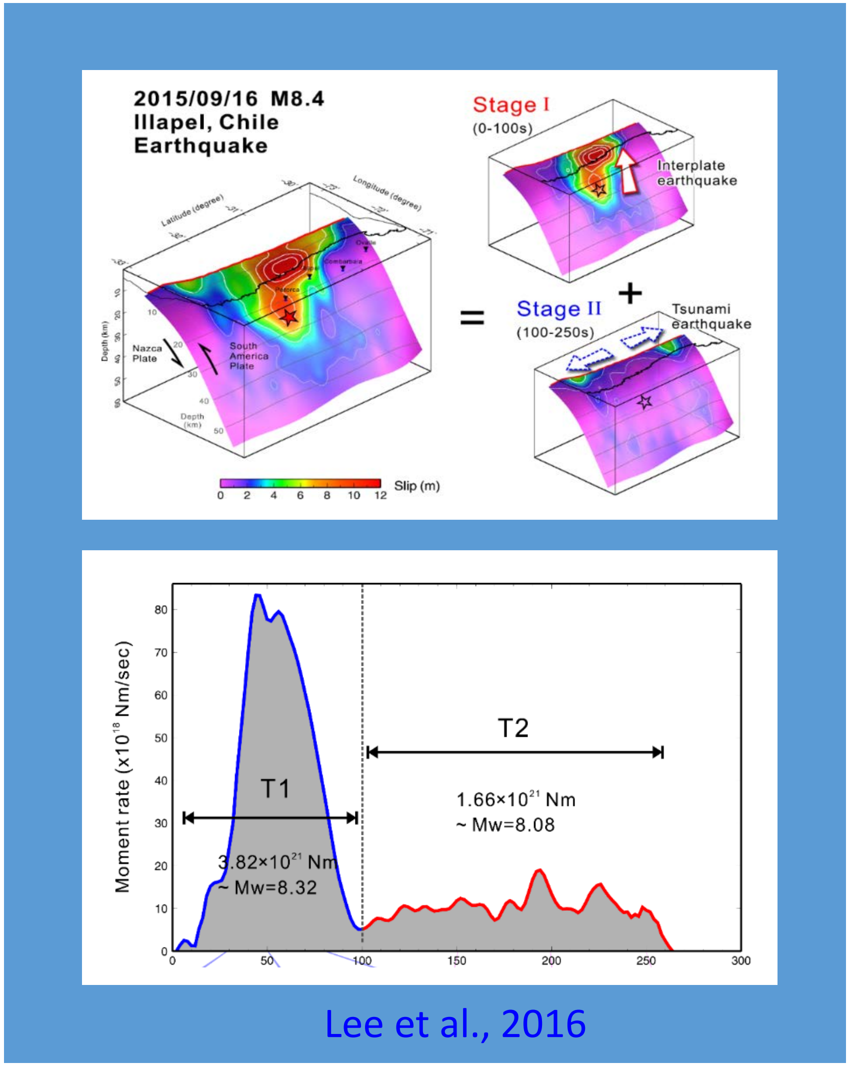
Lay et al., 2012

Rupture process

Accumulated slip



Hypothesis Ⅳ



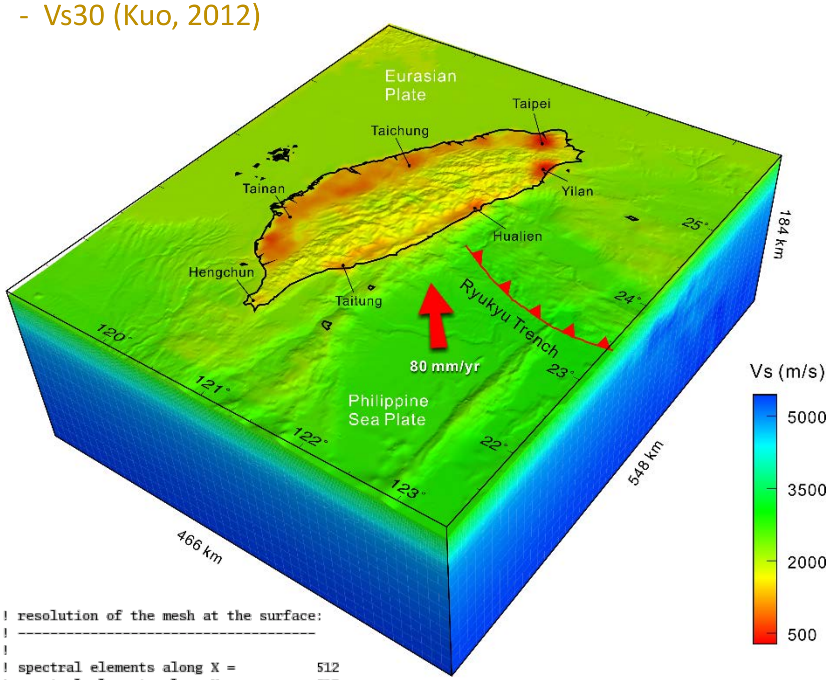
Lee et al., 2016

3D Ground Motion and Tsunami Simulation

Ground Motion Simulation: Spectral-element method

SEM mesh model

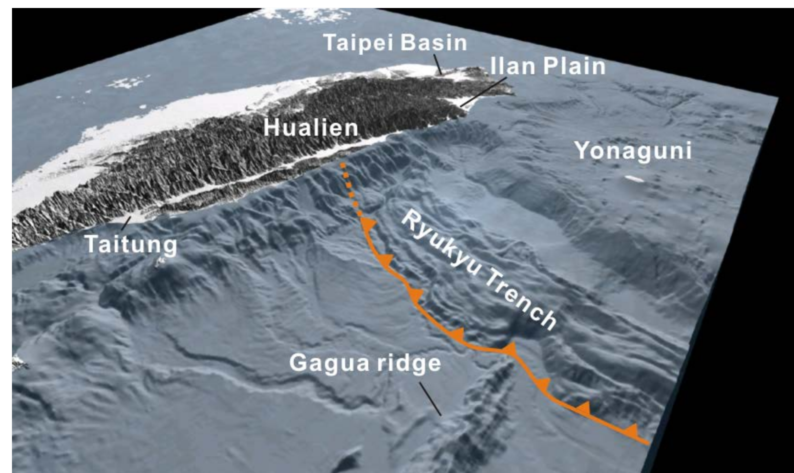
- Large scale velocity model (Huang et al., 2013)
- Local structure model
- Surface topography (40m DEM)
- Basin model (Wang, et al., 2004)
- Vs30 (Kuo, 2012)



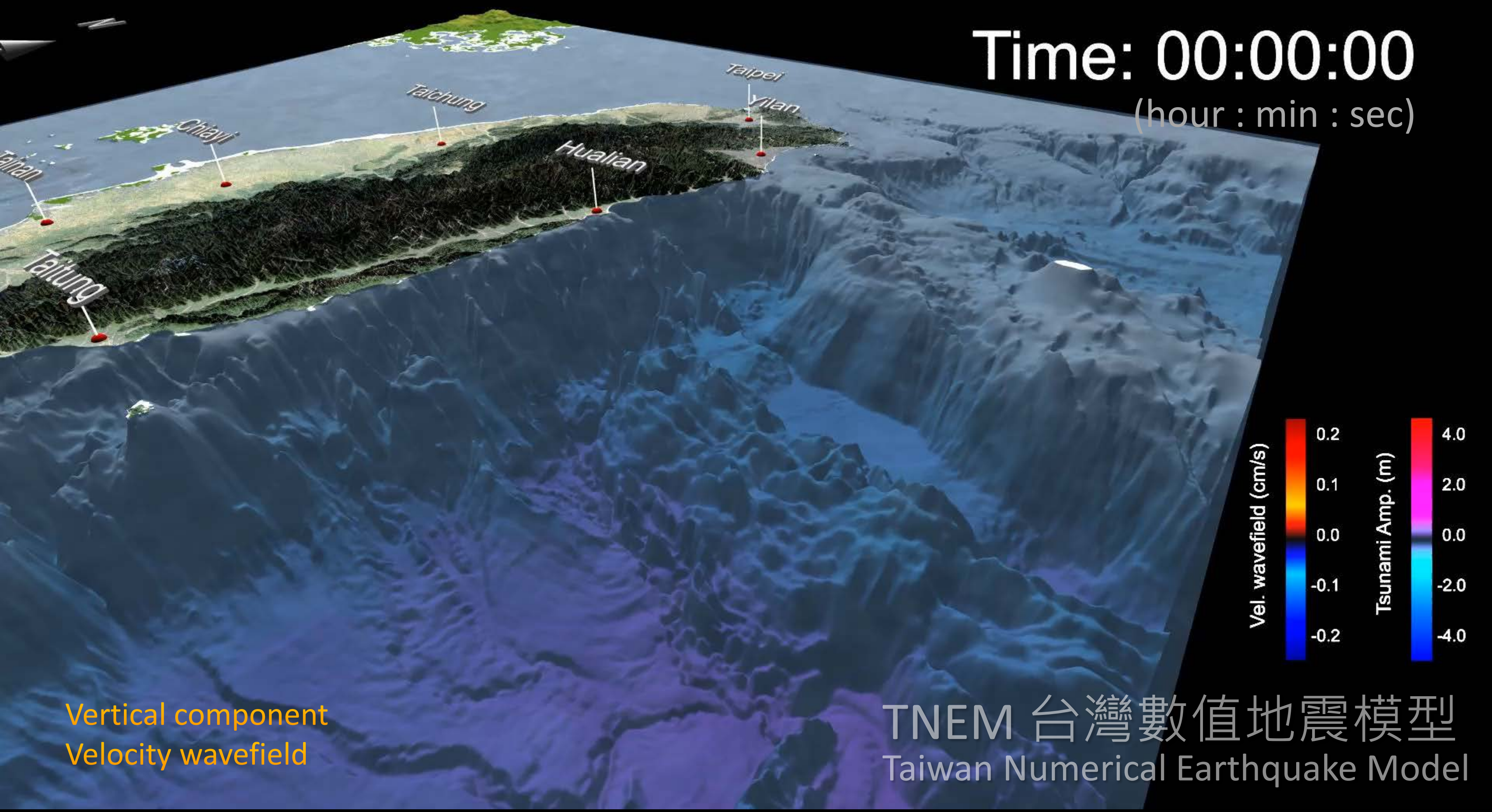

```
! resolution of the mesh at the surface:
! -----------------------------------------
!
! spectral elements along X =          512
! spectral elements along Y =          512
! GLL points along X =         2049
! GLL points along Y =         2049
! average distance between points along X in m =       267.747711
! average distance between points along Y in m =       321.630127
!
```

Tsunami Simulation: Dispersive tsunami model

We calculate the coseismic seabed deformations due to the inverted slip distribution base on SEM, and then use it as initial sea height. A dispersive tsunami propagation model (Saito et al., 2012) is applied to calculate the simulation.

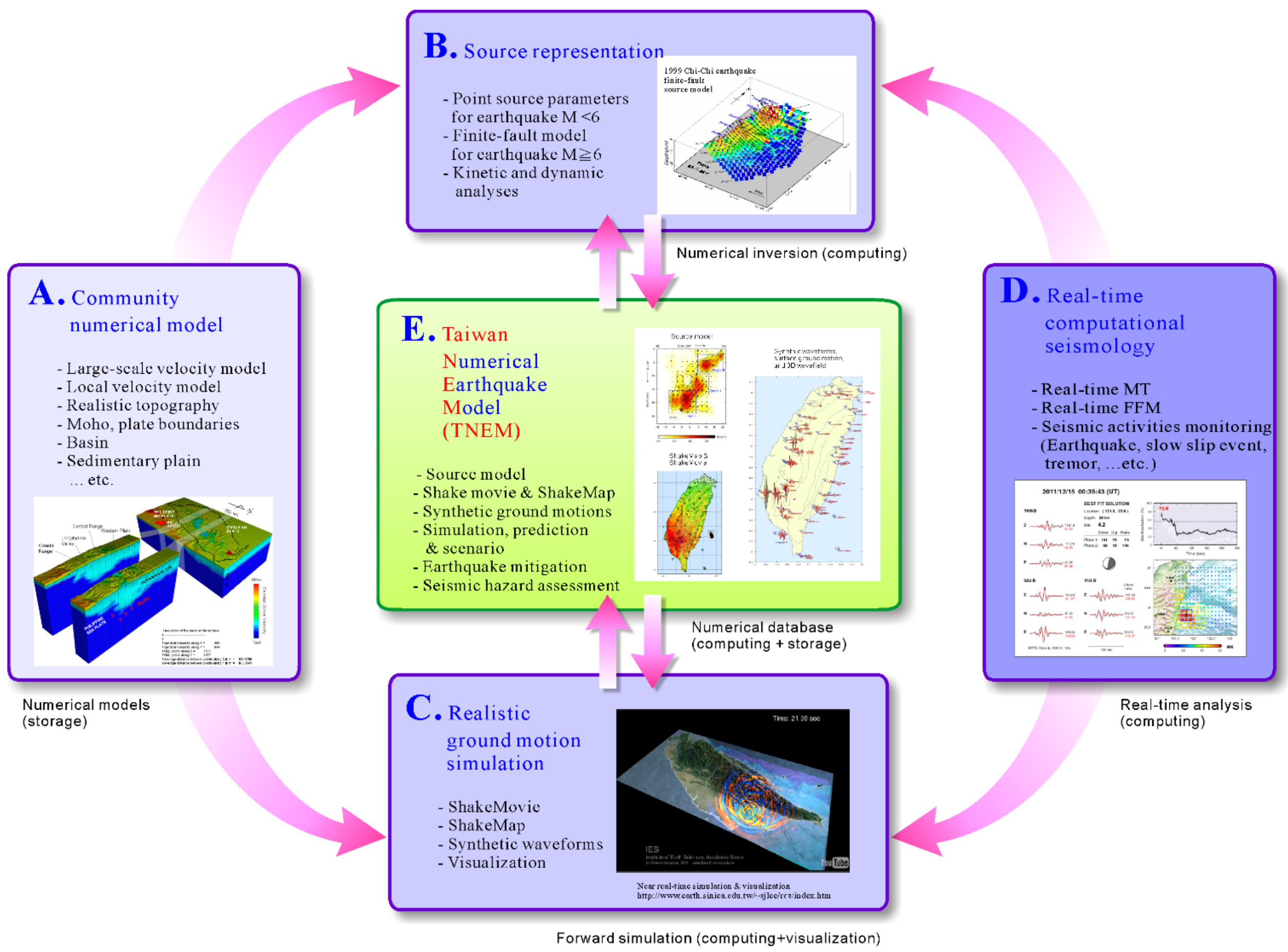


Ryukyu Subduction Zone Megathrust Earthquake M8.0+



四、台灣數值地震模型

Taiwan Numerical Earthquake Model



Scientific problems:

A. Community numerical model
B. Source representation
C. Ground motion simulation
D. Real-time seismology
E. Numerical Earthquake Model

Numerical approaches:

- NNLSP (parallel program)
  Source inversion by NNLS
  (Lee et al., 2006)
- SEM (parallel program)
  3D seismic wave propagation
  (Komatitsch and Tromp, 2004)
- RMT (parallel program)
  Real-time moment tensor
  monitoring (Lee et al., 2014)

People involved:

2 Postdoc
5 Students
4 Assistants

Taiwan Numerical Earthquake Model

Historical earthquake

- **1906** Meishan earthquake (M7.1)
- **1916** Nantou earthquake Sequence (M6.0+)
- **1935** Hsinchu-Taichung earthquake (M7.1)
- **1951** Longitudinal Valley earthquake series (M7.3, M7.1, M7.3)
- **1986** Hualian earthquake (M6.8)
- And others

Before 1999

Modern earthquake

- **1999** Chi-Chi earthquake (M7.3)
- **2002** Hualian offshore earthquake (M7.0)
- **2003** Chengkung earthquake (M6.8)
- **2006** Pingtung earthquake doublet (M7.0, M7.0)
- **2010** JiaShian earthquake (M6.4)
- **2012** Wutai earthquake (M6.4)

1999-2012

Recent earthquake

- **2013/03/27, 06/02** Nantou earthquake I, II (M6.2, M6.5)
- **2013/10/31** Ruisui earthquake (M6.4)
- **2015/04/20** Eastern offshore earthquake (M6.38)
- **2016/02/06** Meinong earthquake (M6.6)
- Real-time Computational Earthquake report

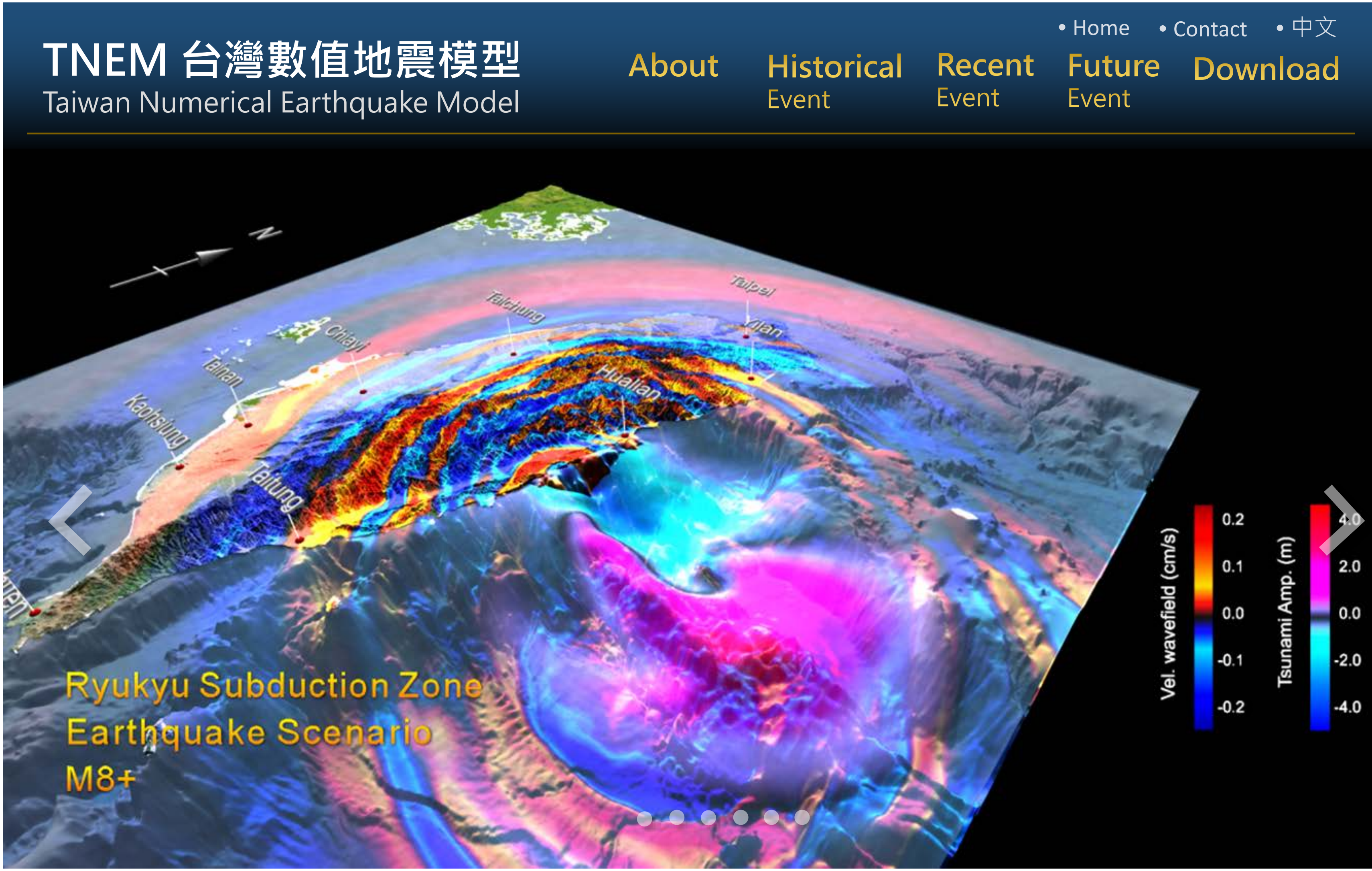
(2013-2018)

Scenario earthquake

- **Shanchiao fault** Taipei earthquake scenario (M7.0+)
- **Manila Trench** megathrust earthquake (M8.0+)
- **Changhua fault** earthquake scenario (M7.0+)
- **Longitudinal Valley** earthquake scenario (M7.0+)
- **Ryukyu Trench** megathrust earthquake (M8.0+)
- And others

2018/08~

Time-line



Latest update: 2016/11/07

台灣數值地震模型網頁: http://tnem.earth.sinica.edu.tw

Thank you