Killer Pulses Observed in Meinong Earthquake Revealed from Dense Strong Motion Seismic Array

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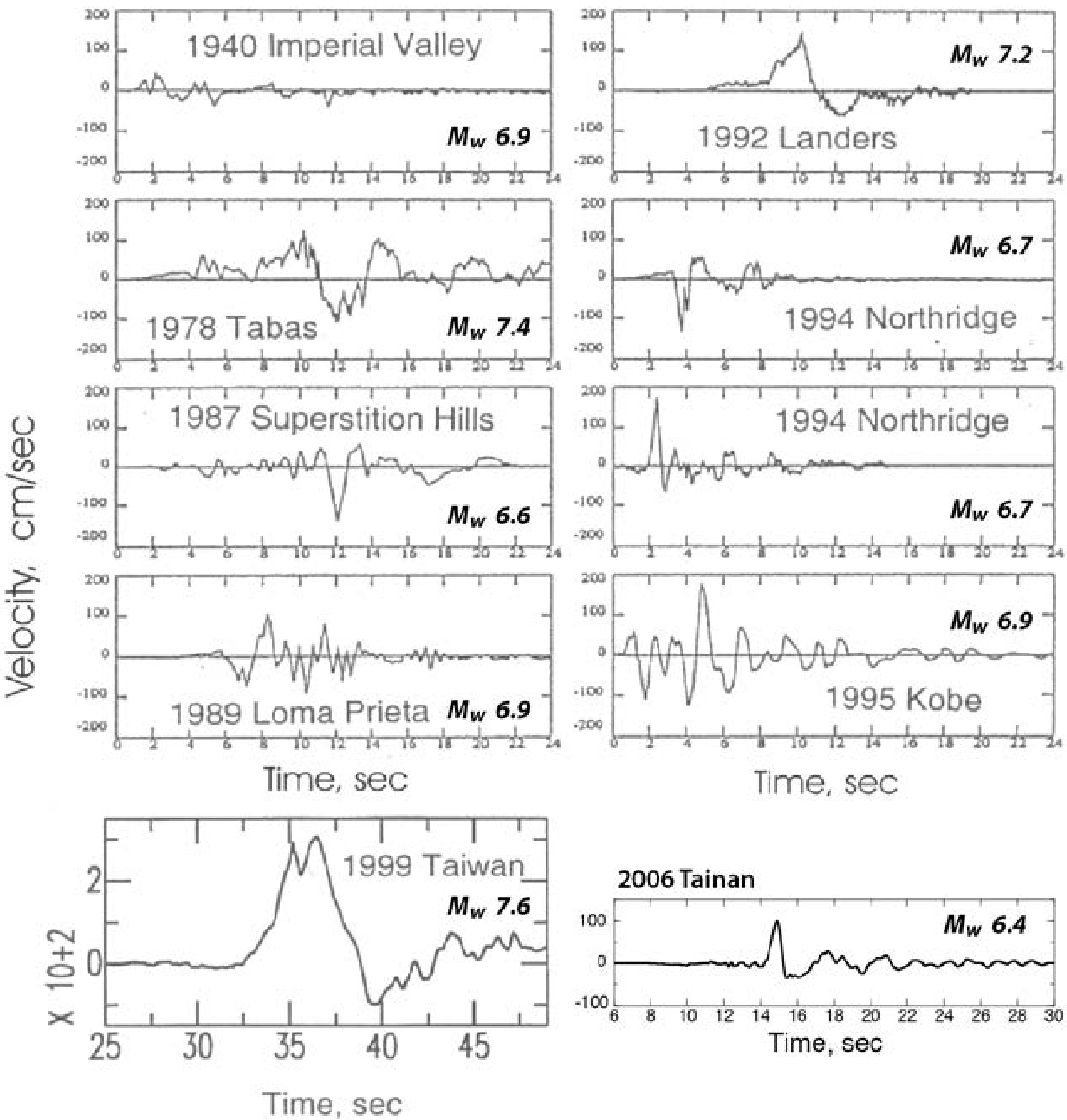
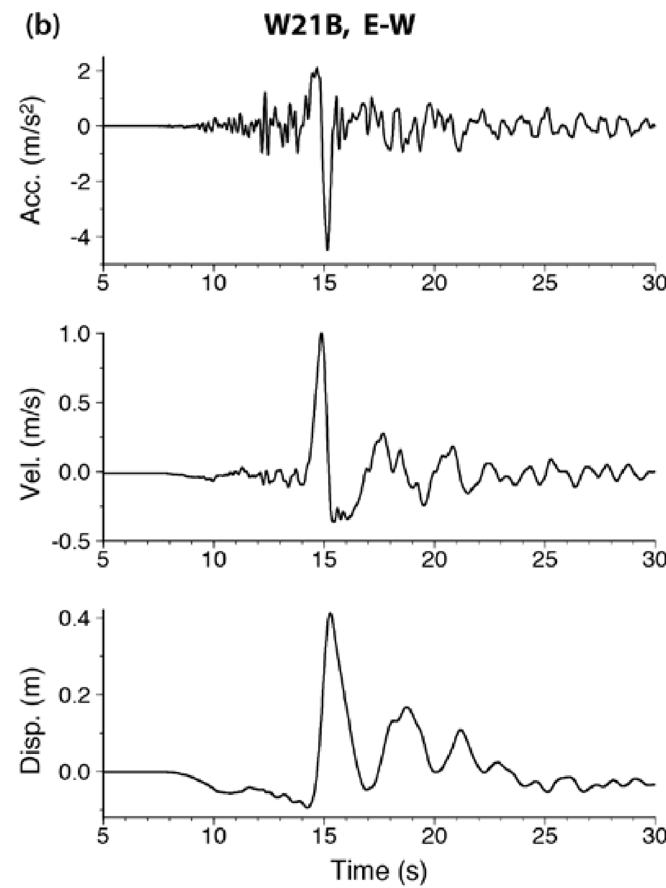
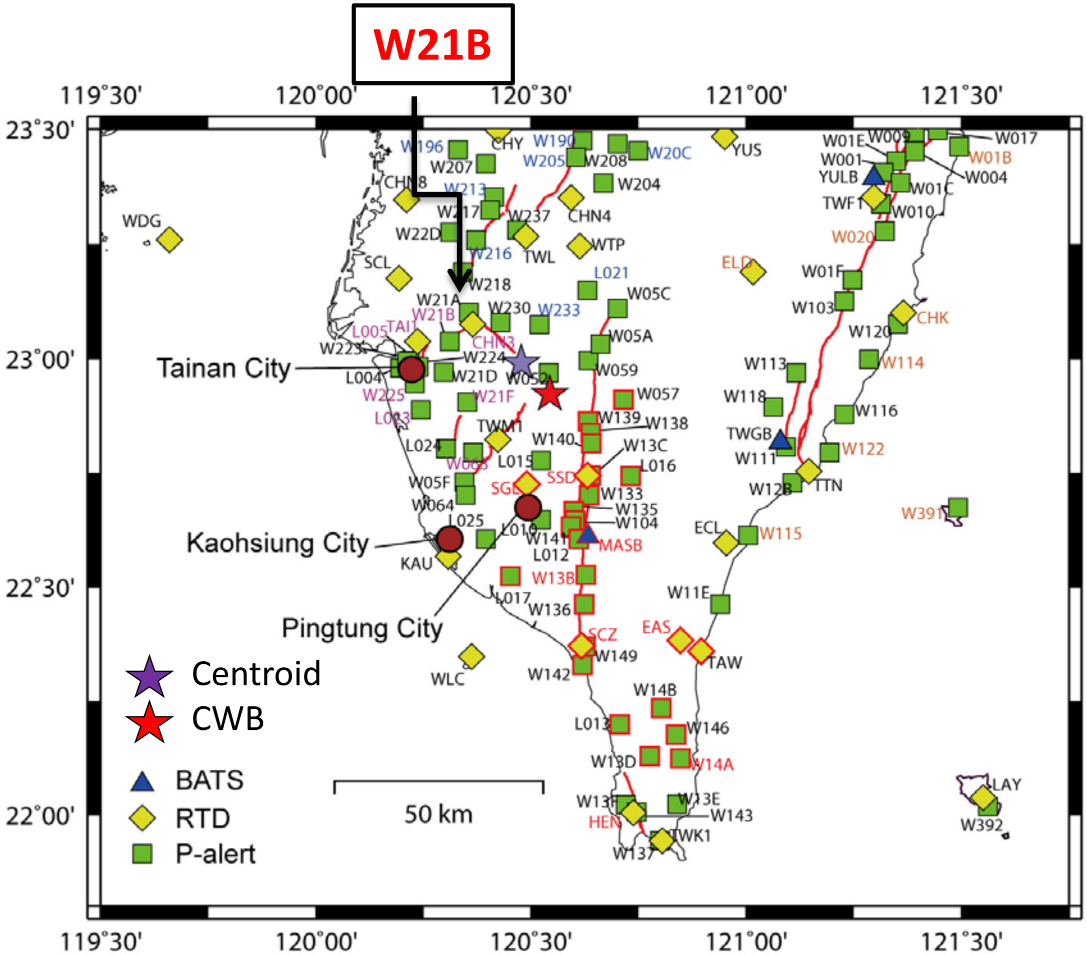
Ground-Motion Velocity from Large Earthquakes

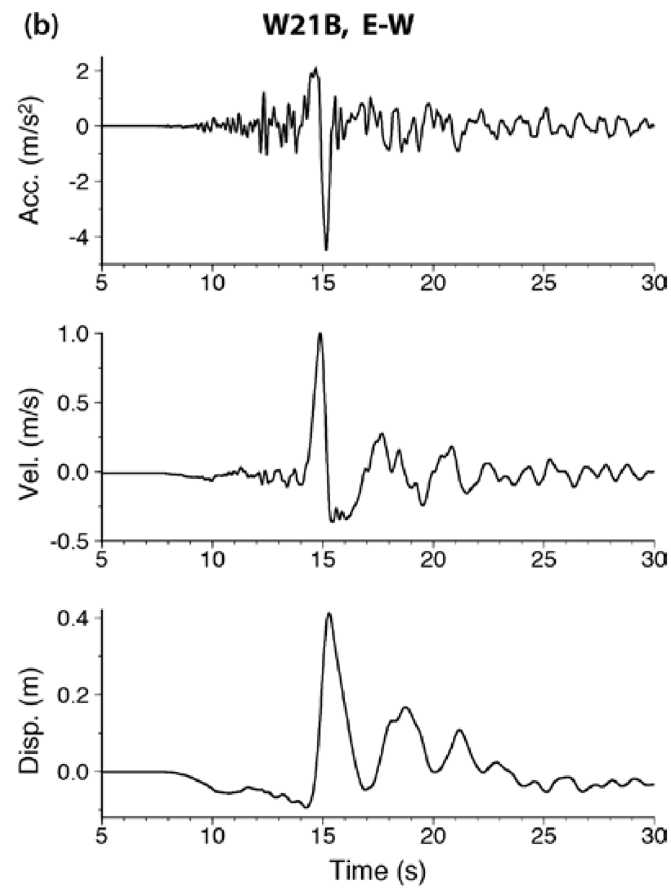


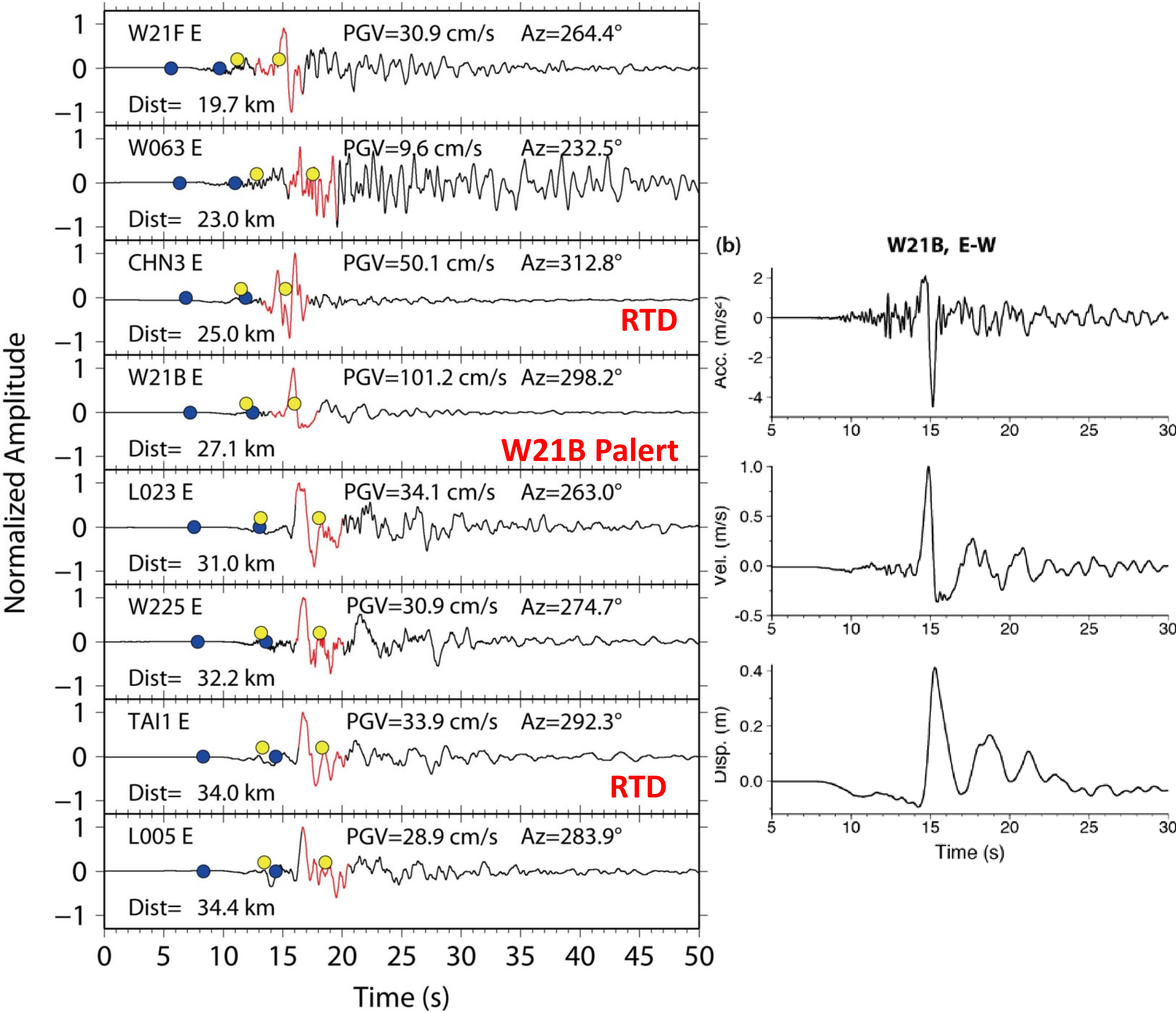


Dense Seismic Array:
Palert, Earthquake Early Warning
CWB RTD, Real-time strong motion
BATS, Broadband stations



20160206 Meinong Earthquake





W21F E
PGV=30.9 cm/s
Az=264.4°
Dist= 19.7 km
W063 E
PGV=9.6 cm/s
Az=232.5°
Dist= 23.0 km
CHN3 E
PGV=50.1 cm/s
Az=312.8°
Dist= 25.0 km
RTD
W21B E
PGV=101.2 cm/s
Az=298.2°
Dist= 27.1 km
W21B Palert
L023 E
PGV=34.1 cm/s
Az=263.0°
Dist= 31.0 km
W225 E
PGV=30.9 cm/s
Az=274.7°
Dist= 32.2 km
TAI1 E
PGV=33.9 cm/s
Az=292.3°
Dist= 34.0 km
RTD
L005 E
PGV=28.9 cm/s
Az=283.9°
Dist= 34.4 km
Normalized Amplitude
Time (s)
(b)
W21B, E-W
Acc. (m/s²)
Vel. (m/s)
Disp. (m)
Time (s)

Mainshock (blue)Mw 6.40

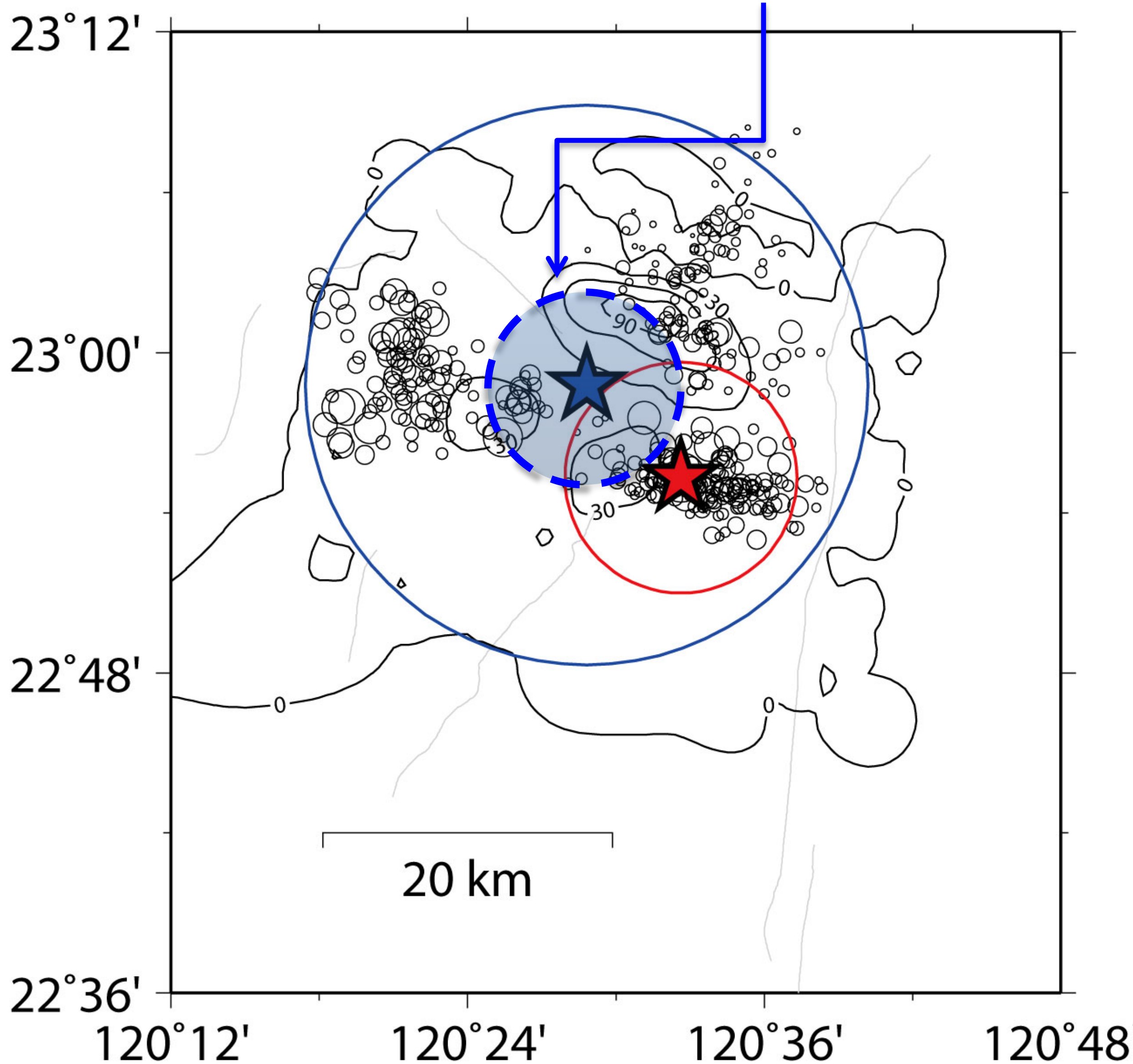
STF~ 2 sec
Rupture Speed: 2.5-3.0 km/sec

Slip Patch Radius~ 5-6 km

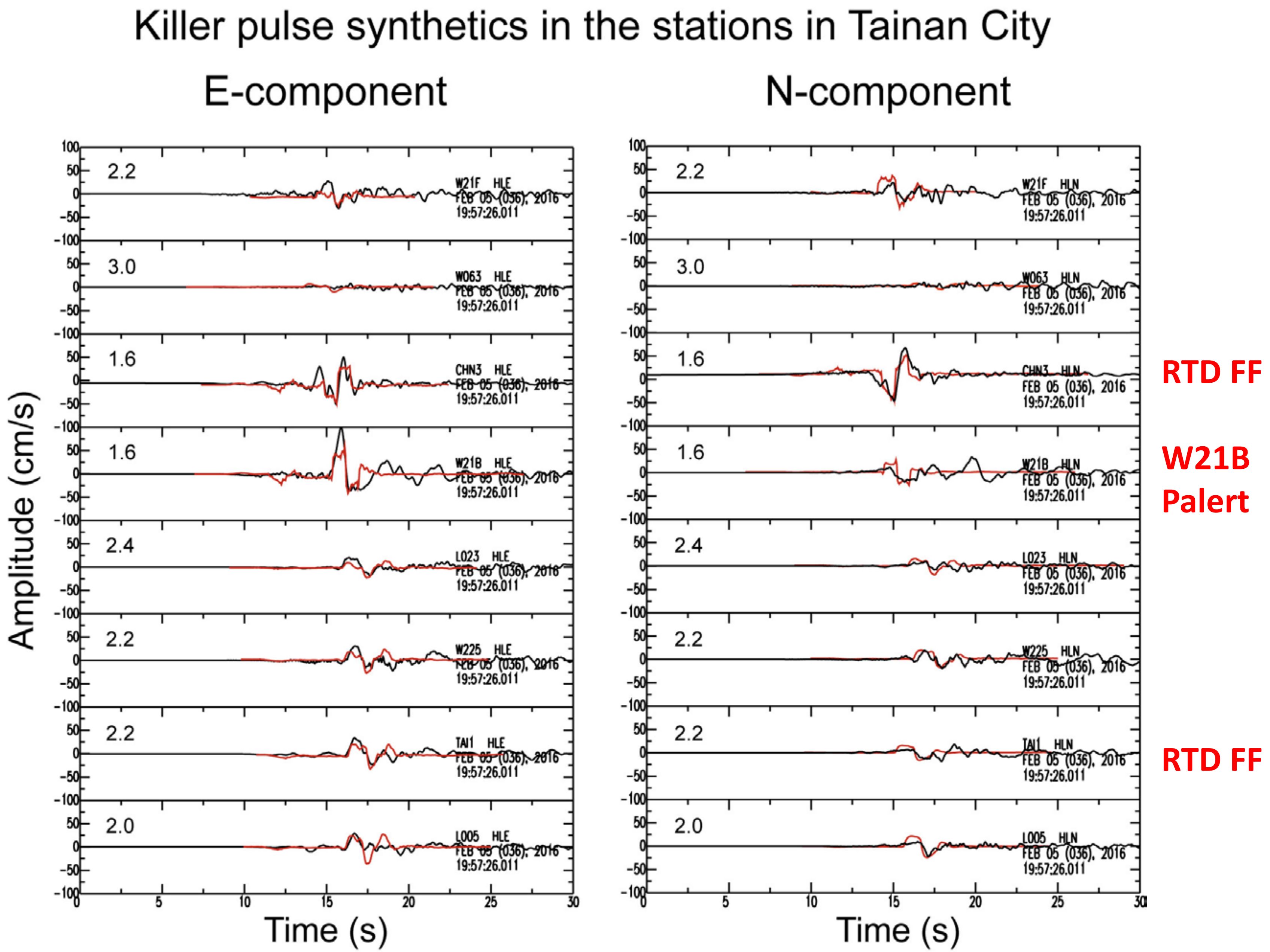
-Shifted westward by 30 degree from slip distribution from finite-fault

-Filled to the gap in aftershock seismicity

Slip patch from direct observation and STF modeling



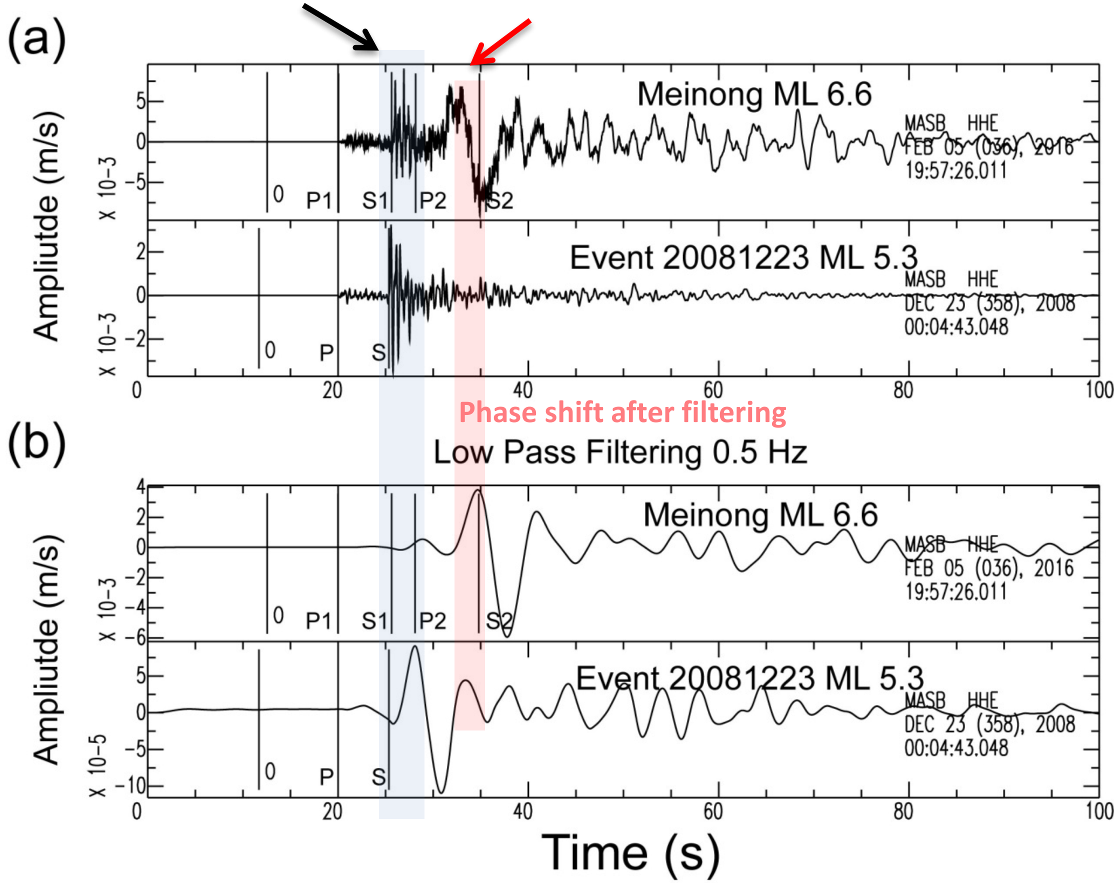
Modeling the Western stations using circular fault model (Asperity) constraints from source tim
function (STF), using moment with Mw6.4, focal mechanism (RMT) s/d/r: 274.6/22.1/17.7



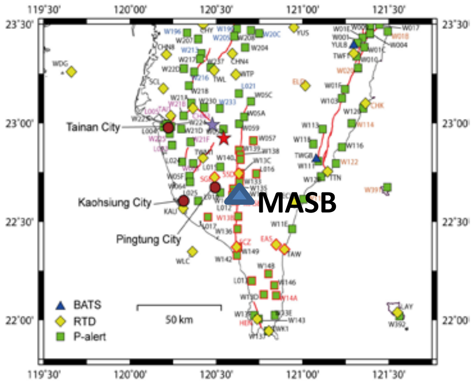
Broadband Waveforms BATS MASB

Foreshock and Mainshock of 20160206 event

BATS
MASB
Original



Filtering
LP 0.5Hz



Foreshock, M_W~5.64 by comparison of the amplitude ratio to the 20081223 M5.3 event

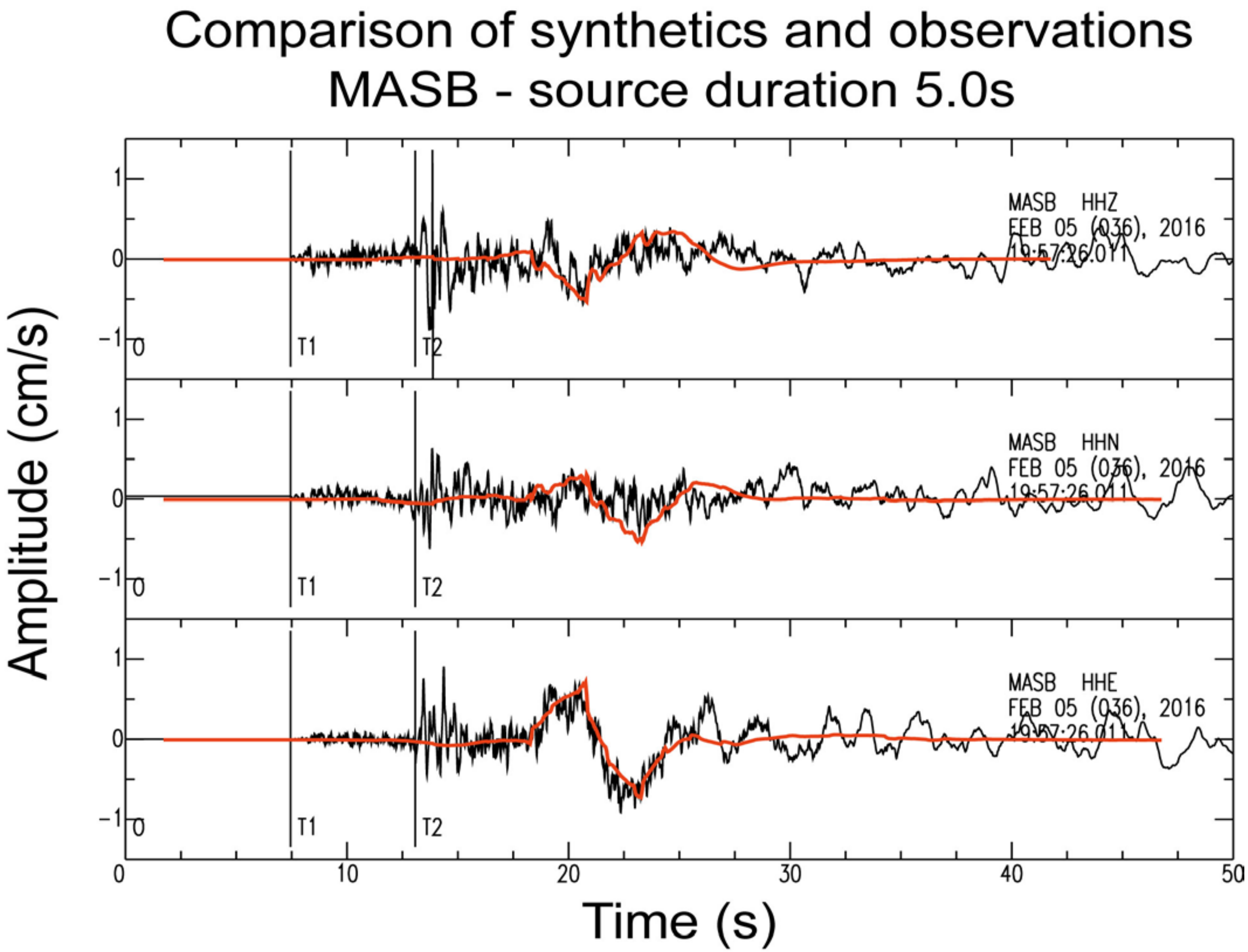
Location, CWB 20160206 location

Mainshock, M_W~6.4 ~4-10 sec after Foreshock from SSA

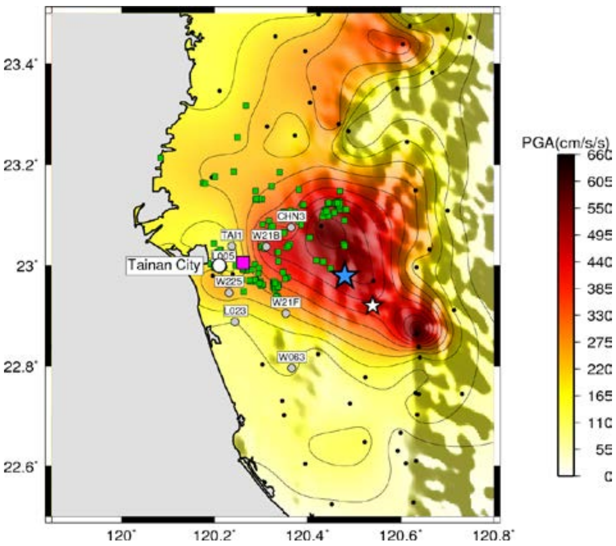
Location, down-dip from the foreshock depth, and to the west of the foreshock

Asperity or double events? Asperity for sure as a large slip patch at the mainshock location. But, we call it Foreshock and Mainshock as the clear observations of P1, S1, and P2, S2.

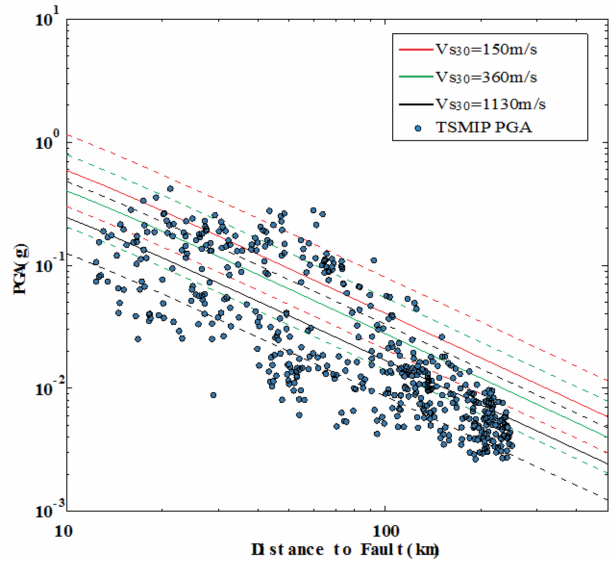
The foreshock and mainshock waveforms with synthetics for mainshock.

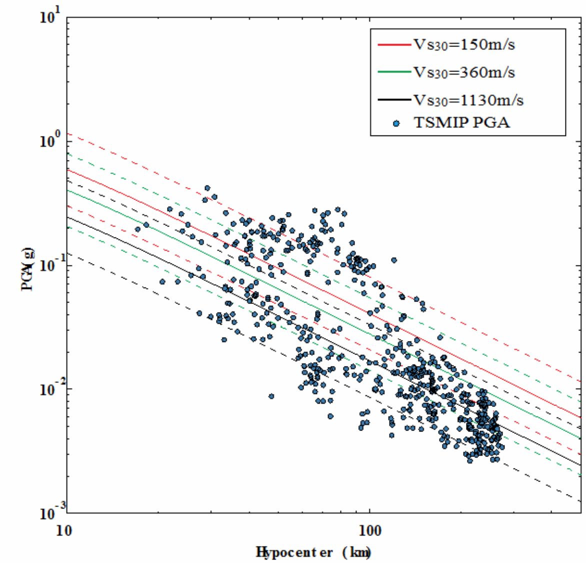


PGA TSMIP



PGA with GMPE Lin et al. (2008)

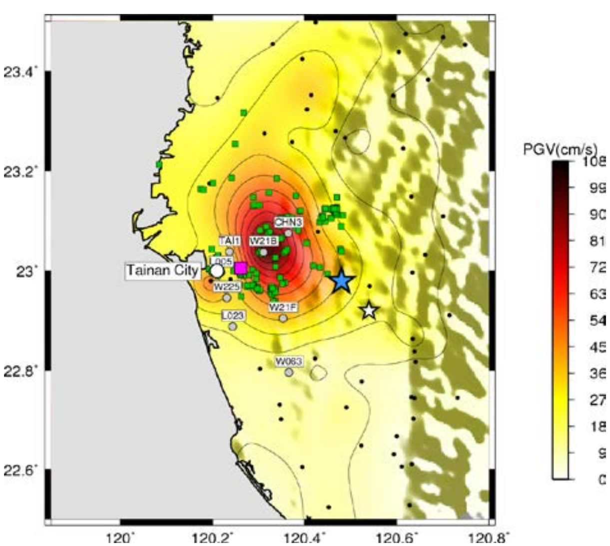




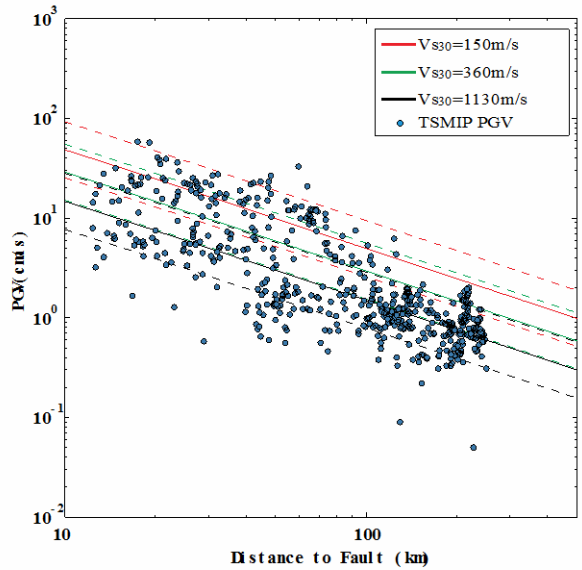
Distance: Fault

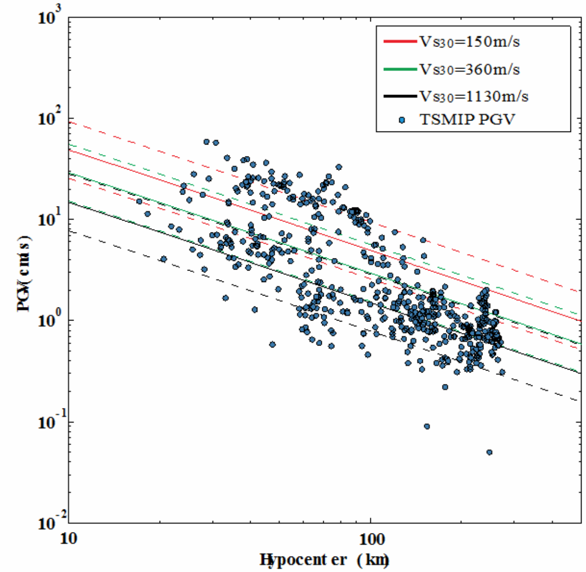
Distance: Hypocenter

PGV TSMIP



PGV with GMPE Lin et al. (2008)





Lee et al., 2016,
personal communication

Conclusions:

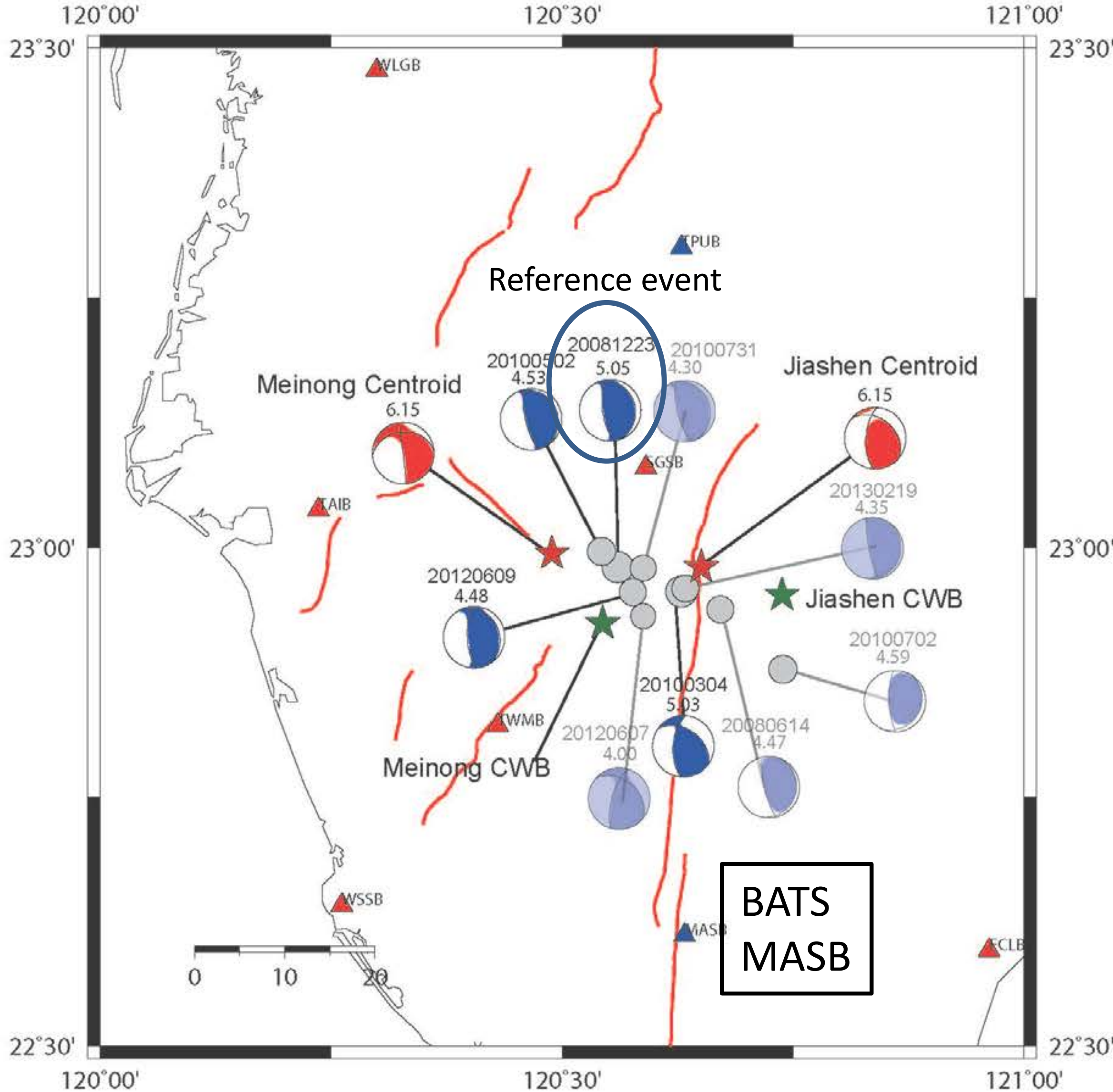
*** Meinong Earthquake with 3 episodes**

1. Small patch Foreshock Mw5.6
2. Strong patch, Mainshock Mw6.4
3. Triggered Shallow NS shallow fault (Mud Diapier related?)

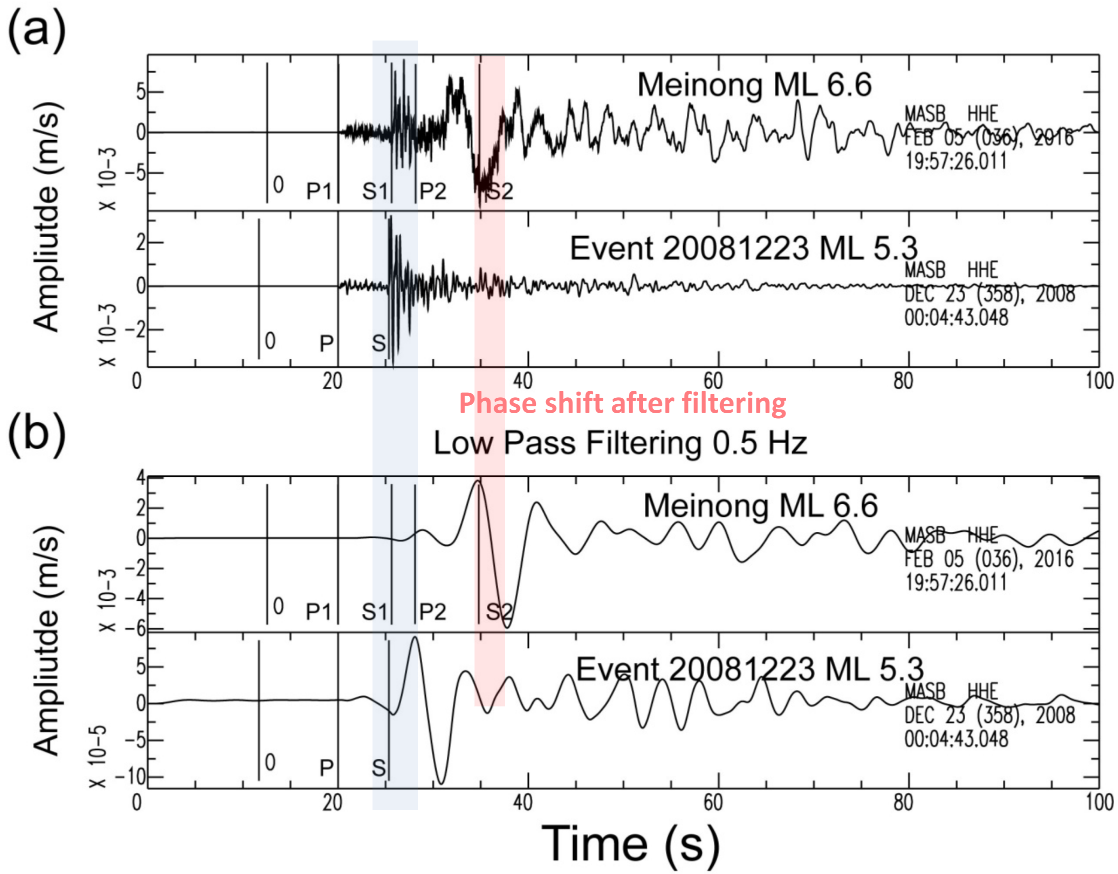
- Dense seismic array from EEW Palert stations providing direct observation on source to give less bias in location of asperity (patches) using less filtering data

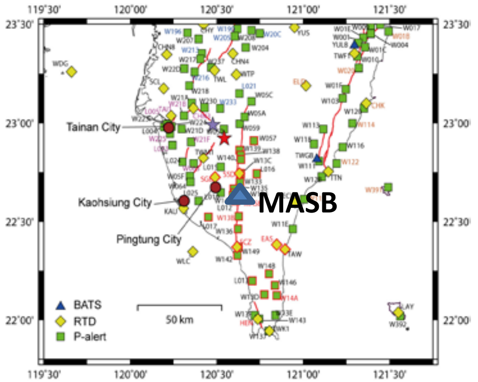
- **The source of the observed Killer pulses were contributed from mainshock Mw6.4 strong patch with radius of about 5-6km and stress drop of about 100-200 bars**

Resolved Focal Mechanism (BATS) for Earthquakes since 2008



BATS MASB records without and with filtering





Filtering at low pass 0.5Hz, the leading event as noted as S1 phase in Meinong earthquake was filtered out, and a phase shift for S2!

⇒ The danger in filtering the data for source mapping; the slip distribution mainly for the S2, and shifted source location.

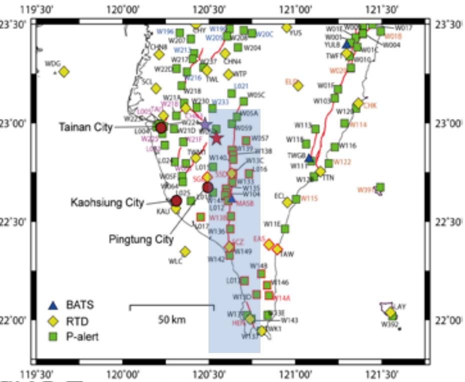
⇒ Filtering makes the data as a continuous waveforms, hard to discriminate the source as a long duration one event or double events. The near-field term in between P2 and S2

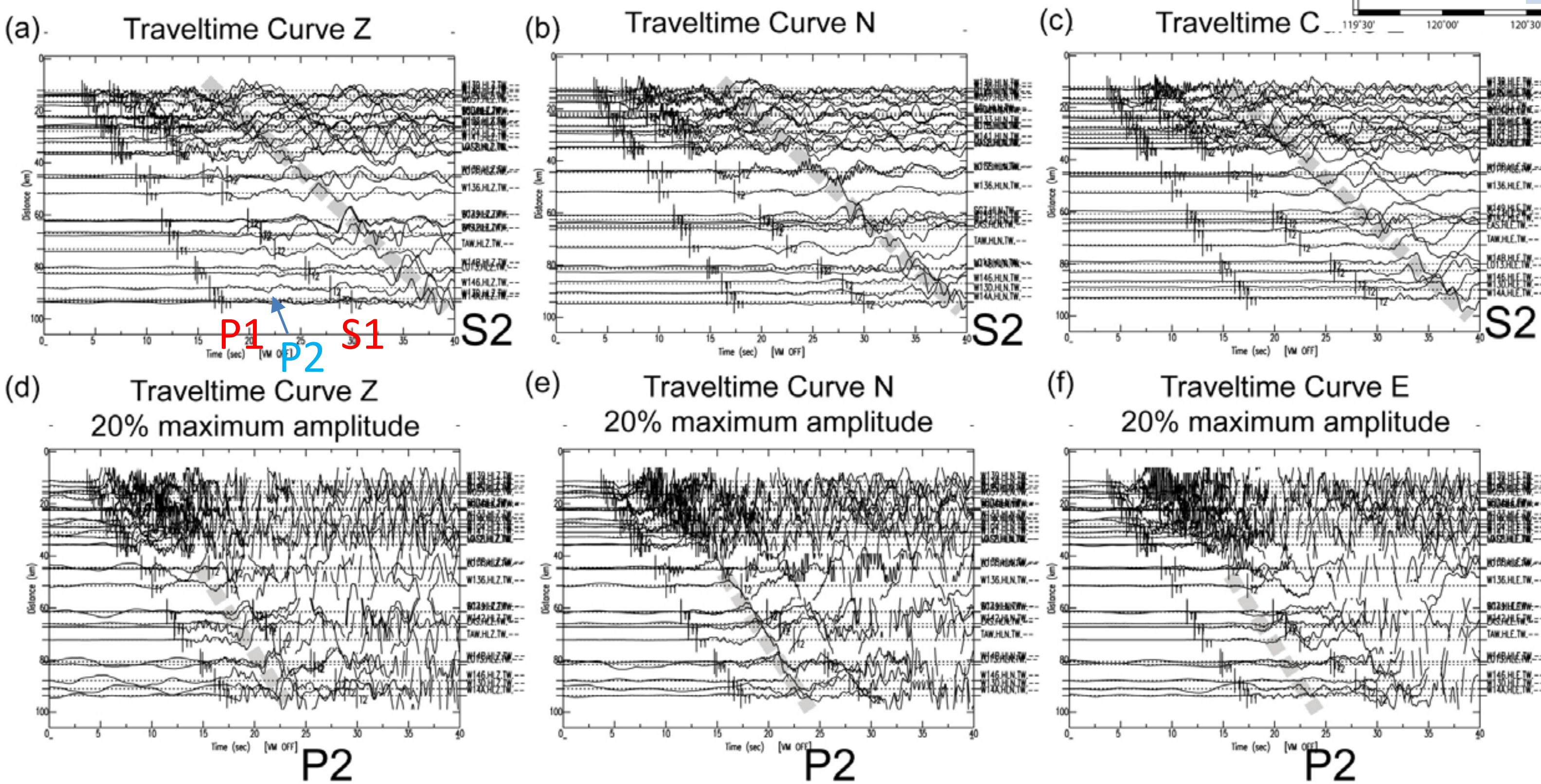
⇒ **Compared to 20081223 event, the equivalent P- and S- arrivals and frequency content and amplitudes, the first event is an magnitude ~5.6.**

Identification of P1, S1; P2, S2 from Southern lineup Palert-RTD array (marked red framed stations)

P1, S1: Foreshock

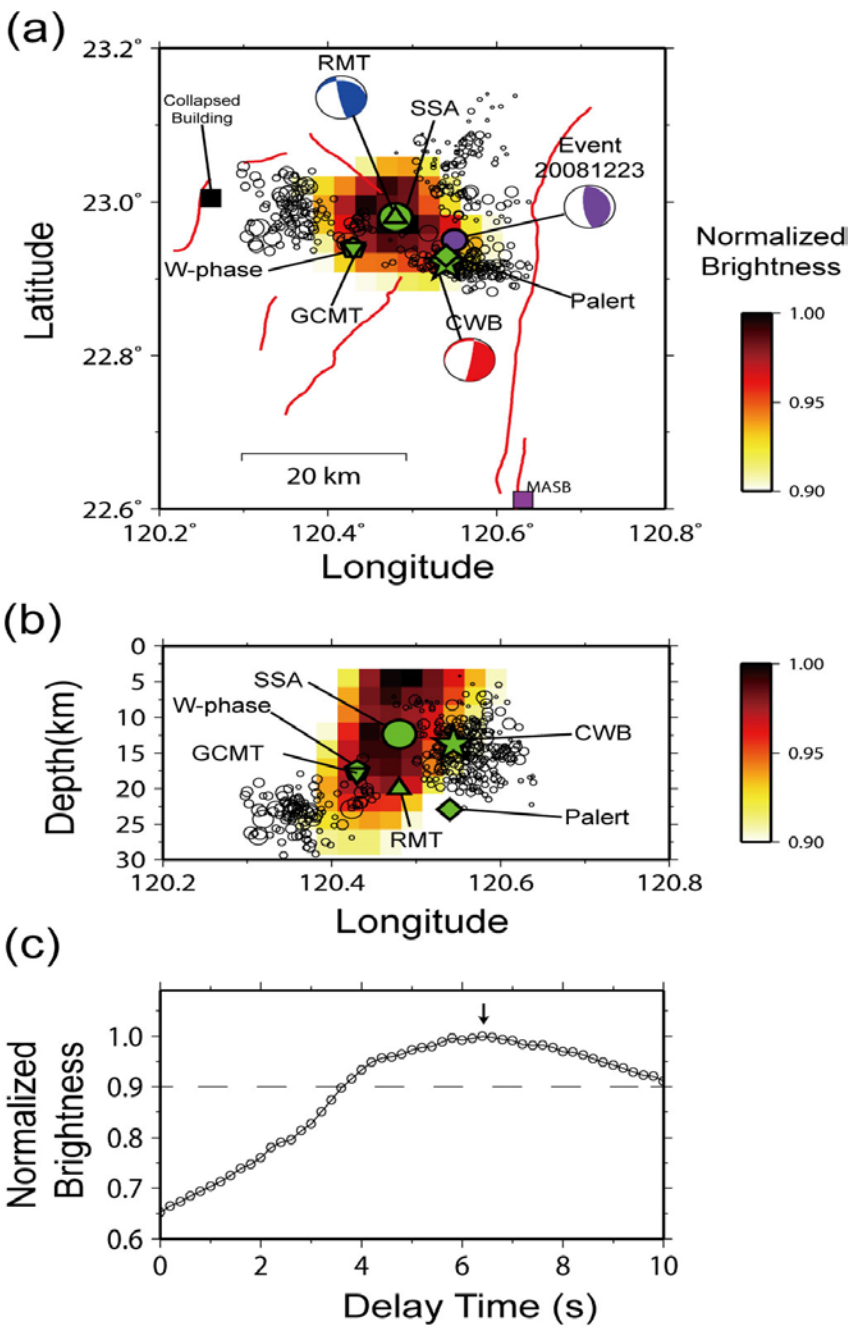
P2, S2: Mainshock





The travel-time curves for (a) vertical and (b-c) both horizontal components from the stations with a red frame mentioned in Fig. 1. The T1 and T2 markers are the P- and S-wave arrival times calculated by the 3D H14 model (P1 and S1 phases). The moveout of S2 is revealed by the gray dashed lines. (d-f) The travel-time curves plot in the 20% maximum normalized amplitude scale. The P2 phases are marked by the gray lines.

Events Locations Determinations Using SSA



The SSA is a grid-search method for determining optimal distribution of the source location based on the seismic waveforms.

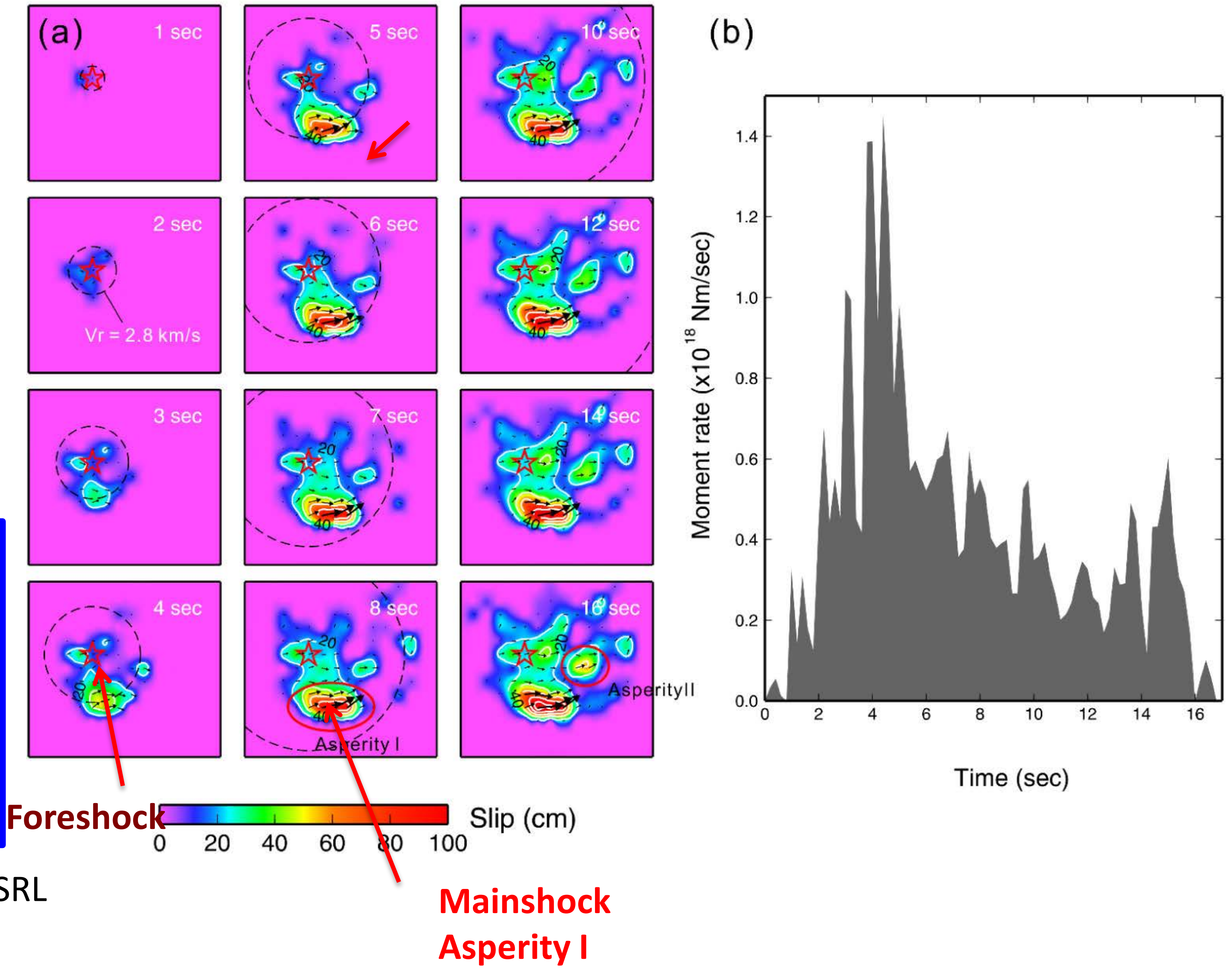
'Brightness'

source point (η) at specific delay time (τ) by using normalized amplitude of seismograms without any filtering from N stations, defined as

$$\mathrm{br}(\eta,\tau) = \frac{1}{N}\sum_{n=1}^{N}\sum_{m=-M}^{M}\left|u_n(\tau + t_{\eta n} + m\delta t)\right|$$

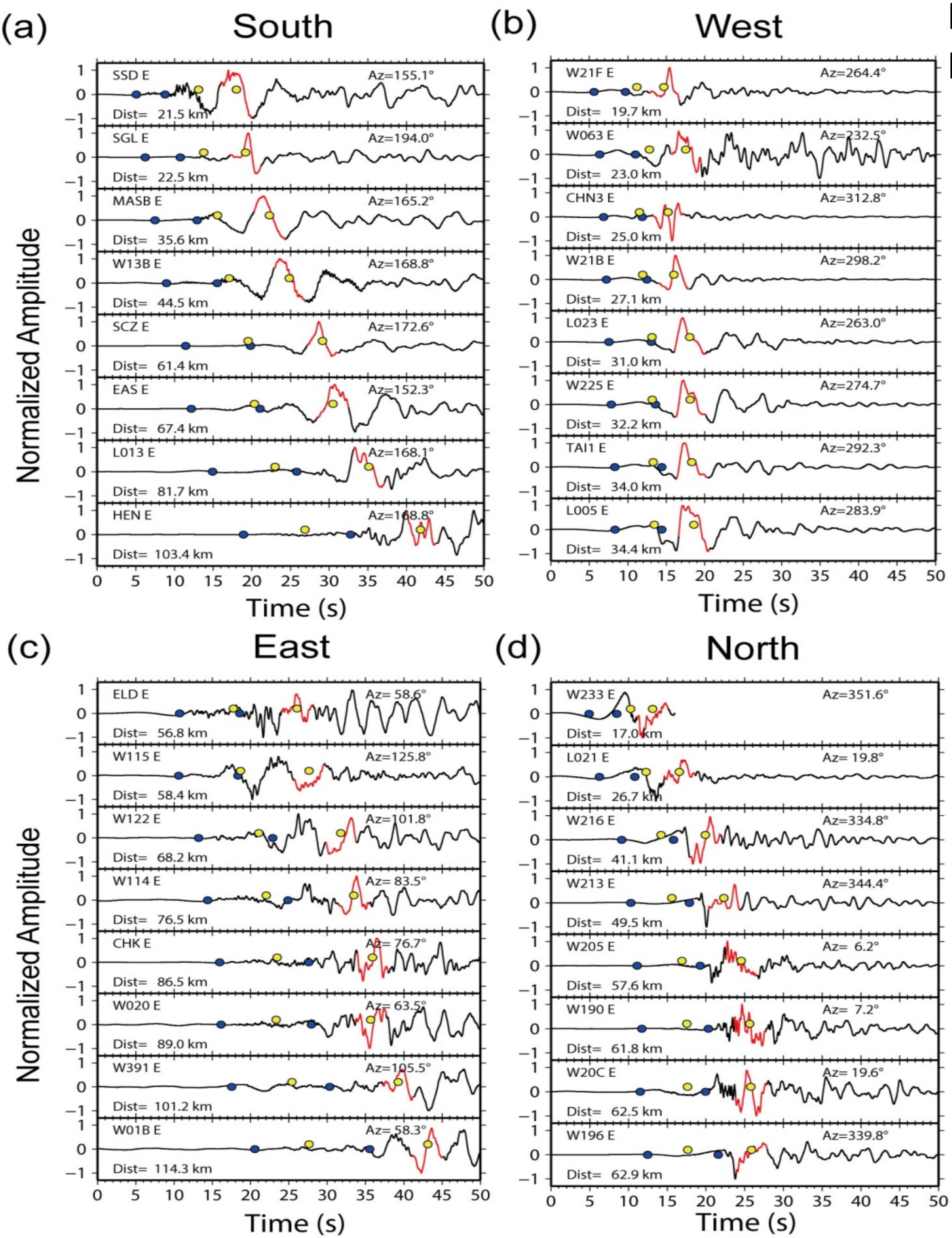
where u_n is the normalized waveform at station n, $t_{\eta\tau}$ is the predicted travel time for S wave from point η to station n. $2M$ is the number of points within the time window centered around the predicted arrival time, δt is the sampling rate. After calculating all combinations of source points (η) and the delay times (τ), the mainshock would be located in the region with extreme high brightness.

Rupture Process

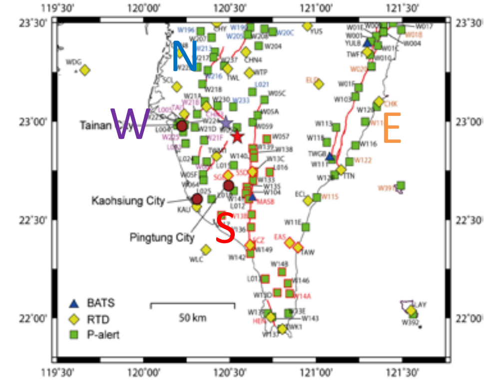


Initiated another rupture at 3- 4sec.

Lee, S. J, et al., SRL submitted, 2016



Normalized Displacement, E-comp.
Palert + RTD + BATS



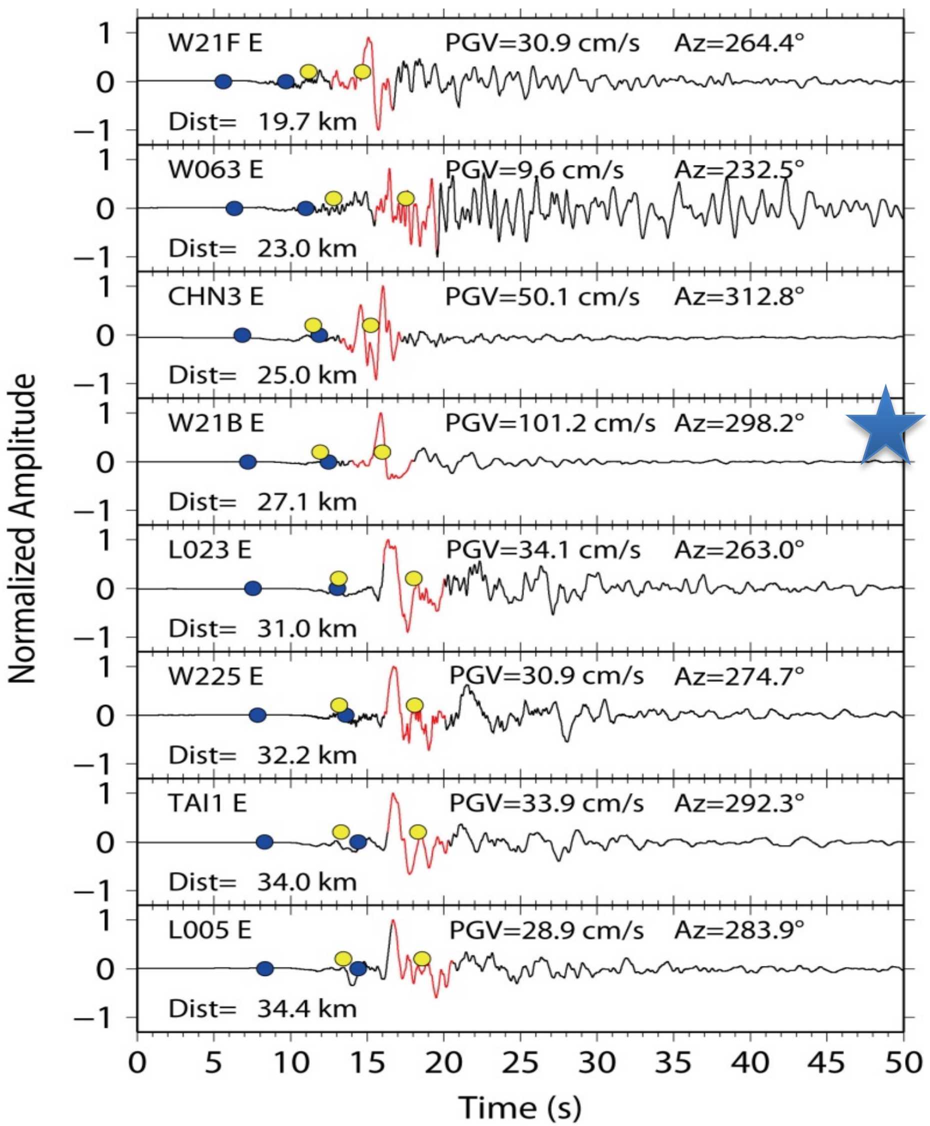
Blue dots:
P1 and S1 phase for the foreshock.
Yellow circles:
P2 and S2 phases for the mainshock.

Waveform in red is the contribution of the S2 phase in each trace.

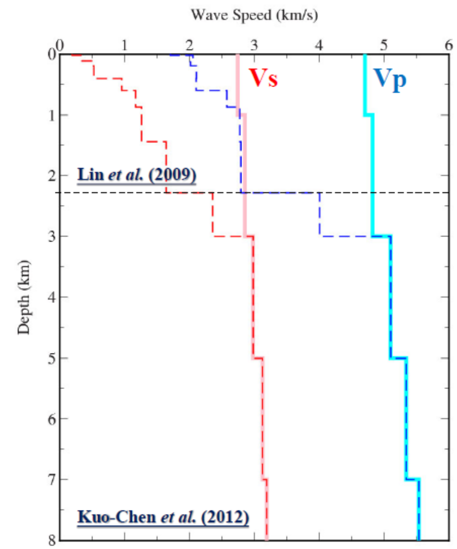
- Broader Phase in the South (backward rupture direction) compared to other regions
- **Western Directivity was well modeled,. (SJ Lee and MC Hsieh)**

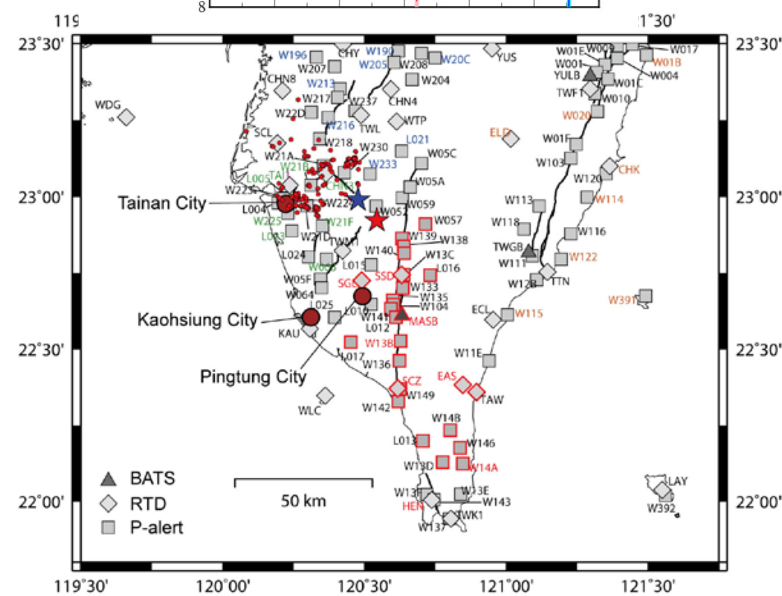
Modeling velocity waveforms In Western Direction (Tainan city) Palert + RTD: **Killer pulse**

Using circular fault modeling with 1-D shallow velocity structure~ Vs=1 km/sec at top 1.5km



- 1-D model averaged from the 3-D model of **Kuo-Chen *et al.* (2012)**
- 1-D model of **Lin *et al.* (2009)** for Western Plain (**WP**)

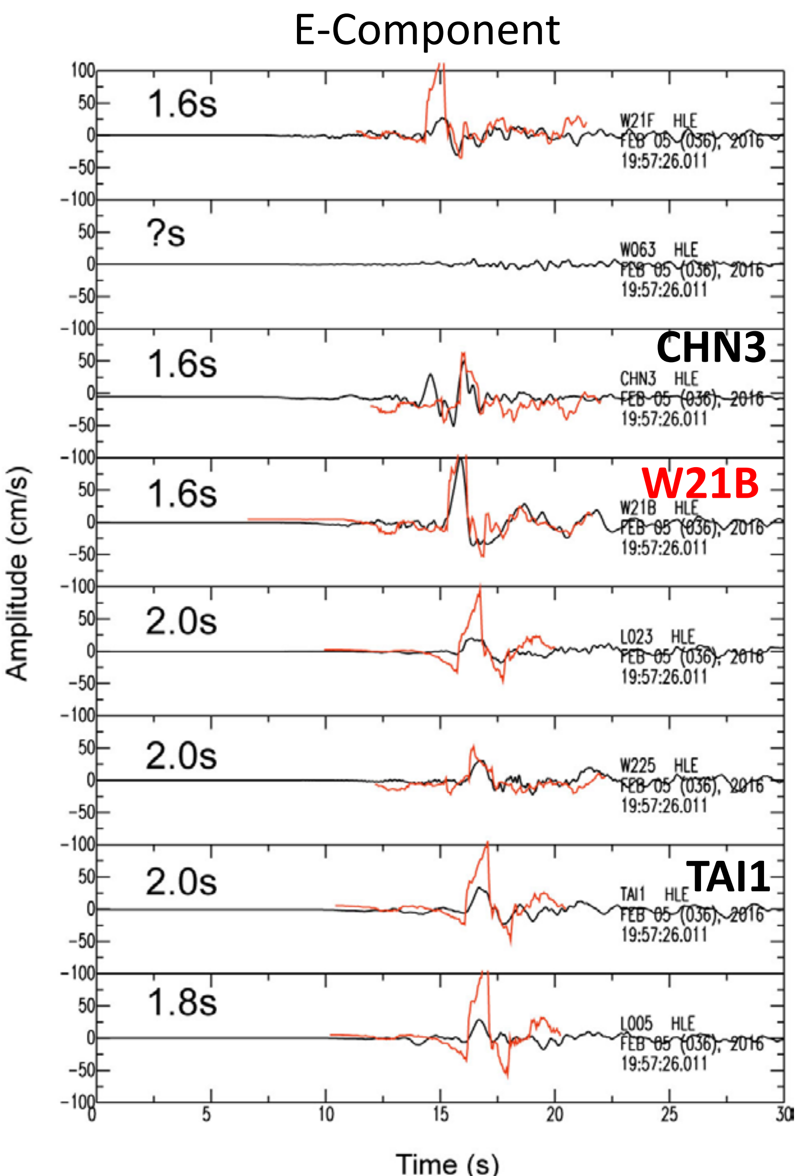


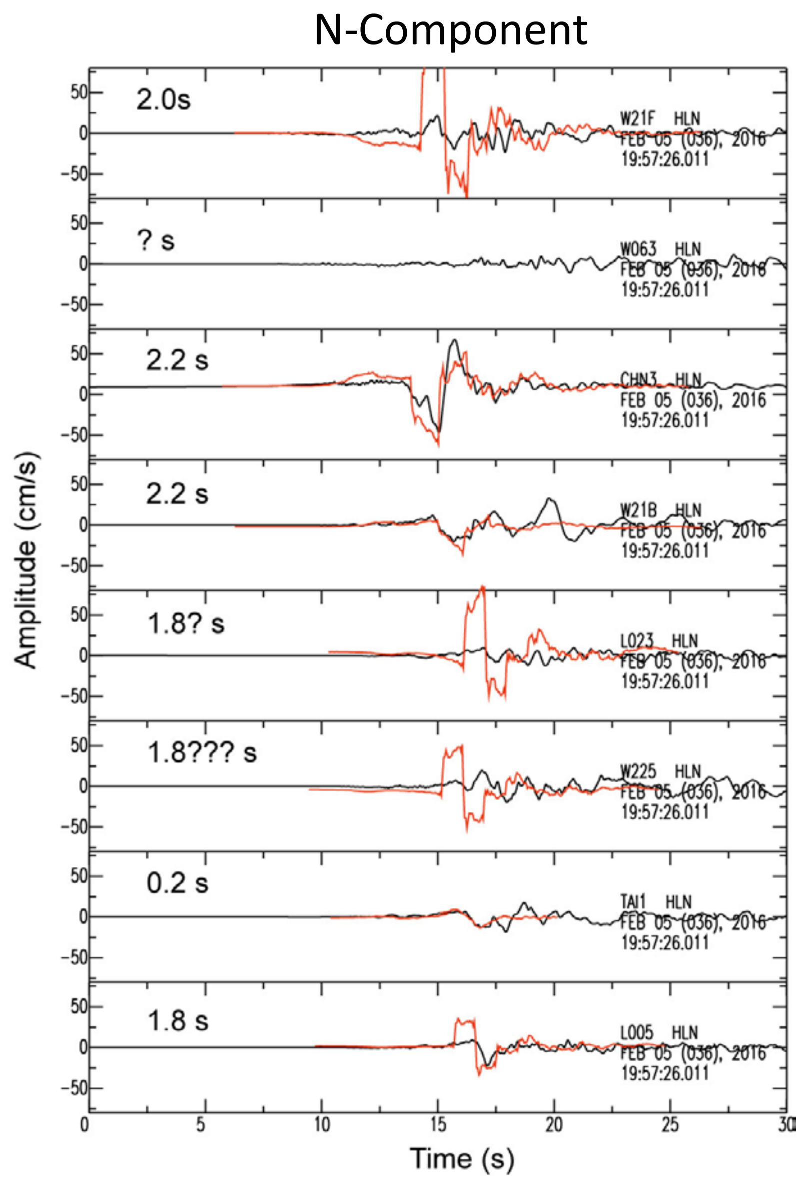


Modeling the Western stations using circular fault model (Asperity) constraints from source time function (STF), using moment with Mw6.4, focal mechanism (RMT) s/d/r: 274.6/22.1/17.7

Most of the stations with STF~ 2sec, Amplitude varied from 1 to 1/3

Well explained in E- and W-components.   Considering shallow 1.5km of low Vs~1km/sec





Comparison of the two events model and aftershocks
the slip model determined by Shiann-Jong

Source Scaling
Foreshock (red)
Mw 5.64,
Mainshock (blue)Mw
6.40

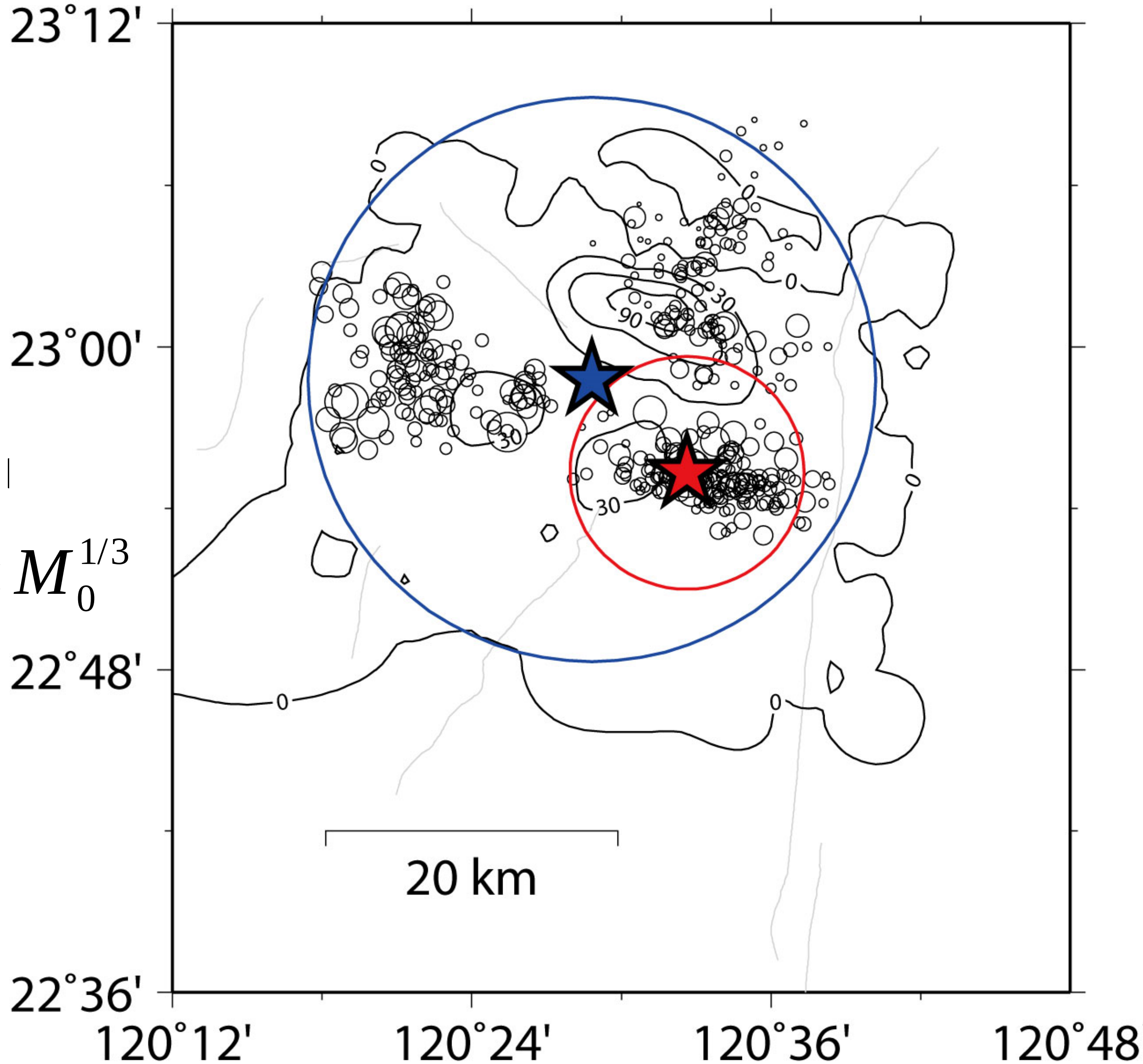
$$M_0 = \frac{16}{7}\Delta\sigma a^3$$

Source duration for 30 |

$$t_w = 2.4\times10^{-8}\times M_0^{1/3}$$

(Duputel et al., 2013)

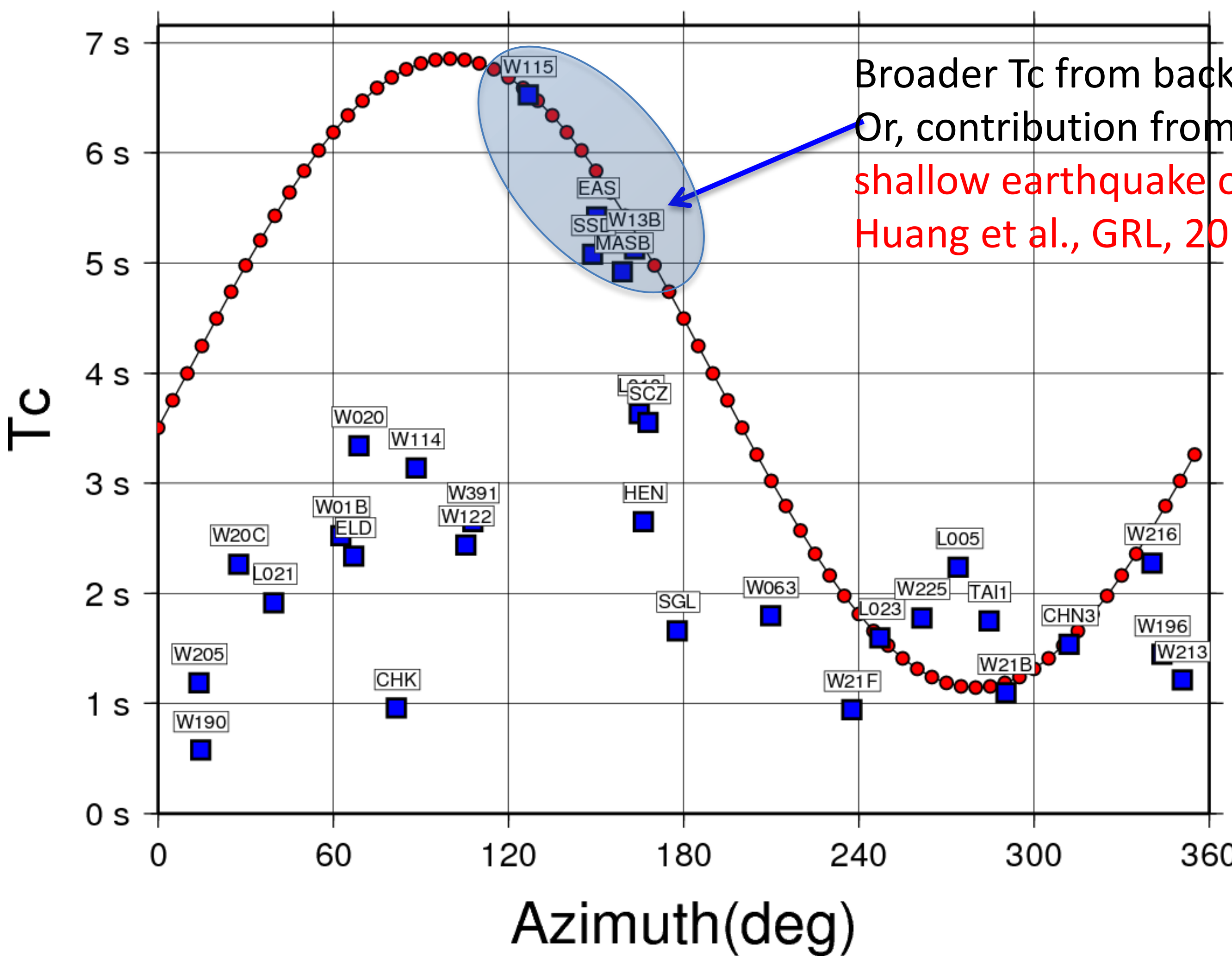
Foreshock
3.7 s
Mainshock
8.8 s



Western Stations,
STF=2sec, Vr-2.5-3.0km/sec, => Source Radius, R=5.0-6.0km

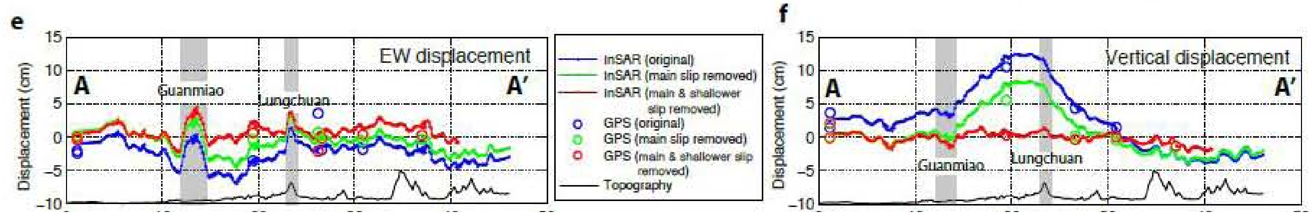
Examination on Directivity

RupLen=10 km, RupAzi=280 deg, Vr=2.5 km/s, C=3.5 km/s

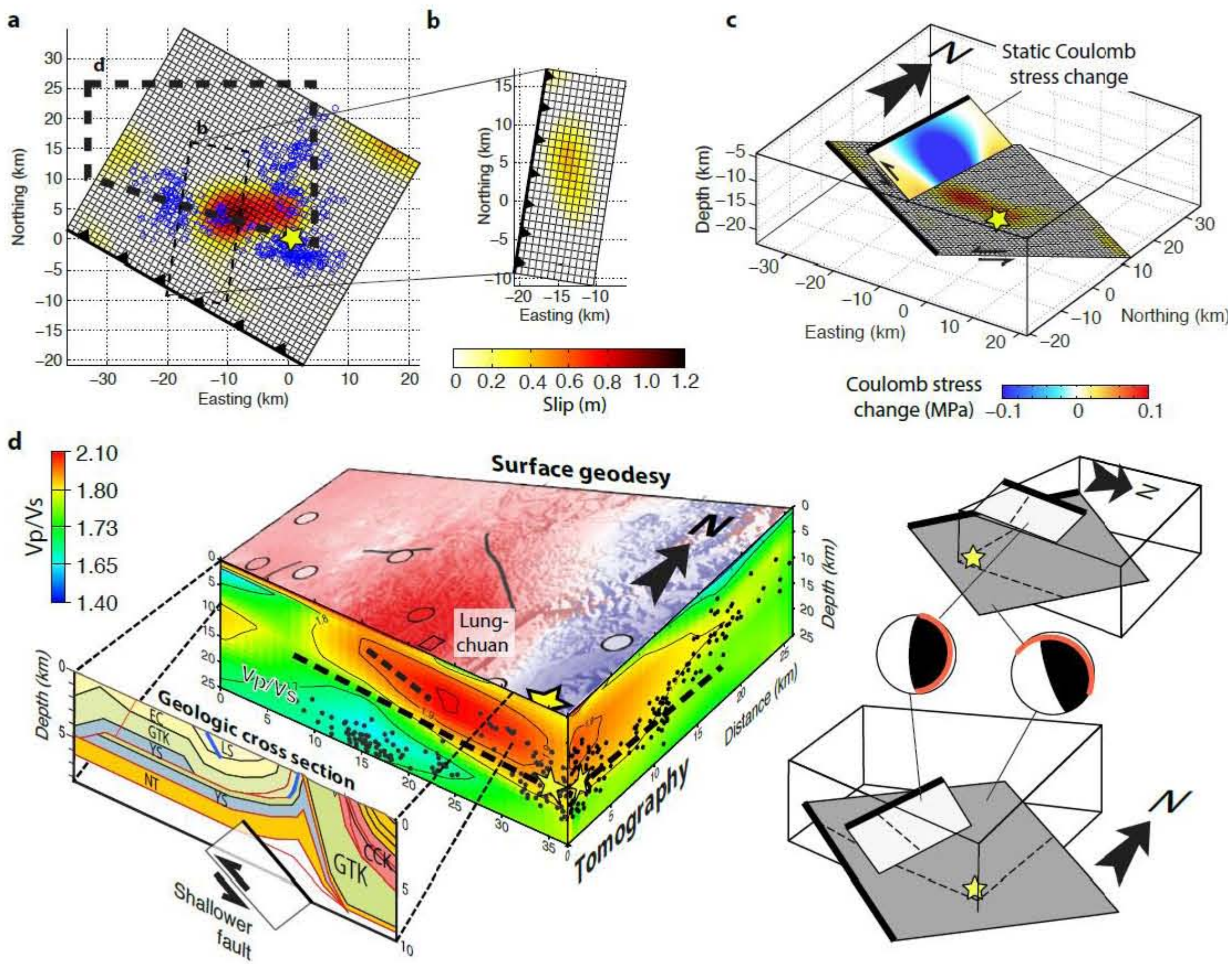


Broader Tc from backward rupture directivity?
Or, contribution from another NS strike shallow earthquake observed in GPS data?
Huang et al., GRL, 2016

Most of stations with STF~
2 sec, except the
Az:120-160, southern
stations with STF>5 sec



Modeling from Seismic, GPS: Explain the GPS and InSAR, required a NS strike shallow Mw5.94



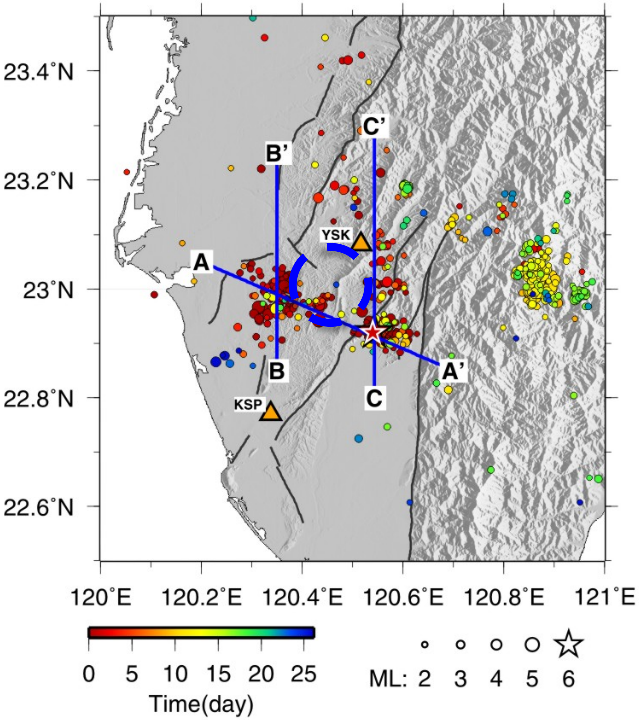
NS Mw5.94
shallow fault
5-15km

Huang et al.,
GRL, 2016

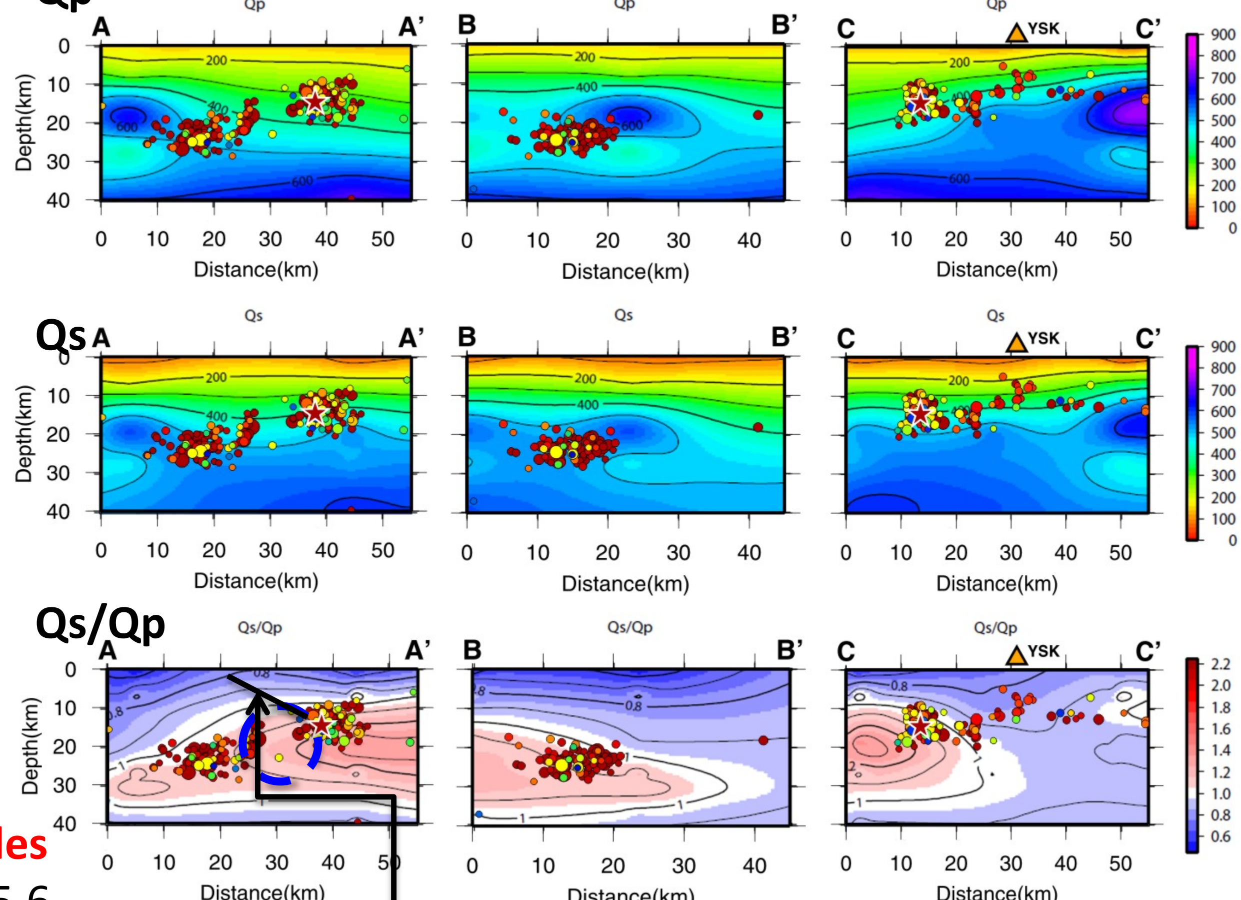
Comparison to the aftershocks distributions

Most of the aftershocks did not coincide with mainshock fault plane as shallow northern dipping, but within the regime of Qs/Qp>1 (Mud Diapirs related?)

YSK, KSP: Mud Volcanoes



Qp, Qs Tomography from Wang, Ma et al., 2008



NS Mw5.94 Shallow fault from InSAR

Meinong Earthquake 3 episodes

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3. Triggered Shallow NS shallow fault (Mud Diapier related?)

Qs/Qp>1 => indication of fluid contribution

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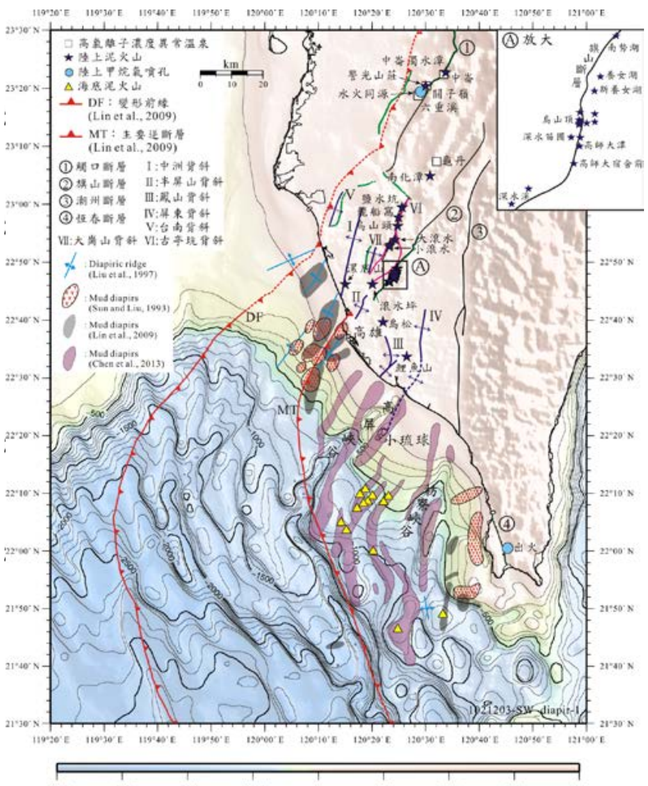
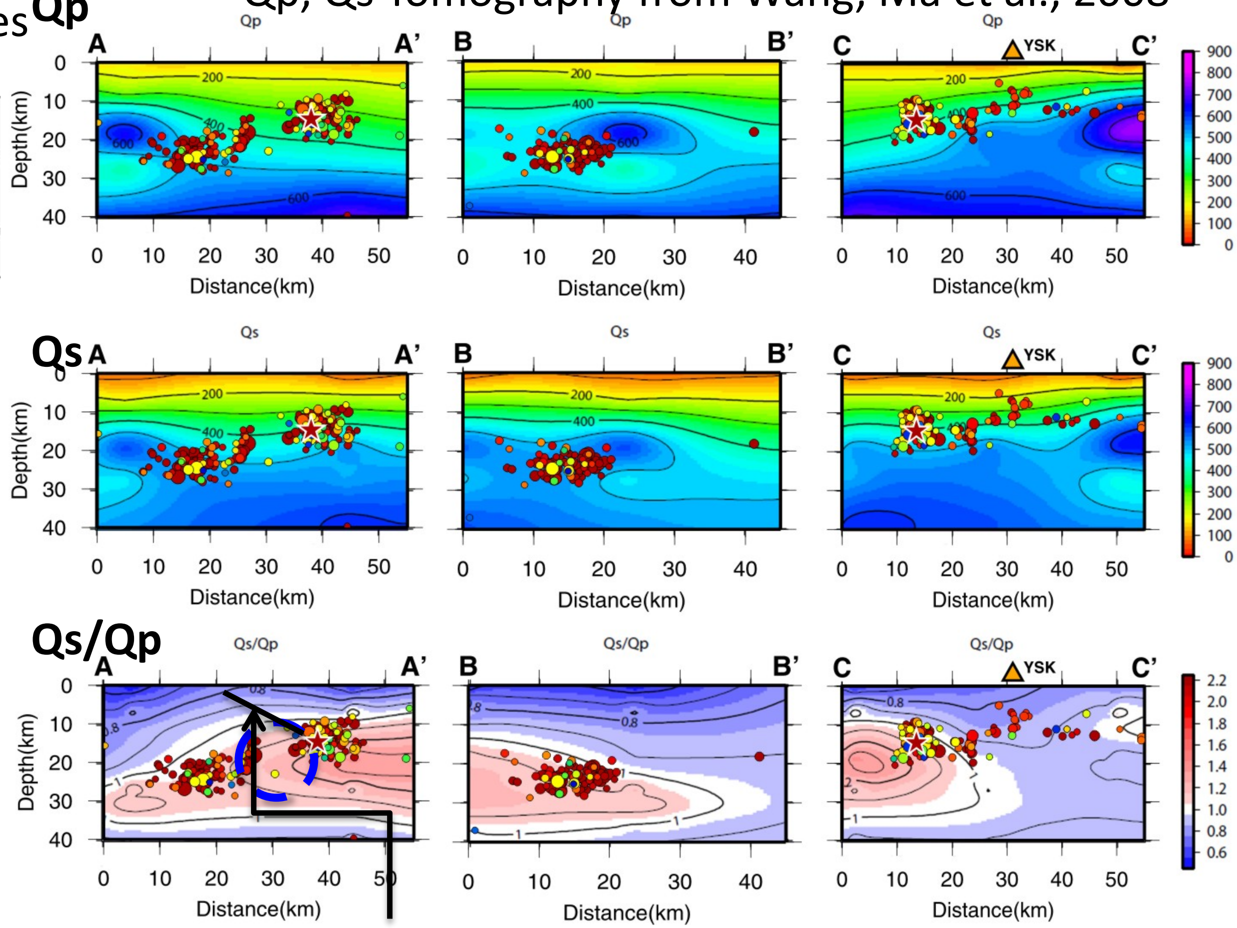
Mud Diapirs and Mud Volcanoes



From Andrew Lin, NCU

Qp, Qs Tomography from Wang, Ma et al., 2008



NS Mw5.94 Shallow fault from InSAR

Thank you!

謝謝！

Western Stations,
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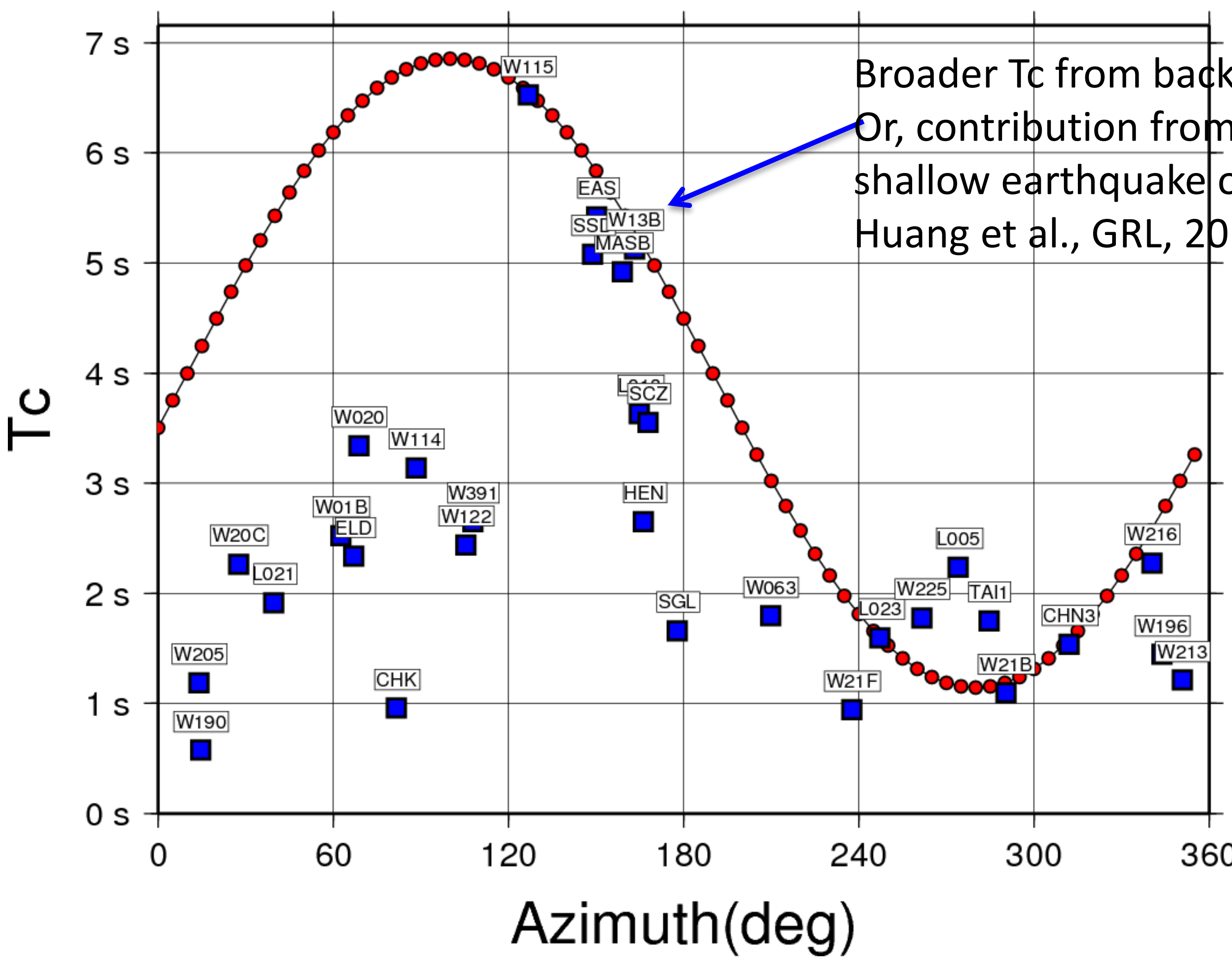
Examination on Directivity

RupLen=10 km, RupAzi=280 deg, Vr=2.5 km/s, C=3.5 km/s



Broader Tc from backward rupture directivity?
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Huang et al., GRL, 2016

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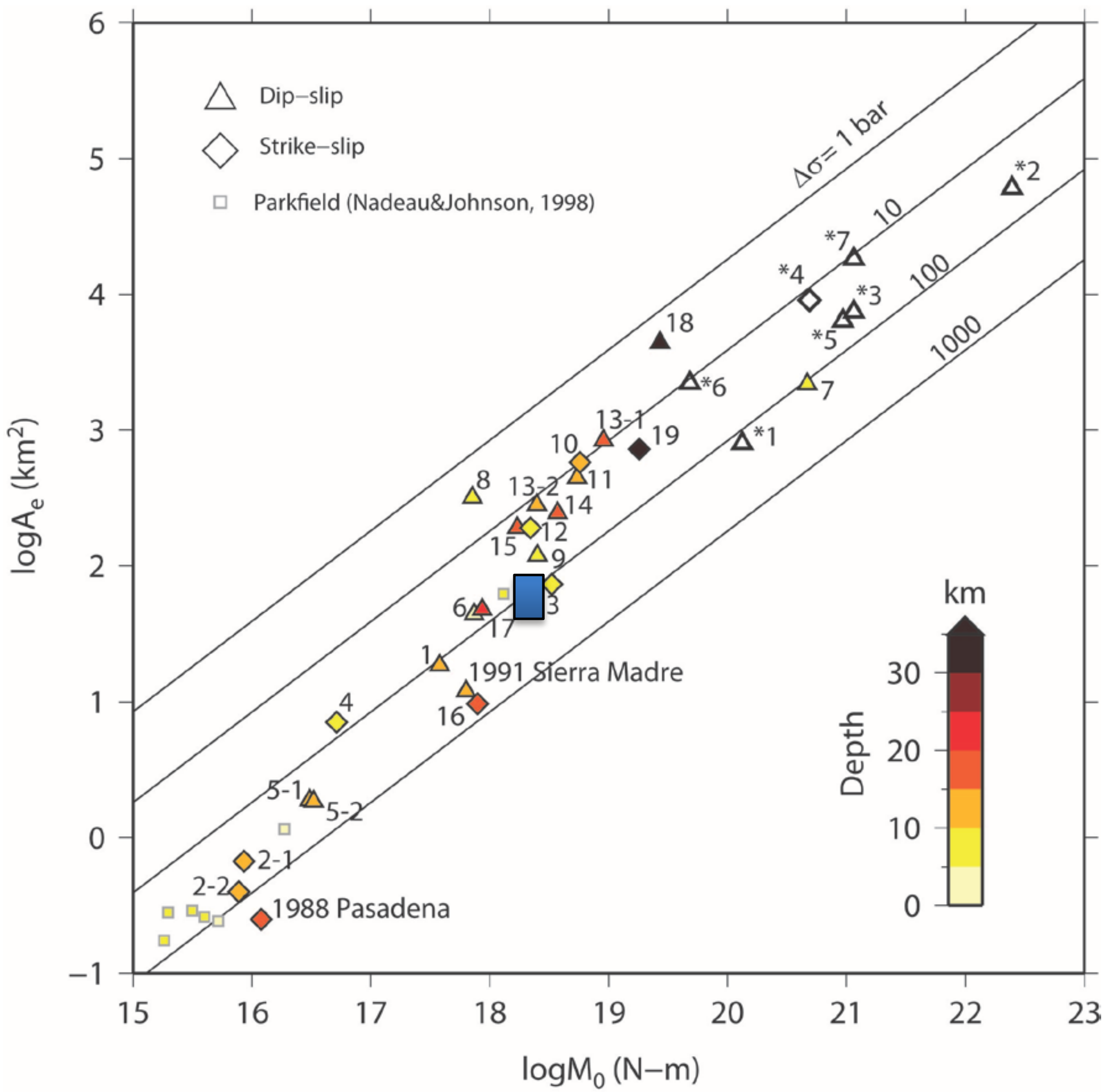
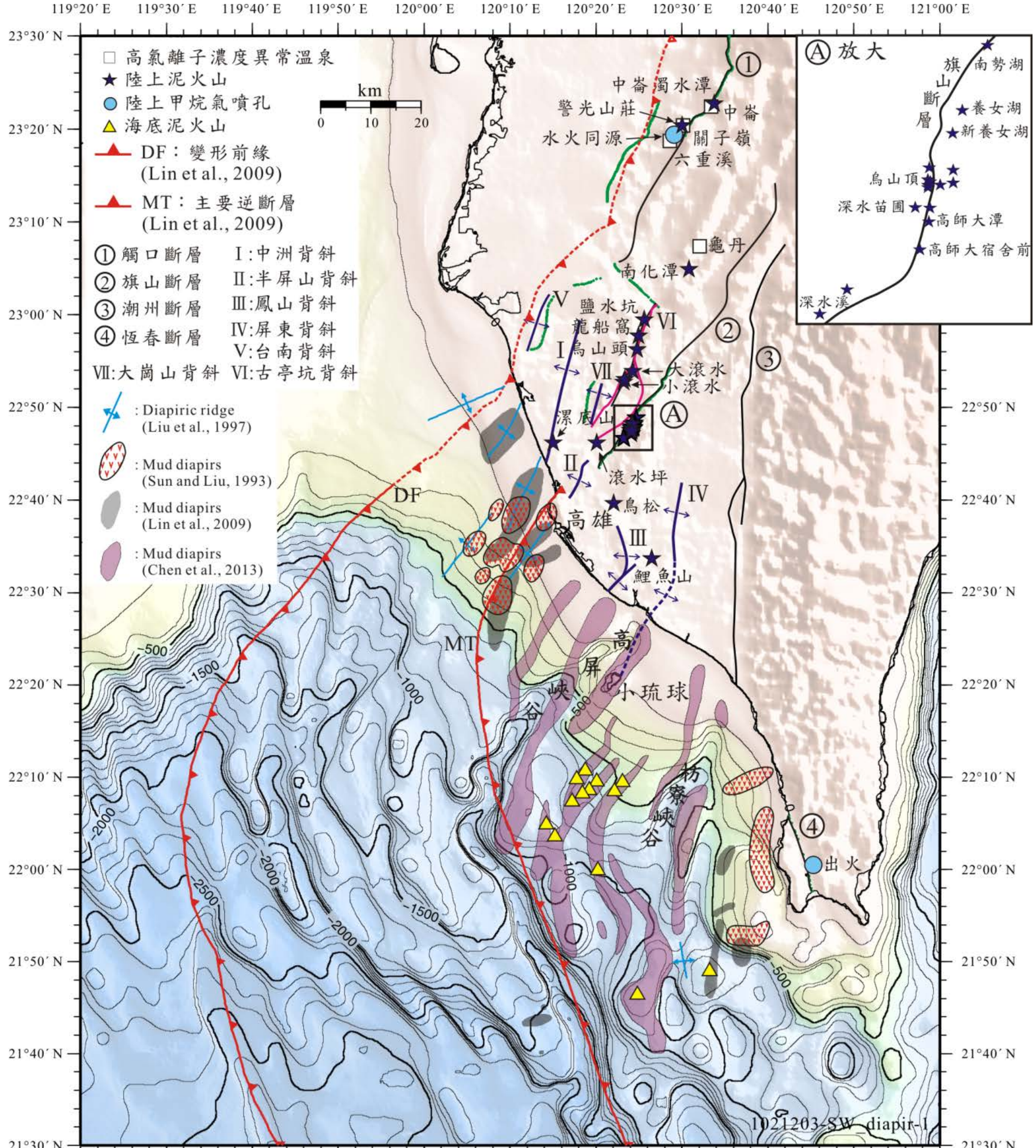


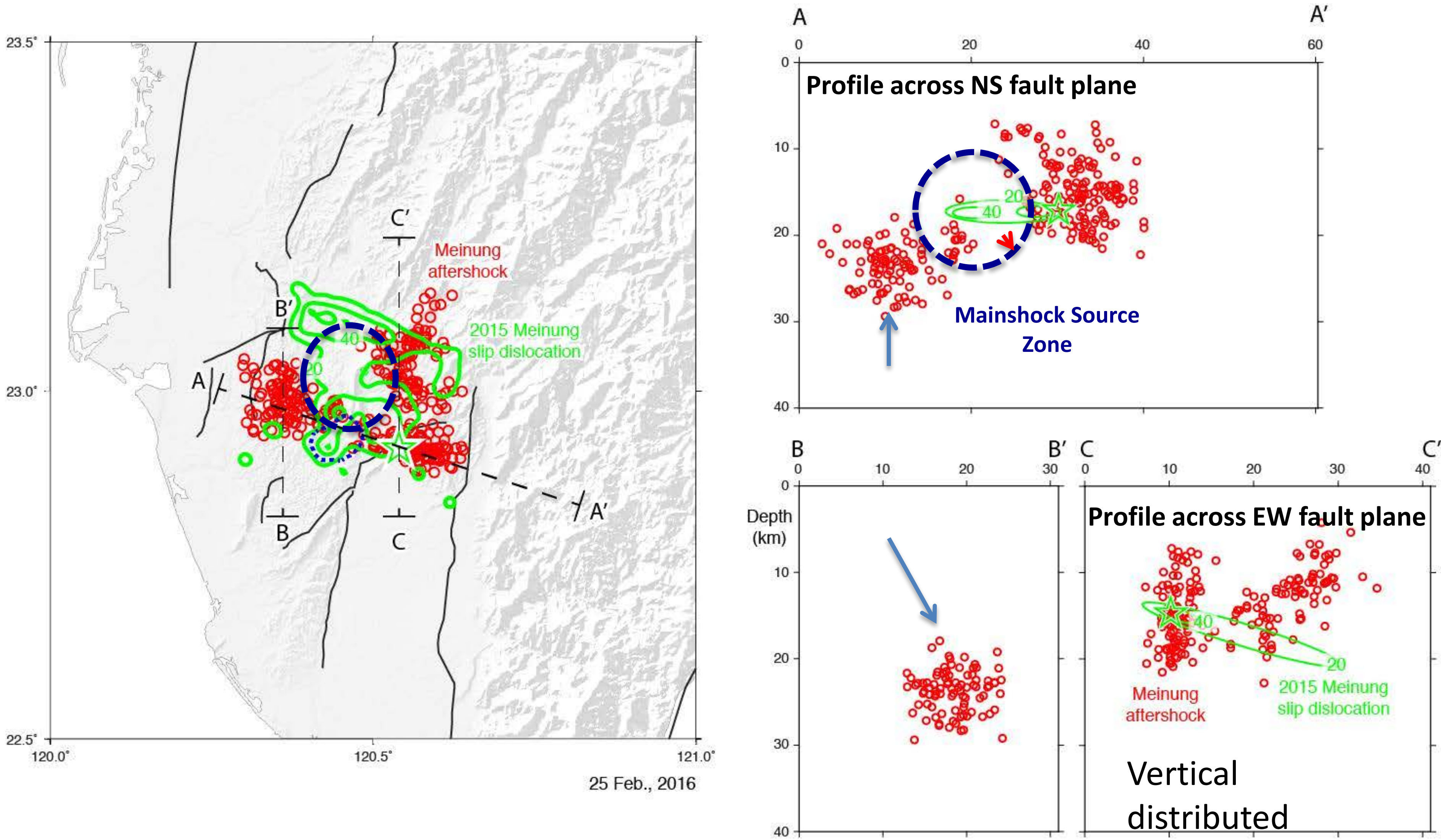
Dip–slip
Strike–slip
Parkfield (Nadeau&Johnson, 1998)
Δσ= 1 bar
10
100
1000
logA_e (km^2)
logM_0 (N–m)
km
Depth
1991 Sierra Madre
1988 Pasadena


高氯離子濃度異常溫泉
陸上泥火山
陸上甲烷氣噴孔
海底泥火山
DF：變形前緣
(Lin et al., 2009)
MT：主要逆斷層
(Lin et al., 2009)
① 觸口斷層
② 旗山斷層
③ 潮州斷層
④ 恆春斷層
I:中洲背斜
II:半屏山背斜
III:鳳山背斜
IV:屏東背斜
V:台南背斜
VI:古亭坑背斜
VII:大崗山背斜
: Diapiric ridge
(Liu et al., 1997)
: Mud diapirs
(Sun and Liu, 1993)
: Mud diapirs
(Lin et al., 2009)
: Mud diapirs
(Chen et al., 2013)
km
0
10
20
Ⓐ 放大
中崙
警光山莊
水火同源
關子嶺
六重溪
龜丹
南化潭
鹽水坑
龍船窩
烏山頭
大滾水
小滾水
滾水坪
烏松
高雄
鯉魚山
高屏峽谷
小琉球
枋寮峽谷
出火
旗山斷層
南勢湖
養女湖
新養女湖
烏山頂
深水苗圃
高師大潭
高師大宿舍前
深水溪
DF
MT
1021203-SW_diapir-1

Comparison to the aftershocks distributions

Most of the aftershocks did not coincide with mainshock fault plane as shallow northern dippin

120 Hrs aftershocks with proposed Mainshoce source zone

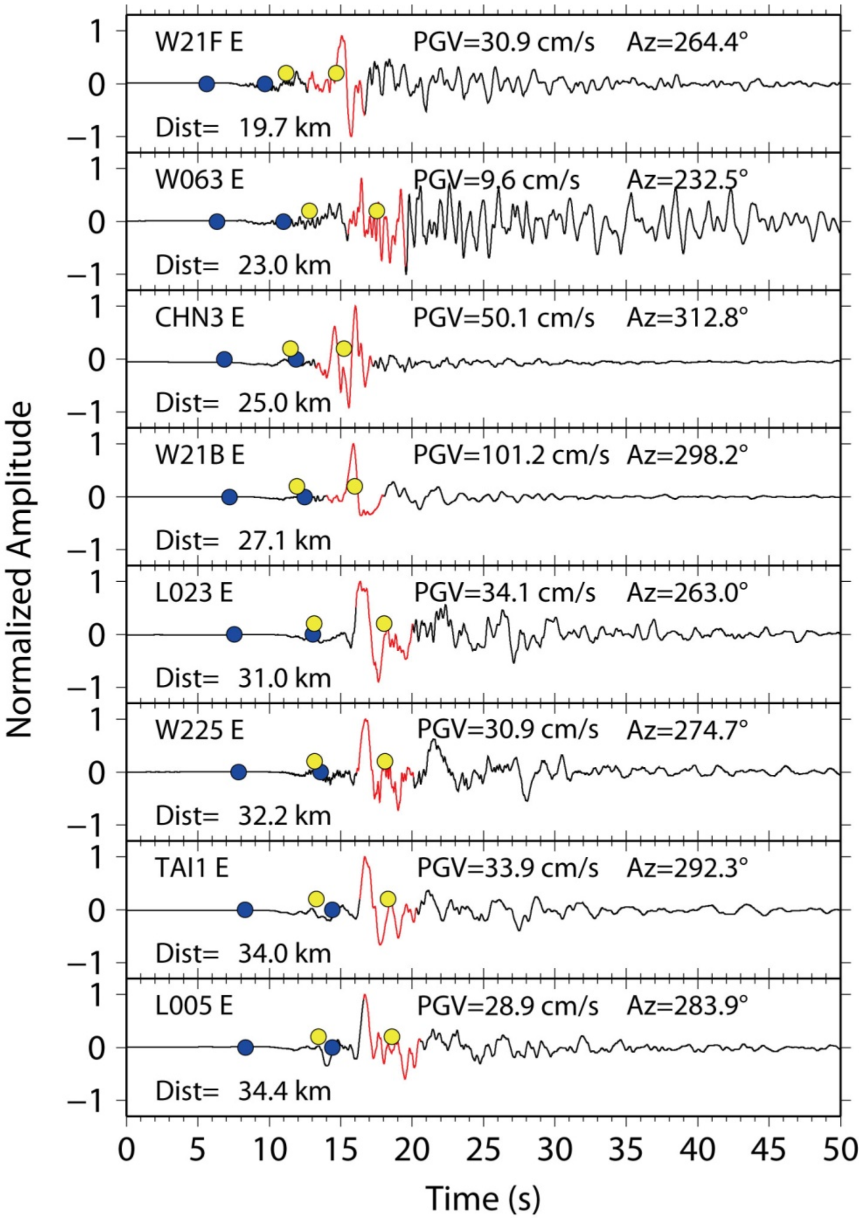


Vertical distributed aftershocks

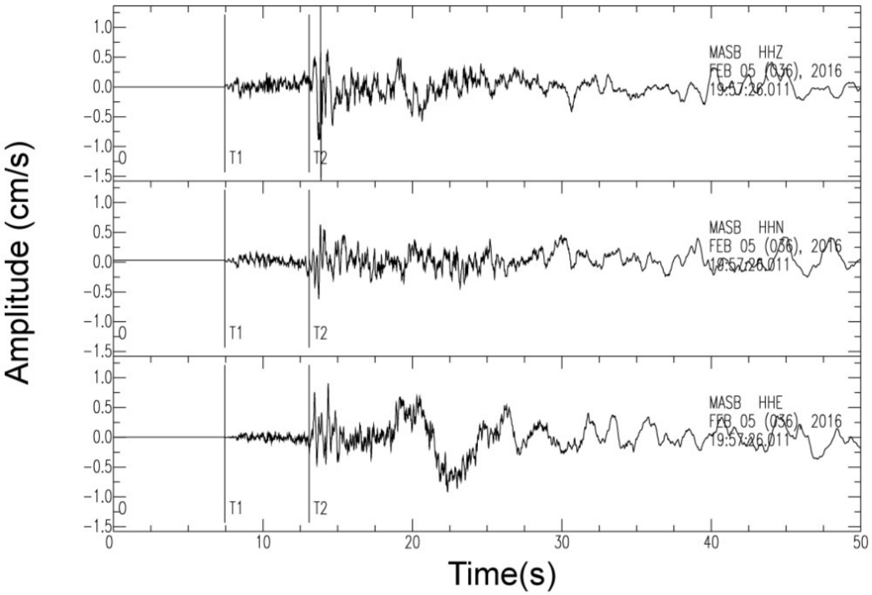
Aftershocks surround the Mainshock source zone

Aftershocks suggest possible conjugate faults rupture

Observations

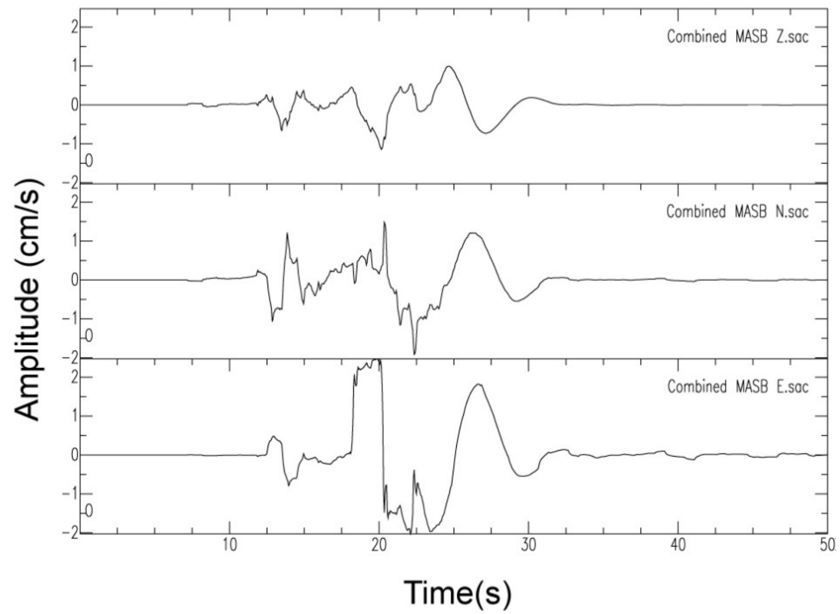


Observations (MASB)

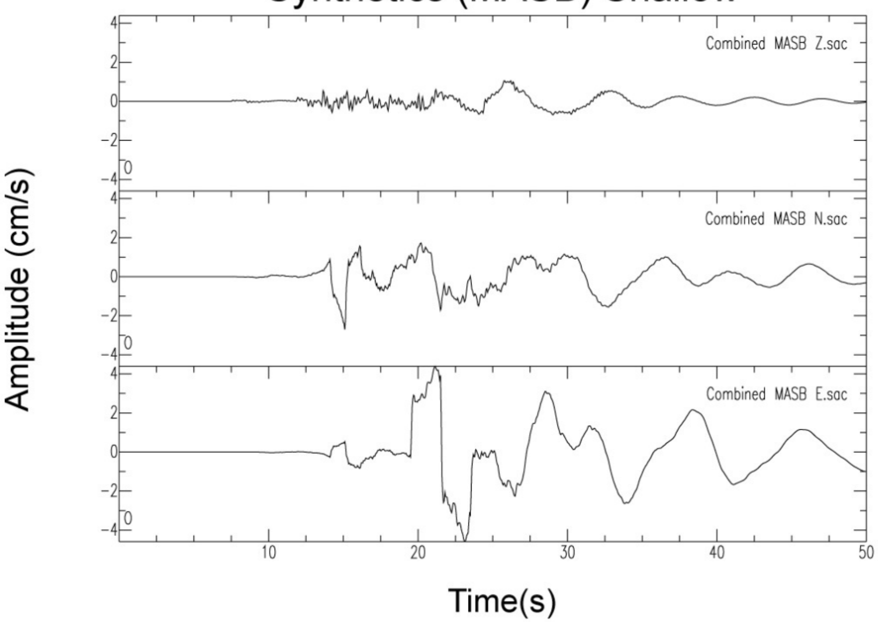


Source duration
for the
Foreshock =2.0 s
mainshock =4.0 s

Synthetics (MASB) CWB-1D

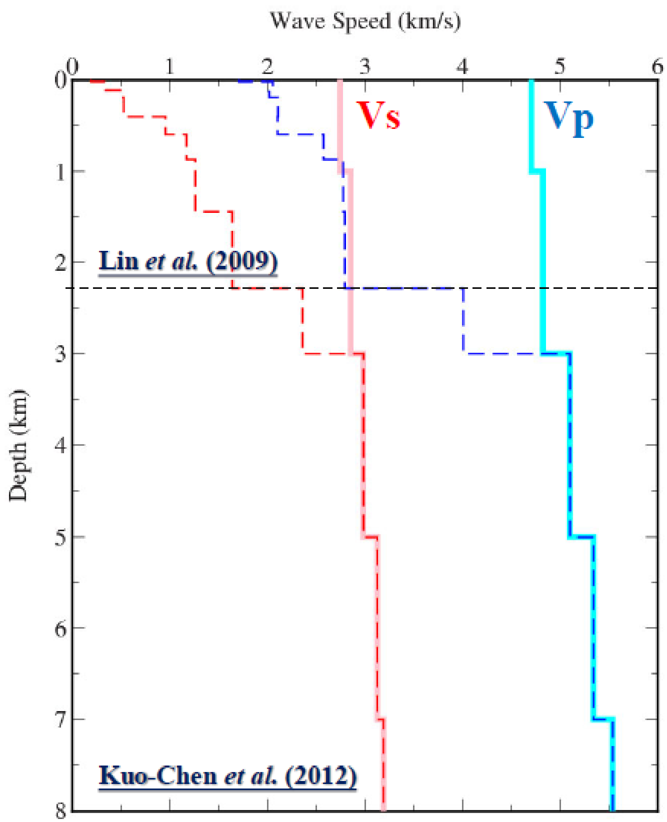


Synthetics (MASB) Shallow



Velocity structure

- 1-D model averaged from the 3-D model of **Kuo-Chen *et al.* (2012)**
- 1-D model of **Lin *et al.* (2009)** for Western Plain (**WP**)



(from Ming-Che' TGA talk)

Sources

Location:
Foreshock: CWB hypocenter
Mainshock: The result from SSA

Focal mechanism:
Foreshock: CWB first motion
Mainshock: RMT

Magnitude:
Foreshock: 5.64
Mainshock: 6.4

Duration:
Foreshock: 2 s
Mainshock: varying

Synthetic parameters

Foreshock (red)
Mw 5.64
Mainshock (blue)
Mw 6.40

Time Delay of Mainshock
4.4 s

Focal mechanism
Foreshock (P first motion)
254/11/-27
Mainshock (RMT)
274.6/22.1/17.7

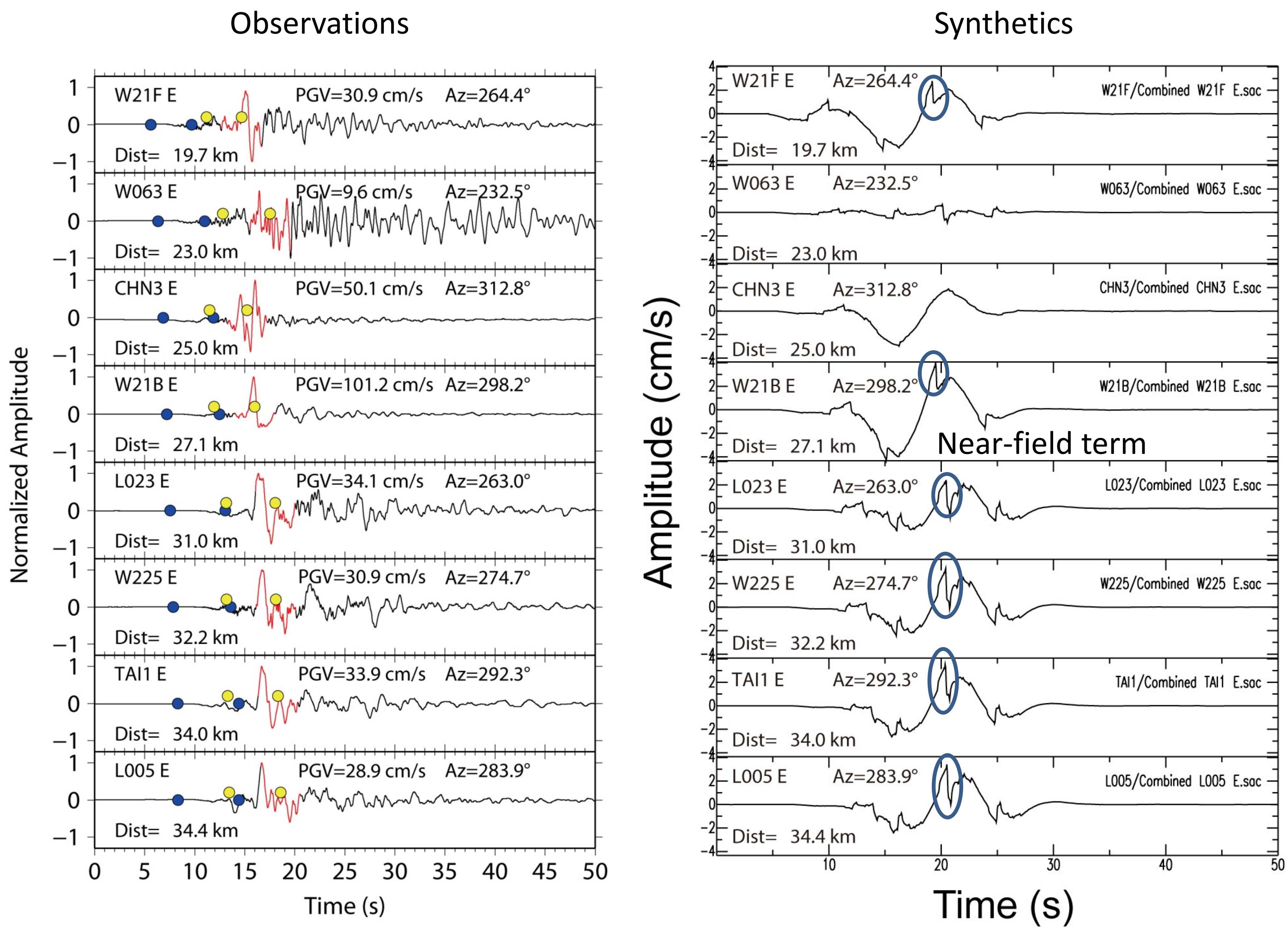
Source duration

$$t_w = 2.4 \times 10^{-8} \times M_0^{1/3}$$

(Duputel et al., 2013)

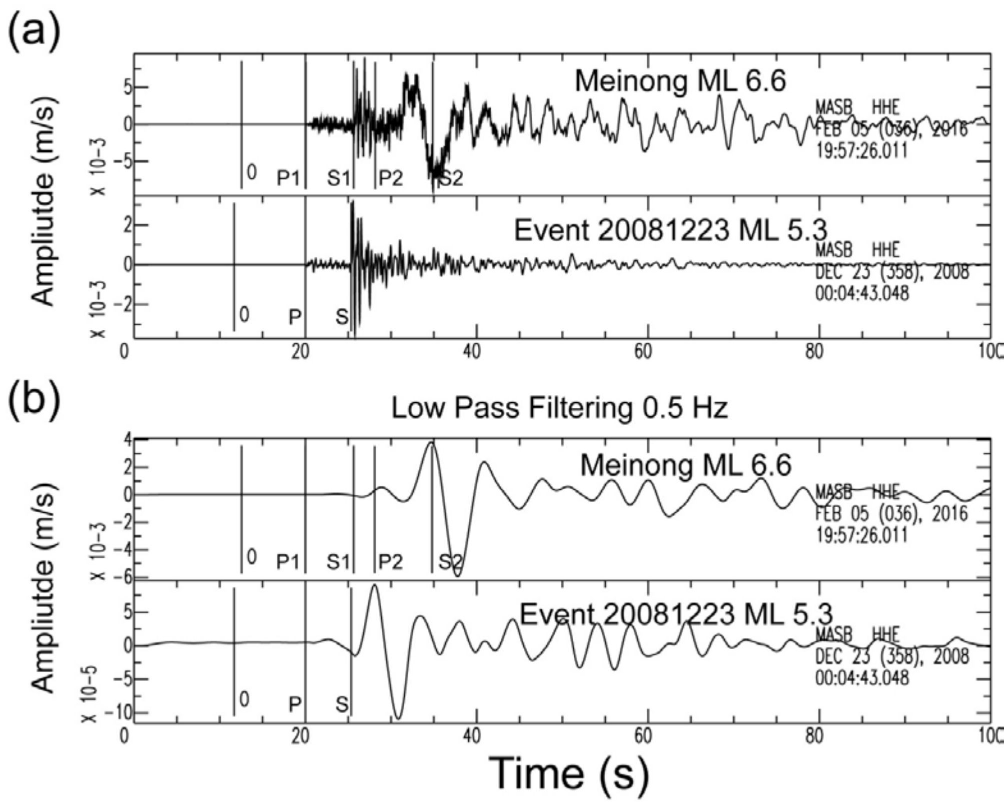
Foreshock
3.7 s
Mainshock
8.8 s

Velocity model
Taiwan 1D velocity model
Chen, 1995 (CWB)

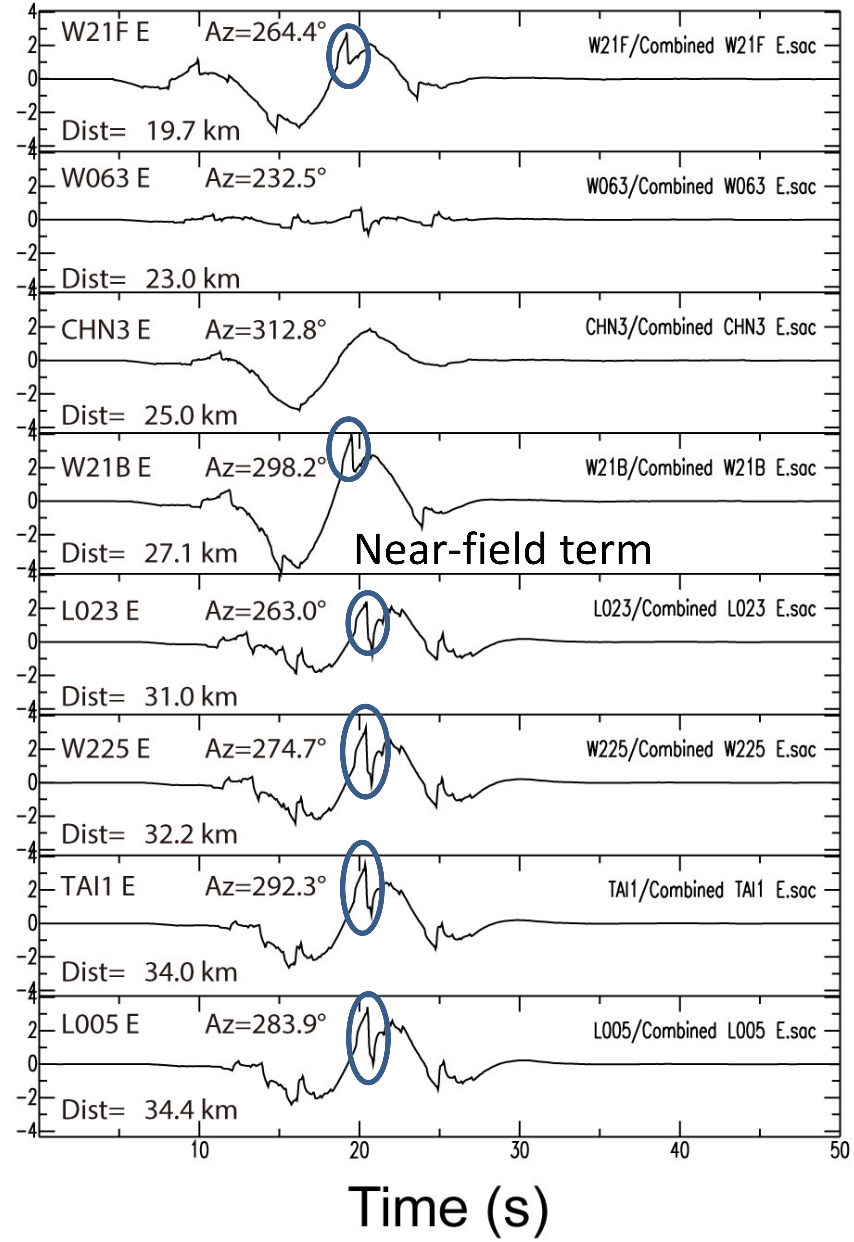


Observations
Synthetics
Normalized Amplitude
W21F E
PGV=30.9 cm/s
Az=264.4°
Dist= 19.7 km
W063 E
PGV=9.6 cm/s
Az=232.5°
Dist= 23.0 km
CHN3 E
PGV=50.1 cm/s
Az=312.8°
Dist= 25.0 km
W21B E
PGV=101.2 cm/s
Az=298.2°
Dist= 27.1 km
L023 E
PGV=34.1 cm/s
Az=263.0°
Dist= 31.0 km
W225 E
PGV=30.9 cm/s
Az=274.7°
Dist= 32.2 km
TAI1 E
PGV=33.9 cm/s
Az=292.3°
Dist= 34.0 km
L005 E
PGV=28.9 cm/s
Az=283.9°
Dist= 34.4 km
Time (s)
Amplitude (cm/s)
W21F/Combined W21F E.sac
W063/Combined W063 E.sac
CHN3/Combined CHN3 E.sac
W21B/Combined W21B E.sac
L023/Combined L023 E.sac
W225/Combined W225 E.sac
TAI1/Combined TAI1 E.sac
L005/Combined L005 E.sac
Near-field term
Time (s)

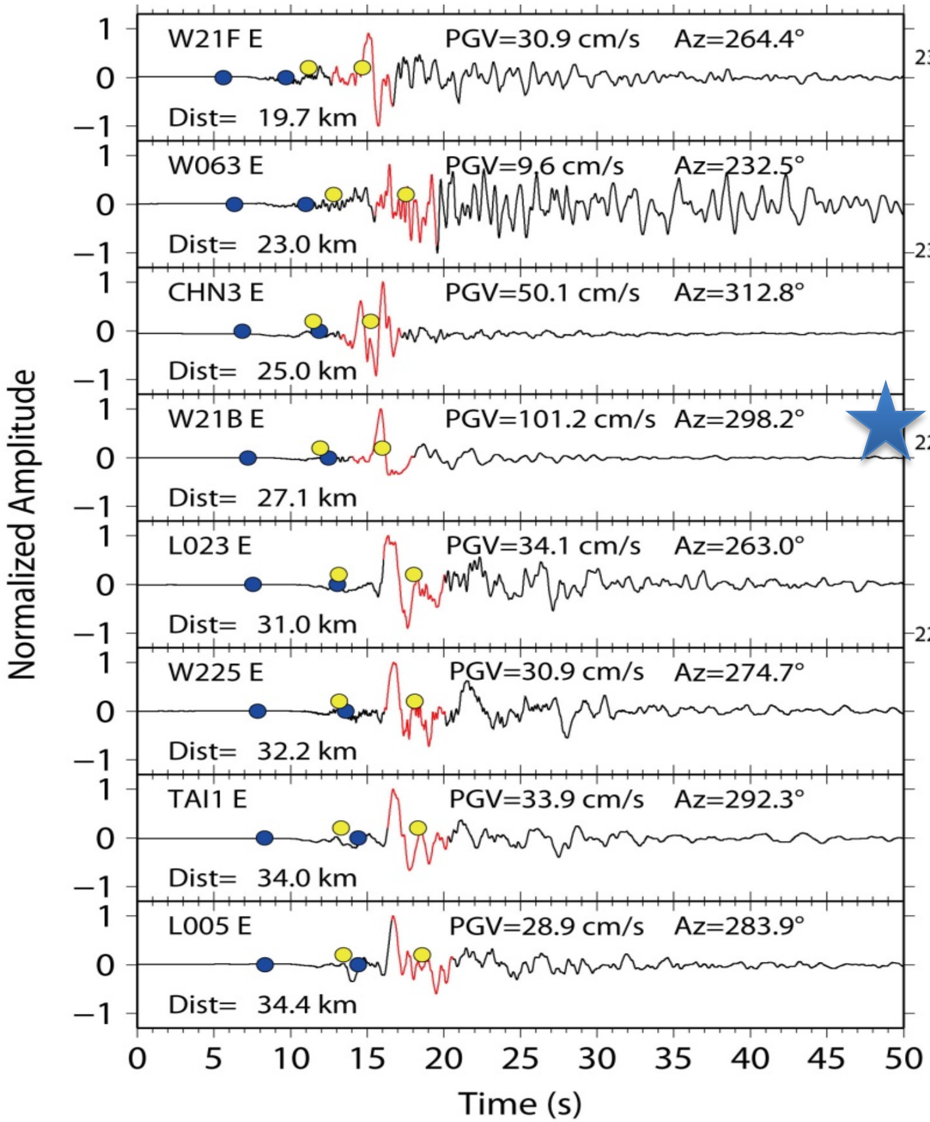
Observations @MASB,
S2-wave on ~10sec long-period wave

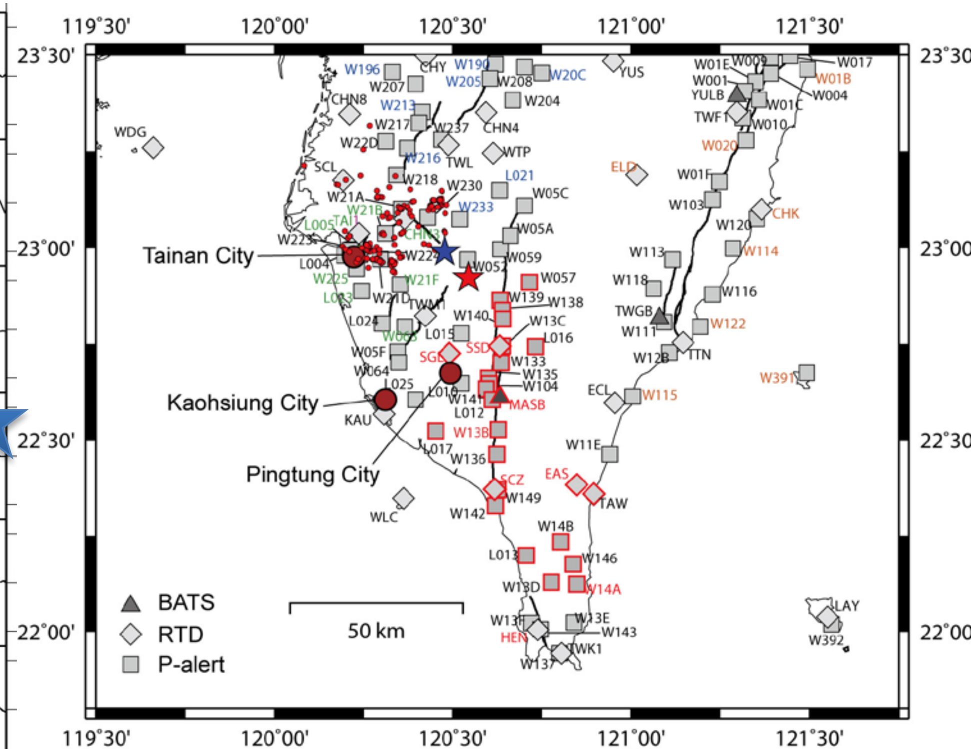


Synthetics



Normalized velocity waveforms of E-component In Western Direction
(Tainan city) Palert + RTD: Killer pulse



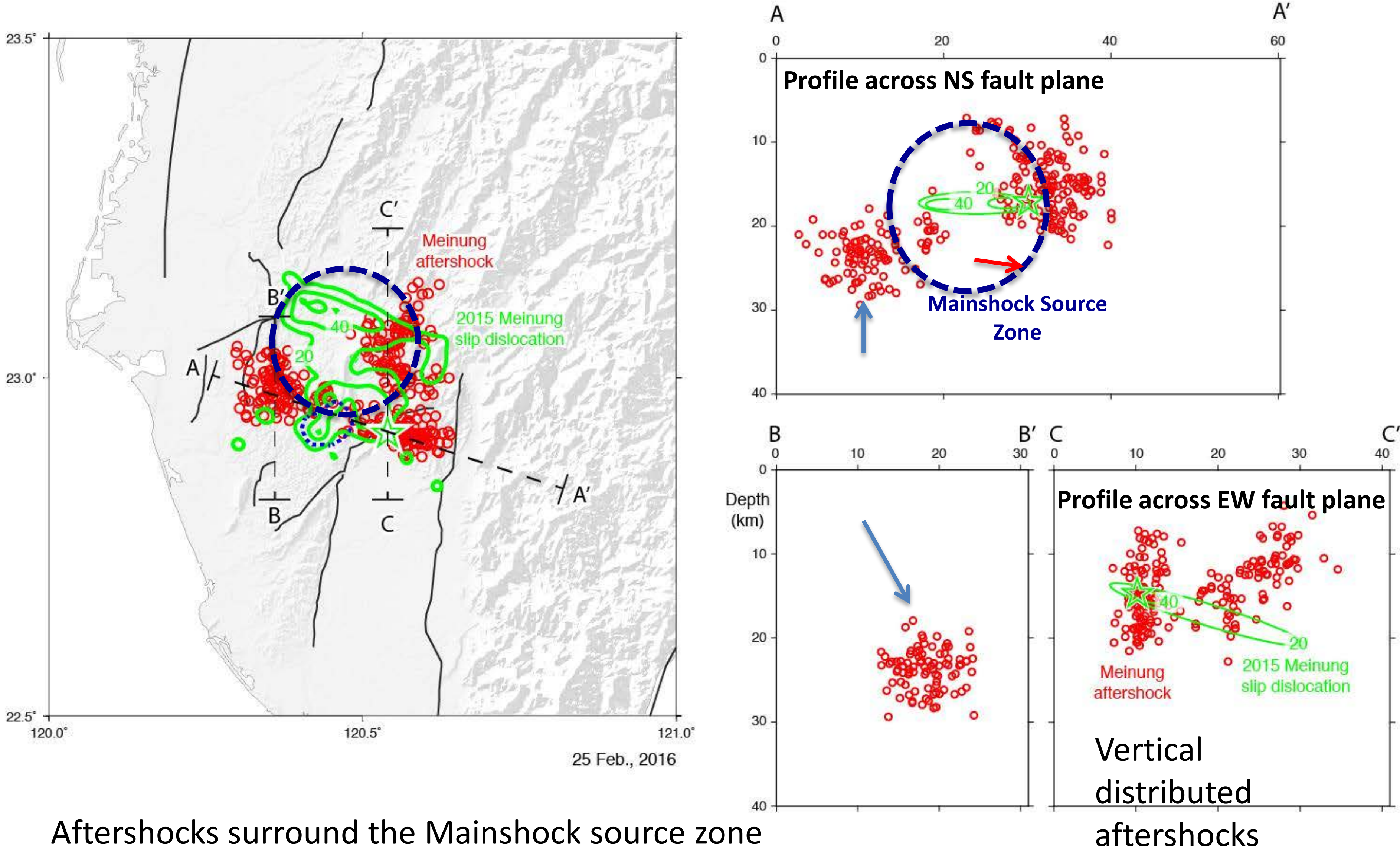


Generation of the Killer pulse

⇒ **Direct S-wave** from a concentrated circular source.

(MC Hsieh, TGA 2016)

120 Hrs aftershocks with proposed Mainshoce source zone



Aftershocks surround the Mainshock source zone

Aftershocks suggest possible conjugate faults rupture

Conclusions

- **Denoted the Foreshock and Mainshock directly from dense seismic array of Palert+RTD+BATS**

  Foreshock, M_W~5.64 Location, CWB 20160206 location

  Mainshock, M_W~6.4 ~4-10 sec after Foreshock from SSA

  Location, down-dip and west from the foreshock

  Circular fault rupture, but, mainly for West and North

- **Asperity or double events?** Asperity for sure as a large slip patch at the mainshock location. But, we call it Foreshock and Mainshock as the clear observations of P1, S1, and P2, S2.

- **Killer pulses** observed in western Taiwan are the **direct S-wave** of the circular source, rather than mostly from surface wave for earthquake destruction.

- **Aftershocks patterns**

  Association with Conjugate faults, rather than the initiated ruptured fault?

  => **First shock triggered conjugate fault for Mainshock event and aftershocks**

- **Doubts. Not yet good explanation of the N-comp (Basin effect?)**

  No significant surface waves, why?

- Suggestions to paper

1. Modeling the FK also for MASB station.

   Using near-field term to constrain the depth of the Mainshock source zone

   How are the waveform fits in NS components?

   ppt14, showing good fits for far-field S-wave, but, near-field term is too large. Adjust the contribution of the near-filed term from the size of the source, the depth, and the amount of slip.

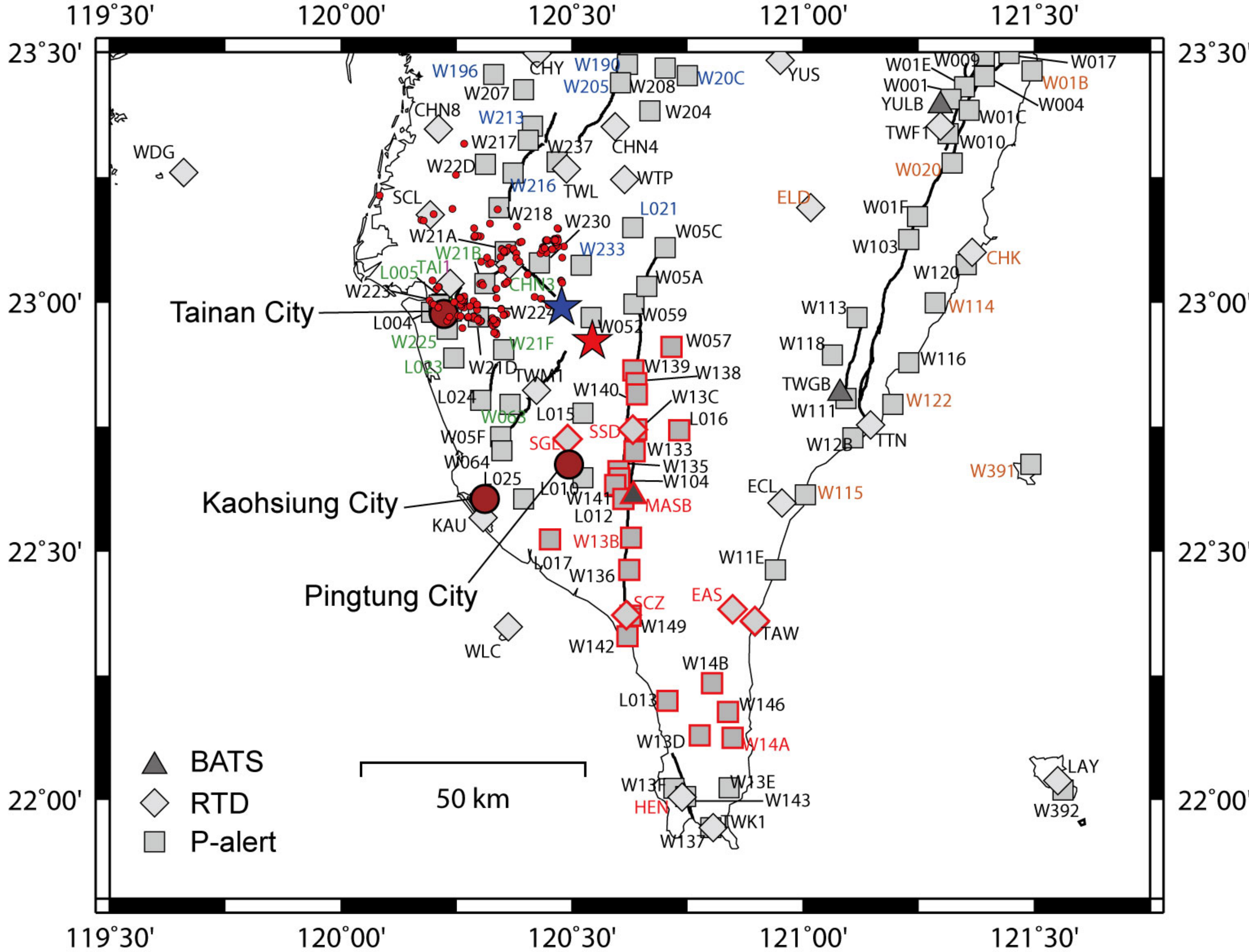
2. SSA or Palert location as the initiation of the mainshock? The implications of the locations differences from Palert or SSA? (Or the source zone as in between of Palert and SSA locations?) I can ask The-Yang during TGA on this.
3. Plot the F+M source zone and SJ slip distribution to aftershock distribution.

4. Emphasize the killer pulse from direct S-wave not the surface wave. (reference to 1995 Kobe, and 2016 熊本地震）

5. I have question. Where is the surface wave of this earthquake. 15km is not too deep, but, why no surface waves were observed….?

Minor to Figure

1. Normalize displacement records. Give the PGDmax values in the record.
2. Show focal mechanisms of the 0206 event and also the 2008 event somewhere in the paper. (No focal mechanism was shown in any figure).
3. If the FK modeling is good, show the similar Figure of ppt14, and also a comparison for MASB station.



119°30'
120°00'
120°30'
121°00'
121°30'
23°30'
23°00'
22°30'
22°00'
Tainan City
Kaohsiung City
Pingtung City
50 km
BATS
RTD
P-alert

初步地震波模擬

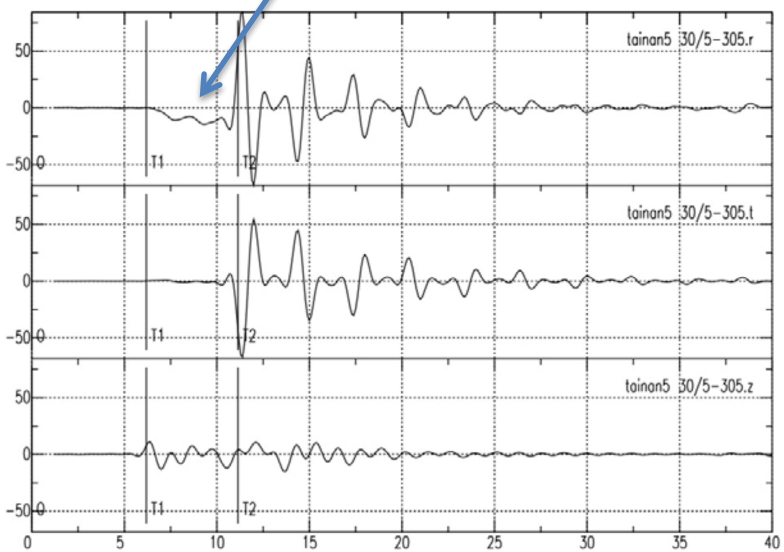
速度構造：地表1.5 公里 低速層 Vs＝1.0km/sec, Vp=1.8km/sec

主震震源機制 Strike/dip/rake 271/41/17

事件二 離台南約5公里 深30 公里

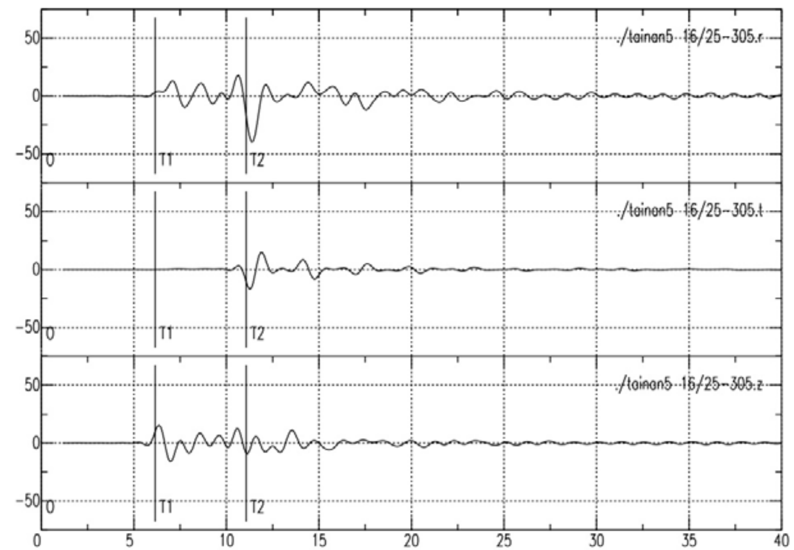
Distance 5km, depth=30km

W21B 站 Near-Field



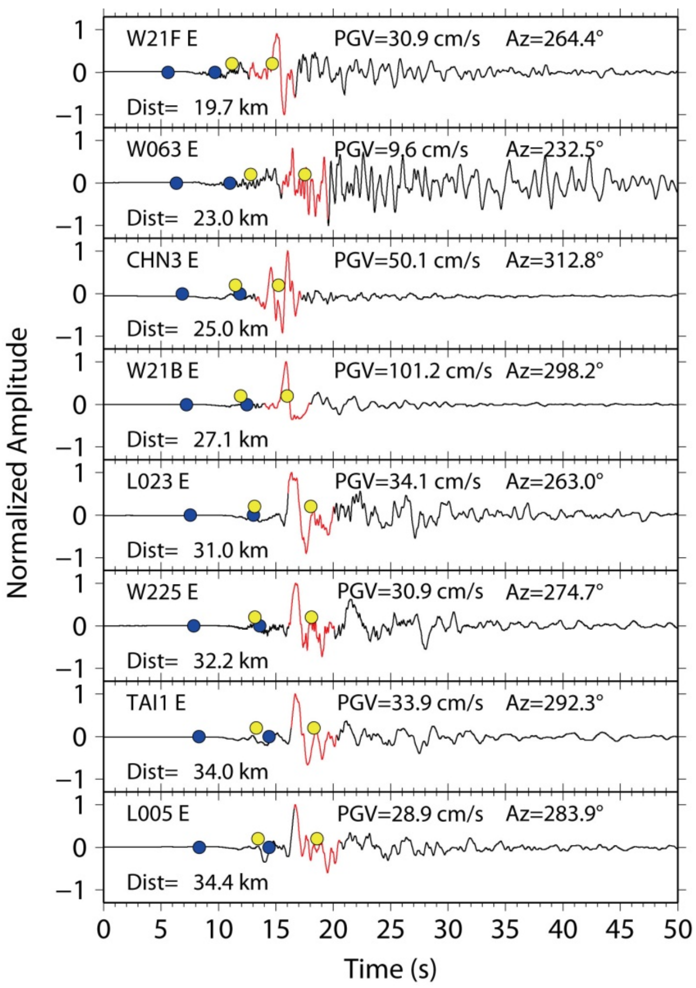
主震 離台南約25公里 深16 公里

Distance 25km, depth=16km



考慮 近台南W21B站 由主震及第二事件的合成地震波

初步分析顯示 在台南的大長週期速度紀錄 可能與近台南地區的深部事件有關



Velocity waveforms of E-com
stations in the south directio
indicate the P1 and S1 phase
The yellow circles are P2 and
mainshock. Waveform in red
contribution of the S2 phase
station name, distance, azimu
indicated on the traces.

Palert Observations of S2 Phase
FK synthetics
=>2nd event with similar focal mechanism with magnitude of about M6 from 10km west of hypocenter