

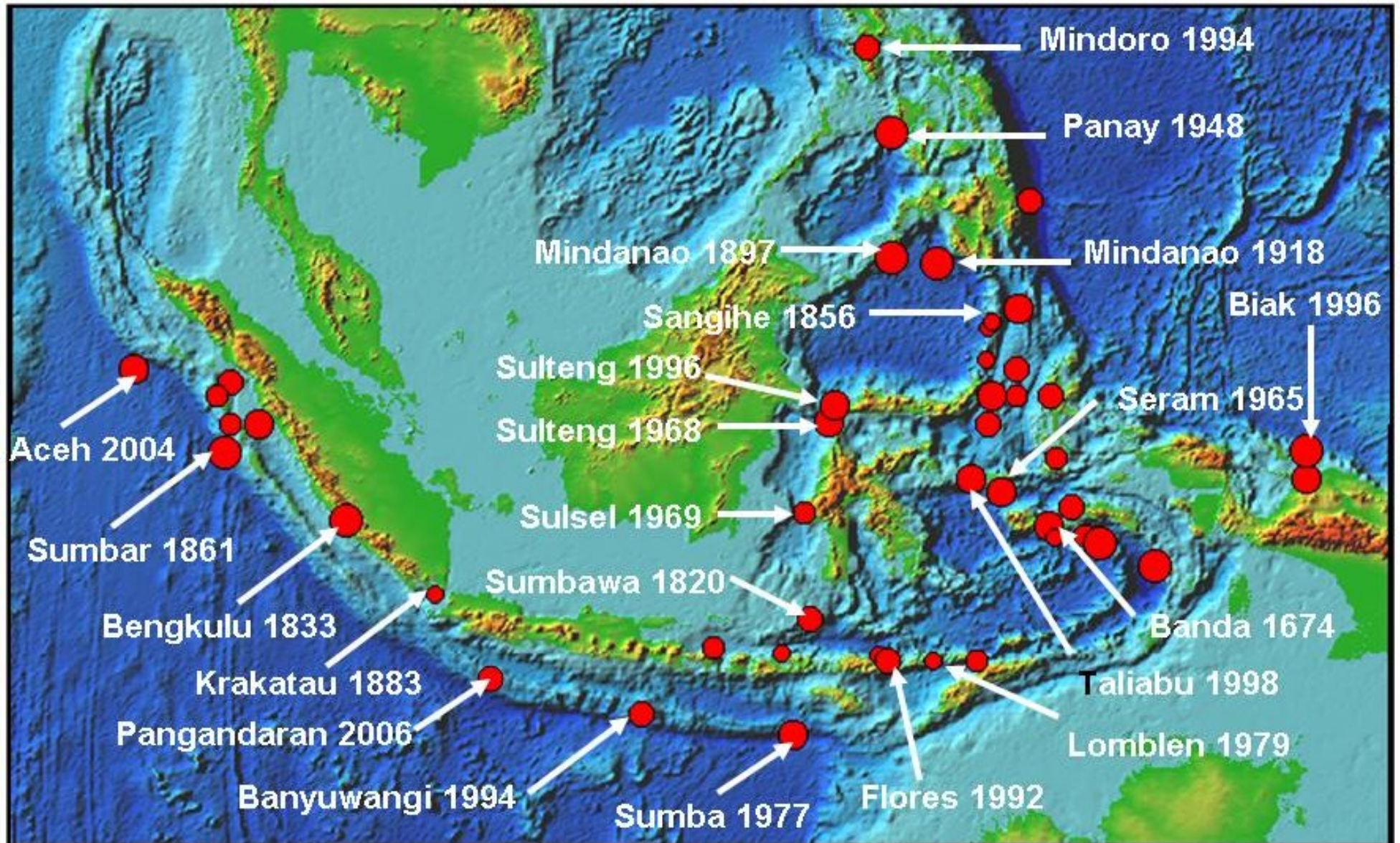
Program Riset ITB tahun 2012



Studi Karakterisasi Gempa Pembangkit Tsunami Berdasarkan Rasio Energi-Momen Seismik

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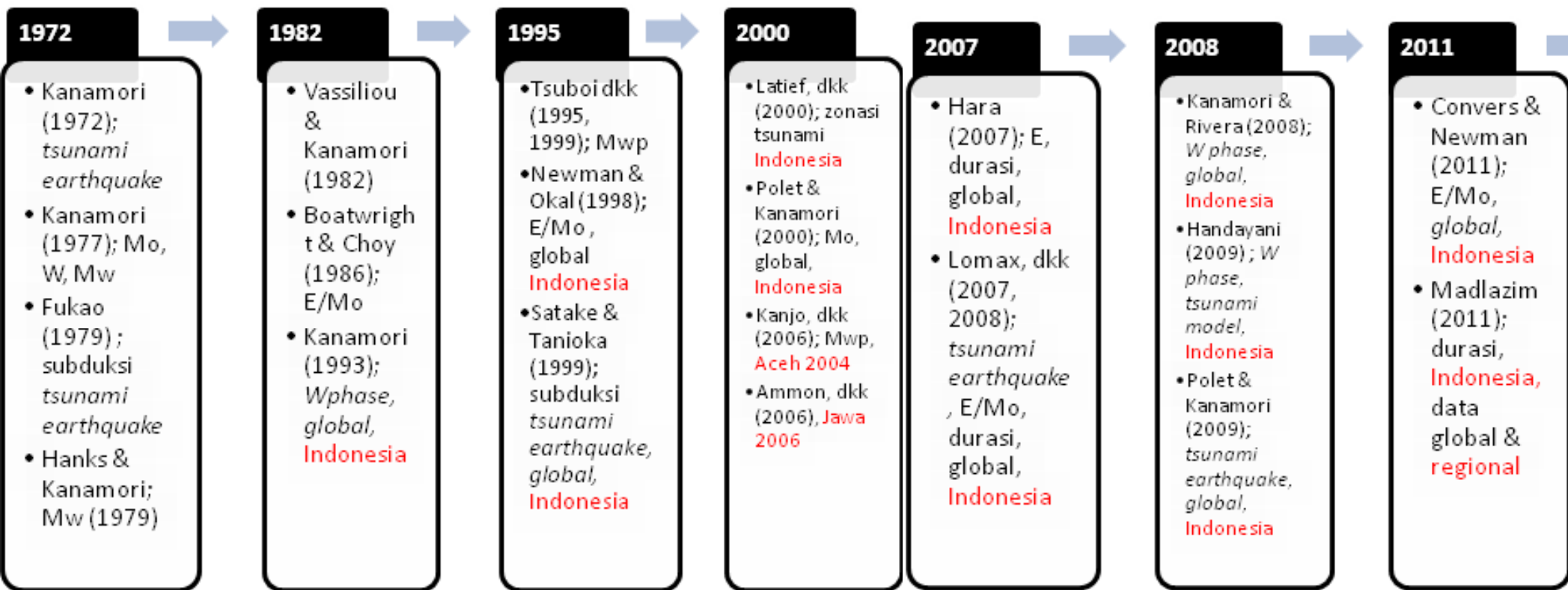
Major tsunami disasters



Most of the tsunamis were generated by earthquakes

Earthquake's characteristics?

Penelitian terdahulu tentang gempa pembangkit tsunami



- Gempa pembangkit tsunami:**
- 1. Tsunamigenic earthquake**
 - 2. Tsunami earthquake**

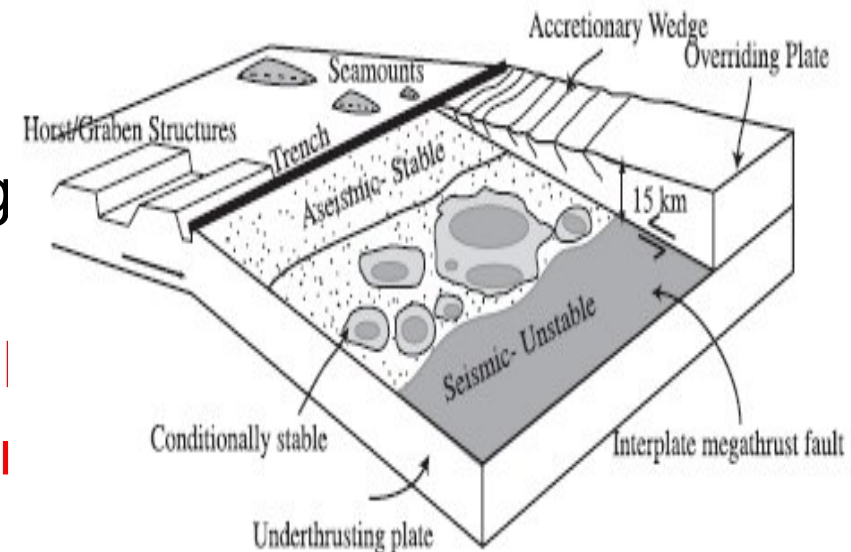
Gempa pembangkit tsunami

- *Tsunamigenic earthquake*

- Magnitudo besar ($M_w > 8$), tsunami besar ($H > 3$ m)
- Magnitudo kecil s.d. sedang ($M < 7.5$), tsunami kecil ($H < 1$ m)

- *Tsunami earthquake*

- (Bilek, dkk., 2007; Kanamori, 1972; Satake dan Tanioka, 1999; Fukao, 1979)
 - Magnitudo sedang ($M_w > 7.5$) tsunami besar ($H > 5$ m)
 - Magnitudo gel. badan (m_b) < magnitudo momen (M_w) Bilek, dkk., 2007
 - Kedalaman dangkal ($D < 20$ km)
 - Dekat zona subduksi
 - Sedimen lemah, tebal, muda, heterog
 - Zona labil gempa sewaktu-waktu
 - *Rupture duration lama, kurang dirasa*
 - *Nilai rasio energi terhadap momen re*

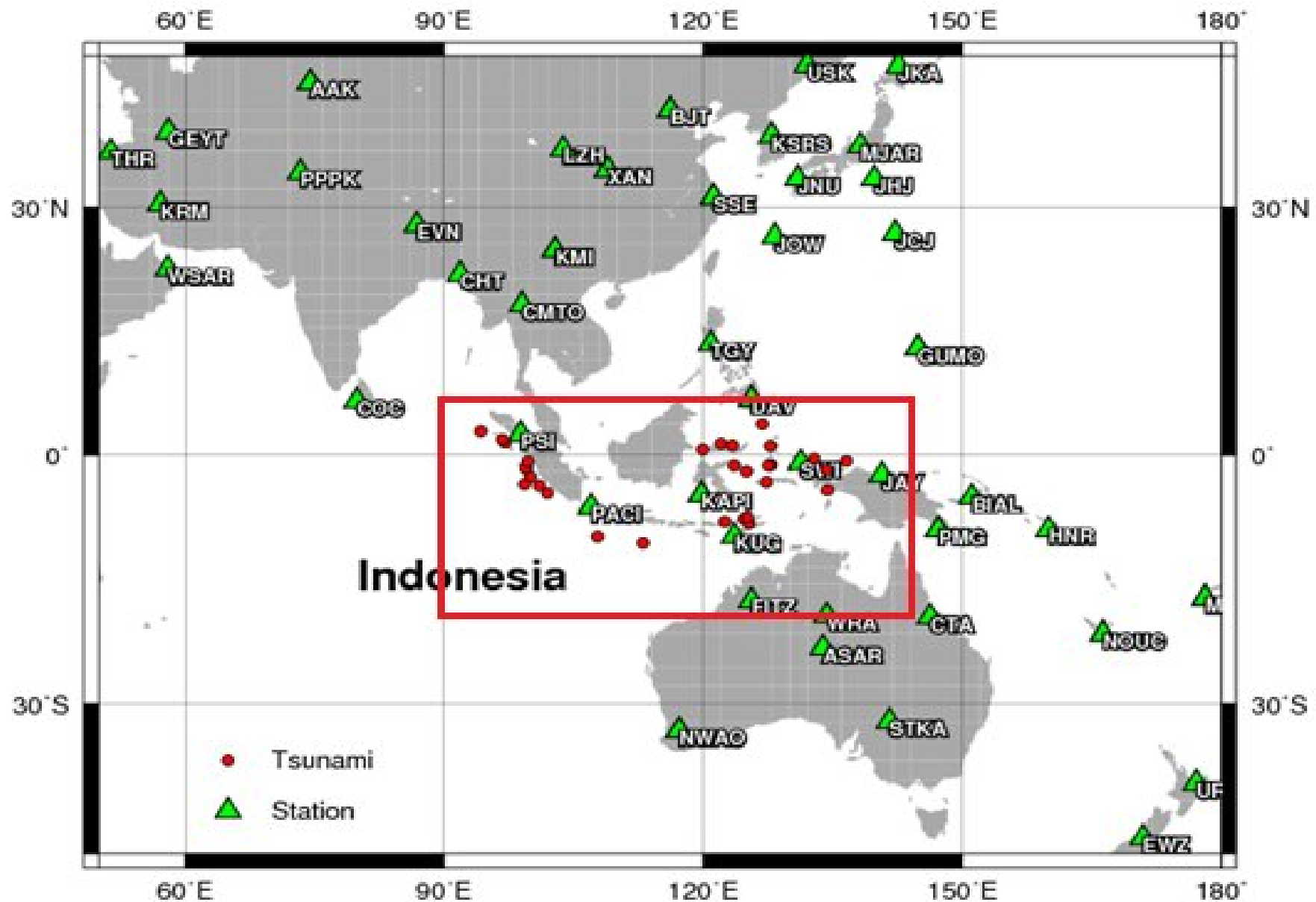


Penelitian kami tentang gempa pembangkit tsunami:

**Program Riset ITB 2011:
Karakterisasi berdasarkan mekanisme sumber
gempa menggunakan metoda W-phase**

**Program Riset ITB 2012:
Karakterisasi berdasarkan rasio energi –
momen seismik**

Wilayah penelitian dan sebaran stasiun IRIS yang digunakan



Data

- Katalog gempa bumi pembangkit tsunami:
 - Wilayah Indonesia :
 - **Juni 1991 s.d. Mei 2012, Mw > 6.5, 27 kejadian**
 - Global CMT, USGS, Engdahl, jurnal,
- Katalog tsunami:
 - NOAA, Lab. Russia, jurnal
 - Peringatan dini regional dan laporan survey BMKG
- Sinyal seismik:
 - IRIS, BMKG, 783 stasiun

<i>No</i>	<i>Location</i>	<i>Event</i>	<i>Time</i>	<i>H</i>	<i>D^G</i>	<i>M_w^W</i>	<i>M_w^S</i>
1	Timor	19910704	11 43 15.6	13.0	17.0	6.7	6.6
2	Flores	19921212	05 29 49.9	26.2	20.4	7.8	7.7
3	Java (TE)	19940602	18 18 15.8	13.9	15.0	7.8	7.8
4	Halmahera	19941008	21 44 13.5	3.0	15.0	6.8	6.6
5	Halmahera	19950213	15 04 30.4	NA	15.0	6.7	6.6
6	Timor	19950514	11 33 28.6	4.0	15.8	6.8	6.7
7	Minahasa	19960101	08 05 23.1	3.4	15.0	7.8	8.0
8	Biak	19960217	06 00 02.8	7.7	15.0	8.1	8.1
9	Sulawesi	20000504	04 21 33.4	5.0	18.6	7.5	7.5
10	Bengkulu	20000604	16 28 46.5	NA	33.0	7.9	8.0
11	Papua	20021010	10 50 41.9	3.0	15.0	7.8	7.5
12	Aceh	20041226	01 01 09.0	32.0	28.6	9.1	8.8
13	Nias	20050328	16 10 31.5	4.0	25.8	8.6	8.4
14	Padang	20050410	10 29 17.8	0.4	15.0	6.7	6.6
15	Seram	20060314	06 57 37.5	5.0	13.0	6.6	6.6
16	Java (TE)	20060717	08 20 38.4	7.5	20.0	7.6	7.7
17	Bengkulu	20070912	11 11 15.6	3.0	24.4	8.4	8.4
18	Pagai	20080225	08 36 42.4	NA	14.4	6.9	7.1
19	Sulawesi	20081116	17 02 43.8	NA	29.2	7.4	7.3
20	Papua	20090103	22 33 44.9	0.4	15.2	7.7	7.6
21	Talau	20090211	17 35 01.2	0	23.9	7.1	7.1
22	Mentawai	20090816	07 38 28.6	0.2	12.0	6.7	6.6
23	Java	20090902	07 55 07.5	0	53.0	7.3	7.2
24	Padang	20090930	10 16 17.4	0.3	77.8	7.5	7.7
25	Sinabang	20100406	22 15 19.1	0.4	17.6	7.8	7.7
26	Mentawai (TE)	20101025	14 42 59.8	7.4	12.0	7.8	7.7
27	Aceh	20120411	08 39 29.8	0.3	40.0	8.6	8.5

**Data gempa
pembangkit
tsunami
(27 gempa)**

Momen Seismik (M_0)

- Kekuatan gempa menggambarkan perubahan fisis dan mekanis batuan sumber gempa akibat tektonik (Boatwright dan Choy, 1986).
- Fase gelombang P-S stasiun teleseismik berjarak lebih dari 30° .
- Merubah sinyal kecepatan menjadi pergeseran dari komponen vertikal sensor *broadband*.

Magnitudo Momen (M_w)

- Skala kekuatan gempa dari momen seismik

- Rumus dasar momen seismik (Kanamori, 1977)

$$M_0 = \mu D A \quad (2.1)$$

μ rigiditas batuan, D pergeseran (*displacement*), A luasan bidang sesar

- Pergeseran

$$u_z(x_r, t) = F^P \cdot \dot{M}_0 (t - T_p) R_s(x_r) Q(t^*) / (4\pi\rho\alpha^3 R^P(x_r, x_s)) \quad (2.2)$$

- *Moment rate* (Tsuboi dkk, 1995)

$$M_0(t) = \int \dot{M}_0(t - T_p) dt \quad (2.3.a)$$

$$M_0(t) = \int u_z(x_r, t) dt 4\pi\rho\alpha^3 R^P(x_r, x_s) / F^P \cdot R_s(x_r) Q(t^*) \quad (2.3.b)$$

- Momen seismik (Tsuboi dkk, 1995)

kedalaman dangkal: R^P (sebaran geometris) = $1.2 r$, $R_s = 1.5$, $Q(t^*) = 0.8$.

$$M_0(t) = \max \left(\int u_z(x_r, t) dt \right) 4\pi\rho\alpha^3 r / F^P \quad (2.4)$$

- Momen seismik absolut

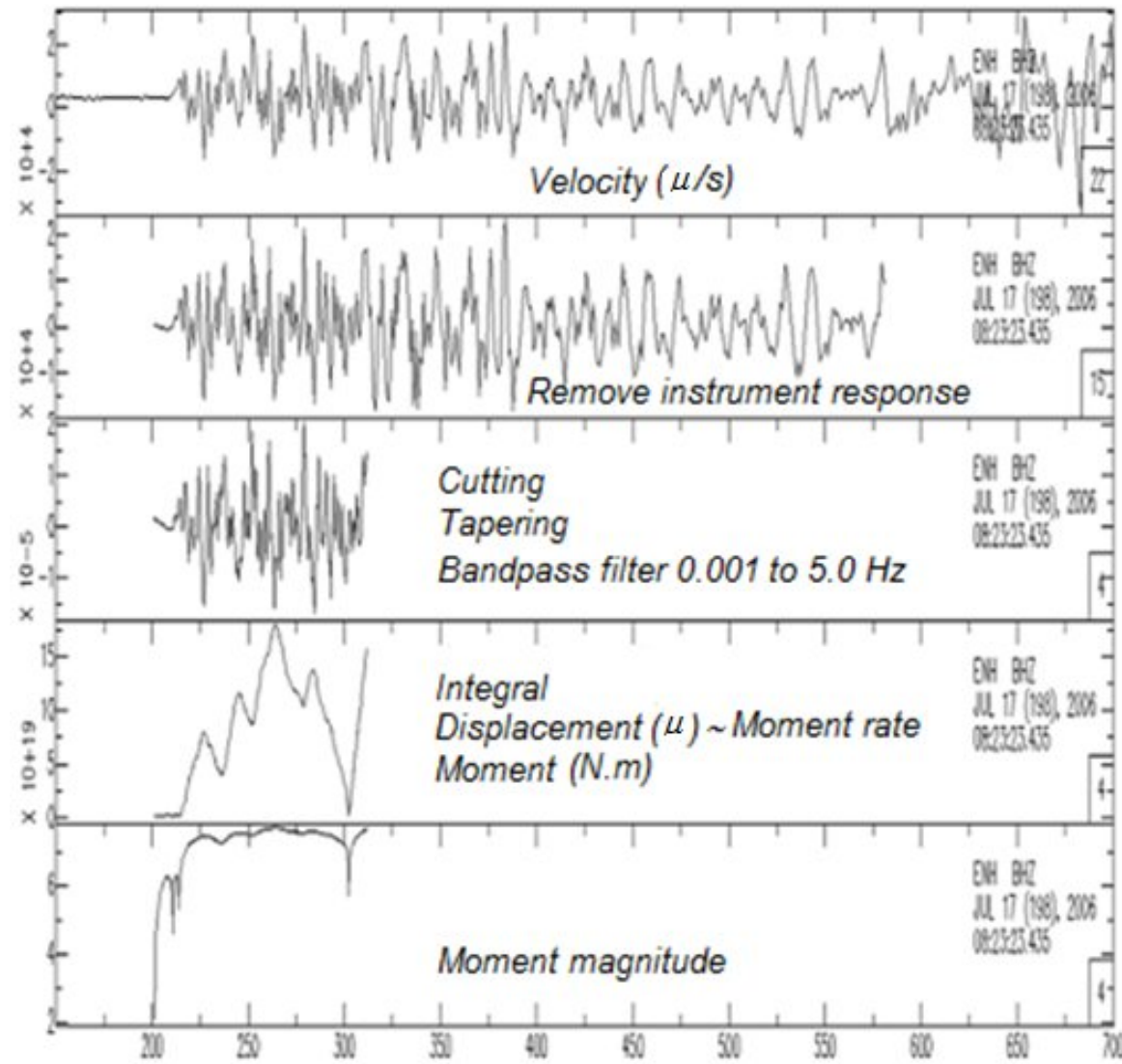
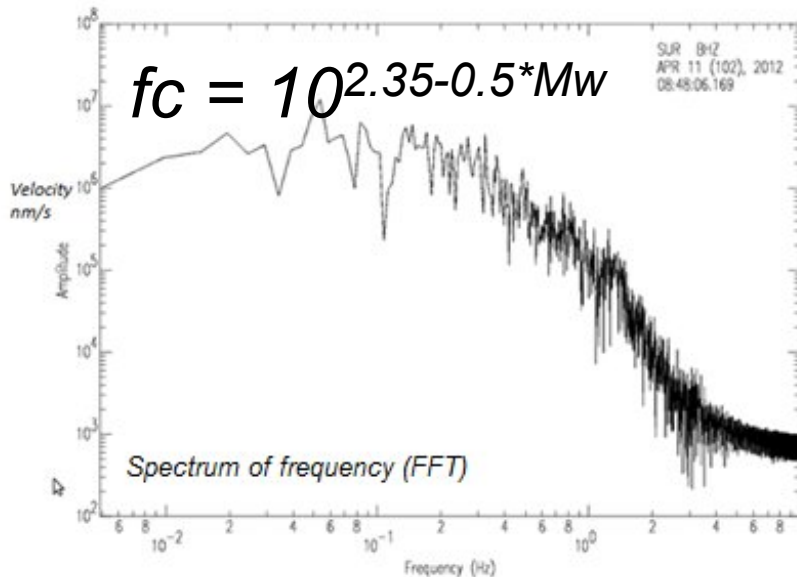
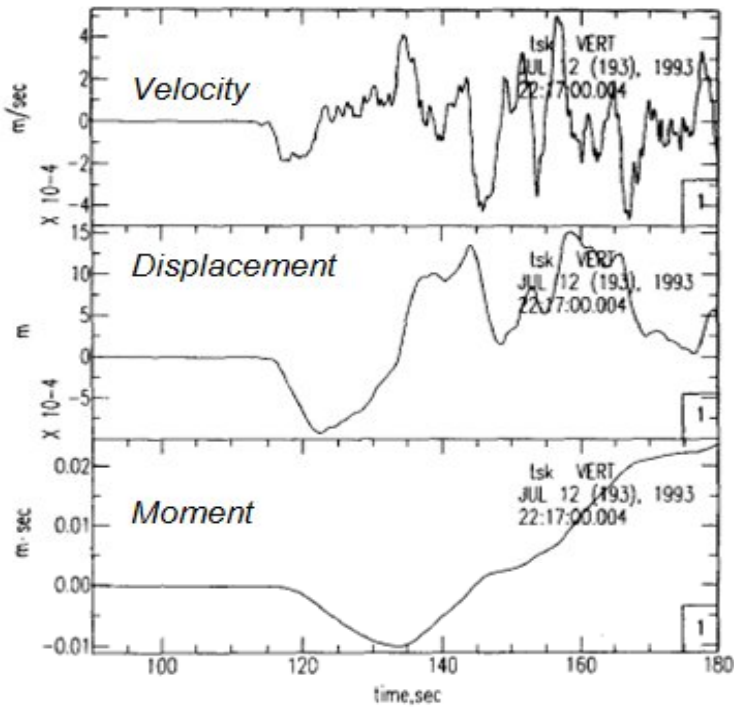
Teleseismik, mantel atas: (Newman & Okal, 1998; Boatwright & Choy, 1986)

F^{gP} (pola radiasi) = 1, $\rho = 3.4 \times 10^3 \text{ kg.m}^{-3}$, $\alpha = 7.9 \times 10^3 \text{ m.dtk}^{-1}$.

$$M_0' = \left| \max \left(\int u_z(x_r, t) dt \right) \right| 4\pi\rho\alpha^3 r \quad (2.5)$$

Penghitungan momen seismik

(Tsuboi dkk, 1995)



Energi Radiasi Seismik

- Energi gelombang seismik yang dipancarkan dari titik sumber gempa ke permukaan melalui lapisan bumi.
- Sebanding dengan jumlah (fluks) frekwensi yang dipancarkan gelombang seismik (Boatwright dan Choy, 1986).
- Fase gelombang P-PP stasiun teleseismik berjarak 30° s.d. 90° (Tabel Jeffrey Bullens, Bormann, 2002).
- Mengkuadratkan sinyal kecepatan dari komponen vertikal sensor *broadband*.

- Titik sumber energi (Boatwright & Choy, 1980)

$$E_s^P = 4\pi \langle F^P \rangle^2 / \langle F^P \rangle^2 (R^P)^2 \varepsilon^{gP} \quad (2.7.a)$$

$$E_s^S = 4\pi \langle F^S \rangle^2 / \langle F^{Si} \rangle^2 (R^{Si})^2 \varepsilon^{Si} \quad (2.7.b)$$

$$\varepsilon^{gP} = \varepsilon^P + \varepsilon p^P + \varepsilon s^P \quad (\text{gabungan fluks energi}) \quad (2.8)$$

$$\varepsilon P = \{E_{sP} / 4\pi \langle F^P \rangle^2\} * \{F^P / R^P\}^2 \quad (2.9)$$

$$\varepsilon p^P = \{E_{sP} / 4\pi \langle F^P \rangle^2\} * \{\dot{P}^P F p^P / R^P\}^2 \quad (2.10)$$

$$\varepsilon s^P = \{(2\alpha/3\beta) q E_{sP} / 4\pi \langle F^P \rangle^2\} * \{\dot{S}^P F s^P / R^P\}^2 \quad (2.11)$$

$$E_{sP} = 4\pi \{ \langle F^P \rangle^2 / \langle F^P \rangle^2 \} * (R^P / F g^P)^2 \varepsilon^{gP} \quad (2.12)$$

$$F g^P = (F^P)^2 + (F p^P)^2 + \{(2\alpha/3\beta) q \langle F^P \rangle^2\} \quad (2.13)$$

$$E_s = (1+q) E_{sP} \quad (2.14)$$

$$\varepsilon^{gP} = \rho \alpha \int v^2(t) dt \quad (2.15)$$

$$E_s = (1+q) 4\pi r^2 \{ \langle F^P \rangle^2 / \langle F g^P \rangle^2 \} \rho \alpha \int v^2(t) dt \quad (2.16)$$

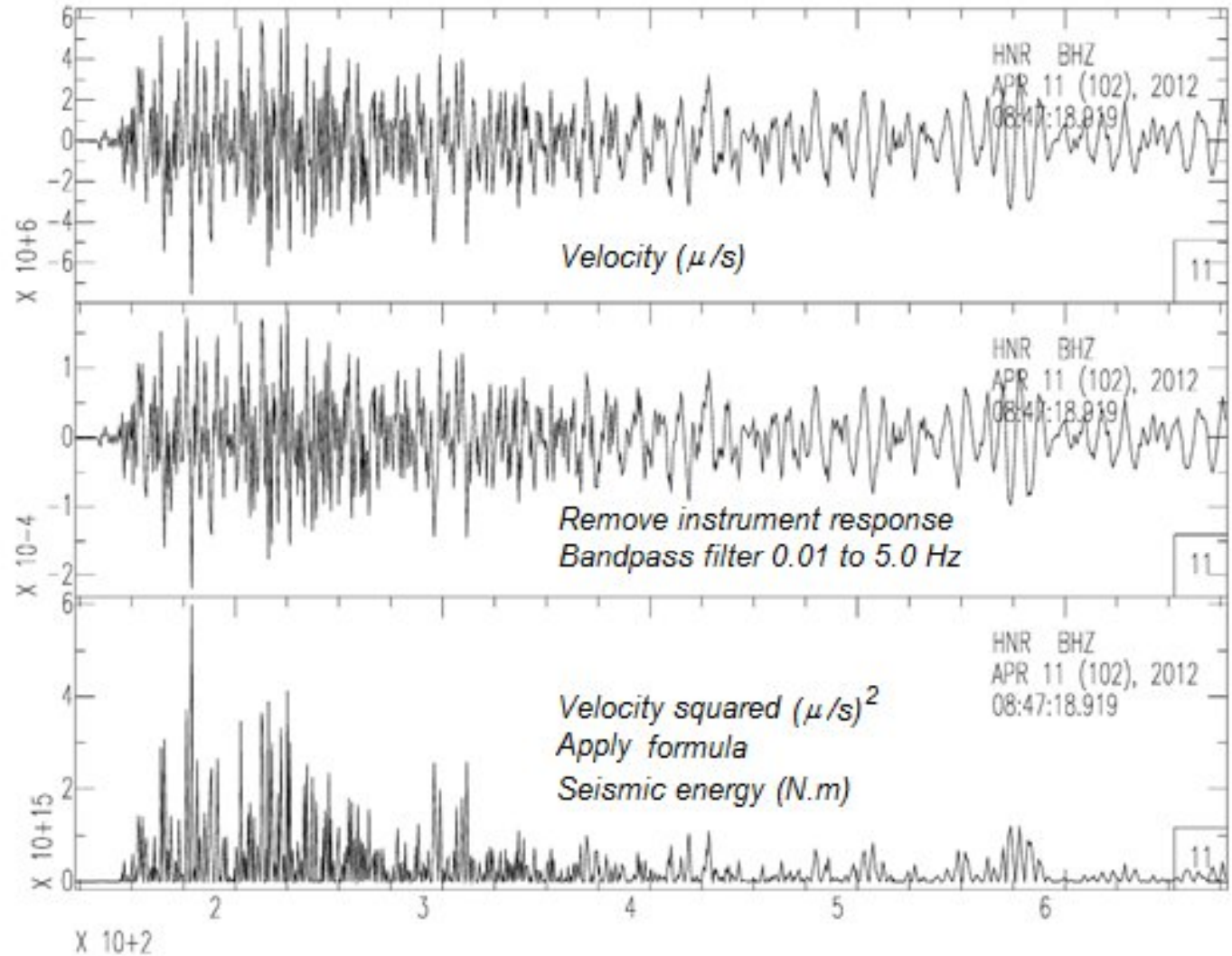
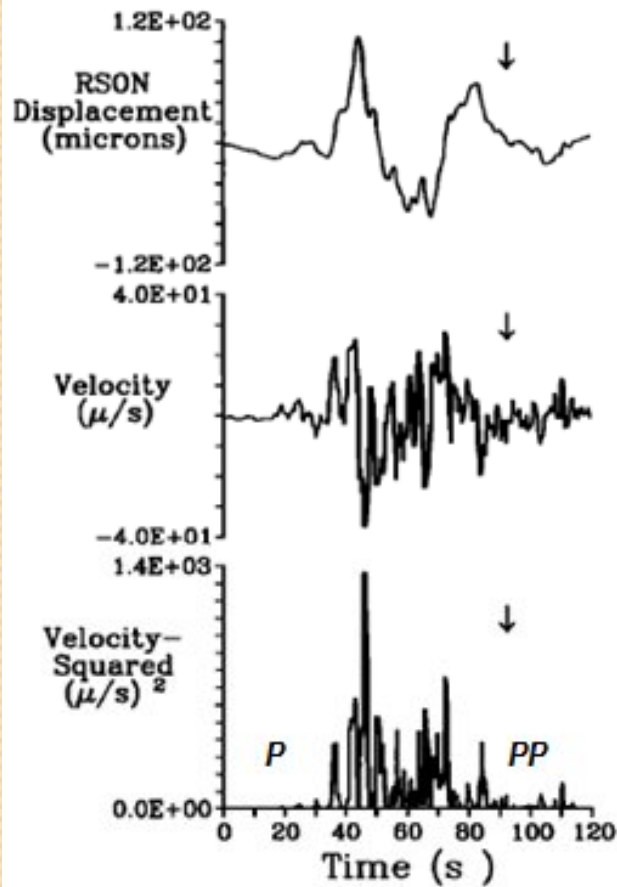
Substitusi tetapan (Choy dan Boatwright, 1995; Lomax dkk., 2007)

$\langle F^P \rangle^2 = 4/15$, $\langle F g^P \rangle = 1$, $(1+q) = 16.6$, $\rho = 2,6 \times 10^3 \text{ kg.m}^{-3}$, $\alpha = 5 \times 10^3 \text{ m. s}^{-1}$, $r = 106 \text{ m}$.

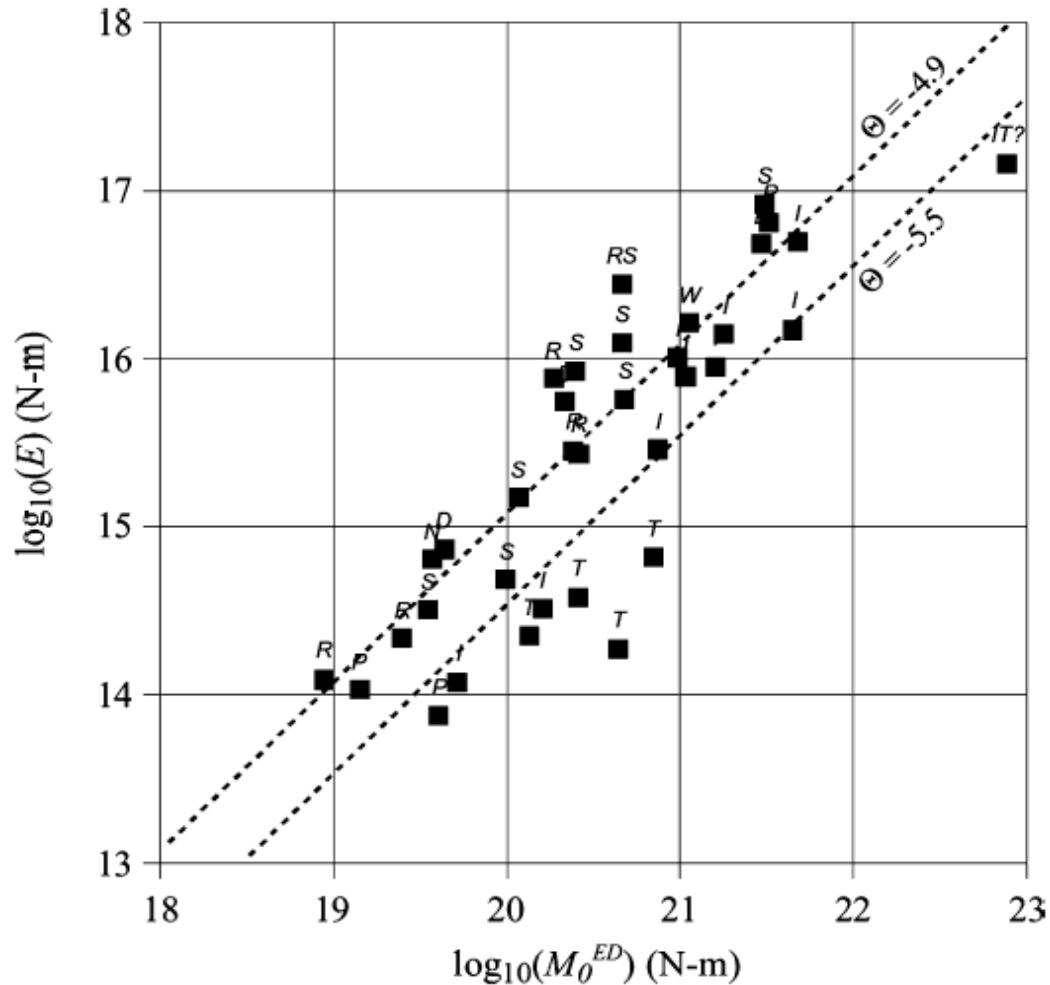
$$E_s = 53 \pi r^2 \rho \alpha \int v^2(t) dt \quad (2.17)$$

Penghitungan energi

(Choy dan Boatwright, 1986)



Rasio Energi dan Momen Seismik



- Mengidentifikasi jenis gempa pembangkit tsunami

(Boatwright dan Choy, 1986; Newman dan Okal, 1998; Weinstein dan Okal, 2005; Lomax dkk., 2007; Lomax dan Michelini, 2008)

$$\Theta = \log_{10} (E / M_0) \quad (2.20)$$

$$\Theta < -5.5 \text{ atau } \Theta < -5.7$$

tsunami earthquake

(Lomax dkk., 2007; Lomax dan Michelini, 2008)

Garis $\Theta = -5.5$ untuk *tsunami earthquake*. Jenis gempa : *I* – *interplate earthquake*, *T* – *tsunami earthquake*, *W*—*downdip*; *P*—*intraplate*; *D*—*deep*; *S*—*strike-slip crustal*; *R*—*reverse-faulting crustal*, *N*—*normal-faulting crustal*. (Lomax, dkk 2007).

Durasi sumber

- Waktu gempa untuk pecah seluas bidang patahan dari proses pembentukan kekuatan hingga berhenti pergeserannya.

$$\tau = L/V \quad (2.21)$$

$$E = [(1/15\pi\rho\alpha^5) + (1/10\pi\rho\beta^5)] * [2/x(1-x)] * (Mo^2/To^3) \quad (2.22)$$

$$Mo = c E^{1/2} To^{3/2} \quad (2.23)$$

$$To^3 \propto Mo, \Theta \quad (2.24)$$

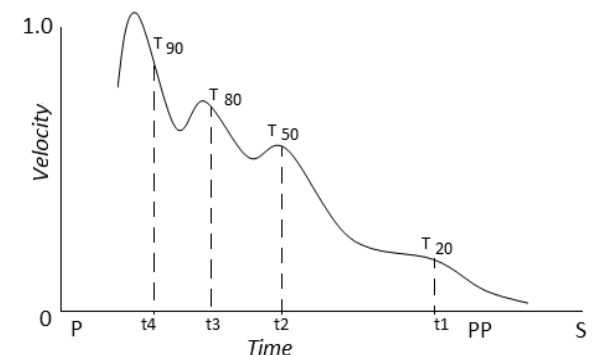
$$To = (1-w) T^{90} + w T^{20} \quad (2.25)$$

dimana $w = [(T^{80} + T^{50})/2 - 20]/40$

- Diukur dari luasan gelombang kecepatan sebagai distribusi polinomial berderajat

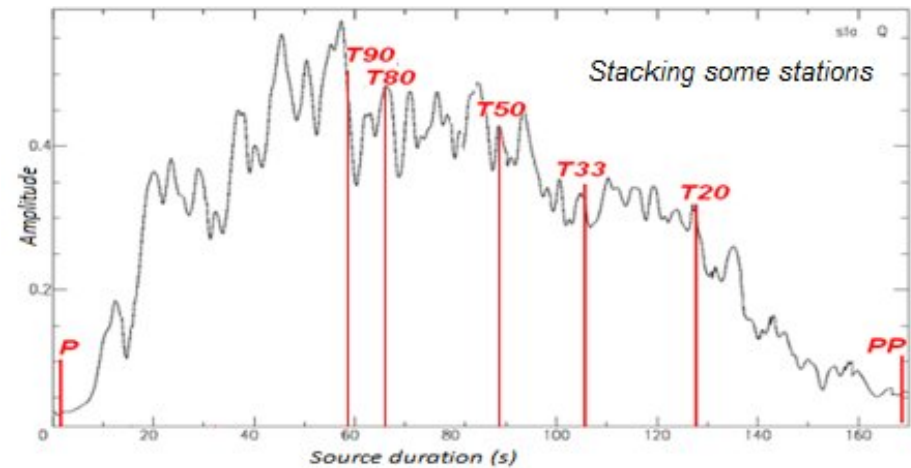
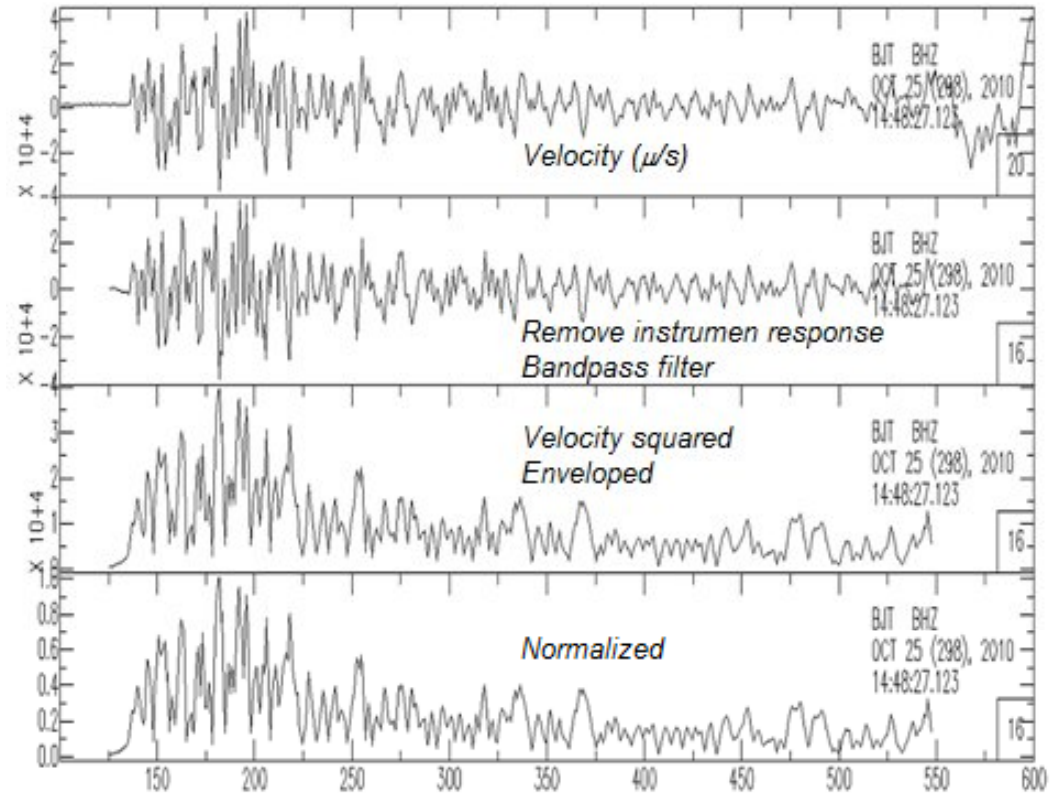
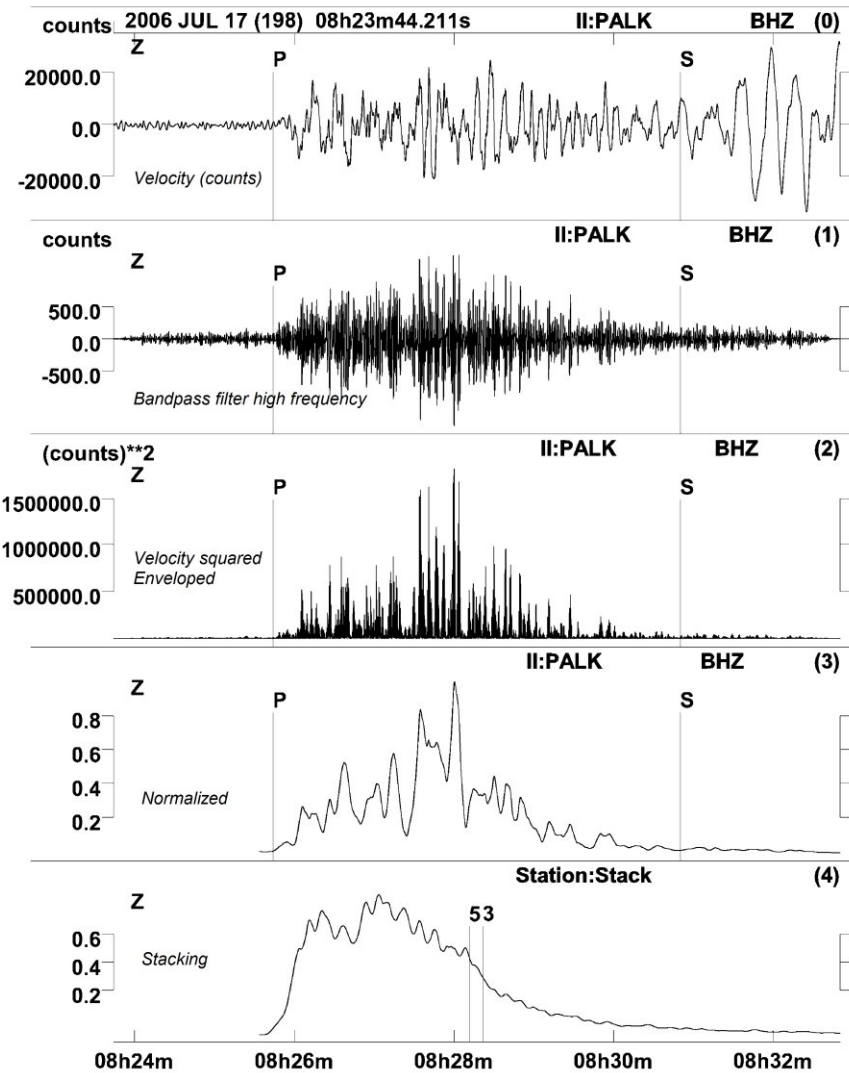
$$To = \int_{20}^{90} T \{(1-w)+w\} dT$$

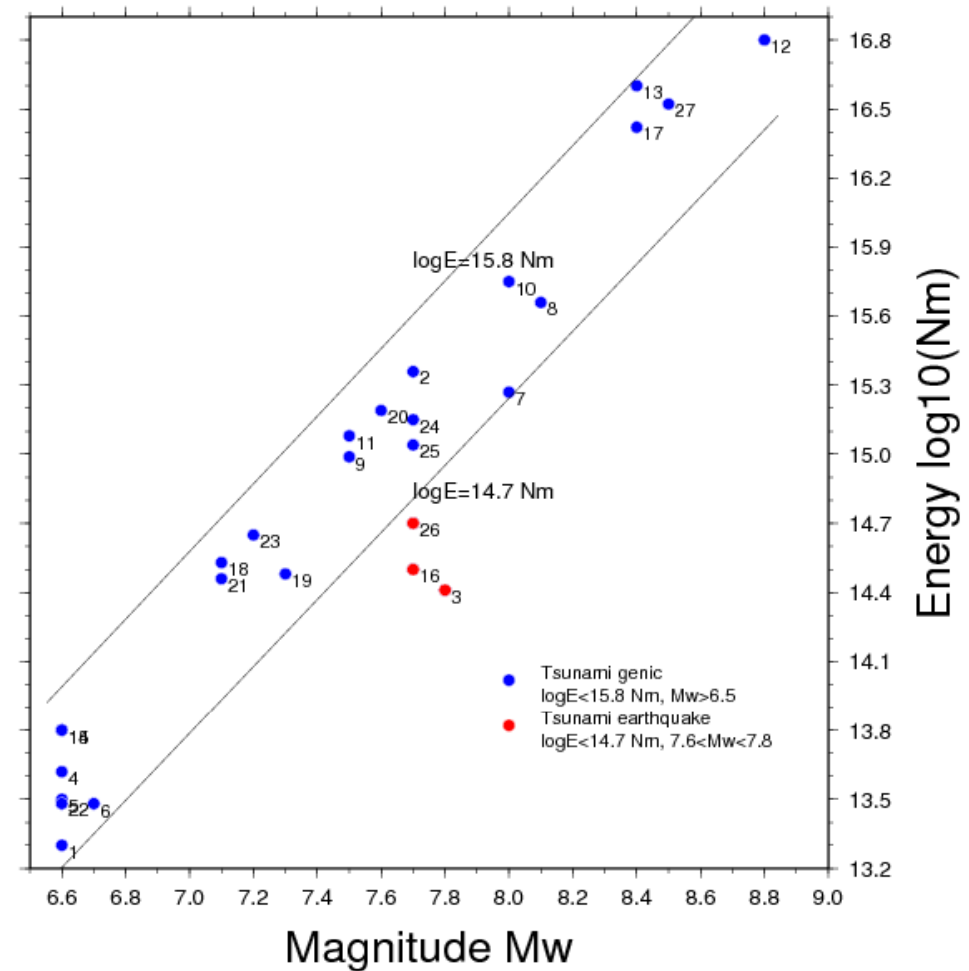
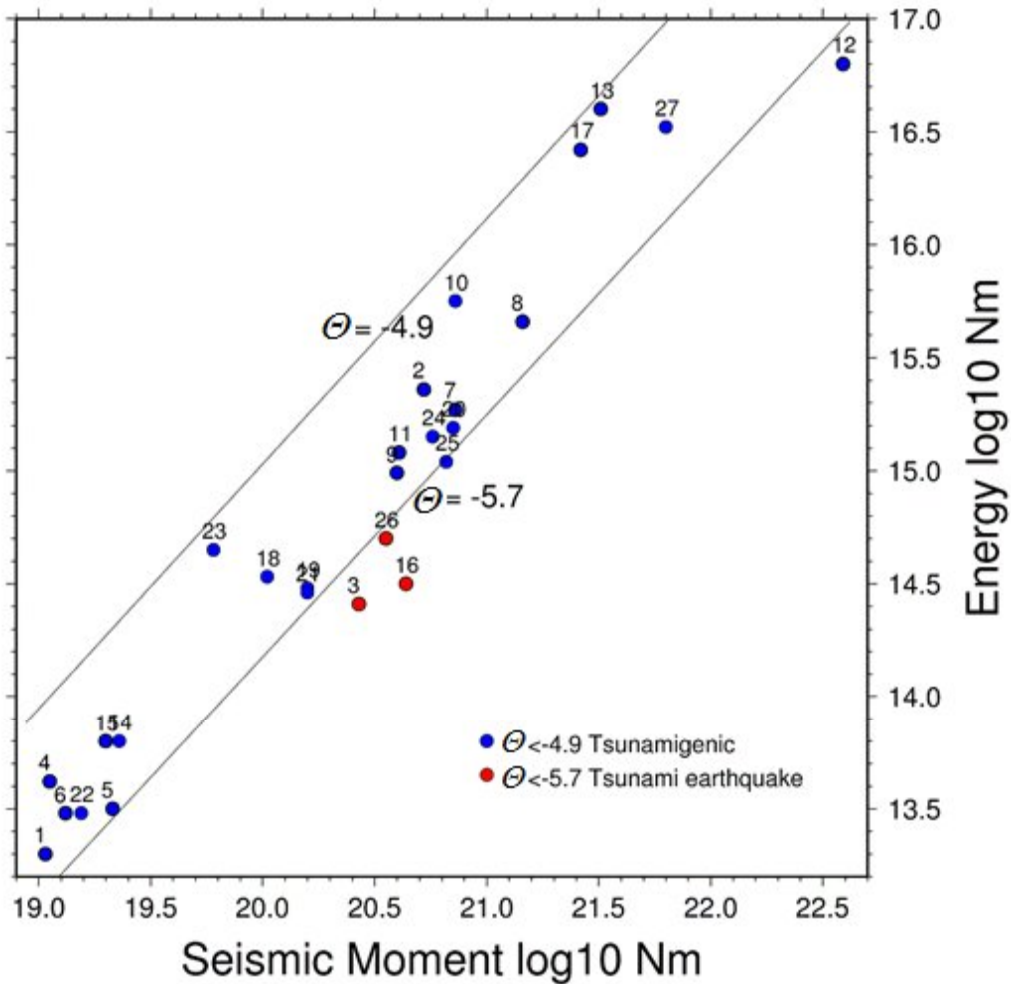
Pembobotan (w) \sim luasan bidang tengah



Penghitungan durasi sumber

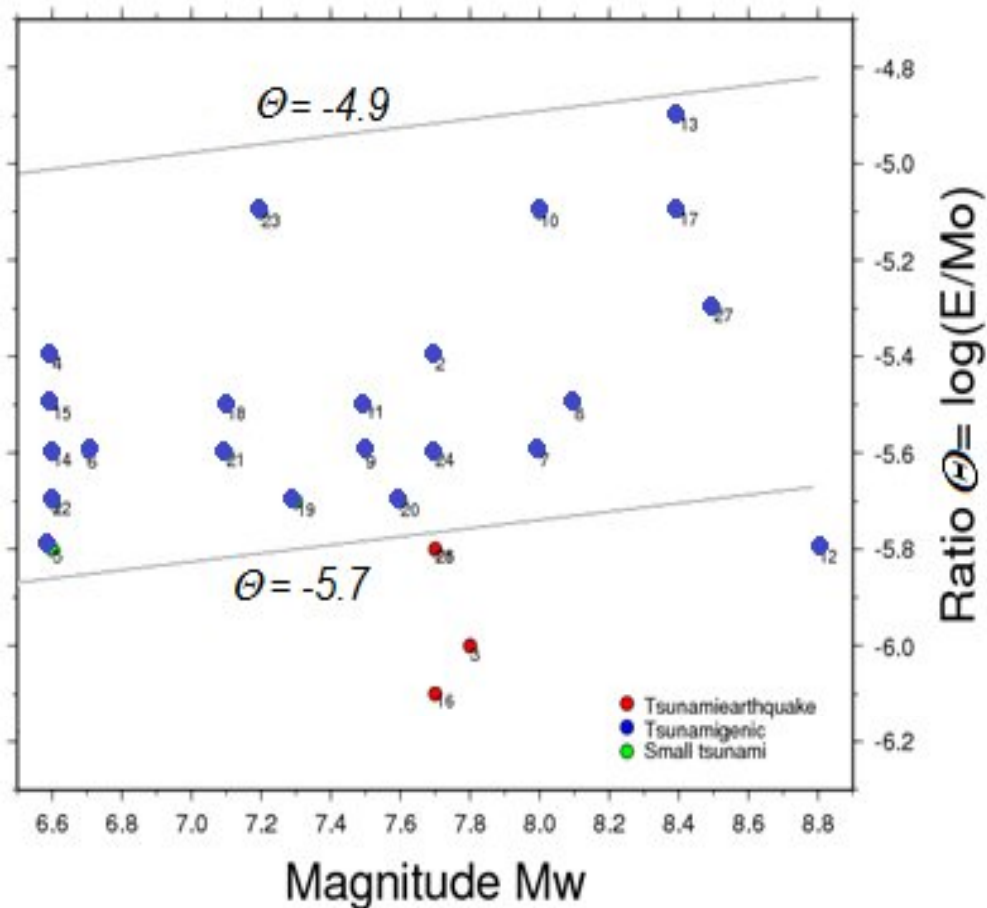
Lomax dkk (2007)



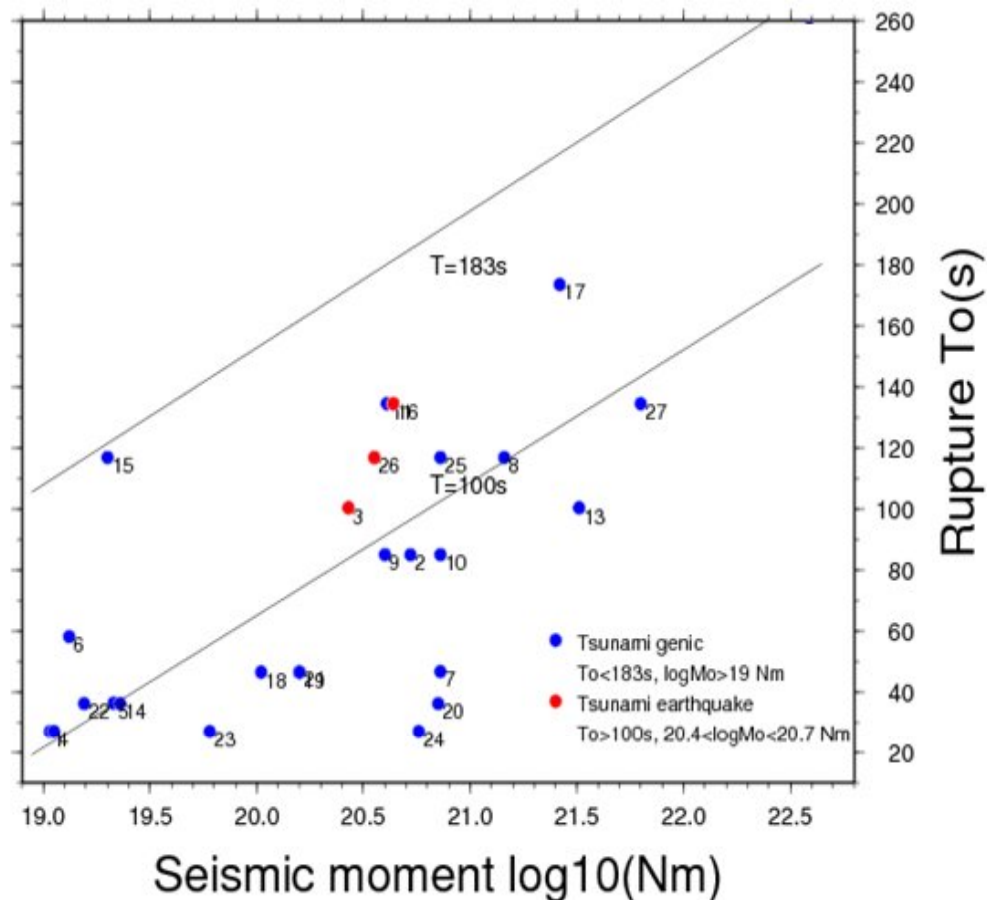


Hubungan momen seismik dan energi
Tsunami genic rasio $\Theta < -4.9$
Tsunami earthquake rasio $\Theta < -5.7$

Hubungan magnitudo dan energi
Tsunami genic log E < 15.8,
Tsunami earthquake log E < 14.7



Hubungan magnitudo dan rasio
Tsunamigenic rasio $\Theta < -4.9$
Tsunami earthquake rasio $\Theta < -5.7$






Hubungan momen seismik dan
 durasi sumber
Tsunamigenic $To < 183 \text{ detik}$
Tsunami earthquake $To > 100 \text{ detik}$






KESIMPULAN

**Disimpulkan dari hasil riset
tahun 2011 dan 2012**

Karakterisasi Sumatra

<i>Event / parameter</i>	<i>Mentawai 2010 (26)</i>	<i>Aceh 2004 (12)</i>	<i>Aceh 2012 (27)</i>
<i>Focal sphere</i>	 <i>Thrust</i>	 <i>Thrust</i>	 <i>Strike-slip</i>
<i>Character</i>	<i>Tsunami earthquake</i>	<i>Tsunamigenic strong</i>	<i>Tsunamigenic low</i>
<i>Position</i>	<i>Accretionary wedge</i>	<i>Inter-plate</i>	<i>Intra-plate Outer-rise</i>
<i>Head of subduction zone (trench)</i>	<i>Very near $P < 50$ km</i>	<i>Very near $P < 50$ km</i>	<i>Very far $P > 100$ km</i>
<i>Magnitude</i>	<i>Medium $M_w = 7.4$</i>	<i>Very big $M_w = 9.1$</i>	<i>Big $M_w = 8.6$</i>
<i>Tsunami</i>	<i>High $H = 7.4$ m</i>	<i>Very high $H = 32$ m</i>	<i>Very small $H = 0.3$ m</i>
<i>Depth</i>	<i>Very shallow $D = 12$ km</i>	<i>Shallow $D = 28.6$ km</i>	<i>Enough deep $D = 40$ km</i>
<i>Ratio energi / moment</i>	<i>Very low $\Theta = -5.8$</i>	<i>Very low $\Theta = -5.7$</i>	<i>High $\Theta = -5.4$</i>
<i>Source duration</i>	<i>Slow $T_o = 116.8$ s</i>	<i>Very slow $T_o = 460.3$ s</i>	<i>Slow $T_o = 134.5$ s</i>

Karakterisasi Jawa

Event / parameter	Banyuwangi 1994 (3)	Pangandaran 2006 (16)	Tasikmalaya (23)
Focal sphere	 Thrust	 Thrust	 Strike-slip
Character	Tsunami earthquake	Tsunami earthquake	Tsunamiogenic low
Position	Accretionary wedge	Accretionary wedge	Intra-plate
<i>Head of subduction zone (trench)</i>	Very near P < 50 km	Very near P < 50 km	Very far P > 200 km
Magnitude	Medium Mw=7.8	Medium Mw=7.8	Medium Mw=7.2
Tsunami	Very high H=14 m	High H=8 m	No
Depth	Very shallow D=15 km	Shallow D=20 km	Deep D=70 km
Ratio energi / moment	Very low $\Theta = -6.0$	Very low $\Theta = -6.1$	High $\Theta = -5.1$
Source duration	Slow To= 100.4 s	Very slow To= 136 s	Fast To= 27 s

Tsunamigenic earthquake:

1. Jumlah 24 kejadian; 12 gempa kuat, 12 gempa kecil
2. Rasio antara $\Theta = -5.7$ dan $\Theta = -4.9$.
3. Gempa kuat
 - Ketinggian tsunami besar $H > 1 \text{ m}$.
 - kekuatan gempa besar
 - $E > 1.58 \times 10^{15} \text{ Nm}$ ($\log 15.2$), $M_0 > 5.01 \times 10^{20} \text{ Nm}$ ($\log 20.7$), $M_w > 7.5$.
 - Subduksi *inter-plate*.
 - Durasi sumber $T_0 > 100 \text{ detik}$.
4. Gempa kecil
 - Ketinggian tsunami besar $H < 1 \text{ m}$.
 - Kekuatan gempa rendah
 - $E < 6.3 \times 10^{14} \text{ Nm}$ ($\log 14.8$), $M_0 < 5.01 \times 10^{20} \text{ Nm}$ ($\log 20.7$), $M_w < 7.5$
 - Subduksi *intra-plate*.
 - Durasi sumber $T_0 < 100 \text{ detik}$.

Tsunami earthquake:

1. Jumlah 3 kejadian

Gempa Banyuwangi, Jawa Timur, 2 Juni 1994

Gempa Pangandaran, Jawa Barat, 16 Juli 2006

Gempa Mentawai, Sumatra, 25 Oktober 2010

2. Rasio $\Theta < -5.7$

3. Ketinggian $H > 1 m$.

4. Kekuatan gempa rendah daripada *tsunamigenic*

- $E = 2.5 \times 10^{14} \text{ Nm}$ ($\log 14.4$) s.d. $E = 6.3 \times 10^{14} \text{ Nm}$ ($\log 14.8$)
- $M_0 = 2.5 \times 10^{20} \text{ Nm}$ ($\log 20.4$) s.d. $M_0 = 5 \times 10^{20} \text{ Nm}$ ($\log 20.7$)
- $M_w = 7.7$ s.d. $M_w = 7.9$.

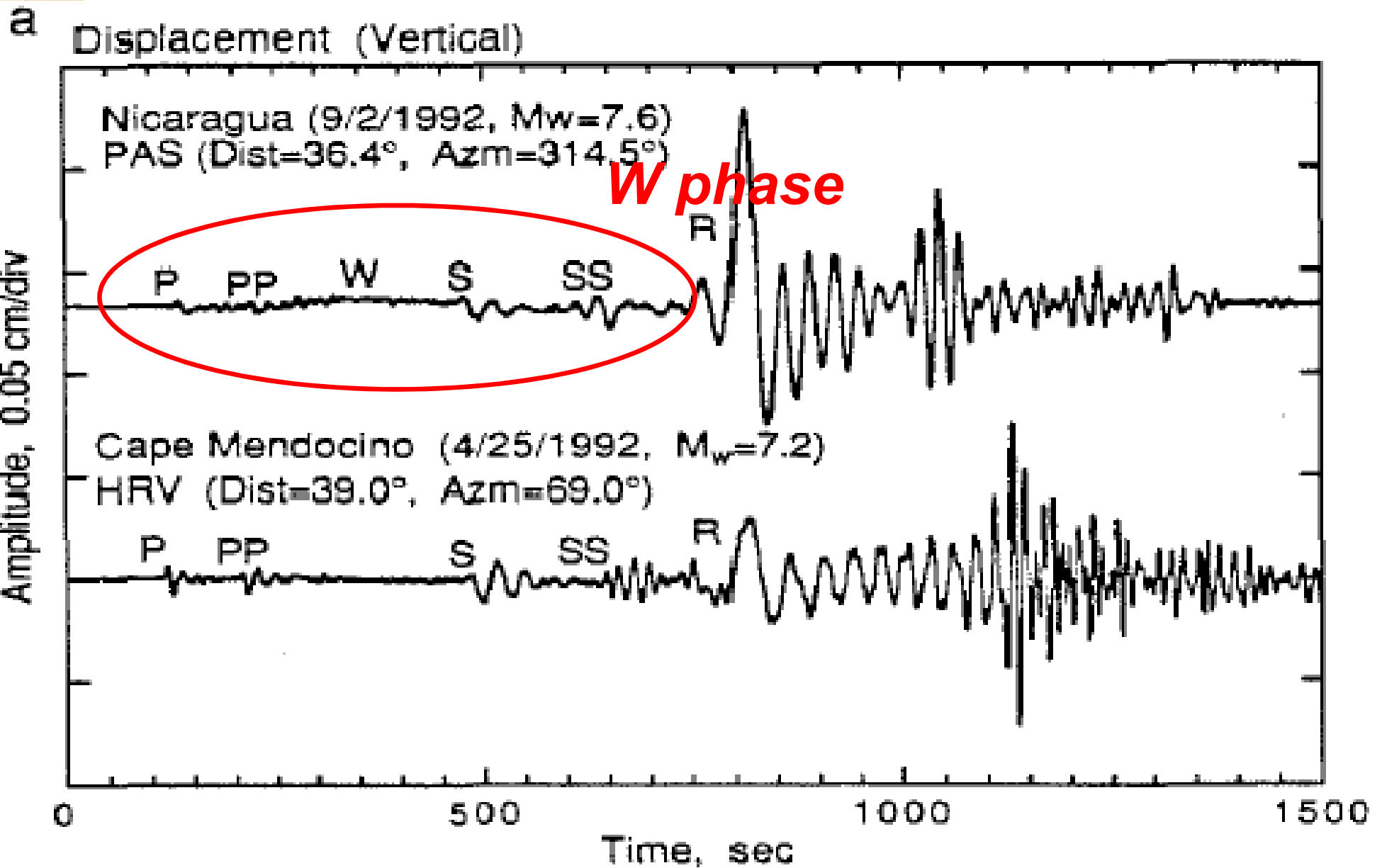
5. Subduksi *inter-plate*.

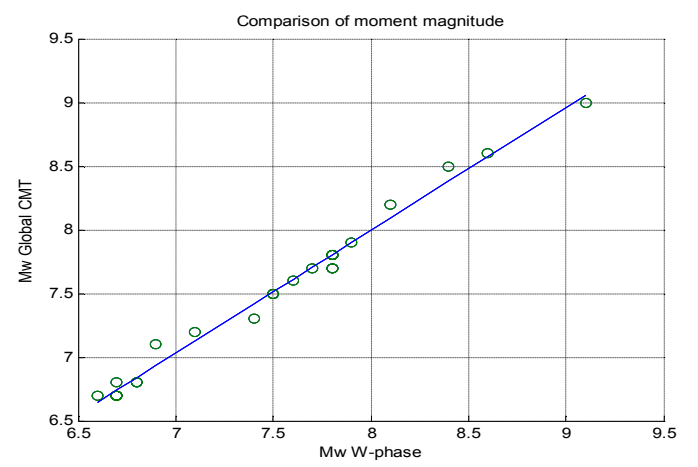
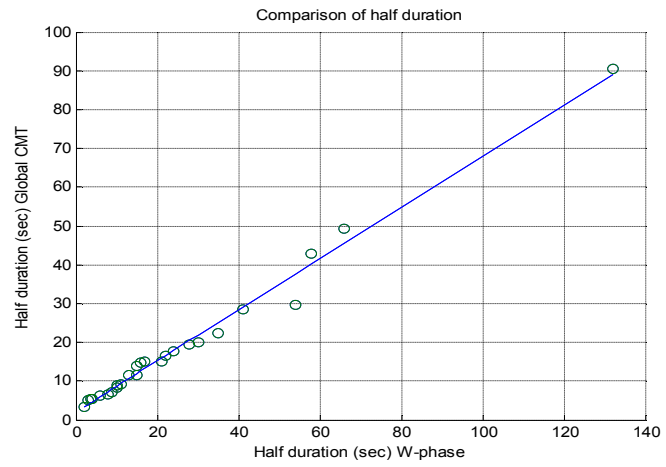
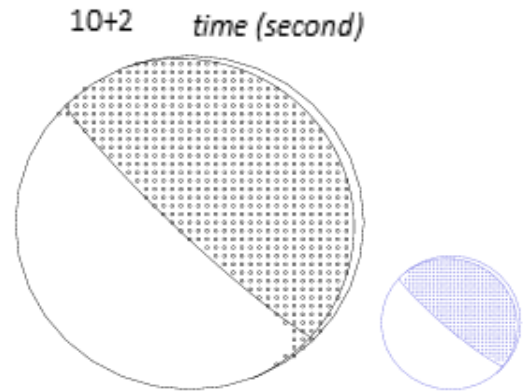
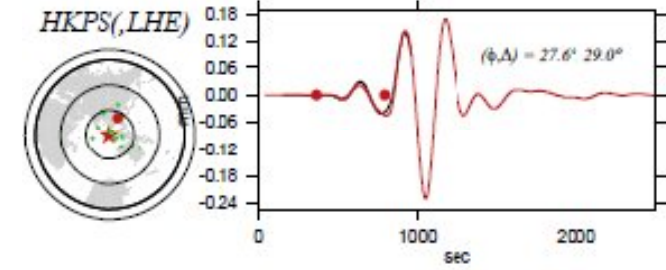
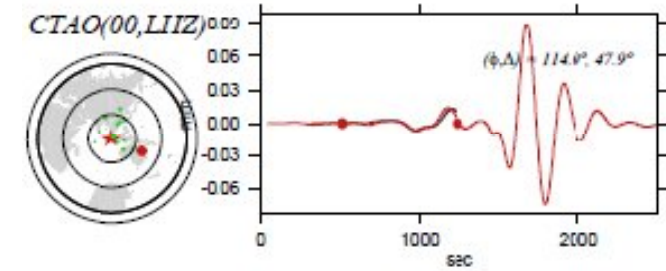
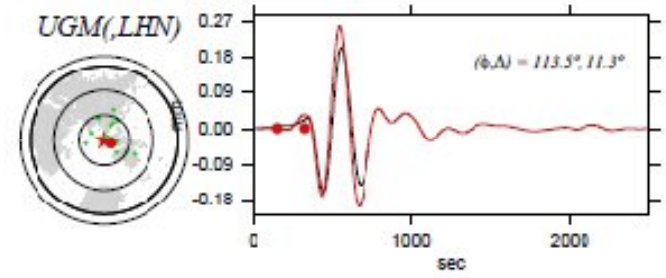
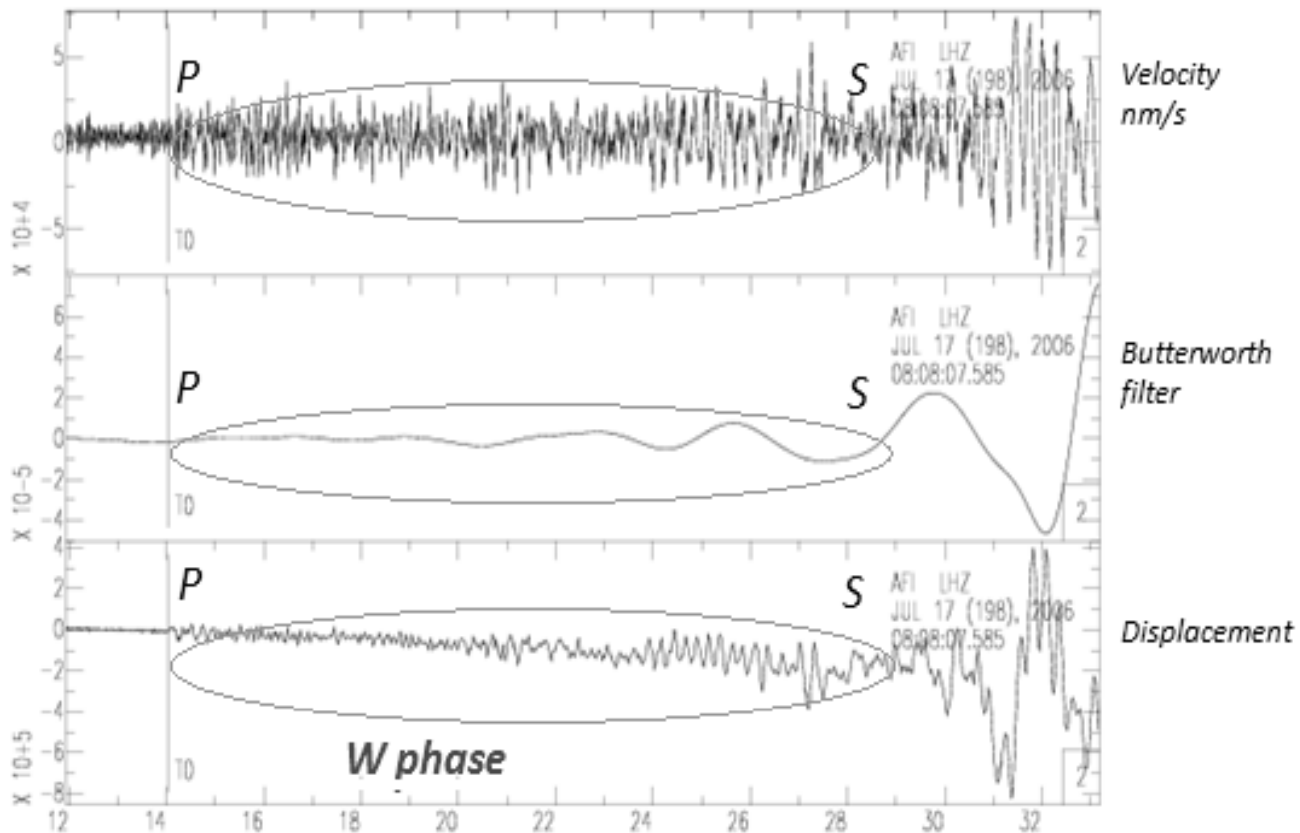
6. Durasi sumber $T_0 > 100$ detik.

Sekian dan
terima kasih

5. *W phase*

- Inversi cepat tentukan mekanisme fokus dan magnitudo momen.
- Mendukung estimasi peringatan dini tsunami.
- Propagasi lurus dan mendatar seperti gelombang bisik yang halus (*whispering gallery*) (Kanamori, 1972).
- Terindikasi pada gempa kuat dan teleseismik berjarak minimal 10°
- Fase gelombang badan (P, S) berperiode panjang ($t > 1000$ detik).
- Frekwensi rendah 0.001 Hz s.d. 0.01 Hz.
- Cukup konsisten (96%) dengan *Global CMT*



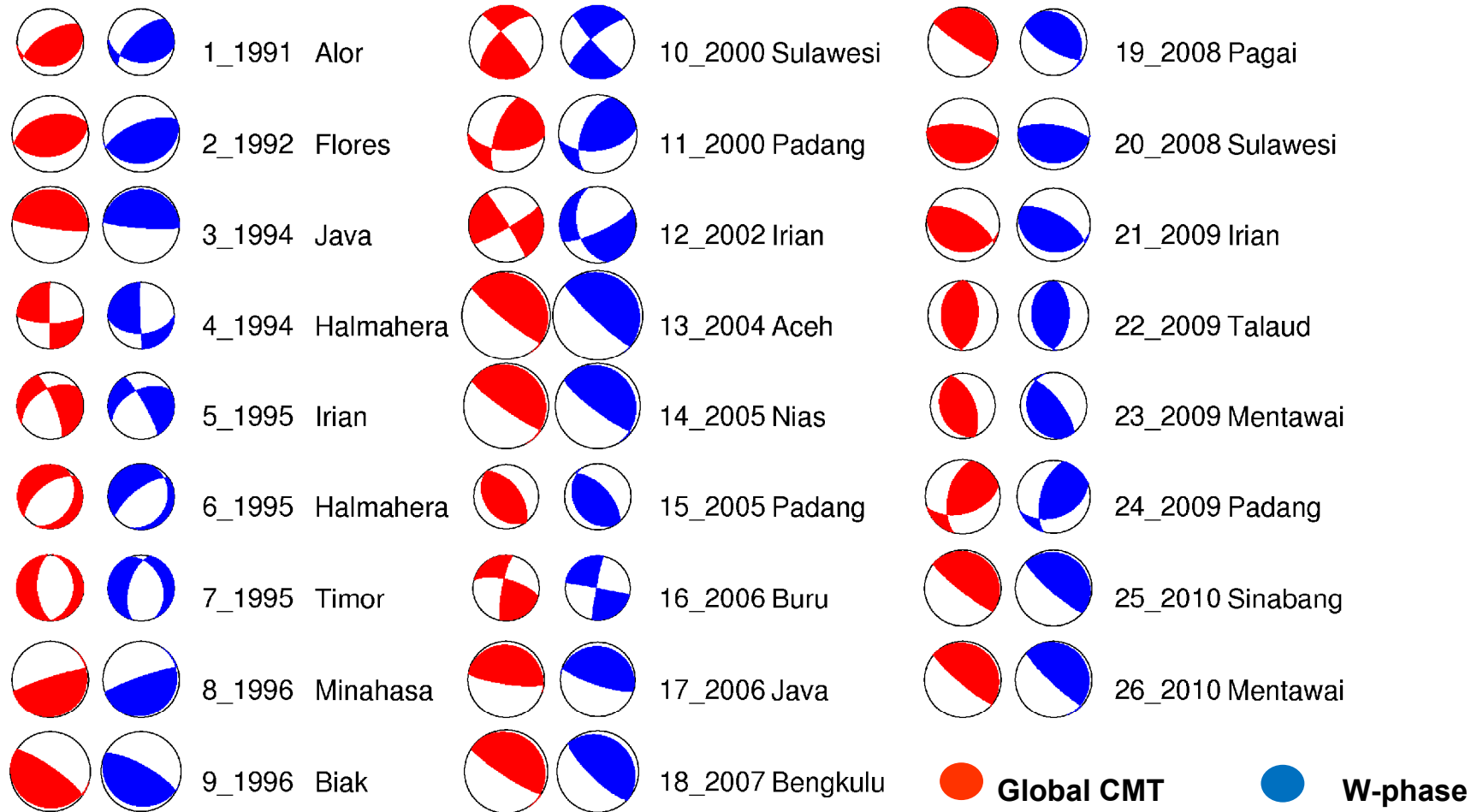


W-phase Global CMT
Mentawai 2010 earthquake

Half duration

Magnitude momen

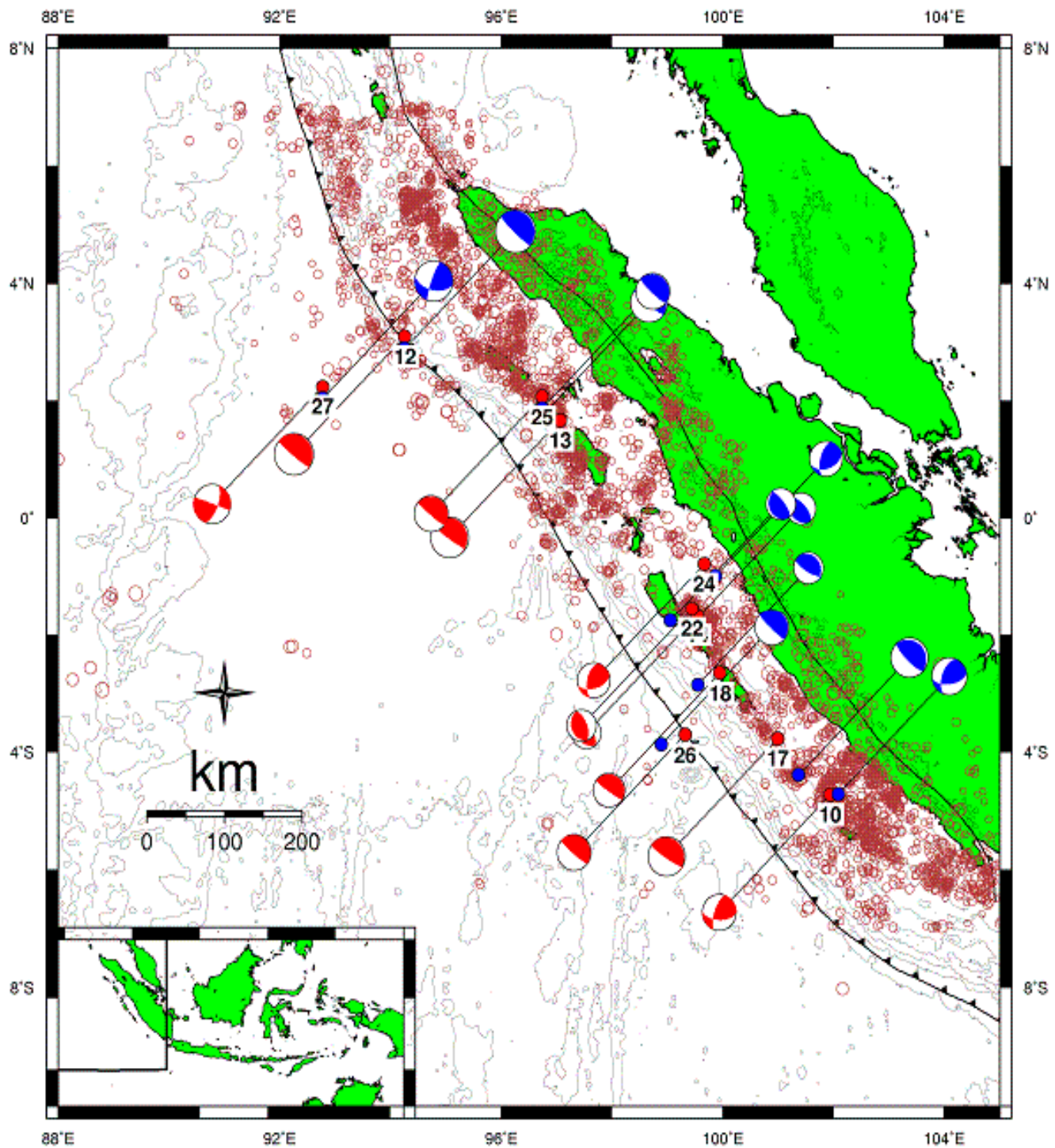
Hasil Seminar II: *W phase*



- Inkonsistensi (1994 Halmahera), (2002 Irian), and (2006 Buru)
- Dipengaruhi gangguan lokal stasiun, jumlah dan jarak stasiun, filter frekwensi, persamaan dan tetapan parameter.

Karakterisasi Gempa Pembangkit Tsunami

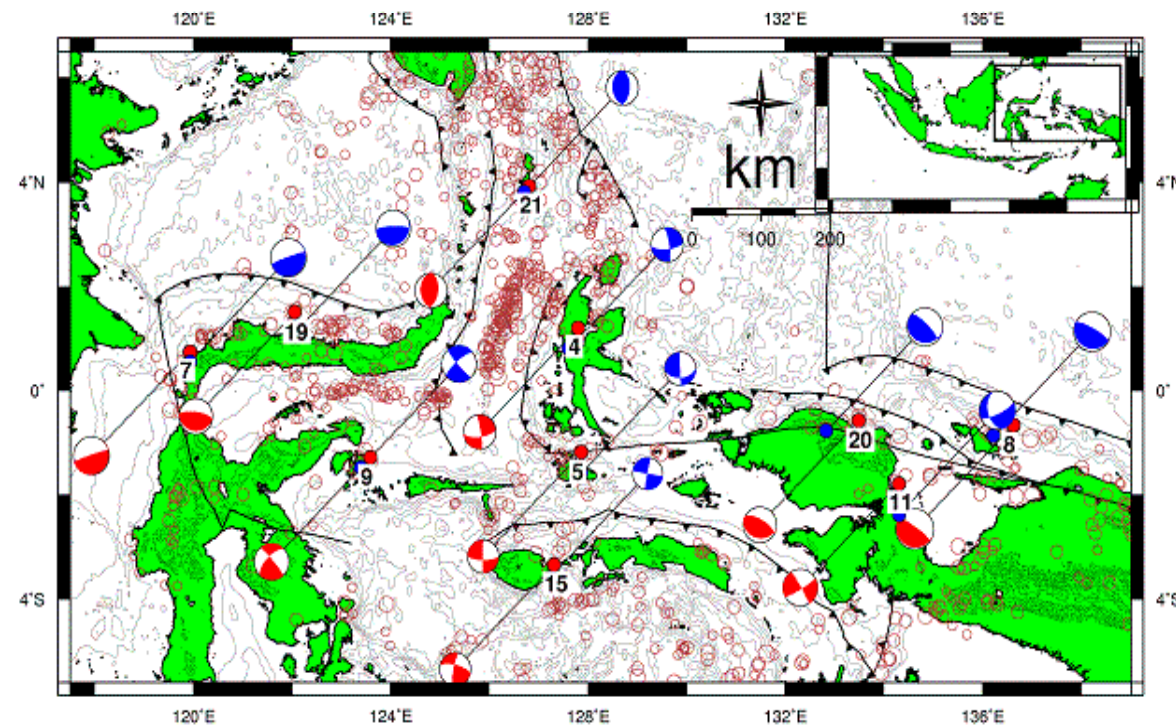
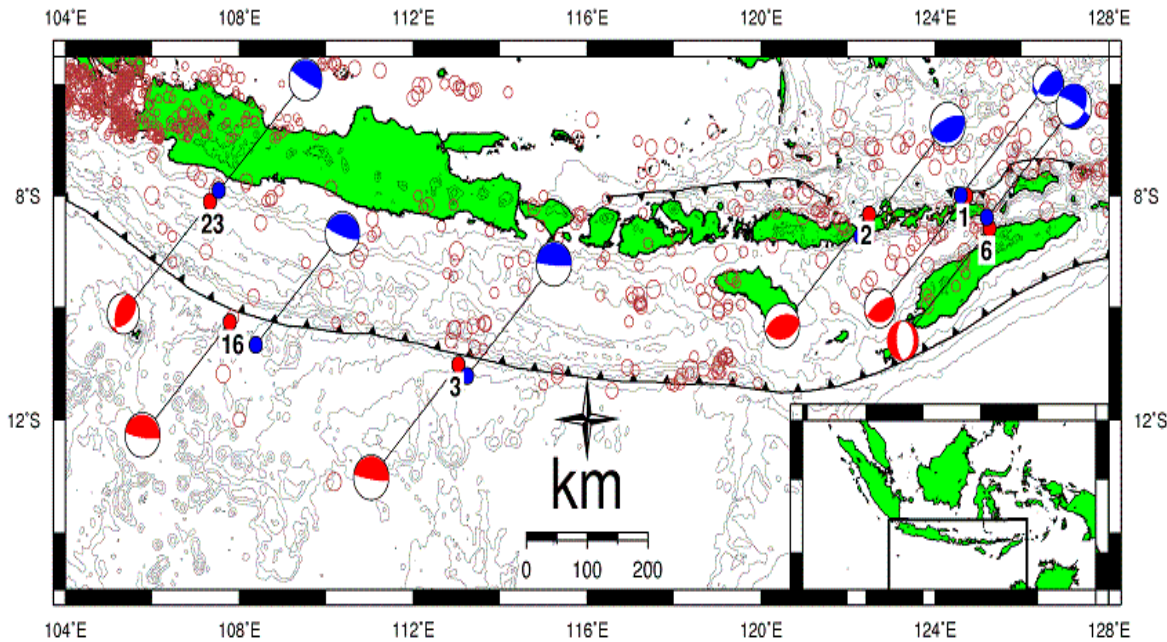
- *Tsunamigenic*
- *Tsunami earthquake*
- Wilayah Sumatera
- Wilayah Jawa dan Nusa Tenggara
- Wilayah Sulawesi, Banda dan Papua



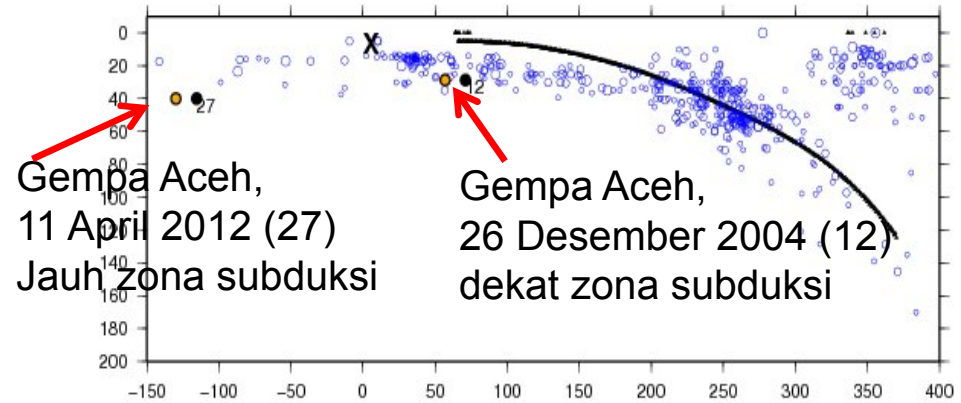
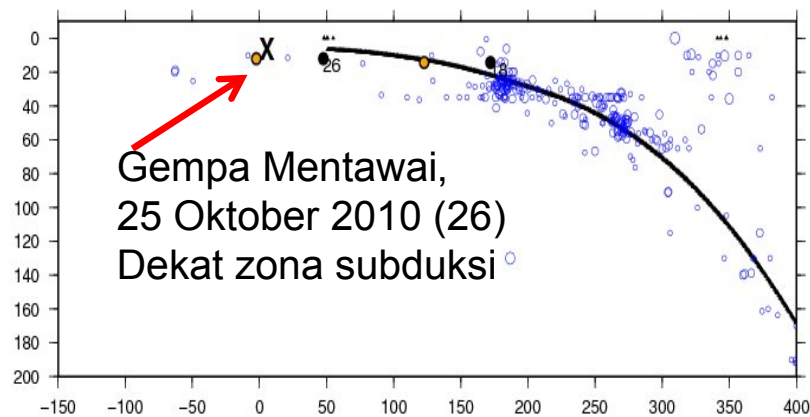
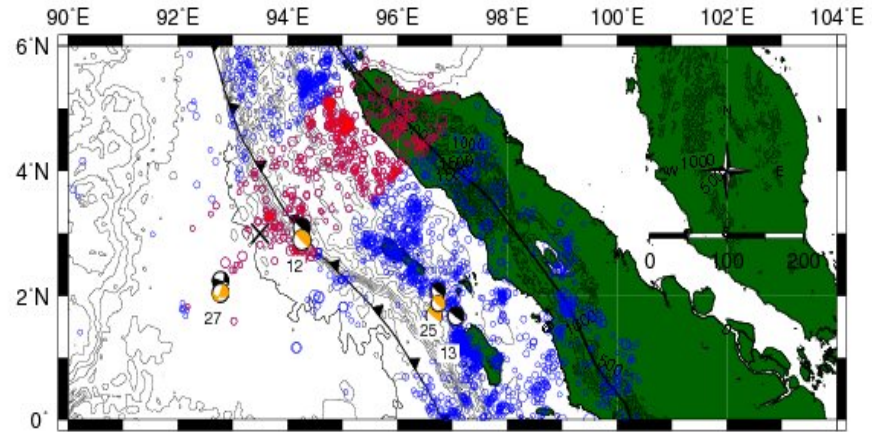
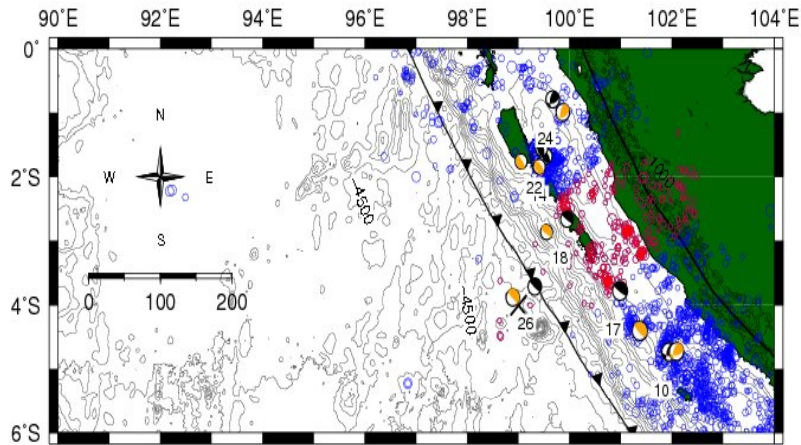
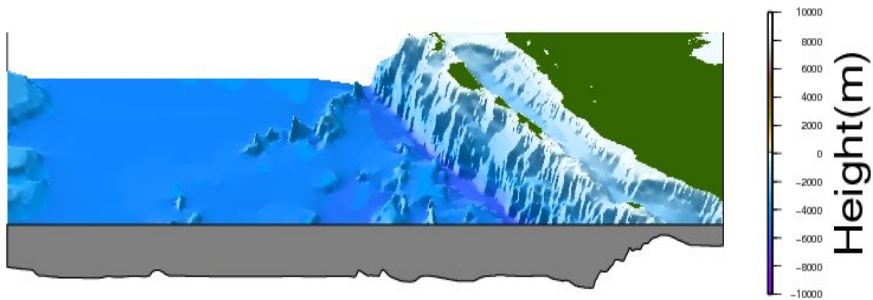
Hasil relokasi
Sumatera
mekanisme fokus
merah (*Global CMT*)
& biru (*W phase*).

Hasil relokasi
mekanisme fokus
merah (*Global CMT*)
& biru (*W phase*)

wilayah Jawa dan
Nusa Tenggara

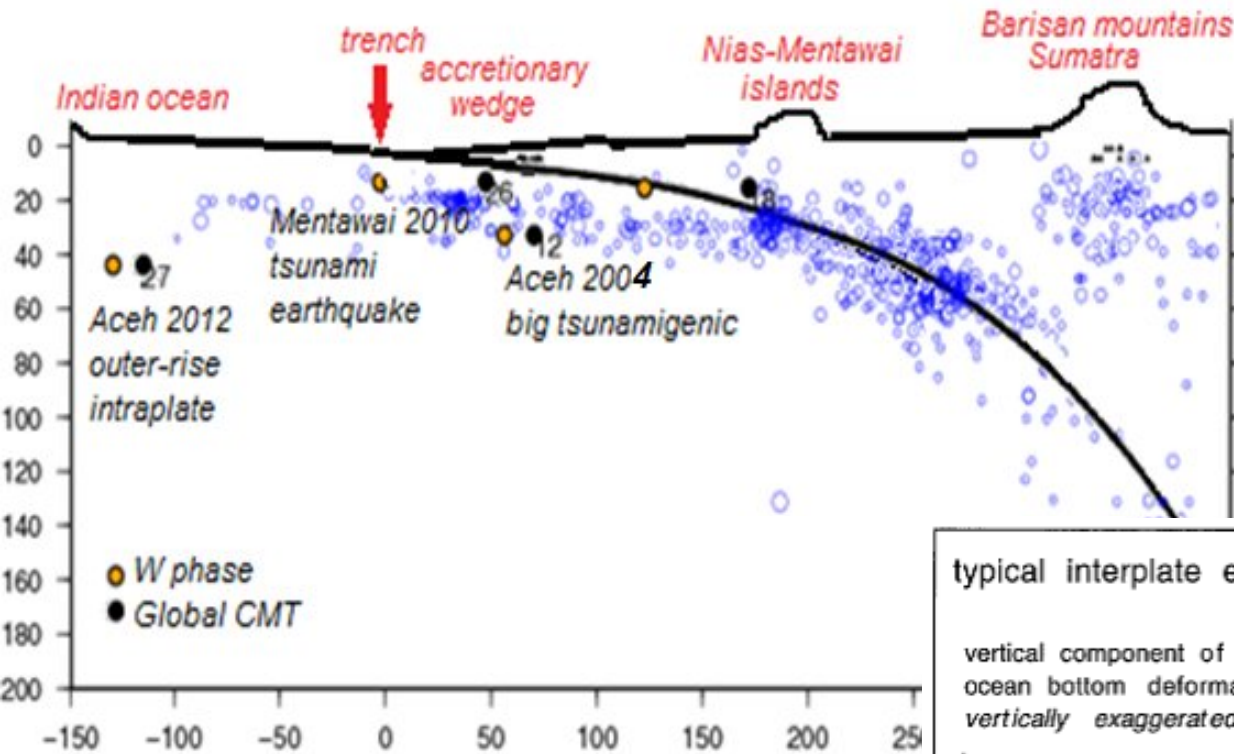


wilayah Sulawesi,
Banda dan Papua

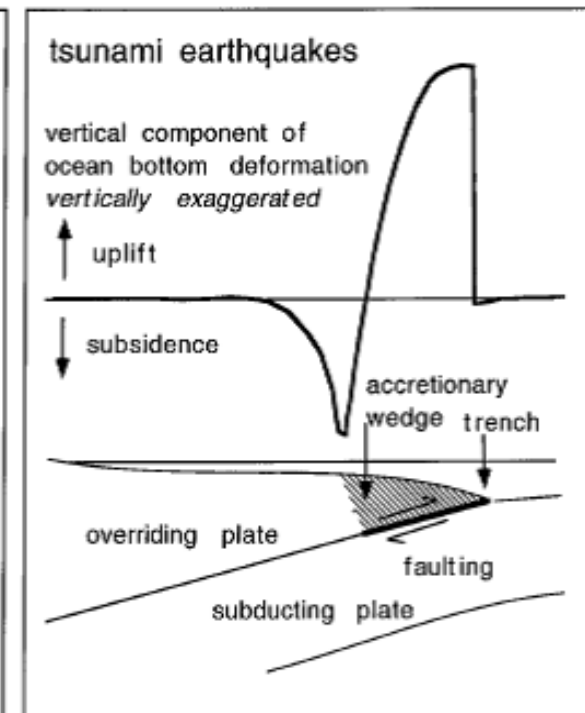
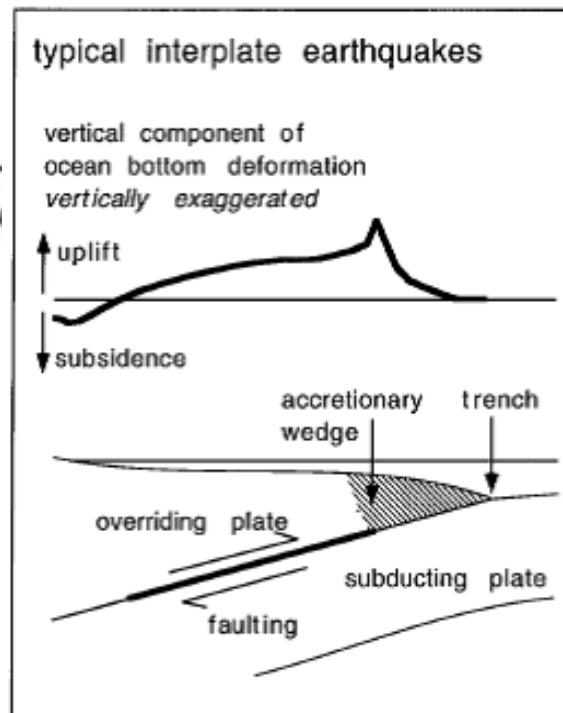


Penampang kedalaman: Sumatra

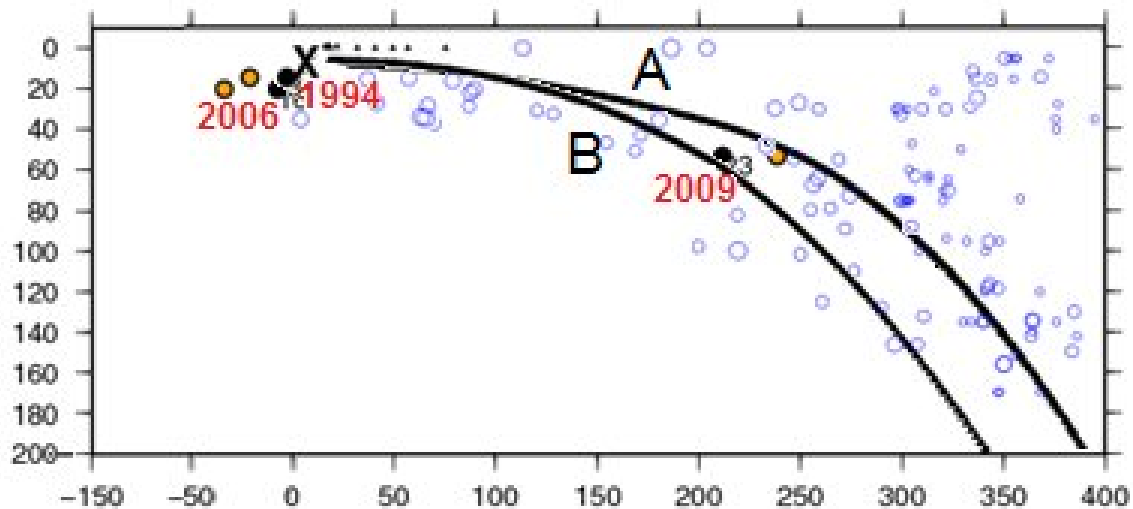
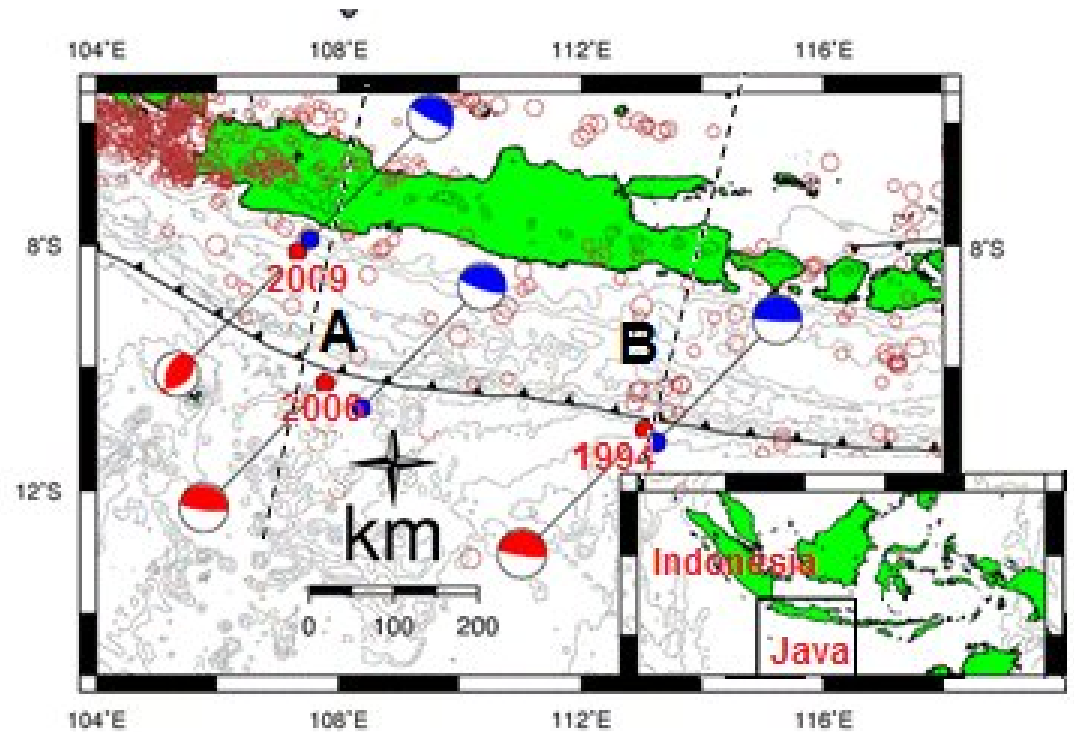
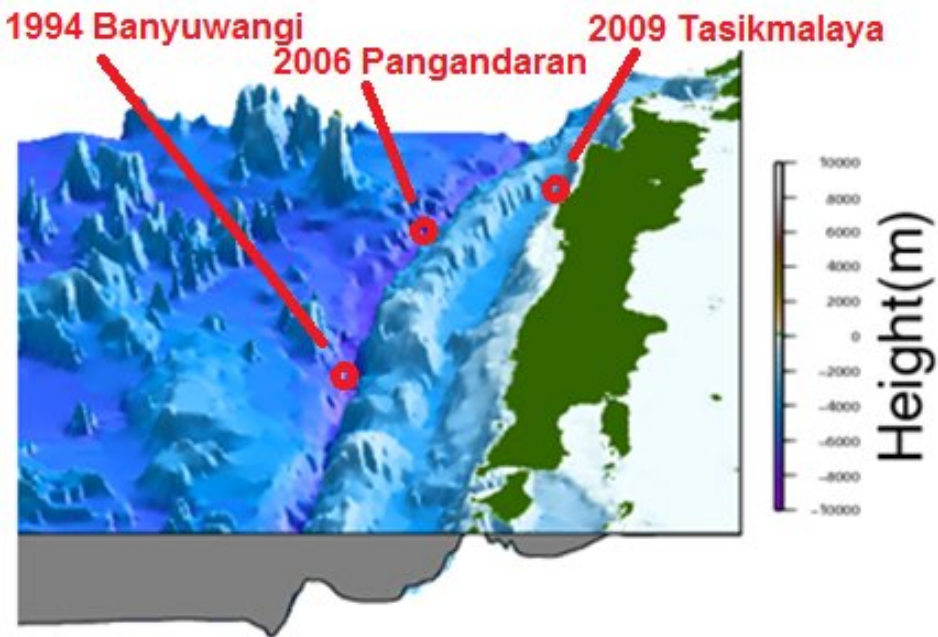
Penampang kedalaman: Sumatra



Satake & Tanioka, 1999



Penampang kedalaman: Jawa



Program komputasi seismik

- ❑ *SAC (Tapley and Tull, 1992; Savage, et. al., 2005)*
- ❑ *Rdseed (FDSN, IRIS, USGS)*
- ❑ *Seisgram2K (Lomax, 2011)*
- ❑ *Tau-P (Crotwell, et. al., 1999)*
- ❑ *W-phase (Kanamori and Rivera, 2008)*
- ❑ *GMT (Wessel and Smith, 1991)*
- ❑ *Slab 3.1 USGS*



Pertanyaan Riset

- Apakah perhitungan parameter mekanisme sumber gempa dapat dipergunakan untuk mengkarakterisasi gempa-gempa pembangkit tsunami di Indonesia ?

Hipotesis

- Perhitungan parameter mekanisme sumber gempa dapat dipergunakan untuk mengkarakterisasi gempa-gempa pembangkit tsunami di Indonesia.

Asumsi

- Konstanta parameter sumber diambil dari peneliti terdahulu.
- Konstanta dianggap sama pada tiap stasiun penerima.

Tujuan

- Mengkarakterisasi jenis-jenis gempa-gempa pembangkit tsunami di Indonesia.

Faktor Karakterisasi

- Kekuatan gempa
- Durasi gempa
- Jenis pergerakan sesar
- Posisi gempa
- Dampak tsunami

Jenis Karakterisasi

- *Tsunami earthquake*
- *Tsunamigenic*

Kebaruan

- Menggabungkan seluruh perhitungan peneliti terdahulu secara terpadu.
- Melengkapi data global dengan regional BMKG sehingga hasil lebih akurat.
- Menganalisis gempa pembangkit tsunami berskala besar dan kecil.

Road map penelitian

Proposal, 2009	Seminar I, 2010	Seminar II, 2011	Seminar III, 2012	Seminar IV, 2012
<ol style="list-style-type: none"> 1. Pemilihan metode 2. Studi parameter sumber 3. Pengumpulan data 4. <i>Proceeding, Int. Symp. on Disasters Management, Saudi Arabia.</i> 	<ol style="list-style-type: none"> 1. Penyusunan katalog 2. Studi dan instalasi <i>W phase</i>. 3. Pengumpulan data 4. Studi parameter sumber 5. Buku ISBN, <i>Gempa Bumi Edisi Populer, BMKG.</i> 	<ol style="list-style-type: none"> 1. Aplikasi <i>W phase</i>. 2. Data global 3. Hasil dari <i>W phase</i>. 4. Hubungan empirik hasil pengolahan 5. <i>Proceeding, CTBTO Austria, PIT HAGI Makassar.</i> 	<ol style="list-style-type: none"> 1. Karakterisasi <i>tsunamigenic & tsunami earthquake</i> 2. Analisis sinyal seismik. 3. Hubungan empirik hasil 4. <i>Proceeding, AIP Journal Amerika, PIT HAGI, GREAT</i> 	<ol style="list-style-type: none"> 1. Karakterisasi 2. Aplikasi <i>W phase</i>. 3. Data regional BMKG. 4. Ringkasan hasil seminar I, II, III, IV.

Parameter Karakterisasi

1. Momen seismik (M_0) dan Magnitudo momen (M_w)
2. Energi radiasi seismik (E)
3. Rasio ($\Theta = E/M_0$)
4. Durasi sumber (T_0)
5. Mekanisme fokus *W phase*
6. Posisi kedalaman terhadap zona subduksi