Fault mechanism and essential parameters for tsunami generation including South China Sea

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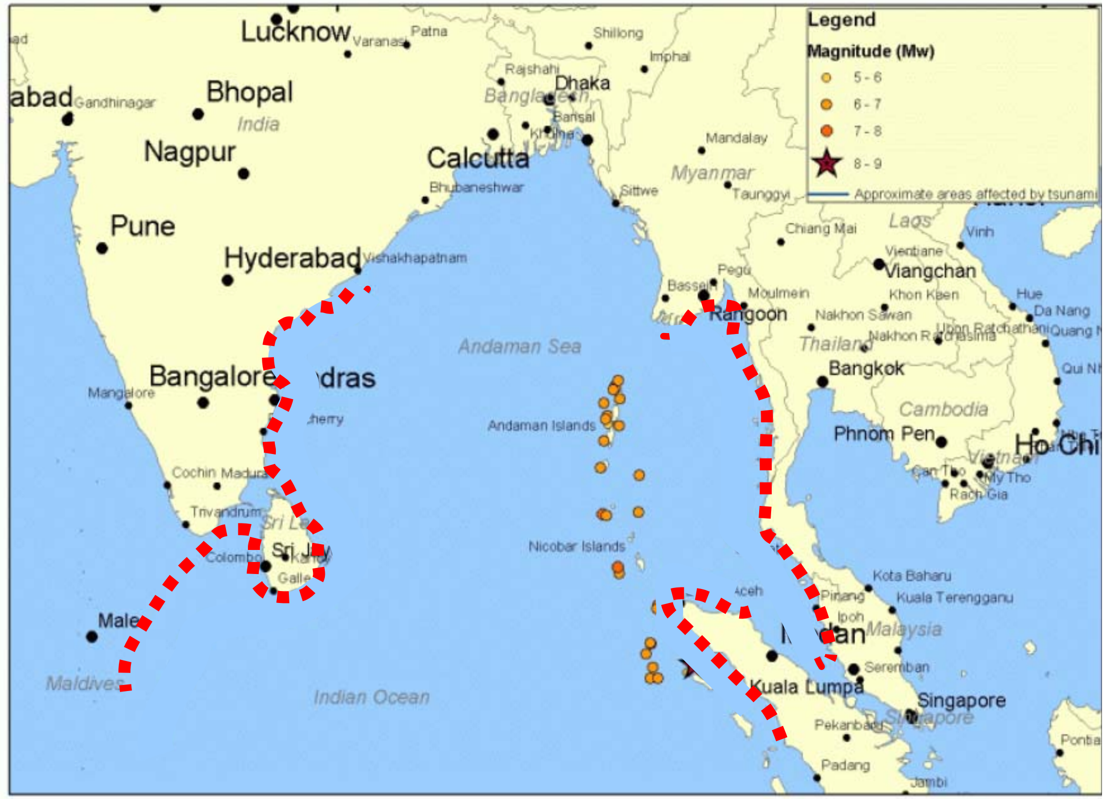
A. Background and significance:

Tsunami Disaster of 2004 Boxing Day Earthquake

December 26, 2004 Sumatra-Andaman Earthquake

- More than 275,000 killed affecting 12 nations
- Over 507,000 homeless
- 1,590,000 displaced

Affected more than 2.4 million people (Source: Red Cross)



Coastlines affected by the tsunami are delimited in red

Earthquake parameters
- M_w = 9.0 (USGS)
- Focal depth = 10-30 km
- Rupture length = 1200 km
- Width = 200 km
- Slip = 10-30 m

A. Background and significance:

Tsunami Disaster of 2004 Boxing Day Earthquake

Banda Aceh, Indonesia – Before Tsunami

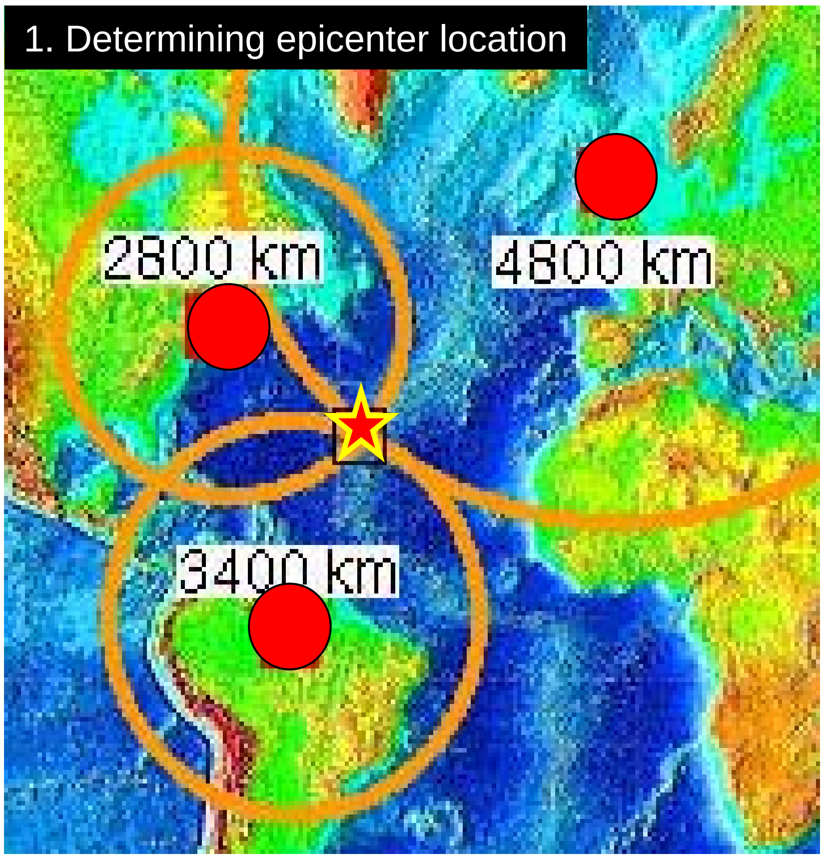
A. Background and significance:

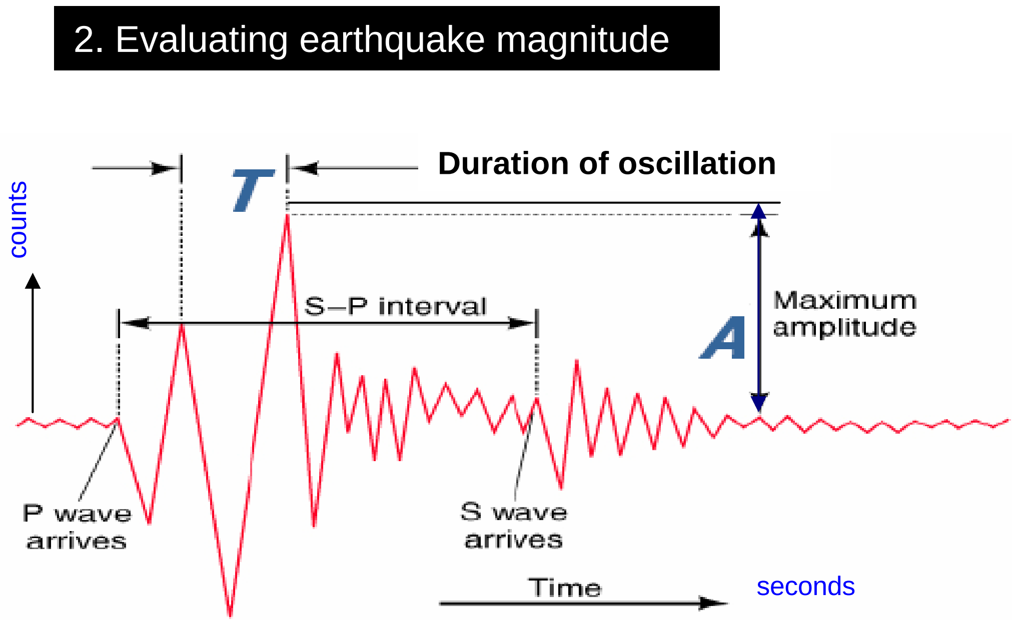
Tsunami Disaster of 2004 Boxing Day Earthquake

Banda Aceh, Indonesia – After Tsunami

B. Limitations of current tsunami warning systems

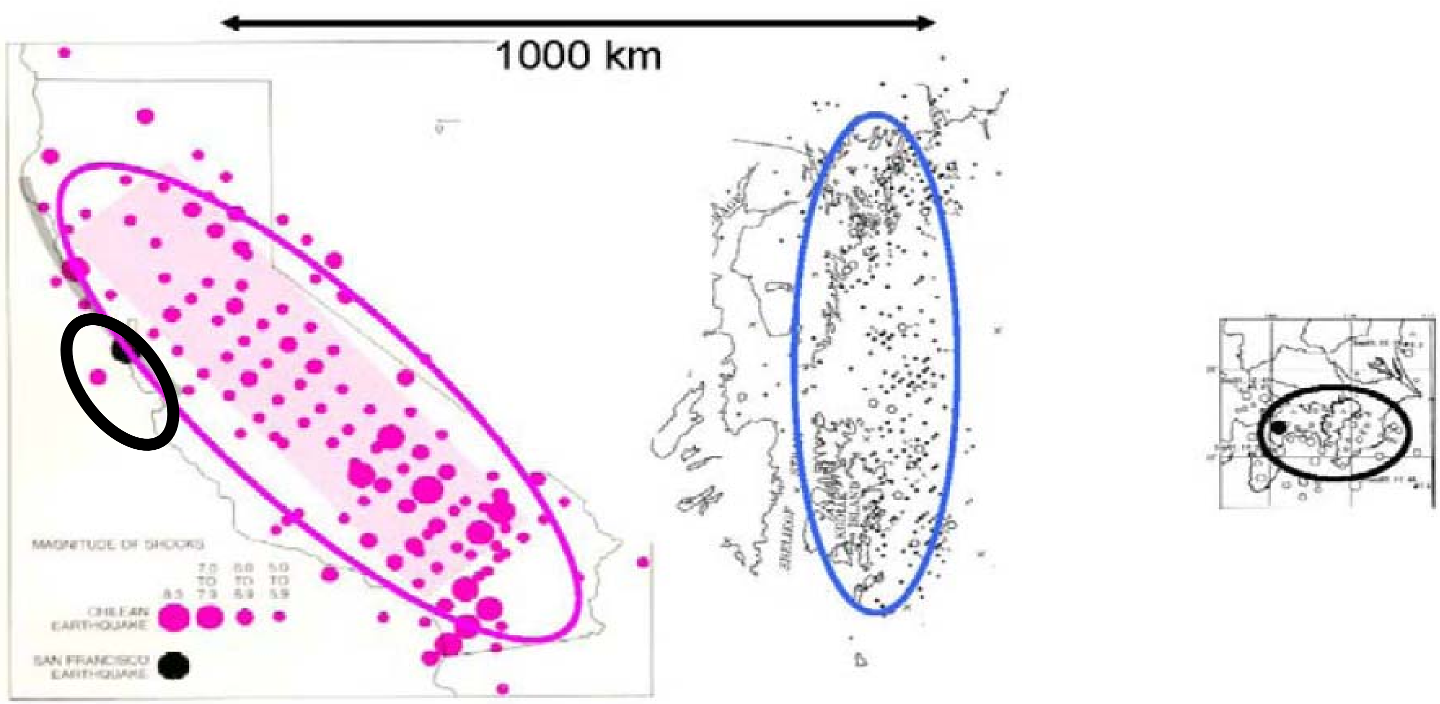
- Reliance mainly on body wave short period (T<20 sec) earthquake magnitudes (M_s, M_b or M_L) and epicenter location
  - Shortcoming : Ms saturates for M>8, hence underestimate the real energy for large EQ
- Consequence: more than 50% tsunami warnings are false.





B. Limitations of current tsunami warning systems

- Actual energy (and the rupture area) causing the ground displacement (→ tsunami wave generation!) can be very difference for different earthquake with same Ms or Mb…



1960 Chile
M_s=8.5, M_w=9.5
gray curve
1906 San Francisco
M_s=8.2, M_w=7.9

1964 Alaska
M_s=8.5, M_w=9.2

1923 Kanto (Tokyo)
M_S=8.3, M_w=7.9

All these cases : Ms ~8.2 to 8.5

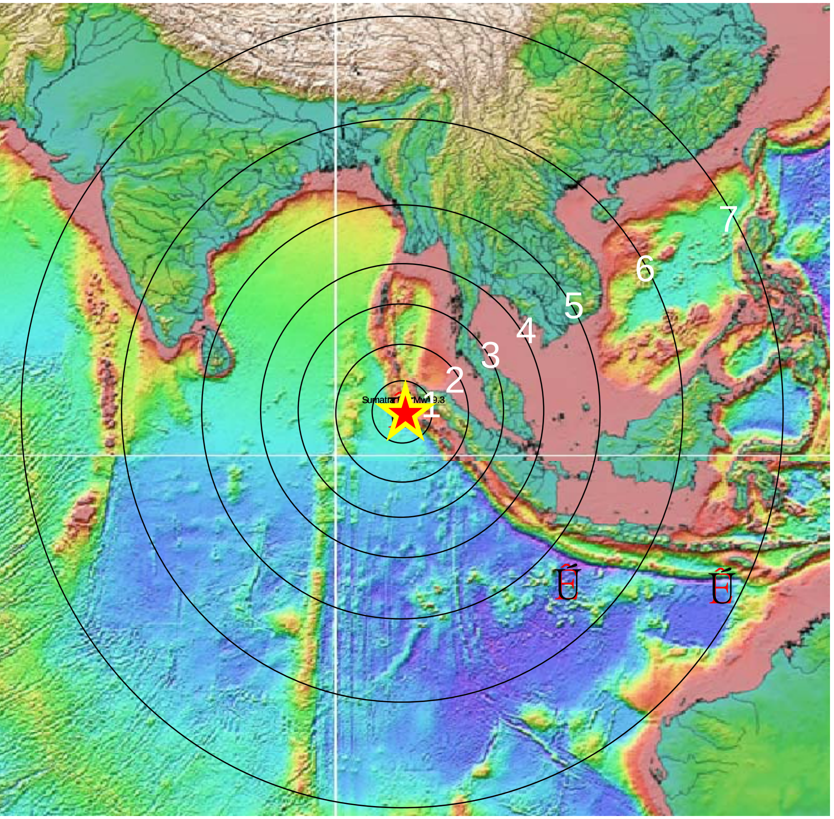
But the Moment Magnitude: Mw=7.9 → 9.5

Motivation

Seismic wave (v=4000-6000 m/s, for up to a depth of 700 km) travels 20 to 30 times faster than tsunami wave (v=200 m/s in deep sea). For example, seismic signal of December 2004 Sumatra earthquake arrived in Sri Lanka in about 5 minutes, tsunami arrived only after 2 hours. *Thus, if the readily available seismic signal can be used to predict tsunami, it can be very effective for early warning.*

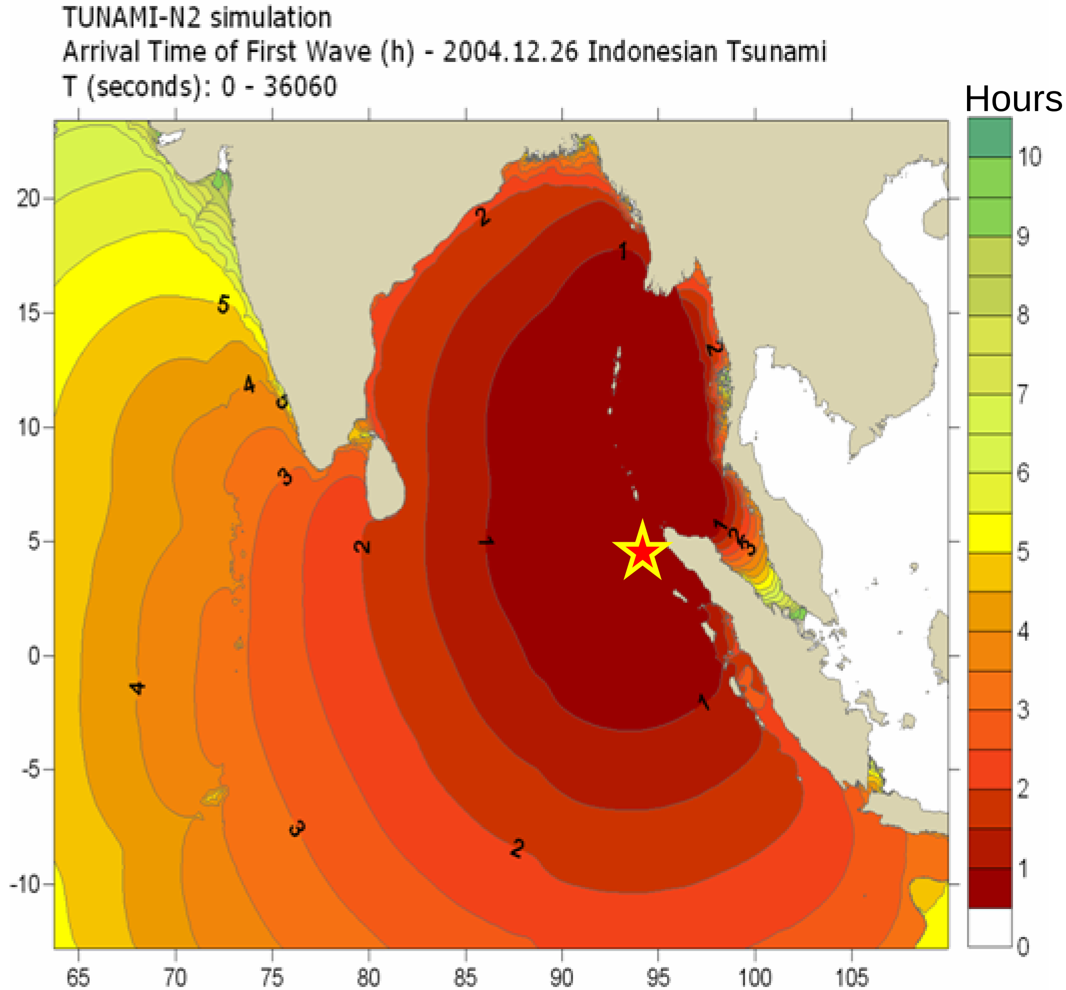
C. Objectives & motivation of the research

P-wave Arrival Times



Source: modified from USGS

Tsunami Arrival Times



Seismic wave took only about 5 minutes while tsunami wave took 2 hours to reach Sri Lanka.

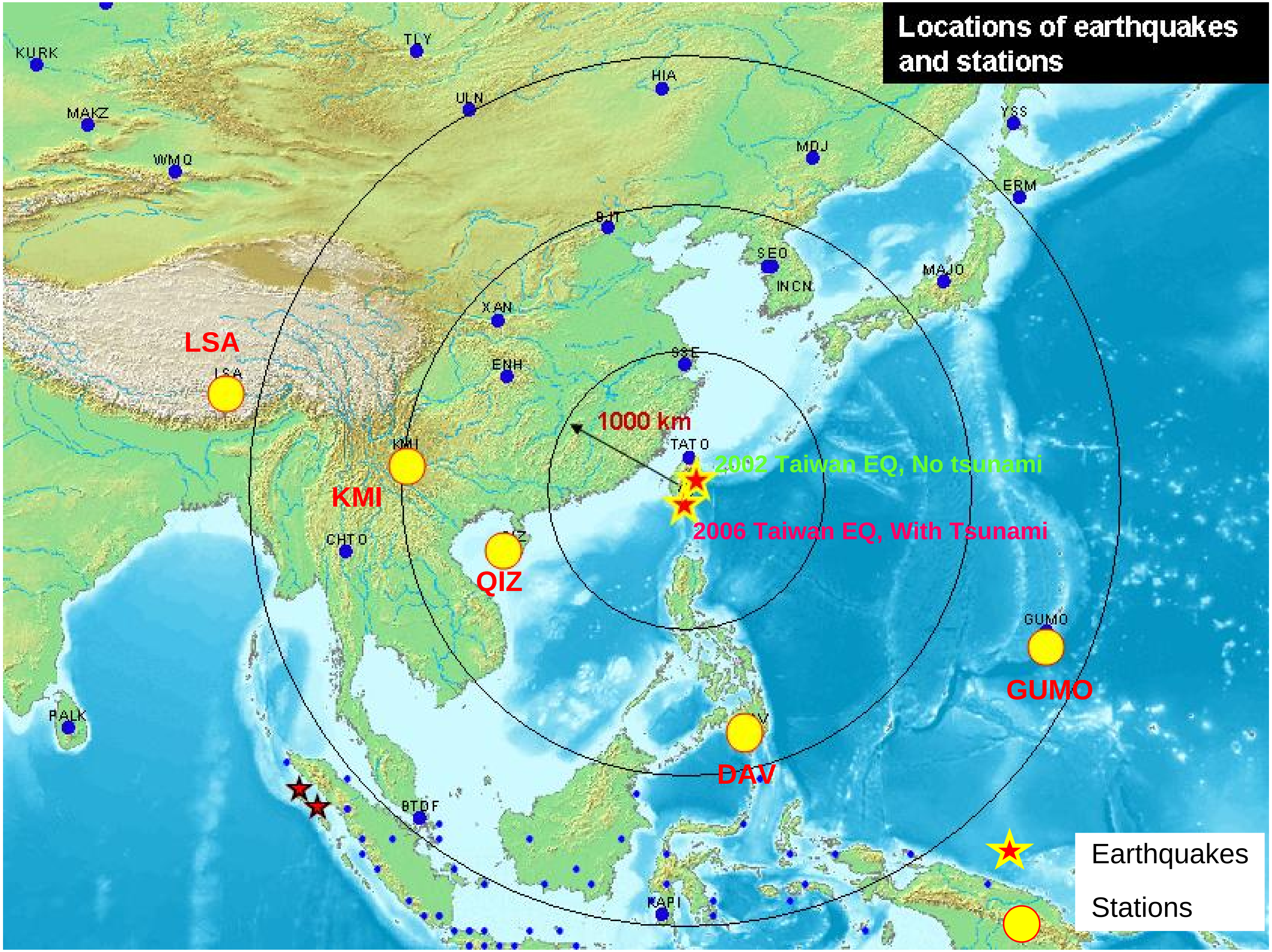
D. Methodology for tsunamigenesis prediction

- Differentiation of tsunamigenic earthquakes from non-tsunamigenic earthquakes based on frequency content

- Near real time computation of moment magnitude and focal mechanism and utilization of these parameters to compute initial tsunami wave profile for tsunami prediction & warning

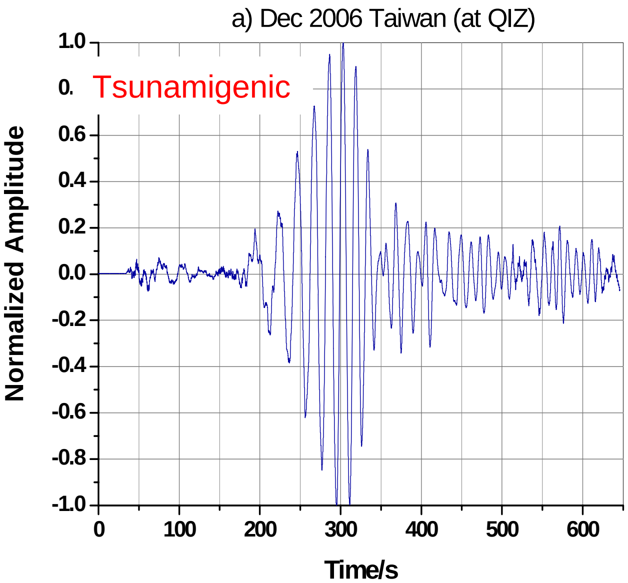
E. Frequency analysis of earthquakes data

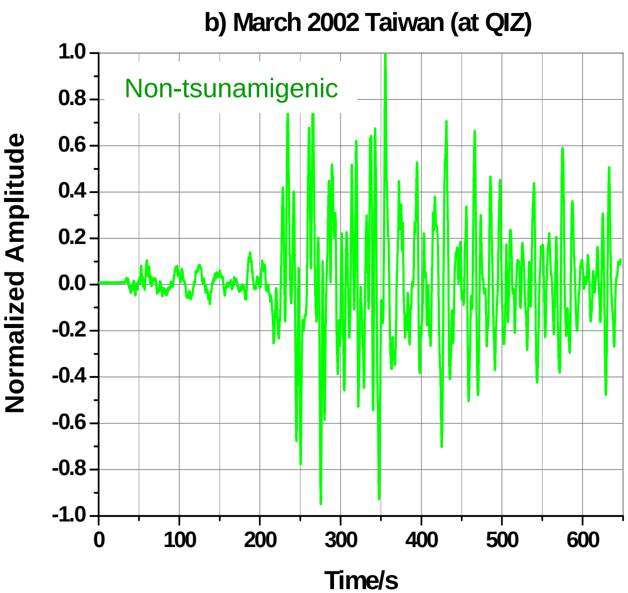
Case 1. Taiwan EQ

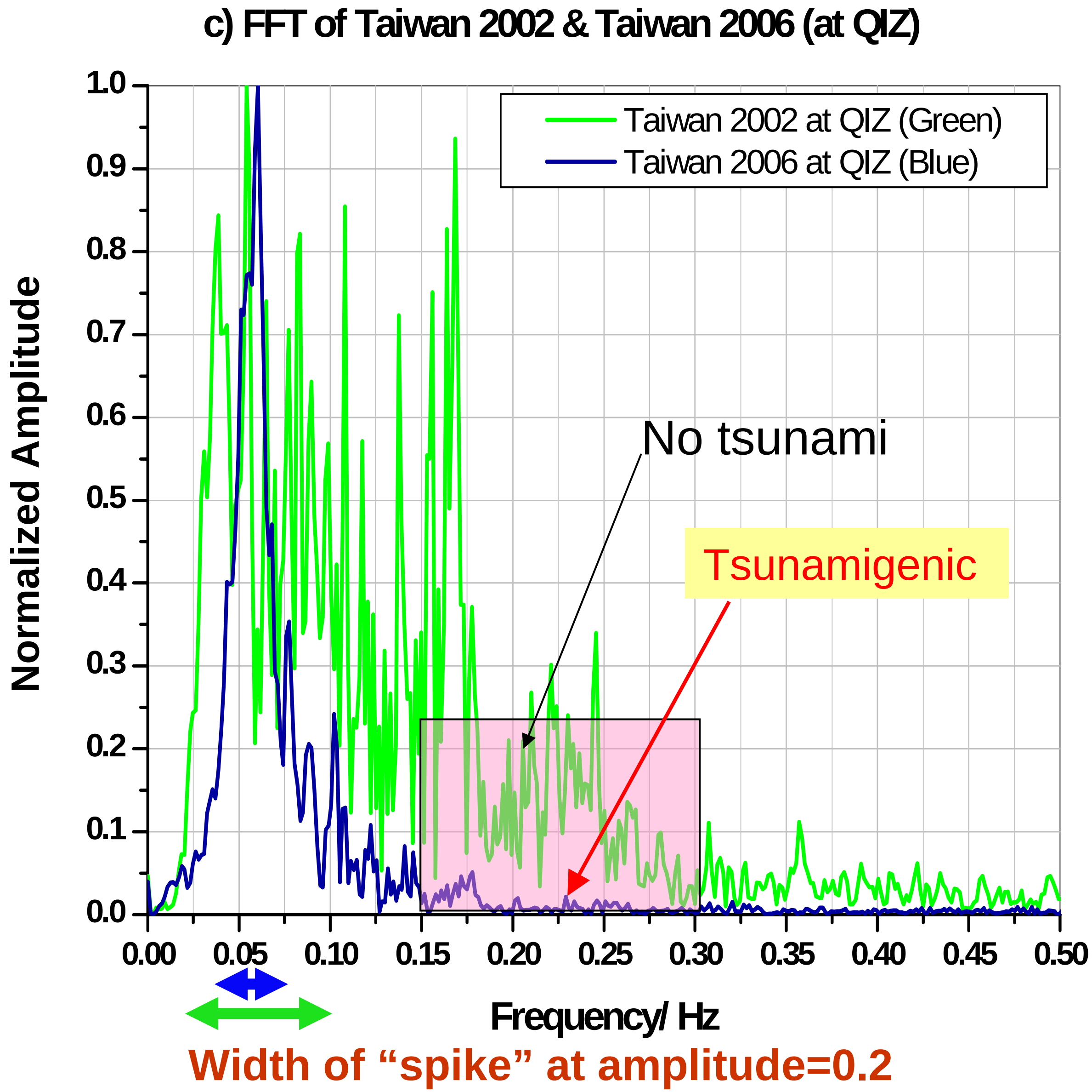


E. Frequency analysis of earthquakes data

Case 1a. Taiwan EQ (at QIZ)







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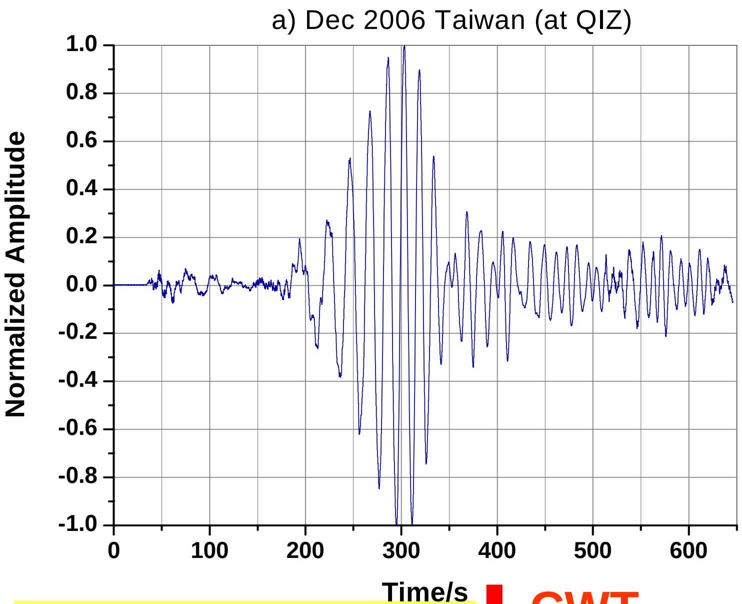
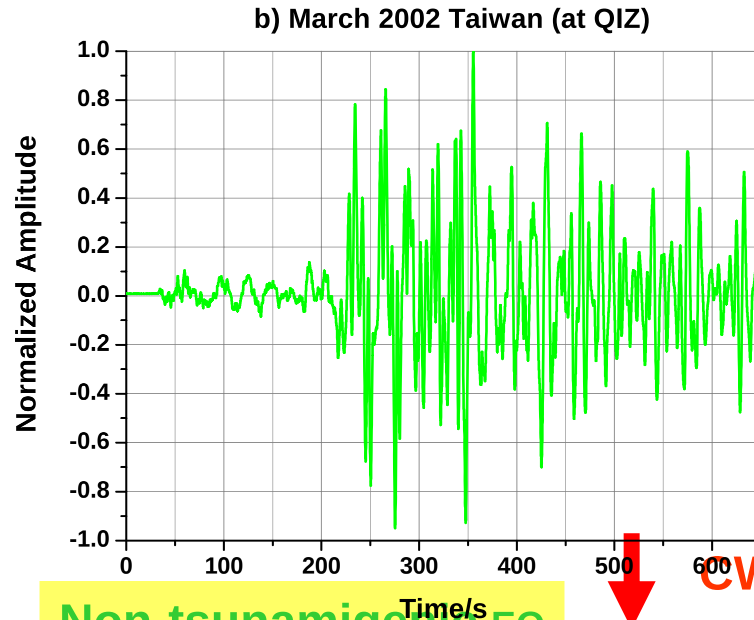
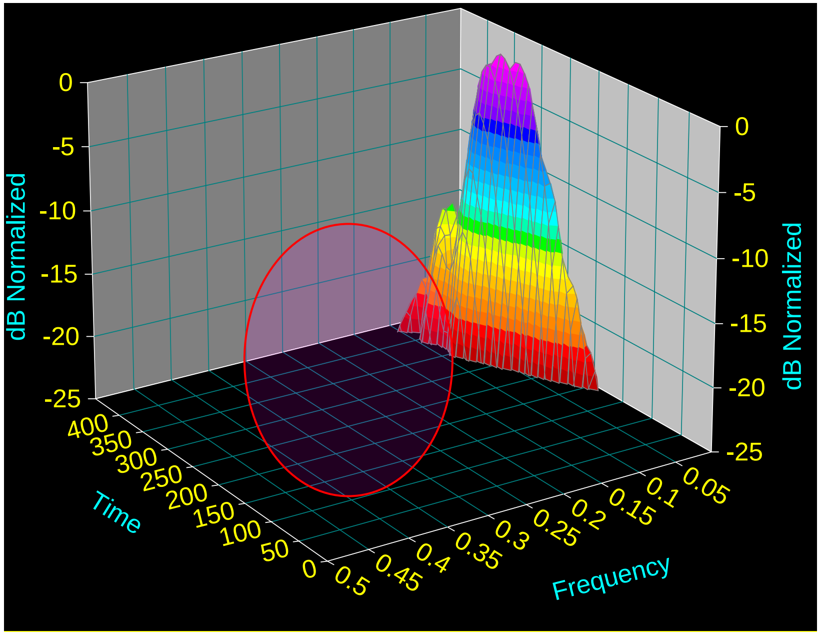




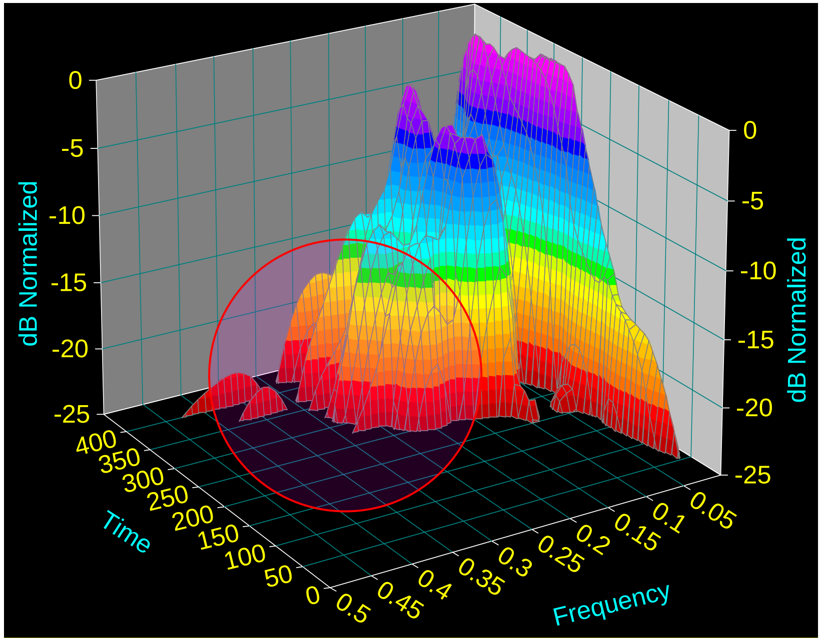
CWT

Tsunamigenic EQ



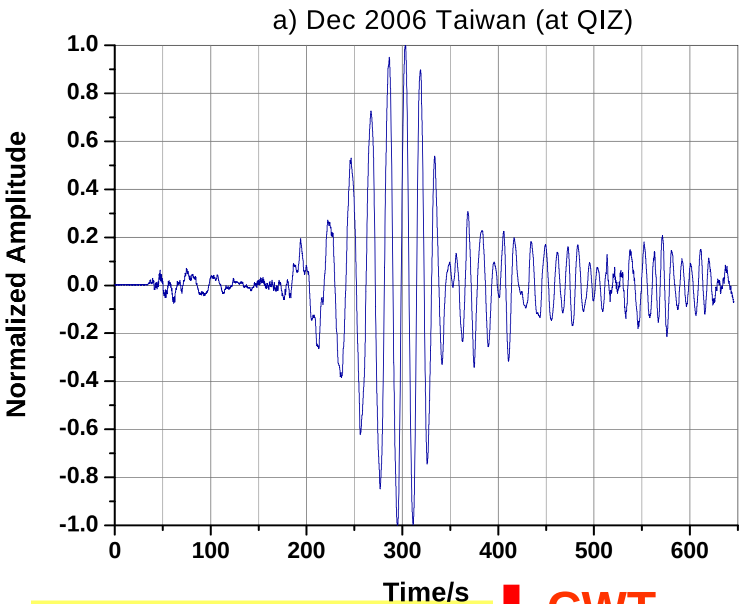
CWT

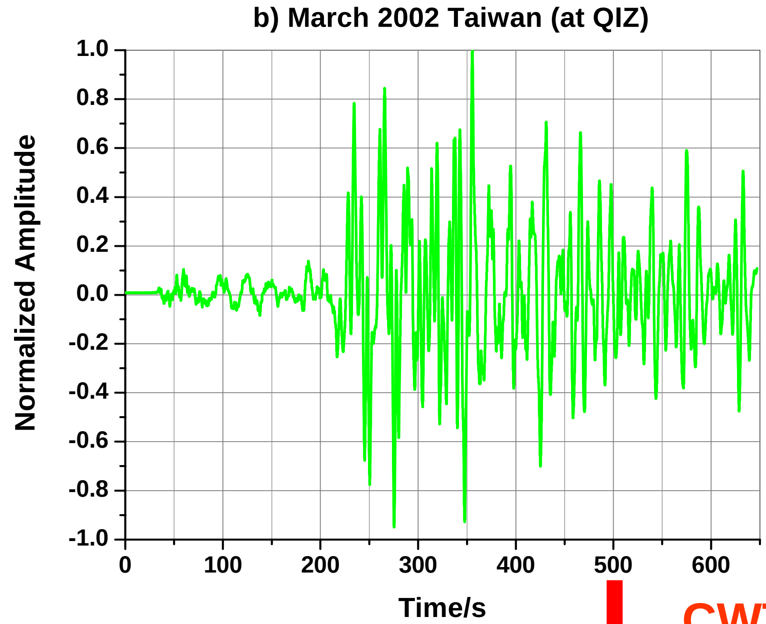
Non-tsunamigenic EQ



E. Frequency analysis of earthquakes data

Case 1a. Taiwan EQ (at QIZ)



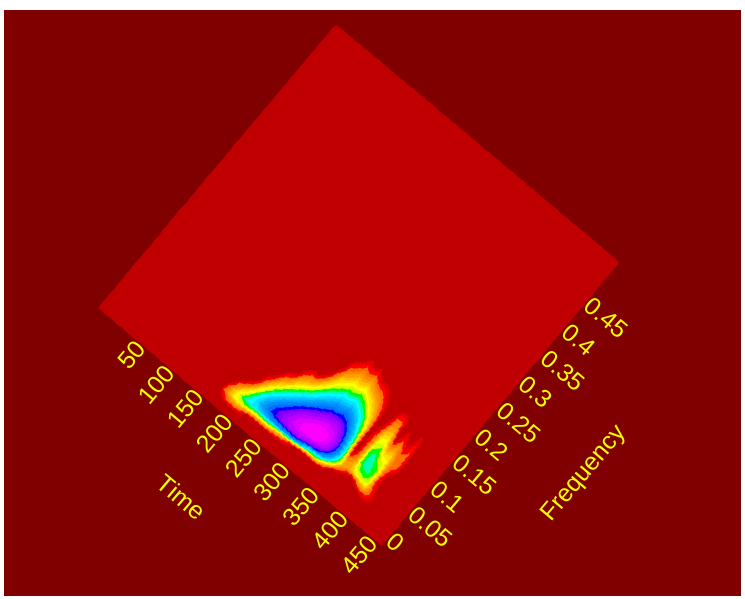


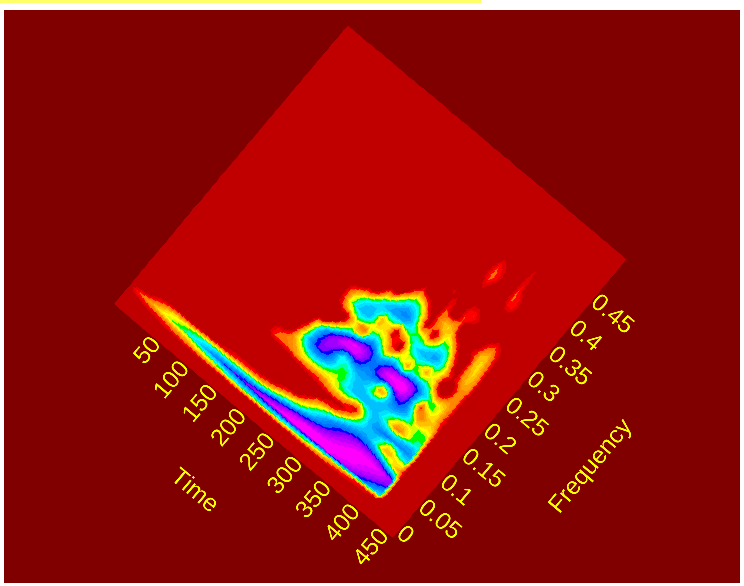
CWT

Tsunamigenic EQ

CWT

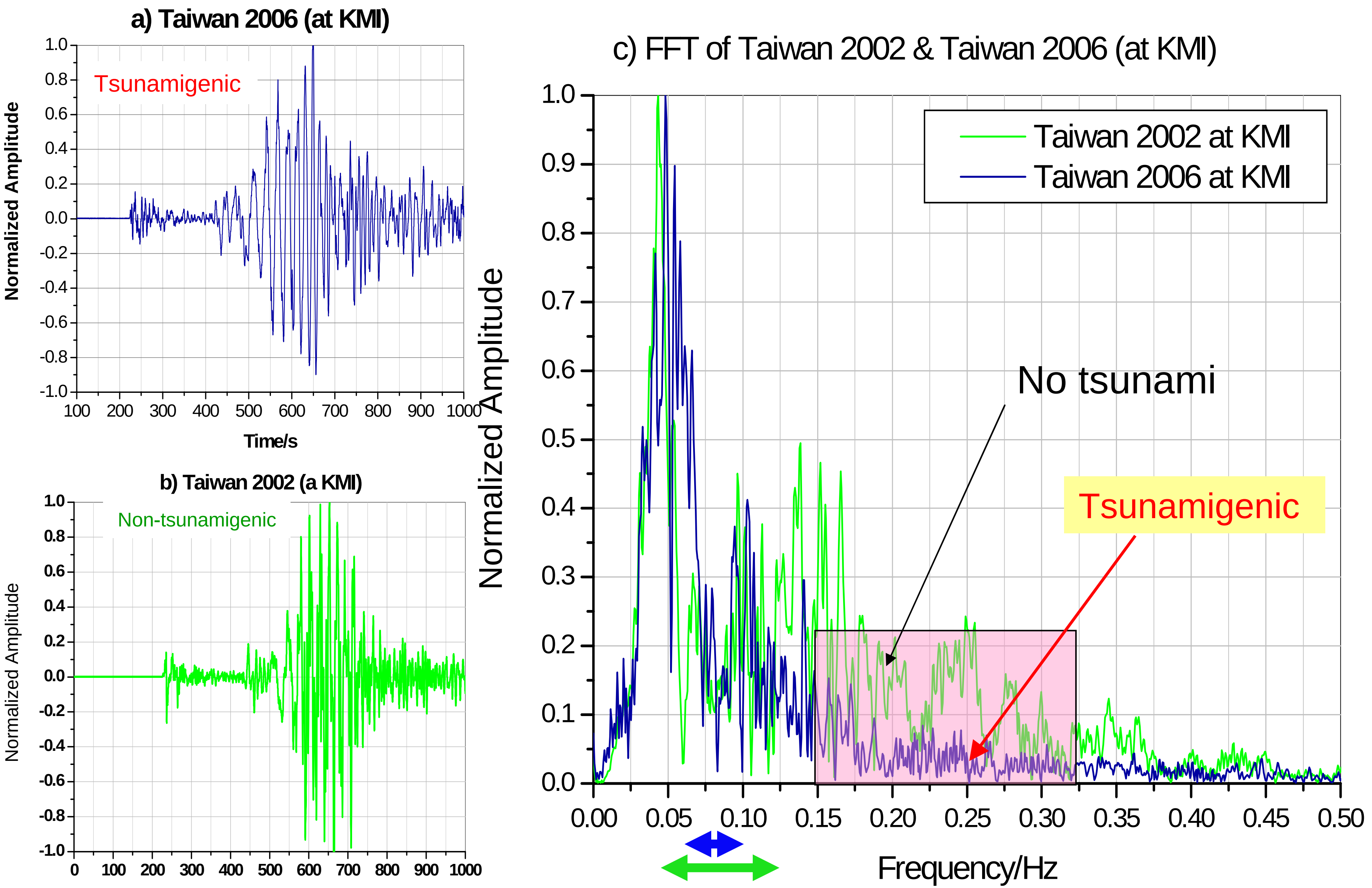
Non-tsunamigenic EQ





E. Frequency analysis of earthquakes data

Case 1b. Taiwan EQ (at KMI)

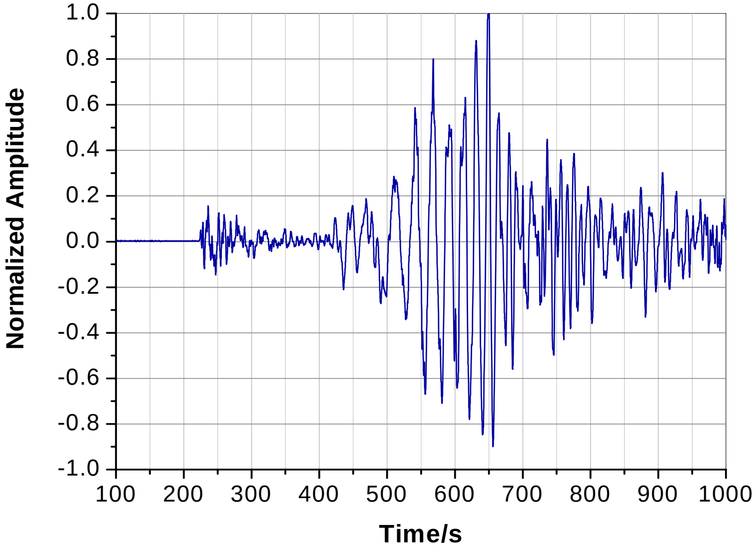


Width of "spike" at amplitude=0.2

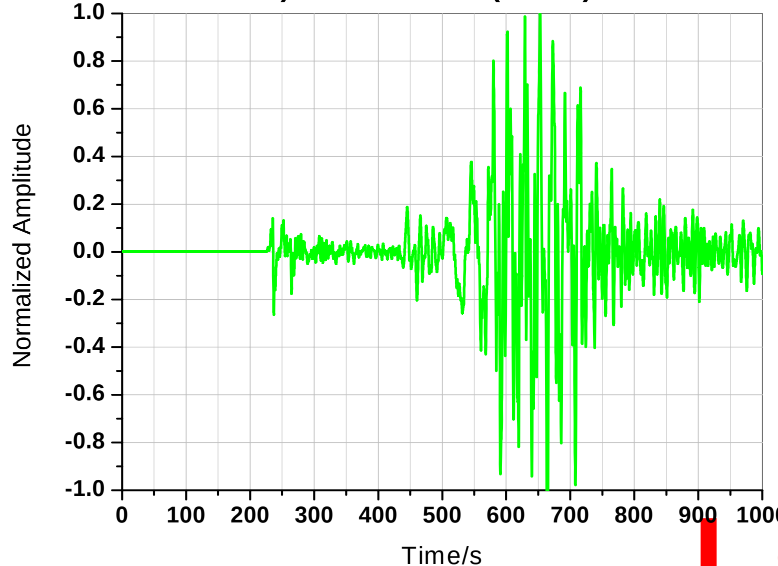
E. Frequency analysis of earthquakes data

Case 1b. Taiwan EQ (at KMI)

a) Taiwan 2006 (at KMI)

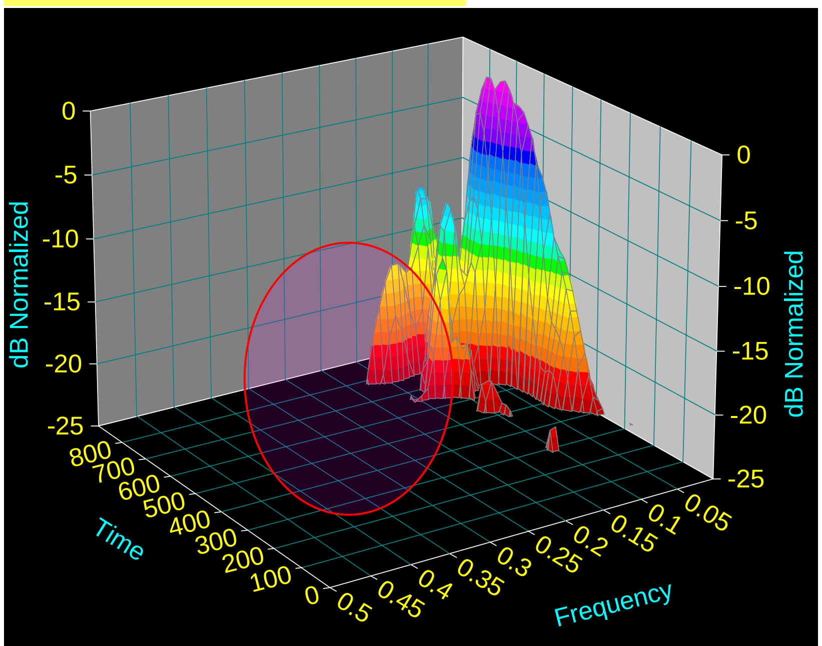


b) Taiwan 2002 (a KMI)



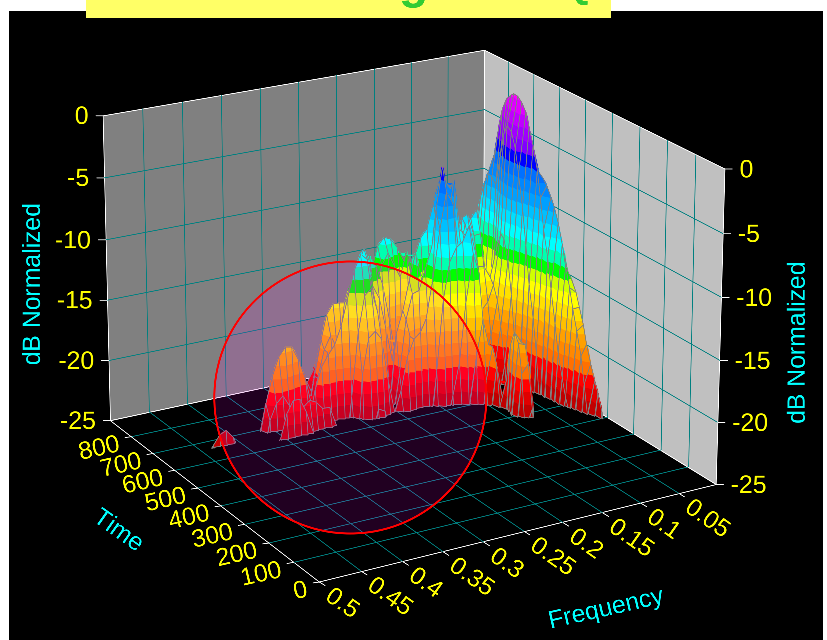
CWT

Tsunamigenic EQ



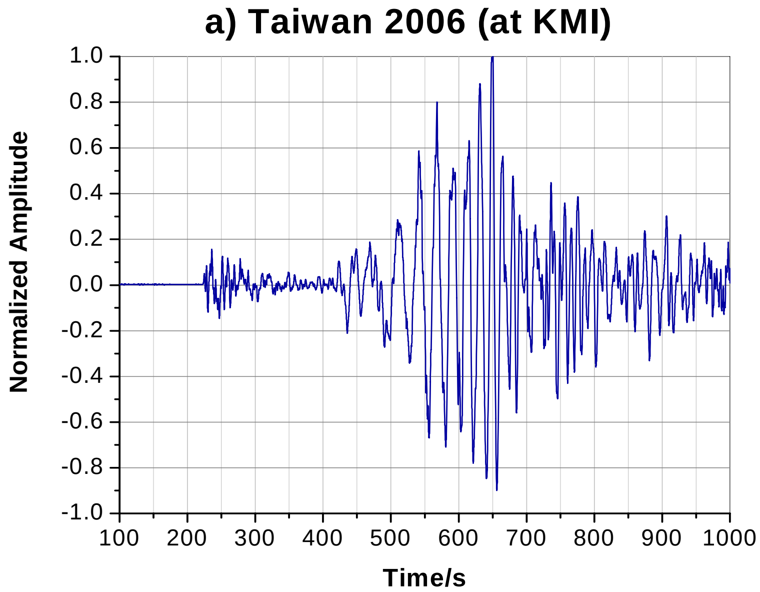
CWT

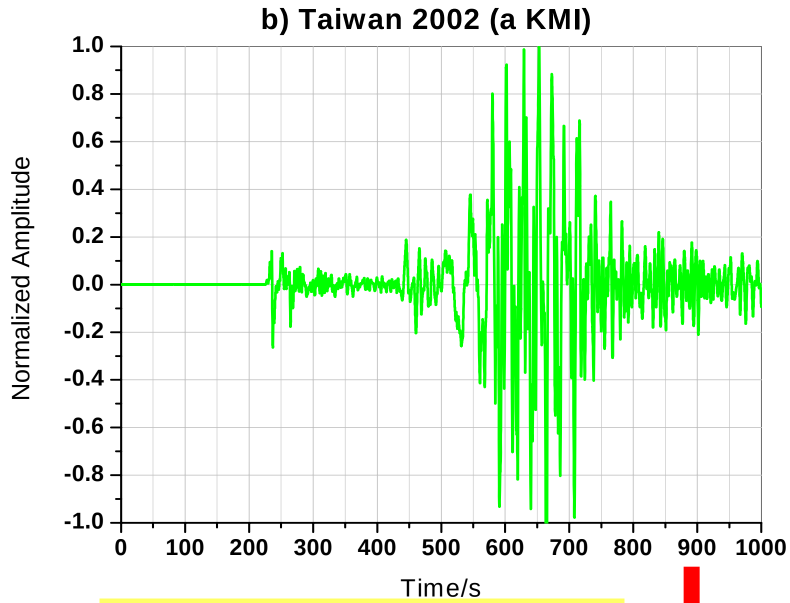
Non-tsunamigenic EQ



E. Frequency analysis of earthquakes data

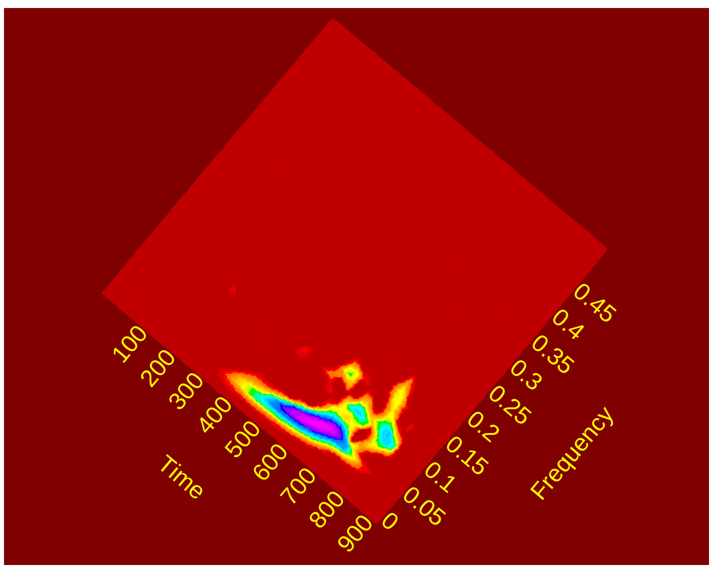
Case 1b. Taiwan EQ (at KMI)

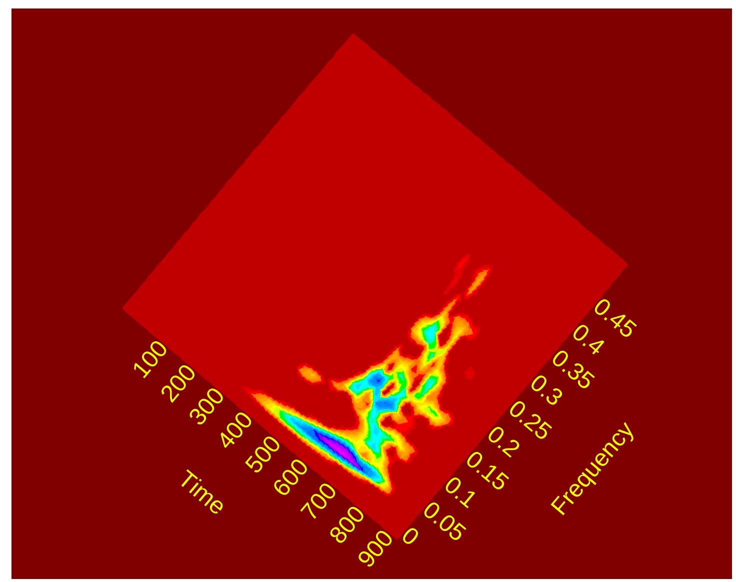




Tsunamigenic EQ → CWT

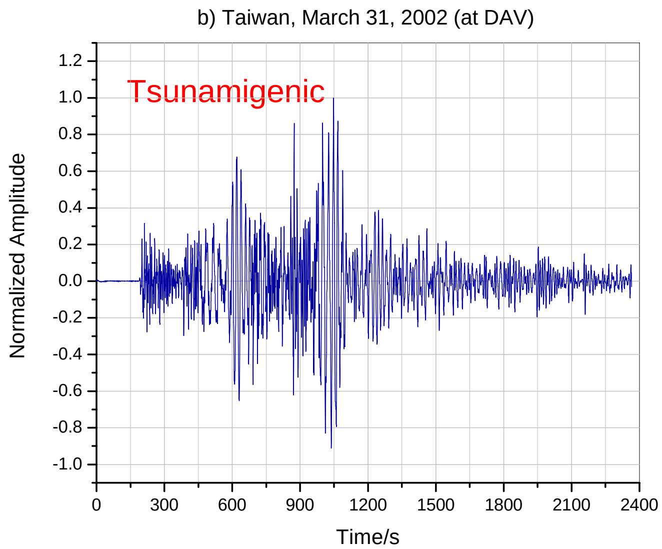
Non-tsunamigenic EQ → CWT

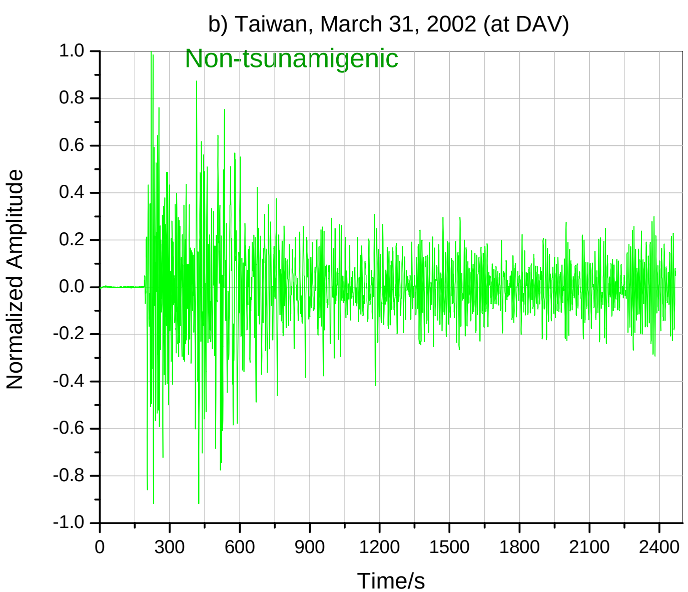


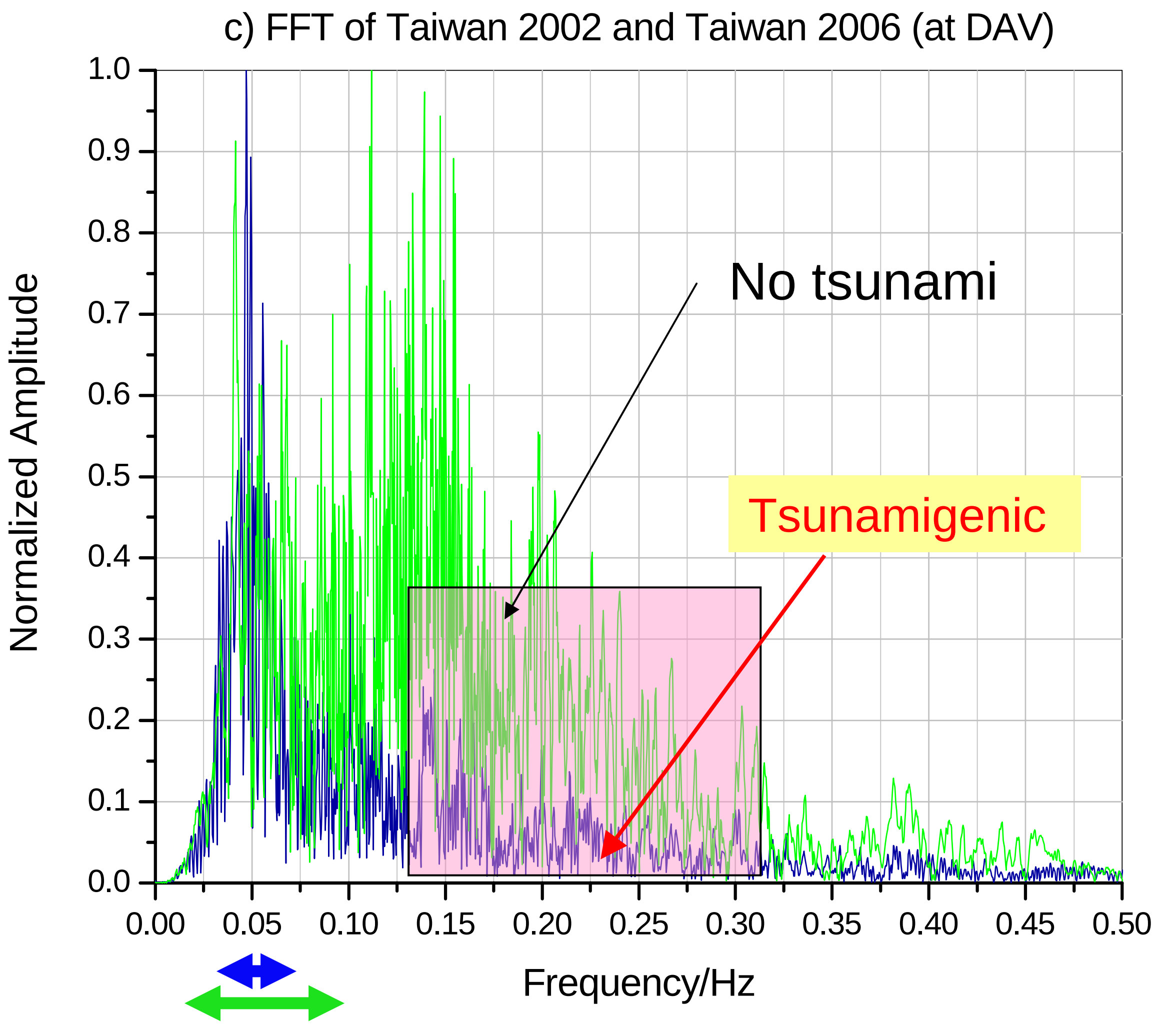


E. Frequency analysis of earthquakes data

Case 1c. Taiwan EQ at DAV

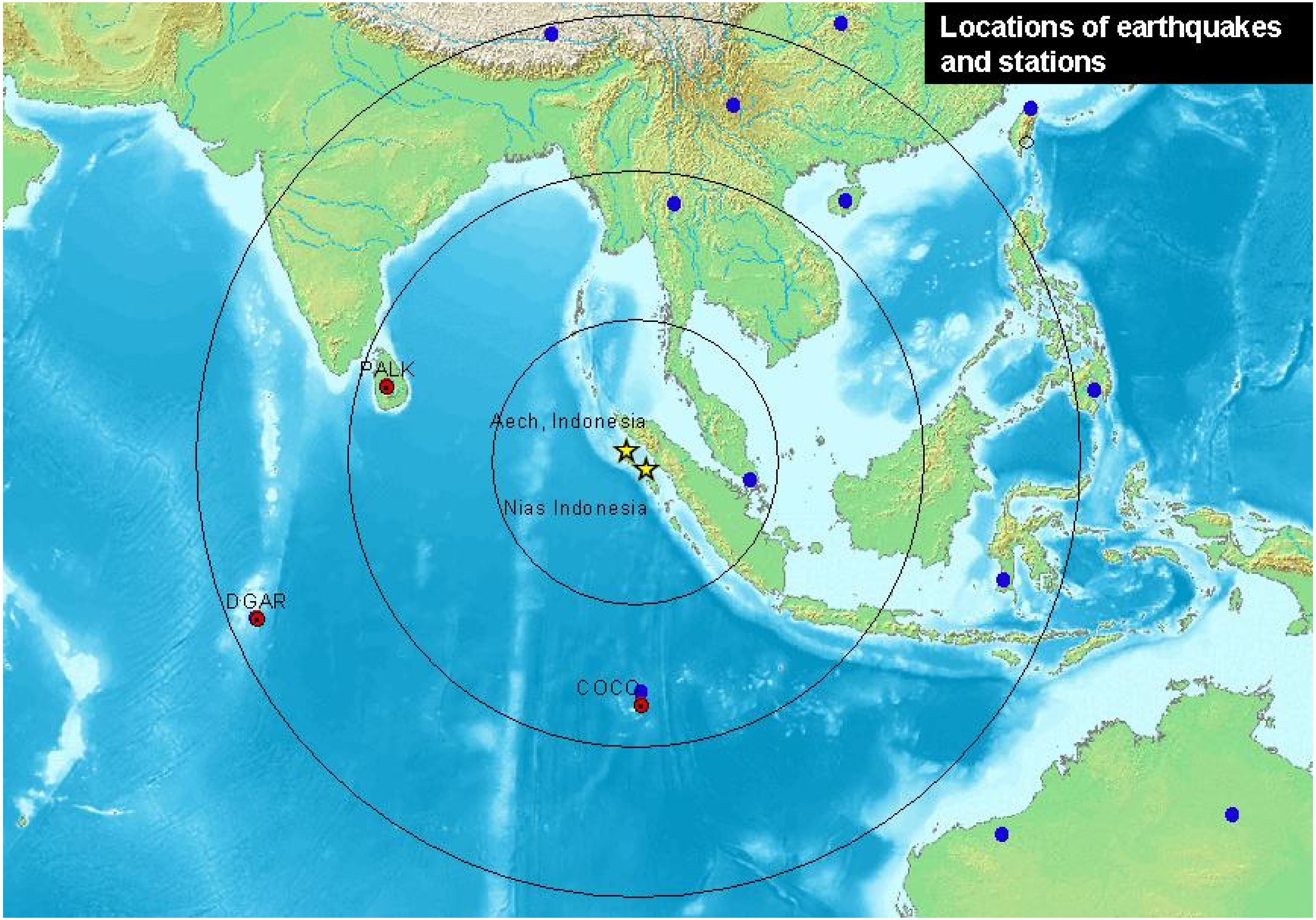






E. Frequency analysis of earthquakes data

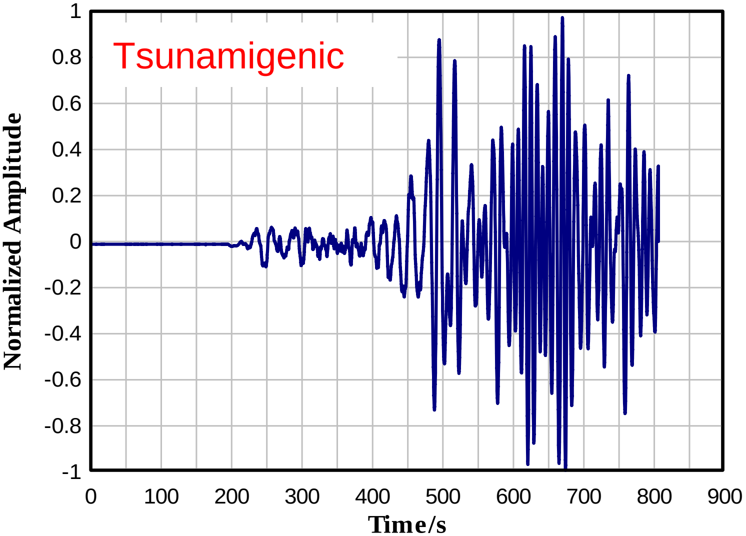
Case 2. Sumatra EQ



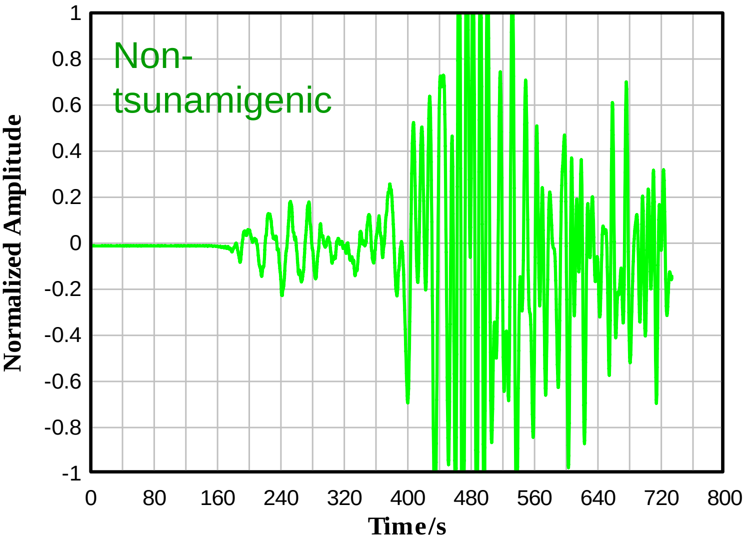
E. Frequency analysis of earthquakes data

Case 2a. Sumatra EQ (at COCO)

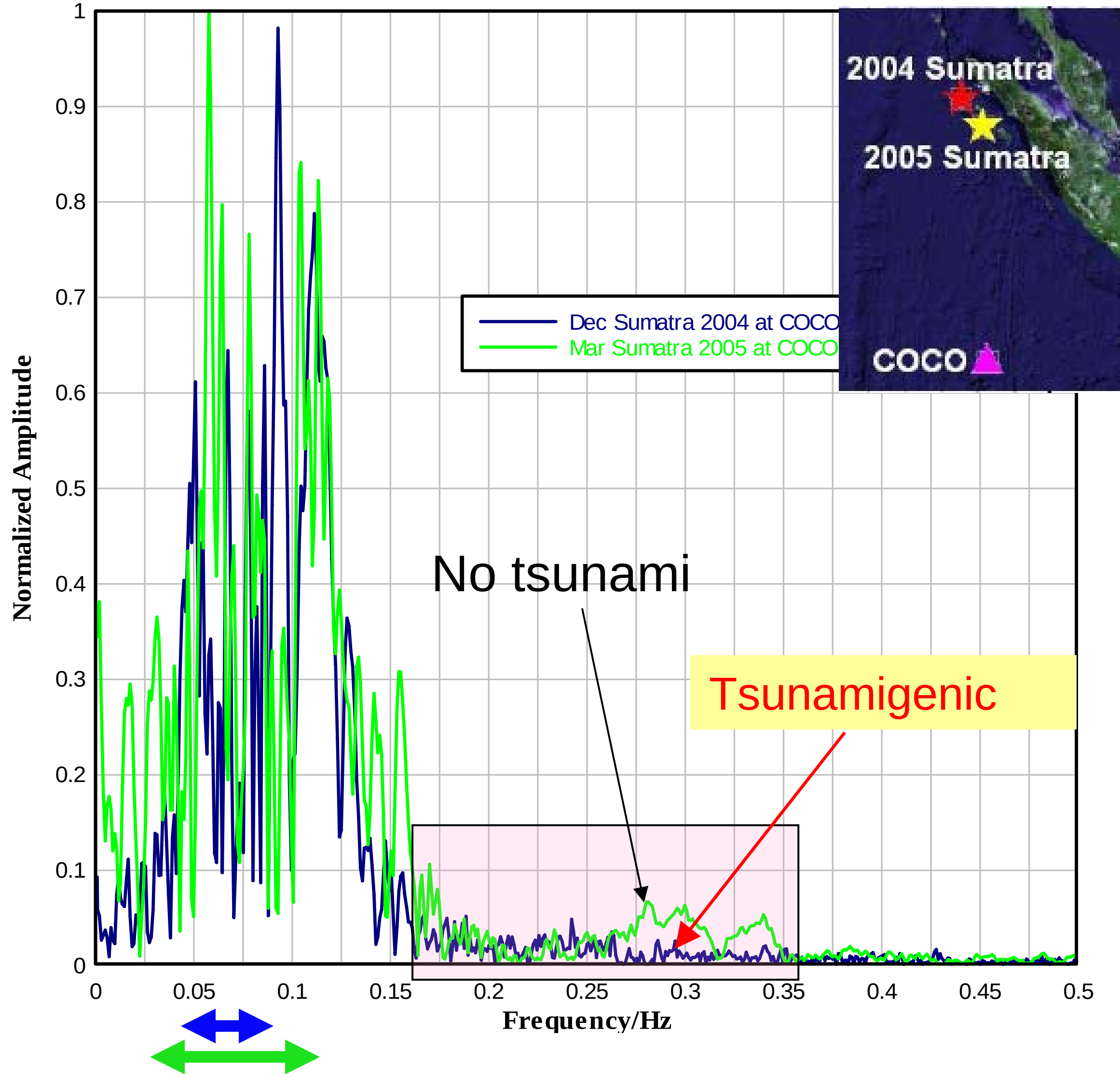
a) Dec 2004 Sumatra (at COCO)



b) Mar 2005 Sumatra (at COCO)



c) FFT of Dec 2004 Sumatra & Mar 2005 Sumatra (at COCO)



Width of "spike" at Amplitude=0.2

E. Frequency analysis of earthquakes data

Case 2a. Sumatra EQ (at COCO)

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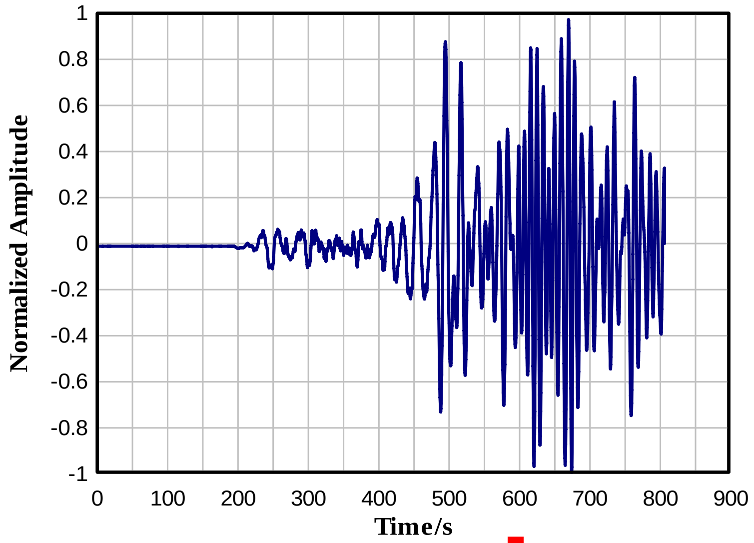
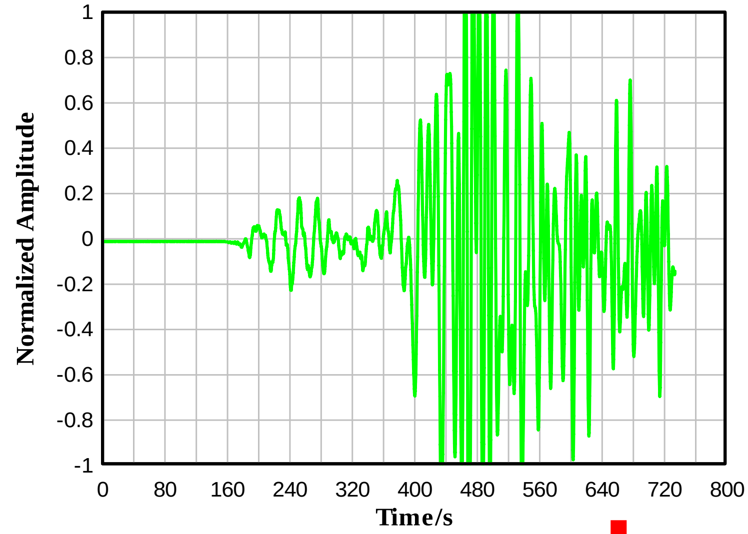
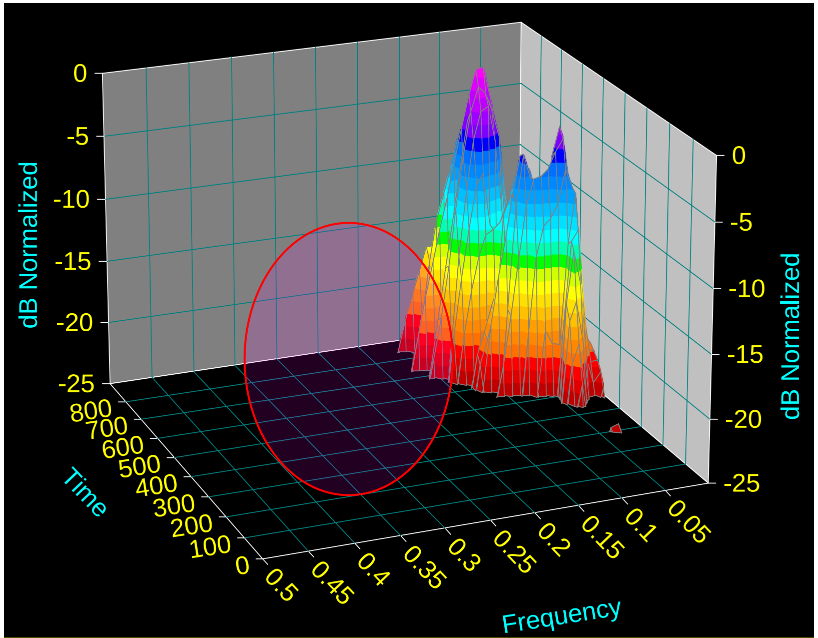


b) Mar 2005 Sumatra (at COCO)



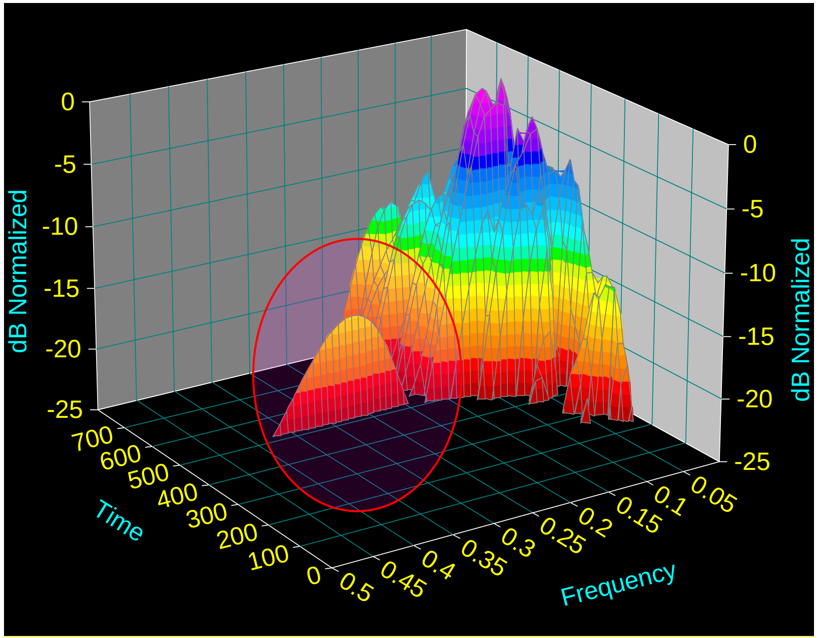
CWT

Tsunamigenic EQ



CWT

Non-tsunamigenic EQ



E. Frequency analysis of earthquakes data

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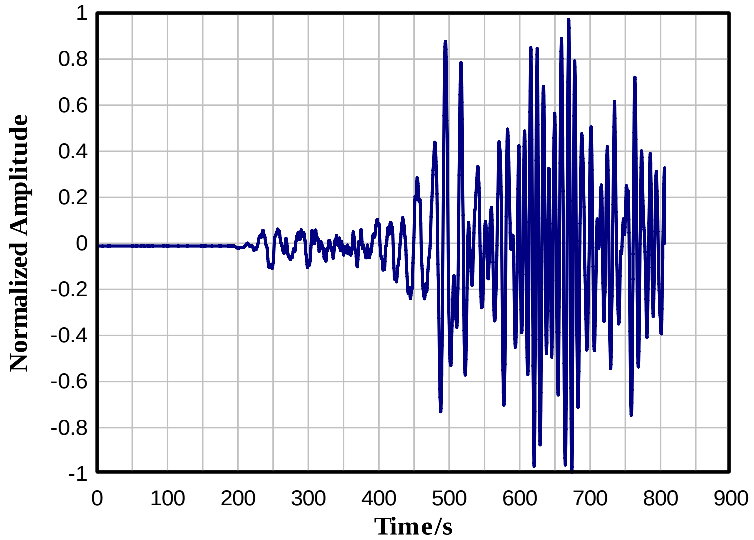
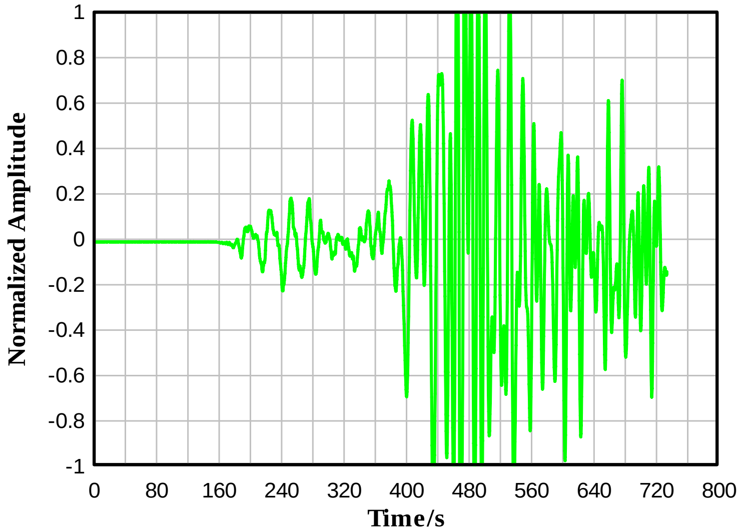
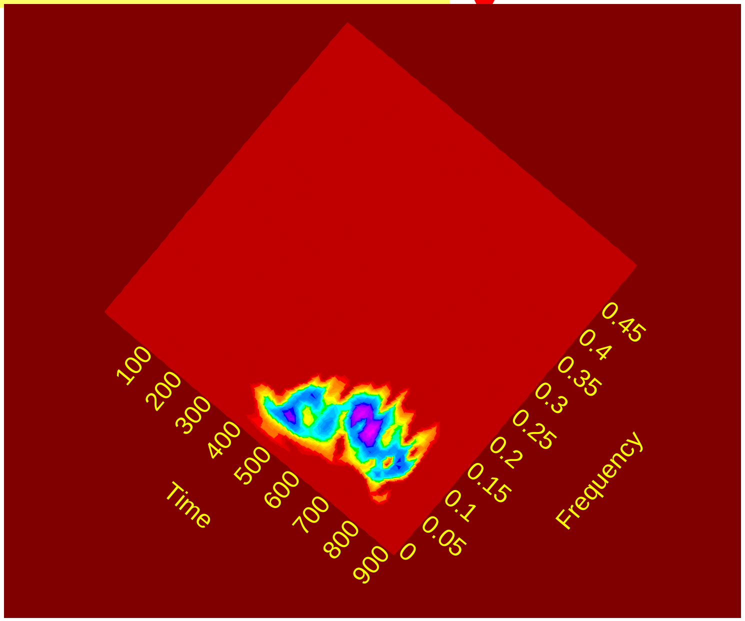


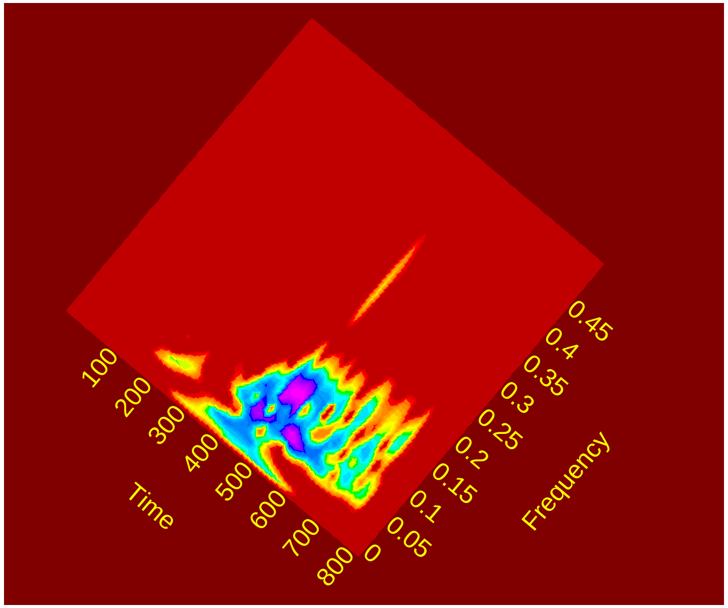
b) Mar 2005 Sumatra (at COCO)



Tsunamigenic EQ — CWT

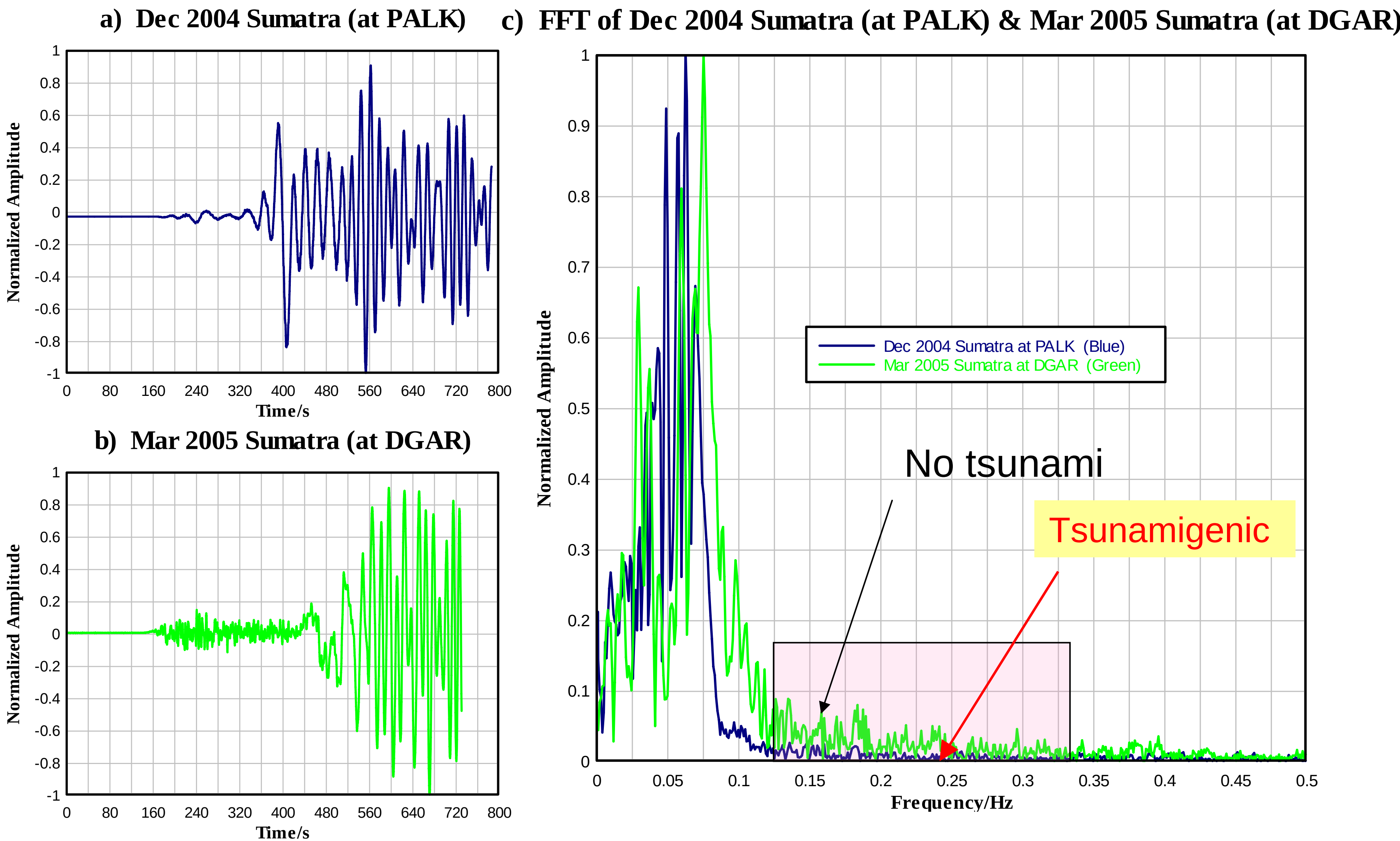


Non-tsunamigenic EQ — CWT



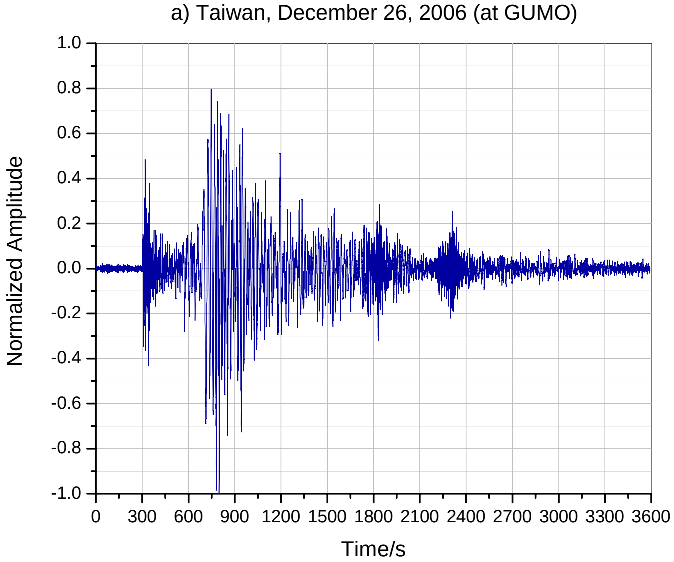
E. Frequency analysis of earthquakes data

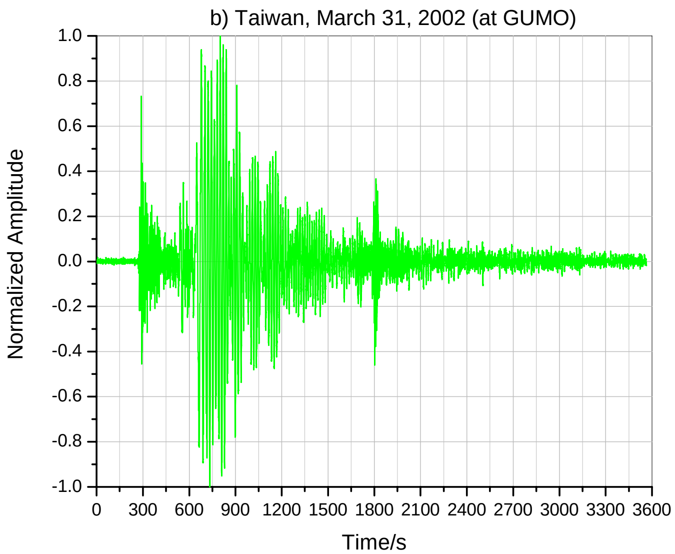
Case 2a. Sumatra EQ (at PALK & DGAR)



E. Frequency analysis of earthquakes data

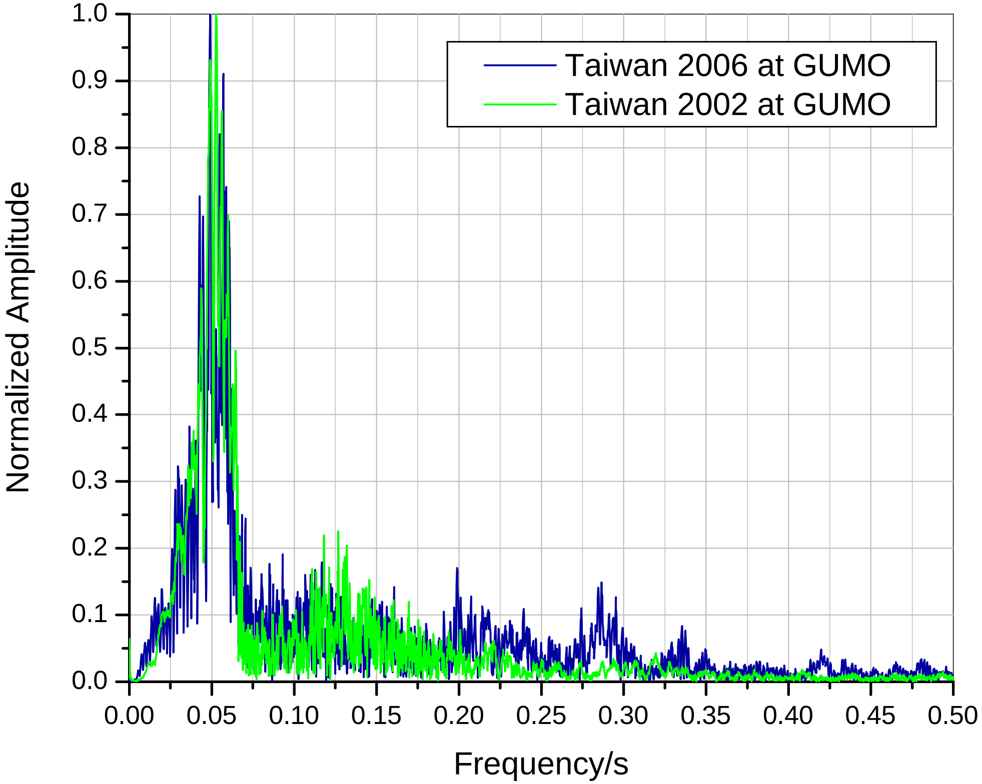
At far-field station GUMO





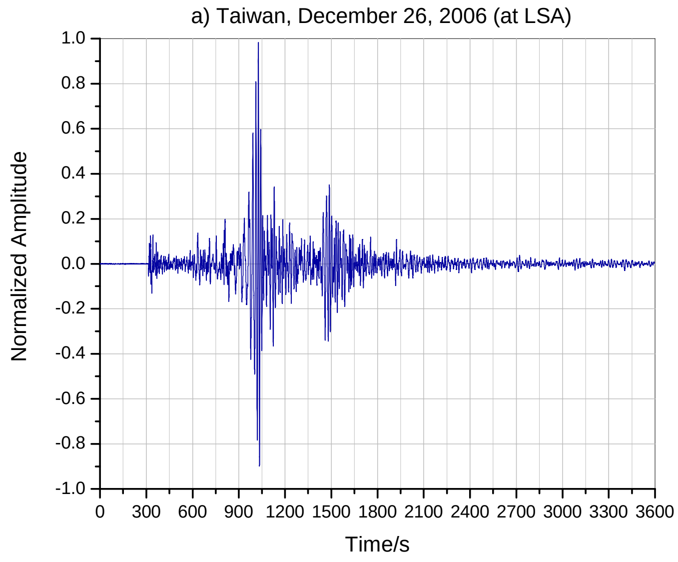
Taiwan EQ (at GUMO, r = 2700 km)

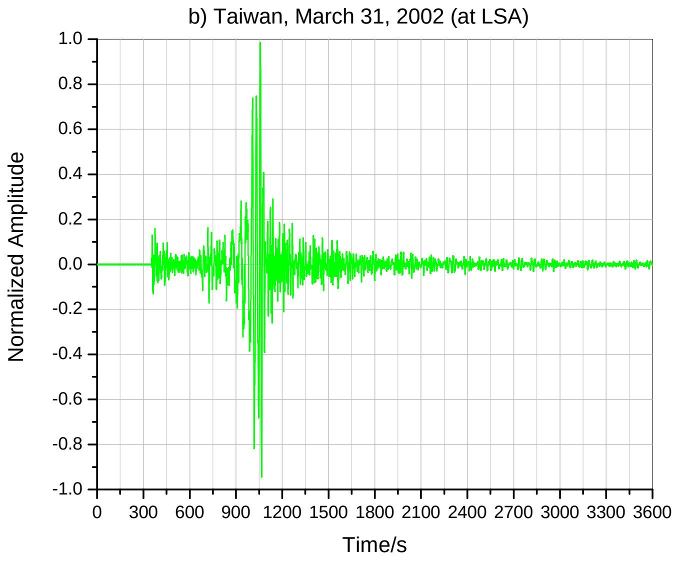
At far-field stations, the frequency content discrimination (seen in surface waves) is less obvious. This may be due to increase attenuation with distance. Furthermore, the surface wave attenuates faster than body waves. So at far stations, frequency discrimination based on body wave part of the seismogram **may** be more appropriate.



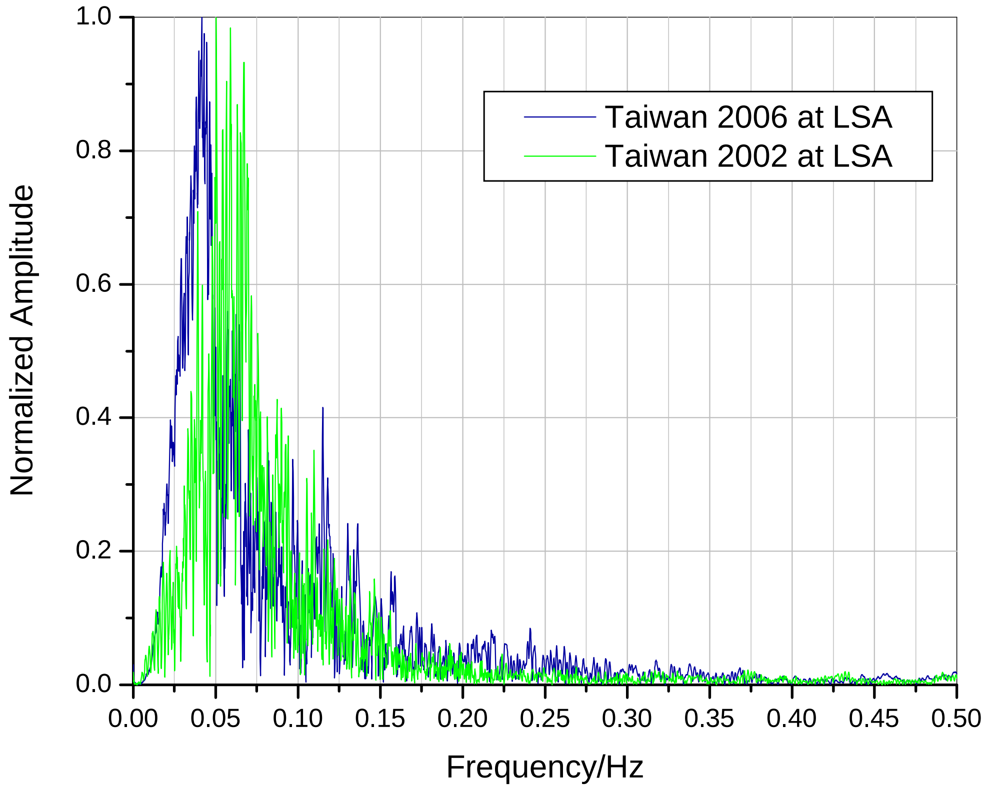
E. Frequency analysis of earthquakes data

At far-field station LSA





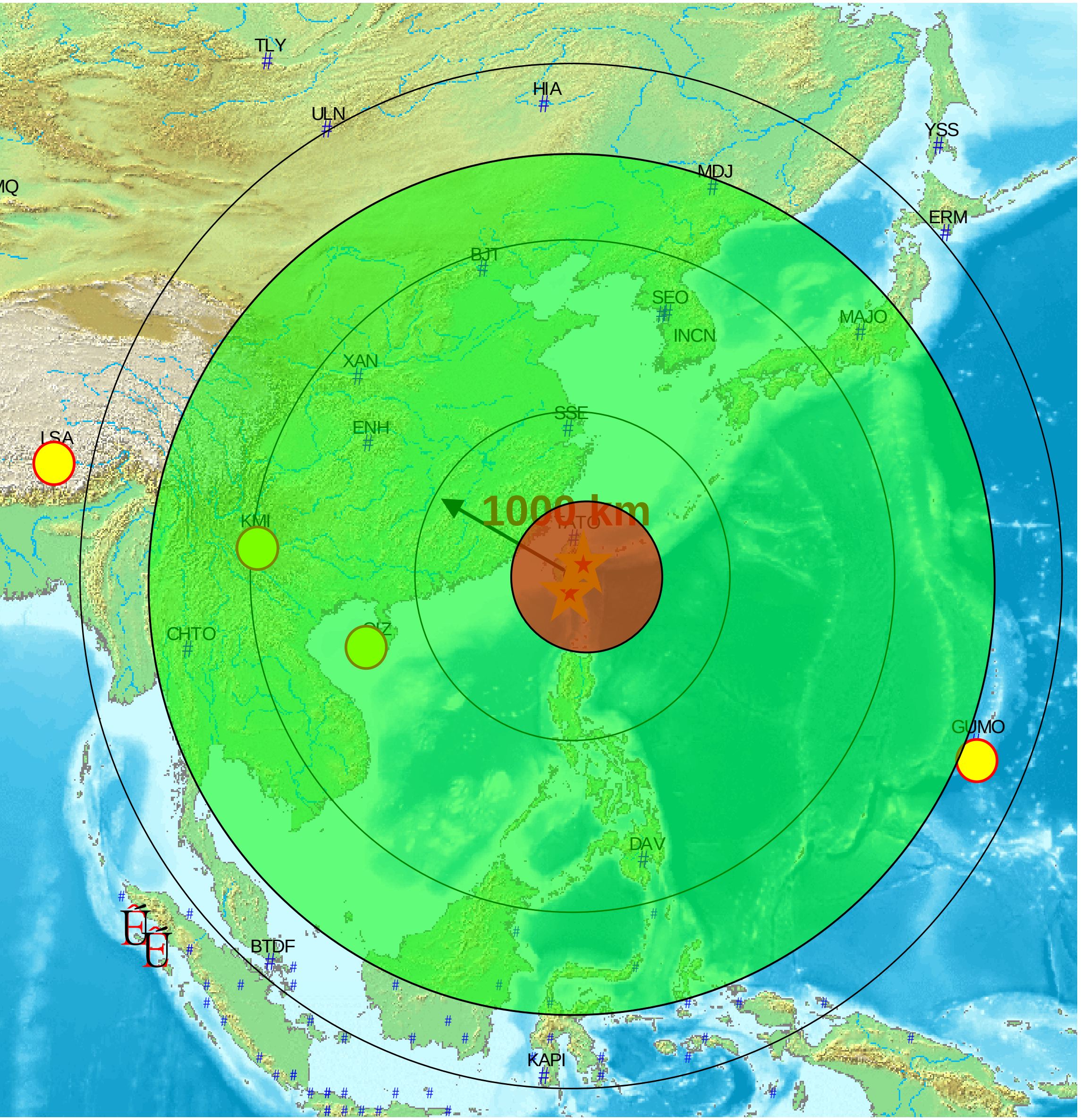
Taiwan EQ (at LSA, r = 3150 km)



At far-field stations, the frequency content discrimination is not clear.

E. Frequency analysis of earthquakes data

Application of the Frequency Analysis Method



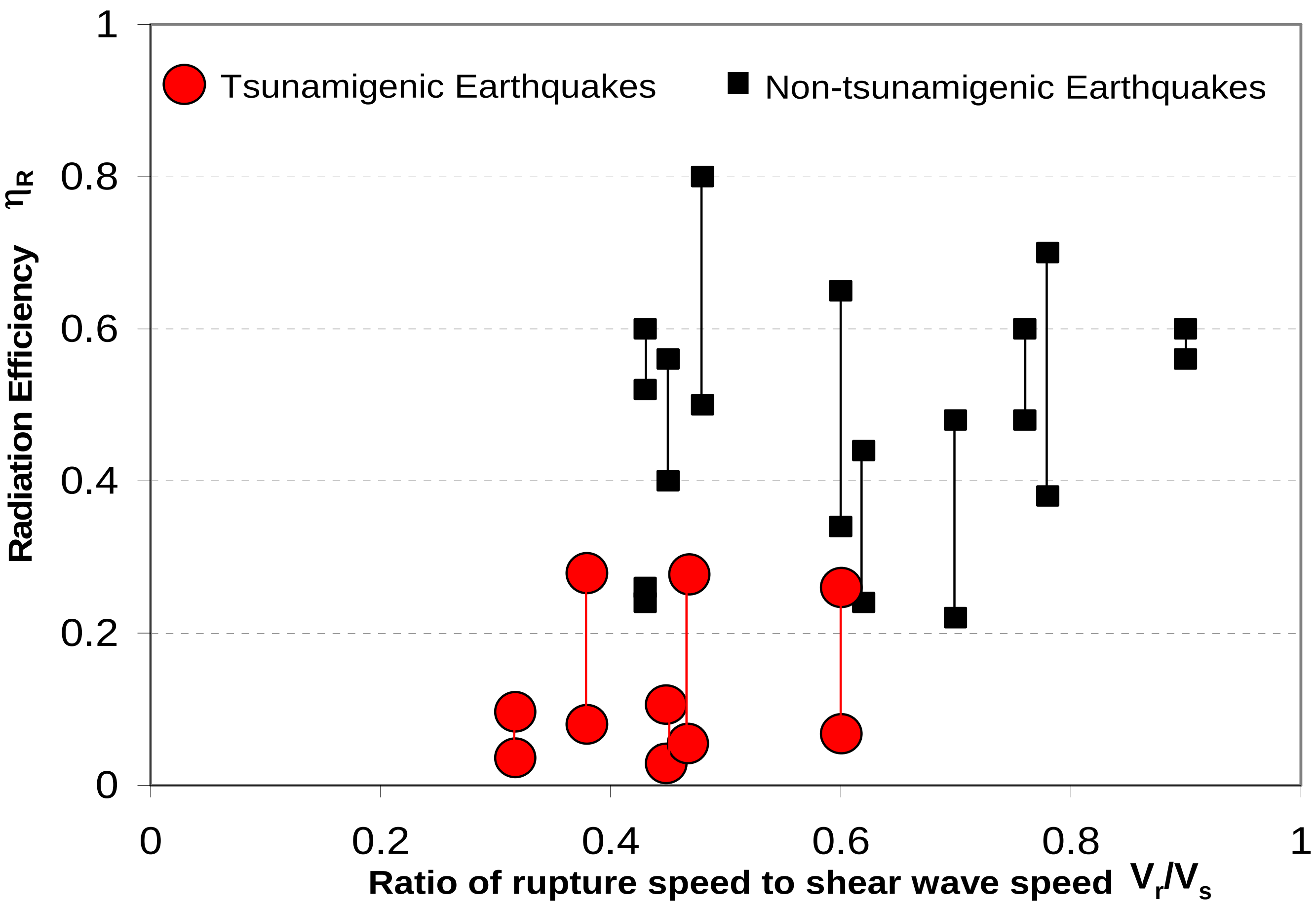
The frequency analysis differentiation for tsunamigenic and non-tsunamigenic earthquakes is best applied at the optimum earthquake-station distance (the green area).

Too close stations (red circle) cannot capture the whole seismic energy radiated by the earthquake while most of the high frequency energy is attenuated at teleseismic stations (out side green area).

The optimum epicenter distance must be correlated to the magnitude of the earthquake. Larger the earthquake, larger the epicenter distance required for clear differentiation of the tsunamigeic earthquakes from non-tsunamigenic earthquakes based on frequency content.

Proposed Mechanism for Tsunamigenic earthquakes → are slow rupture Earthquakes

Tsunamigenic earthquakes have lower rupture speed (30-60% of shear wave speed) compared to non- tsunamigenic earthquakes (45-90% of shear wave speed).

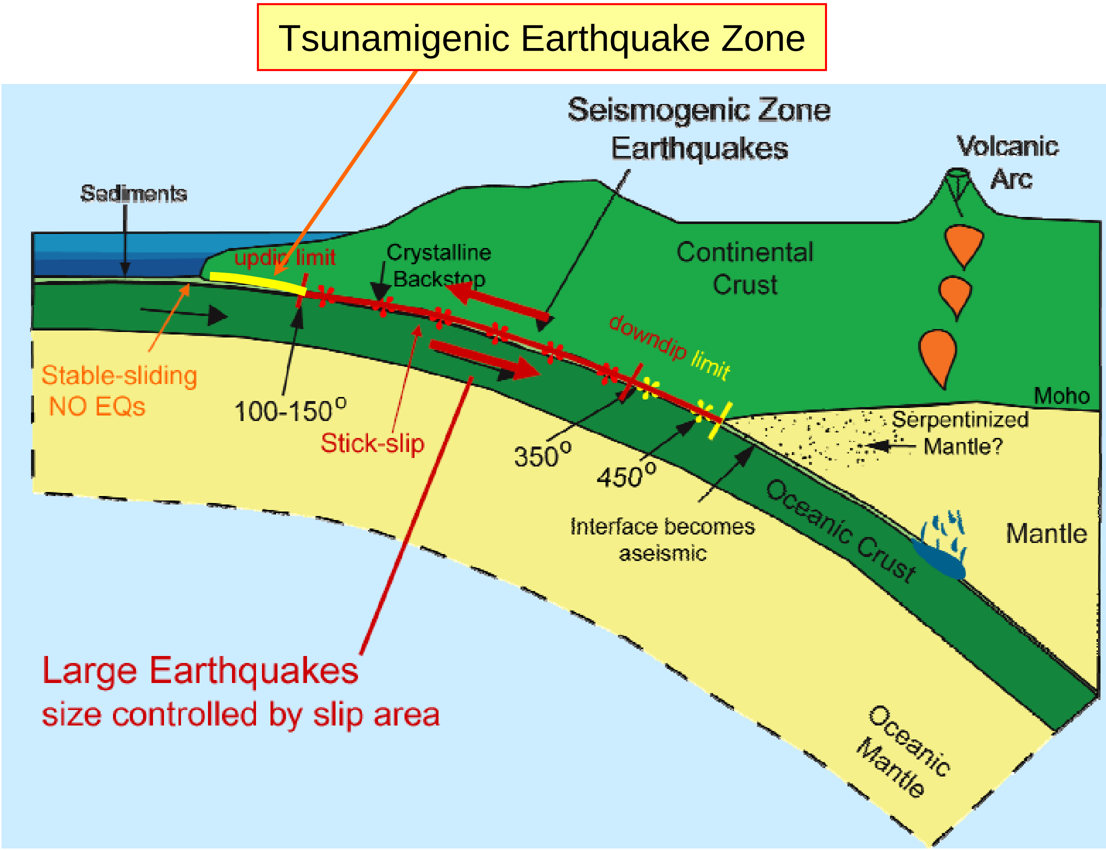


$$\eta_R = \left(\frac{2\mu}{\Delta\sigma}\right)\left(\frac{E_R}{Mo}\right)$$

η_R: Radiation efficiency for tsunamigenic earthquakes are lower than that for non-tsunamigenic earthquakes due to large energy lost in rupture process.

Adopted from USGS website

F. Relating mechanism for tsunamigenesis to proposed analysis method



A comparison of locally detected microseismicity defining the “updip” limit in Nicoya Peninsula, Costa Rica (**Newman** et al., 2002), and interface locking as determined by GPS for the same period (Norabuena et al.,1998, 2004). The region of strong locking in the shallow trench is adjacent to the rupture area of the 1992 Tsunami Earthquake in Nicaragua

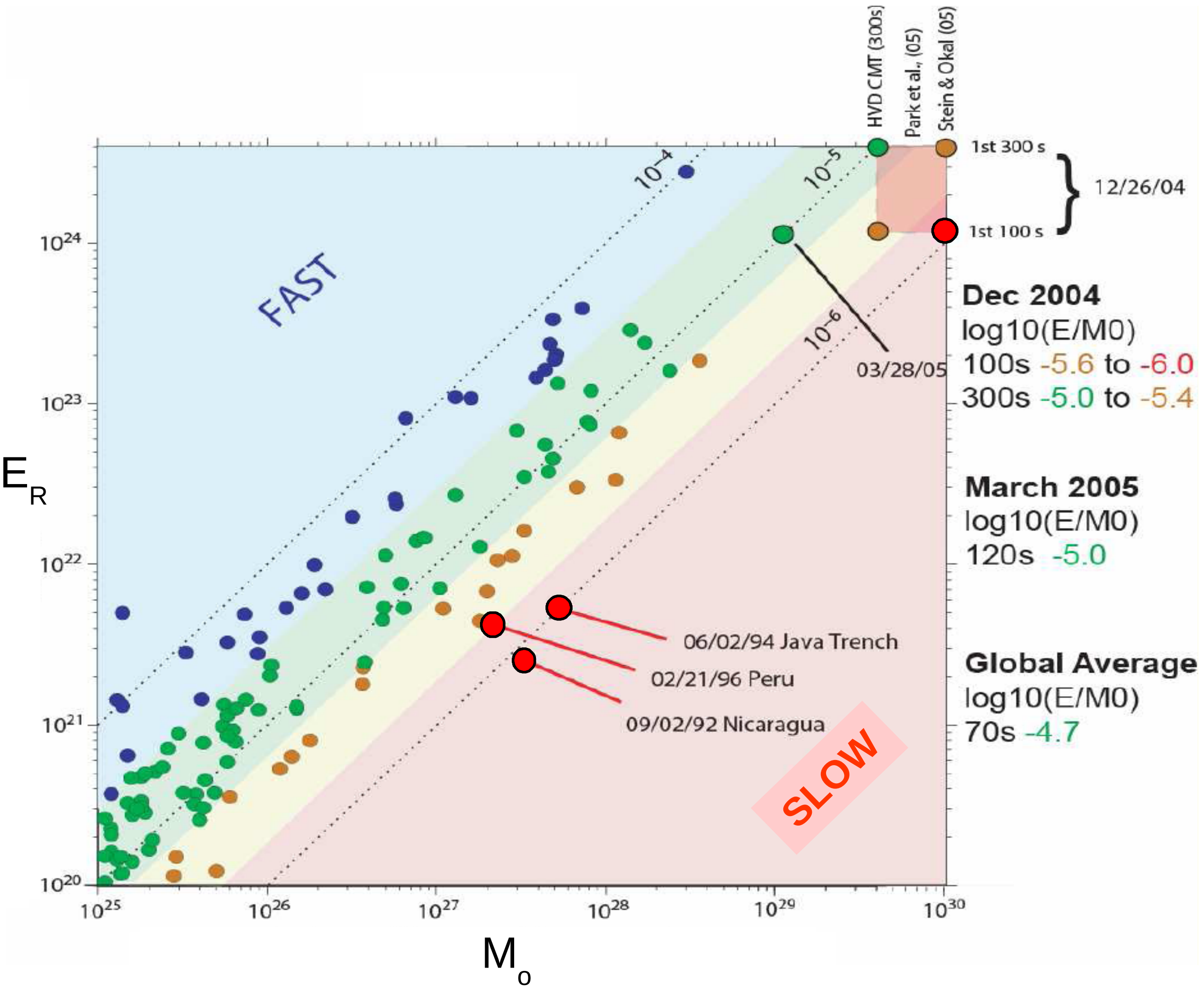
Seismogenesis of suduction zone:

- There existing a limited range for earthquake to take place - Called Seismic zone.
- Above the upper limit of seismic zone => more brittle, Continuous sliding take place here. No build-up, No EQ.
- Below the lower limit of seismic zone => ductile behavior, no differential stress developed. No EQ.

⇒ **However, some earthquakes took place above the upper limit: When this occurs, earthquakes occur in <u>less rigid rocks near the surface</u>, thus at reduced rupture velocity. (Newman, 2007; Bilek & Lay, 1999). This results in slow slip over longer duration -- > may be responsible for tsunami excitation.**

95% of all tsunamigenic earthquakes are located at the subduction zones.

F. Relating mechanism for tsunamigenesis to proposed analysis method



E_R: radiated energy of high frequency body waves

M_o: seismic moment from the whole seismogram (Newman & Okal, 1998)

=>Tsunamigenic earthquakes are deficient in high frequency body wave energy.

Modified from Emile A. Okal, 2007

F. Relating mechanism for tsunamigenesis to proposed analysis method

1. The high frequency component of the seismogram is due to the rupture front propagation.
   =>Slower rupture emitting poor high frequency energy seismic wave.

2. The low frequency component of the seismogram is due to slip (extended large slip).
   =>Large slip producing larger long period energy seismic wave.

Tsunami earthquakes have long duration (or slow rupture). So they are depleted in high frequency energy. This is important for differentiating tsunami earthquakes from non-tsunami earthquakes.

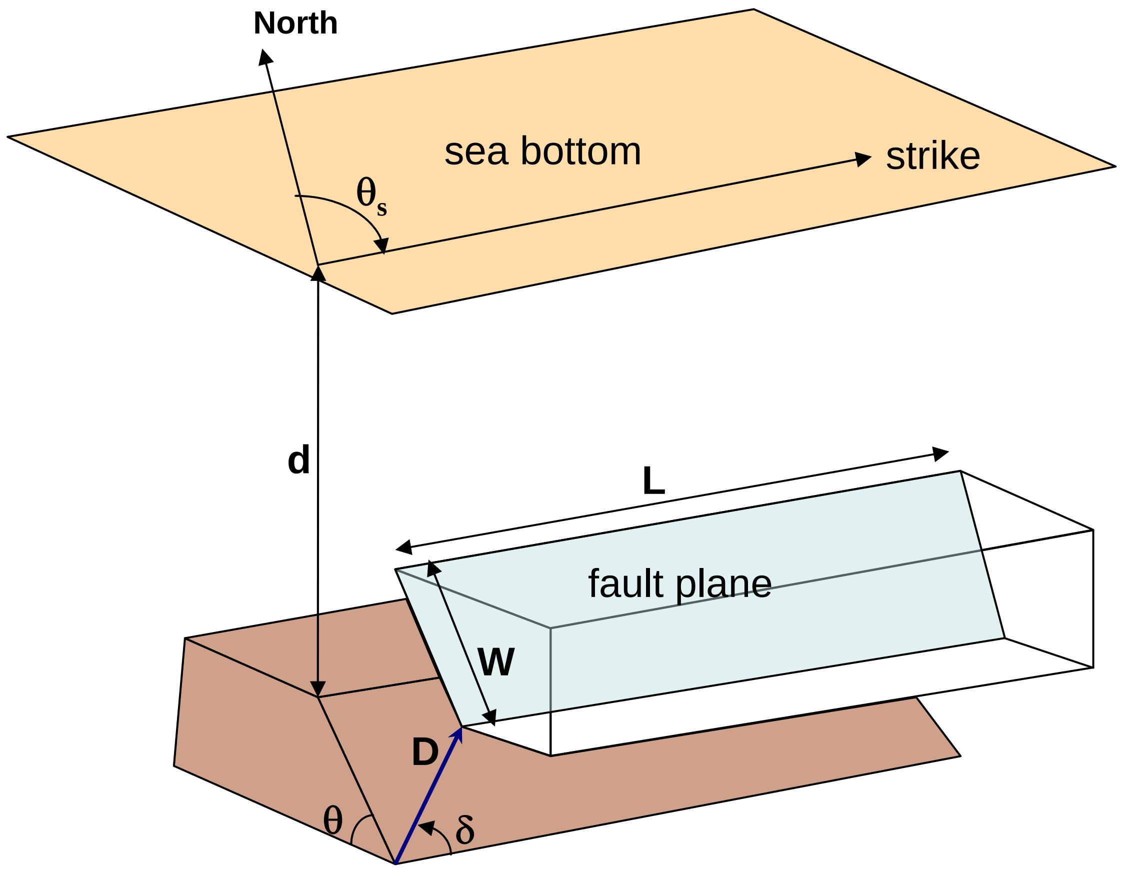
Tsunami earthquakes have large extended slip. So they show high excitation at low frequency. This is responsible for large tsunami generation.

=>Therefore, tsunami earthquakes are rich in low frequency energy and poor in high frequency energy.

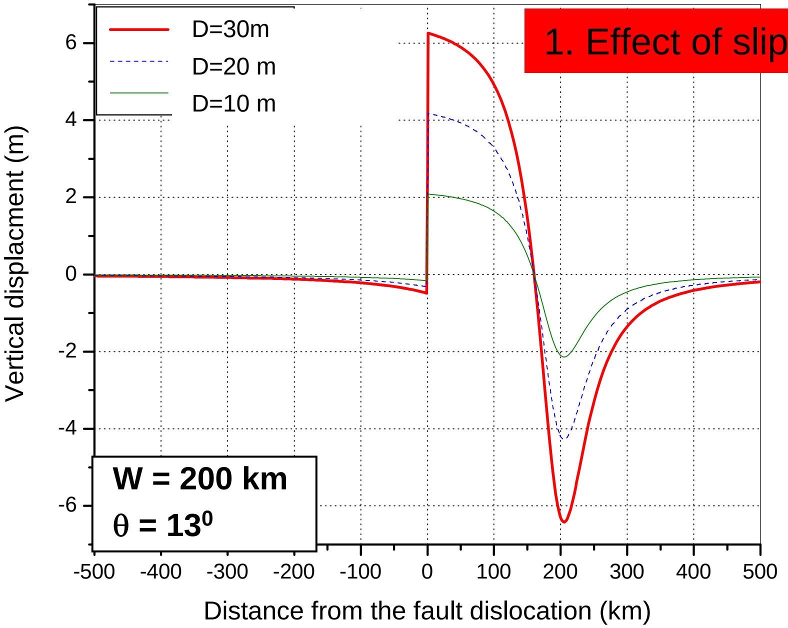
G. Key earthquake source parameters for initial tsunami generation

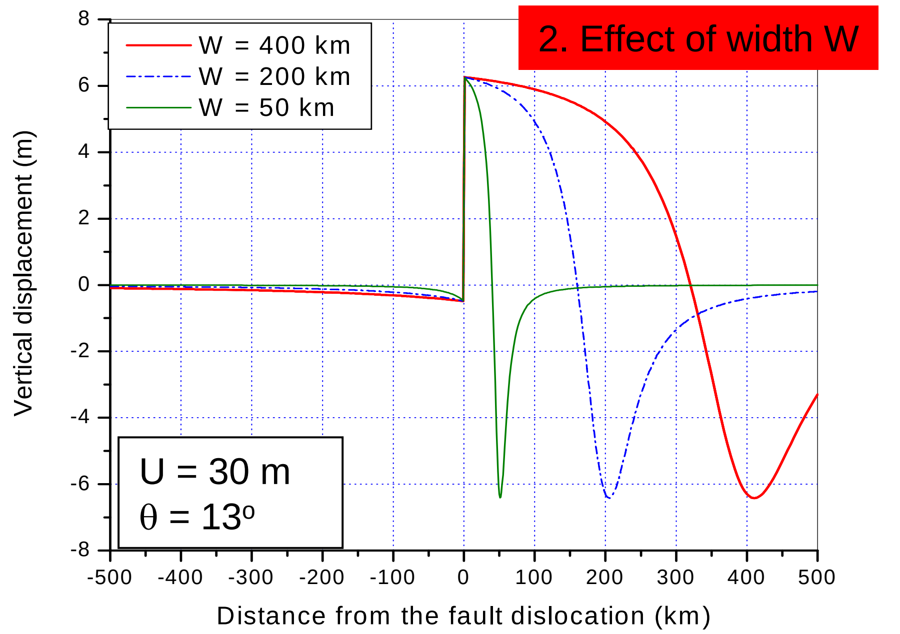
Key fault parameters for tsunami generation

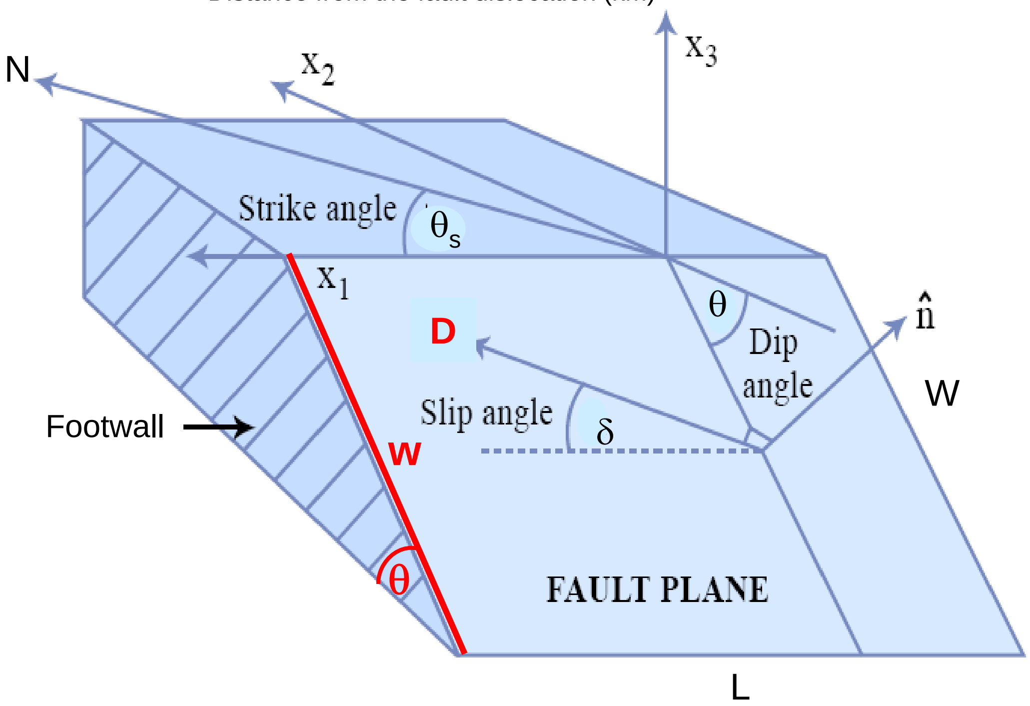
1. **Seismic Moment, Mo**
2. **Strike, θ_s**
3. **Dip, θ**
4. **Rake, δ**
5. Focal depth, d
6. Length, L
7. Width, W
8. Dislocation, D
9. Epicenter location (lat., long.)
10. Rupture duration, τ
11. Magnitude, M
12. Rupture speed, v_r
13. Slip speed, v_s

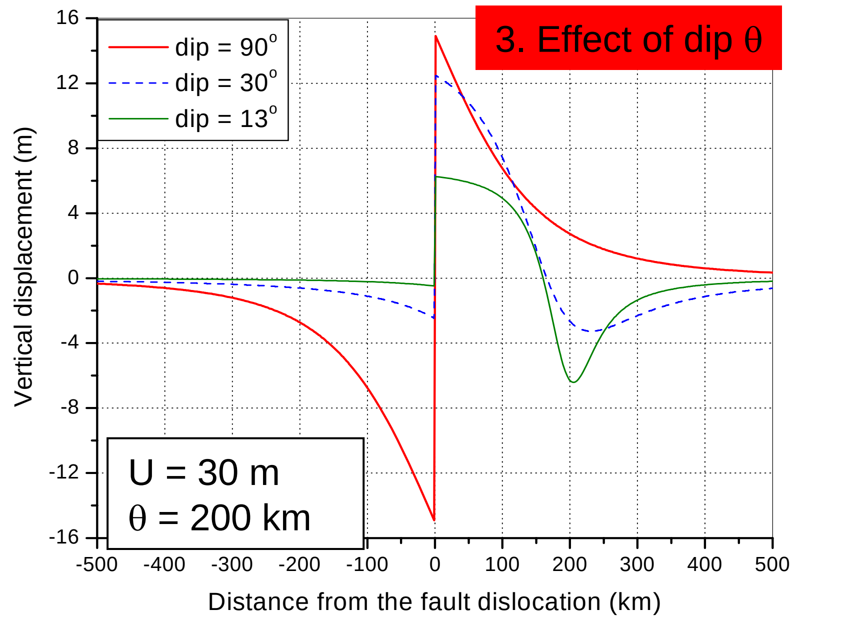


G. Key earthquake source parameters for initial tsunami generation









Evaluation of M_o & focal mechanism through waveform inversion

Ground displacement motion at an epicentre distance r :

$$u(t,\Delta) = \frac{1}{2\pi}\int_{\infty}^{\infty} U(\omega)e^{i\omega t}d\omega$$

and its Fourier Transform

$$U(\omega,\Delta) = \int_{\infty}^{\infty} u(t,\Delta)e^{-i\omega t}dt$$

We represent

$U(\omega,r) = M(\omega)\ E(r,\omega)$ →

M(ω) = FFT of m(t)
=>inverse FFT of M(ω) =m(t)

where M(ω) depends on seismic moment time function:

$m(t) = \mu\ A(t)D(t)$ **and E(r,ω) depends on**

(1) Propagation medium (velocity model)
(2) Focal depth
(3) Focal mechanism (strike, dip, rake)
(4) Epicenter distance, r
(5) Azimuth of station from strike dir (ϕ)

Evaluation of M_o & focal mechanism through waveform inversion

Moment Tensor Inversion

$$u_i(t) = \sum_{j=1} G_{ij}(t) m_j$$

u_i = recorded seismogram at i^{th} component/ station (say, vertical component at station NNA for example)

$G_{ij}(t)$: computed reference seismogram (i.e. Green's function) at the i^{th} component/ station due to moment tensor component m_j where j=1,2,3,4,5,6.

m_j: moment tensor

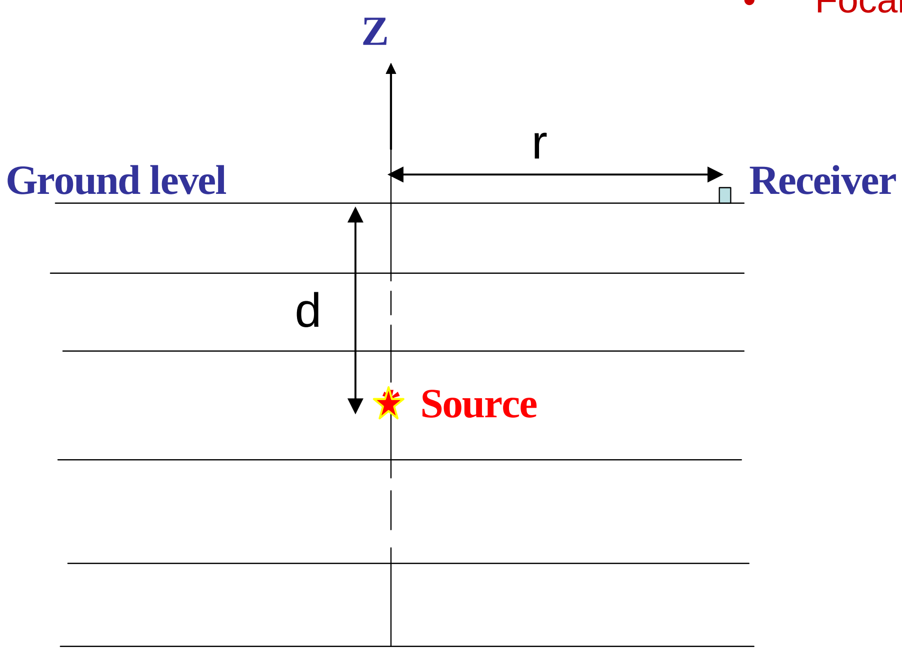
- Seismic data $u_i(t)$ are collected and analyzed quickly (few minutes after a significant earthquake, M>7) through strategically deployed seismic stations.

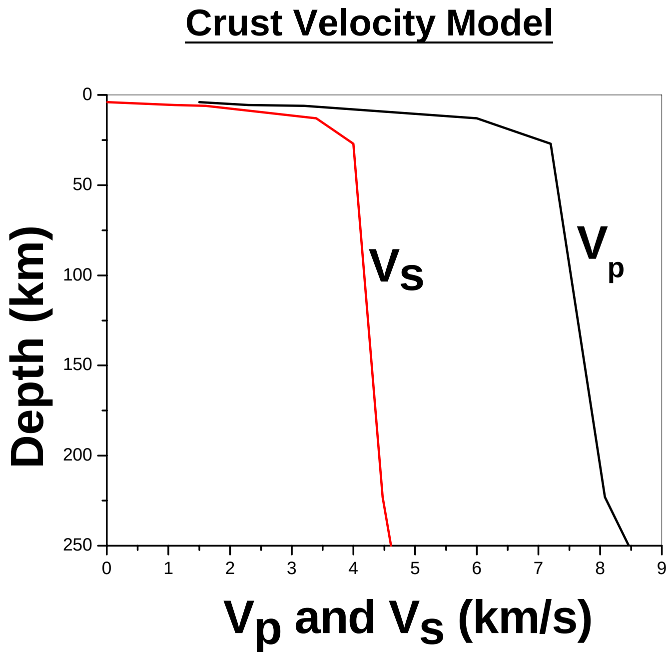
Evaluation of M_o & focal mechanism through waveform inversion

Evaluation of Green's Function

Green's Function (G) depends on:

- **Crust-mantle velocity model**
- source-station distance (r)
- Focal depth (d)





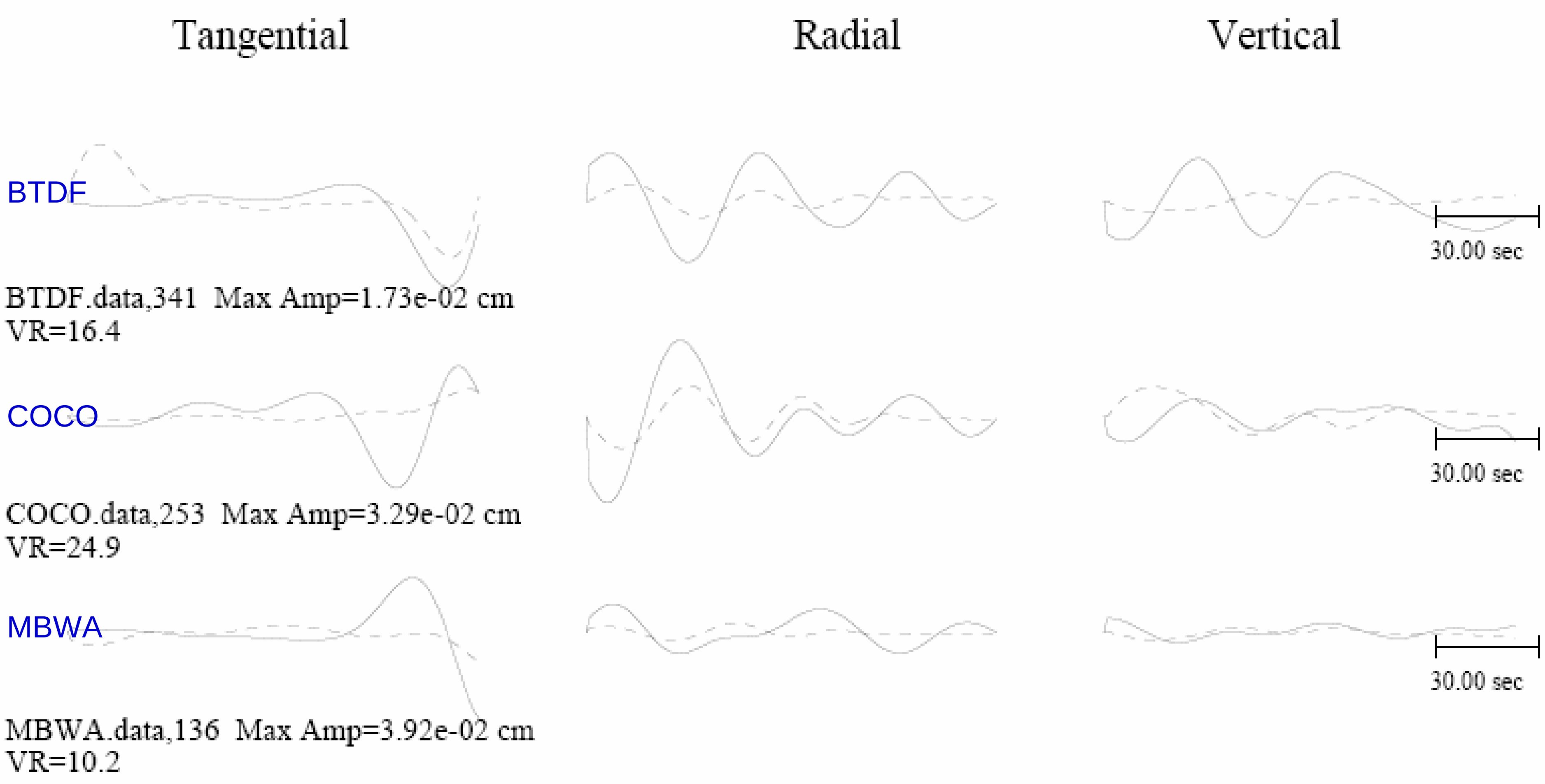
Source: CRUST 2.0

The $G_{ij}(t)$ takes care of source time function s(t), epicenter distance r, focal depth d, azimuth ϕ of the station from epicenter, medium (including attenuation).

H. Near real time evaluation of seismic moment & focal mechanism

Preliminary Results of using only three stations and computed within 12 minutes of EQ

Java EQ (July 17, 2006)



H. Near real time evaluation of seismic moment & focal mechanism

USGS solution

```
Strike=297, 113
Slip=  93, 90
Dip= 84, 6
Mo=8.1*10**26 dyne cm
MW 7.2
             -------
        --############---
     #####################-
   #########################-
 ################   #########--
################# T ##########-
 --###############   ###########
-----###########################-
---------#######################
-------------###################
-----------------###############
----------------------##########
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 ----------   -----------------
  --------- P -----------------
    -------   ---------------
       ---------------------
         ----------------
              -------
```
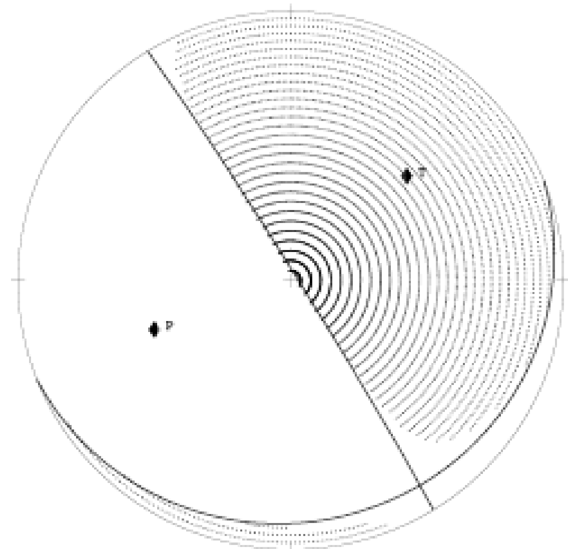

Using 200+ stations, obtained only many hours after EQ!

Our solution

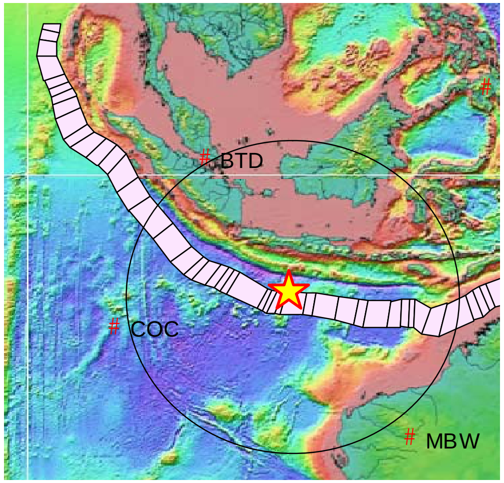
Strike=328 ; 68
Rake =-79 ; -170
Dip =88 ; 12
Mo =2.73e+26
Mw =6.9



Our solution – which is similar to USGS results, with close-enough values of Mo and fault parameters were obtained by analyzing signals from three stations within 12 minutes after EQ using near-field stations data!

Preliminary Results

Java EQ (July 17, 2006)



I. Concluding remarks

- Frequency analysis of seismic signals indicated that tsunami earthquakes are depleted in high frequency energy but rich in long period energy waves. This is directly related to the larger slip and slower rupture speed commonly associated with the tsunamigenic earthquakes.

- Moment Tensor Inversion can estimate Mo and focal mechanism provided that the well calibrated localized crust-mantle velocity models are available and used.

- Evaluation of the earthquake moment magnitude and relevant fault parameters that represents the actual fault slip and rupture orientation is important for running the tsunami generation software. We can do this in 10-20 minutes after earthquake, with regional stations signals.


THANKS FOR YOUR ATTENTION