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Tsunami Hydrodynamics

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Contents

- **Recent events**
  - International natural hazard
- **Life-cycle of tsunami waves**
  - Tsunami generation
  - Tsunami propagation
  - Tsunami hydrodynamics in coastal zone
- **Conluding remarks**
  - Challenges

Recent Tsunami Events (2004 – 2014): International Natural Hazard

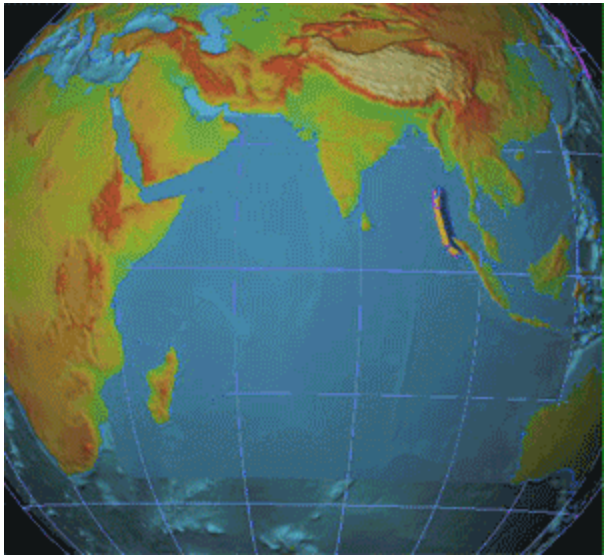
- **2004** Indian Ocean earthquake and tsunami

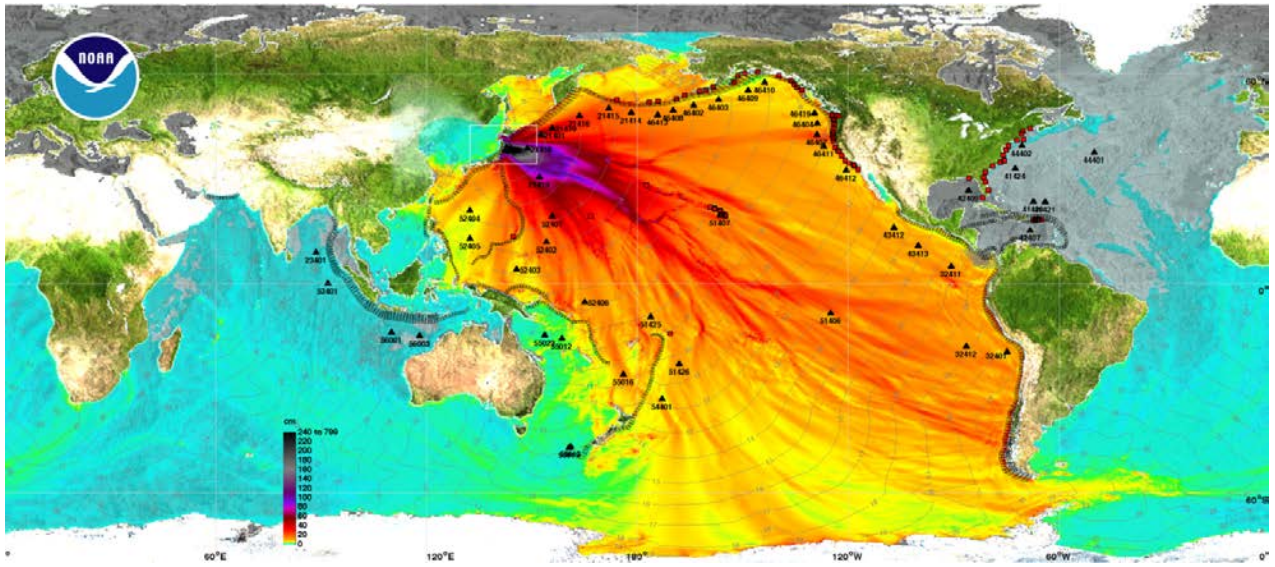
  The tsunamis killed over 230,000 people in fourteen countries, and inundated coastal communities with waves up to 30 meters (100 ft) high.

- **2010** Chile earthquake and tsunami
- **2011** Tohoku earthquake and tsunami

  The tsunami caused the meltdowns at three reactors in the Fukushima Daiichi Nuclear Power Plant complex, and the associated evacuation zones affecting hundreds of thousands of residents. The estimated economic cost was US$235 billion.

- **2014** Iquique earthquake





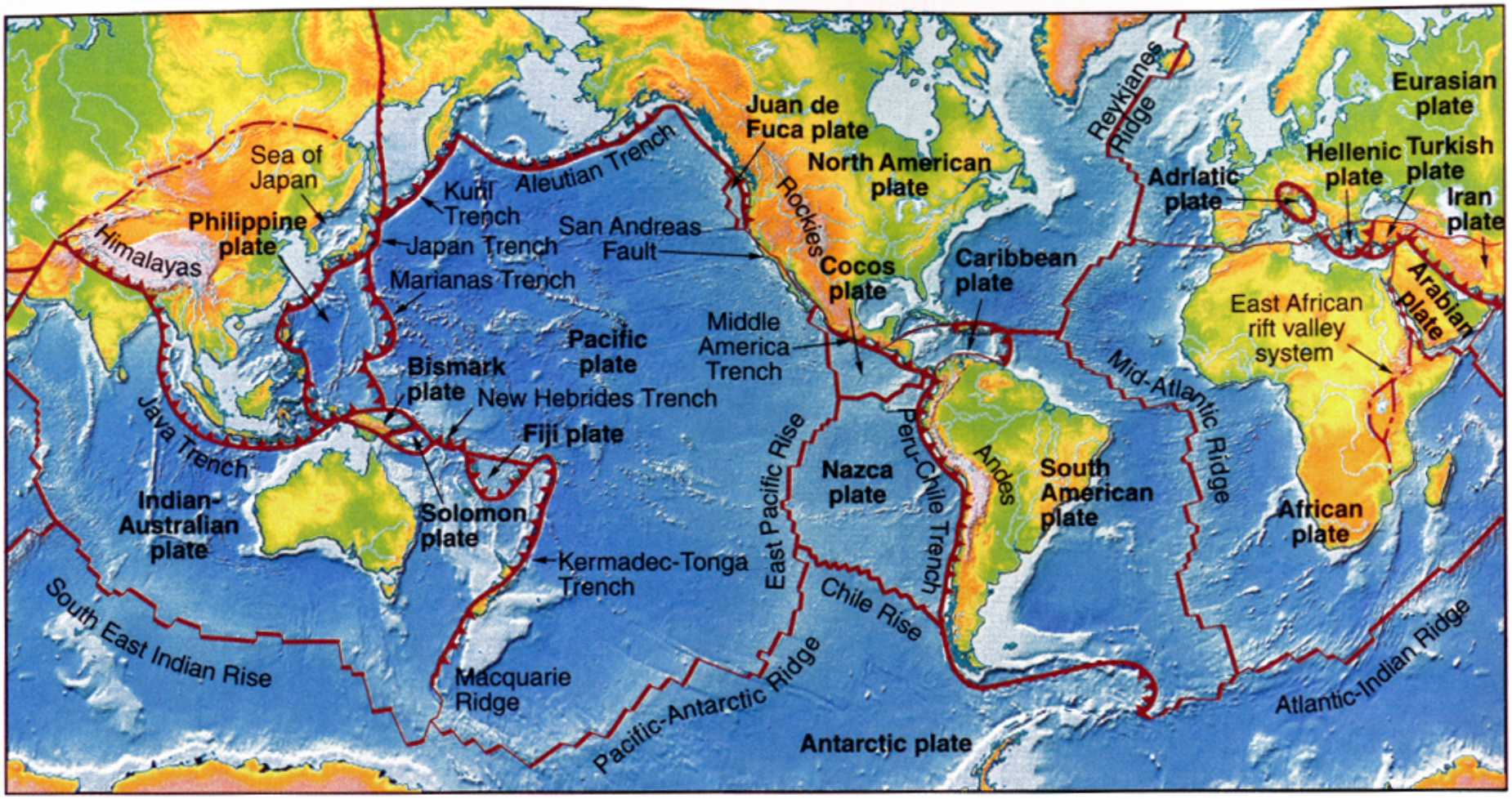
Tsunamis Life - Cycle

- **Tsunami generation**
  - Impulsive waves (generated by seafloor movement);
  - Earthquake; landslide; volcanic eruption

- **Tsunami wave propagation in ocean/continental shelf**
  - Wave refraction, diffraction, shoaling (interacting with bathymetry)
  - Small amplitude long waves; dispersive and/or non-dispersive waves

- **Tsunami waves and overland flows in coastal zone**
  -Wave breaking; scouring, interaction with vegetation and man-made infrastructures;
  - Surging flows; sediment-laden flows; debris flows

Tectonic Plates



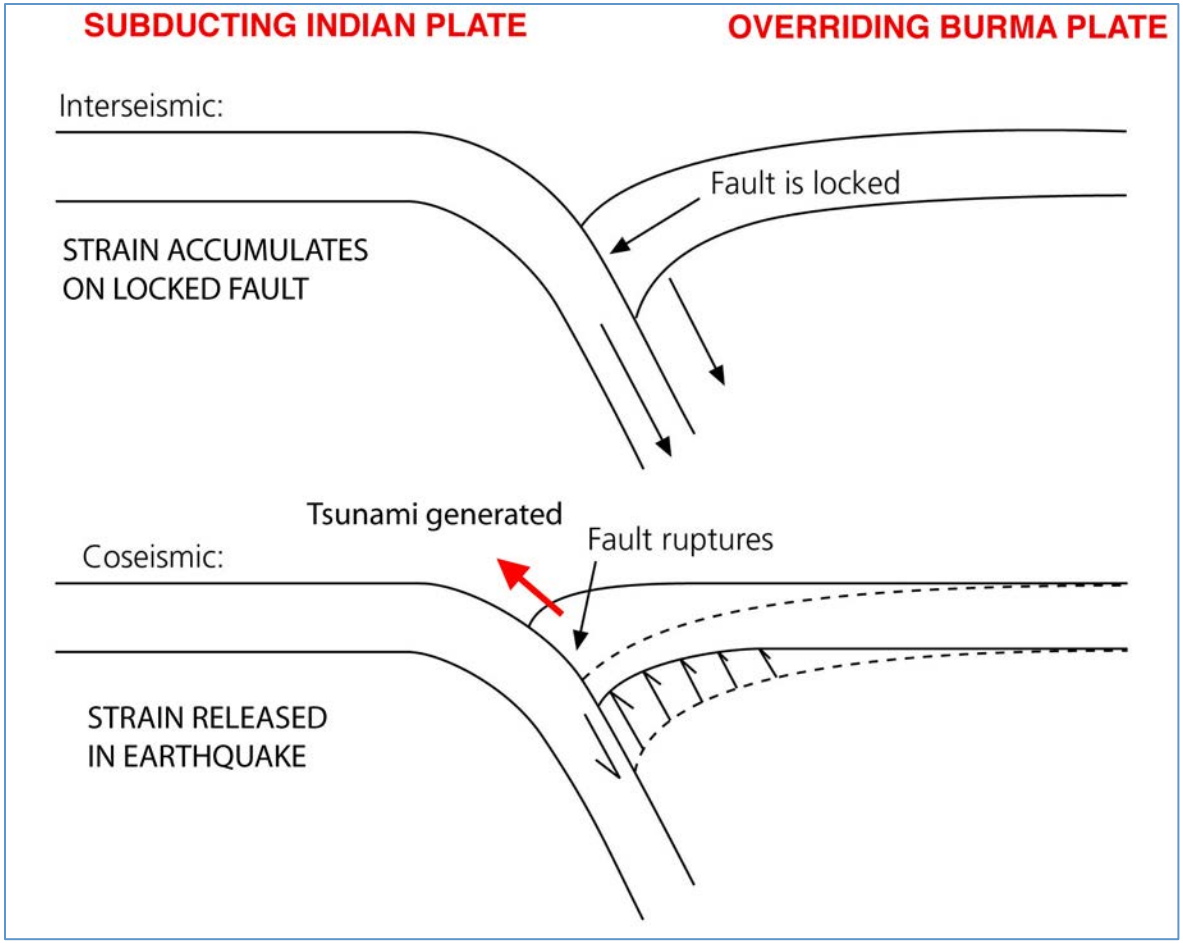
Ridge axis divergent boundary

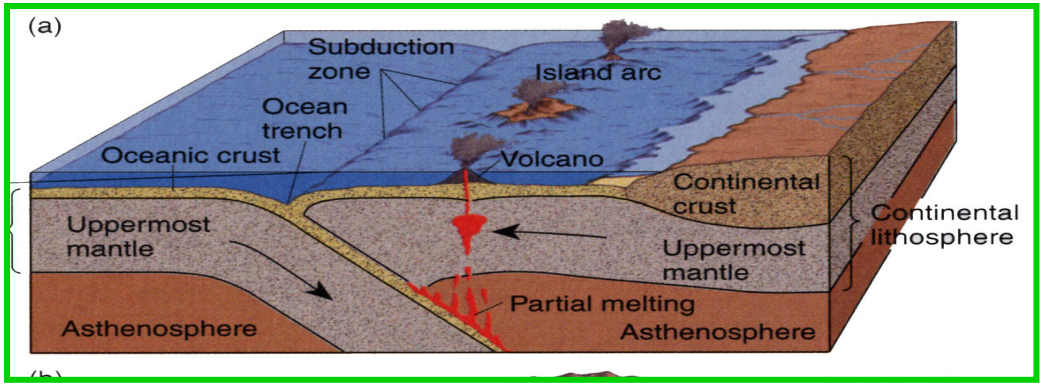
Transform

Subduction zone Convergent boundary

Zones of Extension within continents

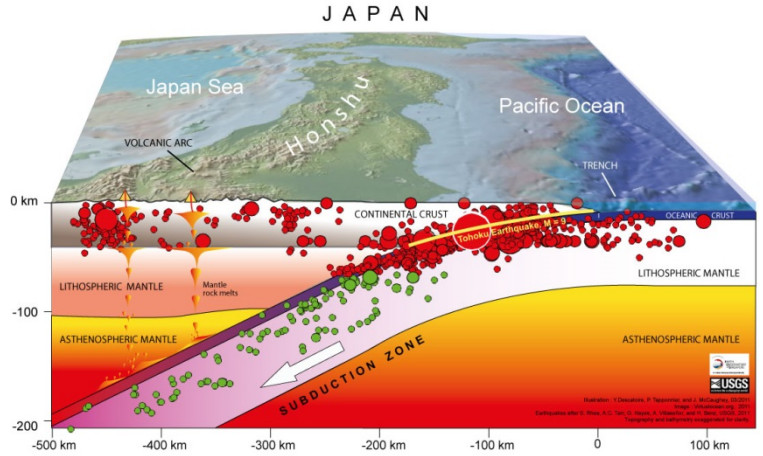
Uncertain plate boundary

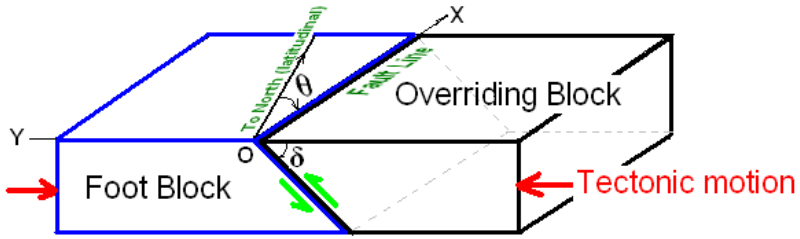

SUBDUCTING INDIAN PLATE
OVERRIDING BURMA PLATE
Interseismic:
Fault is locked
STRAIN ACCUMULATES
ON LOCKED FAULT
Tsunami generated
Fault ruptures
Coseismic:
STRAIN RELEASED
IN EARTHQUAKE

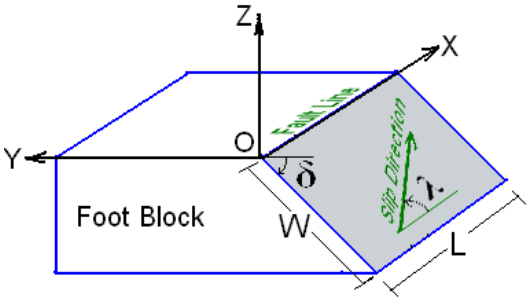

(a)
Subduction zone
Island arc
Ocean trench
Oceanic crust
Volcano
Continental crust
Continental lithosphere
Uppermost mantle
Uppermost mantle
Partial melting
Asthenosphere
Asthenosphere

Tsunami Generation Mechanism – Earthquake

Tectonic plates and subduction zone







Symbols

L	Length of Fault Plane
W	Width of Fault Plane
θ	Strike angle
δ	Dip angle
λ	Slip angle

XOY parallel to the horizontal earth surface; OZ pointing upward;
θ is the azimuth of OX measuring clockwise from the latitudinal.

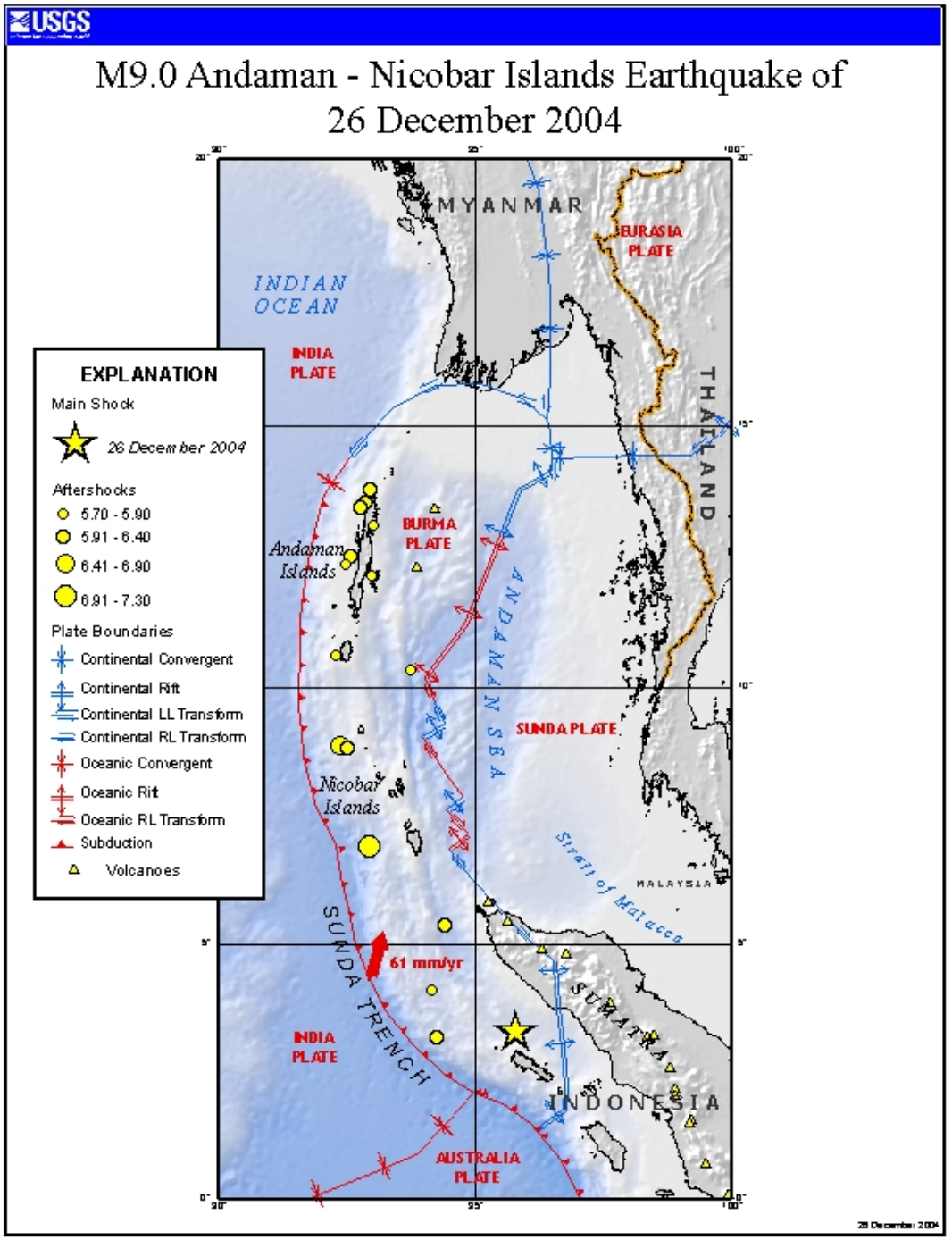
Need to convert the Focal Mechanisms to vertical seafloor displacement to generate tsunamis

The 2004 Sumatra Earthquake

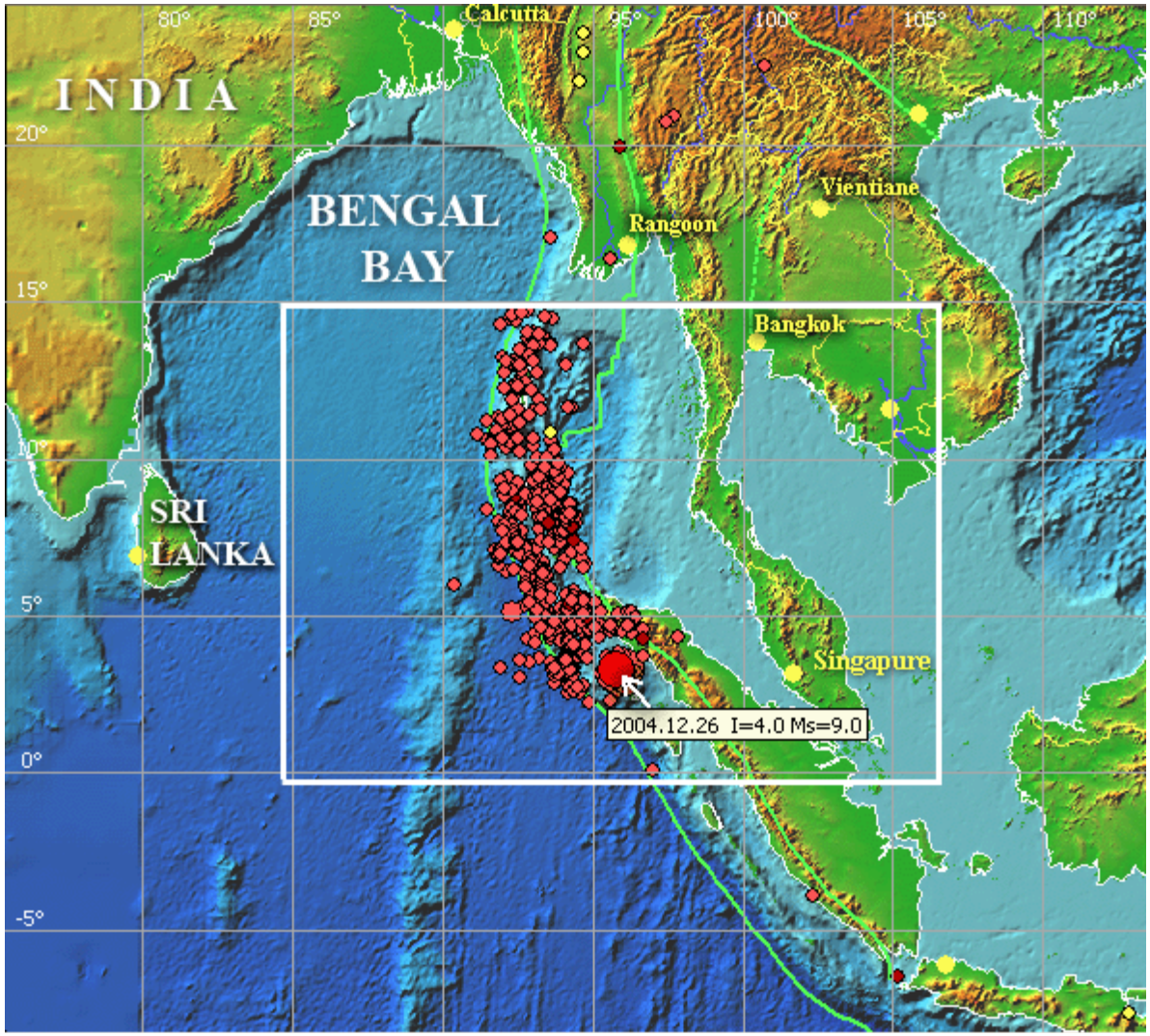
- Time: **Sunday, December 26, 2004, 00:58:53 UTC (Coordinated Universal Time) - Local time: 06:58:09 (at epicenter)**
- Epicenter: **3.4^{o} N, 95.7^{o} E; off the coast of Sumatra in Indonesia**
- Magnitude (M_w): **9.0 (Harvard CMT) (upgraded to 9.3)**
- Depth: **30km**
- Fault Plane: **strike = 320^{o}, dip =11^{o} and slip = 110^{o}**
- Seismic moment (M_o): **3.57x10^{29} dyne-cm (Mw = 9.0); 1.0x10^{30} dyne-cm (Mw = 9.3)**

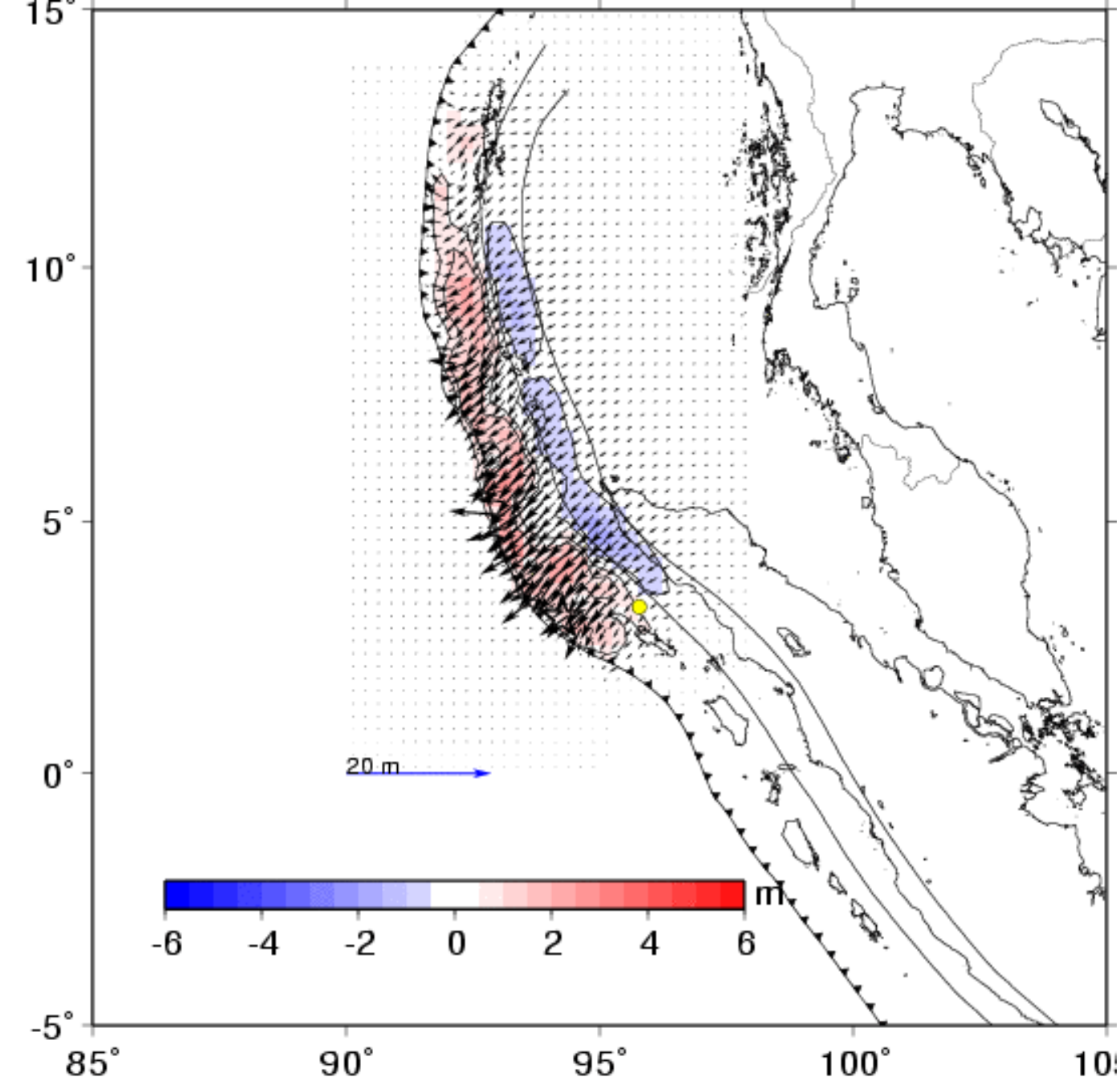
$$M_w = (1/1.5)\log_{10} M_o - 10.7$$

Rupture

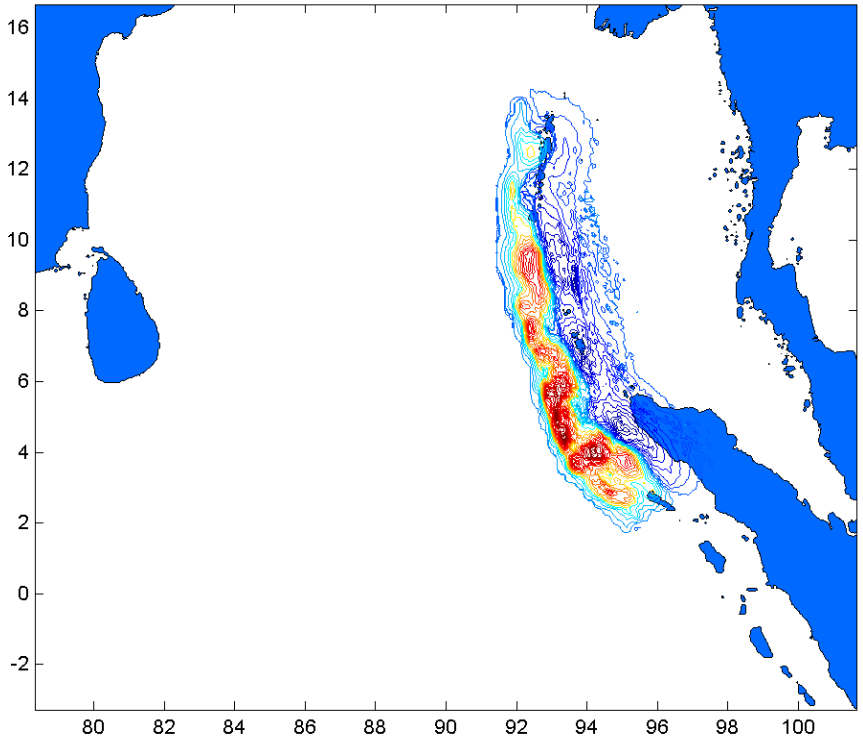

USGS
M9.0 Andaman - Nicobar Islands Earthquake of
26 December 2004
MYANMAR
EURASIA PLATE
INDIAN OCEAN
INDIA PLATE
THAILAND
EXPLANATION
Main Shock
26 December 2004
Aftershocks
5.70 - 5.90
5.91 - 6.40
6.41 - 6.90
6.91 - 7.30
Plate Boundaries
Continental Convergent
Continental Rift
Continental LL Transform
Continental RL Transform
Oceanic Convergent
Oceanic Rift
Oceanic RL Transform
Subduction
Volcanoes
BURMA PLATE
Andaman Islands
ANDAMAN SEA
SUNDA PLATE
Nicobar Islands
Strait of Malacca
MALAYSIA
61 mm/yr
SUNDA TRENCH
SUMATRA
INDONESIA
INDIA PLATE
AUSTRALIA PLATE
26 December 2004

Epicenter and after shocks




15°
10°
5°
0°
-5°
85°
90°
95°
100°
20 m
m
-6
-4
-2
0
2
4
6

Numerical simulation and animation of 2004 Indian Ocean tsunamis
Initial free surface profile for 2004 Indian Ocean tsunamis



Rupture speed: 2 ~ 3 km/s

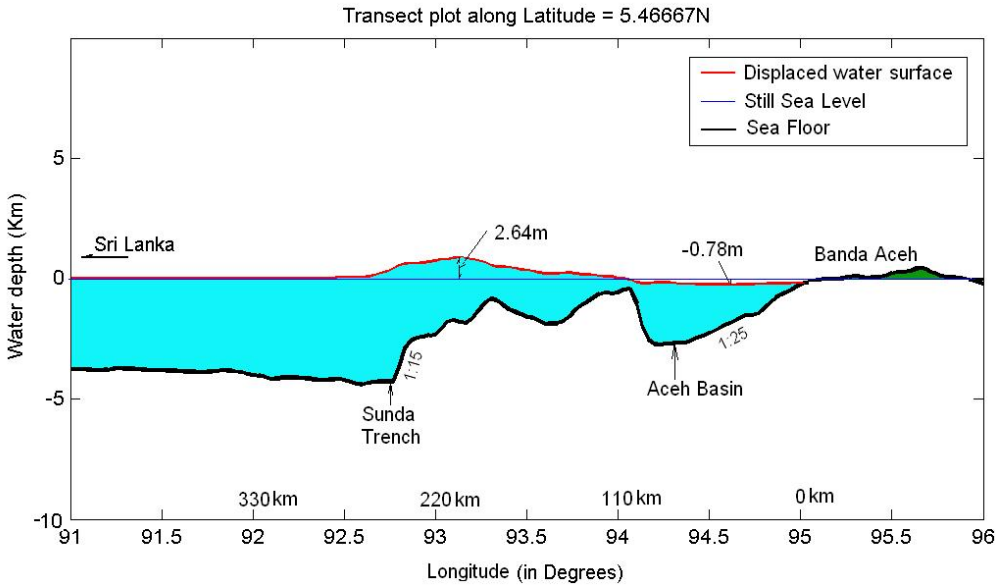
Rupture duration: 10 mins

Fault Plane Width: 150 ~ 200km

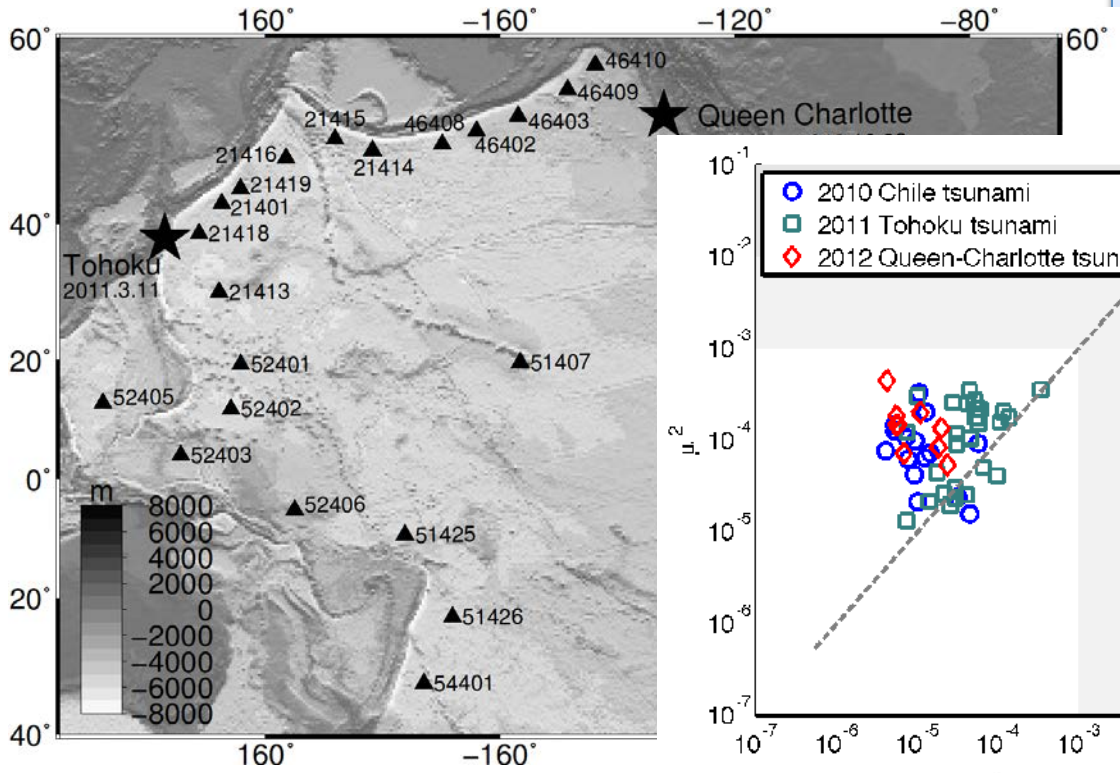
Maximum horizontal displacement: 20 m

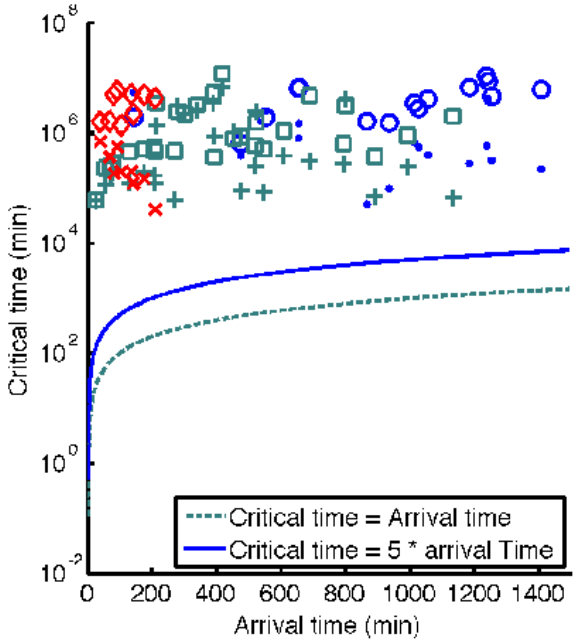
Maximum vertical displacement: 3 m

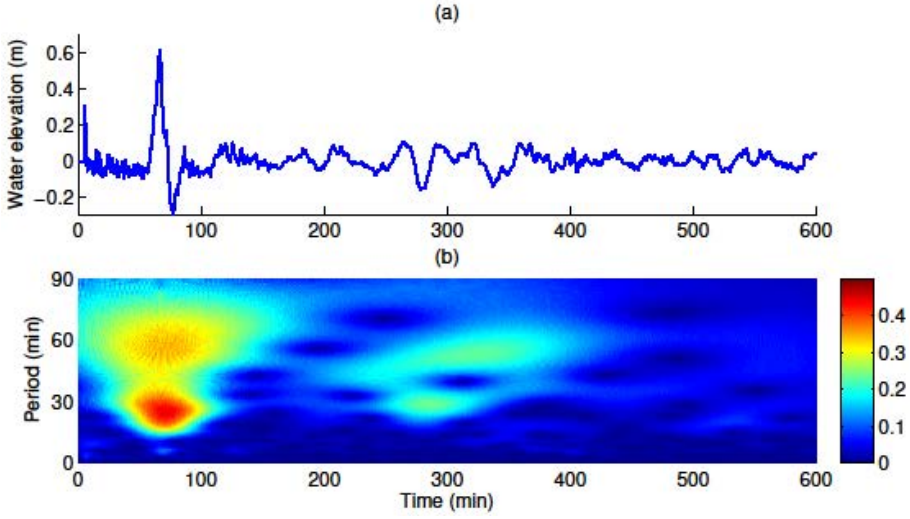
Initial tsunami wave height: 3.5 m
Initial wavelength: 250 km

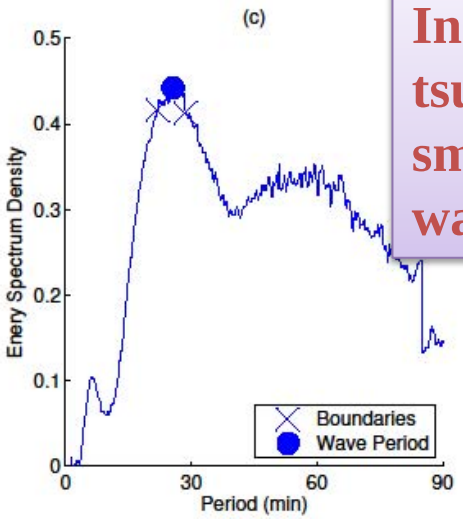


2011TohokuTsunami waves in open ocean









In the open ocean tsunami waves are small amplitude long waves.

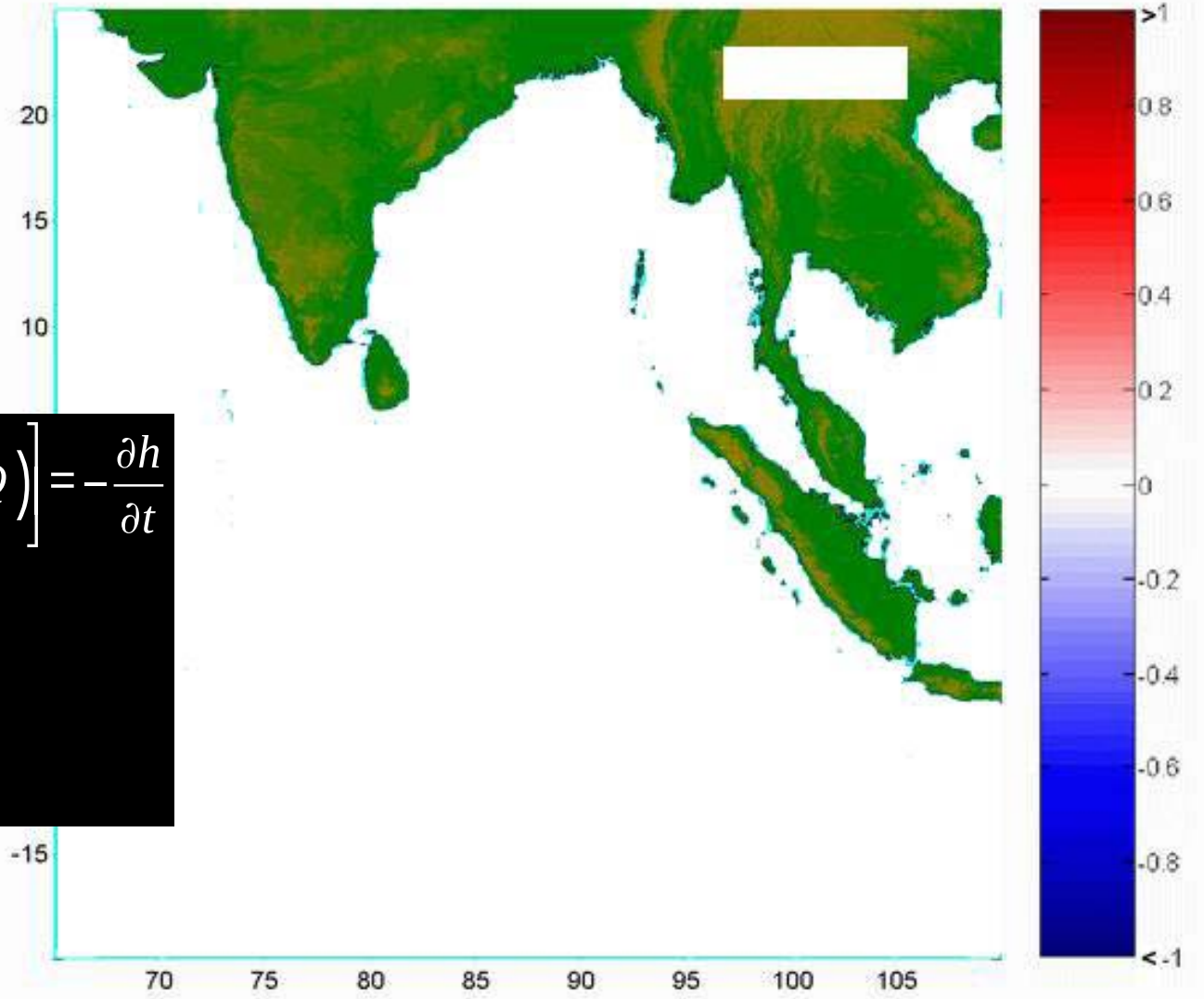
Numerical simulation and animation of 2004 Indian Ocean tsunamis

Numerical model is based on linear shallow water wave equations

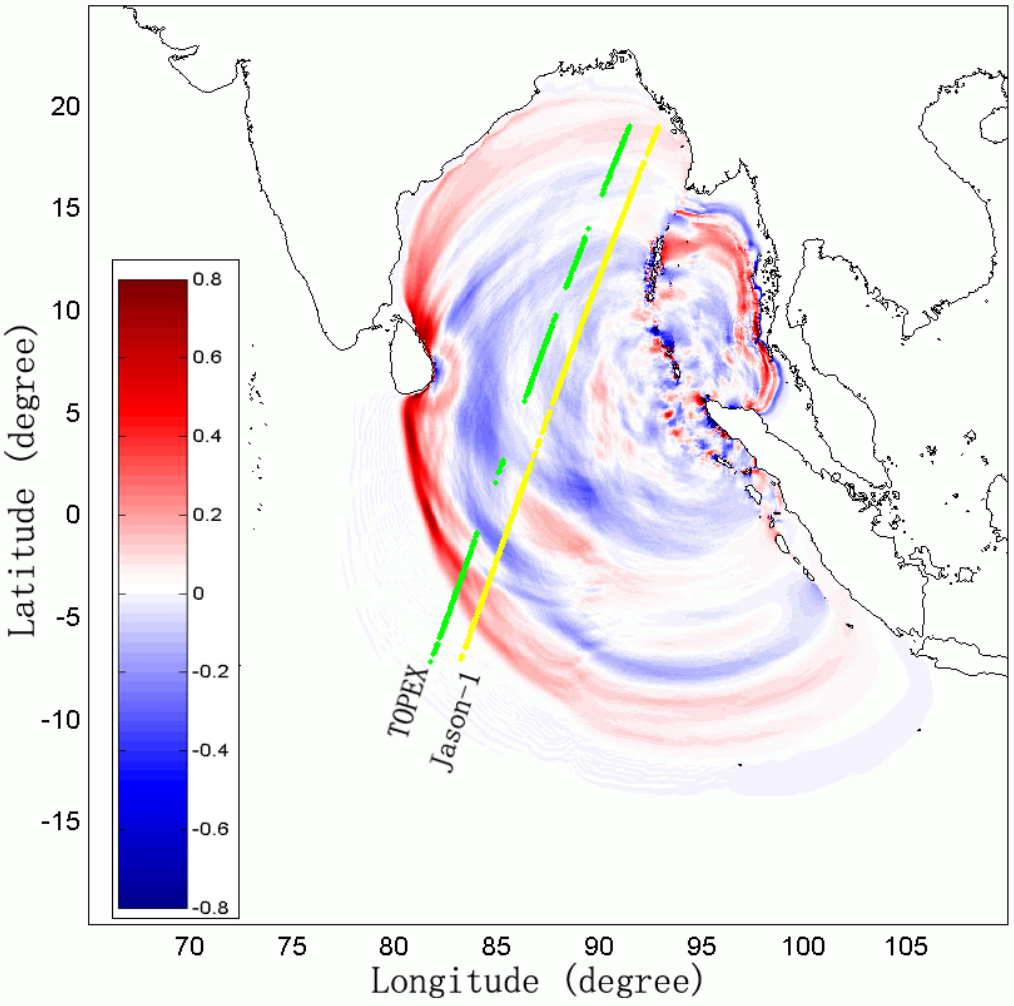
$$\frac{\partial \xi}{\partial t} + \frac{1}{R\cos\varphi}\left[\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}\left(\cos\varphi Q\right)\right] = -\frac{\partial h}{\partial t}$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R\cos\varphi}\frac{\partial \xi}{\partial \psi} - fQ = 0$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \xi}{\partial \varphi} + fP = 0$$



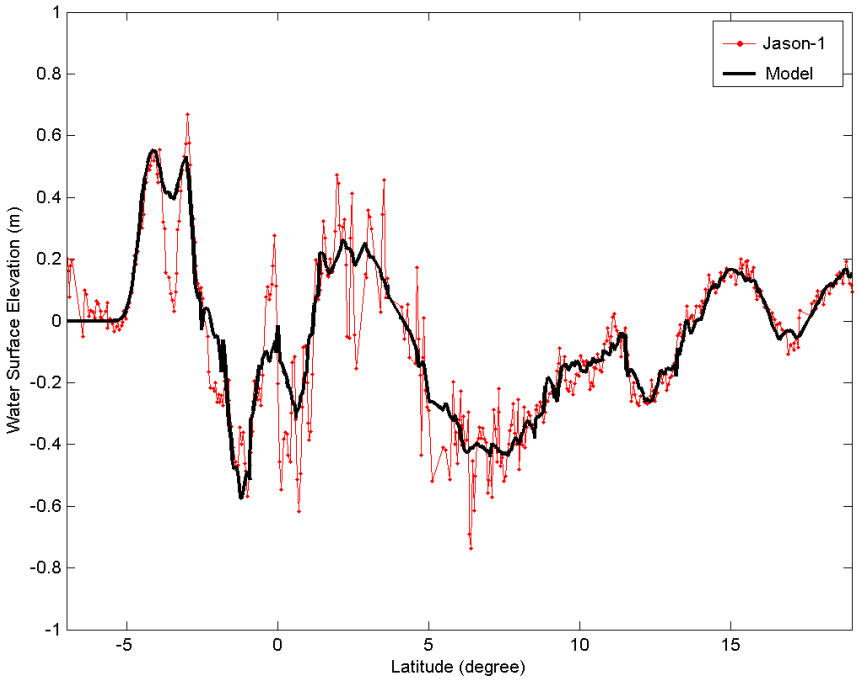
Validation of numerical results with Satellite altimeter data

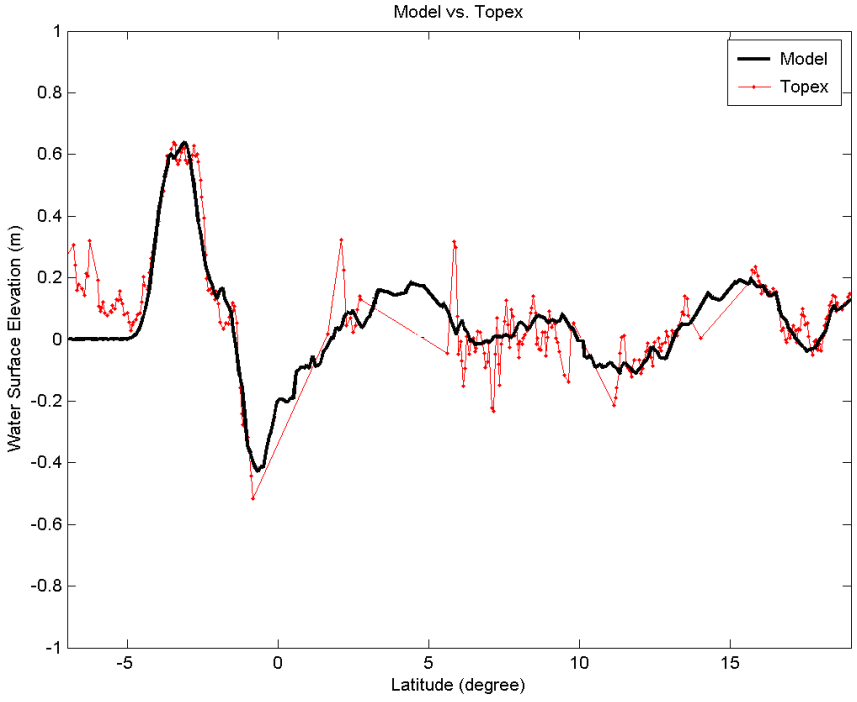


Tracks for TOPEX and Jason-1

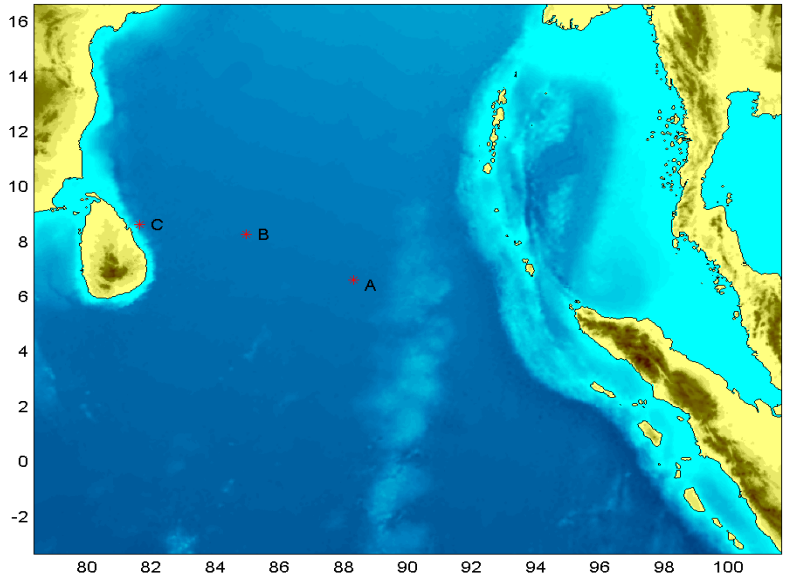
The colors indicate the numerically simulated free surface elevation in meter at two hours after the earthquake struck

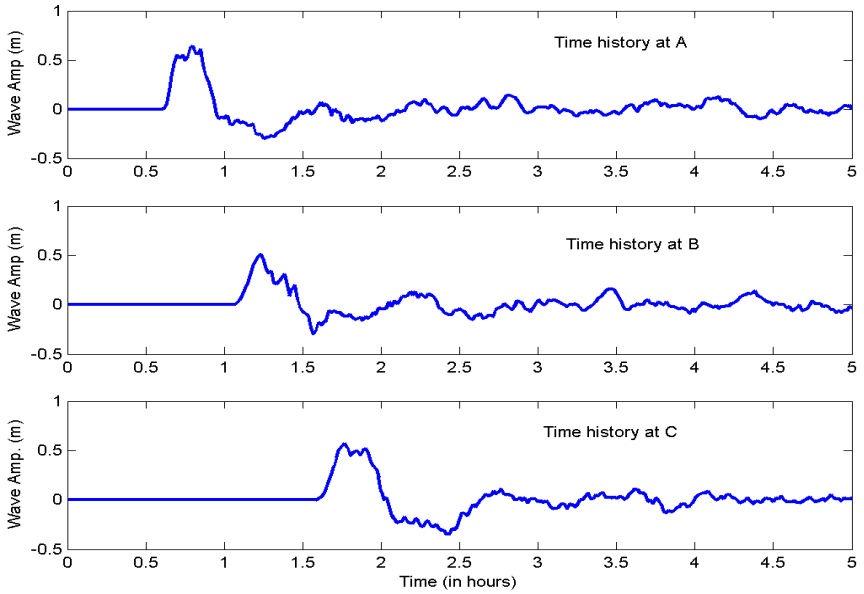
Comparisons between model results and Jason-1 measurements (left) and TOPEX measurements (right)

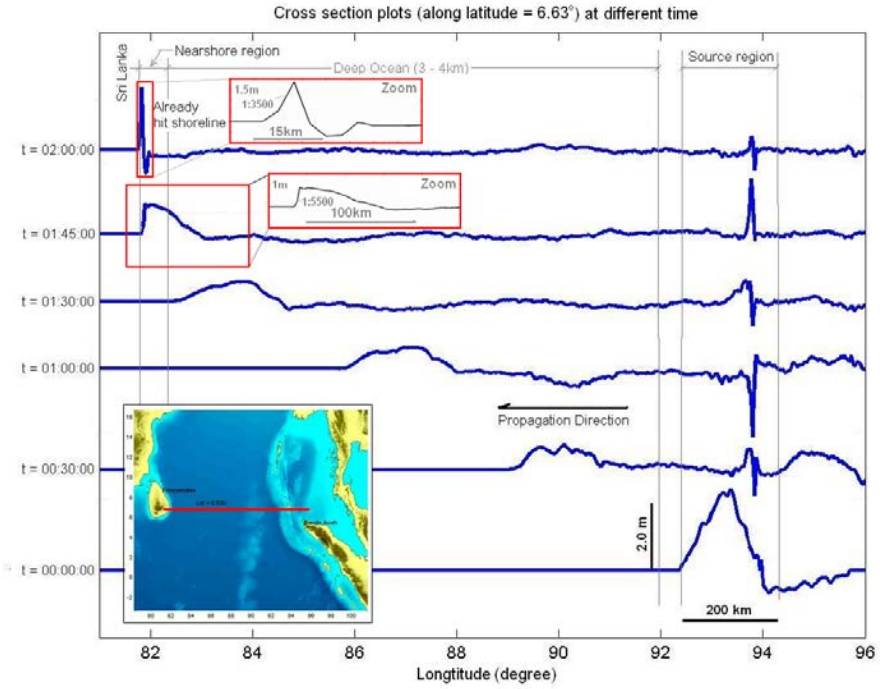




Tsunami characteristics in the open sea -Linear non-dispersive waves

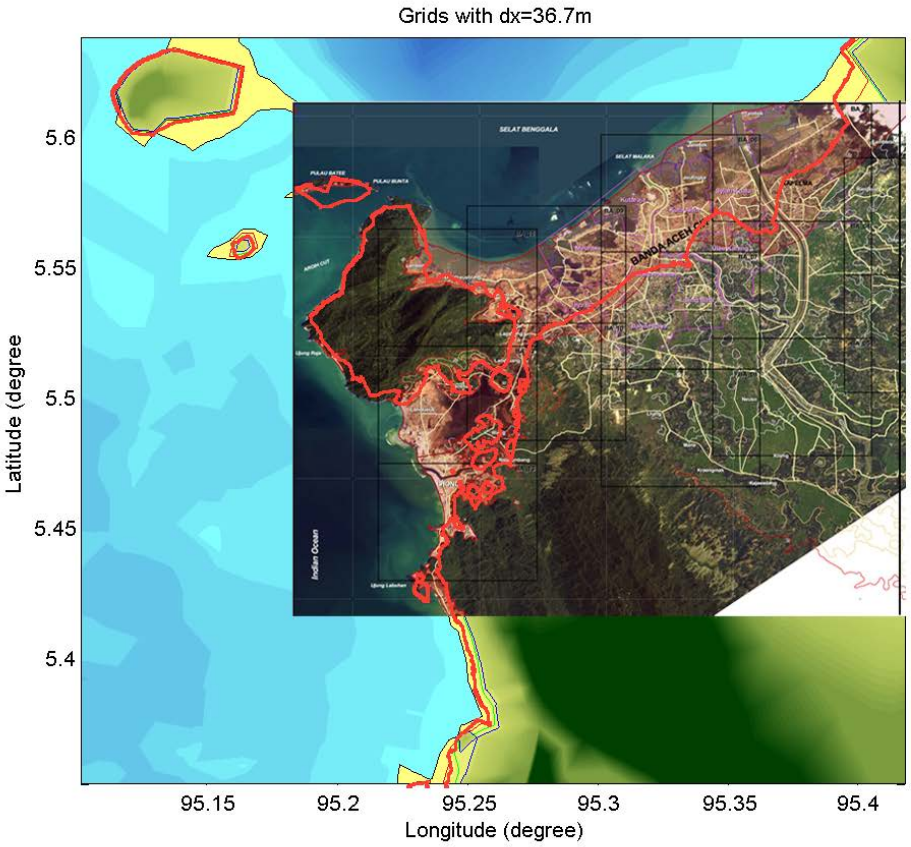






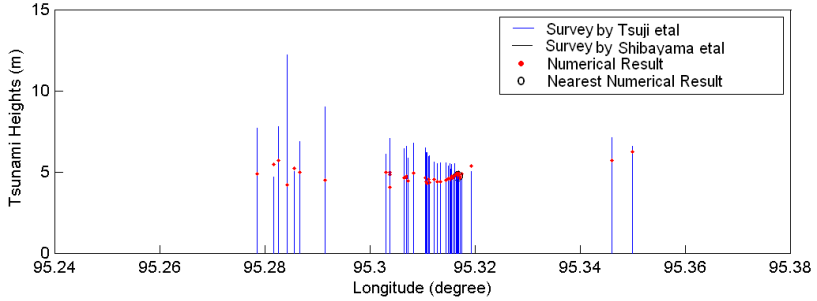
Snapshots of free surface profile along latitude = 6.63)

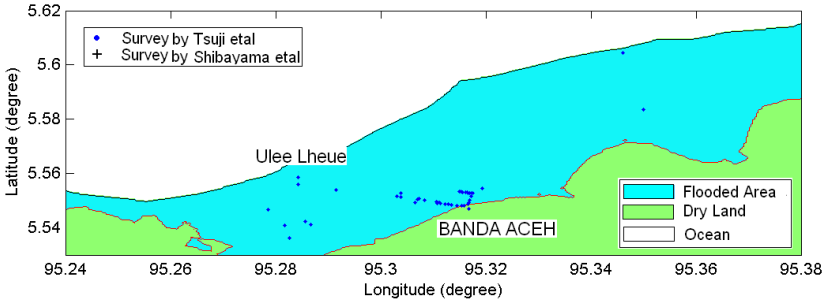
Calculated Inundation area in Banda Aceh with satellite image overlaid

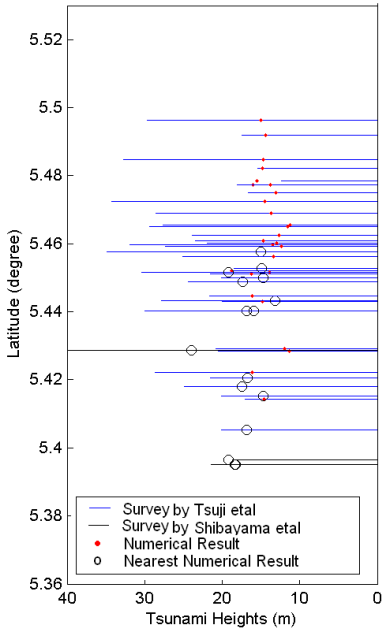


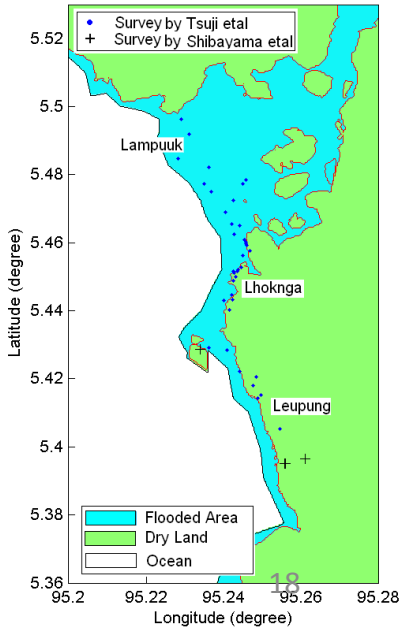
Numerical model is based on Non-linear Shallow water equations

Comparison with field survey data









Tsunami waves and overland flows in coastal zone

- Wave breaking; scouring, interaction with vegetation and man- made infrastructures

- Surging flows; sediment-laden flows; debris flows

Tsunami waves and overland flows in coastal zone

- Comprehensive model is still lacking

CONCLUDING REMARKS

- South China Sea Tsunai Hazard

Toward establishing a regional tsunami warning system in South China Sea region

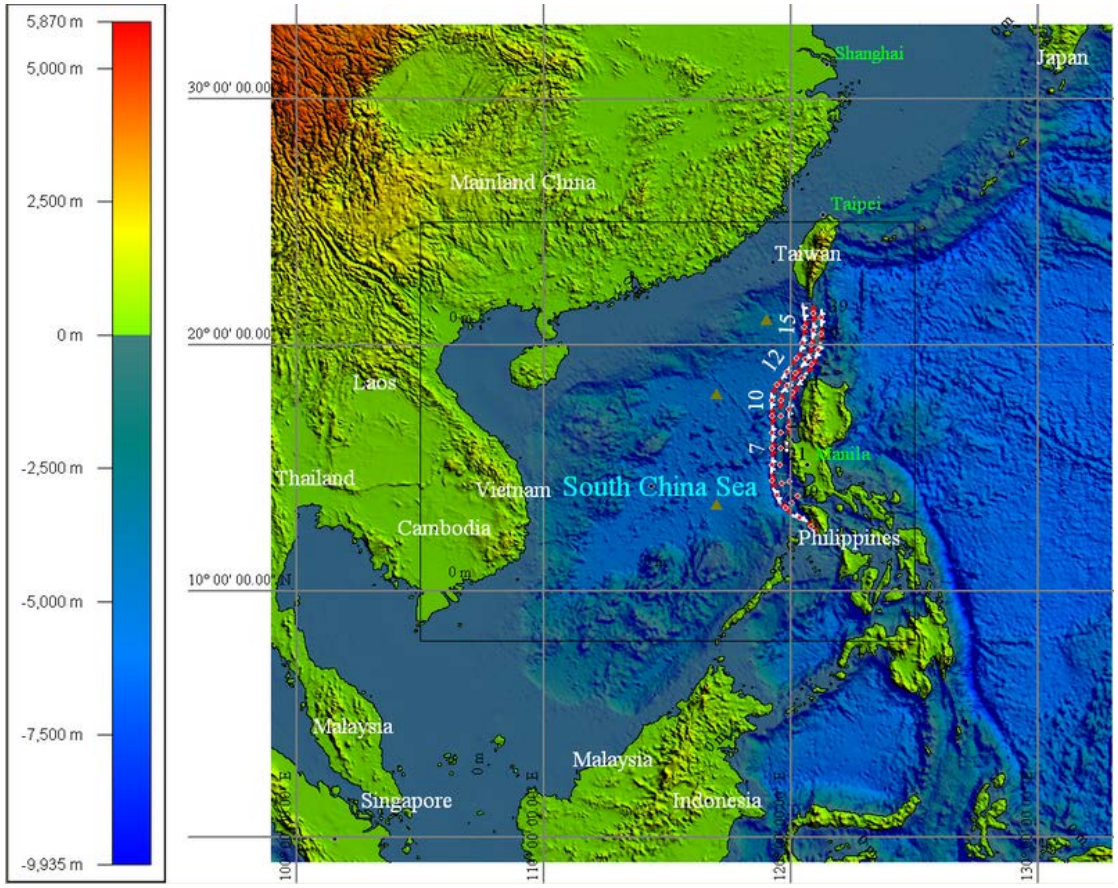
Major Scientific Tasks:

Source region characterization

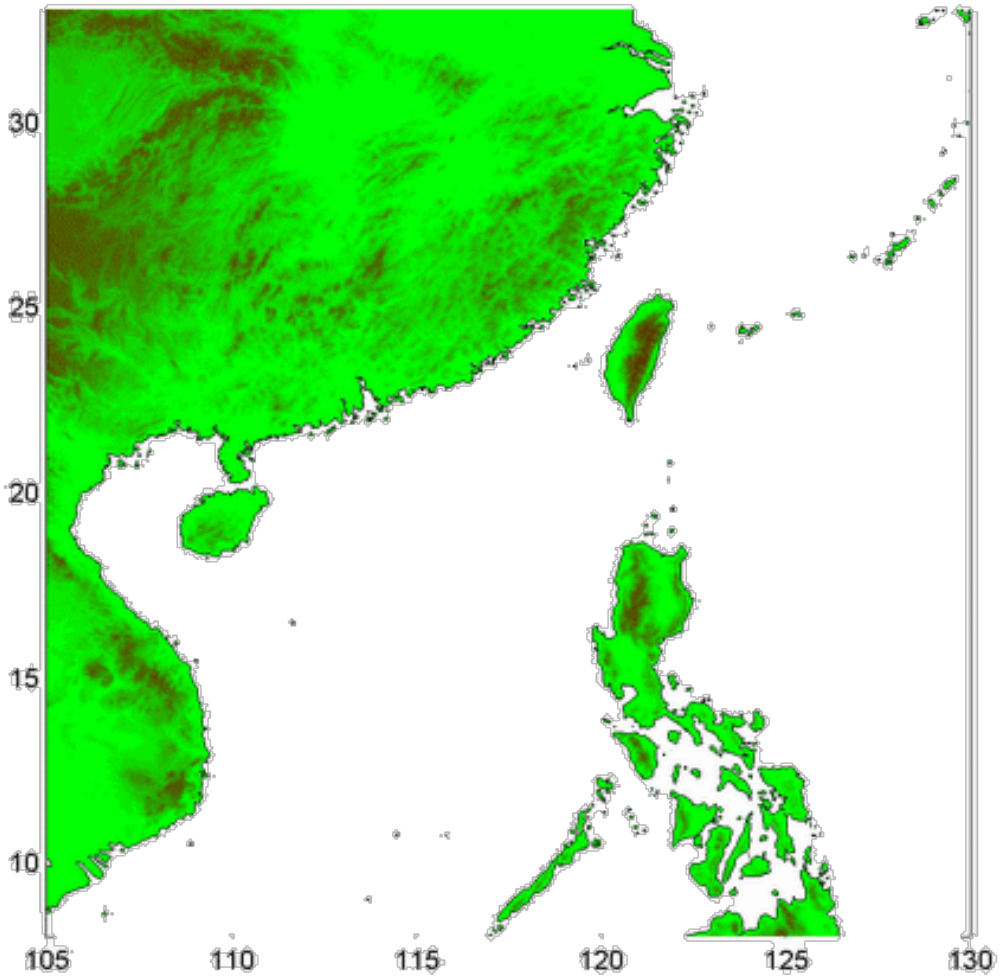
Monitoring source region dynamics

Establish data bases for

- Bathymetry and topography
- Seismic and source region parameters
- Numerical simulation results



A scenario example



Tsunami deposits: a window to see the unseen

Tsunami deposits
- Distribution of tsunami deposits (horizontal, vertical)
- Deposit thickness
- Grain size, etc.

Inverse models

Sediment Transport model

Hydrodynamics of tsunami waves:
Time evolution of spatial distribution of free surface elevation, water depth and velocity

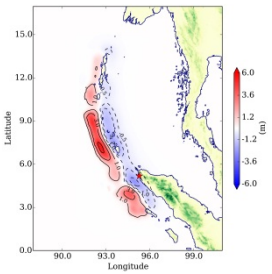
Wave Propagation model

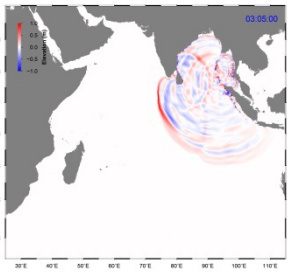
Constraints

Tsunami sources
- Initial free surface elevation
- Magnitude and location of the earthquakes
- The rupture mechanism

Tsunami deposit layers in Phra Thong, Thailand (Jankaew et al., 2008)

The state of knowledge and model skills





Earthquake/ tsunami Source

- **Seismic wave**
- **GPS**
- **InSAR**
- **Tide gauge**
- **DART**
- Satellite altimetry
- Etc.

Some confidence

Tsunami propagation/ inundation

- **Nonlinear shallow water equations (COMCOT; GeoClaw; MOST, etc.)**
- **Fully nonlinear and weakly dispersive equations (FUNWAVE; COULWAVE, etc.)**

Good confidence

Sediment transport

- **Bedload, suspended load, pick-up function, and settling rate**
- **2DH single layer model (COMCOT-SED; GeoClaw-SED, etc.)**
- **2DV/3D (Delft3D, etc.)**
- etc.

Poorly understood

End

Questions?