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Indian Ocean Tsunami Information Centre

ESCAP Economic and Social Commission for Asia and the Pacific

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Tsunami Ready

Earthquake and Tsunami Hazards in Indian Ocean (Seismotectonics and other potential sources)

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TEMPP 2025

Training Workshop on Tsunami Evacuation Plans, Maps, and Procedures (TEMPP) and UNESCO-IOC Tsunami Ready Recognition Programme (TRRP) for Indian Ocean Member States

ITCOOcean, INCOIS, Hyderabad

15-23 April 2025

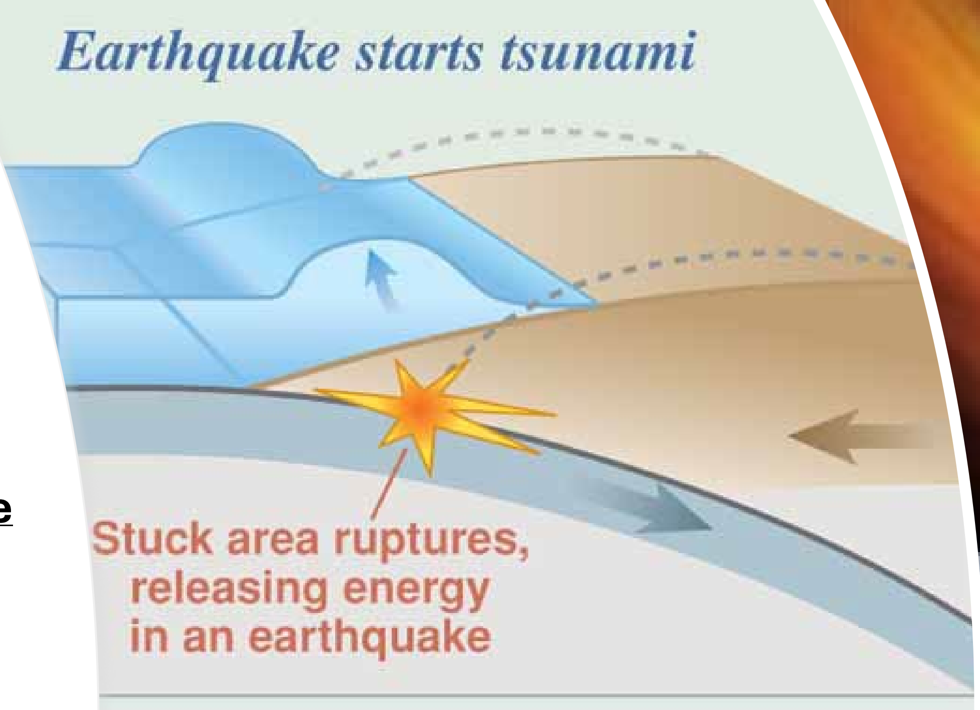
Content

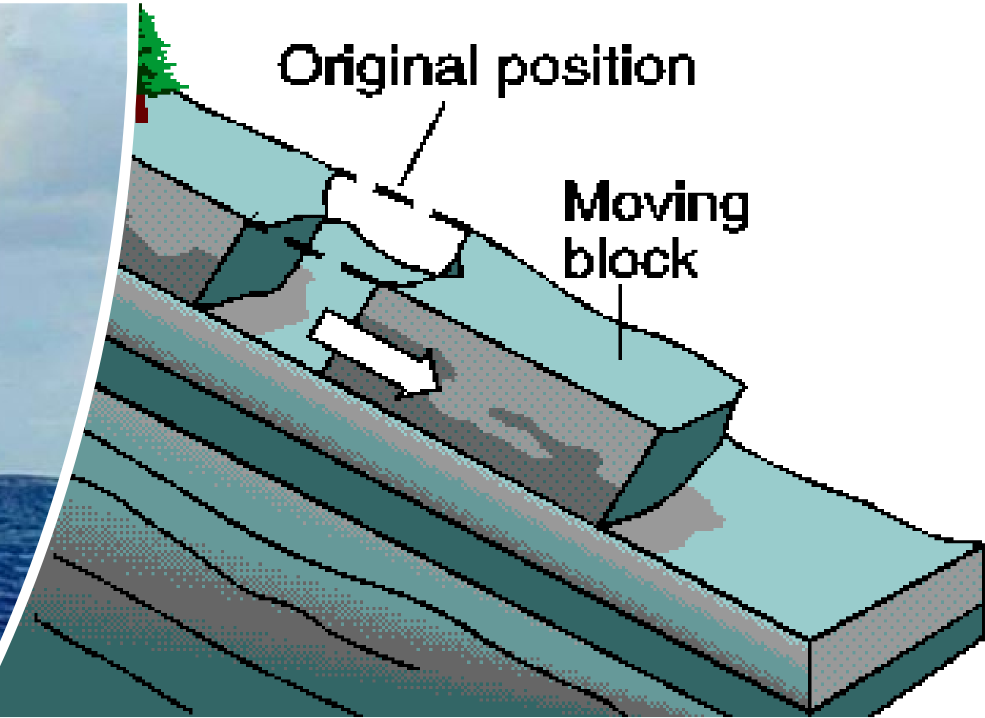
- Causes of Tsunamis
- Earth Structure and Faults
- Earthquakes determination
- Tsunamigenic Source Regions of Indian Ocean
- Seismo tectonics of Andaman-Sumatra Region
- Historical Tsunamis – Sumatra Region
- Seismo tectonics of Makaran Region
- Historical Tsunamis – Makaran Region
- Tsunami Hazards in Indian Ocean

Causes of Tsunami

- Any impulse that causes large scale displacement of the sea surface.

  - Earthquakes
  - Landslide
  - Volcanic eruptions
  - Meteoroids Impact

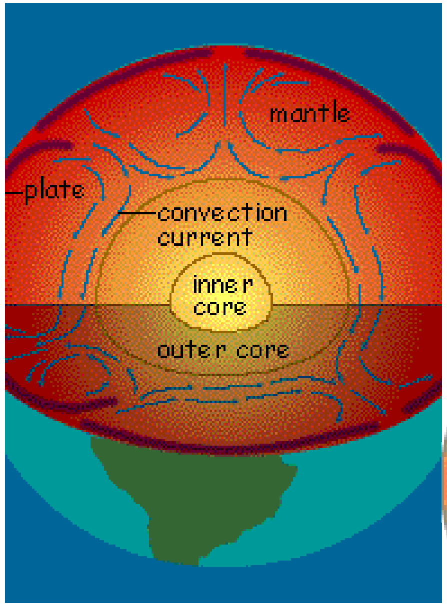


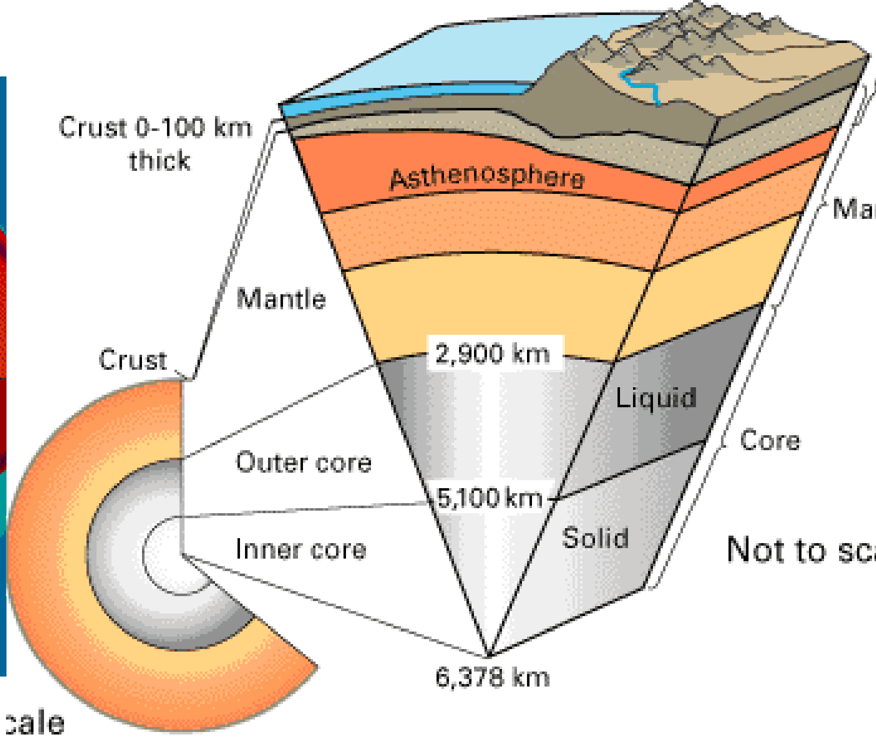


Layered structure of Earth

- Crust – 5 – 10 Km in Oceans & 30 – 50 Km beneath continents
- Mantle – 84% of Volume & 68% of Planet's Mass
- Core – Outer Core & Inner Core

- Lithosphere – 100 km thickness, brittle in Nature (Crust + upper Mantle
- Asthenosphere – Beneath Lithosphere, Viscous & ductile





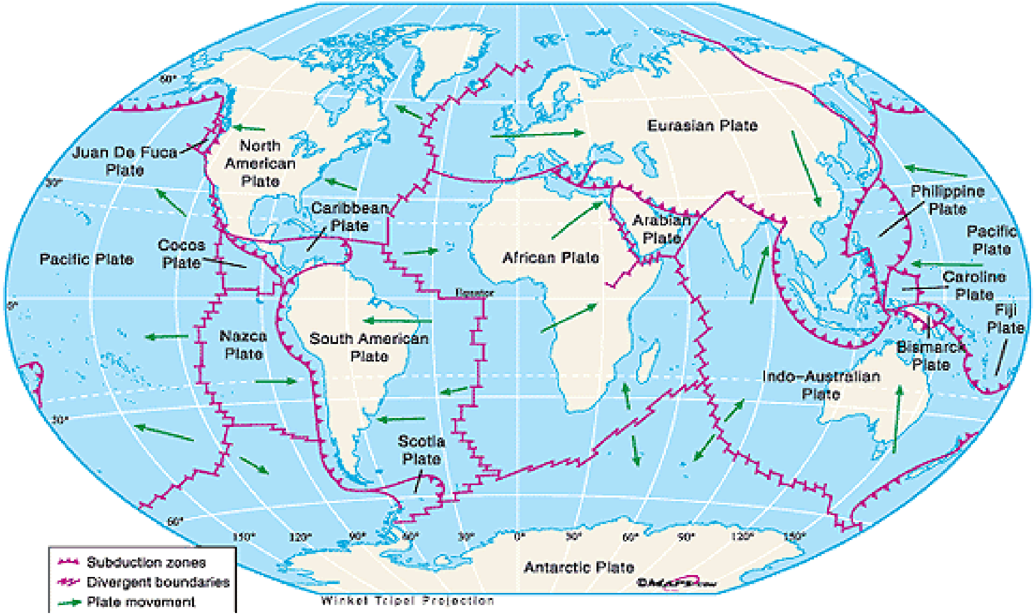


Plate Tectonics

Types of Faults

Faults Are Classified According to the Kind of Motion That Occurs on Them

- Joints - No Movement
- Strike-Slip - Horizontal Motion
- Dip-Slip - Vertical Motion

- Normal Faults: Extension
- Reverse Faults: Compression
  - Reverse Faults are often called Thrust Faults

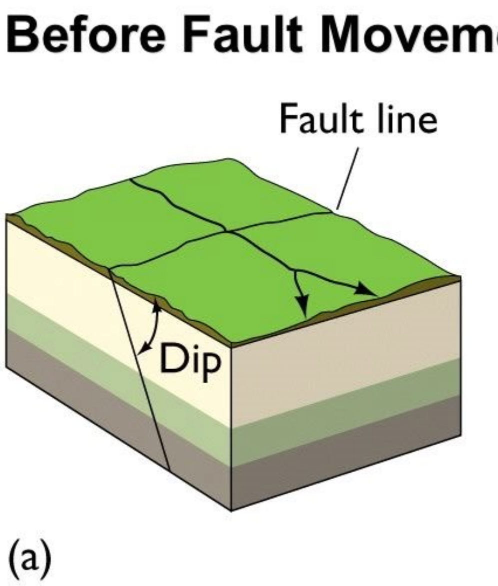


Fig. 18.12a

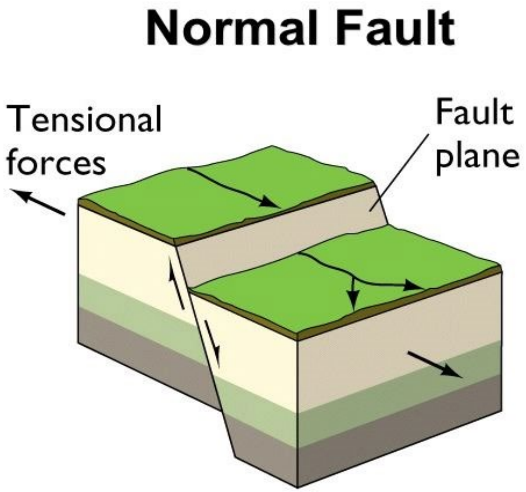


Fig. 18.12b

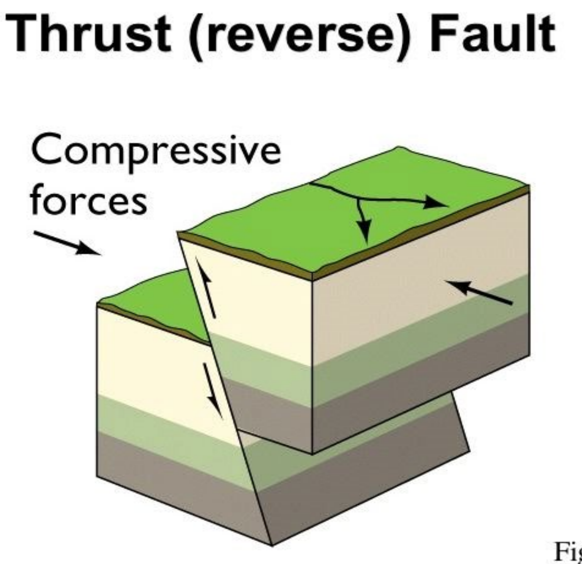


Fig. 18.12c

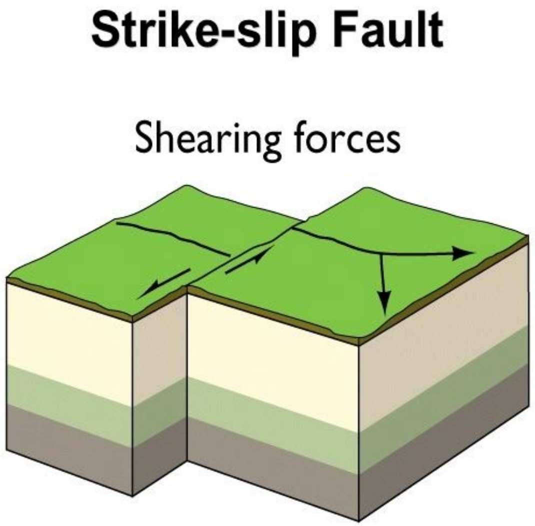
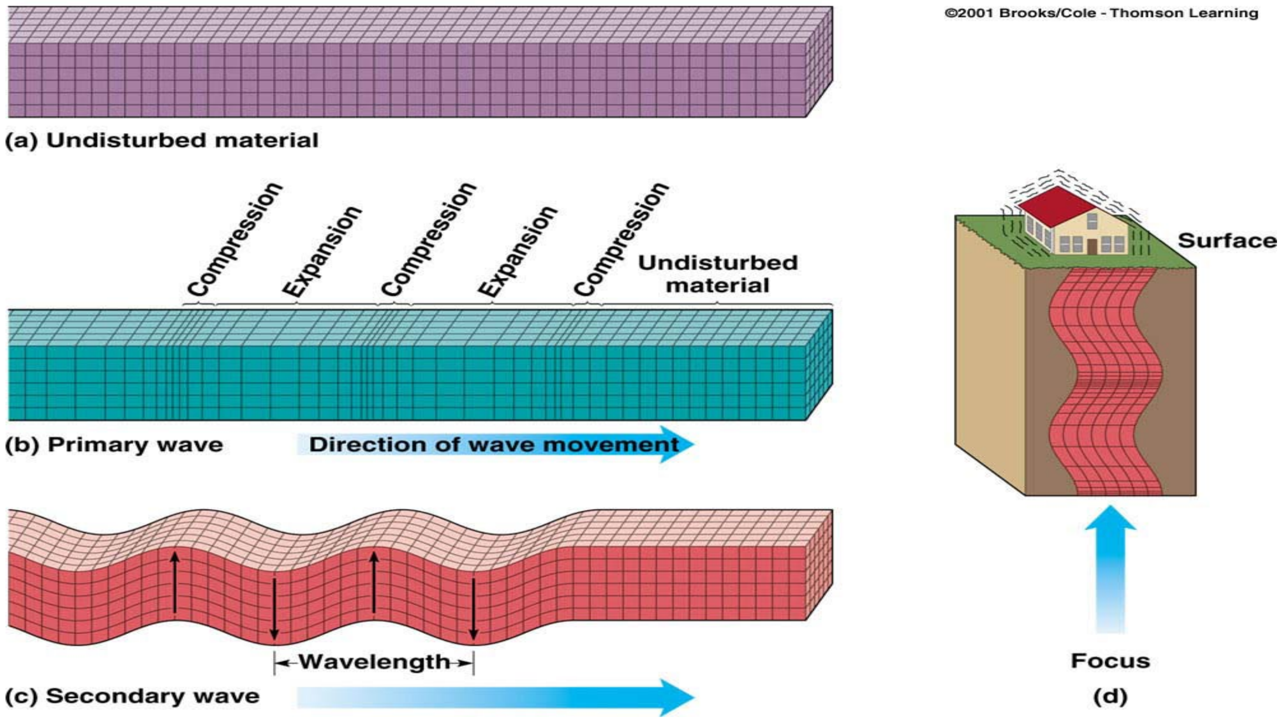


Fig. 18.12d

Types of Seismic waves



Seismic waves are generated in a broad frequency range from at least 0.1s to 1 hour

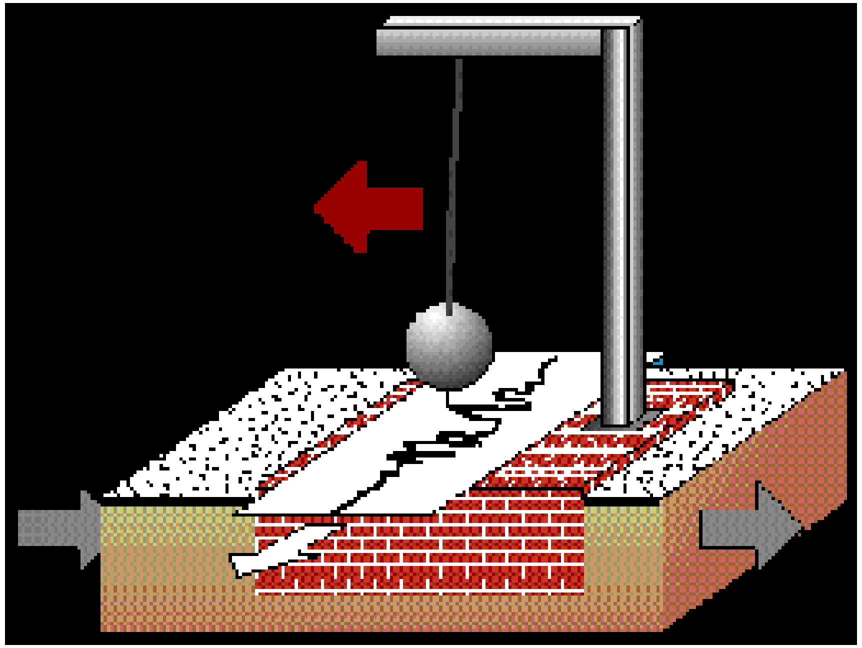
- ***Body waves***

  P waves (Primary, Longitudinal or Compressional waves)

  S waves (Secondary, transverse or shear waves)

- ***Surface waves***
  - Rayleigh waves
  - Love waves

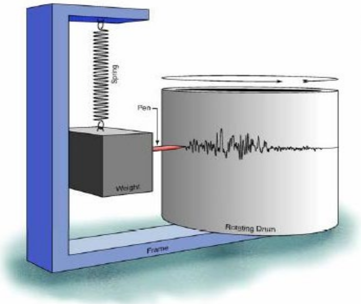
Seismographs

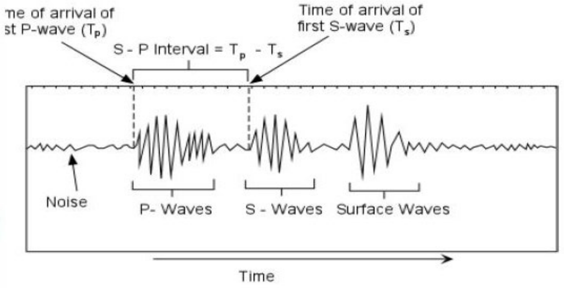


Seismometer

- Modern digital broadband seismographs are capable of recording almost the whole seismological spectrum (50 Hz – 300 s).
- Their resolution of 24 bits (high dynamic range) allows for precise recording of small quakes, as well as unsaturated registration of the largest ones.

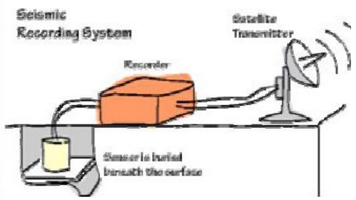
- Seismographs are devices that record ground motion during earthquakes.
- The first seismographs were constructed at the very end of the 19th century in Italy and Germany.





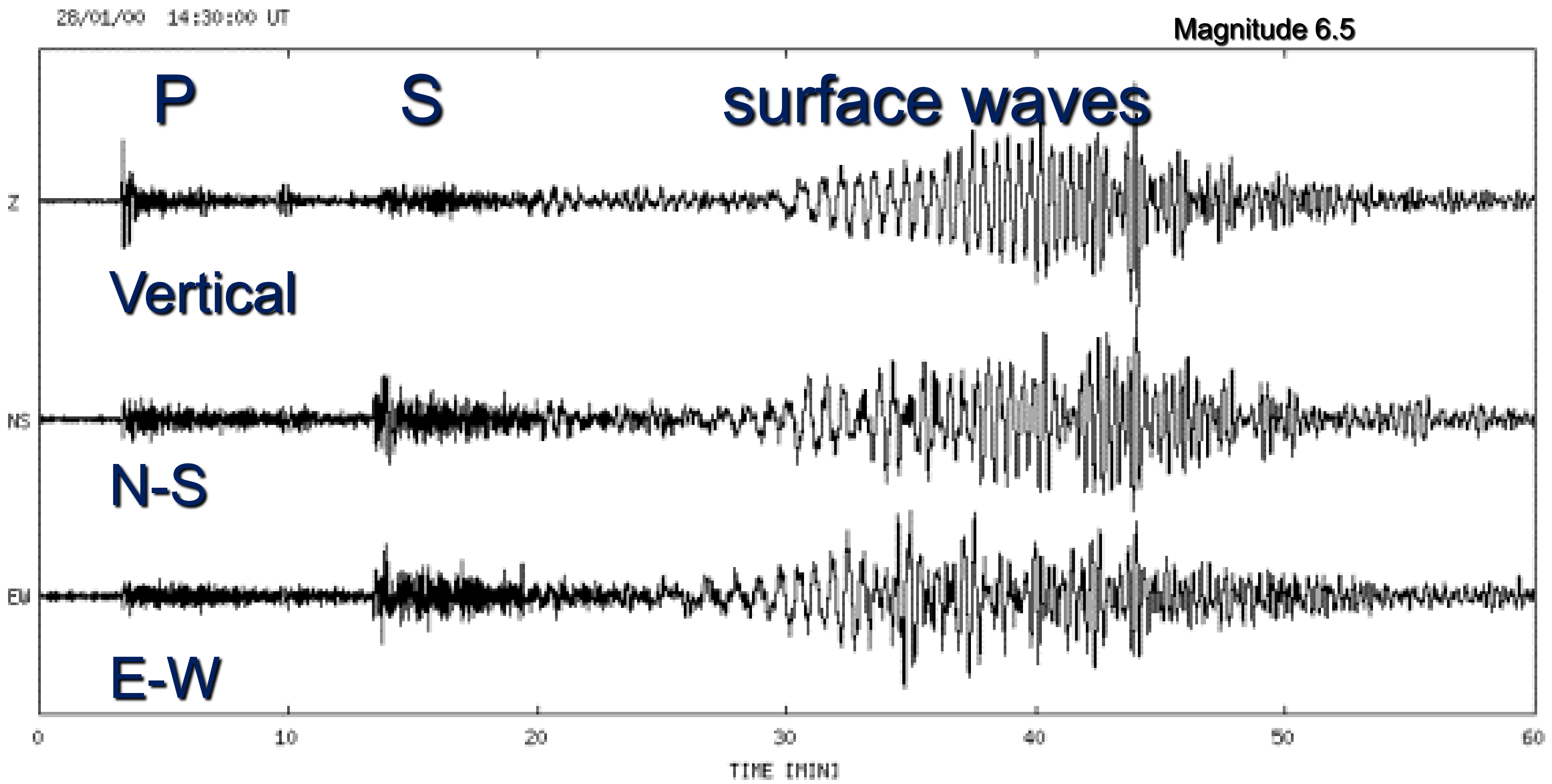
Streckeisen STS-1

Ground vibrations are detected by a broadband sensor, digitally recorded, and then transmitted via satellite.



Earthquake Record (Seismogram)

Earthquake in Japan
Station in Germany
Magnitude 6.5

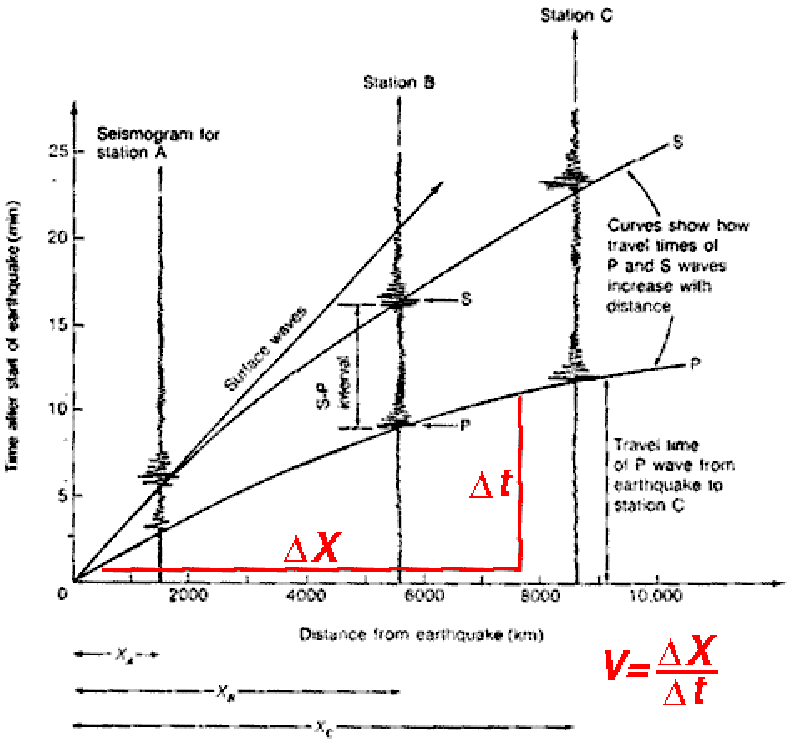


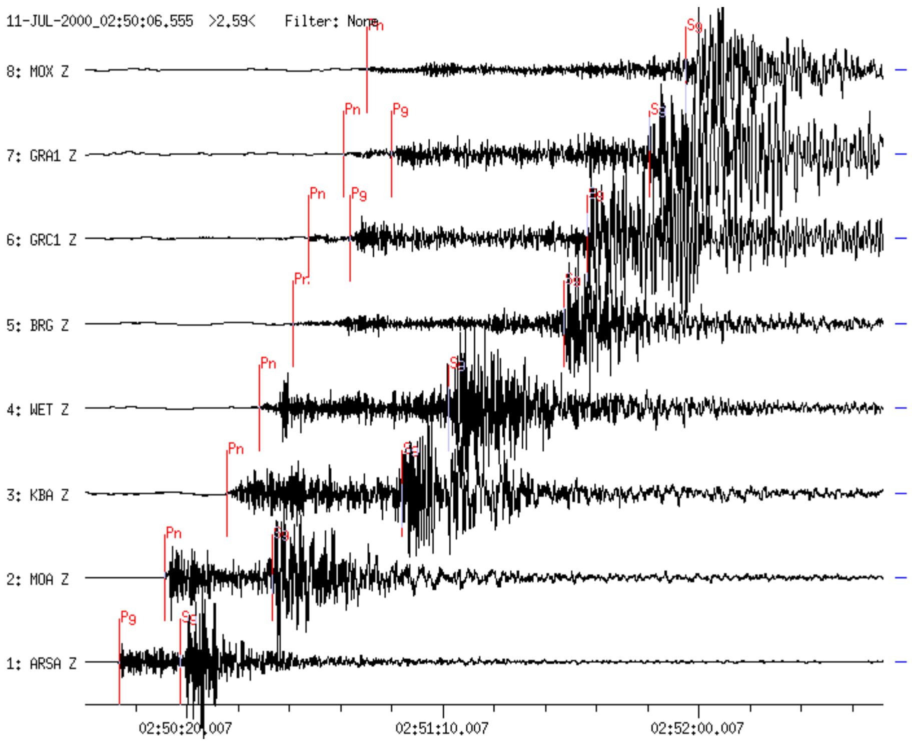
Earthquake parameters

Location
Origin time
Magnitude
Depth

Locating Earthquakes (Travel-time)

- Knowing the difference in arrival times of the two waves, and knowing their velocity, we may calculate the distance of the epicentre.
- This is done using the travel-time curves which show how long does it take for P- and S-waves to reach some epicentral distance.





Magnitude determination

- Formula:

$M = \log(A) + c_1 \log(D) + c_2$

where A is amplitude of ground motion, D is epicentral distance, and c_1, c_2 are constants.

- There are many types of magnitude in seismological practice, depending which waves are used to measure the amplitude: M_L, m_b, M_c, M_s, M_w, ...
- Increase of 1 magnitude unit means ~32 times more released seismic energy!

<u>Moment Magnitude</u>

$Mw = 2/3 \log Mo – 10.7$

Where the seismic moment, M0 is determined from the low frequency ground displacement Ω_0 obtained from the S wave spectrum

Seismic Moment, $M0 = \dfrac{4 \prod \rho v^3 R \Omega_0}{FR\theta\phi}$ dynes – cm

Where, ρ = density (2.7 gm/cm^3)

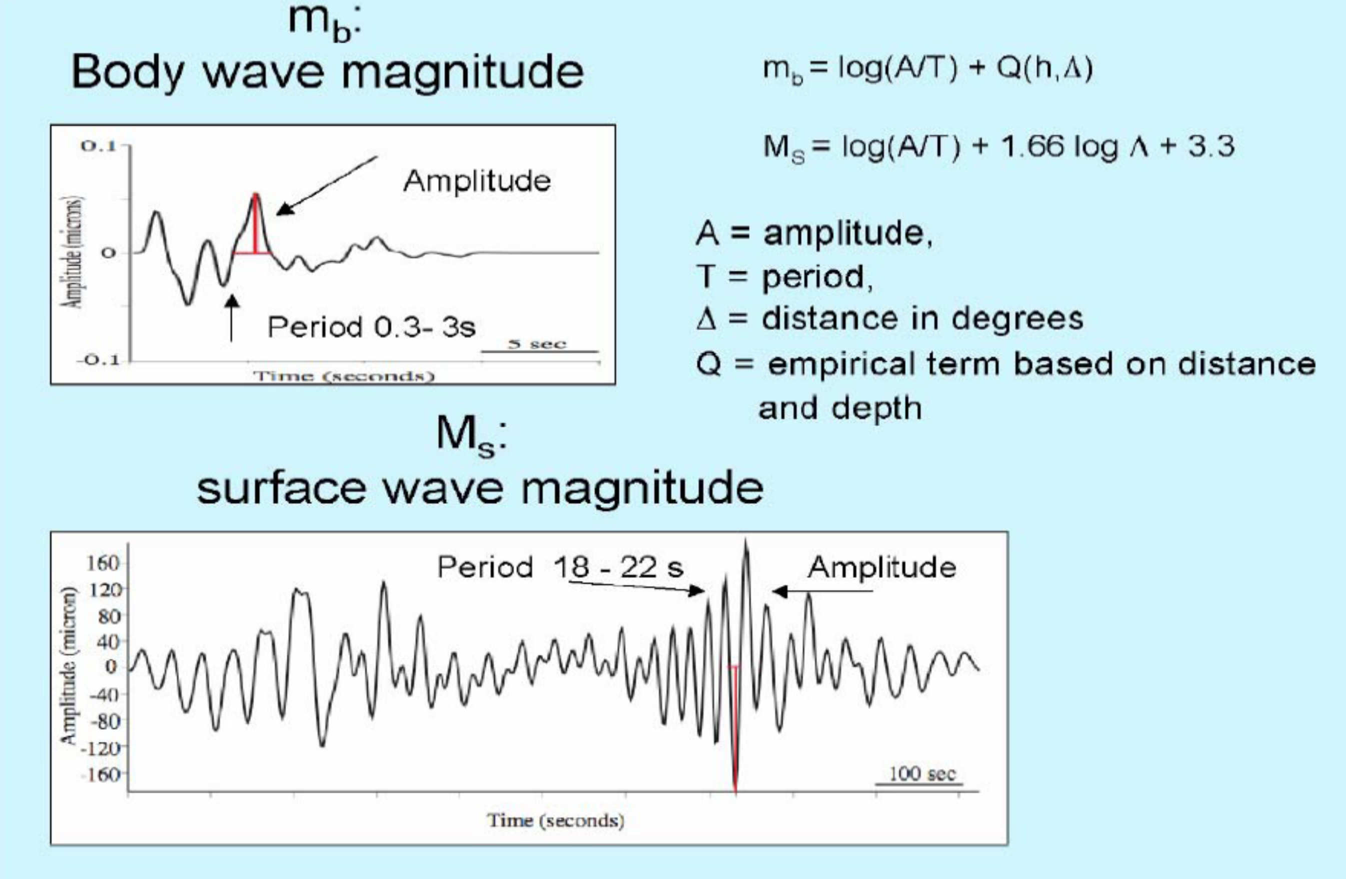
v = Velocity of Shear wave (3.8 x 103 cm/seconds)

R = Epicentral distance

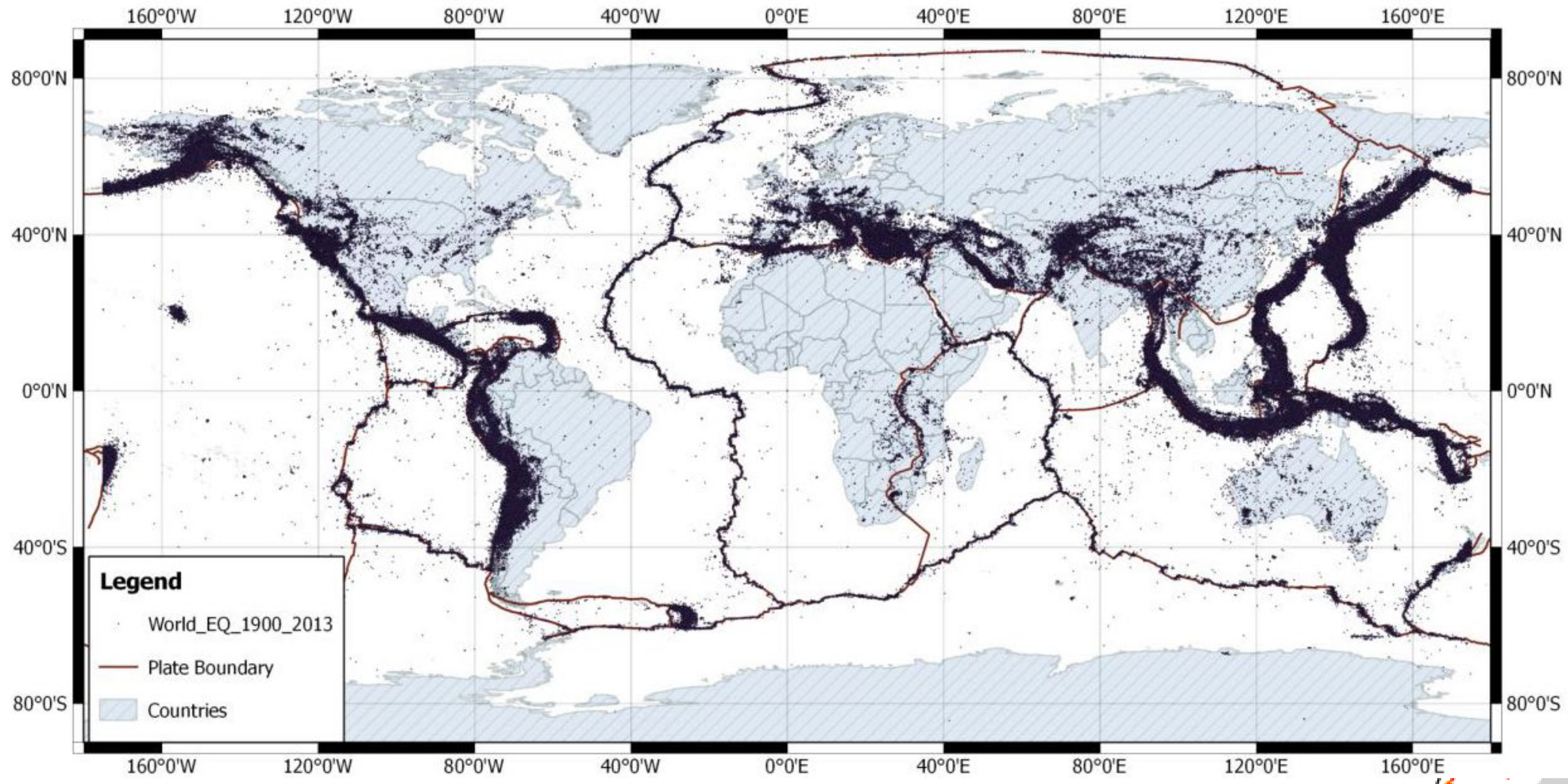
$R\theta\phi$ = Radiation Pattern factor

F = free surface correction factor

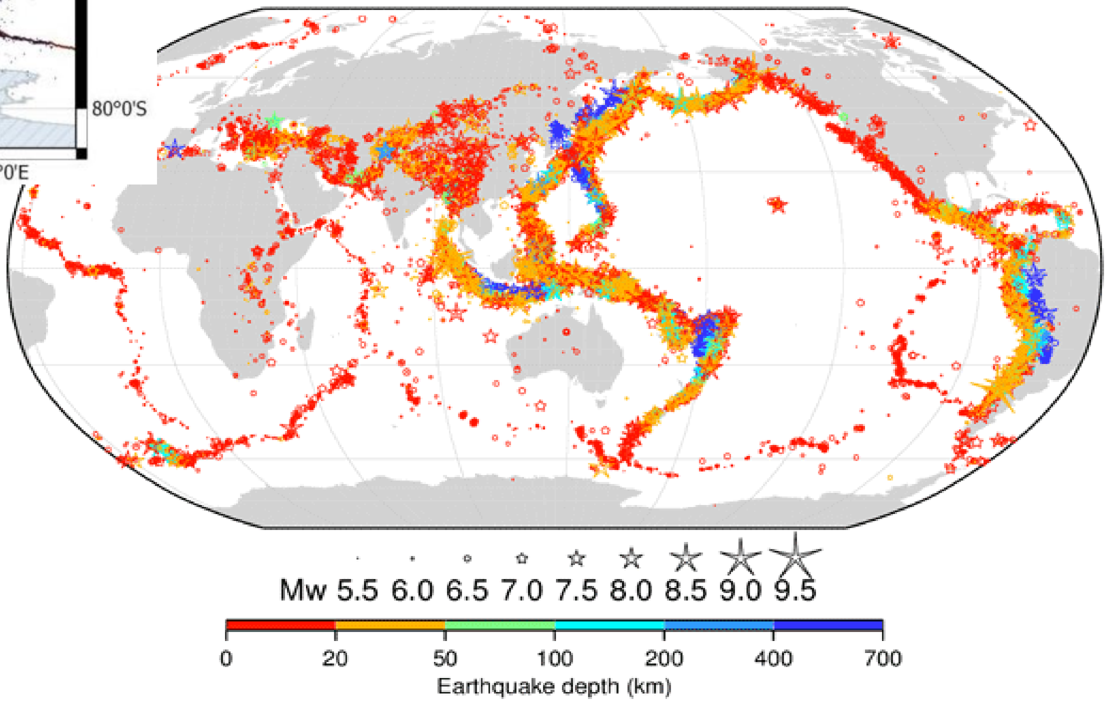
Ω_0 = Ground displacement from S wave spectrum



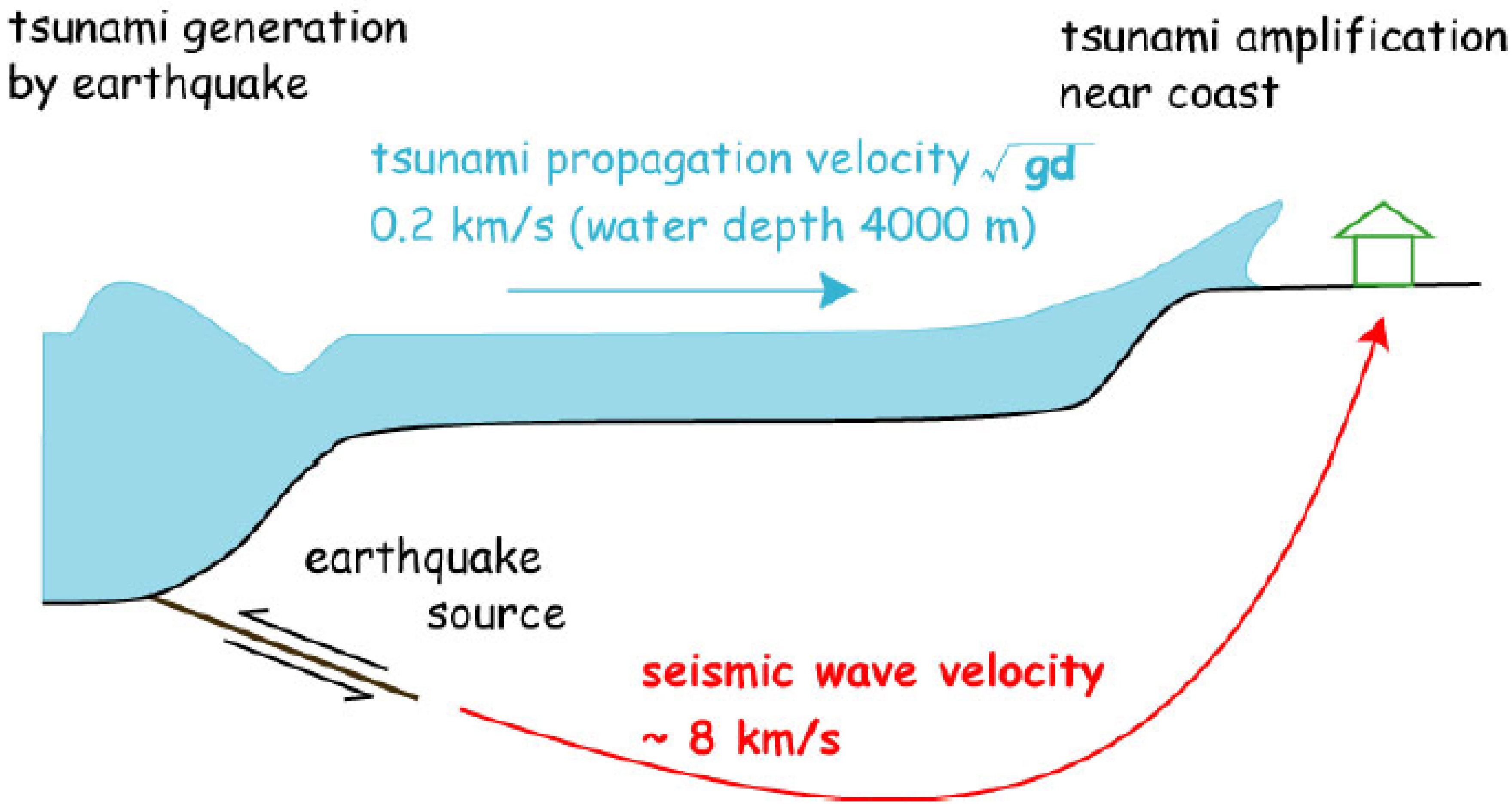
Global Seismicity



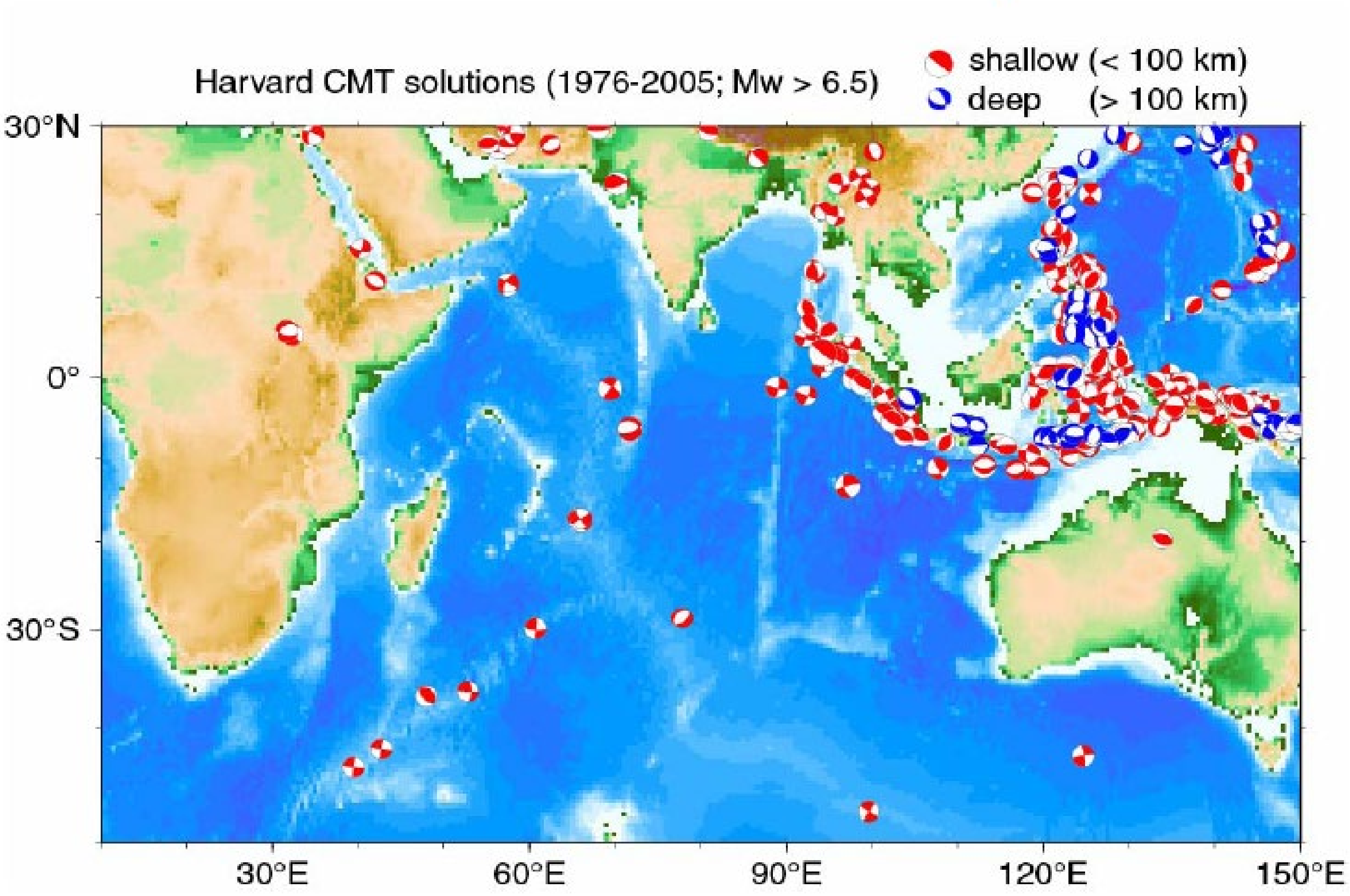
Source: NGDC



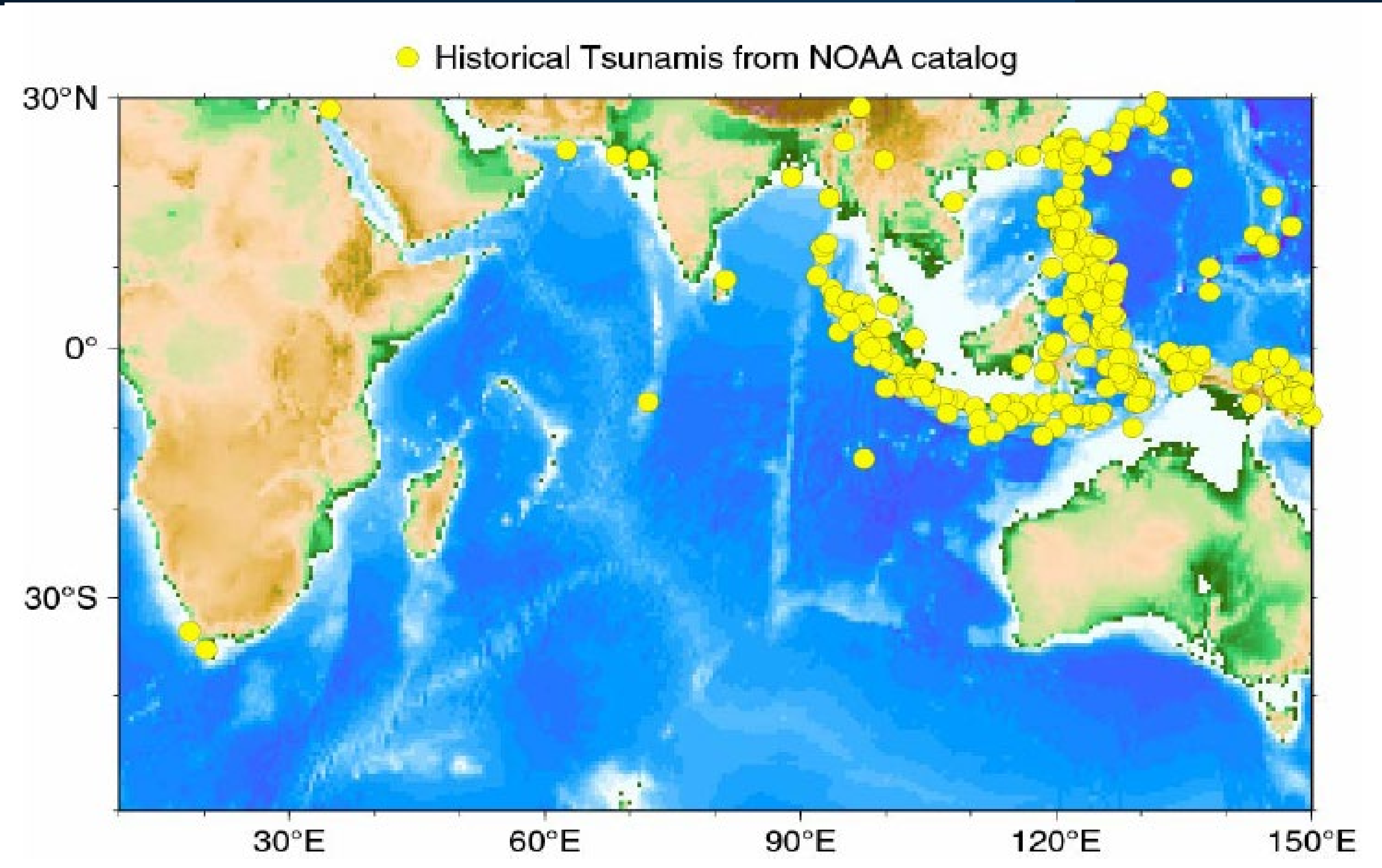
Seismic and Tsunami Waves



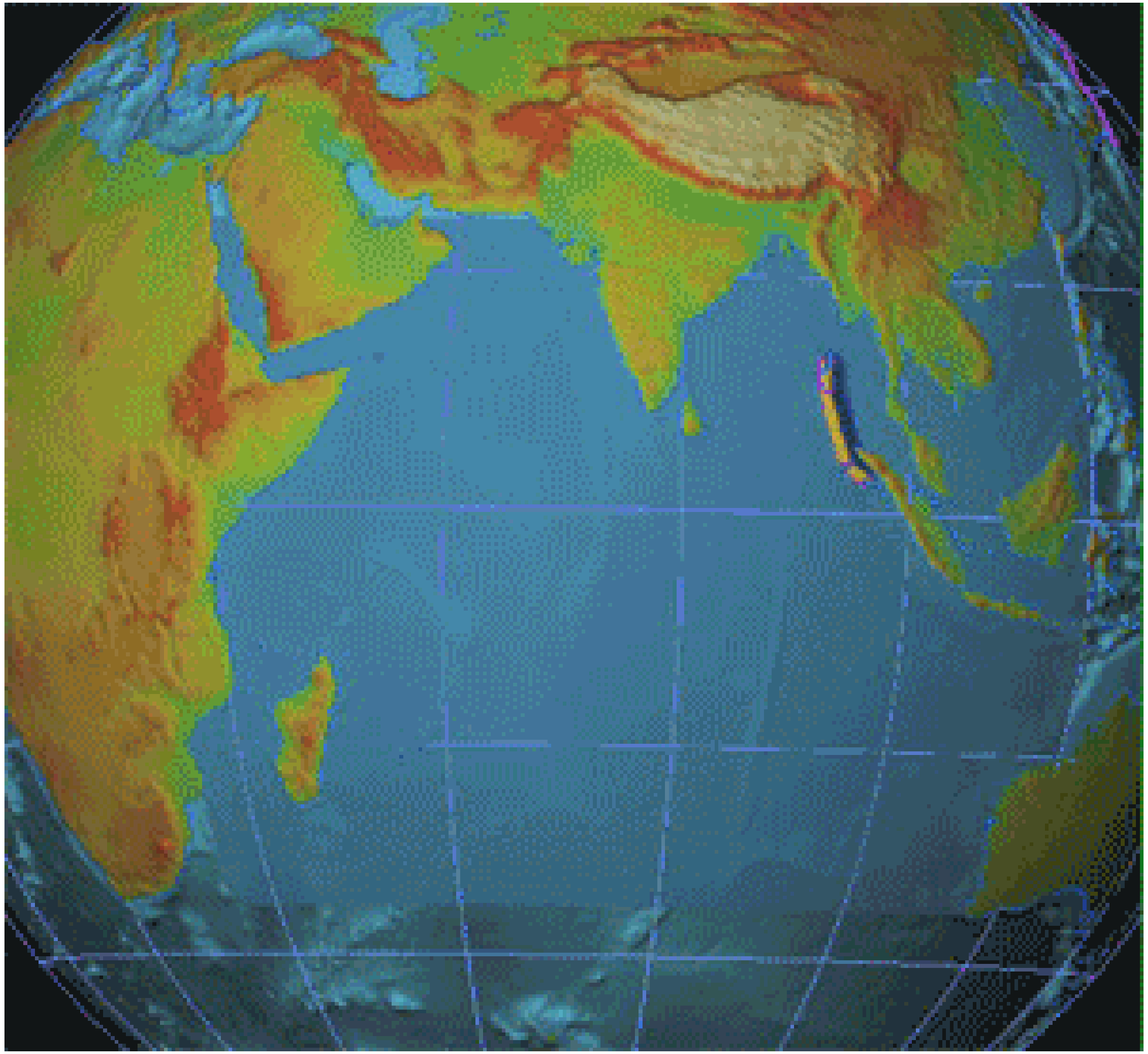
Indian Ocean Seismicity



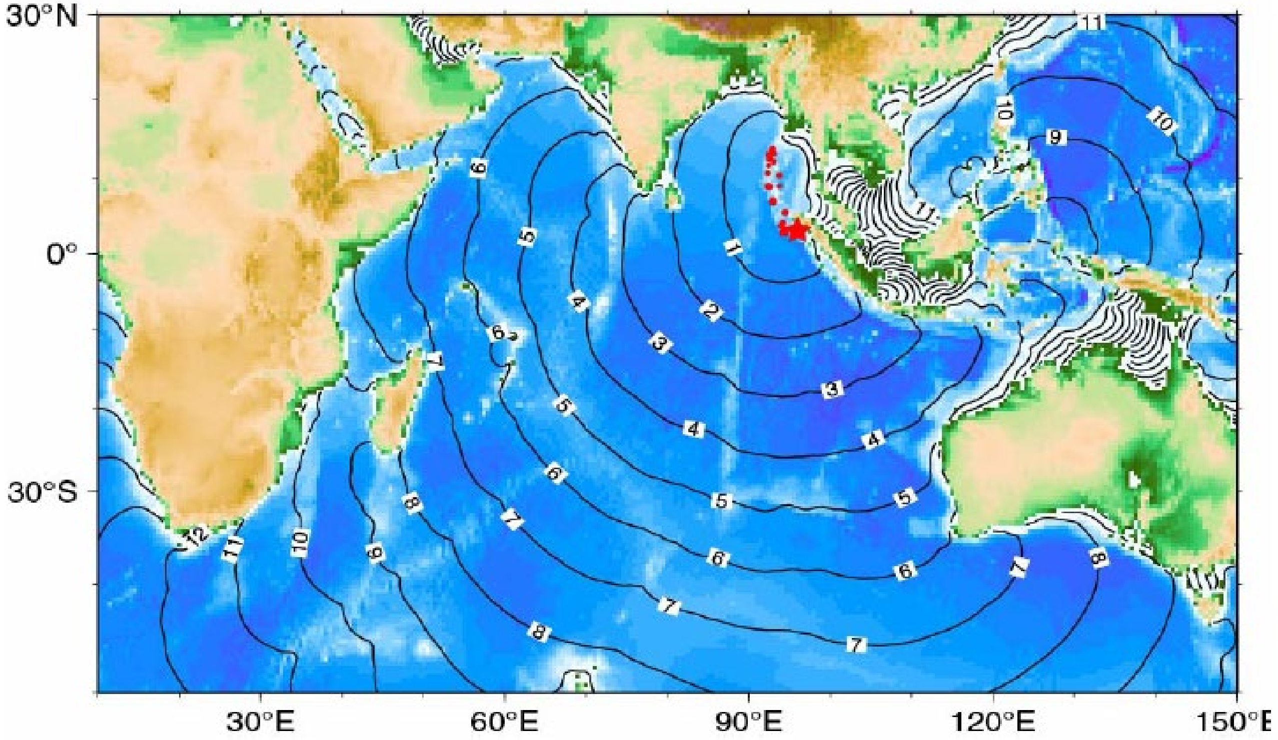
Indian Ocean : Historical Tsunamis

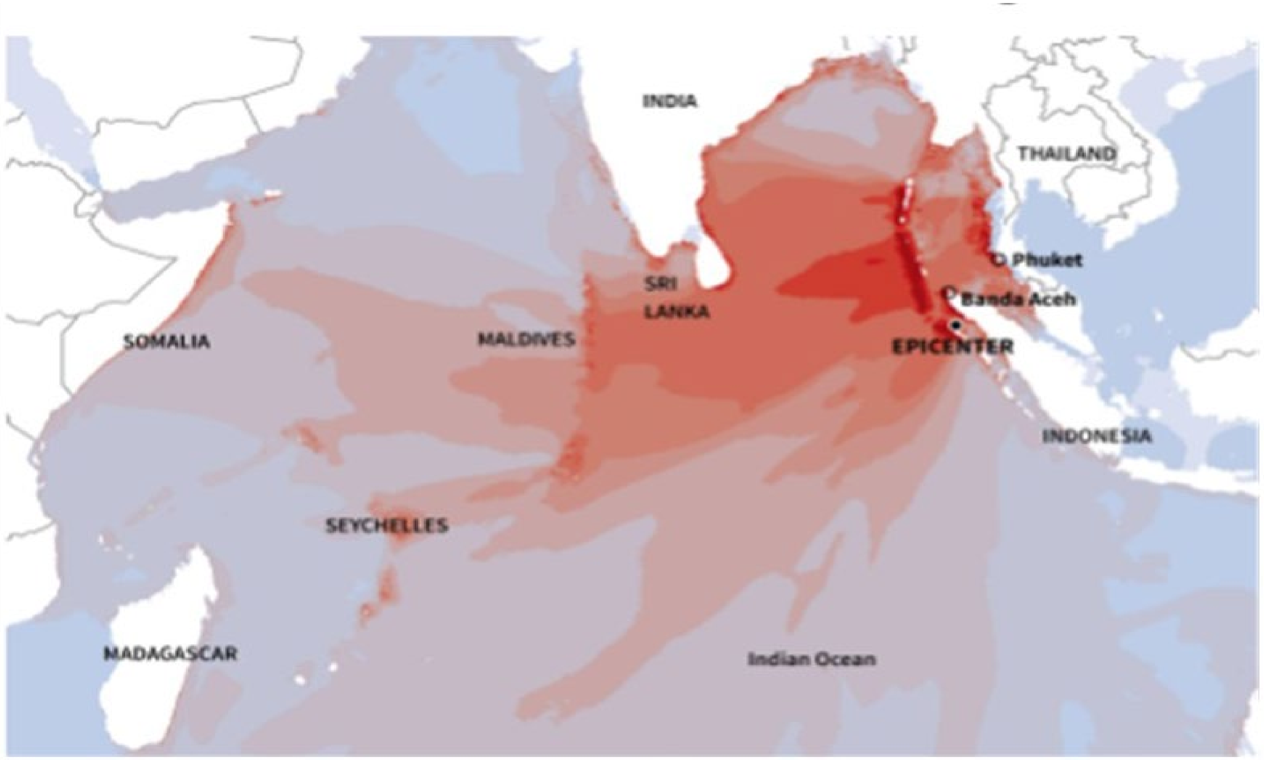


2004 – off Sumatra Earthquake and Tsunami



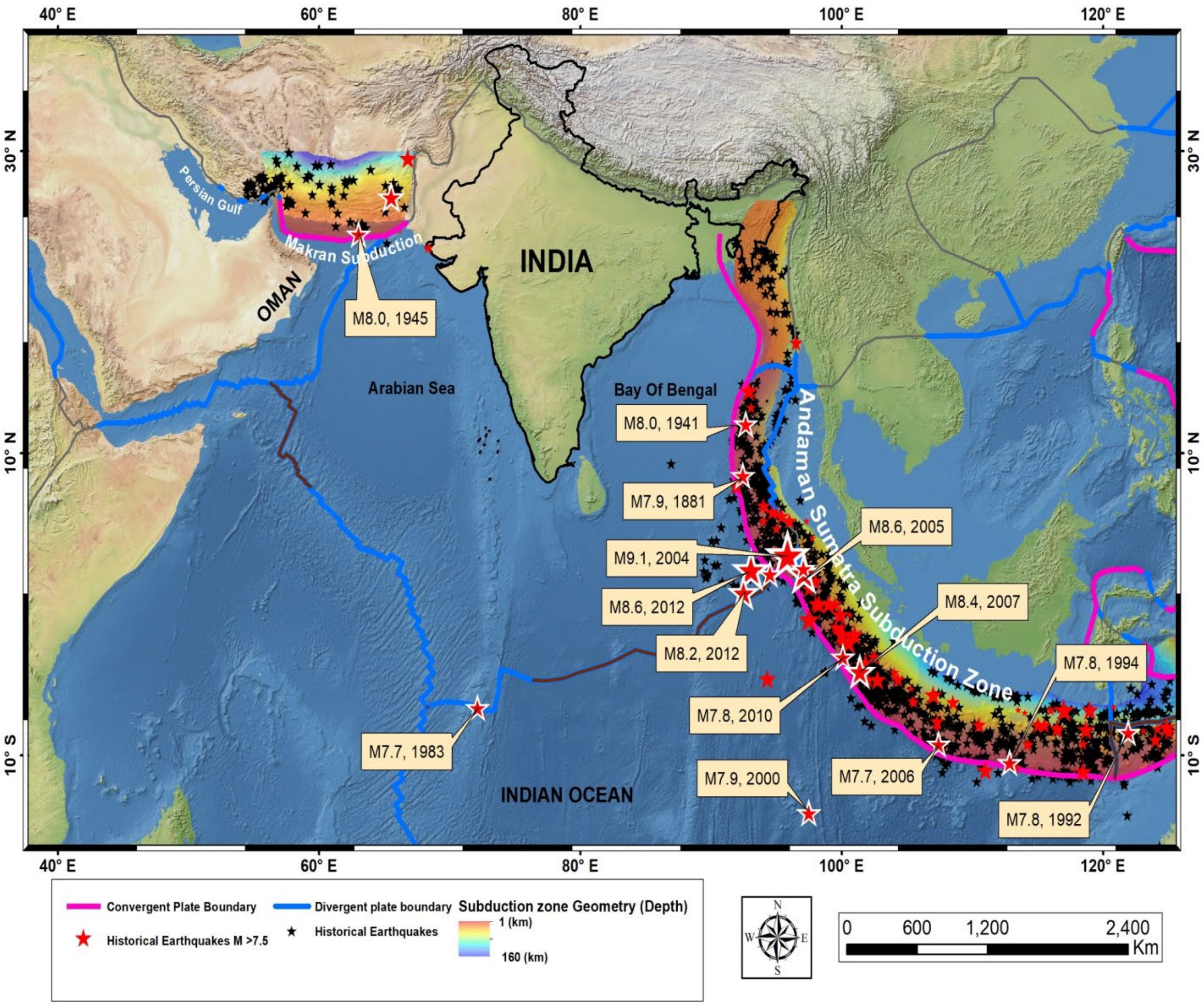
Travel Times and Energy amplitude map of 2004 Tsunami





Satellite image before and after Tsunami Aceh (Sumatra) 26 December 2004

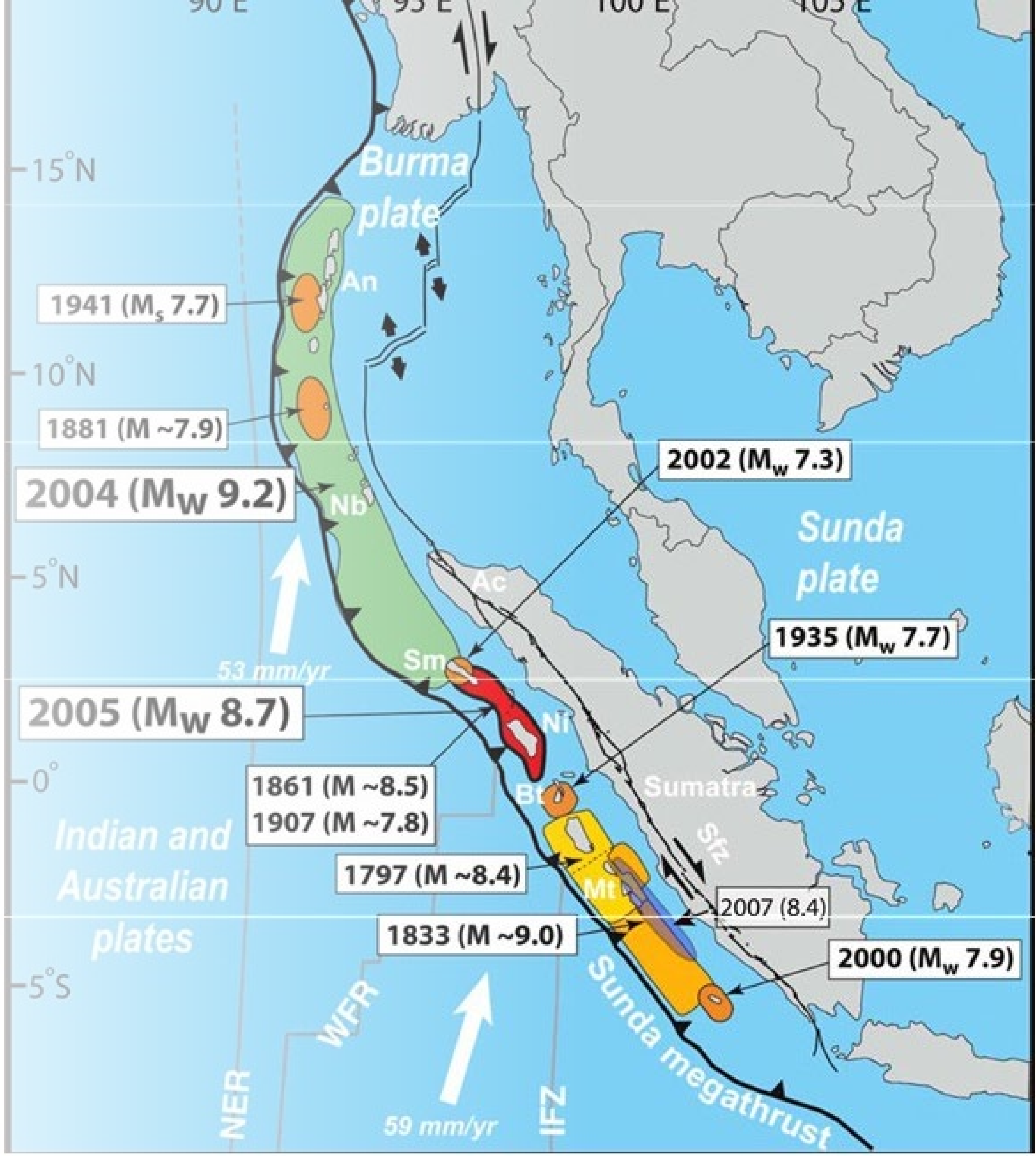
Potential Tsunamigenic Zones in Indian Ocean



- **Tsunamis are primarily caused due to large undersea Earthquakes.**
- **For a tsunami to hit Indian coast, it is necessary that a tsunamigenic earthquake occurs and its magnitude should be larger than M 6.5**
- **Earthquakes with Slow Rupture Velocities are most efficient Tsunami Generators**
- **75% of earthquake energy is released in the circum-Pacific belt – 900 Tsunamis in 20th Century**
- **20% in the Alpine-Himalayan belt – 6 Tsunamis in 20th Century**
- **Historical Tsunami in India**

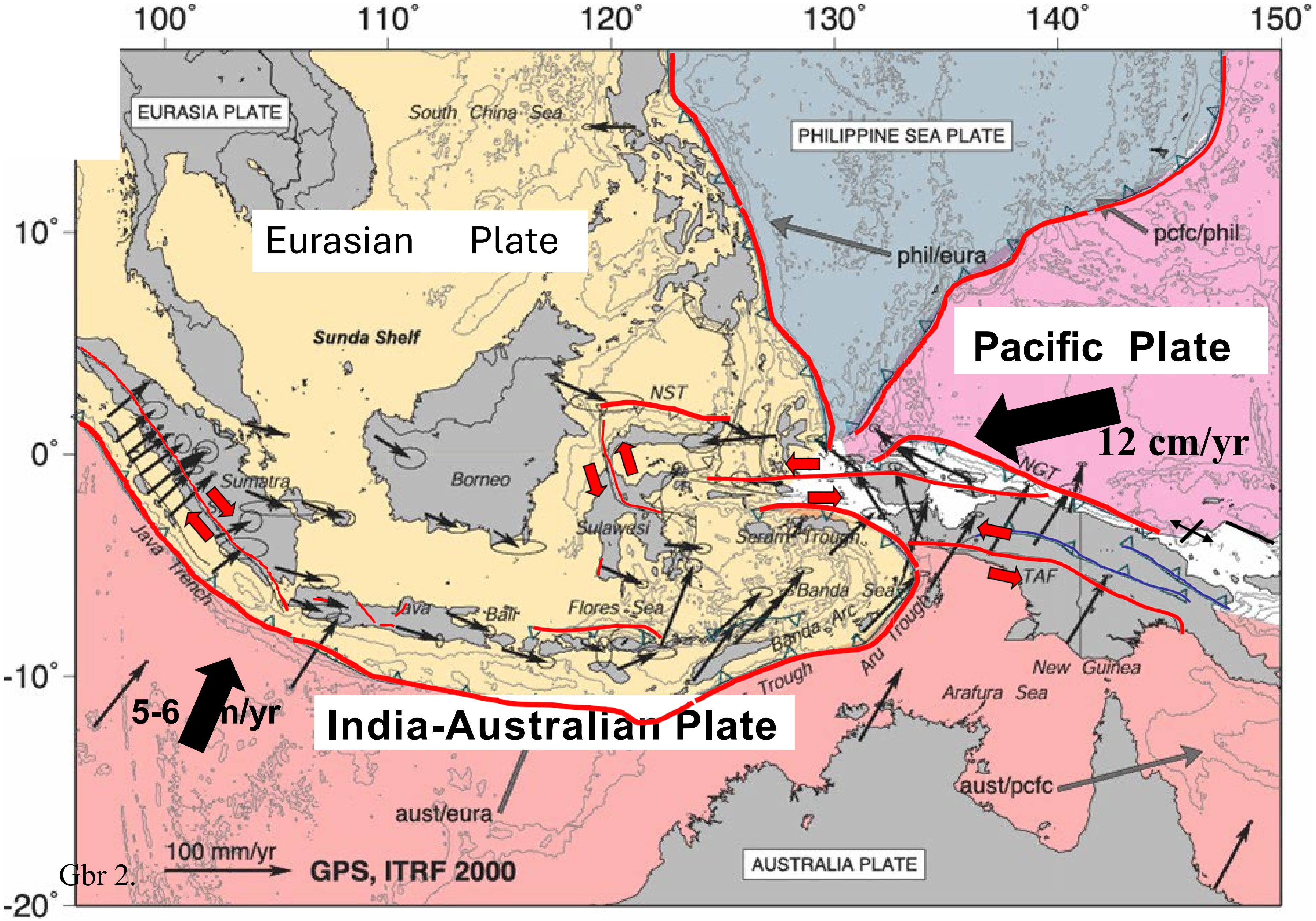
  12 Apr, 1762 (BoB EQ) – 1.8 M
  31 Dec, 1881 (Car Nicobar EQ)
  27 Aug, 1883 (Krakatoa) – 2 M
  26 Jun, 1941 (Andaman EQ)
  27 Nov, 1945 (Makran EQ) – 12 M
  26 Dec, 2004 (Sumatra EQ)

Earthquakes in Sumatra



Satish Singh, 2009

ACTIVE TECTONICS of INDONESIA

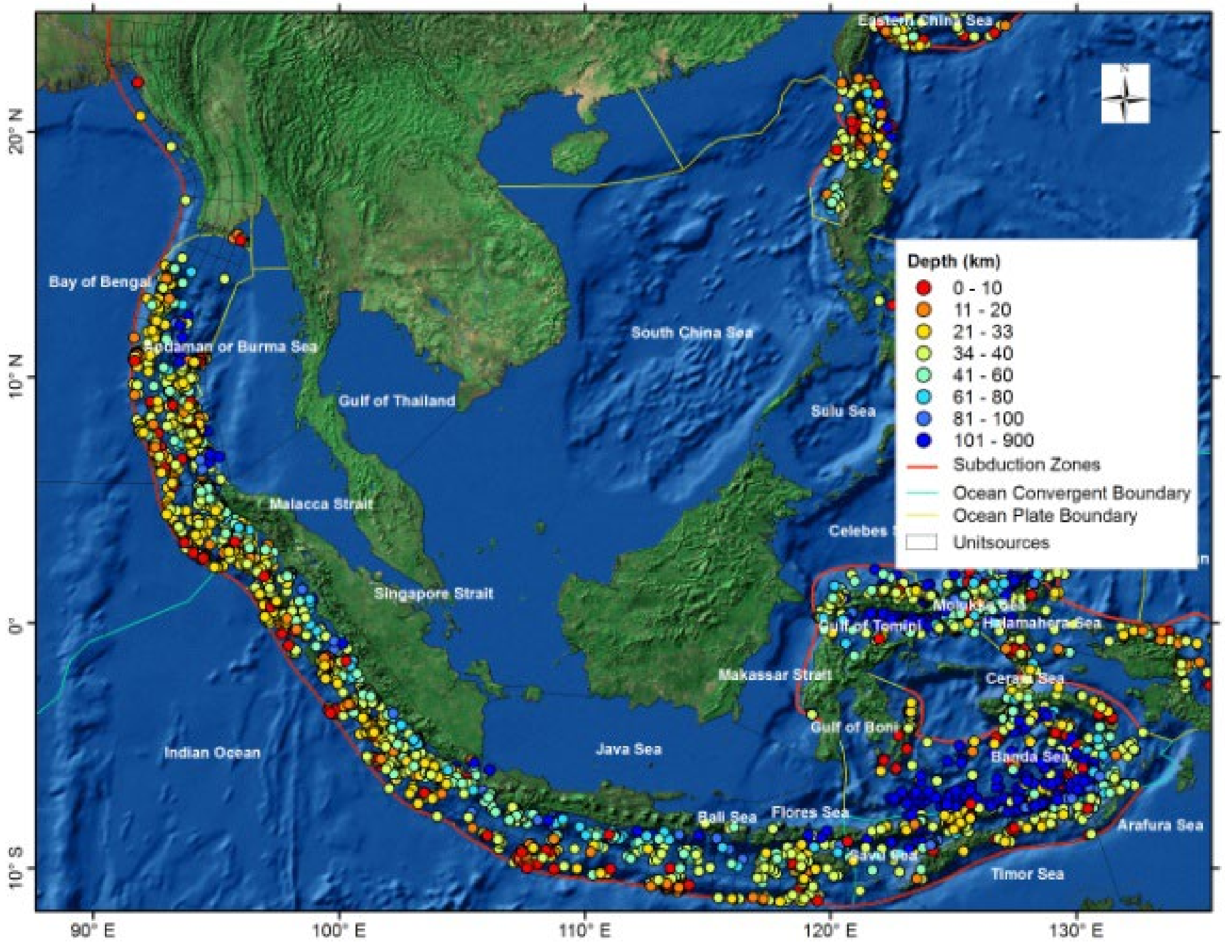


Gbr 2.

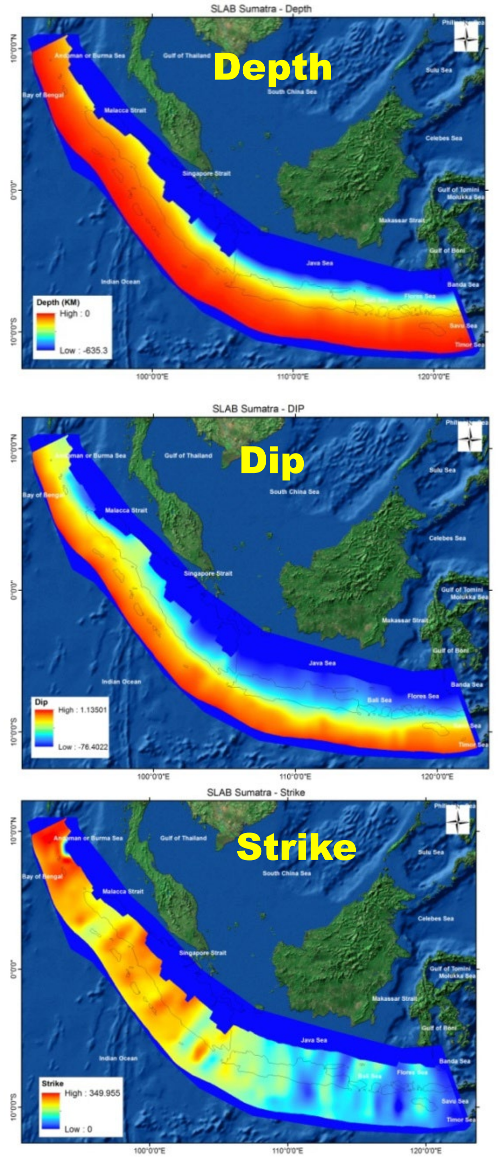
Bock et al, 2004

Courtesy: BMKG

Subduction Zone Geometry

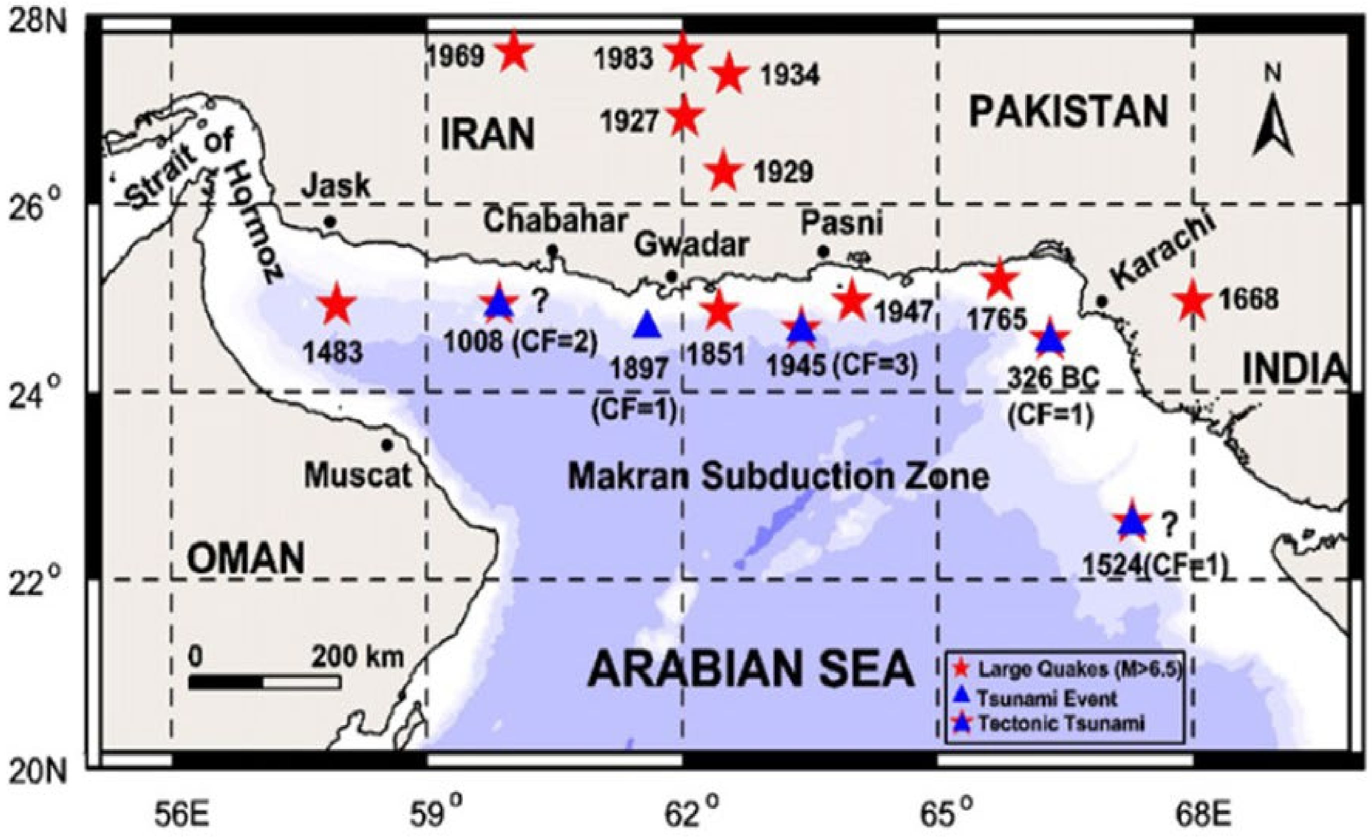


Historical database (HARVARD)



(subduction zone geometry)

Historical Earthquakes in Makran Subduction Zone

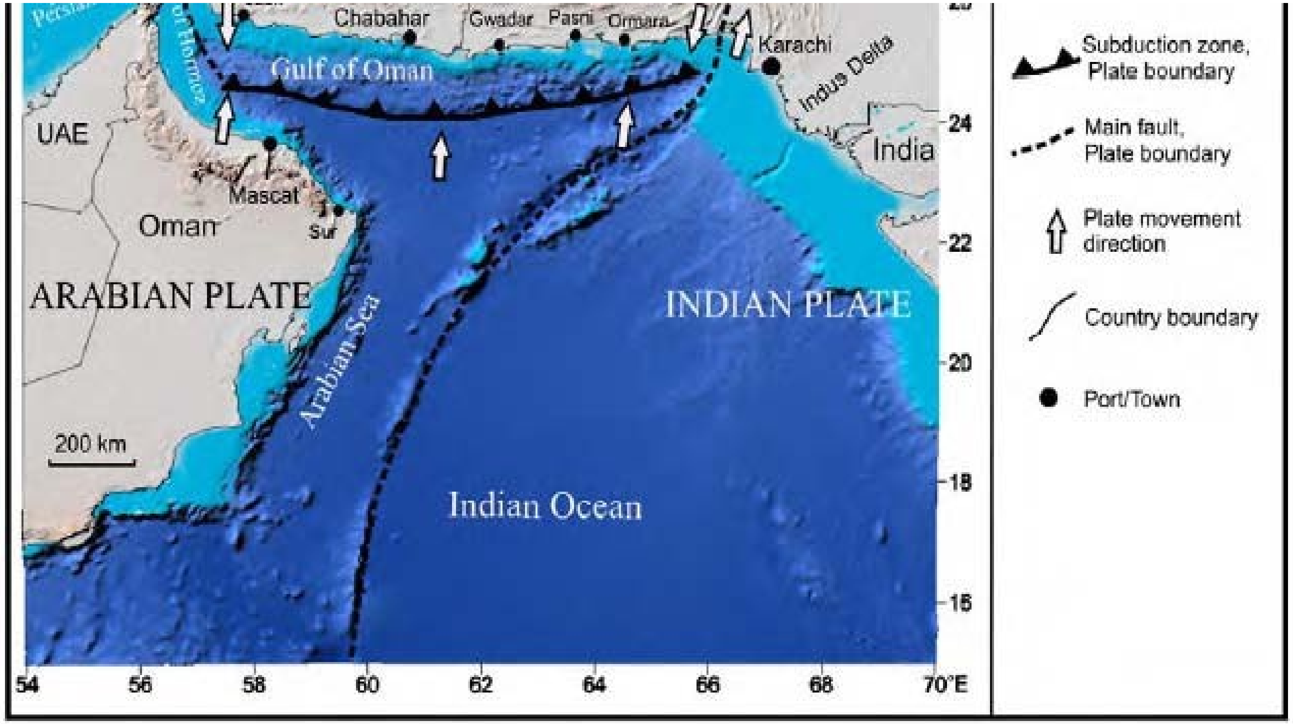


Ref: Mohammad Heidarzadeh et al 2008

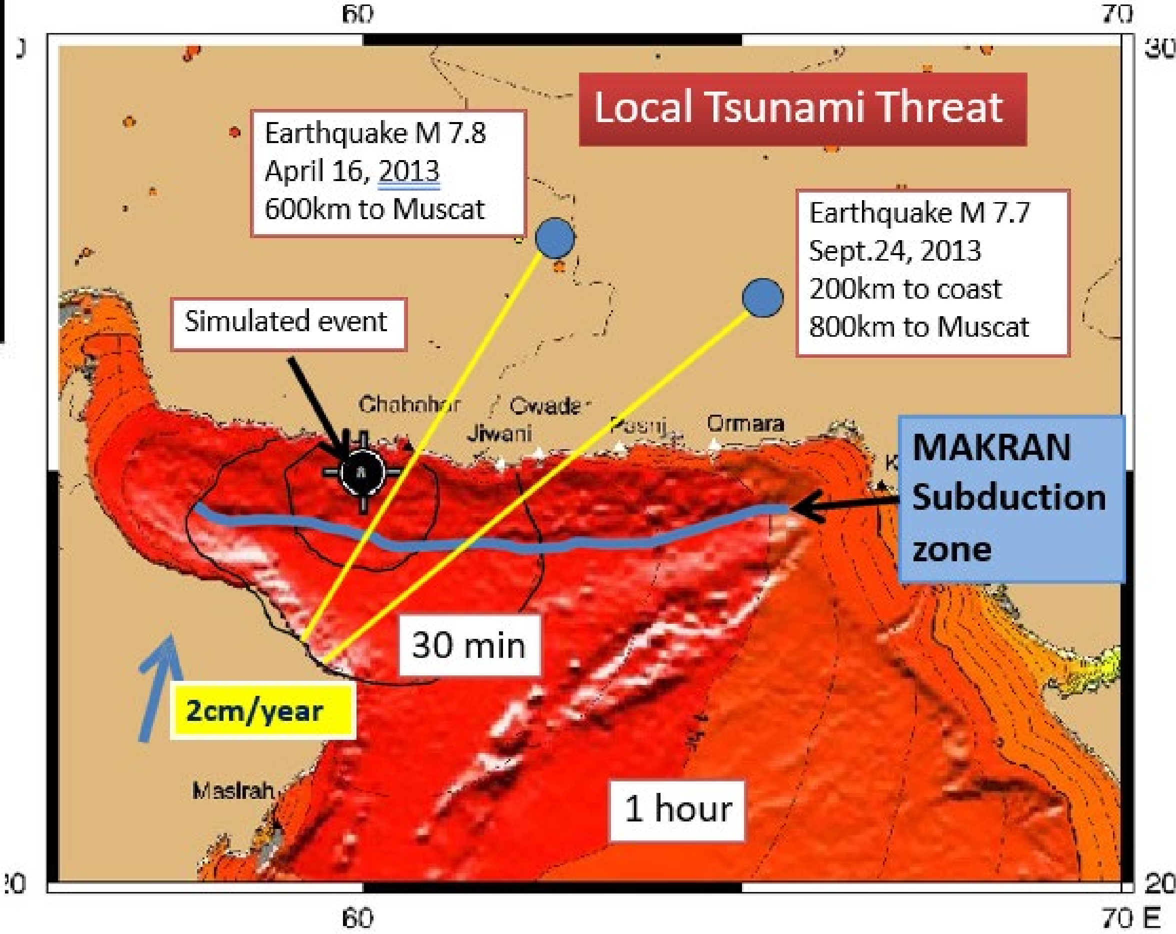
Table 1
List of large earthquakes and tsunamis around the Makran subduction zone as attested in historical records.

Year	Location	Remarks	References
326 BC	Eastern Makran near the Indus Delta	Destruction of a Macedonian fleet in Western India by huge waves is described in Greek and Indian historical records.	Murty and Bapat, 1999; Pararas-Carayannis, 2006b; Rastogi and Jaiswal, 2006.
1008 AD	Western Makran, near the strait of Hormoz	An earthquake and tsunami on the southern coast of Iran.	Ambraseys and Melville, 1982.
1483 AD	Western Makran, near the strait of Hormoz	Destructive earthquake in the strait of Hormoz, northwestern Oman was affected by the earthquake.	Quittmeyer and Jacob, 1979; Ambraseys and Melville, 1982.
1765 AD	Eastern Makran	A strong earthquake in the eastern Makran.	Quittmeyer and Jacob, 1979; Byrne et al., 1992.
1851–1864 AD	Middle part of Makran, Near Gwadar	Two great earthquakes in the middle part of Makran affected the town of Gwadar	Quittmeyer and Jacob, 1979; Byrne et al., 1992.
1945 AD	Offshore Pakistani coast near Pasni	Magnitude 8 to 8.3 tsunami wave run-up was 11 to 13 m in the near coast, claimed about 4000 lives.	Quittmeyer and Jacob, 1979; Ambraseys and Melville, 1982; Pararas-Carayannis, 2006a.

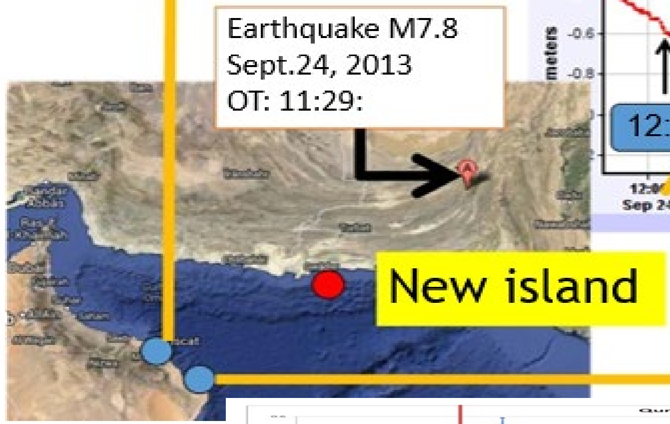
Makran Subduction Zone



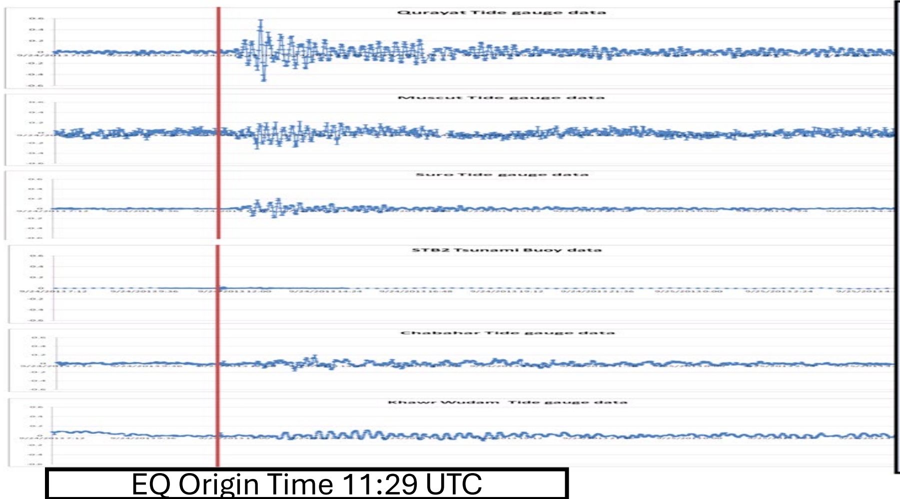
- The convergence between the Eurasian and Arabian plates resulted nearly ~ 900 km – long makran subduction zone.
- This subduction zone has a thick sediment pile estimated ~7km as reported by earlier studies in this region (Kopp et al. 2000; Kukowski et al. 2000).
- The exposure of a sedimentary wedge about 500 km in wide in onshore parts of Pakistan and Iran also reported (Schluter et al. 2002, Kukoeski et al. 2001).
- The offshore Makran accretionary complex with five major structural provinces and elements (Mokhtari M et al. 2008), consists of largely unconsolidated sediments.
- Byrne et al. (1992) showed that a large quantity of unconsolidated sediment does not necessarily indicate a low potential for great thrust earthquakes.



Makran Subduction Zone – Minor tsunami on 24 Sep 2013



Record of the tsunami September 24, 2013.



Qurayat TG – 57 Cm
AT: 12:05 UTC (36 min)

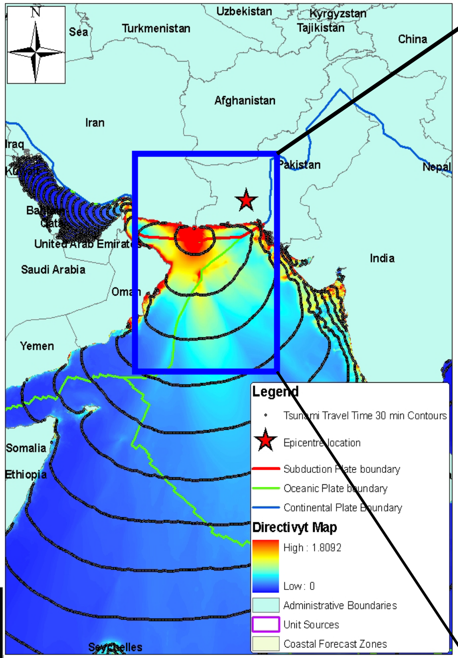
Muscat TG – 31 cm
AT: 12:06 UTC (37 min)

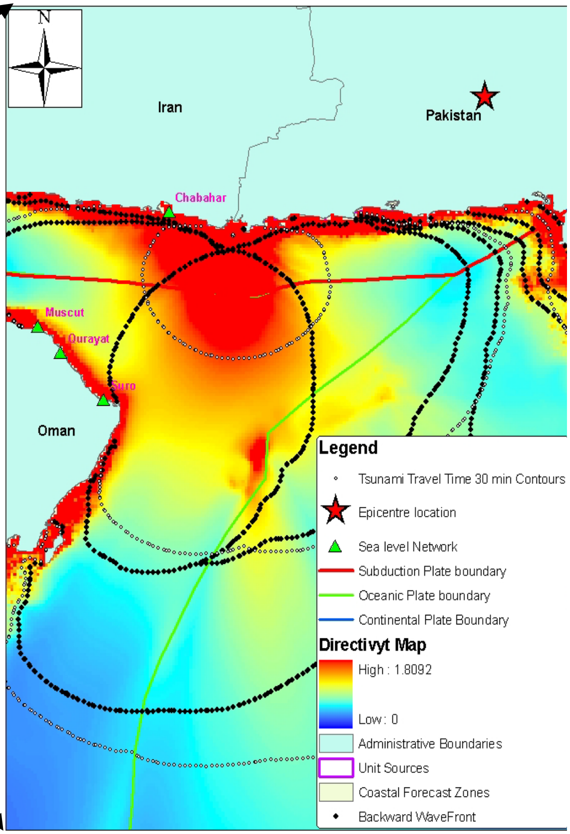
Suro TG – 20 cm
AT: 12:08 UTC (39 min)

STB02 TB – 01 cm
AT: 12:25 UTC (56 Min)

Chabahar TG – 19 cm
AT: 12:40 UTC (71 min)

Wudam TG – 11 cm
AT: 13:14 UTC (105 min)

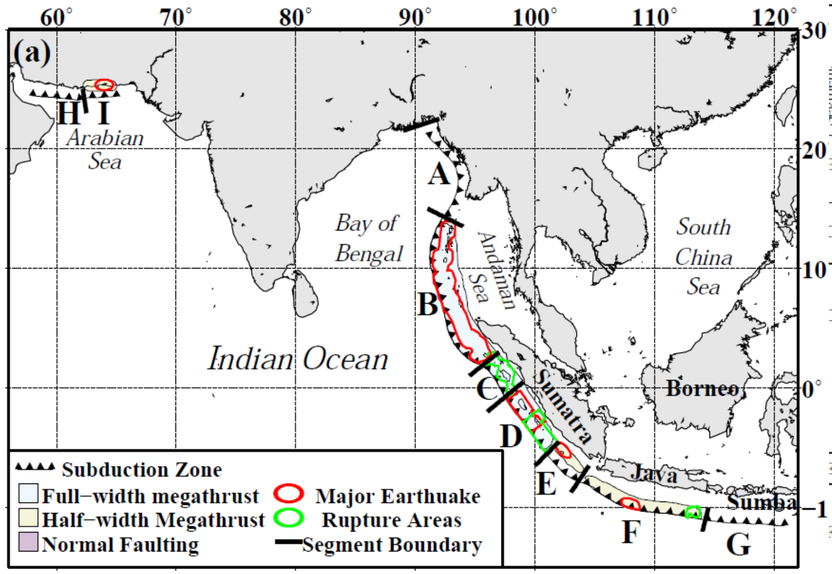




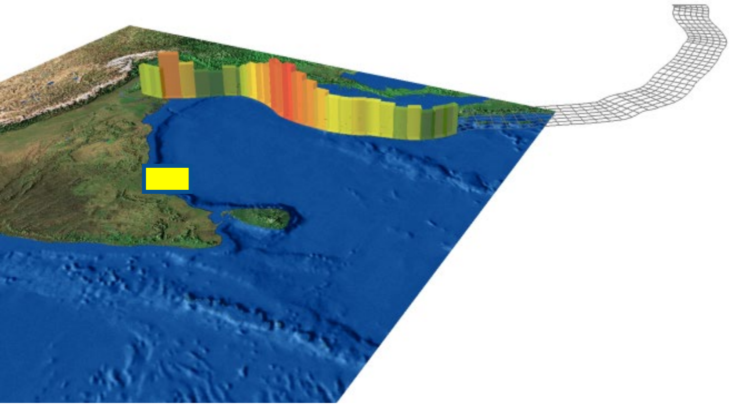
Parameterizing Earthquakes

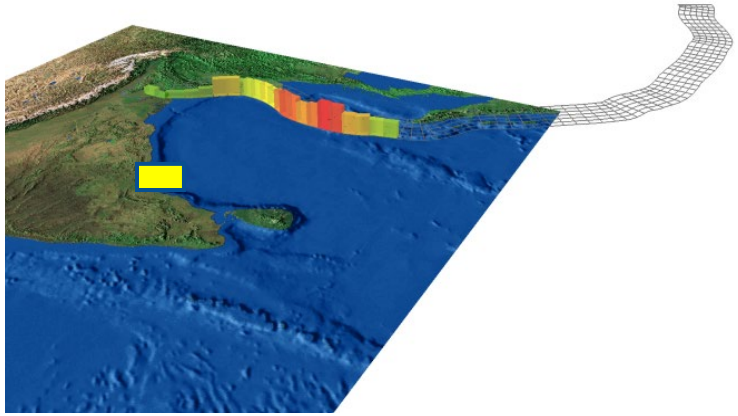
- Determine location and depth of the **epicenter** from arrival times of first seismic wave on nearby stations.
- Estimate the earthquake **moment magnitude** from the amplitude of the first seismic waves on nearby stations (Mwp).
- Compute the location and depth of the **centroid** of the earthquake along with a focal mechanism (**strike, dip, rake, slip**) and a moment magnitude with a W-phase Centroid Moment Tensor analysis.
- Estimate the **rupture area** along with the spatial distribution and timing of **slip** along the fault using a finite fault analysis

Selection of Extreme events Location



Segment	Magnitude	Completeness Interval (years)	No. Earthquakes	Recurrence Interval	Historical Events	References
B	8.0	200	3	67	1881[1],1941[1],2004[1]	Ortiz and Bilham (2003)
	9.0	600	3	300	1400[2],2004[1]	Moneke *et al.* (2009), Jankaew *et al.* (2009)
C	8.0	250	4	62	1843[3],1861[3],1907[3],2005[1]	Newcomb & McCann (1987), Briggs *et al* (2005)
	8.5	250	2	125	1861,2005	
D	7.5	250	6	42	1770[3],1797[4],1818[3],1833[4], 2007a[1],2007b[1]	Newcomb & McCann (1987), Natawidjaja *et al* (2006)
	8.5	250	3	83	1797[4],1833[4],2007a[1]	
	8.5	650	7	93	1350[2],1380[2],1606[2],1685[2] 1797[4],1833[4],2007a[1]	Sieh *et al.* (2008)
E	7.5	250	1	>250	2000[1]	Abercrombie *et al.* (2003)
F	7.5	250	6	42	1840[3],1859[3],1921[3], 1994[1],2006[1]	Newcomb & McCann (1987), Abercrombie *et al* (2001), Ammon *et al* (2007)
	8.0	250	2	125	1994[1],2006[1]	
I	8.0	250	≤3	≥83	1765[3],1851[3],1945[1]	Byrne *et al.* (1992)

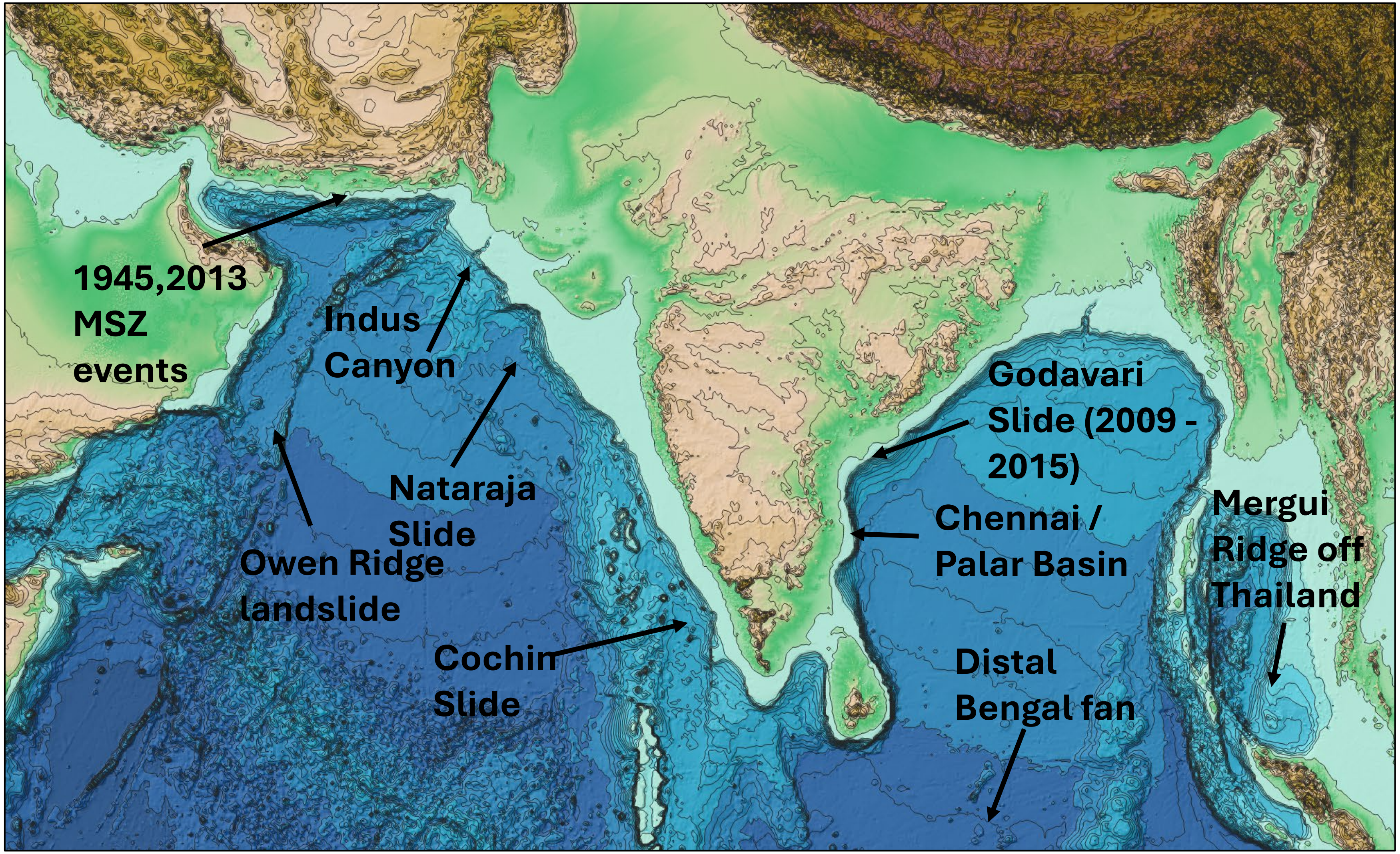




- Careful consideration is to be given to the subduction zone geometry as well as return periods of extreme events while finalizing fault parameters for the "extreme event" to be considered.
- Based on available literature (Moneke et al. (2008), Jankaew et al. (2008), the recurrence interval for M 8.0 event in the A&N subduction zone is 67 years while the recurrence interval for a M 9.0 event is 300 years (as shown in Table).
- The selection of "extreme event" needs careful consideration.

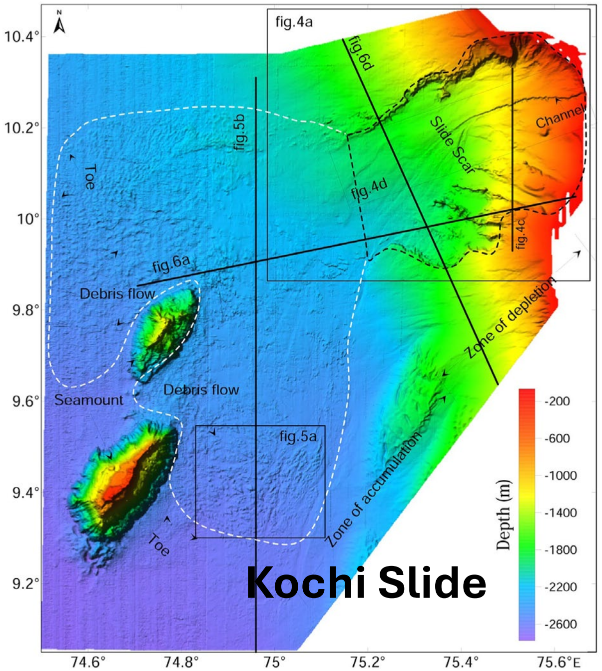
Submarine landslide and generated tsunamis around India

- Nearshore sources that have short travel time
- Impact on life, submarine and offshore infrastructure
- Some evidence but not a lot of direct data to build on
- Need to adopt datasets and assumptions from other regions
- Compliment with numerical modelling of landslide + tsunami

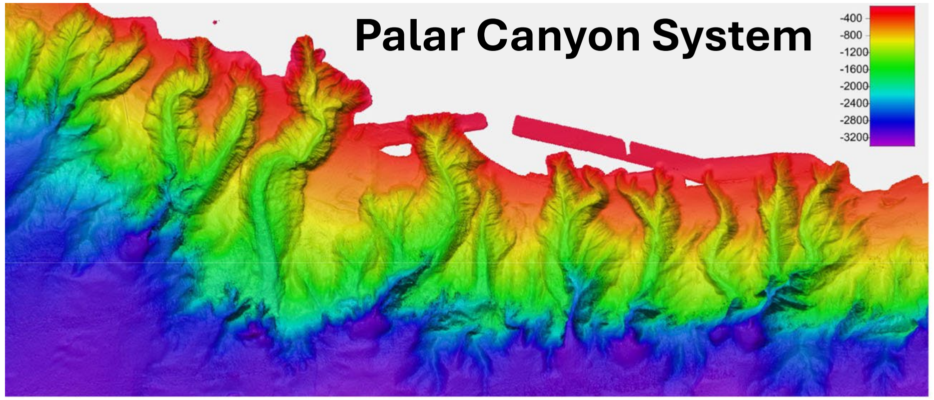


Courtesy: PCTWIN Project: Naveen

Inventory of past events/potential sites



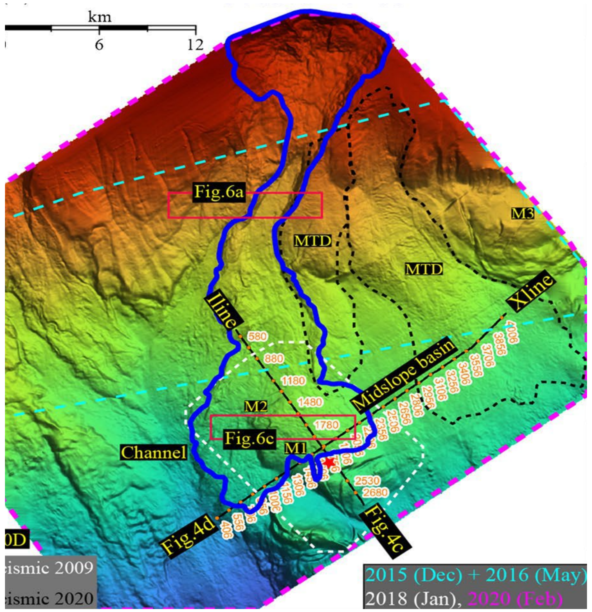
Large-scale submarine landslide in the **Cochin** offshore region, southwestern continental margin of India: a preliminary geophysical understanding (Bijesh et al 2023)

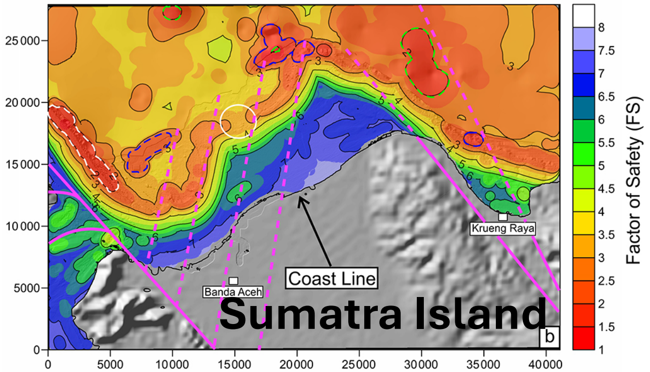


Controls on the evolution of submarine canyons in steep continental slopes: geomorphological insights from **Palar Basin,** southeastern margin of India (Sushanth et al 2021)

A recent catastrophic submarine slope failure in the Krishna-**Godavari** basin, Bay of Bengal, India (Dewangan et al 2025)

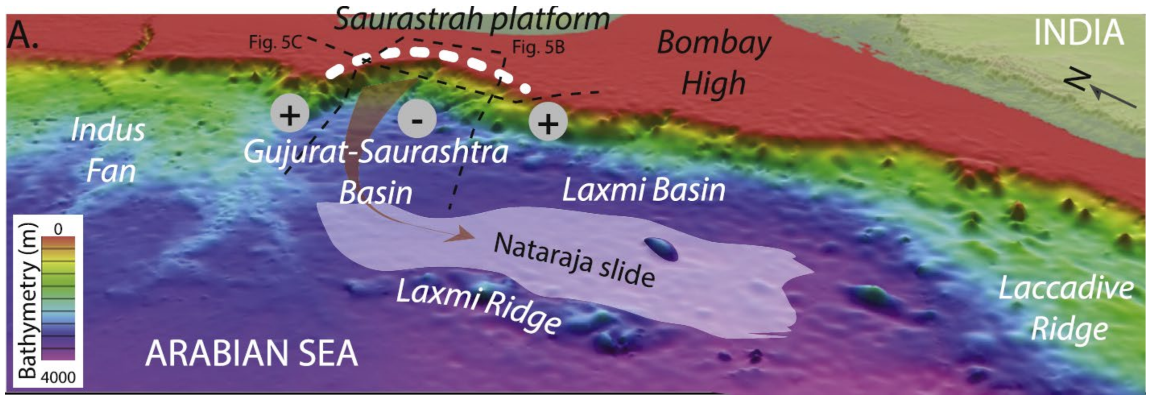
Godavari Slide





Tsunami scenario triggered by a submarine landslide offshore of **northern Sumatra** Island and its hazard assem. (Haridhi et al 2023)

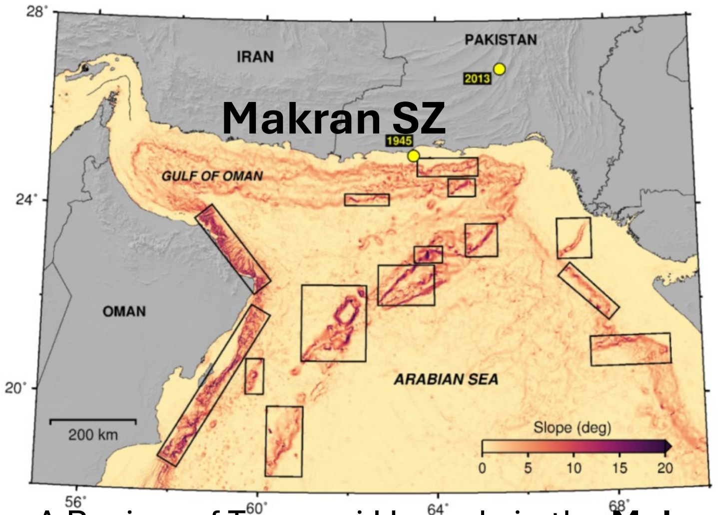
Natraj Slide



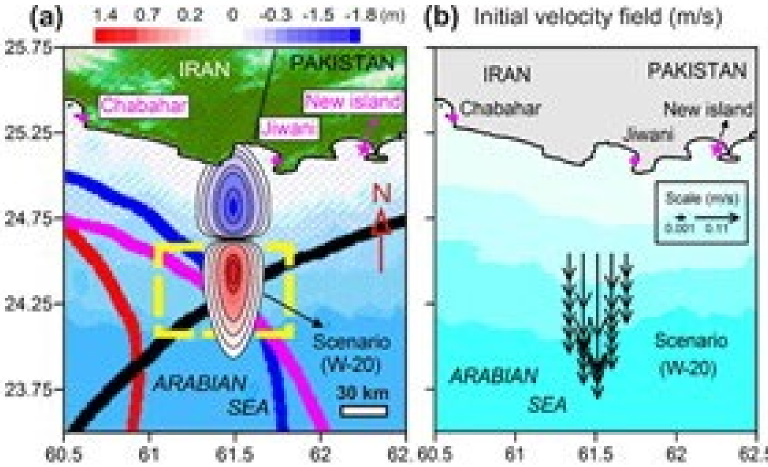
Giant fossil mass wasting off the coast of West India: The **Nataraja** submarine slide (Calves et al 2015)

Courtesy: PCTWIN Project: Naveen

Inventory of past events/potential sites



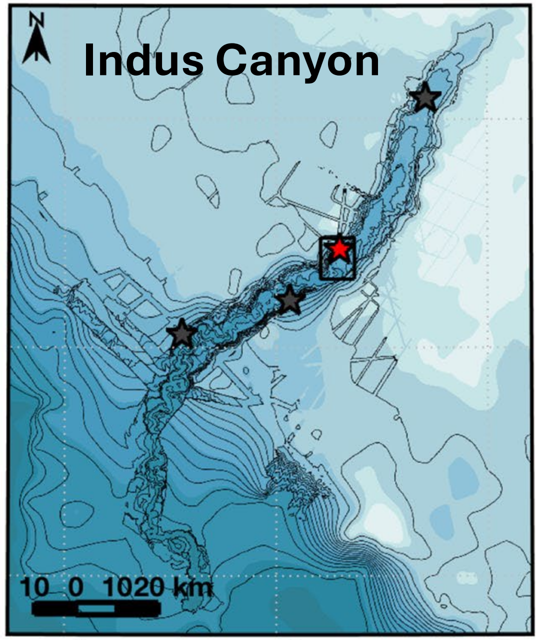
A Review of Tsunami Hazards in the **Makran Subduction Zone** (Rashidi et al 2020)



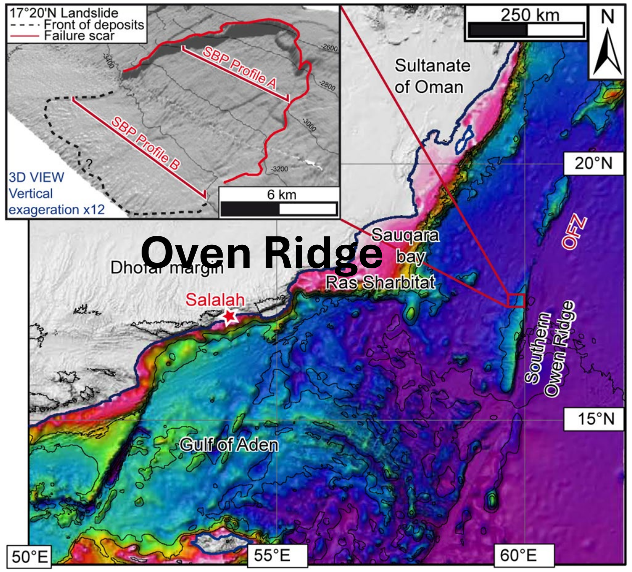
2013 Tsunami MSZ

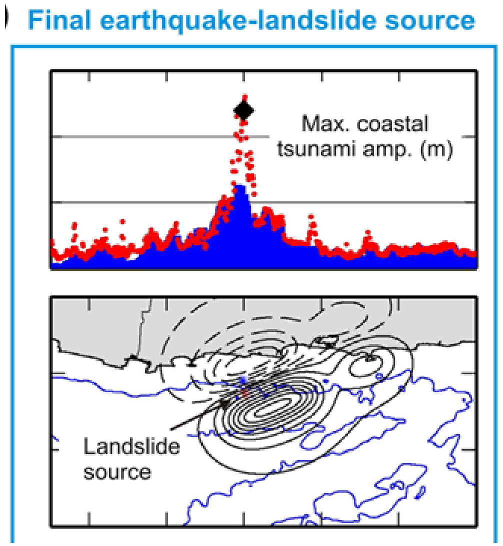
Possible sources of the tsunami observed in the northwestern Indian Ocean following the 2013 September 24 Mw 7.7 Pakistan inland earthquake (Heidarzadeh et al 2014)

Probabilistic Landslide-Generated Tsunamis in the **Indus Canyon**, NW Indian Ocean, Using Statistical Emulation (Salmanidou et al 2019)

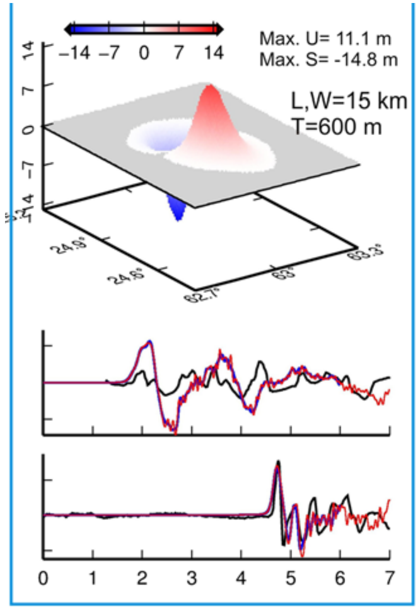


Owen Ridge deep-water submarine landslides: implications for tsunami hazard along the Oman coast (Rodriguez et al 2013)





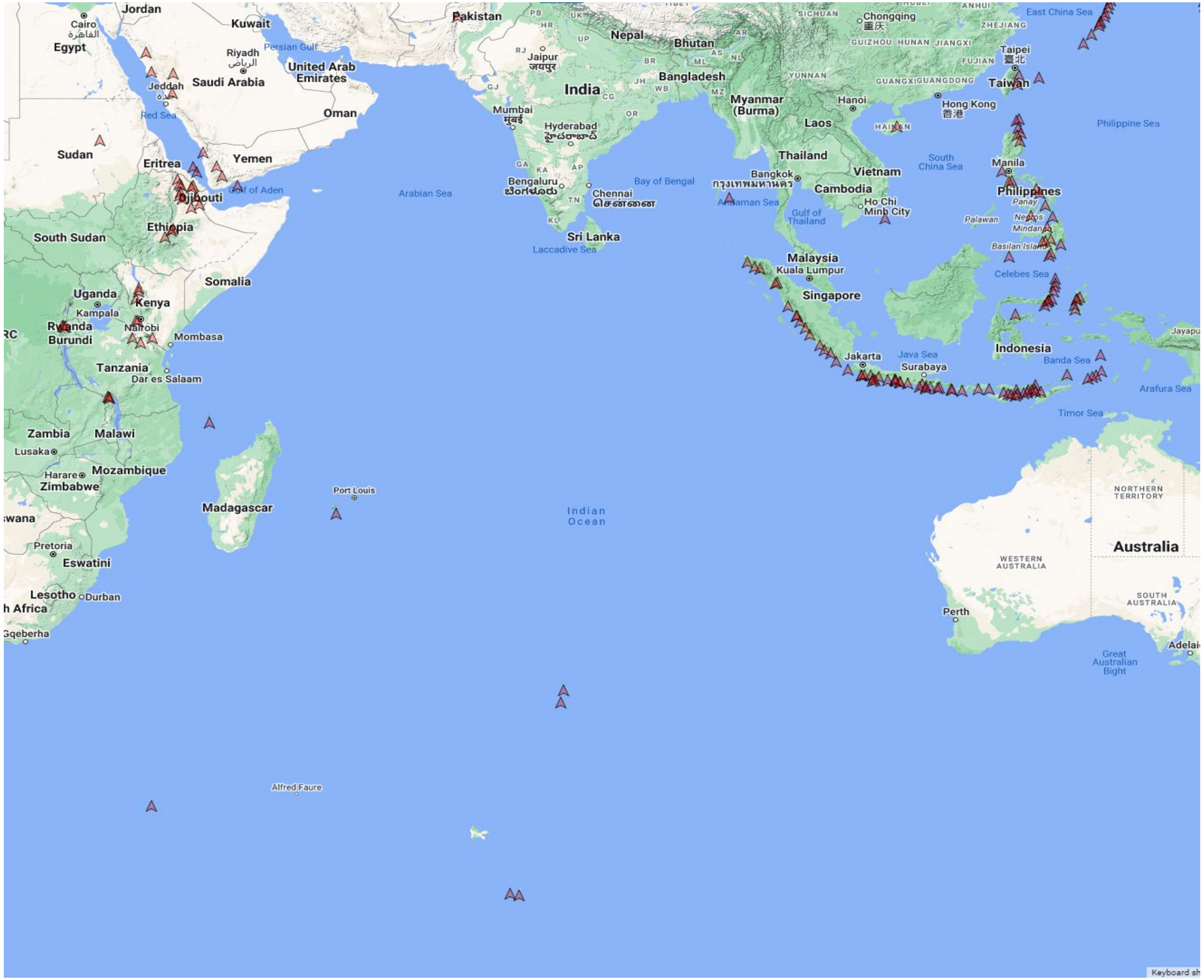
1945 Tsunami



Combined Earthquake–Landslide Source Model for the Tsunami from the 27 November 1945 Mw 8.1 Makran Earthquake (Heidarzadeh et al 2017)

Courtesy: PCTWIN Project: Naveen

Tsunamis Generated by Volcanoes



- About 1350 volcanoes are considered active in the past 12,000 years worldwide
- About 50–85 erupting volcanoes each year
- About 70 in the Indian Ocean

Monitoring Tsunamis Generated by Volcanoes

Volcanoes in the Indian Ocean

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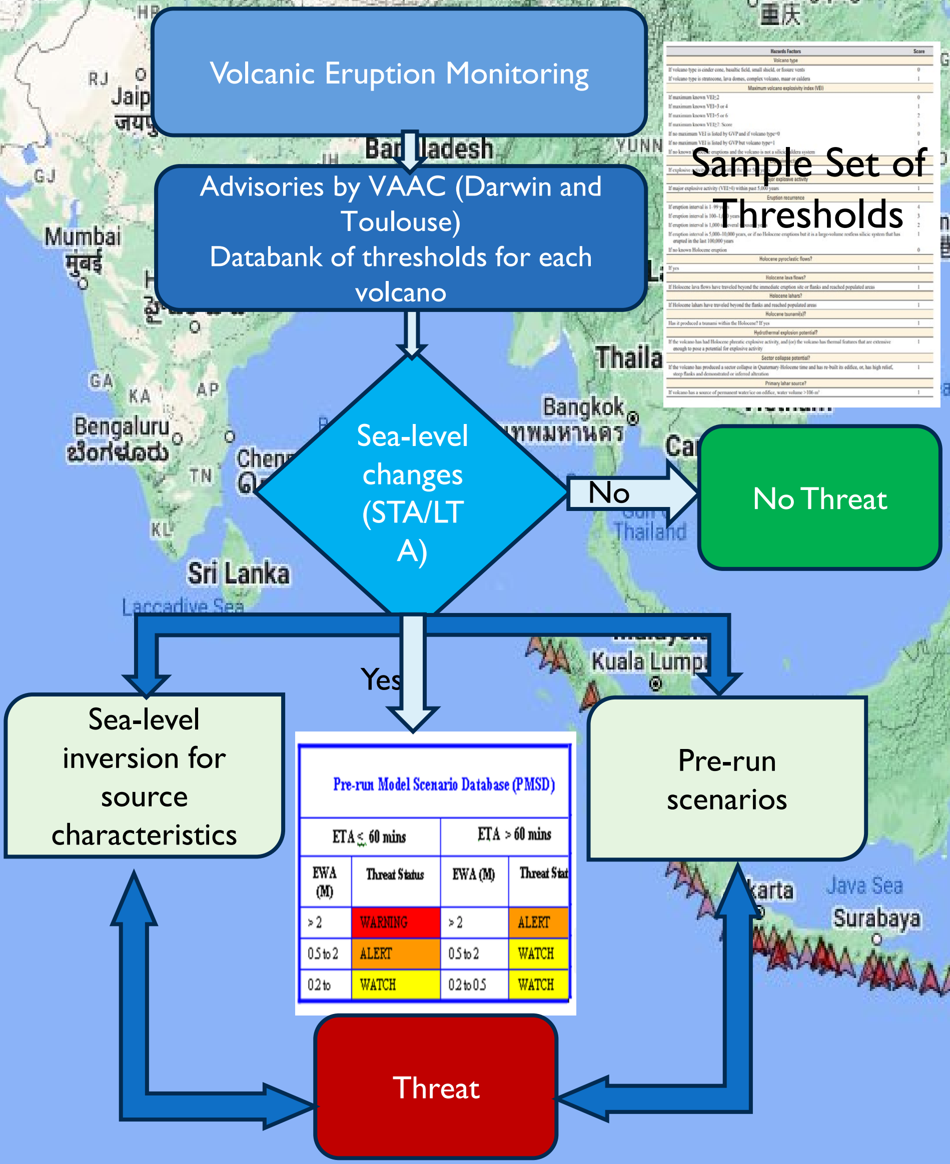

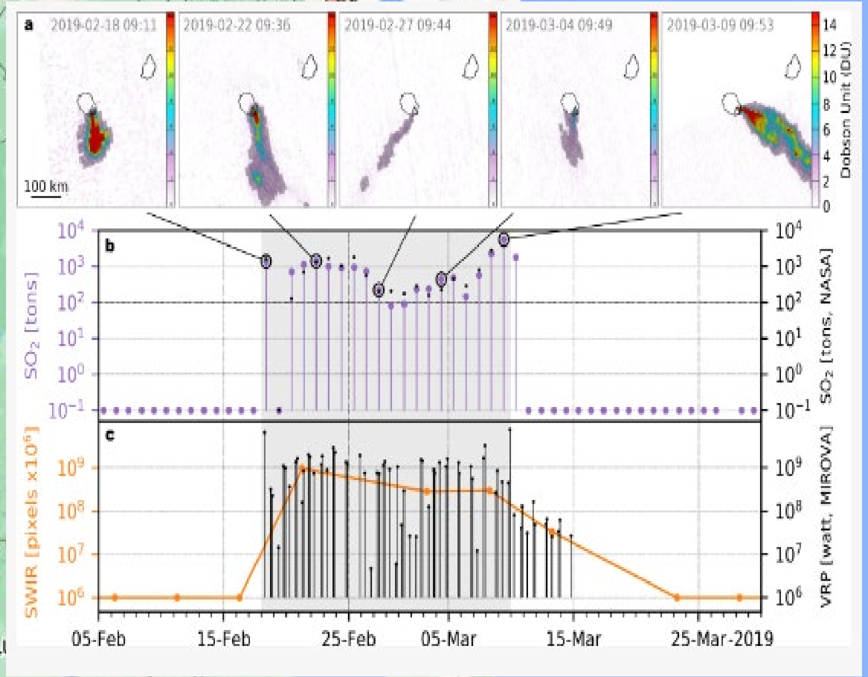

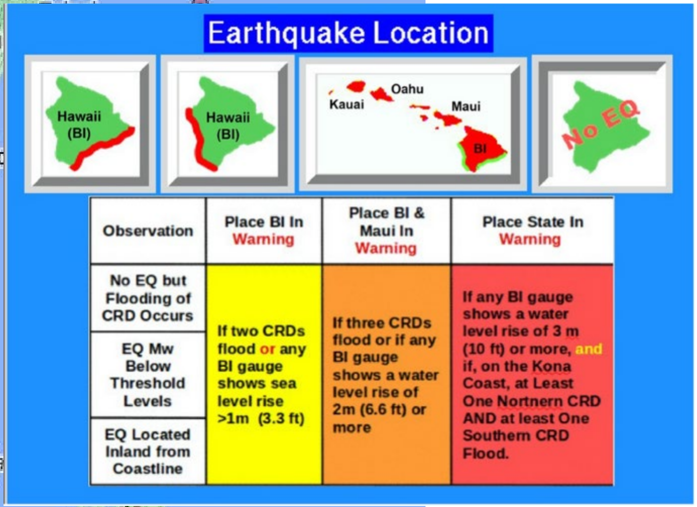

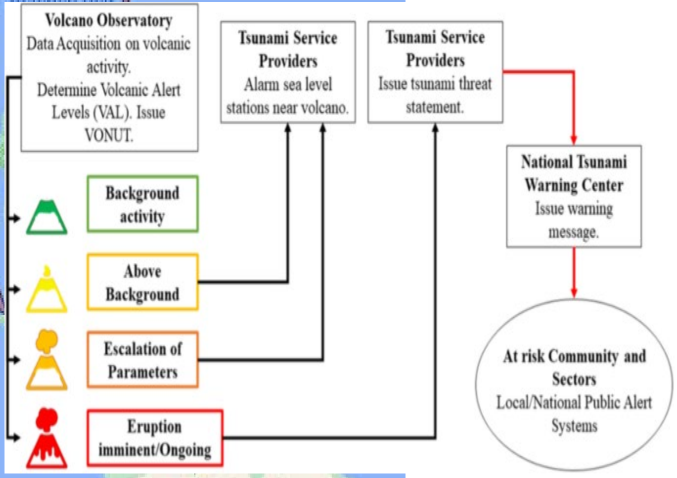

Thank You !

TEMPP 2025

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