

Source region of the 2004 Indian Ocean Tsunami: The northern extent

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Tsunami & Non-linear Waves, SINP, Kolkata, March 2006

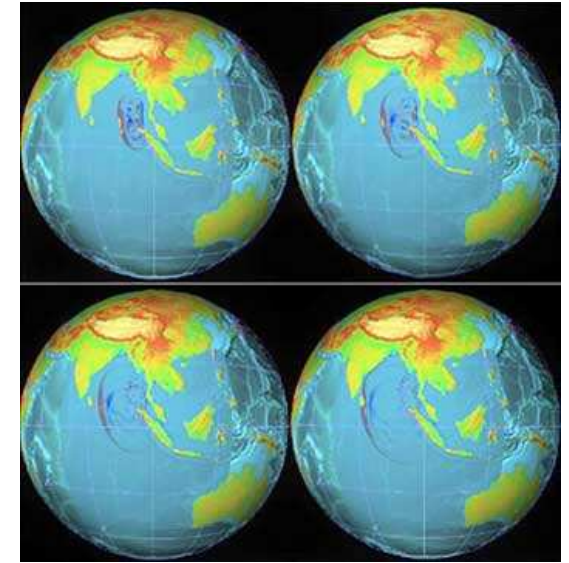
Collaborators

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Dona Paula, Goa.)

and

B. Nagarajan,
(Geodetic and Research Branch,
Survey of India, Dehradun.)

26th December 2004



Earthquake at \sim 06:30 IST
Tsunami hit the Coramandel coast at \sim 09:00 IST

Where did the ocean bed move ?

Where did the ocean surface respond ?

The Earthquake

Lay et. al. Science 308, 1127 (2005).

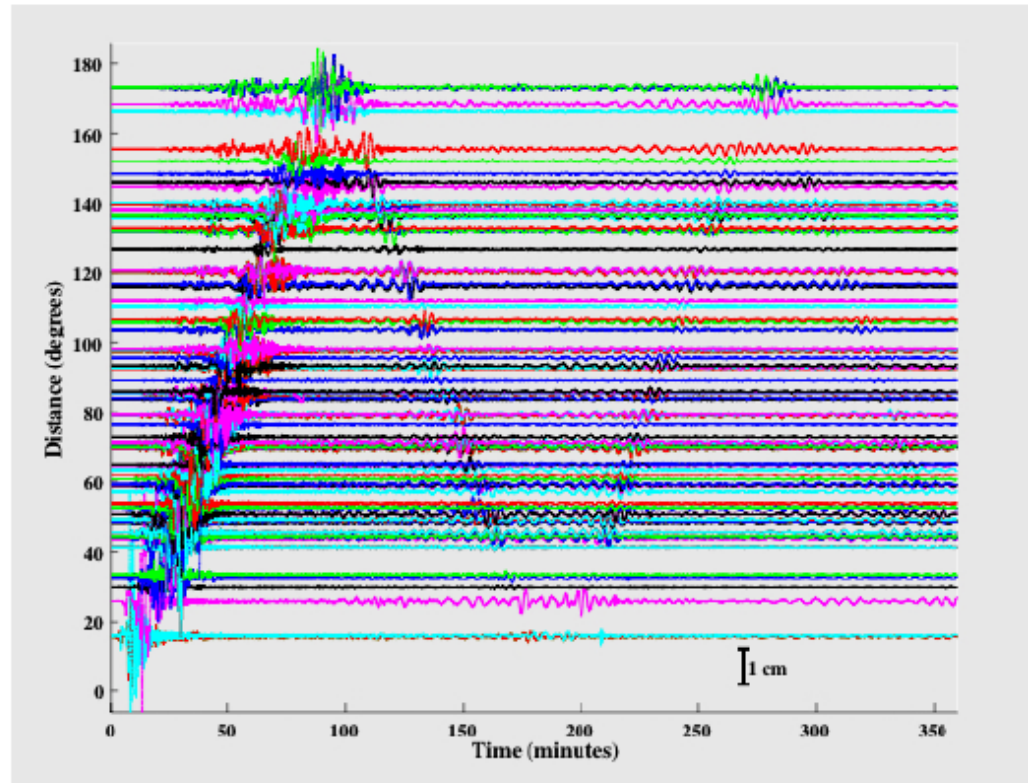
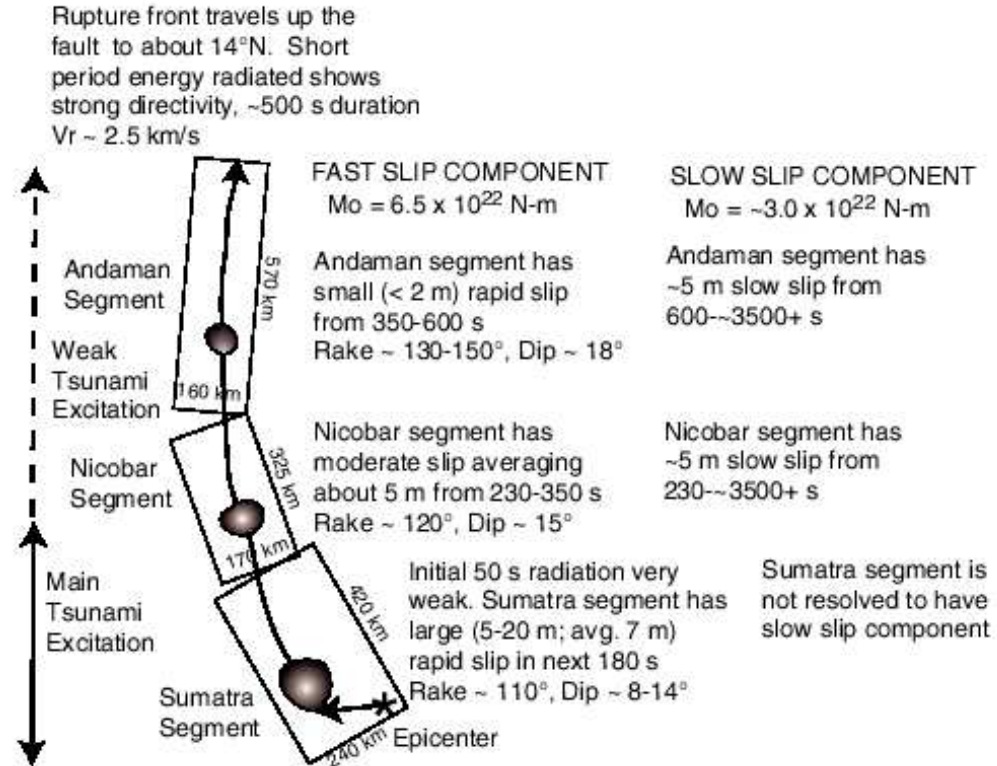


Fig. S4. Global vertical-component displacement records for the Sumatra-Andaman earthquake high-pass filtered at 120 s. The seismograms shown are from 109 Global Seismic Network (GSN) stations and were retrieved from the IRIS DMC. The time interval of 6 hours shows two global circuits of the Rayleigh waves. Note that displacements exceeded 1 cm worldwide.

The rupture process

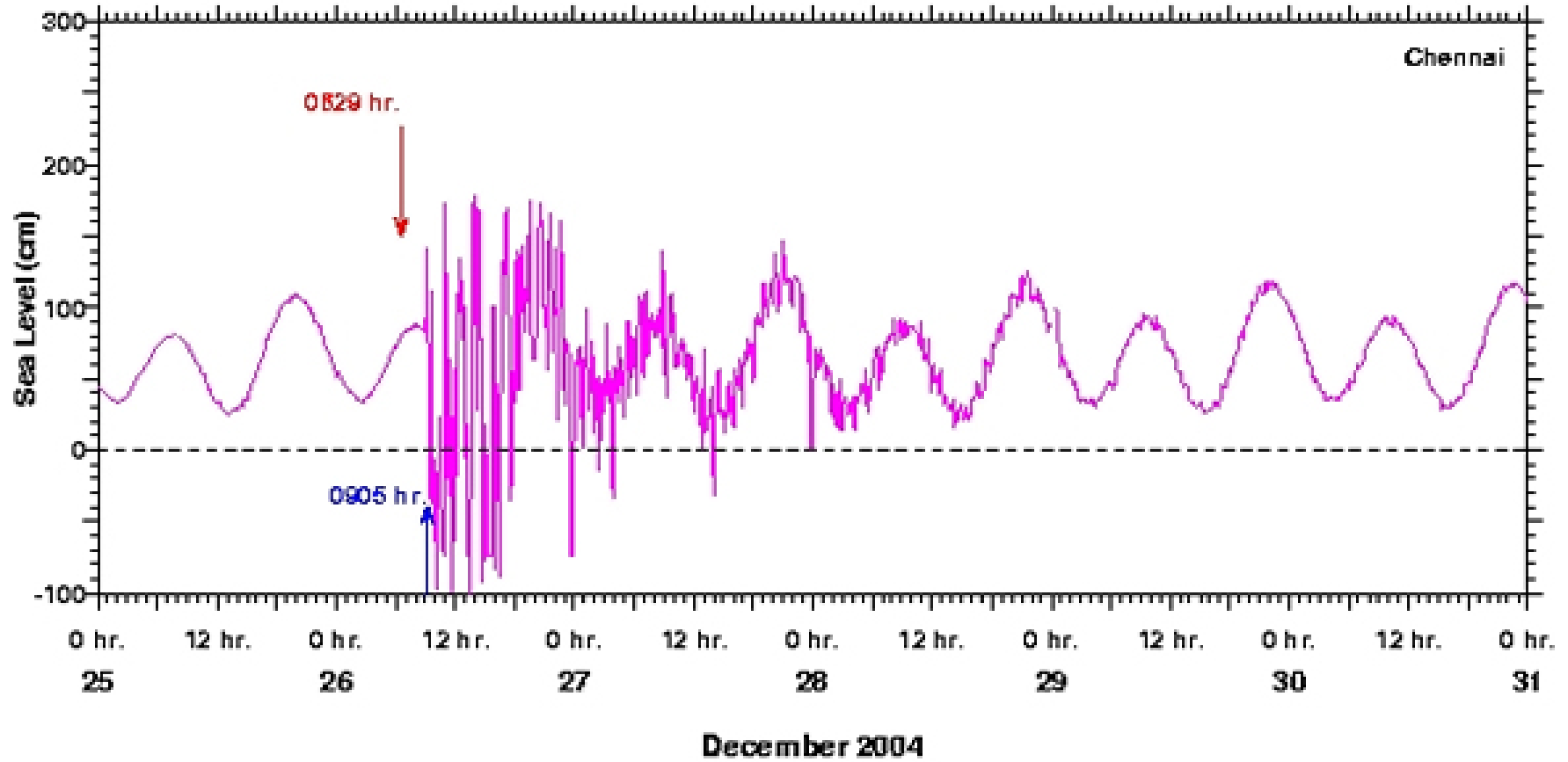
Lay et. al. Science 308, 1127 (2005).

Fig. 8. Summary rupture scenario for the 2004 Sumatra-Andaman earthquake. We subdivide the rupture zone into three segments according to the inferred rupture process, not because of clear physical fault segmentation. The rupture begins at the southeastern edge of the Sumatra segment, with the initial 50 s of rupture characterized by fairly low energy release and slow rupture velocity. The rupture front then expands to the north-northwest at about 2.5 km/s, extending about 1300 km. Short-period radiation tracks the rupture front, with a total duration of about 500 s and clear north-northwest directivity.



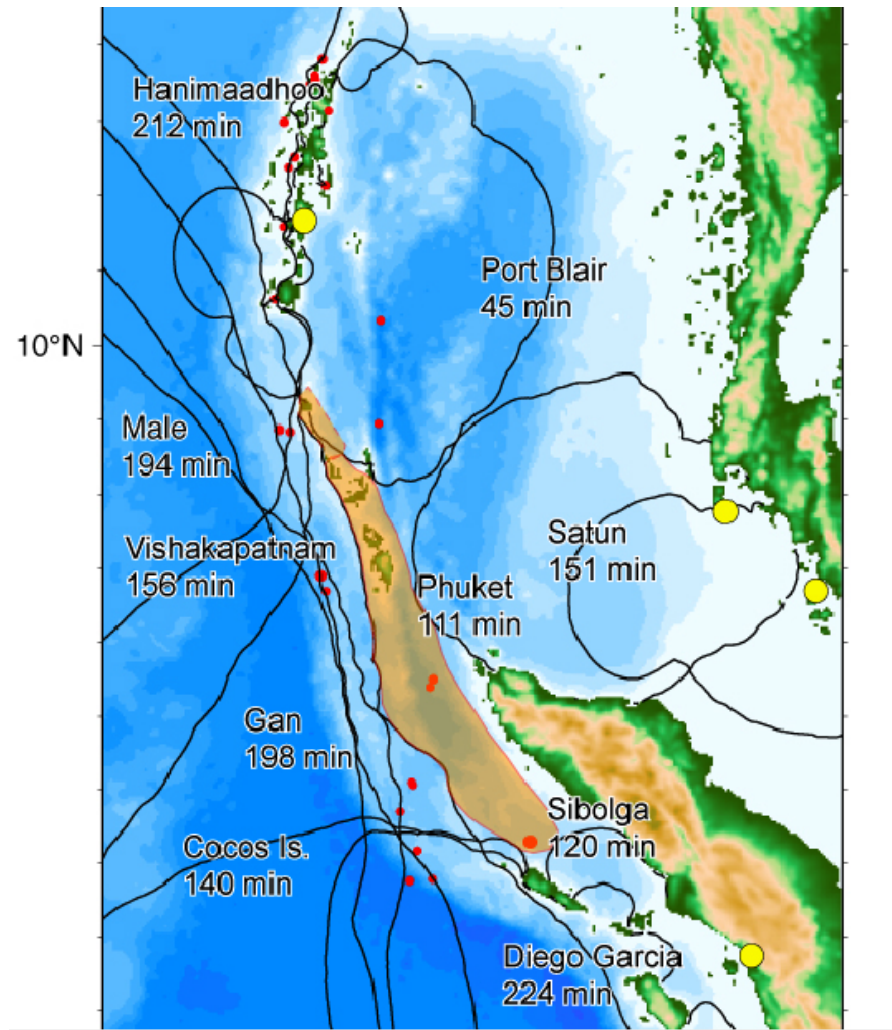
Large, rapid slip occurs in the Sumatra segment, with some patches having slip as great as 20 m during the first 230 s. The Nicobar segment has weaker slip during the next 2 min, and the Andaman segment fails with little (<2 m) rapid slip. Slow slip appears to continue in the Nicobar and Andaman segments, with a total duration of about 1 hour. The precise amount of slip and total moment of the slow-slip component are not well resolved, but about 10 m of slip under the Andaman Islands is required to account for the tilt experienced by the islands.

The Tsunami



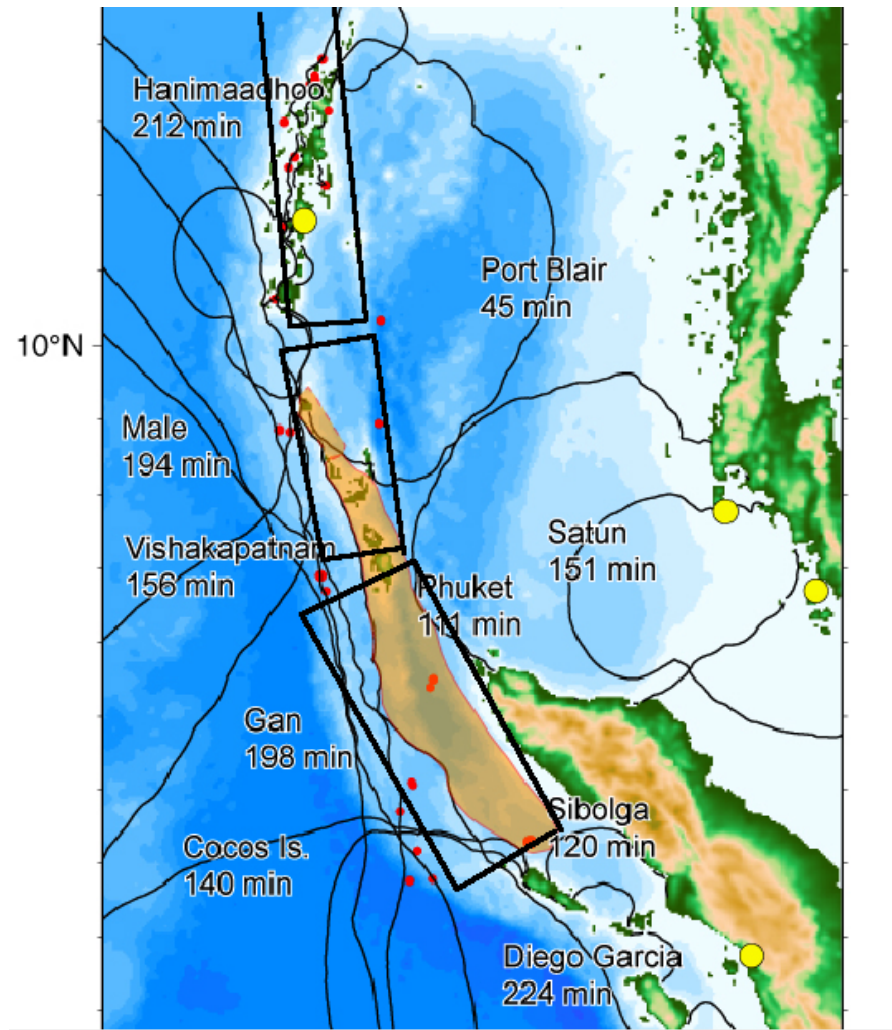
The Tsunami source

Lay et. al. Science 308, 1127 (2005).



The Tsunami source

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The Equations of Hydrodynamics

The dynamical variables:

$\rho(\vec{x}, t)$ - fluid density

$\vec{v}(\vec{x}, t)$ - fluid velocity

Continuity equation

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

The Navier-Stokes Equation

$$\rho \left(\partial_t \vec{v} + (\vec{v} \cdot \vec{\nabla}) \vec{v} \right) = -\vec{\nabla} P - \rho g \hat{z} + \eta \nabla^2 \vec{v} + \left(\zeta + \frac{1}{3} \eta \right) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$$

The Approximations

If wavelengths are much larger than the depth, $kh \ll 1$
Navier-Stokes equations \approx Shallow water equations

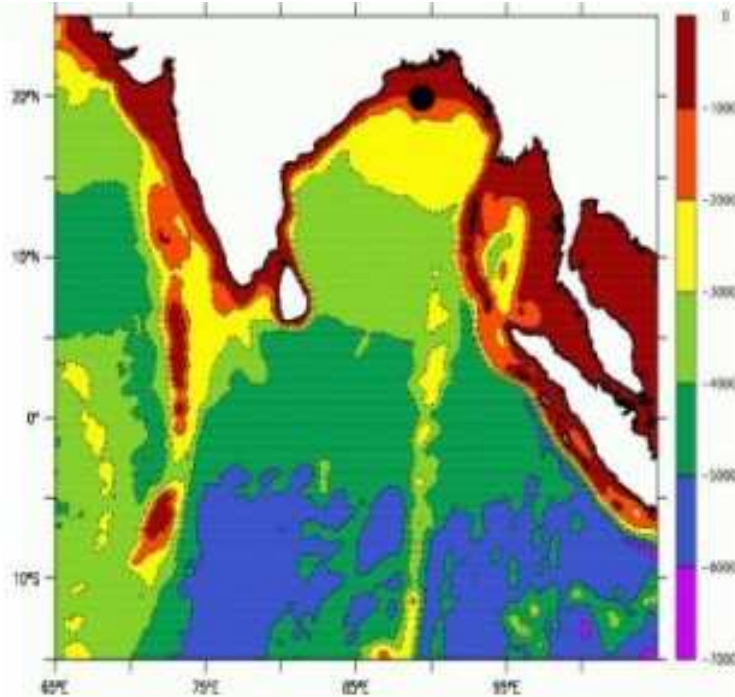
If the amplitude is much less than the depth, $A/h \ll 1$,
Shallow water equations \approx Linear wave equation

$$(\partial_t^2 - \partial_i(c^2)\partial_i) \zeta = 0$$

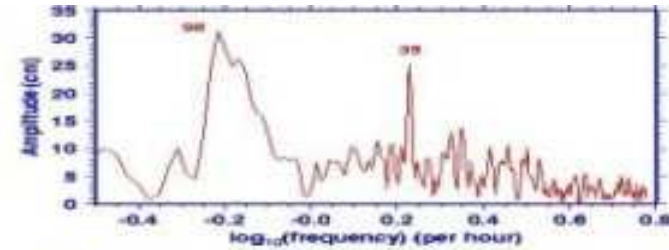
$\zeta(\vec{x}, t) + h(\vec{x}) =$ height of water column above ocean bed

$$c(x, y) = \sqrt{gh(x, y)}$$

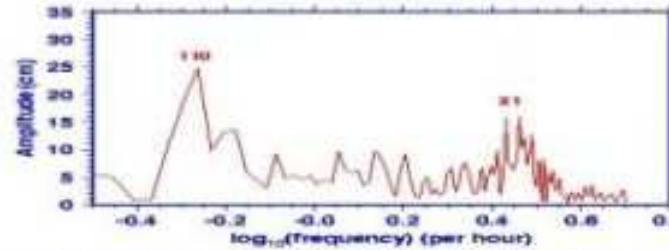
The Regime of Validity



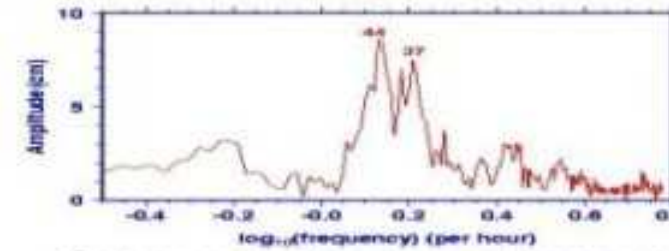
$$kh \sim 0.1 - 0.01$$



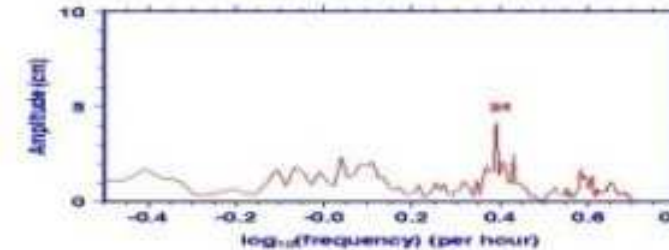
Chennai



Paradip



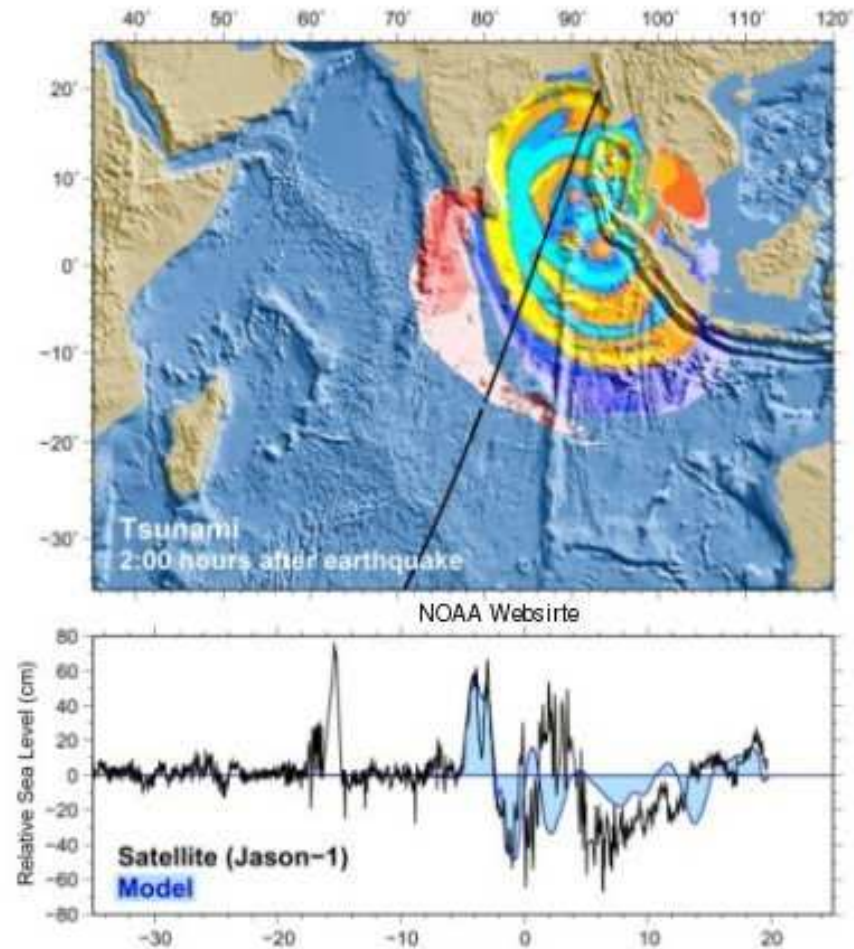
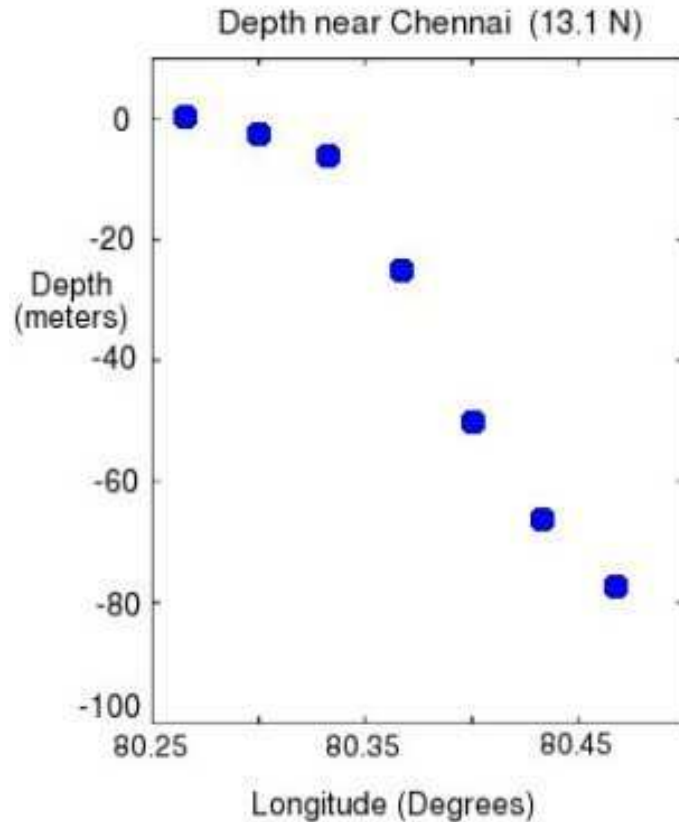
Male



Diego Garcia

B. Nagarajan et. al. *Earth Planets Space*, **58**, 211–215, 2006

The Regime of Validity



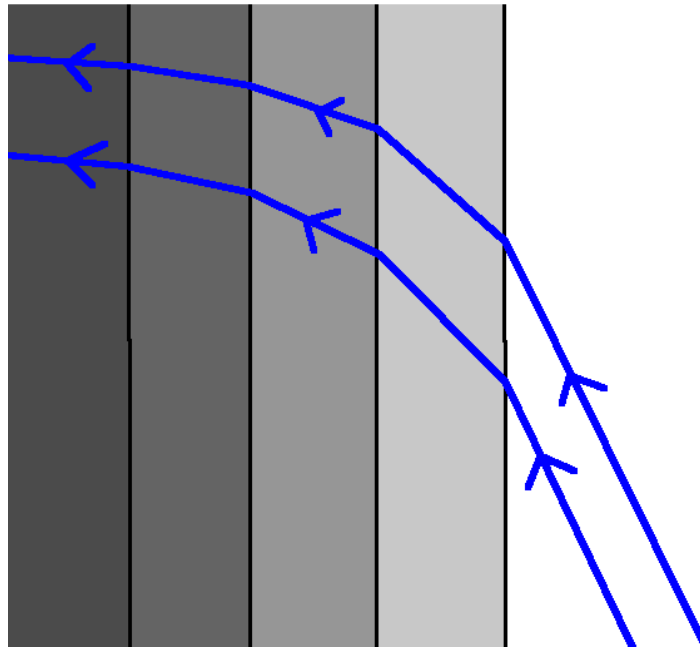
This tsunami was a linear wave with non-linear edges

Ray Optics

If depth varies slowly compared to wavelength (not true for the tsunami), waves propagation is described by rays.

Rays can be traced using Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$



The Ray Equation

For continuously varying refractive index,

$$\frac{dx_R}{dt} = c \cos\chi$$

$$\frac{dy_R}{dt} = c \sin\chi$$

$$\frac{d\chi}{dt} = -\sin\chi \frac{\partial c}{\partial x} + \cos\chi \frac{\partial c}{\partial y}$$

- Solutions can be used to describe the propagation of the leading wavefront.
- Rays give travel times accurately but contain no information about the amplitudes

Smoothing the bathymetry

The tsunami will not see depth fluctuations on a length scale small compared to its wavelength but the rays are deflected by fluctuations at arbitrarily small length scales. So Bathymetry has to be smoothed before using them for tsunami waves

Our Procedure:

$$c_S(x_i, y_i) = \frac{1}{N_i} \sum_{j \in B_i} c(x_j, y_j)$$

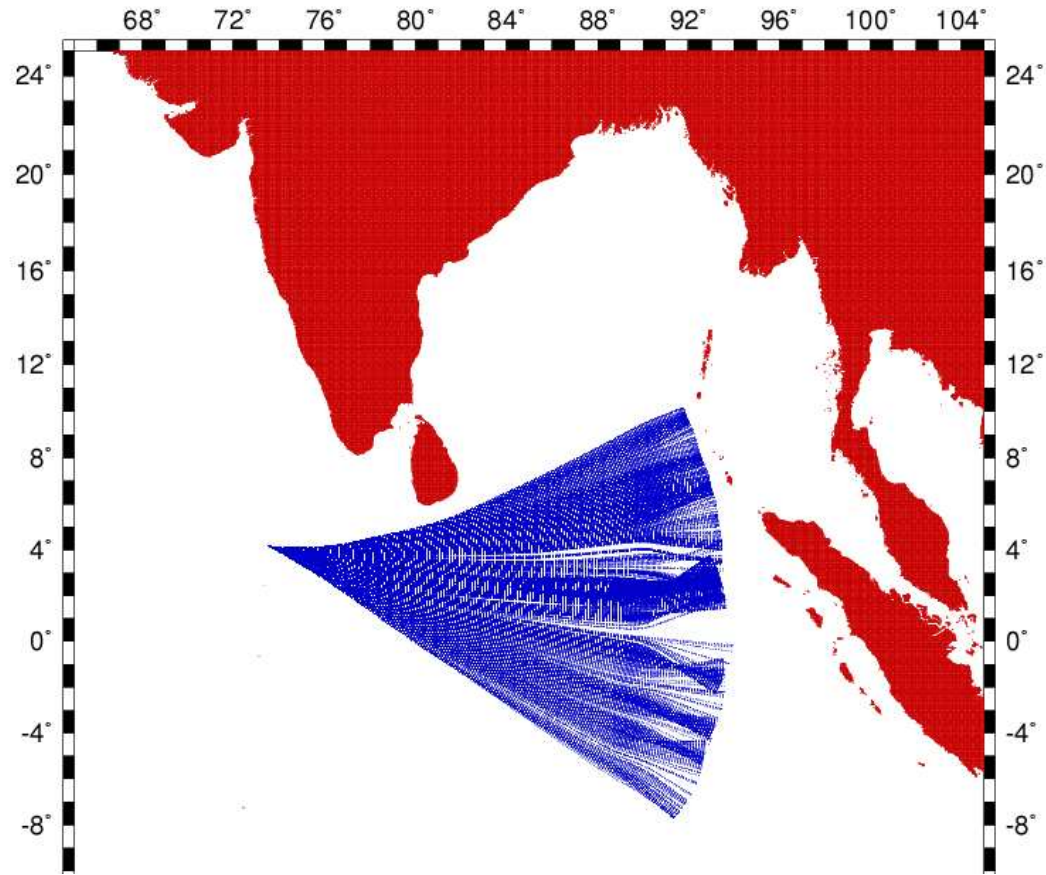
$c(x_i, y_i)$ = Wave speed at $(x_i, y_i) = \sqrt{gh(x_i, y_i)}$

$c_S(x_i, y_i)$ = Smoothened wave speed at (x_i, y_i)

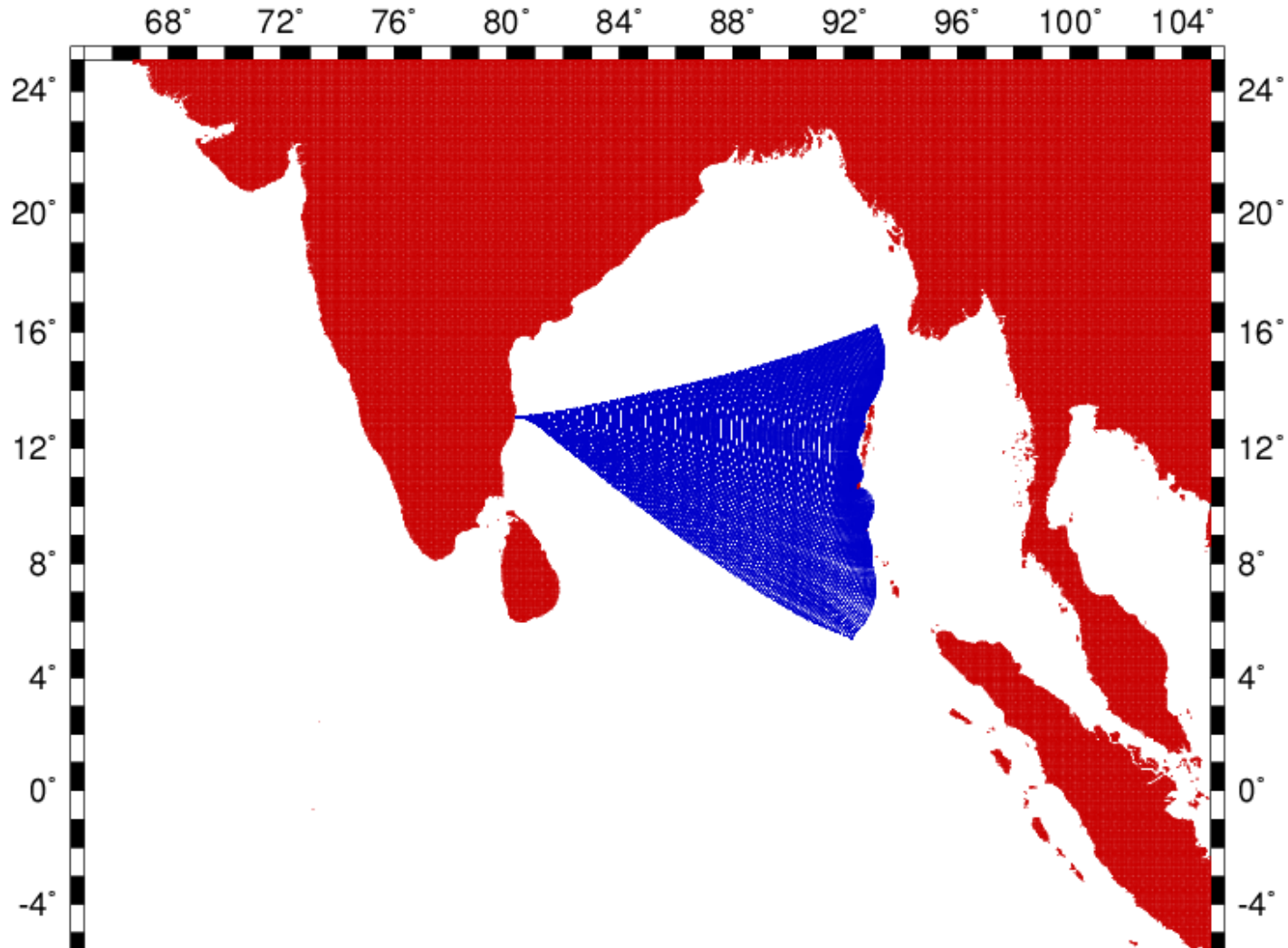
B_i = Grid points in a box of length 0.5 degree around (x_i, y_i)

N_i = Number of grid points in B_i .

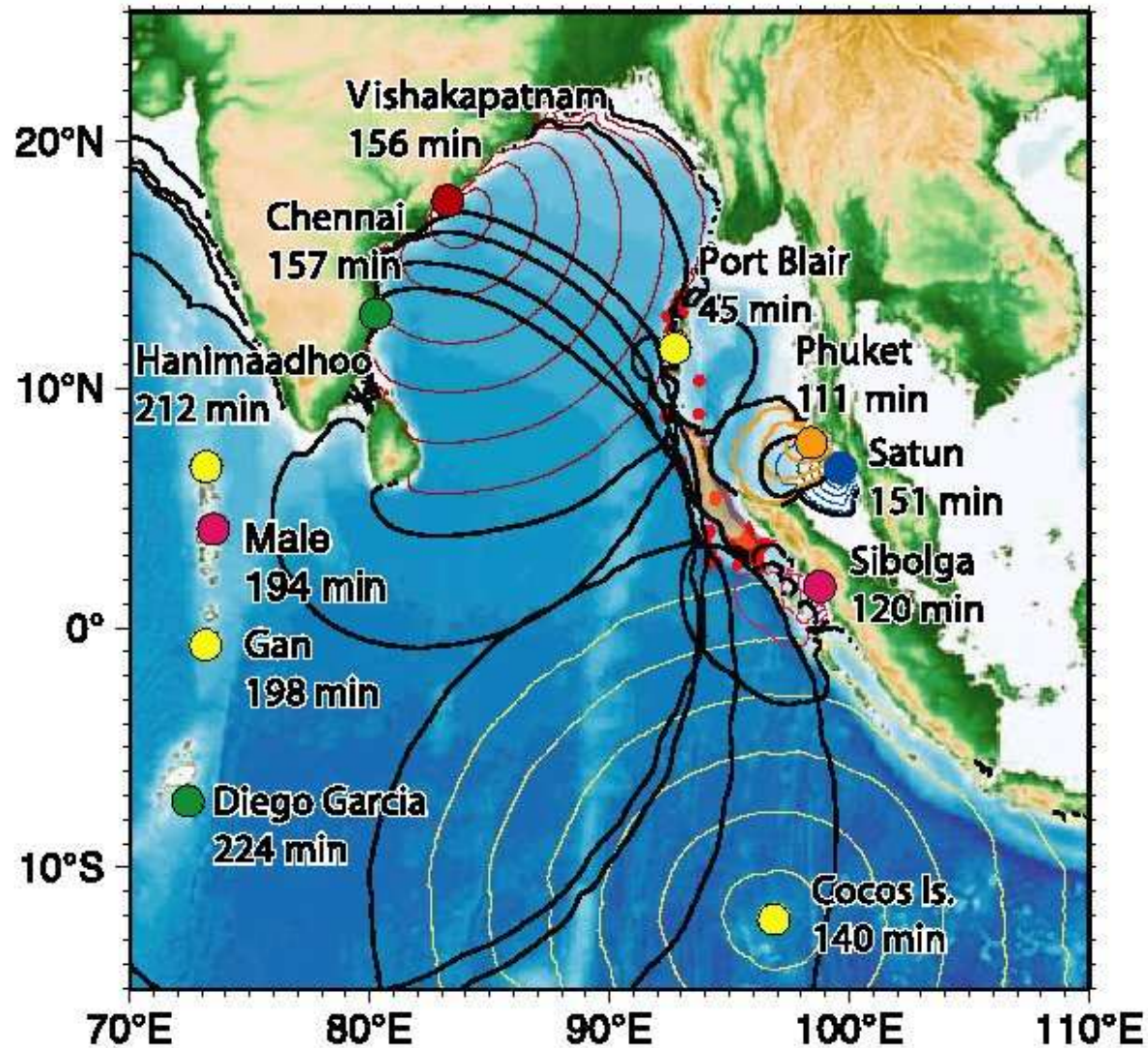
Ray diagrams



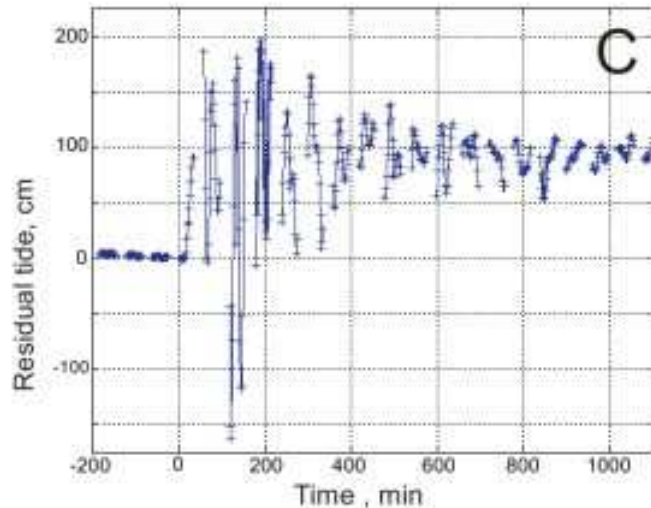
Backward ray tracing



Arrival times



The Port Blair Data



Port Blair tidal gauge clock was fast by 45 minutes

Actual arrival time 31 minutes

Slow Slip below Port Blair, Andaman during the Great Sumatra-Andaman Earthquake of 26 December, 2004

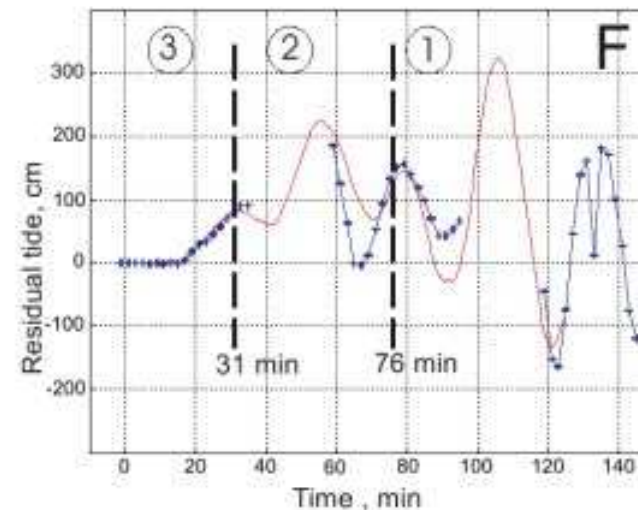
M. Ortiz, S. K. Singh*, H.K. Gupta*, D.G.A. Ramadas*

*Departamento de Oceanografía, CICESE, Ensenada, B.C., Mexico.

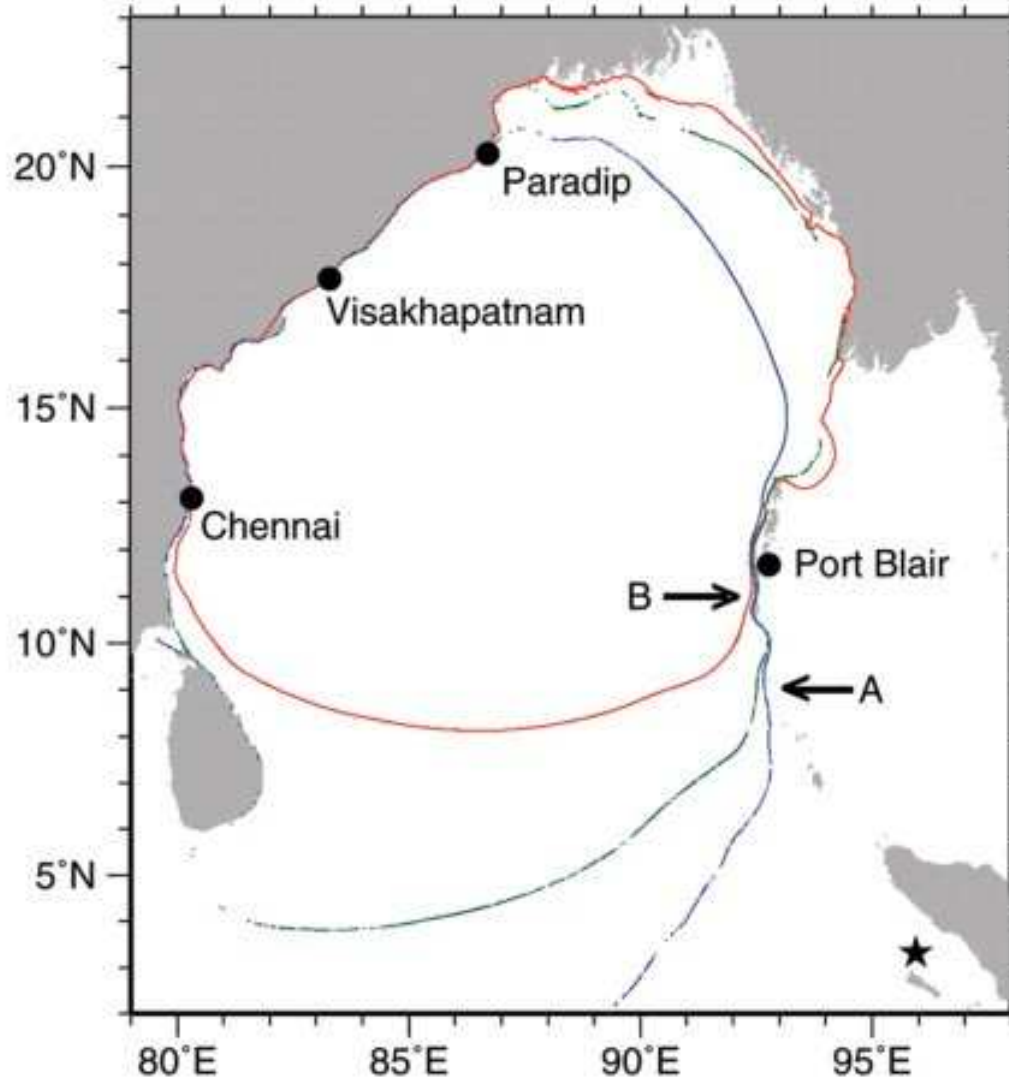
*Instituto de Geofísica, UNAM, CU, Mexico, DF 04510, Mexico.

*National Geophysical Research Institute, Hyderabad 500007, India.

*National Institute of Ocean Technology, Velachery-Talangan Main Road, Chennai 601 301, India.



Paradip for the Northern extent

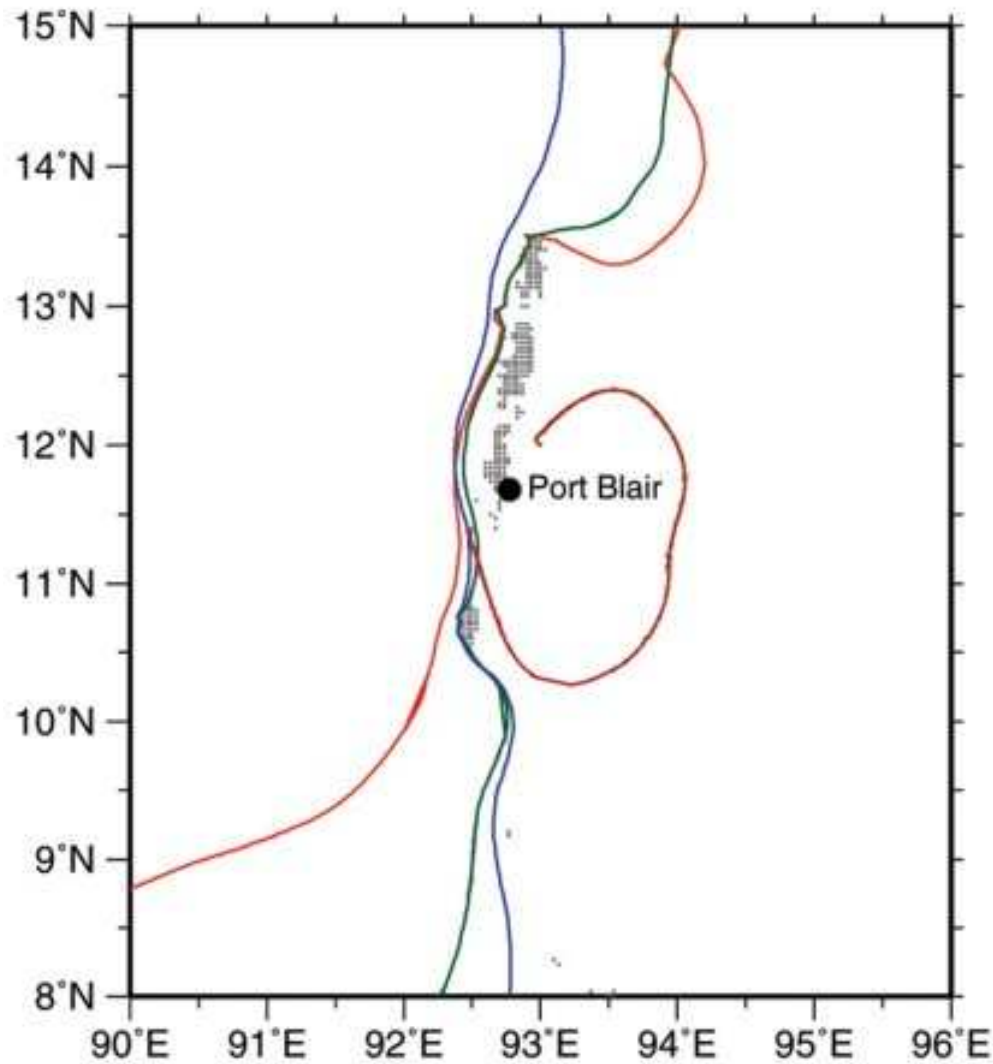


Comment on "The Great Sumatra-Andaman Earthquake of 26 December 2004"

S. Neetu,^{1*} I. Suresh,^{1*} R. Shankar,² D. Shankar,¹ S. C. Shenoi,¹
S.R. Shetye,¹ D. Sundar,¹ B. Nagarajan³

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Port Blair Arrival Time



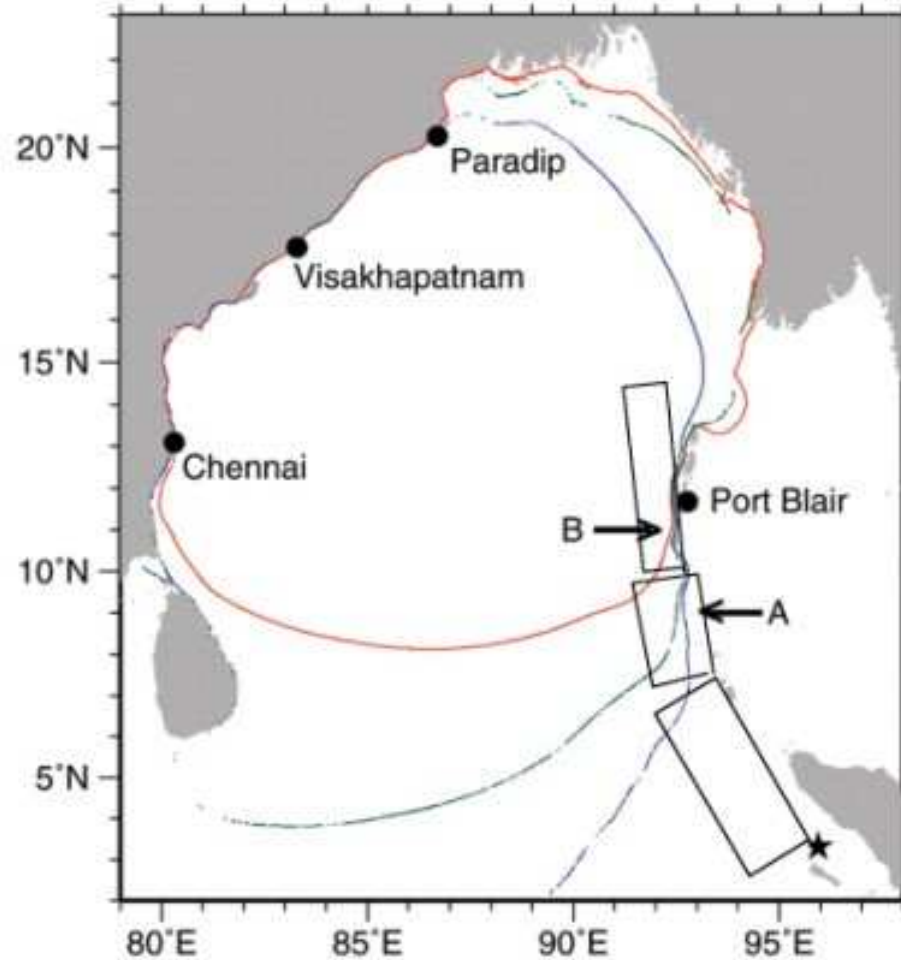
Port Blair Arrival Time 30 Minutes

Response to Comment on "The Great Sumatra-Andaman Earthquake of 26 December 2004"

Thorne Lay,^{1,2*} Hiroo Kanamori,³ Charles J. Ammon,⁴
Meredith Nettles,⁵ Steven N. Ward,² Richard Aster,⁶
Susan L. Beck,⁷ Susan L. Bilek,⁶ Michael R. Brudzinski,^{8,9}
Rhett Butler,¹⁰ Heather R. DeShon,⁸ Göran Ekström,⁵
Kenji Satake,¹¹ Stuart Sipkin¹²

We support the revised estimate of tsunami source length (~800 km) obtained by Neetu *et al.* Sea-level monitoring with a high sampling rate, good azimuthal coverage, and real-time access, along with detailed bathymetry data around the stations, would improve source region estimation from tsunami arrival times.

The Northern Extent



Thank You.