

TECHNICAL COMMENT ABSTRACT

COMMENT ON “The Great Sumatra-Andaman Earthquake of 26 December 2004”

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Lay et al. (Special Section, 20 May 2005, p.1127) estimated a 600-km length for the tsunami source region. Adding tide-gauge data from Paradip, the northernmost of the Indian east-coast stations and therefore the most critical constraint on the northern extent of the source, we estimate that its length was greater by ~30%.

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Determining the length of the tsunami source region is one of the keys to understanding the complex nature of the 2004 Sumatra-Andaman earthquake. Assuming an instantaneous rupture and total slip on the fault, Lay et al. (1) used backward ray tracing to estimate a source region extending up to 600 km ($\sim 9^\circ$ N) north-northwest of the epicenter. The extent increased to 10° N on considering the time delay due to finite rupture propagation and slip rise.

In the analysis of Lay et al., the northern extent of the tsunami source region was constrained by the tsunami travel times reported from the tide gauges at Chennai, Visakhapatnam, and Port Blair (Fig. 1). At the time of the tsunami, however, the clock of the Port-Blair tide gauge was 46 minutes ahead of the actual time (2). A data gap of 24 minutes (between 35-59 minutes after the earthquake) in this record adds to the uncertainty in the tsunami arrival time at Port Blair (2). Hence, we exclude Port Blair from our analysis and re-estimate the length of the tsunami source by including the newly available tide-gauge data from Paradip.

The tide gauges along the east coast of India (maintained by Survey of India (SOI)) show that the entire coast was struck by tsunami waves at almost the same time (3). That Paradip, the northernmost of the stations (86.70° E, 20.26° N), was hit at almost the same time (3, 4) as Chennai and Visakhapatnam, and that the tsunami amplitude here was comparable to that at these stations (Fig. 2), motivates us to examine the compatibility of the tsunami source region reported by Lay et al. with the recorded tsunami travel time to Paradip. (Paradip travel time has not been included in their analysis.) A forward ray tracing simulation shows that while the rays starting from the estimated tsunami source region reach Chennai and Visakhapatnam in the recorded travel times, this is not the case with Paradip, implying that the estimated source region is not consistent with the travel times of all three stations. The tsunami source region must have extended farther north for Paradip to be hit at the recorded travel time.

Including the Paradip travel time as a constraint (in addition to Visakhapatnam and Chennai) and assuming instantaneous rupture propagation and total slip on the fault, we use backward ray tracing (5) to re-estimate the northern extent of the tsunami source region. The backward wavefront for Paradip is in the admissible regions of those of Visakhapatnam and Chennai only $\sim 11^\circ$ N (Fig. 1), implying a source region extending into the Andaman Islands and ~ 900 km long (from the epicenter), ~ 200 km ($\sim 30\%$) longer than the estimate of Lay et al. Including the time delay (1) due to tsunami excitation may extend the effective tsunami source region farther north.

This new northern extent constrains the tsunami travel time to Port Blair to ~ 30 minutes (Fig. 3), close to the data gap in the tide-gauge record. The tsunami had already struck Port Blair by the time the tide gauge started recording again (2).

Thus, an implication of the constraint imposed by the Paradip travel time is that tsunamigenic slip must have occurred over a longer arc than estimated earlier (1). The increase in length is ~ 200 km ($\sim 30\%$), making the event much more destructive. This result also has direct implications (6) for slip distribution on the fault and should help constrain the set of possible geophysical solutions, leading to a better understanding of the processes involved in this mega-event.

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References and Notes:

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2. D.G.A. Ramadass, personal communication, 2005.
3. B. Nagarajan *et al.*, *Earth Planets Space*, (communicated, 2005).
4. The travel times as observed in the SOI tide gauges are: Chennai, 156 minutes; Visakhapatnam, 161 minutes; and Paradip, 151 minutes.
5. The method is presented in the supporting online material.
6. R. Bilham, *Science* **308**, 1126 (2005).
7. NIO is a constituent laboratory of CSIR, New Delhi. We acknowledge the Surveyor General of India for tide-gauge data and Department of Ocean Development, New Delhi for financial support. This is NIO contribution 4048.

Figure caption:

Fig. 1. Backward wavefronts for Paradip (red), Visakhapatnam (green), and Chennai (blue) corresponding to their respective observed travel times. The asterisk marks the epicenter of the earthquake. The northern extent ($\sim 9^\circ$ N) reported by Lay et al. is indicated by arrow A. The arrow B marks the new estimate ($\sim 11^\circ$ N).

Fig. 2. The residual (cm) of the tide-gauge record. The tsunami arrival time (UTC) is given in the bottom right corner.

Fig. 3. The ~ 30 minutes backward wavefront of Port Blair (brown) is consistent with those of Paradip (red), Visakhapatnam (green), and Chennai (blue).

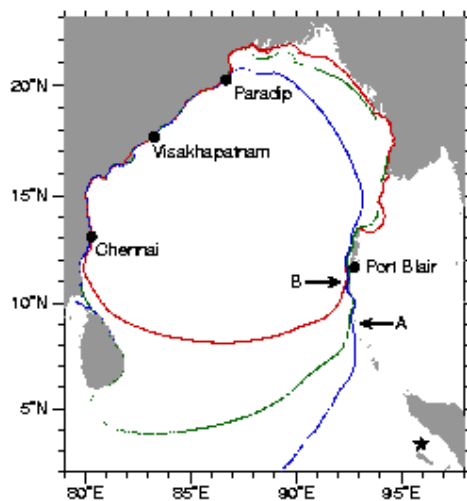


Fig. 1

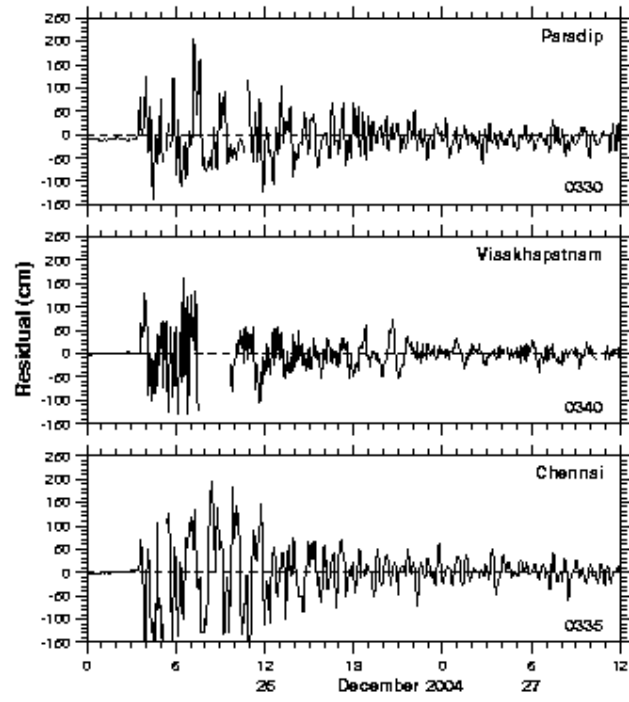


Fig. 2

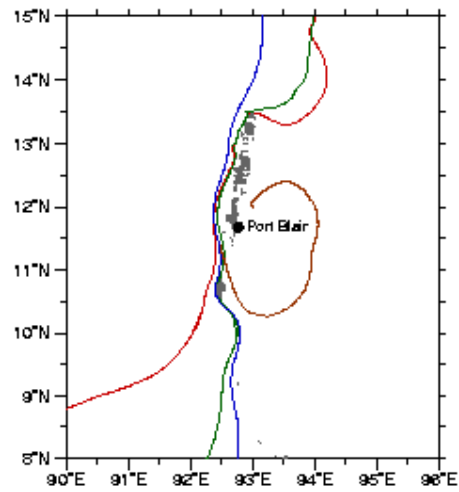


Fig. 3

Supporting Online Material

The Method:

The linearised shallow water equations provide a reasonably good model for tsunami wave propagation. These equations can be solved easily in the geometric optics limit using the eikonal approximation. It is well established that the resulting ray diagrams can be used to compute the travel times of the leading tsunami wavefront to a reasonably good approximation (1). We use the conventional planar ray equations for our analysis.

The ray equations do not incorporate diffraction effects and are exact in the limit of the wavelength being much smaller than the length scale at which the depth varies. There is therefore a need to smoothen the bathymetry before applying ray techniques to analyse tsunami wave propagation (2). We do this by replacing the speed at every grid point by the average speed over a box of size 1° around it. The smoothening is done only over the ocean points and does not involve the land points. We prefer to smooth the speeds rather than the depths because the latter amounts to replacing the speed by the root mean square value of the speeds in the smoothening box. We obtain speed at any point by bilinear interpolation using the smoothened speeds at the grid points. The underlying bathymetry considered for the present study is from ETOPO2 data (3).

The backward ray tracing method uses the fact that the ray equations are reversible to put constraints on the location of the initial leading tsunami wavefront. The ray equations are solved numerically with the tide-gauge location as the initial point, for all initial ray directions, and for a time equal to the observed travel time. The set of points thus obtained forms a curve that we refer to as the backward wavefront. The initial tsunami wavefront cannot include points in the region between the backward wavefront and the tide-gauge location. The envelope of all the backward wavefronts then gives the allowed locations of the initial wavefront, which we term the “admissible region”. The initial wavefront need not include the entire admissible region, but it has to include at least one point from the backward wavefront of every tide-gauge station.

References:

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