REFRACTION OF TSUNAMI WAVES OF 26 DECEMBER 2004, ALONG SOUTHWEST COAST OF INDIA

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ABSTRACT

In this paper the refraction of the tsunami of 26 December 2004, which caused severe damage along the south west coast of India has been studied. Wave refraction diagrams for the possible wave directions indicate convergence around the places like Kolachel, around Kollam and Alappuzha, where greater destructions occurred due to this tsunami and divergence at the places spared by the tsunami. Broad areas vulnerable to tsunamis have been identified. Possible causes for increased destruction in Kolachel at the southern tip of Indian peninsula are discussed. Bottom topography is one of the factors that determine the intensity of the tsunami waves. Bottom steering is caused by the wave refraction. Comparatively gentler sloping topography in a zone north of Kollam at depths beyond 200m and the topographic dome off Kollam appear to have influence on determining the impact of tsunamis.

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INTRODUCTION

The great Indian Ocean tsunami was caused by an earthquake of magnitude 9.3 on the Richter scale (Javed *et al.*, 2005) on December 26, 2004 at 06:28 IST (Chadha *et al.*, 2005) off the western coast of northern Sumatra. The epicentre of the earthquake was at about 3.32^{o} N & 95.85^{o} E, at a depth of about 30 km below mean sea level (http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav). The length of the tsunami source region has been estimated by backward ray tracing to be about 600 km (Lay *et al*., 2005). This has been re-estimated by Neetu *et al.,* (2005) to be about 900 km. The tsunami severely hit mainly Srilanka, Indonesia and India, although some other littoral countries of the Indian Ocean were also affected. The death toll is reported to be more than 2,50,000 (Chadha *et al.*, 2005).

The arrival time of tsunami waves at Colombo, Chennai and Cochin were 0352, 0335, 0541 UTC (IST is 5.30 hours ahead of UTC) respectively (Nagarajan *et al.*, 2006). The affected places along southwest coast of India were around Kollam, Alappuzha and Ernakulam districts in Kerala and the Kanyakumari district in Tamil Nadu (see figure 1). Compared to the east coast, the impact was less along the west coast. Although the impact decreased from south to north, it varied from place to place along the coastline. The impact at Ernakulam district was lesser compared to affected areas further south.

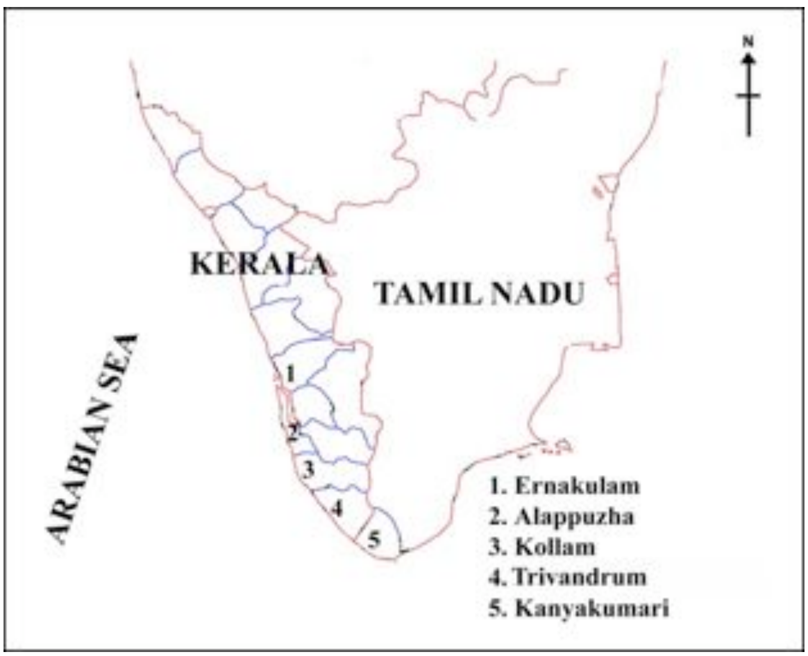

Figure 1. Tsunami affected districts along the southwest coast of India.

The main objective of the present study was to generate the wave refraction diagrams for different directions of approach in the December 2004 tsunami along the southwest coast of India. For the tsunami, the processes that occur as waves approach to the shore is the convergence and divergence of energy, due to wave refraction. This causes greater damage and loss of life in some area, while the other area in the neighbourhood may remain unaffected. It is important to know the possible areas of damage and destruction and wave refraction studies are useful to identify these areas. Varma and Sakkeer (2005), presented preliminary results of refraction of tsunami, limiting to the study area to the Kerala coast. In the present study, the area is extended and the coastline between Kanyakumari and Cochin is considered.

Waves in shallow water and tsunami

Tsunamis are very long waves, with large dimensions in width. For such waves approaching from easterly direction, Srilanka and the peninsular India act as barriers and diffraction brings the waves to the Arabian Sea. On examining the simulations available in the internet (*http://yalciner.ce.metu.edu.tr/sumatra/survey/simulation/index.htm, http://en.wikipedia.org/wiki/2004_Indian_Ocean_earthquake;http://www.nio.org/jsp/tsunami.jsp*), it can be seen that the tsunami waves travelled from the place of origin in all directions of the Indian ocean and on reaching Srilanka and the southern tip of India, these waves turned and moved to Arabian sea. Numerical modeling have also shown (Kowalik *et al*., 2005) that the main energy lobe of maximum amplitude was directed towards Srilanka and the secondary lobe was directed to South Africa and also that large portion of Arabian Sea was in the shadow of main energy lobe. This was the reason for lower intensity that was observed along west coast of India.

In the case of usual wind waves, refraction occurs only in the shallow water, while for tsunamis, which are very long waves, refraction occurs over deep waters also. However, effects due to refraction would become prominent near the coast because of the rapid decrease of depth towards the shore. Helene and Yamashita (2006) used a simple model to understand the behavior of a tsunami in variable depths and indicated the possibility of large-scale variations in the direction of propagation of tsunami due to refraction. In the present tsunami, refraction and diffraction helped it to turn the corner around the southern end of India and cause significant damage and loss of life in the state of Kerala even though Kerala is located on the western side of Indian sub continent (Ahmet *et al*., 2005).

Topography off southwest coast of India

Detailed topography is given in the refraction diagrams. Depth contours below 50m depth are closer to coast, south of Kollam. At the same time, the gap between contours of 50 and 100m is least off Trivandrum. The 1000m contour gradually turn towards offshore south off Cherthala and reaches a distance of around 110km nearly off Azheekkal. Then it turns shoreward, reaches a distance of about 80km from shore and runs at this closer distance to nearly off the tip of peninsula. Thus area between 200m and 1000m is comparatively of gentle slope north of around Azheekkal than south of this.

Methods

Study area is given in figure 2. Computer programme by Dobson (1967) has been used to generate wave refraction diagrames. It is assumed that there is no energy loss due to bottom friction and that no energy is transmitted across the wave rays. This programme was earlier used for studying refraction pattern along the shoreline near Cochin using climatological wind wave data (Varma., 2003). In the present study, the area bounded by latitudes 7° N -10° 30' N and longitudes 74° 30'E -78°E has been chosen and the depths at grid points separated by 9 km were extracted from hydrographic chart No: 22, corrected up to 2001, after drawing additional depth contours. For completing the grid, negative depths were given to grid points lying on land, considering an arbitrary slope. Coarse grid has been used in the study because the area included is large and also because the attempt here is to find out the gross features of refraction of tsunami waves. Variations of depth, as the wave progresses shoreward, are interpolated in the computer programme with a local grid of depths with quadratic surfaces in the neighbourhood.

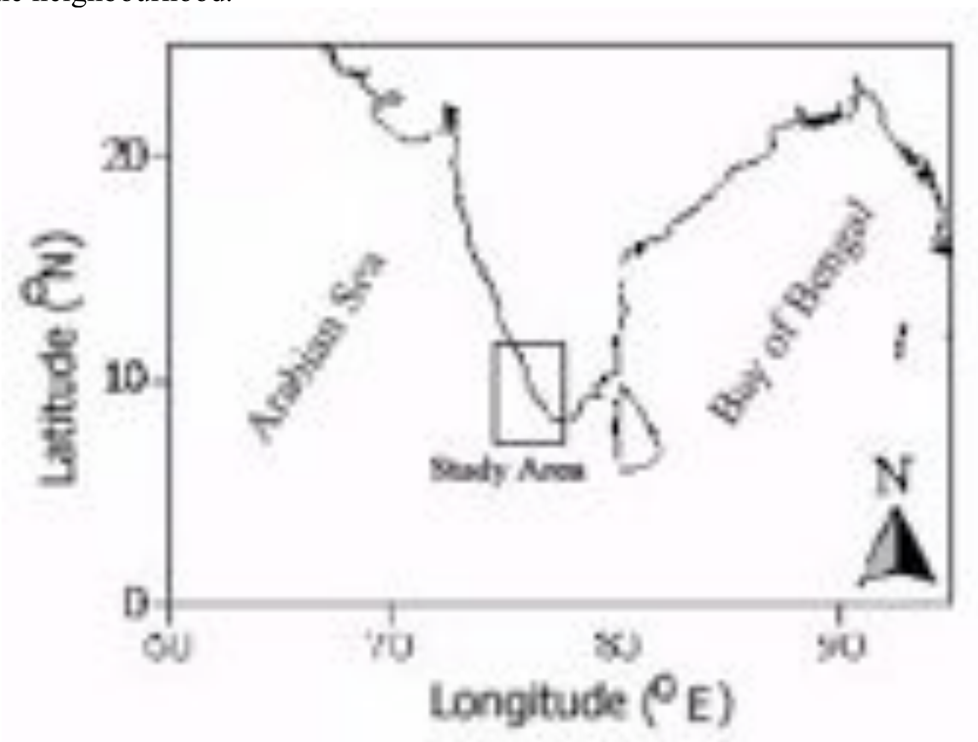

Figure 2. Study area (the rectangle indicates selected domain)

It is necessary to give a starting point of wave rays. These points are selected in such a way that these are at maximum distance from shore, that is possible within the selected domain. Initial directions that are likely to occur when these waves swing into the shadow zone are used and refraction diagrams for different wave directions of approach viz, 180, 190, 200, 210, 220, 230, 240, 250 and 260 degrees (true north), have been prepared (Fig 3 to 11).

For calculating initial velocity, the depth at the starting point is used. In other words, period of tsunami waves does not affect refraction. Since the wavelength is a requirement in the programme, the initial wavelength at the starting point of wave ray is calculated from the estimated speed, using 20 minutes as the wave period. It has been noted that the 2004 December tsunami contained different periods ranging between 20-50 minutes (Kowalik *et al*., 2005). In a recent study of the numerical modeling of tsunami waves, Paul (2006) has taken the period to be about 15 minutes. Also, on, analyzing tide data from several places in the coastal India and neighboring places, during tsunami spectral peaks at about 20 minutes and 35-45 minutes have been noticed (Nagarajan *et al*., 2006).

Results

For180^{o}T (Fig.3) wave rays converge north of Cochin and south of Trivandrum. It can be seen that Trivandrum was a wide zone of divergence. Mild convergence was seen around Arattupuzha.

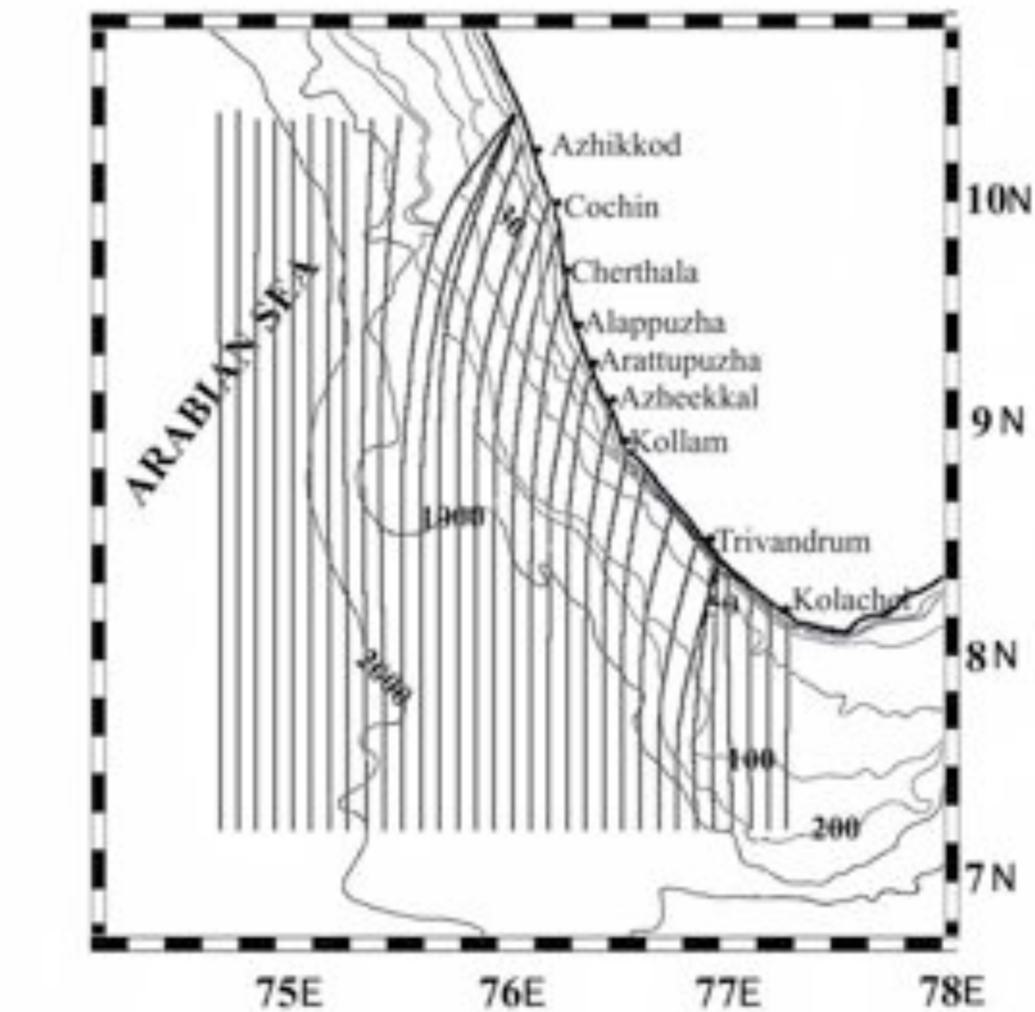

Fig.3 Refraction diagram for tsunami waves coming from 180^{o} T. Depth contours are in metres.

For 190^{o}T (Fig.4) wave rays converge around Cochin and slightly north of Kolachel. Trivandrum was in a zone of divergence. While divergence was seen at Arattupuzha, mild convergence was seen around Azheekkal. It may, however, be noted that the reported impact at Cochin was less than that at Azheekkal in Kollam area and Arattupuzha in Alappuzha zone.

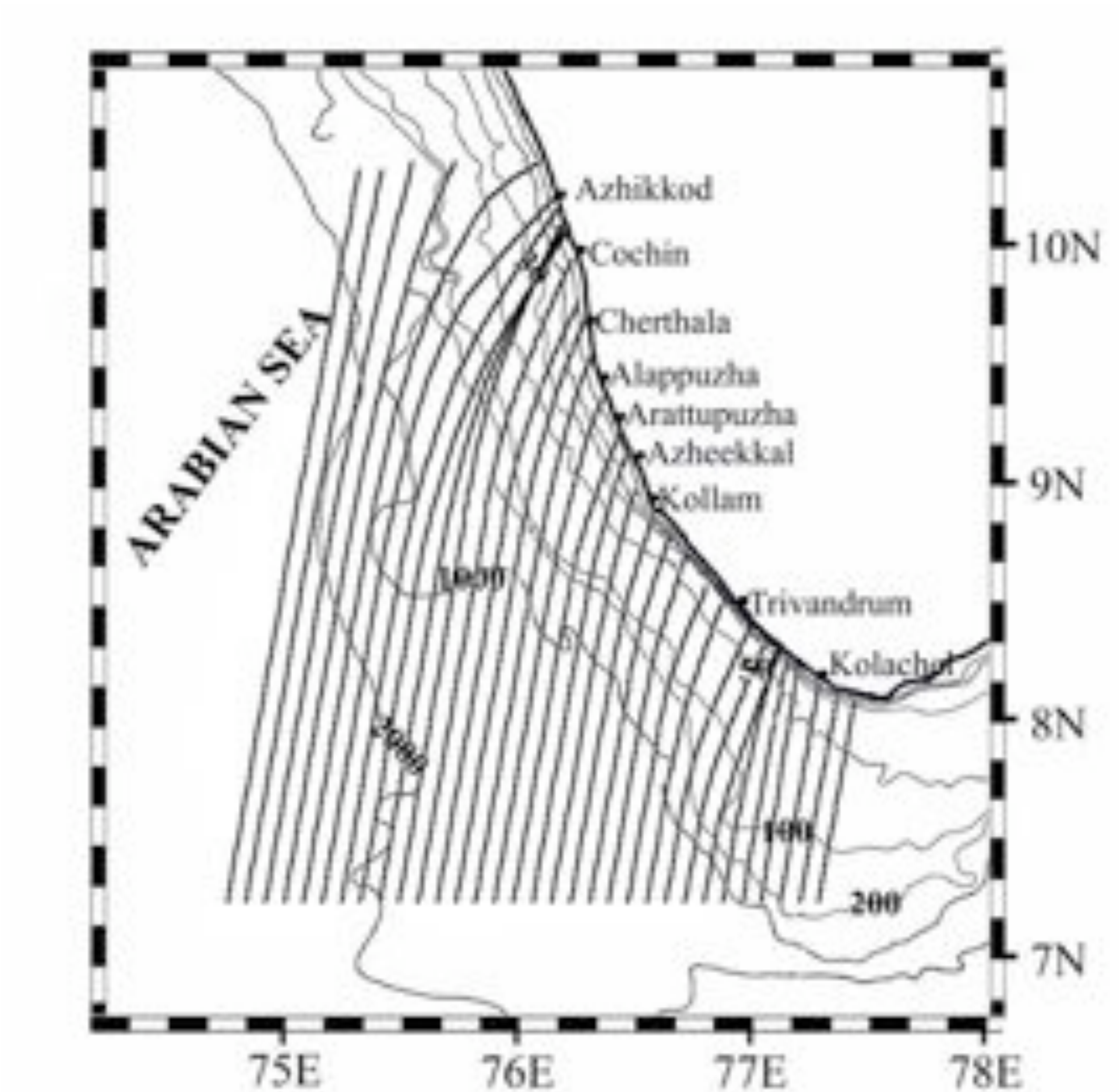

Fig.4 Refraction diagram for tsunami waves coming from 190° T. Depth contours are in metres.

For 200°T (Fig.5), the convergence zone around Cochin has moved to south and was near Cherthala. Strong convergence was seen near Kolachel. While mild convergence occurred near Azheekkal, divergence was seen at Trivandrum and Arattupuzha.

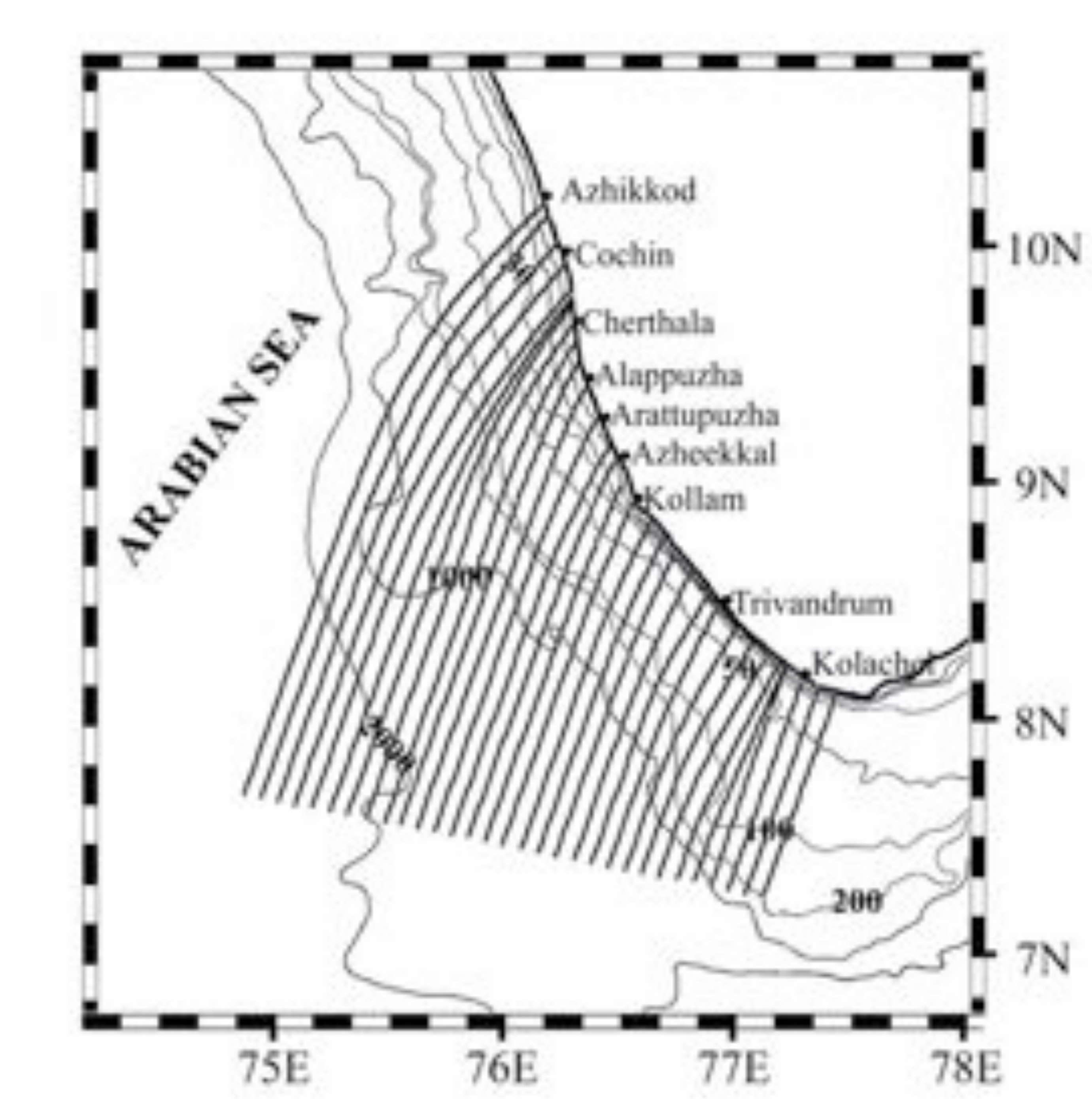

Fig.5 Refraction diagram for tsunami waves coming from 200^{o} T. Depth contours are in metres.

In the case of 210°T (Fig.6), zones of convergence are Kolachel, Alappuzha and Kollam. Divergence was seen at Trivandrum and Arattupuzha. Mild converging tendency around Azheekkal was also seen.

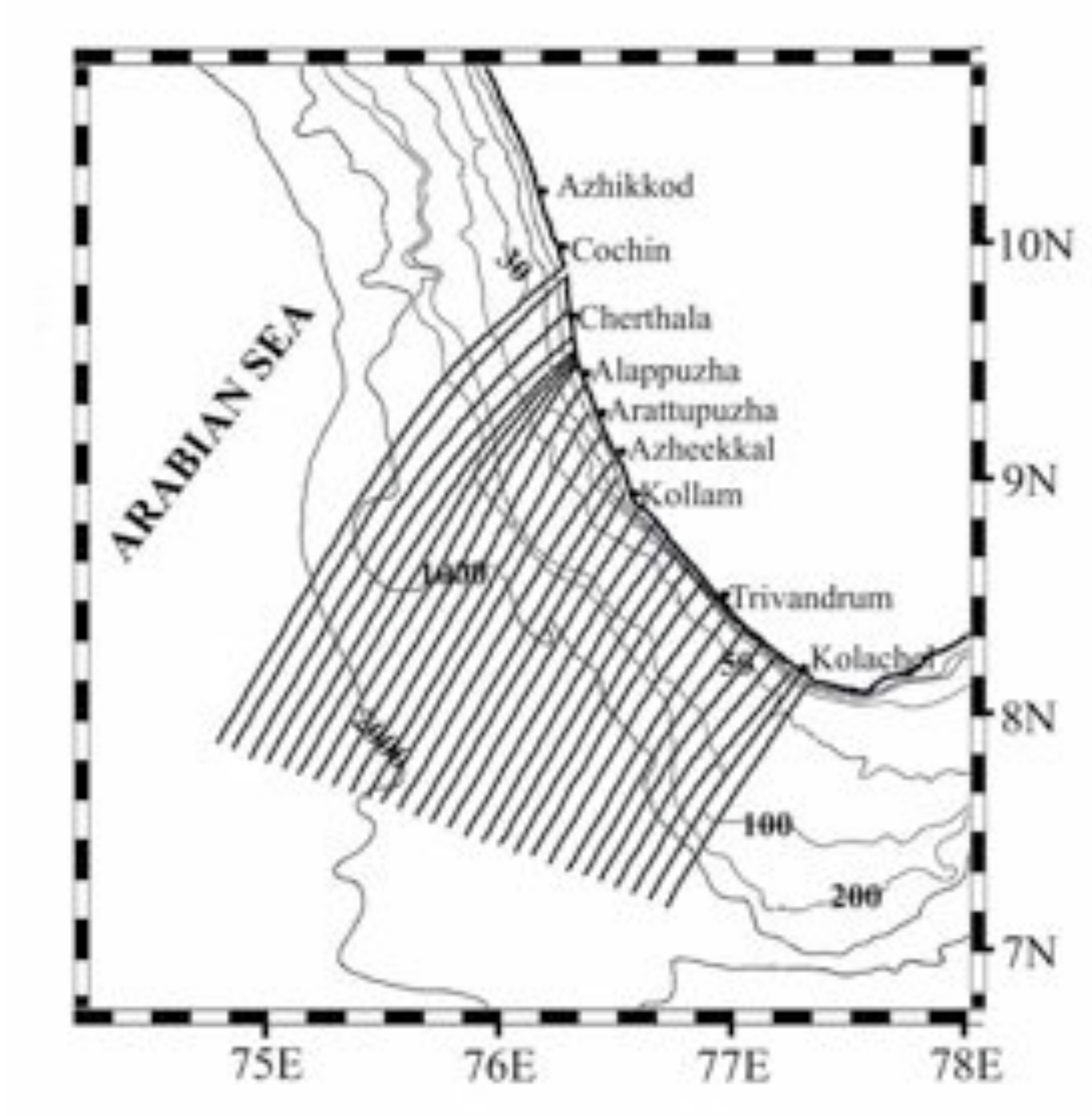

Fig.6 Refraction diagram for tsunami waves coming from 210° T. Depth contours are in metres.

For 220^{o}T strong convergence was seen between Arattupuzha and Alappuzha (Fig.7). Divergence was seen between Arattupuzha and Azheekkal. Mild converging tendency was seen near Kollam and north of Trivandrum.

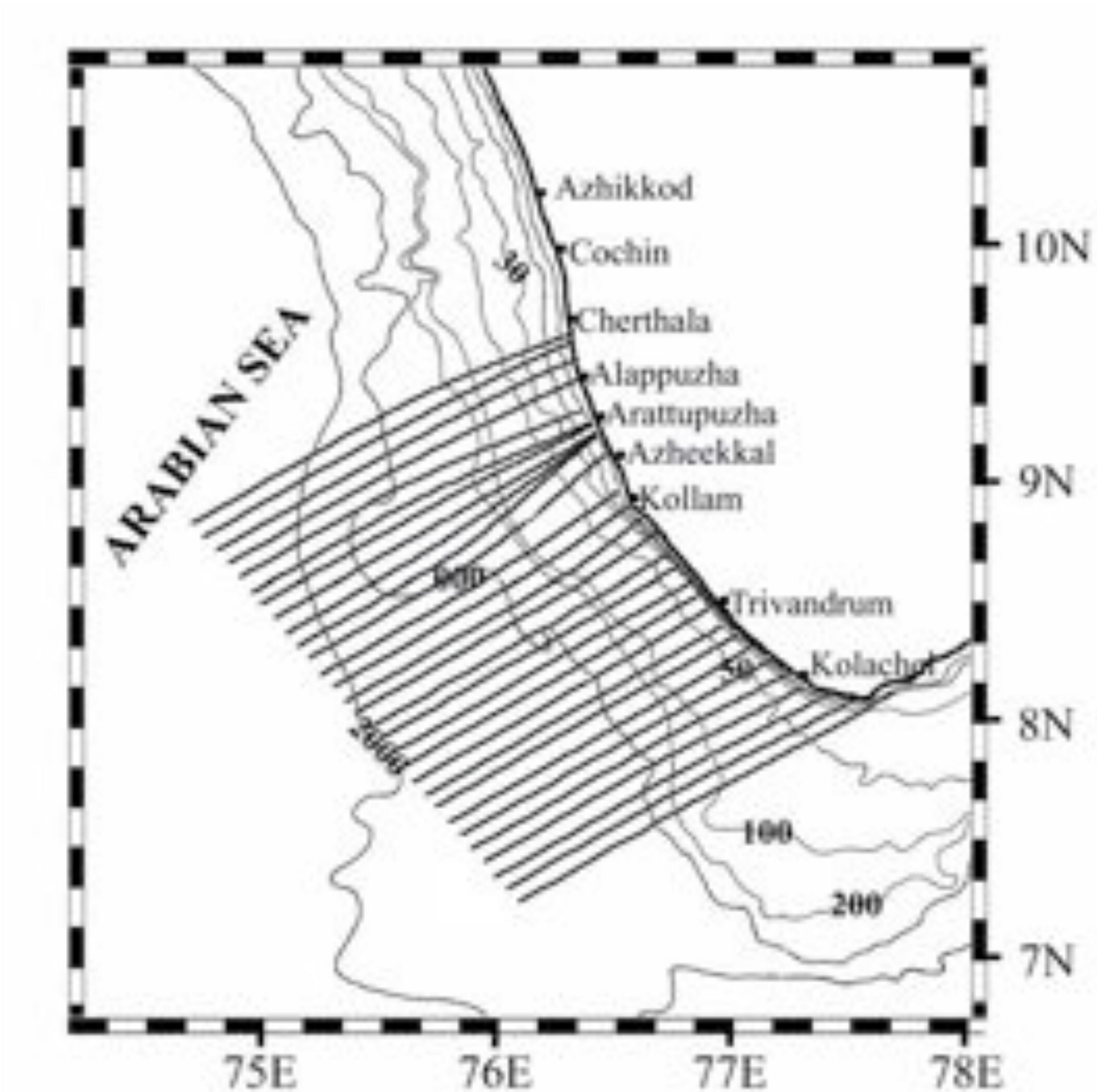

Fig.7 Refraction diagram for tsunami waves coming from 220^o T. Depth contours are in metres.

Directions 230° to 240° T show convergence in the Alappuzha –Arattupuzha region. Interestingly Azheekkal and Kollam were in the divergence zone (Fig 8 & 9).

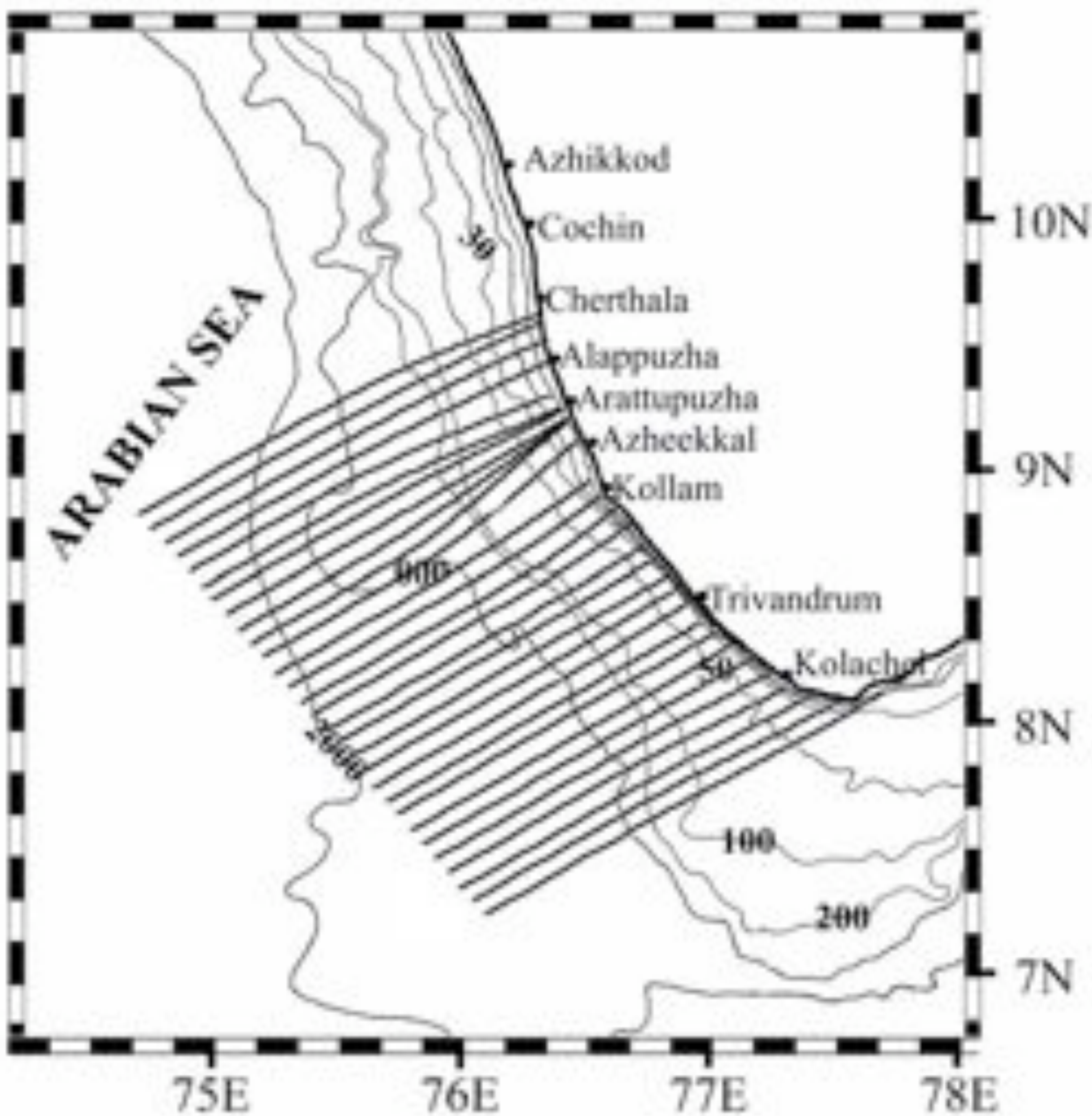

Fig.8 Refraction diagram for tsunami waves coming from 230° T. Depth contours are in metres.

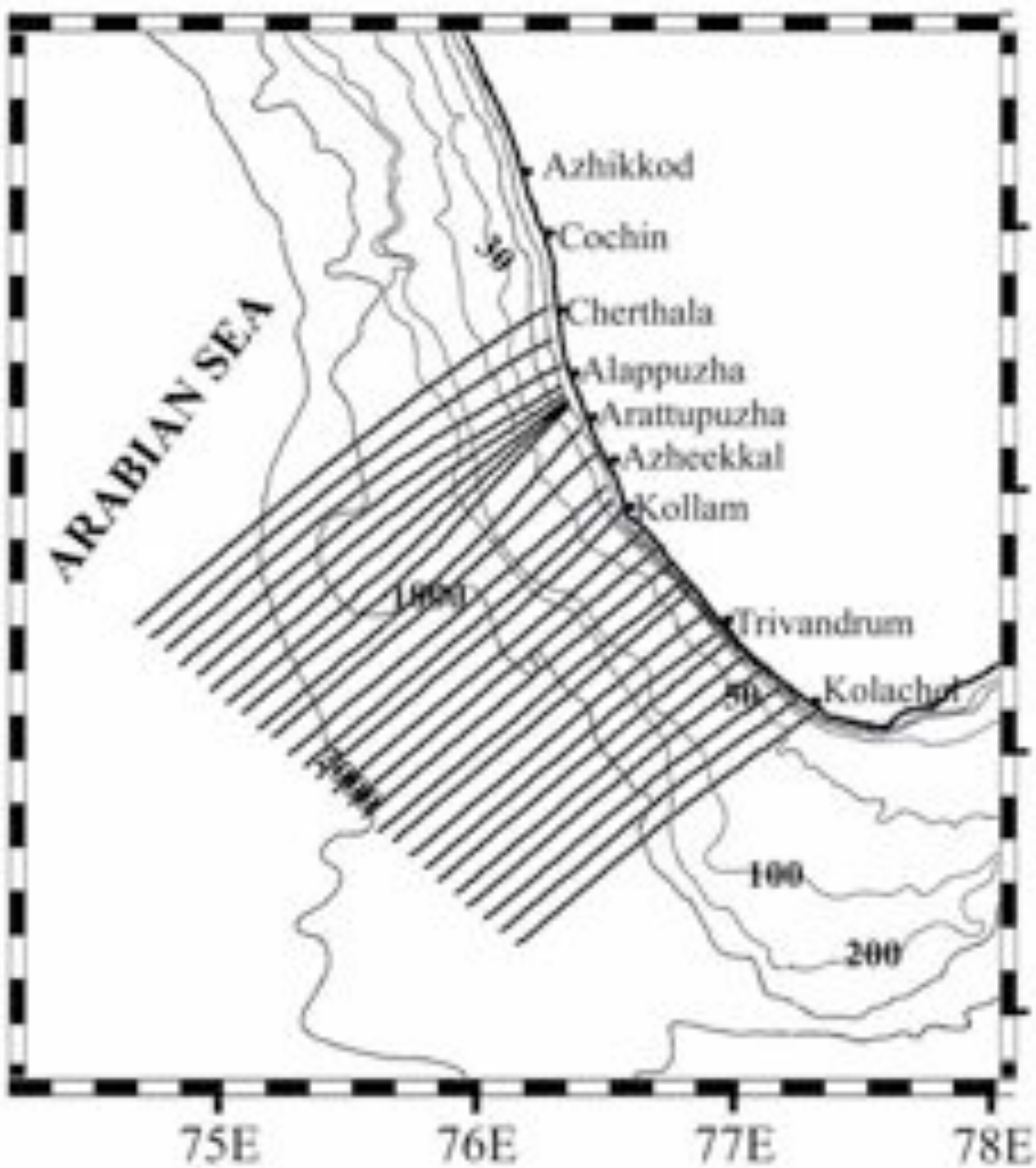

Fig.9 Refraction diagram for tsunami waves coming from 240° T. Depth contours are in metres.

Though it was not sure whether more westerly directions could be there for this tsunami from Bay of Bengal, refraction diagrams for 250 and 260 were also generated (Fig 10 & 11). However, rays in the southern part only were considered because it was thought that these waves from Bay of Bengal might not swing so as to have such an approach all along the coast. For these directions convergence zones were seen in the regions of Azheekkal and Kollam.

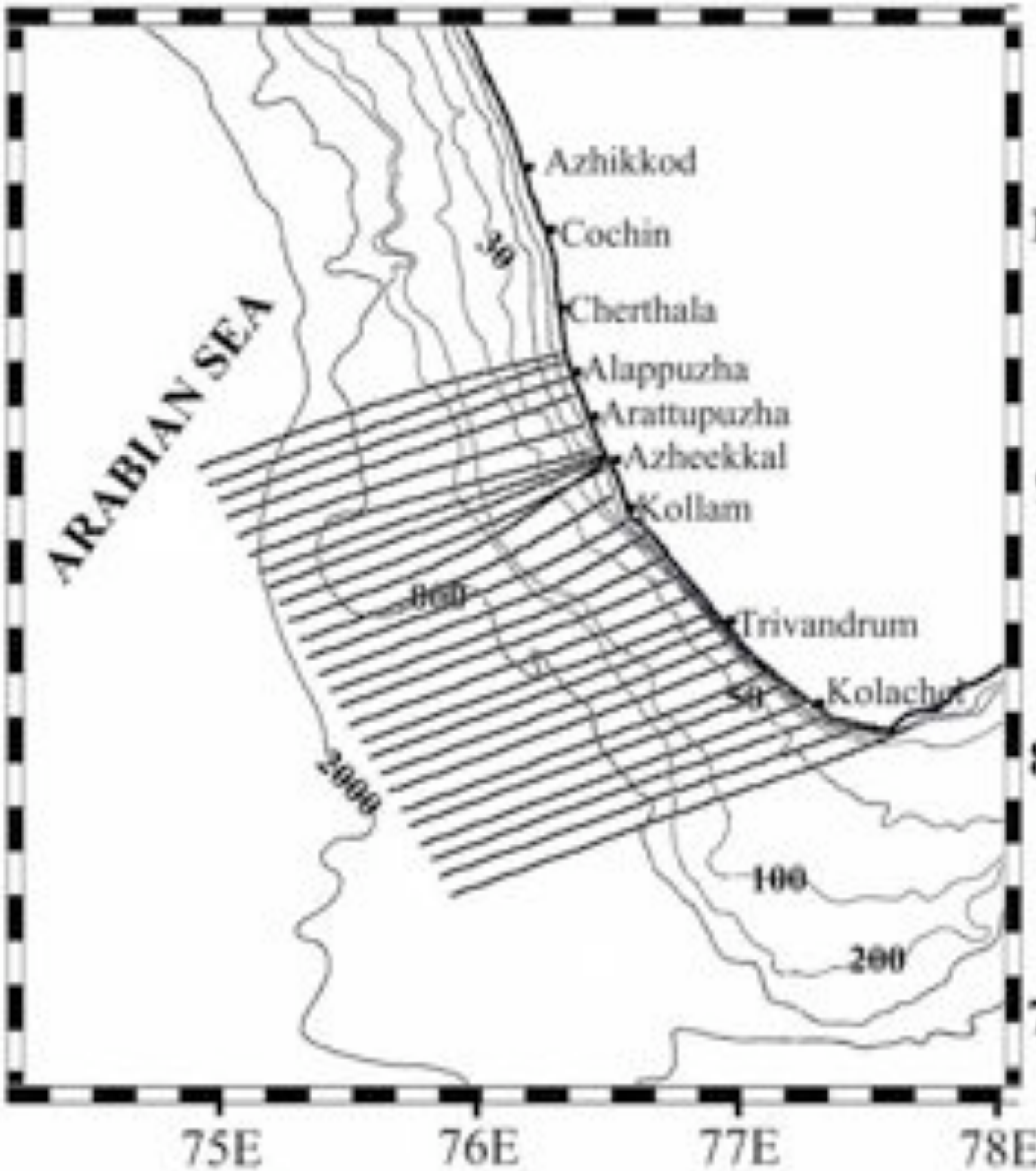

Fig.10 Refraction diagram for tsunami waves coming from 250° T. Depth contours are in metres.

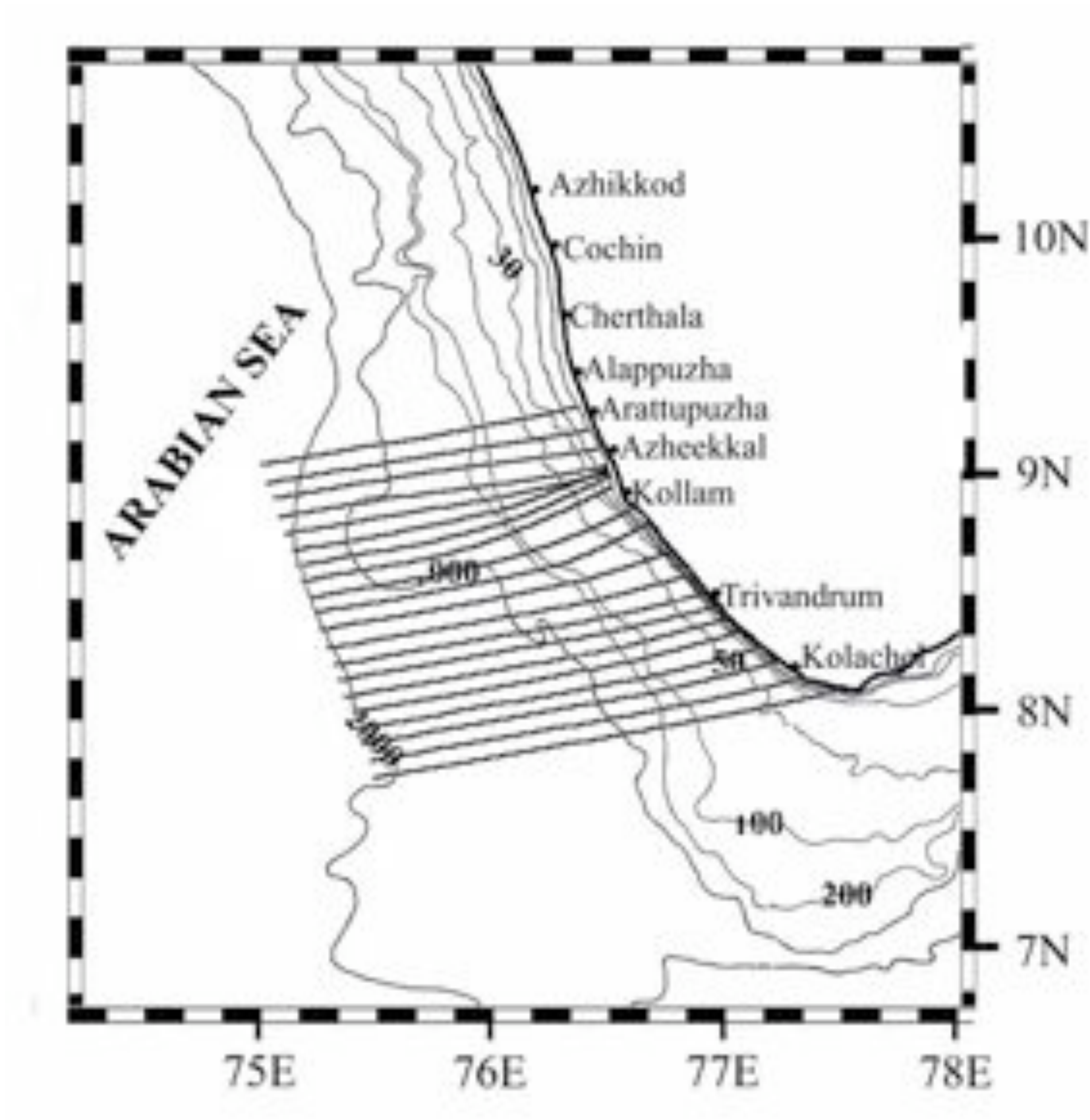

Fig.11 Refraction diagram for tsunami waves coming from 260° T. Depth contours are in metres.

Discussion and conclusion

It is seen that the zones of convergence and divergence for 190^o - 230^{o}T broadly agree with the regions of destruction and those spared by the tsunami. While, areas in and around Kolachel (Kanyakumari district), Azheekkal (Kollam district) and Arattupuzha (Alappuzha district) appear as convergence zones for some directions, divergence is, generally, seen in the region between Kolachel and Kollam, which includes Trivandrum. Further westerly directions show strong convergence at Azheekkal, which is an area of higher tsunami impact. As mentioned earlier, sea bottom beyond 200m north of Azheekkal is gently sloping compared to further south**.** At the southern end comparatively wide area is seen between 500 and 1000m. Tsunamis being long waves, the refraction occurs at deeper regions itself, and the bending of waves due to north south gradient of depth several kilometers away from the coast seems to have caused the divergence around Trivandrum. The wave rays passing over the gentle off shore dome of topography around Kollam are found to cause convergence zones. This topographic feature have an influence on producing the observed impact of tsunami. While discussing about the local system of tsunami defense for Pacific coast of Kamchatka, using numerical estimates, Chubarov *et al.,* (2001) have reported that direction of tsunami movement is strictly determined by the bottom topography.

The destruction in Kolachel has been reported to be more severe, compared to other northern zones of convergence viz, around Azheekkal, around Arattupuzha and Alappuzha. In some animations available on the internet (for eg. http://news.cornell.edu/ release/Jan05/ tsunamiVid320.html), waves are seen to get reflected at Maldives Island and then impinge on southern end of the west coast of India. Thus at this zone, in addition to the convergence of energy, surges due to reflection also occurred. Refraction of such reflected waves from these islands are also to be considered. The chain of islands, Maldives, extending about 500km in north-south direction, is situated south west of the Indian peninsula. Tsunami waves, reflected from different parts of the island can possibly have some of the directions like 190^{o}T, 200^{o}T, 210^{o}T and the waves with these directions are found to be favourable for convergence around Kolachel. Since reflected waves are not likely to occur in regions further northwards along the shore destructions are less severe here compared to Kolachel.

As the tsunami wave are wide, the diffraction of tsunami would have swung it in such a way that the directions over deep water could be slightly different at different parts off the west coast of India. Another aspect is that tsunamis being very long waves, they feel bottom even over deep-water oceanic areas. Hence, in present case, refraction takes place even while the wave diffracts around the land mass. It has been shown that in the case of this tsunami, refraction changed orientation to bring it to south east Arabian Sea (Helene and Yamashita., 2006). Thus different directions of approach towards the shore in the study area are possible. This could be the reason why combinations of directions ranging from 190^{o}T to 240^{o}T generally reproduced the broad areas tsunami impact along this coast.

Refraction diagrams along the southwest coast of India for tsunami waves have been generated, starting the wave rays from depths exceeding 1000m. Areas of convergence and divergence for directions ranging from 190^{o}T to 240^{o}T in general agree with pattern of observed tsunami impact. Areas around Kolachel, Kollam and Alappuzha appears to be more vulnerable for tsunami generated in Bay of Bengal. Trivandrum being in the area of divergence, here the tsunami impact is likely to be less.

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