



Explanations for Specific Devastation Locations in Southern India Due to Tsunami of 26th December, 2004

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Summary

The devastating tsunami triggered by a great megathrust earthquake of magnitude M9.3 that struck the Sumatra trench more than 2000kms to the south east of Chennai in the Indian Ocean wrecked havoc of hitherto unknown proportions in Southern India and Sri Lanka. The major brunt of the devastation was borne besides the Sri-Lankan coast by Tamil Nadu and South Coastal Kerala. The havoc rendered specifically to sea board off Chennai, Nagapattinam, Colachel and Karunagapally in the west coast appears surprising at the outset. A detailed geological appraisal, however, throws insight on the factors responsible for these devastation locations due to tsunami.

The eastern sea board off Chennai and Naggapattinam being located closer to the source area had attendant severe devastations while areas farther away near Colachel and Karunagapally had damages of lesser extent. Prominent radials emanating from Cambay node, one passing through Cuddapah Basin to Chennai further extending into Bay of Bengal and another to Gulf of Mannar through Dharwar Craton influenced the migration of the tsunami wave onto the east coast and the Achancoil Shear zone entry into the Arabian Sea must have influenced the navigation onto the west coast. The ocean current pattern, ocean floor topography, and the earth's rotation played a dominant role in deflecting the tsunami waves onto the west coast. The continuing active NNE drift of the Indian plate following its collision with the Eurasian plate along with progressive increase southward in relative velocity of drift in Peninsular India resultant of welding of the northernmost subcontinent also added to the specific landfall points bearing the damaging power of tsunami waves. Sri Lanka shielded the south-eastern part of Tamil Nadu from receiving direct tsunami waves. The devastations have occurred in areas with comparatively lower electrical surface conductance. The combined effects of these significant geological factors led to steering the powerful tsunami generated waves onto these preferred seaboard points.

Introduction

The devastating megathrust earthquake occurred at the interface of the Indian and Burmese plates in the early hours of December 26th 2004 (Fig-1 and 1a). "Tsunamiogenic" earthquakes are caused when the processes of plate tectonics force heavy, oceanic crustal rock below lighter, continental rock to create a deep trench at the bottom of the sea. The release of stresses was consequent to the subduction of the Indian plate beneath the Burmese plate (Fig-2). The large vertical movements above the epicenter of the quake displaced the overlying water in the ocean. The resultant ocean bottom deformation spawned tsunamis propagating energy in the western quadrant while the eastern quadrant was landlocked. The potential energy that resulted from pushing water above mean sea level was transferred to horizontal propagation of the tsunami waves (kinetic energy). The tsunami traveled west across the Bay of Bengal at rapid pace with abundant energy flux and hit the eastern seaboard of Sri-Lanka and South India and also the south-western tip of India. The tsunami was reported to have hurled

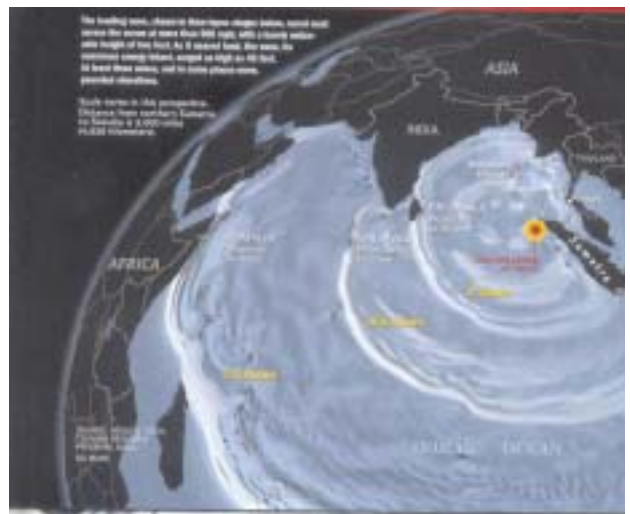


Fig-1: Earthquake generated Tsunami of Dec 26th 2004 (Source- National Geographic)

a wall of water over 20 feet high. The water surged over coastal areas to great distances inland, inundating and

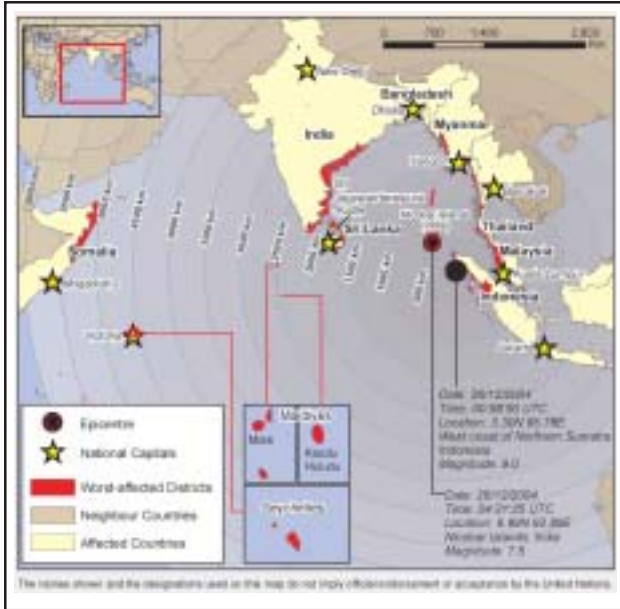


Fig-1a: Effect of December 26,2004 ,mega earthquake(Source-USGS)



Fig-2: Model illustrating the subduction of Indian plate below Burmese plate(Source-National Geographic)

causing much flooding, debris flows, and sweeping materials and people out to sea as the waters receded. The tsunami is typically a series of waves that arrive at a coast over time, sometimes spaced up to an hour apart or more. The trail of destruction left behind is beyond imagination and left 255,000 people dead.

The sudden high tidal waves swelled out of the Indian Ocean without warning, caught people unaware and wrecked havoc of hitherto unknown proportions at specified seaboard locations. A geological explanation as to why only the specific seaboard along the east coast of South India off Chennai, Nagapattinam and Colachel and Karunagapally

in Kerala in the west coast near bore the brunt of the devastations following the striking of tsunami waves is proposed in this paper.

Regional seismotectonics

Globally, there are three major belts in terms of earthquake activity (Fig-3). Most of the earthquakes occur in the Circum- Pacific belt which goes around the rim of Pacific Ocean. The second most active belt is the Alpine-Himalayan belt which encompasses South East Asia near Java- Sumatra through Andaman Islands, Indo-Burmese Ranges, Himalayas, and then moves west through Iran onto Greece and Italy. The third major seismic belt consists of mid-oceanic ridges accounting for minor tremors. Most tremors occur at shallow depths (0-70kms). The Indo-Australian plate long identified as a single plate appears to have split apart just south of equator beneath Indian Ocean. The two are now moving in slightly different directions. The Indian plate is bounded by Sunda Trench in the east and Central Indian and Carlsberg Ridges on the west. The Indian plate is in NNE motion since collision with Eurasian plate 50Ma. The concurrent migration and collision with Australian plate in the eastern boundary is a zone of active seismicity. On the western edge of Indian Ocean, the Indian plate interacts with Arabian and Iranian Microplates of Eurasian block creating a subduction zone. On the east, the Indo-Australian plate subducts beneath the Burma and Sunda plates formed the extensive Sunda Trench- a very active seismic region where large earthquakes are frequent. A divergent boundary separates the Burma Plate from the Sunda Plate in the north. The Burma Plate encompasses the northwest portion of the island of Sumatra as well as the Andaman and Nicobar Islands.

The Indian Subcontinent in particular the Peninsular Shield is sandwiched between two regions of high seismic activity. Indian plate comprises of (i) the two arms of the Indian Ocean viz, Bay of Bengal and Arabian



Fig-3: Major belts of earthquake activity



Sea, (ii) Himalayas including the adjacent Northeast India and (iii) Peninsular Shield. The Indian subcontinent is a mosaic of crustal blocks, unrelated to each other, juxtaposed and sutured together in different periods of earth history by diverse geology and tectonic history. It is riven with transcurrent faults and shears of Precambrian antiquity. The physiographic youth of Western Ghats, predominant eastern drainage of peninsula, antecedent character, occurrence of erosional surfaces at different levels and water falls of great magnitude in the upper reaches of the rivers and flow in deep gorges project the view that the peninsula of India did not represent a rigid stable mass. The Indian plate is bordered to the SW by spreading centre (Central Indian Ridge) subjecting the Peninsular Shield to NNE directed regional compressional stresses that resulted in the Indian plate underthrusting beneath the Eurasian plate with emergence of Himalayas. The backthrust of this collision acts on the shield in addition to the continued NNE drift of the Indian plate.

Ocean current pattern

The ocean current pattern in the Bay of Bengal and Indian Ocean had much critical bearing on the directional trend of the December 26, 2004 tsunami. Currents and tides are controlled by the overall shapes of the ocean basins as well as the smaller sharp ocean ridges. Ocean circulation is influenced by seafloor topography in a variety of ways. Bathymetry can steer the path of currents (Fig-4). Topography also has a vital role in determining vertical motions in the ocean. The surface water circulation in the tropical Indo-Pacific in modern time is marked by weak westward flow of tropical waters from the Pacific into the Indian Ocean through the Indonesian Seaway (Fig-5). The water enters from the Central Equatorial Current System of the Pacific, a very small part flows into the Indian Ocean (South Equatorial Current) and a small part returns back

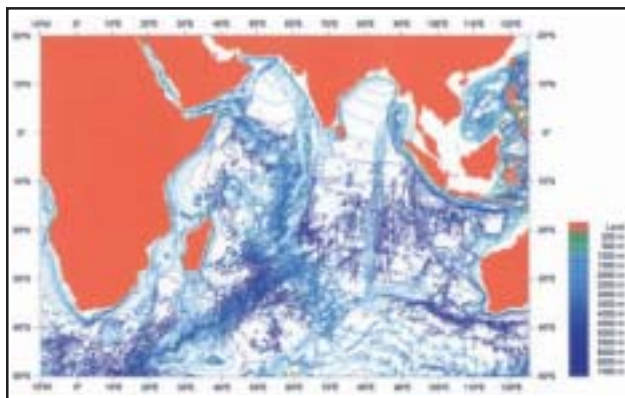


Fig-4: Bathymetry map of the Indo-Pacific

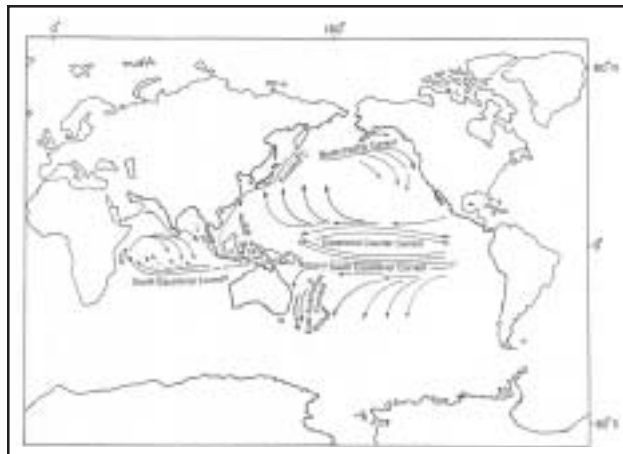


Fig-5: Modern surface water circulation in the tropical Indo-Pacific (after M.S.Srinivasan,)

as East Australian Current in an anti-clockwise motion causing gyral circulation in the waters of the Pacific (M.S.Srinivasan,2000) This incoming of relatively excess fresh waters from the western Pacific to the Indian Ocean through the Indonesian seaway is an important regulator of the meridional overturning of these oceans and hence the global thermohaline circulation. The direction of the currents change with the monsoon drift during the Northern hemisphere's summer called south west monsoon and during its winter as north east monsoon drift. The earthquake occurred during north east monsoon time (Fig-6).



Fig-6: Ocean currents (Oxford Atlas)

Rationale explaining events

The Banda Aceh earthquake was located at the extreme western end of the 'ring of fire' which accounts for 81% of

the world's largest earthquakes. Three days prior to this quake a temblor of magnitude M8.1 occurred in a completely uninhabited region west of New Zealand's Auckland islands. The location is in the extreme eastern rim of the ring of fire. This cannot be treated as an isolated geological event. The quake was a catalyst for the mega quake as the two events occurred on opposite sides of the Indo-Australian plate. Consequent to this seismic activity tsunamis were generated which hit different coasts in the Indian Ocean with devastating effects on both human lives and property. On May 20th and 21st once again both the east and west coasts experienced storm swells following an earthquake of magnitude M6.9 that rocked Northern Sumatra. The waves that rose to the height of even 5m height and run - up inundating inland areas in the Kerala Coast coincided with the travel time of waves from the epicenter. Of course, the season changed to SW monsoon and consequently ocean current pattern. The northern extension of Sunda Trench skirts Andaman Nicobar islands and the continued occurrence of fresh earthquakes suggest that the subduction of the Indian Plate beneath the Burma Plate is active and ongoing.

The rationale for the southern part of Tamil Nadu and Kerala bearing the powerful shoreward propagating wave energy of tsunami waves are discussed below.

- An estimated 1200 kms of fault line slipped 20m along the subduction zone where the Indian plate subducted beneath the Burmese plate causing the generation of tsunami waves. The waves thus radiated from the N-S trending energy line source rather than a point source (Fig-7). This explains why the eastern seaboard of Peninsular India was severely affected and areas northern to the tsunamigenic zones were less affected. The eastern sea board off Chennai and Nagapattinam being closer to the source area experienced attendant severe devastations while areas farther away near Colachel and Karunagapally had damages of lesser extent. The proximity of Nagapattinam to epicenter enhanced its receiving the onslaught of the tsunamis.
- The high speed tsunami waves were topographically (bathymetry controlled) steered as indicated by the different locations in Asia and Africa (Fig-8). The damaging power was maximum westward with reference to the epicenter reducing northward away from the source.
- The earth's rotation called Coriolis force also was

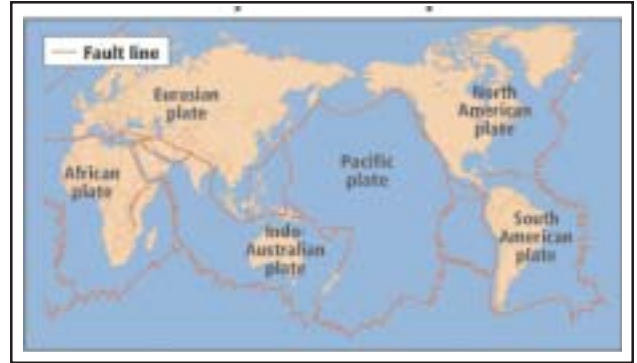


Fig-7: N-S trending energy line source in Indo-Burma interface (Source- USGS)



Fig-8: Tsunami generation location and travel direction (after A.C.Narayana)

significant in steering the waves to the right side of propagation direction in view of the characteristically long wavelength of the tsunami waves. The Earth is a spinning globe where a point at the equator is traveling at around 1100 km/hour, but a point at the poles is not moved by the rotation. This fact means that projectiles moving across the Earth's surface are subject to Coriolis forces that cause apparent deflection of the motion.. The Coriolis force deflects to the right in the Northern hemisphere and to the left in the Southern hemisphere when viewed along the line of motion.

- The continental slope from Sri Lanka to Chennai is steep and the surge of tsunami to the coast at high velocity encountered a barrier through the narrow bathymetric window and gained run up heights in the nearshore areas particularly Nagapattinam, Cuddalore, etc. causing significant high wave amplitude with shoaling effect (Fig-9).
- Run-up height is the height to which water level on the shore is raised above mean sea level or normal



Fig:-9: Ocean bottom topography of Indo-Pacific (Source-USGS)

tide. The extent of vertical run-up of sea water during tsunamis depends on earthquake velocity and frequency of tsunami waves, nearshore bathymetry, beach profile and land topography. The reported run-up heights of the tsunami at various places based on inferences of witnesses is tabulated below after Department of Ocean Development, Chennai:-

Sumatra NW coast	10-15m
Sri Lanka east coast	5-10m
India east coast	5-6m
Andaman islands	5m
Thailand Phuket	3-5m
Karunagapally	5m

Locations having gentle slopes are vulnerable to storm surges and high tides allowed landward penetration of seawater to long distances in Nagapattinam and Colachel. Those areas with elevated landforms adjoining the coastline permitted only short penetration as in Chennai where the elevated beaches acted as barriers. Presence of creeks caused inundation of land with seawater to farther distances. The coastal land slopes are presented here to correlate the run-up levels with respect to land topography.

Nagapattinam	1 in 227	1500m penetration
Chennai-Besant Nagar	1 in 39	200m penetration

- Nagapattinam is located closest to the earthquake epicenter than any other seaboard point in the Indian mainland seaboard. The bathymetry and land topography also played a significant role in Nagapattinam (Fig-10). The proximity factor as already



Fig-10: Bathymetry around South India (Oxford Atlas)

stated, coupled with the diffracted waves from the northern tip of Sri Lanka wrecked havoc there.

- Influence of geomorphology (shape) of the coastline on run-ups was also a factor in determining the damaging activity of the tsunami waves. The eastward concave shape of the coastline is remnant of its dismemberment from Antarctica during 130Ma. These notches are sites where geological events recur reflect fields of active stress along with the favourable hypsometry for wave entry from the sea. These are protracted weak zones or crustal discontinuities undergoing phases of ongoing reactivation.
- High energy tsunami waves traversed horizontally across Indian Ocean, the east coast of Sri Lanka absorbed the energy and only the refracted waves with low energy reached the west coast of Sri Lanka and south-east coast of Tamil Nadu as confirmed by Indian Department of Ocean Development. The southern part of Tamil Nadu falling on the leeward side was to an extent protected by the land cover of Sri Lanka probably the southern most edge deflecting and diffusing the energy propagation onto south western Sri Lanka. Thus Tuticorin situated south of Rameswaram witnessed tsunami almost an hour after it hit Chennai and Nagapattinam coast. It is reported that the rocky seabed which used to be always under water in Tiruchendur coast near Tiruchendur temple got exposed because of the receding water up to 50metres from the normal low tide mark as sea water had receded temporarily before returning to normal.

- Southern Indian shield forms one of the most diverse and dynamic regions among the cratonic shield areas of the earth. The major rivers flow along the surface traces of faults and shears. The Palghat-Cauvery shear enters the sea in the vicinity of Nagapattinam Coast. Radials emanating from Cambay node, one passing through Cuddapah Basin to Chennai further extending into Bay of Bengal and another to Gulf of Mannar through Dharwar craton are prominent (Fig-11). The linear from Cambay triple junction to Gulf of Mannar triple junction and that to Chennai are suggestive of major structural alignments. The linears are interpreted to be vulnerable to reactivation due to resistance offered by the continued convergence of the plates since early Eocene. The pronounced lineaments harbinger future tectonic events likely to deform Peninsular Shield

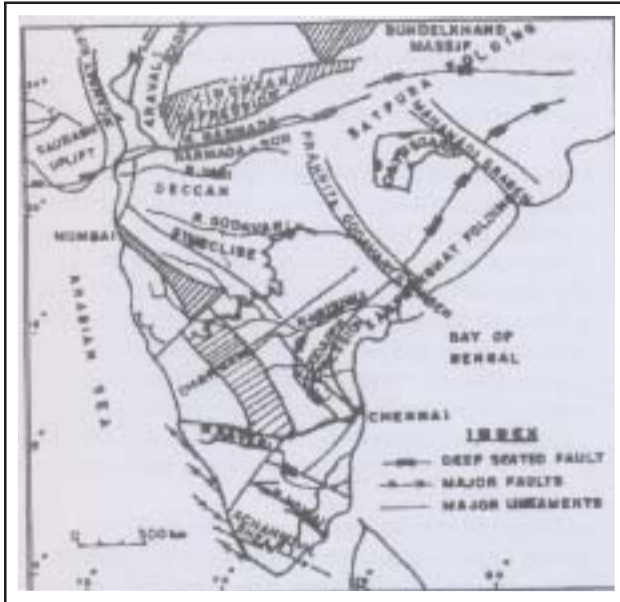


Fig-11: Tectonic map of Peninsular India

- Continents are not only moving horizontally relative to the earth's rotational axis but also relative to each other. The fragmented Indian shield has been differentially moving relative to each other ever since Tertiary times. The present day response to accumulated stresses and attendant seismicity is guided by structure generated as a consequence of tectonic history of the shield. The progressive increase southward in relative velocity of drift in Peninsular India resultant of welding of the northernmost subcontinent also is a relevant factor..

- It is observed that the specific devastation locations fall in areas of low surface conductance but higher than the high resistive granitic terrain in the land (Fig-12). The tsunami hit areas of distinct conductance contrast with their neighbouring areas. The sites bordered by hard rock in the land have low elevation and slopes gradually seaward. Preceding the tsunami, the sea recedes towards the ocean to occupy the created space in the sea as a result of sea water wobbling up in mid ocean due to sudden release of energy. As the sea water recedes from the coast, it is obvious that once tsunami waves transgress landward it enters much into the landward side. The recession of sea near Azhikal in South Kerala had exposed the sea floor, it is reported. Incursion will be greatest at places originally showing contrast in conductance as practically observed with adjoining land. The absence of devastation in river mouths of Krishna and Godavari may be ascribed to this reason in addition to geographical position with respect to epicenter. Waves did rise off Vishakapatnam, Kakinada and Nizampatnam Coasts. The restriction of effects to Kerala Coast sparing Karnataka Coast could also be due to the faulted coastline juxtaposing elevated land against the sea off Karnataka coast.
- The west coast being on the leeward side of the propagating wavefront at the outset should have been unaffected. The forces in action were (i) Coriolis force of earth's rotation (ii) Ocean current pattern during winter months in Northern Hemisphere of a counter clockwise direction due to the orientation of the coast and prevailing wind conditions (iii) NNE drift of the

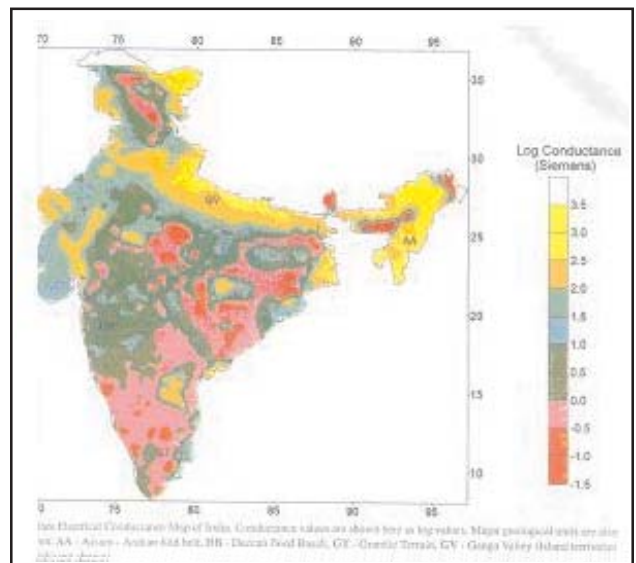


Fig-12: Surface conductance map of India (after T.Harinarayana)



Indian plate following welding of the northern edge at the Himalayas. These forces interacted with the westward moving tsunami waves and prompted the resultant deflection of the fast propagating tsunami waves onto the west coast aided by the shallow hypsometry of the South Kerala coast. The presence of Chagos Ridge to the west of Laccadive Islands in the close vicinity of the west coast of India and within the migration path of the direct tsunami wave front may also be another prominent reason for deflecting the killer waves onto Kerala coast.

- The west coast off Kerala in particular Karunagapally and Kayamkulam were affected as they are located in the vicinity of the western edge of Achankovil Shear and the west coast is faulted with estuaries at relatively lower elevations causing a run up height of nearly 5m.
- The scientists of Arizona State University noted that the brunt of the tsunami had hit Sri Lanka's eastern shore, but that the southwestern, or leeward, side had also been hit hard. Their analysis of the available data concluded that two or three waves hit the area within an hour, having been channeled and bent around the southern tip of the island, and that another wave struck around two hours later, having bounced back after hitting India or the Maldives. They say that existing computer models cannot adequately explain or predict the wave amplitudes in southwest Sri Lanka, likely due to small scale ocean processes, including topographic variations due to coral removal, that are not yet well understood.

The combined effects of ongoing geological and marine processes interacted to steer the powerful tsunami waves onto specific locations on the east and west coasts of India causing damages of unprecedented dimensions.

Conclusions

The major brunt of the devastation following the devastating tsunami triggered by a great megathrust earthquake of magnitude M9.3 that struck the Sumatra

Trench more than 2000kms to the south east of Chennai in the Indian Ocean was borne besides the Sri-Lankan Coast by Tamil Nadu and South Coastal Kerala. The devastations have occurred in areas with comparatively lower electrical surface conductance. Proximity to source, ocean current pattern, earth's rotation, ocean bottom topography and tectonic history of the area played a dominant role in steering the tsunami waves onto specific landfall points which faced the power of tsunami waves.

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