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## Case Study I: Tsunami Hazards in the Indian Ocean

The eastern Indian Ocean basin is a region of high earthquake and volcanic activity, so it should come as no surprise that tsunamis pose a threat to the Indian Ocean basin. (For example, the 27 August 1883 eruptions of Krakatoa produced a series of tsunamis that killed over 36,000 people in Indonesia.) However, most federal governments and international regarded the overall tsunami threat in the Indian Ocean as minor – prior to the 26 December 2004 event. Today we discuss the roots of this complacency and explore how it might be avoided as a consequence of the Mission 2009 design.

### Required Readings

*Tsunami Information, a basic web site, produced by the Australian Bureau of Meteorology, that provides background information on the phenomenon and, specifically, the 26 December 2004 event:*

*[http://www.bom.gov.au/info/tsunami/tsunami\\_info.shtml#physics](http://www.bom.gov.au/info/tsunami/tsunami_info.shtml#physics)*

*Prasetya, G. S., De Lange, W. P., & Healy, T. R. (2001). The Makassar Strait Tsunamigenic Region, Indonesia. *Natural Hazards*, 24, 295-307. (pdf attached)*

*In Wake of Disaster, Scientists Seek Out Clues to Prevention (7 January 2005, Science, pdf attached)*

*Quake follows scientists' predictions (MSNBC story, 28 March 2005, archived at <http://www.msnbc.msn.com/id/7317057/>)*



## The Makassar Strait Tsunamigenic Region, Indonesia

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**Abstract.** The Makassar Strait region has had the highest frequency of historical tsunami events for Indonesia. The strait has a seismic activity due to the convergence of four tectonic plates that produces a complex mixture of structures. The main tsunamigenic features in the Makassar Strait are the Palu-Koro and Pasternoster transform fault zones, which form the boundaries of the Makassar trough.

Analysis of the seismicity, tectonics and historic tsunami events indicates that the two fault zones have different tsunami generating characteristics. The Palu-Koro fault zone involves shallow thrust earthquakes that generate tsunami that have magnitudes that are consistent with the earthquake magnitudes. The Pasternoster fault zone involves shallower strike-slip earthquakes that produce tsunami magnitudes larger than would normally be expected for the earthquake magnitude. The most likely cause for the increased tsunami energy is considered to be submarine landslides associated with the earthquakes. Earthquakes from both fault zones appear to cause subsidence of the west coast of Sulawesi Island.

The available data were used to construct a tsunami hazard map which identifies the highest risk along the west coast of Sulawesi Island. The opposite side of the Makassar Strait has a lower risk because it is further from the historic tsunami source regions along the Sulawesi coast, and because the continental shelf dissipates tsunami wave energy. The greatest tsunami risk for the Makassar Strait is attributed to locally generated tsunami due to the very short travel times.

**Key words:** historical tsunami, hazard mapping, tectonics, source mechanisms, mitigation.

### 1. Introduction

Active seismic zones within the Indonesian archipelago are a result of the convergence of the Eurasian, Indo-Australian, Caroline and Philippines plates. The convergence results in the formation of a complex region containing a subduction zone, collision zone, fault zone, back-arc thrusting zone and back-arc spreading zone (Figure 1). Most of these active zones are located under the sea and produce large shallow earthquakes which possess a high tsunamigenic potential. The historical record of this region indicates that eighteen tsunamis have been generated since 1900 by large shallow earthquakes (Prasetya *et al.*, in press). Fourteen of these tsunamis have occurred in the eastern part of the Indonesian archipelago, showing that the seabed structure of this area is more unstable and more capable of generating tsunamis than other parts of the archipelago.

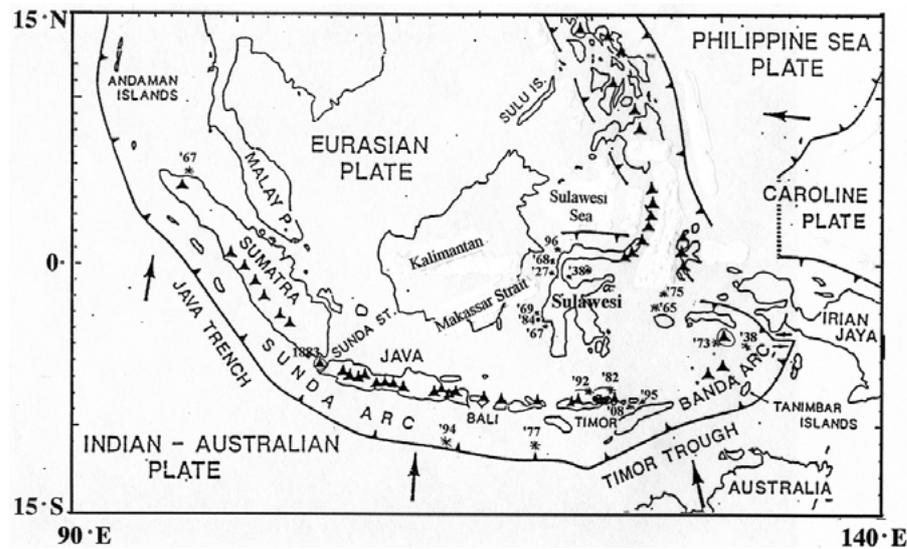


Figure 1. Tectonic and tsunami map of the Indonesian archipelago. Since 1900, eighteen tsunamis have been generated by large shallow earthquakes. Six of these tsunamis have occurred in the Makassar Strait. Numbers on the map represent the year of the tsunami event; arrows represent the direction of plate movement and triangles stand for volcanoes. Bold lines with triangles represent the trench and direction of plate movement (Source: Prasetya *et al.*, in press).

The highest frequency of tsunami events for the Indonesian archipelago occurs in the Makassar Strait (Figure 1); a zone of major geological importance. This strait has been identified as an important boundary between the western and eastern Indonesian archipelago from geotectonic synthesis of available geophysical data (Situmorang, 1976; Katili, 1978; Silver *et al.*, 1983). These data also show the presence of major potential hydrocarbon-containing basins on both sides of the strait.

Of the eighteen tsunamis recorded since 1900, six were generated within the Makassar Strait as a result of back-arc spreading that produced large shallow earthquakes (focal depth <60 km). The epicenters of all tsunamigenic earthquakes lies close to the western coast of Sulawesi Island, and their distribution is related to two fault zones which cross the Makassar Strait (Prasetya *et al.*, 1997, in press). These fault zones are the Palu-Koro fault zone, which connects with the Sulawesi subduction zone in the north and the Pasternoster fault in the south. The bathymetry map for the region (Figure 2) clearly shows two steep lineaments, produced by the faults, across the Makassar Strait (Katili, 1978).

This paper will define the characteristics of the tsunamigenic area of the Makassar Strait based on an analysis of geological and geophysical features, and historical tsunami event data. The tsunami hazard for the coastal regions of the Strait will be defined, and the risk for the development of coastal zone discussed.

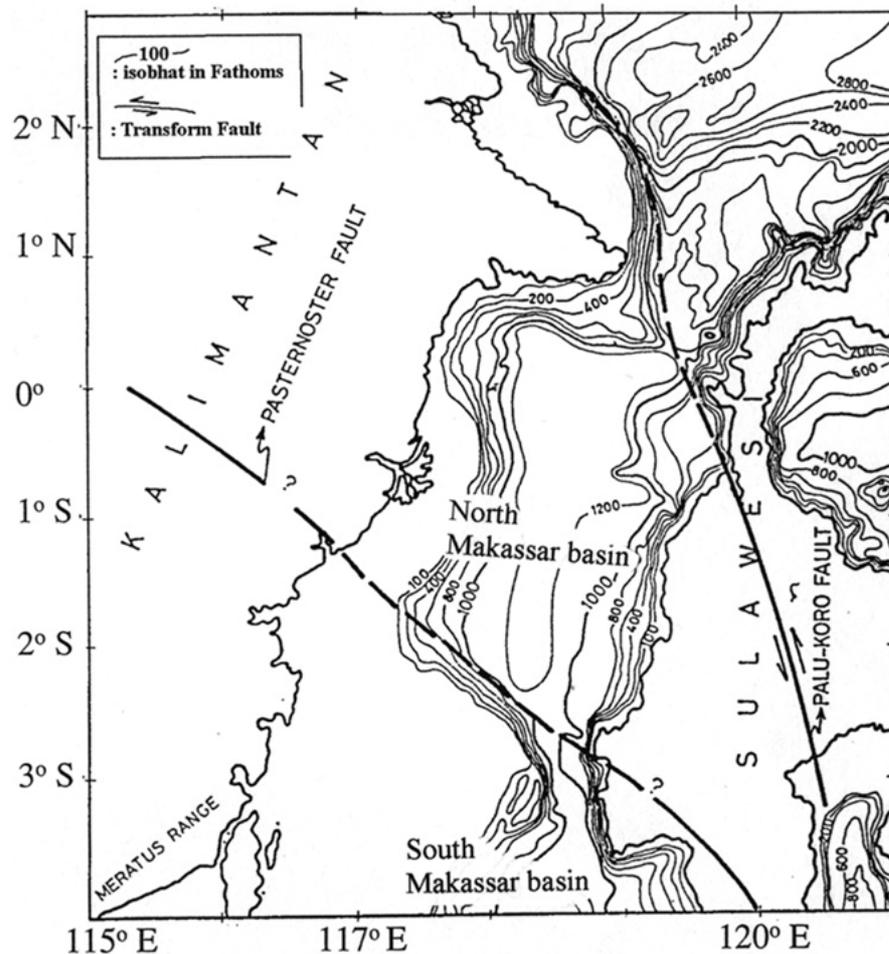


Figure 2. Bathymetry map of the Makassar Strait showing two steep lineaments produced by Palu-Koro fault and Pasternoster fault across the Makassar Strait. The Pasternoster fault divides the Makassar basin into the North and South Makassar sub-basins (adapted from Katili, 1978).

## 2. Tectonic Setting

The Makassar Strait is a marginal basin occupying the continental shelf slope and rise areas between Kalimantan and Sulawesi (Katili, 1978). The marginal basin was formed by the spreading of the sea floor between Kalimantan and Sulawesi during the Quaternary. The spreading is concentrated along the Pasternoster and Palu-Koro transform faults (Figure 2). The Palu-Koro fault zone connects with the North Sulawesi Trench, and separates the Sulawesi Sea from the Makassar basin (Katili, 1978; Silver *et al.*, 1983; Hamilton, 1988). The Pasternoster fault divides the Makassar basin into the North and South Makassar sub-basins as shown by the bathymetry map.

A geotectonic synthesis of the Strait shows that it is a boundary between the western and eastern Indonesian archipelago. The western archipelago comprises the Sunda land of Phanerozoic volcanic/plutonic arcs and their concentrically arranged subduction zones. To the east of the Strait is the Mid- to Late Tertiary volcanic/plutonic arc of Sulawesi with its matching subduction zone (Katili, 1978; Silver *et al.*, 1983).

The bathymetry map of the Makassar Strait clearly shows two lineaments of steep gradient representing the Pasternoster and Palu-Koro transform faults forming the southern and northern boundaries of the Makassar trough respectively (Figure 2). Examination of the 1000m isobath closing the deep water portion of Makassar Strait indicates that it is possible to fit southern and central Sulawesi against the Kalimantan shelf by restoring the presumed east and south-southeasterly movement of this region. The movements are indicated by Pasternoster, Palu-Koro and other parallel transform faults on this area (Katili, 1978; Hutchison, 1990).

The spreading centers of the Makassar Strait in the north have interacted with the younger spreading of the Sulawesi Sea. The more recent spreading moved Sulawesi to the south-southeast along the Palu-Koro transform fault and created the southeast subduction zone to the northwest of Sulawesi. This movement destroyed the spreading centers of the the Makassar trough. In the south, the spreading of sea floor of the Makassar trough along the Pasternoster fault was accommodated by a small east-dipping subduction zone.

Using the inferred structure of Makassar Strait (Figure 3), and seismic profiles (Figure 4) from the southern part of Makassar Strait, Katili (1978) characterised the spreading behaviour of the Makassar trough. Spreading in the northern Makassar Strait has proceeded about a pivot point further north. The spreading has occurred less rapidly near the pivot point, resulting in compressional structures forming within the rocks north of the pivot. More rapid spreading to the south has produced tensional structures involving rifting on the Kalimantan side of the Strait, and undisturbed post-Pliocene sediments overlying the oceanic basement (Katili, 1978; Hutchison, 1990). The east-west seismic profile to the south shows similar features, with a remnant of an older trench filled with slumping material from Sulawesi on the eastern side.

### 3. Seismicity and Focal Mechanisms

To define the tsunamigenic potential of the Makassar Strait, an analysis of seismicity (focal mechanisms, and the stress and slip distributions of the large shallow earthquakes) was undertaken and matched with the historical data of tsunami events. As expected, the earthquake distribution in the Makassar Strait is controlled by the underlying tectonic structure (Figure 5). The transform faults are associated with major shallow earthquakes of focal depth less than 60 km. Most historic epi-

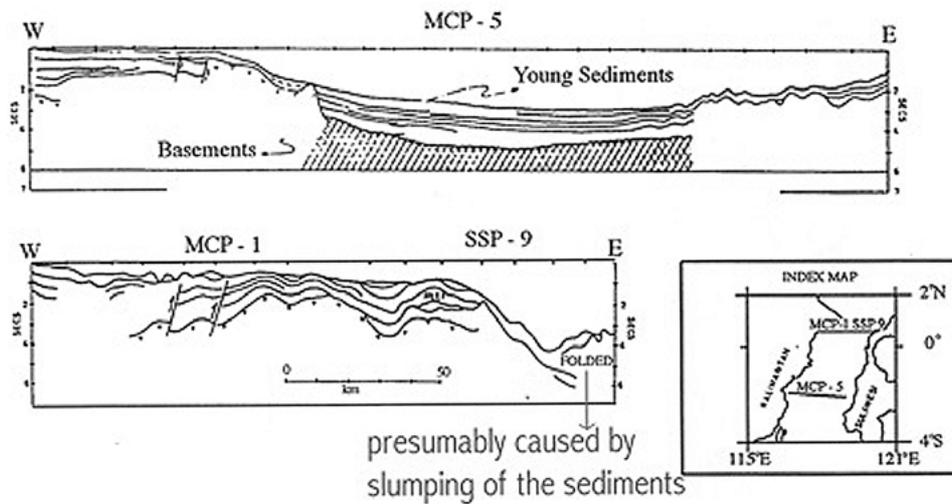


Figure 3. East-west section across the central and northern part of the Makassar Strait demonstrates the tensional structure caused by rifting on the Kalimantan side (western part). The undisturbed post-Pliocene sediments overlying the basement consist of oceanic crust. The eastern part of the section shows some folding, presumably caused by slumping of the sediments into the Makassar Strait basin (Source: Katili, 1978).

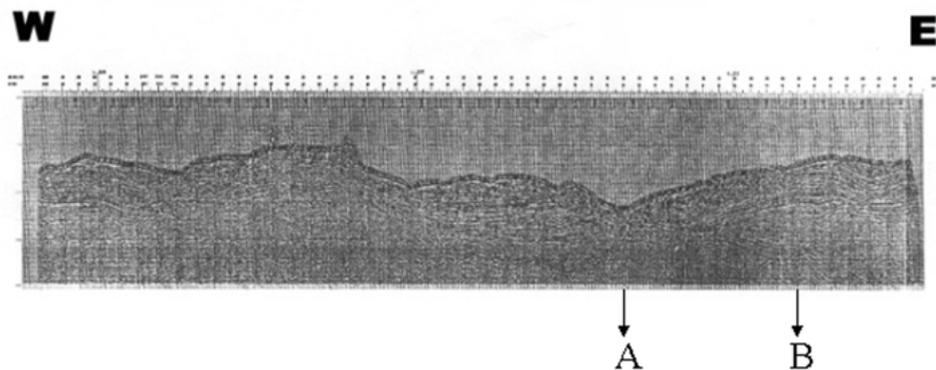


Figure 4. Seismic profile across the southern part of the Makassar Strait showing the remnant of an older trench filled with slumping material from the east (Sulawesi side). This figure shows the possibility of submarine slumping to generate tsunami as a second generating mechanism (Source: Katili, 1978). 'A' is the location of the present trough and 'B' is the location of the remnant of an older trench.

centers occur close to the coastline of the western coast of Sulawesi Island, where the transform faults start to cross the Makassar Strait towards Kalimantan.

The Gutenberg-Richter  $b$ -value and estimated maximum seismic moment were used to examine the seismic activity. The  $b$ -value is the parameter of the likelihood of an area being subject to natural earthquakes. High  $b$ -values indicate a highly seismic region. Puspito (1995) calculated the  $b$ -values and estimated seismic mo-

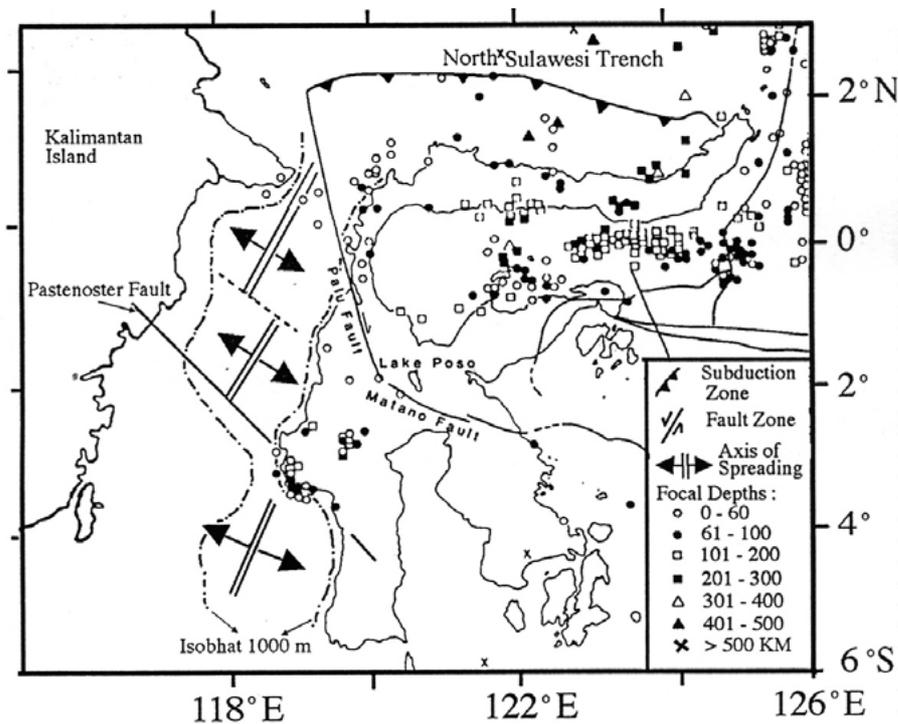


Figure 5. The earthquake distribution in the Makassar Strait is controlled by the Pastenoster and Palu-Koro Fault and associated tectonic structure. Major shallow earthquakes occur close to the western coast of Sulawesi.

ments for the whole Indonesian region based on shallow earthquake data for the period 1975–1994 for every  $1^\circ \times 1^\circ$  block. Within the Makassar Strait, the Sulawesi coast is characterized by high *b*-values and estimated seismic moments (Figure 6). The *b*-value varies from 0.5 to 1.7, and the estimated seismic moment varies from 1025 to 1029 dyne-cm.

Focal mechanisms of large shallow earthquakes in the Sulawesi regions are dominated by thrusting and strike-slip movements. The Palu-Koro fault zone produces strike-slip earthquakes, whereas the subduction zone of the northern Sulawesi and Molluca Sea produces thrust earthquakes (Puspito, 1995). This distribution of earthquake motions can be attributed to the pattern and orientation evident for stresses associated with historic earthquakes. The compression (*P*) and tension (*T*) axes for shallow earthquakes within the back-arc rift of the Makassar Strait and the northern Sulawesi subduction zone are generally perpendicular to the structural trend of Sulawesi Island. Further, the fault slip distribution of shallow earthquakes, whose seismic moments are greater than  $10^{25}$  dyne-cm, is similar to the compression axes pattern (Puspito and Triyoso, 1994; Puspito, 1995). Given this correspondence it is likely that Makassar Strait will continue to experience the same types of thrust and strike-slip earthquakes as observed in the past.

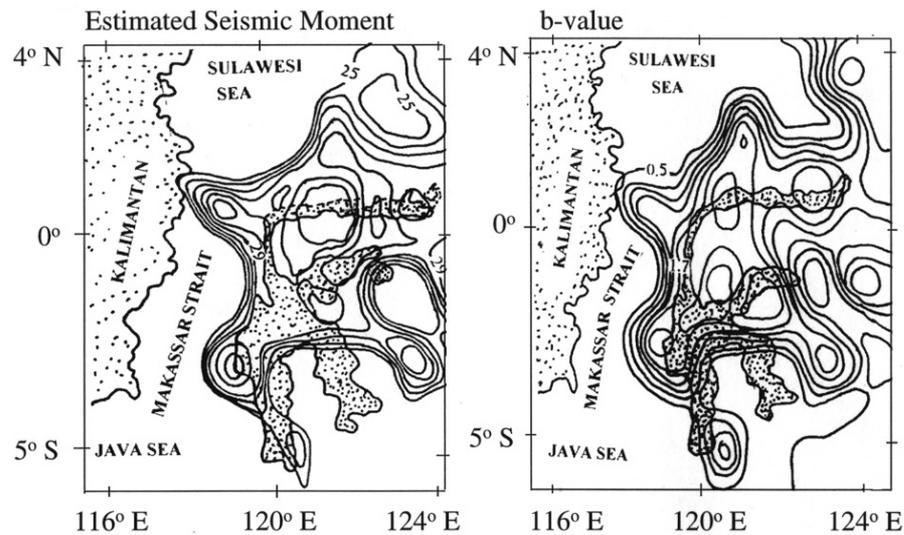


Figure 6. The estimated seismic moment and the b-value map of the Sulawesi and Makassar Strait region. The b-value is the parameter of the likelihood of an area being subject to natural earthquakes. High b-values indicate a highly seismic region. The Sulawesi coast is characterised by high b-value and estimated seismic moment (source: Puspito 1995).

#### 4. Historical Tsunami Events

Fourteen tsunami events were recorded for Sulawesi Island between 1820 and 1982 (Soloviev *et al.*, 1992). Since 1927, the Makassar Strait recorded six tsunamis. All the tsunamis experienced in the Makassar Strait were related to earthquakes involving the Palu-Koro fault zone, the north Sulawesi subduction zone system, and the Pasternoster fault zone (Prasetya *et al.*, in press).

The Palu-Koro fault zone has produced three tsunami events: December 1, 1927 (Palu Bay); August 14, 1968 (Palu Bay); and January 1, 1996 (Simuntu-Pangalaseang). The locations of the epicenters of the generating earthquakes were all close to the west coast of Central Sulawesi. Another three events were produced by earthquakes along an extension of the Pasternoster fault: April 11, 1967 (Tinambung); February 23, 1969 (Majene); and January 8, 1984 (Mamuju). The epicenter locations were close to the west coast of South Sulawesi. The parameters of all six events are given in Table I.

#### 5. Tsunami Source Characteristics

From historical data, tsunami sources in the Makassar Strait are mainly shallow earthquakes with focal depths <25 km. The epicenter locations were close to the Sulawesi coastline (within 10–100 km from the coastline) and are associated with the Palu-Koro fault zone and the Pasternoster fault zone. The focal mechanisms of the tsunamigenic earthquakes were mainly thrusting (4 events), with only one

Table 1. Historical tsunami events in the Makassar Strait

Date	Hypocenter	Magnitude earthquake	Maximum intensity	Mechanism	Wave height (m)	Place, related phenomena and victims
Dec. 1, 1927	0.7 S, 119.7 E	6.3	-	-	15	West Cent. Sulawesi, Palu Bay, subsidence 0.5–12 m, 14 dead, 30 injured
Apr. 11, 1967	3.3 S, 119.4 E, 20 km	5.5–6.3	VII–VIII	THRUST	-	Tinambung, 58 died and 100 injured, the water suddenly retreated.
Aug. 14, 1968	0.7 N, 119.8 E, 25 km	7.4	VII–VIII	NORMAL	10	West Cent. Sulawesi, Palu Bay, subsidence 2–3 m (Mapaga villages), 500 m inland inundated. 200 died
Feb. 23, 1969	3.1 S, 118.5 E, 13 km	6.1	VIII	THRUST	2–6	South Sulawesi, Majene, 64 died
Jan. 8, 1984	2.77 S, 118.8 E, 14.8 km	6.6	VII	THRUST	-	Mamuju, no record (?)
Jan 1, 1996	0.83 N, 120.1 E, 15 km	7.7	VII–VIII	THRUST	1–3.4	West Coast Central Sulawesi, Simuntu – Pangalseang, Subsidence 0.5–2 m, 9 died, 63 injured

ME = magnitude earthquake; MI = Maximum Intensity; MM = Mechanism.

event involving normal movement. The focal depths varied between 13–25 km and the earthquake magnitude ranged from 5.5 to 7.7 (Prasetya *et al.*, in press).

Pasternoster fault zone tsunamigenic earthquakes had lower magnitudes (5.5–6.6) than those from the Palu-Koro fault zone (6.3–7.7). The focal depths were also shallower for the Pasternoster fault zone (13–20 km) than for the Palu-Koro fault zone (15–25 km).

Tsunamigenic earthquakes within the Pasternoster fault zone are located on a steep bottom slope close to the southern Makassar sub-basin at water depths of 400–1000 m. Prasetya *et al.* (in press) calculated the characteristics of the initial tsunami wave for Pasternoster fault zone sources by using empirical formulae and numerical simulations. The results indicated that the initial wave is too small to account for the devastating effects of tsunami waves documented on the coastline. Therefore a secondary source mechanism for generating or augmenting the tsunami is considered necessary.

Submarine slumping as the secondary mechanism for tsunami generation is considered the most likely cause for the large waves observed (Prasetya *et al.*, in press). Seismic profile data of the southern Makassar Strait (Figure 4) show the remnant of an older trench filled with slumping material from the east (Sulawesi side). Coastal land subsidence was also observed in association with all of the tsunami events. Therefore there is reasonable evidence to show that submarine slumping has been triggered by earthquakes. The available seismic data do not show any evidence of slow rupture velocities, or unusually large displacements that could provide an alternative explanation for the larger than expected waves.

## 6. Coastal Tsunami Response

To date all of the tsunami casualties and damage have been located along the west coast of Sulawesi. There are no historical reports of damage on the east Kalimantan coast. Numerical simulations of tsunami propagation in the Makassar Strait (Prasetya, 1997) shows that generally the wave height on the east coast of Kalimantan is less than that on the west coast of Sulawesi. Bore formation by the leading wave on the east Kalimantan coast is possible, due to the broad and relatively shallow shelf area which causes the wave to break offshore. In contrast, the western coast of Sulawesi has a narrow shallow shelf area.

Run up characteristics of tsunami waves vary from coast to coast depending upon the shoreline configuration and bottom topography. Pelinovsky *et al.* (1996) examined the behavior of tsunami waves on the west coast of Sulawesi following the event on January 1, 1996. The tsunami was preceded by recession of the sea, and the wave usually broke on spits shielding the villages from the sea. Within rivers the tsunami waves produced devastating effects; not only by direct forces, but also indirect effects such as river flooding upstream caused by blocking the river flow. The numerical modelling results for this event are shown on Figure 7. The initial wave form at the source (at  $t = 0$  s) showed that the negative wave

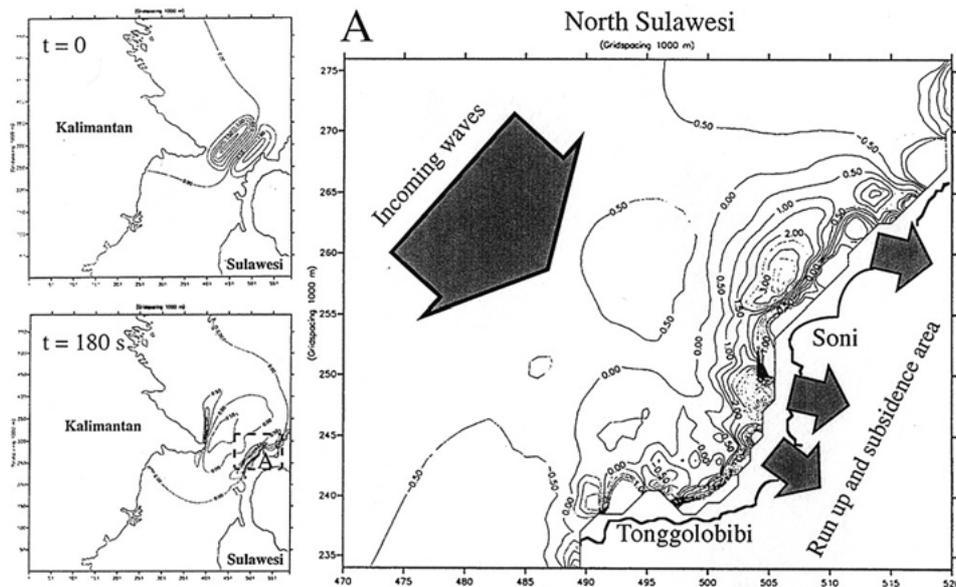


Figure 7. The numerical modelling results of a recent event, January 1, 1996, shows the propagation of tsunami in the Makassar Strait and Sulawesi Sea. 'A' is the location where the tsunami wave has major impacts. The boldline on Fig 'A' represents the inundated and subsidence area; the small arrows show the direction of the wave runup on land.

fronts are facing to the Sulawesi coast and after 180 s, the tsunami waves already attacked the west coast of northwestern Sulawesi. Detailed calculation in the region labelled 'A' showed the dynamic effect of tsunami waves at the coastline with the arrows representing the direction of the wave front. At the eastern coast of Kalimantan the waves are only concentrated at the tip of the Kalimantan Peninsula and not spread out over the large area.

Interestingly all tsunami events are accompanied by coastal land subsidence which varies from 0.5–12 m (Prasetya *et al.*, in press). This subsidence added to the tsunami impact. A recent example of this effect was at Palu Bay, where Mapaga villages were submerged during the 1968 tsunami event. The remains of the villages can still be recognized. The area affected by subsidence mainly had Quaternary and Late Tertiary terrestrial and marine sediments (Katili, 1978). Besides the subsidence, there is transport of sediment during the tsunami action on the shore. For instance, Pelinovsky *et al.*, (1996) found part of the coast was covered with sand in the region of Pangalaseang by the January 1, 1996 event.

## 7. Tsunami Hazard Map

Results from geology and geophysical studies can be combined with historical data of tsunami events, bathymetric data, and numerical modelling to provide the necessary information to permit the construction of a tsunami hazard map (Figure

8). This map summarises the tsunamigenic earthquakes and other potential tsunami sources in the Makassar Strait. It also defines the tsunami hazards affecting the coast around the Makassar Strait. Such a map provides basic information to the coastal planner considering development of the coastal area in this region, so that they can avoid the possible hazard caused by tsunamis.

The source areas shown on the map were derived from seismological studies (Gutenberg–Richter b-value; estimated seismic moment; focal mechanisms; stress, slip and dip distribution; seismic profiles) and bathymetric data (which defines the probability of secondary tsunami generation by submarine slumping). The source areas are divided into two groups: those areas where there is a high probability of tsunami generation based on previous events; and those areas with a high probability of tsunami generation, but where there is no record of previous events. The coastal tsunami hazard areas were derived from historical data (run up characteristics, subsidence, and sediment transport) and numerical modelling results.

From examination of the tsunamigenic source map and analysis of tsunami propagation in the Makassar Strait, it was determined that implementation of a suitable tsunami warning system for local events is difficult due to the rapid arrival time of tsunami waves. The historical tsunami waves occurred almost simultaneously with the earthquake (Pelinovsky *et al.*, 1996). Estimation of the tsunami risk for Central Sulawesi shows that a tsunami ~2 m high can be expected every 25 years, whereas tsunamis 15 m high may be expected once every 100 years (Pelinovsky *et al.*, 1996; Prasetya *et al.*, in press).

## 8. Conclusions

To provide the necessary information to permit the construction of a tsunami hazard map, it is important to carry out geological and geophysical studies, combined with historical data of tsunami events and numerical modelling results. Detailed bathymetric maps and seismic profiles, or structural cross sections, of the region are also valuable to determine the characteristics of tsunami source. These data can also identify the possibility of secondary tsunami generation mechanisms, such as submarine landslides.

The tsunamigenic area of the Makassar Strait has been mapped. Tsunamis are generated directly by thrust earthquakes in the Palu-Koro fault zone. However tsunami generation by the strike-slip Pasternoster fault appears to require a secondary mechanism of tsunami generation by submarine slumping. The coastal tsunami hazard area shows that a local tsunami provides the greatest threat to the western coast of Sulawesi. Local tsunamis also threaten the eastern coast of Kalimantan, but the effects there are reduced by increased wave dissipation compared to the west coast of Sulawesi. All historic tsunami events were accompanied by coastal land subsidence along the western coast of Sulawesi adding to the devastating effects of tsunami and earthquake. This pattern of response is expected to continue. Imple-



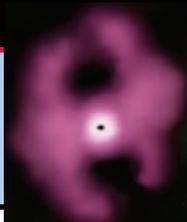
mentation of a suitable tsunami warning system for these local events is difficult due to the rapid arrival time of tsunami waves.

### Acknowledgements

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### INDIAN OCEAN TSUNAMI

## In Wake of Disaster, Scientists Seek Out Clues to Prevention

Having claimed more than 150,000 lives and destroyed billions of dollars' worth of property, nature last week reminded the world of the terrible cost of ignorance. Now the nations devastated by the massive earthquake and tsunami that ravaged the Bay of Bengal the morning after Christmas Day are hoping to marshal the political and scientific will to reduce the toll from the next natural disaster.

A week after the tragedy, the question of how many lives might have been saved had authorities in those countries recognized the danger in time to evacuate their coasts remains unanswered. But it's a hypothetical question, because the information needed to take such steps doesn't exist. That's why researchers are gearing up for an international data-collection effort in the affected countries, aimed at improving models of how tsunamis form and setting up a warning system in the Indian Ocean. "This was a momentous event both in human and scientific terms," says Costas Synolakis, a civil engineer and tsunami researcher at the University of Southern California in Los Angeles. "It was a failure of the entire hazards-mitigation community."

As relief efforts continue, scientists are traveling to the ravaged coasts to survey how far inland the water ran up at different points along the shorelines, how tall the waves were, and how fast they hit. In addition to providing a detailed picture of the event, says Philip Liu, a tsunami expert at Cornell University who is flying to Sri Lanka this week, information from these field surveys will enable researchers to test computer models that simulate the propa-

gation of tsunami waves and the pattern of flooding when they break upon the shore. The geographical span of the disaster presents an opportunity to "run simulations on a scale that has not been possible with data from smaller tsunamis in the Pacific," says Synolakis, who is joining Liu in Sri Lanka.



**Surprise attack.** While tsunami waves ravaged towns such as Lhoknga, Indonesia (as shown in before-and-after satellite photos), scientists across the Bay of Bengal saw no danger coming.

Among other surveys being conducted in the region is one led by Hideo Matsutomi, a coastal engineer at Japan's Akita University, who is studying the disaster's effects on Thailand's shoreline.

Testing and refining tsunami models would increase their power to predict future

events—not just in the Indian Ocean but elsewhere, too, says Vasily Titov, an applied mathematician and tsunami modeler at the Pacific Marine Environmental Laboratory in Seattle, Washington. Synolakis says the goal is to be able to predict, for any given coast with a given topography, which areas are most vulnerable and thus in greatest need of evacuation.

Such predictions would be easier to make if ocean basins resembled swimming pools and continents were rectangular-shaped slabs with perfect edges. But the uneven contours of sea floors and the jagged geometry of coastlines make tsunami modeling a complex engineering problem in the real world, Titov says. Exactly how a tsunami will travel through the ocean depends on factors including the intensity of the earthquake and the shape of the basin; how the waves will hit depends, among other factors, on the lay of the land at the shore.

What makes tsunami warnings even more complicated, Synolakis says, is that undersea quakes of magnitudes as great as 7.5 can often fail to generate tsunami waves taller than 5 centimeters. "What do you do without knowing precisely where and when the waves will strike and if they will be tall enough to be a threat?" he says. "Do you just scare tourists off the beach, and if nothing comes in, say, 'Oh, sorry?'"

It wasn't concerns about issuing a false alarm, however, that prevented scientists in India, Sri Lanka, and the Maldives from alerting authorities to the tsunami threat. Instead, researchers say, the reason was near-total ignorance. At the National Geophysical Research Institute (NGRI) in the south Indian city of Hyderabad, for example, seismologists knew of the earthquake within minutes after it struck but didn't consider the possibility of a tsunami until it was too late. In fact, at about 8 a.m., an hour after the tsunami had already begun its assault on Indian territory by pummeling the islands of Andaman and Nicobar some 200 km northwest of the epicenter, institute officials were reassuring the media that the Sumatran event posed no threat to the Indian subcontinent.

About the same time, in neighboring Sri Lanka, scientists at the country's only seismic monitoring station, in Kandy, reached a similar conclusion. "We knew that a quake had occurred—but on the other side of the ocean," says Sarath Weerawarnakula, ▶

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director of Sri Lanka's Geological Survey and Mines Bureau, who hurried to his office that morning after feeling the tremors himself. "It wasn't supposed to affect us."

Walls of water crashing onto the Indian and Sri Lankan coasts soon proved how wrong the scientists were. The waves flung cars and trucks around like toys in a bathtub and rammed fishing boats into people's living rooms. "We'd never experienced anything like this before," says NGRI seismologist Rajender Chadha. "It took us completely by surprise, and it was a terrible feeling."

The international scientific community fared somewhat better at reacting to the quake, but not enough to make a difference. An hour after the quake, the Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii—which serves a network of 26 countries in the Pacific basin, including Indonesia and Thailand—issued a bulletin identifying the possibility of a tsunami near the epicenter. But in the absence of real-time data from the Indian Ocean, which lacks the deep-sea pressure sensors and tide gauges that can spot tsunami waves at sea, PTWC officials "could not confirm that a tsunami had been generated," says Laura Kong, director of the International Tsunami Information Center in Honolulu, which works with PTWC to help countries in the Pacific deal with tsunami threats.

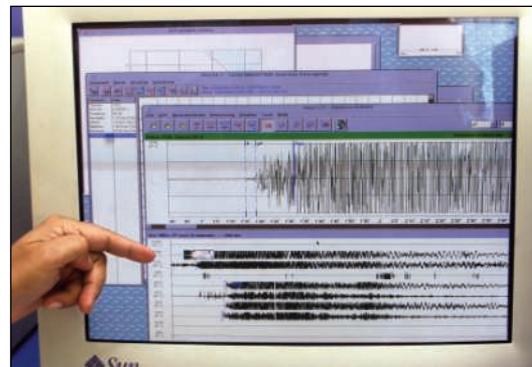
However, some researchers say that the

seismic information alone—including magnitude, location, and estimated length of the fault line—should have set alarm bells ringing. Although not all undersea quakes produce life-threatening tsunamis, the Sumatran quake—later pegged at magnitude 9.0—was "so high on the scale, you had to know that a large tsunami would follow," says Emile Okal, a seismologist at Northwestern University in Evanston, Illinois. What may have made it difficult for officials to reach that conclusion, says Okal, was the rarity of tsunamis in the Indian Ocean: Fewer than half a dozen big ones have been recorded in the past 250 years.

But even if there had been reasonable certainty that a tsunami was building up stealthily under the waters, scientists say they are not sure what they could have done. As the morning wore on, for example, geophysicists in India realized that "a tsunami would be generated, but how it would travel and when it would strike—we simply had no clue," says Chadha.

That's exactly the kind of information that countries in the region hope to have the next time a tsunami comes calling. The Indian government last week announced plans to spend \$30 million to set up a warning system within the next 2 years; Indonesia and Thai-

land have since announced similar plans of their own. Like those in the Pacific, the proposed warning systems will include up to a dozen deep-sea buoys to detect pressure changes that occur as an earthquake's energy



**Off the scale.** The Sumatra quake turned out to be far more powerful than early readings suggested.

travels through the ocean and tide gauges to measure rise and fall in sea level.

Kapil Sibal, minister of state for science and technology and ocean development, says India plans to collaborate with Indonesia, Thailand, and Myanmar to eventually build a tsunami warning network in the region. "We've been jolted hard, and we'll take remedial action," Sibal says.

—YUDHIJIT BHATTACHARJEE

With reporting by Pallava Bagla in New Delhi.

VIROLOGY

## Chemokine Gene Number Tied to HIV Susceptibility, But With a Twist

Like a long-married couple, a virus and its host shape each other in subtle yet profound ways. AIDS researchers investigating this dynamic have detected several changes in both HIV and humans that likely evolved during the high-stakes wrestling match between the virus, the cells it infects, and the immune system. Now a massive review of DNA from more than 5000 HIV-infected and uninfected people has found that the human genome appears to have responded to the virus by stockpiling extra copies of immune genes that influence a person's HIV susceptibility as well as the course of disease in

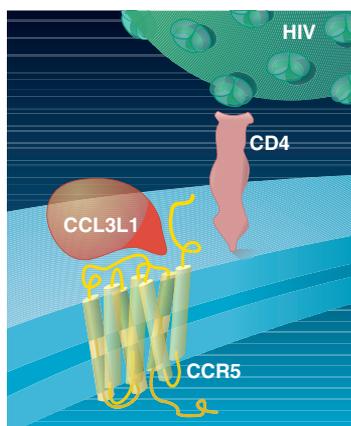
infected people. These findings may lead to an important practical advance: better designed AIDS vaccine studies.

Described in the 6 January *Science Express* ([www.sciencemag.org/cgi/content/abstract/1101160](http://www.sciencemag.org/cgi/content/abstract/1101160)), the DNA analysis focuses on a gene with the ungainly name of *CCL3L1*. Steven Wolinsky, a virologist at Northwestern University Medical School in Chicago, Illinois, whose lab also has studied the relationship between

immune genes and HIV, calls the work "an intellectual and technical tour de force."

Sunil Ahuja, an infectious-disease specialist at the Veterans Administration Research Center for AIDS and HIV-1 Infection in San Antonio, Texas, led an international team that examined the importance of segmental duplications in the human genome. People typically have two copies of each gene (one from each parent), but stretches of DNA sometimes appear repeatedly, causing the overrepresentation of certain genes. Many of the segmental duplications discovered to date include genes related to immunity, inspiring the notion that some duplications protect against invaders such as viruses. Ahuja and co-workers wondered whether HIV might be the target of such an evolutionary response.

The researchers first hunted for segmental duplications that include *CCL3L1* in 1000 people from 57 populations. Immune ▶



**No vacancy.** When *CCL3L1* (red) occupies the CCR5 receptor on CD4 cells, it blocks HIV's entry.

CREDITS (TOP TO BOTTOM): TATAN SYUFLANA/AP PHOTO; K. SUTLIFF/SCIENCE