On the trail of destruction

Quirin Schiermeier travels to Sri Lanka with a team of scientists in the wake of last month's tsunami. Together with locals they search through the damage for clues of where the wave hit hardest.

It was 8:45 on a tropical December morning when Mohamed Nazfer saw the tsunami coming. He remembers the time exactly because he was eating breakfast, listening to the news on the radio. When he heard screaming in the street outside his house on the beachfront of Kalmunai, a fishing village on the east coast of Sri Lanka, he walked a few steps towards the beach to see what all the fuss was about. Then he began to run, fast, from the white wall of water hurtling towards him.

Although the 35-year-old fisherman survived the Indian Ocean tsunami, his home, livelihood, wife, ten relatives and some 6,000 other people here and in neighbouring communities did not. Sometimes, Nazfer tells me as we stand among the wreckage, he thinks that he would be better off dead. He lives in a refugee camp now, a short distance inland, but he comes down every day to roam the remnants of his home. He remembers hearing somewhere that the waves were triggered by an earthquake 1,500 kilometres away, but he doesn't much care about the science behind the disaster. "It was God," he says.

For the scientists who have spent their lives researching the physics of tsunamis, however, there is great reason to care. Philip Liu, a fluid dynamicist and tsunami expert at Cornell University in Ithaca, New York, is one such person. In the aftermath of the disaster, he could be found hastily organizing an expedition to Sri Lanka. He and his team wanted to measure the traces that the flood had left on the soil, vegetation and structures in the 'inundation zone'.

I joined the ten-strong group of coastal engineers, geologists and fluid mechanics from the United States, New Zealand and Sri Lanka as they set out to collect data to determine the height, velocity and extent of the flood at different stretches of the coast. With additional, more detailed information about the local topography and the near-shore ocean depths, they hope to improve numerical tsunami models, and to produce physical maps that local planners can use when rebuilding settlements, hotels and infrastructure. Those same maps could also be used to plan better evacuation routes, and to save lives.

The 26 December tsunami was the first to strike Sri Lanka in living memory. Across the Indian Ocean, tsunamis are rare but not unknown. In June 1994, a tsunami killed

TIMELINE 26.12.04

00:59 GMT
An earthquake of magnitude 9.0 strikes off the west coast of Sumatra. The sea floor moves several metres upwards, sparking a tsunami.

3 minutes
Seismic signals reach Cocos Island Station in the Indian Ocean, a facility that is part of a US-led university consortium.

8 minutes
Seismic signals from the quake are received at the Pacific Tsunami Warning Center (PTWC) in Hawaii from sensors in Australia. An alarm is triggered.

15 minutes
The PTWC issues a bulletin stating a quake of magnitude 8.0 has occurred, with no risk of tsunamis to Pacific nations. The US Geological Survey (USGS) circulates information about the quake to internal officials.

some 200 coastal residents in east Java, after an earthquake occurred off the coast. Waves were reported to have been as high as 15 metres. No one knows for sure, but it has been estimated that large tsunamis may hit this part of the world once every 1,000 years.
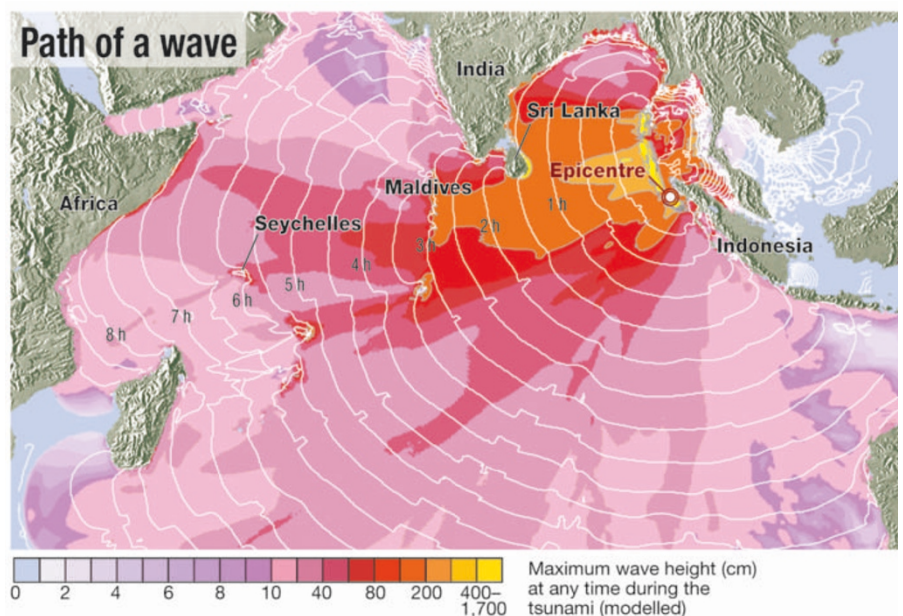
The recent tsunami was one of the world's worst natural disasters in decades. About 33,000 people, almost half of whom were children, died on Sri Lanka's east and south coasts alone. The death toll around the entire Indian Ocean region exceeds 220,000, and numbers are still rising. Although other earthquakes, such as that in Tangshan, China, in 1976, have taken hundreds of thousands of lives, no single incident has had such a devastating effect on so many countries for a long time — and certainly not with the overriding feeling that something could have been done to save many of the victims. Early warning systems against tsunamis do exist, but at present only for the Pacific region, where the waves occur much more frequently (see page 343). The information about this wave took hours to reach the people who could have acted (see Timeline, below).

Tough challenge

Researchers such as Liu know that their efforts should ultimately help improve the warning systems. But collecting the necessary information is no easy task. Liu's expedition on 10–15 January proved to be a first-rate logistical challenge. Plans and schedules had to be changed on a daily basis, as roads proved impassable, bridges were destroyed and hotels closed. But thanks to the team's improvisational skills and much support from the Sri Lankan military, who acted as hosts, it did provide a wealth of data.

Once in Sri Lanka, Liu's team split in two — with journalists in tow. One group, including Liu and myself, set off on 10 January from Colombo to Trincomalee, a small town on the east coast. From there, we headed south, visiting affected coastlines down to Amparai, a former stronghold of the Tamil rebels. A second team, led by Costas Synolakis, a civil engineer and tsunami expert at the University of Southern California in Los Angeles, surveyed the better-developed south coast of the island.

The destruction became increasingly severe the farther south we travelled, often with seemingly random differences in effects from one beach to another. The 50,000-strong town of Trincomalee suffered comparatively modest damage, but the small communities on the neighbouring Koddiyar Bay were hit hard. South of Batticaloa things deteriorated rapidly, until finally we came to the shocking sight of Kalmunai. Here, the clean-up had just begun, and the smell of decay still lingered in the air — when we arrived some local volunteers had just buried a human head on the beach.
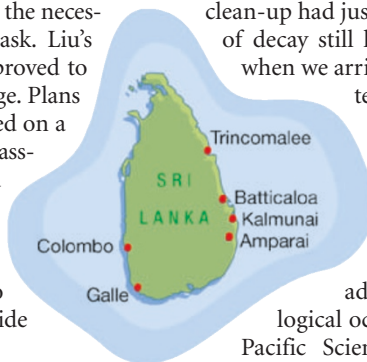
"It is a conflicting experience for me to go to the field amid all this devastation," admits Bruce Jaffe, a geological oceanographer with the Pacific Science Center in Santa Cruz, California. "In a way it makes you feel guilty. But then these data are really invaluable for better assessing the hazard and frequency of tsunamis."
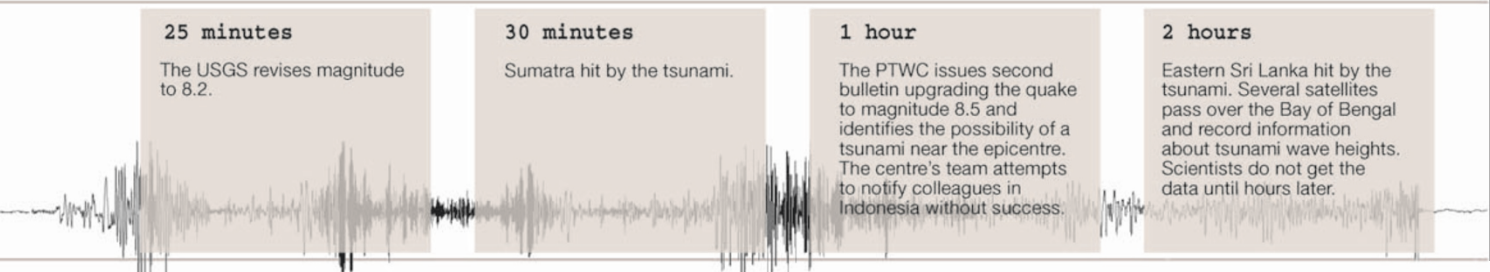
On each beach, Jaffe scanned the ground, the rooftops and even empty swimming pools for sediment deposits left behind by the wave. He also recorded signs of the erosion that the rushing water seemed to have caused hundreds of metres inland. He took sand samples from different sediment layers and packed them in hundreds of carefully labelled plastic bags for analysis back in the lab. From the thickness of the deposits and the distribution of grain size in the tsunami-generated layers, he will later use computer models to back-calculate the number of incoming waves, the flow velocities and water heights at every probed location.

Sifting the clues

"Post-tsunami surveys help us define what kind of resolution we need in our simulations," says Synolakis, who has taken part in 12 such field trips since 1992. As well as Jaffe's approach of looking at grain size, others hope to use different measures to test and calibrate their models. Physicists such as Liu tend to use evidence of high-water marks to back-calculate wave heights and speeds. He and his colleagues used visual clues to determine the direction of the incoming flow on Sri Lankan beaches. Local children, who crowded round us and tried to steal the tools from our hands, helped to seek out buildings with clear water lines and posed for pictures. Despite the tragedy of last month, they were intensely curious and keen to help.

Between the daily forays onto the beaches, the researchers spent hours in the car, with laptops bouncing on their knees, debating the specifics of this wave. Tsunami research is done by a small community: no more than 200 scientists worldwide specialize in the field, says Liu. And many of them are now scouring the beaches of Sri Lanka, Indonesia and the other countries hit by the wave. Late into the night, members of our

Path of a wave

India
Sri Lanka
Epicentre
Maldives
Seychelles
Africa
Indonesia

1 h
2 h
3 h
4 h
5 h
6 h
7 h
8 h

Maximum wave height (cm) at any time during the tsunami (modelled)

| 0 | 2 | 4 | 6 | 8 | 10 | 40 | 80 | 200 | 400–1,700 |

NOAA

SRI LANKA
Trincomalee
Batticaloa
Kalmunai
Amparai
Colombo
Galle

25 minutes — The USGS revises magnitude to 8.2.

30 minutes — Sumatra hit by the tsunami.

1 hour — The PTWC issues second bulletin upgrading the quake to magnitude 8.5 and identifies the possibility of a tsunami near the epicentre. The centre's team attempts to notify colleagues in Indonesia without success.

2 hours — Eastern Sri Lanka hit by the tsunami. Several satellites pass over the Bay of Bengal and record information about tsunami wave heights. Scientists do not get the data until hours later.

team animatedly discussed what the wave looked like at birth, and how it propagated across the Indian Ocean.
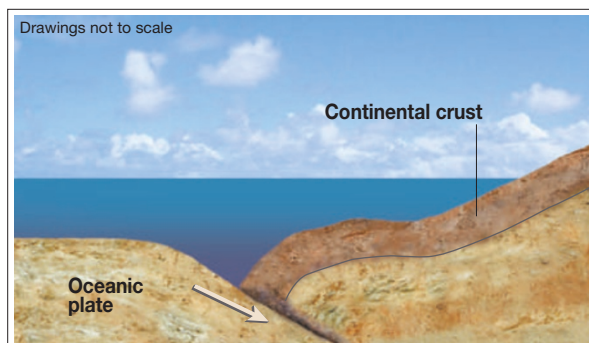
The mechanism by which tsunamis form is relatively simple (see Graphic, right). And the equations that describe their rough characteristics, such as speed and wave height, in deep water are similarly straightforward. But there are complexities that are far more difficult to deal with. December's tsunami was caused when an underwater fault line ruptured across hundreds of kilometres — and no one is sure what a wave formed in this way actually looks like.

Rapid rise

Most of the experts agree that a tsunami is initially shaped like an 'N', with a large crest and trough (see 'During the quake', right), before evolving into more complicated shapes. If the trough of the wave travels ahead, as it seems to have done towards Indonesia, the ocean recedes from the shore line before the wave crest arrives. This phenomenon led many eyewitnesses of the tsunami to wander down to the beach out of curiosity — leaving them little or no time to escape the full force of the incoming wave.

After birth, a tsunami propagates in deep water with stunning speed but with a low wave height. In this case, the wave moved at about 800 kilometres per hour. Models put the maximum wave height to the east of Sri Lanka at more than a metre (see Map, previous page), whereas satellites measured up to 80 centimetres. Aboard a ship, such waves would be hardly perceptible. The small size also means it is extremely difficult to detect tsunamis from the air or with buoys that measure variations in water pressure. Filtering out the loud 'noise' from normal wind-generated waves on top of a long tsunami hump requires sophisticated equations. It took hours to process and analyse the data gathered by satellite for the December wave. Such systems are not designed for, nor suitable for, warnings — by the time the results were ready the tsunami had already struck.

Once tsunami waves reach shallow water, they transform dramatically. Because the speed of a tsunami is a function of the water depth, it slows as it nears the shore. But because its energy remains almost constant, the height of the wave grows tremendously in shallow water. On our trip, we saw one 5-metre-high building that had been completely submerged. Reefs, bays and undersea

features such as canyons all play a role in modifying the wave, buffering or focusing its energy, or changing its direction. Reflected waves interact with each other. And the steeper the sub-sea slope, the more quickly the wave grows and the more energy it retains when it hits land.

This aspect of a tsunami's journey is incredibly difficult to model. "Things start to get really complex once the waves hit the

1 Before the earthquake

The plate holding the Indian Ocean was sliding under the continental plate (holding Indonesia and much of Asia) at about 6 cm per year. The continental crust was bent thanks to the constant pressure of collision.
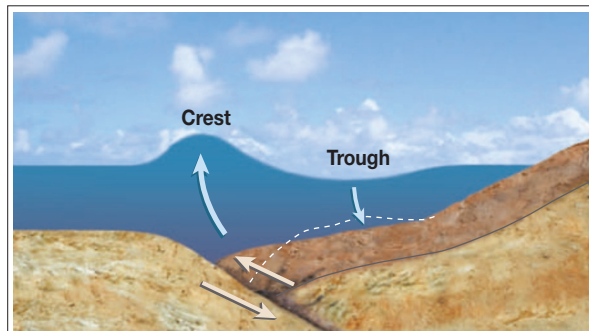
2 During the quake

The fault ruptured violently, allowing the continental crust to unbend and causing portions of the sea floor to move up or down by several metres. The water above the fault responded in kind, creating a wave crest and trough.
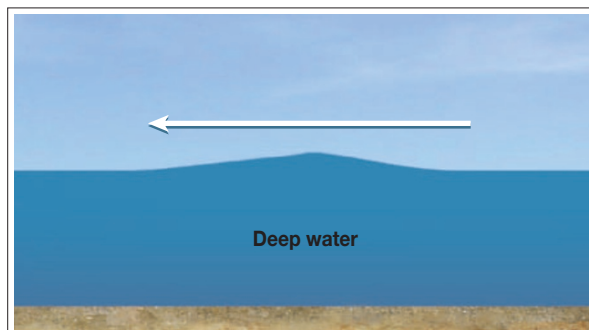
3 The wave travels

One wave crashed towards the nearby shore of Indonesia. Another barrelled westwards at about 800 km per hour in deep water, with a wavelength of 100 km and an average wave height of just tens of centimetres.
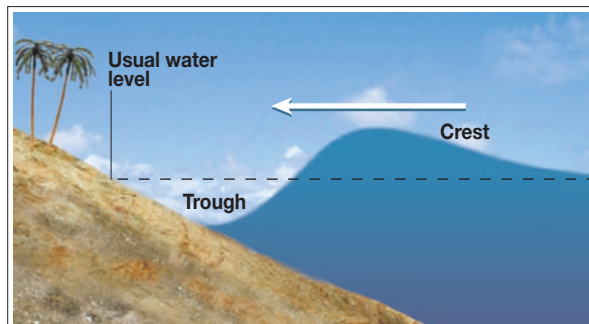
4 Collision

When the wave entered shallow waters, it slowed to tens of kilometres per hour, its wavelength shortened to about 5 km, and its height is thought to have soared to more than ten metres. The trough of the wave often hits before the crest (as shown).

shore and continue to flow on land," says Liu. Topography, land material, friction and numerous small-scale features from trees to houses come into play — creating a modelling nightmare.

Attempts to describe the breaking, turbulence and debris pick-up of a tsunami on land are still very crude and need a lot of development, says Patrick Lynett, a coastal modeller at Texas A&M University in College Station,

2 hours 30 minutes
Internet newswire reports of casualties in Sri Lanka emerge. India hit by the tsunami.

3 hours
The US ambassador in Sri Lanka sets up system to notify the prime minister in case of any large aftershocks, based on information from the PTWC.

3 hours 22 minutes
Aftershock of magnitude 7.1 strikes off the Nicobar Islands. (More than a dozen aftershocks of magnitude 6.0 or greater occurred — this was the largest.)

3 hours 30 minutes
Maldives hit.

who has modelled the 1998 Papua New Guinea tsunami[1]. "Comparison with the real thing is of paramount importance," he says.

A tsunami's final surge onto land rarely resembles the towering waves often drawn by artists. The waves rarely 'break' the way that surfing waves do. Rather the water simply rushes inland, often preceded by a 'bore' — a mass of extremely turbulent white water. What such a bore looks like exactly was also a matter for midnight debates on this trip — not one of the tsunami researchers has actually seen an incoming tsunami.

Instead, fluid dynamicists study the propagation and transformation of waves under simplified laboratory conditions, using large water tanks equipped with wave-making mechanisms and advanced optical-measurement technology.

A rush and a push

The resulting mathematical equations are then marshalled to create computer-generated tsunamis, using software such as the Tunami-N2. This standard model was designed in the early 1990s by Nobuo Shuto, a modelling expert at Tohoku University's Disaster Control Research Center in Sendai, Japan, to calculate wave physics up to a shoreline. With a similar model — the Cornell Multigrid Coupled Tsunami model — Liu has simulated the propagation and wave evolution of the Indian Ocean tsunami.

But these models have limitations. They are based on an idealized ocean floor, and on untested assumptions made about the seismic generation of tsunamis in the source region. Such lab waves are not made by anything approaching a rupturing fault. And there are issues about how water behaves on different scales that cannot be resolved in a lab model. Real-life tsunamis consistently catch these models out. A wave that hit the Indonesian island of Flores in 1992, for example, defied standard models. To explain its behaviour, Liu had to create a more detailed simulation[2], which showed that the tsunami could bend around corners and penetrate into sheltered coastal areas without losing its energy.

The accuracy of models has improved considerably during the past decade, says Synolakis. "At the time of the 1992 Nicaragua tsunami, models underestimated the observed flooding by a factor of ten," he says. "Since then, the difference between models and measurements has diminished to around a factor of two."

Tracking the wave: Sri Lankan children help to measure the high water mark (above) while geologists extract tsunami deposits (below).

Preliminary data suggest that this time the models may have done even better. Vasily Titov, a former student of Synolakis, now at the Pacific Marine Environmental Laboratory in Seattle, Washington, used a model[3] that simulates how a tsunami wave penetrates inland. The results seem to agree with measurements made so far to within 30%.

To close that gap further, the researchers will continue to collect data. They are also pressing for more accurate maps of the sea floor around Sri Lanka. At a concluding meeting on 15 January in Colombo, Sri Lankan navy officials said that they would provide high-resolution maps of the sea floor immediately, and help to collect any missing information. Eventually, says Synolakis, it might be possible to produce inundation maps of threatened coastlines in Sri Lanka, showing how far water is likely to intrude inland under various threats. Such maps currently exist only for some coastal areas in Japan and the United States. The results are unlikely to persuade fishermen to move inland, he concedes, but they will help town planners to rebuild destroyed schools, hospitals and tourist infrastructure at secure locations.

Structurally unsound

The information can't come soon enough: at many places reconstruction has already begun, but is often substandard. Many builders are using bad, crumbling concrete and little steel to reinforce the structures — much like most of the buildings that were destroyed by the wave. "Some hastily rebuilt constructions look like they may collapse without a tsunami," says Synolakis.

The geological work being done by Jaffe's team will also help planners to assess the risk of future events. By digging deeper into coastlines or marshes, where sediments have been preserved for thousands of years, Jaffe hopes to show how often large tsunamis have occurred in this region — a method that has previously worked for Papua New Guinea and the west coast of the United States[4]. A mythological account in the *Mahavansa*, Sri Lanka's national Buddhist chronicle, suggests that a tsunami may have hit the island around 150 BC. This book reports that "the sea flooded the land, as a punishment by God", says Starin Fernando, a geologist at Sri Lanka's Geological Survey and Mines Bureau in Colombo. Using Jaffe's methods, Fernando is hoping to find geological evidence for this religious tale.

Such work may reaffirm that tsunamis in this area are extremely rare. But the lessons learned about modelling by Liu and his team will have far wider implications. They now have reams of valuable data that will improve models of how tsunamis behave near shore and on land. And next time, they hope, all this information will help to curtail the extent of any disaster. ■

Quirin Schiermeier is *Nature*'s German correspondent.

1. Lynett, P., Borrero, J. C., Liu, P. L.-F. & Synolakis, C. E. *Pure Appl. Geophys.* **160**, 2119–2146 (2003).
2. Yeh, H., Liu, P., Briggs, M. & Synolakis, C. *Nature* **372**, 353–355 (1994).
3. Titov, V. V. & Synolakis, C. E. *J. Waterway Port Coast. Ocean Eng.* **124**, 157–171 (1998).
4. Jaffe, B. E. & Gelfenbaum, G. in *Solutions to Coastal Disasters '02* 836–847 (American Society of Civil Engineers, Reston, VA, 2002).

For more on the tsunami visit:
▸ www.nature.com/news/specials/tsunami

4 hours 25 minutes
Team at Harvard University's seismology department upgrades the original quake to 8.9 using a technique that analyses both the size and shape of seismic waves. The USGS is due to get this same technology this year.

7 hours 15 minutes
The PTWC advises the US state department about potential threat to Madagascar and Africa. Africa is hit around the same time.

14 hours 30 minutes
The PTWC warns that waves have reached the Pacific, and may continue for a day or two. Water from the tsunami reaches as high as 2.6 metres above the normal water mark in Mexico — probably due to focusing of energy by a seafloor ridge in the Pacific — and half a metre on both the east and west coasts of North America.

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