



Indonesia's major earthquake last year tilted Nias Island like a seesaw, disrupting villagers' lives and pointing to future dangers

The Day the Land Tipped Over

NIAS, INDONESIA—Jolted awake late in the night of 28 March 2005, Ahmad Chatib staggered outdoors to find fissures in the ground snaking from the beach up to his wooden house. He and others in Tagaulei, a seaside village on Nias Island off Sumatra's west coast, didn't hesitate. "We took our children and ran," says Chatib, a former village head. Fresh in memory was the tsunami that 3 months earlier had claimed more than 160,000 lives in Sumatra's Aceh Province, 500 kilometers to the north. Of Tagaulei's couple of hundred residents, all but four—two mothers with infants who moved too slowly—escaped. Within an hour, most homes had been swallowed by the sea.

It wasn't a tsunami that wiped Tagaulei off the map but subsidence caused by a rupture of the Sunda megathrust, the subduction zone that parallels Sumatra's west coast, 25 kilometers below the village. The great 2005 Nias-Simeulue fault break, which generated an earthquake with a magnitude of 8.7, instantly

yanked down Nias's southeast shore some 30 centimeters. The earthquake's sustained shaking then made vast stretches of beach liquefy and spread, lowering the coast by another meter or more in places and leading to the inundation of buildings during high tide. Erosion since the quake has erased most vestiges of the once-picturesque village. On

Nias and nearby islands, "places with minor subsidence are being massively rearranged," says Richard Briggs, a geologist at the California Institute of Technology in Pasadena and member of a Caltech-Indonesian Institute of Sciences (LIPI) team that has spent a decade probing the region's tectonics.

While the quake lowered southeast Nias, it lifted parts of the island's northwest coast nearly 3 meters, thrusting coral reefs into the air and extending the shoreline by hundreds of meters in places. Although such upheavals go hand in hand with a major earthquake of this kind, the Caltech-LIPI team, led by paleoseismologist Kerry Sieh, has used painstaking geodetic measurements to put together one of the finest-grained maps of seismic deformation. The portrait of Nias reveals in unprecedented detail how subsidence and uplift can utterly remake a landscape. "The ecological changes are profound," Briggs says.

The severe warping of Nias offers an unsettling preview of what may await central Sumatra's

Out of their depth. Near Lahewa, algae clinging to an uplifted reef mark the extent of high tide.



CREDITS (TOP TO BOTTOM): KERRY SIEH AND ARON MELTZNER; DANINY HILMAN NATAWIDJAJA

Sunken city. Villagers in Haloban, on Tuangku, one of the Banyak Islands, must cope with daily flooding.

west coast, including the major city of Padang. It faces a segment of the Sunda megathrust that the Caltech-LIPI team says is likely to rupture within the next few decades (see sidebar, p. 408). If a massive slip does occur, models suggest that the coastline around Padang would subside tens of centimeters, in a reprise of the devastation in Banda Aceh, which subsided by an average of 50 centimeters during the 2004 earthquake. Faced with that bleak outlook, Indonesian authorities must assess the feasibility of girding coastal structures against the subsidence and uplift of future megaquakes, says Danny Hilman Natawidjaja, a geologist at LIPI's Research Center for Geotechnology in Bandung. "It's important, absolutely, to do this," he says.

The social consequences of the 2005 catastrophe for islanders whose homes straddle the Sunda megathrust will take years to overcome. The region's economy lies in tatters. On Nias, patchy reconstruction efforts have left Chatib's family and hundreds of others living in tents and other temporary shelters. In the nearby Banyak Islands, only a few kilometers from the quake's epicenter, primary, or tectonic subsidence during the earthquake pulled the land down as much as a meter in some areas. There, to compensate for regular flooding, villagers have built elevated wooden walkways, as in Venice, and retreat to upper floors when the water creeps in. "I'm not sure that we in the West would put up with this for long," says Briggs.

Vanished mangroves

On a wet September morning, the 3-hour drive by minivan from Nias's main town, Gunung Sitoli, to the northwestern port of Lahewa winds across hills verdant with coconut palms, banana trees, and cocoa trees from which mottled yellow, tear-shaped pods hang like Christmas tree ornaments. It's also a trail of tears. The 2005 earthquake, which released more than a century of pent-up strain in the subduction zone, leveled many homes and rearranged aquifers, causing some wells and rivers to run dry. Problems with water supply in coastal areas are "widespread," says Briggs, who has chronicled deformation of the altered landscape.

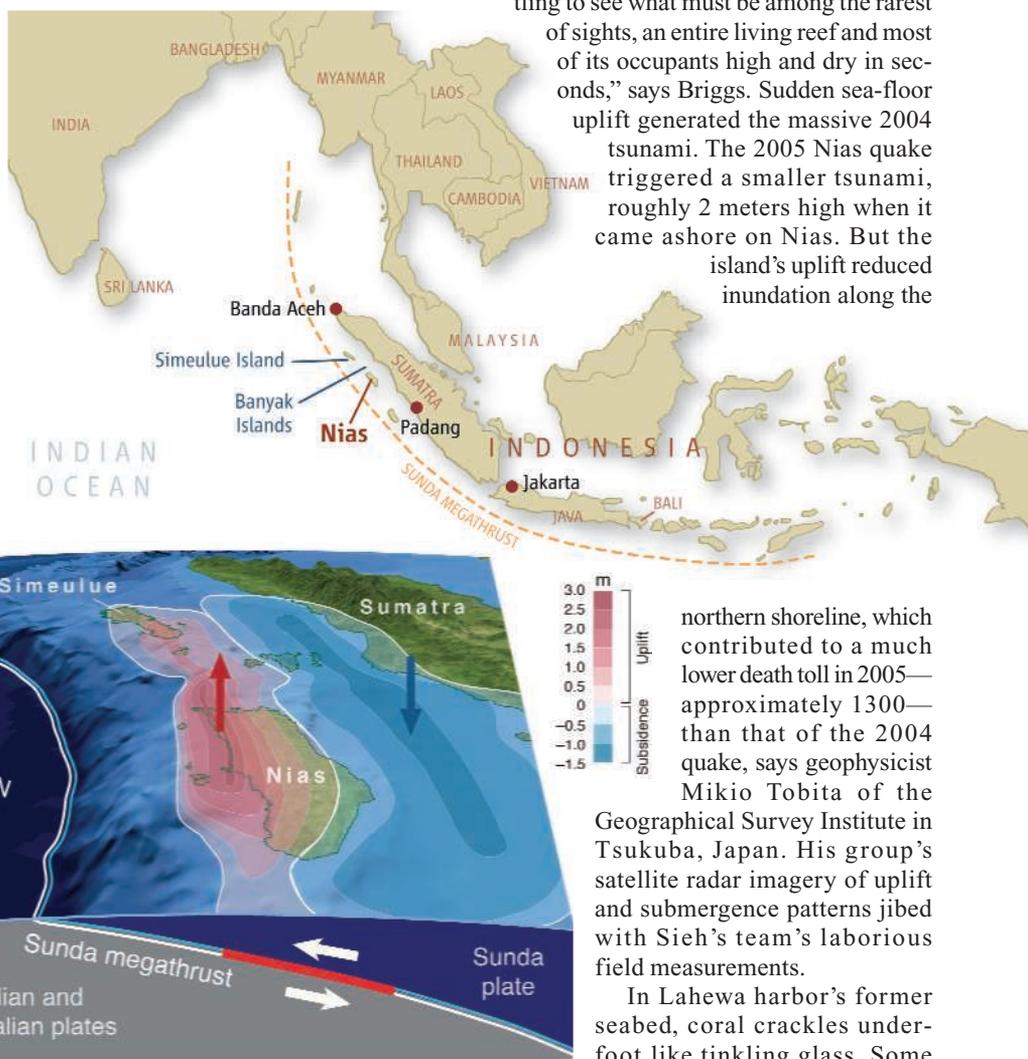
Electricity was out for 3 months, according to Ahmad Yani, a businessman from Gunung Sitoli. After power was restored, it

took a couple more months for Nias's survivors, wearing surgical masks against the stench of rotting flesh, to clear the rubble. All the while, powerful aftershocks terrified many into believing that Nias would just sink and disappear. "A lot of people fled the island," says Yani.

A few kilometers east of Lahewa, the road bends around a wide, sandy beach. "Before the earthquake, this was all mangroves," says Imam Suprihanto, an independent marine

wreaked similar havoc before. Measurements show that the Mentawai Islands off the coast of Padang rose 0.8 meter in 1797 and 2.8 meters in 1833, says Mohamed Chlieh, a geodynamic modeler at Caltech.

Some residents of Lahewa lost their livelihoods as well as their homes. The uplift transformed the harbor and surrounding beaches into an otherworldly vista of exposed coral reef colored in somber shades. "It must have been amazing and startling to see what must be among the rarest of sights, an entire living reef and most of its occupants high and dry in seconds," says Briggs. Sudden sea-floor uplift generated the massive 2004 tsunami. The 2005 Nias quake triggered a smaller tsunami, roughly 2 meters high when it came ashore on Nias. But the island's uplift reduced inundation along the

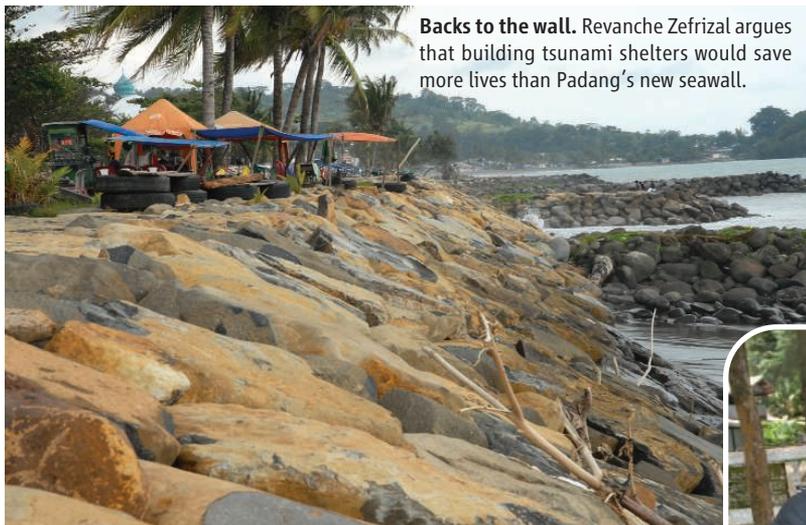


Seismic shift. When a 400-kilometer-long stretch of the Sunda megathrust ruptured on 28 March 2005, the slip yanked down eastern Nias while thrusting up the island's west coast.

biologist and divemaster based in Jakarta who collaborates with the Caltech-LIPI team. Now the beach is bare; the mangrove forest, which had helped prevent erosion and shelter wetland creatures, was wiped out by an uplift of roughly 2 meters, and the shore these days extends several hundred meters farther toward the sea than it did before the earthquake tilted the land. Megaquakes in the region have

northern shoreline, which contributed to a much lower death toll in 2005—approximately 1300—than that of the 2004 quake, says geophysicist Mikio Tobita of the Geographical Survey Institute in Tsukuba, Japan. His group's satellite radar imagery of uplift and submergence patterns jibed with Sieh's team's laborious field measurements.

In Lahewa harbor's former seabed, coral crackles underfoot like tinkling glass. Some microatolls of the coral genus *Porites* are taller than a minivan; the Caltech team zeroed in on these as records of uplift in 2005 and earlier quakes (*Science*, 31 March, p. 1897). Where fishing boats were once moored, hermit crabs and mudskippers skitter in their tidal pools. The earthquake shrugged a concrete jetty off its pillars, which now jut at odd angles. In the days after the quake, waves pulverized the beached fishing boats. Only a few larger vessels at sea escaped intact.



Backs to the wall. Revanche Zefrizal argues that building tsunami shelters would save more lives than Padang's new seawall.

Facing a Tsunami With No Place to Run

PADANG, INDONESIA—It is hard to imagine a more terrible catastrophe than the 2004 tsunami that killed more than 220,000 people in southern Asia. But experts say that the next great earthquake on the Sunda trench could be at least as bad. Geologists warn that within the next 30 years, there will likely be another great Sunda megathrust rupture farther south, just off Padang, Sumatra's second largest city, where 800,000 people live. "We're getting close. Strain has been accumulating for more than 200 years," says Richard Briggs, a geologist at the California Institute of Technology (Caltech) in Pasadena. "The outlook isn't promising."

Even knowing this, planners are struggling to devise an adequate evacuation plan. If the megathrust rupture occurs where it's expected, offshore of Padang, people will have a mere 20 to 30 minutes to reach a safe haven before the resulting tsunami hits. The city's diabolical geography and street grid, hard up against the volcanic Barisan Mountains and criss-



crossed with rivers and swamps, make it impossible for the entire population to flee, says Revanche Zefrizal, a coordinator for the nonprofit Komunitas Siaga Tsunami (Kogami). "We have five death zones," says Zefrizal, making a throat-slitting gesture. He and others are stumped on how to get 200,000 people near the seafront to safety in time. "We haven't overcome this challenge yet."

It's not for lack of trying. Zefrizal, with the Indonesian military, local police, and emergency services personnel, has been staging evacuation drills and school education campaigns district by district in the Padang region. Meanwhile, a German-Indonesian team has deployed sensors off the coast to measure sea-floor vibrations and pressure changes in the water column that could alert the mainland within tens of seconds of an oncoming tsunami. But they are still working out the kinks. "We can't wait for the technology," which might fail in a crisis, says Harmin Rauf, head of Satkorlak PPB, Padang city's disaster-mitigation office. Therefore, he says, early recognition of a tsunami-spawning earthquake is essential. With that in mind, Kogami has been instructing locals to be prepared to act decisively if tremors last more than a minute and are so strong that they fell building supports and knock people off their feet. In that event, Zefrizal says, quake survivors must pick themselves up and flee on foot to high ground or take shelter in the upper floors of designated tall buildings that withstand the quake. "People wouldn't have time to go looking for mothers or their children. They have to just run," says Rauf. He's working

The destruction of the harbor was a cruel blow. At a fish market once lapped by the harbor's waters but now several hundred meters inland, sales have been dismal. Relief agencies donated replacement boats, but most fishers have taken construction jobs, says Syaharfani Aceh, a fisher. And those who still fish "are afraid to go far out to sea," he says, because uplifted corals just below the surface, most yet to be charted, pose a navigation hazard. Before the earthquake, fishers tended to put to sea at night, when catches are greater. So pervasive is the fear of another quake, Aceh says, that now they are afraid to leave their families alone after dark. And even moving the diminished stock is hard. "It's like the disaster just never stops for the fishermen and their families," says Briggs.

An endurance test

The earthquake destroyed the road to Tagaulei, so the only way to reach it now is by a half-hour ride in a skiff from Bozihona, a village up the coast. Several beachfront

homes in Bozihona, which also subsided, are half-buried in muck and sand. But its easier access allowed the Association of Medical Doctors of Asia (AMDA) to quickly erect 30 replacement homes here last July.



Approaching Tagaulei's new beach, the boatman cuts his engine, and the skiff drifts past a few dark, wooden posts poking above the waves—all that remains of beachfront homes. As the skiff is hauled ashore, a shirtless man in his 30s ambles over. Arman Aceh, a former fisher, points out to sea at a wall-less house frame sticking up from the waves—the only structure still with a roof. "That's my home," says Aceh, teeth stained orange from a mix of areca nut and chalk, wrapped in betel leaf, bulging inside his cheek. He says there were houses even closer to the pre-earthquake shoreline, about 300 meters out to sea from the present one; they have vanished.

Joining the conversation on the beach at Tagaulei is Chatib, a long *balatu* blade hanging, sheathed, from his belt. He points to lumber on a white tarp with the logo of the U.N. High Commissioner for Refugees.

Uncertain future. Ahmad Chatib lost his home and his boat to subsidence. "The wood has been there more than a year," Chatib grumbles. "It's just rot-

with the mosques to connect muezzin loudspeakers to a central radio dispatch for broadcasting warnings and instructions.

About 400,000 of Padang's residents live on the beach or in a warren of narrow streets along the coast. Two- and three-story apartment complexes, shops, and restaurants are interspersed with striking buildings with sharply sloping roofs: "bull's horns" symbolizing the bravery and resilience of the Minang people of west Sumatra. Close to shore, not even the imposing Minang architecture could stave off a tsunami. "All these buildings would be swept away," says Imam Suprihanto, a marine biologist who works with the Caltech team. The city has laid down boulders to form a 5-meter-high seawall, "but this will only protect Padang from a small tsunami," Rauf says. The towering waves from a great quake would wash over them. Only a few main roads lead inland, leaving about half of the beachside residents no viable escape route.

City officials plan to widen the main roads, says Rauf. Another idea is to build a series of concrete towers along the beach in which people stranded near shore could ride out a tsunami. One prominent advocate of this approach is Roger Bilham, a geophysicist at the University of Colorado, Boulder, and a top expert on earthquake risk in Southeast Asia. "Tsunami shelters should be constructed every 100 meters along the coast," he says. Bilham envisions 10-meter-high "indestructible platforms" with numerous entry stairs and stocked with supplies. Zefrizal backs the idea, although at present there's a showstopper: "There's no money

ting." During the earthquake, the survivors ran inland about a kilometer to a settlement also called Tagaulei. Halfway to the second Tagaulei, a path through bamboo rushes passes a small clearing with plots for three homes, including one for Aceh's family. All that's been built so far is the concrete base. "We are waiting for our wood," Aceh says.

Before the earthquake, Chatib was a fisher. Now, sans boat, he says he has been reduced to selling fish caught by other men. "We are very poor," he says, before adding, bitterly, "Why are we still living like this? We feel left out and forgotten."

AMDA's senior logistics officer sympathizes with the Tagauleians' plight. "We feel very sorry for them. They have been waiting so long" for help, says Naoto Usami. AMDA chartered an amphibious craft last year to deliver the lumber now sitting on the beach;

in the budget to make the towers," he says. Kogami plans to go cap in hand to international nonprofits.

The potential for severe subsidence would complicate tower construction and an evacuation. Just as the quake that shook southeastern Nias Island last year tilted the landscape (see main text), a Padang earthquake would be accompanied by subsidence along the coast, says Briggs. Modeling by Caltech's Mohamed Chlieh, based on the effects of megathrust ruptures off Padang in 1797 and 1833, predicts tectonic subsidence—a tugging down of the western Sumatran coast near Padang—of up to 50 centimeters, roughly the same as in Aceh Province, on Sumatra's northern tip, in 2004. Slumps and fissures from liquefaction of soft, sandy ground could exacerbate local flooding.

Modeling by Jose Borrero of the University of Southern California in Los Angeles has shown that subsidence will abet the killing power of a

tsunami, allowing water to run farther inland with more energy, threatening about 1 million people along a 500-kilometer stretch of coast. Thus tsunami shelters would have to be built to ride out a stronger wave *and* shifting ground.

Psychology will also come into play. "West Sumatrans believe in science, but as Muslims, we also believe that natural disasters are God's will," says Rauf. "We want to know how to cope with a tsunami better. But we will not be afraid of it." Rauf can only hope that the rest of the population will be so levelheaded when the day of reckoning comes, as it surely will.

—R.S.



Flip-flop. Before the 2005 rupture, Nias's southwest coast was subsiding, as indicated by the stand of dead coconut palms seaward of the beach (top). The rupture lifted the coast here 2.5 meters.

the nongovernmental organization didn't anticipate the difficulty of moving it inland to homesteads in Tagaulei Two. The delays have created tensions with the villagers. "Our staff have been threatened with knives," he says. AMDA is planning a second lumber shipment for next month and aims to complete all homes by the end of January. "Now," says Usami, "we're moving very fast."

Night has fallen, and Chatib says goodbye: a melodious "Ya-ahowu!" "Yahowuuuuu!" yodels Suprihanto, who does not speak the local language. Others chime in with mangled variations like off-key a cappella singers; it's infectious. The skiff sets out for the return to Bozihona. Lightning flares on the horizon. But the sea is glassy calm, and glowing bioluminescent plankton stream off the bow like sparks. The breathtaking serenity is a sharp contrast to the horrors that Chatib and his fellow villagers endured last year.

Over the coming decades, the tilted crust around Nias will settle gradually—returning to its approximate position before the 2005 quake—as strain on the fault builds to a crescendo for the next gargantuan release. But for Chatib and many other islanders, life may never regain its prequake equilibrium.

—RICHARD STONE