when earth attacks!

TSUNAMIS, VOLCANOES, HURRICANES, LANDSLIDES—THE SINGLE CERTAIN THING ABOUT NATURE'S KILLERS IS THAT THEY WILL STRIKE AGAIN, AND AGAIN. OUR ONLY DEFENSE: EVER BETTER PREDICTION AND PROTECTION BY MICHAEL BEHAR

Humans are fleeting visitors on this roiling rock in the universe. On December 26, 2004, at 58 minutes and 49 seconds past midnight GMT, Mother Earth reacquainted us with this immutable fact. For millions of years, a creeping slab of Earth's crust—the India Plate—had been grinding headlong into a similarly stubborn chunk of rock called the Burma Plate. Like a clash of Brobdingnagian armies, millennia of pent-up kinetic energy suddenly exploded from the seabed, a scant 100 miles from Sumatra, Indonesia. The ensuing force—equal to 25,000 Nagasaki-size atomic bombs detonated in tandem—jolted the Earth from its axis, permanently shortened the length of the day, and hurled walls of seawater onto thousands of miles of coastline—from the Andaman to the Arabian—sweeping away at least 200,000 lives in an instant. What's most terrifying about the recent tsunami »

RON CHAPPLE/THINKSTOCK/GETTY IMAGES

is that a repeat performance is virtually guaranteed. Earth, by its very nature, is a prolific architect of mayhem and purveyor of calamity. The only thing we can do to protect ourselves is strive to learn where and when such massive natural disasters will happen—because rest assured, they *will* happen.

Fortunately, advances in remote-sensing satellites, computer-modeling simulations, radar, seismic monitors and weather forecasting are giving scientists an edge, in many cases enabling them to warn us when it's time to skedaddle. Researchers use imaging satellites, for example, to track minute changes in land deformation—an otherwise undetectable pimple might mean that a fault is about to snap or a volcano about to blow.

Not that this high-tech ingenuity is necessarily making the world a safer place. The problem, experts say, is that humans are doggedly encroaching on Mother Earth's most temperamental turf, increasingly building and living in potentially catastrophic hot zones. And more is at issue than just our propensity to boldly skirt the "urban interface," as scientists describe the boundary between a safely inhabitable region and an area known to be vulnerable to nature's wrath. Humans are also relentlessly altering or destroying the planet's natural protection mechanisms. "If you remove mangroves, damage coral reefs, and take away wetlands," argues Ellen Prager, a marine geologist and author of *Furious Earth: The Science and Nature of Earthquakes, Volcanoes, and Tsunamis*, "you are much more exposed to storm impact or tsunami damage."

The bad news is that the danger is only growing, because wherever population densities soar, the landscape must be transformed to sustain more and more people. The good news: Digital-imaging and mapping tools and ever more savvy computer models are improving scientists' ability to calculate where the most deadly disasters might strike next.

volcanoes

» WE KNOW WHERE, BUT WE DON'T KNOW WHEN. SATELLITE MONITORING PROVIDES VALUABLE CLUES

Toll, 1900–2004: 96,000 lives

DANGER ZONES
Italy
Indonesia
Central America

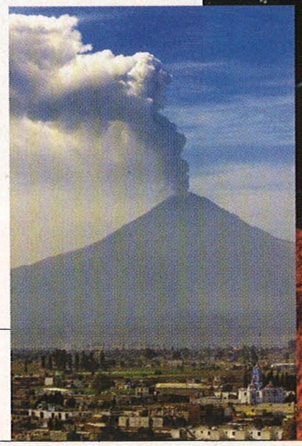
Take a scenic flight over the summit of Mount Vesuvius in Italy, and the view below is chilling. A dense patchwork of urban sprawl from the nearby city of Naples laps at the flanks of one of the most violent volcanoes on Earth. Since A.D. 79, when Vesuvius exploded with little warning and entombed Pompeii and its 3,000 townsfolk under 15 feet of scalding ash, the volcano has erupted at least 30 times. In Pompeii the destruction was so complete that nothing was known of the once-bustling Roman city until archaeologists rediscovered it 1,600 years later.

Blame Earth's explosive nature on what lies beneath its surface. Oceans of seething magma below the planet's crust can top 2,000°F. The intense heat forces rising magma into the crust; if enough magma collects near a weak point, it bursts through to the surface. For centuries, this is exactly what's been happening on Vesuvius, which today has more than two million people living in its shadow. "We know Vesuvius is capable of a major eruption," says William Menke, a professor of earth and environmental sciences at Columbia University. What we don't know is when. Hoping to fathom a guess, scientists at the Vesuvius Observatory have long monitored seismic sensors on the volcano that record tiny rumblings inside the mountain. A case of seismic hiccups might mean that an eruption is looming.

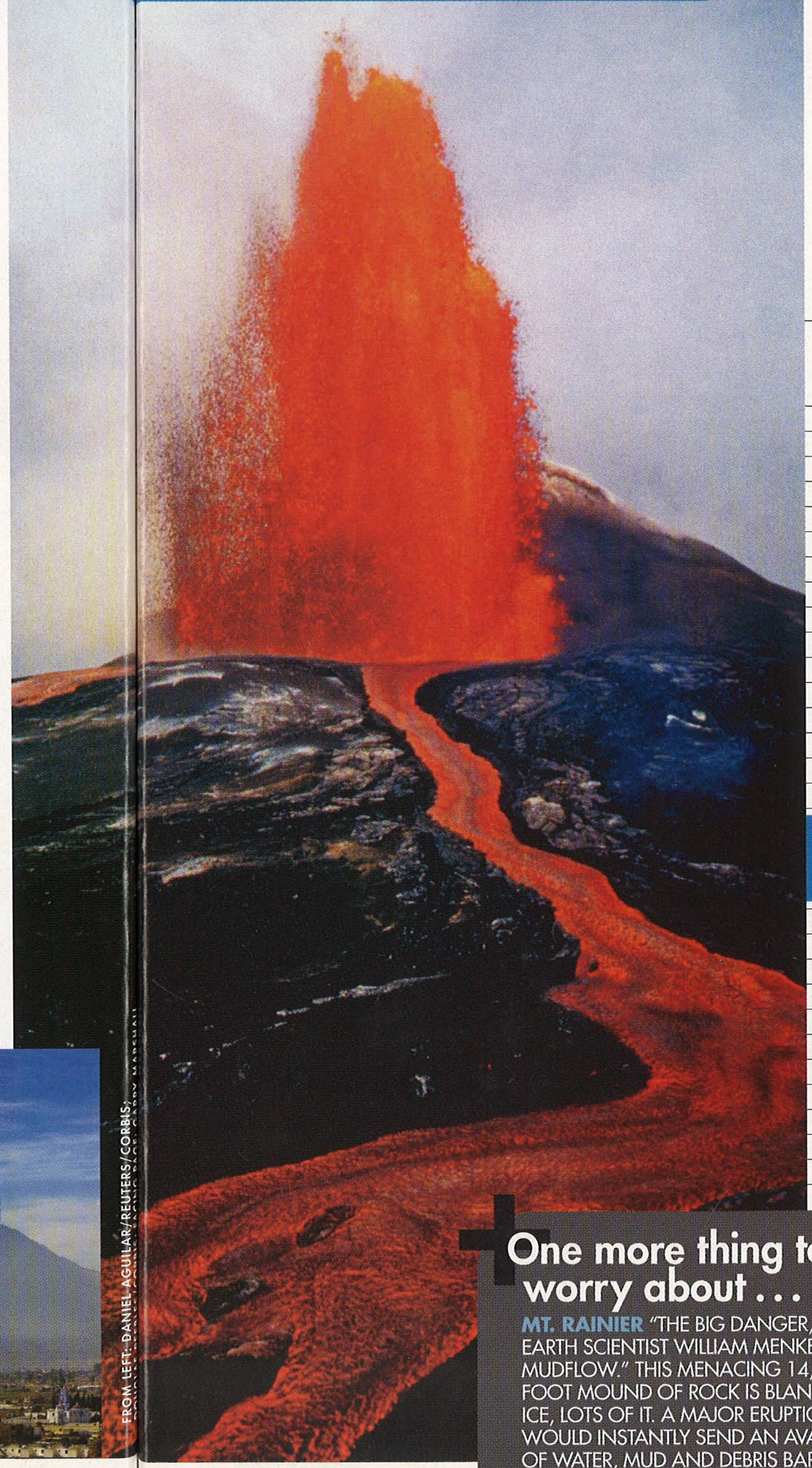
On the other hand, a volcano may be on the brink of eruption without emitting even a single detectable tremor. Perhaps today's most useful tool helping scientists determine when a mountain is about to awaken is satellite-based InSAR (Interferometric Synthetic Aperture Radar). Since the early 1990s, InSAR-equipped satellites have been firing staggered beams of radar waves toward Earth. When the waves bounce back, InSAR records their signal intensity (a measure of the wave's reflection versus absorption) and its phase (how long it takes the waves to make a round-trip). With InSAR, scientists can track tiny deformations in the Earth's surface that occur in the absence of seismic activity.

InSAR is particularly useful for studying volcanoes in countries that tend to be ignored by the usual parade of visiting Western scientists. Although peaks such as Vesuvius, Mt. Rainier in Washington State and Japan's Mt. Fuji garner a lot of attention, there are dozens of other volcanoes just as deadly in Central and South America and Indonesia. The Gede volcano is only 40 miles from downtown Jakarta and its population of nine million. The hill country around Gede has become a favorite weekend getaway for locals—there's even an 18-hole golf course on the volcano. Popocatepetl, at 17,930 feet, soars over Mexico City, a mere 37 miles away. The "Smoking Mountain" is known to have erupted 36 times and sputters steam and gas from its summit almost monthly. Atitlán Caldera is about 75 miles from Guatemala City. Take a stroll in the city, says Stanley Williams, a professor of geology and volcanology at Arizona State University, "and you realize that all the rocks you are standing on came from Atitlán. If that eruption happened today, it would probably kill 90 percent of the population of the country." For any of these volcanoes, predicting an eruption using InSAR depends on groundcover—rocky or barren surfaces tend to produce better images than snow- or tree-covered terrain. Residents of Naples will be glad to know that Vesuvius is perfectly photogenic.

And, thankfully, recent InSAR images show very little swelling. Not that Naples is in the clear, warns Claudio Prati, an electrical engineer and professor at the Polytechnic University of Milan, where he specializes in InSAR research. "When it comes," he says, "the eruption will be very, very fast and explosive."



NAPLES'S NEMESIS **Vesuvius [near right] demolished Pompeii 2,000 years ago. Today two million people live in its shadow.**

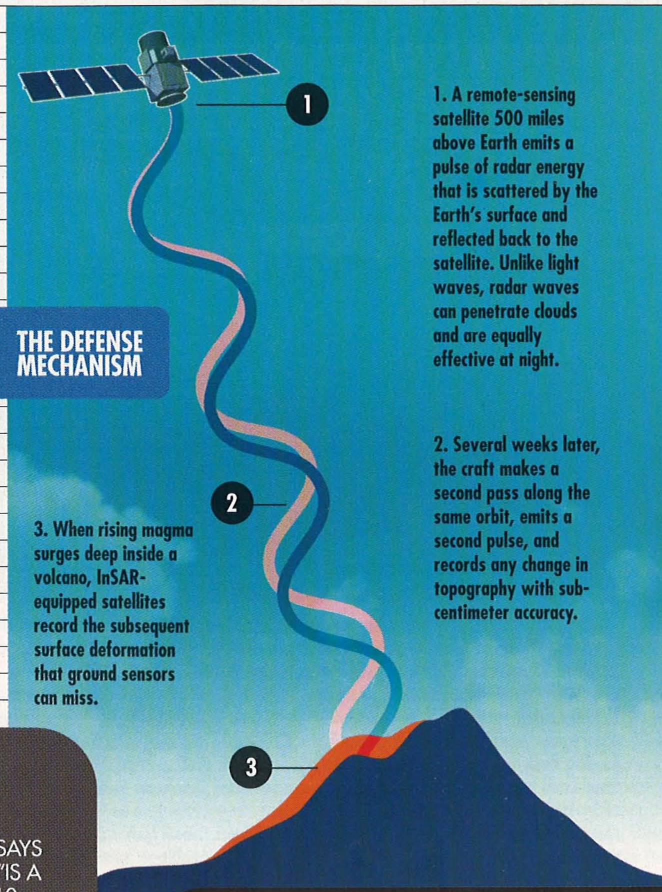


FROM LEFT: DANIEL AGUILAR/REUTERS/CORBIS;

Swell View

INSAR USES RADAR TO PREDICT A BLOW

Traditionally, scientists have relied on seismic data to foretell eruptions. But more than half of all volcanic explosions give no seismic warning calls. Enter InSAR, a time-lapse satellite system that records the bulging of the Earth that often precedes volcanic activity.



One more thing to worry about . . .

MT. RAINIER "THE BIG DANGER," SAYS EARTH SCIENTIST WILLIAM MENKE, "IS A MUDFLOW." THIS MENACING 14,410-FOOT MOUND OF ROCK IS BLANKETED IN ICE, LOTS OF IT. A MAJOR ERUPTION WOULD INSTANTLY SEND AN AVALANCHE OF WATER, MUD AND DEBRIS BARRELING DOWN NARROW RIVER VALLEYS AND INTO SEATTLE'S SUBURBS, 60 MILES AWAY.

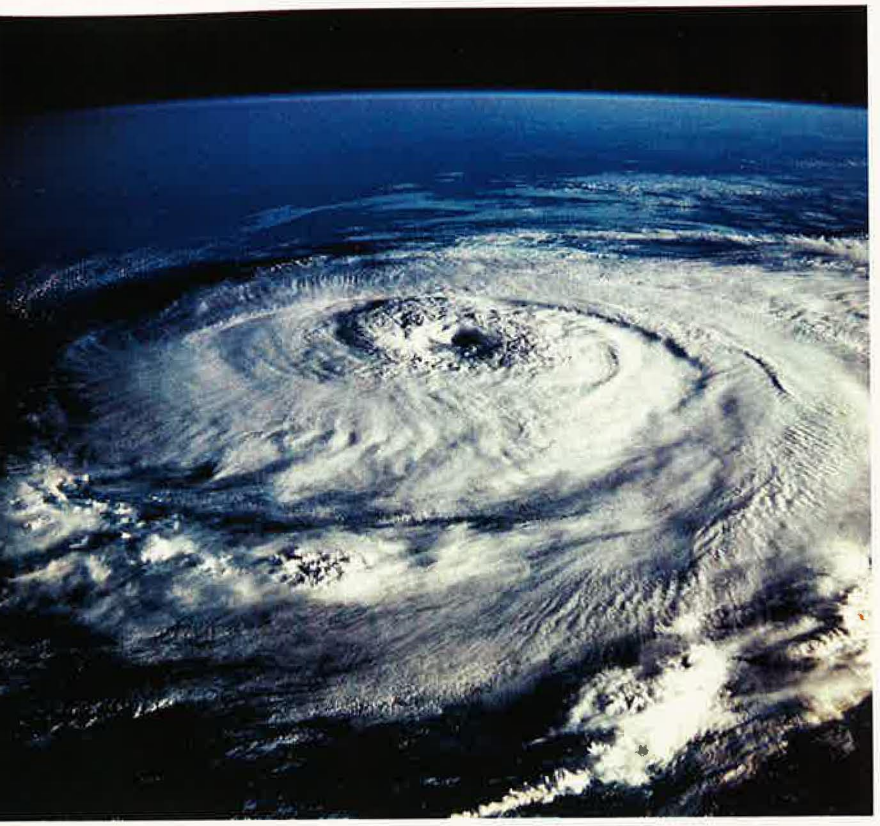
OPEN HERE FOR A WORLD OF DANGER »

hurricanes

Toll, 1900–2004: **1.1 million lives**

» AT 20 FEET BELOW SEA LEVEL, NEW ORLEANS IS A PRIME TARGET. AN AMBITIOUS NEW LEVEE SYSTEM WOULD DECREASE THE RISK

! DANGER ZONES
New Orleans
The Caribbean
Bangladesh



It takes Scott Kiser only a split second to name the one city in the U.S., and probably the world, that would sustain the most catastrophic damage from a category-5 hurricane. "New Orleans," says Kiser, a tropical-cyclone program manager for the National Weather Service. "Because the city is below sea level—with the Mississippi River on one side and Lake Pontchartrain on the other—it is a hydrologic nightmare." The worst problem, he explains, would be a storm surge, a phenomenon in which high winds stack up huge waves along a hurricane's leading edge. In New Orleans, a big enough surge would quickly drown the entire city.

Long before settlers decided that the shores of the Mississippi would be a nice place to raise a family, the river regularly topped its banks, heaping silt and mud onto surrounding wetlands. After a particularly nasty flood in 1927 that killed 300 people and left 600,000 homeless along the length of the river, city leaders in New Orleans decided to construct levees—some up to 25 feet high—to contain the swelling river during heavy rains. Residents had also been battling yellow fever, a viral disease spread by mosquitoes. From 1817 to 1905, the epidemic killed 40,000. "So people decided to drain the swamps," says Al Naomi, senior project manager for the U.S. Army Corps of Engineers in New Orleans. With the levees in place and the swamps pumped dry, the city could now spread into areas that were once uninhabitable. "But when you take the water out of the swampy soils," he continues, "they start sinking."

Today, parts of New Orleans lie up to 20 feet below sea level, and the city is sinking at a rate of about nine millimeters a year. "This makes New Orleans the most vulnerable major city to hurricanes," says John Hall of the Army Corps of Engineers. "That's because the water has to go down, not up, to reach it."

The Saffir-Simpson hurricane scale defines a category-5 storm as one with "winds greater than 155 miles per hour and storm surge generally greater than 18 feet." Although hurricanes of this magnitude slamming directly into New Orleans are extremely rare—occurring perhaps every 500 to 1,000 years—should one come ashore, the resulting storm surge would swell Lake Pontchartrain (a brackish sea adjoining the Gulf of Mexico), overtop the levees, and submerge the city under up to 40 feet of water. Once this happened, the levees would "serve as a bathtub," explains Harley Winer, chief of coastal engineering for the Army Corps's New Orleans District. The water would get trapped between the Mississippi levees and the hurricane-protection levees. "This is a highly improbable event," Winer points out, "but within the realm of possibility."

New Orleans has nearly completed its Hurricane Protection Project, a $740-million plan led by Naomi to ring the city with levees that could shield residents from up to category-3 storm surges. Meanwhile, Winer and others at the Army Corps are considering a new levee system capable of holding back a surge from a category-5 hurricane like Ivan, which threatened the city last year.

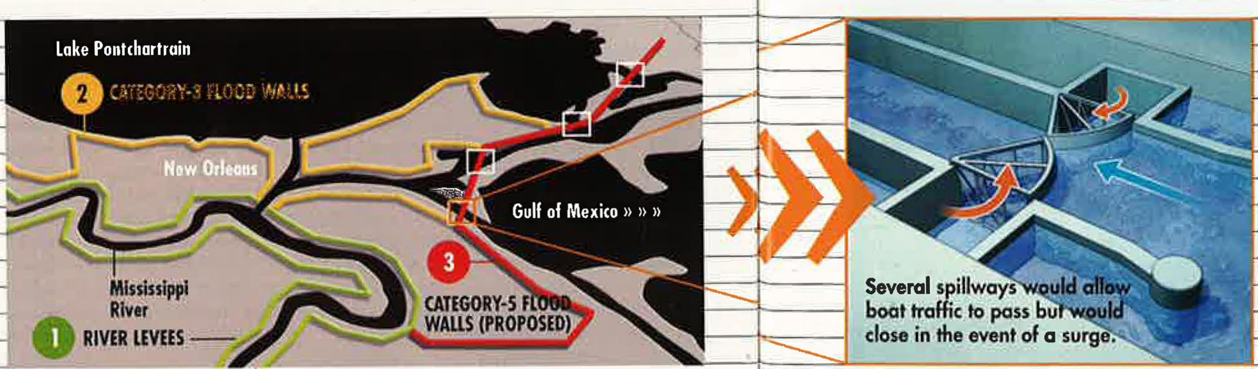
To determine exactly where and how high to build these levees, the engineers have enlisted the aid of a 3-D computer-simulation program called ADCIRC (Advanced Circulation Model). ADCIRC incorporates dozens of data points—including seabed and coastal topography, wind speed, tidal variation, ocean depth and water temperature—and charts a precise map of where the storm surge would inundate New Orleans. The category-5 levee idea, though, is still in the early planning stages; it may be decades before the new barriers are completed. Until then, locals had better keep praying to Helios.

FACING PAGE: ILLUSTRATION: GARRY MARSHALL; PHOTOGRAPH: CORBIS

Surge Protection AS NEW ORLEANS SINKS, SO RISE NEWER, BIGGER LEVEES

THE DEFENSE MECHANISM

U.S. Army Corps engineers have nearly finished a protection system to guard against category-3 hurricanes like those that hit Florida almost annually. Now the city is considering a more ambitious initiative—a floodwall that would stretch across an existing land bridge and block a category-5 storm surge. Levees have controlled Mississippi River flooding since 1927 **[1]**. Existing floodwalls (some 20 feet high) protect the lowest-lying parts of the city **[2]**. The proposed category-5 system **[3]** (one of several possible plans is shown here) would include steel and concrete levees, some as high as 40 feet, to guard against 25-foot surges.



Several spillways would allow boat traffic to pass but would close in the event of a surge.

landslides

» NEW HAZARD MAPS AND MONITORING SYSTEMS AIM TO AID TIMELY ESCAPES

! DANGER ZONES
Central America, Central Asia

Toll, 1900–2004: **45,000 lives**

Landslide, mudslide, debris flow—it doesn't matter what you call it, the outcome is the same: normally stable and stationary soil gets a bad case of wanderlust. In most cases, slides are triggered when too much water saturates a steep slope or when an earthquake shakes the ground loose. This can occur almost anywhere, but Central America—with its precipitous hills, frequent heavy rainstorms and unstable volcanic soil—is probably the number one hotspot. Ed Harp, a landslide geologist with the U.S. Geological Survey (USGS), describes the local soil as "like glass shards that interlock with each other." This cohesion, he explains, enables the soil to adhere to near-vertical slopes without sliding off.

But during earthquakes, the volcanic soil becomes volatile. "If you shake this stuff, it collapses," Harp says. It also has a sponge-like nature and can absorb a lot of water before it finally and catastrophically comes loose. In 1998, Hurricane Mitch stalled over Central America, and fierce rains caused hundreds of landslides. Mountains of mud buried thousands of villagers living near Nicaragua's Casita volcano after torrential downpours saturated its slopes and the ground gave way.

Since then, new "hazard maps" of Central America have begun giving local officials a guide to slide-prone areas. To create many of the maps, geologists are using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), which rides on board NASA's *Terra* remote-sensing satellite. ASTER can snap pictures of Earth in 14 wavelengths and capture data as fine as 15 square meters per pixel. Closer to the ground, researchers are creating hazard maps of potentially unstable terrain with LIDAR (Light Detection and Ranging). A LIDAR camera—usually mounted to a small plane or helicopter—is like radar but employs pulsed light instead of radio waves.

After Hurricane Mitch, the USGS decided that an on-the-ground weather-monitoring network might be the best tool to save lives in Central America. The agency designed and funded a $3.8-million-dollar network for Guatemala, Honduras, Nicaragua and El Salvador. Today there are 56 stations, each of which measures rainfall intensity and river levels in real time and then transmits the data over satellite via radio uplink.

"We have sites in Central America that can receive the information directly," explains Mark Smith, a surface-water specialist with the USGS who was involved in setting up the network. "Data transmits every three hours. But we put a threshold on the equipment, so if it starts raining really hard, then it goes into an emergency mode and sends information every five minutes or less." When the next big hurricane slams into Central America, villagers with homes and farms nestled on unstable hillsides in places such as Tegucigalpa, Honduras, and Zompopera, El Salvador—where some of the worst slides occurred during Hurricane Mitch—might now get a heads-up that their world is about to come crashing down again.

+ One more thing to worry about . . .

CANYON CALAMITIES FROM L.A. TO SAN FRANCISCO TO SEATTLE, SPRAWL IS PUSHING DEVELOPMENT INTO EVER STEEPER, MORE UNSTABLE TERRAIN. "IN SALT LAKE CITY," SAYS GEOLOGIST ED HARP, "PEOPLE ARE BUILDING RIGHT UP TO THE CLIFFS. YOU SEE ALL THESE HUGE BOULDERS SITTING AROUND. SOMEONE SHOULD BE SAYING, 'LOOK, THESE ROCKS *FELL* DOWN HERE, AND YOU'RE PUTTING YOUR HOUSE BESIDE THEM? WELL, GUESS WHAT, GRAVITY DOESN'T TAKE A DAY OFF.' "

tsunamis

Toll, 1900–2004: ~300,000 lives

DANGER ZONES
U.S. West Coast
Alaska
Japan

» WE HAVE THE TECHNOLOGY TO I.D. THEM NEAR THEIR SOURCE, BUT GETTING THE WORD OUT MAY STILL BE THE HARDEST PART

Ask geologists where the next big tsunami might strike, and the answer is a refrain: North America's Pacific Northwest coastline. That's the location of the Cascadia Subduction Zone, a 680-mile-long fault that hugs the shore from Northern California to Vancouver Island.

Akin to the tectonic deadlock that eventually snapped and spawned the Indian Ocean tsunami last December, Cascadia is a geological battleground where the Juan de Fuca and North American plates are duking it out. The subterranean stress building at the front lines could eventually rupture in exactly the same way it did in Southeast Asia—a seismic event geologists call a "megathrust earthquake," so named because it occurs between a subduction plate and an overriding plate in a region known as the inner-plate thrust.

Quakes within this powerful inner-plate subduction zone can readily top magnitude 9.0 on the Richter scale, explains Eric Geist, a geophysicist with the USGS who has created computer models that show how a Cascadia-generated tsunami might swamp Pacific Northwest communities.

"During one of these big earthquakes, the coastline will drop down one or two meters," he says, noting that the collapse would happen instantly. "The modeling suggests that the tsunami run-up could be as much as 20 meters or greater." Towns such as Seaside, Oregon; Crescent City, California; and Westport, Washington, could be swept away in minutes.

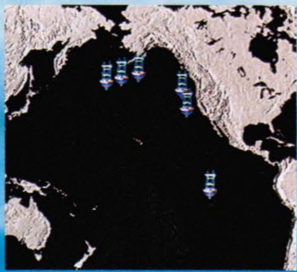
Predicting exactly when Cascadia will crack has stumped geologists. Because the fault has been quiet for so long, it's tricky to calculate the frequency of quakes. Geological clues suggest that major temblors have occurred along Cascadia seven times in the past 3,500 years, leading scientists to believe that a quake-tsunami combo occurs there every three to five centuries.

Researchers recently unearthed evidence that a massive tsunami razed the Pacific Northwest coastline in 1700. They tracked down Japanese records from that same year documenting a major tsunami and »

Wave Watcher

DART BUOYS ARE OUR TOP TSUNAMI DETECTORS

Not every deep-sea earthquake sets off a tsunami. But most of those that do, occur along subduction zones such as the Pacific Ocean's Cascadia fault, where one continental plate overtops another. The Deep-Ocean Assessment and Reporting of Tsunami (DART) buoy system is the world's most advanced warning mechanism for these monster waves. Exactly how effective the buoys would be, however, is still unknown. Although the system has undergone extensive testing, there have been no tsunamis in the monitored area since the buoys began operating in 1998.



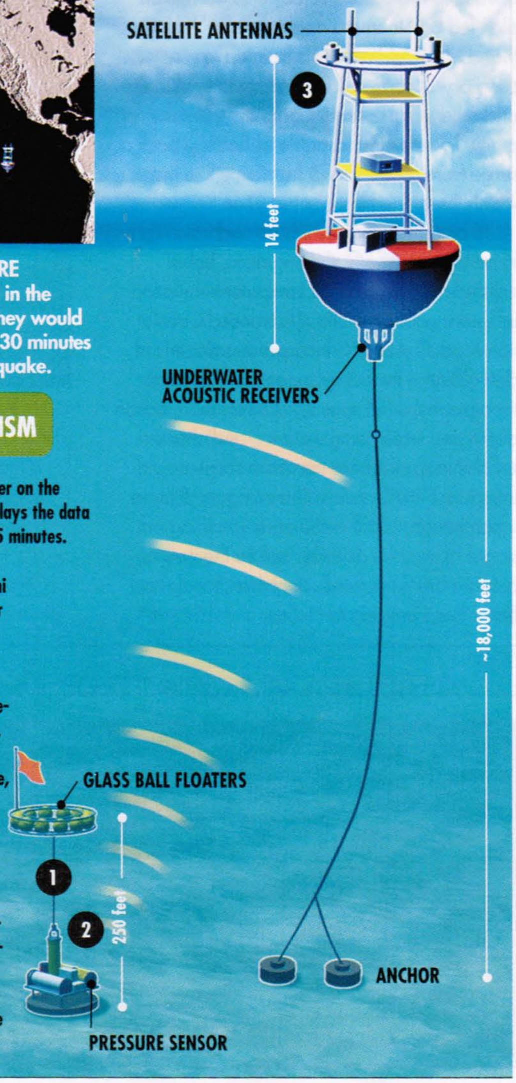
WHERE THE BUOYS ARE
Six buoys are anchored in the Pacific in areas where they would detect a tsunami within 30 minutes of the generating earthquake.

THE DEFENSE MECHANISM

1. A bottom-pressure recorder on the seafloor records tides and relays the data to the surface buoy every 15 minutes.

2. When a potential tsunami passes overhead, the water pressure bearing down on the seafloor increases. The increased pressure makes a quartz oscillator inside the recorder vibrate more quickly. When this happens, DART will switch to tsunami mode, upping its data-transfer rate to once a minute.

3. After receiving the data from the underwater sensor, the surface buoy transmits it via satellite to monitoring stations in Alaska and Hawaii. If a tsunami is detected, local areas will be alerted within minutes.



GARRY MARSHALL

found deposits of ocean sand buried in inland soils along the coasts of Washington and Oregon.

As it does for volcanoes, InSAR proves useful in monitoring shoreline deformation along Cascadia. Additionally, GPS receivers, part of a network called PANGA (Pacific Northwest GPS Array), have been installed on several dozen land-based towers to take daily measurements of "silent slippage," tiny fault-line shifts usually invisible to scientists.

When a quake does occur, the first to know will most likely be staffers stationed at the West Coast and Alaska Tsunami Warning Center in Palmer, Alaska. The center keeps tabs on 150 seismic sensors in the Pacific Rim countries and 100 sea-level gauges scattered throughout the Pacific Ocean. The latest additions to its early-warning system are DART (Deep-Ocean Assessment and Reporting of Tsunamis) buoys. The buoys record the normal rise and fall of tides in the Pacific. But should those tides deviate by as little as three centimeters—even in water up to 18,000 feet deep—the system automatically switches into emergency tsunami mode, beaming up-to-the-minute alerts to satellites.

Geist cautions, however, that we can become too reliant on these sophisticated alert systems. In some cases, Cascadia veers less than 100 miles from shore. Depending on where a quake hits along the fault, it could take just minutes for a tsunami to reach land. DART buoys and seismic sensors will trigger coastal-tsunami sirens and automated radio bulletins in the vicinity of the quake, but the alerts may arrive too late for residents. "The hardest part of the problem," Geist says, "is to have people on the beach know that if you feel strong shaking or see the ocean go way out, that's your sign not to wait for an official warning."

MICHAEL BEHAR grew up in Seattle. His elementary-school science-fair presentation on volcanoes was delayed by the 1980 eruption of Mt. St. Helens.

earthquakes

» THE ONLY THING WE CAN PREDICT IS WHERE A "BIG ONE" COULD DO THE MOST DAMAGE

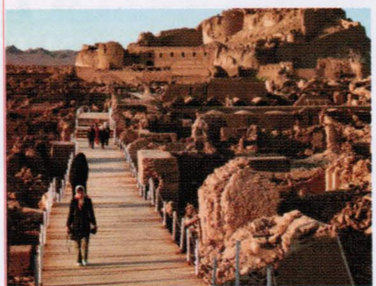
! DANGER ZONES India, Iran Turkey

Toll, 1900–2004: **1.8 million lives**

We know this much: Earthquakes strike along faults—fractures in the planet's crust where plates of rock are thrust into a sort of geological gridlock. The difference between a tremor and an earth-shattering 8.0-plus-magnitude quake depends on whether the plates slip when the tension between them is still relatively low or if they snap after enduring millennia of mounting strain.

Calculating exactly when this might happen, however, is no easy feat. "We're not even getting close to predicting earthquakes," says Thomas Heaton, a professor of geophysics and civil engineering at Caltech. Maybe scientists can't tell us when a quake might strike, but they're getting much better at pinpointing where the biggest ones will result in heavy casualties and financial loss. "The real culprits are cities with a lot of six- to 10-story buildings made of reinforced concrete," Heaton says.

On his shortlist: Tehran, Iran, and Istanbul, Turkey—both cities have populations of more than 12 million and long, deep and very powerful seismic faults nearby. More vulnerable still is the enormous Himalayan thrust fault in Northern India. The three Indian states that border it have a combined population of more than 25 million people who mostly reside in brittle concrete or earthen structures.



SHAKE AND BREAK **Cities made of mud and brick [here, Bam, Iran] are susceptible to huge quake damage.**

Jean-Philippe Avouac, a professor of geology and director of the Caltech Tectonics Observatory, traveled to Nepal last year to study a section of the Himalayan fault. "A large portion of the [fault] between Katmandu and Dehradun, north of Delhi, hasn't produced any known big quakes for at least two centuries," he says. "Sooner or later this [fault] will break, and the death toll could be huge, given the density of population in Northern India, the soil condition—which is prone to liquefaction—and the type of construction."

Heaton praises instruments such as InSAR and GPS, describing them as "stunning tools" that have "helped us recognize where strain is accumulating in the Earth." More promising—though, sadly, not much help to Iran, Turkey or India—is EarthScope, a new partnership between the USGS and the National Science Foundation that involves embedding a "strike-slip" sensor 10,010 feet deep in the San Andreas Fault as well as implementing a nationwide system of hundreds of GPS sensors and strain meters along the edges of the Pacific and North American plates.

For now, however, the best technological hope for the world's earthquake hot zones is the Global Seismic Network (GSN), which consists of 135 seismic monitors positioned worldwide that register quakes in real time and then beam the data to satellites or upload it to the Internet. GSN functions like a seismic watchdog, recording and cataloging quakes as they occur. Ultimately, GSN data will be assembled into a global database of seismic activity. Analyzing the data en masse, the thinking goes, might reveal trends and patterns that are precursors to a fault rupture. ■

+ One more thing to worry about . . .

THE CANARY ISLANDS NINE HOURS. THAT'S HOW LONG IT WOULD TAKE FOR A TSUNAMI WAVE TO TRAVEL FROM ITS BIRTHPLACE IN THE CANARY ISLANDS TO THE HEAVILY POPULATED, LOW-LYING COAST OF THE EASTERN U.S. THE WESTERN SLOPE OF THE AFRICAN VOLCANO CUMBRE VIEJA CONTAINS A 35-MILE SLAB OF LOOSE ROCK THAT GEOLOGISTS THEORIZE COULD SHEAR AWAY AND PLUNGE INTO THE SEA IN THE EVENT OF AN ERUPTION. IF THAT HAPPENED, WAVES UP TO 80 FEET HIGH COULD STRIKE FROM NEW YORK TO FLORIDA.

MORTEZA NIKOUBAZL/CORBIS