NEWS FEATURE

Skimming the surface of underwater landslides

Scientists are just beginning to understand these subaquatic phenomena capable of producing large tsunamis and wreaking havoc on offshore facilities

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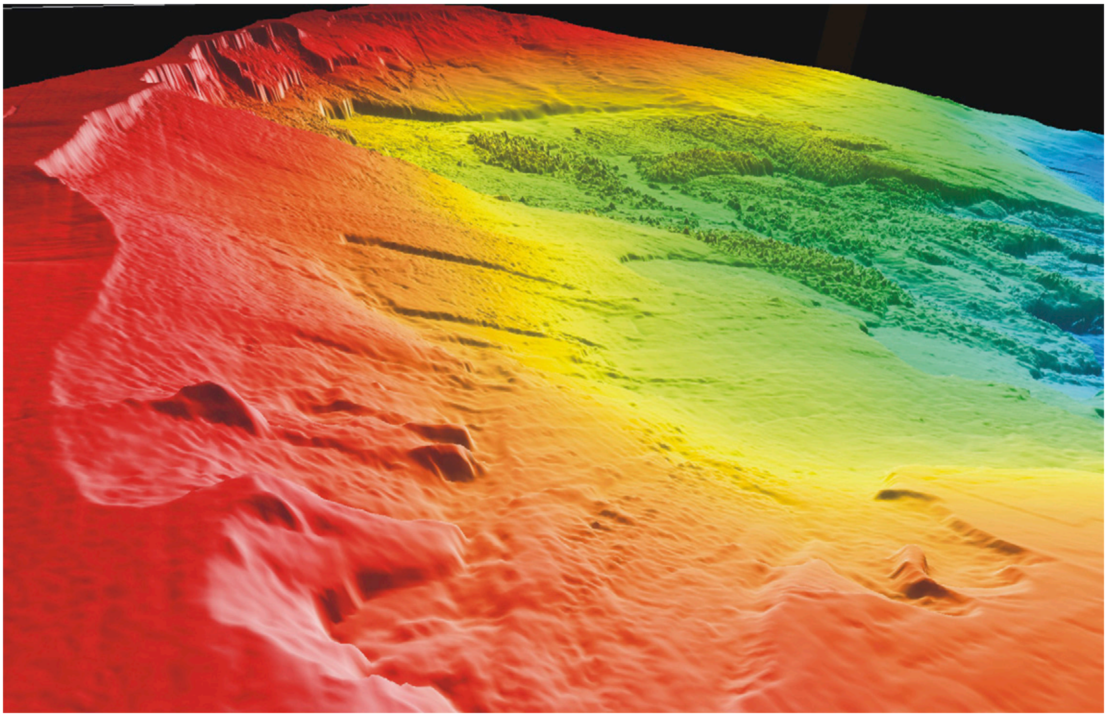
Around 8,200 years ago, a 180-mile-wide section of the ocean floor off the coast of Norway reached a tipping point. Several thousand years prior, ice streams from melting glaciers had been carrying trillions of tons of sediment to the ocean. Over time, the sediment had accumulated at the edge of the continental shelf, where the shallower ocean floor around Scandinavia plunges toward the depths of the Norwegian Sea. But finally, the underwater build-up became unstable; something set it off, perhaps an earthquake. An area of the seafloor roughly the size of Maine started collapsing, sliding down the shelf at speeds reaching more than 40 miles per hour. The vast slide continued for several hours, with material coming to rest as far as 500 miles downstream, halfway to Greenland. The massive movement also riled up the ocean, sending tsunamis racing toward a handful of northern European shores, eventually flooding areas as high as 20 meters above sea level in some places.

"It's hard to even comprehend the size of a landslide like this," says geologist Peter Talling of the United Kingdom's National Oceanography Centre. "A single landslide can move more sediment than all the world's rivers move in a year."

The Storegga Landslide off Norway isn't the only one of its kind, nor the biggest. Geological evidence reveals that submarine landslides as large or larger than Storegga occurred off New Zealand and South Africa in the distant past. In the last century alone, much smaller submarine landslides have generated tsunamis off Alaska, Venezuela, Papua New Guinea, Newfoundland, and the Mississippi Delta. Some recently published evidence even suggests that the



The causes of submarine landslides like this one—the Storegga Slide off Norway viewed here from the north along its 300-kilometer-long head wall—are still not well understood. This slide occurred ~8,150 years ago and caused a 20-meter-high tsunami in the Northeast Atlantic. Image courtesy of Christian Berndt (GEOMAR).

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March 2011 Tohoku tsunami in Japan was so big along some areas of the coastline in part because of submarine landslides set off by the large off-shore earthquakes (1).

A few decades ago, scientists knew these landslides occurred, but little more. The evidence was giant scars in the seafloor, with piles of sediment sitting at the bottom. Now, using new modeling, measurement, and simulation techniques, researchers are beginning to answer basic questions about the landslides' properties. They want to know what triggers these landslides and how they might be predicted.

"We have a really good overview of what these things look like now," says Joris Eggenhuisen of Utrecht University. "But if you really want to predict which type of these landslides happens where, you really need to know the physics of how they operate, and that's where we're trying to catch up."

Like landslides on the land, submarine landslides involve the movement of material down a slope, but the presence of water weakens sediments and eases movements, enabling underwater slides to be vastly larger. And unlike on-shore landslides, submarine landslides—at least, for now—are nearly impossible to catch in the act. There are no bystanders to snap video, and no areas staked out with precise measurement tools to record one in motion.

"The absolute best-case scenario for the field right now would be that we'd be monitoring one of these spots just before a landslide occurred," says Talling. "But we've never been able to do that underwater because we just don't have a good enough idea yet where the next one will be." Instead, scientists are turning to the deep-sea geological record to understand landslides of the past, in an attempt to predict where slides may occur and improve their odds of eventually catching one in the act, and discover whether a warming climate makes the slides more common.

Before and After

The closest researchers have come to catching one of these elusive geologic tumbles in the act was about 50 years ago. On the evening of March 28, 1964, a huge earthquake struck off Port Valdez, Alaska. We now know that it triggered a dozen submarine landslides in Prince William Sound, including one nearly a mile wide. Although the earthquake itself caused large tsunami waves that inflicted casualties as far away as California, the most damaging waves within Prince William Sound—measuring up to 40 feet high and responsible for dozens of deaths—were prompted by the landslides. Just 16 years earlier, in 1948, enabled in part by quickly improving antisubmarine technology, oceanographers had mapped the seafloor around Prince William Sound. More recently, about 10 years ago, the National Oceanic and Atmospheric Administration (NOAA) conducted routine surveys of the sound to ensure safe navigation for ships (2).

"It's very rare that we have an event like this bracketed so closely on either side by seafloor measurements," says geophysicist Tom Parsons of the US Geological Survey. "Combine that with all these first-hand accounts of the tsunamis, wave measurements, and known currents at the time, and we have enough information to really start creating a model."

When they compared the 1948 map and those done 60 years later, the largest of the Port Valdez submarine landslides stuck out like a sore thumb. "We can see the scar where the landslide came down," Parsons says. "And then you see these huge blocks sticking up, each at the bottom of a chute."

But the NOAA mapping was limited to the contours of the ocean floor. Parsons and his colleagues at the US Geological Survey wanted to see below that to the base of the blocks of sediment, to measure their full heights. So in 2013 they launched their own mapping effort, using multibeam sonar, which sends pings in a fan-shape from a boat toward the seafloor, providing a faster and more nuanced map than does a series of conventional sonar pings. And they used sparkers, electrodes that emit high-frequency acoustic pulses, to visualize multiple layers of sediment beneath the bottom (3).

With the new data on the precise size, shape, and path of the primary landslide, as well as the historical tsunami records, Parsons was able to fine-tune computer models showing how landslides can generate tsunami waves by churning up deep water. He found that the size of the largest intact block of sediment at the bottom of a landslide is more predictive of tsunami size than the total volume of the slide (4). The observation is one small step toward being able to predict the damage future landslides could cause.

Landslide in the Lab

Right now, there's only one place to see a submarine landslide in action: in Joris Eggenhuisen's laboratory at Utrecht University. There, Eggenhuisen runs the Eurotank, a 34- by 21-foot indoor basin where scientists can simulate interactions between water and sediment (recently, they even used the tank to recreate processes that could have occurred on the surface of Mars leading to signatures of water).

The researchers hadn't tried to study submarine landslides in the tank until 2010, when a truck full of sand was accidentally bumped against the tank's outer wall. At the time, the tank was filled to the brim with water over a gradually sloping pile of sediment to mimic an ocean floor. When they saw that the shock triggered a submarine landslide, Eggenhuisen says, they set out to reproduce it.

Through many rounds of trial and error, Eggenhuisen's group found what he calls "the perfect recipe" for a submarine landslide. It includes a parfait-like layering of different types of sediment on top of each other. "If you just have a [homogenous] pile of sand or a pile of mud, you won't get anything like this," Eggenhuisen says. In the future, direct observations of these smaller landslides, Eggenhuisen believes, will provide information that can be plugged into computer simulations of larger events.

Parsons' team also strengthened a theory on how the area near Valdez had become primed for a big submarine landslide before the earthquake hit. Valdez Glacier—perched above Port Valdez—had been melting since the beginning of the century, receding more than half a mile between 1901 and 1964 (it has since receded about a mile farther). The town had built a dike and levee system to reroute all of the drainage to a point just south of the town. Sediment had therefore been quickly building up in one spot, a story that recurs across many submarine landslides. Places where sediment accumulates quickly, whether from melting glaciers or changing river deltas, seem more prone to these underwater collapses.

"We can get some feel for oversteepened slopes, and the sediment accumulation rates that are likely to cause pile-ups that can fail," says Parsons. "But it's still difficult to nail down the timing." Researchers don't know whether a slide will happen "tomorrow or 10,000 years from now."

Learning from the Past

Whether submarine landslides are more common during times of global warming, or rising sea levels, is one of the most urgent questions for researchers today. Industries that involve coastal development, deep-sea oil rigs, and transocean telecommunications cables are particularly anxious to predict landslides that could damage their infrastructure.

In 1997, for example, geophysicists discovered Ormen Lange, a gas field just off Norway that now supplies about a fifth of the gas used in the United Kingdom. But the field was situated near the steep underwater cliff left by the infamous Storegga Landslide. Before drilling into it, companies had questions about the risk of a future landslide in the area. Within a few years, Storegga became the most studied submarine landslide in the world. The initial studies assuaged fears of a future landslide; it was concluded to be low risk. From a geological perspective, however, scientists still wondered what Storegga's past could tell them about landslides in general.

Last summer, Talling and others led a research cruise to Storegga. Previous surveys of the seafloor had indicated that an earlier landslide had occurred in the same spot as the 6200 B.C. slide, and the team wanted to know if the same set of preconditions—namely, melting glaciers—led up to it. He and his colleagues collected 88 core samples from the ocean floor and brought them back to the laboratory to analyze.

One hypothesis, Talling says, had suggested that areas could be made prone to submarine landslides after the build-up of glaciers, which move large amounts of sediment. The new samples his team collected hinted that the older landslide in the Norwegian Sea may have been even bigger. But the data didn't clear up whether the slide coincided with an ice age; the error bars on the dates were too large.

When one of Talling's students made a list of other submarine landslides around the world, she ran into the same problem: the dates are often too uncertain to know whether any patterns aligned with climatic shifts (5). Moreover, when they looked at the locations of the landslides, many fell far from the seismically active areas where tectonic plates meet, and far from areas where rivers or glaciers were emptying into the ocean.

Getting more precise dates for the landslides—that can be aligned with data on earthquakes, climate patterns, and tsunamis—is the key to finding out the triggers for these slides, Talling says.

Collecting the Clues

If you ask geologist Lesli Wood about the preconditions for submarine landslides, she starts reeling off a list: the steepness of the slope of a continental shelf; the types of clays, minerals, and rocks that it's composed of and the way they're arranged; the methane hydrate deposits within the sea floor; the temperature and pressure of the water, and so on.

Wood, who's now based at the Colorado School of Mines, started out her career working for chemical and oil company Amoco off the coast of South America, assessing risks in the seafloor associated with drilling. "Most people, even in the industry, had never heard of submarine landslides 15 years ago," Wood says. But the landslides intrigued her and she made it her goal to locate and describe as many of them as possible.

"I started cobbling together this database from information that different companies had," she recalls. "And the first thing that stood out was just how diverse the slides are."

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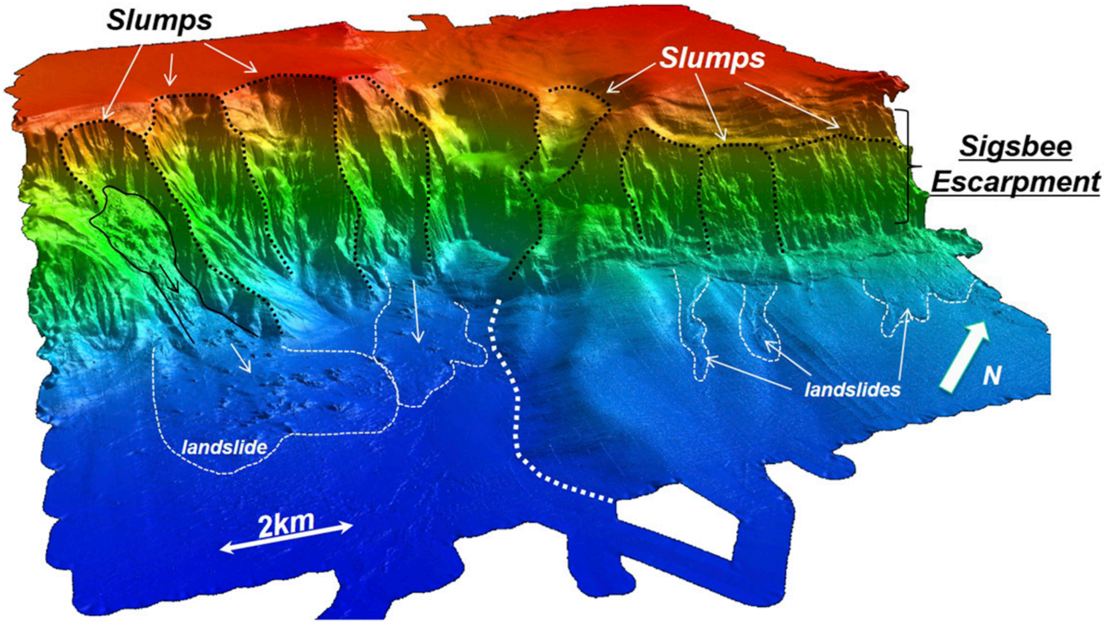
Submarine landslides occur at all size scales, up to thousands of miles across. Some move down steep slopes, others down inclines that are barely one degree, as flat as a sports field. Some scrape into the seafloor as they move, and others, Wood says, "slide like butter." Some end their run as giant intact blocks of displaced sediment, whereas others collapse into unstructured piles of mud. And some submarine landslides fan out from a single point, leaving a triangular scar, whereas others move straight down a slope.

In all cases, the water changes the physics of the sediment and allows a different type of slide than occurs on land. Sediment that's fully saturated is significantly weaker than drier soil, which alters the conditions required for a slide to begin or end, and also affects the movement in between. And landslides tend to occur where pockets of fluid are trapped, a more common occurrence underwater than on land. Moreover, once wet sediment is moving, it can flow a lot like a fluid.

Many questions remain about which types of submarine landslide happen where, but enough is known, Wood says, to start making basic risk assessments. For example, she and her former doctoral student, Lorena Moscardelli of the University of Texas at Austin, have just completed an in-depth analysis of the area around Trinidad. They used data on past tsunamis



Multibeam echosounder data show highly detailed image of sea floor topography in the Gulf of Mexico. The image shows numerous sea floor landslides occurring off the steep Sigsbee Escarpment. The water depth varies from about 4,000 feet below sea level (red) to over 7,300 feet below sea level (blue). Image courtesy of Lesli Wood (Colorado School of Mines, Golden, CO).

and earthquakes, as well as detailed maps of the seafloor—including information on slopes and materials—to run computer models of possible landslide scenarios and identify coastal areas and oil rigs most at risk for damage from landslide-triggered tsunamis. They still can't predict when submarine landslides will happen, but coastal planners can use the information to guide new development.

Such risk analysis would be useful in coastal areas around the globe, but in many places there's not enough data yet to build the models. To help spur similar risk assessments elsewhere, Wood launched a public database of submarine landslides in July 2015 (6). So far, it has 332 landslides, mostly characterized by their size and shape. As researchers increasingly take core samples from landslides, Wood hopes that more information on sediment types will be added to the database, because she thinks that's critical to understanding the slides.

Watch and Learn

If you ask submarine landslide researchers when and where the next big one will be, they just shrug. "Right now, to answer that question, one of the best things we can do is keep looking for evidence of past landslides in places that we know have had big tsunamis," says Wood. The biggest progress in the past decade, she adds, is that "the engineering community is at least aware of these enough that they try to build their offshore facilities in less risky areas."

Talling thinks that basic questions about trends in landslides over time—such as whether they correlate with climate cycles—will be answered better in the next few years as more precise dates for past landslides are determined. And soon, Parsons hopes, researchers will take the leap toward choosing some areas at particular risk and staking them out with monitoring devices. Maybe, he says, they'll finally catch one in the act. But choosing such an area is still daunting.

"One of the things I think is most interesting about these, but also maybe most scary, is that every continental margin has the potential to be where a landslide happens, even if you're nowhere near a seismic zone," says Parsons. "It's really a wide open hazard."

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