Ancient Earthquakes at Lake Lucerne

A recent survey of the sediments beneath a Swiss lake reveals a series of prehistoric temblors

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On Tuesday the 18th of September, 1601, shortly before two o'clock in the morning, a strong and truly frightening earthquake hit the region around Lucerne .… Nobody could remember a similar event and even chronicles do not document that the city ever experienced a similar occurrence." So begins the eyewitness report of Renward Cysat, a city clerk in Lucerne, Switzerland, who amply documented the catastrophic events that followed one of the strongest known earthquakes in central Europe. That temblor caused considerable damage over much of Switzerland and was felt in the parts of France, Germany and Italy. Seismologists estimate that this quake, had it been recorded with modern instruments, would have ranked something like 6.2 on the Richter scale, which would put it on par with many damaging earthquakes that have struck near Los Angeles and San Francisco in recent times.

Of course, Californians expect the ground to shake now and again. But honestly, who imagines earthquakes threatening Switzerland? Even the Swiss, who frequently take precautions against avalanches and floods, rarely consider the possibility of earthquakes in their neighborhood. Yet digging back far enough into the historical record, one finds that Switzerland has in fact experienced several strong earthquakes, ones that brought about considerable damage to property and loss of life. The 1601 Lucerne event is just one example. Another is an earthquake near Basel in 1356, which destroyed large parts of that city.

The Basel quake remains the strongest one ever observed in central Europe. A similar event today would kill and injure many people, and it would cause widespread and costly destruction to property. It is, however, difficult to decide how much time and money should be invested in earthquake precautions without knowing how large or frequent future quakes are likely to be. This is why we are trying to help assess Switzerland's little-known seismic hazards, an effort that requires, at minimum, a good understanding of the recurrence times of rare but strong events.

Up until just recently, the catalogue of past earthquakes was based exclusively on seismographic measurements and historical documents. In Switzerland, the first seismograph was installed in 1911, and the written record covers just the last millennium. Thus the two main sources of information, while valuable, are insufficient to identify places where strong earthquakes strike, say, every few thousand years. This shortcoming is a real concern, because such lengthy intervals between large earthquakes is typical for regions such as Switzerland, which are located away from the edges of tectonic plates, where most seismic activity takes place.

The only method to document the past occurrence (and possible recurrence) of strong earthquakes in such locales is to extend the catalogue of known events to prehistoric times. Although our Stone Age forebears left no description of ancient earthquakes, nature has recorded much of what took place. One just needs to uncover and

Figure 1. Although many of the people living and working around Lake Lucerne are keenly aware of certain natural hazards, such as avalanches and landslides, few think much about the possibility that a large earthquake might strike. Yet powerful temblors have indeed hit this region. One took place in 1601 and caused considerable damage in the city of Lucerne (*foreground*). But there are no historical records of other earthquakes of similar strength, which has made it quite difficult to gauge the likelihood of a recurrence. To better estimate that threat, the authors undertook to study the sediment that accumulates beneath the lake. Their examination of this natural archive revealed that four other large quakes have disrupted this scenic locale during the past several millennia.

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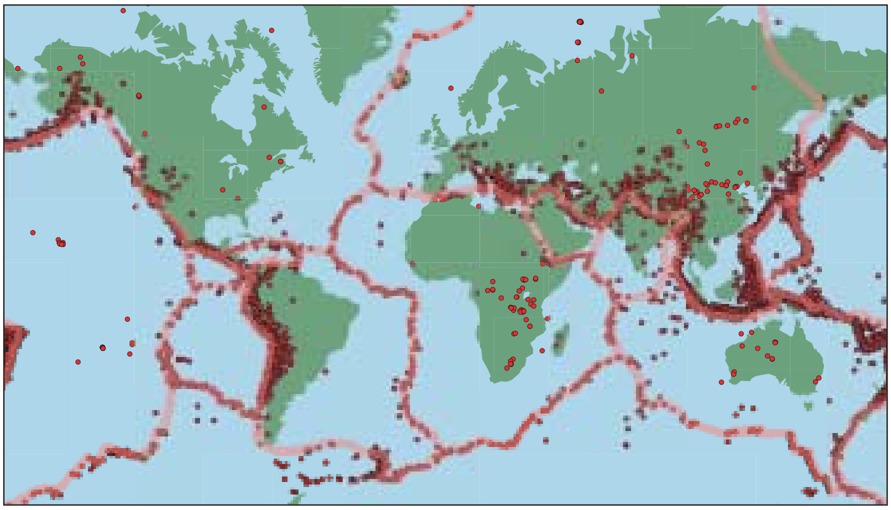


Figure 2. Although most seismic activity takes place at the boundaries between tectonic plates *(pink lines)*, earthquakes of substantial size sometimes strike well within plate interiors. The red dots shows the locations of earthquakes with magnitudes of 5.5 or more that have taken place since 1973. (Plate boundaries are derived largely from Rice University's Discovering Plate Boundaries Project; earthquake epicenters are from the catalog of the U.S. Geological Survey's National Earthquake Information Center.)

interpret the hidden geologic archives to glean information about seismic events in the distant past.

Paleoseismologists—the scientists who specialize in tracking prehistoric earthquakes—often take advantage of the fact that moderate to strong seismic shaking leaves characteristic traces at or immediately below ground level. Thus many of our colleagues in this subfield of geology regularly dig trenches across the surface trace of active faults, a procedure that allows them to measure the offsets and timing of ancient quakes. This strategy does not, however, work very well in areas that are distant from plate boundaries, where surface ruptures are rare and difficult to identify. In such intra-plate regions, one does better to study features that record earthquake shaking at one place regardless of the exact position of the causative fault.

Fortunately, there are many secondary effects of ground shaking: Stalactites in caves can break, precariously poised boulders can topple over, steep slopes can become unstable, and sandy soils can be forced to flow as a liquid. Some of these happenings can, however, come about for other reasons: A stalactite may break under its own weight, for example, or heavy rain may induce a landslide. So the main task of paleoseismologists is to distinguish the triggering mechanism and, once a seismic event has been identified, to date the structures it leaves in its wake.

Land O'Lakes

As any geologist will attest, lake sediments provide some of the most sensitive records of past environmental conditions, and happily for us, Switzerland is a country famous for its many majestic lakes. Such sediments are especially valuable because they accumulate continuously, year by year, and thus contain a complete and often highly detailed record of past events since the lake came into existence. In the parts of Lake Lucerne that we studied, a little less than a millimeter of sediment accumulates each year—and has done so for several millennia. The composition of this material reflects much about local conditions at the time of deposition. Pollen wafted into the lake, for example, becomes buried in the muddy sediment at the bottom, thus recording the changing nature of nearby vegetation. And coarse-grained layers document times when ancient floods swept sandy debris into the lake.

Earthquakes, too, can leave permanent traces on the floors of lakes and oceans, because they often send sediments tumbling down the submerged slopes at the margins of these bodies of water. The most famous example of this nature is probably the Grand Banks earthquake of 1929, which had a Richter magnitude of 7.2 and triggered a giant undersea slide offshore of Newfoundland. The sudden flow of sediments down the continental slope caused a destructive tsunami and cut off transatlantic communication as a great mass of soupy mud successively broke several submarine telephone cables lying in its path.

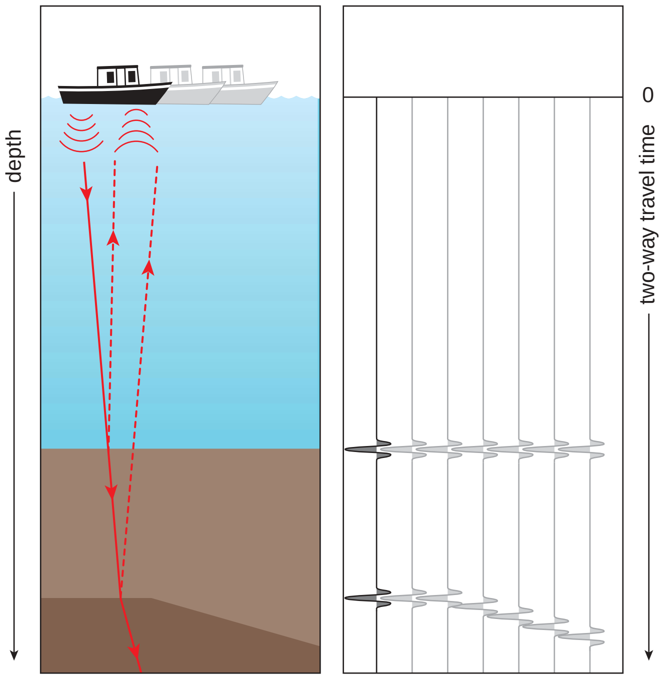
Knowing of such events, we reasoned that the bottom sediments of various Swiss lakes would similarly have recorded past episodes of seismic shaking. It took us a while to test this idea, but after much field and laboratory work probing the depths of Lake Lucerne, we were able to discern that four significant prehistoric earthquakes had indeed shaken this locale. Here we would like to recount in some detail how we mounted our investigation.

A History Lesson

Our first task in putting together our research program was to consider just what sort of earthquake signature would be left in the lake sediments. For that, Cysat's report of the 1601 quake was invaluable. On the morning following the quake, he and his fellow city officials rode on horseback across the strand while assessing the damage. He noted the chaotic scene:

> Along the shore of the lake we observed ships, timber, planks, tubes and other matters that were not only drifting in the lake, but have been washed ashore and deposited 50 paces [40 to 50 meters] behind the regular shoreline and up to two halberds [three to four meters] above lake level.... Closer towards the city, we saw people collecting fishes that were thrown onshore.... In Lucerne the ships were torn off the piers and became pushed far out into the lake. They were drifting rapidly although they were driven neither by wind, nor rudder or sails.... Preternaturally, the big river Reuss [the normal outflow of Lake Lucerne] flew forth and back six times in an hour.

Cysat further recorded that several times the water in the river separating the two parts of the city disappeared almost completely, so that "one could cross the riverbed almost by barely getting wet feet, as numerous young people did to commemorate this extraordinary event.... Also the [water-driven] mills stopped working." Cysat also noted that "subaqueous mountains and hills one could see and reach with bars during low lake were broken apart and sucked down into the depth of the lake" and "pieces of meadows were



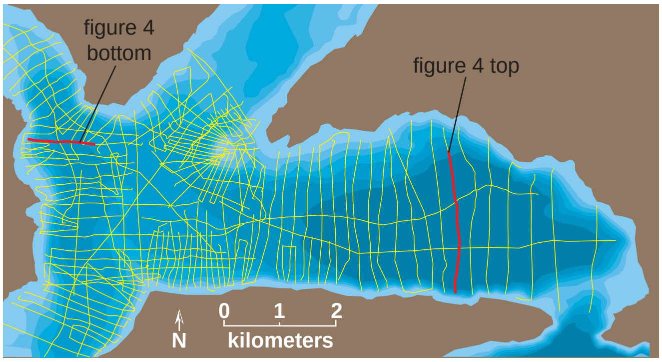


Figure 3. Structural details in the sediments of Lake Lucerne could be charted using reflection seismic profiling. This method uses an acoustic transducer affixed to a survey boat to emit a pulse of sound energy, which partially reflects from the lake bottom and from the interfaces between sedimentary layers of distinctive composition *(far left)*. The same transducer picks up these faint echoes, which are recorded electronically. Repeating this sounding procedure at closely spaced intervals and plotting the results side by side *(left)* produces a facsimile of the structure within the lake-bottom sediments. The authors conducted seismic profiling while cruising some 300 kilometers over a zigzag course that allowed them to chart the western portion of the lake *(top)*.

moved over more than a stone's throw off their original positions and deep gaps opened in the ground."

Reading his account, it was easy for us to imagine that these dramatic events would have left permanent marks on the floor of the lake. And indeed, we were reasonably sure that they did, because in the early 1980s members of the Limnogeology Laboratory at the Swiss Federal Institute of Technology in Zurich (which often goes by its German acronym ETH) had discovered two large deposits at the bottom of the lake, the result of subaqueous mudslides, which they believed the 1601 quake had caused.

In 1996, soon after taking the reins to the Limnogeology Laboratory, one of us (McKenzie) eagerly picked up on this line of research. Together with another one of the authors (Anselmetti), she discovered numerous slide deposits, many of them deeper (and thus older) than the ones previously studied. It was thus clear that these older features must have been deposited in prehistoric times and that if one could distinguish slides triggered by earthquakes from slides brought about by other processes, these ancient lake deposits would provide an earthquake history of the area for the past 15 millennia.

Coincidently, at this time another one of us (Giardini), director of the Swiss Seismological Service, was looking for just such an extended catalogue of earthquakes. Being responsible for the assessment of seismic hazards for Switzerland, Giardini needed to know where, when and how often big earthquakes had taken place. When Anselmetti reported the findings for Lake Lucerne, Giardini quickly appreciated that these slide deposits could be viewed as so many smoking guns, indicators of hitherto unknown earthquakes of Switzerland's distant past. This minor epiphany sparked what remains a close collaboration between the Swiss Seismological Survey and the ETH Limnogeology Laboratory.

Having worked out the goal and strategy of this research project, McKenzie, Anselmetti and Giardini just needed to find a doctoral student, who, of course, they hoped would do the heavy lifting. So they approached another one of us (Schnellmann), just after he returned from doing fieldwork in a borax mine in Turkey. On a boat trip on Lake Lucerne, Anselmetti convinced Schnellmann to sign on and help unravel the secrets hidden below the surface of the lake. Although Schnellmann wondered a bit whether this attempt at tracking ancient earthquakes would prove to be an interesting and meaningful topic for the beginning of a scientific career, the prospect of spending the next few years cruising scenic Lake Lucerne (instead of breathing dust in a distant borax mine) made the decision easy enough.

Fishing for Answers

In June 2001, Schnellman and Anselmetti transported the ETH research vessel *R/V Tethys* to Lake Lucerne and started to explore the bottom sediments using reflection seismology. This method is similar to the sonography that is used in medicine: Just as doctors are able to peek inside human bodies with ultrasound, geologists can image the internal structure of the sediments that collect beneath bodies of water by sending sound waves downward from the surface and recording the faint echoes that return. In this case, the acoustic transducer (which acts as both a loudspeaker and a microphone) is mounted on the hull of a ship, where it transmits an acoustic signal into the water. Some of this sound energy bounces back from the floor of the lake and from distinct depositional layers within the lake-bottom muds. The reflected signal, which is picked up with the same acoustic transducer and recorded aboard the research vessel, thus carries information about the structure of the sediments.

Over many days of fieldwork, we gathered reflection-seismic data over a distance that measured more than 300 kilometers in all. Following a zigzag course, we collected soundings over a dense grid of survey lines, which allowed us to piece together a three-dimensional picture of the lake-bottom sediments after we returned to the lab. In poring over our data, we found much evidence for subaqueous mass movements. These traces were either failure scars on slopes, marking where large chunks of material had fallen

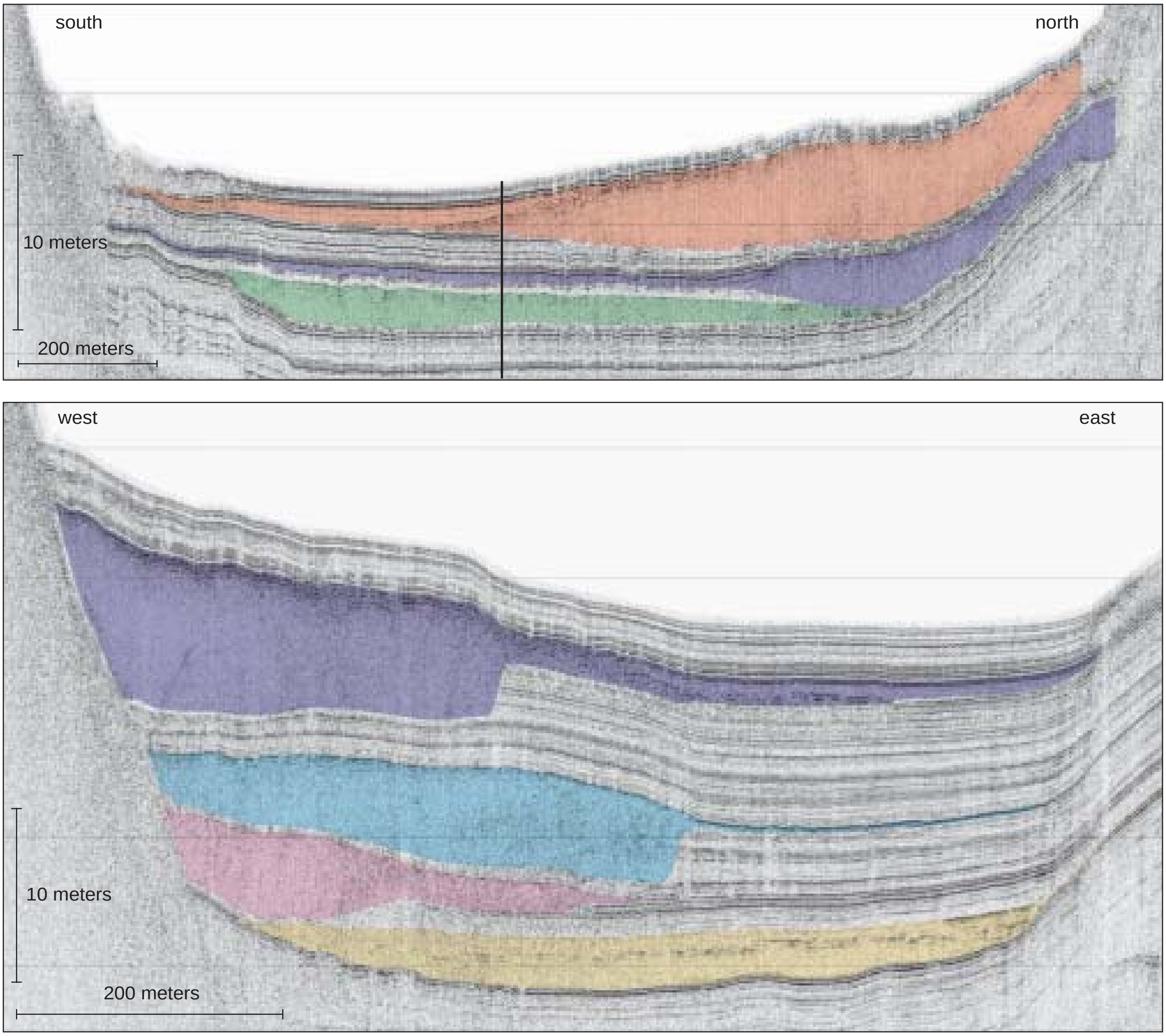


Figure 4. Seismic reflection profiles obtained over two cruise tracks reveal distinctive deposits indicative of slumping along the margins of the lake *(colored zones)*. The top panel shows a north-to-south section that cuts through the center of a large deep basin *(red line at right in the top panel of Figure 3)*. The bottom panel shows an east-to-west section near the western margin of the lake *(red line at left in Figure 3)*. The character of the seismic pattern within the colored zones is somewhat chaotic, like a static-filled television screen, whereas the normal sedimentary layers outside them produce continuous light and dark lines. Guided by these images and many of the other seismic sections they obtained for Lake Lucerne, the authors retrieved sediment cores from key positions, including the center of the large basin *(black line in upper panel)*. This roughly 10-meter-long core penetrated three slump-induced deposits of different ages *(pink, purple, green)*.

away, or buried slide deposits, where the slumped material had settled. Such accumulations can easily be recognized on the seismic sections because normal, undisturbed lake sediments show clear horizontal layering, whereas the intensely reworked slide deposits give a chaotic signature resembling a static-filled TV screen.

Having dozens of closely spaced cross-sections in hand made it easy to track prominent layers and to map the extent of individual slumps throughout the fraction of the lake that we had surveyed. (Lake Lucerne contains several distinct basins, and we decided not to examine those with adjacent river deltas, which we knew could be the source of slump deposits that didn't have anything to do with earthquakes.) At this point we realized that many of the newly discovered deposits were at exactly the same level as the ones the former ETH lake research group had already detected and associated with the 1601 earthquake. Indeed, the horizon corresponding to this event contains at least 13 widespread slumps, indicating that this quake triggered synchronous sliding all over the lake. What is more, we found that in the center of two well-separated sub-basins, these slide deposits are overlain by layers of homogeneous mud that are as much as two meters thick—a result, no doubt, of a great mass of sediment that was held in suspension in the waters of the lake for a short time after the quake before finally settling out.

Figuring that prehistoric earthquakes with magnitudes equal to or larger than the 1601 event would have left similar deposits, we examined the seismic cross-sections with great care. And we quickly discovered a horizon some three meters below the floor of the lake that contains 16 individual slumps. Thick, homogenous mud bodies sit directly on top of these deposits in three different sub-basins. We thus suspected that we were seeing the vestiges of some violent prehistoric quake.

Still, we wondered a bit at the time whether all this slumping could have happened for a more mundane reason. But we made an observation that gave us confidence that an earthquake was indeed at work here: Remnants of these ancient mudslides were not only found at the foot of the slopes that line the margins of the lake, but they also showed up next to two submerged hills, one that crests about 85 meters below the surface of the lake. More commonplace events, such as storm-induced waves or pervasive flooding, could conceivably trigger slides around the margin of the lake, but they would not have affected the stability of lake-bottom slopes that are far from the shore and under 85 meters of water. There was no doubt about it: We had found the traces of an ancient earthquake.

Sizing Up the Catch

Further probing of our seismic records rapidly turned up evidence for three more prehistoric quakes of significant magnitude (that is, ones big enough to cause multiple slides). But just how powerful were these ancient quakes? That has remained a difficult question to answer. We can't even rely on what would at first blush seem a reasonable surmise: that the bigger the earthquake, the more sediment gets shifted around. We hesitate to use such logic because the biggest slide deposit we identified in our studies (containing some 17,000,000 cubic meters of mud) was probably caused by a very small quake—or perhaps by an entirely different process. We believe this to be true because this huge slump represents an isolated occurrence; no other slope failures took place at that time elsewhere in the lake.

Although we can't estimate the magnitude of these quakes in any quantitative way, we can be reasonably sure that they must have been fairly large ones. After all, this area of Switzerland has experienced many small earthquakes over the past century (some five events ranking at magnitude 5 or more have been recorded, for example), and none of those caused multiple slope failures in our study area. So we were clearly seeing the results of big earthquakes in our seismic records.

When did these quakes happen? This question has proved easier to answer—although doing so required us to do a lot more fieldwork. To attach dates to these events, we needed to recover sediment samples from the various slide deposits, which lie deep below the floor of the lake, which itself is submerged under some 150 meters of water. We therefore went back to the lake with a small pontoon boat, really a raft, and a specially designed sampling device called a Kullenberg corer—in this case a 12-meter-long tube of steel with a 300-kilogram lead weight on top. To take sediment cores, we slowly lowered this ungainly probe through the water toward the bottom using a steel cable attached to a powerful winch. When the corer reached 10 meters above the lake floor, a triggering mechanism allowed it to fall freely the rest of the way. The tube was thus driven deep into the sediments, filling it with mud, which was held in place by a springy device on the business end of the corer that prevents the sediment from sliding back out.

Guided by our many seismic cross-sections, we retrieved sediment cores from various slide deposits as well as from undisturbed sediments. After seven days of hard and sometimes messy work, we returned to our lab in Zurich with eight sediment cores, each 8 to 10 meters in length, from two different sub-basins.

For geologists, the splitting and opening of recovered cores is a much-anticipated event. And indeed, it proved thrilling. Having the lake deposits revealed before our eyes was like traveling back in time, experiencing the various swings in climate and changes in local vegetation, seeing the tangible evidence of ancient storms and floods—and, of course, earthquakes. They showed themselves as tortuously folded slide deposits with overlying beds of homogeneous mud. These distinctive packages stood out clearly from the thin horizontal layers found elsewhere in the sediment.

To find the age of each slide deposit, we extracted leaves and small pieces of wood from the undisturbed sediment directly overlying it. The age of this or-

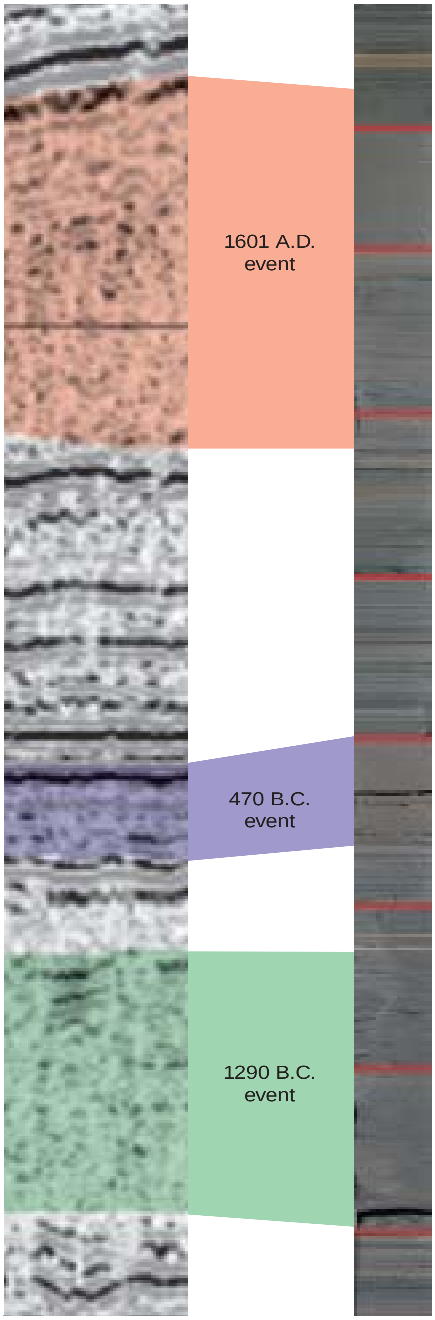


Figure 5. Examination of the retrieved sediment cores allowed the authors to confirm their interpretation of their seismic sections and to obtain organic material suitable for age dating. Images of the sediment recovered from the position shown in the previous figure (*right*, here placed in their proper stratigraphic position and stretched horizontally for clarity) show a good correspondence with the results obtained from seismic profiling at this position *(left)*. The pink layer is a slump deposit laid down in 1601, during and shortly after a historic earthquake. The purple layer shows a thinner slump-induced deposit that formed earlier, in 470 B.C. according to radiocarbon dating. The green layer represents a yet older event, one that produced only a single slump deposit and was thus probably not an earthquake.

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Figure 6. In 1687, this house, built on the shore of Lake Lucerne, was damaged by a 4-meter-high wave, which smashed through the windows on the first floor and flooded the interior, turning over a table and knocking down the landlord. The huge wave also damaged a nearby village and several harbors. It arose during calm, clear weather, the result of a spontaneous slumping of sediments on the opposite shore, where a large chunk of a river delta suddenly disappeared from view. This historic example shows that ground shaking is not required to cause sediment slumps and their associated waves. Hence for their paleoseismic investigations, the authors concentrated on a portion of the lake far from major deltas and ascribed to earthquakes only those events that simultaneously left multiple slump deposits in their wake.

ganic material could then be determined using radiocarbon dating. Further clues about the antiquity of these deposits came from two layers of volcanic ash that we found in the sediments. We were able to tie these ash layers to prehistoric volcanic eruptions in eastern France and western Germany. Combining all the dates, for the organic material and for the two horizons of volcanic ash, we calculated ages for the slide deposits and the four earthquakes that caused them: They happened in about 470 B.C., 7,820 B.C., 11,960 B.C. and 12,610 B.C. We had successfully produced a timeline for prehistoric seismic events in central Switzerland.

Kowabunga!

Our study of the sediments of Lake Lucerne revealed a long history of seismic shaking in the area, but it did not answer an important question raised by Cysat's account of the 1601 earthquake: Why did the water in the lake shift as it did? Can underwater mudslides of the size we observed displace enough water to generate 4-meter-high waves? And do such waves, which might be considered tsunamis of sorts, pose significant hazards to lakeshore communities?

To estimate the type and amplitude of waves one would expect, Schnellman and Anselmetti approached another one of us (Ward), an expert in the numerical modeling of tsunamis. These destructive water waves generally result from large displacements of sediments at the sea floor. Whereas the occurrence of destructive tsunamis in the ocean has long been investigated and is relatively well understood, similar water movements in lakes have rarely been studied.

To better comprehend how earthquake-triggered mass movements in Lake Lucerne can generate dangerously large waves, we modeled the tsunami-like effect of the subaqueous slide of 470 B.C. We chose to study this particular event because we had mapped in good detail one of the places where the bottom had given way, the pathway of sediment movement and the geometry of the resultant deposit, which, we presumed, would allow for an accurate reconstruction of this ancient disruption. Our reflection-seismic data showed that the slide broke loose leaving a 9-meter-high scar behind on the margin of the lake, that it transported a volume of sediment equivalent to a giant cube with edges 100 meters long and that some of this mud moved as much as 1,500 meters laterally.

The numerical model showed waves higher than three meters striking the shore opposite the site of failure within a minute after initiation of the slide. The modeled waves had wavelengths greater than a kilometer, which is entirely different from the situation with ordinary wind-induced surface waves. In this respect, the computer-simulated waves indeed resemble mountains of water rising in the center of the subbasins, just as eyewitnesses to the events of 1601 long ago described. Try to imagine the tempestuous state of the lake at that time, with large chunks of bottom sediment giving way at various points around the lake and the re-

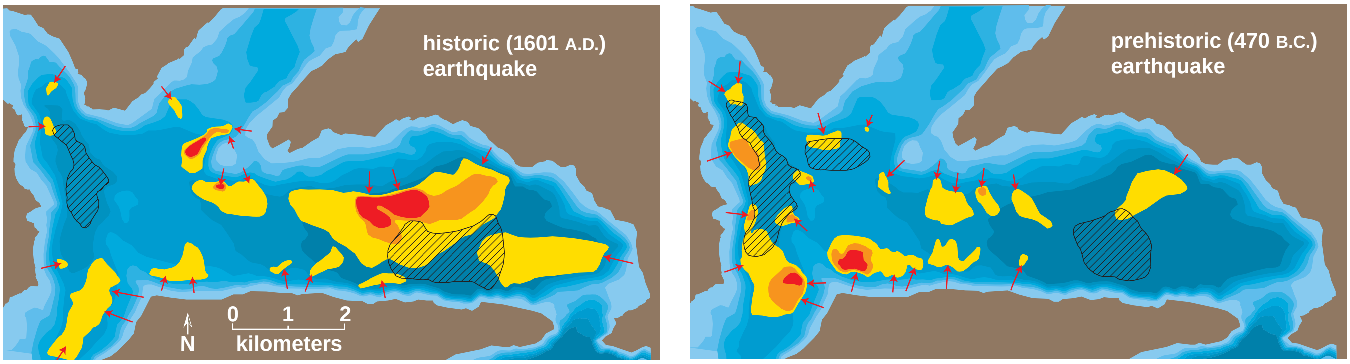

Figure 7. Historic earthquake of 1601 *(left)* resulted in many slump deposits, which range from less than 5 meters in thickness (*yellow*) to more than 10 meters *(red)*. (Orange indicates where such deposits are between 5 and 10 meters thick.) In the deepest parts of the lake, these deposits are overlain by a layer of thick, homogeneous mud *(hachures)*, the result of all the stirred-up material that was temporarily held in suspension within the waters of the lake. Discovery of a similar but older set of deposits *(right)* led the authors to conclude that a prehistoric earthquake must have triggered slumping at various points around the lake *(arrows)*. One key observation was that some of these slumps were shed from the sides of submerged hills, which would not have been affected by more mundane triggering mechanisms, such as widespread flooding.

Figure 8. Numerical modeling illuminates how a single failure at the lake margin *(hachured area)* and its resulting slump deposit *(yellow outline)*, one of several known to have been caused by the 470 B.C. earthquake, would give rise to a tsunami-like disturbance on the surface. Unlike normal, wind-driven waves, the undulation in water level has an enormous wavelength, nearly a kilometer. It also has an enormous size: One minute after the margin of the lake gives way in the simulation, the peak-to-trough amplitude of the wave is almost 6 meters *(left)*. The wave propagates rapidly away from the site of initiation, traveling about 2 kilometers into two of the arms of the lake during the next minute *(center)*—that is, with the speed of highway traffic. Three minutes after the simulated initiation, most of the disturbance is limited to the northwestern limb of the lake *(right)*. In actuality, the multiple slope failures at different points around the lake generated several waves of this type, making for what must have been a highly complex pattern on the surface as the various waves interfered.

sulting tsunamis superimposing. The water movements must truly have been frightening.

In his 1601 report, Cysat indicated that the normal outflow of the Lake underwent reversals, moving back and forth six times in an hour. That is, the period of the water movement was approximately 10 minutes. Curiously, this is more than 10 times longer than the period of the virtual tsunamis in the numerical model.

We suspect that the 10-minute oscillations of lake level in 1601 arose only after some delay, the result of a resonance, as water sloshed back and forth across the lake. The period of such resonant movements of a large body of water, called *seiche*, depends on the geometry of the basin (see "Seiches," July–August 1995). Wind and changes of atmospheric pressure are known to cause similar oscillations (with lower amplitudes). Such meteorologically induced undulations in Lake Lucerne were first studied at the end of the 19th century—revealing characteristic 10-minute shifts, in addition to two longer periods of oscillation. So it makes good sense that earthquake-induced movements showed these periods too.

In all, we felt we were quite successful with our investigation of Lake Lucerne, both in understanding the 1601 event and, most importantly, in using the lake sediments as prehistoric seismographs. But there remains plenty yet to discover. For example, if we are ever to estimate earthquake epicenters and magnitudes, one lake will not be enough; several paleoseismographs will surely be required. Fortunately, in central Switzerland a network of prehistoric seismographs is available, with each of the many lakes there acting as an independent recorder. Because each lake responds slightly differently to shaking, the effect of earthquakes on a specific lake has to be calibrated using historic events. In collaboration with the Swiss Seismological Service, members of the ETH limnogeology group are now focusing their efforts on four smaller lakes in the vicinity of Lake Lucerne, looking for the fingerprints of historic and prehistoric earthquakes in an effort that we hope will allow them to estimate epicenters and magnitudes.

Renward Cysat probably didn't think that, four centuries after the ink had dried, his report would be the basis of a seismological investigation, one that not only probed the event he witnessed but also revealed more-ancient earthquakes in central Switzerland. But maybe he wouldn't have been so surprised by the way things turned out. After all he saw in the aftermath of the 1601 earthquake, perhaps he sensed that a shaken lake could serve as a seismometer of sorts, the best one available for his era.

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