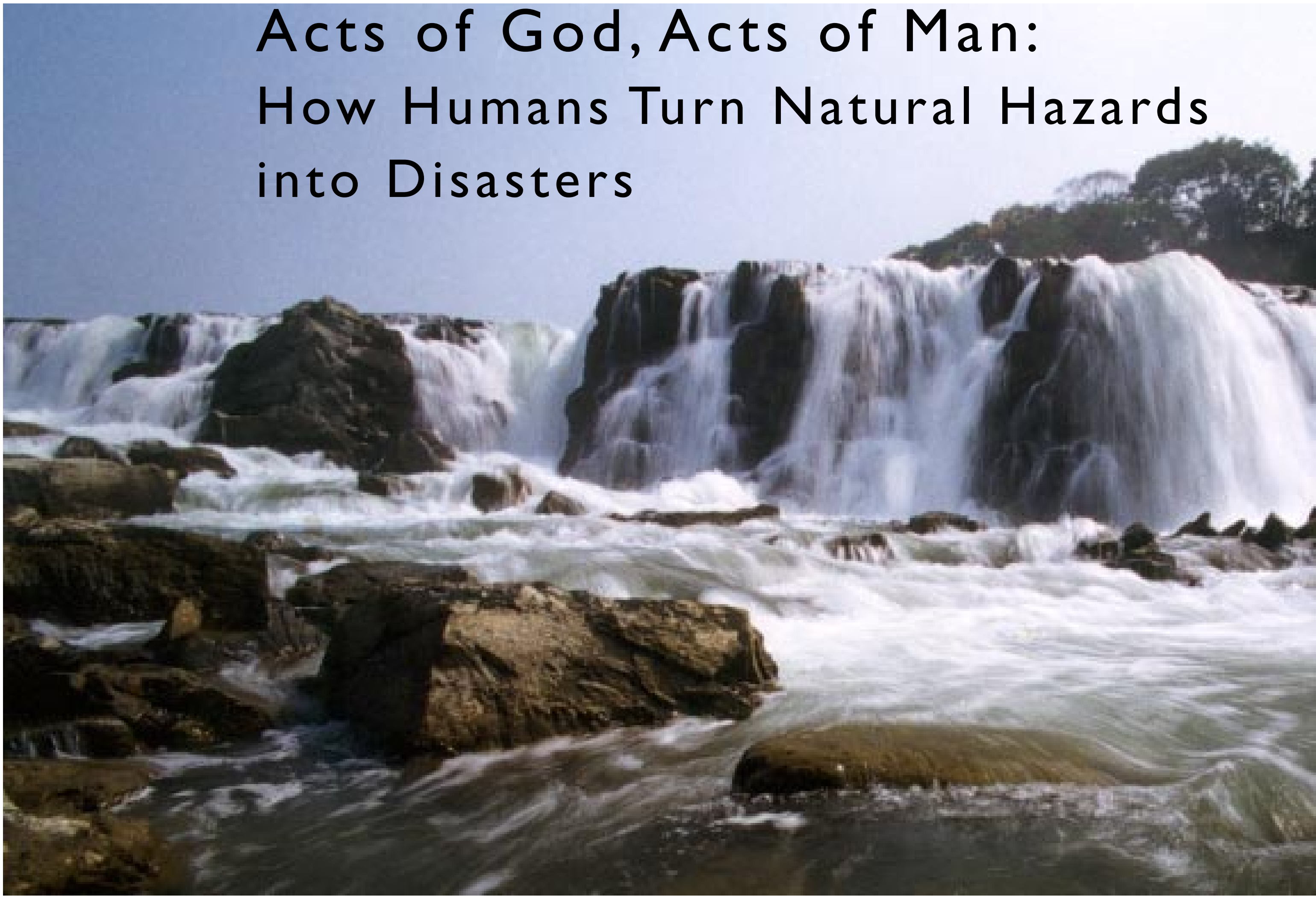
Acts of God, Acts of Man: How Humans Turn Natural Hazards into Disasters



by Kerry Sieh

Geologists have a particular appreciation of Earth's beauty. That's not to say that those of you who are not geologists don't appreciate it. We would probably all agree that the waterfall above is a beautiful thing. But some of the same things that make Earth beautiful also make it dangerous, and to some degree it's the danger in the beauty that attracts the geologist. I'm going to discuss the hazardous side, and I'm going to argue for a different approach to handling the natural hazards that this beautiful Earth puts beneath our feet.

In the 20th century, and in fact in the first and second millennia, we just reacted to natural disasters. We basically cleaned up after they happened and continued on as before, leaving our great-grandchildren to suffer the same fate, next time around. Now, at the turn of the century, the turn of the millennium, I suggest we start looking at hazards differently than we have looked at them in the past. Let's understand them as the geologist or the earth scientist does, so that they don't destroy our cities, homes, and lives. Let's actively reduce our exposure to hazards, rather than being just reactive to them.

The dramatic increase in human population over the past several decades has resulted in an enormous increase in the actual dollar losses and in the loss of human life associated with natural disasters. You see the same basic trend with earthquakes, with landslides, with tsunamis, with almost every hazard—an almost exponential increase over the last couple of decades. This trend will most likely continue if we don't change the way we act with respect to our planet's behavior.

Worldwide, about 200 cities with a population of more than 500,000 lie within 100 kilometers of known active faults; Los Angeles is one such city, as are San Francisco, Wellington (New Zealand), and Taipei (Taiwan). Ahmedabad (India) and San Salvador only recently suffered large earthquakes. Central America, the Mediterranean countries, the Middle East, and large parts of Asia are particularly susceptible to earthquake damage. But we associate very few of these 200 cities with earthquake hazards, because the Earth's metabolism is so much slower than ours that most of them have not been devastated by an earthquake in living memory. We think in terms of years or months,

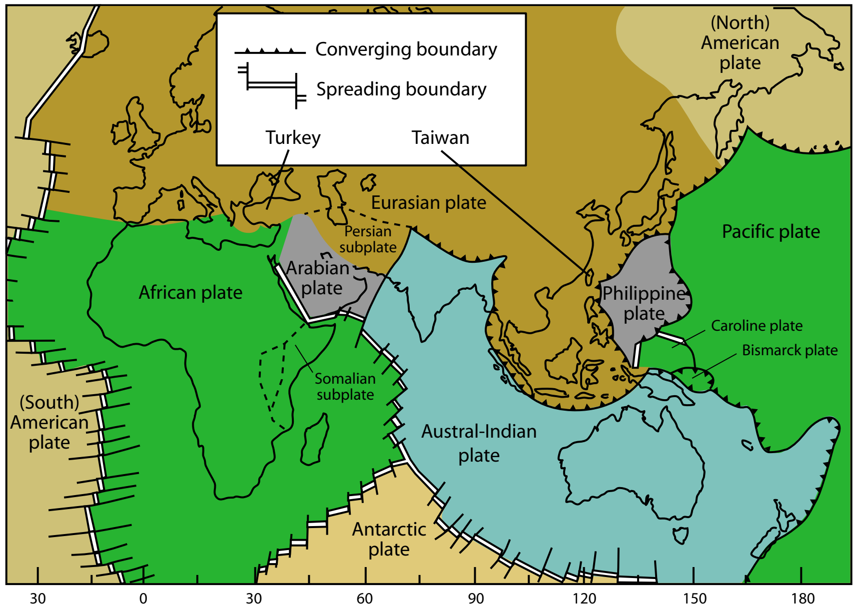

Photo by Sheng-Tao Kuo

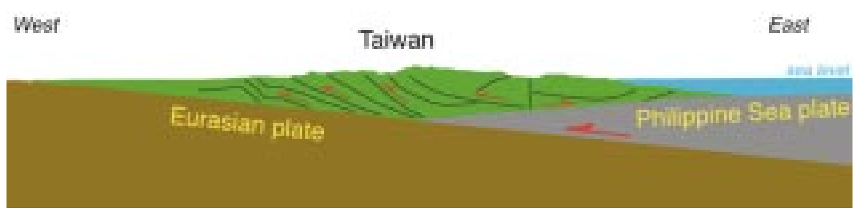
This is a tale of two countries, Taiwan and Turkey, and the devastating earthquakes that hit them in 1999. When I look at the waterfall on Taiwan's Tachia River, I'm reminded of one of the reasons why I became a geologist: to understand why this big escarpment rose in the middle of this river is a joy and a delight.

not decades or centuries. We teach our kids not to cross the street without looking both ways, but we don't teach them to worry about something that might happen in 50, or 100, or 500 years. Of the earthquakes that we've heard about in the last decade, none has a recurrence interval of less than about a thousand years, with the exception of the Turkish earthquake that I'll be discussing. This low metabolic rate inures us to the fact that the faults are there, that earthquakes happen. Generations come and go, thinking they are perfectly safe, when in fact they are living on a time bomb with a very long fuse.

This is a tale of two countries, Taiwan and Turkey, and the devastating earthquakes that hit them in 1999. When I look at the waterfall on Taiwan's Tachia River above, I'm reminded of one of the reasons why I became a geologist: to understand why this big escarpment rose in the middle of this river is a joy and delight. But if I were an engineer, looking at what happened to my bridge (right), my feelings would be very different. I'd be very upset. Before the earthquake, the geologist could have told the engineer: "You really

The fault scarp, about seven meters high, could be seen clearly from the air, even without a broken bridge for emphasis. The earthquake's lesson, however, was not learned; see page 13. (Photo provided by Jack, Yung-Wan Lien, Flying Tiger Photographic, Inc.)





Taiwan sits on the boundary of the large Eurasian plate and the Philippine Sea plate (above). As they converge, the Philippine Sea plate rides up over the larger plate (right), crunching up the shallow marine sediments into a mountainous island (far right). Note also in the map above the collision of the Arabian plate with the Eurasian plate, which has made Turkey subject to earthquakes.

shouldn't put your bridge abutment here because there's a big fault under it. And when that fault moves, it moves with many meters of slip, and you're going to lose that $10 million bridge." But the engineer, as is typical, didn't talk to the geologist until after the earthquake. And we'll see that, even then, the engineer wasn't encouraged to rebuild with any accommodation for future fault ruptures.

Taiwan spans the boundary between a small plate called the Philippine Sea plate and the great Eurasian plate, which runs all the way from the middle of the Atlantic and Iceland eastward to Japan. Taiwan used to be sediment sitting in the shallows of the continental shelf on the edge of the Eurasian plate. When the continental margin of the bigger plate started getting jammed down the subduction zone that separates the two plates, the Philippine Sea plate began to ride up over the continental shelf, doubling up the sediments between thrust faults to create the 300-kilometer-long island that we see today. Not all of these faults are active now, but the one that moved to produce the 1999 earthquake obviously is. The mountainous mass along the eastern side of the island has risen in just a geological twinkling of an eye—4 million years or so. It's starting to go back down again in the north, near Taipei, but it's still rising up in the central reach of the island and is just getting started in the south—the rate of uplift in some places is nearly a centimeter per year.

The fault that broke on September 21, 1999, the Chelungpu fault, runs along the western edge of the mountain front in the center of the island. A well-known Princeton geologist, John Suppe, determined its geometry in the early 1980s, using borings and seismic reflection data collected for oil exploration. The pictures on the opposite page give some idea of the damage the fault rupture wrought. One side of the fault rode up and over the other, forming an escarpment several meters high; fields that once were flat are now three or four meters higher on one side than on the other; buildings and bridges across the fault were wrecked.

Now, fields and rice paddies can be regraded. Those are perfectly good things to have on a fault, but cemeteries are a different matter. The Taiwanese have great reverence for their ancestors, and it was of great concern that many graveyards were ripped asunder by this earthquake. It's a serious matter that they will have to consider in making new zoning laws after this earthquake.

Buildings don't behave very well if they straddle fault ruptures, either. Most didn't actually collapse, though playing billiards in some of them would be a bit difficult now. Buildings very close to the fault but not directly on it commonly survived intact and are still habitable, but buildings right on the rupture did not fare so well. One estimate is that 35 to 50 percent of the building damage was due to ground deformation under foot. The fault came up so fast in one building that, on the hanging-wall block (the rising side of the fault), the first story simply collapsed, but it was left intact on the foot-wall block (the lower side). The entire scarp formed in a matter of about two seconds. One guy on the first floor of a building woke up, opened his door, and looked right into his neighbor's second-floor window, which used to be across the street.

This earthquake was very important because it showed that the engineering problem has been basically solved. The Taiwanese know how to build buildings that don't collapse, even during some of the heaviest shaking imaginable. Well-engineered buildings didn't fail at all. Some improperly built structures collapsed, and many people died, but the point is that we know basically how to build buildings to survive earthquake shaking.

But the improper use of land is a problem we have barely begun to tackle—land use with respect to faulting, with respect to hazards from floods, landslides, tsunamis, slumping into the ocean, and so on. Let's go back to the beautiful waterfall on the first page and the bridge across the river. When it failed, people wondered why. Well, it's really quite simple: the bridge was built across the fault. The waterfall is the fault scarp, and when one side moved up and over the other side, the bridge fell off its abutments. A large dam upstream was also partially destroyed by the fault rupture. The main portion of the dam rose nine meters over the left abutment. How fortunate that the dam didn't fail catastrophically and kill thousands of people downstream.

So, if you lived in central Taiwan and were building a bridge or a dam, would you prefer hiring a geological consulting company to investigate possible problems? Or would you favor saving the few hundred thousand dollars in consulting fees, and gambling that nothing would happen? To me the answer is obvious, but, of course, as a geologist I'm biased toward the longer view.

At left above is a shaded-relief map made from topographic mapping at 40-meter postings. It's similar to data that will be produced from the Shuttle Radar Topography Mission (SRTM), which NASA flew early in 2000. This latest mission will be giving us topography between 60 degrees north and 60 degrees south at about 30-meter postings. Now, if the National Mapping Agency agrees to release to us civilians the 30-meter data, we're going to have a fantastic time mapping many of Earth's geologic hazards. It will be much easier to map faults *before* they break, and then use the maps for land-use planning. I got the shaded-relief map from one of my Taiwanese colleagues just before I went to Taiwan half a year after the earthquake, and I thought I'd practice with it, to see how useful the high-resolution SRTM data might be. I mapped the fault just from this map, before I ever looked at the map of the ruptures that were produced after the earthquake. I mapped about 80 percent of it correctly within the 40-meter resolution of the map, including many of the little secondary faults.

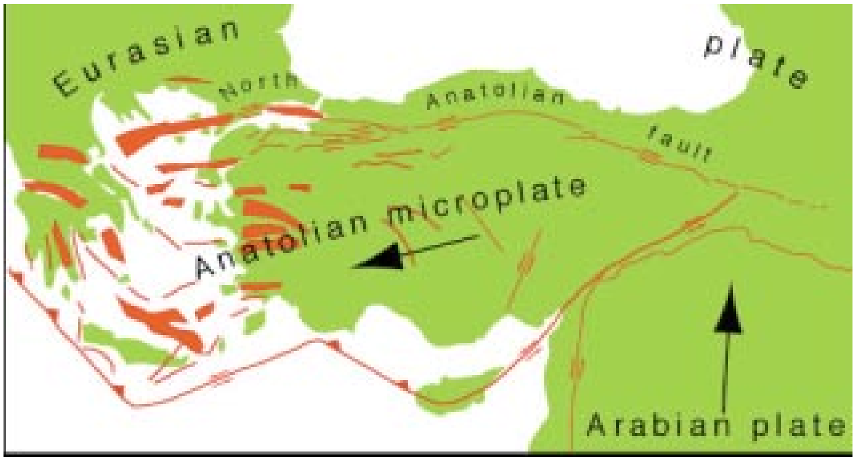
During the Chi-Chi earthquake, as it was named, the Chelungpu fault broke from stem to stern. It was a beautifully behaved thrust-faulting event. It may well be a good analogy to what will happen when our own Sierra Madre fault ruptures and the San Gabriel Mountains fling themselves out toward the foothill communities, from San Fernando, through Pasadena, to Upland. Paleoseismic data collected to date suggest that our fault also slips in large events, about five meters each, along its entire 60-kilometer length. We don't yet know exactly how often this fault breaks, but we're working on that. But its recurrence interval is probably measured in thousands of years rather than hundreds.

The mountains of Taiwan's Central Range, which rise steeply east of the Chelungpu rupture, are very rugged and extremely steep. They have been rising for about the same period of time as the San Gabriel Mountains—three or four million years. But they have risen many times faster—several millimeters per year. During the 1999 earthquake, massive landslides rolled down into many of the mountain valleys and caused spectacular damage. Of the people caught up in this myriad of seismically induced landslides, very few survived (in all, more than 2,000 people died in this earthquake). In the case of the biggest slide, some survivors rode the slide about a kilometer and a half down. The Chi-Chi earthquake shows us, once again, that seismically induced landslides

Rupture of the Chelungpu fault produced the 1999 earthquake; the fault is marked by the red line in the shaded-relief map above.
Some of the damage from the fault rupture can be seen below: part of what was formerly a flat field rose up four meters (left); buildings tilted, and bridges were ripped apart. More than 2,000 died in the quake.



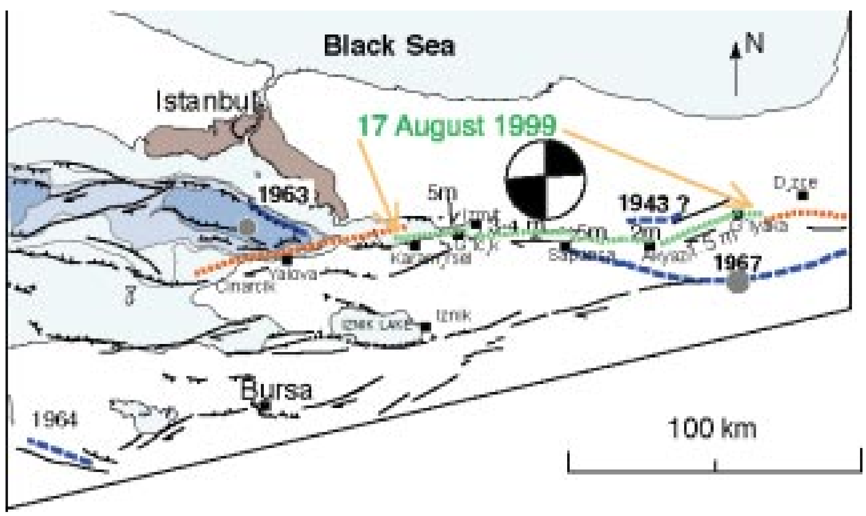
Photo provided by Jack, Yung-Wan Lien, Flying Tiger Photographic, Inc.



The collision of the Arabian plate (above) with the Eurasian plate is squeezing Turkey westward, creating the 2,000-kilometer-long North Anatolian fault, numerous segments of which have broken in the past 60 years. The last segment, closest to Istanbul, has yet to break. The four segments that ruptured on August 17, 1999 are shown in green at right. The red section near Düzce ruptured just three months later, on November 12.

can be a very significant hazard. From the experience in Taiwan, I would caution against dense development within our own precipitous San Gabriels and encourage our policy makers to seek geological advice before issuing permits.

The Taiwanese fault moved primarily vertically. Now, let's go to Turkey and look at a fault that moved horizontally, more like our San Andreas fault. The North Anatolian fault is the indirect result of the ongoing collision of the Arabian plate and the Eurasian plate, which is causing Saudi Arabia and the Persian Gulf to slide under Iran. This contraction of the Earth's surface is squeezing Turkey westward toward Greece and Libya. The fault, which runs nearly 2,000 kilometers from the Kurdish part of Turkey past Istanbul, is the northern margin of this extruding block.



Many sections of the North Anatolian fault have broken in the past 60 years. An extraordinary westward progression of earthquakes in 1939, 1942, 1943, 1944, 1957, and 1967 pointed right toward the place where the earthquake happened on August 17, 1999. Several published papers had made this long-term forecast. The only sections left to break in this remarkable sequence are those that constitute the 300-kilometer portions closest to Istanbul. Unfortunately, this seismic gap lies predominantly under water, so direct access for geological investigation is impossible. People in Istanbul are quite concerned about this forecast, with good reason, but nonetheless, Istanbul's population is growing by something like 100,000 a year, as people come in from the countryside in search of a better life. Many of them live in hastily erected buildings at the city's edges.

The North Anatolian fault is similar to the San Andreas only in that it moves horizontally; otherwise it's quite different, particularly in its segmentation. Four major segments broke in 1999. We don't have such segments on the San Andreas. The San Andreas is very smooth, which may well be why it produces earthquake ruptures several hundred kilometers long and magnitudes in the upper 7s. Turkey gets mostly 7.5s and less, because the segmentation seems to stop or at least impede the rupture from growing longer than a hundred kilometers or so. In the 1999 earthquake, four segments with a combined length of about 110 kilometers broke in a single magnitude 7.4 event. Tens of thousands died. Right after the August earthquake, my Turkish colleague, Aykut Barka, noted that a short neighboring segment, just to the east, near Düzce, was the only remaining segment between the new break and eastern Turkey that had not yet ruptured. He warned that it might well be the next to go. Sure enough, less than three months later it too broke, with about four meters of slip, causing a magnitude 7.1 earthquake.

Although the fault zone isn't paper-thin, it's fairly narrow—only a few meters wide. Everything right on top of the fault was completely destroyed, but you didn't have to be right on the fault to sustain great damage. A resort hotel built on loose, saturated sediments on the shore of Lake Sapanca is now swamped. The swimming pool tips into the lake, and the beautiful little cabanas are much wetter than they were ever intended to be. The hotel itself looks in relatively good shape, but if you should step up to the bar, you'll find that the bar rail is a foot under water. The sediments are so young and unconsolidated that

The resort hotel on Lake Sapanca (above left) was not heavily damaged, but when earthquake shaking caused the shallow sediments on which it was built to compact, the land slumped and the lake waters rose up over the swimming pool (and into the first floor, as well). The photo at far right, above, of Gölcük shows that it can be a costly mistake to build so close to a shoreline. Many apartment buildings suddenly slumped into the sea atop a small landslide. The new coastline in the photo is several buildings farther inland than before the earthquake.

Another mistake can be seen here (right): the same bridge seen on page 9, a few months later being rebuilt in exactly the same place—right on the fault.

the ground shaking caused them to compact; and when the sediments compacted, the sea rolled in 100 meters or so. The ancient record tells us that young sediments in such settings are notoriously good slumpers. So you're well advised not to build in such places. A parkway or a golf course would be just fine there, but it's best not to build a major metropolitan region right up to the shoreline. It's just asking for trouble.

In the town of Gölcük, close to the epicenter, the old waterfront is now 150 to 200 meters out in the water. People who lived near the waterfront suddenly found themselves sleeping beneath 40 meters of water; many hundreds of people and many millions of dollars were submerged beneath the waves.

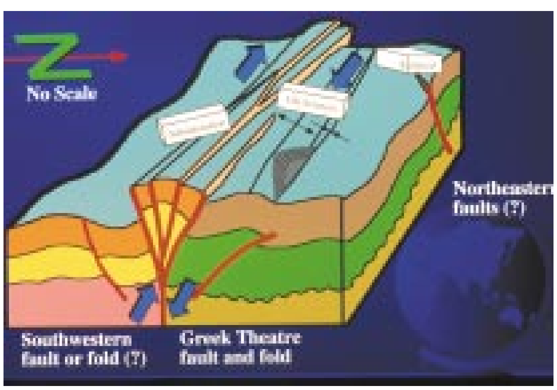
When the World Bank, along with several other agencies, made a loan of about $1.7 billion to the Turkish government for rebuilding, their first requirement was that a mitigation study be done first. They said, "Before you do anything to rebuild anything anywhere, do the hazard study first to tell you where to put your new buildings and where not to put them." It's a step in the right direction, but it remains to be seen whether or not Turkey will use the loan effectively.

What can we do better, or at least differently, in the third millennium to reduce our exposure to these natural hazards? I haven't given you the entire spectrum of geological disasters, but I've given you a taste of a few of them: landslides, fault rupture, slumping, submergence of young sediments. But of course, there are others—tsunamis, and even asteroid impacts, for example. We can't really do much about the latter, which are fortunately exceedingly rare, but we can do something about the others.

What can we do about the hazard of fault rupture? When I visited Taiwan, six months after the earthquake, I found that in many places the houses that had been torn in half along the fault had been hauled away, and that new structures were being built in the same place. These new structures will probably be just fine, at least for 100, 200, maybe even 300 years. But when the next earthquake rupture occurs, property will once again be destroyed, and people may well perish.

This construction is happening before the government has enacted regulations to guide rebuilding. Remember the photo of the bridge at the beginning of this article? The photo below shows what's left of it; and it shows an excavator digging a deep pit where one of the supporting

San Bernardino Valley College (right) sits astride the San Jacinto fault, which runs directly through the administration building (the vertical blue rectangle to the left), the library (next to it in blue and gold), the campus center (the purple square below it), and the life sciences building (also blue). Other buildings, such as the Greek theater and the auditorium (top, green) are not right on the fault but could be damaged by folding. A schematic drawing of the fault zone is shown below: buildings on the fold will experience vertical motion in an earthquake, while strike-slip motion will affect those along the fault.



pillars used to be. According to Clarence Allen, professor of geology and geophysics, emeritus, who was there less than a month after I took the photo, this excavation for the new support pillar had been dug through the fault plane, from the hanging wall into the foot-wall block, and the fault separating young gravels underneath from the bedrock above had been beautifully exposed. If the bridge lasts more than a few hundred years, it will be there when the fault breaks again, and somebody is going to have to spend millions of dollars to rebuild it once more. What is the rationale, I wonder, for not rerouting the road now and crossing the fault at a point where it can be done with a less expensive roadbed rather than with a bridge?

Let's turn now to Southern California, where we have our own share of earthquake hazards. We can take a holier-than-thou attitude and claim that we do things right here, but that's not as true as we'd like to believe. Nevertheless, let's take a look at one example of a long-range vision of hazard mitigation. A few years ago we did a little study of the San Jacinto fault, a major fault that runs through Colton and San Bernardino. In fact, it runs right through San Bernardino Valley College. I live up in Lake Arrowhead, and a lot of my kids' friends go to Valley College after high school. It has a beautiful auditorium, one of the nicest Spanish-colonial-style buildings in Southern California. They built the campus there to avoid the hazard of flooding, because the location is up on a little ridge—the fault zone, it turns out. So they were smart about flood hazard, but not about earthquake hazard—out of the frying pan and into the fire.

Back in 1935, after the Long Beach earthquake, Valley College hired John Buwalda, the first geologist here at Caltech, to come out and see if they had any problems with regard to earthquakes. And he said, "Oh, my gosh; you've got a big fault going through the campus." In fact, he recommended a thousand-foot-wide zone of no building, which basically took in almost the entire campus. They ignored his advice, even though they paid for his report. A few years ago, the trustees called me (Buwalda's been gone a long time) and asked what they should do. They wanted to have a long-term master plan, a 30-, 40-, 50-year master plan for development. And they knew they had a fault problem.

We went out and dug a series of trenches during their winter break. We actually pinpointed where the fault traces are, where they've been moving for 10,000 years or longer. We located where there was deformation going on—tilting and anticlines and so on. In one of the trenches, we found a fold over a blind thrust, about three meters high. The Hollywood fault is doing the same thing near the Capitol Records building, but with a scarp about 15 meters (50 feet) high. And if you could look deep under the Library Tower building in downtown Los Angeles, you'd see the blind-thrust fault there. At the surface it shows up as a big escarpment. At Valley College one little blind-thrust fault is about five meters down, deforming older 10,000-year-old sediments and not deforming the very youngest ones, which are mainly fill containing concrete blocks and bricks. When we locate a fault like this, we can actually see how it's deforming the ground. And we can determine what sort of deformation a building will experience, whether it's vertical or strike-slip.

We can make a map showing precisely, within a foot, where the fault lies. In the main zone, we would expect to have anywhere from a meter to five meters or so of horizontal motion when the San Jacinto fault breaks again. We gave Valley College a 100-year earthquake scenario and a 400-year scenario, and told them they had to worry about folding as well as faulting. When the fault breaks, the administration building is going to get ripped in half, as well as the library built in the early '70s; the life sciences building is also in trouble. The campus center, built in 1970, is right squarely on the fault; the auditorium I like so much is off the fault but on the fold.

This went to the state architect, who spent two or three years figuring out what the college should do in terms of retrofits, building removal and demolition, new building construction, and so on. Then Congressman Jerry Lewis (R-San Bernardino) managed to get $34 million for the community college district, which is going to rebuild. The college is going to remove all the buildings from the fault zone and put replacements else-

A new layout for San Bernardino Valley College moves all buildings off the fault zone and orients them parallel to the long axis of the fault.

In Gölcük, Turkey, a partially built automobile factory sustained the greatest damage—more than two meters of vertical motion—in its body shop (right, below), which was visibly evident in the body shop's sunken pillars (right, above). When rebuilding after the quake, the owners, on the advice of geologists, moved the body shop to higher ground, farther from the fault.

where. And the long axis of the buildings will be oriented parallel to the fault, so that, just in case the geologists didn't find everything, the buildings will present less of a cross section to be hit by the fault. The college is doing a really responsible thing. For those of us who deal with these tragedies time and time again, it's gratifying to see someone caring about their children and great-grandchildren.

San Bernardino Valley College is a model for how the whole world might behave in the third millennium. What about Taiwan? With the information we already have, it is eminently possible to make a very detailed map of the active faulting and folding in Taiwan. Once that's done, I hope in the next couple of years, someone wanting to locate, say, a new chip-manufacturing plant could look at what the seismic or other geotechnical hazards are. If there are problems, they still have some choices at that early stage. Probably they would choose to put the plant a long way away from an active fault. Or, if they don't have that choice, a seismologist can calculate "synthetic" seismograms for the potential earthquake on that fault to estimate likely ground motions, which can be taken into account in the design. I chose this as an example, because chip prices increased twofold after this last earthquake, due, I'm told, not to damage to the buildings, but to damage to the actual manufacturing equipment inside the plants.

One smart thing to put along a fault is a park, and the Taiwanese are preserving parkland along this fault as a monument. If this were Japan, of course, they would preserve 50 kilometers' worth of park and create a $50 million museum—this is what they've done along the 1995 fault rupture near Kobe!

What needs to be done about the slumping and subsidence hazard? Going back to Turkey, an American-Turkish automotive company was building an assembly complex of four large buildings near Gölcük, very near the fault and just on the coast. The company is putting half a billion dollars into the construction of this plant, and the earthquake happened about $50 million into it. Fortunately, only a small piece of the fault zone hit the buildings directly, but unfortunately, there was also a lot of warping; the buildings hadn't been set back far enough from the fault.

The body shop, the building closest to the fault, provided us with some information about what occurred during the earthquake. The building's pillars, spaced about 10 to 15 meters apart, had been surveyed before the earthquake, and knowing their elevations to the nearest millimeter allowed us to reconstruct the folding. (When we first saw what had happened to the pillars during the earthquake, we thought it was just fantastic, which caused our clients to look at us a bit funny, wondering just what sort of consultants they had hired.) Along the fault plane, the vertical dislocation was 1.5 to 2.4 meters. And where you had the highest vertical slip, you also had the highest amount of subsidence. The pits down in the floor of this building were actually under water after the earthquake. Having put $50 million into this already, these guys came to us and asked if they should just abandon the site. The government had given them the land; the geologist they had talked to had said there were no problems, but one more earthquake like this and they're under water. They asked us when this is likely to happen again.

So, should we tell these guys to move or should we tell them to stay? Let's look at the history. In 1509, there was a big earthquake, and we think that it was produced by the rupture of most of the segments of the North Anatolian fault near the

The image at left was created by draping Landsat data over a Shuttle Radar Topography Mission map of Pasadena and the San Gabriel Mountains. The Sierra Madre fault, very similar to the Chelungpu fault, runs along their base, right through JPL, at center left. The Rose Bowl in the Arroyo Seco can be seen at lower left.

A cross section through the Sierra Madre fault (from the north end of Lincoln Boulevard) shows two sedimentary deposits (blue and pink) that are evidence for large fault ruptures in the last 15,000 years.

site. It was the most destructive earthquake in Istanbul in the last thousand years. In 1719 another earthquake occurred with, we think, almost the same rupture pattern as in 1999. In 1766, there was an earthquake in May that damaged Istanbul, and later that year another one damaged the Gallipoli Peninsula. So there was this cluster in the 1700s —bang, bang, bang, all in a matter of about 50 years. Could this happen again and mess up this plant if it's sitting right here? The answer is almost certainly not, because it looks as if these earthquake clusters have about 230-year intervals—almost like clockwork. In our report, we said to the automotive company: "Don't worry about the main fault; worry about adjacent earthquakes shaking your facility and about minor, secondary faulting on your site. If you really can afford a longer vision, don't build here at all, because it's going to submerge in two or three centuries, and somebody will have to deal with the problem then." They decided to deconstruct the entire 200-meter by 100-meter body shop and build it higher on the site and away from the secondary faulting so that when submergence occurs, they'll at least have the body shop. They're doing the right thing for a 100-year vision, but not for the 250-year vision that we had encouraged. They took a middle road toward mitigation, because they wanted to be making cars for the local market within a year of the earthquake. But they are consciously leaving much of the problem to a future generation.

What about landslides and liquefaction? Geologists can tell you where these will occur. We can see it in the prehistoric record; we can see it in the geotechnical details of the soil; and we can see it close to home. In the SRTM image at left (with Landsat imagery draped over it) of Pasadena and the San Gabriel Mountains, you can see the Arroyo Seco at lower left. You can see the Jet Propulsion Laboratory up at the top of the arroyo (it has a big fault running right through the administration building). At left is a trench we dug at Alta Loma Park at the north end of Lincoln Boulevard, exposing the fault. It shows that there have been two five-meter displacements in the last 15,000 years, where the mountains have shoved up over Altadena. They're very rare events, only about every 7,000 or 8,000 years. But the last one was about 8,000 years ago, so the next one could well happen within the next few centuries.

The California Division of Mines and Geology has provided hazard maps for much of the urban part of the state. The maps were mandated after the 1989 Loma Prieta earthquake in Northern California. These maps show liquefaction to be a potential hazard in the Arroyo Seco, but nowhere else in Pasadena. Landsliding and rock falls are shown to be a problem in parts of the Verdugo Hills and large parts of the San Gabriels. City planners are now wondering what to do with this information. Should we be worrying about these things? We have to worry about them now, because if something happens and we already had the maps from the state and we did nothing, we're

We have a clear choice: we can live with our beautiful, dangerous Earth as we have in past millenia, or we can learn where to put our bridges, campuses, houses, and factories to minimize the destruction.

going to get our socks sued off. So we want to act responsibly. Municipalities in California are now dealing with this problem. Turkish and Taiwanese municipalities need first to develop the infrastructure just to *begin* to deal with these sorts of problems.

Geologists can map volcanic, flood, and tsunami hazards very effectively, but there are some hazards we probably have to ignore—immense, catastrophic volcanic eruptions, for example, hundreds of times more voluminous and extensive than the eruption of Mount St. Helens. The valley downslope from Mammoth Mountain blew up 700,000 years ago and covered most of the western United States with ash. Yellowstone has gone up twice in the last million years. But these are very infrequent events; we'd probably better just duck and cover. Pieces of Hawaii go sliding off into the ocean every once in a while, producing tsunamis that are on the order of 350 meters high. I don't think we can design around those or plan for them. There was a large runout landslide in the Mojave 17,000 years ago, off the northern flank of the San Bernardino Mountains; this *could* happen to San Bernardino on the urban side of the mountains, but I guess we have to cross our fingers and hope that doesn't happen. I don't see any way to rationally plan for such an immense catastrophe.

PICTURE CREDITS:
10 — Doug Cummings; 10, 11 — C. T. Lee; 11, 13, 15, 17 — Kerry Sieh; 12-13 – Aykut Barka; 13 — Timothy Dawson; 14-15 — Earth Consultants International; 16 — NASA, Charles Rubin

Earthquakes, floods, and landslides: would you want to live in this Chinese village?

But what we *can* plan for, we should. The little Chinese village below is a city that is waiting to die. This city has everything going against it. It sits on an active alluvial fan that could well bury it in a flood. It has an active mountain front; there's a beautiful normal fault right at the base of the mountain. Talus from seismic shaking could bury the city in rocks. There are clear signs of young landslides. So there's flooding, faulting, rock falls, and landslides. This is a place you don't want to spend a lot of time! As world population grows from 6 billion to 12 billion or whatever it's going to be in the next 50 years, we have an opportunity now that will not come around again—an opportunity to choose the places that we're going to expand into. When the Taiwanese and Turks expand into the mountains, I hope they avoid places where landslides can happen. When they expand further onto the coastal plains, I hope they are aware of the potential for slumping and liquefaction. And when they build near their faults, I hope they choose to mitigate against ground ruptures. They need to talk to their local geologists, who can advise them on how to avoid all these natural hazards.

We have a clear choice: we can live with our beautiful, dangerous Earth as we have in past millennia, or we can learn where to put our bridges, campuses, houses, and factories to minimize the destruction. On my best days, I'm optimistic that we will choose a new vision for the future rather than acquiesce to enduring the damage and death brought by natural disasters as we have in the past. □

Professor of Geology Kerry Sieh has been a member of the Caltech faculty since 1977, the same year he earned his PhD from Stanford; his AB (1972) is from UC Riverside. Sieh is a paleoseismologist, that is, he studies the patterns of earthquakes from the perspective of a geologist, over hundreds to thousands of years. His initial interest in the San Andreas fault has expanded to include faults all over the world, motivated by a concern for human welfare. This article is adapted from the Watson Lecture he gave in the spring of 2000. Since then, devastating earthquakes in El Salvador and India have provided additional examples of poor land-use planning.