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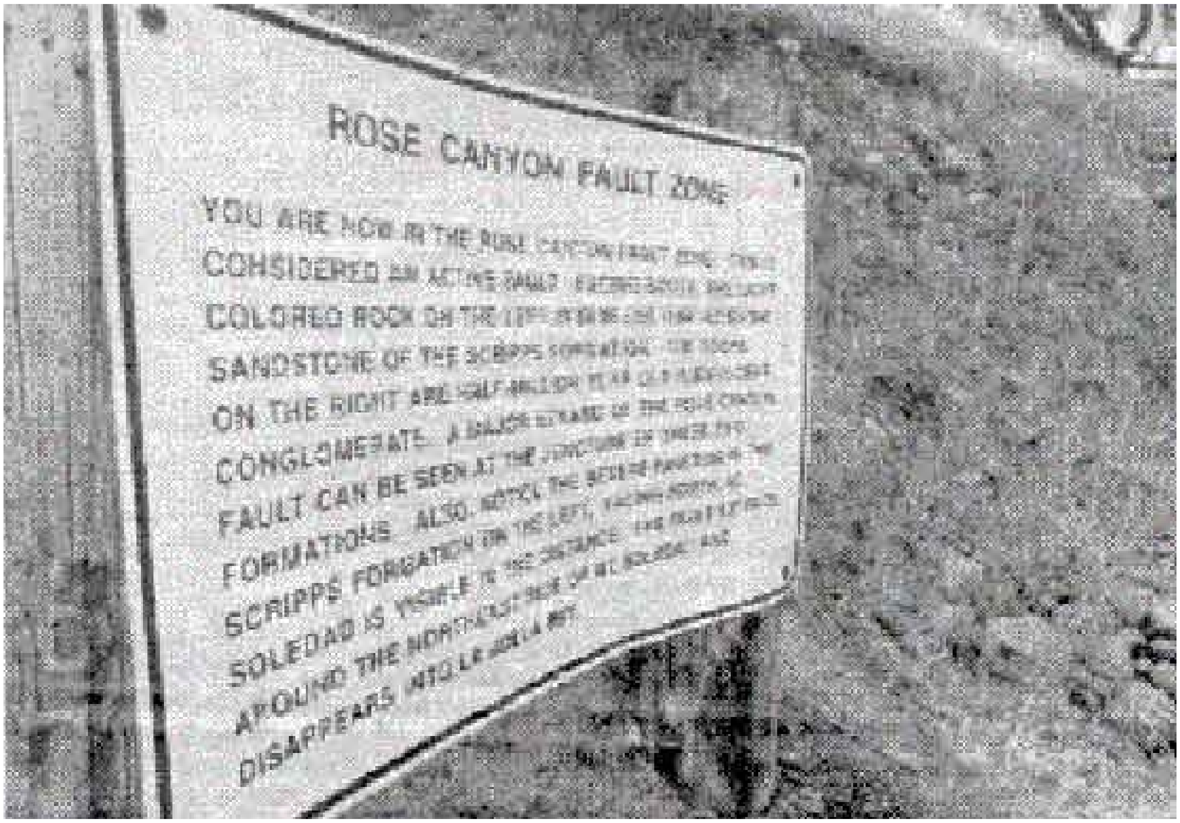
EARTHQUAKE
San Diego Danger Zones

Ten years ago, the California Division of Mines and Geology came up with a scenario for what would happen if a magnitude 6.8 quake occurred on the Silver Strand Fault. Interstate 5 would “be closed from Balboa Avenue on the north to Palm Avenue on the south,” the report predicted. “Both I-5 and old Route 101 will also be closed where they cross each of the coastal lagoons south of Oceanside…. The Coronado Bridge will be closed.... For planning purposes, San Diego International Airport will be closed for all but emergency or vital operations for a period of two weeks due to liquefaction affecting runways, access, electric power supply…. Service along the [railway] line from Los Angles can be expected to be disrupted south of Oceanside… for three weeks after the earthquake.”

Other predictions in the planning scenario added detail to the grim picture. Major SDG&E transmission substations “are particularly vulnerable to damage by earthquake shaking,” and conductor lines swinging together could cause many “burn downs.” Furthermore, “for planning purposes, the South Bay Power Plant should be considered to be out of operation for three days and at a significantly reduced capacity for one and a half weeks following the scenario earthquake.” Water mains bordering Mission Bay and San Diego Bay, the coastal areas, western Mission Valley, and the Otay Valley “will suffer several breaks per mile of pipe. Landslides in the Mt. Soledad area, coastal regions of La Jolla, the north wall of Mission Valley, and the edges of Otay Mesa may also damage facilities and distribution mains. As a result, several of the above-mentioned areas will be without water for up to four weeks following the scenario event.” The main sewage interceptor along San Diego Bay “will be out of service for six weeks,” and the natural gas transmission line that runs along the coast “will be out of service for more than 72 hours.” Older hospitals “may be considerably damaged – not collapsed, but nonfunctional.”

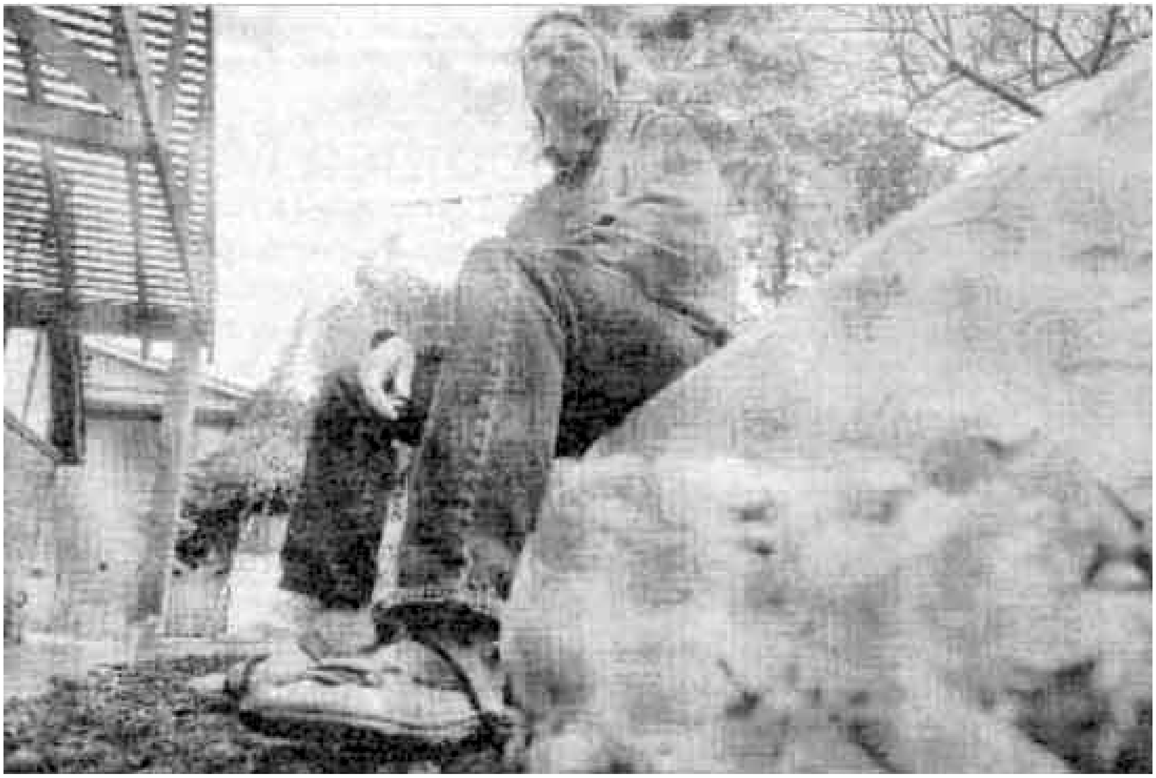
The report pointed out that similar consequences would follow a magnitude-6.9 quake on the Rose Canyon Fault. Recently my two sons and I paid a visit to where the fault cuts across Tecolote Park a block east of Interstate 5’s Sea World Drive/Tecolote Road exit. Beyond the park’s recreation center, on the south side of the road, two baseball fields occupy separate levels of the hillside. If you climb to the upper one, you glimpse a small sign posted behind the fence to the left of centerfield. The Rose Canyon Fault runs up the exposed slope next to the white metal placard.



Tecolote Park

The sign explains that the tan and cantaloupe-colored rock on the left side of the fault is 50-million-year-old Eocene sandstone, while the putty-colored conglomerate on the right was formed only a half-million years ago. The two adjoin each other today because great masses of the earth on either side of the trace have moved in opposite directions over the eons and brought dissimilar formations such as these two into alignment. They could grind past each other again at any instant, and as we tried to stand astride where the fault continued northward under the grassy ball field, I wished it would move. A major quake at that spot at that moment might have knocked us off our feet, bucked us like a wild stallion, and panicked us for 15 or 20 seconds. But it wouldn't have killed us. Imagine we would have marveled at the experience for the rest of our lives.

No one can conjure up an earthquake. Otherwise not just journalists but geologists might be the death of us. They reap a wealth of information every time a big one pops, though they usually do it after the fact. San Diego State University Professor Tom Rockwell confessed to me, "Most of us who study earthquakes would love to be right on the San Andreas Fault in a magnitude 8. But only if we were out in the desert and there was nothing to fall on us. None of us have a death wish.... If you're out in the open, however, you don't have to worry about the earth opening up and swallowing you. That doesn't happen."



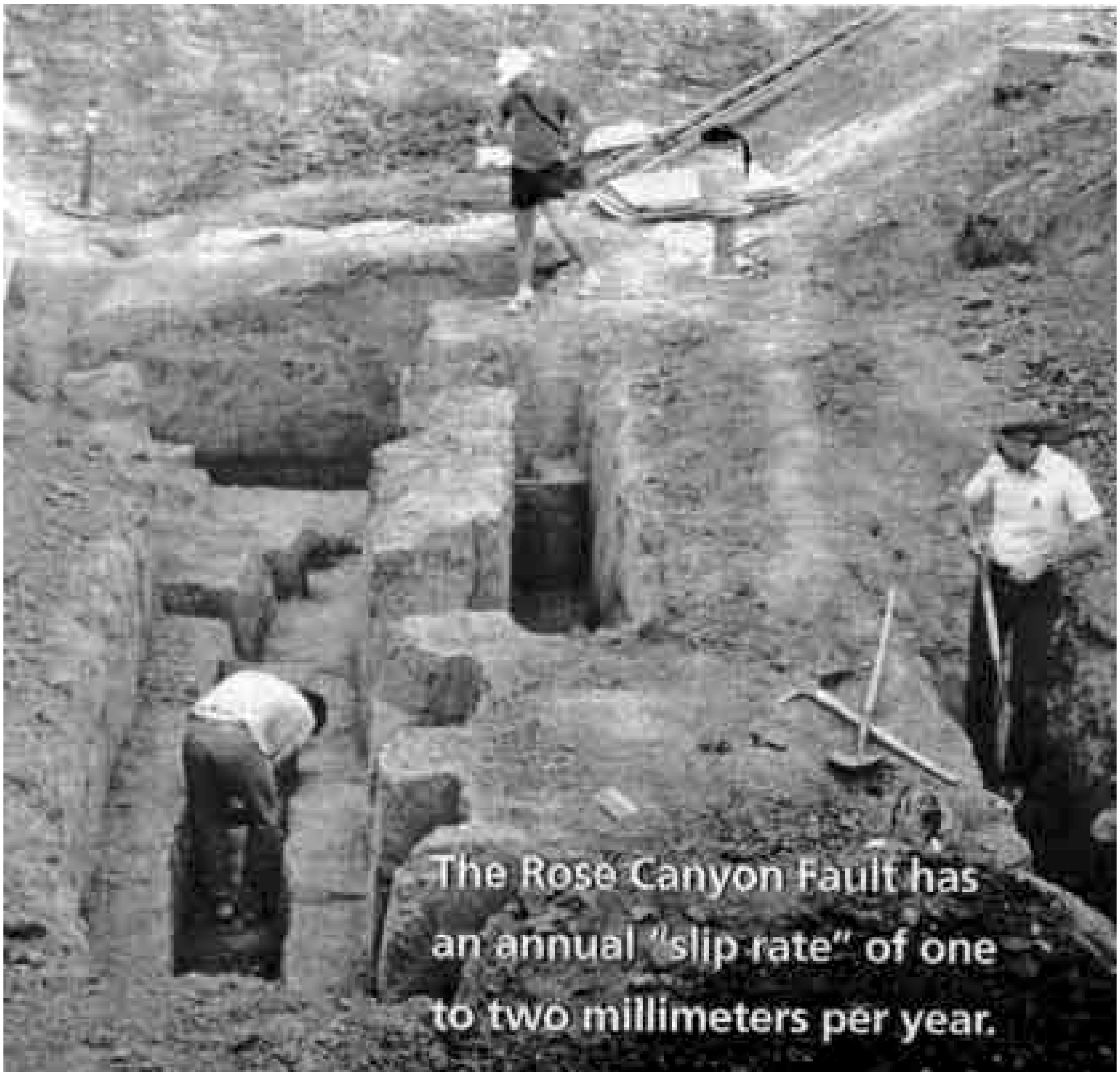
Tom Rockwell

One thing I've learned from Rockwell and other local geologists is that when a big quake does hit San Diego County, where you happen to be standing will make a big difference indeed. Forget about the citywide aftermath, the messy picture sketched out by the state report. That's another story. I'm talking about the minute or so during and immediately following the quake – the interval in which the great majority of the terror, destruction, and death will occur. I'm talking about the particular patch of the earth that's underneath you then.

A number of factors will make an earthquake intense or dangerous, the geologists say. One is the location of the epicenter. The earth's crust in San Diego County has fractured in thousands of places, and the Rose Canyon Fault is only one zone where significant slippage has occurred in recent geological history. It's the one that slices through the most populated and vulnerable neighborhoods in the heart of the city, however. So let's consider it first.

The Rose Canyon Fault is one segment of fault that extends northward at least to Los Angeles. (North of San Diego County it's known by other names.) It never actually crosses the county line but instead can be found about three miles off the coast of North County. It approaches the land and reaches it at La Jolla Shores, cutting inland at Princess Street. Just south of there, the fault bends east, and in Rose Canyon it resumes its southward course, running along the east side of Mission Bay, through Old Town, and under eastern downtown San Diego. Geologists think it splits into many branches after that. Some of these cross the bay and Coronado, then run south along the coast past Baja, until they finally merge into the Agua Blanca Fault.

According to Tom Rockwell, geologists identified the Rose Canyon Fault sometime early in the 20th Century. But when Rockwell joined the faculty of San Diego State in 1983, a debate was roiling over whether the fault was active (defined by geologists as having moved in the past 10,000 years). The answer seemed obvious to Rockwell. Something had pushed up the landmass south of La Jolla Shores to form Mt. Soledad. Farther south, the same force had depressed the ground below sea level to create the city's two bays. It also had created finer scale features that Rockwell thought would have disappeared if more than 10,000 years had passed since the Rose Canyon Fault's last rupture.


The Rose Canyon Fault has an annual "slip rate" of one to two millimeters per year.

Rose Canyon excavations, 1991

But others refused to see it that way. “I was sitting on a seismic safety subcommittee,” Rockwell recalls, “and the engineer on the committee was adamant that the Rose Canyon Fault was not active.” The issue carried important economic consequences. Everyone knew that if the fault were found to be active, stricter building requirements would probably result. It also might mean that older buildings would have to be strengthened. Rockwell finally resolved to settle the issue.

It wasn’t the easiest task. Rockwell says the Rose Canyon Fault traverses sediments that for the most part were deposited between 10,000 and 1.6 million years ago. Over the course of several decades, geologists had dug trenches across the fault and found evidence of movement in the offset layers revealed by the cuts. But in very old ground it can be difficult to demonstrate when that movement took place. You might see that something ripped through layers that were laid down 50,000 years ago but not know, for example, if that rupture occurred 45,000 years ago or 500.

Rockwell’s achievement was to find an area along the banks of Rose Creek in eastern Pacific Beach where the fault crosses sediments deposited only 8000 years ago. SDG&E owns a facility there, and in 1989 Rockwell and Scott Lindvall, one of Rockwell’s former students, approached the utility and proposed digging a trench in the parking lot off Santa Fe Street. SDG&E agreed to pay for all the direct expenses; Rockwell and Lindvall provided their geological expertise for free.

They dug the trench two days before a scientific conference on earthquake preparedness convened in San Diego. “We hauled a lot of geologists to this trench before and during the conference,” Rockwell says. “And quite a few talks were rewritten as a result.” In that initial work and subsequent investigations, Rockwell and Lindvall found conclusive evidence that during the last 8000 years, the two sides of the Rose Canyon Fault have slid past each other a total of 8.7 meters – close to 30 feet. Rockwell says his work at various points along the fault has now shown that at least three earthquakes in the range of magnitude 7 to 7.3 have probably caused that movement. That size is equivalent to October’s Hector Mine earthquake in the Mojave Desert, he points out, adding that a similar quake today would produce “extremely strong shaking and considerable damage.”

That’s not to say Rockwell expects to see such a quake break loose on the Rose Canyon Fault in the next week or so. From the amount of movement he’s documented, he calculates that the Rose Canyon Fault has an annual “slip rate” of 1 to 2 mm per year. The fault doesn’t move that much every year. Rather, it accumulates strain at that rate, then relieves the strain in sudden slippage that produce the earthquake. Rockwell believes that roughly 2000 years pass between each magnitude-7 quake on Rose Canyon.

Moreover, by using radiocarbon dating, he and others have determined that the last one occurred about 1500 to 1600 A.D. “We’ve dated it in La Jolla and downtown San Diego. And we get consistent dates from both areas.” That makes the next Rose Canyon earthquake of that size due around the year 3500 – give or take a few hundred years - assuming that earthquakes are produced at regular intervals. Unfortunately, this is not always the case for low-slip-rate faults like the one at Rose Canyon, so Rockwell says people should still be prepared.

Rockwell also hastens to point out that he has no way of knowing how often smaller earthquakes along the Rose Canyon Fault have rocked San Diego County. Trenching only tells you about seismic events that have broken the ground all the way to the surface. While most huge quakes (magnitude 7 or greater) do that, a magnitude 6 or even 6.5 might not. Rockwell says historical records strongly suggest that one temblor about that size occurred on the Rose Canyon Fault in 1862. "A repeat of that earthquake today could cause considerable damage in San Diego itself," he continues. "So we're not earthquake-safe by any means.

He seems at ease with that. He is more alarmed, in fact, by the ceaseless phone calls and e-mails that lie in wait for him in his cluttered office on the SDSU campus. A direct, intense man with a casual demeanor, Rockwell carries a cell phone that rings a lot too, when he's not traveling to other earthquake-prone places all over the globe. He flew to Turkey last summer in the wake of the killer quake there, and he was part of the team that mapped the rupture produced by the Hector Mine earthquake. Closer to home, he has studied the major faults that run through the eastern part of the county. Most significant are the Elsinore and San Jacinto faults.

The Elsinore Fault slices through San Diego's high ground, skirting the eastern flank of Palomar Mountain and ripping through the heart of Julian before continuing south down Banner Grade to the Mexican border. (South of there it's known as the Laguna Salada Fault.) Rockwell says studies of the Elsinore Fault indicate its annual slip rate is on the order of 4 to 5 mm per year. "Portions of it have moved historically." In 1892, for example, the section in northern Baja produced an estimated 7.3-magnitude earthquake that moved the ground 17 or 18 feet. In San Diego, many buildings and chimneys cracked, while in the East County the motion was sufficient to later be judged an VIII to IX on the Modified Mercalli scale. Other moderate to large early historic and prehistoric quakes have ruptured along the Elsinore Fault's northern reaches. But the portions near Julian have not moved in a very long time – "probably a couple thousand years," Rockwell says. Considering the amount of elastic strain energy that must have built up along that stretch, he thinks a greater-than-magnitude-7 earthquake could occur at anytime on the Elsinore Fault.

To the east of it, the San Jacinto Fault Zone is another time bomb. Roughly 6 miles wide and 150 miles long, the zone joins up with the San Andreas Fault northeast of Los Angeles, and it extends all the way south to the Gulf of California. Locally, it cuts across the northeastern part of San Diego County. "San Jacinto has an even higher slip rate - about 12 mm a year," Rockwell says. "So it's almost ten times more active than the Rose Canyon." (It's still only a third as active as the San Andreas Fault, which has a slip rate of 35 mm a year in central California.) The San Jacinto Fault has produced upwards of ten earthquakes that were more than a magnitude 6 in just the last 100 years. But the fault's central portion has not ruptured in 300 years, according to Rockwell. "That's the section we expect to produce an earthquake in the 7 to 7.5 range in the not-too-distant future," he says. "It would be centered near Anza, but potentially the rupture could include everything from Hemet down to Clark Valley in the Imperial Valley region. It could produce a crack 100 kilometers long – one very similar in size to the earthquake that struck Turkey, although in a much less populated area."

There's another big class of active faults that run through unpopulated regions but could rupture with disastrous consequences for San Diego County residents – the offshore ones. No one knows more about these than Mark Legg. A graying soft-spoken Orange County resident, Legg started studying the offshore region in the mid-′70s when he was a graduate student at Scripps. He continued this work while obtaining his Ph.D. from the University of California at Santa Barbara. Today it's clear there's nothing he'd rather be doing than mapping the fractures in the seafloor and figuring out what has moved and when. To do this, you cruise around in boats sending sound waves through the water and bouncing them off the layers of rock and sand and mud on the bottom, looking for offset layering of the rocks below the sea floor. Once you identify a fault, you take a core sample and then use techniques similar to those employed on land (e.g., radiocarbon dating, fossil identification, and so on) to figure out when earthquakes have occurred. Legg says the cost of renting a boat is high, but then the cost of doing seismic work is far cheaper offshore than onshore, and the quality of the data is better. Still, little funding has been available over the years. So Legg earns a living by advising the finance industry about potential earthquake losses and doing other consulting. At the same time, he's still analyzing offshore data he collected in the ′70s and ′80s, writing up his findings and hoping to do more offshore research in the future.

He says we know quite bit about the structural geology off the coast of San Diego. "It's not a regular continental shelf like the Atlantic, which is fairly broad and gently sloping." The topography off the Southern California coastline resembles the onshore mix of basins and mountain ranges, "only under water," Legg explains. "You have a ridge, then a basin, then a ridge, then a basin." The Coronado Islands are part of one ridge system. Much farther out and to the north, San Clemente Island crowns another.

Faults cut through the entire borderland. Closest, of course, is the Rose Canyon Fault, where it plunges into the sea south of downtown and north of La Jolla Shores. Next comes the Coronado Bank Fault Zone, about 12 miles west of the top of Mt. Soledad. "There is no nice single Coronado Bank Fault," Legg says. "It's a very complex zone of faulting, especially west of San Diego." If you could look at the top of it, it might remind you of the cat's-cradle game that children used to play, he suggests. "Take one of those string games, only really stretch it out. It's like that. Only they're not strings. These are surfaces, and they're not only intersecting on the seafloor, they are also intersecting in various ways under the surface."

Between the Coronado Bank and the 30-Mile Bank, another significant fault can be found running through the feature known as the San Diego Trough. "This one is beautiful!" Legg says. "Very well defined, very simple. One major trace." It runs parallel to the messy Coronado Bank Fault Zone. He says this fault controlled the location and the aftershock sequence of the magnitude 5.8 earthquake that rattled North County in 1986 and caused $700,000 worth of damage.

Still farther out, about 48 miles offshore, the San Clemente Fault runs just to the east of San Clemente Island, moving closer to the coast the farther south you go. “The San Clemente Fault clearly has the most earthquake activity and the greatest number of large earthquakes – magnitude 5 and higher,” Legg says. He adds that these have occurred about every six years, although at the moment, “We’re way overdue.”

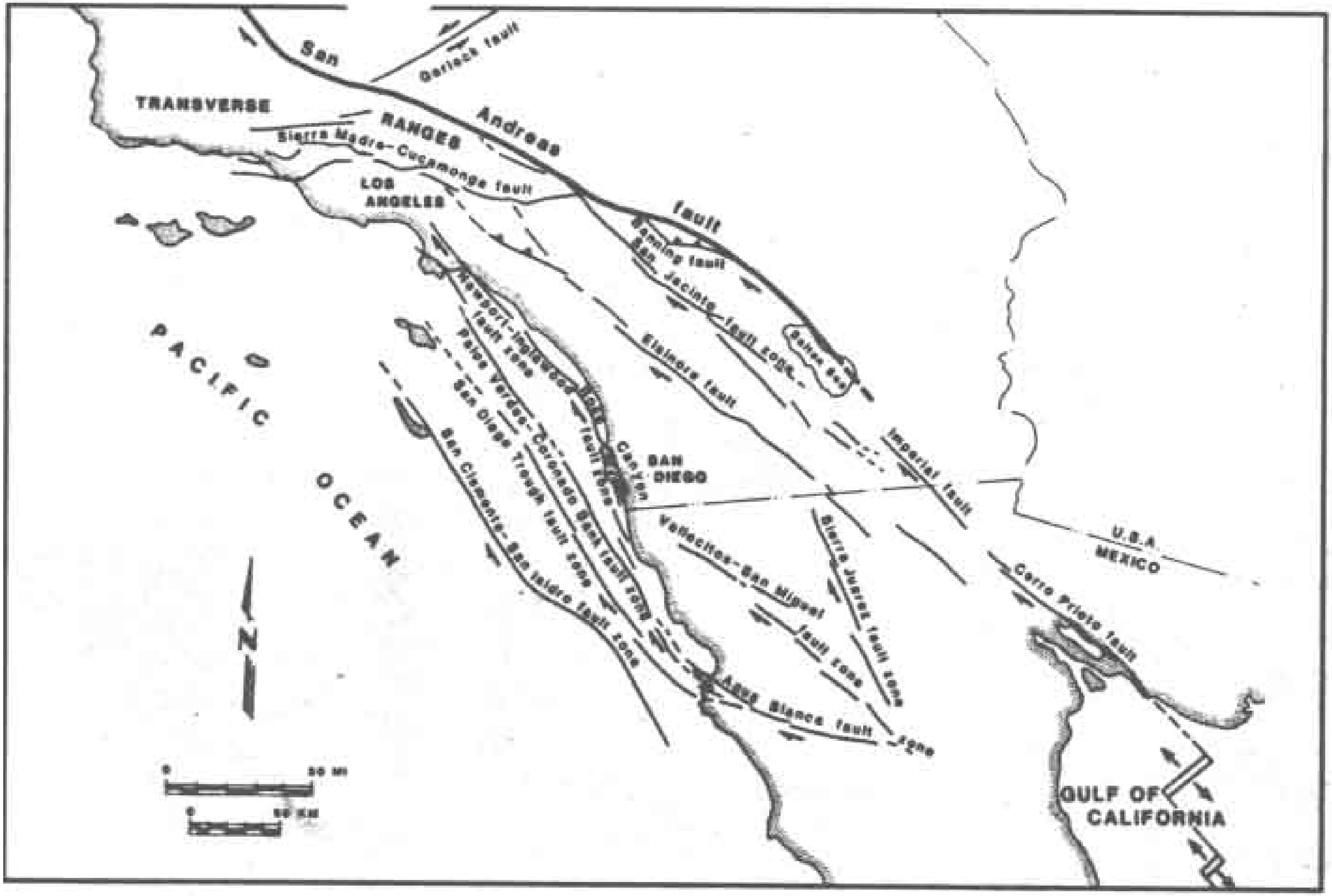
When I asked Legg how he rates the potential hazard of the offshore faults, he laughed. “The greatest hazard is the next earthquake that damages your house or office.” You never know which one that will be, however. Legg says because of its proximity, the Rose Canyon Fault might seem the greatest hazard. “But its slip rate is lower. The Coronado Bank Fault Zone is moving three times as fast, but it’s ten miles offshore, so the shaking won’t be as strong. Likewise, as you get farther out, the shaking will be less and less, but with the San Clemente Fault, it’s moving so much faster, it’s more likely to have a big earthquake.” Legg thinks most of the offshore faults can probably produce magnitude-7 earthquakes, and “the San Clemente, I’m convinced, could have a magnitude 8. It was the main strike/slip fault of the plate boundary prior to when the San Andreas in Southern California became active. So it’s very well developed, very well defined, and it’s very long and continuous.”

Along with the San Andreas Fault, which lies about 100 miles east of downtown San Diego on the east side of the Salton Sea in Imperial County, these big faults – Rose Canyon, Elsinore, San Jacinto, the offshore complex – are the ones local geologists tend to mention when they talk about potential earthquakes. They’re the best understood. But before we consider how specific areas of San Diego are likely to fare when the earth moves along one of these faults, it’s worth noting that the earth could also move somewhere unexpected – along an unknown fault or one considered inactive.

The magnitude-7.1 Hector Mine quake happened on such a fault. Until the moment that particular crack in the ground surged into life, anyone would have been free to build houses on top of it. Another example is the magnitude-6.5 earthquake that rocked Coalinga in 1983. Until it blew, no one thought it could.

Seismic ambushes can lie in wait, and one afternoon in November, I got some insight into the obstacles – both literal and metaphorical – that may hide them from our view. I was tagging along with Mark Legg and Gerald Kuhn. The two have known each other since the 1970s, when Legg was a graduate student at Scripps and Kuhn was working there as a research associate. On this particular day, Legg had driven down from Orange County to see what Kuhn thought might be a previously unknown active fault in a populous new section of Carlsbad.

Kuhn grew up in Encinitas, and he has a love of the earth that must be rooted in his childhood. But he says he didn’t become interested in the seismic history of this part of the county until about 14 years ago. For one thing, popular wisdom had declared that all the faults of Carlsbad became inactive millions of years ago. In the late ′70s, and early ′80s, Kuhn’s work instead focused on coastal erosion.



Major Southern California faults

That work, however, reinforced his natural tendencies to observe and record geologic phenomena, and by 1986 he was noticing features in Carlsbad's terrain that puzzled and intrigued him. He began documenting what he saw and trying to discern patterns in the exotic framework of faulting. This task grew easier as large-scale development of Carlsbad accelerated and bulldozers stripped away topsoil to bare the rock layers beneath. To a geologist, every such event is like opening the cover of a rare and previously inaccessible book. Kuhn estimates he has inspected the building sites of more than 50 subdivisions, sometimes acting as a paid adviser to the builders and other times scrutinizing the sites as an independent, even covert, observer. Although he left Scripps in 1988, Kuhn by then had become convinced that northern Encinitas and Carlsbad represented a treasure chest of geological information – an opportunity to gain fundamental knowledge about the way the earth in this area has changed and deformed over time. He says in 1995 he cashed in an $80,000 IRA in order to support his continuing research. Occasional consulting jobs also enable him to survive.

The afternoon I met with him, he hauled out some of the results of his obsessive labors. He showed me a photograph of Carlsbad taken by a spy plane 25 years ago. On it he pointed out subtle variations in the ground colors that he said provided clues to the geology. He showed me detailed charts and maps that he had all but covered with complex, cryptic symbols. By analyzing the patterns of various Paleolithic features, Kuhn had been developing a picture of the area's geological history. He'd come to believe that a fault ran through one hillside that was slated for development, and he'd waited a year for developers to uncover it. The road cut had just taken place the previous week, and Kuhn was very excited by the huge, obvious geologic feature revealed by the earth-moving operations. Now he wanted Legg to see it.

One impediment to this plan had developed. Since Kuhn had first inspected the building site, the developer had posted No Trespassing signs and stationed guards on the property. "We're talking millions and millions of dollars here," Legg said when he arrived. "People don't want faults found on their property."

Kuhn was undeterred "This is combat geology!" he said as he led us through an opening in the construction fence, which adjoined the cul-de-sac of an expensive new development. Inside the fence, acres of denuded sandstone greeted us. At first, the property appeared deserted. But Kuhn skulked around a bend and spotted a cruising guard truck. Stymied from getting close to the suspect formation, we retreated to a spot on public property near Cobblestone Drive and Aviara Parkway, about a block away from the development's front entrance. From there Kuhn directed our attention to a huge funnel-shaped wedge of light-colored rock embedded in the cut-away hillside. On the broad top of the wedge, Kuhn pointed out a layer of dark "colluvium" that he said was probably only 3000 to 5000 years old. The base of it looked jagged and disrupted. "You can see how everything is just twisted and contorted and mangled," Legg said. He sounded awed by the sight.

The following day, I asked Legg over the phone what he had concluded from the field trip. He replied that the formation was bigger than he had expected. "It's very impressive,” he said. Any competent geologist would see at a glance that it was a fault, he said, but determining whether it was active was difficult. “You really have to get up close...to see if the faulting definitely cuts the young material.” Legg speculated that the best time to assess that would have been when the graders first made the road cut. “But obviously they just kept on cutting and hoping it wouldn’t be a problem.”

That happens all the time, Legg said. Developers uncover suspicious formations, “and they immediately build houses on them or they cover them with grass or bushes or something.” It’s illegal but very hard to stop. Because this particular fault was so hard to ignore (“You can see it from Palomar Airport Road!” Legg said), he predicted that a geologist from the state Division of Mines and Geology would wind up inspecting the site. But the inspector might decide that the fault was inactive or not active enough to merit changing the zoning, Legg said. “The third possibility is that he could say, ‘Holy Toledo! This thing is moving! It is an active fault. We’re going to send a team down to map this area in detail and zone it Alquist-Priolo.’ Such zoning wouldn’t halt the entire project. “At worst, they wouldn’t be able to build a few houses,” Legg said. “They’d have to put in a greenway or something. But that would cost them money. It would delay the project. And society today just wants to get rich now.”

What I concluded from the field trip is that some San Diego County residents may be living closer to active faults than they think. But maybe that’s not such a big deal, Pat Abbott suggests. “It’s a very natural thing for people to feel that the closer you are [to the fault that’s slipping], the more dangerous it is,” says Abbott, a professor in SDSU’s Department of Geological Sciences for 20 years. “That’s not actually so.

Natural disasters – including earthquakes – have long been one of Abbott’s specialties. He’s written a textbook on the topic, and in 1987 he developed a class with that title that has attracted more than 3000 students per year. A lean, alert-looking man, he welcomes visitors to his office on the eastern edge of the campus. “I wouldn’t want to be in here during an earthquake, he commented the first time we met there. Although the ground itself is quite strong – a sedimentary conglomerate deposited some 50 million years ago on top of volcanic rock – the building sits on metal stilts. “This is a very bad place,” Abbott said. Rocks of every size and shape perch on every available surface in the office. “They’re sort of like books in a library,” he said, defending their presence. “You don’t squeeze all the information out of them the first time you look at them.” When I asked about the hazards of being close to a fault when it produces an earthquake, Abbott replied, “First off, you have to think about it three-dimensionally.” He says in both the 1994 Northridge quake and the 1989 Loma Prieta (BayArea) quake, the respective faults began their rupture 11 miles below the surface of the ground. If that happens, “Whether you’re one block away or one mile away, it’s not going to make that much difference.” Abbott says he wouldn’t offer any discouragement if one of his friends were thinking about buying a house a block away from the Rose Canyon Fault.

Pat Abbott

The intensity of any earthquake usually diminishes with distance, he says. But we can think of two very recent examples that violate that rule," he said. "In Loma Prieta, the earthquake waves traveled more than 60 miles to Oakland and caused a collapse of that I-80 elevated roadway. I think that's the most horrifying image of that particular earthquake. And yet if you'd been told there was going to be an earthquake 60 miles away, that wouldn't have struck terror in your heart." Even worse, Abbott points out, was the quake that devastated Mexico in September of 1985. Its epicenter was near Acapulco, yet 10,000 people were killed in buildings that collapsed in Mexico City – 220 miles away. Most of us would never worry about anything that took place 220 miles away, he notes.

Both those tragedies occurred because of a fatal match between the types of seismic waves sent out by the earthquakes, the ground the structures that collapsed were sitting on, and the size of the structures that collapsed. "An earthquake puts out energy in lots of different frequencies – very much like a song," Abbott explains. "And just as songs vary widely, so do earthquakes. All the frequencies come out in every earthquake, but their relative strengths can vary from earthquake to earthquake.... So with any earthquake, you have to ask where the energy is concentrated. In that Mexico City quake, the energy was concentrated in the one to two-second frequency."

Abbott simulates a seismic wave with a long (one-to two-second) frequency by holding up a finger and moving it back and forth like a metronome counting off slow beats. In contrast, to illustrate the short-frequency seismic waves, he shortens his finger's movement to a fast jiggle. Although both kinds of shaking emanate from every earthquake, the waves react differently as they spread out. The high-frequency waves lose their energy very quickly. Another geologist whom I interviewed suggested the image of a car with its stereo on full blast. If you pass it in the street, you hear the (low-frequency) bass notes. But the high-frequency notes are absorbed by the car's interior; you never hear the violins. To consider another example: You can hear the low rumble of a train a mile away, but the high-pitched cries of a baby a few doors away will not reach you.

The damage a seismic wave can inflict thus depends in part on how far it has traveled. "High-frequency seismic waves do their damage relatively near the epicenter, Abbott says. Low-frequency seismic waves can travel along way and still deal lethal punches. But whether the punches are lethal also depends on the targets, that is, what kind of ground the seismic waves travel through.

Abbott says the high frequencies of the seismic-wave spectrum have the greatest impact on very hard, dense rock. Two kinds of San Diego County rock – both igneous – fall into this category. "Some are magmas that cooled near the earth's surface, i.e., volcanic rock," Abbott says. "And then some of them are plutonic igneous rocks-magmas that cooled one, two, three miles below the surface" but ended up closer to the surface after the overlying rocks eroded away. Abbott says the parts of San Diego County that are made up of this kind of rock include Mt. Helix, Dictionary Hill, and Del Cerro. "Also areas like Rancho San Diego. Or the hills around the southern and eastern end of El Cajon." Julian rests on such rock. "Also parts of Ramona," he says. "The hilly parts of Lakeside. The eastern parts of Rancho Bernardo, up on the hills – not all of them but a lot of the hills there. Also areas of Escondido and San Marcos."

If you hit the rocks in these places with a hammer, "They ring," Abbott says. "They're hard to break." Their strength ensures that they won't crumble and create landslides. "But they're going to ring like a bell when they're hit with lots of high frequency seismic energy." Because they are located far from the coast, and because the high-frequency seismic waves lose much of their energy with distance, these places probably won't suffer much when the San Clemente Fault (40 miles offshore) gets slammed with that magnitude-8 quake that Mark Legg is expecting or when a magnitude-6.5 movement explodes on the Rose Canyon Fault.

But a big earthquake on the Elsinore Fault would be a very different story. "Visualize Julian when the Elsinore Fault moves," Abbott suggests. "The Elsinore Fault runs right through town. So they're going to get all the high-frequency waves." An Elsinore Fault earthquake will severely test everything in Julian, Abbott predicts. "If we got in the car and drove around [Julian], I'm sure we would find things like hillsides where people have wanted to accentuate the views, so maybe they've had their house come out of the hillside; and there's a few vertical uprights holding up one side." If cross-hatching and other kinds of support tie into those vertical uprights, they may be fine, he says. But unsupported columns will collapse. “Any building that’s bad is going to suffer serious damage. If there are any weak ones, they will be discovered.”

Besides the strength and quality of construction, another factor affects how a building will fare in an earthquake. Just as different types of ground resonate to different frequencies of seismic waves, objects – including buildings – have natural resonances. In general, smaller things amplify high frequency waves, while larger objects amplify the lower ones. That’s why violins are small and double basses large. When it comes to seismic waves, high-frequency ones have the greatest effect on shorter buildings (such as the ones found in Julian), while low-frequency waves jeopardize taller structures like bridges and high-rise buildings. “The oscillation period of buildings is about a tenth of a second per story,” says Kevin Robinson, a geologist who has taught at SDSU for the past six years.

Robinson says 10- to 20-story buildings thus have an “oscillation period” of between one and two seconds. “Now, if the size of the [seismic] waves just happens to match the oscillation period of that building, the building’s going to sway over and back, and the next wave is going to high and make it go farther the next time and farther the next time.” Robinson compares this to being on a swing in a playground. If you deliver a kick at just the right moment, you increase the amplitude of your ride. Because of this phenomenon and the fact that low-frequency seismic waves can carry *a* lot of energy over long distances, Robinson and other local geologists say a magnitude-8 earthquake on the San Andreas Fault or far offshore could damage older multistory buildings in and near downtown San Diego. Where such buildings happen to sit on weak substrates, the potential for disaster will be compounded.

Where is the weakest ground in San Diego County? I put that question to Pat Abbott. He’s written at length about the sedimentary rock of San Diego County (including a book for lay readers, *The Rise and Fall of San Diego*, just published last fall), and he confirmed that the weakest rock is sedimentary. But he hastened to add that many kinds of sedimentary rock are not weak. That’s a good thing, considering that the vast majority of county residents live on top of sedimentary formations that were deposited between 150 and 150,000,000 years ago. Abbott thinks most of the homes on these deposits will fare quite well in any earthquake. But there are exceptions.

“If I’m talking about land I would not want to live on, my number-one fear would be of slopes that were prone to landslide.” He says he wouldn’t even try to build anything on one of these. Such slopes for the most part are those made of mudstones containing clay minerals. One of the worst culprits is a belt of soil known to geologists as the Friar’s Formation. “To generalize,” says Abbott, “it’s a greenish mud with some sand in it;” It formed about 45 million to 50 million years ago in a dry coastal lagoon that flooded from time to time. Today it runs through parts of San Carlos, Fletcher Hills, Santee, Tierrasanta, Poway, and Rancho Bernardo.

The Friar’s Formation causes problems because it contains such a high concentration of clays, Abbott explains. “A clay mineral looks like a book, except it’s maybe only two microns across. It’s so small you can’t even see it under a regular microscope.”

Moreover, the thin side of it is split into a bunch of even smaller sheets. “On an ionic scale, it can take water between each one of these layers – puff up, expand and lose strength.” Abbott points out that “you don’t want your foundation swelling and shrinking. You want it to sit still and be solid.”

Back in the late 1970s, and early 1980s, an interval during which San Diego experienced heavier-than-normal rainfall, a number of landslides destroyed homes, the professor reminded me. With that in mind, he believes, “the worst time for San Diego to be hit by a big earthquake would be a high-rain-fall interval when the ground was deeply saturated – say the second February in back-to-back El Niño years. The more the water gets a chance to soak slowly below the surface, the more weight it would add to the slopes, the more weakness is made in the clays, and the more things would be prone to slide.” An earthquake at such a time “would be very ugly in terms of property damage,” Abbott says. “You’ll have houses that will move several feet.”

The time of year or the point in the rainfall cycle at which any earthquake strikes – like the time of day – is a random and unpredictable factor. But Abbott says it’s possible to identify other elements that will affect how the local mudstones will react to earthquakes. Hillsides where the clay-rich soils have been overlaid with stronger sedimentary conglomerates spell trouble, he says. “Let’s just talk about Fletcher Hills for a minute.” Long ago it acquired a cap of strong protective rock over the weak Friar’s Formation. As a result, parts of the community occupy ground that isn’t really strong enough to be as high as it is. Abbott says in an earthquake, the slopes of the weak bottom will tend to fail, and it will take chunks of the strong top with it. He says he could pick out many other examples in Rancho Bernardo, Poway, Santee, and Tierrasanta.

Abbott expects a strong local earthquake to produce landslides in a couple of other areas besides the top-heavy hillsides of the Friar’s Formation. One is the bay side of Point Loma, just north of Ballast Point. The rock there is called Point Loma Formation. Created around 74 million years ago during the Cretaceous Period, it contains clay layers. “Not as bad as the Friar’s,” Abbott says. “But still not good” The same rock can be found all along the west side of the point, but there it has been tilted up and inclined into the hill. “That’s strength, right?” Abbott says, ”The layers can’t slide into the hill. But if you come around to the San Diego Bay side, now what?” The rock layers next to the bay tilt downhill like a sled that’s ready to ride. Abbott says at the ends of some of these beds you can see daylight. “They’re naturally poised to slide. The place where you can see some of that sliding most easily is the Navy’s big oil tank farm. It covers quite a large area there. And it’s right on top of an active landslide.”

The Ardath Shale found on both sides of Interstate 5 near La Jolla is another clay rich formation that may not tolerate severe shaking well, Abbott indicates. “Again, it’s not as bad a clay as the Friar’s.... But clays in general bring more problems than do the sands or gravels. You can drive along Morena Boulevard in Rose Canyon near Costco and see the cliffs failing.” Now imagine saturating that rock and having the Rose Canyon Fault move. “Ooh, there’s going to be lots of problems,” Abbott predicts. Every home won’t suffer damage, he stresses. Many will be fine. “But you will be able to go up both sides of Rose Canyon and see sides there where houses will be taken out," he says. "And a lot of that will end up [falling] on the houses that are down on the bottom."

One other area where Abbott sees a landslide potential is in the Otay River Valley. Until recently that area was devoted to farming. "It hasn't been a desirable living area heretofore," he says. But now when you drive south on Interstate 805 past the Otay River Valley and look to the east, you see incredible amounts of development going in near the Coors Amphitheater." The soil and rocks on which the new buildings are being constructed contain a lot of volcanic ash deposited about 29 million years ago, and "it's terribl*e* foundation! Absolutely terrible!" the geologist says. "It's these days that expand." Abbott says in the past, commercial mining operators have even extracted this particular rock and sold it for things like cat litter and other industrial applications that need materials that absorb water and swell up.

He's not certain landslides will occur here. "I haven't gone around and followed what they've done at each site, engineering-wise, to ameliorate this problem." Although "they picked some terribly bad rock to build on," the builders may have fixed the problem by taking measures such as removing all the weakest soil layers and replacing them with stronger sediments, Abbott says. "But the question always is, is the bar raised high enough or not?" Future earthquakes will answer that.

One subset of landslides that concerns Abbott is the steep sea cliffs along the northern half of the county. I asked if any of them were stable. "To a geologist, no," he replied. "We think through time a little bit. Some of them are shockingly unstable." Abbott often leads field trips from Torrey Pines to Scripps. "You walk along the beach, and on the cliffs you can see some of these giant slabs of rocks with big fractures that go through them. There's no strength holding these things up at all." Chunks fall down once in a while even when no earthquake occurs. Such an event killed a young woman in January on the beach in Encinitas. In an earthquake, pieces of the cliff top will come crashing down all along the coastline, Abbott predicts. "That's bad for people below, but a lot of them are going to be bad for homes up on the hill as well.

Apart from the unstable steep ground, the second general category of sedimentary rock that Abbott worries about is "loose, water-saturated land that might liquefy and flow." He urged me to talk to Vera Berger to learn more about this source of danger.

At first glance, Berger seems an unlikely candidate to be an earthquake expert. Born in Leningrad, she got a Ph.D. in civil engineering from a prestigious research institute there and spent the first 15 years of her career researching and designing concrete in the Soviet Union. She and her husband left the communist stronghold in 1979, however, and he eventually accepted a job in San Diego. Here "there were no concrete dams anywhere in sight," Berger notes. A local engineering consulting firm hired her to work as a geotechnical engineer. In that discipline, "I had no experience whatever," Berger says, "but they were willing to help me."

When in 1982 the United States Geological Survey hired the consulting firm to study liquefaction potential in San Diego, Berger was included on the study team. In the years since then, she has continued to learn about the phenomenon. Today she runs her own geotechnical consulting business, one specializing in seismic issues. In careful, Russian-accented English, she explains that liquefaction occurs when seismic waves move through loose sandy soil that has been saturated with water. The shaking puts the water in the soil under high pressure, and the solid particles lose contact with each other. They start “floating in this liquid, and because of that, they lose nearly all their strength.” The liquefied soil resembles quicksand, Berger says, though it doesn’t stay liquid for long. Within a few minutes after the shaking ends, most liquefied soil solidifies again. But in that brief interval, “really weird things happen,” the engineer says.

“Remember that liquefaction only happens below the groundwater table. On top of that, there may be a layer of relatively dry soil.” If the high-pressure liquefied material can find a crack in the overlying soil, it may boil up to the surface and erupt like a small volcano. Berger says whether this occurs depends upon the depth at which the liquefaction occurs. “If it’s 10 feet under ground, it probably would break through the cover. But if it’s at 30 feet, it may not.”

If the liquefaction takes place at a relatively shallow depth and sand boils break the surface, “A certain amount of soil from underneath will get out,” she continues. Or water may flow away from the overstressed area. In either case, when the shaking stops, the ground may settle unevenly. Such “ground subsidence,” along with the sand boils, can crack foundations and tilt buildings, but these effects don’t kill people. Berger says even when “lateral spreading” occurs and chunks of the ground slip sideways (usually on a slope or a grade), the consequences are often less than catastrophic.

That’s not the case with “areal flows” she says. These occur when entire layers of soil liquefy and the overlying blocks of land move – usually from higher to lower ground. In the 1964 Alaskan earthquake (the largest ever recorded in the United States), a stretch of land about a mile and a half long “just slid into the ocean,” Berger says. “The buildings and *everyone* in them.” That same year, the magnitude 7.4 quake that struck Niigata, Japan, produced smaller scale, but nonetheless damaging, areal flows. Berger reached for a textbook and showed me photos from that disaster; tall apartment buildings lay pitched sideways like children’s playthings. People climbed out of the windows of those buildings, according to Berger. But when serious liquefaction effects combine with structural weakness – as happened in San Francisco’s Marina District in 1989 -- the buildings can collapse and kill the occupants.

Berger says the two 1964 quakes jolted engineers around the world into figuring out ways to mitigate the damage in areas where earthquakes may cause the ground to liquefy. She says one early approach was to build strong, rigid foundations. “You tie the footings together, so they move together.” If liquefaction occurs, the building may tilt or even fall over – some damage may occur – but at least all the occupants won’t be crushed or buried alive. Berger says a second approach has been to build pilings that penetrate the vulnerable layers and bear the weight of the building on competent ground. “This is much more expensive, so therefore it was done usually for larger buildings, more important structures.” Pile foundations can prevent a lot of damage, but Berger says they’re not foolproof. When earthquakes have supplied enough lateral force, the piles have broken.

"The best solution is to modify the site itself." Berger says that in the past ten years, many builders have employed a variation on this theme. In some cases, they inject thin cement slurry into the ground. Another approach is to stud the ground with submerged stone columns. "That's what was done for the trolley line in Mission Valley," Berger says. "Basically, you drill a large hole, like 4 feet in diameter, and you go down to good soil, which could easily be 20, 30, 40 feet." You fill the hole with rock, then you repeat the process over a grid. The result is a denser soil that is strong enough to resist liquefaction. Yet another approach is to drop heavy weights from a considerable height, "bombing the soil." When the upper 25 feet of the ground appear vulnerable to liquefaction, "There is a good record that this approach works," Berger says, although she adds that the accompanying noise and vibration make it infeasible for sites in developed areas.

Builders only take such drastic measures when the scope of the project is large and the soil tests reveal that the ground is soft and saturated. Plenty of areas in San Diego meet at least the second condition. Liquefaction can be expected in "alluvial soils," Berger says, areas created when sands and gravel settled out of rivers. "All river valleys are immediately suspect," she says – Mission Valley, the Sweetwater River Valley, the Otay River Valley, the Tijuana River Valley. "If you are in the Mission Valley area, you definitely have a high potential for liquefaction." She adds that upstream sites are more likely to liquefy than those closer to the bay, since sands carried down from the mountains drop out first, whereas clays tend to be deposited farther downstream. "And loose sands are the bad guys in terms of liquefaction," Berger says. "Clays are the good guys."

She continues that the land around the edges of both Mission Bay and San Diego Bay are suspect, "including of course, Lindbergh Field and Harbor and Shelter Islands." A central chunk of North Island and most of the residential portions of Coronado rest upon stable sedimentary rock known as the Bay Point Formation. However, big swathes around the edges of North Island could liquefy; so could some of the Silver Strand.

Berger thinks all the man-made islands in the local bays have a potential for areal flows. "If you are on Harbor Island in a building that is on shallow footings, you may be in very bad shape," she said. She also grimaces at the thought of anyone standing on Fiesta Island should liquefaction cause it to slide into the bay. "You would be carried, together with debris and various heavy parts, and you could get really hurt. It's not like a water slide. It's a bad situation."

It seemed to me that if scientists were to make significant advances in their ability to predict earthquakes, we could just avoid the liquefiable parts of town whenever a big quake was expected. But Kevin Robinson, the SDSU geologist, says the hopes for such advances have faded over the past 30 years. He explains, "The people I learned geology from probably thought somewhere in their careers that by this time we'd be able to predict earthquakes. In the late ′60s, early ′70s, people really thought we were learning so much that it looked promising." In the 1980s, a group of researchers even set up shop in Parkfield, California, south of the Loma Prieta area, to tackle this challenge head-on. The Parkfield area has had a 6.0 earthquake every 22 years on average, Robinson says. "So they thought it would be a really good place to test earthquake prediction.... In prediction, you’re always looking for what are called precursors – things that happen before an earthquake.” A number of potential precursors near Parkfield have received attention, Robinson says. One researcher, for example, by chance recorded a radio ground signal right before the Loma Prieta earthquake that had never been detected before. If this happened again right before the next Parkfield earthquake, it might shape up as a warning for impending temblors, people hoped.

But “they’re still waiting for that earthquake in Parkfield to happen,” Robinson says. “The longest interval they’d seen up until that time was 32 years. But 32 years has now come and gone.... Some geologists just could not wait any longer and have gone on to other jobs.” Robinson says the difficulties of identifying precursors have also come to seem more daunting, as people have realized that “each fault has a different personality. And each earthquake on a fault might be wearing a different hat each time. There’s a whole lot of variables. Maybe in one place something might be a precursor, but maybe you’d have to wait 250 or 300 years to see it happen again.

“You want to be able to accomplish something in your career,” Robinson says, yet with earthquake prediction you run the risk that you might never witness the right earthquake in your lifetime. “There actually is not a huge camp of people who work on prediction anymore,” he says. Seismologists have turned their attention to other challenges. Some, like Tom Rockwell, are studying the history of earthquakes on specific faults. Others are trying to understand how the ground in various places will move when various quakes do happen.

“We know there are going to be earthquakes,” Harold Magistrale, another research geologist at SDSU, told me. But understanding the ground motion caused by those quakes is “what you need to know for emergency response. That’s what you need to know to set up engineering standards – not only knowing where you need to make structures stronger but also where you might be able to save efforts and *not* worry about making buildings stronger.”

Magistrale says when you ask how the site response will vary from place to place for any given earthquake, you have to consider two separate questions. “One is the nature of the material near the surface – the kind of ground you’re standing on. And the other is the effect of any larger-scale geologic structure you might be on. For example, a basin filled with soft sediments is going to wiggle a lot more than hard rock.”

Much of Magistrale’s work has focused on the second question. For five years, he and an SDSU professor of seismology named Steve Day have been creating and analyzing computer-based models of the Los Angeles Basin and other basins in Southern California. “We haven’t done San Diego yet. There’s a little sediment-filled basin here that’s occupied by San Diego Bay. But the Los Angeles Basin is a huge hole in the ground that’s filled up with sediments. The middle of it is ten kilometers deep. It’s really extraordinary. And the Ventura Basin is another incredibly thick one.

After Magistrale and his colleagues create complicated, three-dimensional computer models of some of the most important of these basins, they use numerical techniques to see how seismic waves will behave when an earthquake occurs. “You watch to see what happens to the seismic energy as it moves around,” Magistrale says. “Then you can compare the models to real earthquakes.” When the model doesn’t fit the observations, Magistrale changes it and runs the analyses again. As a result of this work, the researchers are beginning to understand how seismic waves move through these big basins. Sometimes they get trapped in them. “Or as they enter the basin, the original waves can get converted into different kinds of waves that can cause more damage. Waves that travel along the surface can cause a lot of ground motion,” Magistrale says.

Research into how specific sites will react in particular earthquakes has also begun. And it’s drawing information from a source that didn’t much interest previous generations of seismologists, namely small earthquakes. “Many people are interested in recording strong ground motions,” says Francois Heuze, a leader of geotechnical programs at the Geophysics and Global Security Division of the Lawrence Livermore National Laboratory in Northern California. “But strong motions are very few and far between.” Weak earthquakes, on the other hand, “happen all the time,” he points out. “And in fact, we can do a lot with weak motions.” They can help us estimate what will happen in a strong earthquake, he says.

Heuze is now directing a program that provides a glimpse at how we might prepare for earthquakes in the future – not by running for the hills when a quake is predicted and resigning ourselves to inevitable destruction, but by building structures that have been designed to survive any earthquake that would affect the ground on which the buildings stand. This program is studying specific sites on several University of California campuses, including the one in San Diego. So far most of the work in the local study has unfolded on the grounds UCSD’s Thornton Hospital, situated across Interstate 5 from the main campus. In June 1997, the researchers drilled two holes there, one 92 meters (302 feet) deep and another half that. At the bottom of each hole, the scientists installed permanent seismometers. Two more sensors were set up on the surface, next to the two deep sensors. With these instruments, they have now recorded more than 30 earthquakes. “Some of these are within 10 to 15 kilometers,” Heuze says. “Some of them are hundreds of kilometers away. We have been able to record a lot of them because the instruments are very sensitive. These are small motions. You might not even feel them if you were sitting on the ground.... But they are telling us how the ground responds between the surface and several hundred feet of depth.”

Figuring out how the grounds of Thornton Hospital would respond in a 6.9 magnitude earthquake on the Rose Canyon Fault requires more than simply scaling up the data collected by the sensors, he says. “If we know the fault, and we know what the expected magnitude of the earthquake is, this fault can still release this energy in a zillion different ways.” Heuze’s team thus is simulating, if not a zillion, 100 or so ways that a 6.9 Rose Canyon quake might release its energy. Coupling those simulations with the data that the hospital sensors have collected will enable scientists to predict the range of ground motions at the hospital during any 6.9 Rose Canyon earthquake.

This might seem like just an academic exercise. But the university plans to add a structure next to the hospital, and the ground motion information can be used in designing it. Across the freeway, on the main campus, other work being done now should also have substantial practical value. Three additional surface seismometers have been placed on three sites where large buildings will be erected. Heuze says it's not necessary to install deep earthquake sensors at these sites, since the same Ardath Shale found 300 feet below Thornton Hospital also lies under each of these new sites. "When you get down deep enough into rock and the rock is rather homogenous, you can go a number of kilometers and the downhole motion is not likely to change," Heuze says. The surface motion can be quite different, however, depending on the soils near the surface. Data collected by the new surface sensors will provide insight into that motion; core samples of the soil may add more. After all this information is analyzed, the structural engineers who design the buildings for the three sites should have one of the dearest pictures ever created of the forces that may one day work to shake those buildings down.

"What we're doing here is not something you're going to apply to a single-family dwelling," Heuze says. "But my message to the university is that each campus of the university needs this kind of study." He says it costs about $100,000 to set up a vertical array of seismometers and do an extensive site characterization. To estimate the strong motions costs another $300,000 or so. After that, however, to determine the ground motion at any additional nearby sites, all you have to do is drill and analyze the contents of a deep hole there. That's a fraction of the first cost, perhaps $30,000. "And when you have a campus that may have tens or hundreds of millions of dollars of future buildings, it's very reasonable to invest in knowing better what your ground motion is going to be.

The vision of a future in which the inhabitants of earthquake-prone areas match their buildings to the ground below them inspires Pat Abbott. People are becoming more aware of how buildings react in quakes, he says. But the cutting edge of seismology, he believes, is this nascent awareness of how differently each piece of ground responds. "The bottom line is there's no reason anybody should have to worry about any earthquake," he says. We've grown accustomed to passively accepting them as tragedies and pouring out billions of dollars to repair their aftermath. "But this is stupid! Why don't we build things right to begin with? Why do we have to go through all this?" Abbott maintains that "if you build these things properly, an earthquake ought to be about the same as when a gigantic weather front comes through. Sure, there's still going to be some moron who drives across the San Diego River and drowns. Stuff like that. But when a heavy rain comes through, that doesn't cause damage and destruction around here to speak of. An earthquake shouldn't be any different."

He acknowledges that "an immense amount of data-gathering, rethinking, reengineering building codes" and other measures will be necessary before this day comes. In the meantime, Abbott sounds sanguine about the overall risks of living with our earthquakes. By no stretch of the imagination will they ever be as bad as those that menace Los Angeles and San Francisco. For one thing, he says, earthquake faults are distributed over a much broader area around San Diego than they are in L.A. or the Bay Area. "We have faults running from the Salton Sea to well out offshore, so you're dividing up the load across a broad area. As you go to Los Angeles, there are fewer of them, and they're running right through the city limits. In San Francisco, for the most part, it’s two faults, one on each side of San Francisco Bay.” Abbott says Los Angeles’s enormous sedimentary basin structure and the that the San Andreas Fault takes two huge bends through the heart of the metropolitan area further exacerbate the seismic problems there. In contrast, San Diego seems benign.

Abbott was forthright when I asked if he buys earthquake insurance for his home. “No, I do not! And not only do I not, but I think the vast majority of people would be far better served by spending a bit of money retrofitting things in their homes. I don’t mean hiring expensive consultants. I’m talking about the things you buy at Home Depot – little angle-iron braces, bags of cement, things like that. I’m not even saying that everybody needs it. What I’m saying is look around and do these checklists – strap down the water heater, those kinds of things. Spend the money now fixing things in your house rather than waiting for an earthquake to happen and trying to collect from the insurance company to get it back.” It’s a variation of his larger theme about the way we ought to build – “right to begin with, rather than waiting until after there’s a problem.”

Abbott thinks most people in San Diego will get to feel the distant effects of at least a magnitude-7.5 San Andreas quake. “That’s going to cause some problems,” he says. “Certain structures will be tested. But the worst-case scenario we would have here is still not going to be any bigger than a Loma Prieta or a Northridge quake in terms of the effects. You had roughly 60 to 65 people dying in each. That’s not nice. But they’re not the kinds of things that people should go around in fear of in their day-to-day life. Figure how many people that is out of how many people are in that area, and it’s relatively small.”

-Jeannette De Wyze