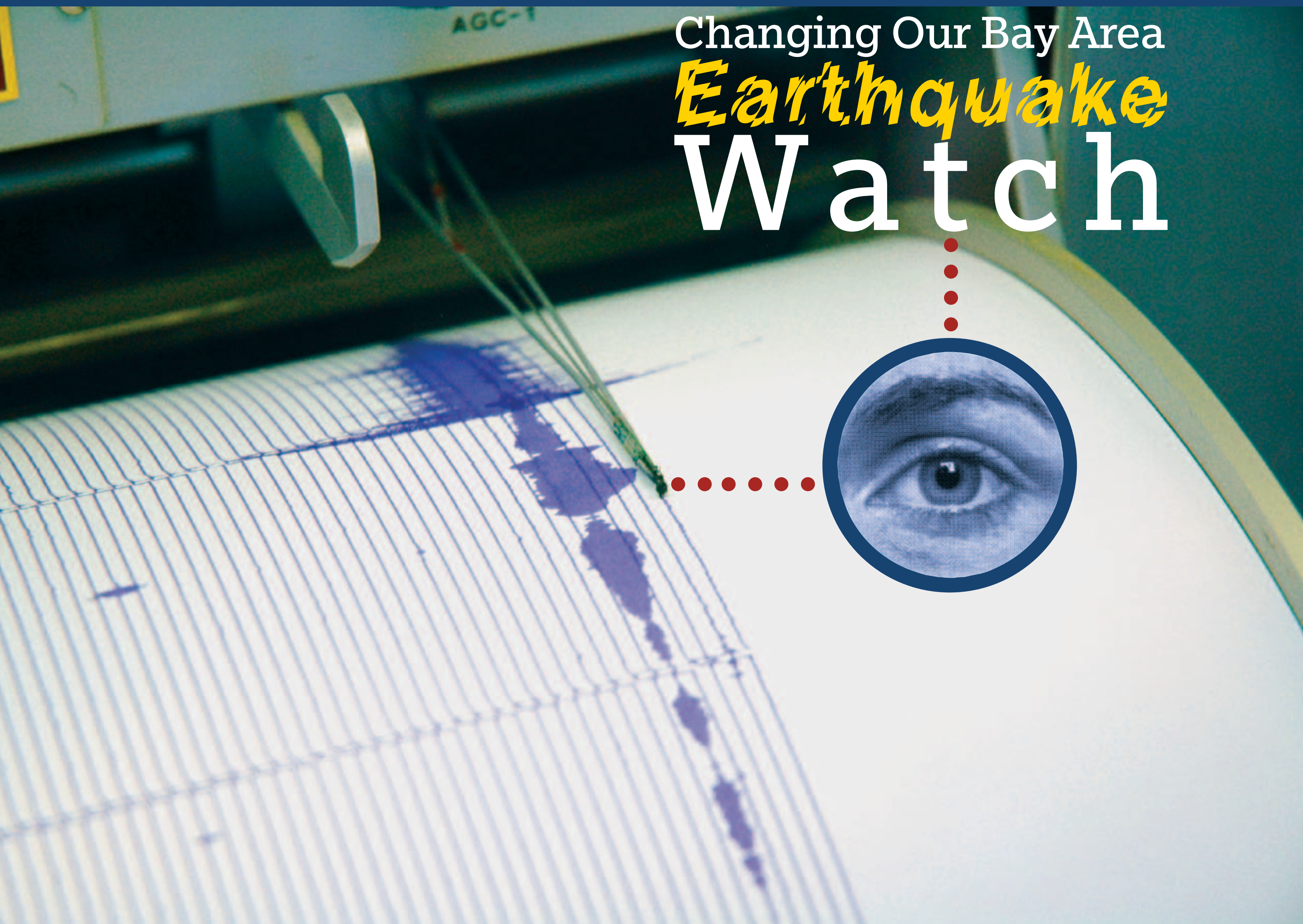
Point Reyes Fault:



Changing Our Bay Area Earthquake Watch

by Sarah Kotcher

Grove's research is posing new questions as well as providing new clues: If Point Reyes Fault is in fact an active deep-water dip-slip fault, does it have the potential to create a tsunami?

The first thing you notice when you walk into Dr. Karen Grove's office is the small floor space, the high ceiling—and for want of a better word—the chaos. Grove has stacked books, scrolls, papers, and topographical maps as if in a present-day Archimedes's office. The precarious floor-to-ceiling piles hint at her role as a geological researcher and professor of geosciences at San Francisco State University. Then you notice Grove, herself. She is tall and striking with white, closely cropped hair and the deeply tanned skin of someone who works in the field. Her smile is quick, her energy tangible, and she talks enthusiastically about her work with little coaxing.

Grove is an expert in sedimentation and stratigraphy, the geological study of sedimentary rocks and their layering. She reads Earth's layers, finds unusual trends or formations, and decodes what they mean. She was doing just this kind of work in 1992 when the Point Reyes Peninsula first caught her eye. The Point Reyes Peninsula, just north of San Francisco, is a long green ribbon of cliffs, tree-studded hills, and rocky outcroppings that reach over 10 miles into the Pacific Ocean. On an aerial map, the peninsula appears like an "i" dotted by a sea-bleached, 140-year-old lighthouse. In the early 1990s, Grove was researching older sediments in California's central Coast Range. She traveled to Point Reyes to help a friend dig a trench across the San Andreas Fault. Part of her friend's Ph.D. work was researching the layers offset by the fault. While digging near the dusty trench, Grove paused to stretch and looked west towards the vast ocean and the lighthouse. At that moment, she asked herself, "Why is that peninsula up there and why does it have terraces that indent the slope surfaces?" The terraces seemed like an unusual landform for the area. As it turned out, few had asked those questions before or researched in detail how Point Reyes had formed over geologic time. Her subsequent research not only filled in a knowledge gap, but may someday improve the way geologists predict Bay Area earthquakes.

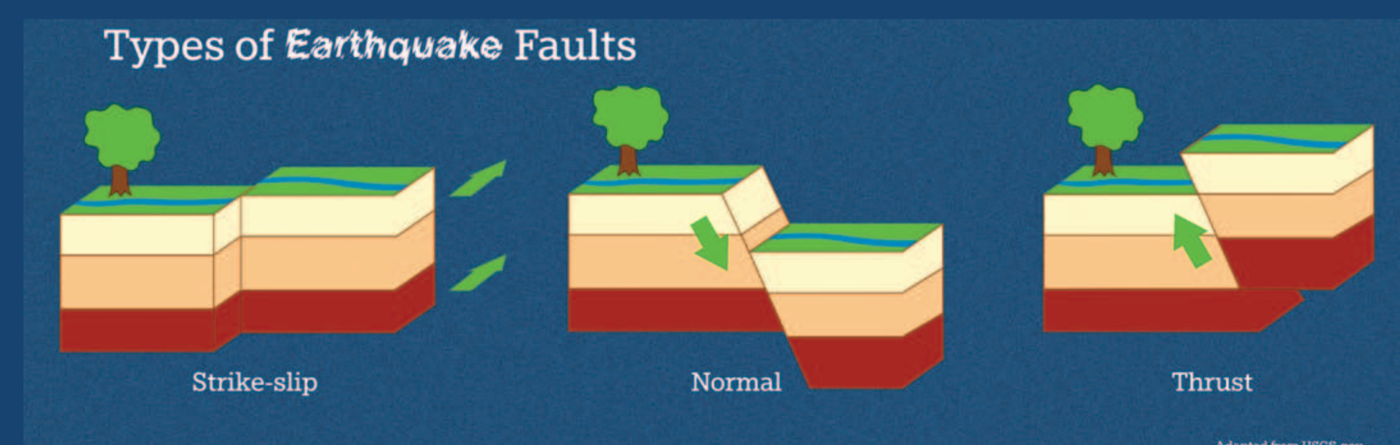
Grove learned that Point Reyes is unusual for Northern California and is geologically quite different from the area to the east of it. It actually formed millions of years ago in Southern California, 480 kilometers south of its current location. Along with Bodega Head, the Peninsula is riding the quick-moving Pacific Plate northwestward about 2.5 centimeters per year, on average. The Pacific Plate lies under the Pacific Ocean and is the largest of Earth's tectonic plates. It moves along at a quick clip compared to other plates, and millions of years from now will eventually deliver the Point Reyes Peninsula and Bodega Head north to Alaska. Relative to Point Reyes, the rest of California and the United States are riding slowly southeastward on the North American Plate.

When two large plates, such as the Pacific and the North American, meet and grind past each other in opposite directions, there is bound to be some seismic activity. This activity comes alive along the San Andreas Fault, which separates Point Reyes and Bodega Head from the rest of California. The fault slices through Tomales Bay, Olema Valley and Bolinas Lagoon and then turns east and inland, just south of San Francisco. Large and small faults coexist where these two plates come together in what scientists call the San Andreas Fault Zone. These faults interact and run parallel or at odd angles to each other. Only after the 1906 earthquake on the San Andreas Fault that destroyed much of San Francisco did scientists figure out how fault activity creates major earthquakes.

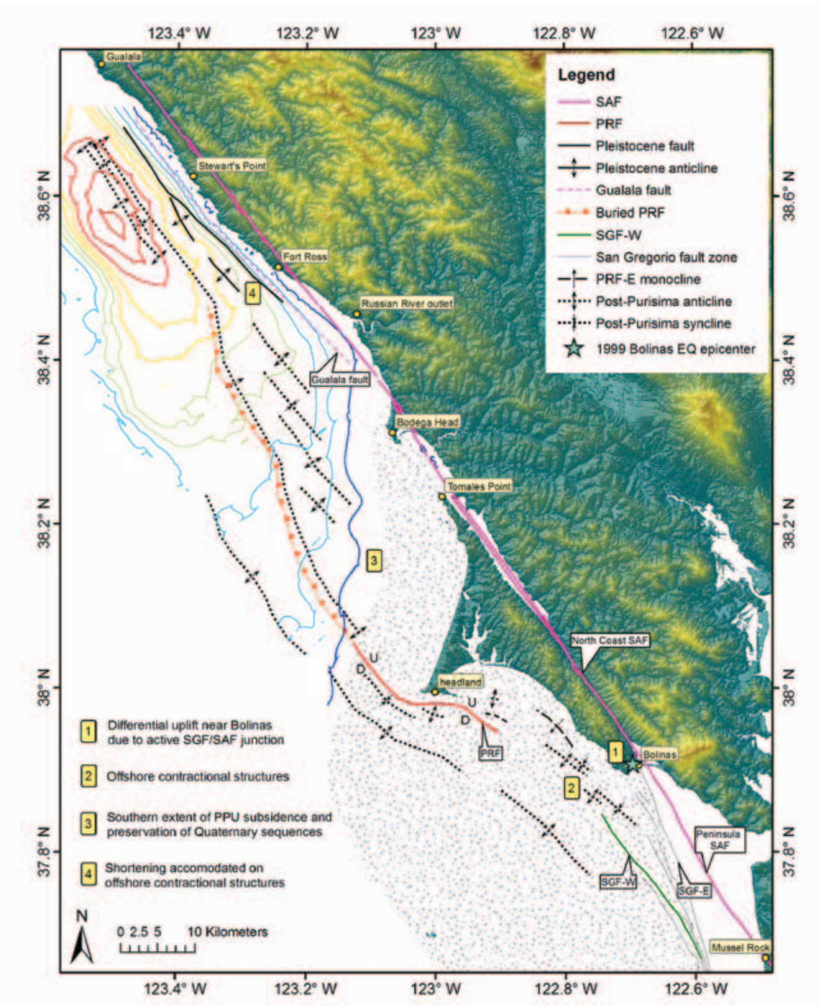
Shortly after helping her friend dig trenches across the San Andreas Fault, Grove switched her area of research interest to the Point Reyes Peninsula. Within a few years, she realized that a small and relatively unknown offshore fault, the Point Reyes Fault, which hooks around the southern and western sides of the Point Reyes Peninsula, is the likely candidate for producing the peninsula's uplifted shape.

Once she understood the link between the fault and the peninsula's uplifted terraces, she started looking for evidence of "recent" movement on the Point Reyes Fault—within the last two million years. Scientists call this period the Quaternary. If the fault has moved within the Quaternary, Grove notes, it is likely still active today and could interact with or affect other faults. Scientists have gathered data about the Bay Area's large faults but they know little about many of the smaller faults, including the Point Reyes Fault. Grove suspects that, like marathon runners tightly crowded by other runners in the crush, these large and small faults interact with each other, even if they do not touch. If Grove's hypothesis is correct, the current earthquake and tsunami models from the United States Geological Survey (USGS)— based solely on data points from the large faults in the area—may be inaccurate and may fail to predict future activity.

Understanding Bay Area earthquake faults requires a sum-



Grove is fascinated by this interconnectivity of faults— how they form a loosely woven spider-web that could possibly set each other off.



mary of local fault types. Holly Ryan, research scientist at the USGS and collaborator on Grove's project, explains the three basic types of faults: normal faults, reverse faults, and strike-slip faults. Faults occur when two separate rock bodies, or tectonic plates, move next to each other in different directions. Normal faults form when two rock bodies pull apart from each other, downward and outward. Reverse faults—which are the opposites of normal faults—form when rock bodies move towards each other, one climbing onto the other's back. Scientists call both normal and reverse faults "dip-slip faults" because their movement is vertical, either up or down. Dip-slip faults lying offshore near continental margins such as off the coast of Japan create tsunamis: Rock bodies moving up or down vertically in deep water cause a rapid displacement of water that creates a huge wave. Like the massive tsunami that struck Japan in March 2011, the rushing wall of water can move onto shore and wreak havoc, sometimes with very little warning.

Whereas dip-slip faults move vertically, strike-slip faults move horizontally. Because strike-slip faults carry rock bodies past each other on the same horizontal plane, they create very little vertical displacement of water and don't usually cause tsunamis.

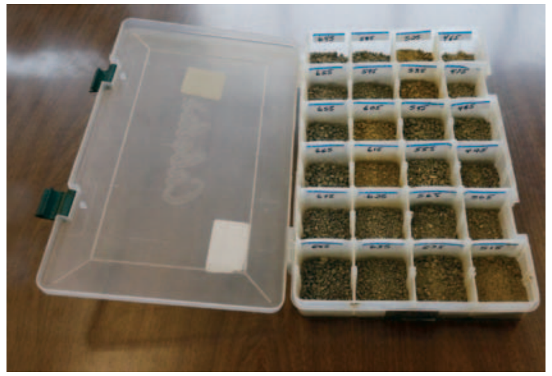
The Bay Area's three major faults are the San Andreas Fault, the Hayward Fault, and the San Gregorio Fault. All are horizontally moving strike-slip faults. The San Andreas Fault runs for roughly 1200 km through northern and southern California. It acts as a long boundary between the Pacific Plate and the North American Plate and moves 25–35 mm per year—one inch or so. The Hayward Fault lies east of, and parallel to, the San Andreas Fault: It stretches for 66 kilometers and moves approximately 9 mm per year (about one-third of an inch). The Hayward Fault originates in the San Francisco Bay northwest of Berkeley, grinds directly through Hayward and Livermore, and tapers off south of San Jose. The San Gregorio Fault is the least well-known: It splits off from the San Andreas Fault south of Bolinas Lagoon and continues subparallel to the San Andreas, running southward for 240 kilometers before tapering off near Monterey Bay, where it continues to the south as the Hosgri fault. It moves just 3–6 mm per year. Only in Bolinas Lagoon at the split-off point do two of the three faults—The San Gregorio and San Andreas—actually touch at Earth's surface.

Faults need not touch, however, to put stress or pressure on each other. As points out Brian Stozek, Karen Grove's research student who recently completed his Master's degree at SF State, fault activity is much more complicated than that. Explains Stozek, a slim, dark-haired young man who favors fitted jeans and dark hooded sweatshirts, "The (San Andreas) Fault could be slipping and there could be a reverse fault that's taking into account other stresses. The uplift (of the Point Reyes Peninsula) is not due just to horizontal stresses that are along the San Andreas fault. Stress could be coming in other angles." Stozek provided this reporter with detail on that complexity. Although most seismic activity happens along large faults, he says, small faults are important because, while they move more slowly than large ones, they absorb and relieve stress from larger faults. They have a part to play in the fault zone, he concludes, but currently that part is little researched, little mapped and little understood.

Years ago, Grove noticed that most movement on Bay Area faults takes place on strike-slip faults, with activity on dip-slip faults being much rarer. "The ratio of strike-slip to dip-slip [activity] in the Bay Area is about 25 to 1," Grove says. One place that dip-slip faults do appear, however, is around Grove's main research area: the Point Reyes Peninsula. This unusual activity piqued Grove's interest and led her to investigate how all the faults in the area affect each other.

Northern California—from the peaks of the Sierra Nevada to the cool waters of the Pacific—is spider-webbed with big and small faults. "Everybody knows this area because of the San Andreas Fault; it's super famous," Grove notes. She goes on to explain that the San Andreas Fault is remarkable because it moves more than any other fault in the area—approximately 25 mm per year—and this creates larger and more newsworthy earthquakes. Compared with the Point Reyes Fault, which moves only 1 mm or so per year, the San Andreas is a record-breaking marathon runner.

Although 25 mm per year seems small, Grove insists that it is actually substantial. "If you think about 25 mm per year over 5 million years," she points out, "it's a lot." In order to relieve the stress of that cumulative creep on the San Andreas Fault, she says, a major earthquake must suddenly "catch up" with 5 to 7 meters of movement approximately every 200 years on that fault. The other faults in the area move more slowly, but also must eventually relieve built-up stress. Stozek notes that scientists believe faults have the potential to set each other off, in a domino effect. Looking at the Bay Area's many faults, each one like a marathon runner connected to all the other runners as if by rubber bands of tense, elastic earth, one can imagine the potentially disastrous pile-up that could occur if one runner takes a major fall.



Grove is fascinated by this interconnectivity of faults—how they form a loosely woven spider-web that could possibly set each other off. Her research is difficult, however, because rather than looking at faults on land, she studies their activity

Dr. Karen Grove
Department of Geosciences

Page 44 top:
Map from MS thesis of Brian Stozek, who used seismic profiles to identify areas where Earth's crust is uplifting or subsiding, and where faults and folds (anticlines and synclines) have been active.
Graphic courtesy of Brian Stozek

Page 44 bottom:
Students in Grove's geology class make observations of sedimentary rocks on Sculptured Beach at Point Reyes. Students left to right are Morgan Selby, Holly Olson, Geza Demeter, Jonathon Perkins, and Curtis Barnes.
Photo by Karen Grove

Left:
Tackle box with "cuttings"–sediment samples collected during drilling of a water well in San Francisco. The samples help geologists understand what is going on beneath Earth's surface.

Grove's husband, Jay Ach, points to a thrust fault—left side moved up relative to the right side—along the coast at Montara Beach.

Photo by Karen Grove

deep below the cold Pacific Ocean. Stozek, who helps with this research, explains, "The (Point Reyes) Fault is not like the San Andreas Fault which can come to the surface and have surface 'expression.' The fault is actually 'blind,' meaning it doesn't 'see' daylight. It's below the sea floor and it doesn't even come to [that submerged] surface." Grove cannot lift up the Pacific's edge to study the underlying fault lines as one could lift a backyard kiddie pool to investigate earthworm tunnels beneath it. Instead, she and Stozek must look in indirect, unexpected places such as old oil company seismic records that give clues to how faults may connect and interact with others.

Grove and Stozek compile old data, mapped on paper scrolls and now available on computer screens, generated from sound pulses and wells drilled deep under the ocean. Oil companies collected this data in the 1960s, 1970s, and 1980s when they were searching for oil off the California Coast. The data is now in the public domain. Sitting in her Thornton Hall office on the SF State campus, Grove pulled out a long white scroll from beneath a cluttered drafting table. She unrolled it to reveal a slightly fuzzy-looking chart of tiny dots in varying shades of green with a few small X's dotting the pattern here and there. It gives an impression of offshore terrain immortalized by a 19th century Pointillist painter.

Each dot represents a sound pulse, Grove explains, and each "X "represents a deep-ocean well. "Basically, on land they might just have [used] dynamite or a big truck that goes thump. In the ocean," she continues, "they've got air guns for looking for oil.... It's like you're creating a mini-earthquake. They're much, much smaller than what the Earth creates, but that sound pulse actually goes down through the sea floor and bounces off of [underlying] layers. Where there is a contrast in the layers [the pulse] will actually bounce off and give a picture of what is happening." On the chart, most of the tiny green dots form soft, curved layers. Grove explains that the density and clarity of the dots is a clue to each layer's composition—granite, mudstone, or sandstone, for example. In one place, the points become greener and closer together and create an angled line of demarcation. "So there's the granite and these are all sedimentary layers and there's a fault there," she says, pointing at the weirdly angled line.

Under Grove's watchful eye, Stozek compiles and compares oil company data points with new information that USGS researchers recently gathered from sites much closer to shore. When Stozek has enough comparative data, he will provide it to USGS research scientist Tom Parsons, who has generated a computer model of Northern California faults. Holly Ryan explains, "Why we became interested in the Point Reyes fault is that (the computerized) model of the interaction between the San Andreas and San Gregorio faults showed no uplift of the Point Reyes Peninsula. The model did not agree with (Grove's) work, which showed uplift rates as high as 1 mm per year. Thus, we plan to rerun the model, adding the Point Reyes Fault (data)...that bends to the west around the Point Reyes Peninsula causing uplift." Grove and Stozek believe that with their newly compiled data in place, Parsons' model will mirror the movement and uplift that Grove has found and that she predicts will continue in the Point Reyes region. This will support her hypothesis that the Point Reyes Fault is active and that it both affects and reacts to other faults in the region.

Grove, Stozek, Ryan, Parsons and the USGS are all interested in confirming any activity on the Point Reyes fault because this would place it on the new state hazards maps coming out in 2012. "Redoing fault trends (by adding new data) is probably going to require edits to (the earthquake models) and tsunami hazards offshore," Stozek points out. If the faults differ from existing hazard maps, scientists would need to reevaluate fault interaction and the potential consequences for Northern California.

Scientists and researchers are anxious to forecast how earthquakes will affect the heavily populated and seismically-active Bay Area. Fault interactions that set each other off would necessitate revisions to current hazard warnings. Stozek recalls an earthquake in Alaska a decade ago: "There was a big earthquake that started on a strike-slip fault and propagated to... a reverse fault. It was like a domino effect." Evidence from the Grove lab suggests that the many small and large faults in the compact Bay Area could create similar potential interaction.

Grove's research is posing new questions as well as providing new clues: If Point Reyes Fault is in fact an active deep-water dip-slip fault, does it have the potential to create a tsunami? Grove considers it possible, although the wave action would not be as large as the recent one in Japan. Historically, scientists have predicted potential tsunami activity in the Pacific Northwest but not in the Bay Area. As Stozek points out, "The closest [confirmed] source for a large tsunami (is) off the coast of Oregon... and that would give (the Bay Area) an advance warning. So it would not be like Japan where [there] was only 10 minutes warning because the fault was right offshore." If Point Reyes is indeed an active dip-slip fault, it is, as Grove points out, "One more... active structure to add to the (Bay Area's) earthquake risk (model)." Although the Point Reyes Fault moves infrequently, its links to more quickly moving faults could be significant.

Grove, Stozek, and Ryan do believe that Bay Area faults interact. As they further research small active faults in the San Andreas zone, their finding will surely expand scientific understanding and improve earthquake forecasts. However, until Stozek finishes compiling enough data points from the old and new research to impact Tom Parsons' USGS model, Grove says, and until Parsons incorporates the data into his model, it will continue to spit out flawed results. The update, she adds, "Isn't going to solve everything. But [it will] add one more piece to the overall understanding" of how all the faults in the area—constantly pushing, stretching and stepping on each other's "toes"—will react when the one of them takes its next big fall. ❖

Studying Faults Under the Seafloor

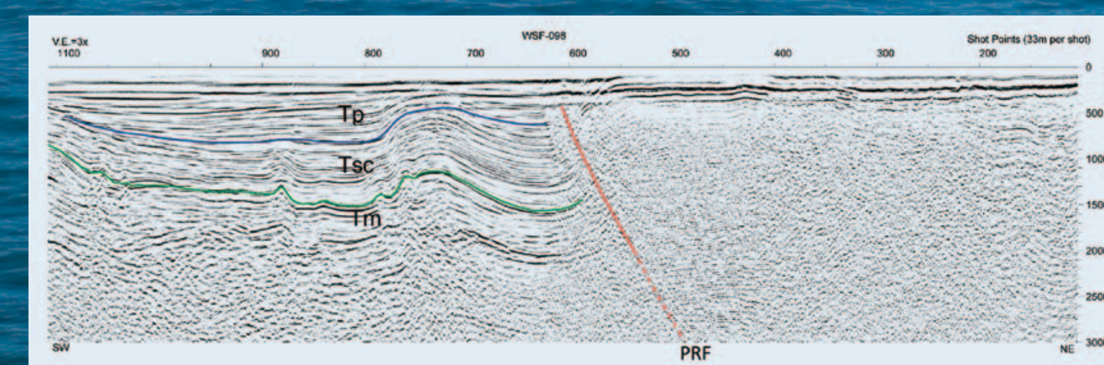
by Dr. Karen Grove

When studying faults on land, geologists can get direct views of the fault and the layers that have been offset by the fault's movements. These observations are used to estimate how much the fault moves during earthquakes and how often those earthquakes recur. Studying faults buried beneath ocean water is a different challenge that requires less-direct, higher-tech methods to collect data remotely via sonar and drilling.

Sonar is used to collect data over large areas using a ship that can generate sound pulses and record the signal generated after the sound pulse bounces off of layers beneath the sea floor and then returns back to the ship. Sonar data are processed to produce seismic profiles that are images of the layers beneath the sea floor; if the layers are offset, the fault's location and amount of offset can be estimated. The vertical axis of time can be converted to depth using density and sonar velocity data obtained by drilling a seafloor well.

Drilling from a ship can collect sediments and rocks from beneath the sea floor. Samples can be "cuttings"—bulk samples that are collected every several meters—or "core"—continuous samples that are a long tube of sediment or rock typically 10–20 centimeters in diameter. This information can be used to match the sediment/rock type with the layers that are visible in a seismic profile.

Because strike-slip faults involve side-by-side motion, they are difficult to see in seismic profiles. Dip-slip faults involve up–down motion and are easier to see on the profiles. The Point Reyes fault we have been studying is a reverse-motion, dip-slip fault that has vertically offset sedimentary layers at least 2 km. Our studies of this fault suggest that it was most active 5–0.5 million years ago. The uplift we have measured on the south part of the Point Reyes Peninsula probably results from fault intersections in the offshore region south of Bolinas. The Point Reyes fault, located farther to the west, has certainly uplifted the western side of the Point Reyes Peninsula, but in terms of generating large earthquakes today, it appears to be largely "off the hook"! It could still move, however, when its neighbors get the action going. ❖



Seismic profile created from bouncing sound waves off of layers beneath the sea floor. Profile oriented southwest (SW) to northeast (NW) across the Point Reyes thrust fault (PRF). Vertical axis is two-way-travel time (TTWT in milliseconds); 3000 ms is about 3500 m depth. Left side of profile shows layered Tertiary-aged sedimentary units (Tm=Monterery Formation; Tsc=Santa Cruz Mudstone; Tp=Purisima Formation) that have been folded by contraction in the region. Right side of profile is unlayered granitic bedrock that has been lifted to the surface because of contraction and movement on the PRF.

Graphic courtesy of Brian Stozek