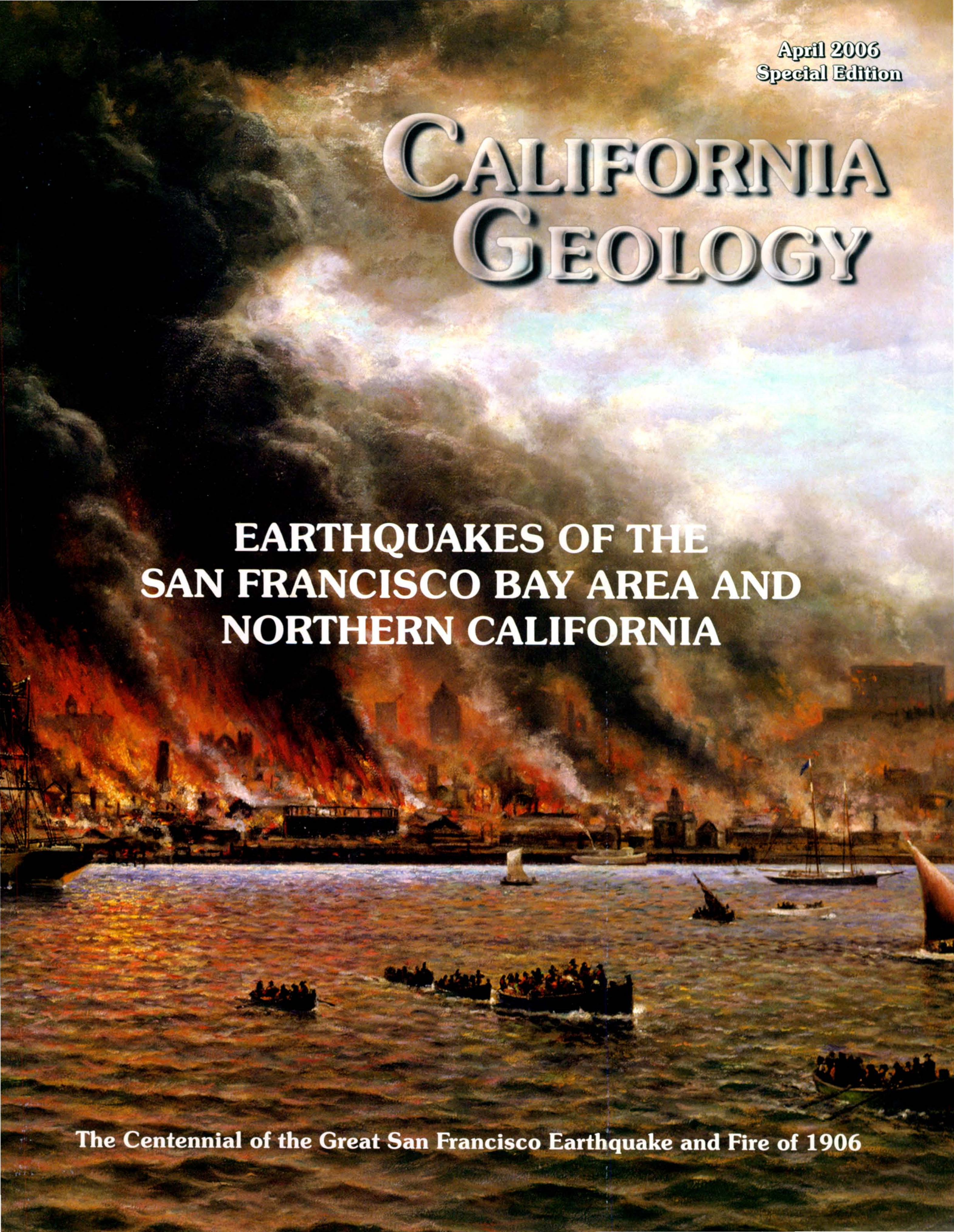
April 2006
Special Edition

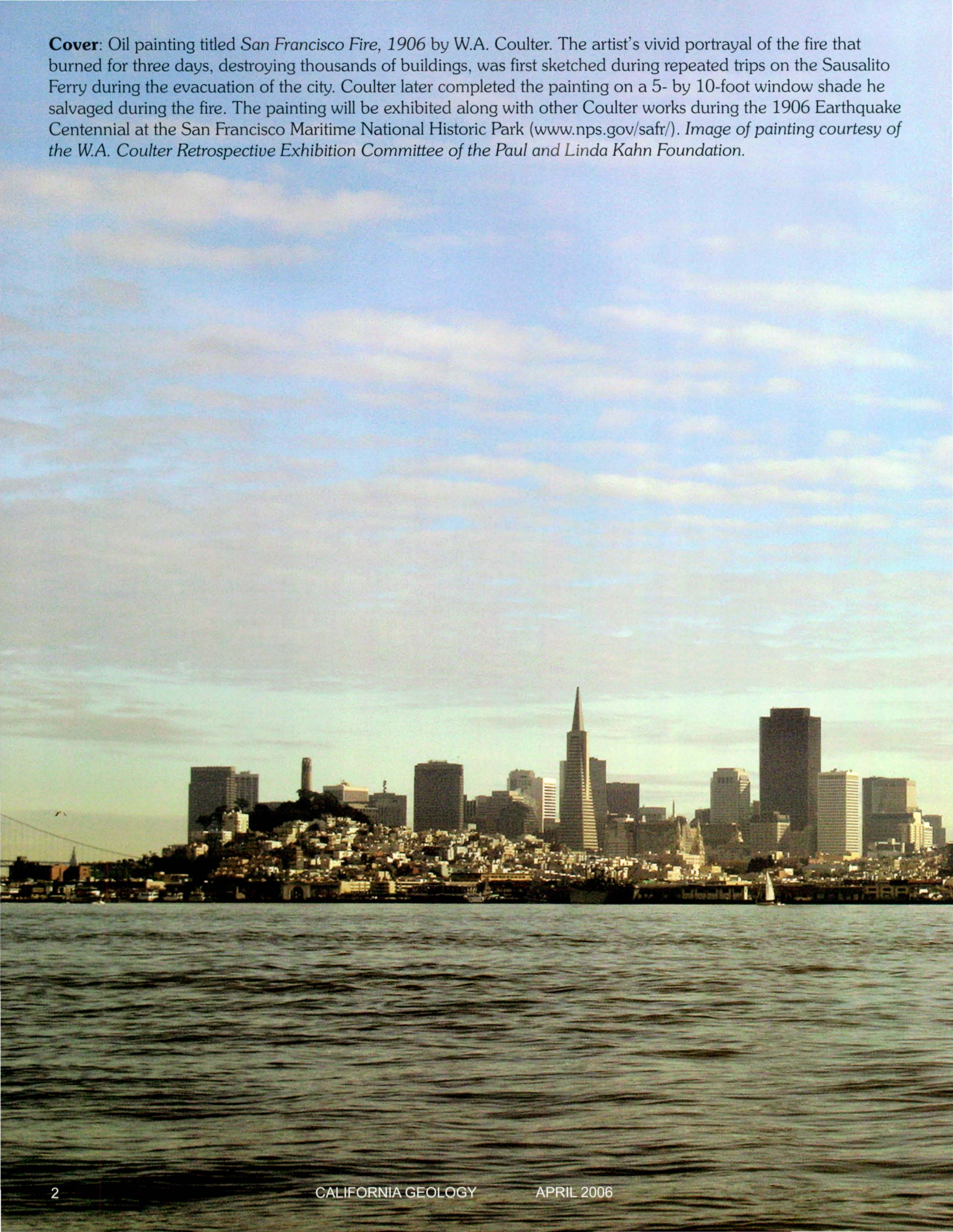
California Geology



EARTHQUAKES OF THE SAN FRANCISCO BAY AREA AND NORTHERN CALIFORNIA

The Centennial of the Great San Francisco Earthquake and Fire of 1906

Cover: Oil painting titled *San Francisco Fire, 1906* by W.A. Coulter. The artist's vivid portrayal of the fire that burned for three days, destroying thousands of buildings, was first sketched during repeated trips on the Sausalito Ferry during the evacuation of the city. Coulter later completed the painting on a 5- by 10-foot window shade he salvaged during the fire. The painting will be exhibited along with other Coulter works during the 1906 Earthquake Centennial at the San Francisco Maritime National Historic Park (www.nps.gov/safr/). *Image of painting courtesy of the W.A. Coulter Retrospective Exhibition Committee of the Paul and Linda Kahn Foundation.*



Inside Cover: This 2006 photograph of San Francisco incorporates the same view that Coulter captured in his painting 100 years earlier. The Ferry Building, Telegraph Hill, Fairmont Hotel, and Knob Hill are among landmarks that are discernable in both images. *Photo by Vladimir Graizer, California Geological Survey.*

CALIFORNIA GEOLOGY

A PUBLICATION OF THE CALIFORNIA GEOLOGICAL SURVEY

State of California	Arnold Schwarzenegger *Governor*
Resources Agency	Mike Chrisman *Secretary for Resources*
Department of Conservation	Bridgett Luther *Director*
California Geological Survey	John G. Parrish, Ph. D. *State Geologist*

CALIFORNIA GEOLOGY

Editors:	Ralph Loyd Elise Mattison Rick Wilson
Graphics and Design:	Dinah D. Maldonado
Graphics Support:	Jerry Wampole Ante Perez

Printed: University of California Printing Press

California Geological Survey Headquarters
801 K Street, MS 12-30
Sacramento, CA 95814-3532
(916) 445-1825

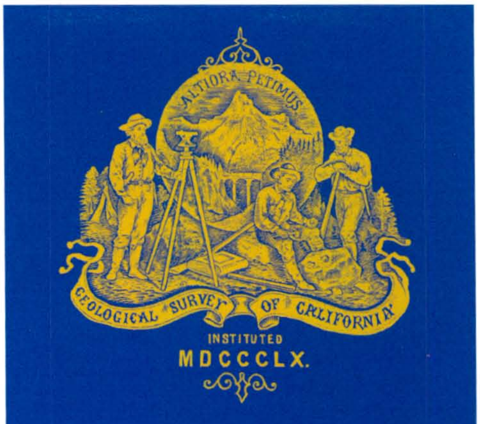
Publications and Information Office/Library
801 K Street, MS 14-33
Sacramento, CA 95814-3532
Publication Information: (916) 445-5716

Southern California Regional Office
888 South Figueroa, Suite 475
Los Angeles, CA 90017
(213) 239-0878

Bay Area Regional Office
345 Middlefield Road, MS-520
Menlo Park, CA 94025
(650) 688-6327

www.consrv.ca.gov/cgs

In This Issue



circa 1860

April 18th—To American History buffs, this is the date in 1775 that Paul Revere began his legendary midnight ride to Lexington and Concord to warn patriots that British troops were approaching; to delvers of the intrigue, it is the day in 1480 that the notorious Lucrezia Borgia was born; lovers of symphonic music remember this day in 1882 as the birth date of the great conductor Leopold Stokowski; and certainly no self respecting lawyer can forget that this day in 1857 marks the birth of Clarence Darrow—but to Californians, and especially those who live in San Francisco—April 18th is chiseled in history as the date of the Great 1906 San Francisco Earthquake.

The 1906 Earthquake was not the first time in the City's history that San Francisco had been hit with a "big one." On October 21, 1868 a magnitude 7.0 earthquake occurred on the Hayward Fault, across the Bay from the City. This earthquake killed 30 people and did about $350,000 (1868 dollars) in damage. The Great Quake of 1868 was the big one until 1906, when shifting of the San Andreas Fault resulted in 3,000 lives lost and about $525 million in damage (1906 dollars).

The California Geological Survey (CGS) was there for both events. Established as the Geological Survey of California in 1860, and later reorganized as the State Mining Bureau on April 16, 1880, the Bureau had its offices in San Francisco. The newly opened Ferry Building at the foot of Market Street became the Bureau's headquarters in 1899, where it remained until 1984. The purpose of the Bureau at that time was, "to encourage the development of the great mineral resources of California."

In 1928 the Bureau became the Division of Mines, and continued to focus on the State's mineral resources. Gradually, the attention of the Division broadened into other facets of geology, and in 1961 the Division underwent another descriptive name change and became the California Division of Mines and Geology.

Not until the 1952 Arvin-Tehachapi Earthquake did the Division really begin to look more closely at earthquakes. Although the Mining Bureau had its headquarters in San Francisco at the time of the 1906 Earthquake, the only mention of the disaster was in a Bureau publication that noted about $1,500 in damage was sustained by Bureau facilities.

It was the San Fernando Earthquake in 1971 that brought legislation and programs to the Division that were designed to mitigate the dangers of earthquakes. These programs have resulted in the CGS operating one of the largest seismic monitoring networks in the world (Strong Motion Instrumentation Program, 1971), mapping more than 5,000 miles of surface faulting throughout the State (Alquist-Priolo Earthquake Fault Zoning Act, 1972), and zoning more than 6,600 square miles of seismic hazards such as liquefaction and landsliding (Seismic Hazards Mapping Act of 1990).

Today, the California Geological Survey is part of the Department of Conservation within California's Resources Agency. CGS is regarded as the primary source for information about California's geology, and it operates major programs relating to regional geological mapping, inventorying of California's mineral assets and locating hazardous mineral deposits, and earthquake engineering and seismic hazards assessments. CGS is proud of its long tradition of service to California's citizens, and we look forward to serving California in the 21st Century.

John G. Parrish, Ph. D.
California State Geologist

ABOUT THIS SPECIAL EDITION . . .

CALIFORNIA GEOLOGY magazine and its predecessor, the *MINERAL INFORMATION SERVICE*, were in print from 1948 to 2001 providing information on the latest academic and applied geologic studies, written with the public in mind. Many of the articles in these publications were tied to events affecting California and its residents. Whether it was mining and mineral hazards, or landslides and earthquakes, the readers knew they were getting pertinent facts that might help them make decisions about daily living in California.

Had *CALIFORNIA GEOLOGY* been published back in 1906, it is likely that several issues would have been dedicated to the "Great San Francisco Earthquake and Fire." The truth of the matter is that, although the CALIFORNIA GEOLOGICAL SURVEY existed as the State Mining Bureau and was headquartered in the Ferry Building in the city of San Francisco, the focus of the organization was on minerals and mining activities, not seismic activity. Surprisingly, the State Mining Bureau's annual report for 1906 made no mention of the earthquake. A later report explained:

> *After the San Francisco disaster, what little funds the Bureau had and which would have been available for field work had to be used for the purpose of repairing damages sustained during the earthquake. The last legislature made no provision to rehabilitate the Bureau, although it sustained damage by breakage of cases and other losses to the extent of approximately $1,500.*

California did not routinely map faults and study earthquakes until after the magnitude 7.7 Arvin-Tehachapi earthquake of 1952.

Today, the CALIFORNIA GEOLOGICAL SURVEY is one of the premiere geologic and seismologic organizations in the world. CGS is mandated by state legislation to provide maps and information vital to help protect the public from earthquake hazards. A comprehensive earthquake program has set the standard in seismic hazard zonation, earthquake strong-motion instrument monitoring, and probabilistic earthquake-shaking modeling. Other government agencies enlist the expertise of SURVEY geologists and seismologists to review technical documents for the siting and construction of new schools and hospitals. The SURVEY also advises and participates with other state and local agencies in emergency response following damaging earthquakes, landslides, and tsunamis.

The centennial anniversary of the 1906 earthquake is an opportunity to reflect on how far science has advanced in its understanding of earthquakes and how much more there is to learn. We have produced this Special Edition issue of *CALIFORNIA GEOLOGY*, focusing on the earthquakes that have affected the San Francisco Bay Area and the rest of northern California. In the following pages are some unique eye-witness accounts from Bay Area residents who survived the 1906 earthquake and its aftermath. We provide some basic information on earthquakes and the hazards they present, and summaries of some northern California earthquakes. We also provide an overview of the CALIFORNIA GEOLOGICAL SURVEY'S wide-ranging earthquake programs including valuable maps of specific seismic hazards within the Bay Area and northern California.

The editors thank those authors whose condensed articles appear in this publication. Because we found it difficult to borrow only portions of these excellent articles published in *CALIFORNIA GEOLOGY* and the *MINERAL INFORMATION SERVICE* magazines, each original version has been reproduced digitally, in its entirety, and placed on the CALIFORNIA GEOLOGICAL SURVEY 1906 earthquake web site: www.1906quake.ca.gov.

Editors' special notes to the readers about this magazine:

- The CALIFORNIA GEOLOGICAL SURVEY has been known by other names, most recently, the California Division of Mines and Geology.
- The magnitude of a given earthquake may vary in different articles of this issue because the originally published values are retained. The table on page 30 gives the more accepted, modern measurement (moment magnitude) for a given moderate or large earthquake.
- Please refer to the simplified fault map on page 31 to see earthquake epicenters and associated faults discussed in articles that do not include a detailed location map.
- Sources of information numbered in the articles are listed in the back of the magazine in the order of occurrence, by section.
- Although the epicenter for the magnitude 7.9 Fort Tejon earthquake of 1857 is located on our northern California fault and epicenter map (page 31), the fault rupture from the earthquake propagated southward and its impact was greater in southern California. For this reason, the earthquake was not highlighted in this special edition dedicated to northern California earthquakes.
- Metric units used in the original articles have been converted to standard.

At 5:12 A.M. on Wednesday, April 18th, 1906, the earth shook with a terrific force . . .

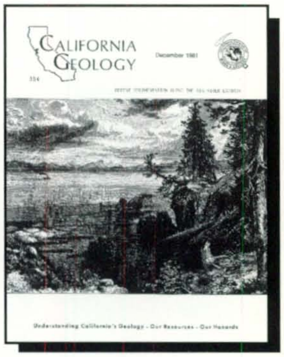
. . . I was wakened by the crash of falling furniture, and a rocking, heaving house. . . . I felt very calm, paralyzed perhaps, but I thought, "This is the worst thing I ever knew, and we may be going to be killed . . . ."
— **Eleanor Watkins, from San Francisco**

. . . I was warm and comfortable, but the whole room seemed to be undergoing a rocking on its edges. My first thought was that it could not stand much of that sort of beating . . . .
— **Stuart H. Ingram, from Berkeley**

. . . Since my bed was walking all over my bedroom and I was sure that the house would land on its side, I just hung on. I had been sleeping soundly until just the very second the great temblor came . . .
— ***Olaf P. Jenkins, from Palo Alto***

. . . their stories of the Great San Francisco Earthquake and Fire begin . . .

~ San Francisco, April 1906 ~



What occurred during the "Great San Francisco Earthquake and Fire" was beyond the experience or imagination of the people living in 1906. San Francisco and the surrounding area had experienced large earthquakes in the years 1838, 1865, and 1868, but those events were nothing like the destructive power of the magnitude 7.9 earthquake that ruptured nearly 270 miles of the then little understood San Andreas fault.

CALIFORNIA GEOLOGY *magazine was privileged to have three separate first-hand accounts of the "Great San Francisco Earthquake" from three different locations (San Francisco, Berkeley, and Palo Alto) and three very different perspectives (a surgeon's wife, a college student who was also a cadet, and a high school student, who would later become "State Geologist" of California).*

The first account is that of Mrs. Eleanor Watkins, the wife of a San Francisco surgeon, from the December 1981 issue of CALIFORNIA GEOLOGY, *p. 260-266. The following excerpts are her observations written during the days following the earthquake in a letter to relatives in Virginia describing San Francisco's plight. Photos on pages 8 and 9 are courtesy of the Museum of the City of San Francisco. . . .* editors, 2006

". . . the effects of the earthquake . . ."

[*After the earthquake*] . . . the streets were instantly full of throngs of people, many in their night clothes. The sun was rising red behind a queer brown cloud. I said "That is the typical sun of earthquakes and cyclones that we read about."

In a few moments I noticed five billowy columns rising in this queer cloud in different directions, and I realized it was smoke. The great fire had begun, though no one realized what it would be. . . .

We had heard people calling, "Look at the Power House!" "Look at the City Hall!" The Power House was within a square of us—one of three in the city. Its tower had fallen and mashed in the roof.

The City Hall [*pictured below*] was straight down Hyde Street, about six squares from us. It was granite, and occupied a square—a magnificent building. The dome was standing (this was the Hall of records which fortunately contained the City's most valuable records and title papers), but the rest was a pile of ruins. The effects of the earthquake were in spots—not universal. We saw whole fronts of office buildings and of assembly halls fallen outward. Sometimes the asphalt pavement had heaved up in a hillock, where gas had exploded.

We heard that the old Valentia Street Hotel, in the Mission, had sunk 20 feet, collapsed and killed 50 people. This was true. It had the severest shock in San Francisco. The handsome residence district on Pacific Heights, overlooking the ocean, was scarcely injured, except fallen chimneys. . . .

As we crossed Union Square to the Saint Francis Hotel, the crowd came in surges and Union Square was full of poor people, who had fled from the fire south of Market Street, where the poorest people lived. Around them were piled trunks and bundles, parrots and babies. A woman had fainted at the corner and was lying on the grass in the crowd.

Strange to say the Statue of Victory, which is perched on one toe at the top of a column one hundred feet high in Union Square was uninjured. We went into the Saint Francis to find its lobby crowded with dress suit cases and tourists, who were begging for carriages or wagons, to take them to the ferry. The ornate ceiling, the frescoes and carvings were broken at every corner, and the waiters too excited to bring us anything but coffee. We collected rolls, sugar, knives and forks and spoons from other uncleared tables. The coffee braced us up, for I was on the verge of tears over the homeless people in Union Square, little thinking that I should soon be one of them.

". . . the flames burst . . . the fire spreading . . . ."

We walked down to Market Street [*pictured at right, during the fire*], the chief business street of the city. On Mission Street, next south of Market, about six squares were burning. Let me draw a rough sketch of the city, of course inaccurate. It is, you know, at the end of a peninsula. Market Street divides the city diagonally in two. South of it were the residences of the poorer people and wholesale houses, and at the end of it was the ferry building. It was the main business street, and held most of the skyscrapers, the newspaper buildings, office building, large hotels, government buildings, and it began the business section which extended further north, along Kearney, Montgomery, Grant Avenue etc., holding the great shops, importing houses, etc. South of it were the Post Office and the Mint, almost the only large buildings to be saved from the fire, and they only by marvelously heroic fighting.

We saw the flames burst through the windows of the first building to burn on Market. We saw the fight to save the Palace Hotel—a historic landmark [*wreckage pictured at right*]. We saw a fire break out on each side of Market, between us and the Ferry. We saw the troops coming, and the first dynamite brought, and still no one thought of the fire spreading to the northern part of the city. The water mains were broken by the earthquake, there was no water . . . .

". . . fleeing from the flames . . ."

The soldiers were dynamiting the buildings along the fire line, so we decided to go home and make sure of our insurance papers and jewelry. Even then our friends laughed at us. It was a strange obsession. No one seemed to realize that there was no water, and each one believed that the fire could not reach him. Most people escaped with only the clothes that they wore. When the fire was within two squares of us, a woman in our house declared that our house could not burn and she would not pack her clothes. . . .

The very poor could pack their possessions in a trunk, and drag it with a rope along the pavement for miles. I shall never forget that sound of dragging trunks, all night long. Some of the rich people saved their houses, for this one fourth of the city which still stands was one of the richest sections. But they suffered most in the business section. One of my ex-rich friends, with a big house, is already trying to get boarders.

We got our papers, life insurance, fire insurance, burglar insurance, and a few shares in an eastern company, bank books, check books, our jewelry, and what cash we had in the house. All this we concealed on our persons. . . . I had almost $200. This was the only cash in the house. On this money, we and six other families have been living since the earthquake. I have heard of only one other person who saved so much cash. Men who were millionaires had only a dollar or two. I heard one young fellow remark cheerfully that he had lost everything and had 25 cents in his pocket, but that he was young, and did not need money.

The spirit of this people is the most wonderful thing I ever dreamed of, cheerful, happy, laughing while they were fleeing from the flames, saying nothing of what they had lost but rejoicing over their lives. I have seen one woman fainting and one in tears, that is all. . . . Humanity has showed up well. I am proud to call myself a San Franciscan. . . .

We spent the night on the stone front steps [*of the house*], wrapped in blankets. No one slept, except the men took cat naps. We women could not sleep. I lay down for two hours on the couch in the reception room, but could not sleep. . . . Every few moments there was an explosion of dynamite, or a slight earthquake shock. Across the street was a vacant lot, where a big house was pulled down last summer. It was filled with people sleeping, rolled up in blankets. The streets were filled with trunks.

All night the crowds went by dragging, dragging trunks. It was a horrid sound. A man had a fit on the opposite pavement. A paralytic went by dragging his foot on the pavement, going towards the fire. An invalid was carried past in a big chair. A young mother trundled her baby in a gocart, with a bundle as big as a bushel hanging to the handle of the gocart. The baby sat up so straight and interested, watching the fire. . . . The father was dragging a trunk, with the rope over his shoulder. I shall always wonder if that baby escaped.

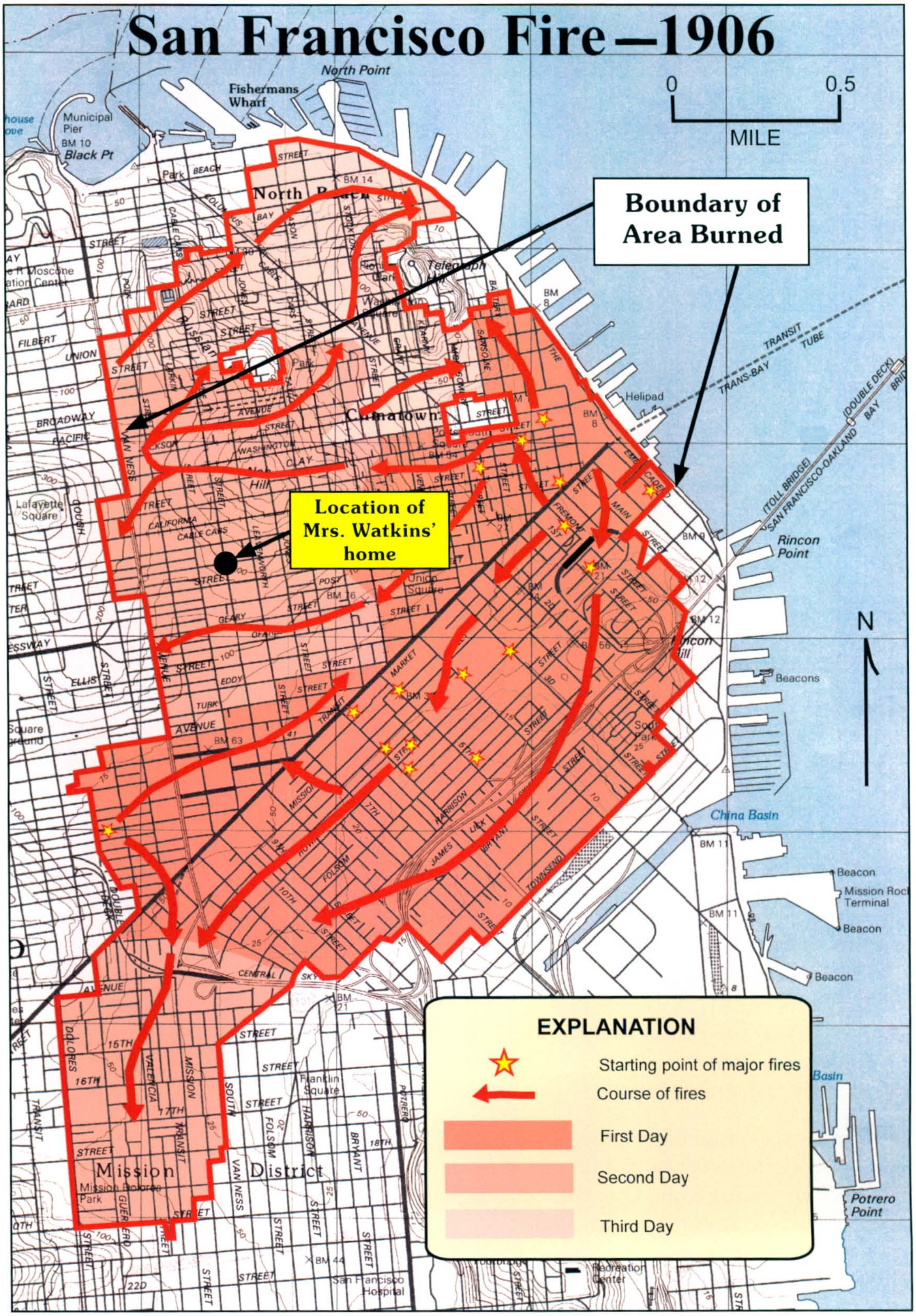
Wild rumors reached us constantly. Every half hour two of us walked down the street, to see for ourselves how the flames were. The sky was lit up with the awful glare for three-fourths of the Heavens; on the other side was the black fog from the sea. We could hear the crackle of flames, the crash of falling roofs and walls, the roar of dynamite. Showers of cinders fell over us, and continued to fall for three days and nights. Fortunately the heat was so fierce that the sparks went very far in the air and were cold before they reached the ground. . . .

At about 5 A.M. the fire was within two squares of us on the south and west, so we gave it up and started [*to leave for a safe area*]. . . . Fortunately, there was no wind and the flames did not travel fast enough to endanger life except to some people who were hemmed in between the water and three lines of fire, on Russian Hill, but everything escaped as a rule. . . .

Thursday night the fire crossed Van Ness in two places. It is the broadest street in the city, has no car lines, and divides this, the upper fourth of the city, from the three fourths that burned. Every one felt that it was the last stand; if the fight was lost at Van Ness, the whole city would go. The military and fire department had started a back fire for two squares below Van Ness, which really saved the rest of the city. . . . The soldiers had adopted the plan of dynamiting every house that caught fire and the houses around it. . . .

No words could describe what we saw from that hill. Flames as far as eye could reach, on three sides a roaring inferno of fire. Where the fire was almost burned out, the squares and houses were outlined by creeping things. The sky was a horrid glare around; round us on the grass were the refugees, mostly asleep, within a square of the flames, trusting to the soldiers to tell them to move on. . . .

". . . a roaring inferno of fire . . ."



Map showing three-day progression of the fire that followed the earthquake. The map is modified from the first edition of William Bronson's book, "The Earth Shook...The Sky Burned" (1959).[1] Attempts made by this publication's editors failed to find the original source of the map. However, the editors believe the information within the map was derived from the text of a 1908 Master's thesis by Lawrence Kennedy describing the progress of the fire.[2]

". . . San Francisco's heroism . . ."

We are under martial law, and we have a vigilance committee. Sentries are posted on every corner, and it is comforting in the night to hear them call, "Twelve o'clock and all is well." . . .

We still have no water, except from a few isolated hydrants, from which it is carried. We are allowed to use it for drinking and cooking only. All cooking is done in the streets, on stoves or improvised brick ovens [*pictured at right*]. . . .

The Federal troops are guarding the ruins, the vaults, the post-office, and the mint. Any man caught stealing is shot down at once, or if he disobeys a soldier's first command. Any one can leave San Francisco, but no one can come back, except with a government or Red Cross pass.

We stand in line to get food at the distributing station. The contents of the few grocery stores were seized at once by the troops, nothing can be bought in San Francisco. We have been living for the most part on what was brought from our house . . . I believe there is no scarcity of food at the distributing stations; the only difficulty is transporting it from the receiving stations over such great distances, and distributing it to such vast multitudes.

Yesterday I walked down through the nearest camp. It covers about half a mile and is a comparatively small one. It is about a mile away from here on the water front, and in full view from our hill. Thousands of tents have been sent and distributed [*pictured at right*]. The parks, the cemeteries and the Presidio, are full of campers, but they are too far for me to go. The cemetery vaults have been broken up, and people are sleeping in them. The city records have been stored in the vaults of the crematory, with soldiers guarding them.

The people in these low, shelter tents are cheerful and uncomplaining. It is wonderful, wonderful. Forty babies were born in the Park in one night. One case was triplets. Many emergency Hospitals have been started, in barns, churches, etc. I spend much of my time at the headquarters of the Red Cross and the Doctors' Daughters. Jim [*Eleanor's husband*] is busy all day with Red Cross work. It is all charity. No Doctor charges anything these days. . . .

The death rate will never be known, but it is guessed at 2,000. This is comparatively small, when there are 300,000 homeless. If the earthquake had happened two or three hours later, there would have been thousands of deaths in the business buildings and on the streets. . . .

Not less wonderful than San Francisco's heroism has been the quick generosity of the country and other countries. I believe the relief fund has reached ten million dollars. This will not last long, feeding three hundred thousand at thirty cents a day, and they must all begin again. Many trains of supplies have come in; if any one has starved, it must surely have been his own fault. Doctors and nurses have come by the train load. Perhaps God sent it to show how good the world is after all—or to develop its goodness. . . .

The people are wonderful, wonderful. San Francisco is going to rebuild and quickly. Nothing is left except a small residence section on Pacific Heights, a miserable little second-class business street (Fillmore St.), and small residences in the outlying districts. . . .

The slight earthquakes continue—two last night, and quite a severe shake at noon. They say it is the settling of the earth after the main upheaval. . . .

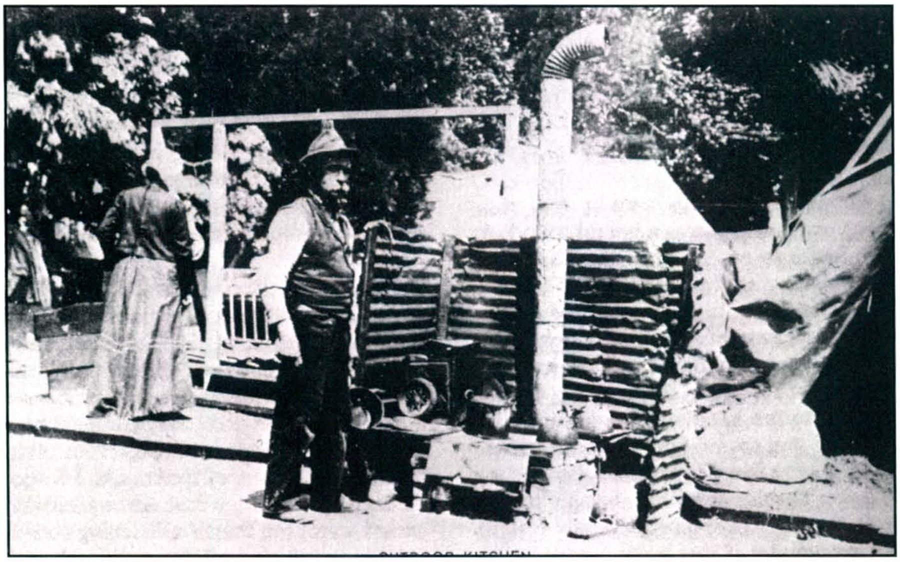
No one can know yet what is ahead of us. Our dear love and thanks go to you all. We can hardly think of anything except the present situation and not much about our own troubles. This is an unprecedented situation, and there are no rules to go by. Each day has new developments, and no day is like the last.

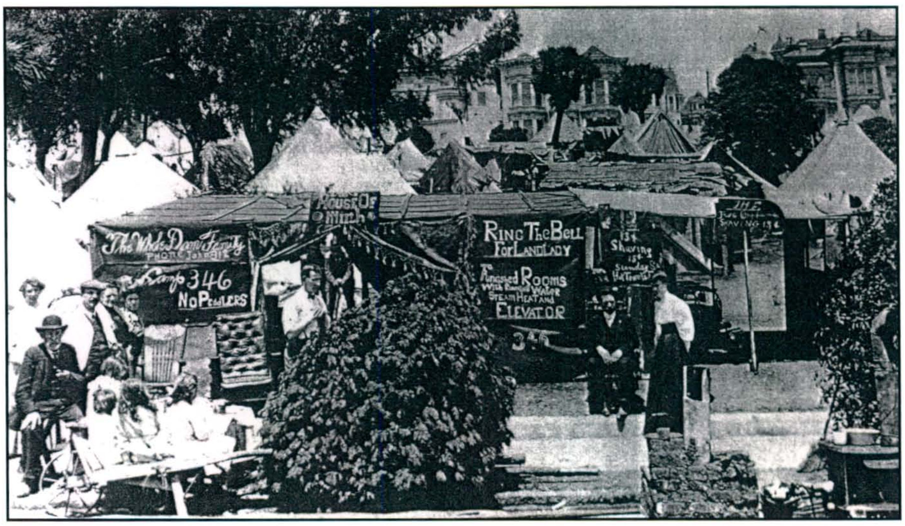
Lovingly,

[*signed*]

Eleanor.

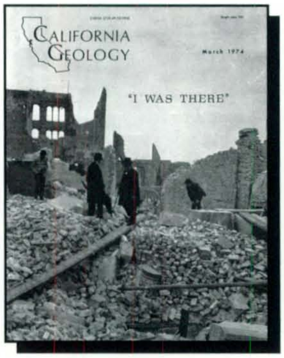
"The people are wonderful, wonderful. . . ."





These three photos, described or referenced in the accompanying article, show life in San Francisco after the earthquake. *Photos from the California Geological Survey archives.*

~ Impressions from Berkeley ~



The following excerpts are from an article published in the March 1974 issue of CALIFORNIA GEOLOGY magazine, p. 57-63. Simply, but effectively, titled, "I Was There," the article gives an account of an engineer, Mr. Stuart H. Ingram, who was a student and cadet at the University of California at Berkeley at the time the 1906 earthquake struck. Not only does Mr. Ingram discuss his experience in Berkeley during and after the earthquake, but he recounts his impressions of the city of San Francisco as part of the first peace-keeping force dispatched to the city. Despite the fact that the events in the article were written much later in his life, Mr. Ingram is able to relate the episode as if it had happened only days before. . . . editors, 2006

". . . absolute consternation . . ."

One's first earthquake is the worst, and my first was the one that hit San Francisco 18 April 1906, close after five o'clock A.M. . . . To most people the first shock brings a feeling of absolute consternation with the ground rolling and jolting, and apparently about to dissolve beneath you. Your brain freezes and your legs melt, but within seconds a measure of conscious thought returns, and usually before the movement ceases you regain control of your body. . . .

On that 18 April I was a sophomore at the University of California in Berkeley. . . . [*After the earthquake, my room*] was O.K., and I lost the feeling of being in danger. By then I heard the noise of my fraternity brothers "getting the H out", so I threw on some clothes and joined them. The street was full of fraternity men and sorority sisters. The latter seemed to have gotten out as fast as the men but in no time they realized the informality of their attire and started getting back indoors as fast as they came out. In those days the girls were truly modest. . . . There was really very little [*damage*], for Berkeley was almost entirely two-story frame dwellings with give enough to withstand the shaking. Chimneys were nearly all thrown down, but the campus buildings seemed undamaged. . . .

After breakfast it was soon apparent that everyone was shaken completely out of orbit. The University announced that no classes would be held for that day. Later, news began to come in that San Francisco had been hard hit with buildings down, fires all over town, streets cracked up and filled with rubble, and no streetcars running. Many Berkeley commuters did not go to work, leaving people walking the streets, talking and worrying over San Francisco's sad plight. About noon the University announced that college work for the rest of the term was abandoned, all students graduated or promoted without the usual examinations. With the announcement the whole town took on a kind of holiday air of gaiety. As news continued to get worse the air of gaiety faded. San Francisco was hard hit, more fires started, and uneasiness began to arise that total demoralization was close and the danger of riots would require National Guard troops.

Example of the destruction caused by the earthquake and resulting fire. *Photo is from the California Geological Survey archives and was used on the back page of the March 1974 edition of* CALIFORNIA GEOLOGY *magazine, from which this article originated.*

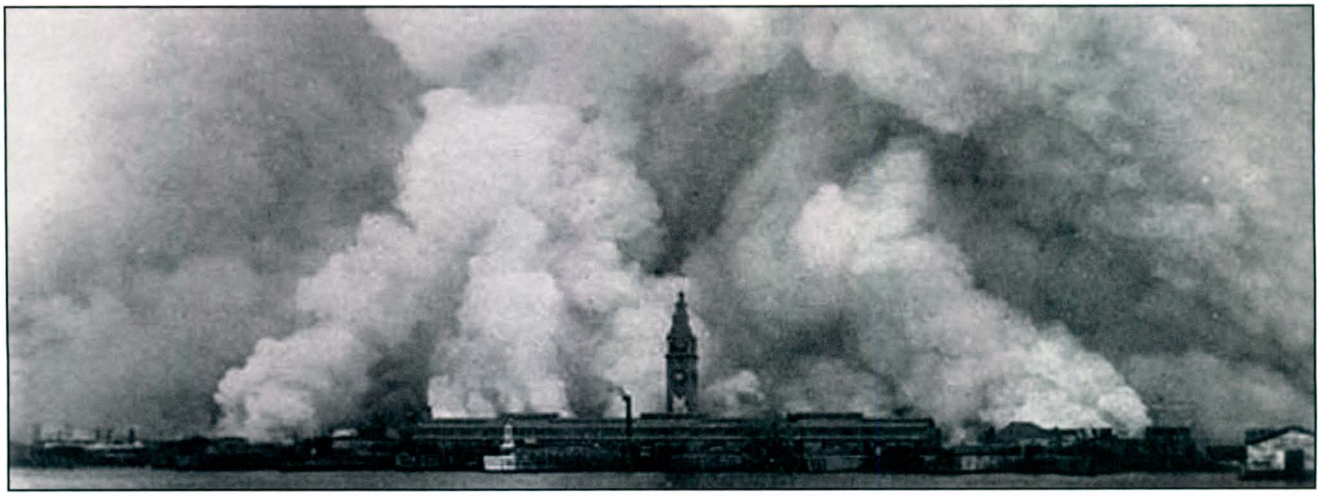
"We became soldiers. . . ."

The University had a cadet corps of about 500 Freshmen and Sophomores, and we heard that we might be sent in as a stop gap until the National Guard could be mobilized. That rumor grew and was confirmed late in the afternoon by orders for the cadets to report to Harmon Gym after dinner in uniform with a blanket and lunch. It was about 7pm before we were assembled with rifles and bayonets, to which were added five rounds of ammunition. So we became soldiers. The normal transportation of train and ferry took us across the bay, but when we passed through the Ferry Building we seemed truly at the front. The pavement of Market Street was broken up, rubble from quake- and fire-destroyed buildings, coupled with fire hoses everywhere made the streets impassable. There were of course no streetcars.

We were marched north, close to the waterfront to the vicinity of Telegraph Hill, then west along I don't know what street or streets to Divisadero St., then east to Ellis where we made our camp in the yard of a school. We had to march clear around the fire area, probably 4 miles, for it was 10 o'clock by the time we encamped. Half of us were immediately put on guard duty, and as I was one of them I was posted on a corner near our camp with orders "to keep order, and fire if necessary." . . .

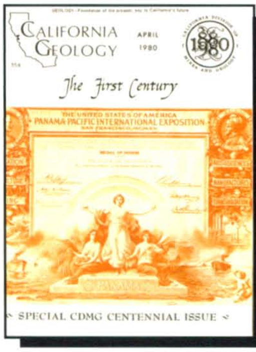
[*One*] example of high morale came from the proprietor of a small corner grocery. He hailed me and said that he thought the fire would reach his store, that it was impossible to remove his stock, and that if I would have a couple of my men keep it orderly he would like to throw his doors open and let the neighbors and neighboring campers come in and help themselves. He seemed to feel that all the neighbors were customers anyway, and that the refugee campers needed all the help they could get. I told him I appreciated his spirit, and I called in one man and the two of us ran his charity show. We let in 25 at a time, then cleared the store for another 25. There was no crowding, everything went off quietly, and the proprietor was thankful. He showed his appreciation by giving each of us a long slim loaf of French bread, a square of honey in the comb, and a half pint of whiskey. In my youthful idealism I thanked him for the bread and honey but refused the whiskey as an improper gift for a sentry doing his duty to accept. . . .

We were returned to Berkeley [*a couple of days later*], the National Guard or the army, or both, taking our places, to find the town a hive of activity. My fraternity house, and practically all the other houses were jammed with San Francisco relatives and friends: burned out refugees. Whole families were stacked in, one room per family, the football field was a large camp of small tents, complete with commissariat and round-the-clock guards. The beds in my house were doing double duty, one lot in the early evening, the second on the graveyard shift. . . . College was over for the year, and within a few days I left for my home in Los Angeles, taking with me a memory of a part of a week with people of a city who faced desolation and destitution, and faced the problems of rebuilding cheerfully, in a spirit of mutual helpfulness. . . . I say destitution, for all one afternoon I watched an unending procession of people trying to save a pitiful amount of small necessities, and going —where? Any place they could lay their heads. . . .



View (facing west) of the San Francisco fire from the San Francisco Bay with the Ferry Building in the foreground. The author landed at the Ferry Building when he crossed the bay, entering the city as a member of the cadet corps from Berkeley. *Photo courtesy of the Museum of the City of San Francisco.*

~ Observations from Palo Alto ~ (Stanford University)



The following excerpts are from an article written by Dr. Olaf P. Jenkins in the April 1980 edition of CALIFORNIA GEOLOGY *magazine, p. 84-87. At the time of the "Great Earthquake," Dr. Jenkins was a high school student in the city of Palo Alto. Even at an early age, Dr. Jenkins knew he wanted to become a geologist and, as evidenced by his curiosity and exploration to the area of earthquake fault rupture, he was destined for great things in the field. He went on to become the Chief and State Geologist of the California Division of Mines (now known as the California Geological Survey) from 1928 to 1958. Photos on pages 16 and 17 are from the California Geological Survey archives and were used in the original* CALIFORNIA GEOLOGY *magazine article. . . .* editors, 2006

"The dome of the Chapel . . . was gone! . . ."

[*After the earthquake*] I jumped up to look out my little window on the third floor of our home on the Stanford University campus. The view was of the beautiful sandstone buildings of Stanford University; but now there was a great cloud of dust rising. Only when the dust started to settle could I make out that not all was there. The 100-foot stone Chimney was gone! . . .

And the dome of the Chapel [*pictured below*], Mrs. Stanford's joy and pride, was gone too! . . .

[*Our*] house seemed to be in good shape—how could it, after having gone through such a shake?

After breakfast we decided to try living out on the lawn under the trees for awhile, at least during the day, to avoid the effects of aftershocks. We ate out there, where we could meet and talk to others and learn what all had happened. We could hear rumbling from far-off San Francisco—blasting of buildings to clear them in front of the great fire which was reported to be sweeping over the City, uncontrolled because of complete lack of water. . . .

Near at hand we found out that when Stanford's great Chimney fell, the guard ran out and it fell on him and killed him. If he had stayed where he was, sitting in a chair at the foot of the Chimney taking care of the furnace, he would have been safe, for the chair still remained untouched. The Chimney fell across a long arcade which went down like a row of nine pins. The Chapel back of it suffered not only the collapsed dome, but the fine mosaic across its front was jerked off and now lay in slabs on the sidewalk below.

Most of the recent buildings were damaged more than the older ones. The great top-heavy arch facing the front of the University was split, but not hurled down as one would have expected; the keystones on many of the smaller arches were dropped slightly. Encino Hall, the boys' dormitory, had one particularly bad spot: a section of a room on the top story dropped straight down, carrying the rooms below with it.

Near the University buildings a bookstore which was made of brick collapsed. It was said that the mortar did not contain sufficient cement and the bricks had not been properly wetted before being set up. There was plenty of criticism of materials and workmanship everywhere we went, but the shake was more severe than most people realized. . . .

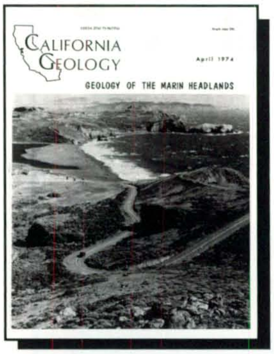
". . . exploration along the great fault . . ."

[*In Portola Valley*] the ground in places was all churned up [*as in the photo to the right*]. We came across a great oak that had been split in two; the upper branches were still intact, but the lower trunk and roots had been pulled apart, the west half going north while the east half was pulled south. We were on the great Portola fault (now known as the San Andreas fault). A little way farther on there was a country store or house where the front porch had been carried north, separating it from the rest of the house, for the fault crack ran between them.

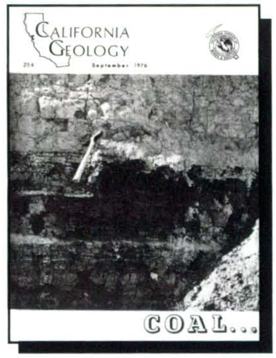
I was already quite familiar with all this country, especially Alpine Road where it climbed Black Mountain, for it went to some of my favorite camping places. A few days before the earthquake I was on this mountain road with some other boys to examine the road damage caused by the recent heavy rains. We now found that landslides had torn out the road. I can remember where the slides exposed some small coal seams and clay beds on which they had moved. Later, we read in the newspaper that the earthquake had caused the slides and that cattle had been trapped in a valley because landslides closed off the front of the steep sided valley. No doubt the earthquake helped the slides along, but the heavy rains had started them.

Continuing our journey of exploration along the great fault, we saw most of the examples of earthquake disturbance that were to be photographed and published many times over in various books.

Near Searsville Lake the road was torn up as if a giant plow had been down the middle of it. Displaced fences were quite common [*pictured above*]. One particularly impressive thing we saw was where the huge water main, leading from Crystal Springs Reservoir to San Francisco and built right along the fault line, had been torn apart in places [*such as in the picture shown to the left*]. Where it crossed the fault from east to west this strong pipe was jerked and pulled apart several feet; but [*in other places*] it had been rudely telescoped several feet. The force that it took to do that destruction simply amazed us. It was certain that anything in line of the moving fault had to give and that feature many people found hard to believe. Very few people at that time had given a single thought to earthquakes, and even now it takes a lot of explaining to get the fact across. . . .



~ The Earthquake Trail ~ at Point Reyes National Seashore

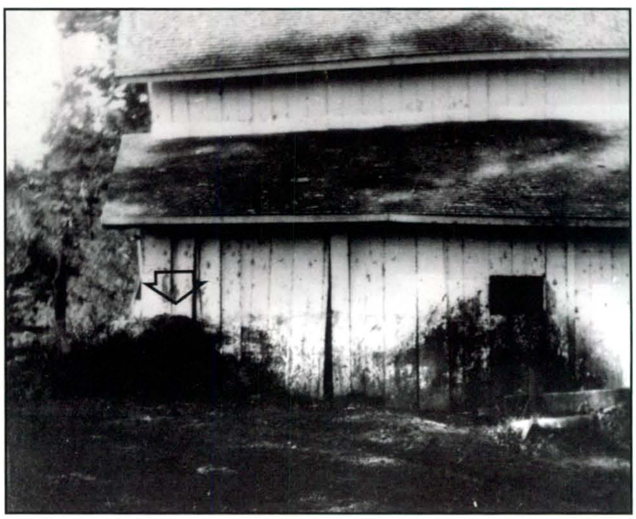


As the reader can gather from Olaf Jenkins' observations in the previous article, the surface rupture along the San Andreas fault from the 1906 earthquake was quite significant in the Portola Valley area, offsetting roads, fences, pipelines, and even tree trunks. However, the maximum displacement from the earthquake occurred 30 miles north of San Francisco, in the area now designated Point Reyes National Seashore. The San Andreas fault ruptured approximately 20 feet laterally in this area.

To capture this geologically significant event for future generations, the National Seashore created an "earthquake trail" along which visitors can follow the location of the surface rupture from the San Andreas fault where it sliced through the area in 1906. The following excerpt and some of the images are from two CALIFORNIA GEOLOGY articles (April 1974, p. 87-89, and September 1976, p. 206-207) describing the hard work by volunteers from Foothill College, Los Altos Hills, Santa Clara County in refurbishing this interpretive trail. . . . editors, 2006

Surface fault rupture from the 1906 earthquake through the Skinner Ranch, Marin County. *Photo by G.K. Gilbert.*

The Point Reyes Peninsula has been called an "Island in Time." Geologically speaking the park is an "island" of granite bedrock that has slid into its present position from southern California along the San Andreas fault. This great fault system marks the boundary between two great plates of the earth's crust which have been grinding slowly past each other for millions of years. Friction along the plate boundaries causes the plates to move with a series of destructive "jerks" or jumps which generate earthquakes like the 1906 episode. Since the plates continue to move and build up the energy stored along the fault, Bay Area residents can expect more major shakes in their future. This earthquake trail is dedicated to helping Bay Area residents better understand their physical environment so that they can minimize the geologic hazards posed by it.



Offset deposits provide evidence for plate movement. All but the southeast corner of the Skinner barn, pictured here, was situated on the Pacific Plate side of the San Andreas fault. When the crust moved, the barn remained intact but the southeast corner was shifted 15 feet off its foundation. Notice the dark conical stain on the barn wall beneath the window. The deposit of "biogenic colluvium" (manure) indicated by the arrow is now 15 feet from its point (or window) of origin. *Photo from J.C. Branner collection, courtesy of Stanford University.*

These two photographs were taken in nearly the same location, but 100 years apart. The 1906 photo (from the J.C. Branner collection, Stanford University) shows the surface fault rupture from the "Great Earthquake" as it cuts through the edge of the Skinner barn to the right. The 2006 photograph (taken by Rick Wilson, California Geological Survey) shows the trace of the old surface rupture marked by the blue posts and the three children. Note in the 2006 picture that, other than the markers, there is no surface evidence of the fault rupture. It has disappeared (likely eroded) over the past 100 years, demonstrating the difficulty geologists face in locating active faults.

The Point Reyes National Seashore website: http://www.nps.gov/pore/home.htm

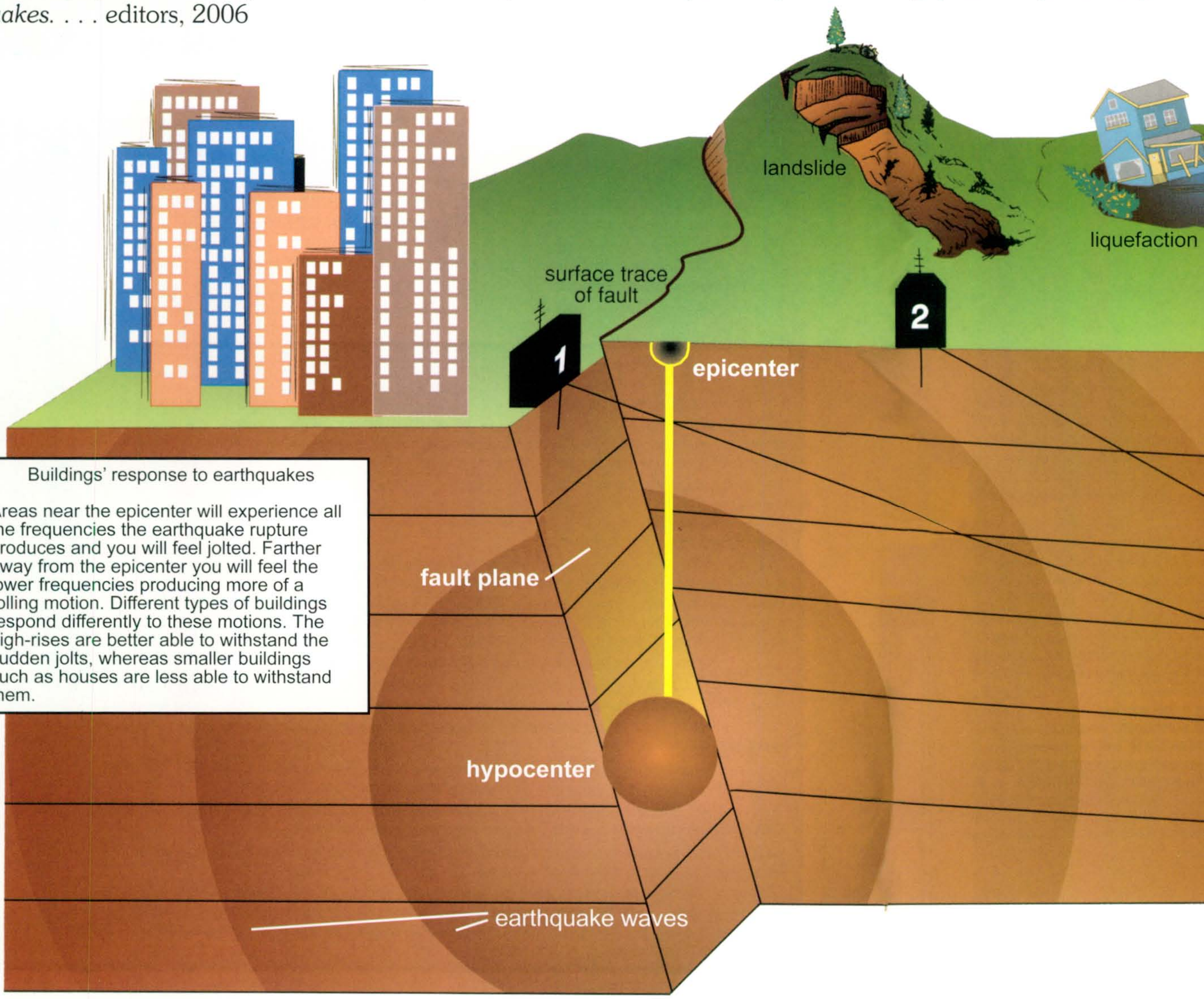
EARTHQUAKE BASICS

INTRODUCTION

Since the devastating 1906 earthquake, our understanding of and ability to deal with earthquakes and their associated hazards have greatly increased. Today, we better understand the sources for earthquakes through advancements in geologic mapping and seismology, and, with a greater historical record and new technologies, we have developed long-term probabilities of when and where earthquakes might strike. We can now identify where ground effects like intense shaking and surface displacement could damage buildings and infrastructure. We might not be able to predict exactly when earthquakes will strike but we can help the public prepare for them by providing information about seismic hazards.

CALIFORNIA GEOLOGICAL SURVEY *staff believe that everyone living in California should have a basic understanding of earthquakes—their causes and their effects. On the following pages, we present some basic earthquake information that examines the impact of earthquakes. We provide: (1) an illustrated "Anatomy of an Earthquake," (2) an index of earthquake-related terms, (3) a discussion about the different types of faults, (4) definitions of earthquake magnitude and intensity, (5) information on earthquake hazards, and (6) a simplified description of the plate tectonic setting of northern California.*

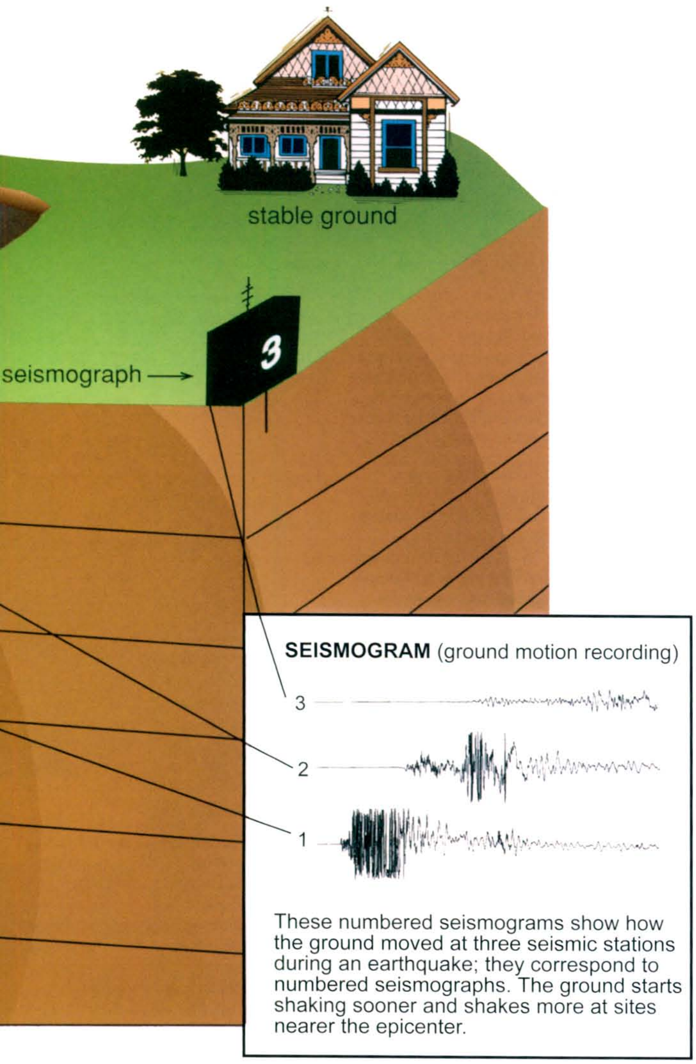
Hopefully these pages will be useful to the reader, serving as a valuable reference for answering questions pertaining to earthquakes. . . . editors, 2006



EARTHQUAKE BASICS

ANATOMY OF AN EARTHQUAKE

The figure below, "Anatomy of an Earthquake," was published in the March/April 1998 issue of CALIFORNIA GEOLOGY. *It diagrams the impact of earthquakes at the earth's surface, specifically on structures, seismograms, and hazards. The information for the original article was compiled from the following sources:* "Prepare for the Quake" by the Governor's Office of Emergency Services; "Earthquakes" *by the U.S. Geological Survey; and* "Putting Down Roots in Earthquake Country" *by the Southern California Earthquake Center.*[1]
. . . editors, 2006



These numbered seismograms show how the ground moved at three seismic stations during an earthquake; they correspond to numbered seismographs. The ground starts shaking sooner and shakes more at sites nearer the epicenter.

EARTHQUAKE TERMS

The following earthquake-related terms appear in this special publication. The page numbers to the right are where these terms are best defined or best diagrammed in this document. The words are in **bold** type on those pages so that the reader can find them easily:

KNOW YOUR FAULTS

Much of the information below is from the January/February 1992 (pages 18-19) and July/August 2000 (pages 20-23) issues of CALIFORNIA GEOLOGY. *Similar descriptions are on the California Geological Survey's web site: http://www.consrv.ca.gov/cgs/information/publications/teacher_features/faults.htm. . . .* editors, 2006

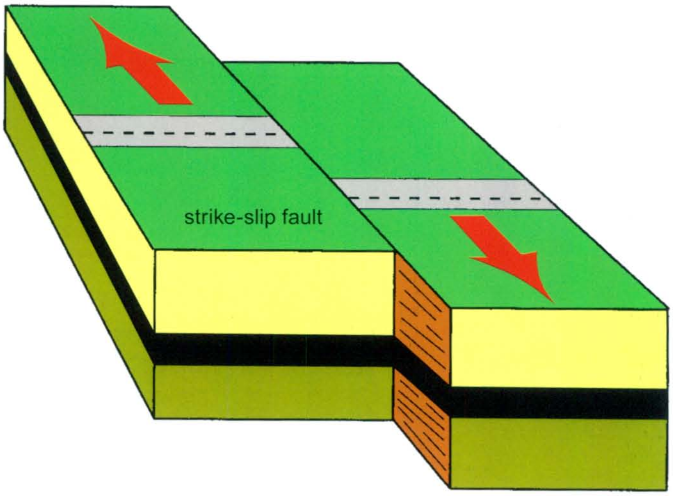
A **fault** is simply a fracture in the ground along which there is movement. Some faults are actually composed of several fractures called **fault branches**. Collectively, the branches form a **fault zone**. For example, the San Andreas fault zone is composed of many individual fault branches that, together, extend 600 miles through California. Separate but tectonically associated faults and fault zones are called a **fault system**. In the Bay Area, the San Andreas fault zone, along with the Calaveras, Hayward, Rodgers Creek, and other associated faults, are commonly referred to as the San Andreas fault system (see the fault map of California on page 31).

California's highly varied landscape and complex geology are in large part attributed to faulting. In fact, most scenic valleys, mountain ranges, and desert basins of the state were formed through repeated rupture of thousands of faults over millions of years. Faults also create underground traps in which reservoirs of petroleum form and spaces in which underground waters deposit various mineral ores, like the gold-bearing quartz veins of the Mother Lode Belt. These famous veins, whose valuable contents led to the 1849 gold rush and statehood soon thereafter, formed along ancient faults that together extended the length of the Sierra Nevada foothills (see map on page 31 and articles on pages 50-55).

Faults and fault zones are classified by how rocks on each side of the fault or fault zone move past each other. There are two main types of movement along faults, a sideways movement called strike slip, and an up or down movement called dip slip. Faults are distinguished by abrupt changes in rock structure or composition. Some good places to see dip-slip faults are road cuts, quarries, and sea cliffs, where features such as a rock layers or veins have been displaced. Strike-slip faults are more commonly apparent on the ground surface, where faults can be recognized by the displacement of linear features such as roads and fences (see the photos on pages 17 and 60).

Strike-Slip Faults

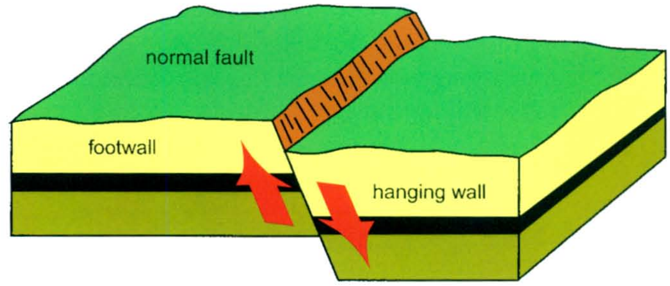
The movement along a **strike-slip fault** is principally parallel to the strike of the fault, meaning the rocks move past each other horizontally (laterally). The San Andreas is a strike-slip fault that has displaced rocks hundreds of miles over millions of years. As a result of this horizontal movement along the fault, rocks of vastly different age and composition have been placed side by side (juxtaposed). Strike-slip movement may occur along any of the many fault branches in the San Andreas fault zone.



KNOW YOUR FAULTS

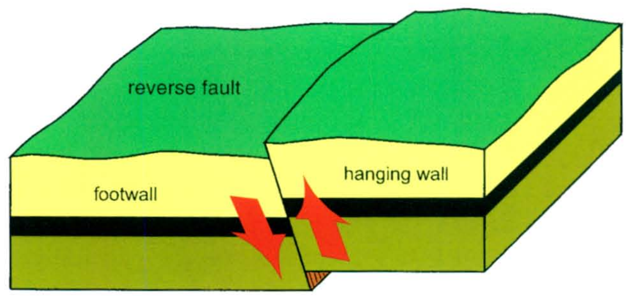
Dip-Slip Faults

On a **dip-slip fault**, movement is mainly up or down the dip of the fault plane. **Normal faults** are dip-slip faults on which the **hanging wall** (the rocks above the fault plane) moves down relative to the **footwall** (the rocks below the fault plane). **Normal faults** are the result of extension (forces that pull rocks apart). A steeply dipping normal fault is called a high-angle normal fault, examples of which are along the east side of the Sierra Nevada.



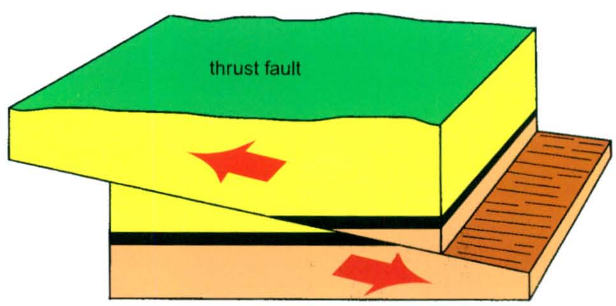
Reverse Faults

Reverse faults are dip-slip faults in which the hanging wall moves up relative to the footwall. Reverse faults are the result of compression (forces that push rocks together). The Point Reyes fault is an example of a reverse fault (see map on p. 31).



Thrust Faults

A **thrust fault** is a reverse fault with a gently dipping fault plane. There are a number of thrust faults in the north coast region of California. The Cascadia subduction zone along the California, Oregon, and Washington coast is an example of an active thrust fault along which tectonic forces are pushing the Pacific plate under the North American plate.



EARTHQUAKES — ENERGY, MAGNITUDE, and INTENSITY

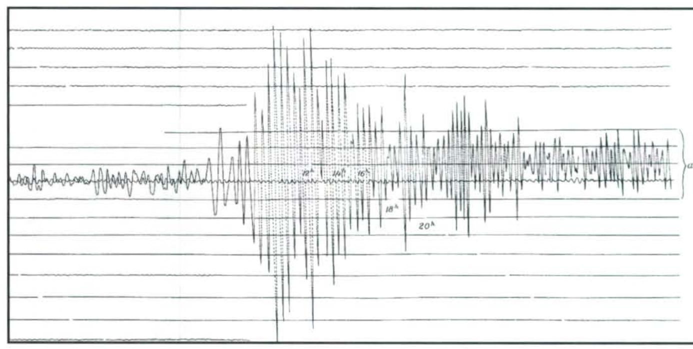
Faults rupture when accumulated stresses caused by plate tectonic processes exceed the ground's breaking point. When the faults rupture suddenly, shock waves radiate out as accumulated energy in a ground-shaking phenomenon commonly known as an **earthquake**. The amount of energy released during the rupture episode determines the strength of the earthquake. Generally, the more seismic energy released, the stronger the shock, and, thus, the larger the earthquake.

The impact of an earthquake on the earth's surface is called **intensity**. The **Modified Mercalli Intensity Scale**, expressed in Roman numerals or whole numbers from 1 to 12, reflects the effects of the earthquake on people, buildings, or other structures, and varies with location. Where shaking is too weak to be felt by most people, the intensity is designated I (1) or II (2). Where strong enough to bend railroad tracks, the intensity would be X (10) or higher. Accordingly, there can be many values of intensity for any one earthquake, as indicated on the map on page 49. For example, a large earthquake in a densely populated area would cause more damage than one of the same size in a remote area, where there would be nothing to damage. The amount of damage is also governed by the duration of the shaking, the type of soil or rock, and building materials and design. All of these factors normally vary from place to place.

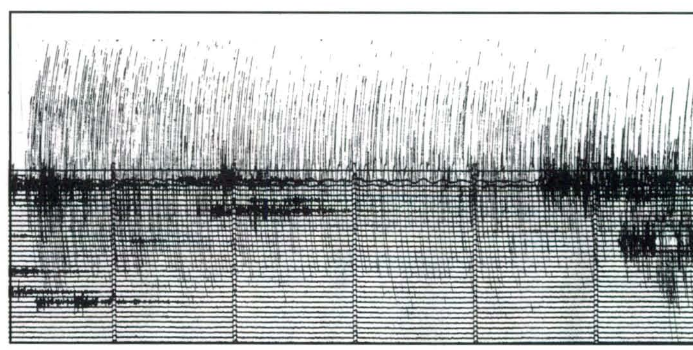
The strength of an earthquake is best described by **magnitude** (**M**), which is related to the amount of energy released during an earthquake. Magnitude is expressed in whole numbers and decimals. The magnitude for any one earthquake is the same at all points in the world. Note that a M 6.0 earthquake is not twice as large as a M 3.0. Each whole number increase in magnitude represents an increase of 31.62 times the amount of energy, but a two-unit increase represents 1,000 times the amount of energy released. So a M 7.0 earthquake releases about 32 times the energy as a M 6.0, but 1,000 times the energy as a M 5.0. The largest earthquake ever recorded was a M 9.5 event off the coast of Chile in 1960.

Seismologists have developed several magnitude scales. **Richter magnitude** ($\mathbf{M_L}$), which is derived from the measure of earthquake vibrations recorded on seismograms, has been in use since 1932. The subscript "L" (for "Local") is used because Richter magnitude measurements should be applied only to earthquakes within 400 miles of the recording seismographs. Magnitudes of earthquakes over 400 miles away can be measured as **surface wave** ($\mathbf{M_s}$) and **body wave** ($\mathbf{M_b}$) **magnitudes**.

Currently, the most common scale used for measuring moderate to large earthquakes is **moment magnitude** ($\mathbf{M_w}$), which is based on the area of rupture on the fault plane and the amount of displacement caused by an event. Because there were no standardized methods to measure earthquakes before 1932, modern seismologists use information gained from recent events to estimate magnitudes for earthquakes that occurred prior to that year.



A **seismograph** (the instrument that detects and measures earthquakes) in Potsdam, Germany, recorded this seismogram during the 1906 San Francisco earthquake.[2]



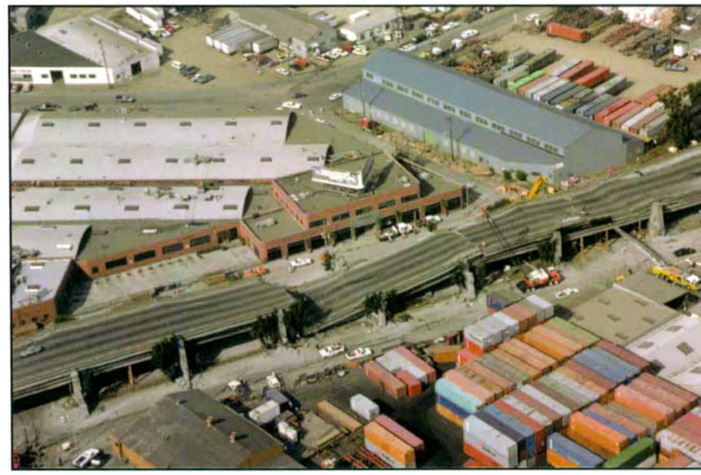
A California Geological Survey seismogram of the 1989 Loma Prieta earthquake, from a station located in Columbia, Tuolumne County, California.

For more information, visit the California Geological Survey's web site to read Note 32, *How Earthquakes and Their Effects are Measured* (http://www.consrv.ca.gov/CGS/information/publications/cgs_notes/index.htm).

EARTHQUAKE HAZARDS

Ground Shaking

As the Loma Prieta earthquake clearly demonstrated, **ground shaking** can damage or destroy buildings, bridges, and other structures, inflicting injury and death on the inhabitants of affected areas. Shaking also can trigger liquefaction and landslides that have similar devastating effects. **Ground motion** detectable by humans is commonly called **strong motion**, and characterizing ground motion as strong or weak is analogous to describing rain as heavy or light. The dampening effects, or **attenuation**, of earth materials reduce ground motion with increasing distance from the earthquake source and epicenter. Some soil, such as the soft mud underlying the Cypress freeway structure of Interstate Highway 880 in Oakland that collapsed during the 1989 Loma Prieta earthquake (pictured to the right), can actually **amplify**, or increase, the amount of strong shaking during an earthquake.

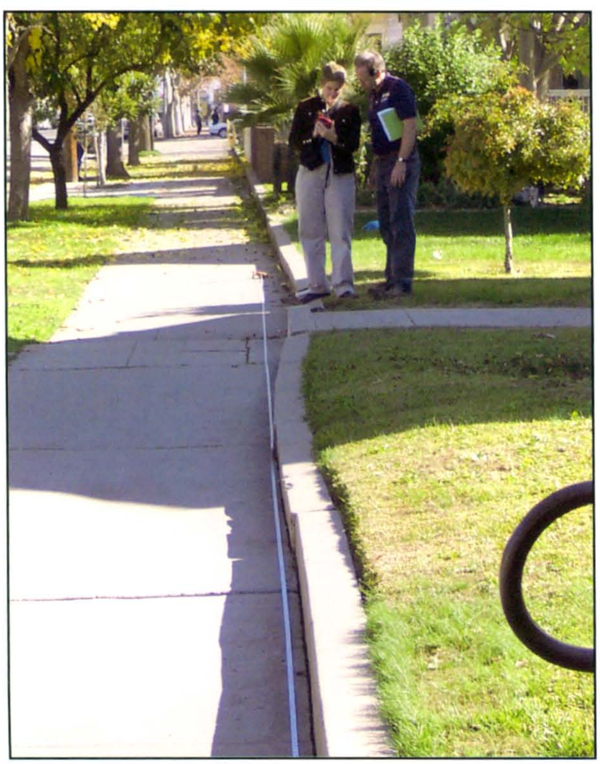


Aerial view of collapsed sections of the Cypress freeway structure of Freeway 880 in Oakland caused by the 1989 Loma Prieta earthquake. *Photo by H.G. Wilshire, U.S. Geological Survey.*[3]

Fault Rupture, Fault Creep

Surface rupture occurs when movement on a fault within the earth breaks through to the ground surface. Surface rupture associated with the 1906 San Francisco earthquake extended approximately 270 miles from the San Juan Bautista area to Cape Mendocino, with ground displacement measuring as much as 20 feet. However, not all earthquakes result in surface rupture. The Loma Prieta earthquake of 1989 caused major damage in the San Francisco Bay Area, but fault movement over a distance of 31 miles in the subsurface is not believed to have broken through to the surface.

Fault rupture commonly follows pre-existing faults, which are less resistant to tectonic-induced stresses than is the adjacent, competent bedrock. A fault may rupture suddenly to produce a "felt" earthquake, or slowly in the form of **fault creep** (movement without earthquakes). Examples of creep are well known in the Bay Area along the Calaveras and Hayward faults where they cut across densely urbanized land in Santa Clara, Contra Costa and Alameda counties (see page 31). Displaced and deformed curbs, streets, buildings, and other structures that straddle these faults are conspicuous along their respective traces as illustrated on the photo to the left.



The Calaveras fault is characterized by aseismic fault creep along its southern and central sections. The Calaveras fault in Hollister offsets the ground surface at a rate of about one-quarter inch per year in a right-lateral strike-slip sense. This view to the east shows a right-laterally offset sidewalk and curb caused by creep on the Calaveras fault. *Photo by J.C. Tinsley, U.S. Geological Survey.*

EARTHQUAKE HAZARDS

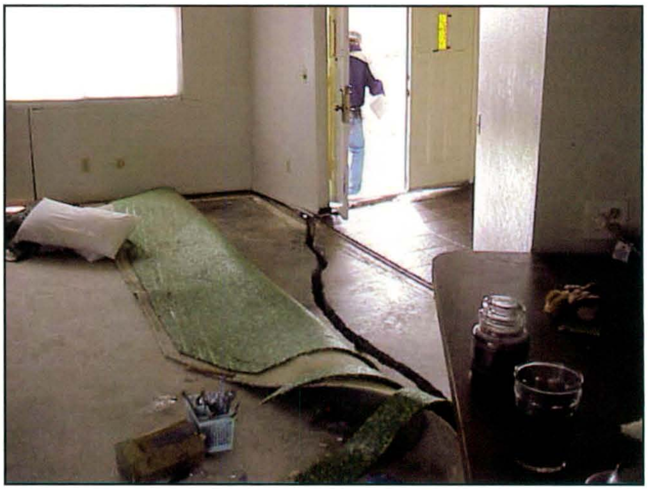
Liquefaction

Liquefaction refers to the loss of strength of saturated soils when subjected to strong ground motion. Soil particles in saturated ground can actually become buoyant as they shift and separate during shaking, which weakens the ability of a soil to support overlying structures. Liquefaction was responsible for some of the destruction of buildings in San Francisco's Marina District during the 1989 Loma Prieta earthquakes. In fact, widespread evidence of liquefaction was reported throughout the Bay Area following the 1989 Loma Prieta, 1906 San Francisco, and other historical earthquakes. To observe liquefaction on a small scale, put sand in a container (a small plastic tub works well) and saturate it with water. Place a heavy object on the surface and repeatedly strike the sides of the container until the object sinks or falls over.

Liquefaction from the 1989 Loma Prieta earthquake in recent deposits of the Pajaro River formed these sand volcanoes along fissures in this furrowed field near Pajaro and Watsonville. Furrows are about 4 feet apart. *Photo by J.C. Tinsley, U.S. Geological Survey.*[3]

A **sand blow** (also known as a sand volcano), in the median of Interstate Highway 80 west of the Bay Bridge toll plaza, measures 6.6 feet long. It erupted when ground shaking from the 1989 Loma Prieta earthquake transformed a loose water-saturated deposit of subsurface sand into a sand-water slurry (liquefaction). *Photo by J.C. Tinsley, U.S. Geological Survey.*[3]

The two pictures below show the exterior and interior of a house in Oceano, approximately 50 miles south of the epicenter of the magnitude 6.5 San Simeon earthquake (2003). The cracks in the home's exterior wall and concrete foundation were caused by liquefaction and **lateral spread** (movement of liquefied soil downhill or towards an open-faced slope). *Photos by Ralph Loyd, California Geological Survey.*



EARTHQUAKE HAZARDS

Landslides

A **landslide** is the downhill movement of ground caused primarily by gravity acting on weakened rock or soil. Slope material is weakened by weathering, erosion, and saturation; addition of weight in the form of snow, artificial fill, or construction; making cuts into or at the base of the slope; and vibrations produced by earthquakes, explosions, or even thunder.

Landslide-displaced trees, pictured at right, reflect slope failure triggered by the 1989 Loma Prieta earthquake. Coastal bluff, New Brighton Beach area, Santa Cruz County. *Photo by J.C. Tinsley, U.S. Geological Survey.*[3]

Aerial view of large slides caused by the 1989 Loma Prieta earthquake. North of Fort Funston in San Francisco. *Photo by S.D. Ellen, U.S. Geological Survey.*[3]

EARTHQUAKE HAZARDS

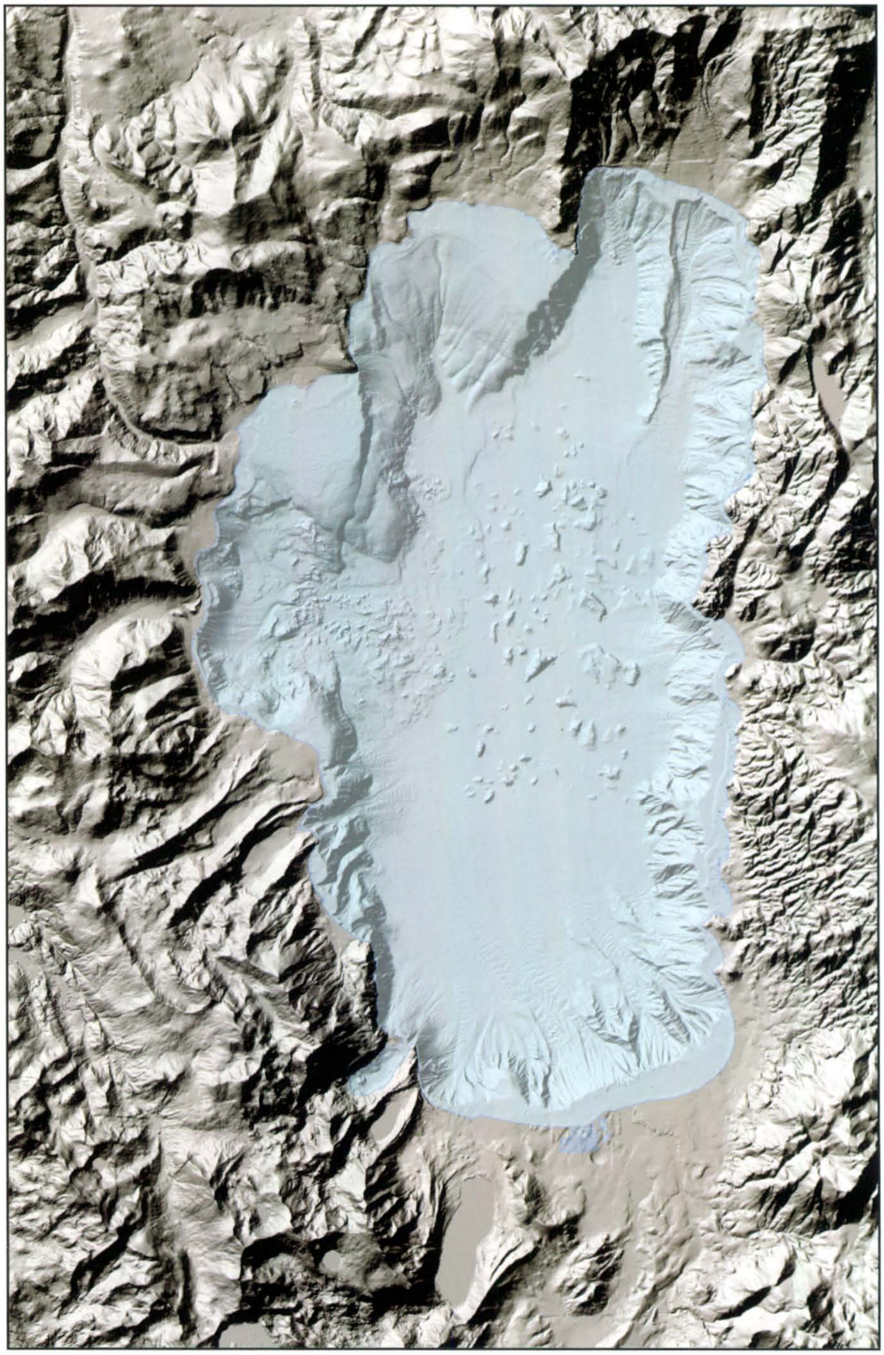
Tsunami and Seiches

A **tsunami** (the Japanese word for harbor wave, pronounced sue-nah'-me) is a wave generated by an earthquake, landslide, volcanic eruption, or even a large meteor. Such events can displace a large amount of water, which causes a rise or mounding at the water's surface that travels away from the source of the disturbance. These waves can move at a rate exceeding 500 miles per hour. However, as they approach shallow, offshore waters, the waves slow down, but grow in height.

In smaller, non-oceanic water bodies, like inland seas and lakes, tsunamis are most commonly caused by slope failure below the water surface or along the shoreline. Given its geomorphology, depth, and size, Lake Tahoe (map at right) is the inland water body in northern California that is most susceptible to a damaging tsunami.

The most devastating tsunami to affect California in recent history was generated by the 1964 magnitude 9.2 Alaskan earthquake. The first wave struck Crescent City about 4 hours after the Alaska event, but the fourth and largest wave arrived 2 hours later. Reaching about 16 feet above the tide, the tsunami flooded low-lying communities and river valleys, destroying homes and businesses, and killing 11 people.

A **seiche** (a Swiss-French word pronounced say-sh) is a wave that oscillates, or sloshes, in an enclosed or semi-enclosed body of water, such as a swimming pool, lake, or bay. In California, small-scale seiches are commonly observed in lakes, ponds, swimming pools, and bathtubs during earthquakes. However, a strong earthquake in northern California could trigger a large seiche in San Francisco Bay or Lake Tahoe with considerable damaging effects.

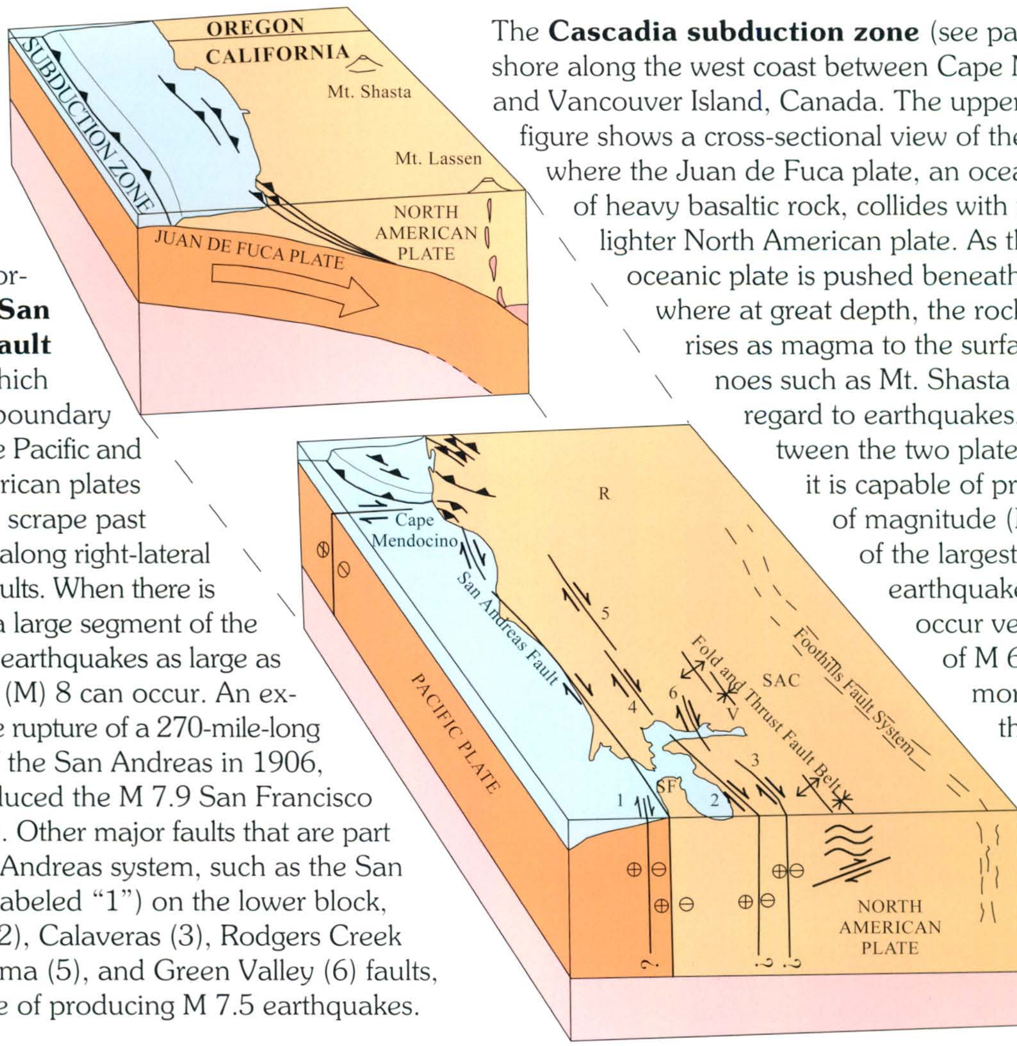


The shaded relief image above shows the bottom of Lake Tahoe and the surface expression of the surrounding area. The features at the center of the lake are likely blocks from a landslide that originated from the west (left), creating a large, underwater embayment where land used to be. A landslide like this would cause a large wave (tsunami) in the lake. The distance from east (right) to west across the figure is approximately 20 miles. *The source of the topographic and bathymetric relief is a U.S. Geological Survey digital elevation model (resolution unknown).*

PLATE TECTONIC SETTING OF NORTHERN CALIFORNIA

Many people might find it peculiar that the processes that have created California's world-famous landscapes—scenic cliff-lined seahores, fertile valleys, barren desert highlands, and forested mountains—are, in fact, the same processes that are responsible for the severe shaking, destructive ground failure, and devastating tsunamis generated by the state's nortorious earthquakes. For millions of years California has straddled the boundaries of colliding crustal plates along which the violent grinding of rock has been continuous.

Plate tectonics, the movement and interaction of crustal plates on the earth's surface, dictate the location, size, and frequency of earthquakes. In northern California, the two significant types of tectonic interactions are **convergence**, which takes place along the Cascadia subduction zone off the shores of Humboldt and Del Norte counties, and **transform movement**, which takes place along the San Andreas fault zone.



The lower block of the figure is a map and cross-sectional view of the northern portion of the **San Andreas fault system**, which marks the boundary between the Pacific and North American plates where they scrape past each other along right-lateral strike-slip faults. When there is rupture of a large segment of the main fault, earthquakes as large as magnitude (M) 8 can occur. An example is the rupture of a 270-mile-long segment of the San Andreas in 1906, which produced the M 7.9 San Francisco earthquake. Other major faults that are part of the San Andreas system, such as the San Gregorio (labeled "1") on the lower block, Hayward (2), Calaveras (3), Rodgers Creek (4), Maacama (5), and Green Valley (6) faults, are capable of producing M 7.5 earthquakes.

The **Cascadia subduction zone** (see page 31) extends offshore along the west coast between Cape Mendocino, California and Vancouver Island, Canada. The upper block of the adjacent figure shows a cross-sectional view of the subduction zone where the Juan de Fuca plate, an oceanic plate composed of heavy basaltic rock, collides with the much thicker and lighter North American plate. As the plates converge, the oceanic plate is pushed beneath the continental plate where at great depth, the rock eventually melts and rises as magma to the surface, forming volcanoes such as Mt. Shasta and Mt. Lassen. With regard to earthquakes, the sloping fault between the two plates is so long and deep, it is capable of producing earthquakes of magnitude (M) 9 or higher, some of the largest on earth. Although earthquakes of this size do not occur very often, smaller ones of M 6, 7, and 8 that occur more frequently along this zone can still cause considerable damage. Also, the compression caused by the collision of the plates has created other faults in the region capable of significant earthquakes.

The San Andreas fault zone, being a major plate boundary, has wide-reaching influence on other, far removed faults in northern California. Some studies indicate that plate motions along this boundary may have contributed to the development of the fold-thrust fault belt in the western part of the Central Valley of California, and reactivation of some of the faults of the western Sierra Nevada foothills. Each of these seismic sources can produce earthquakes in the magnitude range of 5 to 6.

Simplified block diagrams of the plate tectonic setting of northern California. SF=San Francisco, SAC=Sacramento, V=Vacaville, and R=Redding. The plus (+) and minus (-) signs in the block diagrams represent the relative movement of each side along the fault (a plus indicates that the side is moving into the diagram; a minus indicates that the side is moving out, toward the viewer).[4,5,6]

Significant Historical Earthquakes

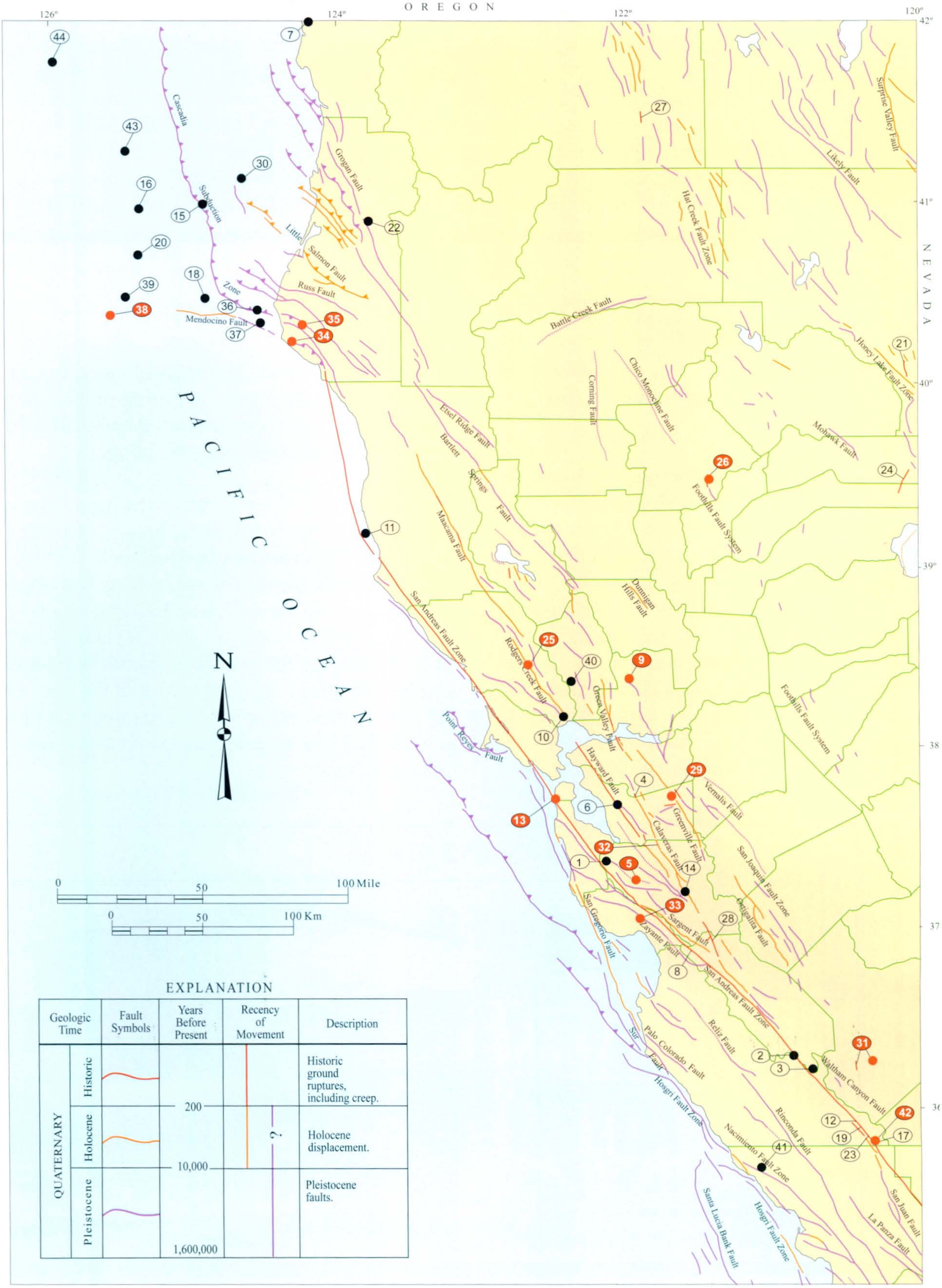
Map Number	Year	Earthquake Name/Location	Source Fault	Moment Magnitude	Approximate Length of Surface Rupture (miles)
1	1838	*unnamed event*	San Andreas	~ 7.4	36
2	1853	Lonoak	San Andreas	~ 6.0	*
3	1857	Fort Tejon	San Andreas	7.9	200
4	1861	Dublin	Calaveras	5.8	*
5	1865	Santa Cruz Mountains	?	6.5	*
6	1868	*unnamed event*	Hayward	7.0	30
7	1873	Crescent City	?	6.9	*
8	1890	San Juan Bautista	San Andreas	6.3	*
9	1892	Vacaville, Winters, Allendale	?	6.6	*
10	1898	Mare Island	Rodgers Creek	6.4	*
11	1898	Mendocino *(offshore)*	San Andreas	~ 6.7	*
12	1901	Parkfield	San Andreas	6.4	"several"
13	1906	San Francisco	San Andreas	7.9	270
14	1911	Morgan Hill	Calaveras	6.4	*
15	1918	Eureka *(offshore)*	?	6.5	*
16	1922	Eureka *(offshore)*	?	7.3	*
17	1922	Cholame	San Andreas	6.3	0.25
18	1923	Cape Mendocino *(offshore)*	?	7.2	*
19	1934	Parkfield	San Andreas	6.0	*
20	1941	Cape Mendocino *(offshore)*	?	6.6	*
21	1950	*unnamed event*	Fort Sage	5.6	5.5
22	1954	east of Arcadia	?	6.6	*
23	1966	Parkfield	San Andreas	5.6	23
24	1966	Truckee	?	6.0	10
25	1969	Santa Rosa	Rodgers Creek	5.7	*
26	1975	Oroville	Cleveland Hills	6.1	3.4
27	1978	Stephens Pass	?	4.6	1.2
28	1979	Coyote Lake	Calaveras	5.7	23
29	1980	Livermore Valley	Greenville	5.6	3.9
30	1980	Trinidad *(offshore)*	?	7.4	*
31	1983	Coalinga	Nunez	6.5	*
32	1984	Morgan Hill	Calaveras	6.2	0.7
33	1989	Loma Prieta	San Andreas	6.9	0.6
34	1991	Honeydew	*unnamed*	6.0	*
35	1992	Petrolia / Cape Mendocino	Cascadia	7.1	*
36	1992	Cape Mendocino *(offshore)*	?	6.5	*
37	1992	Cape Mendocino *(offshore)*	?	6.7	*
38	1994	Mendocino Fault *(offshore)*	Mendocino	7.1	*
39	1995	Cape Mendocino *(offshore)*	?	6.8	*
40	2000	Yountville (Napa Valley)	?	5.2	*
41	2003	San Simeon	?	6.5	*
42	2004	Parkfield	San Andreas	6.0	25
43	2005	Gorda Plate *(offshore)*	?	7.2	*
44	2005	*unnamed event (offshore)*	?	6.7	*

*** Surface rupture either not observed or not documented.**

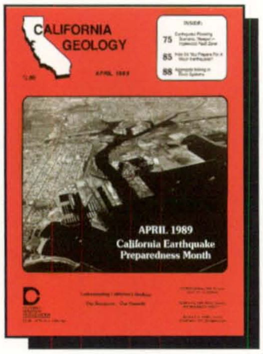
Note: Earthquakes featured in articles of this publication are displayed in red. Also, moment magnitudes listed above, which may differ from those of the same earthquakes presented in articles of this issue, are at present time the generally accepted magnitudes among seismologists.

Table and map modified from California Geological Survey Map Sheet 54, 1999.

and Faults Active in Quaternary Time



Map and table are modified from California Geological Survey Map Sheet 54.
Note: Earthquakes epicenters on the map are linked to table on facing page by location number.



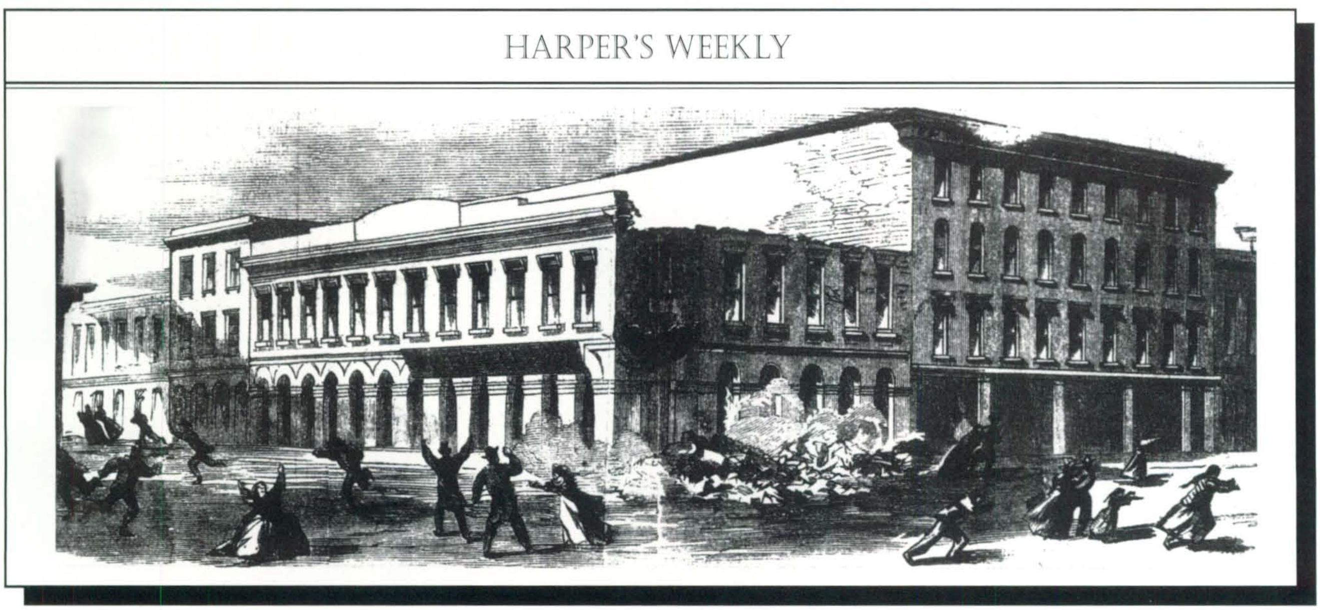
The following article, from HARPER'S WEEKLY (November 18, 1865), was submitted by D.D. and Pat Trent of Claremont, California for publication in the April 1989 issue of CALIFORNIA GEOLOGY (p. 87). The news item reports on what was considered "the great San Francisco earthquake" of October 8, 1865. The magnitude (M) 6.5 shock is thought to have been generated on the San Andreas fault in Santa Cruz County but caused considerable damage in the San Francisco Bay Area, as depicted in the sketches in HARPER'S WEEKLY. The photographs on the opposite page are from the 1868 (M 7.0) San Francisco earthquake. Other large pre-1906 events in the San Francisco Bay Area struck in 1836 (near San Juan Bautista; M~6.4) and 1838 (M~7.4). . . . editors, 2006

1865 EARTHQUAKE IN SAN FRANCISCO

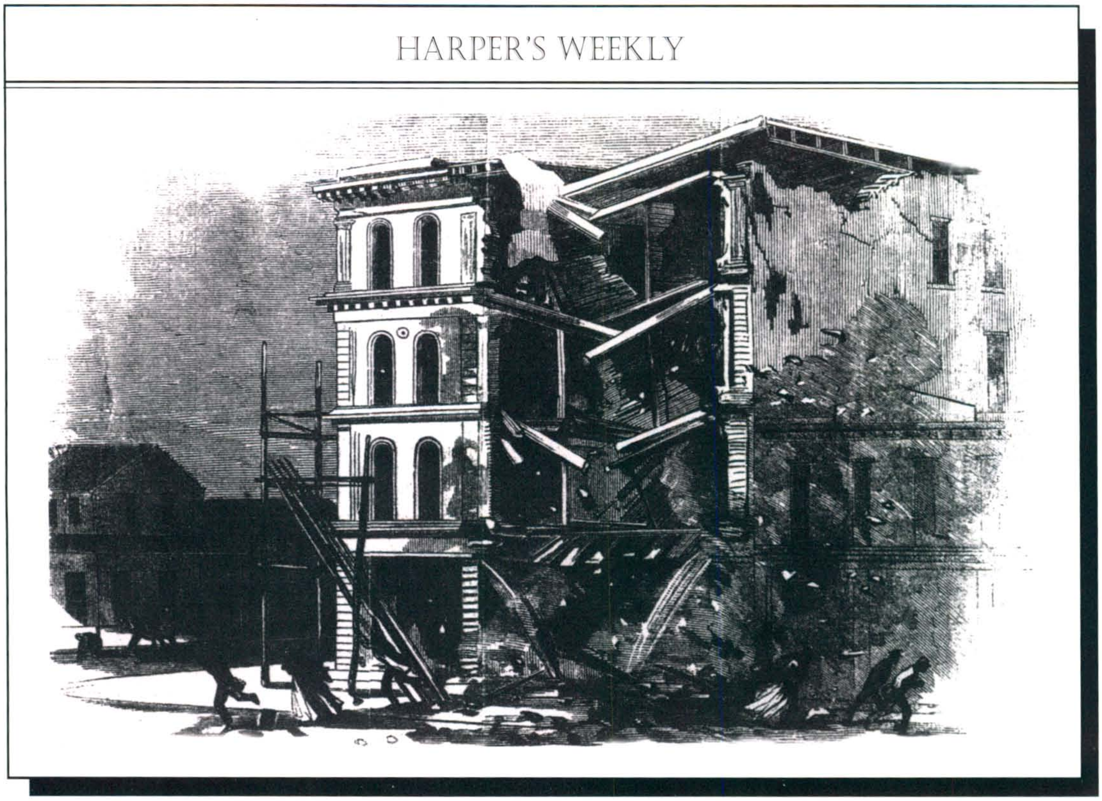
We [*Harper's Weekly*] illustrate on this page the recent earthquake in San Francisco, the most severe shock of the kind ever known in that city.

The shock occurred at 1:15 P.M., October 8, frightening almost the entire population from their houses into the streets. During half a minute there were two tremendous shocks, which caused the buildings to rock to and fro in a manner altogether alarming. It was on Sunday, and services were just over in the churches, the congregation of the Unitarian church was being dismissed when the shock commenced, and the excitement among the women and children threatened serious consequences. The rush from the Catholic church on Vallejo Street was so great that the doors to the main entrance were carried away, and several persons were injured by being trampled upon. The walls of many buildings were cracked in several places, and more or less plastering fell from perhaps half the ceilings in the city. The cornices and fire walls fell from many buildings.

We show in one of our sketches the injury done to a building on Third and Mission streets. Two-thirds of the front fell to the street, and a small section of the side into an adjoining building. The rear wall of the upper story fell upon and through a frame building nearest to it. Another illustration which we give is a view of the two-story brick building on the northwest corner of Sacramento and Battery streets. Here the front of the upper story fell out. The motion of the shock appeared to be from east to west. The tide, as is usual in such cases, rose to an unusual height.



Earthquake in San Francisco, California, October 8, 1865—View on the corner of Battery and Sacramento streets. *Sketch by C.L. Bugbee.*



Earthquake in San Francisco, California, October 8, 1865—View on the corner of Third and Mission streets. *Sketch by C.L. Bugbee.*

Damage caused by the October 21, 1868 San Francisco earthquake, Tobacco and Cigar Warehouse on Clay Street, San Francisco. *Photo from the California State Library archives.*

Damage caused by the October 21, 1868 San Francisco earthquake, Pacific Pump Manufacturing Company building on Sacramento Street, San Francisco. *Photo from the California State Library archives.*

Damage caused by the October 21, 1868 San Francisco earthquake, building at the corner of Battery and Sacramento streets, San Francisco. *Photo from the California State Library archives.*

The following is condensed from the article in
MINERAL INFORMATION SERVICE, March 1970, v. 23, no. 3, p. 43-63.

THE SANTA ROSA EARTHQUAKES OF OCTOBER, 1969

W.K. Cloud, D.M. Hill, M.E. Huffman, C.W. Jennings, T.V. McEvilly,
R.D. Nason, K.V. Steinbrugge, D. Tocher, J.D. Unger, and T.L. Youd

On October 1, 1969, the city of Santa Rosa was severely shaken by two earthquakes of magnitudes 5.6 and 5.7. These quakes were distinctly felt throughout the San Francisco Bay Area, but most of the damage was in Santa Rosa, which is about 2 miles south of the epicenters. The quakes were the most severe to hit that city since 1906, when, along with San Francisco, Santa Rosa experienced catastrophic destruction.

Santa Rosa is 50 miles north of San Francisco and on the east side of Santa Rosa Valley in the Coast Ranges. At the time of the quake, it had a population of about 49,000, most of whom lived in single family dwellings. It is the seat of Sonoma County and a center of light industry, agriculture and merchandising.

Mr. Huffman, one of the authors of this article and a staff geologist of the California Division of Mines and Geology, could provide this interesting account of "how it was" the night of the quake, because he was there. . . . *editor*

The astonished residents of Santa Rosa gave no thought to epicenters, magnitudes, or faults in those first moments when the onslaught of the quake at 9:56 p.m. plunged their pitching dwellings into darkness. Each individual lived those few moments intensely there in the overwhelming grip of the natural events which had so suddenly seized him.

First came the state of dumfounded bewilderment, before recognition that the increasing rumble of his vibrating dwelling and the clatter of falling books, dishes, lamps and even television sets meant an earthquake was occurring. Then, moments of fear as the tempo of shaking reached its peak and the thought of loved ones, falling debris, and injury entered his mind. Parents groped and staggered their way into darkened bedrooms to rescue their now awakened children. Persons stumbled to get outside onto their lawns and as they did so, saw the skyline flashing eerily as, in neighborhood after neighborhood, the lights flashed rapidly on and off before finally going out. Drivers were jerked about by automobiles suddenly bucking unmanageably, some even swerving into adjacent lanes.

Electric power was restored in most areas quickly, but some remained dark until well after the second main tremor at 11:19 p.m. Telephone lines were jammed and service often irregular as relatives tried to contact one another and others sought information.

Traffic became heavy, for such a late hour on a Wednesday, as people traveled about to check up on kin. Little groups of people stood about on their front lawns, undecided about returning inside lest another, more serious, tremor occur. Liquor stores had become reeking pools of broken glass and spirits, and businessmen hurried to their stores to check the damage.

By morning, the assessment began, and would continue for months to come. It was a costly quake, but luckily—almost miraculous—not a life was lost. Now, the scientists and engineers began their evaluation and analysis, which is not complete even as we go to press. Their aim, to understand better the causes and results; hopefully, to be better prepared for the future.

The October 1969 Santa Rosa earthquakes reflect the historical record of repeated moderately strong earthquakes and earthquake sequences in the region. The mechanisms appear to be right lateral slip on steeply dipping fault planes roughly parallel to the Healdsburg fault to the northwest or the Hayward fault to the southeast. This mechanism seems characteristic of earthquakes in the Coast Ranges east of the San Andreas fault in the Bay Area and northward. The hypocenters of the 12 largest aftershocks within seven days of the main shocks form a linear pattern trending N 25° W through the northern and eastern outskirts of Santa Rosa and in line with the southern extension of the Healdsburg fault.

In a general sense, the Santa Rosa earthquake damage followed the patterns of other earthquakes. The serious hazards to lives were principally confined to the failures, or near failures, of unreinforced brick buildings. The hazard from such light mass buildings as wood frame dwellings was comparatively insignificant. Even when a wood frame dwelling went off its foundation, the occupants were in no significant danger of losing their lives. Fortunately, there were no fatalities attributable to the earthquake.

Toppled and/or broken light objects were the most widespread and numerically most common type of damage; few homes, stores or public facilities in the Santa Rosa area escaped this type of damage. The prevalent orientation of fall appeared to be north or south. Commonly, on shelves facing these directions, contents were hurled off; items on shelves facing east or west, in the same room, showed only minor disturbance.

Extensive window breakage occurred in the downtown section of Santa Rosa; other sections of the city also suffered heavily from this type of damage. Windows mounted in rubber gaskets fared much better than those more rigidly fixed. Relatively few broken windows were reported from areas other than Santa Rosa and the Rincon Valley to the east.

Collapsed chimneys were another common effect of the shock. Older, unreinforced units proved to be most susceptible. Other damage to constructed works included chipped and buckled curbs and sidewalks, and broken waterlines.

Falling debris damaged a car and dropped a fire escape. *Photo by Robert D. Nason.*

The earth-fill approaches to the Highway 12 bridge over Highway 101 subsided several inches in response to the shaking. The only other known bridge damage was from repeated pounding at the construction joints in the sidewalks over the abutments of the Brookwood Avenue bridge at Matanzas Creek.

A fire of chemical origin in a laboratory at the Santa Rosa Memorial Hospital was attributed to the shock. Fire damaged the laboratory facilities, technical equipment, and supplies. In addition, the earthquake damaged the building extensively. Another fire occurred in a commercial building on Mendocino Avenue the morning after the two main tremors. It may have been a delayed effect of the earlier shocks or possibly a result of the strong aftershock early the next morning.

As indicated above, the major effects were confined to the city of Santa Rosa. Two probable factors in this concentration are the major release of seismic energy near or under the city, and the amplification of base motion by soils underlying the city.

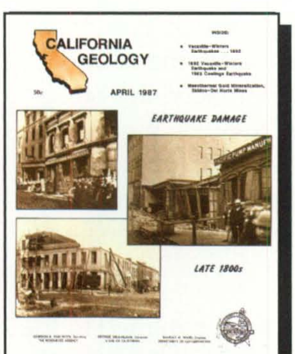
Approximate locations of principal faults and the 1980 earthquake epicenters (and dates) in the Livermore area. San Francisco Bay is about 25 miles to the west (left). *Relief base map from U.S. Geological Survey 90-meter digital elevation map of California*

The following is condensed from the article in *CALIFORNIA GEOLOGY*, April 1980, v. 33, no. 4, p. 88-92.

THE LIVERMORE EARTHQUAKES OF JANUARY 1980

Contra Costa and Alameda Counties, California

California Division of Mines and Geology Staff



At 11:00 a.m. on Thursday, January 24, 1980, an earthquake of magnitude (M) 5.9 shook the San Francisco Bay region. The epicenter of the quake was approximately 7.5 miles southeast of Mount Diablo, in the sparsely-populated hills north of Livermore Valley. Discontinuous surface rupture associated with the earthquake was found where the Greenville fault[1] crosses Vasco Road, about 7.5 miles south of the epicenter. Two days later, a M 5.8 earthquake jolted the same area. The epicenter was in the vicinity of Frick Lake, 8.7 miles south of the previous event's.

Additional surface rupture was observed along the projected mapped trace of the Greenville fault south of Vasco Road and across Laughlin Road.[2,3]

Damage from the earthquakes was most evident in Livermore, the largest city close to the epicenters. Plate glass windows shattered and piles of merchandise were scattered in shop aisles. Many mobile homes were knocked off their foundations, buildings swayed and cracked in numerous places, and gas lines snapped. The overpass along Interstate 580 at Greenville Road was closed when paving on the east side of the structure settled nearly a foot as a result of shaking of fill materials. Although the overpass did not break, traffic was diverted until repairs and resurfacing of the road were completed. One death, possibly from a heart attack, and a few minor injuries were associated with the events.

Damage to mobile home in Sunset Mobile Home Park, Livermore. *Photo by Donn Ristau.*

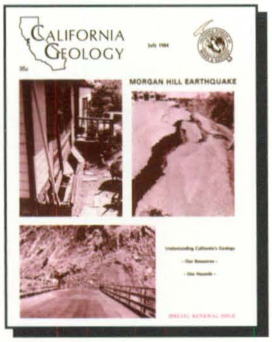
Damage to Lawrence Livermore Laboratory was estimated to approach $10 million, though most of the damage was non-structural. Buildings housing radioactive materials and a reactor were unharmed. At Wente Bros.' Livermore winery, more than a dozen giant stainless steel tanks were overturned by earthquake shaking and 168 out of 208 wine tanks suffered collapse or failure to some degree.

The Greenville-Mount Diablo fault, which produced the Livermore Valley earthquakes, is one of several active faults along the east side of the Coast Range. Lying to the east of the major cities of the San Francisco Bay Area, these faults have not gained the same notoriety as the San Andreas, Hayward, and Calaveras faults. Though there had not been any earthquakes on the eastern Coast Range faults greater than M 5 since the great San Francisco earthquake of 1906, there were six as large or larger than the Livermore Valley earthquakes prior to that historic event. Of these, the one nearest Livermore was the Antioch earthquake of May 19, 1889. Newspaper accounts at that time indicate that the greatest damage was suffered by the communities of Antioch, Clayton, and Collinsville where glassware and crockery were shaken from shelves and chimneys were toppled. The epicenter was most likely on the Antioch fault or on the northern end of Greenville-Mount Diablo fault.

The largest earthquake, other than the 1906 event, known to have struck the San Francisco Bay region occurred on April 19, 1892 in the Vacaville-Winters area. This M 6.8 earthquake caused extensive damage in Vacaville, Winters, Dixon, and other nearby communities. As with the Livermore Valley earthquake, it was followed two days later by another large event of M 6.3. On May 19, 1902, a M 5.5 earthquake knocked chimneys down in Elmira, Solano County, and caused minor damage in Vacaville and Fairfield. Causative faults have not been identified for either the 1902 Elmira earthquake or the 1892 Vacaville-Winters earthquakes.

Also reported are two earthquakes, a M 6 on April 10, 1881 and a M 5.7 on July 14, 1866, in a sparsely populated area southeast of Livermore, near the edge of the San Joaquin Valley. Local newspapers reported no serious damage in accounts of these earthquakes.

Offset chimney in house along Laughlin Road in the epicentral area of the January 26 earthquake. *Photo by T.L. Bedrossian.*



The following is condensed from the article in
CALIFORNIA GEOLOGY, July 1984, v. 37, no. 7, p. 146-148.

MORGAN HILL EARTHQUAKE OF APRIL 1984

Tousson R. Toppozada, Seismologist
California Division of Mines and Geology

On April 24, 1984, at 1:15 p.m., an earthquake of Richter magnitude (M) 6.2 occurred along the Calaveras fault near Mt. Hamilton, 10 miles east of San Jose, Santa Clara County. This earthquake was felt strongly throughout the San Francisco Bay Area and as far away as Sacramento, 86 miles to the northeast. Fortunately, the epicenter was in the sparsely populated Coast Ranges. Most of the damage associated with earthquake shaking was in and around the city of Morgan Hill, where some houses fell off unbraced foundations. Morgan Hill is 12 miles south of the epicenter of the main shock, but only 2 miles west of the aftershock zone, which extended southward from the epicenter along the Calaveras fault about 15 miles.

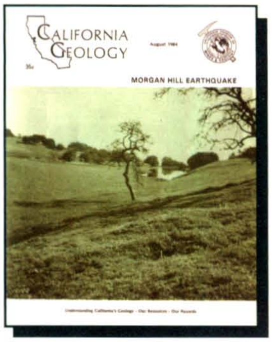
The southeastern end of the 1984 Morgan Hill aftershock zone coincided with the epicenter of the 1979 Coyote Lake earthquake. The aftershock zone of the 1979 earthquake also extended to the southeast of its main shock. During the 1979 and 1984 earthquake sequences, the Calaveras fault zone ruptured in the subsurface along a total length of 28 miles extending to the southeast from Mt. Hamilton. The maximum observed surface displacement, about 8 inches of right-lateral strike slip,[4] occurred during the 1984 earthquake.

Since the 1849 gold rush, when earthquake reporting became commonplace, 23 earthquakes of M 5.8 or greater have occurred within 60 miles of San Francisco Bay.[5]* None in that magnitude range occurred near San Francisco Bay between 1926 and 1979. From 1979 to 1984, there have been three of M 5.8 or greater in the east San Francisco Bay Area: the August 1979 Coyote Lake earthquake,[6] the January 1980 event 10 miles northwest of Livermore,[7] and the 1984 Morgan Hill earthquake.

Structural damage, Morgan Hill

The increase in seismicity since 1979 suggests a return to the higher seismic rates of the last century. This could be a sign that the crustal stresses are building up to the levels that preceded the 1906 (M 8.3) and 1868 (M 6.8) earthquakes.

******The only seismic event of M 5.8 or greater in this area since the 1984 Morgan Hill earthquake was the M 6.9 Loma Prieta earthquake in October, 1989. . . .* editors, 2006



The following is condensed from the article in
CALIFORNIA GEOLOGY, August 1984, v. 37, no. 8, p 163-164.

MORGAN HILL EARTHQUAKE CAUSED RECORD SHAKING FORCE

Anthony Shakal, Thomas E. Gay, Jr., and Roger Sherburne
California Division of Mines and Geology

The magnitude (M) 6.2 Morgan Hill earthquake that damaged the San Jose area on April 24, 1984 caused the strongest horizontal earthquake acceleration ever before measured.* The unprecedented measurement of a shaking force one and a third times the force of gravity (1.3g) was recorded by the California Department of Conservation's Division of Mines and Geology (CDMG) on a strong-motion recorder at Coyote Dam, 17 miles south of the epicenter near Mount Hamilton.

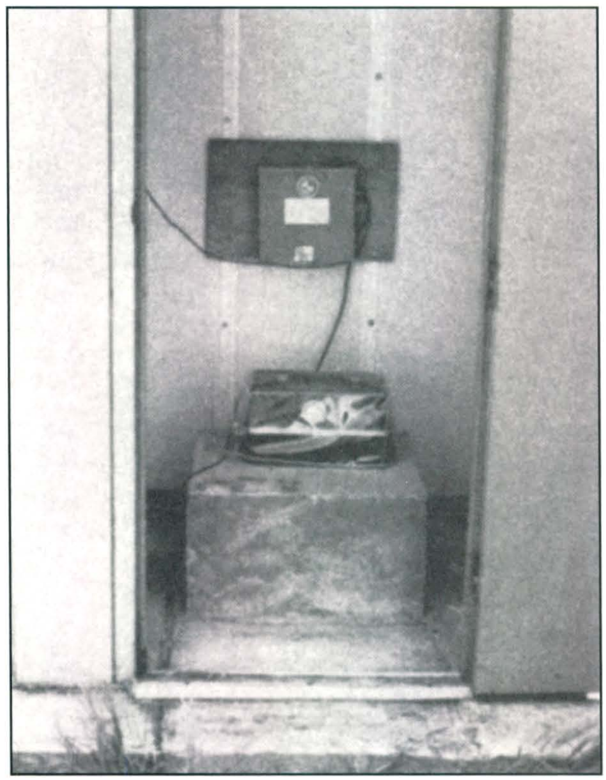
The previous maximum recorded horizontal acceleration, 1.25g, was recorded near Pacoima Dam, Los Angeles County, in the M 6.2 San Fernando earthquake of February 9, 1971. If vertical, an **acceleration** of 1.0g would exactly counterbalance the force of gravity, and make objects weightless; accelerations higher than 1.0g would throw objects into the air.

Seismologists and structural engineers are studying the unprecedented shaking force of the relatively mild Morgan Hill earthquake and are questioning the technical reasons for the earthquake's unexpected powerful punch. Was it due to the focusing of seismic waves generated by the fault, to local topography along the wave path, or to the mass and shape of Coyote Dam itself?

Seismologic theory has predicted an energy-concentration effect called **directivity focusing** which states that an earthquake's force may be concentrated in a particular direction, rather than pulsing equally in all directions. The data from this earthquake may represent the first measurement of that effect in California, with 1.3g shaking 17 miles south of the epicenter, and only 0.3g at Halls Valley, just 2 miles north.

CDMG seismologists are studying detailed tracings of the Morgan Hill earthquake's motions as recorded by more than 50 instruments in ground stations, dams, and typical buildings throughout the shaken region.

Since 1971, the CDMG Strong Motion Instrumentation Program (SMIP) has deployed a statewide network of instruments to capture detailed motions of all damaging earthquakes. Seismologists and structural engineers are then able to study the exact shaking effects of each earthquake, such as the Morgan Hill event, in order to design future buildings for greater safety.



Interior view of a strong-motion housing like the one at Coyote Dam. The accelerograph is bolted to the concrete pedestal attached to the base; the housing itself is made of light aluminum panels.

**SMIP recorded shaking forces of about 1.8g during the 1994 Northridge earthquake, and about 1.9g during the 1992 Cape Mendocino earthquake. A map of SMIP instrument locations is on page 63 of this 2006 issue. . . .* editors, 2006

The following is condensed from the article in
CALIFORNIA GEOLOGY, January 1990, v. 43, no. 1, p. 3-7.

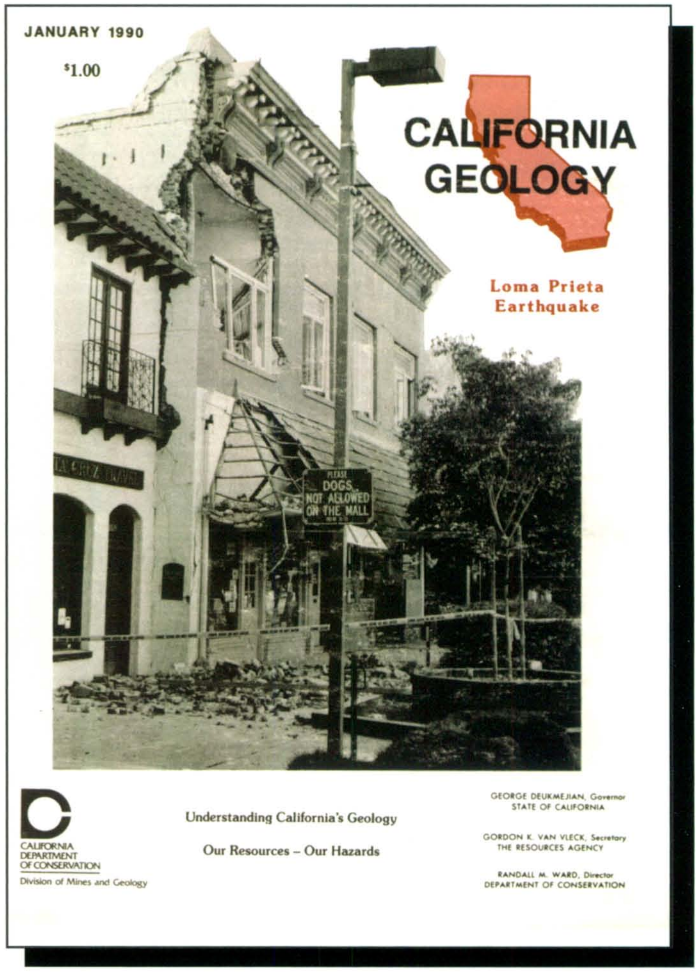
LOMA PRIETA EARTHQUAKE, OCTOBER 17, 1989
Santa Cruz County, California

Steve McNutt, Seismologist
Division of Mines and Geology

On October 17, 1989 at 5:04 p.m., a magnitude (M) 7.1 earthquake occurred along the San Andreas fault zone 10 miles northeast of Santa Cruz. The Loma Prieta earthquake, named after the highest peak in the Santa Cruz Mountains, was the largest to occur in the San Francisco Bay Area since 1906, and the largest anywhere in California since 1952. The earthquake, with strong shaking lasting 15 seconds, was responsible for 67 deaths and about 7 billion dollars in damage, making it the highest dollar-loss natural disaster ever in the United States.*

Earthquakes of M 7 or larger occur, *on average*, about once every 18 years in California at irregular intervals. For example, the period from 1895 to 1915 was seismically active in northern California, whereas the next 50 years were quiet.[8] The segment of the San Andreas fault that ruptured on October 17 probably also ruptured in 1865 and 1906. Since 1906, no significant earthquake events have occurred along this section.

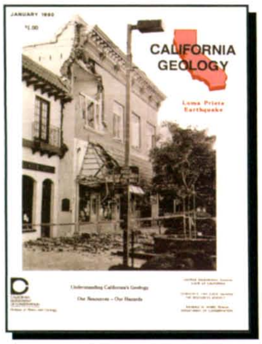
Numerous smaller earthquakes called **aftershocks** occur after every moderate or large earthquake. In general, the largest of these events is about one magnitude unit smaller than the mainshock, although there are exceptions. There are two other rules of thumb about aftershocks. First, as the events get smaller, they become more numerous. Within 10 days after the Loma Prieta mainshock, there were two aftershocks of M 5.0 or larger, 20 of M 4.0 or larger, and 79 of M 3.0 or larger. The second rule of thumb is that the frequency of aftershocks tends to decrease proportional to one (1) divided by the number of days since the mainshock. For example, if there are 100 aftershocks the first day, there will be about 50 the second day (1/2), 10 the tenth day (1/10), and so on. The number of Loma Prieta aftershocks and their magnitudes is roughly typical for earthquakes in California.



A building in the Pacific Garden Mall, Santa Cruz, damaged by the 1989 Loma Prieta earthquake. Many such brick-faced structures had to be razed.

Generally, the aftershock zone delineates the rupture area of the mainshock—the larger the earthquake, the larger the aftershock zone. The aftershock zone for the M 7.1 Loma Prieta earthquake was about 31 miles long, about average for earthquakes of that size. One unusual feature of the Loma Prieta was the lack of primary surface fault rupture, that is, the rupture did not extend to the surface.

* Damage caused by the 2005 hurricane *Katrina* will prove more costly. . . . editors, 2006



The following is condensed from the article in
CALIFORNIA GEOLOGY, January 1990, v. 43, no. 1, p. 8-13, 24.

EFFECTS OF THE LOMA PRIETA EARTHQUAKE, OCTOBER 17, 1989, SAN FRANCISCO BAY AREA

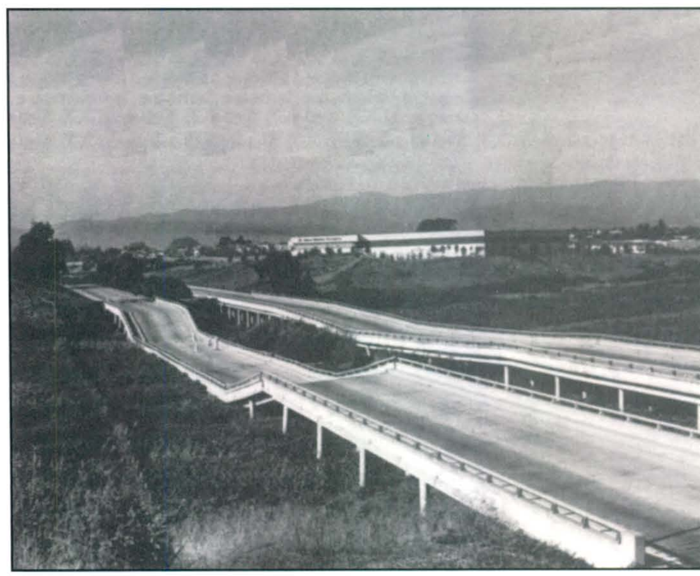
David R. Montgomery
Department of Geology and Geophysics
University of California, Berkeley

Anyone who was watching the world series on Tuesday, October 17, 1989 knows what happened in the San Francisco Bay area at 5:04 p.m. Immediately after the shaking subsided, clouds of dust rose from crumbled structures in west Oakland. Later that night the only light visible in the city of San Francisco was from the fire raging in the Marina District. Sixty-seven people were killed by the direct effects of the earthquake and hundreds of others were injured. Damage was generally limited to locations near the epicenter, where ground shaking was severe, and to more distant areas underlain by poorly consolidated deposits or artificial fill, particularly where ground settling and liquefaction occurred.

The most affected area of San Francisco was the Marina District, where 35 buildings were destroyed and about 150 others were structurally damaged. The area is underlain by sand emplaced in preparation for the Panama Pacific Exhibition in 1915. Many buildings on landfill in the area south of Market Street were heavily damaged and some will be demolished. Liquefaction of artificial fill in the Mission District also damaged some buildings beyond repair. Scattered damage occurred in the Richmond, Sunset, Haight-Ashbury, and other districts, but generally damage was less severe than in areas underlain by artificial fill or unconsolidated deposits.

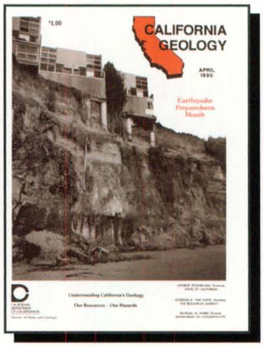
In Santa Cruz, virtually the entire downtown mall and several hundred houses were either severely damaged or destroyed. Many homes were flattened in the nearby Santa Cruz Mountains. In Watsonville and Los Gatos, major damage occurred in both downtown and residential areas. Stanford University sustained structural damage to several buildings (including the Geology Corner of the Quad). Collapsed and structurally compromised buildings were also reported from Gilroy, Hollister, San Jose, and Oakland. The most serious catastrophe was the collapse of the Cypress structure on Interstate 880 in Oakland.

The major lesson learned from the Loma Prieta earthquake is not a new one. To minimize the damage, it is important both to identify areas and structures that are susceptible to severe damage during earthquakes and to adapt engineering designs to local geologic conditions.



Collapsed portion of Highway 101 over Struve Slough near Watsonville. Note the support collumns that punctured the roadway.

Partially collapsed house, Los Gatos, California.



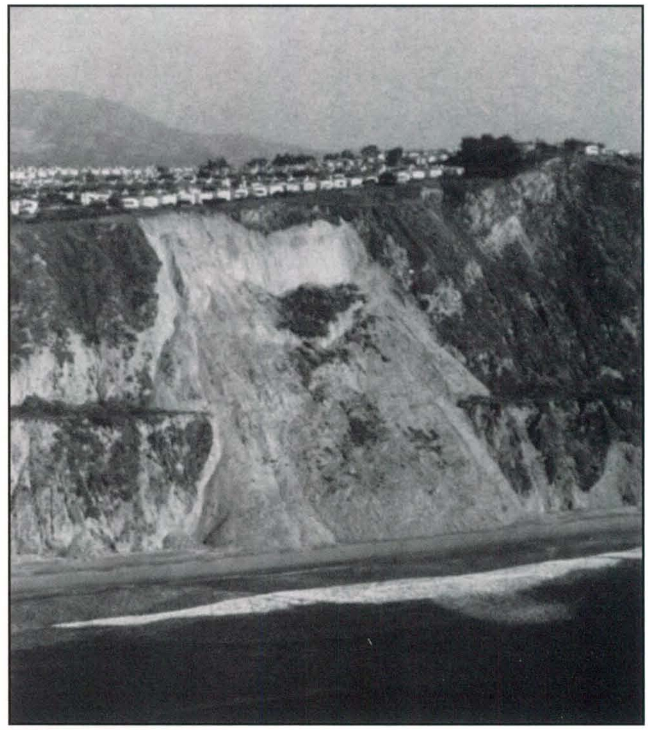
The following is condensed from the article in
CALIFORNIA GEOLOGY, April 1990, v. 43, no. 4, p. 75-84.

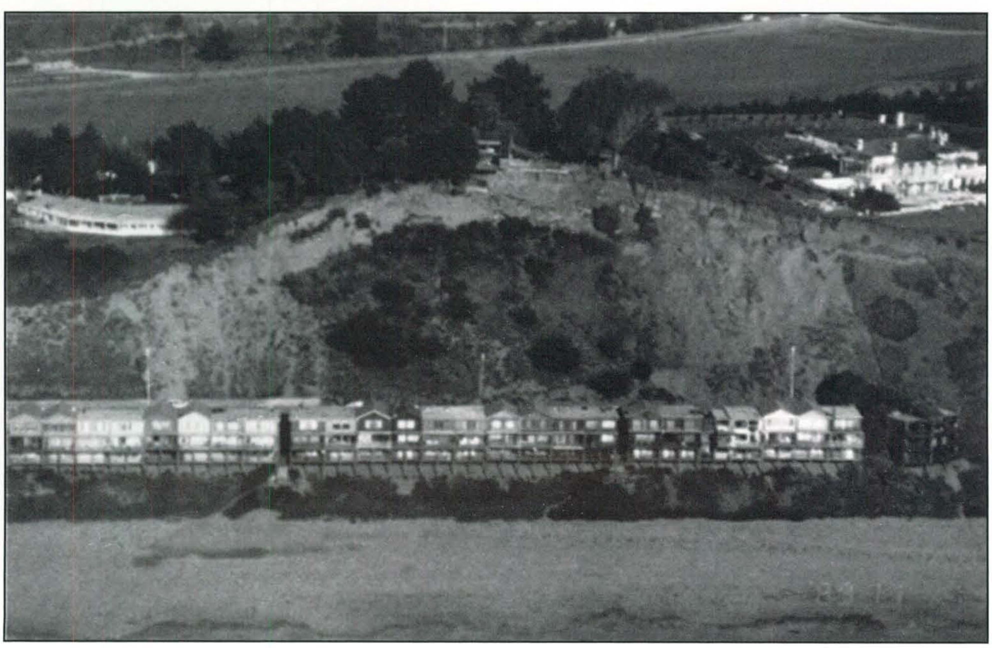
COASTAL LANDSLIDES CAUSED BY THE OCTOBER 17, 1989 EARTHQUAKE

Santa Cruz County, California

Nathaniel Plant and Gary B. Griggs
Department of Earth Sciences University of California, Santa Cruz

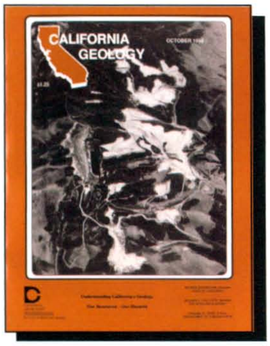
The Loma Prieta earthquake provided an opportunity to observe the effects of a large earthquake on slope stability along the Pacific coastline. Sea cliff failures along the extensively developed northern Monterey Bay shore demonstrated both the hazard induced by earthquakes and the general instability of coastal bluffs. The recent earthquake-induced failures were along bluffs that were actively eroding and in those that were protected from marine erosion. Furthermore, structures built on narrow ridges and promontories were observed to be the most likely to sustain severe damage. Although the earthquake caused massive instantaneous failure, strong ground shaking can also hasten erosion and failure of weakened bedrock and soils as the continuing cycle of winter storms batters the coastline. Development proposals along the coast should consider the evidence and experience gained from this earthquake to evaluate building constraints and the feasibility of hazard mitigation measures.





Above: Although there were fewer landslides farther from the epicentral region, several large slides and rockfalls occurred as far north as Daly City, San Mateo County. Note how close the houses are to the top of the slide.

Left: Place de Mer development, south of Manressa State Beach, Monterey Bay, Santa Cruz County. Houses at the top and base of this 300-foot-wide dry sand flow were at risk.

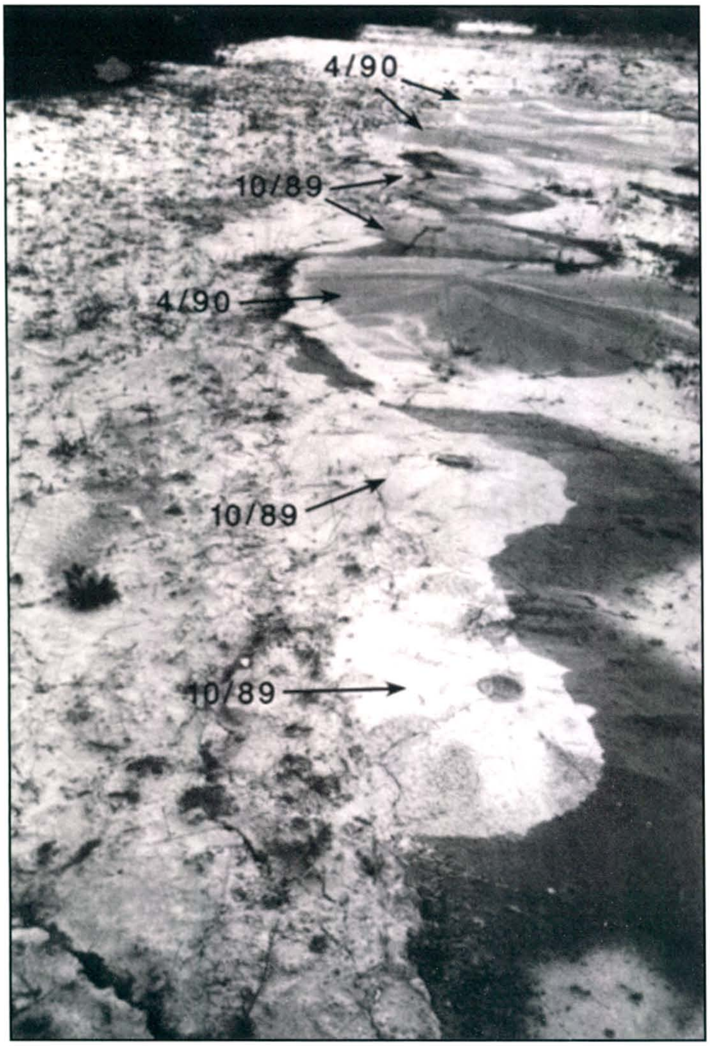


The following is condensed from the article in
CALIFORNIA GEOLOGY, October 1990, v. 43, no. 11, p. 225-232.

LIQUEFACTION AT SODA LAKE

Effects of the Chittenden Earthquake Swarm of April 18, 1990
Santa Cruz County, California

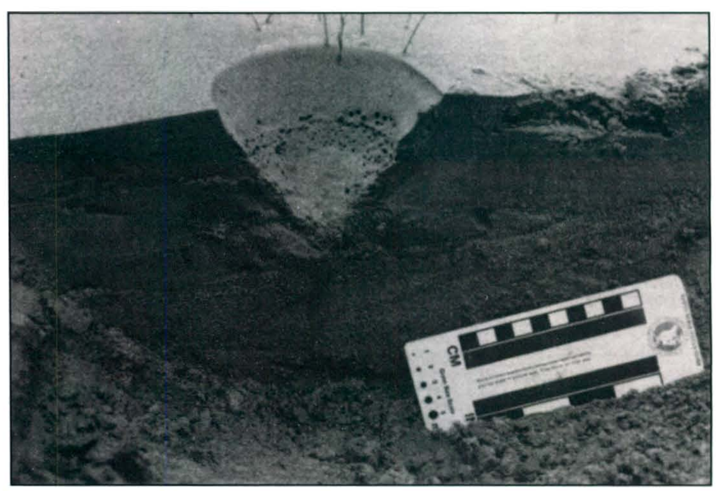
C.J. Wills and M.W. Manson, Geologists
Division of Mines and Geology

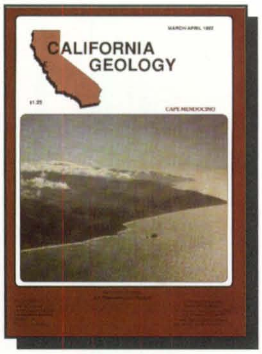


Sand blows from the 1989 Loma Prieta and 1990 Chittenden earthquakes. The lowermost sand blow is about 3 feet across.

On April 18, 1990, the anniversary of the great 1906 San Francisco earthquake, a series of aftershocks of the October 17, 1989 Loma Prieta earthquake occurred near Chittenden, a community about 20 miles southeast of Santa Cruz. Many of the aftershocks, the largest having a magnitude of 5.4, were felt throughout the San Francisco Bay area. They caused no surface rupture and relatively little landsliding, but did cause liquefaction at Soda Lake, a 66-acre tailings pond just north of Chittenden. Even though the sandy silt that filled the pond by the mid 1980s had already liquefied and consolidated as a consequence of strong ground shaking during the 1989 Loma Prieta earthquake, the deposits remained susceptible to liquefaction. This repeated liquefaction of hydraulic fill suggests that repeated liquefaction of similar hydraulic fills along the margins of San Francisco Bay is also possible, including those underlying the Marina District and the low lying areas along the eastern shores of San Francisco Bay.

To the right is a photo of an excavated sand blow formed at Soda Lake by the Loma Prieta earthquake. Note the "feeder dike" of fine sand below the vent and the fine layering within the sand blow.





The following is condensed from the article in
CALIFORNIA GEOLOGY, March/April 1992, v. 45, no. 2, p. 40-53.

SOURCES OF NORTH COAST SEISMICITY

L. Dengler, G. Carver, and R. McPherson, Geologists
Humboldt State University, Arcata, California

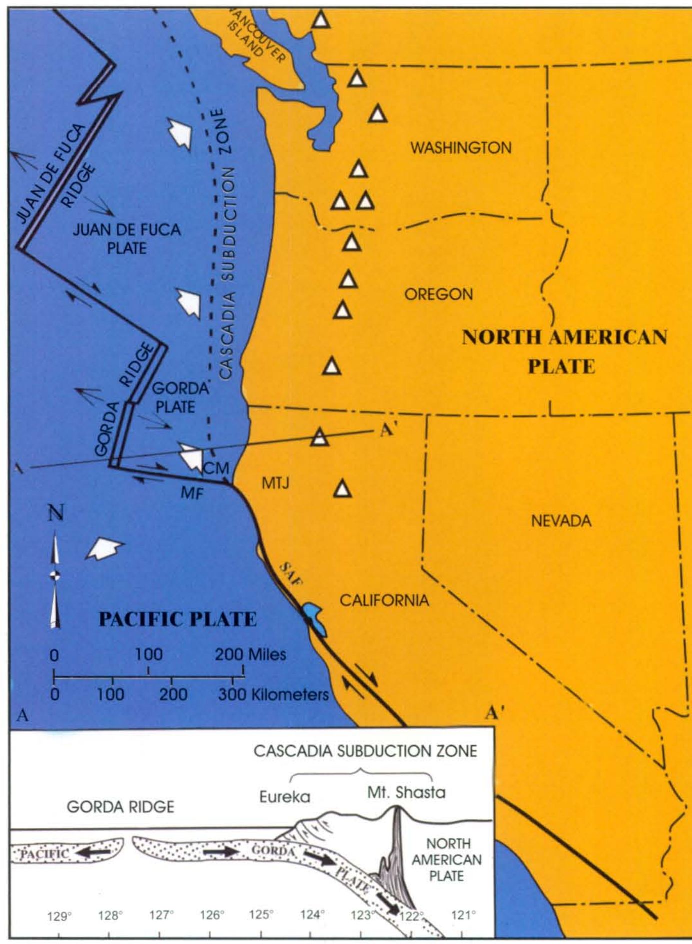
The vicinity of Cape Mendocino is one of California's most seismically active areas.[1, 2] The Mendocino triple junction is the geologically dynamic area where the east end of the Mendocino fault meets the south end of the Cascadia subduction zone and the northern extension of the San Andreas fault. These faults define the boundaries between the Gorda, Pacific, and North American tectonic plates. We recognize five distinct but related sources of earthquakes posing seismic risks for the coastal areas of northern California:

1) San Andreas Transform System Earthquakes

These earthquakes are the result of motion between the North American and Pacific plates. The transform system includes a number of northwest trending faults from just offshore to east of Garberville.[3] Fault motion is predominantly right-lateral strike-slip. The only major historic plate-boundary earthquake on the northern segment of this system was the April 1906, magnitude 8.3 San Francisco earthquake which probably produced the strongest ground shaking known to occur in Humboldt County.[4] There was surface rupture in Shelter Cove, duration of strong ground-motion in excess of 40 seconds throughout the Humboldt Bay region, and extensive damage to communities in the Humboldt Bay area and in southern Humboldt County.[5] The Modified Mercali Intensities were at least VIII in Briceland, Eureka, and Fortuna and may have reached IX in Petrolia and Ferndale.[6] In Ferndale, not a chimney remained standing and brick buildings were badly damaged. Liquefaction features were observed in the Eel River Valley and around Humboldt Bay.

2) North American Plate Earthquakes

The potential sources of these earthquakes are thrust faults within the North American plate north of the triple junction. Epicenters would be onshore and at depths of fewer than 12 miles. Only one damaging event in historical time, the December 21, 1954, magnitude 6.5 earthquake, appears to have been within the overriding North American plate. This earthquake caused one death, much structural damage, and numerous landslides and rockfalls, and it temporarily reversed water flow in the Mad River.[7]

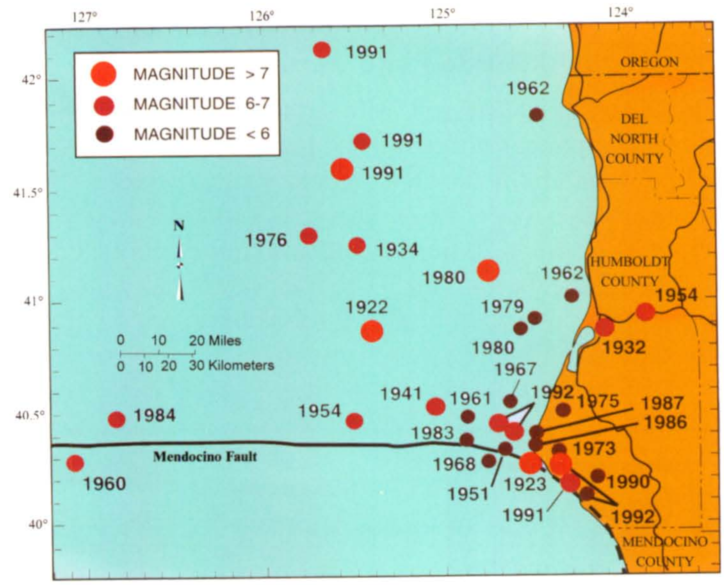


Simplified map of northwestern California regional tectonics. To the south of the Mendocino **triple junction** (MTJ), the San Andreas fault system (SAF) is the transform (strike-slip) boundary between the Pacific and North American plates. North of Cape Mendocino (CM), the Juan de Fuca and Gorda plates are converging with the North American plate along the Cascadia subduction zone. West of Cape Mendocino, the Mendocino fault (MF) is the transform boundary between the Pacific plate and the Gorda plate. White arrows denote plate motion relative to North America; black arrows denote relative plate motion at plate boundaries. The inset is a simplified cross section of the southern Gorda plate being subducted beneath the North American plate in northern California.

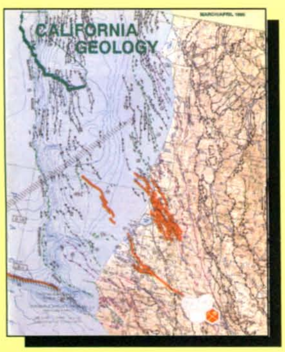
3) Mendocino Fault Earthquakes

These earthquakes are the result of the relative plate motion between the Pacific and Gorda plates and are the second most common source of historical damaging earthquakes. The 1923, 1941, 1951, 1952, and 1968 earthquakes may have been generated by this source and all produced peak intensities of VII or more in the Petrolia area. However, because of location uncertainties, it is difficult to distinguish Mendocino fault earthquakes from those within the southern part of the Gorda plate.

The Punta Gorda earthquake (M 5.6) struck the Cape Mendocino area on January 21, 1997, after the publication of this 1992 article and the 1994 article below. The epicenter was on the Mendocino fault near its junction with the San Andreas fault and the Cascadia subduction zone.[8] *Residents in the Cape Mendocino and Humboldt Bay regions felt the earthquake but did not report significant damage. . . .* editors, 2006



Epicenters and dates of best located north coast historic earthquakes of magnitude ≥5.5 and/or intensity ≥VI.



The following is condensed from the article in *CALIFORNIA GEOLOGY*, March/April 1995, v. 48, no. 2, p. 43-53.

THE SEPTEMBER 1, 1994 MENDOCINO FAULT EARTHQUAKE

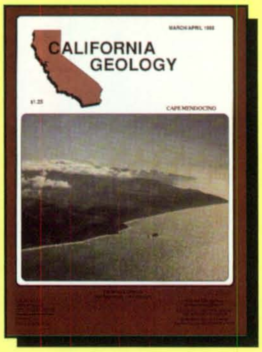
Lori Dengler, Kathy Moley, Robert McPherson, Humboldt State University, Arcata, California; Michael Pasyanos, University of California, Berkeley, California; James W. Dewey, U.S. Geological Survey, Denver, Colorado; Mark Murray, U.S. Geological Survey, Menlo Park, California

On September 1, 1994, a large region of northern California and southern Oregon was shaken by a moment magnitude 6.9 earthquake. This earthquake was felt over an area of approximately 50,000 square miles from the San Francisco Bay Area to southwestern Oregon and was the largest magnitude earthquake to occur in 1994 within the territorial limits of the United States. Although the earthquake was large in magnitude and widely felt, it produced virtually no damage because its epicenter was about 85 miles west of Cape Mendocino and the nearest coastal communities. This earthquake is important for several reasons: (1) It is the largest historical earthquake clearly associated with the Mendocino Fault, (2) A detailed post-shock intensity study allows understanding of the felt effects of far-offshore earthquakes and better location of pre-instrumental historical event, (3) A Global Positioning System (GPS) survey in the Cape Mendocino region allowed direct observation of the coseismic displacements, (4) This was the eighth magnitude 6 or larger earthquake in three years previous to this 1995 article, which illustrates the extremely high seismic activity of the north coast region, and (5) The earthquake produced a 5.5-inch tsunami which, although not damaging, underscores the problem of tsunami warning in a region that has the potential to produce large tsunamis.

4) Gorda Plate Earthquakes

These earthquakes result from strike-slip faulting within the Gorda plate. Although these faults may extend inland beneath the North American plate, they do not reach its surface. Epicenters are usually offshore, although perhaps 10 percent are within the subducted portion of the Gorda plate. The majority of damaging earthquakes recorded in the Humboldt Bay region are this type.

The Eureka earthquake (moment magnitude 5.4) struck the Humboldt Bay region on December 26, 1994, after the publication of this 1992 article.[9] The Governor declared a state of emergency after this MMI VII Gorda Plate event, the most damaging earthquake in that area since 1954. Other damaging Gorda Plate earthquakes struck in 1932 and 1980. The latter, the M 7.4 Trinidad earthquake, caused the collapse of a highway overpass.[10] . . . editors, 2006



The following is condensed from the article in
CALIFORNIA GEOLOGY, March/April 1992, v. 45, no. 2, p. 31-39.

THE HONEYDEW EARTHQUAKE, August 17, 1991

Robert C. McPherson and Lori A. Dengler, Geologists
Humboldt State University
Arcata, California

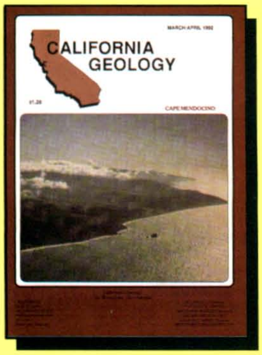
The north coast of California was shaken by a unique series of four large earthquakes in July and August of 1991. Three of the earthquakes (July 12, surface wave magnitude (M_s) 6.9; August 16, M_s 6.3; and August 17, M_s 7.1) were located in the Gorda plate off the northern California and southern Oregon coast,[11, 12] the region that has produced the majority of the area's historical damaging earthquakes.[13, 14] The magnitudes of these events are not unusual for the Gorda plate, but the short time intervals are unprecedented in the historical record.

On August 17 at 12:29 p.m., nearly 21 hours after the August 16 and 3 hours before the August 17 plate events, a much more unusual earthquake occurred on land about 7 miles south of Petrolia and west of Honeydew.[15, 16] This magnitude 6.2 event, the Honeydew earthquake, was the largest on-land earthquake in the continental United States during 1991. This earthquake is important because: (1) It was the largest earthquake on land in the vicinity of the Mendocino triple junction in this century, (2) The shallow depth of focus (7 miles) suggests a previously unrecognized source for damaging earthquakes in the region, which has now produced three damaging earthquakes in slightly over a two-year period, (3) The earthquake produced a conspicuous zone of northwest oriented surface cracks which coincided with a previously recognized shear zone, (4) The epicentral region has undergone a very high rate of Quaternary uplift and the proposed style of faulting for the Honeydew earthquake is consistent with uplift of this region, and (5) A large region surrounding the epicenter experienced changes in ground water and stream flow related to the earthquake.

A displaced concrete lid in vicinity of Honeydew. The lid has moved west relative to the tank.

5) Cascadia Subduction Zone "Great" Earthquakes

These earthquakes would be caused by movement along all or part of the Cascadia subduction zone between the Gorda and/or Juan de Fuca plates and the North American plate. Rupture of the southern portion of the zone might extend from Cape Mendocino to north of the Oregon border; rupture of the whole zone could extend to Vancouver island. These earthquakes would have magnitudes of more than 8.5, and could produce strong ground-motion lasting a minute or more, cause coastal uplift and subsidence of several feet, and generate large local tsunamis affecting coastal areas of northern California, Oregon, and Washington.



The following is condensed from the article in *CALIFORNIA GEOLOGY*, March/April 1992, v. 45, no. 2, p. 56-57.

THE CAPE MENDOCINO EARTHQUAKES April 25-26, 1992

Three large earthquakes of surface wave magnitude 6 to 7 rocked the Cape Mendocino area, Humboldt County, California during April 25 to 26, 1992. They were felt throughout much of the northern California and in southern Oregon. Peak intensities were IX in the Petrolia area.[17]

The earthquakes triggered numerous landslides, damaged roads and bridges, and caused widespread liquefaction in the Eel River Valley. A 3-foot-high tsunami devastated Crescent City. Structural damage was concentrated in Ferndale, Fortuna, Petrolia, Rio Del, and Scotia. President Bush declared Humboldt County a major disaster area.

The April 25 event occurred along a northeast-dipping reverse fault very close to the postulated location of the Cascadia subduction zone. Thus, this may be the first historical earthquake along the Cascadia subduction zone. However, the area is geologically complex so the rupture could have occurred along any one of the other thrust faults in the area. The April 26 earthquakes struck along a northwest-striking right-lateral strike-slip fault in the Gorda plate (Lori Dengler, Humboldt State University, California, written communication). No surface rupture has been discovered.

The front door was at the top of the stairs before this Ferndale house was shaken off its foundation. *Photo by Kevin Bayliss.*

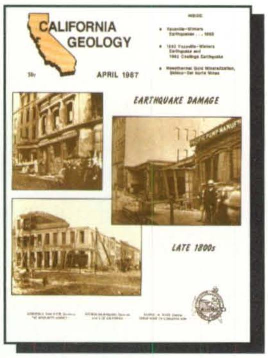
Magnitude 9.0 Cascadia Subduction Zone Earthquake, about 9 p.m. January 26, 1700[18]

Tree ring and carbon dating, along with soil analysis, revealed evidence of a great earthquake about 300 years ago in North America's Pacific Northwest. Historical reports of a tsunami in Japan helped researchers pinpoint the date and time, and determine the origin and magnitude of the mother quake.[19]

The 1700 event lends clues to a quandary that has plagued historians in their efforts to correlate Vizcaino's 1602 chart with the present-day northern California coastline, particularly Humboldt Bay. Researchers now suggest the discrepancies can be attributed to changes in coastal topography caused by the earthquake that occurred nearly 100 years after Spanish explorers mapped the coast.[20]

The water also went into the pine trees of Ego. The receding water went out very fast, like a big river. It came in about seven times before 10 a.m. of that day and gradually lost its power. . . . Because the way the tide came in was so unusual, and was in fact unheard of, I advised the villagers to escape to Miho Shrine. . . . It is said that when an earthquake happens, something like large swells result, but there was no earthquake in either the village or nearby. . . . Translation of an account of the 1700 tsunami by the head of Miho, a coastal village about 90 miles south of Tokyo[21]

Tsunamis are rarely big, crashing waves as depicted in Katsushika Hokusai's print, reproduced here, in part. More often, they arrive as surges like those described above.



The following is condensed from the article in *CALIFORNIA GEOLOGY*, April 1987, v. 40, no.4, p. 75-83.

VACAVILLE-WINTERS EARTHQUAKES . . . 1892

Solano and Yolo Counties

John H. Bennett, Geophysicist, California Division of Mines and Geology

Three earthquakes of magnitude 5.5 to 6.5 struck the Vacaville-Winters area in April 1892. The sequence is noteworthy because it is one of the most significant seismic episodes to directly affect California's Central Valley in historical times. Newspaper and other reports were used to define the source area and identify the most probable causative fault or faults.

The most intense shaking was reportedly in the area generally bounded by Pleasants Valley, Putah Creek, Winters, and Allendale. The northern limits of this area are vague, however, since there was no significant settlement and, hence, no reports originating within the hills north of Putah Creek.

From the various accounts, there appears little doubt that the source area lies in the hills west of the lower Sacramento Valley, east of the crest of the Vaca Mountains in Solano and Yolo counties, thereby eliminating the known Holocene-active Green Valley fault, or other faults within Napa County. This conclusion is predicated on the absence of any significant damage at Monticello in Berryessa Valley, at Pope Valley, and generally throughout Napa County and on Dunton's observation that shaking effects in Putah Canyon diminished rapidly westward towards Berryessa Valley. These observations are in marked contrast with the reports of intense shaking at all locations east of the county line.

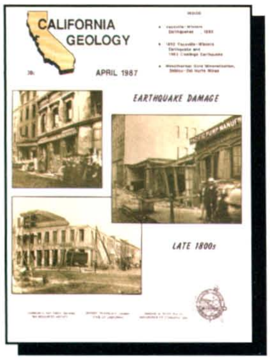
From a letter from the Cantelow Ranch in the English Hills, dated April 19, 1892:

The chimney here broke off at the top of the house, but did not break through the roof. All the back fell out and it is badly cracked around the fireplace. . . . In the sitting room the tables and desk were thrown over and pictures turned wrong side to. . . . I think at one time the east end of the house was four feet from the ground. The underframing is all knocked galley west and the two parts of the house are split apart so there is a crack in the door big enough for a cat to go through. The cap is knocked off the stovepipe. . . .
Lawrence A. Cantelow

From *The Morning Call*, April 23, 1892:
. . . on Thursday (April 21) morning. . . . he noticed that the cultivator, on which he was riding, plunged violently. At the same moment, there was a loud, roaring noise, and cloud of dust sweeping rapidly along toward the town of Winters. The ground rose and fell like the sea in a storm, and a moment later a tremendous crash announced that it had struck the Devilbiss house. Successive crashes showed when it reached other houses as it passed along, and when it reached the town, the noise was tremendous. . . .

This earthquake sequence appears to have originated within an area of some 6 to 8 miles in width centered on the English Hills, the area extending from near the Sacramento Valley margin to just west of the Vaca Valley-Pleasants Valley trough. Within this area, possible sources of the 1892 earthquake sequence include: (a) an unrecognized thrust fault or faults related to the development of folds along the western margin of the Great Valley, a source similar to that which produced the 1983 Coalinga earthquake, (b) a concealed fault within the Vaca Valley-Pleasants Valley trough, possibly the northern extension of the Vaca Fault, and (c) a bedding plane fault within the steeply dipping Great Valley sequence.

Vacaville-Winters earthquake damage, 1892. *Photo from* CALIFORNIA GEOLOGY, *MARCH/APRIL 1992.*



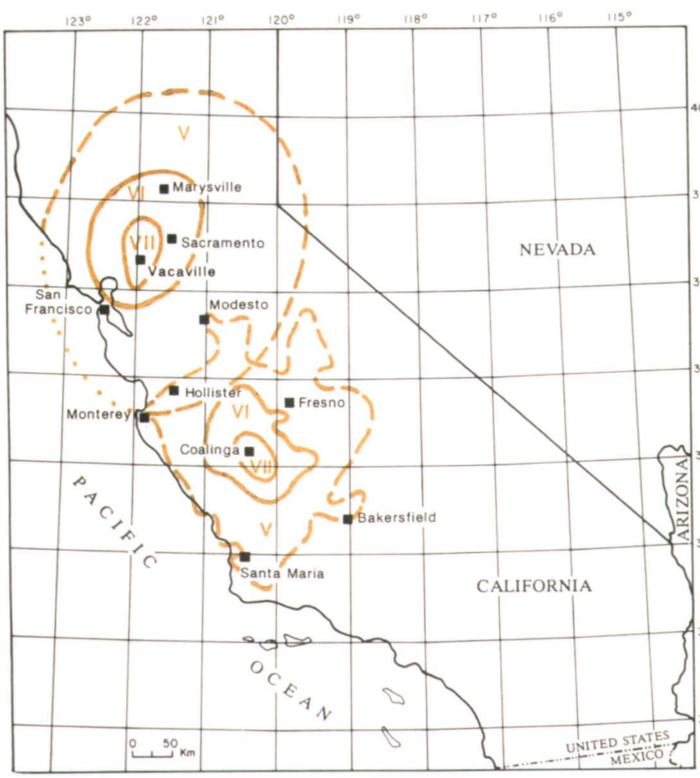
The following is condensed from the article in
CALIFORNIA GEOLOGY, April 1987, v. 40, no. 4, p. 84-85.

1892 VACAVILLE-WINTERS EARTHQUAKE AND 1983 COALINGA EARTHQUAKE

Tousson R. Toppozada, Seismologist, California Division of Mines and Geology

The April 19, 1892 Vacaville-Winters earthquake was notably similar to the May 2, 1983 Coalinga earthquake in that: (1) they are the two largest historical seismic events known to have occurred along the western margin of the Great Valley, (2) the main shocks were in the range of magnitude 6 to 7, (3) neither sequence produced obvious primary surface rupture indicative of a causative fault, and (4) both events occurred in areas devoid of surficial evidence of recent active faulting. Because of these similarities in geologic setting and probable earthquake source characteristics, a comparison of the areas shaken at different intensities for the two events affords a means to estimate the magnitude of the pre-instrumental 1892 event.

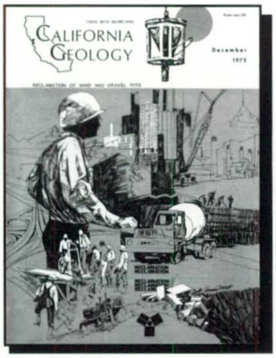
Building damage at Coalinga, California, May 2, 1983. *Photo by James Strata.*



Isoseismal maps (showing lines of equal earthquake intensity) for the April 19, 1892 Vacaville-Winters earthquake and the May 2, 1983 Coalinga earthquake.[1, 2]

The areas shaken at intensities V, VI, and VII for both events are shown on the figure to the left. The relationship of magnitude to areas shaken[3] is such that doubling the size of the area shaken corresponds to about a 0.3 increase in magnitude. Comparison of the areas shaken by the two earthquakes indicates that the magnitude of the April 19, 1892 Vacaville-Winters event was at least equivalent to that of the May 2, 1983 Coalinga event, and up to 0.2 of a magnitude unit larger.

The University of California, Berkeley and the California Institute of Technology assigned the 1983 Coalinga event magnitudes of 6.7 and 6.1, respectively. Because this earthquake occurred near the boundary between the two seismographic networks, the appropriate magnitude is the average of 6.4. Based on this, and on the intensity data, it is concluded that the magnitude of the April 19, 1892 earthquake was in the range of 6.4 to 6.6.



The following is from a letter published in the December 1975 issue of CALIFORNIA GEOLOGY, v. 28, no. 12, p. 277. It details personal impressions of the Oroville earthquake and related phenomena experienced at a concrete and sand and gravel plant about 5 miles south of Oroville, near the epicenter of the magnitude 5.7 event. . . . editors, 2006

OROVILLE EARTHQUAKE

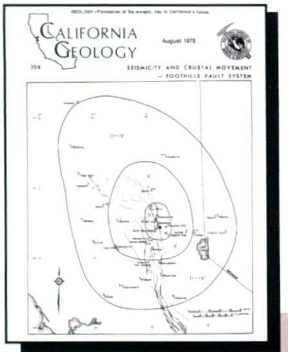
Friday, 1 August 1975 . . . . I arrived at the plant approximately 10:15 A.M. . . . During the batching observation, I was standing in the control room and noticed the entire plant seemed to rock slightly with a subtle jar. I assumed this to be typical of the plant itself as there are approximately 100 tons of material in bins directly overhead and the batching operation necessarily requires shifting of material, "banging" of gates, and cycling of water valves which must cause the plant to move somewhat. Apparently this shock was 3.5 Richter and I was unaware of the earlier 5.0. The batchman told me they had felt shocks frequently this morning. We continued to feel small "bumps" and "shakes." . . . I had made a mental note that if a severe shock hit, I would run away from the plant in a direction to avoid the numerous high voltage lines in the area.

At approximately 1:20 P.M., I had just sat down in my truck to have lunch. My first indication was a distant "roar," perhaps like the rumble of a train. The shaking started within a few seconds and seemed to increase sharply after a few seconds of relatively minor movement. At this time, I made the decision to move away quickly from the plant. . . . so I ran approximately 50 yards and stopped and looked back at the plant. At this time, the major shaking was still going on and the entire earth and plant and auxiliary buildings appeared to be moving up and down 6± inches. The feeling was one of being on a giant rock crusher, very severe and very rapid, perhaps 10 cycles per second. There was a lot of noise, both from the equipment shaking and the surrounding stockpiled materials settling and also a background roar of the quake itself.

I would estimate the major motion lasted less than 30 seconds. In the minutes after the quake, I stayed in one place and could feel the earth "quiver" as if resonating. The aftershocks were frequent, every 5 minutes more or less and were, for the most part, gentle bumps. However, at least one was severe enough to cause us to run out of the control room. . . .

If the quake had caused major damage, I feel it would have been every man for himself for several hours. My point being, generally people are not prepared for a major disaster that could come at any time. . . . Don Tidwell, Lowry and Associates, Geotechnical Engineers, Sacramento

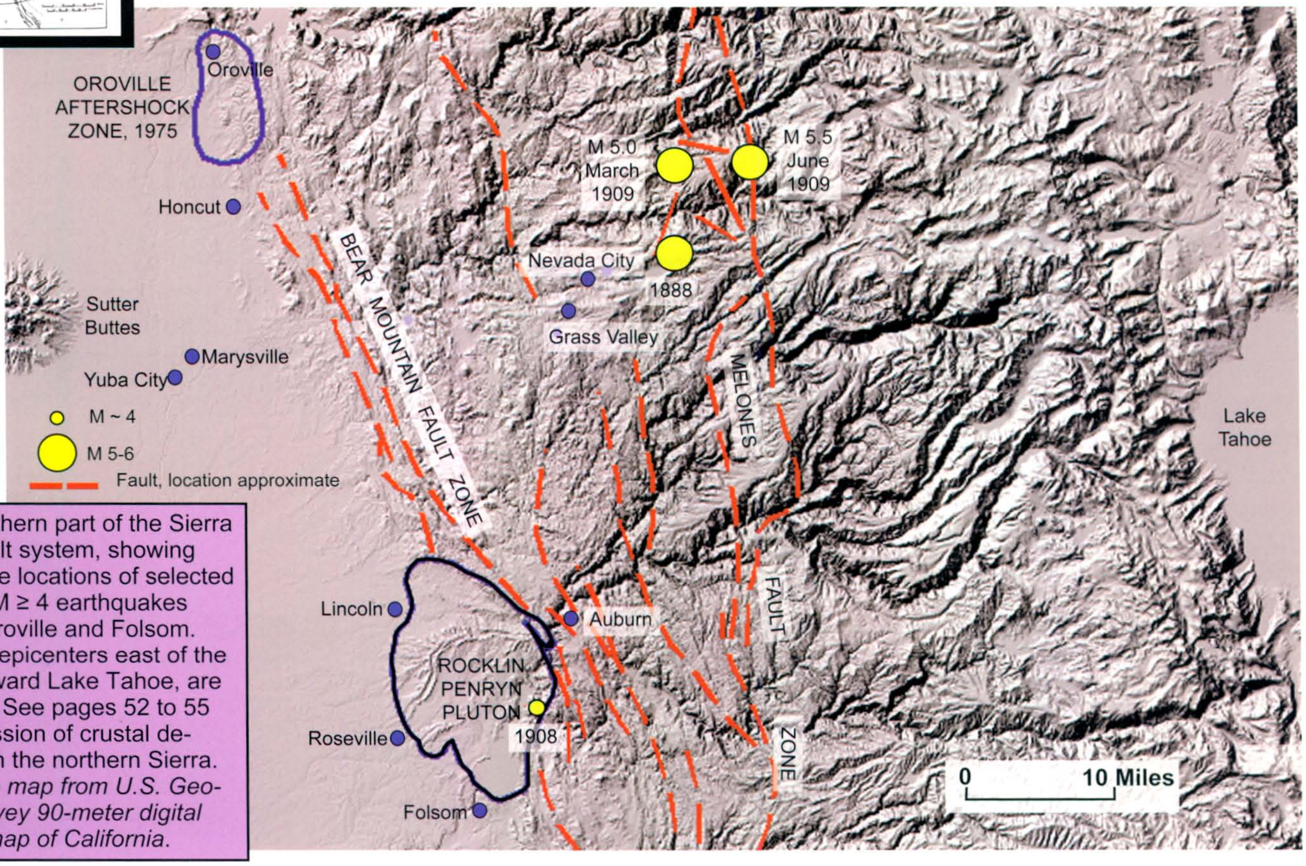
Prior to the magnitude 5.7 Oroville earthquake of August 1, 1975, the Foothills fault system was generally regarded as seismically inactive. The U.S. Bureau of Reclamation (USBR) Auburn dam site lies within the northern extension of the Bear Mountain fault zone, a major part of the Foothills fault system. Although USBR had already concluded there was a remarkably low level of seismicity and corresponding high level of crustal stability in the area, the Oroville earthquake generated concern that the Foothills fault system might still be active, at least in part. Of particular interest were the faults near and within the Auburn dam site. The geologic and tectonic similarity between the Oroville and Auburn areas and the possibility that the Oroville earthquake may have been induced by the filling of Oroville reservoir a few years earlier increased concern for possible induced seismicity at Auburn. . . . *John H. Bennett, Geophysicist, California Division of Mines and Geology, 1978*[1]



The following is condensed from the article in *CALIFORNIA GEOLOGY*, August 1978, v. 31, no. 8, p. 183-185, which first appeared in the Bulletin of the Seismological Society of America.[2]

SEISMICITY OF THE FOOTHILLS FAULT SYSTEM BETWEEN FOLSOM AND OROVILLE, CALIFORNIA

Chris H. Cramer, Tousson R. Toppozada, and David L. Parke
California Division of Mines and Geology



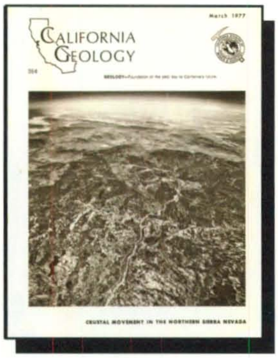
Map of northern part of the Sierra foothills fault system, showing approximate locations of selected faults and M ≥ 4 earthquakes between Oroville and Folsom. Faults and epicenters east of the system, toward Lake Tahoe, are not shown. See pages 52 to 55 for a discussion of crustal deformation in the northern Sierra. *Relief base map from U.S. Geological Survey 90-meter digital elevation map of California.*

The Foothills fault system, between Folsom and Oroville, is bound on the east by the northward trending Melones fault zone and on the west by the northwestward trending Bear Mountain fault zone. Recent studies have revealed more extensive Late Cenozoic faulting than previously recognized within the northern Sierra Nevada, including portions of the Foothills fault system.[3, 4] Damaging earthquakes, in the magnitude (M) range of 5 to 6, occurred within this portion of the Foothills fault system in 1975, about 6 miles south of Oroville, and in 1909[5] and 1888 about 10 miles northeast of Nevada City.

Microearthquake studies in the Sierra foothills from 1975 to 1978 indicate a pattern of ongoing low level seismicity between Oroville and Folsom.[6-8] The occurrence of several M~1.0 events during this period suggests this portion of the Foothills fault system is active, and historical reports[9-11] and earthquake recordings by modern instruments[12, 13] support this conclusion.

Detailed investigations in the vicinity of Auburn, California have shown microearthquake activity within the Rocklin-Penryn pluton with the main cluster of recorded events in the middle of the pluton. Another cluster of small events is near the northern margin, where the intrusive body truncates the Foothills fault system. Data indicate normal faulting, down to the east, on northwest trending faults, which is compatible with regional geology and fault trends of the Foothills fault system. These results suggest that the Rocklin-Penryn pluton is being deformed by the same regional stress pattern that cause Cenozoic movements elsewhere on the Foothills fault system.

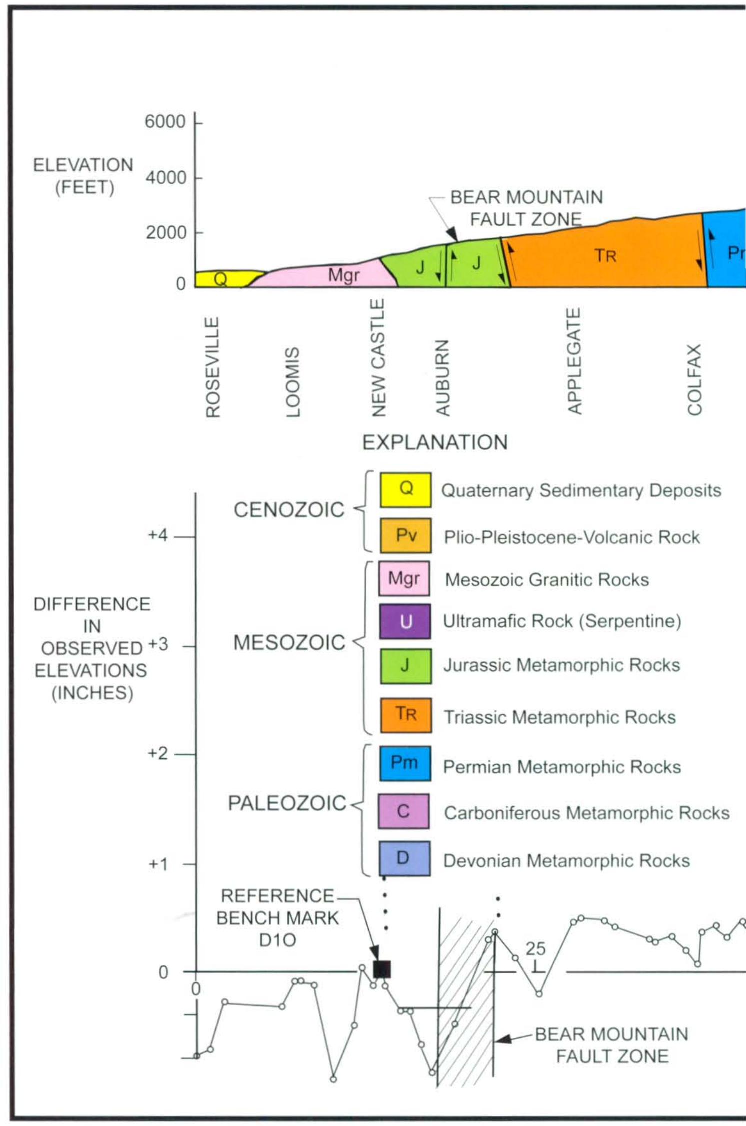
Newspaper accounts of an earthquake felt in the Folsom area on May 30, 1908 suggest its maximum intensity was IV-V; a total felt area of about 4,000 square miles suggests a Richter magnitude of about 4 for this event. Newspapers reported earthquakes in 1885 and 1892 as being felt only in the town of Newcastle, which is between Rocklin and Auburn.



The following is condensed from the article in CALIFORNIA GEOLOGY, March 1977, v. 30, no 3, p. 51-57. It compares a 1976 first-order elevation survey between Gold Run and Blue Canyon, Placer County with earlier such surveys performed in the Sierra Nevada along the Southern Pacific Railroad route (parallel to Interstate 80) from Roseville to Reno. The authors include a licensed surveyor, a geologist, and a seismologist of California's state survey who, subsequent to the 1975 Oroville earthquake, were assigned by the State Geologist to investigate possible crustal movement associated with the Foothill faults system. . . . editors, 2006

CRUSTAL MOVEMENT IN THE NORTHERN SIERRA NEVADA

John H. Bennett, Gary C. Taylor, and Tousson R. Toppozada
California Division of Mines and Geology

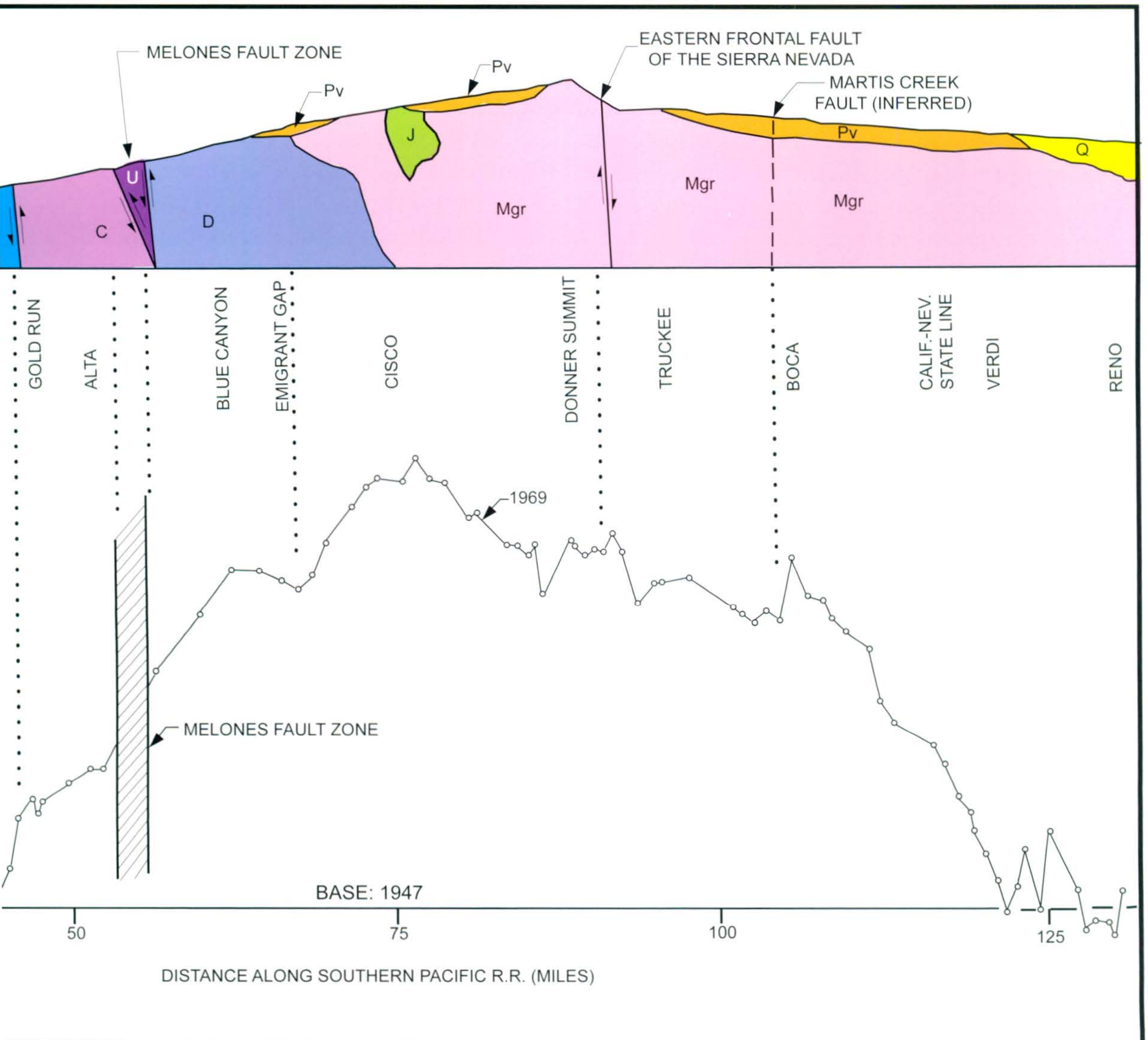


The only high-precision leveling data spanning this part of the Sierra Nevada are the results of first-order leveling of the Donner Pass line, which follows the Southern Pacific Railroad across the Sierra Nevada from the vicinity of Roseville in western Placer County to Reno, Nevada (see cross section and map on following pages). The National Geodetic Survey (NGS) completed initial leveling along this route in 1912[14] and subsequent releveling in 1947 and 1969. The NGS releveled portions of the line in 1938 (Roseville to Gold Run) and 1953 (Emigrant Gap to Cisco). The data considered in this study are from those surveys and one by the California Division of Mines and Geology during June 1976 (Gold Run to Blue Canyon).

Elevation differences resulting from the 1947 and 1969 surveys between Roseville and Reno, Nevada are compared in the figure to the right. One of the most significant conclusions to be drawn from the comparative data is the virtual absence of any relative elevation change over the entire 49-mile distance from Roseville to near Gold Run. Except for the area of slight depression centered near Auburn, there is no more than about a half inch of relative elevation difference between the two surveys over this entire segment during this 22-year period. Although the magnitude of the elevation differences is very small, the segment within which several marks are depressed near Auburn coincides remarkably well with the Bear Mountain fault zone.

Just west of Gold Run, however, and in the immediate vicinity of a major branch of the Foothills fault system, relative uplift is indicated by the 1969 survey. Just over an inch of positive elevation change accrues over the 6 miles from this contact to the community of Alta at the western boundary of the Melones fault zone. There is an increase in the rate of relative uplift, with an additional 2 inches accumulating over the next 9 miles to Blue Canyon. We see just over an inch of uplift in the segment that starts a couple of miles east of Emigrant Gap, near the contact between the Paleozoic metamorphic rocks (Shoo-fly Formation) and the Mesozoic granitic rocks of the Sierra Nevada batholith, and ends in the vicinity of Cisco. The total difference in elevation over the 22 years between surveys is just over 4 inches. East of Cisco, the magnitude of indicated uplift gradually decreases, then, east of Boca, rapidly decreases by about 3.5 inches over the 15 miles to Verdi. The result is a total absence of any net elevation change between the two ends of the profile during this period.

The June 1976 releveling produced no evidence of relative elevation change (in excess of a tenth of an inch or so) in the 5 miles to just southwest of Alta. The Alta location coincides with the western boundary of an extensive serpentine unit in the metamorphic rock belt that marks the Melones fault zone. Eastward from this contact, small persistent changes amount to less than an inch over the 2 miles to just west of Blue Canyon. Significantly, the sense of movement on the east side of the Melones fault zone was relatively "up" during the 22 years between the 1947 and 1969 surveys, and "down" during the seven-year period between 1969 and 1976. From these comparative data, it appears that the major units in contact at the Melones fault are responding to imposed regional stresses that are deforming, or tilting, about an axis coincident with this major zone of weakness.



Profiles from Roseville, California to Reno, Nevada showing topography, generalized geology, and differences in elevations observed between leveling surveys in 1947 and 1969. Differences in elevation are based on an assumed constant elevation of bench mark D10 near Newcastle. *Adapted from Clark.*[15]

Comparison of the 1912 and 1947 data reveals nearly a 3-inch disparity between Emigrant Gap and Cisco. Releveling along the same segment in 1953 indicated differences of about an inch, with the sense of movement opposite to that of the 1912-1947 interval. No appreciable change is indicated between the 1953 and 1969 surveys, so the inch of change between Emigrant Gap and Cisco from 1947 to 1969 evidently occurred between 1947 and 1953.

On December 29, 1948, during the period between the 1947 and 1953 surveys, a magnitude 6 earthquake occurred near Verdi. A foreshock two days earlier was "felt with greatest intensity at Emigrant Gap (Lake Spaulding) where there was visible swaying of buildings and trees, floor lamps, Christmas trees, pictures on walls, and doors. Distant roaring subterranean sounds heard at time of shock."[16] Though the greatest intensity was experienced at Emigrant Gap, the epicenters of the two events were assigned to an area about 37 miles to the northeast [*see map on opposite page*]. It is uncertain whether there was sympathetic movement or some other relation between the seismic activity in the Truckee-Verdi area and the vertical movements in the Melones-Emigrant Gap area.

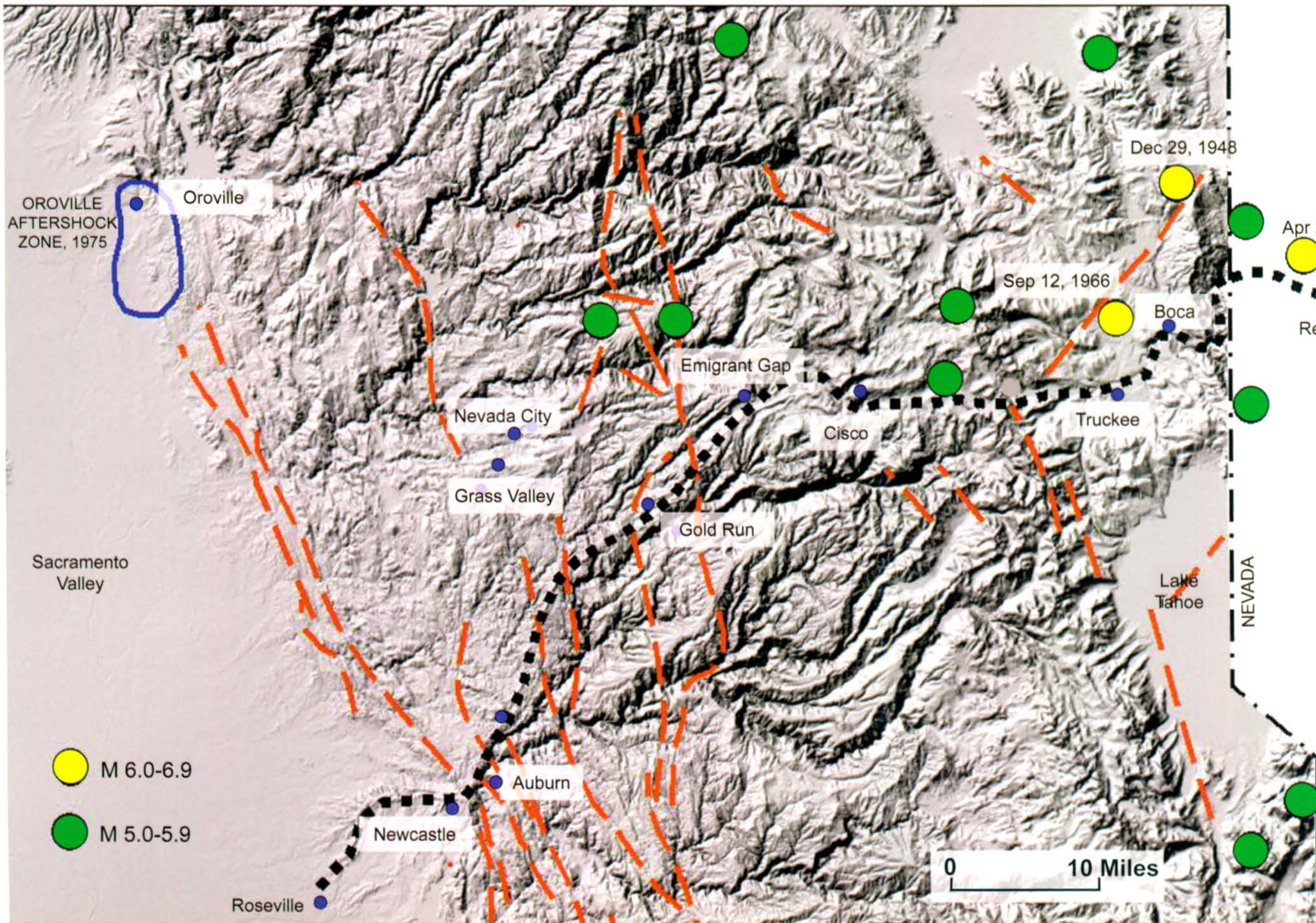
The M 6 Truckee earthquake of September 12, 1966 also occurred near the leveling line between the 1947 and 1969 surveys, so it seems reasonable that the indicated movement near Boca-Verdi could be attributed to strain release accompanying either or both of the events. There is no evidence of major seismic activity that might account for the movement on the western Sierra Nevada slope during this 22-year interval.

The repeated precise leveling surveys reveal vertical crustal deformation within the Sierra Nevada, with the observed elevation changes generally closely associated with known faulting or contacts between major structural units. On the western Sierra Nevada slope, vertical deformation is clearly localized in the immediate vicinity of the Melones fault zone near Alta. Significant elevation changes are also evident near the intrusive contact between the Paleozoic metamorphic rocks (Shoo-fly Formation) and the Mesozoic granitic rocks of the Sierra Nevada batholith near Emigrant Gap. To the east of the Sierra Nevada, geologically recent movements have occurred within the Basin and Range Province between Truckee and the California-Nevada state line. Within the Sierra Nevada the observed elevation changes have not been associated with significant seismic activity and are thus attributed mainly to aseismic deformation. Near the eastern front of the Sierra Nevada, however, the observed differences are probably related to Quaternary faulting and the more pronounced seismic activity that has occurred in the region since 1900.

Significantly, the sense of movement indicated by the leveling surveys has not been consistent; indeed, distinct reversals have occurred which suggest that periodic adjustments between major structural units may be the "normal" regimen of movement. The time elapsed between successive surveys spans too many years to determine whether the differences in elevation have accumulated during periods of more or less steady state deformation, whether they are the result of short-term episodic events, or are a combination of these. The observed elevation changes represent the condition at the time of the survey, and may not be the maximum changes that have occurred between surveys.

While the long-term trend of vertical movement in the northern part of the Sierra Nevada and other tectonically active areas of California may be one of gradual uplift, this consequence may derive from countless varied and predominantly aseismic adjustments between major individual structural units. Perhaps it is only when these adjustments cannot be accommodated by fault creep or plastic deformation that brittle failure accompanied by seismic activity occurs along zones of weakness.

Today, minor elevation changes can be measured using a global positioning system (GPS) and/or remote sensing technologies. GPS allows modern surveyors to monitor ground movement at a particular site any time of day. Satellite-borne interferometric synthetic aperture radar (IFSAR) sensors provide a stable platform for repeated elevation measuring over large areas. These and other techniques help earth scientists monitor regional surface uplift and/or subsidence. . . . *editors, 2006*



Approximate locations of principal faults and epicenters of earthquakes since 1900, of M ≥ 5 (with dates for M ≥ 6 events) in the northern Sierra Nevada: pre-1900 events are tabulated below. The Donner Pass leveling line is along the railroad from Roseville, California east to Reno, Nevada. *Relief base map from U.S. Geological Survey 90-meter digital elevation map of California*

PRE-1900 EARTHQUAKES WITHIN 60 MILES OF ALTA, PLACER COUNTY[17]

Four earthquakes in the table appear to have occurred near Grass Valley and Downieville; the other four near the eastern front of the Sierra Nevada. Because of uncertain location, the epicenters are not on the above map.

Date	Maximum Intensity	Approximate Location Latitude	Location Longitude	Remarks
1855, January 24		39.5°	-121°	A pinnacle of rock was thrown down from Downieville Buttes. Felt strongly from Gibsonville to Georgetown and Nashville, Sierra and El Dorado counties.
1867, December 1		39.5°	-121°	Strong at Nevada City, no details known.
1869, December 20		39.5°	-121°	Severe at Downieville. Felt at Grass Valley and Sacramento.
1869, December 26		39.5°	-120°	Strong at Railroad Flat. Felt at Marysville, Stockton, Sacramento, Grass Valley, Mokelumne Hill, Nevada City, and Chico, California, and at Gold Hill and Virginia City, Nevada.
1869, December 27	VI-VII	39.5°	-120°	Considerable damage at Virginia City, Genoa, Dayton, Carson City, and Steamboat Springs, Nevada. Damage was also reported at Downieville and Oroville.
1887, June 3	VII	39.0°	-120°	Stone and brick walls cracked in Carson City.
1888, April 28	VII	39.5°	-121°	Walls of courthouse cracked at Nevada City. Tops of chimneys fell at Grass Valley. Felt as far as San Francisco.
1896, January 27	VI	39.0°	-120°	Plaster fell and buildings cracked in Carson City.

PARKFIELD: CALIFORNIA'S NATURAL EARTHQUAKE LABORATORY

Charles R. Real, Geophysicist

California Geological Survey

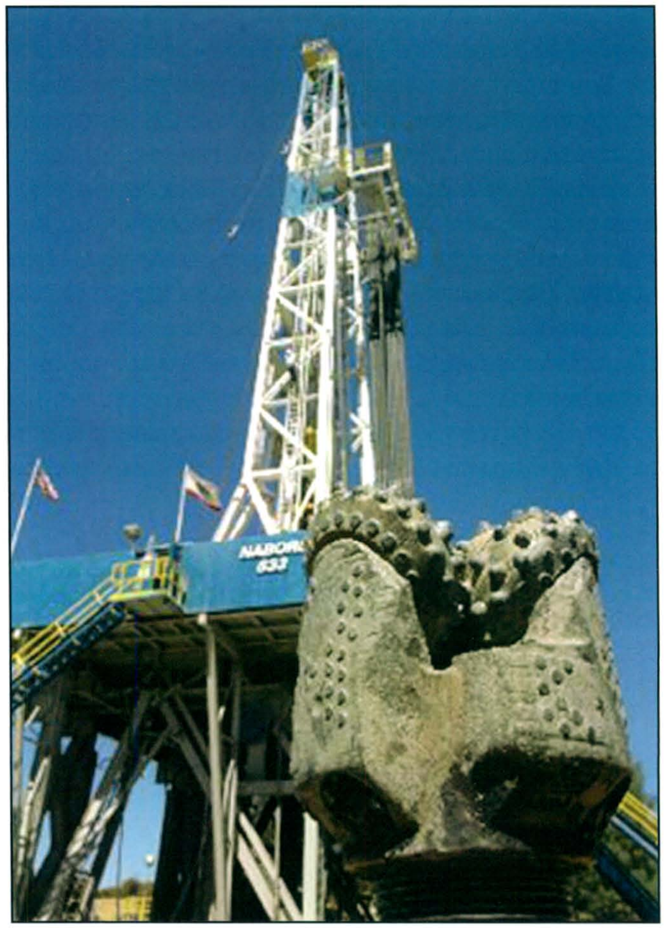
Two-color (red and blue) laser geodimeter at Carr Hill measures crustal deformation in the Parkfield vicinity. Repeated measurements of travel-time of a laser pulse from the instrument to a reflector and back allow detection of minute changes in distance (tenths of inches over distances up to about 6 miles) caused by deforming ground adjacent to the fault. *Photo by James L. Stanfield, National Geographic Image Collection.*

The tiny town of Parkfield, California, in the central California Coast Ranges, gained international attention in 1985, when it became the site of the first official earthquake prediction in the United States.[1] With a population of 34, Parkfield lies atop the infamous San Andreas fault, at a location considered by scientists to be unique. The San Andreas fault forms a boundary between the North American and Pacific crustal plates, which relentlessly grind past one another driven by heat within a revolving earth. Most segments of the San Andreas fault stay locked tight until stress, built over a few centuries, surpasses the breaking point, causing the earth's crust to suddenly slip along the fault. But the Parkfield segment lies at a transition between a locked segment, which last moved in the great 1857 Fort Tejon earthquake, and the so-called "creeping" segment to the north. The latter allows the earth's crust to "creep" imperceptibly in opposite directions on either side of the fault. Having produced several earthquakes of similar size, about magnitude (M) 5-6, on average every 22 (± 7) years, Parkfield became a natural laboratory for earthquake research. Because the last event had occurred in 1966, it was reasonable to expect another in the not-too-distant future, sometime between 1988 and 1992. Instead, the earthquake occurred on September 28, 2004.

Ground motions are recorded by digital strong-motion instruments (accelerographs) at four sites at Turkey Flat. Sensors that measure the severity of ground shaking are located on the ground surface, within valley sediments, and in bedrock beneath the valley.

Why did this event occur later than expected? Continued research on historical earthquakes near Parkfield identified previously unknown events that, when taken into consideration, reveal an overall pattern of decreasing size and frequency of earthquake occurrence. This pattern can be explained by a relaxation of the earth's crust after the M 7.9 great Fort Tejon earthquake of 1857.[2] The fault rupture for that event is thought to have originated near Parkfield, and ruptured more than 200 miles south to Cajon Pass. Although the anticipated Parkfield event occurred some 12 years later than predicted, it was still soon enough to provide a good return on the invested research, and has shed new light on the feasibility of earthquake prediction and how ground shaking varies near the causative fault.

Following the earthquake prediction, the federal government and State of California each contributed $1 million to support installation of instrumentation in what became known as the Parkfield Earthquake Prediction Experiment conducted by the U.S. Geological Survey.[3] Hours before the 1966 event, rupture of an irrigation pipe that crossed the fault suggested the possibility that carefully monitoring for such small movements might provide evidence of an impending earthquake. The Parkfield segment of the San Andreas fault soon became the most highly instrumented site for earthquake research in the world. Analysis of the voluminous data prior to and following the 2004 Parkfield Earthquake did not reveal any precursor on which to base a prediction—the event was a surprise.



The San Andreas Fault Observatory at Depth (SAFOD) drill rig and bit, used to drill to the San Andreas fault about 1.5 miles below the ground surface. Scientists hope to collect data there to study earthquake mechanics and the physical and chemical properties of the fault. *Photo courtesy of EarthScope.*

Researchers and practitioners in the U.S. and abroad are participating in the Turkey Flat "blind" test. A team from a geotechnical services company in Japan helped to determine the physical properties and subsurface configuration of the sediments and rock beneath the valley.

The success of the Parkfield Earthquake Prediction Experiment, however, is not judged on whether it accurately predicted the 2004 event, but rather on whether it definitively answered if there is measurable precursory crustal movement upon which to base an earthquake prediction. Although society would like to have discovered the Holy Grail of earthquake prediction, "no" was an important answer. Many other benefits have resulted from this experiment, including development of the ability to accurately measure, with high resolution, slow movement of the earth's crust over time, and development of public policy and procedures to evaluate, issue, and respond to an earthquake prediction.[4] From that perspective, the Parkfield experiment has been a success. Research to better understand earthquake processes is still underway in Parkfield, with the latest addition a project to drill deep into the San Andreas fault zone to examine the physical conditions within the fault zone at depth where earthquakes have occurred.[5]

Several boreholes were drilled into the sediments and rock to collect samples for laboratory testing, and to conduct field measurements. Shown is a crew conducting borehole measurements of how fast vibrations travel through the rock and sediments that make up Turkey Flat.

Distinct from the societal value of earthquake prediction is the ability to build structures that can withstand violent shaking regardless of when an earthquake occurs. Informed land-use and construction practice are currently our greatest defense against earthquake peril. Earthquake engineering and planning rely on our knowledge of how buildings behave during earthquakes and how the severity of shaking and other earthquake effects vary over the affected regions. In 1985, with the prospect of

Measurement of the speed of ground vibrations caused by a dynamite blast are made to determine the geometry of subsurface layering and other physical properties of rock and sediments that determine whether shaking from earthquake waves traveling into the valley will be either increased or subdued.

an imminent moderate earthquake, Parkfield became the top choice among sites for studying the character and causes of strong ground shaking, the greatest cause of earthquake loss. The California Geological Survey's Strong Motion Instrumentation Program installed two important arrays of instruments designed to record such motions: (1) the Parkfield Strong-Motion Array, a broad array of nearly 50 stations across the surface trace of the San Andreas fault, and (2) the Turkey Flat Site Effects Array, a 7-station array across a small sediment valley about 5 miles east of the fault.

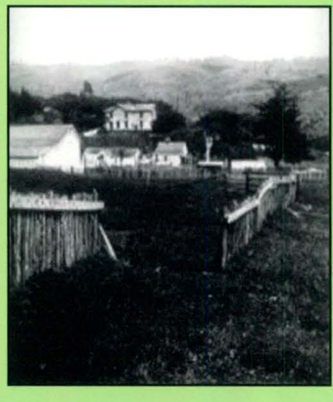
The broad array is designed to measure ground shaking very near the fault, as few such records exist in the world.[6] Such information helps scientists improve theoretical models of an earthquake to better understand how the earthquake-generating process along a fault rupture distributes strong shaking at the ground surface, and helps engineers better understand the kinds of forces that buildings near active faults must be designed to withstand. Recordings from the 2004 Parkfield event reveal a surprising factor of ten in variability of ground shaking near the fault at stations separated by only a few miles, a phenomenon not yet explained by current knowledge of earthquake processes.[7]

The smaller Turkey Flat array was designed as part of a "blind" test of contemporary methods, and results of the experiment will be used to develop new methods of estimating the effects of near surface rock and soil on ground shaking.[8] It has long been observed that earthquake damage is greater to buildings located on soft ground. How near-surface ground conditions in an area affect earthquake shaking is important to estimating the appropriate levels of resistance to which safe construction must be designed and built. Although the performance of ground shaking prediction models have been evaluated *post facto*, a true test of performance must be done without knowledge of the actual ground recorded motions, that is, without being given the answers before taking the test. Such a validation is now underway with records obtained from the 2004 Parkfield event. Engineering firms and researchers in the U.S. and abroad are participating in the test, which will reveal how well today's methods are able to predict how shallow alluvial valleys respond in an earthquake. Such sites are usually the first choice for development because of the relative ease of construction on broad flat plains compared to rugged terrain.

The Parkfield area is a natural earthquake research laboratory. In addition to what has already been learned, the vast warehouse of data from the 2004 earthquake and its aftershocks will be a valuable resource for scientific and engineering research for decades to come. There is little doubt that the decision to invest significant research dollars in the Parkfield area, based on the 1985 prediction, was a wise and profitable one.

SEISMIC HAZARD ZONATION PROGRAM

An important responsibility of the California Geological Survey is to produce Seismic Hazard Zone maps that delineate areas susceptible to liquefaction (soil failure on flat land), areas prone to earthquake-induced landslides (slope failure), and areas within which there is elevated likelihood of surface fault rupture. These areas are officially referred to as Zones of Required Investigation. Cities and counties are required by state law to withhold building permits in these zones until geotechnical investigations are conducted to assess seismic hazards on a site specific basis. If liquefaction or earthquake-induced landslide hazard is identified, appropriate design and/or ground improvement measures must be applied in order to reduce potential for structural failure. More restrictive measures are applied within earthquake fault zones, where proposed structures must be set back at least 50 feet from the traces of active faults. In all cases, real property sellers are required to check seismic hazard maps produced by CGS to determine whether property being sold falls within a seismic hazard zone. If it does, the seller is required to provide a "Natural Hazard Disclosure Statement" to the prospective buyer.



Fault rupture along San Andreas fault near Woodville, Marin County (about 3 miles north of Bolinas). Total displacement of the fence is about 11.5 feet. *Photo by G.K. Gilbert.*

A landslide triggered by the 1989 Loma Prieta earthquake blocked the northbound lanes of Highway 17 for 33 days. *Photo by T. Holzer, U.S. Geological Survey.*

CGS geologists generate seismic hazard maps for liquefaction by evaluating geologic and geomorphic data, analyzing geotechnical borehole logs to determine the engineering properties of subsurface material, estimating historically high ground-water levels, and examining local seismicity. Earthquake-induced landslide zonation is based on landslide inventories and evaluations of terrain data, stratigraphy, geologic structure and earthquake ground motion records. As of April 2006, CGS has released 112 official maps covering about 7,000 square miles. These maps show liquefaction and earthquake-induced landslide zones only. Twenty-two of the completed maps cover parts of San Francisco, Santa Clara, San Mateo, and Alameda counties (see index map on opposite page). CGS will continue producing seismic hazard zone maps for liquefaction and earthquake-induced landslides in the San Francisco Bay region until those for remaining urbanized and developing areas are completed.

On a separate series of maps, CGS geologists delineate earthquake fault zones along segments of faults where mapping demonstrates surface fault rupture has occurred within the past 11,000 years (Holocene time). Construction within these zones cannot be permitted until a geologic investigation has been conducted to verify that structures will not be built across active faults. These types of site evaluations principally address recency and recurrence of rupture along traces of the faults and are typically based on observations made in trenches excavated across fault traces.

Thus far, CGS has completed zonation for all active faults identified in the state, but continues to generate or modify zone maps for active faults as new ones are discovered or previously mapped faults are further evaluated.

Damage in the San Francisco Marina District caused by liquefaction triggered by the 1989 Loma Prieta earthquake. *Photo by D. Perkins, U.S. Geological Survey.*

Seismic Hazard Zonation of Northern California

April, 2006

Zones of Required Investigation

Liquefaction
Areas where historic occurrence of liquefaction, or local geological, geotechnical and groundwater condtions indicate a potential for permanent ground displacements such that mitigation as defined in Public Resources Code Section 2693(c) would be required.

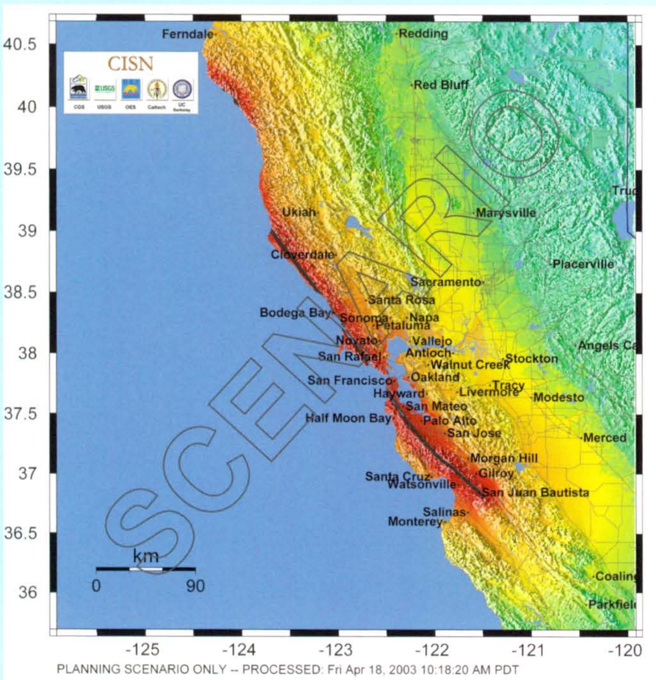
Earthquake-Induced Landslides
Areas where previous occurrence of landslide movement, or local topographic, geological, geotechnical and sub-surface water conditions indicate a potential for permanent ground displacements such that mitigation as defined in Public Resources Code Section 2693(c) would be required.

Alquist-Priolo Zones
Regulatory zones encompassing active faults so as to define those areas within which fault-rupture hazard investigations are required prior to building structures for human occupancy.

USGS 7.5 Minute Quadrangles
Used as basemaps for Official Seismic Hazard Zonation Maps

CALIFORNIA STRONG MOTION INSTRUMENTATION PROGRAM

Soon after the devastating San Fernando earthquake of 1971, legislation established the California Geologic Survey's Strong Motion Instrumentation Program (CSMIP) to record, collect, process, and distribute earthquake-generated strong motion data. To date, CSMIP has installed over 5,000 instruments known as accelerometers at about 1,100 sites statewide. These measurements provide the engineering and scientific communities with valuable data that characterize the performance of structures such as buildings, bridges, and dams during significant seismic events. This information is critical to engineers engaged in designing structures to better withstand earthquake shaking.

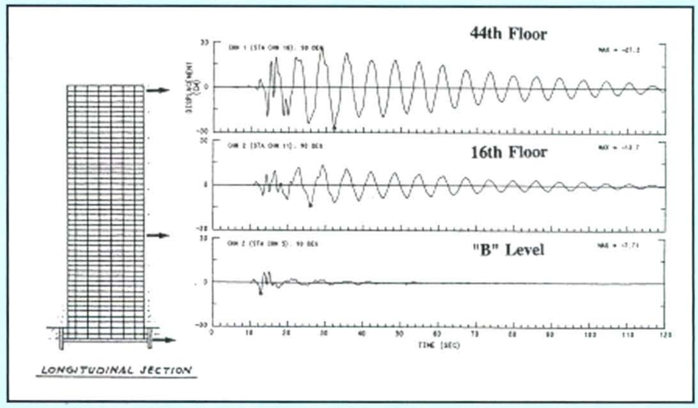


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY*	I	II-III	IV	V	VI	VII	VIII	IX	X+

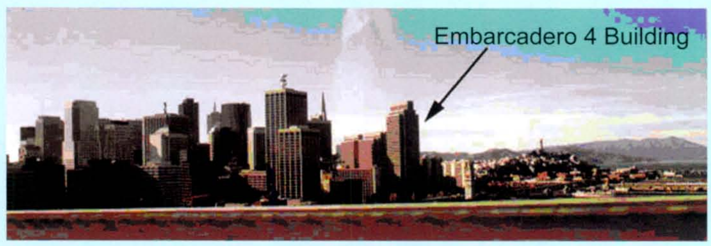
*Intensity is not the same as magnitude. Intensity is the shaking at a given point, independent of the earthquake's magnitude.

Scenario ShakeMap generated on modeled ground motions calculated for the 1906 San Francisco earthquake.

Most CSMIP instruments electronically collect and transmit strong ground motions almost as fast as they are recorded. Within minutes, system computers have automatically compiled and analyzed the incoming data to generate a preliminary version of a digital map appropriately named the ShakeMap. These maps enable agencies like the California Office of Emergency Services to quickly assess the areal extent and severity of earthquake shaking and formulate plans for appropriate levels of disaster response. CSMIP releases its rapidly derived data via the California Integrated Seismic Network, a cooperative program established by the California Geological Survey, Governor's Office of Emergency Services, U.S. Geological Survey, California Institute of Technology in Pasadena, and the University of California, Berkeley.

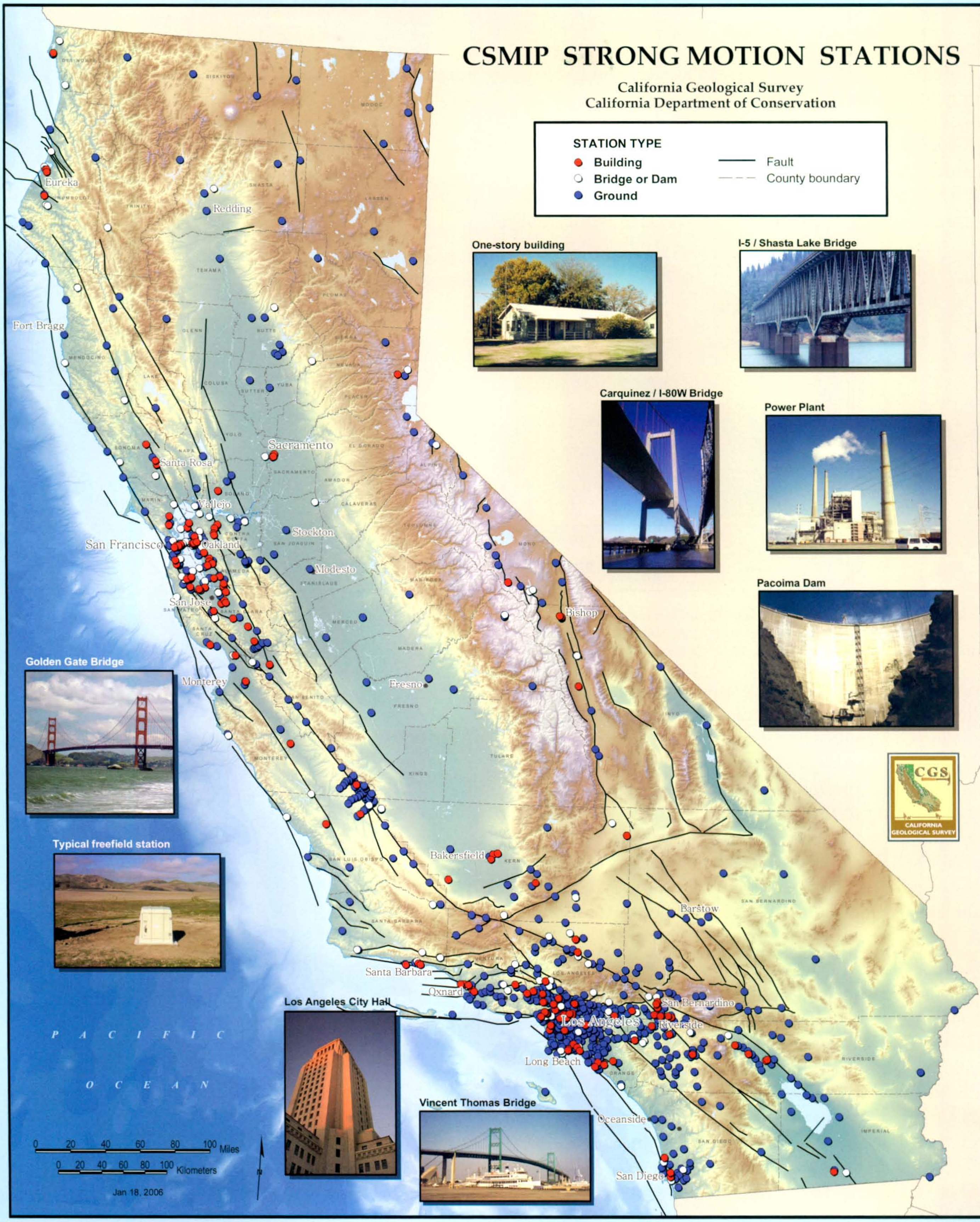


Motion of the Embarcadero 4 Building, San Francisco, as recorded by CSMIP instruments during the Loma Prieta earthquake of 1989. Time in seconds is measured along the horizontal axis. The amount of horizontal motion of the building as it swayed back and forth is given in centimeters on the vertical axes.



View of San Francisco looking west. Note the Coit Tower, middle right, and the Ferry Building, to the right and in front of the Embarcadero 4 Building. *Photo from California Geological Survey.*

One example of CSMIP instrumentation is the Embarcadero 4 Building in San Francisco. The building is a 47-story structure that the program instrumented with 18 sensors in 1987 to record building motion during earthquake shaking. The records displayed above were produced during the 1989 Loma Prieta earthquake. They show that the top floor of the building swayed back and forth every 5.5 seconds, with up to 1 foot of movement relative to its base. The shaking lasted more than two minutes. The building, which was not damaged, was designed in 1978 to allow up to 1 foot of movement to either side of center. The building rests on piles driven to depths of 150 to 200 feet. The piles penetrate about 100 feet of soft bay mud before anchoring in bedrock that adequately supports the structure's weight and greatly reduces the damaging effects of ground shaking.



Strong motion recording stations installed statewide by California Strong Motion Instrumentation Program.

SEISMIC HAZARD ASSESSMENT PROGRAM

Given its tectonic setting, earthquakes are inevitable in California. When large ones strike, they can have a significant effect on almost every aspect of people's lives. Unfortunately, a majority of the state's population lives and works near major faults that occasionally rupture, sometimes producing strong earthquake shaking. The California Geological Survey's (CGS) Seismic Hazard Assessment Program's mission is to reduce the catastrophic impact of large earthquakes by acquiring a better understanding of seismic-related processes; assessing California's active faults; delineating earthquake shaking hazards; and most importantly, disseminating that information to agencies and engineers who rely on it to improve public safety. The Seismic Hazard Assessment Program is composed of five projects: Probabilistic Seismic Hazards Mapping, Loss Estimation, School and Hospital Site Review, Tsunami Advisory, and Historical Earthquakes and Earthquake Catalog.

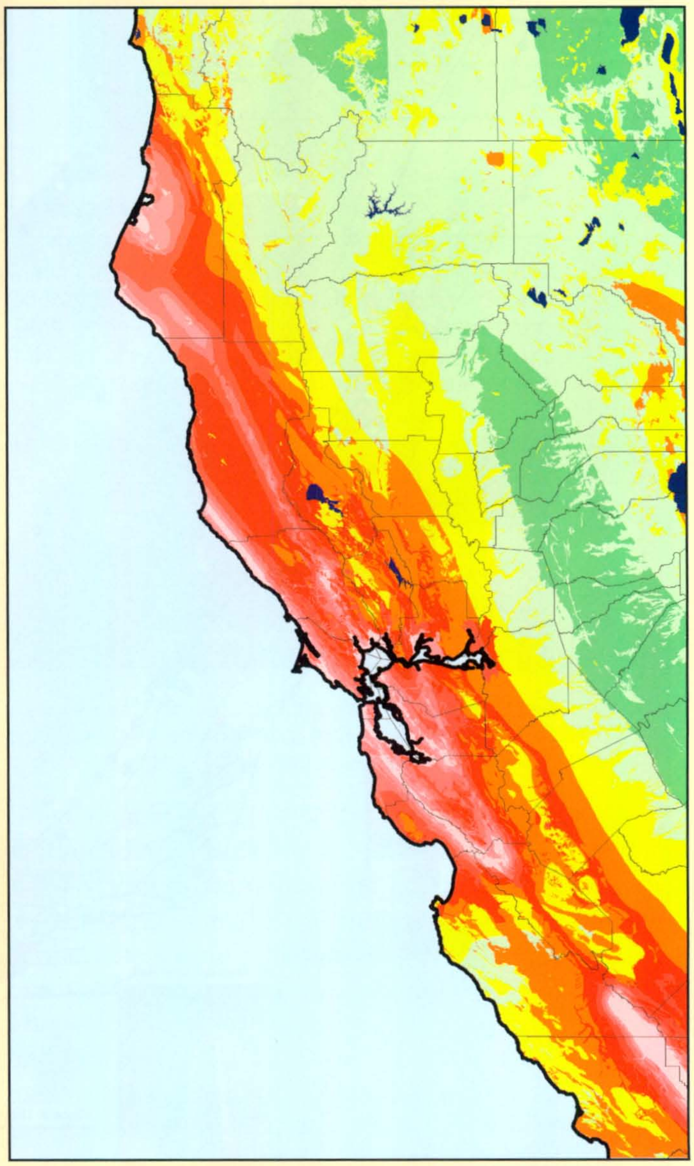
The collapse of a building in the Marina District of San Francisco was caused by liquefaction triggered by the 1989 Loma Prieta earthquake. *Photo by D. Perkins, U.S. Geological Survey.*

Probabilistic Seismic Hazards Mapping

CGS seismologists generate and maintain a statewide ground motion map derived through probabilistic seismic hazard analyses (PSHA). Analysis leading to the development of the map considers all possible sources of earthquakes and probabilities of their occurrences. The PSHA map shows ground motions that have a specific level of probability of being exceeded within a prescribed interval of time. For example, the PSHA map of northern California to the right displays ground motions that have a 10% probability of being exceeded within a 50-year period. Because they take into account both seismic and geologic site conditions, these maps provide information crucial to the construction of earthquake-resistant buildings.

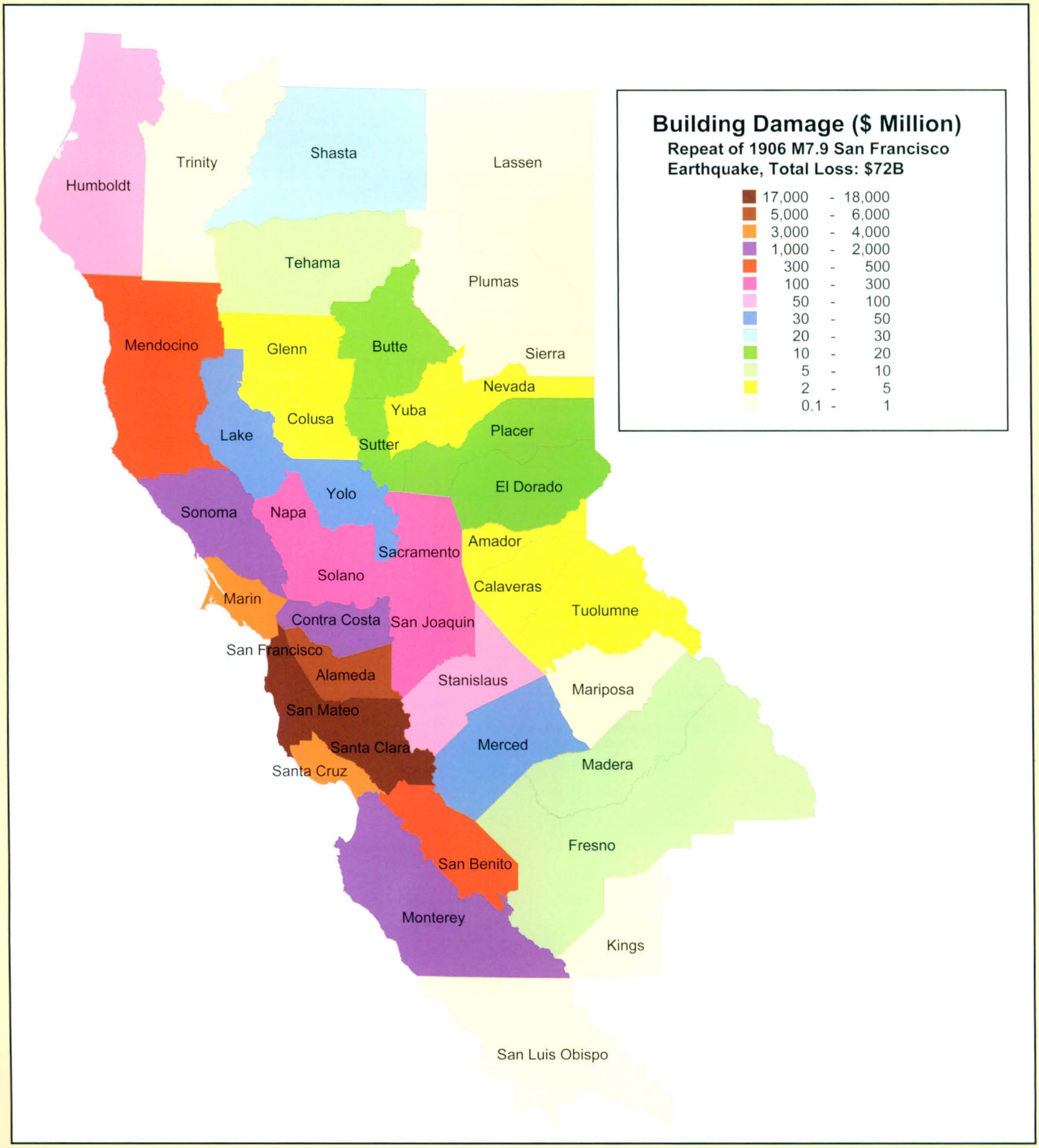
Earthquake Loss Estimation Project

The earthquake loss potential in the San Francisco Bay region has increased considerably within recent decades, mainly because of dramatic increases in population and property values. The Earthquake Loss Estimation project evaluates potential losses from future



Earthquake shaking potential map of the San Francisco Bay region derived from probabilistic analysis using 10% probability of exceedance in 50 years for one-second spectral ground acceleration. In the region covered by the map, such accelerations range from about 20% gravity (yellow) to more than 90% gravity (lightest pink).

damaging earthquakes in terms of scenario earthquakes and annualized losses, using computer modeling. For scenario analysis, CGS seismologists and engineers quantify the damage and loss in the region assuming specific earthquakes. For annualized loss, staff estimate the overall long-term damage and loss, taking into account all possible future earthquakes and their likelihood. Results reported here are limited to direct economic losses resulting from building damage. Indirect losses could be several times greater, although there is a high degree of uncertainty in the estimate. One major finding is that the largest economic loss for northern California would result from a repeat of the 1906 event, which would cause approximately $72 billion in building



damage alone. Other expected damaging earthquakes include a magnitude 6.9 event resulting from rupture of the entire Hayward fault with estimated losses of more than $26 billion, and a magnitude 7.3 earthquake caused by rupture along the entire Hayward and Rodgers Creek faults, causing an estimated building loss of over $40 billion.

Column failure and collapse of the Cypress viaduct in Oakland resulting from amplified strong shaking in soft mud underlying the structure. *Photo by H.G. Wilshire, U.S. Geological Survey.*

School and Hospital Site Review

There are more than 450 hospitals, 1,400 skilled nursing facilities, 9,200 public schools, and 110 community college campuses in California. Construction on these and future facilities is overseen by the Office of Statewide Health, Planning, and Development (hospitals and skilled nursing facilities) and the Division of the State Architect (public schools, community colleges, and essential services buildings). These facilities are by law subject to the highest building standards, so both agencies contract with the CGS to review geologic site reports prior to construction. These reviews, performed by engineering geologists, ensure that all pertinent geologic and seismic hazards have been identified for siting, site preparation, and building design purposes. Project staff review about 400 school-site geotechnical reports per year.

Tsunami Advisory

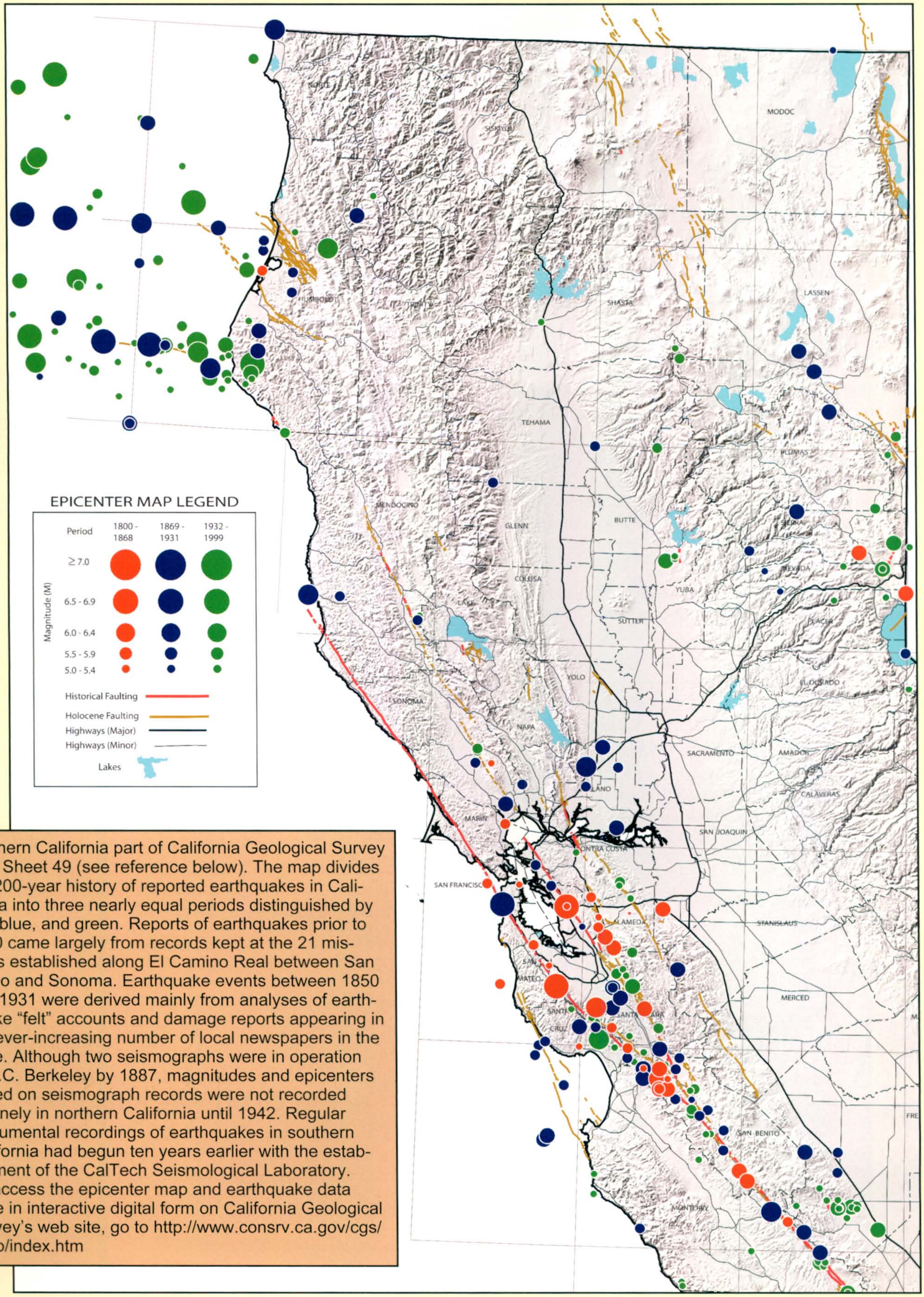
The Seismic Hazard Assessment Program includes a Tsunami Advisory project. Its primary function is to provide technical expertise to the Governor's Office of Emergency Services as part of the National Tsunami Hazards Mitigation Program and to local agencies to

The Stair tower (indicated by arrow) of the Medical Care and Treatment Building overturned and fell on the adjacent one-story section of Olive View Hospital in Los Angeles County during the 1971 San Fernando earthquake. Soon after, the California Legislature enacted the Hospital Facilities Seismic Safety Act of 1973, which regulates hospital siting and design. *Photo from California Geological Survey archives.*

assist in risk assessment and disaster planning for tsunami events. Damaging tsunamis are low-probability, high-impact events in California. Tsunamis striking the state's 1,000-mile-long coastline can be generated by submarine earthquakes, landslides, volcanic events, and meteor impacts occurring anywhere in the Pacific Ocean. The most likely cause, however, would be a major earthquake centered somewhere along offshore convergent plate boundaries (subduction zones) that extend northward from northern California to the Aleutian Islands. Such an event took place in 1964 when the magnitude 9.2 Alaskan earthquake produced a 16-foot tsunami that struck Crescent City, killing 11 people and causing considerable damage there and in other low-lying communities along the north coast.

Historical Earthquakes and Earthquake Catalog

The Historical Earthquakes and Earthquake Catalog project maintains a database of detailed information on historic earthquakes in California. The catalog is recognized as the primary source of background data used in many types of seismic studies, including those that address seismic hazards and project earthquake losses throughout the state. The project also maintains a state map displaying historic earthquakes of magnitudes greater than 5.0 (see map on opposite page). At the time of this printing, the project is set to release a digital version of the earthquake epicenter map on its web page (http://www.consrv.ca.gov/cgs/rghm/), which will enable easy access to records in the Earthquake Catalog database.



Northern California part of California Geological Survey Map Sheet 49 (see reference below). The map divides the 200-year history of reported earthquakes in California into three nearly equal periods distinguished by red, blue, and green. Reports of earthquakes prior to 1850 came largely from records kept at the 21 missions established along El Camino Real between San Diego and Sonoma. Earthquake events between 1850 and 1931 were derived mainly from analyses of earthquake "felt" accounts and damage reports appearing in the ever-increasing number of local newspapers in the state. Although two seismographs were in operation at U.C. Berkeley by 1887, magnitudes and epicenters based on seismograph records were not recorded routinely in northern California until 1942. Regular instrumental recordings of earthquakes in southern California had begun ten years earlier with the establishment of the CalTech Seismological Laboratory. To access the epicenter map and earthquake data base in interactive digital form on California Geological Survey's web site, go to http://www.consrv.ca.gov/cgs/shap/index.htm

Map from California Geological Survey Map Sheet 49: Epicenters of and Areas Damaged by M ≥ 5 California Earthquakes, 1800-1999, by T. Toppozada, D. Branum, M. Petersen, C. Hallstrom, C. Cramer, and M. Reichle, 2000.

REFERENCES

(Photos for these pages are from the 1906 earthquake, courtesy of the Museum of the City of San Francisco.)

THE 1906 GREAT SAN FRANCISCO EARTHQUAKE AND FIRE

1 Bronson, William, 1959, The earth shook, the sky burned: Doubleday and Company, Inc., Garden City, New York, 192 p.

2 Kennedy, L.J., 1908, The progress of the fire in San Francisco, April 18th-21st, 1906: Master's Thesis, University of California, Berkeley, May 1908, 26 p.

EARTHQUAKE BASICS

1 Southern California Earthquake Center, 1995, Putting down roots in earthquake country: 32 pages.

2 Lawson, A.C., *chairman*, 1908, The California earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 2 v.

3 Nakata, J.K., Meyer, C. E., Wilshire, H.G., Tinsley, J.C., Updegrove, W.S., Peterson, D.M., Ellen, S.D., Haugerud, R.A., McLaughlin, R.J., Fisher, G.R., and Diggles, M.F., 1999, The October 17, 1989, Loma Prieta, California, earthquake—selected photographs: U.S. Geological Survey Digital Data Series DDS-29, version 1.1.

4 Wallace, R.E., *editor*, 1990, The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, 283 p.

5 Wakabayashi, J., and Smith, D.L., 1994, Evaluation of recurrence intervals, characteristic earthquakes, and slip rates associated with thrusting along the Coast Range-Central Valley geomorphic boundary, California: Bulletin of the Seismological Society of America, v. 84, no. 6, p. 1,960-1,970.

6 Unruh, J.R., Loewen, B.A., and Moores, E.M., 1995, Progressive arcward contraction of a Mesozoic-Tertiary fore-arc basin, southwestern Sacramento Valley, California: Geological Society of America Bulletin, v. 107, no. 1, p. 38-53.

SAN FRANCISCO BAY AREA EARTHQUAKES

1 Rogers, T.H., 1966, Geologic map of California, San Jose sheet: California Division of Mines and Geology, scale 1:250,000.

2 Herd, D.G., 1977, Geologic map of the Las Positas, Greenville, and Verona faults, eastern Alameda County, California: U.S. Geological Survey, Open File Report 77-689, 25 p., scale 1:24,000.

3 Huey, A.S., 1948, Geology of the Tesla quadrangle, California: California Division of Mines, Bulletin 140, 75 p., scale 1:62,500.

4 Hart, E.W., 1984, Surface faulting associated with the Morgan Hill earthquake of April 24, 1984: CALIFORNIA GEOLOGY, v. 37, no. 8, p. 168-170.

5 Toppozada, T.R., Real, C.R., and Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes: California Division of Mines and Geology, Open-File Report 81-11 SAC, 182 p.

6 Armstrong, C.F., 1979, Coyote Lake earthquake, 6 August 1979: CALIFORNIA GEOLOGY, v. 32, no. 11, p. 248-251.

7 California Division of Mines and Geology, 1980, The Livermore earthquakes of January 1980: CALIFORNIA GEOLOGY, v. 33, no. 4, p. 88-92. See also p. 36-37, this 2006 special edition.

8 Toppozada, T.R., Real, C.R., and Parke, D.L., 1986, Earthquake history of California: CALIFORNIA GEOLOGY, v. 39, no. 2, p. 27-33.

NORTH COAST EARTHQUAKES

1 Real, C.R., Toppozada, T.R., and Parke, D.L., 1982, Earthquake epicenter map of California: California Division of Mines and Geology, Map Sheet 39.

2 Toppozada, T.R., Real, C.R., and Parke, D.L., 1986, Earthquake history of California: CALIFORNIA GEOLOGY, v. 39, p. 27-33.

3 Kelsey, H.M. and Carver, G.A., 1988, Late Neogene and Quaternary tectonics associated with the northward growth of the San Andreas transform fault, northern California: Journal of Geophysical Research, v. 93, no. 85, p. 4,797-4,819.

4, 5 Lawson, A.C., 1908, The California earthquake of April 18, 1906: Carnegie Institute, Washington, D.C., v. 1, p. 54-59, 165-170.

6 Toppozada, T.R. and Parke, D.L., 1982, Areas damaged by California earthquakes 1900-1949: California Division of Mines and Geology Open-File Report 82-17 SAC, 65 p.

7 TERA Corporation, 1977, Tectonic significance of large historic earthquakes in the Eureka region, September 9, 1977; unpublished report to the Pacific Gas and Electric Co., San Francisco, California.

8 Dengler, L.A., 1997, The Punta Gorda earthquake sequence, January 1997: http://www.humboldt.edu/~geodept/earthquakes/most_recent.html

9 Dengler, L.A., 1995, The Eureka earthquake, December 26, 1994: CALIFORNIA GEOLOGY, v. 48, no. 3, p. 79.

10 Kilbourne, R.T., and Saucedo, G.J., 1981, Gorda Basin earthquake, northwestern California: CALIFORNIA GEOLOGY, v. 34, no. 3, p. 53-57.

11 Gee, L.S., Uhrhammer, R.A., and Romanowicz, B., 1991, Source parameters and rupture characteristics of the Gorda basin earthquakes and their tectonic implications [abstract]: EOS, Transactions of the American Geophysical Union, v. 72, p. 312.

12 Nabelek, J., 1991, Parameters of Gorda plate earthquakes of July and August, 1991 [abstract]: EOS, Transactions of the American Geophysical Union, v. 72, p. 312.

13 Smith, S.W., McPherson, R.C., and Severy, N.I. 1981, Breakup of the Gorda Plate [abstract]: Seismological Society of America, Earthquake Notes, v. 52, p. 42.

14 Dengler, L., Carver, G., and McPherson, R., 1992, Sources of north coast seismicity: CALIFORNIA GEOLOGY, v. 45, no. 2, p. 40-53.

15 McPherson, R.C., Dengler, L.A., and Oppenheimer, D., 1991, Evidence of compressional tectonics in the King Range, California: The 1991 Honeydew earthquake [abstract]: EOS, Transactions of the American Geophysical Union, v. 72, p. 315.

16 Oppenheimer, D.H., and Magee, M.E., 1991, The 1991 M6.0 Honeydew, California earthquake [abstract]: EOS, Transactions of the American Geophysical Union, v. 72, p. 311.

17 Humboldt State University, California, Department of Geology: http://sorrel.humboldt.edu/~geodept/earthquakes/CapeMendoeqk_isoseis.gif

18 Atwater, B.F.; Satoko, Musumi-Rokkaku; Sataki, Kenji; Yoshinobu, Tsuji; Kazue, Ueda, 2005: The orphan tsunami of 1700—Japanese clues to a parent earthquake in North America: U.S. Geological Survey Professional Paper 1707; p. 78-79.

19 Satake, Kenji, Wang, Kelin, Atwater, B.F., 2003, Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions: Journal of Geophysical Research, v. 108, no. B11, 17 p.

20 Sparks, Virginia, 2003, The lost bay: Humboldt . . . the arm of the sea that wasn't there?: California Historian, Spring 2003, p. 8-12.

21 Flynn, Ray and Fletcher, Kyle, 2002, The 1700 Cascadia Subduction Zone earthquake—A tsunami strikes Japan: The Pacific Northwest Seismograph Network http://www.pnsn.org/HAZARDS/CASCADIA/historic_records.html

CENTRAL VALLEY EARTHQUAKES

1 Stover, C.W., 1983, Intensity distribution and isoseismal map in Bennett, J.H., and Sherburne, R.W., editors, The 1983 Coalinga, California earthquakes: California Department of Conservation, Division of Mines and Geology, Special Publication 66, p. 1-4.

2 Toppozada, T.R., Real, C.R., and Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes; California Division of Mines and Geology, Open File Report 81-11 SAC, 182 p.

3 Toppozada, T.R., 1975, Earthquake magnitude as a function of intensity data in California and western Nevada: Bulletin of the Seismological Society of America, v. 65, p. 1,223-1,228.

SIERRA NEVADA AND FOOTHILLS EARTHQUAKES

1 Bennett, J.H., 1978, Foothills fault system and the Auburn dam: CALIFORNIA GEOLOGY, v. 31, no. 8, p. 175-176.

2 Cramer, C.H., Toppozada, T.R., and Parke, D.L., 1978, Seismicity of the Foothills fault system between Folsom and Oroville, California: Bulletin of the Seismological Society of America, v. 68, no. 1, p. 245-249.

3 Alt, J.N., McCrumb, D.R., Schwartz, D.P., and Cluff, L.S., 1977, Characteristics of Late Cenozoic faults in the northern Sierra Nevada, California [abstract]: Geological Society of America abstracts with programs v. 9, no. 7, 877 p.

4 Schwartz, D.P., Alt, J.N., and Packer, D.P., 1977, Relationship of Paleozoic and Mesozoic structures to Late Cenozoic faulting in the northern and western Sierra Nevada, California [abstract]: Geological Society of America Abstracts with Programs, v. 9, no. 7, p. 1,165.

5 Toppozada, T.R., Parke, D.L., and Higgins, C.T., 1978, Seismicity in California, 1900-1931: California Division of Mines and Geology, Special Report 135, 39 p.

6 Cramer, C.H. and Sherburne, R.W., 1977, Microearthquake activity in the Rocklin-Penryn pluton west of Auburn, California [abstract]: CALIFORNIA GEOLOGY, v. 30, no. 6, p. 140.

7 Cramer, C.H., Sherburne, R.W., Toppozada, T.R., and Parke, D.L., 1977, A microearthquake survey of the Rocklin-Penryn pluton in the Sierra Nevada foothills west of Auburn, California: California Division of Mines and Geology, Open File Report 77-11SAC, 29 p.

8 McNally, K.C., Simila, G.W., and Von Dollen, F.J., 1978, Microearthquake activity adjacent to the Rocklin pluton near Auburn, California: Bulletin Seismological Society of America, v. 68, p. 239-243.

9 Townley, S.D. and Allen, M.W., 1939, Descriptive catalog of earthquakes of the Pacific coast of the United States 1769-1928: Bulletin Seismological Society of America, v. 29, p. 1-297.

10 Bolt, B.A. and Miller, R.D., 1975, Catalogue of earthquakes in northern California and adjoining areas, 1 January 1910-31 December 1972, seismograph stations: University of California, Berkeley, California, 567 p.

11 Cloud, W.K., 1976, Report on evaluation of seismic data in the Auburn dam area, Consultant's Report to the U.S. Bureau of Reclamation, 36 p.

12 Eaton, J.P. and Conens, S., 1977, Report on microearthquake monitoring in the vicinity of Auburn dam, April-July, 1977: U.S. Geological Survey report to the U.S. Bureau of Reclamation.

13 Eaton, J.P., McHugh, C., and Lester, F.W., 1977, Report on microearthquake monitoring in the vicinity of Auburn dam: November 1976-March 1977: U.S. Geological Survey report to the Bureau of Reclamation, 73 p.

14 U.S. Department of Commerce, 1914, Precise leveling from Brigham, Utah to San Francisco, California: U.S. Coast and Geodetic Survey, Special Publication 22.

15 Clark, L.D., 1976, Stratigraphy of the north half of the western Sierra Nevada metamorphic belt, California: U.S. Geological Survey Professional Paper 923, 26 p., scale 1:316,800.

16 U.S. Department of Commerce, 1948, United States earthquakes, 1948 (Serial No. 746): U.S. Coast and Geodetic Survey.

17 Coffman, J.L. and von Hake, C.A., 1973, Earthquake history of the United States: U.S. Department of Commerce, NOAA, publication 41-1, 208 p.

PARKFIELD EARTHQUAKES AND EXPERIMENT

1 Bakun, W.H. and Lindh, A.G., 1985, The Parkfield, California, earthquake prediction experiment: Science, v. 229, p. 619-624.

2 National Earthquake Prediction Evaluation Council Working Group, 1994, Earthquake research at Parkfield, California, for 1993 and beyond: U.S. Geological Survey, Circular 1116, 14 p.

3 California Division of Mines and Geology, 1988, The Parkfield opportunity: CALIFORNIA GEOLOGY, v. 41 , no. 3, p. 59-60.

4 Andrews, Richard and Goltz, James, 1988, Parkfield earthquake prediction experiment and public policy issues: CALIFORNIA GEOLOGY, v. 41 , no. 9, p. 208-210.

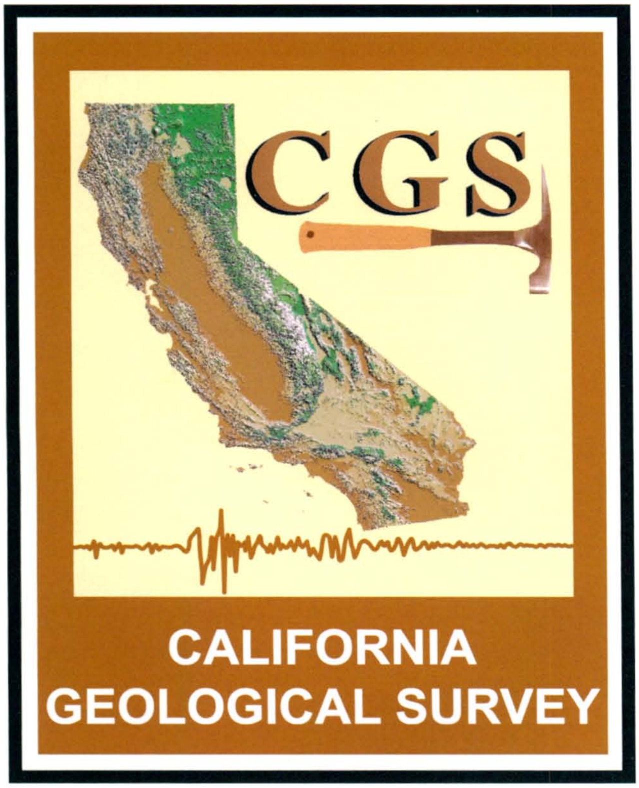
5 Hansen, Kathryn, 2005, Drilling project finds fault: Geotimes Web Extra, August 12; http://www.geotimes.org/aug05/WebExtra081205.html.

6 McJunkin, R.D. and Shakal, A.F., 1983, The Parkfield strong-motion array: CALIFORNIA GEOLOGY, v. 36, no. 2, p. 27-34.

7 Shakal, A.F., Graizer, Vladimir, Huang, Moh, Borcherdt, Roger, Haddadi, Hamid, Lin, Kuo-wan, Stephens, Christopher, and Roffers, Peter, 2005, Preliminary analysis of strong-motion recordings from the 28 September 2004 Parkfield, California earthquake: Seismological Research Letters, v. 76, no. 1, p. 27-39.

8 Sherburne, R.W., 1988, Ground shaking and engineering studies near the San Andreas fault zone, Parkfield, California: CALIFORNIA GEOLOGY, v. 41, no. 2, 32 p.

New Logo for California Geological Survey



This special edition of CALIFORNIA GEOLOGY introduces the recently adopted logo of the California Geological Survey (CGS). Some might not be aware that CGS formerly was known as the California Division of Mines and Geology. In fact, as mentioned by the State Geologist in his introduction, CGS has undergone several name changes since it was first created in 1860. These periodic changes were not the result of whimsical notions, but were made to better reflect the ever-evolving scope of the survey's mission to provide useful geologic information for the improvement of the general welfare and economy of California.

Every organization, to one degree or another, acquires and conveys a unique institutional personality that evolves through time. The character of an organization is governed not only by the collection of the people who form it, but also by ever-changing factors such as mission, technology, and practices. Such factors often are expressed in logos.

For example, the logo of the 1860 Geological Survey of California displayed to the right clearly reflects the fundamental purpose and the driving force behind the formation of the institution. Its mission was to begin surveying and mapping the vast, unexplored regions of a new state and to provide information meant to encourage development of the state's rich mineral resources—particularly gold. Note the logo's Latin phrase *ALTIORA PETIMUS*, which roughly translates to "We Reach Higher." At the time, the newly created and highly motivated survey was just beginning a task that would last through to the present time, and it set standards for those who would follow.

As expressed in the new logo, to the left, the mission and accomplishments of the Survey have increased significantly over the past 146 years. For example, the colored relief map of California signifies the survey's past accomplishments, as well as its continuing application of the latest technological advances in geologic mapping. Secondly, CGS mineral resource studies, represented by the geologist's rock pick, continue to provide valuable information to California industries, businesses, land-use planners, government agencies, and the public. Lastly, the appearance of the seismic record on the logo is reflective of the valuable contribution CGS is making in the areas of seismology, earthquake engineering, and seismic hazard mapping (see articles on CGS programs beginning on page 60).

In the spirit of the words displayed on the 1860 survey logo, today's California Geological Survey continues to "reach higher" in its efforts to provide the best geologic information possible to the people of California.