CALIFORNIA GEOLOGY

OCTOBER 1990

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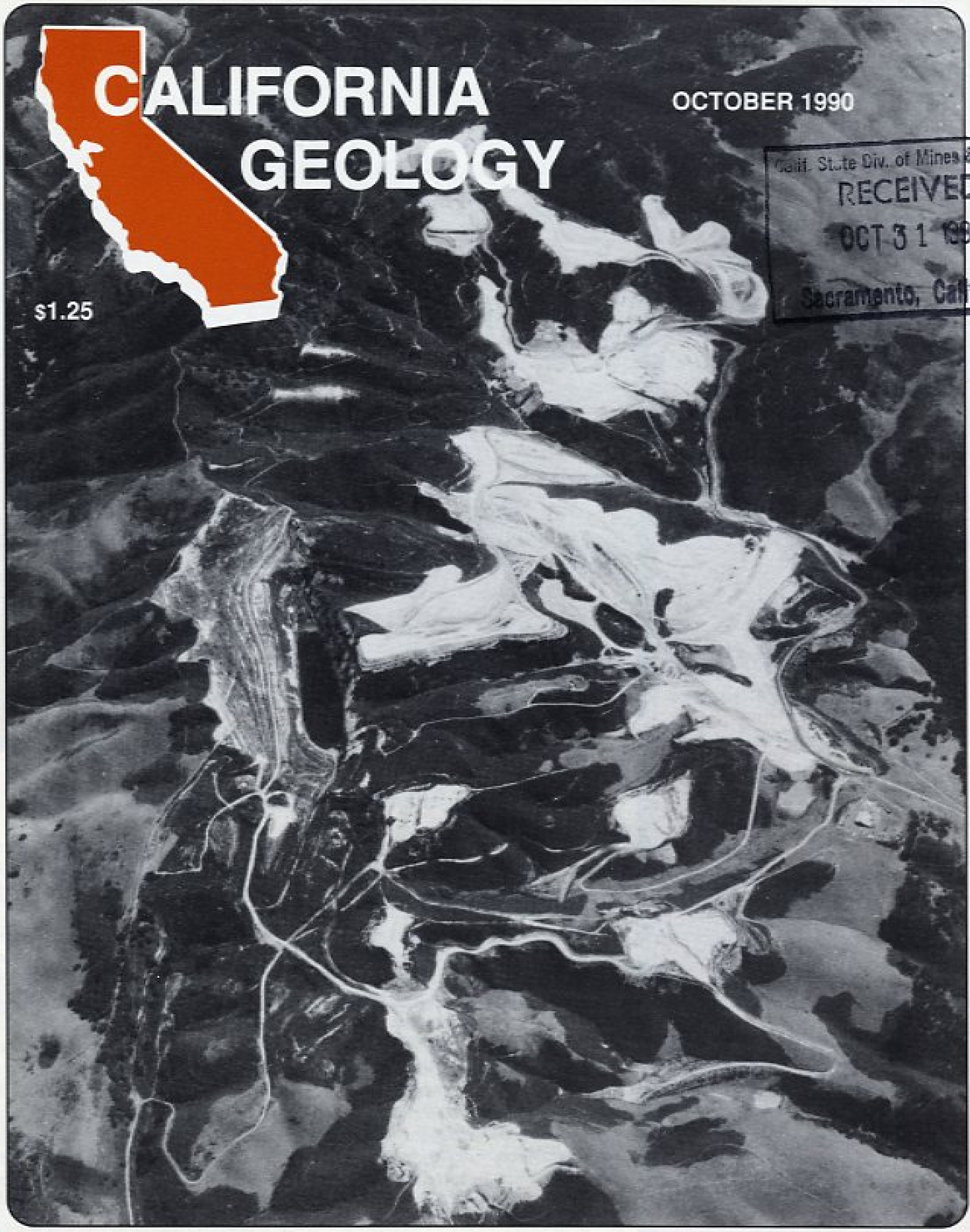

CALIFORNIA DEPARTMENT OF CONSERVATION
Division of Mines and Geology

Understanding California's Geology

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Liquefaction at Soda Lake:

Effects of the Chittenden earthquake swarm of April 18, 1990

Santa Cruz County, California

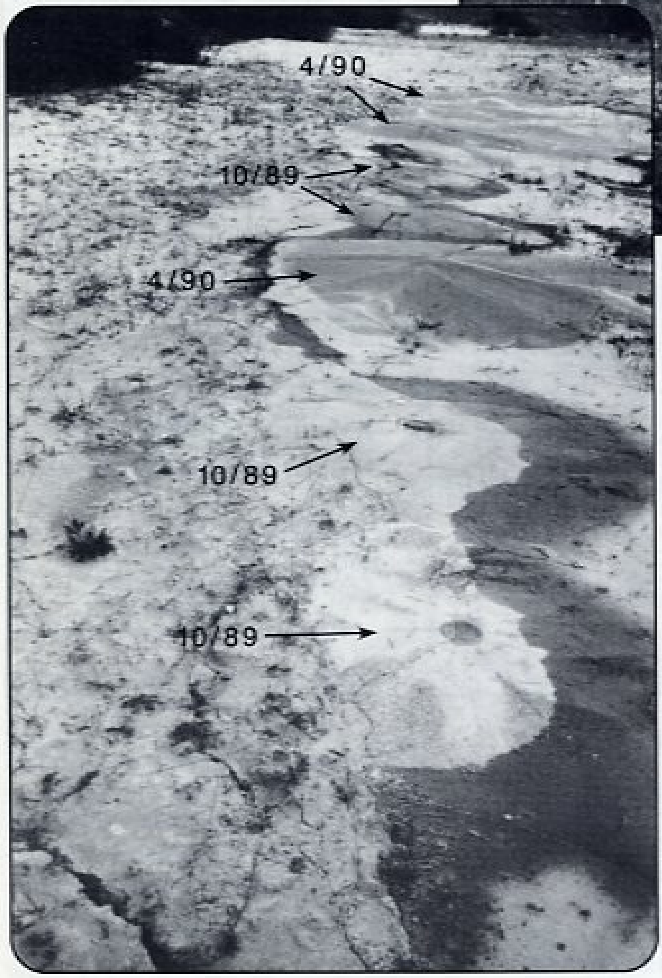
By

C.J. WILLS and M.W. MANSON, Geologists
Division of Mines and Geology

INTRODUCTION

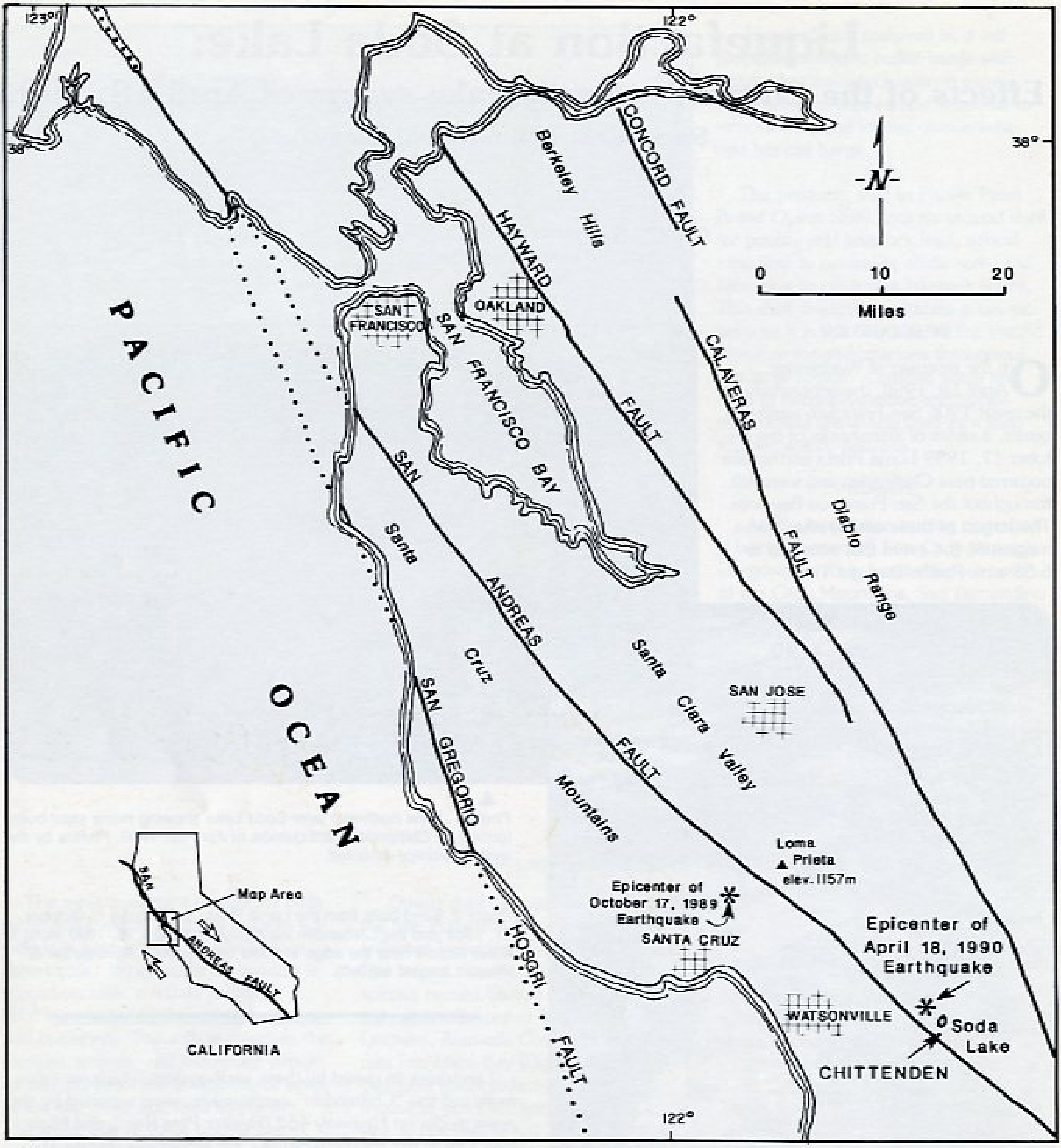
On the morning of Wednesday, April 18, 1990, the anniversary of the great 1906 San Francisco earthquake, a series of aftershocks of the October 17, 1989 Loma Prieta earthquake occurred near Chittenden and were felt throughout the San Francisco Bay area. The largest of these earthquakes was a magnitude 5.4 event that occurred at 6:53 a.m. Pacific Daylight Time.

▲ Photo 1. View northeast over Soda Lake showing many sand boils formed by Chittenden earthquakes of April 18, 1990. *Photos by the authors except as noted.*



◀ Photo 2. Sand boils from the Loma Prieta earthquake of October 17, 1989 and the Chittenden earthquakes of April 18, 1990 along a linear fissure near the edge of Soda Lake (view is from center of Photo 1 toward top left).

Landslides triggered by these earthquakes, which we informally call the "Chittenden" earthquakes, were reported by the news media on Highway 152 (Hecker Pass Road) and Highway 129 in the southern Santa Cruz Mountains (Figure 1). Because earth scientists anticipated that significant aftershocks of the Loma Prieta earthquake could cause surface rupture on the San Andreas fault, particularly if the aftershocks were shallow, and because of the reported landslides, we made a brief field reconnaissance to assess the amount of landslide damage and search for surface fault rupture. At Soda Lake, north of Chittenden, the Chittenden earthquakes caused liquefaction of deposits that had also liquefied during the Loma Prieta earthquake (Photos 1 and 2).



▲

Figure 1. Map of the San Francisco Bay area showing faults that make up the San Andreas fault system and epicenters of the Loma Prieta and Chittenden earthquakes. *Modified from Wagner, 1990.*

GEOLOGY AND LANDSLIDES

The Chittenden earthquakes occurred along the San Andreas fault at the southeast end of the Santa Cruz Mountains in the central Coast Ranges geomorphic province (Figures 1 and 2). The San Andreas fault is the major component of the San Andreas fault system and is the boundary between the North American plate and the Pacific plate. Crustal movement along the San Andreas fault in the Santa Cruz Mountains has a long-term average of about 0.52 inches (13 mm) per year (Minster and Jordan, 1987; Perkins and others, 1989).

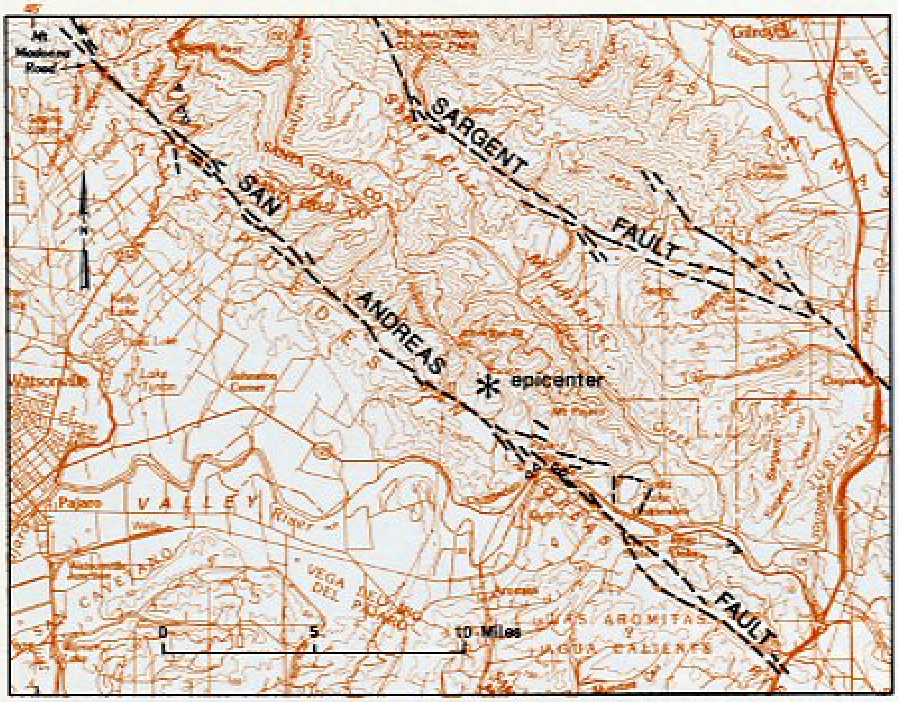


Figure 2. Active faults of the Watsonville-Chittenden area *(adapted from Bryant and others, 1981)*. Epicenter of M 5.4 earthquake, largest of the Chittenden earthquakes *(from Lindh and Lester, 1990)*. Δ = landslide or rockfall triggered by Chittenden earthquakes of April 18, 1990.

both, and locally have been cut off and displaced by fault movement (Allen, 1946; Dibblee and Brabb, 1978; Wagner, 1990).

Landslides triggered by the Chittenden earthquake swarm were minor. A shallow slump of poorly consolidated sand buried one lane of Highway 129 east of River Oaks in San Benito County. This slump and several very small debris avalanches occurred in the Tertiary Etchegoin(?) Formation (Figure 3). The debris consisted of light-brown sandy soil, bedrock blocks or fragments, brush and trees. Similar shallow slumps occurred along the banks of the Pajaro River in the same area. There were also minor rockfalls onto Highway 129 at Chittenden and in Chittenden Pass, and onto Highway 152 west of Hecker Pass. All of these minor slides on the roads, with the exception of the largest one on Highway 129, were cleaned up by California Department of Transportation crews by noon on the day of the earthquakes.

LEGEND

Quaternary	Qal	alluvium
	Qls	landslide debris
	Qoa	older alluvium
	Qa	Aromas sand
	Qtp	Paso Robles Formation
Tertiary	Te	Etchegoin Formation
	Tp	Purisima Formation
	Tmp	shale of Mt. Pajaro area
Cret.	qg	hornblende quartz-gabbro
		geologic contact
		active fault
		dike around margin of Soda Lake

Bedrock units in the Soda Lake area are quite different on either side of the fault (Figure 3). Northeast of the fault the units are dominantly fine-grained marine sedimentary rocks of Tertiary age. Southwest of the fault, bedrock consists of Mesozoic hornblende quartz-diorite overlain by Quaternary and Tertiary eolian sand, and both marine and non-marine sand and gravel. These units have been fractured or folded or

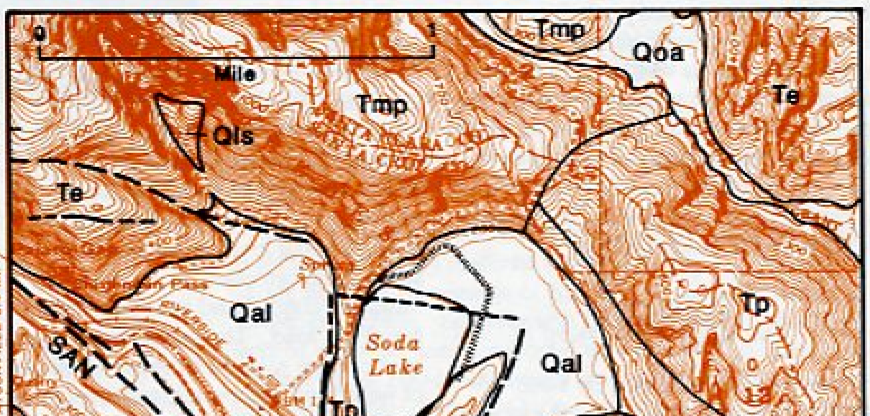


Figure 3. Geologic map of the Soda Lake area *(from Dibblee and Brabb, 1978)* with traces of active faults *(by Bryant and others, 1981)*.

FAULT RUPTURE SEARCH

The San Andreas fault cuts through the southern Santa Cruz Mountains, where it has formed a series of right-laterally offset drainages, side-hill benches, and scarps. Following the Chittenden earthquakes, we checked as much of the fault in the quake epicentral area as possible for surface rupture. State Highways 129 and 152, Mount Madonna Road, and Green Valley Road all cross the San Andreas fault east of Watsonville. All of these roads were damaged in the Loma Prieta earthquake by slumping of road fill and pavement cracking that was commonly perpendicular to the roadway. The cracks on Mount Madonna Road in October 1989 suggested right-lateral faulting, although they may have been due to down-slope movement of the road fill (Hart and others, 1990). The Chittenden earthquakes caused some longitudinal cracks in the pavement of Highway 152 to re-open slightly but no new cracks were observed along the trend of the fault at any of the road crossings.

Following the reconnaissance of the paved roads, a section of the San Andreas fault that crosses pasture land east of Watsonville was examined. This segment of the fault is well defined by a series of tectonically produced geomorphic features such as fault scarps, offset drainages, and sidehill benches. There were some minor shaking cracks in a dirt road within the fault zone, but no cracks that indicated right lateral faulting.

Photo 3. "Flowing" sand boil. At about noon on April 18, 1990 several sand boils were still active. When this photo was taken, water was still issuing from the central crater of this sand boil and flowing evenly over all sides of the volcano-shaped mound (note ripples on the sides of the sand boil).

LIQUEFACTION AND RELATED EVENTS

Liquefaction is defined by Youd (1973) as the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore pressure (pressure exerted by groundwater within the voids among mineral grains in soil, alluvium, and bedrock). It is a relatively common earthquake-related phenomenon in Holocene sediments (Youd and Hoose, 1977). It can be induced by rapid application of stresses that result in increased pore pressure by pore water migration.

The stresses that produce liquefaction may be natural (shaking from earthquakes or volcanic eruptions) or artificial (vibrations from heavy equipment or blasting). Vibration of a saturated, porous sand or silt causes pore water to migrate toward the direction of least confinement. If pore water cannot escape, pore pressures can approach the lithostatic pressure (the weight of the overlying sediment). When liquefaction occurs, the saturated sediment no longer acts as a solid but becomes a liquid with suspended mineral grains. Such material loses its internal resistance to deformation by shearing (or "shear strength") and can no longer support a load. The excess pore pressure may be relieved by rapid ejection of water and sediment in suspension to the ground surface to form sand boils (also known as sand blows or sand volcanoes), or by lateral spreading or hydraulic fracturing.

Simultaneous measurements of seismically induced pore pressure changes and ground accelerations at a site in Imperial County that was undergoing liquefaction during an earthquake indicated that total pore pressures approached the weight of overlying sediments after most of the strong motion ceased, and excess pore pressures were generated once horizontal acceleration exceeded a threshold value (Holzer and others, 1989). The Imperial County site did not undergo liquefaction during earlier earthquakes with measured peak accelerations of less than 18 percent of the force of gravity (gravitational acceleration is 32 feet per second per second), but did so when the triggering earthquake had a peak acceleration of 21 percent gravity. The unexpected delay in recorded onset of liquefaction (until after the strong motion ended) was attributed by the researchers to redistribution of pore pressures throughout the deposit.

Liquefaction occurred in many places at the time of the Loma Prieta earthquake. It was extensive along Monterey Bay, Soda Lake, and the Pajaro River and caused severe damage to the Moss Landing Marine Laboratory of the California State Universities and Colleges. Farther away from the epicentral area, the Marina District of San Francisco, Treasure Island, the eastern approach to the San Francisco-Oakland Bay Bridge, and the Port of Oakland were heavily damaged, partly as a result of liquefaction (Earthquake Engineering Research Institute, 1989; Plafker and Galloway, 1989).

Photo 4. Sand boil formed by the Loma Prieta earthquake (central fissure in foreground) with two sand boils that were erupted on April 18, 1990, possibly from the same fissure.

SODA LAKE

The Loma Prieta earthquake caused sand boils to erupt from the dry bed of Soda Lake. The volcano-shaped (conical) sand deposits were as large as 10 feet in diameter by 1 foot high. Water continued to flow from several sand boils for four days after the main shock. The sand boils tended to be clustered along fissures, some of which paralleled the edge of the lakebed. Violent shaking from the Loma Prieta earthquake also caused the entire lakebed to subside; fissures and scarps along the edge of the lake indicated that the lakebed sank as much as four feet during the earthquake (Manson and others, in progress). The loose sandy sediment consolidated, becoming both denser and more compact. This permanent consolidation of the sandy material reduced the amount of pore space and should have made the deposit less prone to future liquefaction.

There are no reports of liquefaction in Soda Lake caused by the April 18, 1906 San Francisco earthquake, although severe ground shaking in the surrounding area was documented (Lawson and others, 1908; Youd and Hoose, 1978). At Chittenden, several buildings were shifted off of their foundations and the Southern Pacific Railroad bridge over the Pajaro River was shifted three feet away from one of its abutments. A large landslide was triggered at the mouth of a canyon just west of the lake, and there was severe liquefaction and fissuring in the Pajaro River and the Salinas River. Soda Lake was probably full of water during the 1906 earthquake, which followed a winter of above normal rainfall (Lawson and others, 1908, p. 399).

Extensive liquefaction occurred at Soda Lake as a result of the Chittenden earthquakes (maximum magnitude 5.4). Much of the 66-acre lakebed was covered by fissures and sand boils (Photos 1-4). The lakebed area affected by this episode of liquefaction was as extensive as that resulting from the Loma Prieta earthquake (magnitude 7.1). There have been no reports of renewed liquefaction from other localities where it occurred in October 1989. Apparently, the relatively small earthquakes of April 1990 were strong enough to cause liquefaction only in the immediate epicentral area and the deposits in Soda Lake may be especially susceptible to liquefaction.

Soda Lake was originally a natural lake in an abandoned meander bend of the Pajaro River (Jenkins, 1973). The surficial deposits and the material that formed the sand boils (Photo 5) appear to be tailings from the Granite Rock Company's Wilson quarry 0.6 mile west of the lake (for a description of this quarry see Higgins, 1989). The material being quarried by Granite Rock Company is hornblende quartz-diorite (Dibblee and Brabb, 1978). Capacity of the natural lake was increased by the construction of dikes along part of its shoreline and the lake was used as a tailings pond for very fine-grained quarry tailings from 1968 to the mid-1980s (Bruce Woolpert, Jr., Granite Rock Company, personal communication, 1990).

Grain-size analysis of the material erupted from the sand boils shows that the material that liquefied is a well-sorted sandy silt, with an average of 87 percent passing through a 200-mesh screen. Screen mesh numbers indicate the numbers of wires per inch for woven wire screens, particles passing through a 200-mesh screen are less than 0.074 mm in diameter (Table 1, Photo 6). An average of about 10 percent fine sand was also erupted from the sand boils, along with a very small percentage of clay.

If the effects of liquefaction can produce denser deposits, why has Soda Lake undergone repeated (at least two) episodes of liquefaction? There are numerous reported instances of repeated liquefaction at many sites and in the laboratory (Borchardt and Kennedy, 1979, p. 217). It is not unusual for a sand sample to have a cyclic reaction to applied strain; the sample liquefies then solidifies in less than one second. As long as pore water drainage is blocked, the sample (or natural deposit) can liquefy again and again (Youd, 1973, p. 3).

The sediments at Soda Lake are probably susceptible to liquefaction for the following five reasons:

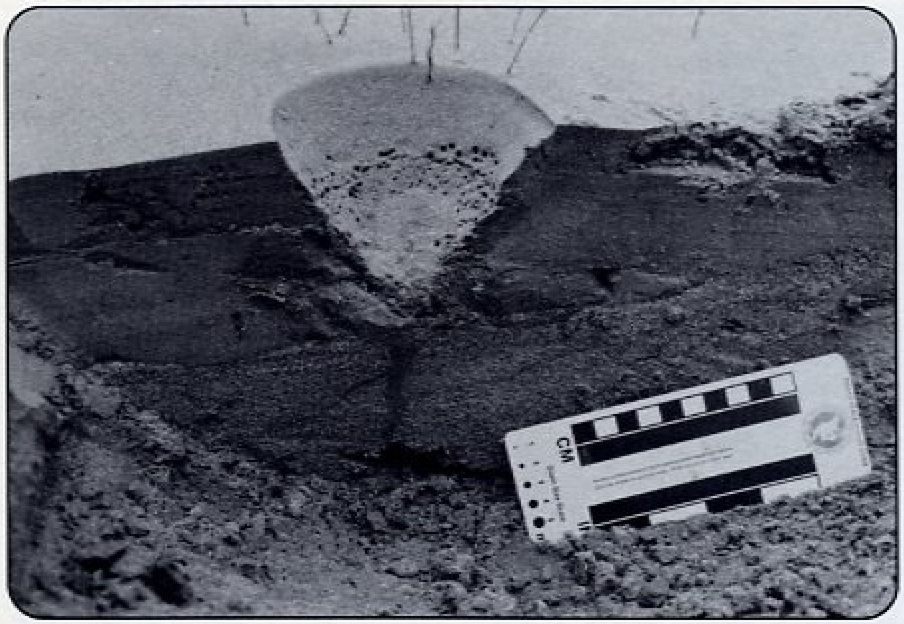


Photo 5. Cross section of a sand boil formed at Soda Lake by the Loma Prieta earthquake. Note "feeder dike" of fine sand below vent and fine layering within the sand boil. *Photo by W.A. Bryant.*

(1) The deposits have a uniform grain size and almost total lack of cohesive clays that would tend to bind the particles together. The grain-size analysis (Figure 4) shows that these sediments plot within the range of "potentially liquefiable soil" though not within the "most liquefiable soil" range.

(2) They were emplaced as a "hydraulic fill" that was deposited in and settled out of a still body of water. Prior to the Loma Prieta earthquake this fill had not been compacted. In this way, the fill at Soda Lake is similar to the fill that underlies much of the San Francisco Marina District. The hydraulic fill underlying the Marina Disrtict also underwent extensive liquefaction during the Loma Prieta earthquake, which contributed to the wide-spread damage to buildings. The Marina District fill is coarser than the material at Soda Lake but similar in its uniform grain size and lack of cohesive clays (Bonilla, 1990).

(3) The Soda Lake deposits are probably saturated, even when the lake appears dry, because it is a natural basin. The level of the water table (depth to groundwater beneath the land surface) may be just below the surface of the lakebed. Any addition of rainwater and the water expelled by liquefaction seeps back into the deposit.

(4) Soda Lake lies within the Modified Mercalli (M-M) VII intensity zone for the Loma Prieta earthquake (Plafker and Galloway, 1989). Lateral spreading or flows caused by liquefaction have occurred in areas with intensities of M-M V to M-M XI, with the greatest proportion (9 of 22 events, or 41 percent) lying within M-M VII zones (Keefer, 1984). The lower peak acceleration and shorter duration of strong shaking associated with a M 5.4 earthquake, compared to a M 7.1 earthquake, presumably is much less likely to cause liquefaction.

Keefer (1984) constructed a chart based on data from several hundred earthquakes showing the distance of liquefaction effects from the source fault rupture zones. From Keefer's chart, a magnitude 5.4 earthquake should cause liquefaction no farther than 3.7 miles from its hypocenter. Soda Lake is about 3.7 miles from the hypocenter of the largest Chittenden earthquakes (hypocenter data from Lindh and Lester, 1990).

(5) Shaking from the Loma Prieta earthquake may have caused uneven consolidation of the sediments, compacting portions of the deposit but not affecting others. A model for repeated liquefaction of a deposit due to partial compaction has been proposed (Finn and others, 1970) and is summarized as: "A series of small previous shakings either too weak to cause liquefaction or just barely strong enough to cause [initial liquefaction], allows the soil to densify

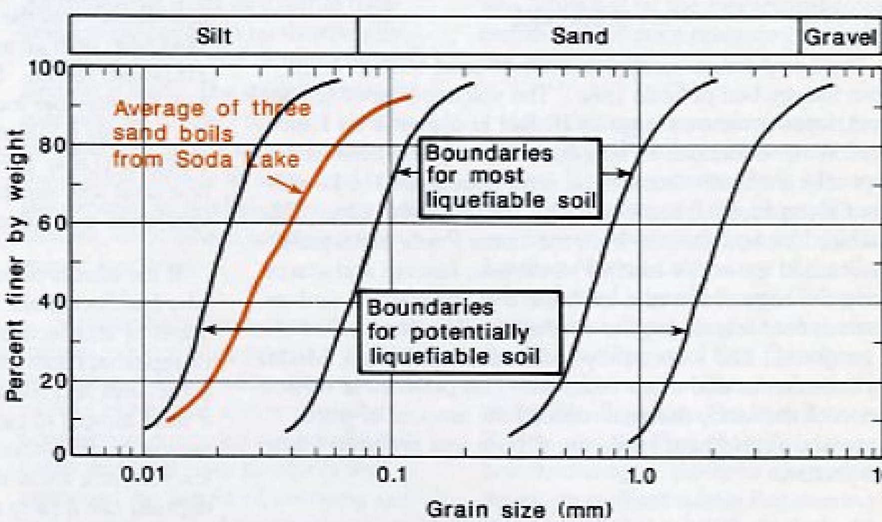


Figure 4. Grain size distribution of the average of three samples taken from Soda Lake sand boils plotted on chart showing "most liquefiable" and "potentially liquefiable" soil. *By Tsuchida, 1970, as reprinted in Housner and others, 1985.*

uniformly and increases subsequent resistance to liquefaction. However, a very strong shaking may cause uneven densification, leaving a topmost looser layer with increased susceptibility to liquefaction" (Housner and others, 1985, p. 58).

CONCLUSIONS

The earthquakes of April 18, 1990 occurred on the anniversary of the 1906 quake and six months after the Loma Prieta event. They were a distinct reminder to the people of the San Francisco Bay area of the earthquake hazards associated with the San Andreas fault system. No surface rupture and relatively little landsliding occurred during the April 18 event, but the earthquakes did cause liquefaction of a sandy silt deposit in Soda Lake that had also liquefied as a result of the Loma Prieta event in October, 1989.

The liquefaction of this deposit from a relatively small earthquake with a relatively short period of strong shaking shows that the hydraulically emplaced deposits of Soda Lake are especially susceptible to liquefaction, even after they were made more dense by liquefaction during the October 17, 1989 earthquake. This repeated liquefaction of a hydraulic fill at Soda Lake suggests that repeated liquefaction of similar hydraulic fills around the margins of San Francisco Bay is also possible. Future earthquakes in the San Francisco Bay area could cause repeated liquefaction of the deposits that the Loma Prieta earthquake showed to be susceptible to liquefaction, such as those underlying the Marina District and along the eastern margin of San Francisco Bay.

ACKNOWLEDGMENTS

We wish to thank Mark Molinari, of Dames and Moore, Inc., who brought the liquefaction at Soda Lake to our attention following the Loma Prieta earthquake. We also wish to thank J. David Rogers of Rogers-Pacific Inc., Pleasant Hill, California for test data and review of this article. Analyses were performed by F.H. Chin of Rogers-Pacific Company on samples collected by personnel of the Division of Mines and Geology and Rogers-Pacific Inc.

TABLE 1. GRAIN SIZE ANALYSIS OF THREE SAMPLES FROM SODA LAKE SAND BOILS. *Adapted from F.H. Chin and J.D. Rogers written communication, 1990.*

Screen size*	% Retained on screen /Cumulative % passing**			
	Sand Boil 1	Sand Boil 2	Sand Boil 3	Average
No. 10				
No. 20	0.04/99.95	0.02/99.98	0.03/99.97	0.03/99.97
No. 40	0.02/99.93	0.12/99.86	0.40/99.57	0.18/99.78
No. 60	0.04/99.89	0.83/99.03	0.92/98.65	0.60/99.19
No. 140	3.19/96.70	8.59/90.44	5.05/93.60	5.61/93.58
No. 200	5.09/91.61	7.64/82.80	5.24/88.36	5.99/87.59
Pan	91.61	82.80	88.36	87.59

* Screen size indicates the number of wires per inch for woven wire mesh.
** Totals may not equal 100% due to rounding.

Photo 6. Electron micrograph of silt grains that erupted from a sand volcano at Soda Lake. Bar scale is in microns. *Photo taken at the U.C. Davis Facility for Advanced Instrumentation.*

REFERENCES

Allen, J.E., 1946, Geology of the San Juan Bautista quadrangle, California: California Division Of Mines Bulletin 133, p. 75, 2 plates, scale 1:62,500.

Borchardt, G.A. and Kennedy, M.P., 1979, Liquefaction potential in urban San Diego: A pilot study: CALIFORNIA GEOLOGY, v. 32, no. 10. p. 217-221.

Bonilla, M.G., 1990, Natural and artificial deposits in the Marina District, *in* U.S. Geological Survey, Effects of the Loma Prieta earthquake on the Marina District, San Francisco, California: U.S. Geological Survey Open File 90-253.

Dibblee, T.W., Jr., and Brabb, E.E., 1978, Preliminary geologic maps of the Chittenden, Los Gatos, and Watsonville east quadrangles, California: U.S. Geological Survey Open File Report 78-453, 3 sheets, scale 1:24,000.

Earthquake Engineering Research Institute, 1989, Loma Prieta earthquake—October 17, 1989: Preliminary reconnaissance report: El Cerrito, California, 51 p.

Finn, W.D.L., Bransby, P.L., and Pickering, D.J., 1970, Effects of strain history on liquefaction of sands: Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, 96 (SM6), p. 1917-1934.

Hart, E.W., Bryant, W.A., Wills, C.J., and Treiman, J.A., 1990, The search for surface faulting and significance of ridgetop fissures, *in* S. McNutt and R.H. Sydnor, editors, The Loma Prieta earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology Special Publication 104, in press.

Higgins, C.T., 1989, Arthur R. Wilson quarry—where nature gives man a break: CALIFORNIA GEOLOGY, v. 42, no. 11, p. 256-259.

Holzer, T.L., Youd, T.L., and Hanks, T.C., 1989, Dynamics of liquefaction during the 1987 Superstition Hills earthquake, California, Science, v. 244, p. 56-59.

Housner, G.W. and the Committee on Earthquake Engineering, National Research Council, 1985, Liquefaction of soils during earthquakes: National Academy Press, Washington, D.C., 240 p.

Jenkins, O.P., 1973, Pleistocene Lake San Benito: CALIFORNIA GEOLOGY, v. 26, no. 7, p. 151-163.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

Lawson, A. C., and others, 1908, The California earthquake of April 18, 1906; Report of the State Earthquake Investigation Commission: Carnegie Institute of Washington Publication 87, 2 volumes, 452 p.

Lindh, A. and Lester, R., 1990, Weekly earthquake report for the San Francisco Bay area, 16—23 April, 1990: U.S. Geological Survey, 5 p.

Manson, M.W., Keefer, D.K., and McKittrick, M.A., compilers, Landslides and other geologic features in the Santa Cruz Mountains, California, resulting from the Loma Prieta earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology Preliminary Report 29, in progress.

Minster, J.B., and Jordan, T.H., 1987, Vector constraints on western U.S. deformation from space geodesy, neotectonics, and plate motions: Journal of Geophysical Research, v. 92, no. B6, p. 4798-4804.

Perkins, J.A., Sims, J.D., and Sturgess, S.S., 1989, Late Holocene movement along the San Andreas fault at Melendy Ranch: Implications for the distribution of fault slip in central California: Journal of Geophysical Research, v. 94, no. B8, p. 10,217-10, 230.

Plafker, G. and Galloway, J.P., editors, 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Tsuchida, H., 1970, Prediction and countermeasure against the liquefaction in sand deposits: Abstract of the Seminar in the Port and Harbor Research Institute, p. 3.1-3.33 (in Japanese).

Wagner, D.L., 1990, Geologic and tectonic setting of the epicentral area of the Loma Prieta earthquake, Santa Cruz Mountains, central California, *in* S. McNutt and R.H. Sydnor, editors, The Loma Prieta earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology Special Publication 104, in press.

Youd, T.L., 1973, Liquefaction, flow, and associated ground failure: U.S. Geological Survey Circular 688, 12 p.

Youd, T.L., and Hoose, S.N., 1977, Liquefaction susceptibility and geologic setting: Proceedings of the Sixth World Conference on Earthquake Engineering, v. 3, p. 2189-2194, Prentice Hall, Inc.

Youd, T.L., and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, 177 p. ⚒

CALIFORNIA GEOLOGY Welcomes New Editor

CALIFORNIA GEOLOGY *is pleased to welcome Lena Tabilio to its staff. Lena, a graduate of the University of San Francisco, will assist the Technical Editor in researching, editing, and writing articles.*

Lena comes to State service after 13 years of private industry and freelance technical and promotional writing experience. She also has an extensive marketing and public relations background. ⚒