The Loma Prieta, California, Earthquake of October 17, 1989—Hydrologic Disturbances

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STRONG GROUND MOTION AND GROUND FAILURE

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HYDROLOGIC DISTURBANCES

INTRODUCTION

By Stuart Rojstaczer,
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Seismic events have long been known to cause changes in the level of oceans, streams, lakes, and the water table. The great San Francisco earthquake of 1906 induced significant hydrologic changes (Lawson, 1908) that were qualitatively similar to those changes observed for the Loma Prieta earthquake. What is different is that the hydrologic data sets collected from the Loma Prieta event have enough detail to enable hypotheses on the causes for these changes to be tested. The papers in this chapter document changes in ocean level, stream morphology and flow, water table height, and ground-water flow rates in response to the earthquake. Although hydrologic disturbances may have occurred about 1 hour before the main shock (Roeloffs, 1993), the papers in this chapter deal strictly with postevent hydrologic changes. The hydrologic responses reported here reflect changes that are not the result of surface rupture. They appear to be the result of landslides, the static displacements induced by the earthquake, and changes in the permeability of the near surface.

The Monterey Bay tsunami is examined by Ma and others. They use elastic half-space models of the earthquake in conjunction with a finite difference model of tsunami motion in Monterey Bay to examine the origin of the tsunami. The waveform of the tsunami cannot be explained solely by the static displacement of the ocean floor induced by the earthquake. To mimic the observed response, Ma and others include earthquake-induced slumping of 0.01 km^3 of sediment into the ocean from Moss Landing.

The response of stream morphology to San Andreas fault motion is the subject of Harden and Fox. Stream channels in the Santa Cruz Mountains have been altered by prehistoric earthquakes in this region. Harden and Fox have made repeat surveys of a channel within Fern Canyon. This channel was chosen for detailed study because it shows evidence of geologically recent disruption by the San Andreas fault and because it has a relatively straight channel that enters the fault zone at a right angle. The surveys indicated that the channel elevation increased along a 30-m segment upstream of the fault. The middle 17 m of this reach showed an average of 28 cm of aggradation; the aggradation appears to reflect a decrease in the gradient upstream of the fault. The postearthquake surveys of this channel suggest that earthquakes without significant surface rupture may induce changes in stream-channel morphology that, over geologic time, can produce the offset streams characteristic of the San Andreas fault. Tectonic deformation of stream channels occurs at a faster rate than the ability of the channel to readjust by aggradation or erosion.

Changes in the magnitude of streamflow in response to the Loma Prieta earthquake are well documented and are the subject of three papers in this volume. Briggs examines changes in stream flow in Waddell Creek. The earthquake induced a transient increase in discharge in the Creek and associated springs that exponentially declined over a period of one to two months following the earthquake. Spring flow at higher elevations ceased at an earlier time than spring flow at lower elevations suggesting that the water table elevation declined over time.

On a regional scale, Curry and others state that verifiable changes in stream discharge were noted as far away as 88 km from the epicenter. Increases in flow that persisted for several months following the earthquake were restricted to the Santa Cruz Mountains and San Francisco peninsula. The source of this water appears to be the ground-water system. Chemical analyses of about 100 surface water and ground-water samples demonstrated modest increases in ionic concentration in some, but not all, sampled waters.

The ground-water and surface-water response of the San Lorenzo and Pescadero drainage basins is discussed by Rojstaczer and Wolf. Streamflow increased at most gaging stations within 15 minutes after the earthquake. Groundwater levels in the highlands parts of the basins were locally lowered by as much as 21 m within weeks to months after the earthquake. Streamflow reduction in these basins followed an exponential rate similar to that shown by Briggs. In the San Lorenzo basin, changes in stream chemistry were significant. Although cation/anion ratios of the major constituents remained relatively constant, overall ionic concentrations and the calcite saturation index of the streamwater increased. Solute concentrations declined significantly within several months after the earthquake.

Although increases in stream and spring flow have been sometimes ascribed to fluid sources from the midcrust, the cause of streamflow increases examined in three of the papers described above appears to be a permeability increase of the near-surface aquifers and aquitards. Hence, the observed ground-water and surface-water response are not apparently coupled to the earthquake-generation process. The permeability increases seem to persist for a period longer than the time of increased streamflow. Rojstaczer and Wolf present a simple diffusional model that mimics the observed streamflow and ground-water changes. The cause for the permeability increases is not known. Curry and others speculate that the permeability increase is due to microbiologic processes. Rojstaczer and Wolf propose that the permeability increase is due to seismically induced fracturing and microfracturing.

In the papers presented in this chapter, hydrologic changes associated with the Loma Prieta earthquake are spatially variable, but the overall character of the changes can be explained by relatively simple conceptual models. In a study of ground-water disturbances in South Carolina associated with the New Madrid earthquakes of 1811-1812 (Smith, 1819) the following was noted: Whatever may be the cause of this phenomenon, the effects are so inconvenient, and it is so generally believed that they are likely to be permanent, that the inhabitants of the town are beginning to build cisterns, in order to accumulate artificial reservoirs of water (p. 95).

The hydrologic changes in response to the Loma Prieta earthquake are much more local in extent than those of the New Madrid, but the impact on communities in the region was significant. Unlike the hydrologic disturbances observed at the time of the New Madrid earthquakes, the causes for these changes appear to be well understood. They reflect the dynamic response of the ocean, streams, and ground water to earthquake-induced physical changes in the morphology and internal fabric of near-surface rocks and sediment.

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HYDROLOGIC DISTURBANCES

THE ORIGIN OF THE TSUNAMI EXCITED BY THE EARTHQUAKE—FAULTING OR SLUMPING

By Kuo-Fong Ma, California Institute of Technology,
Kenji Satake, University of Michigan,
and
Hiroo Kanamori, California Institute of Technology

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ABSTRACT

The first arrival of the tsunami recorded at Monterey, California, was about 10 min after the origin time of the earthquake. Using an elastic half space, we computed vertical ground displacements for many different fault models for the Loma Prieta earthquake and used them as the initial condition for computation of the tsunami in Monterey Bay. The synthetic tsunami computed for the uniform dislocation model determined from seismic data can explain the arrival time, polarity, and amplitude of the beginning of the tsunami. However, the period of the synthetic tsunami is too long compared with the observed. We tested other fault models with more localized slip distribution. None of the models could explain the observed period. The residual waveform, the observed minus the synthetic waveform, begins as a downward motion at about 18 min after the origin time of the earthquake and could be interpreted as due to a secondary source near Moss Landing. If the large-scale slumping near Moss Landing suggested by an eyewitness observation occurred about 9 min after the origin time of the earthquake, it could explain the residual waveform. To account for the amplitude of the observed tsunami, the volume of sediments involved in the slumping is approximately 0.012 km^3. Thus the most likely cause of the tsunami observed at Monterey is the combination of the vertical uplift of the sea floor due to the main faulting and a large-scale slumping near Moss Landing.

INTRODUCTION

The Loma Prieta earthquake (M_W=6.9) generated a tsunami in Monterey Bay, just south of the epicenter (fig. 1*A*). Such nearfield tsunamis are relatively rare in the United States; the 1906 San Francisco earthquake (Lawson, 1908), the 1927 Lompoc earthquake, the 1964 Alaskan earthquake, and the 1975 Kalapana earthquake are among the few examples. Since large coastal earthquakes, either onshore or offshore, can cause serious tsunami hazards, we investigated the tsunami excited by the Loma Prieta earthquake in an attempt to understand the generation mechanism of such nearfield tsunamis. We will show that two elements contributed to tsunami excitation—the vertical deformation of the sea floor caused by faulting and the secondary submarine slumping presumably caused by shaking.

DATA

The tsunami was recorded (fig. 1*B*) on the tide gauge in Monterey Bay. Schwing and others (1990) described this instrument as a bubble gauge. We digitized and detrended the record (fig. 1*C*) for one hour starting from the origin time of the earthquake. The first arrival of the tsunami is about 10 minutes after the origin time of the earthquake, and the peak-to-peak amplitude is about 40 cm.

METHOD

Tsunami waveforms are computed either analytically for the case of uniform depth (see Takahashi, 1942; Kajiura, 1963; Ward, 1982; Comer, 1984; Okal, 1988) or numerically for actual bathymetry (Hwang and others, 1972; Houston, 1978; Aida, 1978; Satake, 1985). Since the bathymetry in Monterey Bay (fig. 2) is very complex—a canyon runs northeast to southwest—an assumption of uniform depth is not valid. We used a finite difference method to compute the tsunami in the bay using the actual bathymetry, which is known very accurately.

As the initial condition for tsunami computation, we used the vertical ground displacement caused by faulting. For this computation, we used Okada's (1985) program, which computes ground deformation caused by faulting in a homogeneous half space. Since the source process time of the earthquake is less than 10 seconds and the water depth is much smaller than the scale length of the ground deformation, we assumed that the water surface is uplifted instantaneously exactly in the same way as the bottom deformation. The amplitude of the tsunami is of the order of 10 cm and is much smaller than the water depth, about 100 m. Also, the wavelength of the tsunami, about 10 km in the bay, is much longer than the water depth. Hence we can use the vertically integrated linear long-wave equation and continuity equation as basic equations of tsunami propagation. In a Cartesian coordinate system (x, y) these equations are given by

$$\frac{\partial Q_x}{\partial t} = -gD\frac{\partial H}{\partial x}$$

$$\frac{\partial Q_y}{\partial t} = -gD\frac{\partial H}{\partial y}$$

and

$$\frac{\partial H}{\partial t} = -\frac{\partial Q_x}{\partial x} - \frac{\partial Q_y}{\partial y}\ , \qquad (1)$$

where Q_x and Q_y are the flow rate obtained by integrating the velocity vertically from the bottom to the surface in the x and y directions respectively, g is the acceleration of gravity, D is the water depth, and H is the water height above the average surface. These equations are solved with a finite difference method. The bathymetry in Monterey Bay and the area for which the computation is made are shown in figure 2. The grid size is 1/4 min, which is about 400 m and 500 m in the x and y directions, respectively, and the number of grid points is about 14,400. The time step of computation is 2 s, which is chosen to satisfy the stability condition for the finite difference calculation. Since the bathymetry is known in detail, the tsunami can be computed very accurately.

FAULT MODEL

The fault model of the Loma Prieta earthquake has been determined very accurately using seismic, geodetic, and

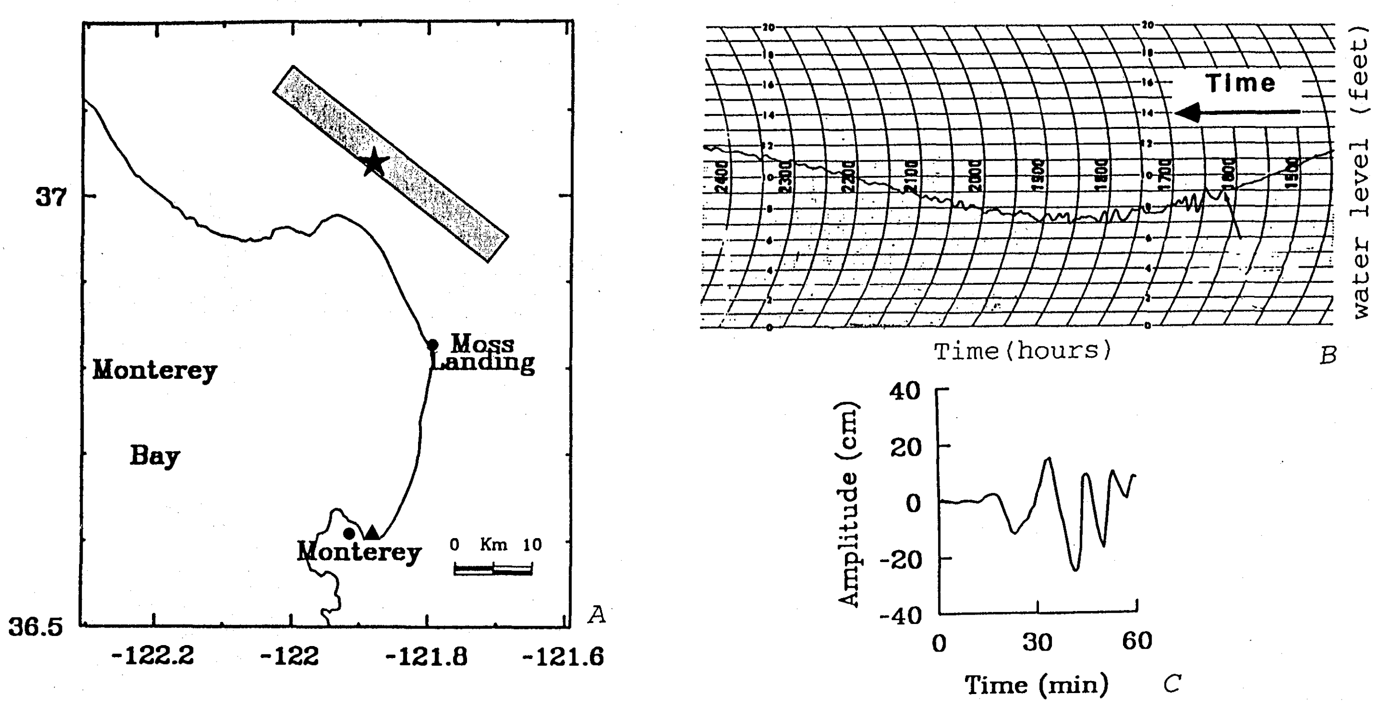

Figure 1.—*A*, Locations of earthquake epicenter (star) and fault (shaded strip) and tide gauge station (solid triangle). *B*, Tsunami record from tide gauge at Monterey (after Schwing and others, 1990). *C*, Detrended tsunami record for one hour starting from origin time of earthquake.

aftershock data. Kanamori and Satake (1990) inverted teleseismic body- and surface-wave data and obtained a mechanism with dip=70° SW., rake=138°, and strike=N. 128° E. The seismic moment is 3×10^{26} dyne-cm (M_W=6.9). The total length of the aftershock area is about 40 km, and the main shock is located near the center of the aftershock (U.S. Geological Survey Staff, 1990), which suggests bilateral faulting. Kanamori and Satake (1990) suggested a uniform fault model having a fault length, L, of 35 km. The coseismic slip on the fault is 238 cm, if the fault width, W, is assumed to be 12 km. Lisowski and others (1990) compared the observed geodetic data with several dislocation fault models; their preferred fault model has a fault length of 37 km and fault width of 13.3 km. The coseismic slip on the fault is 204 cm. The focal mechanism has dip=70° SW., rake=144°, and strike=N. 44° W. The total seismic moment determined from geodetic data is the same as that determined from seismic data by Kanamori and Satake (1990).

RESULTS

We first computed the vertical crustal deformation for the uniform seismic fault model (L=35 km, W=12 km, and D=238 cm) determined by Kanamori and Satake (1990) and used it as the initial condition for tsunami computation. Figure 3A shows the location of the epicenter and the vertical crustal deformation. The displacement beneath the sea floor, a maximum of 25 cm, was responsible for tsunami generation.

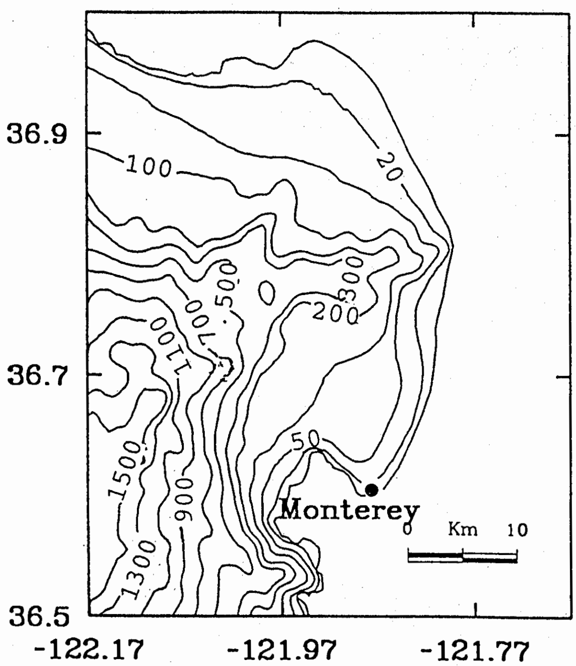

Figure 2.—Bathymetry in Monterey Bay and area over which tsunami computation was made. Contour lines indicate water depths in meters (contour intervals are variable).

To see the contribution of the sea-floor displacement to the observed tsunami, we computed an inverse travel-time

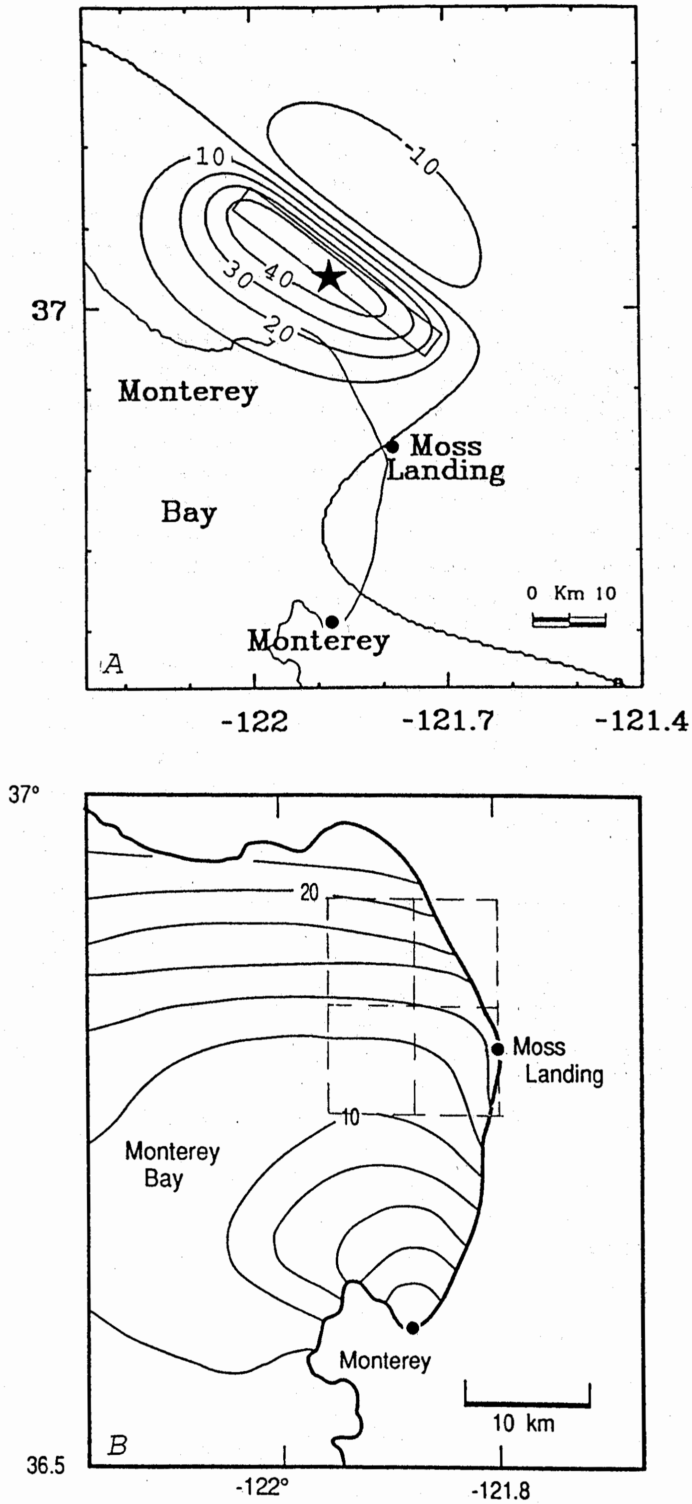

Figure 3.—*A*, Vertical crustal deformation with 10-cm contour intervals for uniform seismic fault model (L=35 km, W=12 km, and D=238 cm); earthquake epicenter indicated by asterisk. *B*, Inverse tsunami travel-time isochrons (contours indicate tsunami wavefronts at every 2 min); dashed box indicates area for inversion computation (see text for discussion).

diagram by placing a source at the tide-gauge station and propagating tsunamis backward into the bay. Figure 3*B* shows the inverse tsunami travel-times every 2 min. The isochron at 10 min is close to the south edge of the displacement field defined by the 0 cm contour line. This is consistent with the onset time of the tsunami at 10 min after the origin time of the earthquake. Figure 4 shows the snapshots of computed tsunamis at 5, 10, 15, 20, 25, and 30 min after the origin time.

Figure 5*A* compares the synthetic tsunami computed for this model with the observed. The synthetic tsunami can explain the arrival time, polarity, and amplitude of the beginning of the observed tsunami. However, the period of the synthetic tsunami is too long compared with the observed.

The reason for the long period of the synthetic tsunami is that the sea floor deformation caused by faulting is very broad. If the slip on the fault is more localized than that in the model used in the above computation, the period of the synthetic tsunami could be decreased. To test this, we computed tsunamis for three localized sources and for the geodetic fault model obtained by Lisowski, Prescott, Savage, and Johnston (1990) for comparison.

In the first case we localized the entire slip in the northwest half of the fault (fault length=17.5 km). In the second case, the slip is localized in the southeast half (fault length=17.5 km). In the third case, we localized the displacement in the bottom half of the fault plane (fault length=35 km, width=6 km). In all cases, the seismic moment is the same as for the uniform model. These cases represent the three extreme cases of localized sources. The fourth model is taken from Lisowski, Prescott, Savage, and Johnston (1990). Figures 5*B*-*E* compare the synthetics for these cases with the observed. The waveform of the synthetics is not very different from that for the uniform model. This result indicates that the displacement field caused by faulting is smoothed out in Monterey Bay, and it is not possible to explain the short period of the observed tsunami.

The difference in the period suggests that a secondary source may be responsible for the tsunami observed at

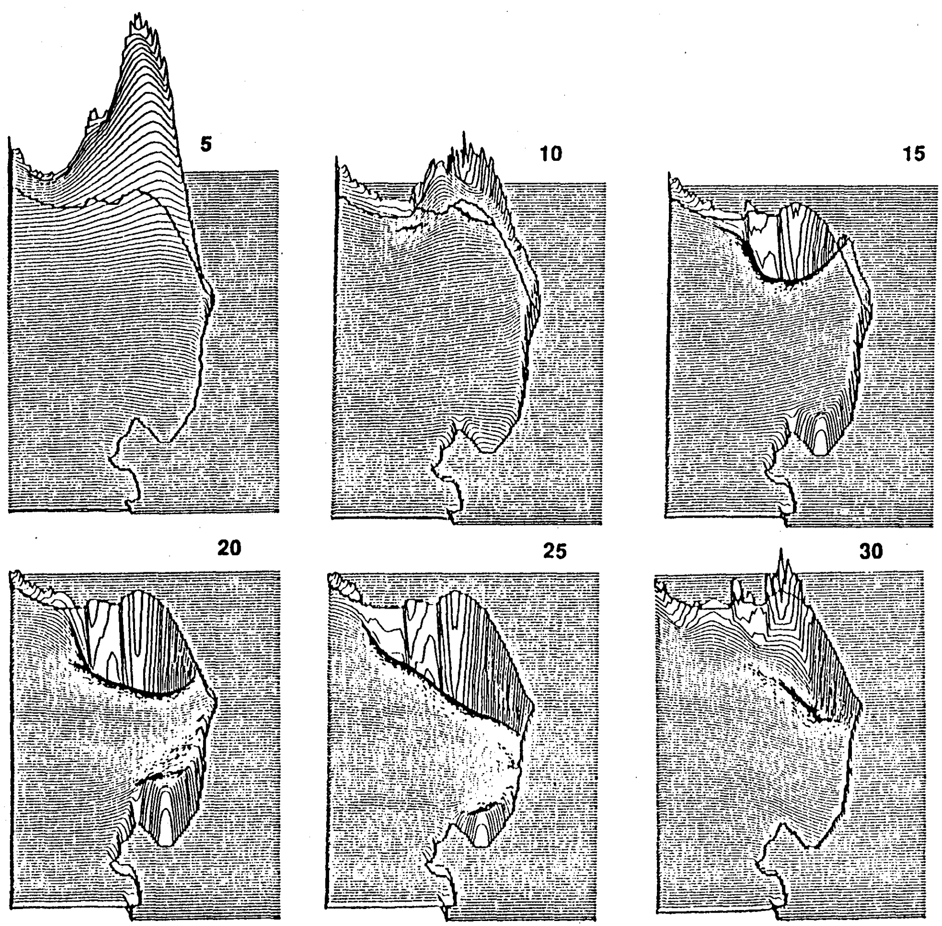

Figure 4.—Snapshots of the computed tsunami computed for the fault model at 5, 10, 15, 20, 25, and 30 min.

Monterey. To explore this possibility, we computed the residual waveform; that is, the observed minus the synthetic waveforms. The residual waveform, shown in figure 5*F*, begins as a downward motion at about 18 min after the origin time of the earthquake. Figure 3*B* shows that the isochron at 18 min is slightly north of Moss Landing. Schwing, Norton, and Pilskaln (1990) suggested the possibility of large-scale slumping near Moss Landing. Sea level fell by 1 m or more near Moss Landing soon after the earthquake. This sea level change is larger than the change expected solely from the direct effect of faulting. The inverse travel-time curve shown in figure 3*B* suggests that if this slumping occurred 9 min after the earthquake, the arrival time of the residual tsunami shown in figure 5*F* could be interpreted as due to the slumping at Moss Landing.

To determine more details of the secondary source responsible for the tsunami, we divided the sea floor into four blocks (8×10 km^2 each) as shown in figure 3*B*. Owing to the time delay of the secondary source, we shifted the residual waveform by 9 min and inverted the shifted residual tsunami waveform to determine the displacement for each block. The inversion is formulated as

$$A_j(t_i)\,x_j = b_j(t_i) \qquad (2)$$

where $A_j(t_i)$ is the tsunami amplitude at time t_i due to a unit displacement at the *j*th block, x_j is the displacement at the *j*th block, and $b_j(t_i)$ is the observed tide gauge record at time t_i. The displacement x_j for each block is estimated with a linear least squares inversion of equation (2).

Figure 6*A* shows the vertical displacement of the sea floor determined by the inversion. The displacement shows an isolated subsidence at the southeast block near Moss Landing, which is consistent with our assumption. The synthetic tsunamis computed for the displacement field shown in figure 6*A* and for a subsidence in the southeast block only are shown in figure 6*B* and 6*C*, respectively. Both can explain the period and the amplitude of the shifted residual tsunami. The southeast block near Moss Landing has a subsidence of about 15 cm over an area of 80 km^2. Figure 6*D* compares the synthetic waveform computed for faulting and slumping combined with the observed.

A slump may be most adequately modeled by a sudden subsidence followed by a gradual uplift. However, the details are unknown. If the later uplift was gradual, the tsunami source could be modeled using a single subsidence source. If this is the case, our result suggests that the volume of sediments involved in the slumping is approximately 0.013 km^3. However, this estimate depends on the details of the slumping. Unfortunately, from the single observation we cannot determine further details.

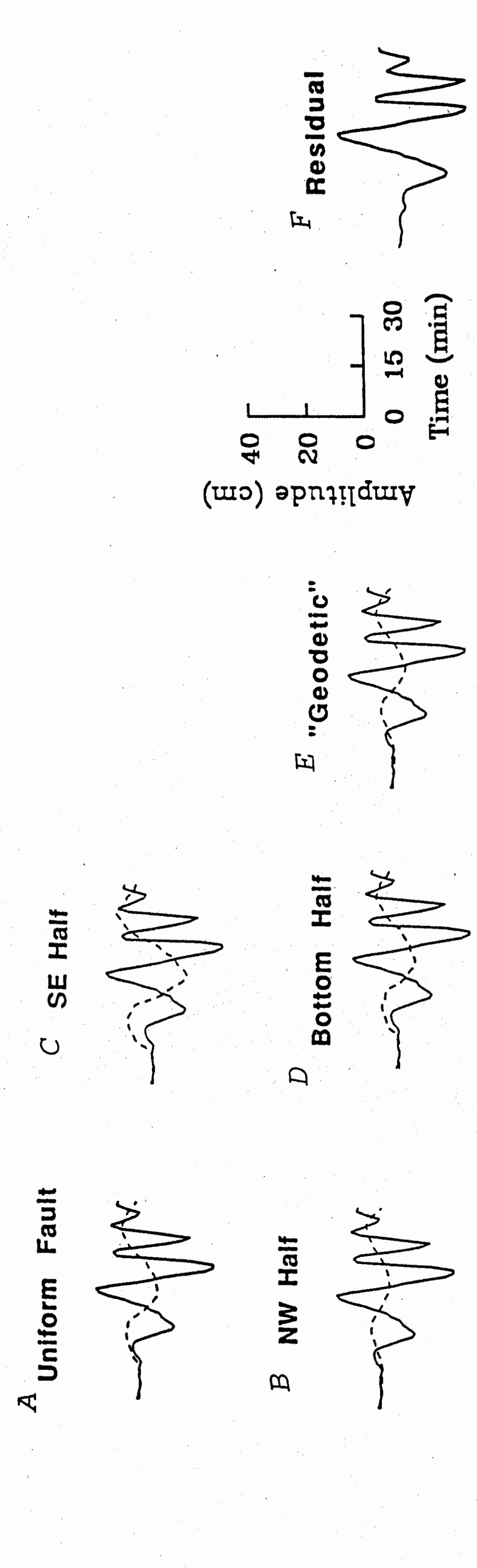

Figure 5.—*A–E*, Comparison of synthetic tsunami (dashed line) computed for various fault models with the observed tsunami (solid line). *F*, Residual waveform (observed minus synthetic waveform for uniform fault model).

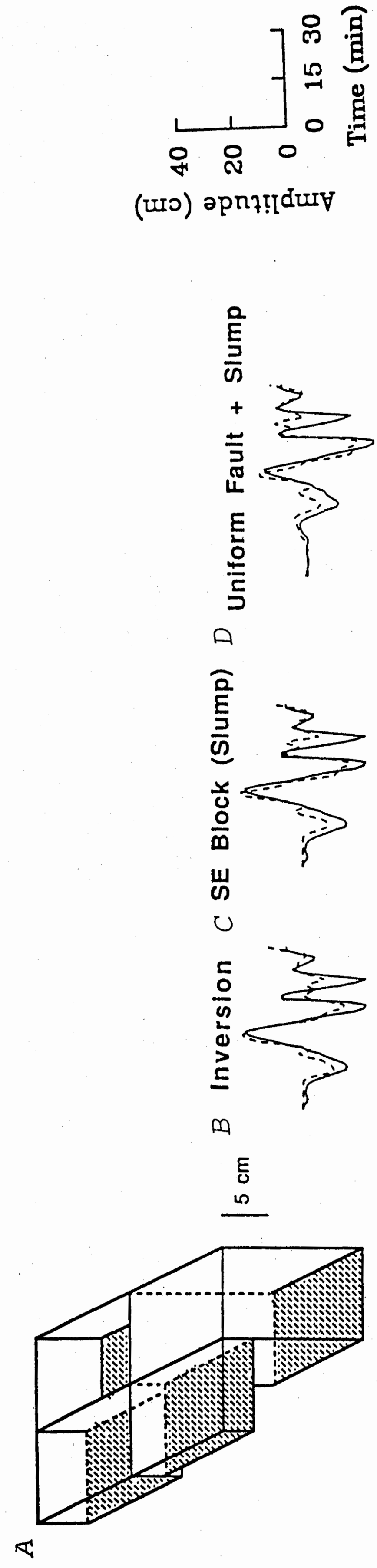

Figure 6.—*A*, Sea-floor displacement obtained from the inversion of observed tsunami. *B–C*, Comparison of residual waveform (solid line) with synthetic (dash line) for the displacement field obtained from inversion and computed for a 15-cm subsidence at southeast block (shown in *A*). *D*, Comparison of synthetic tsunami (dashed line) computed for faulting and slumping combined with observed (solid line).

CONCLUSIONS

The uniform fault model determined from seismic data can explain the arrival time, polarity, and amplitude of the beginning of the observed tsunami, but the period of the synthetic tsunami is too long. We tested fault models with a wide range of nonuniform slip distribution, but none of them could explain the observed period satisfactorily. This suggests that a secondary source is required to explain the tsunami observed at Monterey. The residual waveform, the observed minus synthetic waveform computed for the seismic source, suggests that the most likely secondary source is a sediment slump near Moss Landing; evidence for such a slump has been reported by an eyewitness.

Since the tsunami excited by the secondary source can be more extensive than that by the earthquake faulting itself, as is the case for the Loma Prieta earthquake, the possibility of tsunamis caused by secondary sources needs to be carefully evaluated in assessing the tsunami potential of nearshore earthquakes.

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STREAM-CHANNEL ADJUSTMENT IN FERN CANYON NEAR WATSONVILLE, CALIFORNIA, AFTER THE EARTHQUAKE

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ABSTRACT

Fern Canyon, which contains a small stream crossing the San Andreas fault zone 8 km northeast of Watsonville, has formed a broad floodplain upstream of two compressional ridges that deflect the present channel in a right-lateral sense and that have at least partly dammed it during late Holocene time. Between March 1990 and June 1991, repeated surveys along the Fern Canyon channel revealed an increase in the channel elevation along 30 m of the channel upstream of the fault. The middle 17 m of this reach showed an average of 28 cm of aggradation. We infer that the aggradation occurred during the March 1991 storms that produced the only significant postearthquake runoff during a period of less-than-average precipitation. Between March 1991 and June 1992, a period of less-than-normal runoff, about one-third of the total 1990-91 increase in bed elevation persisted. Aggradation, which resulted from the infilling of the streambed alluvium with fine-grained, organic-rich sediment, appears to reflect a decrease in the gradient upstream of the fault. Alluviation in the low-gradient reach upstream of the fault is one indirect hydrologic response to ongoing tectonic disruption in the fault zone. Results suggest that earthquakes without significant surface rupture may induce changes in stream channels that, over geologic time, can produce the offset streams characteristic of the San Andreas fault zone. Both the evidence of postearthquake aggradation and the anomalously flat longitudinal profiles of the streams where they cross the fault indicate that the stream channels are being deformed tectonically at a faster rate than their ability to readjust by aggradation or erosion.

INTRODUCTION

Quaternary slip rates and long-term earthquake frequency along segments of the San Andreas fault zone have been established in part by studies of Holocene alluvial deposits and surfaces (Wallace, 1990); however, little is known about the adjustments made by streams in response to lateral faulting. Fault-related alluvial deposits have been attributed to channel aggradation within the fault zone, ponding of drainage due to tectonic blockage, or capture and diversion.

Stream channels of all sizes have been disrupted by movement along the traces of the San Andreas fault zone, including along segments which are inferred to have no large, ground-rupturing earthquakes. Sudden changes in channel geometry can clearly occur when earthquakes produce significant lateral surface offset of a stream crossing the fault trace. Even along traces with events that offset stream channels, channel deflection may occur during intervening periods, making it difficult to correctly identify earthquake-induced offset (Wesnousky and others, 1991). Along fault segments which experience only small or moderate earthquakes, channel adjustment may be an indirect, and perhaps long-term, process involving channel shifting, ponding and alluviation, or incision. Because these indirect adjustments can be accomplished only if significant runoff occurs, they may be hydrologically controlled rather than true tectonic adjustments. For example, a slight change in stream gradient following a moderate earthquake might result in channel changes only in cases where effective flows can modify the channel. The Loma Prieta earthquake provided an opportunity to investigate changes in channel geometry following an earthquake that produced no major surface rupture. The results reported here document changes observed through June 1992, and we plan to continue measurements at the study site over the next several years.

The area of study is in the Santa Cruz Mountains at the southern end of the rupture zone of the Loma Prieta earthquake (U.S. Geological Survey Staff, 1990), approximately 10 km northeast of Watsonville (fig. 1). Several small tributaries of the Pajaro River with drainage areas of less than 8 km^2 flow southwest across the trace of the San Andreas fault zone in the area, dropping from elevations of approximately 450 m to approximately 60 m at the Pajaro River floodplain (fig. 2). The active trace of the fault zone extends along the mountain slope approximately midway between the ridgecrest and the floodplain (Sarna-Wojcicki and others, 1975). The area is underlain by marine sedimentary rocks, predominantly sandstone and shale, of late Tertiary age (Allen, 1946; Brabb, 1989). The weak consolidation of many of the units is a likely contributing factor in the development of large complex slump-earthflows along the fault zone at the northern end of the study area.

Streams in the study area show strong geomorphic evidence of disruption across the San Andreas fault zone (figs. 3, 4). Most stream courses show marked right-lateral offset, and the drainage basins themselves are strongly skewed to the southeast, reflecting progressive right-lateral offset during drainage integration. Sag ponds and linear alluviated valleys parallel to the fault zone are common.

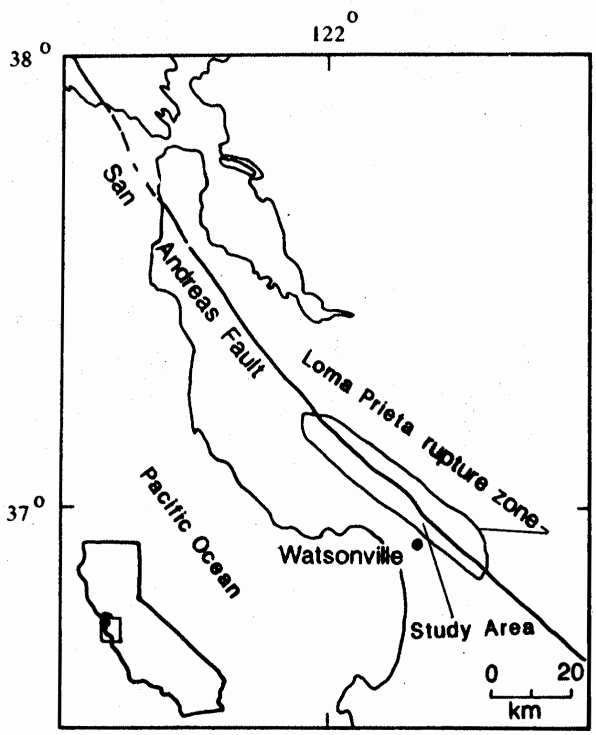

Figure 1.—Index map, modified from U.S. Geological Survey Staff (1990), showing location of study area. Earthquake rupture zone defined by occurrence of aftershocks.

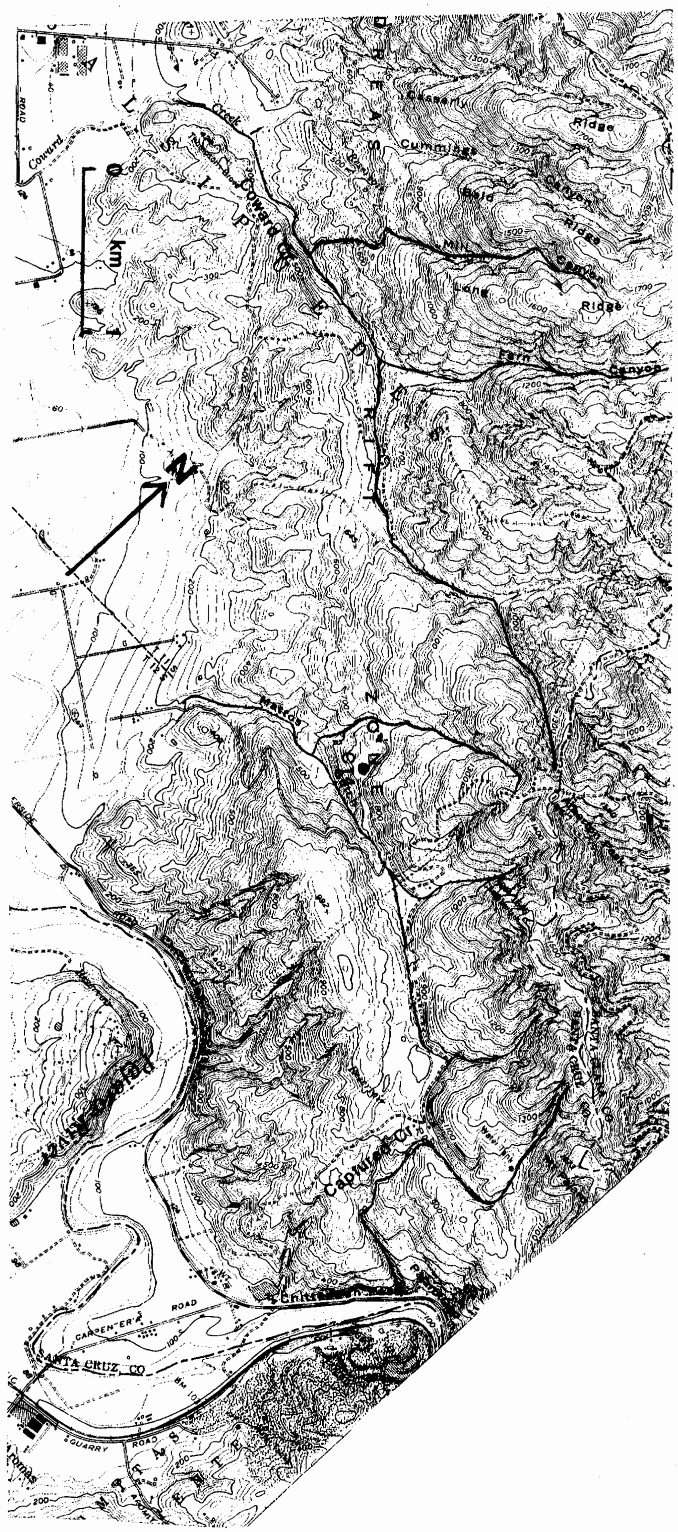

Figure 2.—Map showing several streams crossing San Andreas fault in study area (from Watsonville East 1:24,000 quadrangle, contour interval 20 ft). Highlighted streams are shown in the topographic profiles in figure 4.

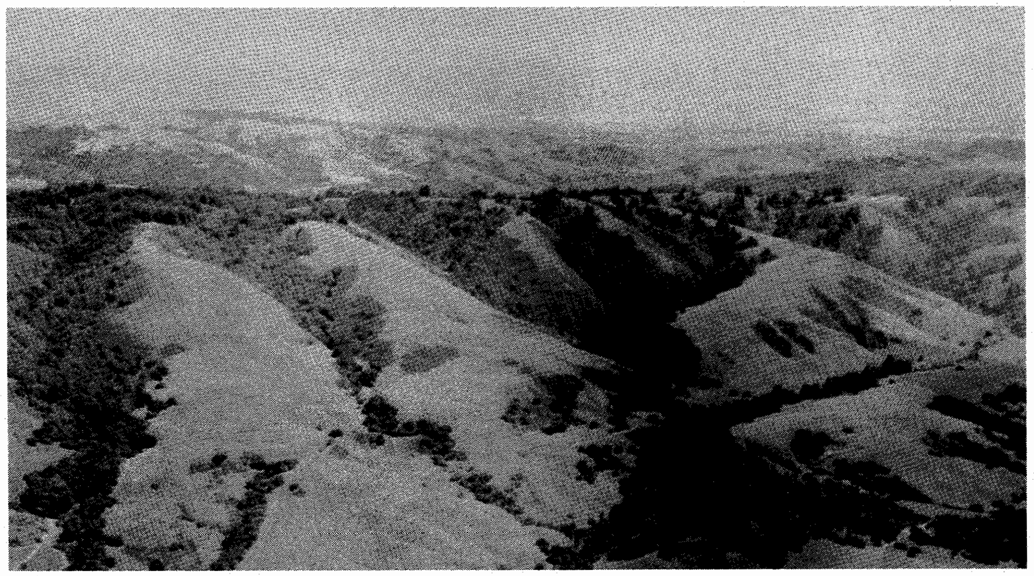

Figure 3.—Study area, showing vegetated channels of Mill Canyon and Fern Canyon in center. Note apparent left-lateral offset, caused by stream capture, of Mill Creek across San Andreas fault. Both streams are tributary to Coward Creek, which flows from right center to lower center, View to east across the Santa Clara Valley.

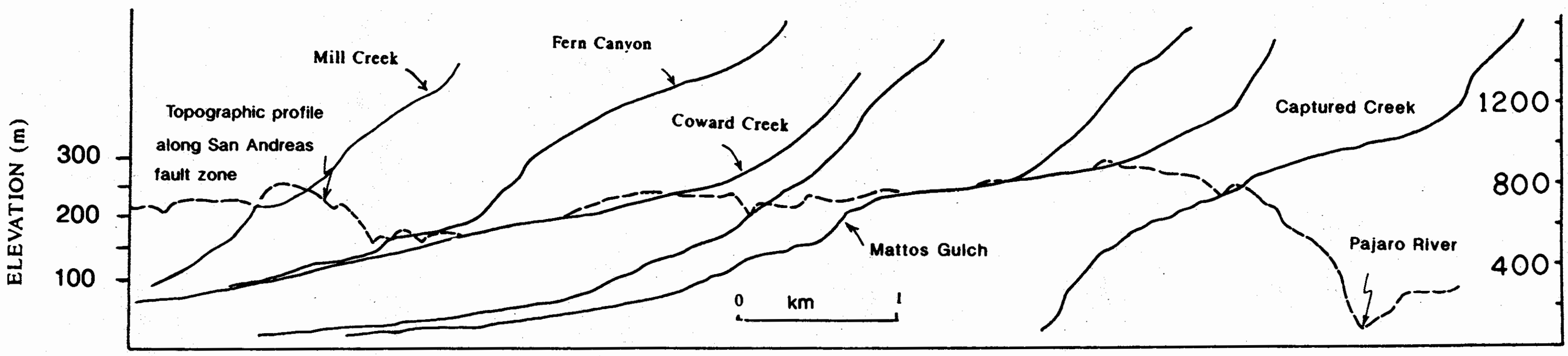

Figure 4.—Longitudinal profiles of small streams crossing San Andreas fault zone in portion of Watsonville East quadrangle, Horizontal distance along each stream is plotted relative to the point where each stream crosses the fault zone, Profiles of Mill Canyon, Fern Canyon, and other tributaries to Coward Creek and Mattos Gulch do not intersect the profiles of those streams because of this projection technique (profiles modified from U.S. Geological Survey Staff and Cummings, 1972), Vertical exaggeration ×3.8.

Longitudinal profiles of these streams show marked flattening where the streams cross the fault. In addition, many profiles show evidence of recent capture in the form of steep, irregular reaches, such as the downstream reaches of Fern Canyon, Mattos Gulch, and Captured Creek (fig 4).

Natural exposures of deposits within alluviated valleys show evidence of episodic deposition and (or) ponding in the form of buried organic-rich horizons and alternating layers of clay and gravelly alluvium. Organic deposits cored by A.M. Sarna-Wojcicki from between 4.4 and 5.1 m depth in a sag pond in Mattos Gulch in 1973 yielded four radiocarbon ages between 3,200 and 3,860 years B.P. (Kelley and others, 1978), suggesting a long history of drainage disruption in the area.

During February 1990, we conducted our initial field surveys of Fern Canyon (fig. 5), which contains a small tributary to Coward Creek (figs. 2, 3), to examine the topography near the fault zone in detail and to detect possible changes in channel geometry after the earthquake. Theodolite and electronic distance meter surveys enabled construction of topographic maps at 1:500 scale with a 0.5-m contour interval (fig. 6). Reoccupation of marked points during repetitive surveys indicates that horizontal coordinates of points are precise to within at least 0.15 m and elevations within 0.05 m. Points and profiles were plotted using Surfer and Grapher, produced by Golden Software, Inc., Both programs can be used on a DOS personal computer. Hand-contoured topographic maps proved more representative of the topography than computer-generated maps (fig. 6). Longitudinal profiles of the channel of Fern Canyon and the floodplain surface were also generated from the survey data (fig. 7) and were used to examine alluviation of the channel.

FERN CANYON

Fern Canyon was selected for detailed study because it shows clear evidence of recent disruption by the San Andreas fault and because it has a relatively straight channel that enters the fault zone at right angles. The fault zone near Fern Canyon is marked by classic geomorphic features diagnostic of strike-slip faults, including two linear compressional ridges flanked by a linear valley on the northeast that contains small sag ponds (figs. 5, 6, 8). The juxtaposition of dark clay-rich gravel (east side) against sandy alluvium (west side) across the fault trace was revealed in preliminary trenching by D. Schwartz of the U.S. Geological Survey.

The modern channel of Fern Canyon is diverted to the north around the compressional ridges. The gradient flattens markedly above the fault (fig. 7), and a steeply incised canyon cuts through the northern pressure ridge and flows into Coward Creek. A 0.8-m-high nick point marks the apparent fault trace (fig. 7). Riparian vegetation indicates that the modern lower channel, downstream of the

Figure 5.—Compressional ridges and sag pond deposits near Fern Canyon. Fern Canyon channel bends northwest in center of photograph. Denser vegetation upstream from compressional ridges reflects ponding of water upstream of fault. View west-northwest.

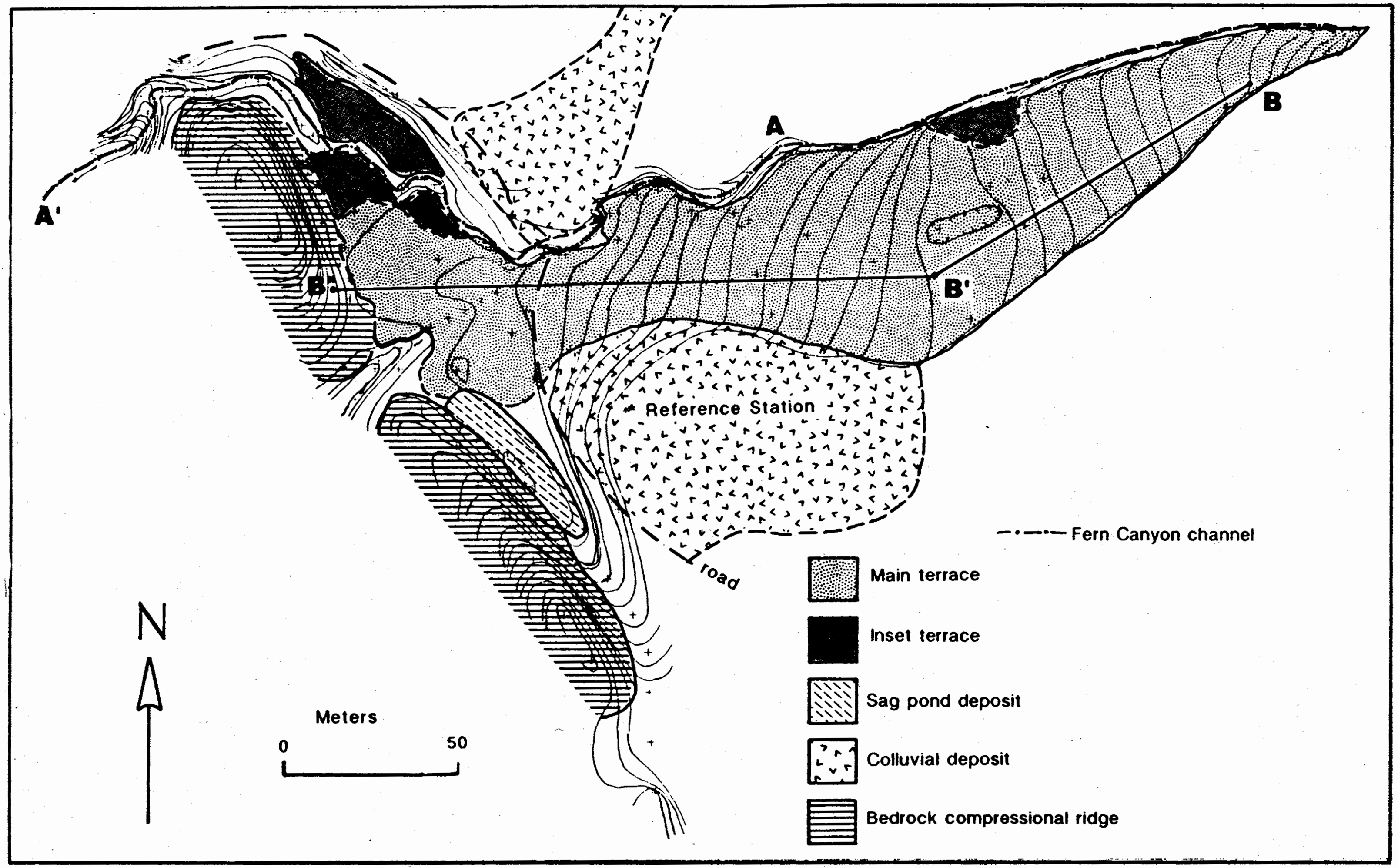

Figure 6.—Topographic map of Fern Canyon, hand contoured using surveyed points and field notes, and geologic map of surficial units. Contour interval is 0.5 m, and elevations are relative to reference station, assigned elevation 167.64 m. End points and projection line of profiles shown in figure 7 are shown by letters and solid line. Large dot shows location of site in figure 11.

northward bend (fig. 5), has been established for at least a few hundred years. Within the canyon, stumps of redwood trees at least 250 years old at the time of cutting are surrounded by stump-sprouted trees at least 80 years old. Because redwoods grow only in riparian zones in the study area, they establish a minimum age for the lower channel.

An older course of the Fern Canyon channel is defined by the alluviated flat forming the main terrace in the area (figs. 6, 8). During formation of the flat, the stream flowed in a relatively direct path. We propose that at this time the upper and lower reaches of the Fern Canyon channel were directly opposite each other and that the current 60-m right-lateral offset represents more recent lateral displacement of the channel along the fault.

Geomorphic evidence also suggests that, prior to assuming its current deflected course. Fern Canyon at least temporarily flowed through a steep abandoned channel between the compressional ridges (fig. 6), perhaps when the lower channel was blocked by the toe of a large landslide on the northern edge of lower Fern Canyon. The landslide deposits bury the northern end of the northern compressional ridge. At this time, we are uncertain as to the timing of the landsliding or its effect on the Fern Canyon channel.

EFFECTS OF THE EARTHQUAKE ON FERN CANYON

After the Loma Prieta earthquake, two zones of semilinear, subparallel cracks with 1-2 cm of southwest-side-up relief were observed at the base of the ridges (fig. 8). The cracks may be the result of differential settling during ground shaking, with the bedrock compressional ridges settling less than the alluvial and sag pond deposits. Hall and others (1991) noted two sets of fractures with up to 15 cm of northeast-side-up offset along a ridgecrest approximately 7.5 km southeast of Fern Canyon.

Increased spring activity and the appearance of ponded water at the head of the abandoned Fern Creek channel were noted immediately after the earthquake (fig. 6). It is difficult to assess the hydrologic conditions in Fern Canyon because streamflow records are not available for the small streams in the study area. Conversations with local ranchers indicate that Fern Canyon maintains a perennial low discharge (estimated by us to be 1-2 ft^3/s) because of discharge into the stream by springs. Along the sag pond near the fault trace, the water table is elevated, and standing water appears after even minor rainfall.

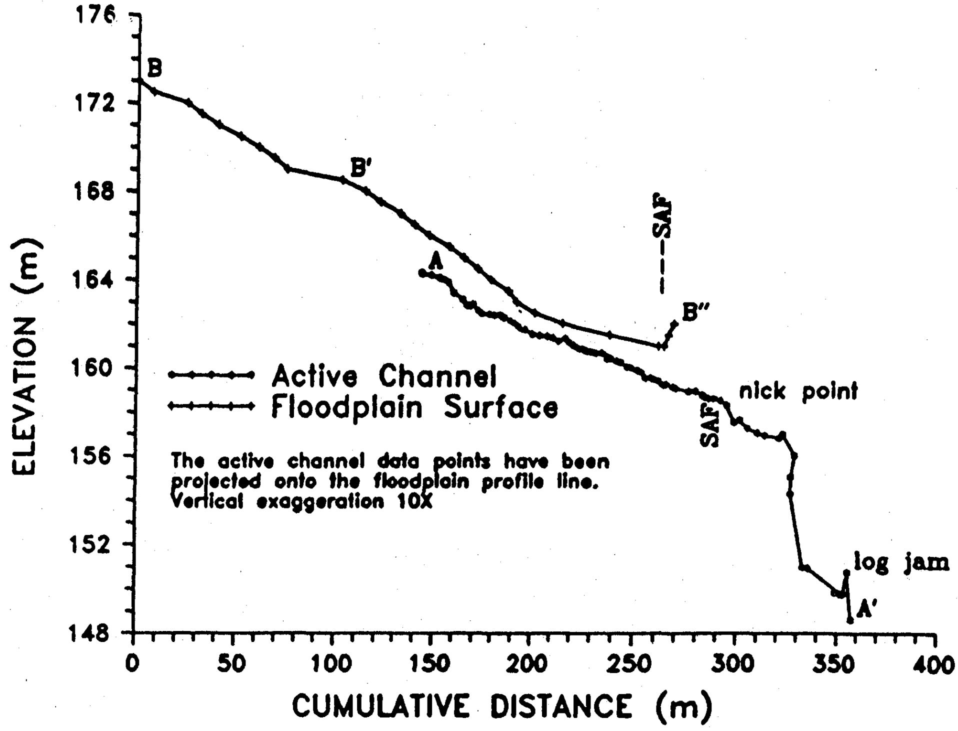

Figure 7.—Longitudinal profiles of main alluvial surface and present Fern Canyon, with points projected onto common line. Note downstream flattening of the surface reflecting partial damming along the fault.

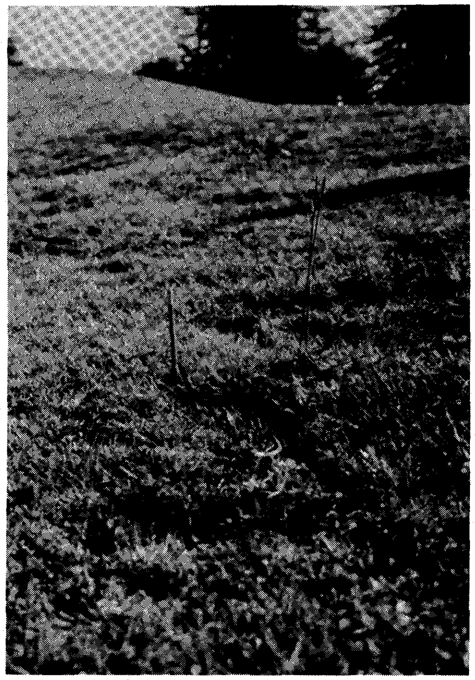

Figure 8.—Cracks formed during the Loma Prieta earthquake along trace of the San Andreas fault zone near Fern Canyon. Cracks were accentuated by diggings of ground squirrels. Pencil for scale, view to southeast.

Although no channel surveys were made prior to the earthquake, we postulate that the February 1990 survey of the channel provides a reasonable approximation of pre-earthquake conditions because no significant runoff occurred in the channel between November 1989 and March 1990. The average annual precipitation at Watsonville, the climatological station closest to the area, is 533 mm. No significant storms occurred between October 1989 and February 1990, and we infer that the channel surveyed in February 1990 had not been significantly modified since the earthquake. Between the initial survey and the June 1991 survey, average precipitation at Watsonville was much less than normal, with the exception of two storms in March 1991 that produced 298 mm of rainfall. Channel modifications detected by the 1991 survey reflect modifications during those storms. During the June 1991-June 1992 interval, rainfall was again somewhat less than average at Watsonville. Three storms in February and March 1992, produced approximately as much rainfall as the two 1991 storms. Channel modifications made during 1990-92 can therefore be assumed to be less than would have occurred during normal or wetter-than-average rainfall years.

The June 1991 resurvey of the Fern Canyon channel was made in order to detect any changes that occurred during the runoff events of March 1991, following the first significant storms to occur since the earthquake. The surveys detected no change in the channel planform within the detectable limits of the surveys (fig. 9). However, the longitudinal profile of the Fern Canyon channel showed significant

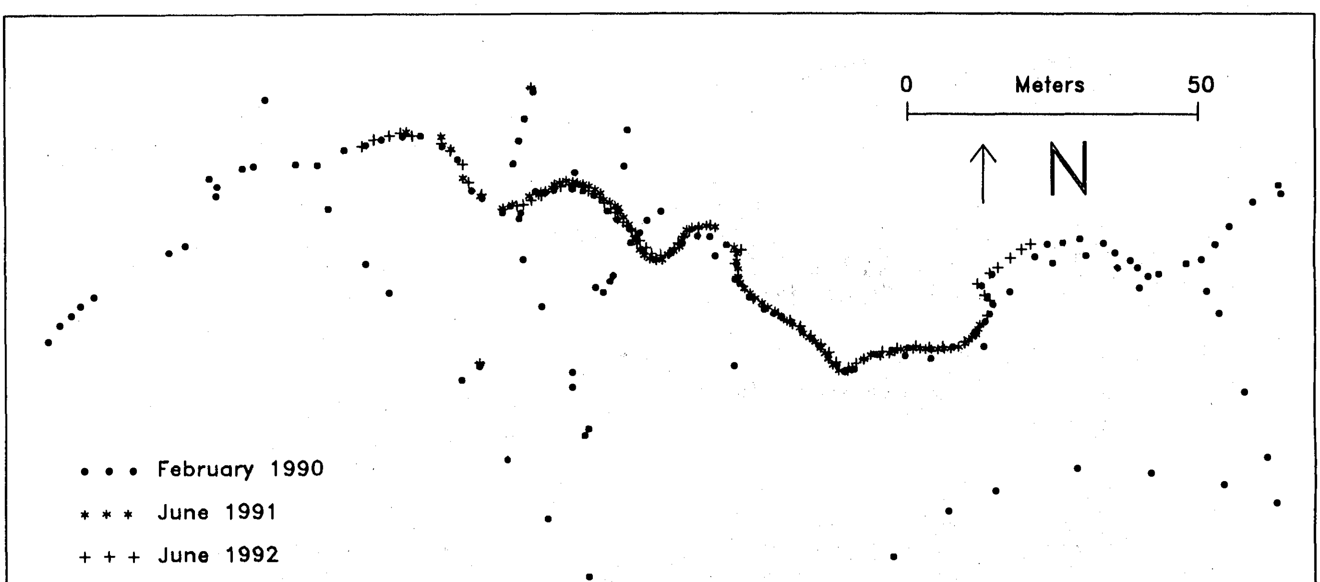

Figure 9.—Plot showing surveyed points for 1990, 1991, and 1992. Position of Fern Canyon channel shows no appreciable shifting within limits of surveying precision.

elevation increase for 80 m upstream of the fault (fig. 10). The increase averaged 30 cm in the 17-m reach immediately upstream of the fault, with a maximum of 70 cm aggradation at some points. Field observations indicated that the increase in bed elevation was not caused by deposition of discrete flood deposits or sand and gravel bars, but rather resulted from the inundation of the streambed and surrounding low flats with fine-grained, organic-rich sediment.

Between June 1991 and June 1992, approximately two-thirds of the 1990-91 increase in bed elevation was removed (fig. 10). Field observations support survey results that indicate some aggradation persisted in the low-gradient reach immediately upstream of the fault trace. Here the inundation of the streambed with 15 cm or more of dark, fine-grained silt and clay between the 1991 and 1992 surveys caused the target pole to consistently sink into the bed, thus making the 1991-92 degradation to some extent an artifact of surveying problems. It will not be known whether any of the streambed elevation will persist long enough to provide a permanent record of post-Loma Prieta hydrologic adjustments in Fern Canyon until several more years of survey data are collected.

HOLOCENE HISTORY OF FERN CANYON

Natural streambank exposures reveal up to 2 m of gravelly alluvium underlying the Fern Canyon floodplain upstream of the fault trace. At one site investigated in detail, the deposits consist of alternating sandy gravel, with little or no silt and clay, and organic-rich clayey and silty gravel (fig. 11). Preliminary observations lead us to hypothesize that the gravels inundated by fine sediment represent times of partial damming of the creek, whereas sandy deposits may represent times of unimpeded flow. The sandy alluvial layers display cross bedding at some localities and may represent individual flood events. The gravelly clay layers, which contain little sand (fig. 11), are similar to those exposed on the northeast side of the fault trace in the excavated trench. The upper parts of the clay-rich layers, which are dark colored, are also enriched in organic carbon (fig. 11), suggesting that they may represent buried A horizons.

The youngest recognized deposits along the upper streambanks are historical, as indicated by the presence of old bottle glass immediately upstream of the deposits shown in figure 11. The glass was found in deposits equivalent to the horizons immediately beneath the "disturbed" zone at the described site, where the upper 25-35 cm exposed show signs of human disturbance. These deposits overlie the first buried organic-rich horizon (depth 60-90 cm, fig. 11), which we interpret as the presettlement floodplain surface. Large samples of charcoal from the sandy alluvium between the disturbed horizon and the original floodplain surface (fig. 11) yielded two radiocarbon ages of modern and 430±90 yr B.P. The spread in the ages may partly reflect the presence of riparian redwoods along Fern Canyon; complete burning of trees several centuries old could yield radiocarbon ages spanning several centuries. The ages suggest that the upper deposits are probably no older than several hundred years old.

Radiocarbon dating of small charcoal samples from sandy gravel below the upper buried soil and from a dark clay-rich

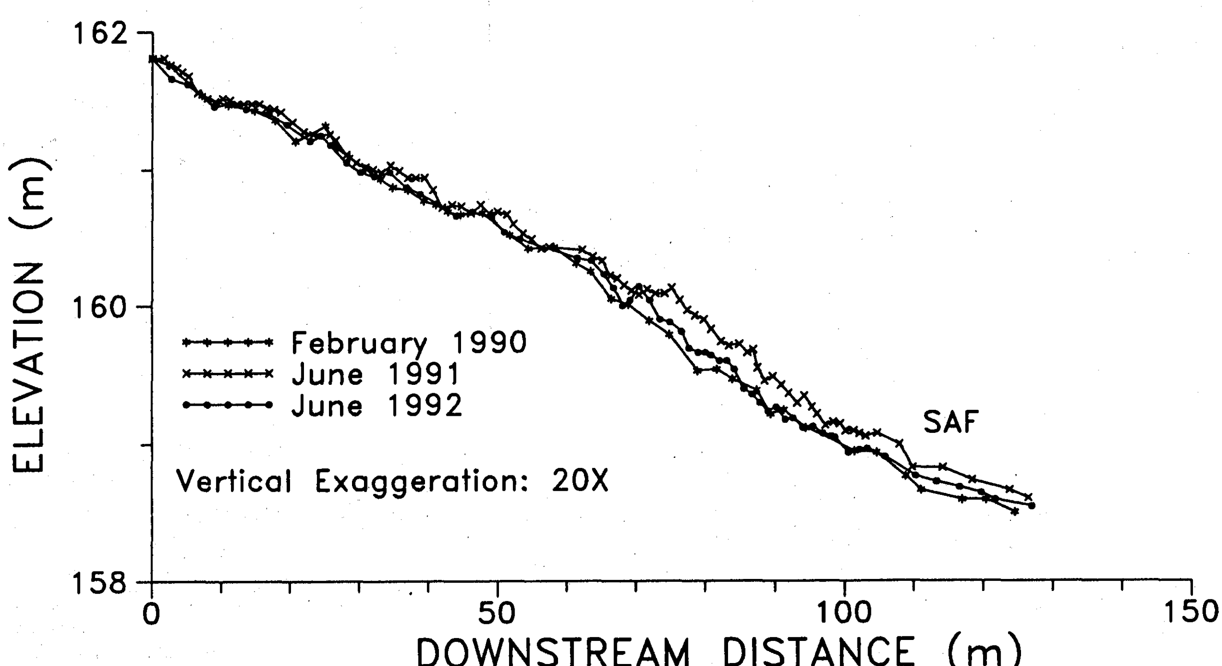

Figure 10.—Longitudinal profiles of the Fern Canyon channel near San Andreas fault. Data were obtained from repeated field surveys.

layer at the base of the exposure yielded ages that are stratigraphically inverted (fig. 11). These results probably reflect the remobilization of detrital charcoal from upstream colluvial deposits and redeposition in Fern Canyon alluvium. The lower sample was also contaminated with unknown sulfide material. Despite the lack of age resolution, it is clear that both clay-rich layers were deposited since late Holocene time. If these layers do indeed represent earthquake-induced partial ponding of Fern Canyon, then two late Holocene events prior to 1906 could be recorded in the alluvial record.

DISCUSSION OF RESULTS

Stream offsets can be accomplished by a variety of processes, including uplift of compressional ridges and large-scale landsliding, as well as by simple lateral separation. It is clear that Fern Canyon, Mill Creek, and similar small streams crossing the San Andreas fault zone have responded to disruption by the fault with a variety of channel adjustments. Whether older alluvial deposits in Fern Canyon reflect periodic partial damming of the channel is uncertain at present because deposits are not well dated and correlated. In addition, the effects of variables such as major flood events, intense timber harvesting in the early 1900's, and currently active grazing have not been evaluated.

The repeated surveys of the profiles of Fern Canyon and its floodplain demonstrate that gradient decreases upstream of the fault are the most obvious channel change effected by faulting. Alluviation of the Fern Canyon channel following the Loma Prieta earthquake has been concentrated in the low-gradient reach immediately upstream of the fault trace and has resulted partly from inundation of the streambed by fine-grained, organic-rich sediment. This recent aggradation may represent a hydrologic response to a gradient decrease created by the Loma Prieta earthquake. However, several years of survey data must be collected to evaluate the pattern of alluviation during significant runoff events which do not follow moderate earthquakes. It is also unknown at this time whether sediment still stored in the reach upstream of the fault will remain there. Evidence of post-earthquake aggradation, combined with anomalously flat long profiles of the streams where they cross the San Andreas fault, indicates that the stream channels are being deformed tectonically at a faster rate than their ability to readjust by aggradation or erosion. Continued study of

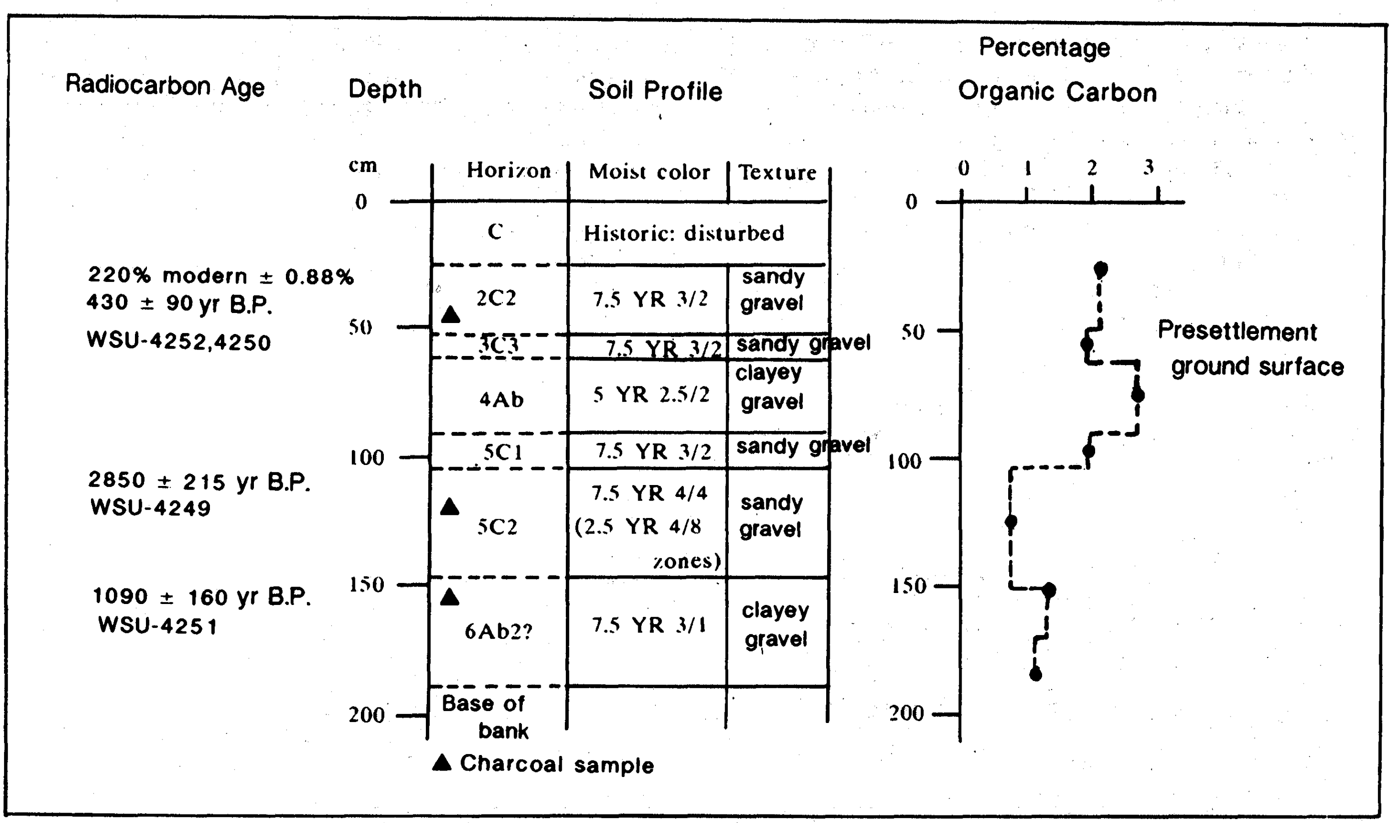

Figure 11.—Soil horizons and alluvial units exposed along floodplain edge (fig. 6), showing relative positions and radiocarbon ages of charcoal samples. Presence of buried soils is indicated by bulges in organic carbon. Clay-rich gravel may be formed during times of partial ponding and alluviation, whereas sandy gravel indicates unimpeded streamflow. Organic carbon content was determined by the Walkley-Black method (Singer and Janitzky, 1986), and radiocarbon ages were determined by Y. Welter, Washington State University.

changes in bed elevation and sediment storage will yield valuable understanding of the mechanisms by which laterally offset streams become displaced.

ACKNOWLEDGMENTS

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HYDROLOGIC DISTURBANCES

EFFECTS OF THE EARTHQUAKE ON SURFACE WATERS IN WADDELL VALLEY

By Robert O. Briggs

CONTENTS

ABSTRACT

Waddell Creek is a perennial stream near Santa Cruz, Calif., which discharges into the Pacific Ocean about 38 km from the epicenter of the Loma Prieta earthquake. The earthquake caused no significant changes or damage to structures or surface features in the area but was followed by transient increases in discharge of Waddell Creek and nearby springs. The increases approximate an order-of-magnitude step rise and were followed by an exponential recession with time constants of from 37 to 59 days. The flow recession pattern of Waddell Creek was obscured by heavy rains after about 50 days; however, the nearby springs maintained an exponential recession with minimal rain interference for periods of several time constants, then ceased flowing abruptly. Spring flow cessations progressed systematically from higher to lower altitudes, suggesting a descending water table. A comparison of the pre- and post-earthquake chemical signature of one of the springs shows only minor changes in water chemistry, indicating a common source for pre- and post-earthquake waters. Increased permeability of the subsurface material due to the earthquake appears to be the most probable cause of the hydrologic changes. Postearthquake restoration to preearthquake permeability has not been observed or inferred.

INTRODUCTION

Waddell Creek, a perennial central California coastal stream, discharges into the Pacific Ocean about 38 km from the epicenter of the Loma Prieta earthquake. Temporary increases in surface water flow throughout its 48-km^2 watershed followed the seismic disturbance.

Figure 1 shows the location of the Waddell Creek valley with respect to Loma Prieta and other geographic features. Figure 2 maps the Waddell Creek watershed and identifies specific points of interest. To locate the points more precisely, their Metric Universal Transverse Mercator grid coordinates from the U.S. Geological Survey maps (U.S. Geological Survey, 1955) are cited in the text.

Hydrologic changes similar to those reported herein were observed elsewhere in the coastal area impacted by the Loma Prieta earthquake (Rojstaczer and Wolf, 1992), and a variety of hydrologic anomalies were reported following the 1906 San Francisco earthquake (Lawson, 1908). The 1906 reports include increased discharge of springs and streams similar to those reported here; however, other phenomena attendant to the 1906 event, such as the emergence of geysers and hot springs and the appearance of turbidity, salt, and elevated temperatures in spring and well water, were not observed in the Waddell valley relative to the Loma Prieta earthquake.

PHYSICAL EFFECTS OF THE EARTHQUAKE IN WADDELL VALLEY

Although residents of the Waddell valley reported vigorous ground motion during the earthquake, very little residual physical change resulted. Except for failure of two aged unreinforced brick chimneys, there was no earthquake-related damage to the six residential structures or to the several miles of gravel and dirt roads, two bridges, and several miles of underground water pipes. A landslide of moderate scale occurred in a historically slide-prone area outside the valley on the coastal slope of the western ridge, (fig. 2) but no slides or ground cracks were evident in the valley. However, immediately after the earthquake the air in the valley was filled with dust, which, in the absence of major physical changes, suggests numerous small slides.

The physical effects of the earthquake in the Waddell valley are consistent with a modified Mercalli intensity of 7, which agrees with U.S. Geological Survey contours in figure 1 (Plafker and Galloway, 1989).

HYDROLOGIC EFFECTS OF THE EARTHQUAKE IN WADDELL VALLEY

The most evident aftereffect of the earthquake in the Waddell valley was an abrupt increase in the discharge of creeks and springs followed by an exponential flow recession. Numerous new springs appeared, and springs which had been inactive for many years resumed flow. Discharge measurements were made of the creek for which considerable historical flow data are available and two springs for which some preearthquake information is on record.

HYDROLOGIC CHARACTER OF WADDELL CREEK

A study conducted by the California State Department of Fish and Game between 1933 and 1942 provides continuous records of Waddell Creek discharge for that period (Shapovalov and Taft, 1954). Since 1942 flow has not been continuously monitored. However, since 1975 spot data have been recorded frequently by the author, the California State Department of Fish and Game, the County of Santa Cruz Planning Department and the Department of Geology, University of California, Santa Cruz.[1] These data were the basis of a hy-

[1]During the summer of 1977 flow measurements of Waddell Creek were made by the author using a 9-inch Parshall flume. All other creek data were measured by current meter surveys in open stream.

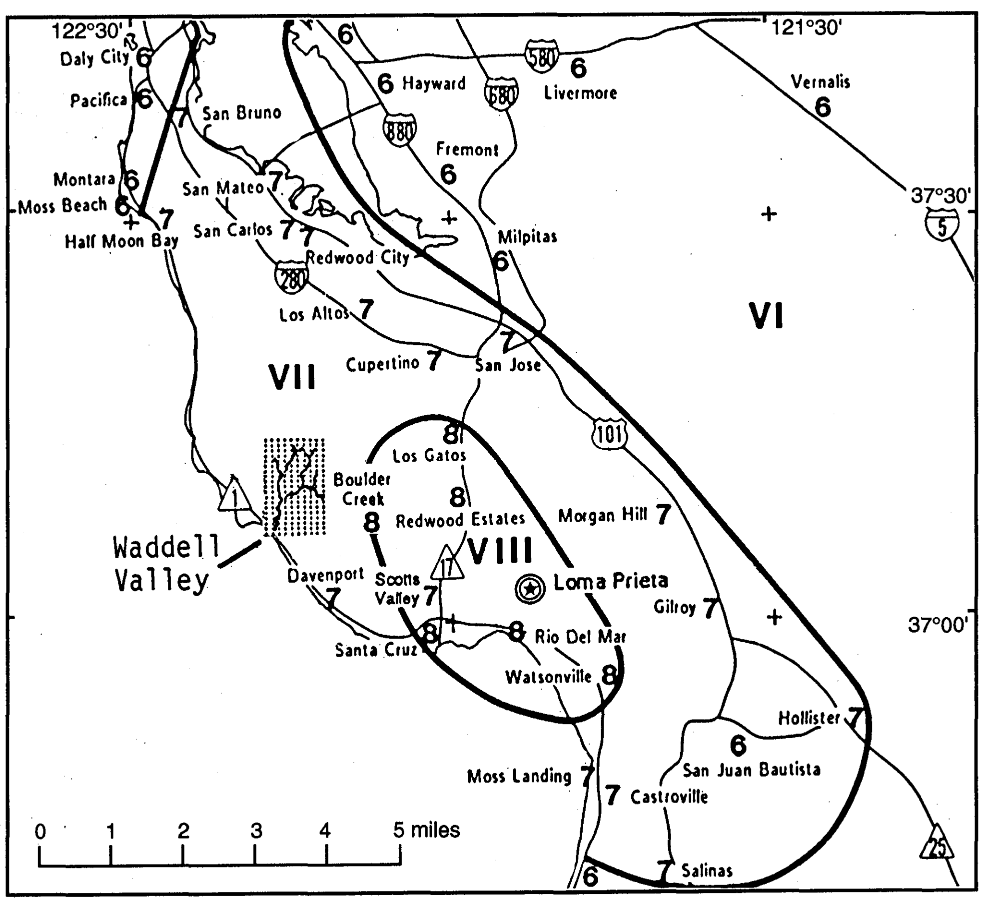

Figure 1.—Map of central California coastal area showing location of Waddell valley, Loma Prieta, and other points of reference and displaying U.S. Geological Survey modified Mercalli intensity contours (Plafker and Galloway, 1989).

drologic study sponsored by the California State Coastal Conservancy wherein monthly flow duration curves for Waddell Creek were derived (Robert Coats, written commun., 1988).

Shapovalov and Taft (1954) report greater summer discharge during the 1930's than is observed currently for similar meteorologic patterns. The change cannot be attributed to increased water usage from the creek or aquifer, because agricultural diversion above the points of measurement has never been practiced and there is very little domestic usage in the watershed. The reduction in summertime flow may be due to reforestation of the watershed, which was heavily impacted by timbering and fires prior to the 1930's. In recent years the watershed has been protected, resulting in prolific regrowth of redwood and douglas fir. This result of reforestation on watershed yield has been reported for areas with similar histories (Dunne and Leopold, 1978). Coats' monthly flow duration curves are a more accurate reference for present creek behavior than the Shapovalov and Taft (1954) records. Waddell Creek's typical summer flow decreases from the beginning of the dry season (early summer) until the first major rain the following fall. Figure 3 presents the measured flow from March 27, 1989, to March 1, 1990, together with

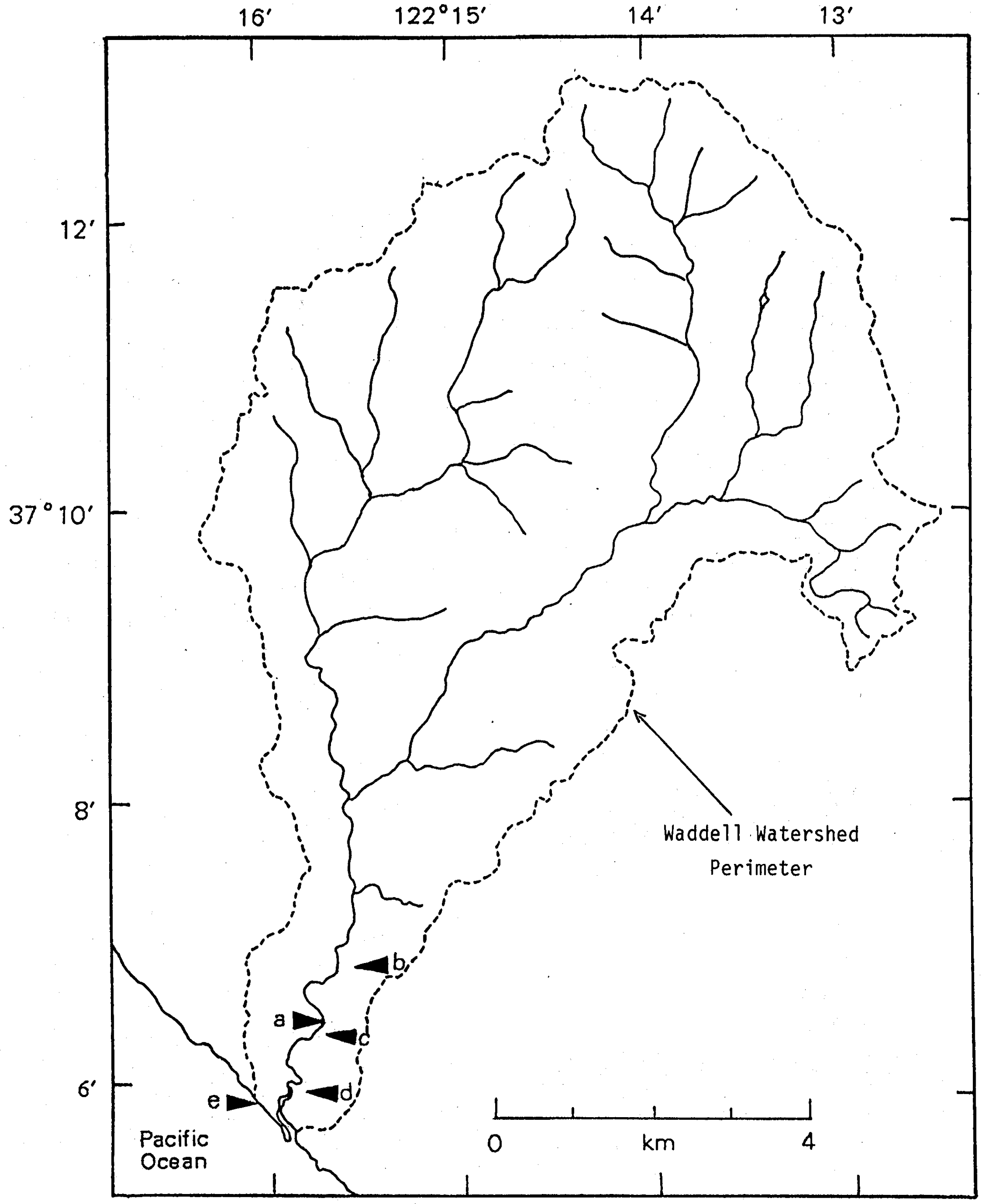

Figure 2.—Map of Waddell Creek drainage basin showing locations mentioned in text: a, Waddell Creek flow measurement station, b, Brown House Spring, c, Casa Spring, d, Entry Road Spring, e, site of earthquake-induced slide.

the 50th percentile values from the monthly flow duration curves. The discharge during the summer of 1989 closely approximates the 50th percentile until the October 17 earthquake, when discharge increased dramatically.

EARTHQUAKE-RELATED INCREASE IN FLOW OF WADDELL CREEK

Discharge near the mouth of Waddell Creek (4,106,730 meters N., 564,900 meters E.) showed an eightfold postseismic increase and a further rise to 12.5 times the pre-earthquake discharge, followed by a gradual recession which was obscured by rain runoff beginning in mid-January (fig. 4). Before it was obscured, the recession approximated a straight line in semilog space and is empirically described by the following exponential equation, with the time constant (the time required to reach 1/e of initial value) equal to 59 days:

$$Q_2=Q_1 e^{-[(t_2-t_1)/T]}$$

where

t_1 = time 1
t_2 = time 2
Q_1 = discharge at time 1
Q_2 = discharge at time 2
T = time constant
e = base of natural log.

The last flow measurement prior to the October 17 earthquake was 43.6 L/s on October 12. Flow was 359 L/s two days after the earthquake on October 19 and peaked at 671 L/s on October 24. No measurements were made between October 12 and 19 or between 19 and 24, so the character of the rise in discharge following the earthquake is not known. However, continuous records in several nearby streams (Rojstaczer and Wolf, 1992) show increasing discharge for several days following the seismic event and it is probable that Waddell Creek behaved similarly.

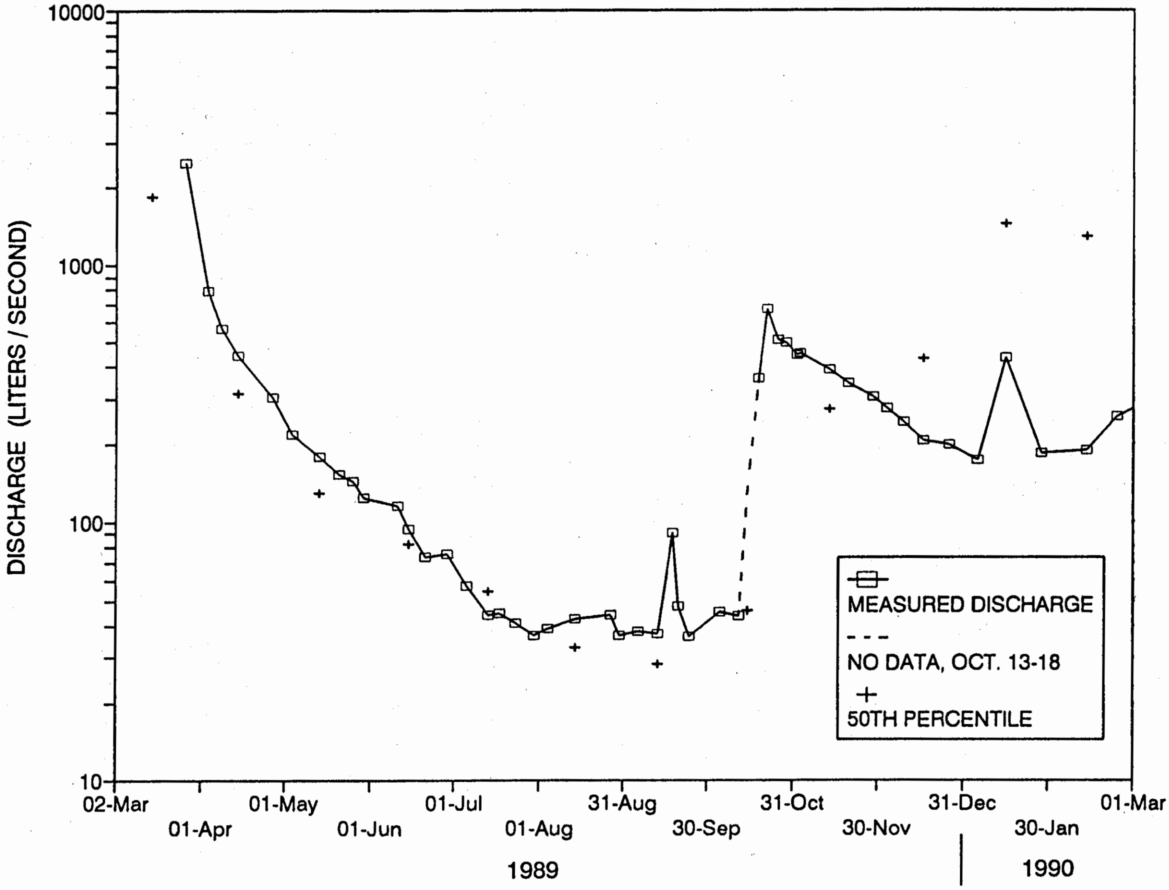

Figure 3.—Discharge of Waddell Creek from March 27, 1989 to March 1, 1990, showing the discontinuity caused by the October 17, 1989, Loma Prieta earthquake together with the 50th percentile probable discharge of Waddell Creek as determined from monthly flow duration curves by Coats (written commun., 1988).

The season's second measurable rain (October 21 through 24, peaking on October 23) totaled 3.9 cm and accounts for the sharp spike early in the postseismic discharge[2] (fig. 4). Rains following a dry season normally have only a short-term effect on Waddell Creek discharge and flow returns quickly to near its pre-rain baseline.[3] Note the rapid recession of the early-season 2.5 cm of precipitation on September 17 (fig. 3). The October 23 precipitation appears to have a similarly brief impact on creek discharge, not significantly distorting the more slowly receding earthquake-induced transient.

[2]Rainfall is measured near the location of the creek gaging station. Greater precipitation is frequently observed in the higher elevations of the watershed, but records at these locations are unavailable.

[3]The Waddell Creek runoff pattern of an early season isolated rain was carefully recorded by the author following a 4.5-cm rainfall on October 25-26, 1991. It approximated an exponential decay with a time constant of 3.8 days.

Although it has not been rigorously determined, Waddell Creek appears to have resumed its typical annual cycle of discharge for the water year 1990-91. For that year the 63 cm of rainfall was 80 percent of the 100-year average (78.7 cm), with the majority of precipitation occurring toward the end of the season. Monthly flow duration curves place the 1990-91 summer discharge at the 55th percentile.

INCREASED YIELD FROM BROWN HOUSE SPRING

Brown House Spring is located about 2.2 km upstream from the mouth of Waddell Creek (4,107,500 meters N., 565,280 meters E.) at about 60 meters above sea level. The spring, which has reliably supplied domestic water to several residences since about 1940, has been observed frequently by the author since 1970 and gaged on

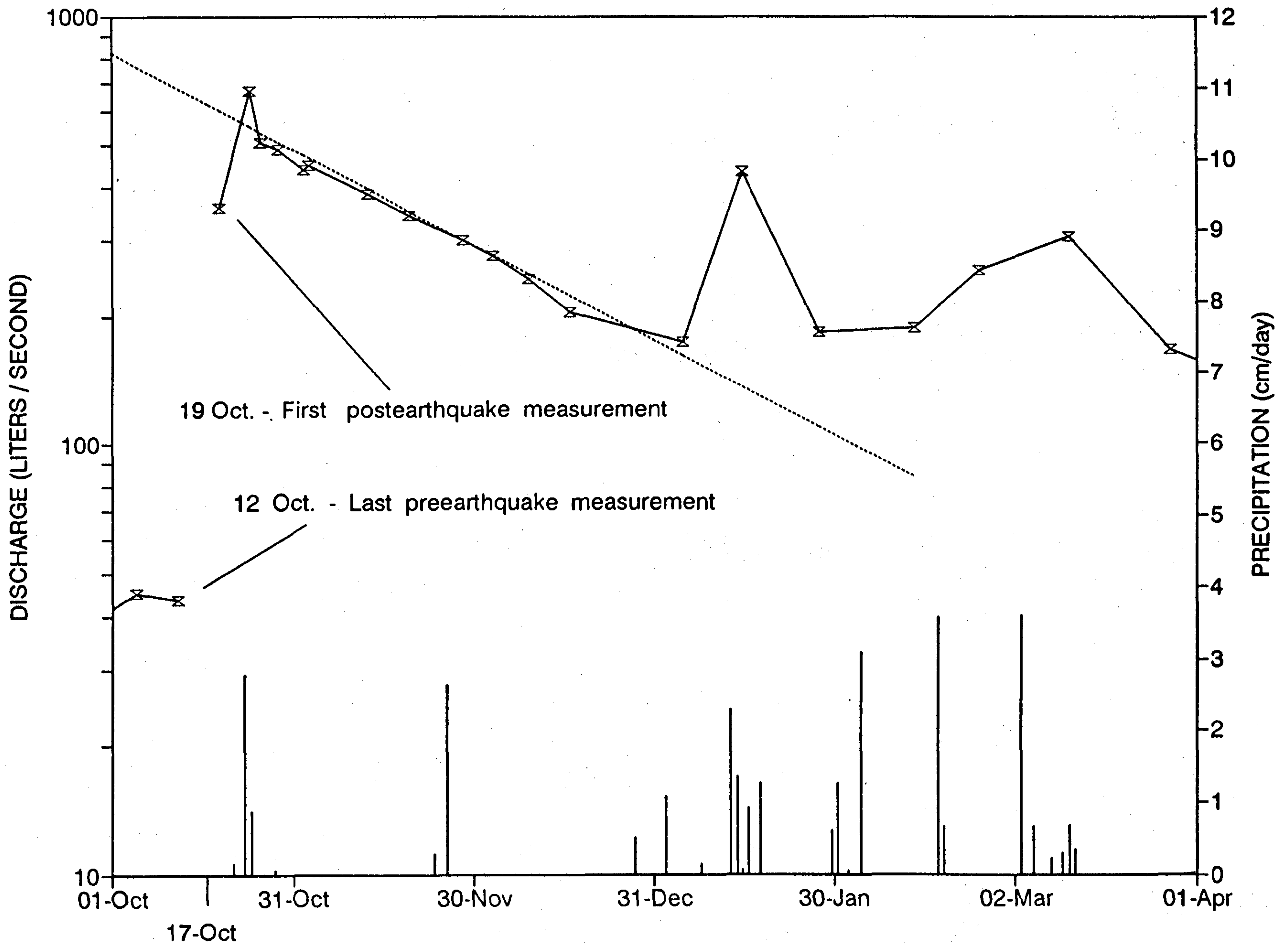

Figure 4.—Discharge of Waddell Creek prior to and after the earthquake showing steep rise followed by gradual recession, until obscured by rain runoff. Dotted line is an exponential function with a time constant of 59 days, which empirically simulates the postearthquake creek flow recession pattern. A bar chart displays daily precipitation.

infrequent, random occasions since 1977.[4] Its lowest recorded discharge was 0.126 L/s on October 10, 1977, following a severe drought and the greatest was 0.788 L/s on August 31, 1983, following a rain year with 152 cm of precipitation (about twice the 100 year average). Before the earthquake, discharge of this spring was within its normal range: 0.252 L/s on January 29 and 0.189 L/s September 21. The earthquake-induced behavior of Brown House Spring is graphed in figure 5.

On October 20, 1989, three days after the earthquake, the first postearthquake measurement was 2.37 L/s, a 12.5-fold increase from preearthquake discharge and three times the highest value previously recorded. Discharge then receded exponentially with a time constant of 37 days. The recession pattern, which was unaffected by the January and February rains, continued its exponential decay for 152 days. The discharge then deviated sharply downward, ceased within a few days, and had not resumed as of March 1992.

[4]Spring discharges were determined by clocking the fill time of a calibrated vessel.

CHEMICAL SIGNATURE OF BROWN HOUSE SPRING

A comparison of the pre- and post-earthquake chemistry of Brown House Spring (which is the only source under observation for which a preearthquake chemical analysis is available) is presented in table 1. Analysis of samples taken July 23, 1981 (Kent, 1981), and November 9, 1989 (Galloway, 1989), are sufficiently similar to indicate that the waters are from the same source.

The only significant difference between the two samples is the reported postearthquake increase in sulfate concentration. However, the preearthquake sulfate concentration of 7.6 mg/L may be an error. A value of 76 mg/L yields a better electrical balance and is more consistent with typical values of sulfate in water sources of the area. The error cannot be confirmed since original laboratory notes and records no longer exist; however, it would not affect conclusions drawn from the data.

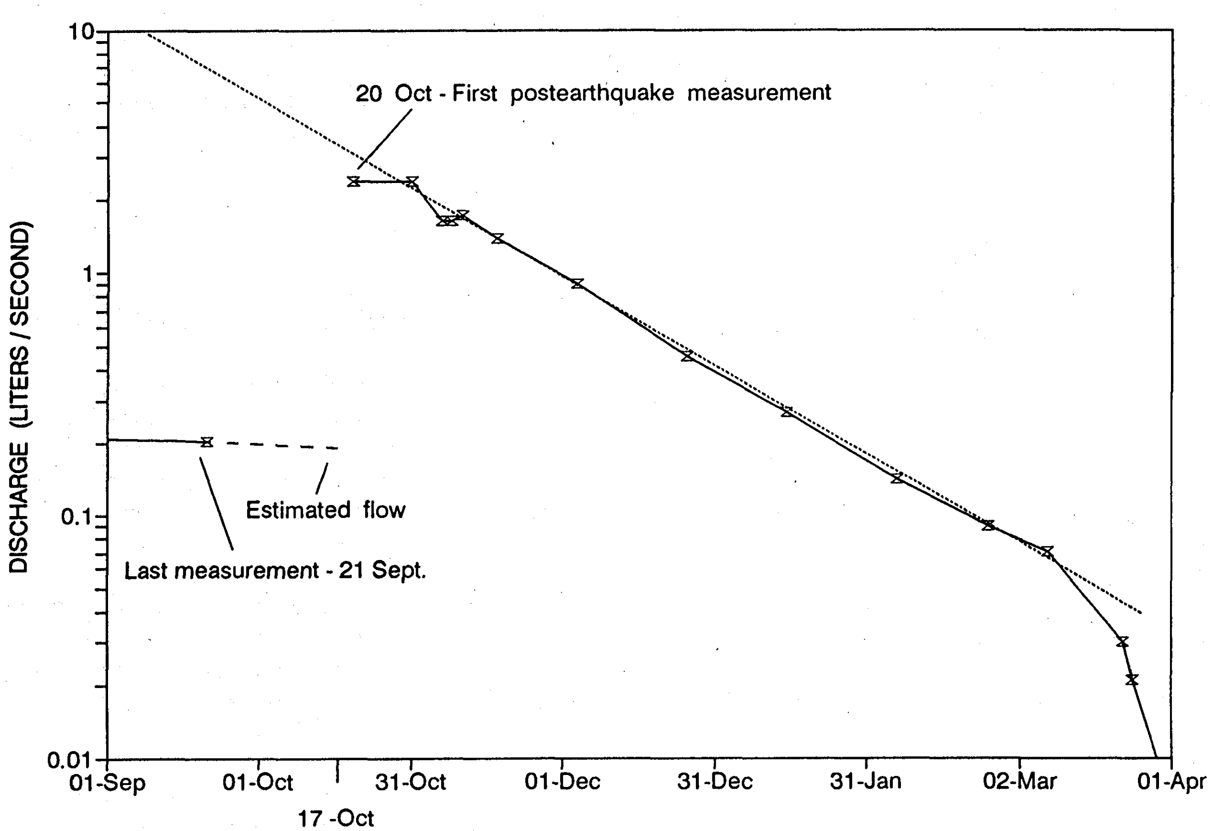

Figure 5.—Discharge of Brown House Spring prior to and after the earthquake, showing a steep rise followed by a gradual recession. Dotted line is an exponential function with a time constant of 37 days, closely simulating the flow recession.

Table 1.—*Pre-and post-earthquake chemical analysis of Brown House Spring*

[Chemical concentrations expressed in parts per million]

		July 23, 1981	Nov. 9, 1989
pH value (units)		8.35	7.1
Conductivity (micromhos/cm)		590	630
Carbonate alkalinity	(as $CaCO_3$)	4.8	0
Bicarbonate alkalinity	(as $CaCO_3$)	188.4	230
Total alkalinity	(as $CaCO_3$)	193.2	230
Total hardness	(as $CaCO_3$)	185	160
Total dissolved solids	(as NO_3)	397	400
Nitrate		7.3	<1
Chloride (Cl)		40.8	40
Sulfate (SO_4)		7.6	60
Fluoride (F)		0.5	0.39
Calcium (Ca)		32.1	28
Magnesium (Mg)		25.5	23
Potassium (K)		3.5	4.6
Sodium (Na)		64	71
Total iron (Fe)		0.227	1.4
Manganese (Mn)		0.072	0.12

RESUMPTION OF FLOW IN PREVIOUSLY DORMANT SPRING

Several springs that had been inactive for many years resumed discharge after the earthquake and then returned to dormancy after several months of activity. One such source is Casa Spring, about 1.6 km from the mouth of Waddell Creek at about 37 meters above sea level (4,106,650 meters N., 565,040 meters E.). According to the recollection of residents and owners of the property, it was used as a domestic water source from 1914 until about 1925, when it was abandoned because of reduced productivity. Its flow ceased completely in about 1970, and (based on frequent observations by the author) it remained dormant until it was reactivated by the earthquake. Its postearthquake record is presented in figure 6.

On October 20, 1989, flow was observed from Casa Spring, with gas bubbles rising through the water. A gas sample taken on December 6, 1989, consisted of 91 percent nitrogen, 2 percent oxygen, and 4 percent carbon dioxide, with traces of methane and other gases. The gas chemistry suggests that the ground water issuing from the spring contained air which was depleted of oxygen along its flow path. The gas discharge rate was not measured but appeared to diminish as the water discharge receded. Measurements of water discharge were begun on October 28, 1989, and at that time a flow of 1.58 L/s was measured. The discharge recession approximates an exponential function with a time constant of 49 days and responds to the mid-January precipitation. Measurements were discontinued in mid-April and discharge ceased in early May of 1990. As of March 1992 the spring remains dormant.

APPEARANCE OF NEW SPRINGS

Numerous new springs appeared after the earthquake. One such spring, designated Entry Road Spring, was first seen by the author within 30 minutes after the earthquake. It emerged in the middle of a gravel road near the mouth of Waddell Creek at an altitude of 11 meters above sea level (4,105,825 meters N., 564,760 meters E.). Flow rate was not measured, but it was estimated by the author (visually comparing the discharge with other sources whose flow is known) at 1.5-2 L/s. This spring expanded over the next several days to form a quicksand-like material, making the road unusable. The water was diverted on October 22, 1989, by installation of a drain which continued a substantial discharge for approximately 365 days.

Similar new, temporary sources were observed at many other locations throughout the watershed, but none were quantitatively recorded and all ceased flowing within the first postearthquake year.

POSTEARTHQUAKE WATER-TABLE DROP

The mathematical model describing the postearthquake flow recession of springs and creek also predicts an exponential descent of the water-table height concurrent with the flow recession. Anecdotal reports indicate that the water level of several wells on the east ridge of the Waddell watershed fell after the earthquake. A number of wells were deepened, abandoned, or replaced by deeper wells. However, quantitative data defining these water level changes are unavailable.

At lower altitudes in the watershed, a systematic water-table drop is suggested in the sequence of spring flow terminations (fig. 7). The termination times progress from the highest altitude source to the lowest in a pattern consistent with an exponentially descending water table. However, the significance of this observation is uncertain since it is supported by only three data points from sources separated horizontally by nearly 2 km.

PROBABLE CAUSE OF HYDROLOGIC ANOMALIES

The increase in Waddell Creek discharge coincident with the earthquake cannot be attributed to release of surface stored water, since there are no significant manmade or natural ponds or impoundments on the creek or in the watershed.

The similarity of the postearthquake and preearthquake chemical signature of Brown House Spring (indicating that the waters are from the same source), together with the postearthquake water-table drop, suggests that the step increase in surface discharge associated with the earthquake resulted from increased permeability of the subsurface material, allowing more rapid release of ground water from storage.

A simple model consisting of a finite reservoir discharging through a restricted aperture yields an exponential flow recession versus time, which conforms with the flow recession patterns of the springs and creek. This model

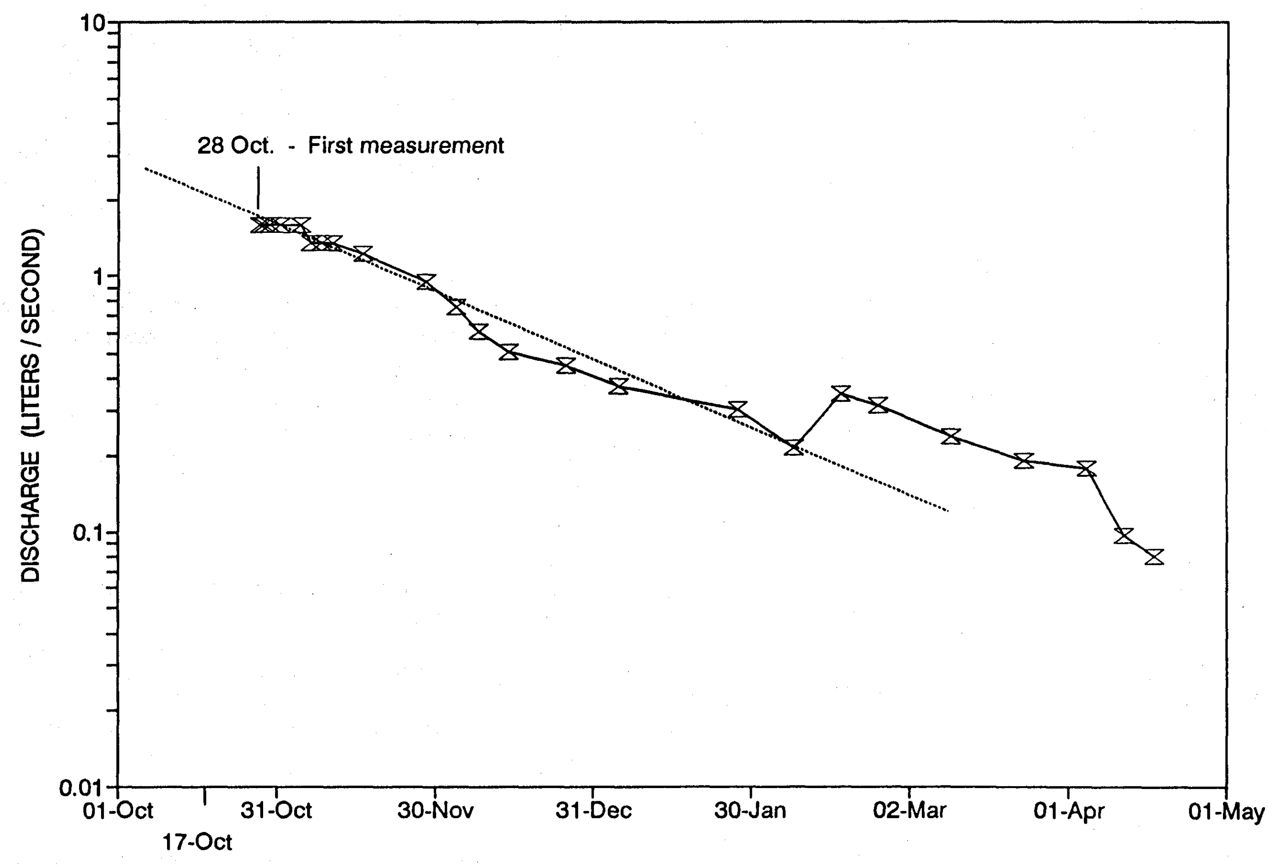

Figure 6.—Discharge of Casa Spring (dormant since 1970) after the earthquake. Dotted line is an exponential function with a time constant of 49 days, which closely simulates the recession until the mid-January rain introduces a perturbation.

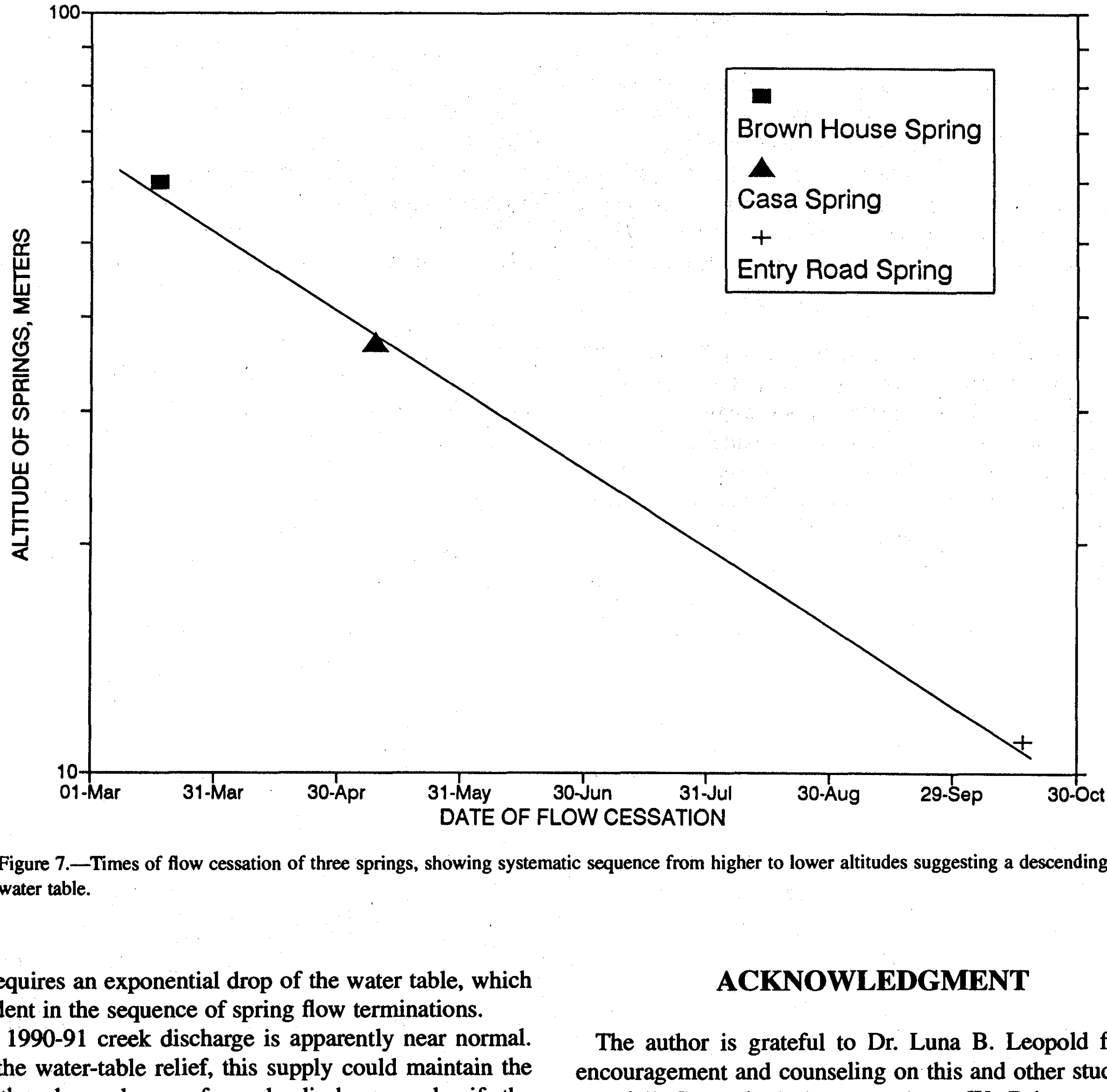

Figure 7.—Times of flow cessation of three springs, showing systematic sequence from higher to lower altitudes suggesting a descending water table.

also requires an exponential drop of the water table, which is evident in the sequence of spring flow terminations.

The 1990-91 creek discharge is apparently near normal. With the water-table relief, this supply could maintain the preearthquake volume of creek discharge only if the ground permeability remains relatively high. The pattern of continued dormancy of intermediate altitude springs together with normal flow of Waddell Creek suggests that restoration to pre-event permeability has not occurred.

CONCLUSION

When or whether the permeability will return to preearthquake values is not apparent. However, it is of practical as well as scientific interest to understand the full cycle of the earthquake-induced hydrologic changes.

Perhaps an insight to changes attendant to previous seismic events could be found in natural historic records. For example, indications of the pattern of water-table perturbations coincident with historical or prehistorical earthquakes may exist in such records as tree ring patterns.

ACKNOWLEDGMENT

The author is grateful to Dr. Luna B. Leopold for his encouragement and counseling on this and other studies of Waddell Creek hydrology; to Anne W. Briggs and Dr. David G. Willis, who have contributed to the observations and interpretations presented in this paper; and to Evelyn Roeloffs and William C. Evans for the gas sampling and analysis.

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HYDROLOGIC DISTURBANCES

SOURCES AND MAGNITUDES OF INCREASED STREAMFLOW IN THE SANTA CRUZ MOUNTAINS FOR THE 1990 WATER YEAR AFTER THE EARTHQUAKE

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CONTENTS

ABSTRACT

The Loma Prieta earthquake caused the release of about 87 hm^3 of stored, shallow ground water from the Santa Cruz Mountains on the San Francisco peninsula in the 1990 water year. This release of ground water was manifest primarily by increased base flow of surface streams. About 33 percent of the augmented flows were estimated from gauge records of the U.S. Geological Survey, and the remainder were estimated in proportion to their ungauged watershed areas.

Chemical analyses of about 100 surface-water and ground-water samples demonstrated modest increases in cation concentration in some but not all sampled waters. However, there were no significant differences in cation-cation and cation-anion ratios that could be attributed to the earthquake directly. Thus the water chemistry data support an interpretation of shallow ground-water origin for the augmented postearthquake flows based upon the observation of no significant changes in chemical signatures between pre- and post-earthquake water in shallow aquifers and springs and in streams that drain them. Water quality chemical data for over 1,500 ground water and over 1,500 surface-water samples were compiled and reviewed to assess trends and background variation. The patterns of changes in flow, ground-water levels, and water chemistry all support a hypothesis of simple strain-induced increased permeability of near-surface (above sea level) bedrock units as the source of increased surface-water flows. However, the intermediate and far-field hydrologic changes do not preclude a hypothesis of coseismic strain-release forced dewatering of shallow water-bearing rocks. The existing San Francisco peninsula stream gauging network and record appear adequate to record shallow strain-induced changes in rock permeability.

INTRODUCTION

PURPOSE AND SCOPE

Significant streamflow increases were observed throughout the San Francisco peninsula immediately after the Loma Prieta main shock. This study was conceived to explore the geochemistry of surface and ground waters to try to determine the origins of the increased flows. Through analysis of sequential changes in chemistry of base flow and ground waters at fixed stations, it was postulated that the part of the chemical signature of the waters that decayed in proportion to postearthquake base flow decreases would indicate origins of that component of the flow. Sources of increased base flow can also be explored through analysis of the timing of this peak and other hydrograph analyses.

The earthquake occurred during a time of prolonged regional drought. For the full water year after the earthquake, flows increased from 1 to 24 percent of mean annual long-term runoff, with up to 70 percent increase in total flow for some gauging stations estimated for the drought year itself (see table 1). Questions about the expected duration of those increases and impacts of those increases upon future surface-water flow volumes were raised. If pore or void volumes have decreased to provide the increased yields from bedrock or upper watershed surface materials, that decreased storage capacity could lead to decreased future base flow for surface-water supply sources. If void volumes have increased or become more permeable, other future water supply effects may be anticipated.

The basic questions addressed in this report are as follows: What are the origins of the increased spring and streamflows associated with the earthquake, and how do these origins affect prognoses for surface-water base flow and ground-water availabilities after this and potential future seismic events? Secondary questions include those associated with perceived and real changes in water quality, times, and volumes of recharge required to replenish ground-water resources, mechanisms of changes in permeability and porosity of water bearing rocks, and long-term recovery times for restoration of preearthquake hydrologic conditions.

PREVIOUS WORK

Postevent increases in surface-water flows have been long recognized at places such as the 1952 M 7.1 Arvin-Tehachapi earthquake (Briggs and Troxel, 1955), the Alaska Good Friday earthquake (M 8.6, 1964; Waller, 1966), and Borah Peak, Idaho (M 7.0, 1983; Whitehead and others, 1985). Rojstaczer and Wolf (1991) summarize the proposed mechanisms for inducing such changes as reported in the literature. Postevent changes in ground-water levels and conditions have also been long reported (Lawson, 1908; LaRocque, 1941). Prior investigations support a very wide range of near-surface and deeper causal mechanisms for observed changes (Wood and others, 1985; Wood, 1985; Swenson, 1964; Sibson, 1981; Nur, 1974; Bell and Katzer, 1987). Multiple hypotheses for the origins of coseismic and postevent hydrologic change is fully supportable since such changes are observed in a wide variety of geologic conditions with both confined and unconfined aquifers and with both shallow and deep epicentral foci. Muir-Wood and King (1991a, 1991b) have explored the general subject of earthquake related changes in hydrology in crustal rocks.

Rojstaczer and Wolf (this volume) have released preliminary analyses of the hydrologic changes associated with the earthquake, with specific focus on the San Lorenzo and Pescadero Creek drainage basins. Their work demonstrates similar but lesser magnitude responses associated with the Lake Elsman earthquake of August 8, 1989 (M 5.2), which has been considered a foreshock to the Loma Prieta M 7.1 event (Lisowski and others, 1990). Rojstaczer and Wolf conclude that the origin of the increased surface flows is primarily from shallow ground waters released through a "wide scale increase in near-surface permeability" (p. 16). This is in accord with our findings.

Prior investigations of coseismic and postevent changes in geochemistry of shallow and surface waters have largely focused on use of such observations as precursory tools (King, 1981; Wesson, 1981; Wang, 1985; Varshal and others, 1985). The general subject of chemical change associated with earthquakes has led to the field of seismogeochemical research in China (Li and others, 1985). These investigations have been conducted extensively in Japan (Wakita, 1981) and China (Jiang and Li, 1981; Li and others, 1985). Chemical changes, other than those simply associated with outgassing of volatile rock components (Varshal and others, 1985), have been investigated on the San Andreas fault, where a chloride brine is found below -300 m and waters saturated in calcite may originate in the depth range of 50 to 280 m (Stierman and Williams, 1985). Finkel (1981) reports marked changes in uranium concentrations and activity along the San Andreas 70 km from the October 1979 M 6.6 Imperial Valley earthquake.

HISTORICAL INFORMATION

There are well-founded reports of hydrologic changes similar to those observed in 1989 that occurred in the Santa Cruz Mountains after the October 8, 1865, M±6.5 earthquake on the Santa Cruz segment of the San Andreas fault as well as the major April 18, 1906, San Andreas fault event. These data have been summarized in an unpublished report (Jeff Marshall, University of California, Santa Cruz, Earth Sciences Board, 1990). Local newspaper accounts report (Santa Cruz Sentinel, 14 Oct. 1865, p. 3):

> All the mountain streams, immediately after the earthquake, commenced rising. The Pajaro has half more water; Coralitas, twice as much, and the Soquel near the same. The flour mill of Hames and Daubenbiss is now running night and day; before last Sunday the water only allowed eight hours' work. The San Lorenzo is considerably higher, also the streams north of this, up the coast.

Three months after that 1865 event, a Santa Cruz Sentinel commentator (Dec. 9, 1865, p. 1) notes:

> But we intended, at the outset, to give some facts as connected with the great rise of mountain streams noted after the earthquake of October 9th: These streams have re-

mained full of running water, ever since, up to the time of the recent rains, without diminishing in volume.

The 1906 M±8 event again caused significant hydrologic change locally, and these changes were documented by Lawson (1908), as well as by newspaper reports: "At a sawmill near Boulder Creek, water stops running from a hitherto permanent spring, but another in the neighborhood was flowing more freely than before" (Lawson, 1908, p. 408). Of the Wrights area, near the Summit, Lawson also states: "Most of the springs are running with a greater flow since the earthquake; but the water in [a] well on top of the ridge sank rapidly to the level it usually holds in August***. The well at the summit, from which the Summit Hotel obtains it water, has its bottom on solid rock. After the shock the level of water in the well rose 12 feet."

In 1906, at the Pajaro River, the southern limit of clear hydrologic effects of the 1989 earthquake, it was noted that: "The flow of the Pajaro River suddenly increased with the earthquake. Some running wells went dry, whereas some old dry wells sprang to life" (Watsonville Register-Pajaronian, July 2, 1952, p. 57). Although lack of mention in newspaper articles may not indicate lesser effects, changes in streamflow associated with the 1906 earthquake did not receive the attention that they did in 1865. More attention was noted for ground-water changes than for surface water in 1906. This may be due to the fact that earthquake occurred during a period of above normal rainfall, in the spring, during the rain season. Lawson (1908, p. 399) notes: "At Boulder Creek, in Santa Cruz County, 55.70 inches of rain fell during January, February, and March alone, and 16 inches fell during the four months preceding." It is thus reasonable to assume that immediate changes in base flow were masked in April of 1906. The rainfall of the 1906 water year occurred after a period of modest drought (fig. 1). Although Lawson's statements suggest significant departures, in fact the 1905 water year (July 1, 1904-June 30, 1905 for precipitation data at the time) for Santa Cruz was 91.14 cm, and for 1906 was 81.94 cm, with a long-term (115-year) average of 70.90 cm. With hindsight, we see that the 1906 regional precipitation, as indexed by the Santa Cruz station, was about 116 percent of normal.

Careful review of newspapers and other historical sources did not provide any clues to the recovery times for displaced ground water, dewatered wells, or surplus streamflow. We know, from the 1865 semiquantitative notes on increased streamflow, that conditions then were approximately comparable to those in 1989 (see Rojstaczer, this volume). Since accounts of 1866 and 1867 no longer noted the "permanent" changes associated with the 1865 event, it is possible that subsequent precipitation and streamflow decay periods comparable to those of 1989 (50-400 days) restored preearthquake hydrologic conditions within 1 to 2 water years.

SETTING

The runoff hydrology of the Santa Cruz Mountains has been summarized by Rantz (1974), and by Blodgett and Poeschel (1984). About 85 percent of the annual precipitation occurs from November through March, with mean annual precipitation from 35 cm at San Jose (on the lee side of the highest peaks) to over 147 cm at Boulder Creek in the San Lorenzo basin on the southwest side of the range. Ground-water hydrology for parts of the range has been summarized by Muir and Johnson (1979), Johnson (1980), and by Akers and Jackson (1977). Clark's (1981) mapping of the central range has been supplemented by a newly compiled synthesis of bedrock geology for Santa Cruz County (Brabb, 1989). Drought conditions and the effects of the earthquake on water supplies in Santa Cruz County are summarized by Goddard and Laclergue (1991).

DROUGHT

The October 17, 1989, earthquake occurred near the beginning of the 1990 water year and before any significant precipitation in that year. The 1989 water year was the third of a series of drought years with significant cumulative departure from long-term normal precipitation. Using the 1879-1991 long-term Santa Cruz city precipitation record, for which a clean complete record exists from July 1, 1878, to the present without urban influence or inversion effect changes through time, the precipitation-year (July 1 of prior year through June 30 of named-year) data show that the earthquake occurred at the point of the second-most-severe drought of record (fig. 1).

The peak drought for 113 years of record culminated in 1931, with a 4-year cumulative departure from long-term normal of –25.18 cm. The 1990 precipitation water year, during which the earthquake occurred, had a cumulative departure for that and the preceding three years of –23.35 cm. Unlike the drought of the 1920's and 1930's, the drought during the earthquake was preceded by a period of significant excess precipitation, with the second largest positive 4-year cumulative departure of the period of record. That precipitation excess persisted until 1985-86 (100.43 cm/yr at Santa Cruz; cumulative departure +20.5 cm). The years surrounding the earthquake (1987-1991) all had significantly below normal regional precipitation as follows: 1986-87 (44.7 cm, 87 percent of mean for period of record, –0.55 cm cumulative departure); 1987-88 (47.04 cm, 65 percent, –5.38 cm); 1988-89 (59.1 cm, 82 percent, –9.35 cm); 1989-90 (44.42 cm, 62 percent, –23.35 cm); 1990-91 (51.13 cm, 71 percent, –21.74 cm). Rojstaczer (oral commun., 1992) finds some headwater precipitation stations with slightly higher precipitation in the 1990 water year than in 1989. For the San Lorenzo watershed (six stations), and for those reviewed for regional trends

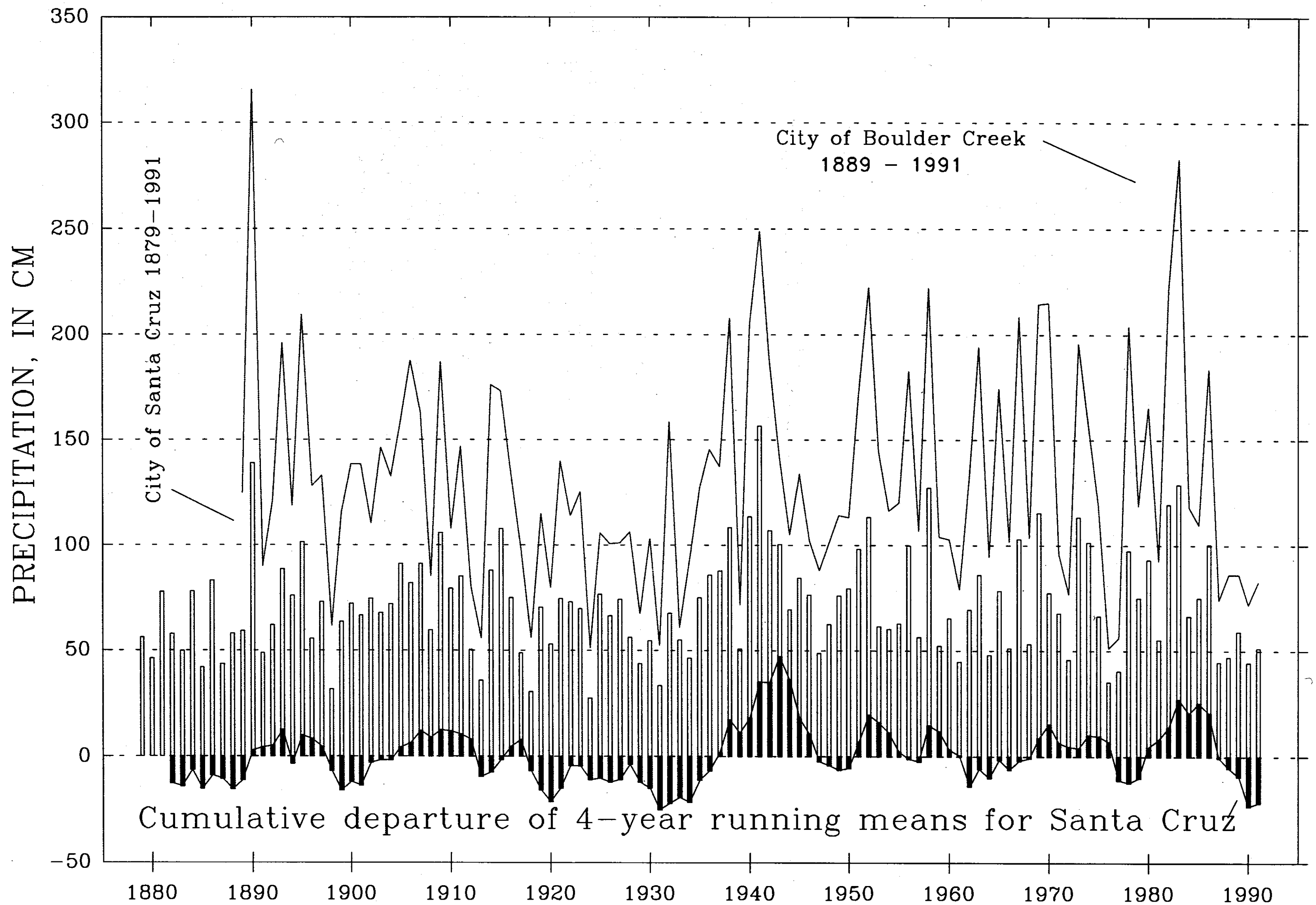


Figure 1.—Santa Cruz regional area long-term precipitation and cumulative departures from 4-year running means. Annual data are presented for city of Santa Cruz (bar chart) and city of Boulder Creek (lines) in the upper San Lorenzo Creek watershed. The two data sets are parallel, although higher values of mountain station (Boulder Creek) best reflect runoff. Cumulative departure data (filled bars) for longer continuous Santa Cruz record best reflect three years of antecedent precipitation that control water table elevations and ground-water-fed base flow. Last year of record is July 1, 1990, to June 30, 1991. Year of the earthquake is that designated 1990. Santa Cruz data are for July 1, 1878, through June 30, 1991, for precipitation water years (July 1 of the previous year through June 30 of the named year).

Table 1.—*Summary of selected Santa Cruz Mountain stream records from October 1, 1989, to September 30, 1990*

[Column A (mean annual precipitation) is based on isoheyet-weighted basinwide average; column B (distance to epicenter) is measured to the area-weighted watershed basin center; columns J and K (mean annual runoff) are based on Rantz (1974); all other values are based on hydrograph disaggregations detailed in this paper (see fig. 2, Soquel Creek, for example). NA, not applicable]

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Station Name	Mean annual precipitation (cm)	Distance to epicenter (km)	Watershed area (km²)	Post earthquake change in Baseflow (acre-ft/yr)	Total quantity minus storms (acre-ft)	Total quantity with storms (acre-ft)	Increase in total quantity (percent)	Increase in baseflow (percent)	Increased yield per unit area (cm)	Mean annual runoff (cm)	Mean annual runoff (acre-ft)	Increased yield (m³/km²)	Increased yield (hm³/yr)	Increase in mean annual runoff (percent)
Pajaro R near Chittenden	NA	NA	3,070	NA	1,441	2,281	NA	NA	[1]0.04	4.42	110,100	[1]433	[1]1.33	[1]0.98
Corralitos Ck at Freedom	96.5	6.5	72.00	481	481	1,497	32	100	0.82	18.85	11,010	8,232	0.59	4.37
Soquel Ck nr Soquel	101.6	6.5	104.10	2,889	3,649	7,812	37	79	3.42	36.65	30,940	34,234	3.56	9.34
San Lorenzo R at Big Trees	121.9	21	275.00	6,984	7,485	9,775	71	93	3.13	42.88	95,630	31,326	8.61	7.31
San Lorenzo R nr Boulder Ck[2]	140	28.5	15.98	1,133	1,569	1,696	67	72	8.75	37.19	4,820	87,487	1.40	23.52
Boulder Ck nr Boulder Ck[2]	147	30	29.30	984	1,326	2,236	44	74	4.14	52.14	12,390	41,417	1.21	7.94
Bear Ck at Boulder Ck[2]	137	23.5	41.40	1,010	1,264	1,982	51	80	3.01	37.97	12,750	30,101	1.25	7.93
Zayante Ck nr Zayante	114.3	15.5	28.70	372	1,135	1,370	27	33	1.60	35.49	8,260	15,988	0.46	4.51
Bean Ck nr Scotts Valley	99.1	13	22.79	399	1,861	2,172	18	21	2.16	NA	NA	21,568	0.49	NA
Pescadero Ck nr Pescadero	104.1	38	118.90	4,926	5,876	7,514	66	84	5.11	31.03	29,920	51,105	6.07	16.47
San Gregorio Ck near San Gregorio[2]	81	49.5	131.80	2,768	3,206	5,219	53	86	2.59	25.55	27,310	25,901	3.41	10.14
Pilarcitos Ck at Half Moon Bay	94.0	67	70.40	405	637	1,725	23	64	0.71	18.65	10,650	7,093	0.50	3.80
Redwood Ck at Redwood City	61.0	56.5	4.71	24	40	205	12	60	0.62	21.44	819	6,196	0.03	2.89
Saratoga Ck nr Saratoga	114.3	29	23.88	614	829	1,345	46	74	3.17	37.80	7,320	31,726	0.76	8.39

[1] Assumes 1,080 acre-ft/yr of base flow between October 17, 1989 and July 19, 1990 is all attributable to earthquake; in fact, it was not possible to differentiate multiple sources of base flow. Value includes interbasin waste discharges.

[2] Estimated from Rantz (1971); all other basinwide values (Cols A, C, J and K) from Rantz (1974).

(seven stations), the above values and those illustrated in figure 1 are representative.

The earthquake occurred at a time when water levels in regional shallow open aquifers in unpumped areas were close to or slightly above long-term normal. This estimation is based on the observation that streamflow records for the period following the 1973 and 1983 high-precipitation water years in the Santa Cruz Mountains indicate that about 4 years are required to drain the "excess" stored water after periods of positive cumulative precipitation departures. "Normal" is here considered the low point in a water year annual cycle of variation for any one point. Thus, ground-water levels just prior to the earthquake were at their normal annual low point but were not significantly below the levels expected at the same time of year within a series of water years with about average precipitation. This point is illustrated by an observation well in the Pescadero basin cited by Rojstaczer and Wolf (1991, fig. 8, p. 13).

Since ground-water supplies base flow for streams and springs in the Santa Cruz Mountains and normal October base flow conditions existed at the time of the earthquake, it is reasonable to assume that streams and springs were at about their normal lowest annual flow levels at the time of the earthquake. This is verified by analysis of successive annual stream hydrographs for the gauging stations in the region. However, Rojstaczer and Wolf (1991) show that after the August 8, 1989, M 5.2 Lake Elsman foreshock, the base flow levels in both the San Lorenzo and Pescadero basins were somewhat above normal compared to the prior year. This minor effect can be discerned in most of the gauging records in the region. Without the drought conditions of this period of years, it is doubtful if such a clear hydrologic signature of the foreshock—or of the regional strain manifest at the time of the foreshock—could be observed.

FLOW INCREASES

Table 1 summarizes information on increases in flow for 14 selected stations on the San Francisco peninsula and Santa Cruz Mountains. Flow changes in springs were anecdotally reported as far as Sonoma County, 200 km north of the epicenter. Verified changes in stream discharge as recorded by recording gauges were noted as far away as the city of San Francisco, 88 km from the epicenter. Similar gauges also recorded flow increases outside the area of the Santa Cruz Mountains and San Francisco peninsula, but only at a distance of about 60 km from the epicenter

Table 2.—*Stream gauging stations reviewed within the study area, including lag time in days after October 17 to the time of gauged peak earthquake-induced base flow peak discharge*

[– – –, not discernible]

STREAM GAUGING STATIONS - Study Area

USGS gauge	Station name	Area (km^2)	Lag (days)	Comment
11143200	Carmel River at Robles del Rio	500	– – –	South of area
11152000	Arroyo Seco near Soledad	632	– – –	South of area
11159000	Pajaro R. at Chittenden	3,070	37	South of area, >3/4 alluvial
11159200	Corralitos Creek	72	21	SW-most station, 1/2 alluvial
11160000	Soquel Ck. at Soquel	104.1	22	West side, 1/4 alluvial
11160020	San Lorenzo R. nr Boulder Ck.	275	[1]5 and 24	West side, bedrock
11160060	Bear Ck. at Boulder Ck.	41.4	[1]4	West side, bedrock
11160070	Boulder Ck. at Boulder Ck.	29.3	[1]4 and 13	West side, <1/4 alluvial
11160300	Zayante Creek at Zayante	28.7	(1)	West side, bedrock
11160430	Bean Ck. at Scotts Valley	22.8	[2]2	West side, <1/2 alluvial
11160500	San Lorenzo R. at Big Trees	275	[1]4	West side, <1/4 alluvial
11161000	San Lorenzo at Santa Cruz	298	[1]4	West side, <1/4 alluvial
11161300	Carbonera Ck. at Scotts Valley	9.3	– – –	West side
11161500	Branciforte Ck.	46.8	– – –	West side
11162500	Pescadero Ck. nr Pescadero	118.9	[1]6	West side, bedrock
11162570	San Gregorio Ck. at San Gregorio	131.8	(1)	West side, <1/4 alluvial
11162600	Purisima Ck.	21.6	– – –	West side
11162630	Pilarcitos Ck.	70.4	[1]5 and 23	West side, <1/4 alluvial
11162720	Colma Ck. nr Colma	28.0	– – –	NE-most station
11162800	Redwood Ck. at Redwood City	4.71	4	East side
11164500	San Franscisco Ck. at Stanford	96.9	– – –	East side
11166000	Matadero Ck. at Palo Alto	18.8	– – –	East side
11166480	Stevens Ck.	44.8	– – –	East side
11167980	Los Gatos Ck. at Los Gatos	95.8	– – –	East side
11169000	Guadalupe River at San Jose	373	– – –	East side
11169500	Saratoga Ck. at Saratoga	23.9	(1)	East side, bedrock

[1] Peak obscured by rainfall of October 21-25 in Santa Cruz County, and 21-26 in San Mateo County.

[2] Time to maximum flow *decrease* immediately post-earthquake.

in Monterey County, and near the Hayward fault in southern Alameda and Santa Clara Counties.

Although minor changes in flow are recorded, for example, in the Carmel River about 60 km south of the epicenter, the marked increases in flow that persisted for months after the earthquake were restricted to the Santa Cruz Mountains and San Francisco peninsula. It is probable that flow changes recorded beyond the area of focus of this study were due to mechanisms different from those investigated in more detail here. A total of 26 recording gauging stations were reviewed in detail for this study (table 2). The initial selection was based upon long-period high-quality records and the magnitude of the seismogenic signature recorded on the gauges. Stations with marked annual variations due to pumping or release of interbasin-transfer water and treated effluents were eliminated. The Pajaro River station at Chittenden is included in the table 1 tabulation as the largest end of the scale of watershed size, but it cannot be interpreted in the same fashion as can the other stations because it does receive treated effluents and irrigation flows that distort the base flow regression and is fed by major alluvial aquifers.

The base flow estimates of table 1 differ markedly from those reported by Rojstaczer and Wolf (1991). Their estimates of excess base flow were based upon comparisons with the prior water year (1988-89), which started only two years after the second largest precipitation excess of 110 years of record, and was itself a year with 82 percent of normal precipitation. That year may thus have had somewhat excess base flow volume, despite a negative cumulative 4-year precipitation departure of –9.35 cm. The base flow was certainly higher than that of the subsequent year without the seismogenic excess, since the year of the earthquake had a –23.35 cm cumulative precipitation deficit and only 62 percent of normal precipitation.

The estimates by Rojstaczer and Wolf (1991, p. 5-7) of seismically augmented flows are therefore smaller than our estimates, despite similar straight-line hydrograph separations, because we used a straight-line method to separate both background base flow and storm-recharged seasonal base flow (fig. 2, Soquel Creek), whereas they subtracted these values for the prior year to calculate flow excess. Both methods acknowledged base flow increases during storms and assume that storm-induced base flow recession continues after the storm surface runoff ends. Our different methods provide bounds for the range of possible flow

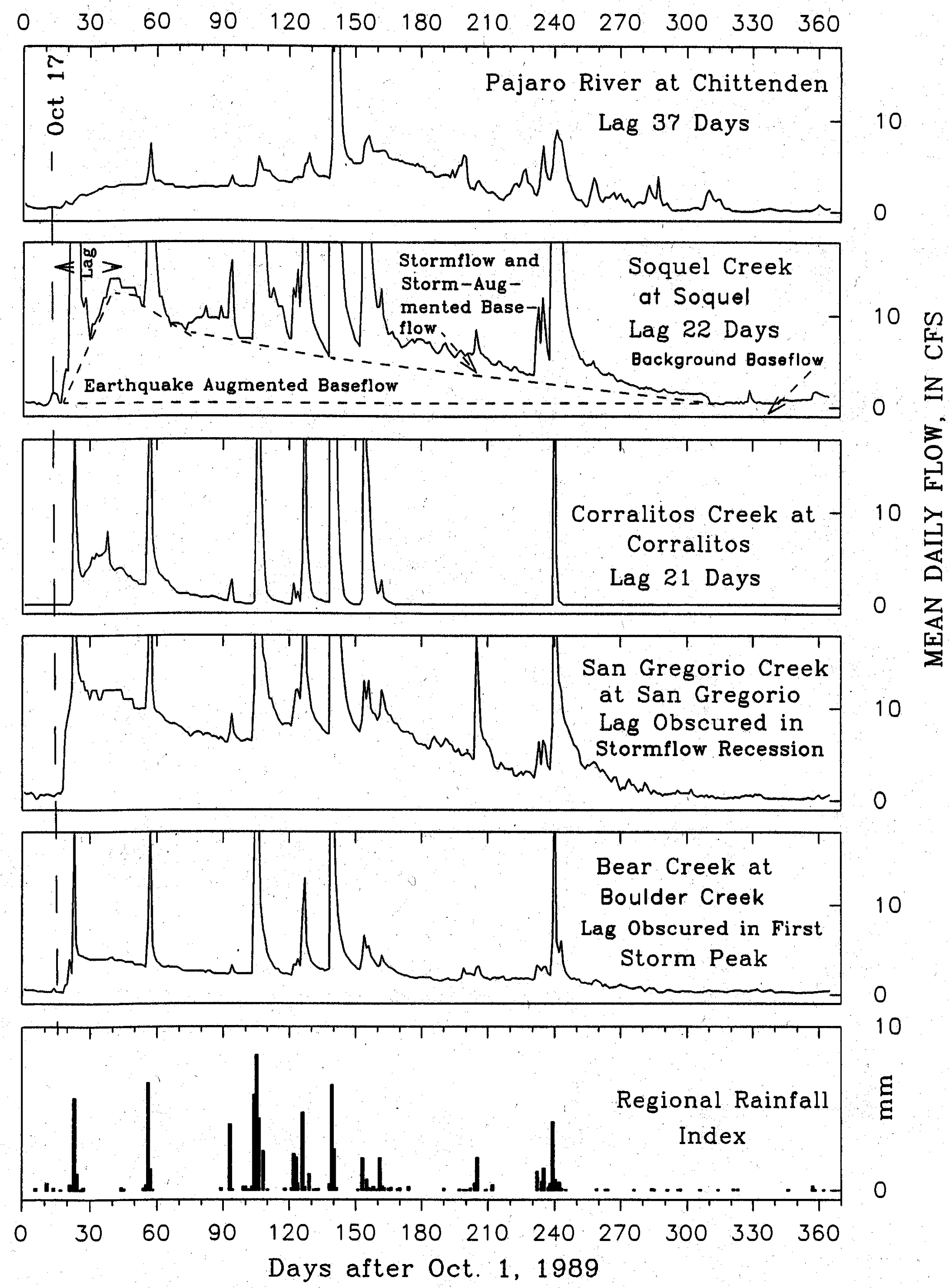


Figure 2.—Hydrographs of mean daily flow for 1990 water year for Pajaro, Soquel, Corralitos, San Gregorio, and Bear Creek gauging stations (details provided in table 1). In general, lag in increase in base flow of earthquake origin becomes progressively delayed from stations at bottom of this figure to those at top. Rainfall index is the sum of daily totals for San Bruno Mountain, Skyline College, and Watsonville Water Works. Hydrograph disaggregation is diagrammatically illustrated for Soquel Creek station where volume of water enclosed in dotted polygon is assumed to be earthquake-augmented base flow.

augmentation, and the actual values for base flow increase probably lie between the estimates of Rojstaczer and Wolf and those of table 1.

Table 1 illustrates base flow increases from about 20 percent to 100 percent. This increase translates into increased yields from zero to almost 9 cm, with the highest values being in the upper San Lorenzo, Pescadero, and Soquel watersheds. In terms of mean annual runoff, the excesses released owing to the earthquake are small, ranging from 1 to 23 percent of total mean annual flows. Except where otherwise noted, all average values in this table are based upon Rantz (1974) for the periods 1931-70.

The total volume of ground water that may have been released by the earthquake from the 14 selected gauged basins and from other ungauged basins is on the order of 84 hm^3. This figure represents the excess base flow component from the gauged watersheds on the San Francisco peninsula and Santa Cruz Mountains north of the Pajaro River (excluding the Pajaro River basin completely except for Corralitos Creek) to which is added an estimate of the proportion of excess base flow runoff expected from ungauged basins and from those for which reliable disaggregation of gauging records was not possible owing diversions, pumping, and waste-flow releases within the same geographic area.

Excess base flow discharge for the 1989 water year was estimated by comparing the ratios of watershed areas supplying excess gauged flows to hydrographically and geologically similar areas of ungauged upland watersheds. Only the areas of the three before-mentioned counties within the study area that represented fractured bedrock above the levels of the lowest coastal marine terrace (≥30 m elevation), and outside of areas of alluvial basin fill were tabulated. The basin fill mapping was based upon generalized maps of hydrographic basins after Rantz (1972a, fig. 2) and the geologic maps of Brabb (1989), and Clark (1981). The area represented by gauged flows records of sufficient accuracy for this work was 823.5 km^2, which represented 33 percent of the total upland area assumed to contribute excess ground-water flows. The County of San Francisco (236 km^2) was considered not to contribute any appreciable naturally recharged ground water. As pointed out by Rojstaczer and Wolf (1991) it is likely that most Santa Cruz Mountains ground water is released into the deeply incised watercourses, and that little upland bedrock basin ground-water flows directly into the ocean. However, postevent observation of rapid rises in ground water in lowland alluvial basins in Santa Clara Valley (J. Berklund, oral commun., 1990, reports wells becoming artesian) suggests that not all the estimated excess flows entered watercourses.

The data in table 1 were evaluated to determine if there were patterns of hydrologic change related to epicentral distance, geologic parent material, or elevation indices of basins. No statistically significant trends could be discerned for watersheds normalized with respect to size (table 1, column I). Watersheds with only a few percent increase in mean annual runoff (for example, Zayante Creek) were closer to the epicenter than those with the highest increases per unit area (for example, San Lorenzo at Boulder Creek, 8.75 percent; Pescadero Creek, 5.11 percent). Particularly when anecdotal observations of changes in spring flow and water table rise and fall are plotted and compared to the gauge records, we find that there is great heterogeneity in observed distribution of hydrologic responses. The Pescadero area, and particularly the coastal San Mateo County areas around the San Gregorio-Hosgri fault, showed disproportionately great increases in streamflow and in rising water tables at distances of 30 to 50 km from the epicenter. Areas south of the epicenter, both southeast and southwest, together demonstrated lesser hydrologic responses than did those north of the epicenter.

A lag in peak hydrologic response was noted in many stations (table 2). Not all stations had a seismically induced peak flow that was masked by the October 21 storm period. In general, it was found that gauging stations in streams that were not flowing in alluvial valleys and those that lacked alluvial terraces above the gauging stations responded more rapidly to increased base flow discharge. This was found to be the case wherever the gauging station was located in a bedrock-controlled reach in an inner gorge, regardless of the presence or absence of potential alluvial storage upstream that could release additional base flow into the channel. On the other hand, where the gauging station was located in an alluvial reach, and where significant alluvial storage was found above the gauge, peak flow was not observed until well after the October 17 event. This effect is illustrated in figure 2, for annual hydrographs of daily means flows for Bear Creek at Boulder Creek, located in bedrock close to the summit zone of maximum surface rupture, San Gregorio Creek far from the epicenter in a valley with very little alluvium, Corralitos Creek in an alluvial valley very close to the epicenter, Soquel Creek that drains the epicenter region itself and is characterized by a significant lower alluvial reach extending several kilometers above the gauge and bedrock above that, and the Pajaro River gauge at Chittenden that drains a very large watershed with low-gradient alluvial sources supplying its minimal base flow. In general, the lag until initiation of rise in base flow was not correlated with distance to epicenter. Lag times were shortest for the lower San Lorenzo River, and north coast stations such as Pescadero and San Gregorio, where the bedrock adjacent to the gauges supplied increased base flow. In more alluvial channels such as Corralitos Creek only 6.5 km from the epicenter, the onset of seismically induced flow was masked by the October 21 storm, 4 days after the earthquake, but the base flow peak did not occur until 21 days after the earthquake, during a time of no precipitation. Bear Creek may have peaked during the first rain of October 21, and then peaked again about 22 days after the initial shock (fig. 2). At San Gregorio augmented base flow peaked about 11 days after the event, whereas Soquel Creek did not peak for 22 days, during a period of minimal rainfall. The Pajaro River record is complicated by possible releases of urban storm and sewage effluents, as well as irrigation return flows in season. However, if the first primary base flow peak is of seismogenic origin, the Pajaro peaks at the end of November, 37 days after the earthquake. Base flow for the Pajaro River is controlled by a major component of rainfall-induced increased ground-water flow over its 3,070 km^2 watershed, and its flow record cannot be disaggregated into base flow and storm flow components with the facility of those smaller watersheds in the Santa Cruz Mountains.

Details of epicentral distances from the gauges and watershed areas may be found in tables 1 and 2. The regional rainfall index, illustrated in figure 2, is based upon the sums of daily values for San Bruno Mountain in South San Francisco at the north end of the study area, Skyline College in the east-central part of the area, and Watsonville Water Works at the extreme south end of the region. In general, precipitation at these three stations is not highly correlated internally, since storm patterns differ. An aggregation of the sum of the three stations provides an index of regional precipitation, but the presence of measurable precipitation for any given day does not imply that all watersheds received rain. General decreases in precipitation from north to south tend to weight the value of the index toward northern watersheds.

METHODS OF INVESTIGATION

Initial sampling was directed to surface and ground-water stations that could be used for sequential collection of samples through several months of postearthquake base flow decline. These point-sampling stations were later augmented with three other strategies that included individual cooperator point sampling, agency cooperator data collection, and detailed assessment of the pre- and post-earthquake chemical analyses made by Santa Cruz County. The first point sampling station was established in November 1989, approximately 6 weeks after the earthquake. Such stations were equipped with staff plates and gauged at times of sampling for water chemistry. An array of precipitation gauging and sampling stations was also begun. After completion of chemical analyses on samples collected during the 1990 water year, further analyses of gauging station and precipitation records were used to set limits on the volumes of water released by the earthquake.

INDIVIDUAL COOPERATOR PROGRAM

Through public outreach, we sought sources of preearthquake water that could be compared with postearthquake samples, where such sampling could reasonably be associated with observed changes in well levels, spring flow characteristics, or surface-water flow changes. From about 300 public responses and offers of cooperation we selected 51 sites for resampling that had preearthquake water samples or chemical analyses. These sites were visited in March, April, and June 1990 to collect preearthquake water and to resample from the same supply systems. In total, 107 ground water (wells and springs) and 100 surface-water (streamflow) samples were ultimately selected for analysis out of about 350 collected samples. All samples were analyzed for Ca, Na, Mg, and K using a Perkin Elmer 2380 Atomic Absorption Spectrophotometer, using standard methods. Selection of samples for analysis was based primarily upon reproducibility of sampling conditions for pre- and post-earthquake water, and elimination of possibilities of contamination or postsampling treatment. We sought raw unfiltered preearthquake samples stored in cool dark nonreactive conditions. Some samples frozen before the earthquake remained so 5 months or more after the event.

Postearthquake sampling was conducted so as to minimize potential sources of chemical water variation when compared to preearthquake samples. With the exception of ice-cubes in metal refrigerator trays, every attempt was made to collect samples through the same distribution system, from the same tap, or hose, or dipped from the same spring, as the preearthquake sample. Where preearthquake samples were not available, but postearthquake differences were deemed potentially significant chemically, added sampling was done over a period of several months.

At two sites, one near the headwaters of Stevens Creek in Santa Clara County, east of the San Andreas fault, and another on Zayante Creek in Santa Cruz County, just below the USGS gauging station, sequential observation stations were established with staff plates and local observers. At these sites detailed observations of flow changes and water chemistry were correlated with water sampling programs for streamflow. One hundred samples were collected and analyzed through this program to assess sequential changes and to explore possibilities for associating postearthquake water chemistry changes with aftershock time series. In the Zayante Creek site, our observer reported marked episodic changes in sulfur odors. Samples were thus collected to assess possible changes in sulfur compounds.

All sampling was done in triple-acid washed bottles suitable for trace metal analyses. Samples were refrigerated until analyzed. Originally frozen preearthquake samples were maintained frozen until moved to the analytical lab for buffering and dilution. In the lab all samples were buffered with cesium chloride and diluted to give readings in the 1-10 ppm range. Selection of Atomic Absorption Spectrophotometric tubes and instrument settings was developed to establish linear response over the range of concentrations measured.

AGENCY COOPERATOR PROGRAM

In addition to individual and small water association cooperators, 16 public agencies and 16 water associations were selected for data exchange. The most valuable data were found in the county planning and water agencies. Santa Clara County provided extensive data on flow and water level changes. In 1975 Santa Cruz County Planning Department established a water quality laboratory and sampling program. By the time of the earthquake, this lab had compiled a carefully organized database of multielement analyses of 1,667 ground-water samples from 116 sample locations throughout the county. About 30 of these stations were sampled regularly at least once a year. Analyses included temperature, electrical conductivity, depth to water, lab pH, alkalinity, total dissolved solids, chloride, sulfate, orthophosphorus, calcium, magnesium, sodium, potassium, iron, manganese, copper, zinc, lead, chromium, and cadmium. Silica, boron, and fluoride were tested occasionally.

Santa Cruz County preearthquake surface-water data were compiled for 1,432 samples at 205 stations beginning in 1975. In addition to the same suites of major and trace elements that were assessed for ground-water samples, surface-water data sets included gauge height and discharge (where available), sulfate, nitrate, nitrite, orthophosphate, total phosphate, chloride, alkalinity, lab pH, turbidity, ammonia, total phosphorus, chemical oxygen demand, organic nitrogen, and organic carbon. Twenty-nine surface-water stations were part of the long-term core group sampled twice a year before the earthquake. U.S. Geological Survey WATSTOR data were searched for analyses that would supplement the Santa Cruz County surface and ground-water data for the late 1970's and early 1980's. About 240 samples not in the county database were found with the major element suite of Mg, Na, K and Ca, and about 80 trace-element samples with data for Cd, Cr, and Pb.

ESTIMATION OF AUGMENTED STREAMFLOW

To determine the amount of water released by the earthquake, hydrographs for the full 1990 water year (Oct. 1-Sept. 30 of named year) were disaggregated to estimate base flow volumes. A conservative manual separation technique was used to separate storm hydrographs from base flow. We used the assumption that base flow responds to the storm hydrograph concurrently with surface runoff and that no base flow recession continues after the time storm surface runoff ends. This model is best suited only for mountainous upland watercourses without significant bank or alluvial storage. Thus, the volumes estimated for each storm period are separated by drawing a straight line from the point of first storm flow inflection on the rising storm hydrograph to the point of intersection of base flow recession with the tail of the storm peak (see Nathan and McMahon, 1990; Sklash and Farvolden, 1979).

The storm peak flows thus tend to be overestimated because no allowance is made for rise in base flow during storm times. Thus, the estimates of increase in base flow in table 1 may be a few percent low, but this error is compensated by assumptions about the constancy of base flow. In general, ground water can be expected to contribute a significant portion of runoff from streams such as those of the Santa Cruz Mountains that flow in deep bedrock gorges and canyons without significant alluvial storage above the gauging stations (Pinder and Jones, 1969). There were only 7 to 8 periods of precipitation-induced runoff in most studied watersheds during the water year, and these were well separated by dry periods; consequently, storm hydrograph peaks were not compounded so as to render manual base flow separation techniques difficult.

The single atypical condition that required judgment for hydrograph separation was the occurrence of a storm period which began on October 21 during the general period of rise in volume of water released by the earthquake in most but not all watersheds. In this instance, it was necessary to assume an exponential decay in the rate of increase of earthquake-induced base flow through the period of the initial storm of the water year.

The base-flow index (Rantz, 1972b) is defined as the percentage of total annual runoff that occurs in August and September, the months of lowest precipitation input in streams in this region. The base flow index for all watersheds studied in this region was less than 1.3 percent. Ground-water pumping decreases the base flow in the Pajaro basin, yielding a distorted base-flow index of 0-0.05 percent only, but the other study basins average 0.3 to 0.5 percent, with the upper and lower San Lorenzo stations yielding the highest values of 1.1 and 1.3 percent, respectively.

Once storm peaks were removed from the annual hydrographs, an estimation of the contribution of the earthquake to the base flow was made by projecting the October 1-17 base flow horizontally to the point of subsequent intersection with the base flow recession. In most watersheds, this occurred within 8-10 months. The exceptions were the smaller watersheds ($\leq$30 km^2) where the duration of the seismogenic water was on the order of 4 months or less and Pescadero Creek near Pescadero (118.9 km^2) where the effect persisted beyond the end of the 1990 water year.

Several months after the main shock, we learned of an apparently anomalous site on the Zayante Creek tributary of the San Lorenzo River where flow depths were highly variable and reported to be linked to aftershock activity. This site was only a few hundred meters below a continuous recording gauge, but that gauge did not reflect much of the observed variation. At that Zayante Creek site, the stream was on fractured bedrock and residents reported highly variable spring-flow activity within and immediately adjacent to the channel. Subsequent instrumentation verified that the primary source of augmented flows for that middle reach of the Zayante originated in a short (150 m) reach near where that creek cuts the axis of the Scotts Valley syncline. Subsequent investigations revealed several other similar sites on other watercourses, including the Pajaro, Stevens Creek, Big Creek tributary to Scott Creek, Butano Creek tributary to Pescadero, the lower San Lorenzo, and others. There were not always obvious structural or bedrock controls to explain the sources of the in-channel variable springs, but we learned to recognize them readily by growth of distinctive white and black algae-like mats and filaments that appear to be associated with flows of oxygen-depleted ground-waters and reduced sulfur and iron compounds.

From these observations and the analyses of lags, it appears to us that the augmented flows originate at multiple diffuse or discrete sites along the bedrock channels. As pointed out by Rojstaczer and Wolf (1991, p. 7) some streamflow increases were preceded by an apparent decrease in flow. This immediately postevent decrease was noted by us in Soquel Creek, Bean Creek, and San Francisquito Creek, as well as in the reported incidence in Bear Creek.

CHEMICAL DATABASE

Analyses of major cations (Ca, Na, Mg, K) from the initial samples of pre- and post-earthquake water demonstrated somewhat increased ionic concentrations for postevent water, but consistent ratios. This was found in all geographic areas for which we had been able to locate pre-earthquake water samples and where it was possible to subsequently sample from the same sources through essentially the same distribution systems. Review of field samples, both in the near field and at distant points 30 km or more from the epicenter, revealed that there were no significant differences in the patterns of change for the major cations. To attempt to learn more about the preearthquake variability of both surface and ground-water chemistry, we reviewed the Santa Cruz County data base of over 3,000 samples developed from 1975 to the time of the earthquake. The lab data base is updated at least twice a year for 29 surface water and annually for 30 ground-water stations. The record is nearly continuous for these primary stations (with the exception of a break in the 1982 water year), but U.S. Environmental Protection Agency-approved analytical methods have changed in some instances. The break in the record for 1981-82 was associated with a change in funding, personnel, and some analytical equipment and procedures. This raised some possible questions associated with the sometimes-significant changes seen before and after that hiatus.

It was necessary to select a limited subset of analytical values where there were adequate numbers of samples from the same sites at a range of times but with reasonably regular seasonal sampling and consistent analytical procedures. Because of uncertainties that arose when the entire period of record was reviewed for certain constituents in certain aquifers (for example, Na, K, and sulfate in the Santa Margarita Sandstone in the Scotts Valley area, see fig. 9 for Ca:Na ratio), we chose to restrict detailed analyses to the records for the 1984 and subsequent water years. We also chose to evaluate only records for sites where there were equal numbers of samples for all years of record and where such record was continuous from 1984 to and including the 1990 water year. Thus, data here reviewed and presented include two samples for each surface-water station and one for each well or spring for each year from 1984 through the 1990 water year. A full record of the databases is available from the U.S. Geological Survey on CD-ROM as explained in the section "Supplemental Information" at the end of this chapter for both the cleaned and verified subset used here and the larger base record.

RESULTS OF CHEMICAL ANALYSES

Analysis of the chemical data revealed that well waters collected between 3 and 90 days after the main shock demonstrated increases in concentrations of calcium from 0 to 5 times, with an average doubling of concentration (n=12, near field). As discussed by Rojstaczer and Wolf (1991, fig. 7), the regional waters are dominated by calcium and bicarbonate in the mountainous areas. We looked at ratios of Ca:Na, Ca:Mg, Na:Ca+Mg, and Ca:sulfate to try to determine any possible changes in sources of ground waters (Hem, 1985, p. 166 ff). We found that, in general, cation ratios remained constant within the limits of one standard deviation about the mean for pre- and post-earthquake water samples.

Analyses were conducted to evaluate ionic concentrations and ratios by watershed, by individual wells, spring, and stream sampling points, and by township. All pre-earthquake samples taken between October 1 and the time of the earthquake during the 1990 water year were assigned to the 1989 water year for the purposes of plotting, to insure that the points for the 1990 water year all represented values after the earthquake.

Examples of summary plots of surface-water chemistry in the near field of south-central Santa Cruz County are represented by figures 3 and 4. For Aptos Creek, directly downstream from the epicenter, a slight increase in Na concentration without a similar change in Ca concentration changed the Ca:Na ratio distinctively for the average of the two postearthquake samples for the 1990 water year. However, for nearby Soquel Creek, differences before and after the earthquake are not apparent. The minor changes in Na and chloride concentration in these watersheds nearest the epicenter is seen in figure 4. There is a general

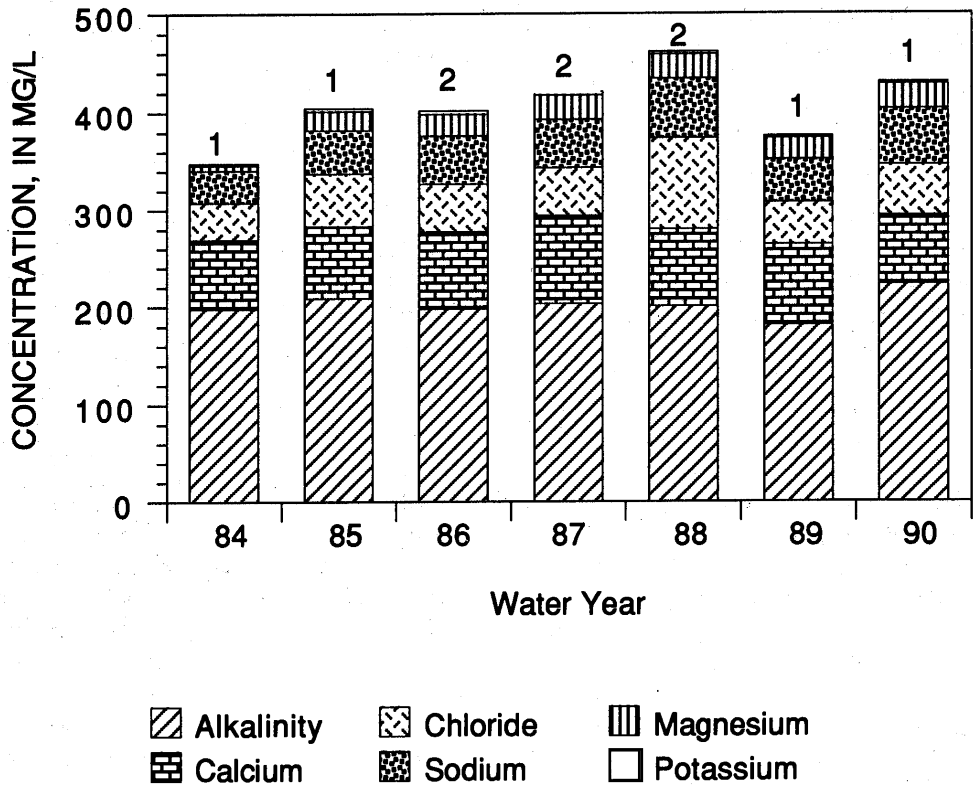
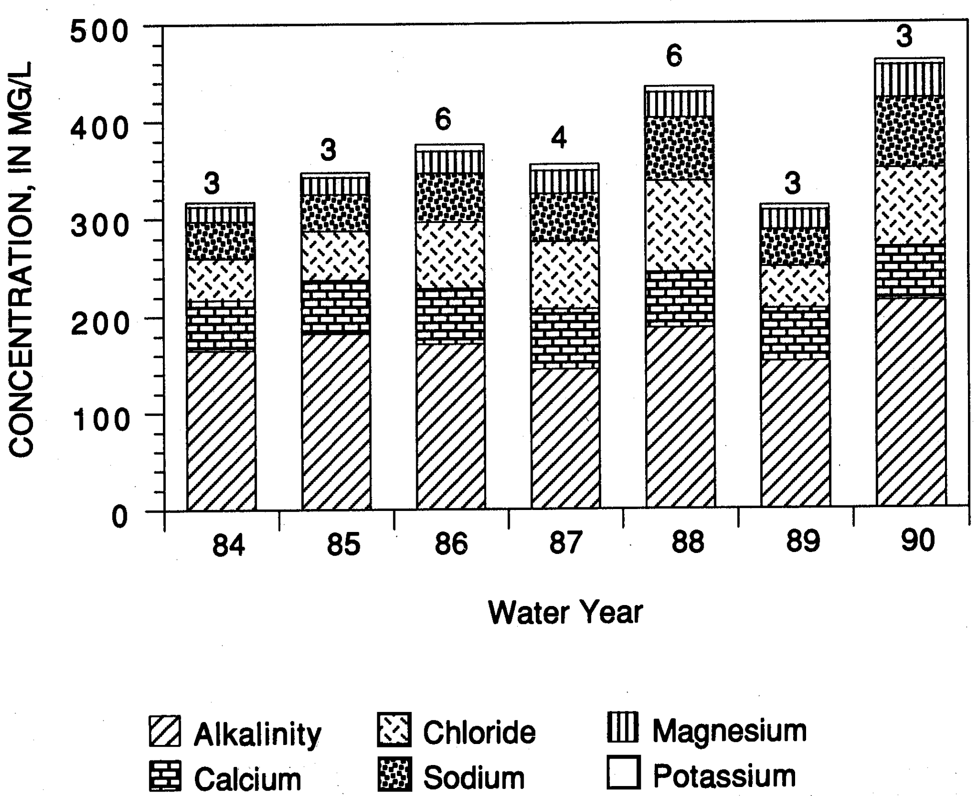


Figure 3.—Average concentrations of potassium, magnesium, sodium, chloride, calcium, and alkalinity for Soquel Creek station at Soquel Bridge, 1984 to 1990. This is one of three primary Soquel Creek sampling stations. Numbers at top of columns are the number of samples per year.



◀ Figure 4.—Concentrations of selected ions averaged for Aptos Creek, Soquel Creek, and Schwan Lake, all within 6 km of the epicenter in south-central Santa Cruz County, 1984 to 1990. Schwan Lake station receives urban runoff, but all these stations show homogeneous responses for 1990 water year after earthquake. Numbers at top of columns are the number of samples per year.

trend in Na and chloride concentrations upward through time since 1984. The anomalously low values of the 1989 water year may be primarily related to dilution by the anomalously higher base-flow discharge during the 1989 sampling times. As pointed out by Rojstaczer and Wolf (1991) and by Sylvester and Covay (1978), this slight inverse correlation between ionic concentrations and discharge is attributable to dilution by interflow.

Figures 5 through 8 explore variations in surface water observed in the far field in watersheds in northwestern Santa Cruz County. These are in sites of only very minor human habitation with forested parklands as the primary watershed cover. Statistically significant changes occur in most cation concentrations. In most cases, the single postearthquake ionic concentration analysis falls above one standard deviation or more above the value for all previous analyses, and there is no statistically significant upward trend prior to the earthquake (fig. 7). The increase in Na and Cl concentrations is dramatic in these surface waters, collected above marine water influence. Since they are matched by similar increases in other major cations, the most logical explanation is simply that these coastal watersheds have significant concentrations of NaCl in their meteoric-origin ground waters. These are released by the seismic activity.

Shelton and others (1991) present a figure plotting total dissolved solids for the Pajaro River in southern Santa Cruz County before and after the earthquake on a monthly basis. Their data illustrate that the postearthquake ionic concentrations, whereas higher than the 1974-89 long term means, do not exceed the maximum range recorded before the earthquake. Our data for all southern Santa Cruz County watersheds served primarily by the open alluvial and Aromas and Purisima sand aquifers also show slight increases for the 1990 water year of about the same orders of increase of 1 to 2 times. Chloride is the most variable ion, but this may reflect in part deeper ground-water pumping with more agricultural return flows to surface streams in this region of rapidly increasing salt water intrusion. However, chloride concentrations are also seen to rise in the San Lorenzo watershed, as well as other ions by lesser amounts. For the same Pajaro River station, we indicate increased cation concentrations and decreased sulfate concentration.

Overall, surface waters in Santa Cruz County seem to have the largest noted changes after the earthquake in the geographically isolated extreme southern part of the county south of the epicenter, and in the northwestern part of the county, farthest from the epicenter. The differences have more to do with rock type and ground-water chemistry than proximity

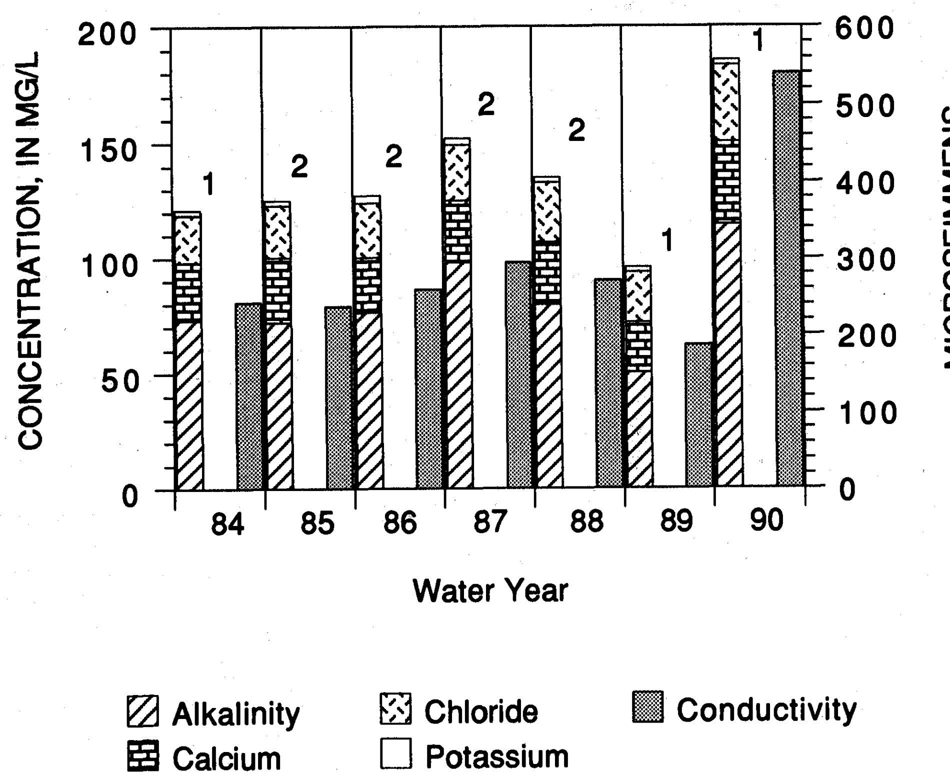


Figure 5.—Alkalinity, calcium, potassium, chloride and conductivity values for single surface-water station on Waddell Creek draining granitic rocks of Ben Lomond Mountain in northwestern Santa Cruz County, 1984 to 1990. Postearthquake increases in streamflow in this region were associated with increased ionic concentrations. Numbers at top of columns are the number of samples per year.

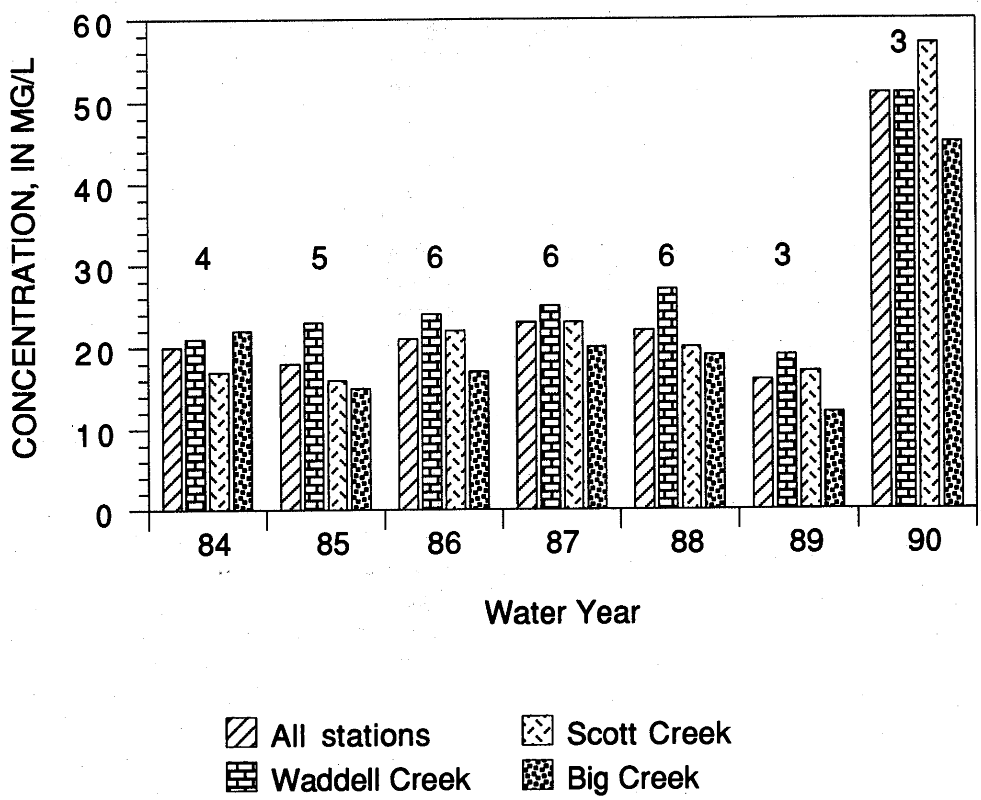
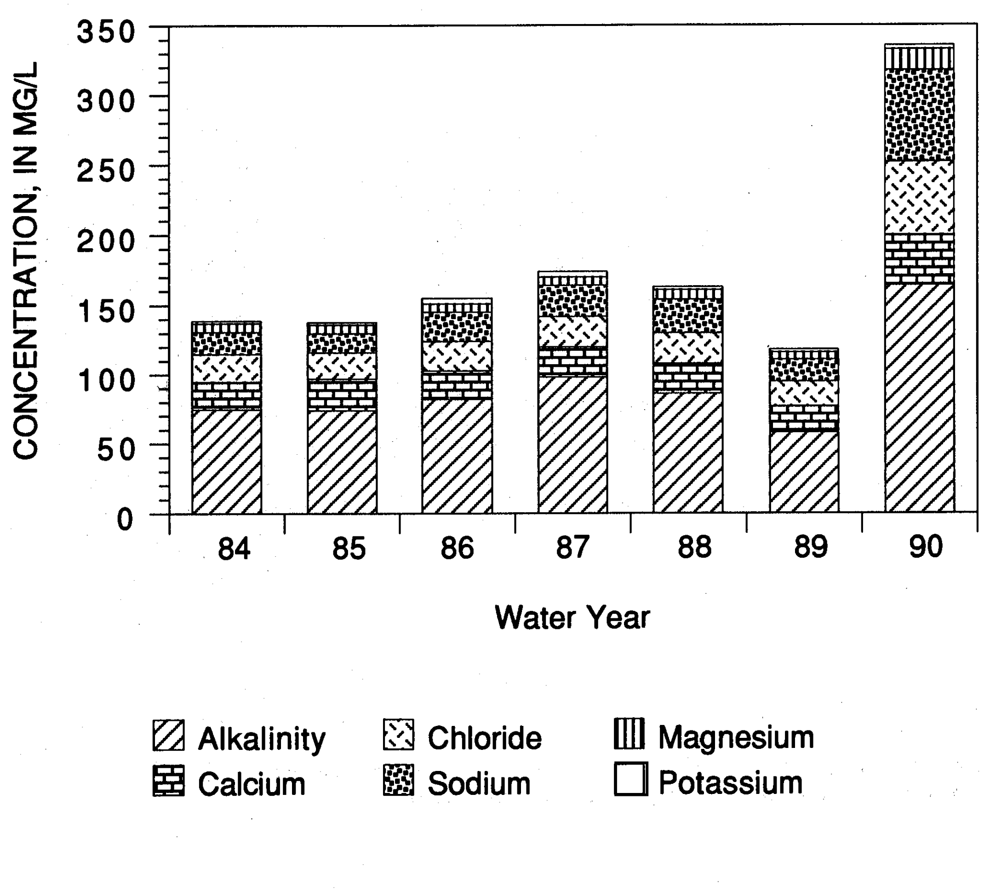


Figure 6.—Surface-water chloride concentration for three watersheds in northwestern coastal Santa Cruz County draining granitic Ben Lomond Mountain, 1984 to 1990. This was a region of marked increases in ionic concentrations.



◀ Figure 7.—Averaged values for magnesium, alkalinity, chloride, potassium, sodium, and calcium concentrations for the same area and dates of northwestern coastal Santa Cruz County as in figures 5 and 6.

to the epicenter or to the zones of greatest surface fracturing and ground acceleration.

Ground-water chemistry reflects the same patterns as shown in surface-water sampling. Aggregating all samples from 1976 to the present by major aquifers (fig. 9) illustrates little discernible change after the earthquake in these diverse sites. Although there is an apparent increase in ionic concentrations in some geographic locales after the earthquake, this may be at least in part an artifact of the lower (more dilute) concentrations noted in 1989. Taken as a whole, the ground-water data suggest slightly increased concentrations in the far field, but not beyond the range of one standard deviation higher than preearthquake values (fig. 10).

DISCUSSION

HYPOTHESES OF ORIGIN OF AUGMENTED FLOWS

The following multiple working hypotheses were originally to be explored: (1) Increased surface-water discharge is due primarily to increased effective permeability due to new or reactivated bedrock fracture systems, allowing the drainage of previously perched water tables or facilitating increased rates of lateral flow and resulting decreased gradients on ground-water effluent to surface streams and springs. (2) Increased surface-water discharge is due to regional compressional forces that decrease pore volume or void volumes in the phreatic zone and thus increase piezometric head and hence surface flow. In this model, which was suggested for explanation of hydrologic change associated with Idaho's Borah Peak earthquake, extensional and compressional conditions in adjacent quadrants may be anticipated with resulting decreases in well water levels or spring flows in some areas and rising water levels in alternate quadrants (Wood, 1985). (3) Increased flow is the result of deep old ground water in the vicinity of the hypocenter (18.29 km depth in this case) that is displaced upward, probably as the result of changes in the storage coefficient at depth (Wood and others, 1985). Water from 1 km depth emerged after the Borah Peak event. (4) Flows are the result of settlement and compaction of partly saturated and saturated surface soils and rock forcing water previously stored in fracture voids in bedrock, soils, the capillary fringe, and massive landslides to the surface.

Combinations of the above and modifications to this preliminary list were explored through this study. Discovery of quantities of colloidal materials after the earthquake in headwater streams and wells led to an alternate favored hypothesis. In this model iron-rich anaerobic organo-metallic colloids may serve to slowly decrease permeability

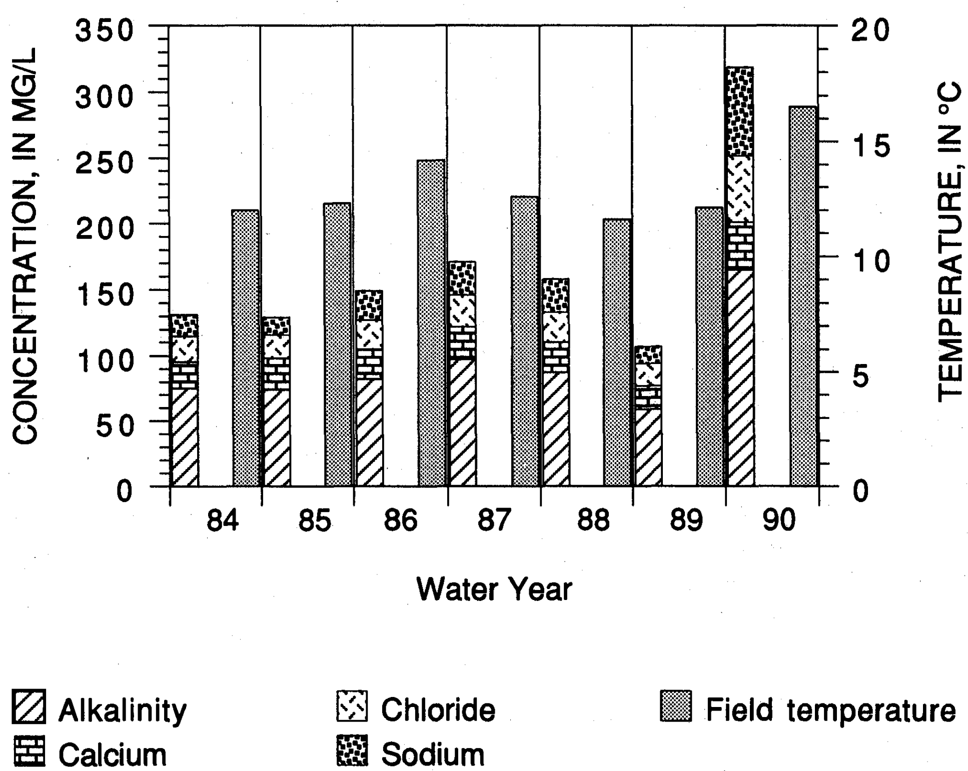


Figure 8.—Field temperature (in degrees Celsius), alkalinity, chloride, calcium, and sodium values averaged for all long-term surface-water stations in northwestern Santa Cruz County, 1984 to 1990.

of shallow bedrock units such as sandstones. Pressure transients associated with seismic energy release force those colloids through the pores that they previously blocked, thus temporarily restoring unimpeded permeability. After a major seismic event, the colloids may rebuild and gradients on water tables may again increase gradually to preearthquake levels.

MECHANISMS FOR INCREASED STREAMFLOW

Surface-water runoff in the study area is dominated by ground water, and thus ground-water chemistry and surface-water chemistry are found to be very similar. McDonnell and others (1991) have recently completed a study in a small headwater catchment that clearly shows that the ionic concentrations in runoff may be explained primarily by the chemistry of the shallow ground water and soil water. Our results verify this. Increased ionic concentrations observed by us are attributed to longer residence times but not to differing or deeper sources. The constancy of ionic ratios indicate that earthquake-induced excess flows originated locally in shallow ground-water storage sites above the topographic levels of the receiving streams and springs. The primary origin of increased ionic concentrations is the release of waters that were previously inaccessible because of lack of readily interconnected pore space.

Rojstaczer and Wolf (1991, p. 17 ff) have summarized the possible causes of the seismically triggered increased surface flows and observed ground-water changes. On the basis of fundamental ground-water hydrologic flow-path limits, they dismiss the possibilities of transport of overpressured fluid from hypocentral depths (18.3 km for the initial event). The response time of surface-water stream gauges throughout the near and far field is simply too rapid to allow diffusive pore-pressure transfer upward for distances of 5-18 km within several days, let alone minutes. The shallow ground-water chemical responses to such a mechanism might not differ from those observed within the first few months since this mechanism postulated a pore pressure transient traveling much faster than actual pore water, but the observation of increased stream and spring flow at the base of upland areas where concomitant dropping of ground-water levels is observed argues against such an origin. The chemical signature of such a

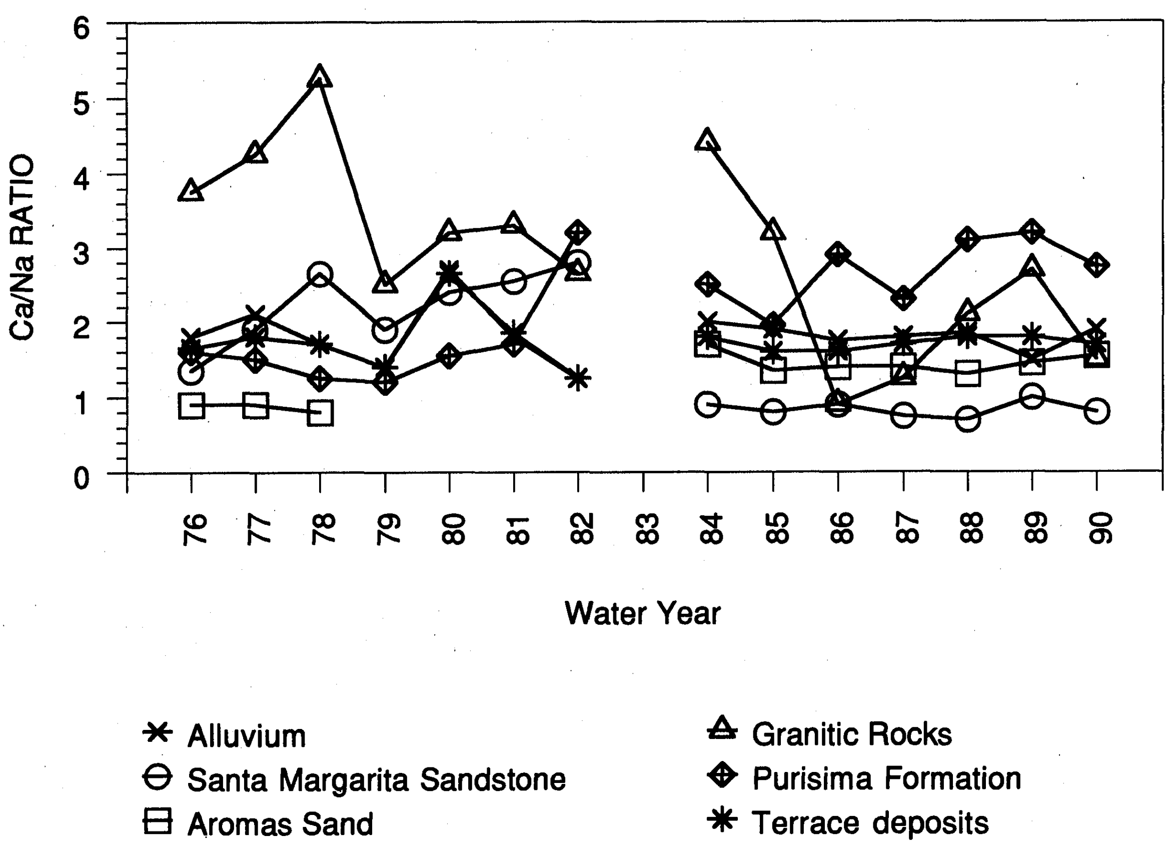


Figure 9.—Ratio of calcium to sodium for ground waters drawn from known aquifers throughout Santa Cruz County, 1976 to 1990. No analyses were performed in 1983, and some sampling points changed after that time. Data are not comparable for the two separate time series. Over 100 ground-water sampling stations are reflected in these averaged data. Individual consistently sampled stations reflect these general trends for Ca:Mg, Ca:Na, Na:Ca+Mg and Ca:sulfate ratios.

pore-pressure transient may be expected to ultimately bring deeper water to the surface, yet the limited sequences of postearthquake water monitoring performed at two daily sampling sites preliminarily suggest that ionic concentrations rapidly return to preearthquake levels in a matter of months without any evidence of admixture by deeper waters.

Postulated compressional forces collapsing open fractures and reducing near-surface pore volume, as posed for explanation of the Borah Peak, Idaho, event (Wood and others, 1985; Wood, 1985) cannot explain the distribution of changes in flow and water table levels observed in the Santa Cruz event. Compressional collapse should cause water table levels to rise in those areas subject to maximum compressional distortion. Anecdotal evidence suggests rises in water tables primarily in the lowland areas and basins adjacent to mountainous areas, widely distributed to the west, south, and east of the epicenter and of the areas of maximum surface rupture and upthrusting of 0.5 m or more. Although rising water tables were locally reported in some upland sites, most high-elevation sites adjacent to lowlands with observed surface-water flows, experienced steadily dropping water tables. Chemical signatures of water expelled from compressionally collapsed dilatant fractures would be expected to show significant increases in ionic concentrations of materials derived from the bedrock minerals crushed in that collapse. Although we do see increased ionic concentrations, the magnitude of most are on the order of 2X, and many sites show changes of only a few percent (figs. 3, 10). Coseismic strains much larger than those estimated from surface changes that were observed (Lisowski and others, 1990; Anderson, 1990) would have to have occurred in both the near and far field to account for compressionally induced simultaneous increases in flows over regions of many thousands of square kilometers. Further, one would expect such a mechanism to result in increased flows in the areas of maximum compression. These would be the northwest and southeast quadrants for right-lateral strike-slip motion and the southwestern block for high-angle reverse motion. Such regional differences were not discerned. Robert Muir-Wood (written commun., 1992) notes that the flow augmentation figures derived in our work are fully typical of a M 7 oblique reverse strike-slip event and are in accord with their strain-modeling approach.

Coseismic hydrologic response mechanisms that increase the effective permeability of near-surface rocks to release stored ground waters from a wide geographic area are needed

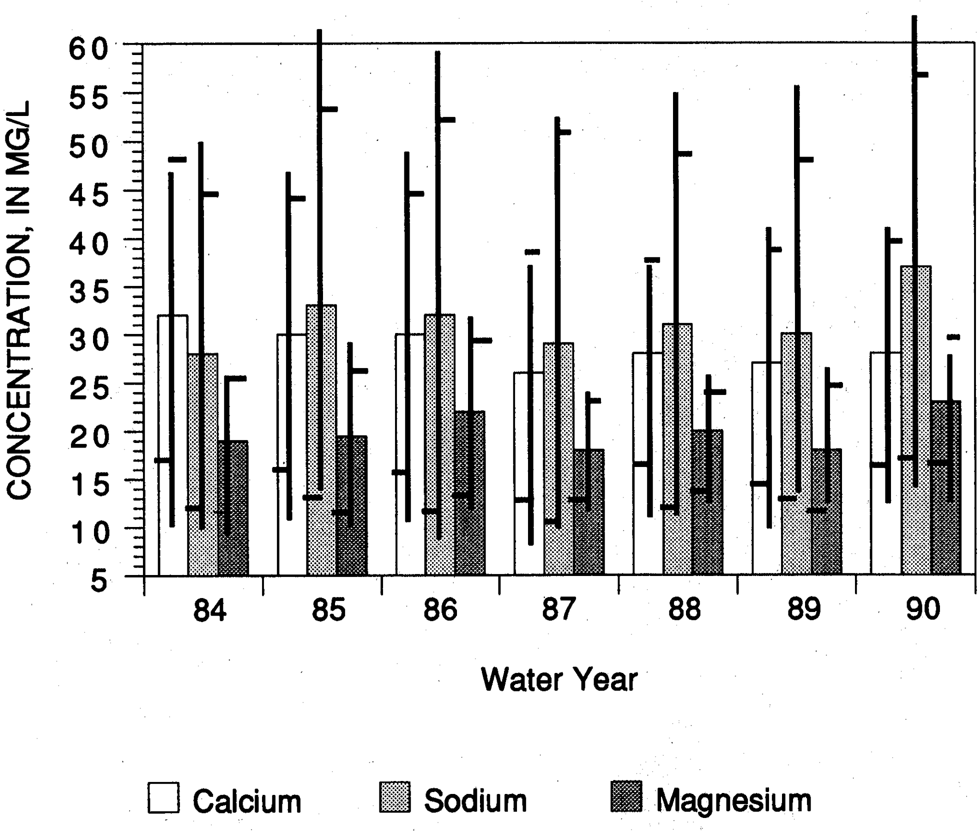


Figure 10.—Averaged values for calcium, sodium, and magnesium concentrations for three consistently sampled wells drawing from Pleistocene Aromas alluvial and aeolian sands, 1984 to 1990. Bars show mean, minimum, and maximum values, and ticks represent one standard deviation.

to explain the observed physical and chemical changes. One such mechanism may be a pressure transfer process that increases the fracture permeability of shallow surface bedrock. Such a microfracturing process is postulated as a possible mechanism by Rojstaczer and Wolf (1991). This mechanism would have to work in both brittle rocks such as the granitic rocks and Tertiary sandstones, and in the unconsolidated or loosely consolidated Pliocene to late Pleistocene marine and dune sands. Particularly difficult is the propagation mechanism that creates increased fracture permeability in an isolated topographic hill of poorly consolidated sand, such as the Aromas Sand hills west of Corralitos. In sites such as those, observations of rapid rises in ground water adjacent to such hills and mobilization of saturated debris slides and seep zones around the base of the hills suggest much increased hydraulic conductivity of the sand hills. The strain-induced permeability model is the most logical of the various options considered, but it must be modified to make it independent of fracture permeability.

Chemical data suggest a modification of the stress-induced fracture-permeability hypothesis. Among the most striking changes recognized in postearthquake waters by some respondents was a marked increase of an order of magnitude or more in iron compounds in ground waters and springs. Springs were reported to fill with gelatinous colloidal brown material despite higher flows. Filamentous and gelatinous masses of brown, black, and white algal-like growths were seen associated with at least 30 percent of the reported springs and headwater streams that increased in flow following the earthquake, and these effects persisted for on the order of 8 months or more. At one site along the Pajaro River, a series of drainage pipes placed into the Mt. Pajaro shale by the Highway Department began discharging greatly increased volumes of red-brown, black, and white-coated flow streams, each color from a different immediately adjacent pipe. All drained an apparently homogeneous bedrock mass and the different color effluent systems were no more than 30 m apart. In another instance in Zayante Creek, the smell of reduced sulfur compounds (sulphur and sulfite) was reported to be associated with increased flows from bedrock fractures on the bed of the shallow stream, with red-brown, black and white filamentous growths associated with nearby distinct bubbling streambed springs. Careful sampling and analysis for sulfate, sulfide, and trace elements from the Zayante "fissures" showed no significant trends of variations (R. Golling, oral commun.). However, dissolved oxygen and temperature variations suggest that microbial populations may be playing an important role that we were not able to evaluate.

We postulate that shallow surface aquifers, to depths of 100-200 m, become plugged with colloidal organo-metallic compounds, particularly those associated with iron and sulfur. This colloidal coating and plugging of pore voids would slowly reduce permeabilities of near-surface aquifers. Mineral cements such as silicates and calcite may also effect similar progressive reductions in permeability. During earthquakes, that permeability changes dynamically as shear strain or pressure transients shake loose or force saturated voids to dislodge their colloidal plugs.

Microbially mediated stress-induced transient permeability changes are well beyond the focus of this study. The inverse relationships between sulfate and metal cations found to characterize some sites of postearthquake water change (for example, Pajaro River) suggest that oxygen concentration differences may play an important role in mediating variable rock permeability (see Elder, 1988). Direct microbial interaction of chemo-autotrophic organisms with iron, sulfide, and carbon-dioxide in ground water can form substances that effectively plug smaller voids and dynamically change rock permeability (Olson, 1983). These are little-studied phenomena, especially as associated with seismogenic ground-water flow changes.

Whether due to dislodging of mineral cementing agents or organo-metallic colloids, or both, coseismic strain appears to directly affect aquifer permeability in an almost instantaneous fashion. Much work remains to be done around the concept dynamic permeability. Seismogenic flow increases in 1865 and 1906 evidently allowed permeabilities to eventually return to preearthquake levels and water tables to again equilibrate with greater heads and steeper flowpath gradients. This suggests that the mechanisms of permeability change may be deduced by observing the recovery times for the Loma Prieta hydrology. Rapid restoration of ground-water gradients within 1 to 2 years may favor a biogeochemical process, and restoration within periods of decades may suggest mineral cementation origins. Both mechanisms will presumably work equally well in unconsolidated isolated sand hills and in fracture-porosity bearing brittle bedrock.

ACKNOWLEDGMENTS

We wish to thank the several hundred respondents to our public information pleas for earthquake-related water information. Particular thanks must go to Barbara Gilwood and Kathy Bowers, the two cooperators who maintained detailed records of staff plate readings, filled refrigerators with sample bottles, and pressed their families to sample and gauge in difficult conditions. Santa Cruz, Santa Clara, and San Mateo County Planning Departments all contributed considerable staff time and effort. Particular gratitude is expressed to Bob Golling of the Santa Cruz County Planning Department Water Lab for his review, encouragement, and personal interest. Finally, Kathy Hall and Steve Ryder, University of California Santa Cruz undergraduate students who volunteered much time, helped to keep this project organized and on course. Special acknowledgment is made to Tom McMannus, of TowSoft, Inc. for his extraordinary personal programming contribution of several months of full-time work.

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SUPPLEMENTAL INFORMATION—DATABASES COMPILED

A series of data bases have been compiled in machine-readable formats. The Santa Cruz County water quality data base consists of 4 DBase-III files separated into surface water, ground water, and location files for each. These are provided as straight ASCII comma-separated files for entry to spreadsheets, DBase, or other database management formats.

These files, updated with aquifer information, and selectively reduced to emphasize continuous records, have been imported to Quattro-Pro and Lotus-123 spreadsheet files for manipulation and graphic analysis. Eight files are available in uncompressed formats readable by most versions of these popular software packages.

Additional Quattro-Pro and Lotus files of analyses completed for this project, sampling completed, WATSTOR data compiled from USGS records, and miscellaneous data are also available with required documentation.

These files are available in CD-ROM format to accompany this and subsequent papers. Total size of the archive is on the order of 3.5 MB. Accompanying the database is a location map showing sampling sites on a regional geologic base.

HYDROLOGIC DISTURBANCES

HYDROLOGIC CHANGES ASSOCIATED WITH THE EARTHQUAKE IN THE SAN LORENZO AND PESCADERO DRAINAGE BASINS

By Stuart Rojstaczer, Duke University
and
Stephen Wolf, U.S. Geological Survey

CONTENTS

ABSTRACT

The earthquake caused significant changes in the hydrology of the San Lorenzo and Pescadero drainage basins. Streamflow increased at most gaging stations within 15 minutes after the earthquake. Ionic concentrations and the calcite saturation index of the streamwater also increased. Streamflow and solute concentrations decayed significantly over a period of several months after the earthquake. Ground-water levels in the highland parts of the basins were locally lowered by as much as 21 m within weeks to months after the earthquake. The spatial and temporal character of the hydrologic response suggests that the earthquake increased rock permeability and temporarily enhanced ground-water flow rates in the region.

INTRODUCTION

Hydrologic changes associated with moderate and large earthquakes have long been recognized (Lawson, 1908; La Rocque, 1941). While some changes are associated with the dilatational waves generated by earthquakes and are ephemeral (Eaton and Takasaki, 1959; Cooper and others, 1965; Liu and others, 1989), other changes persist and have less obvious explanations. Postevent increases in spring flow and streamflow followed such events as the Arvin-Tehachapi earthquake (M 7.1) of 1952 (Briggs and Troxel, 1955), the Borah Peak earthquake (M 7.0) of 1983 (Whitehead and others, 1985), and the Matsushiro earthquake swarm of 1968 (Nur, 1974); the increases lasted from months to years. Postevent changes in ground-water level have also been observed (Waller, 1966; Bell and Katzer, 1987); these changes are often too large to be explained by the static compression or extension induced by the earthquake (Bower and Heaton, 1978).

Many mechanisms have been postulated to explain these long-term changes in ground-water level and rate of surface discharge. Some studies suggested that these phenomena are intimately related to the earthquake cycle. They have been attributed to the expulsion of overpressured fluids in the seismogenic zone (Sibson, 1981) and to the collapse of a broad network of preearthquake-induced dilatant fractures (Nur, 1974). Other studies have suggested that these near-surface changes strictly reflect near-surface processes. Streamflow and spring flow changes have been attributed to elastic compression of confined aquifers (Wood and others, 1985). Changes of water level in wells may be due to seismically induced ground failure near the borehole (Bredehoeft and others, 1965). Streamflow and ground-water changes have also been related to permeability changes in near-surface materials (Waller, 1966; Bell and Katzer, 1987).

If near-surface changes in hydrology are directly related to the state of midcrustal pore fluids or preearthquake instabilities, then hydrologic monitoring in areas of active seismicity may provide information on the role of fluids in earthquake generation. Hydrologic monitoring may also be used as an aid in earthquake prediction. If, on the other hand, the hydrologic changes reflect only shallow processes, then hydrologic monitoring tells us little about earthquake generation; however, it provides insight in the rheologic response of shallow earth materials to earthquakes.

The Loma Prieta earthquake provided a unique opportunity to examine hydrologic changes associated with earthquakes. Long-term changes in both surface discharge and ground-water levels were observed in the region after the earthquake. Minor changes were also noted in response to the Lake Elsman earthquake (M 5.2, 8/8/89), an event which has been described as a foreshock to the Loma Prieta earthquake (Lisowski and others, 1990). Many of the changes were well documented and their possible origins can be examined in some detail. In this paper we examine surface water and ground water response of the Pescadero and San Lorenzo drainage basins to the Loma Prieta earthquake. The Pescadero drainage basin is well outside the Loma Prieta rupture zone; most of the San Lorenzo drainage is a minimum of 10 km outside of the rupture zone (fig. 1). Although other nearby drainage basins were affected by the Loma Prieta earthquake, the San Lorenzo and Pescadero drainage basins are particularly worthy of examination because the postevent response of the ground-water system in parts of their recharge areas can be partially quantified. The San Lorenzo drainage basin was also worth examining because unlike other basins in the region, it contains numerous gaging stations that monitor streamflow (Markham and others, 1988). In this report, we examine the character of the streamflow response. We also examine the spatial and temporal response of ground-water levels in parts of the recharge areas of these basins. Finally, we attempt to relate the observed surface and subsurface hydrologic changes to extensive permeability changes within the basins.

DESCRIPTION OF STUDY AREA

The San Lorenzo and Pescadero drainage basins comprise a region greater than 600 km^2 in area and are located west of the ruptured segment of the San Andreas fault associated with the Loma Prieta earthquake (fig. 1). The ba-

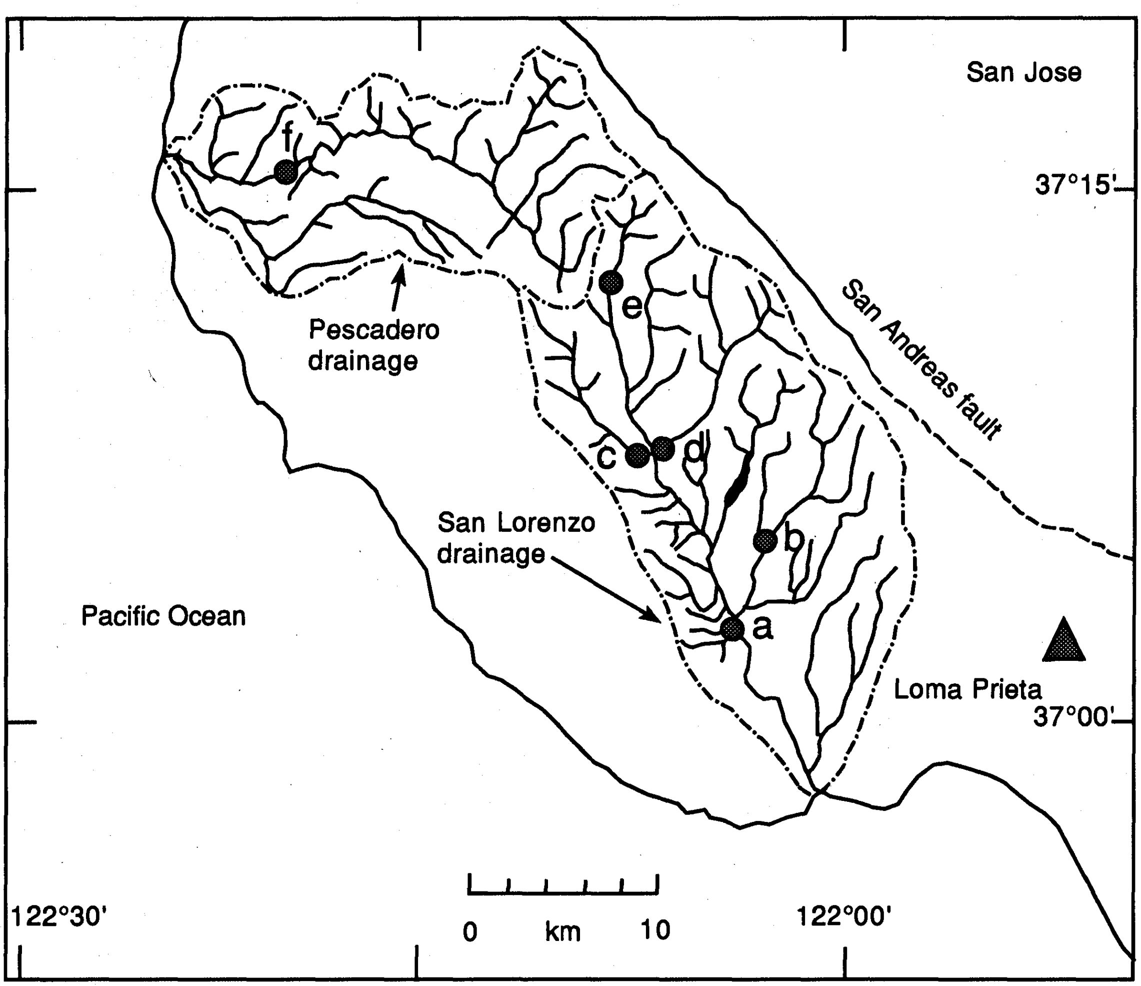


Figure 1.—Location of study-area drainage basins (light dashed lines demarcate boundaries of basins) in relation to San Andreas fault, Loma Prieta epicenter (triangle), and northern part of Loma Prieta rupture zone (heavy dashed line). Stream gaging stations (circles): a, Big Trees; b, Zayante; c, Boulder; d, Bear; e, San Lorenzo Park; f, Pescadero.

Table 1.—*Mean annual base flow from July 1, 1988, to July 1, 1989, in relation to drainage area of six gaging stations in the study area*

Station	Bear	Big Trees	Boulder	Pescadero	San Lorenzo Park	Zayante
Base flow (L/s)	20	400	40	100	20	20
Area (km^2)	41	271	29	118	16	28

sins are mountainous, with slopes commonly exceeding 30 percent. Elevation increases to over 900 m along the boundary of the basins closest to the San Andreas fault. Stream gradients range from 0.003 to 0.2 m/m, with the steepest gradients occurring along small low-order tributaries in the extreme upper portions of the drainage basins (Nolan and others, 1984). These small channels are only slightly incised into the surrounding hillslopes, and bedrock exposures are common along such channels. Low-order channels usually contain relatively thin deposits of alluvium over the underlying bedrock. Larger intermediate-order channels in the middle parts of the watersheds are typically V-shaped and narrow and are incised into the surrounding landscape more than the lower order channels. The channels contain varying amounts of bedrock and characteristically have beds composed of sandy alluvium or boulders surrounded by sandy alluvium. Mean annual rainfall ranges from about 500 mm near the coast to about 1,500 mm in the higher elevations (Rantz, 1971). Rainfall is generally absent from May through September, although fog is common during these months.

Bedrock in the study area consists predominantly of Tertiary marine sandstone, mudstone, and shale, as well as some interbedded volcanic units (Clark, 1981). In the high elevations of the basins, the San Lorenzo Formation, Vaqueros Sandstone, and the Lambert Shale are the most common bedrock formations and aquifers. These formations are heavily fractured at the surface, and the degree to which they are permeable is highly variable and dependent on the degree to which they are fractured at depth (Johnson, 1980; Akers and Jackson, 1977). Stratigraphically beneath the Tertiary marine rocks are Cretaceous granitic and metasedimentary rocks which crop out along the southeastern margin of the San Lorenzo drainage basin. As with the Tertiary rocks, permeability in the Cretaceous units is variable and highly dependent on the degree of fracturing present.

The region contains many extensive zones of structural weakness, both in the near surface and at depth. In the highlands, many ancient and active landslides can be found in the Tertiary formations (Hector, 1976). In addition to the San Andreas fault, major active faults in the basins include the San Gregorio, Butano, and perhaps parts of the Zayante (Clark, 1981). Most folds and faults in the area follow the trend of the San Andreas fault, which is northwest-southeast.

STREAMFLOW RESPONSE

Steamflow has been monitored in the region by the U.S. Geological Survey since the 1930's. The stream gaging stations shown in figure 1 have all been operating for at least 13 years. Regulation and diversion of these rivers and their tributaries is minor upstream of all the gaging stations (Markham and others, 1988). Mean annual base flow in water year 1989 (July 1, 1988 to July 1, 1989) at the six gaging stations ranged from 20 to 500 L/s, with the amount of base flow generally proportional to the drainage area associated with each gaging station (table 1). The hydrograph shown in figure 2 from the San Lorenzo Park station is indicative of the seasonal character of the discharge at all the gaging sites. During the dry summer months, streamflow is generally governed by the contribution of ground water. In the winter months, streamflow is greatly augmented by rainfall-induced runoff and interflow. The effects of the Loma Prieta earthquake can be seen as a rapid rise in water level during late October 1989 superimposed on the normal seasonal pattern.

In all drainage areas monitored, there was an increase in streamflow associated with the earthquake, indicating the greatly enhanced contribution of ground water to the streams (fig. 3). Except for the Bear Creek station, streamflow increases were observed at the first sampling after the earthquake (within about 15 minutes of the earthquake) at all stations which were not temporarily disabled by the ground motion. At Bear Creek, streamflow increases were preceded by a postevent decrease, which persisted for 22 hours. The San Lorenzo Park station was not recording for a period of 70 hours after the earthquake. Streamflow increases were monotonic for several days after the earthquake, but were masked by rain which began on October 21. Peak streamflow due to the earthquake was generally an order of magnitude greater than preearthquake streamflow.

At Big Trees and Boulder Creek, streamflow increases were more modest, reflecting that the magnitude of the response was not spatially uniform. There is no coherent relation between the magnitude of streamflow increases and proximity to the rupture area.

Although there were large increases in streamflow due to the earthquake, the long-term postevent response indicates that these increases were generally short lived. We estimated the longer term effects of the earthquake on streamflow by comparing the base flow over the period after the earthquake with the base flow of the previous year. Base flow for each year was estimated by straight-line hydrograph separation. The excess base flow produced by the earthquake was determined by calculating the difference between the postearthquake base flow and the base flow for 1 year prior at the same station. This base flow was adjusted by subtracting or adding any differences between the base flow on October 17, 1988, relative to the base flow on October 17, 1989. In determining excess base flow, we made the assumption that, independent of the earthquake, streamflow did not vary greatly, for the seasonal character and annual amount of precipitation for both years was very similar (72 cm for 1988 and 76 cm for 1989). For all stations except Boulder Creek, the difference between base flow on October 17, 1988, and October 17, 1989, was less than 10 percent of the amount of the excess peak base flow. The flow at three of the stations from July 1, 1988, to July 1, 1990, is shown in figure 4. The inferred excess flow produced by the earthquake is shown in figure 5. Excess base flow decays rapidly at all but the Boulder Creek station. Forty-five days after the earthquake, excess base flow is roughly one-half that of peak flow. After 150 days, excess flow is difficult to identify in the records.

The increases in base flow due to the earthquake were generally small in comparison to the total annual flow for the 1989 water year. Figure 6 shows the relation between precipitation and total annual flow at all of the stations for 5 years of similar total annual precipitation during the decade of the eighties (1985, 1987, 1988, 1989 and 1990). Despite the 1989 increased base flow, total streamflow decreased at three of the stations relative to the previous year; two other stations' streamflow increases were very small. Only San Lorenzo Park station showed a significant change in total annual flow, with an increase of roughly 1 billion liters. This amount of increase is approximately equal to the total amount of inferred earthquake-induced base flow at this station during this time period. The absence of significant increase in total flow at most stations indicates that the earthquake did not greatly enhance the surface water supply in this region; for example, the amount of inferred earthquake-induced base flow is about 20 percent of the total annual flow at Big Trees.

Stream chemistry at two of the stream gaging stations in the San Lorenzo drainage basin (Big Trees and San Lorenzo Park) has been monitored on a biannual basis. The data

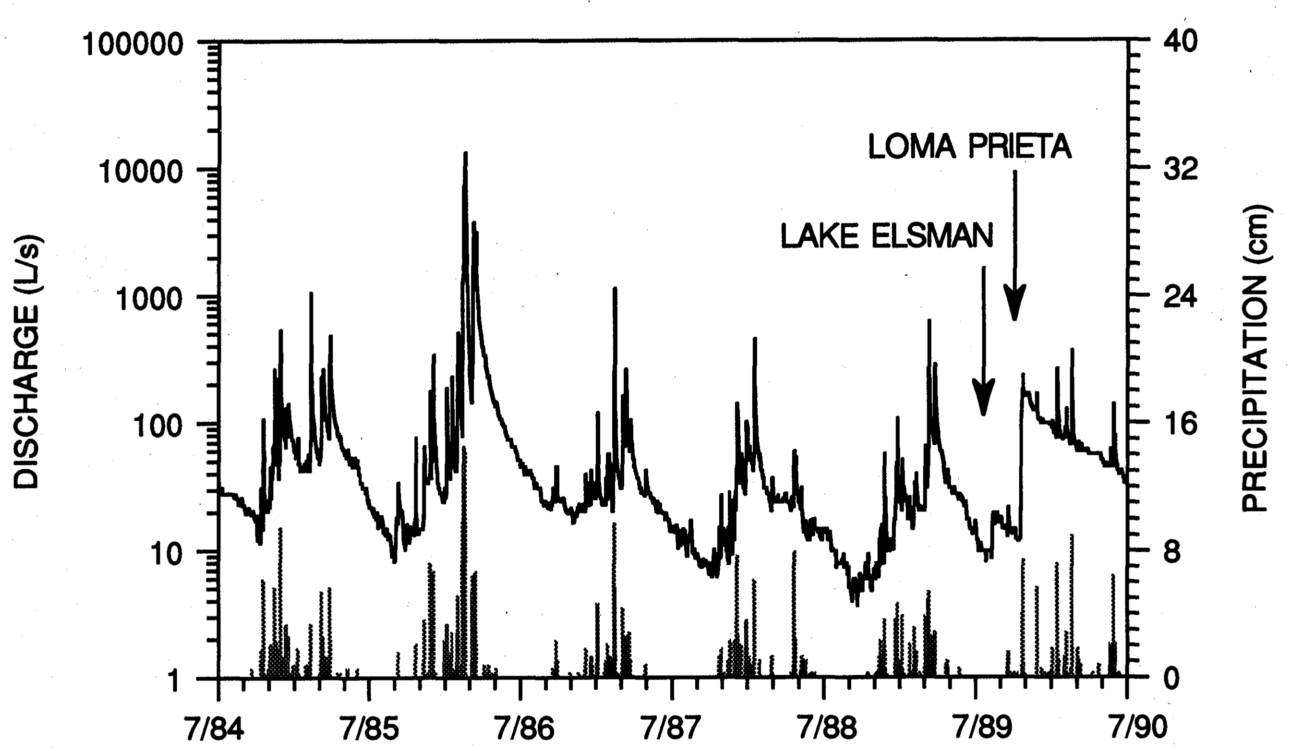


Figure 2.—Hydrograph showing discharge of San Lorenzo Park gaging station from July 1984 to July 1990, and accompanying record of daily precipitation (gray line). Dates of Loma Prieta and Lake Elsman earthquakes shown.

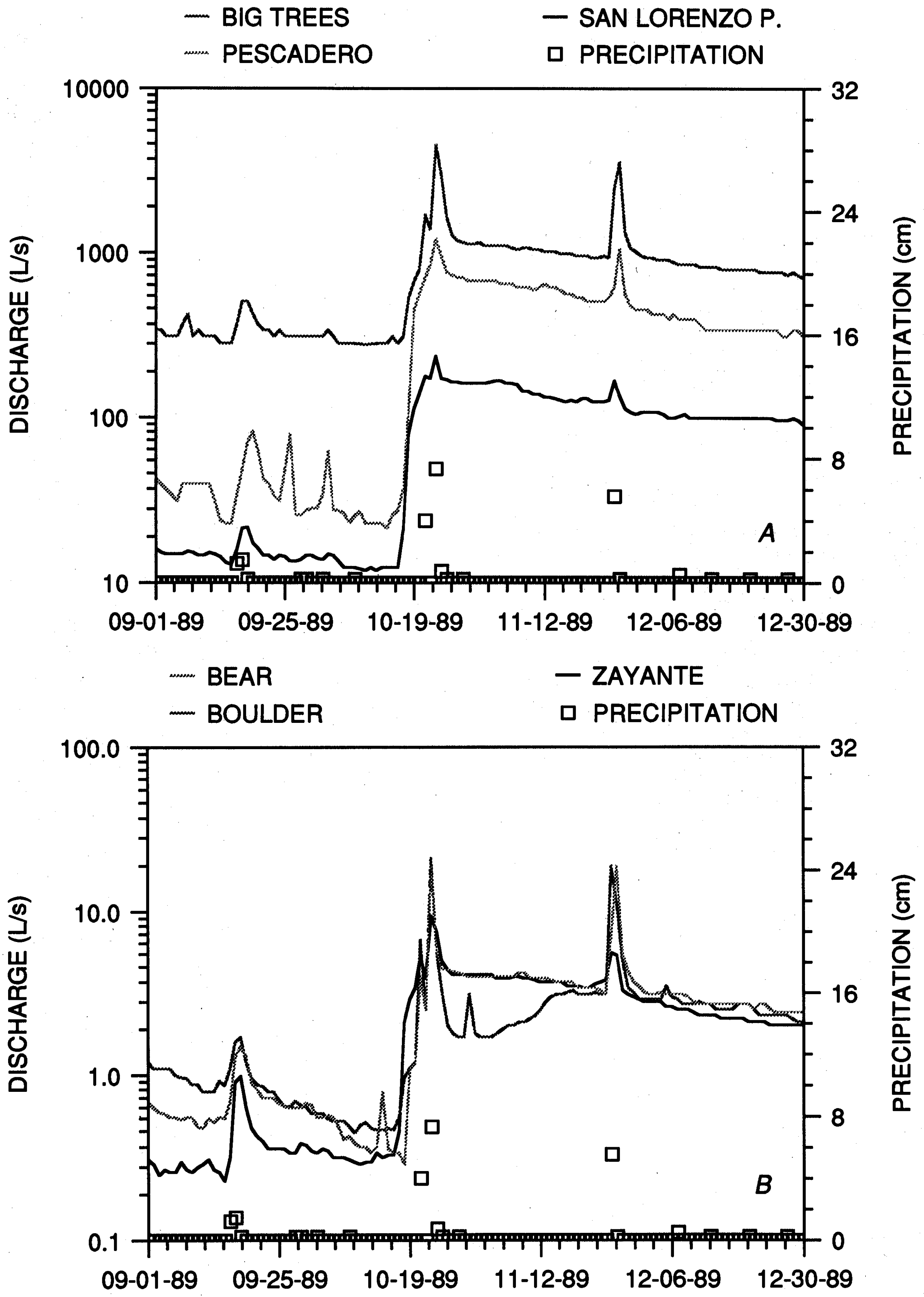


Figure 3.—Streamflow discharge in response to earthquake at (*A*) Big Trees, Pescadero, and San Lorenzo Park, and (*B*) Bear, Boulder, and Zayante gaging stations. Streamflow values are daily means. Precipitation values are daily totals.

shown in figure 7 indicate that at both sites the water chemistry is dominated by calcium and bicarbonate. Hardness and overall ionic concentrations are slightly higher at the San Lorenzo Park gaging station. The differences in water quality between the two sites have been attributed to the geology of the southwestern part of the San Lorenzo drainage basin (Sylvester and Covay, 1978). The biannual analyses of major ions at the two sites prior to the earthquake suggests that overall concentrations are slightly inversely related to stream discharge rates. The inverse dependence has also been noted in other streams in the region and is likely due to the influence of surface runoff and interflow during winter storms (Steele, 1968; Sylvester and Covay, 1978). The waters are slightly oversaturated with respect to calcite (preearthquake saturation index was 0.4 at both sites). Stream chemistry at these stations is similar to the chemistry of ground-water samples which tap the Vaqueros Sandstone and Lambert Shale in the highlands of the Soquel-Aptos drainage basin, the neighboring drainage basin to the east (Johnson, 1980).

In response to the earthquake, stream chemistry increased markedly in terms of its overall ionic strength, but the overall proportions of the major ions were nearly the same as under preearthquake conditions. The increase in bicarbonate and calcium caused the calcite saturation index to increase to 0.8. Water temperature in early November 1989 was 7° C at both stations, nearly 4° cooler than any previous measurement either in spring or fall. By April 1990, the stream chemistry had begun to approach preearthquake conditions at both locations. The changes in temperature and chemistry suggest that the additional water caused by the earthquake was derived from ground water from the surrounding highlands. The source rock of the ground water likely contributed to streamflow before the earthquake, but to a smaller degree.

The hydrologic response of the study area to the Loma Prieta earthquake was similar to the area's response to the Lake Elsman earthquake of August 8, 1989, but much larger in extent and magnitude. The Lake Elsman earthquake produced a two-fold increase in flow at the San Lorenzo Park and Pescadero stations; at the other stations, changes were too small to be detected. The Lake Elsman earthquake of June 27, 1988 (M 5.0), did not cause a detectable change at any of the gaging stations.

Anecdotal reports suggest that for two ungaged streams in basins neighboring the study area, large increases in streamflow preceded the Loma Prieta earthquake by roughly an hour (D. Friend, oral commun.; K. Tarkuchi, oral commun.). At the stations examined in this report streamflow is monitored at 15-minute intervals, and preearthquake increases were not detectable in the data. Any precursory changes in streamflow which occurred in ungaged streams were local in extent and not representative of the hydrologic response of the region.

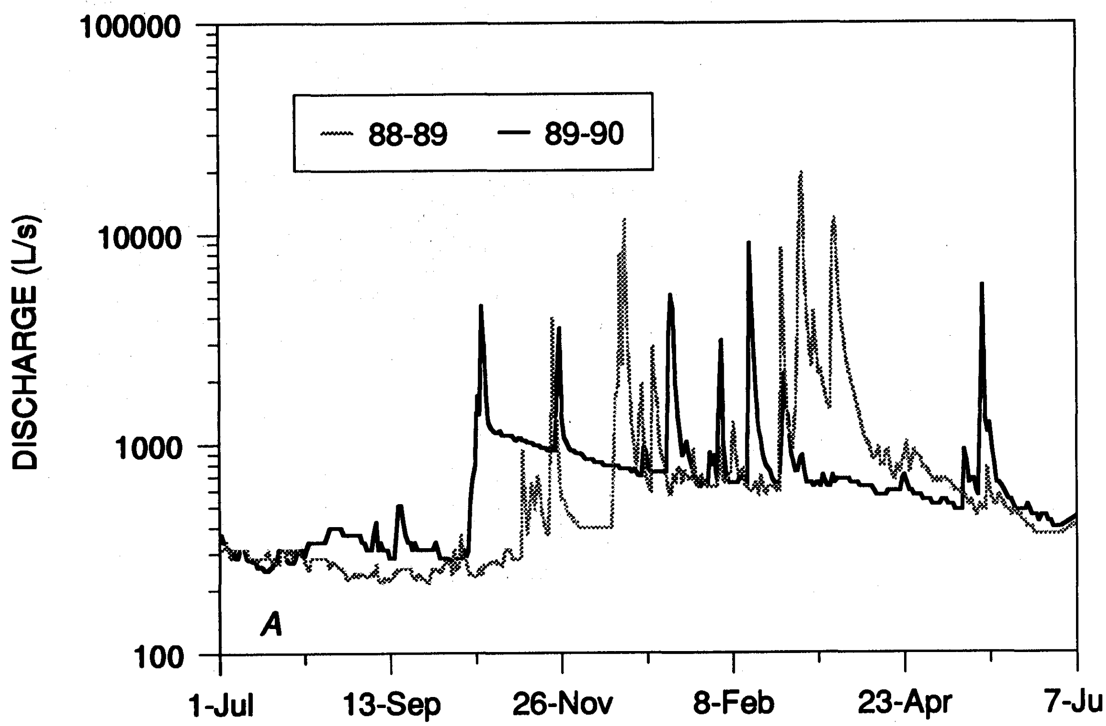
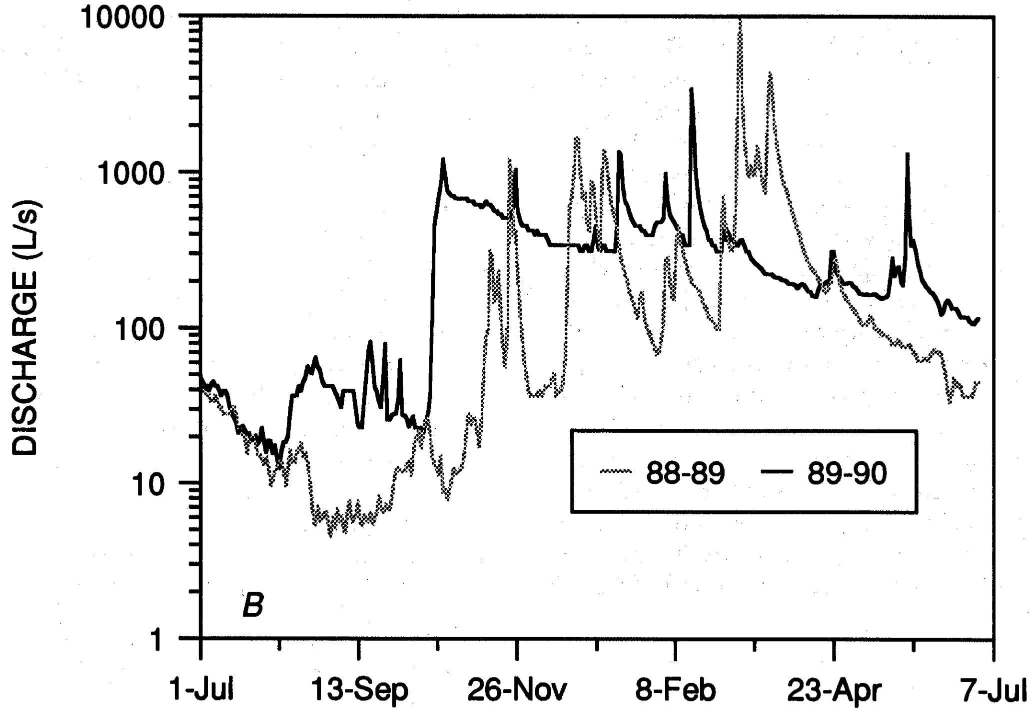


Figure 4.—Comparison of mean daily streamflow over the time periods July 1988 to July 1989 and July 1989 to July 1990 at (*A*) Big Trees, (*B*) Pescadero, and (*C*) San Lorenzo Park.

GROUND-WATER RESPONSE

Ground-water flow in the study area is predominantly controlled by fracture orientation and density. Ground water is derived from local precipitation and moves downward through fracture networks (Akers and Jackson, 1977). A study of ground-water flow in the neighboring Soquel-Aptos drainage basin indicated that 90 percent of all ground-water



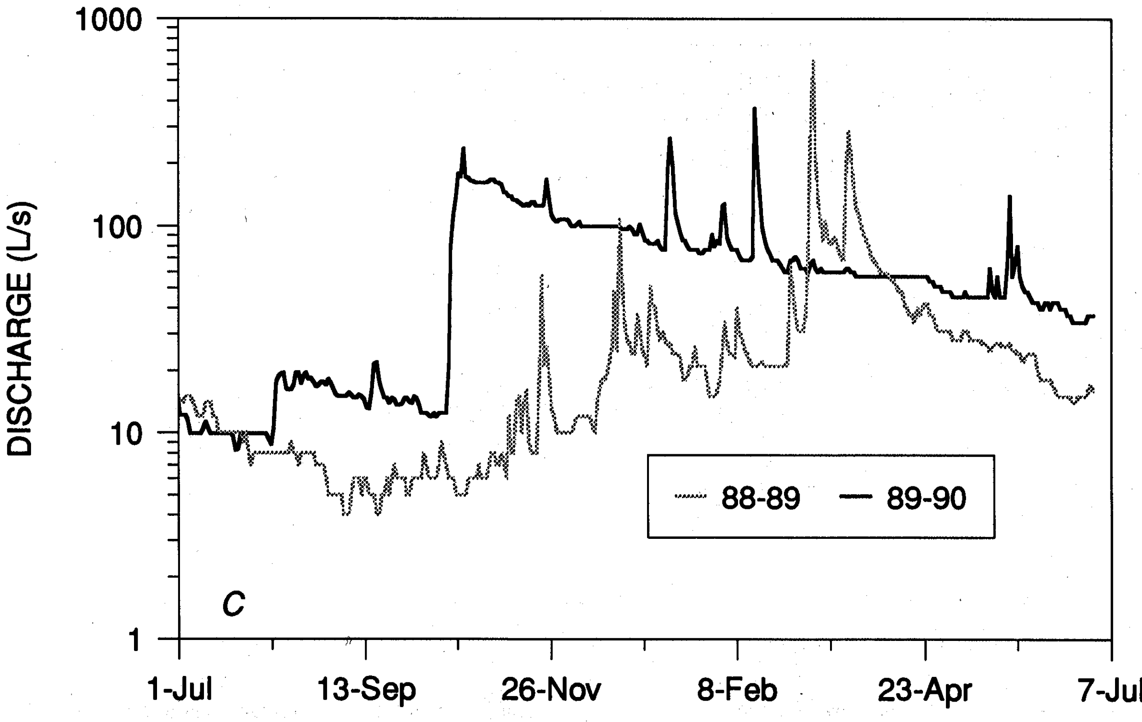


Figure 4.—Continued.

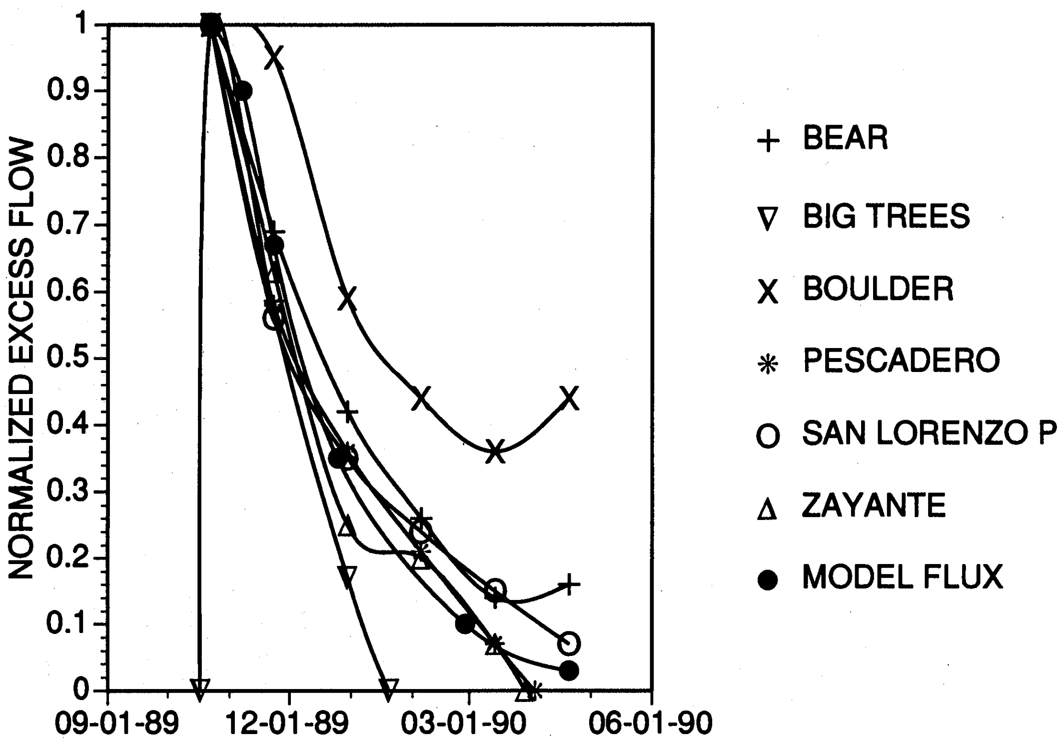


Figure 5.—Base flow after the earthquake plotted against time at the gaging stations. Base flow at each gaging station is normalized by the peak excess base flow following the earthquake at each station: Bear, 110 L/s; Big Trees 920 L/s; Boulder 40 L/s; Pescadero 690 L/s; San Lorenzo Park, 170 L/s; Zayante 110 L/s.

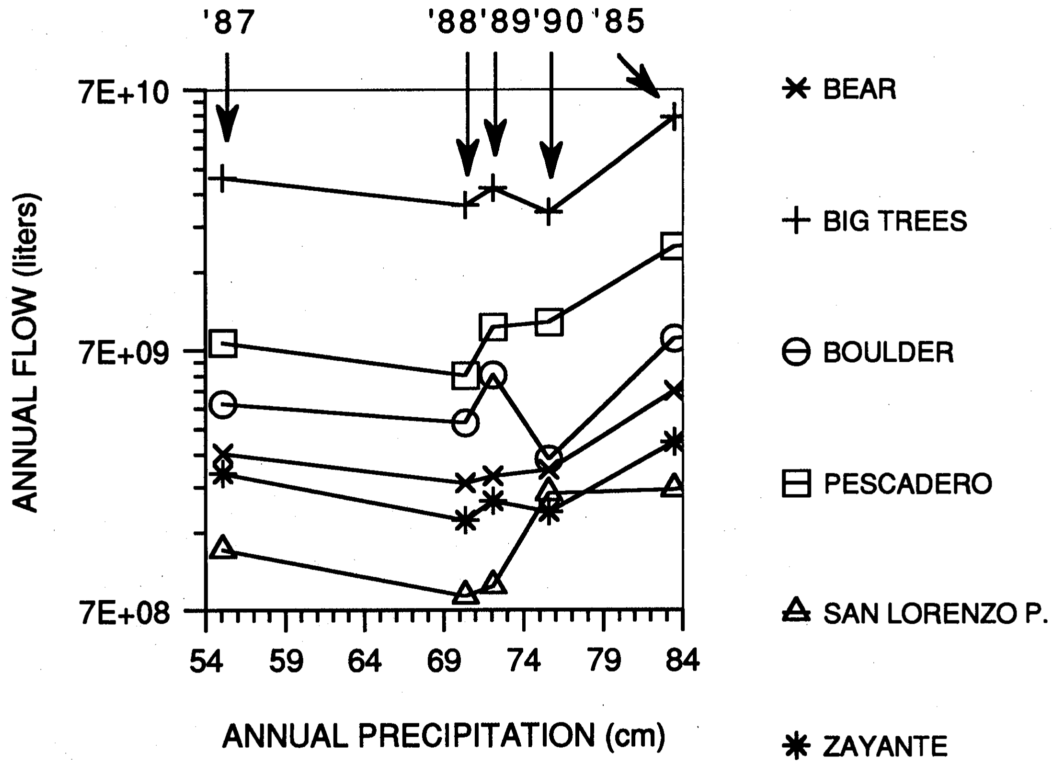


Figure 6.—Total annual flow plotted against precipitation at the six gaging stations for water years 1985 and 1987-1990 ('89 refers to the water year July 1988 to July 1989).

discharges into local streams and springs (Essaid, 1990). Very little basin-derived ground water flows directly into the ocean. Because the climate and geometry of the basins in this study are similar to those of the Soquel-Aptos basin, it

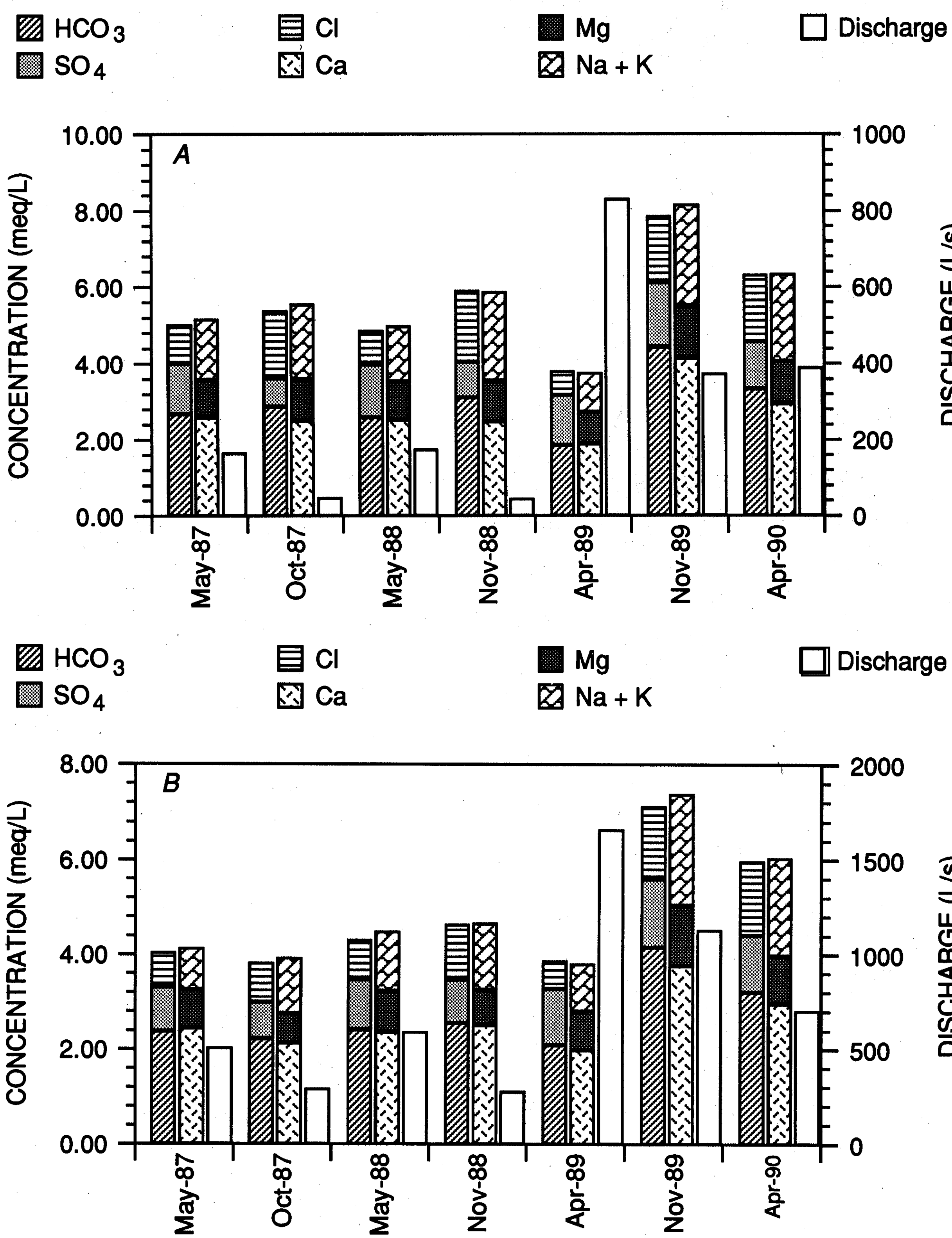


Figure 7.— Major-ion stream chemistry plotted against time and streamflow discharge at (*A*) San Lorenzo Park and (*B*) Big Trees.

is likely that almost all ground-water flow in the San Lorenzo and Pescadero basins also discharges into local streams and springs.

There were numerous anecdotal reports of earthquake-related changes in water level and water quality of wells in the study area as well as reports of changes in spring flow. Exact measurements of preearthquake water levels are generally not available in the region. A well that taps an unconfined aquifer located in the eastern headwaters of the Pescadero Creek has been monitored weekly since 1976 (fig. 8; location of well is northernmost well shown in fig. 9*A*) and has a strong semiannual cycle. The amplitude of the water-table-elevation cycle is highly dependent on the amount of rainfall but is on the order of 5 m during years of near-average rainfall. Although the effects of drought had an influence on the water-table elevation, the earthquake caused the water-table elevation to drop 4 m within several weeks after the earthquake.

Although water-level changes in the recharge areas of the study area are generally difficult to quantify, we infer that drops in water-table elevation similar to that just described occurred in a significant part of the basins' highland area. Throughout the study area, numerous wells either went dry or underwent a significant reduction in their capacity to pump water within several weeks after the earthquake. We focus our attention on measured and inferred ground-water-level changes in two highland areas. One area, which includes the well that is noted above, is shown in figure 9*A*. This area is along the crest of the Santa Cruz Mountains and straddles the border of the Pescadero drainage basin. The other area is near the headwaters of the San Lorenzo River and is shown in figure 9*B*. These areas were selected owing to their well density and the level of cooperation on the part of the landowners. The wells shown in figure 9 are used by single homes and range in depth from 40 to 140 m.

Of the wells shown in figure 9*A*, roughly one-half experienced a reduced capacity to deliver water for home uses or were completely dry by January 1990. In general, the wells which were most affected were in the southern part of the area (where elevation is highest). In most of the wells which were adversely affected (wells which either went dry or no longer provided enough water for home use), changes were noted within several weeks after the earthquake. In other affected wells, the changes were gradual, and wells which became dry did so over a period of 2 to 3 months. It is difficult to quantitatively relate the adverse impact of the wells to a water-table decline. Wells in the region which were not adversely affected generally have water levels which are in excess of 7 m above the well bottom. If earthquake-impacted wells had water-table elevations that were at this level above the well bottom, then the water-table declines produced by the earthquake would be of this order of magnitude or greater.

In the San Lorenzo headwaters area (figure 9*B*), wells adversely affected were generally confined to two ridgetops. Wells along the northeast edge of the area and wells located near the valley floor were not adversely impacted. Although no extensive preearthquake water-level records exist for this area, there is limited anecdotal information

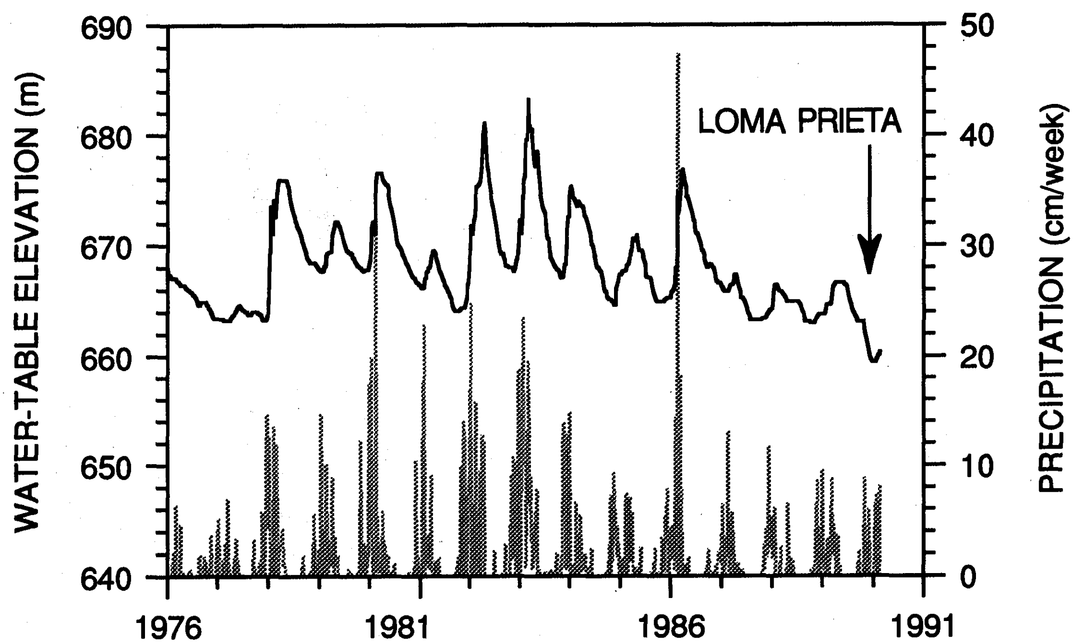


Figure 8.—Water-table elevation (black line) plotted against precipitation (gray line) for 1976-90 in a well on the eastern edge of Pescadero basin. Well is northernmost well in figure 9*A*.

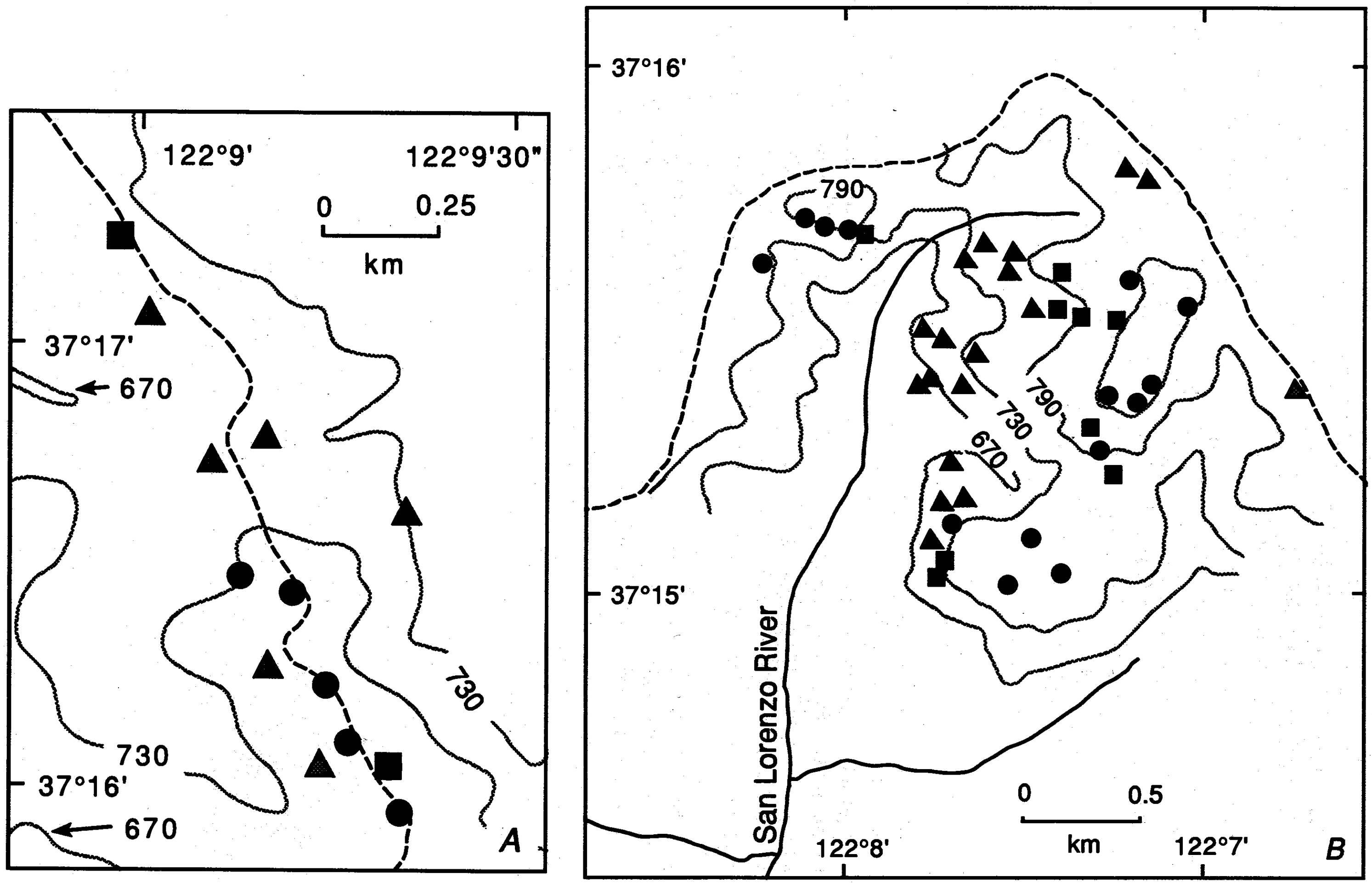


Figure 9.—Effect of the earthquake on ground-water wells in the (*A*) Pescadero and (*B*) San Lorenzo headwaters. Symbols indicate that the well went dry (circle), the well developed a reduced ability to yield water for supply (square), or the well was unaffected (triangle). Elevation contours (light lines) are in meters. Dashed line is boundary of drainage basin.

on preearthquake levels in some wells. In one well which became dry, the water level was 21 m above the bottom on October 11, 1989. In another well which became dry, the water level was 40 m above the bottom during February 1989. In two wells whose water levels began to be monitored after October 17, water levels dropped over 20 m within a period of weeks to months after the earthquake. Subsequent measurements in the region of unaffected and impacted (but not dry) wells over the time period January through July 1990 indicated that water levels declined gradually in many wells (on the order of 1.5 m/month or less). The rates of decline during 1990 were too gradual to be uniquely identified with the Loma Prieta earthquake; more likely they were due to the effects of drought in the region. The water-level data suggest that the impact of the earthquake on ground-water levels in the northern tip of the San Lorenzo drainage basin had either greatly diminished or had essentially disappeared after several months following the earthquake.

POSSIBLE CAUSES OF RESPONSE

The observed hydrologic changes (temporary excess streamflow, dropping water table, changes in stream chemistry) were likely due to a common cause. The mechanism responsible produced changes which were spatially nonuniform. Streamflow increases ranged from a factor of 4 to 24 above preearthquake conditions and generally decayed rapidly. Water-table drops examined were common but patch-like in distribution. The stream chemistry changes indicate that the difference in the excess water was ionic strength, not ionic composition. The mechanism which most likely explains the postearthquake hydrologic observations is a permeability increase caused by seismically induced formation of fractures and microfractures.

It is difficult to ascribe the observed hydrologic changes to processes occurring at mid-crustal depths. Transport of overpressured fluids from the mid-crust to the surface would require highly permeable vertical pathways at great depth. Streamflow increased at most of the monitoring stations within 15 minutes of the earthquake, indicating that any pore-pressure propagation due to a mid-crustal source would have to travel at a rate on the order of 10 m/s. Assuming that pore-pressure propagation was a diffusive process, the hydraulic diffusivity of the pathway would have to be impossibly high to allow for such rapid rates of pore-pressure propagation. If, for example, expulsion of overpressured fluids at depths of 5 km were responsible for the response of the streams (a rise to peak flow within several days of the earthquake), then the hydraulic diffusivity of the pathway would be on the order of 1×10^6 cm^2/s. This value for hydraulic diffusivity is orders of magnitude above that which has been inferred or observed in the crust (Brace, 1980, 1984). The mechanism of transport of overpressured fluids is also incompatible with the water-table drops observed in the area and the lowered temperatures of the stream water.

Collapse of near-surface dilatant fractures or squeezing of near-surface pore fluids owing to static compression induced by the earthquake are also unlikely mechanisms. They run counter to the water-table drops seen in the area. They also require an unrealistic amount of pore volume collapse to account for the amount of excess stream discharge. For example, consider the 1 billion liters of earthquake-related excess discharge at San Lorenzo Park. If we assume that this excess fluid has its source area in the near surface (to a depth of 200 m below the water table), then there would have to be compressional strains on the order of 3×10^{-3} in this region to account for the excess discharge. This amount of shortening is at least an order of magnitude greater than that which can be inferred from geodetic measurements of the displacements caused by the earthquake (Lisowski and others, 1990).

The mechanism which accounts for both excess discharge and a lowered water table in the study area is widescale increase in near-surface permeability. If the fracture networks which control ground-water flow in the region were enhanced owing to the earthquake, we would expect to see many of the effects actually observed: (1) Ground-water flow rates would initially increase in proportion to the permeability increase; (2) the water table would drop because the ground-water system would be effectively drained by the increased discharge; (3) areas of high elevation would be most susceptible to water-table drops because they would tend to have the highest water-table elevations prior to the earthquake.

The increased fractures and microfractures in the ground-water system would also be expected to temporarily alter the chemistry of the ground water. They would tend to expose previously near-stagnant water in small pores to enhanced ground-water flow paths. This near-stagnant pore water, because it would have a great deal of time to interact with rock-mineral surfaces, would have a relatively high concentration of solutes. As a result of the generation of new flow paths, a greater proportion of high solute concentration water would be expected to enter the major ground-water flow paths and the ionic strength of the exiting ground water would be increased.

To account for the initial surge in discharge, the fracturing would have to effectively increase the permeability in parts of the aquifers and aquitards in the highlands by roughly an order of magnitude. Subsequently, streamflow would decay rapidly because the hydraulic gradient which drives fluid flow would decay as the water table dropped. The fall in water-table height would be expected to decline at a rate similar to the decline of streamflow.

The relatively shallow depth of the water table in the highlands part of the study area suggests that permeability increases and concomitant water-table drops are temporary in nature. If they were permanent, the numerous historic and prehistoric earthquakes in the region would likely have lowered the water table to great depths. Apparently, between earthquakes, the fracture networks likely heal and the water table partly recovers to its preearthquake level. We propose that permeability in this region is a time-dependent parameter, increasing during times of seismicity and relaxing during interseismic periods. The temporal nature of permeability in response to shear strain in the region would be consistent with time-dependent variability in permeability of laboratory samples subjected to shear (Kranz and Blacic, 1984). In the laboratory work of Kranz and Blacic the cracks were sealed by silica cementation. Because the base flow is oversaturated with respect to calcite, we speculate that calcite cementation would be a likely mechanism for fracture healing and concomitant permeability reduction. The time constant for this inferred process, however, is not identifiable in this analysis of the data.

A SIMPLE DIFFUSIONAL MODEL OF HYDROLOGIC RESPONSE

In order to examine the theoretical response of streamflow and ground-water levels to permeability changes, we employ a very simple diffusional model of ground-water flow along a hillside. Prior to the earthquake, the water-table increases linearly with distance from the stream at a rate of 0.05 m/m and flow rates in the ground-water system are constant. Preearthquake ground-water-flow rates can be estimated from the ratio of base flow to area given in table 1 and are on the order of 1×10^{-7} cm/s for all the drainage areas. Employing Darcy's law and assuming the aforementioned water-table gradient of 0.05 yields a bulk preearthquake permeability for the drainage basins of 20 milliDarcies. This permeability estimate is obtained by assuming that the gradient of hydraulic head can be approximated by the gradient of the water table.

Assuming that the earthquake increases permeability by an order of magnitude, the gradient of the water table will decline and the ground-water flow rate into the stream will initially increase by an order of magnitude. The governing equations and boundary conditions for this simple model are:

$$\partial^2 h/\partial x^2 = c^{-1}\partial h/\partial t \quad (1a)$$

$$h(x,0) = w((L-\mathrm{abs}(x))/L) \quad (1b)$$

$$h(L,t) = h(-L,t) = 0 \quad (1c)$$

where h is the hydraulic head, x is the horizontal distance, c is the hydraulic diffusivity, t is time, w is the maximum height of the water table relative to the stream, and L is the maximum length of the ground-water flow path. Solution of equation 1 and use of Darcy's law yields the ground-water flux, v, into the stream as a function of time, t:

$$v = [4k\rho g w/\mu L] \sum_{n=0}^{\infty} [(-1)^n/(2n+1)] \exp[-(2n+1)^2\pi^2 ct/(4L^2)] \quad (2)$$

where k is the permeability, ρ is the fluid density, g is gravity, and μ is the fluid viscosity.

The fit of the model to the excess flow data is shown in figure 6. The fit is based upon a value for the hydraulic diffusivity, c, of 3,700 cm^2/s, and a value for L of 2,000 m. The model is able to mimic the magnitude and decay characteristics of the streamflow. However, the model overestimates the magnitude of the ground-water response. The model would indicate that water-table drops in the high elevation regions would be 90 m rather than the observed drops of tens of meters. This discrepancy may reflect the inappropriateness of the assumed gradient or length scale, L. It also indicates that this model is too simplistic to provide for more than a first-order description of the hydrologic response.

CONCLUSIONS

This study has focused on the ground-water and surface-water response of two basins to the Loma Prieta earthquake. Because streamflow in the San Lorenzo River is monitored extensively and because the Santa Cruz Mountains contain numerous land owners who utilize ground-water supplies, the hydrologic response can be examined in some detail. The signature of the hydrologic response is one which is consistent with earthquake-enhanced ground-water flow paths.

The enhancement of ground-water flow paths may also be responsible for hydrologic changes seen in response to other earthquakes. This mechanism may explain why the general response of streams to earthquakes is one of increased flow. Because streams are usually the exit area for ground water flow, any enhanced ground water motion would be readily detected in the base flow signature of the stream. For one order-of-magnitude increase in permeability to produce identifiable streamflow response, base flow must be a significant contributor to the stream. In addition, the permeability increases must either be areally extensive or occur in key locations.

The hydrologic response suggests that the shallow materials in the highlands areas of the study area are in a state of incipient failure. Dynamic or static shear strains produced by both the Loma Prieta and Lake Elsman earthquakes are large enough to generate new cracks and microfractures in the upper 200 to 300 m of the crust. The fractures generated must be able to form a new continuous flow path or enhance an old continuous flow path in order to cause increases in ground-water flow rates. The weak nature of the near surface is evident by the numerous active and ancient landslides in the area; it can also be inferred from the influence that fracture permeability had on the preearthquake state of ground water flow in the region. This area has been subjected to repeated earthquakes, and it is likely that seismic events, both historic and prehistoric, have had a large impact on the geologic evolution of permeability and ground-water flow paths in the region.

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