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RESEARCH ARTICLE

The 1984 Morgan Hill, California, Earthquake

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Abstract. *The Morgan Hill, California, earthquake (magnitude 6.1) of 24 April 1984 ruptured a 30-kilometer-long segment of the Calaveras fault zone to the east of San Jose. Although it was recognized in 1980 that an earthquake of magnitude 6 occurred on this segment in 1911 and that a repeat of this event might reasonably be expected, no short-term precursors were noted and so the time of the 1984 earthquake was not predicted. Unilateral rupture propagation toward the south-southeast and an energetic late source of seismic radiation located near the southeast end of the rupture zone contributed to the highly focused pattern of strong motion, including an exceptionally large horizontal acceleration of 1.29*g *at a site on a dam abutment near the southeast end of the rupture zone.*

On 24 April 1984 at 21:15:18.8 UTC (coordinated universal time), a moderate-sized (*1*) earthquake occurred on the Calaveras fault to the east of San Jose, California (Fig. 1). The earthquake was felt throughout central California (*2*), with damage estimated at $7.5 million (*3*). Because of the concentrated damage near the south end of Anderson Reservoir and the town of Morgan Hill, the 24 April event has been called the Morgan Hill earthquake.

The epicenter (37°19.02′N, 121° 40.89′W) of the main shock was located on the Calaveras fault zone 5 km west-southwest of Mount Hamilton and about 65 km northwest of the junction of the Calaveras and San Andreas faults. Nearly all the aftershocks were located on the 26-km-long section of the Calaveras fault zone southeast of the epicenter of the main shock, with concentrations of aftershocks near San Felipe Valley and Anderson Reservoir (Fig. 2). We use the spatial extent of the aftershocks (Figs. 1 and 2b) to define the rupture zone of the Morgan Hill earthquake, although rupture during the main shock probably did not extend over the entire length. This distribution of the aftershocks suggests that the source mechanism of the earthquake can be described by unilateral rupture propagation south-southeast from the main shock epicenter to the south end of Anderson Reservoir.

As yet, no unambiguous surface fault rupture has been found. Prominent discontinuous postearthquake surface cracks in the fault zone near the south end of Anderson Reservoir may be the result of slumping during the strong shaking rather than an expression of fault slip. No coseismic fault slip was observed at the small-aperture Grant Ranch geodetic network located in Halls Valley 5 km northwest of the main shock epicenter (*4*). The nearest creepmeter, at Shore Road (Fig. 1a), recorded 12.9 mm of surface slip in the 18 hours after the Morgan Hill earthquake (*5*).

There are, as yet, no identified precursors that might have permitted a prediction of the time of the 1984 Morgan Hill earthquake (*6*). The rupture zone lies within the dense network of seismographic stations operated by the U.S. Geological Survey in central California so that all earthquakes there with magnitude ≥1.5 are recorded and located. Only two foreshocks, both magnitude <1.0, were observed (*7*). Significant activity did occur near the two ends of the rupture zone in the 16 months before the Morgan Hill earthquake (Fig. 2c); the pattern of precursory seismicity near the ends of the rupture is consistent with seismicity observed before large earthquakes on plate boundaries (*8*) and also

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before earthquakes of M_L 4 to 6 on the San Andreas fault system (*9, 10*). The 1979 Coyote Lake earthquake (magnitude 5.9) occurred on the section of the Calaveras fault immediately to the southeast of the rupture zone (*9, 11*), and a number of earthquakes of magnitude 3 to 4 have occurred in the last 6 years immediately to the northwest of the rupture zone (*9, 12*). Thus, seismicity in recent years has outlined the rupture zone as a section of the Calaveras fault where cumulative seismic slip has lagged.

The rupture zone of the Morgan Hill earthquake also lies within a dense geodetic network, so that displacements associated with the earthquake are relatively well determined. The observed base lines range from 12 to 43 km, and the coseismic changes average a few centimeters (*4*). Using a 25-km-long rupture length and the 4- to 10-km depth range of the aftershocks as the rupture width, we find that the observed line length changes are consistent with a constant right-lateral displacement of 42 ± 4 cm over an area of 25 × 6 km² (*13*).

The 32-km-long Loma Prieta–Mount Hamilton line (Fig. 1b) has been measured about once a month since late 1981. The length was measured both 8 days and 1 day before the earthquake (Fig. 1b); these two measurements are within 1.7 and 3.9 mm, respectively, of the average of four earlier measurements made in 1984. Because the standard deviation of any single measurement is 7 mm, these changes are not significant (*4*). These observations limit the amount of any preearthquake slip that might have occurred the week before the earthquake to less than 7 cm if the slip occurred over the entire rupture area. A survey of the Grant Ranch geodetic network in Halls Valley (Fig. 1a) made 2 weeks before the earthquake also showed no anomalous deformation.

The length of the Llagas-Sheep geodetic line increased markedly in the 4.5 years between the 1979 Coyote Lake and the 1984 Morgan Hill earthquakes (Fig. 1c). Significant postseismic slip occurred along the 20-km-long section of the Calaveras fault to the south of Coyote Lake after the 1979 earthquake (*14*); this afterslip probably accounts for all of the accelerated extension of the Llagas-Sheep geodetic line. During this same time period, the shocks of magnitude 3 to 4.5 (Fig. 2c) near Halls Valley and Coyote Lake may have increased the shear stress on this fault segment.

A remarkable set of strong ground motion recordings was obtained for the Morgan Hill earthquake. Ground accelerations were generally larger south of the rupture zone than to the north (*15*). Severe damage was limited to the vicinity of Morgan Hill, and the largest horizontal accelerations were recorded near there as well (Fig. 3). These observations

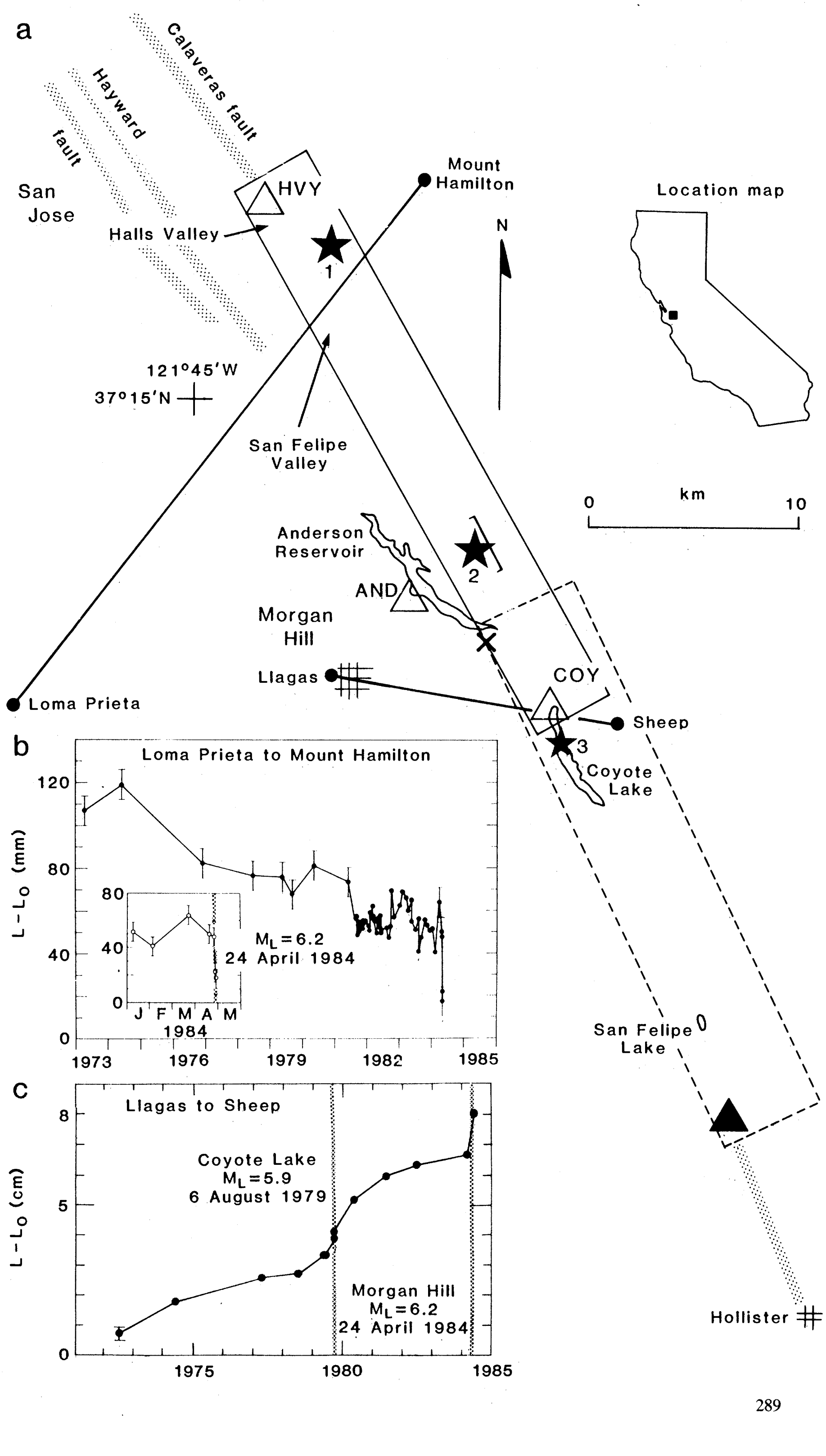
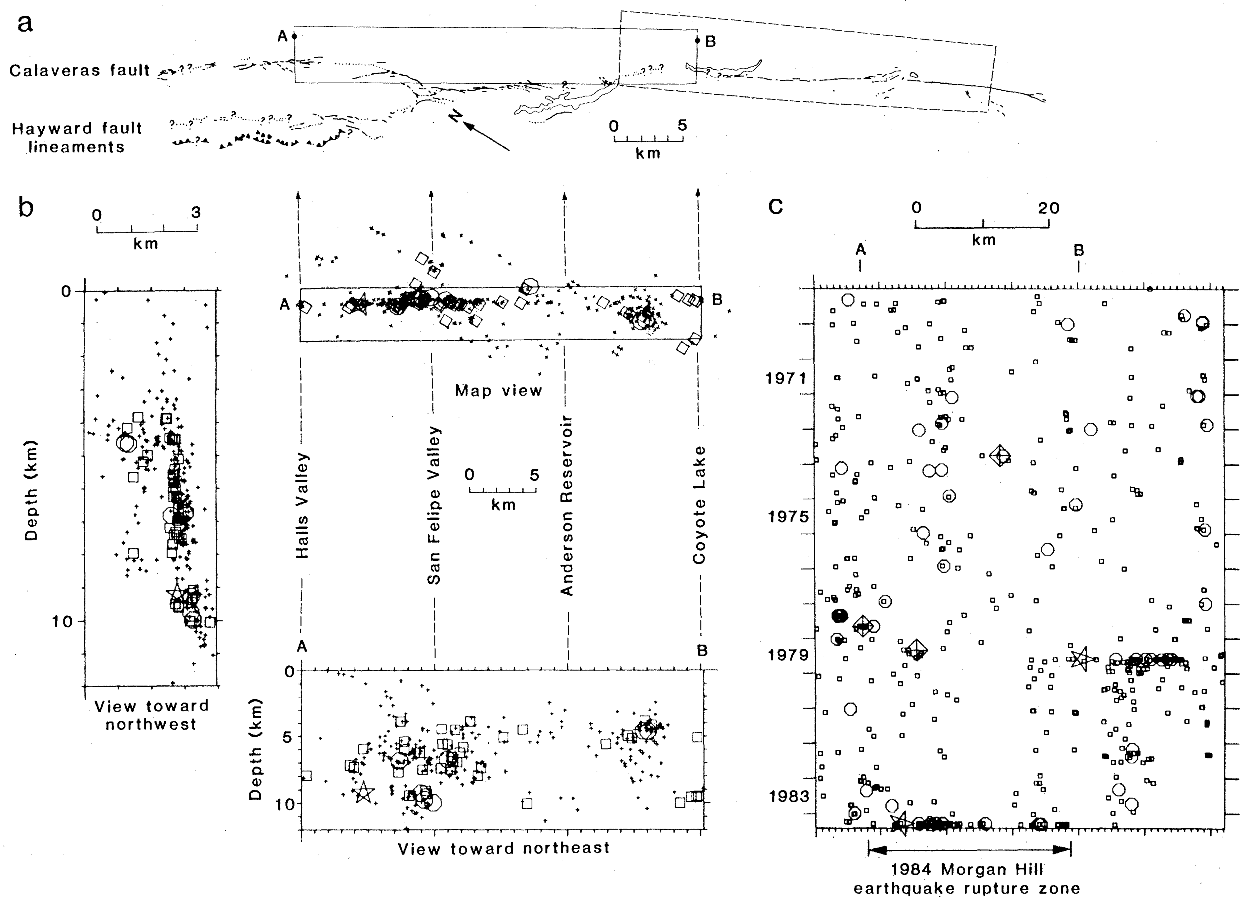


Fig. 1. (a) Map showing the Calaveras and Hayward fault zones (stippled bands) outside the rupture zone of the 1984 Morgan Hill earthquake (solid box) and the aftershock zone of the 1979 Coyote Lake earthquake (*11*) (dashed box) relative to the locations of selected geophysical instrumentation. Stars represent epicenters: 1, main shock; 2, delayed source; 3, 1979 Coyote Lake main shock. Open triangles designate strong-motion accelerographs: Halls Valley (HVY); Anderson Dam downstream (AND); Coyote Dam abutment (COY). The solid triangle indicates the location of the Shore Road creepmeter; X is the locus of severe damage, in the unincorporated Jackson Oaks area of Morgan Hill. (b) The length of the line from Loma Prieta to Mount Hamilton as a function of time. Recent measurements are shown at an expanded time scale in the inset. Error bars are ±1 σ. (c) The length of the line from Llagas to Sheep.



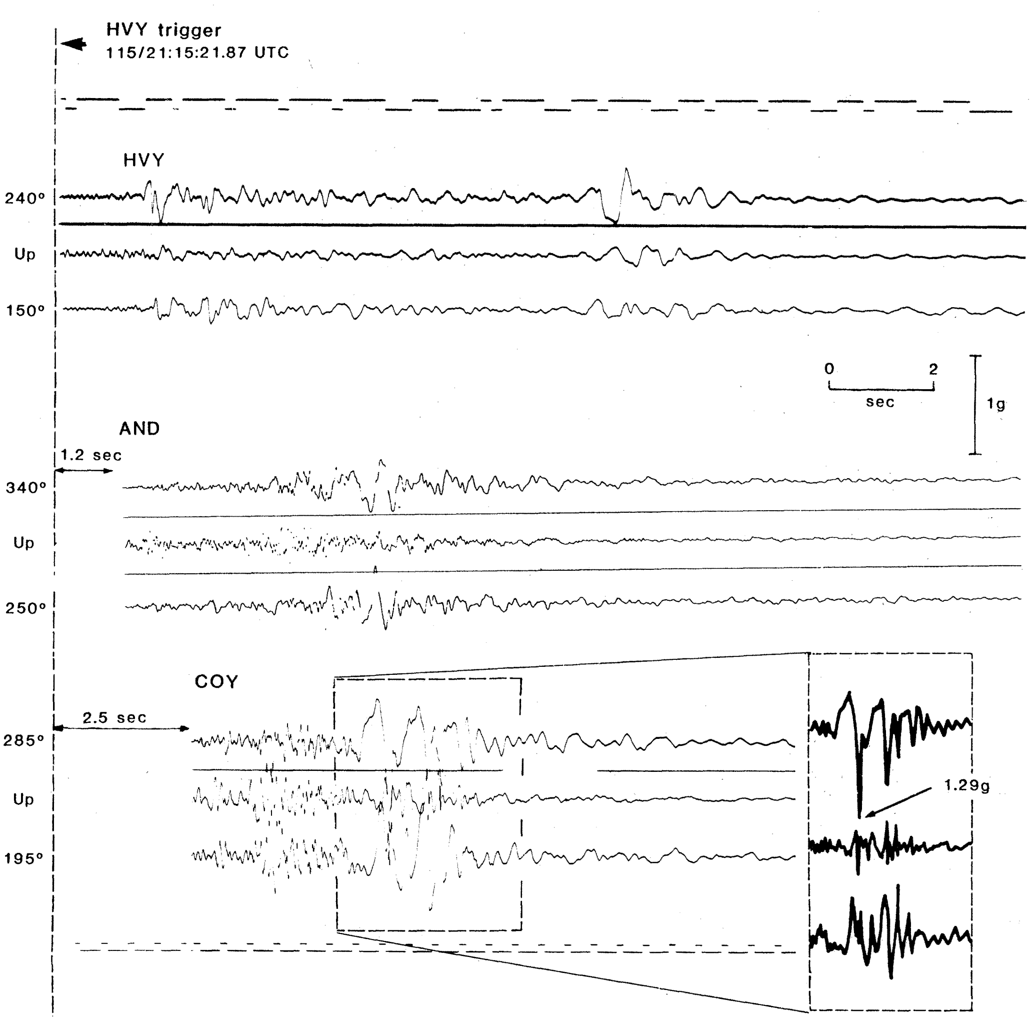


Fig. 3. Strong-motion accelerograms recorded at Halls Valley (HVY), Anderson Dam downstream (AND), and Coyote Dam abutment (COY). Traces are aligned on a common absolute time base. The dashed vertical line at the left marks the trigger time of the HVY recorder. Delays in trigger start times at the other sites are indicated. "Up" on the records corresponds to ground motion directions indicated at the left. A tracing of the COY accelerograms near the $1.29g$ peak acceleration toward 105° is shown in the inset. The straight horizontal lines between accelerogram traces are reference marks.

Fig. 2 (facing page). (a) Traces of the Calaveras fault (*24*) relative to the 1984 Morgan Hill and 1979 Coyote Lake earthquake rupture zones (Fig. 1a). (b) Map and cross sections of seismicity (24 April 1984 21:15 UTC to 11 May 1984 00:00 UTC) along the 1984 Morgan Hill earthquake rupture zone. Only epicenters within the box (map view) are shown on the cross sections. The star is the hypocenter of the main shock. Hypocenter locations were obtained from the use of a regional velocity model (*25*); displacement of epicenters off the fault traces probably reflects crustal velocities near the rupture zone not accounted for in the model. (c) Space-time plot of seismicity ($M_L \geq 2$) along the Calaveras fault zone. Symbol type is proportional to event magnitude: +, □, ○, ◇, and ☆ for magnitude 1, 2, 3, 4, and 5, respectively.

are consistent with pronounced focusing of seismic energy to the southeast of the rupture zone caused by the predominantly unilateral southeast rupture expansion. A large, late pulse on some of the strong motion records, such as the pulse 11 seconds after trigger on the Halls Valley accelerogram, shows the existence of an energetic source of seismic radiation (Fig. 3) near the southeast end of the rupture zone. The timing of the S waves from this source is consistent with a location (*16*) near Anderson Reservoir (Fig. 2b) that is noticeably deficient in located aftershocks. Although this location suggests a minimum rupture length of 16 km, it is not yet clear how far the rupture traveled or how the pulses from the second source were generated. Both deceleration of rupture (*17*) and the breaking of a region of concentrated stress are possible causes, but it is difficult to distinguish between the two on the basis of ground motion data (*18*). Whatever the cause, the location is coincident with geometric obstructions in the Calaveras fault zone at the southeast end of Anderson Lake (*19*).

The features of the Morgan Hill earthquake appear to support the hypothesis that the active faults in the San Andreas fault system are segmented by mapped complexities (offsets or bends) that control the dynamics of earthquakes. This hypothesis provides a potentially powerful tool for evaluating future earthquake behavior and seismic shaking (*9, 10, 20*). Fault complexities mark the places where stress might be concentrated and earthquakes might start, so that earthquake precursors should be sought near these places. Moreover, the probable size of future earthquakes might be estimated from the distance between adjacent geometric complexities. Furthermore, the nature of the complexity might be used to identify those places on the fault zone, like the southeast end of Anderson Reservoir, that are likely to generate strong ground motions.

The 1979 Coyote Lake earthquake and the 1984 Morgan Hill earthquakes apparently were repeats of earthquakes in 1897 (*11*) and in 1911 (*21*), respectively, implying recurrence intervals of about 75 years. Recent studies (*20, 22*) of the Parkfield section of the San Andreas fault suggest that the seismicity on a fault segment bounded by geometric complexities can be described by characteristic earthquakes that repeat with a predictable recurrence time. This support for the concepts of characteristic earthquakes and predictable recurrence intervals adds credence to long-term forecasts of earthquake potential (*23*) and represents progress toward the goal of reliable earthquake prediction.

References and Notes

1. The National Earthquake Information Service in Golden, Colo., reported a surface-wave magnitude $M_S = 6.1$ and a body-wave magnitude $m_b = 5.7$. The moment magnitude [T. C. Hanks and H. Kanamori, *J. Geophys. Res.* **84**, 2348 (1979)], based on a geodetic moment of 1.9×10^{25} dyne-cm (*13*), was 6.2. A preliminary local magnitude M_L of 6.2 was obtained by the University of California, Berkeley, Seismographic Station from seismographs located north and northwest of the rupture zone; M_L from seismograms written in southern California is about 6.4 to 6.5. The relatively low m_b of 5.7 reflects the size of the initial source; the larger M_s, moment magnitude, and M_L estimates reflect the extended source, including the energetic source near the southeast end of the rupture zone (*16*).
2. High-rise buildings in San Francisco, 75 km northwest of the epicenter, although strongly shaken, did not suffer structural damage. Transient distortion during the shaking did, however, break fasteners and soldered joints in copper sheets that covered the steel-frame cupola atop the dome of San Francisco City Hall (N. M. Karasick, personal communication).
3. Damage of $7.0 million to private property and $0.5 million to local government facilities, according to preliminary damage assessment by the California Office of Emergency Services.
4. W. H. Prescott, N. E. King, Gu G., *U.S. Geol. Surv. Open File Rep. 84-498* (1984).
5. The afterslip at Shore Road is the largest creep event recorded in the 13-year history at this site. For comparison, slip at Shore Road in the 24 hours after the 1979 Coyote Lake earthquake was 8.9 mm (S. Schulz and B. D. Brown, personal communication).
6. Although the time of the earthquake was not predicted, both its magnitude and location were anticipated in 1980 (*9*). Also, an increase in the number of shocks of magnitude 6 to 7 in the San Francisco Bay area was anticipated on the basis of long-term cycles of strain accumulation and release [W. L. Ellsworth, A. G. Lindh, W. H. Prescott, D. G. Herd, *Am. Geophys. Union Monogr. Earthquake Prediction* (1981), pp. 126–140].
7. Two small foreshocks on 24 April at 03:41:37.0 UTC (magnitude 0.7) and 18:11:37.7 UTC (magnitude 0.4), both located at the main shock epicenter, have been identified. For comparison, more than 150 earthquakes (magnitude ≥1.0) occurred within the rupture zone in the preceding 12 months.
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12. Earthquakes near Halls Valley since 1979 include the events on 15 January 1981 (M_L 4.8) and 23 October 1983 (M_L 3.8).
13. The geodetic moment is 1.9×10^{25} dyne-cm (*4*). For comparison, the geodetic moment for the 1979 Coyote Lake earthquake was 1.6×10^{25} dyne-cm.
14. M. Lisowski and N. E. King, unpublished manuscript.
15. For example, peak horizontal accelerations were five to eight times as high to the southeast of the rupture zone as to the northwest at distances of 25 to 50 km.
16. The inferred time of this source is 5 seconds after the main-shock origin time. It is located between 16 and 20 km southeast of the main-shock epicenter. If this source is part of continuous rupture from the main shock epicenter, the minimum average rupture velocity is 80 to 90 percent of the shear-wave velocity β; a rupture velocity greater than β cannot be ruled out at this time. These calculations use details of the local velocity structure (P. Blümling, W. D. Mooney, W. H. K. Lee, *Bull. Seismol. Soc. Am.*, in press).
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19. Available maps [D. H. Radbruch-Hall, *U.S. Geol. Surv. Misc. Geol. Inv. Map I-813* (1974); T. W. Dibblee, Jr., preliminary geologic maps of the Lick Observatory, Gilroy, Morgan Hill, and Mount Sizer quadrangles, Santa Clara County, Calif., *U.S. Geol. Surv. Open-File Rep. 72-90* (1972) and *73-59* (1973); D. G. Herd (*24*)] show this complexity either as a major left step or bend. Investigations in progress should clarify the character and dimension of this complexity.
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