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A SLOW EARTHQUAKE IN THE SANTA MARIA BASIN, CALIFORNIA

BY HIROO KANAMORI AND EGILL HAUKSSON

ABSTRACT

An $M_L = 3.5$ earthquake near Santa Maria, California, was recorded by the Southern California Seismic Network and a TERRAscope station at Santa Barbara (SBC) on 31 January 1991. The waveform of this event is dominated by 2- to 5-sec waves, and is different from that of ordinary events with similar size. Inquiries into operations in several oil fields in the area revealed that hydro-fracturing at a pressure of about 80 bars was being done at a depth of 100 to 300 m in the Orcutt oil field in the Santa Maria basin from about 9 to 11 a.m. on 31 January and the earthquake occurred in the afternoon. Field evidence of 30-cm displacement to a depth of 300 m was reported. The field evidence as well as the first-motion data indicates that the event had a thrust mechanism with the *P* axis in the NNE–SSW direction, which is in agreement with the regional stress field. From the analysis of the SBC record and the field evidence, we conclude that the source must be shallower than 1 km and the ratio of the radiated energy to the seismic moment is about 6.2×10^{-7}, one to two orders of magnitude smaller than that of ordinary earthquakes. The occurrence of this earthquake demonstrates that release of regional tectonic stress in shallow sediments can yield significant seismic radiation at periods of a few seconds, the period range of engineering importance for large structures, and has important implications for excitation of long-period ground motions from large earthquakes in sedimentary basins.

INTRODUCTION

On 31 January 1991, an anomalous earthquake was recorded at seismic stations of the Southern California Seismic Network (SCSN). This event was located at 34.8°N and 120.4°W (origin time: 23:28:18 GMT) near Orcutt in the Santa Maria basin, California (Fig. 1a), felt in the Santa Maria area, and was given $M_L = 3.5$. The P wave was very emergent, and no S wave could be identified on the short-period SCSN seismograms (Fig. 1b). It was also recorded with the three-component broadband seismograph of the TERRAscope station at Santa Barbara (SBC) at a distance of 70 km (Fig. 1a). However, the seismogram recorded at SBC was so unusual that we could not immediately identify it as a regional earthquake; we accidentally noticed it while we were examining the S-wave coda of a large ($M_S = 6.6$, depth = 150 km) intermediate-depth earthquake in the Hindu-Kush region that occurred at about the same time.

Figure 2a compares a Wood-Anderson seismogram of this earthquake (simulated from the SBC TERRAscope broadband record) with the seismogram of an ordinary event with about the same magnitude recorded at about the same distance. The anomalous nature of this event is evident. Neither P nor S wave is distinct, and the duration, about 2 minutes, is unusually long for an $M_L = 3.5$ event.

Kovach (1974) analyzed seismograms of events caused by collapse in the Wilmington oil field near Long Beach, California. The SBC record of the Santa

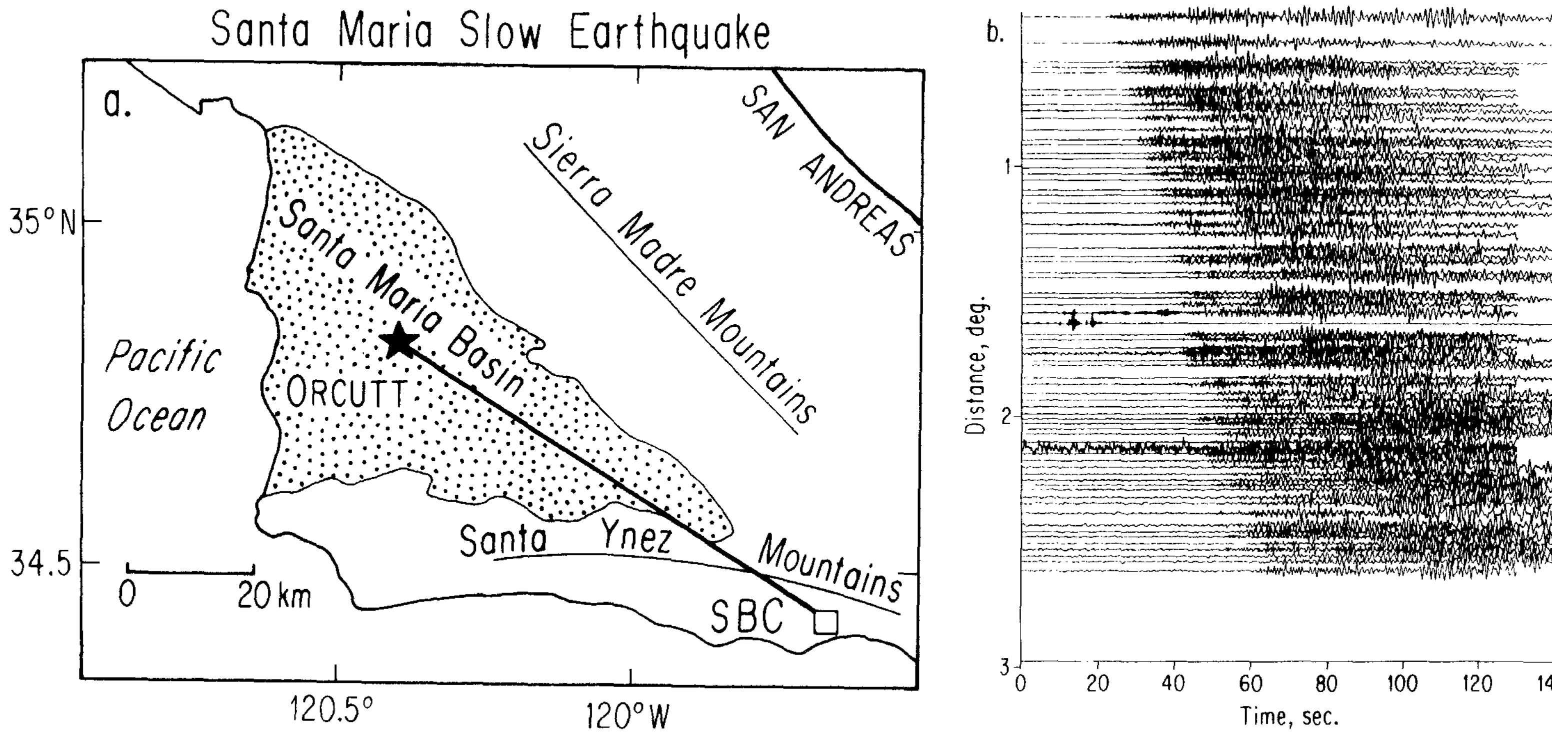


FIG. 1. (a) A map showing the epicenter of the Santa Maria earthquake, Santa Maria Basin, Santa Ynez Mountains, and the path to the Santa Barbara station (SBC). (b) The Santa Maria earthquake recorded at stations of the Southern California Seismic Network.

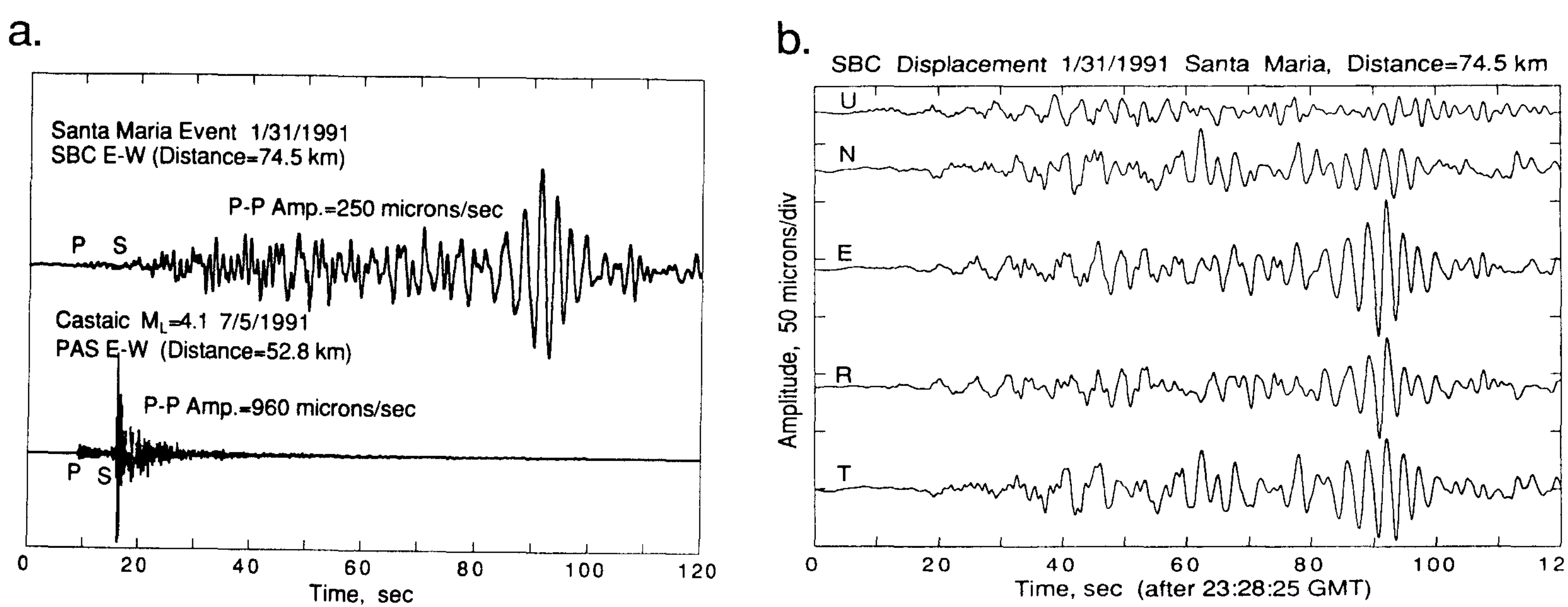


FIG. 2. (a) Comparison of the Santa Maria earthquake (*top*) with an ordinary earthquake with a similar magnitude recorded at about the same distance (*bottom*). (b) Displacement records (vertical, N-S, E-W, *radial*, and transverse components) of the Santa Maria earthquake recorded at the SBC TERRAscope station.

Maria event is very similar to the records of the Wilmington events and suggests a similar origin for the Santa Maria event. The epicenter is within the Orcutt oil field in the Santa Maria basin (see Fig. 1a). After several inquiries about oil extraction activities in the oil fields in the area, we found that hydro-fracturing at a pressure of about 80 bars was being done at a depth of 100 to 300 m in the Orcutt oil field from about 9 to 11 a.m. on 31 January 1991. While perforation gear was being lowered into one of the wells, the earthquake occurred (Charlie Catherman, personal comm., 1991). The deformation of liners in several wells at similar depths suggests that the Santa Maria event was caused by failure of sediments at shallow depth. Because of its very shallow depth, the earthquake excited large surface waves at periods near the resonance period of the sedimentary layers.

Waveform at SBC

Figure 2b shows the displacement record at SBC. In addition to the standard three-component (Z, N, and E) traces, the radial and transverse components are shown. The first 60 sec shows a coherent dispersive wave train, suggesting a Rayleigh wave on the vertical and radial components and a Love wave on the transverse component. The latter half (60 to 120 sec) of the wave train is dominated by the E-W component. This is probably a Love wave scattered by the structure between the epicenter and SBC. The path from the epicenter to SBC is primarily in the Santa Maria basin, but it crosses the Santa Ynez mountains near the SBC station. The scattering could be due to the structures near the basin boundaries. We used the unscattered first 60 sec of the Love wave for the analysis.

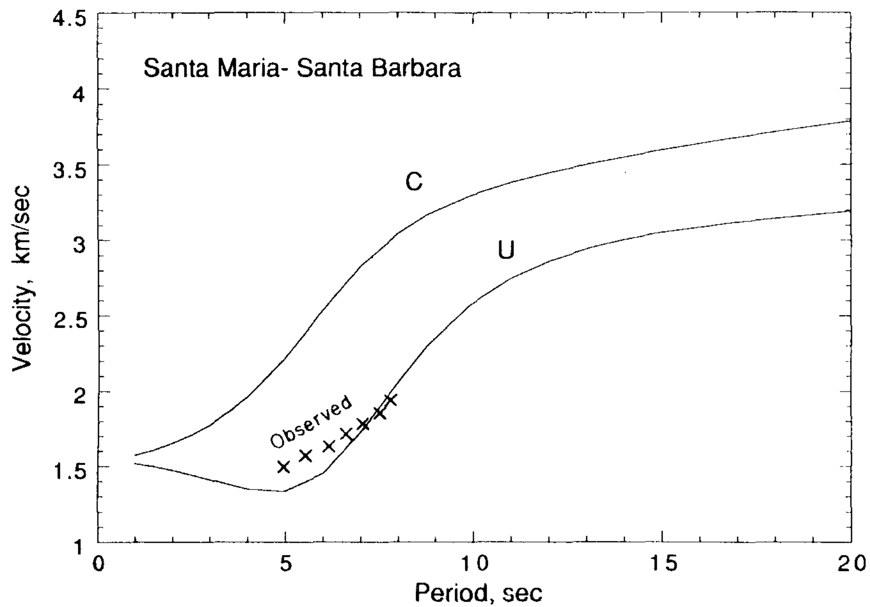
The group velocity of this wavetrain, ranging from 1.5 to 2 km/sec for a period of 5 to 8 sec, is in agreement with the group velocity (Fig. 3) computed for the structure shown in the figure. The P velocities for this structure are taken from the southeastern end of a Gabilan Range profile published by Walter and Mooney (1982). The S velocities were first computed from the P velocities with a Poisson's ratio of 0.25, and later were slightly modified to match the observed group velocities.

Field Data

The field data provided by Catherman (personal comm., 1991) and Shemeta (written comm., 1992) are summarized in Figure 4. The Orcutt oil field where the hydro-fracturing was performed has five wells in a circular area about 360 m in diameter. All the liners in the casings were deformed into S shape with a maximum offset of approximately 30 cm. The depths to the S-shaped deformations range from 135 to 280 m. Catherman estimates the fault dip to be about 40° to SSW. Most bedding planes in the area have dips of 10 to 15°. The direction of the slip on the fault plane could not be determined.

Source Parameters

The first motions from this event recorded at SCSN and the Pacific Gas and Electric Company (PG and E) seismic network were very emergent. Out of 41 first-motion data, 34 were reported as "up," with only seven being reported as "down." Three impulsive first-motion data were all up. Since the event is very shallow and the velocity in the source region is very low, all the first motions should plot near the center of the focal mechanism diagram. All the first



Thickness (km)	α (km/sec)	β (km/sec)	ρ (gm/cm3)
1.5	2.63	1.54	1.8
0.75	3.0	1.79	1.9
0.6	3.8	2.19	2.0
1.9	5.5	3.18	2.4
4.0	6.0	3.46	2.67
2.0	6.15	3.55	2.7
10.0	6.35	3.67	2.7
15.0	6.55	3.78	2.8
30.0	8.0	4.62	3.3

FIG. 3. Love-wave group velocity determined from the record shown in Figure 2b. The solid curves indicate the phase (C) and group (U) velocities computed for the structure shown in the figure.

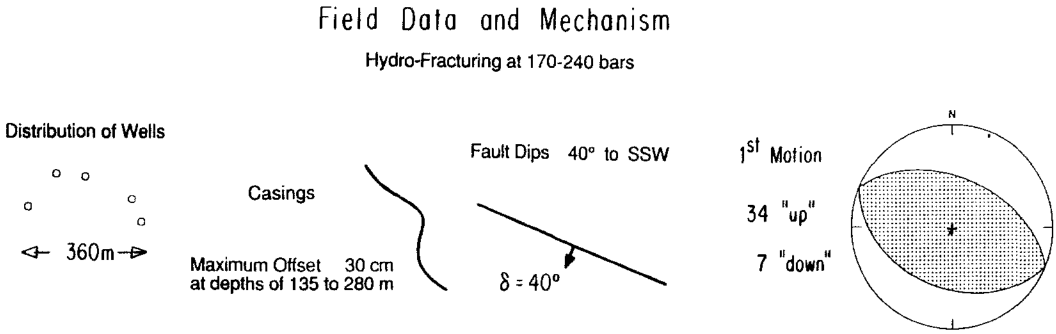


FIG. 4. The field data obtained from the Orcutt oil field. The S-shaped curve is a sketch of the deformed casings. The mechanism diagram (stereographic projection of the lower focal hemisphere) is constructed from the field data and the first-motion data.

motions should be up if the faulting was reverse on a dipping plane, and down if it was a normal faulting. Thus, the overwhelmingly up first motions suggest a thrust faulting, as shown in Figure 4. Here, the rake is assumed to be 90°. We interpreted the SBC record using the thrust mechanism.

Figure 5a shows the spectrum of the observed Love wave (0 to 60 sec on Fig. 2b). Curve *a* shows the excitation spectrum for a point source placed at a depth of 500 m in the crust shown in Figure 3. It is computed for a pure reverse fault with a dip angle of 40° and a strike of 112.5°, as suggested from the field data and the first-motion data. The method described in Kanamori and Stewart (1976) is used for this computation. If a source depth of 5 km is used, the excitation function peaks at 7 sec with a rapid roll-off above 0.2 Hz. Thus, the observed large amplitude in periods shorter than 5 sec requires a very shallow source.

The observed spectrum exhibits a spectral hole at about 0.3 Hz with a rapid roll-off at frequencies higher than 0.5 Hz. Kovach (1974) found a similar behavior for earthquakes in the Wilmington oil field and explained it with a slow rupture propagation model. We could not determine whether the observed spectral hole and the rapid roll-off at high frequencies were due to slow rupture or slow dislocation particle velocity, but an overall source time constant, τ_0, of about 3 sec is required. Since only one record is available, any combination of rupture length and rupture velocity with a ratio of 3 sec explains the data. Kovach (1974) obtained a very slow rupture velocity, about 0.13 km/sec, for the events in the Wilmington oil field. In Figure 5a, we used a combination of a rupture velocity of 0.13 km/sec and a rupture length of 0.4 km. Although this combination is not unique, the rupture length of 0.4 km is comparable to the linear dimension of the area where the wells are distributed and is also consistent with the source dimension estimated from the seismic slip and moment, as will be shown later. Multiplying the finiteness spectrum (Ben-Menachem, 1961), $\sin(\pi f \tau_0)/\pi f \tau_0$, computed for this combination by the point source spectrum, we obtained the source spectrum shown by curve *b* in Figure 5a, which is similar to the observed spectrum. A seismic moment of 6.1×10^{21} dyne-cm is required to explain the observed amplitude. Figure 5b compares the observed Love wave with the synthetic waveform computed for the source model shown in Figure 5b. In this calculation, the Love-wave Q is assumed to be 100. The overall agreement of the waveform is satisfactory. Thus, although we could

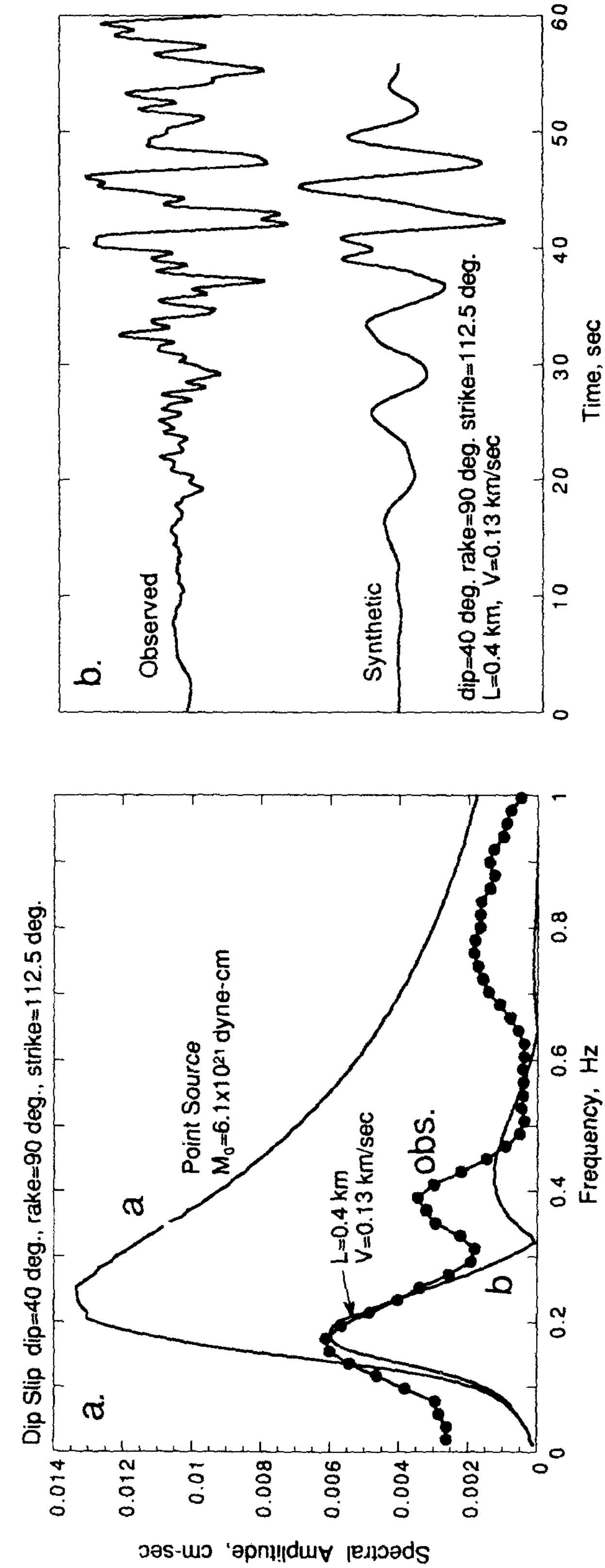


FIG. 5. (a) Spectral excitation function and the observed source spectrum. Curve *a* is for a point source, and curve *b* is for a finite propagation source. (b) Comparison of the observed and synthetic Love waves.

not determine the rupture characteristics uniquely, we consider the slow rupture model described above to be reasonable.

The compression axis of the mechanism shown in Figure 4 is in NNE-SSW direction, which agrees with the direction of regional shortening determined from the geodetic data (Feigl *et al.*, 1990).

The thrust mechanism shown in Figure 4 places the Santa Barbara station fairly close to the radiation node of Love waves. Considering the uncertainties in the mechanism, we then consider an alternative strike-slip mechanism, which puts SBC near the radiation maximum. For this mechanism, we obtained a seismic moment of 1.2×10^{21} dyne-cm, which can be considered a minimum seismic moment for this event.

Slip, Seismic Moment, and Energy

In the following calculation, we use a seismic moment 4×10^{21} dyne-cm as the average of the two seismic moments estimated above. Using $\rho = 1.8$ g/cm^3, and $\beta = 1.54$ km/sec from Figure 3, we obtain $\mu = \rho\beta^2 = 4.3 \times 10^{10}$ dyne/cm^2. If the displacement is 30 cm as suggested by the field data, the area S is $M_0/\mu D = 3.1 \times 10^5$ m^2, which gives a representative dimension of the source, $S^{1/2}$, of 560 m. This value is comparable to that inferred from the spectral hole and the dimension of the area where the wells are distributed.

The total energy radiated from this event can be approximately estimated as follows. Since the spectrum of the transverse component of the ground-motion velocity at SBC has a sharp peak at 0.35 Hz, as shown in Figure 6, we assume that the most energy is contained in the fundamental mode Love wave at $f = 0.35$ Hz. Then the total radiated energy is given by

$$E = 2\pi\Delta\bar{h}\,\exp(2k\Delta)c\rho\int_0^\infty v^2(t)\,dt. \tag{1}$$

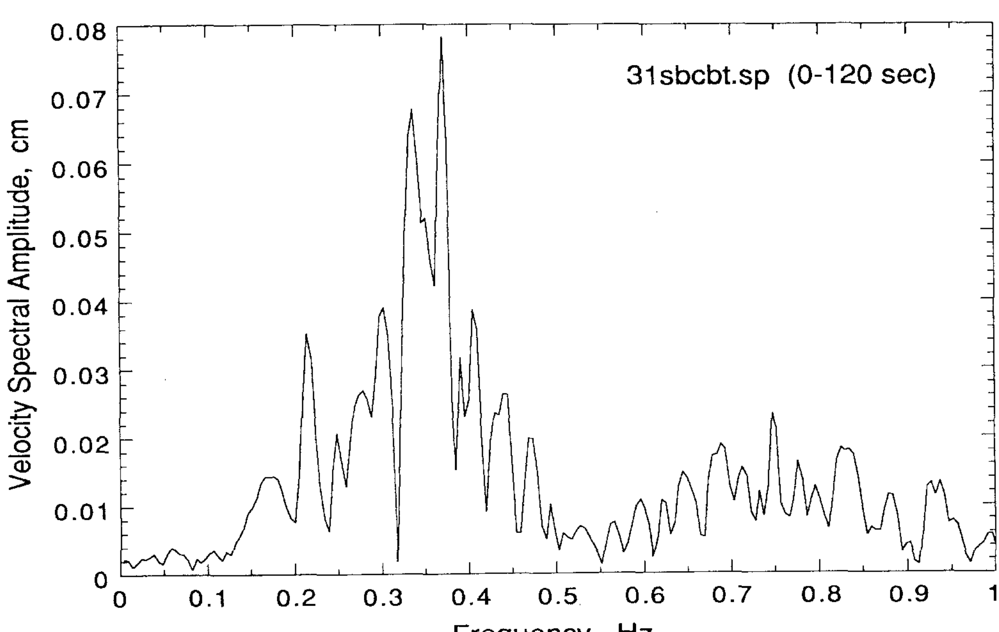


Fig. 6. Spectrum of the transverse component of the ground-motion velocity at SBC.

Here, $v(t)$ is the ground-motion velocity at distance Δ, ρ is the density at the surface, c is the phase velocity at 0.35 Hz, k is the attenuation constant (i.e., $\pi f/Qc$), and $\bar{h}$ is the thickness of the effective wave guide, which is given by

$$\bar{h} = \frac{\int_0^\infty \rho(z) y^2(z)\, dz}{\rho(0) y^2(0)},$$

where $y(z)$ is the Love-wave amplitude as a function of depth at 0.35 Hz. Using the normal mode computed for the structure shown in Figure 3, we obtained $\bar{h} = 1.2$ km. Integrating the velocity trace of the transverse component, we obtain

$$\int_0^\infty v(t)^2\, dt = 0.68 \times 10^3\ cm^2/sec.$$

Substituting this and using $c = 1.75$ km/sec, $\rho = 1.8$ g/cm^3 in (1), we obtain $E = 2.4 \times 10^{15}$ ergs.

The ratio of the energy E to seismic moment is thus

$$E/M_0 = 6.2 \times 10^{-7},$$

which is much smaller than the ratios 5×10^{-5} to 5×10^{-6} for ordinary earthquakes (Kanamori, 1977; Vassiliou and Kanamori, 1982), reflecting the slow nature of this earthquake.

Conclusion

Although we could not uniquely determine the detailed geometry of the source mechanism, the present result demonstrates that release of regional tectonic stress in shallow sediments can yield significant seismic radiation at periods of a few seconds. The dominant period is much longer than that of ordinary earthquakes with a comparable magnitude and is within the period range of engineering importance for large structures. In this regard, the present result has important implications for excitation of long-period ground motions from large earthquakes in sedimentary basins.

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Seismological Laboratory
California Institute of Technology
Pasadena, California 91125

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