DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Santa Cruz Seismic Investigations

Following the October 17, 1989 Loma Prieta Earthquake

by

K. King[1], D. Carver[1], R. Williams[1],

D. Worley[1], E. Cranswick[1], and M. Meremonte[1]

Open-File Report 90-307

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1]Golden, Colorado

1990

SANTA CRUZ SEISMIC INVESTIGATIONS

FOLLOWING THE OCTOBER 17, 1989 LOMA PRIETA EARTHQUAKE

BY

King, K., Carver, D., Williams, R., Worley, D., Cranswick, E., Meremonte, M.

INTRODUCTION

Ground shaking induced by the aftershocks from the October 17, 1989 Loma Prieta, California, earthquake provided a unique opportunity to study the effects of the ground motions induced by earthquakes and to contribute to the on-going process of developing methods to mitigate damage from earthquakes. This report presents results of a preliminary inspection of the seismic data acquired in the Santa Cruz, Calif., area during the Loma Prieta earthquake aftershock sequence. The report shows site information, seismic time histories (seismograms), and response spectra derived from data recorded at selected sites during the aftershock sequence. The data in this report will be useful to other researchers working with the complete data set, which will be available on a read-only compact disk in the near future.

Thirty-six sites in the Santa Cruz, Calif., urban area were occupied with portable seismic systems during the aftershock sequence. The selection of sites in the urban area took into consideration the site geology and spatial locations. The seismic systems were meticulously calibrated and impressed with accurate world time to produce high-resolution data for additional future studies. The objectives of the instrument deployment were:

Comparison of Aftershock Seismograms With Main Shock Seismograms

The comparison of the amplitude, phase, and spectral content of the aftershock ground motions with amplitudes, phase, and spectral content of the ground motions from the main shock will allow several scientific investigations, including source investigations. To achieve this objective, portable seismic systems were co-located with seismic instruments that recorded the main shock at the University of California, Santa Cruz, Saratoga, Hall's Valley, and Moss Landing Thermal sites.

Urban Area Site Response

To achieve this objective, a total of 31 sites were located on various geologies, topographic relief, and areas which had different degrees of damage from the main shock within the Santa Cruz, California urban area.

Basin Seismic Model

Eleven sites were located on a general east-west line across the San Lorenzo River alluvial basin in the Santa Cruz urban area. Several aftershocks were recorded at these sites. The data show the variance in the ground response and may, through ray-tracing, show a subsurface model of the basin.

Topographic Effects

Six sites were instrumented with portable seismic systems located across an area of high relief in the northwestern part of Santa Cruz. The data may show a ground motion variance due to topographic relief.

Refraction Study

Shallow subsurface seismic refraction profiles were made at ten urban sites in Santa Cruz. Shear wave profiles were made at seven of the ten sites. The data will supplement the site data for the site response study and will be useful for developing near-surface velocity values for other studies.

Chimney Damage Study

A large portion of the urban residential structures were visually inspected for degree of chimney damage to supplement the damage-intensity investigations.

Field Data Consolidation System

The project field tested and experimented with a new field-data-consolidation system using off-the-shelf PC systems. A PC-oriented processing system which consolidates field data from portable seismic digital systems was used to facilitate the data-storage management and data inspection during the field operation.

ACKNOWLEDGMENTS

Any field operation such as this is deeply indebted to the residents, and city, county, and State personnel.

Even though they were in a sense "in harms way", we received complete cooperation and support from all. A special thanks is due to Armand Levesque, schools, Ruby Quintanar, parks, and Larry Erwin, public works, of the city of Santa Cruz.

All efforts were in cooperation and coordination with various U.S. Geological Survey researchers under specific coordination of Paul Spudich, Tom Holzer and Kaye Shedlock. A. Tarr (USGS) supplied base maps and integrated data into a GIS system. Authors are USGS employees Denver, Co.

DATA ACQUISITION

Aftershock Data

Ground shaking induced by the aftershocks of the Loma Prieta earthquake were recorded by portable digital seismic systems at 36 sites in the Santa Cruz urban area (figs. 1 and 2). The seismic systems used triaxial velocity-sensing transducers that have a natural period of 0.62 second and damped at 60 percent of critical. The data are digitally recorded on magnetic tape at 200 samples per second per channel.

Digital recordings of the induced ground motion from thirty aftershocks were recorded at four or more locations in the city of Santa Cruz and vicinity (fig. 3). Between five and eleven seismic systems per study were installed at temporary locations in the Santa Cruz city area. The seismometers were leveled, oriented to magnetic north, and calibrated for each event using standardized procedures (Carver and others, 1986). All seismometers were either buried and tamped approximately 0.2 - 1.0 m deep or attached to a firm, well coupled surface with epoxy cement. The procedure for triggering (turning on) the recording system to record the induced ground shaking from the aftershocks was to use a long term average-short term average (LTA/STA) algorithm within the field system. The system's internal control is set to activate the recording system for a 30 s duration when the STA = 0.2 s data signal exceeds the LTA = 6.6 s by a ratio of approximately 3-6 dB. The system is continuously active and buffers 6.6 s of data which are recorded with at least 30 seconds of data following triggering. The field systems' clocks were set with a master-clock which was synchronized with UTC. Time corrections have been entered into the data base and are included with the data that will be distributed. Most times are considered to be ± 0.003 s in accuracy. Some of the peak motions produced clipped traces due to overloading the amplifiers. These are shown on the various figures by an asterisk. The clipped data traces are included since the signals contain such useful information as duration, phase and arrival times, and relative amplitudes.

Sites were selected on the basis of four criteria:

1 The spatial distribution of sites was according to a line distribution across the study area.

2 The site was at or near the location of an intensity observation or a recording of the large ground motions from the main shock of the Loma Prieta earthquake.

3 The surficial geology of the site was known.

4 The site could accommodate future subsurface investigation by drilling or by short seismic-reflection and -refraction lines.

The surficial geology of all sites is known from Clark (1981). Twenty locations were located on various thickness of marine terrace deposits (Qm), which is defined as unconsolidated moderate-yellowish brown fine sand and granular gravel. Fourteen locations were on alluvium (Qal), unconsolidated gravel, sand and silt. One site was on metasedimentary rocks (Sch), mainly pelitic schist and quartzite; one site was on the Purisima Formation (Tp) a thick-bedded yellowish-gray tuffaceous siltstone with interbeds of bluish-gray fine-grained andesitic sandstone; one site was located on marble which contains interbedded schists, and one site was located on the third floor control room of the thermal electrical generating plant at Moss Landing (fig. 2, table 1).

Refraction Data

A 12-channel digital-seismograph with 8-Hz (resonant frequency) geophones was used in this study to acquire compressional- (*P*-wave) and shear-wave (*S*-wave) seismic-refraction profiles at 10 sites in Santa Cruz (fig. 2). Compressional *P*-wave ground motion was induced by either an 8-lb sledgehammer impact on a steel plate placed on the ground surface, or a buried explosive charge equal to about 1/12- to 1/3- lb dynamite. The explosive shot holes were 1.0-1.5 m deep. The explosive charges were used at two sites (B and F of table 3) where long geophone arrays could be used and where high seismic-velocity subsurface (bedrock) was not detected using the sledgehammer. *S*-waves were produced using sledgehammer impacts against a timber oriented perpendicular to the geophone array and placed under the wheels of a car or truck. To facilitate identification of the *S*-wave, two *S*-waves were recorded, one each from hitting opposite ends of the timber to reverse the polarity.

Three reversed seismic refraction profiles were obtained at each site except for sites B and F. The seismic source for the profiles was offset from the nearest geophone by 3.05, 15.2, and 30.5 m, combined with a 3.05-m geophone interval. The available space at sites B and F allowed additional profiles with 220 m between the explosive charge and the farthest geophone and a 9.1-m geophone interval.

The slope-intercept analysis method was used for the preliminary analysis with the first-arrival time visually determined from the seismograms. Plotting the first-arrival times against the offset distance produced a travel-time graph from which the seismic-velocity structure versus depth was determined.

Chimney Damage

The approximate degree of damage to 1,950 chimneys was documented to supplement the intensity studies. Figure 4 indicates the spatial distribution of the damaged chimneys in the city of Santa Cruz. The inventory does not include the business-mall sections of the city since most of the damage of those areas was extreme and the structures were not similar to the urban areas. Data were obtained by an actual count of residential homes.

DATA PROCESSING

Data consolidation and preliminary reduction was accomplished in the field during operations. The field computer system used to perform processing of the data from the portable digital seismographs deployed in Santa Cruz is illustrated in figure 5. The hardware consisted largely of IBM PC-compatible microcomputer components which were installed in a local motel. The waveform analysis, and data consolidation software had been developed for the Armenia Project of the Eurasian Seismic Studies Program (Cranswick and others, (1989). The digital cassette playback system was connected by an RS-232 port to a PC/AT-compatible microcomputer equipped with a 40-Mb hard disk. The data for each event were stored in an ASCII file which was data-compressed and then transferred to a larger and faster microcomputer (IBM PS/2, 20MHz, Model P70) for data consolidation and storage. The latter computer was equipped with a write-once-read-many (WORM) optical disk drive for archiving the raw data, a 120-Mb hard disk for interim data consolidation, and a laser printer/plotter. A portable laptop computer was used to calculate spectra and spectral ratios of the seismograms. Earthquake-summary information, which was downloaded via modem from computers at USGS, Menlo Park, was correlated with the field records.

DISCUSSION

Aftershock Data

Thirty-two sets of seismograms (particle-velocity, time histories) from the documented data are shown (fig. 6-42). Table 1 gives the locations of each site and the events that were recorded at that site. Table 2 gives the location of the aftershocks. Table 3 shows the compressional and shear wave velocities recorded at locations A-J shown on figure 2.

The earthquake seismic time-histories shown are derived from the recorded digital data. The time length (15 seconds), filtering (20 Hz., 4-pole, low-pass), and component orientation are identical on all of the figures. The amplitude scale bars allow visual comparison. Figures 8, 11, and 14 show comparisons of the sites located at or near California State strong-motion instrument locations. Figures 12 - 23 show seismograms from sites located near areas of low damage compared to those located near areas of high damage. Figures 27 - 37 show the seismograms from an east-west line which transected the alluvial basin in Santa Cruz. Figures 40 - 42 show the seismograms from the east-west topographic line. All of the events were located 10 - 30 km from central Santa Cruz except for the event represented in figure 42 which was located on the Hayward fault approximately 50 km from the city of Santa Cruz.

Figures 43 - 49 show examples of spectra derived from the digital data. The vertical and horizontal scales are identical on all of the sepctra to allow visual comparisons. For each event at each site, a 10-s time duration of digitally recorded ground motion was selected for analysis, centered on the largest *S*-wave amplitude. The window was tapered with a whole-cosine bell (Hanning window) before being transformed by a standard Fast Fourier Transform (FFT) program. It was not necessary to normalize spectral amplitudes for window length because all spectra in this study were derived from time series of identical duration. The spectra were smoothed by a moving 5-point averager in each of 90 equal-frequency band-widths from 0.5- to 30-Hz.

Figures 43 and 44 show the spectra at sites located near sites which recorded the main shock, (LOE and FRE), and areas of low-to-moderate damage. Figures 54, 46, and

47 show the spectra of sites located on the east-west basin line across Santa Cruz. Sites BAR and KLA are near or on rock sites; TRE is on the marine terrace; and WAL through BAS are on varying depths of alluvium. Sites WAL, BLA, and CE2 in figure 4 were in areas of heavy damage from the Loma Prieta earthquake. The spectral amplitudes are greater in the areas of heavy damage and sites located on the alluvium basin and less in those areas underlain by the older and consolidated materials.

Refraction

Refraction profiles were made at 10 sites in Santa Cruz. A summary of the preliminary interpretation of the seismic refraction data is presented in table 3. Three distinct seismic-velocity layers in the 0- to 20-m-depth range below the surface were detected at all sites except where noted in table 3.

The *P*-wave seismic velocity (V_{p1}) of the near-surface layer ranges from 155 m/s to 338 m/s; the layer is only about 1- to 3-m thick. This layer probably represents the dry, aerated loose soil horizon at each site and 80% of the sites had a V_p less than the V_p of sound in air at sea level.

Layer 2 is immediately below layer 1 and had a V_p range of 623 m/s to 2459 m/s with a wide range of thickness. Sites with a V_{p2} of between 1500 m/s and 1675 m/s indicate the presence of an unconsolidated saturated material (sand, clay, and silt). At sites A, B, E, and F the base of layer 2 was not detected.

The V_{p3} at all sites is equal or larger than V_{p2} while the V_{p3} at sites C, D, E, G, and J was 2,500 m/s or greater suggesting the detection of bedrock at these sites. At site G, the refraction profile was located such that the line was perpendicular to the cliff face and started about 10 m from its base. In the cliff face, an indurated sandstone rock was exposed; we believe the 4,157 m/s V_{p3} at this site suggests detection of this sandstone in our refraction profile at about 14.5 m depth 50 m south from the base of the cliff. In table 3 a question mark following the thickness estimate means that the value is a minimum thickness for that layer and that the base of that layer was not detected. At sites A, B, H, and I, a material with a bedrock velocity was not detected.

The *S*-wave velocity (V_s) of layer 1 ranged from an extremely slow 76 m/s and 91 m/s at sites F and G respectively to 198 m/s at site A. At site G, this extremely low V_s was maintained for a depth interval of almost 4 m. These two sites, plus site B, which are located in the San Lorenzo River flood plain (B, F, and G), show that the V_s does not increase much in the 15 m depth range targeted in these profiles. At site F layer 2 is about 7.3 m thick and has a velocity of 111 m/s with an increase to 168 m/s for layer 3. The *S*-wave data recorded at sites located outside of the San Lorenzo flood plain show an increase in V_s at much shallower depths than the flood-plain sites, and eventually reach velocities (above 600 m/s) which were not detected at the flood-plain sites. Site G show a V_s of 497 m/s, but because this site was located near the cliff close to the high-velocity sandstone, the higher V_s is not surprising.

Chimney Study

The general distribution of the chimney damage may indicate a microzonation of damage/or ground motion. Approximately 3,890 homes were visually inspected. Of the homes inspected, 1,356 had chimneys with no apparent visual outside damage and 594 had chimneys that were severely damaged. The homes on the marine-terrace deposits in the northwest part of the town seem to have more chimney damage than the homes located on similar geology in the southern and eastern part of the city fig. 4).

REFERENCES

Carver, D.L., Cunningham, D.R and King, K.W., 1986, Calibration and acceptance testing of the DR-200 digital seismograph: U.S.Geological Survey Open-File Report 86-430, 28 p.

Cranswick, E., King, K.W. and Banfill, R., 1989, A program to perform time and frequency domain analysis of vector timeseries' recorded by portable autonomous digital seismographs: U.S. Geological Survey Open-File Report 89-172, 62 p.

Table 1 Station Locations

CODE	ADDRESS	LATITUDE (N)	LONGITUDE (W)	ELE ft	GEOLOGY
ALM	407 Almar Ave	36.9549	-122.0421	41	Qm
BAR	Glenn Coolidge Dr	36.9811	-122.0530	370	m
BAS	313 Barson St	36.9710	-122.0180	15	Qal
BES	126 Plymouth St	36.9864	-122.0209	40	Qal
BLA	223 Blackburn St	36.9679	-122.0303	21	Qal
CBL	738 Cable St	36.9702	-121.9944	40	Qm
CE2	121 Cedar St	36.9682	-122.0250	10	Qal
CED	205 Cedar St	36.9687	-122.0250	10	Qal
CEN	809 Center St	36.9744	-122.0281	18	Qal
DIC	224 Dickens Wy	36.9798	-122.0482	365	Qm
EFF	126 Effey St	36.9760	-122.0086	63	Qm
ESC	110 Escalona Dr	36.9770	-122.0323	100	Qm
EST	621 Highland Av	36.9796	-122.0377	260	Qm
GIL	116 Gilbert Ct	36.9902	-122.0079	172	Qm
HIG	548 Highland Av	36.9800	-122.0364	258	Qm
HIL	139 Hillcrest Ter	36.9796	-122.0323	245	Tp
HLU	1504 Laurent St	36.9800	-122.0418	270	Qm
HOL	125 Hollywood Av	36.9747	-122.0367	95	Qm
KAL	112 Kalkar Dr	36.9788	-122.0435	260	Qm
KEY	215 Keystone	36.9855	-122.0096	92	Qm
KIN	1722 King St	36.9639	-122.0461	85	Qm
LAU	Se corner Laurel & Front St	36.9693	-122.0220	8	Qal
LAV	105-111 Barson St	36.9705	-122.0205	8	Qal
LOE	U.C. Santa Cruz	36.0005	-122.0561	800	sch
MAI	315 Main St	36.9660	-122.0213	45	Qm
MAY	225 May Av	36.9778	-122.0179	22	Qal
MON	137 Monterey St	36.9575	-122.0263	42	Qm
NOB	340 Nobel Dr	36.9705	-122.0515	240	Qm
NPA	2117 N Pacific Av	36.9797	-122.0262	12	Qal
PAC	Pacific & Soquel	36.9734	-122.0247	10	Qal
ROS	721 Highland Av	36.9793	-122.0399	265	Qm
SBR	239 Branciforte Av	36.9719	-122.0126	60	Qm
SHE	122 Sherman St	36.9722	-122.0388	90	Qm
TRE	154 Trescony St	36.9659	-122.0361	65	Qm
WAL	116 Walti St	36.9680	-122.0322	25	Qal
WAS	333 Washington St	36.9683	-122.0273	18	Qal

Table 1. Santa Cruz seismic station locations and surface geology. Qal = Alluvium. Holocene, unconsolidated gravel, sand and silt. Qm = Marine Terrace Deposit, Pleistocene, unconsolidated moderate fine sand and granular grave. Tp = Purisima Formation. Upper Miocene to Pliocene, thick bedded tuffacious siltstone with interbeds of fine-grained andesite sandstone. sch = Metasedimentary rocks. Mesozoic or Paleozoic, mainly pelitic schists and quartzite. m = Marble. Mesozoic or Paleozoic, contains interbedded schist. Elevation in feet, 1 foot = 0.305 m. Coordinates reference to 1927 N.A. datum.

Table 2 Aftershocks documented

Fig.	UTC day-hr-min	LOCATION deg-min	deg-min	DEPTH km	SIZE coda	STATIONS RECORDED (code ref.table 1)
6	294-00-11	37-06.11	121-58.53	13.8	2.5	LOE,DIC,ESC,BES
7	294-00-49	37-02.01	121-52.38	11.9	4.1	LOE,DIC,ESC,BES
8	294-00-49	37-02.01	121-52.38	11.9	4.1	LOE,HAL,SAR,FRE,CO1
9	294-01-02	37-02.70	121-51.59	10.7	2.6	LOE,DIC,ESC,BES
10	294-08-32	37-06.49	122-00.37	13.4	2.7	LOE,DIC,ESC,BES
11	294-12-54	37-08.04	121-57.22	4.3	3.1	LOE,DIC,ESC,BES,FRE,CO1
12	294-22-14	37-02.96	121-53.65	13.0	4.4	KAL,HOL,PAC,CED,HAL,SAR,CO1,FRE
13	295-00-31	37-03.35	121-54.43	12.3	2.5	KAL,HOL,PAC,CED
14	295-14-24	36-58.73	121-49.57	15.6	3.7	KAL,HOL,PAC,CED
15	295-14-24	36-58.73	121-49.57	15.6	3.7	KAL,SAR,HAL,FRE,CO1
16	296-21-27	37-06.75	121-55.98	8.2	3.0	LOE,LO2,KIN,SHE,PAC
17	297-04-48	37-02.47	121-48.94	4.8	3.2	LOE,LO2,SHE,KIN,PAC,CED
18	297-07-02	37-10.03	121-57.92	5.7	2.8	LOE,LO2,SHE,KIN,PAC,CED
19	297-08-56	37-10.39	121-58.07	5.7	2.5	LOE,LO2,SHE,KIN,PAC,CED
20	297-14-45	37-04.37	121-54.97	12.6	2.3	LOE,LO2,SHE,KIN,PAC,CED
21	297-22-26	37-10.38	121-58.17	4.3	2.5	LOE,SHE,KIN,CED,BAS
22	298-01-27	37-03.77	121-50.18	10.0	4.2	BAR,KAL,SHE,KIN,ALM
23	299-09-01	37-02.12	121-53.71	11.4	3.6	LOE,BAR,KAL,ALM,MON,MAI,BAS
24	299-12-18	37-03.14	121-52.58	11.1	(2.2 as No. 20)	
25	299-12-18	37-03.14	121-52.58	11.1	(2.2 as No. 22)	
26	299-13-26	37-02.74	121-54.84	15.2	(2.4 as No. 21+EFF)	
27	302-13-10	37-02.62	121-55.25	14.3	2.9	BAR,KAL,TRE,WAL,BLA,WAS, CE2,LAU,LAV,BAS,SBR
28	302-13-10	(as No. 23, vertical component only)				
29	302-13-10	(as No. 23, horizontal-EW component only)				
30	302-13-10	(as No. 23, horizontal-EW component only)				
31	302-20-44	37-03.51	121-54.09	13.8	2.2	BAR,KAL,TRE,WAL,BLA,CE2,LAV,BAS
32	302-21-55	37-04.41	121-54.31	10.2	2.9	(as No. 27+LAU)
33	303-04-52	37-03.27	121-54.22	14.5	2.5	(as No. 28+SBR)
34	303-06-31	36-55.03	121-41.90	11.7	2.9	(as No. 29)
35	303-11-17	37-03.11	121-49.40	9.9	3.6	(as No. 29)
36	304-06-50	37-07.58	121-59.85	12.2	2.2	(as No. 29)
37	304-08-34	37-03.70	121-48.62	8.4	3.4	(as No. 29)
38	306-05-12	37-03.70	121-48.09	7.8	2.5	BAR,GIL,MAY,CBL,KEY,HIL,NOB,NAP,CEN
39	306-10-11	37-03.77	121-55.53	13.4	2.3	CEN,GIL,HIL,MAY,NAP,CBL,KEY
40	307-10-48	36-55.27	121-44.25	10.1	3.1	BAR,KAL,HLU,ROS,HIL,NOB,CEN,MAY
41	308-00-20	37-06.33	122-04.15	11.8	2.0	(as No. 36)
42	308-07-16	37-46.35	122-22.22	7.1	2.2	KAL,EST,HIG,HIL,CEN,MAY,NOB

* day is in number of days in year; October 21 = 294

TABLE 3. Shallow seismic refraction results in Santa Cruz.

	P-wave data						*S*-wave data					
Site Code	V_{p1} m/s	H_{p1} m	V_{p2} m/s	H_{p2} m	V_{p3} m/s	H_{p3} m	V_{s1} m/s	H_{s1} m	V_{s2} m/s	H_{s2} m	V_{s3} m/s	H_{s3} m
A	338	1.8	1593	23?	----		198	2.7	378	3.7	628	>14?
B	229	3.8	1622	10?	1768	>60?	137	3.0?	?		?	
C	213	1.0	1524	5.8	2477	>10?	-----------------no s-wave data-----------					
D	320	2.0	953	5.2	3049	>10?	-----------------no s-wave data-----------					
E	204	1.8	2459	9?	3049	>10?	127	0.6	152	2.1	889	>12?
F	168	1.5	1631	70?			76	2.4	111	7.3	168	>11?
G	155	1.1	1290	13.4	4157	> 7?	91	3.7	137	8?	497	> 4?
H	169	0.6	623	1.2	1642	>15?	122	0.9	595	>15?		
I	381	1.8	726	0.9	1524	>14?	110	1.0	300	5.5	701	>10?
J	213	1.3	1673	3.5	2994	>15?	-----------------no s-wave data-----------					

Site Code	Location
A	Bay View Elem School
B	County Admin. Bldg
C	Garfield Park
D	Lighthouse Park
E	Mission Hill School
F	Neary Lagoon
G	Santa Cruz High School
H	Star of the Sea Park
I	Trescony Park
J	Westlake Park

Definition of terms use in above table

V_{p1} = *P*-wave velocity of layer at the surface.
H_{p1} = Thickness of layer with V_{p1}.
V_{p2} = *P*-wave velocity of layer below H_{p1}.
H_{p2} = Thickness of layer with V_{p2}.
V_{p3} = *P*-wave velocity of layer below H_{p2}.
H_{p3} = Thickness of layer with V_{p3}.

V_{s1} = *S*-wave velocity of layer at the surface.
H_{s1} = Thickness of layer with V_{s1}.
V_{s2} = *S*-wave velocity of layer below H_{s1}.
H_{s2} = Thickness of layer with V_{s2}.
V_{s3} = *S*-wave velocity of layer below H_{s2}.
H_{s3} = Thickness of layer with V_{s3}.

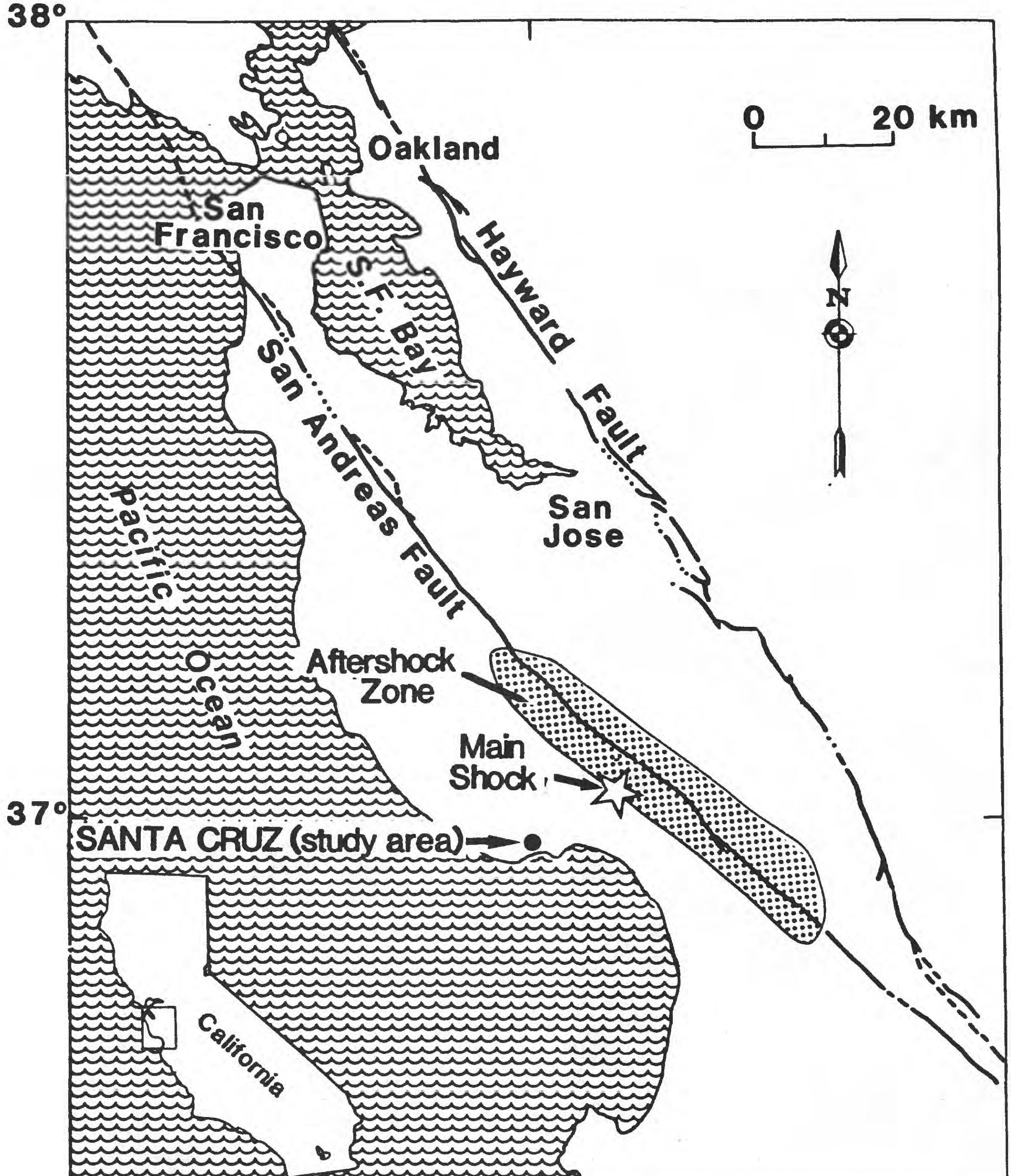

Figure 1.-- Location map showing Santa Cruz study area, main shock, and general outline of aftershock zone.

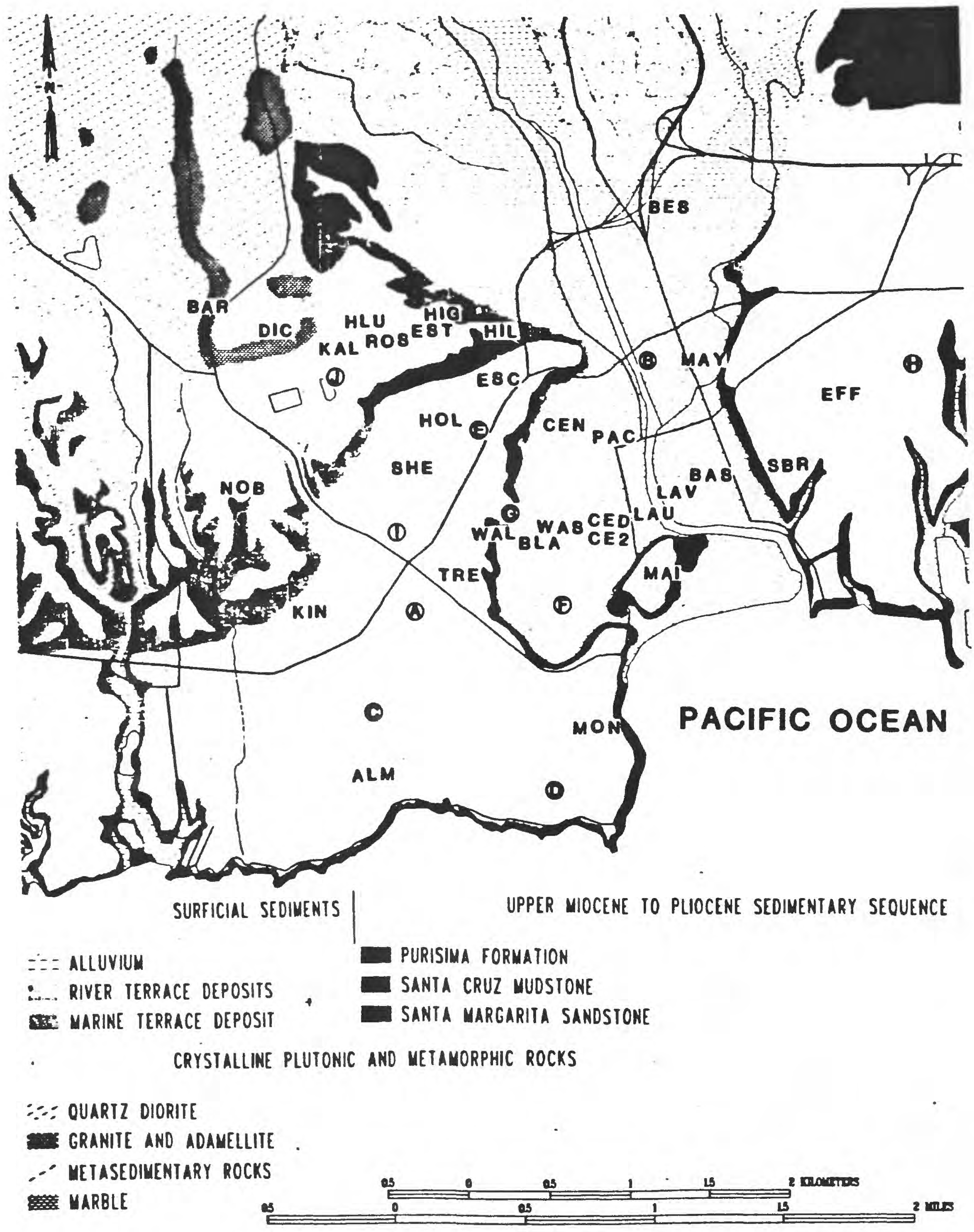

Figure 2.-- Surficial geologic map of the city of Santa Cruz showing primary geologic units, DR-200 recording stations (3 letter code), and seismic reflection/refraction recording sites (letters A-J).

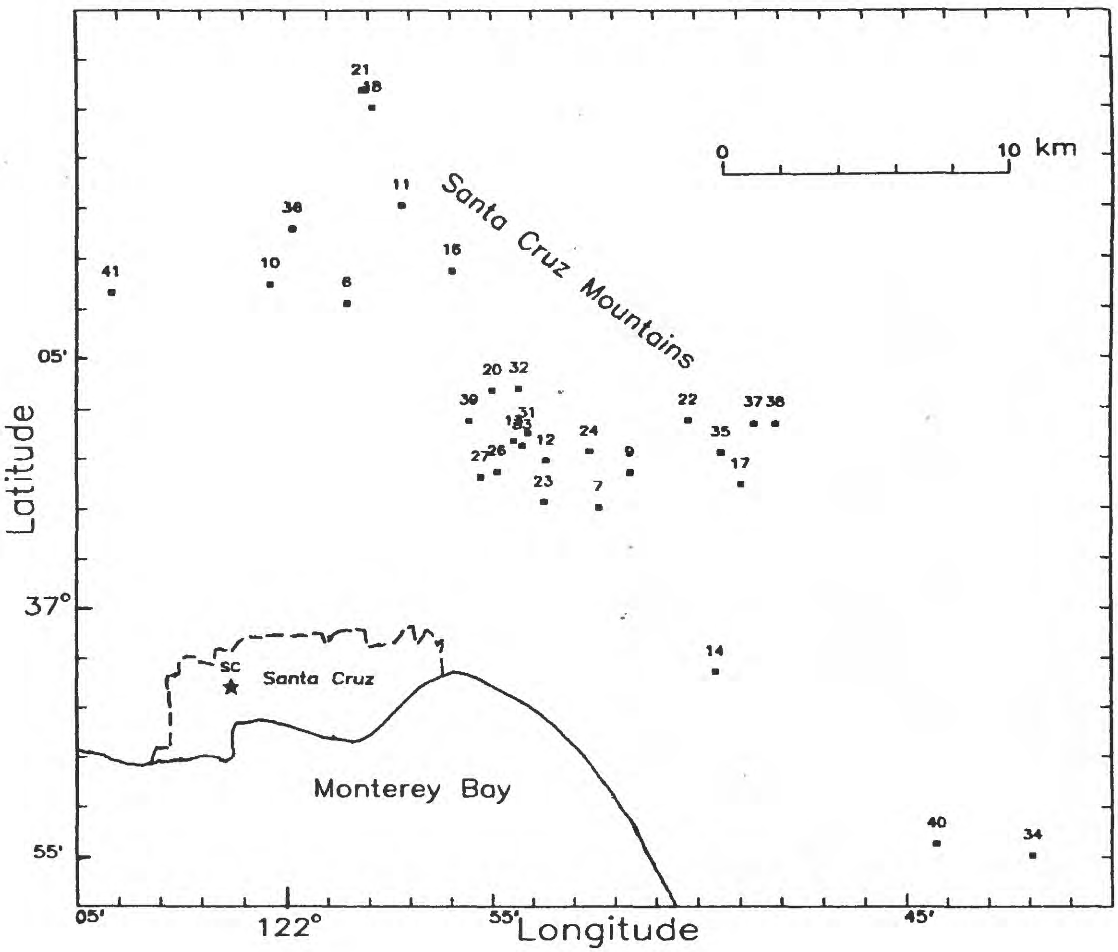

Figure 3.-- Epicentral locations (black squares) of earthquakes included in this report. The number above the square indicates the figure number which shows the seismograms for that aftershock (see table 2). Approximate epicentral distances described in figures 6-42 were measured from location SC in Santa Cruz. Earthquake locations for figure numbers 8,15,19 and 25 are not shown in this figure as they are essentially co-located with earthquakes 7,14,18 and 24, respectively. Earthquake 42 is located outside the boundary of this map on the Hayward fault.

Figure 4.-- Santa Cruz map showing surficial geology and spatial distribution of damaged chimneys. Numbers refer to number of damaged chimneys per city block. Geologic units as show on Fig.2.

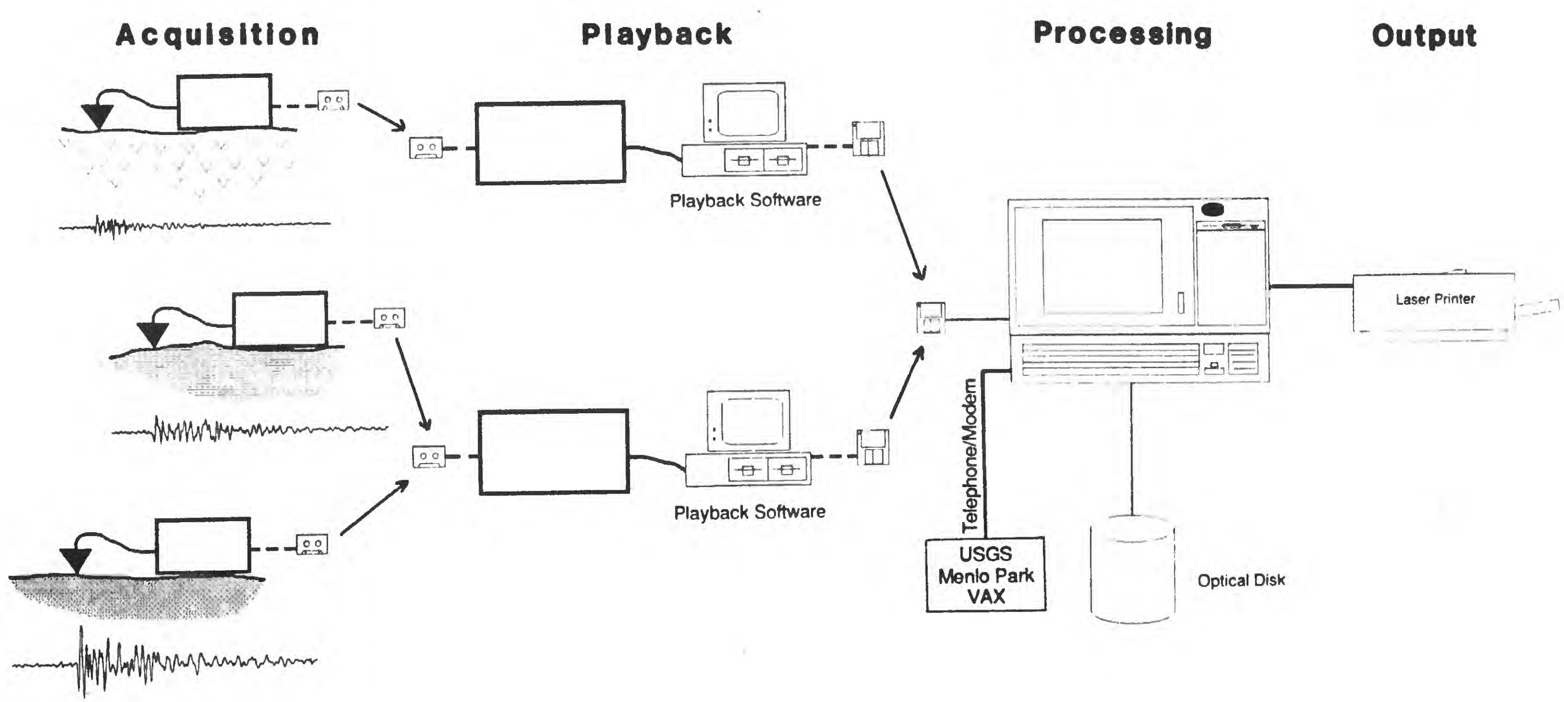

Figure 5.-- Block diagram of data flow from point of acquisition to hard copy output.

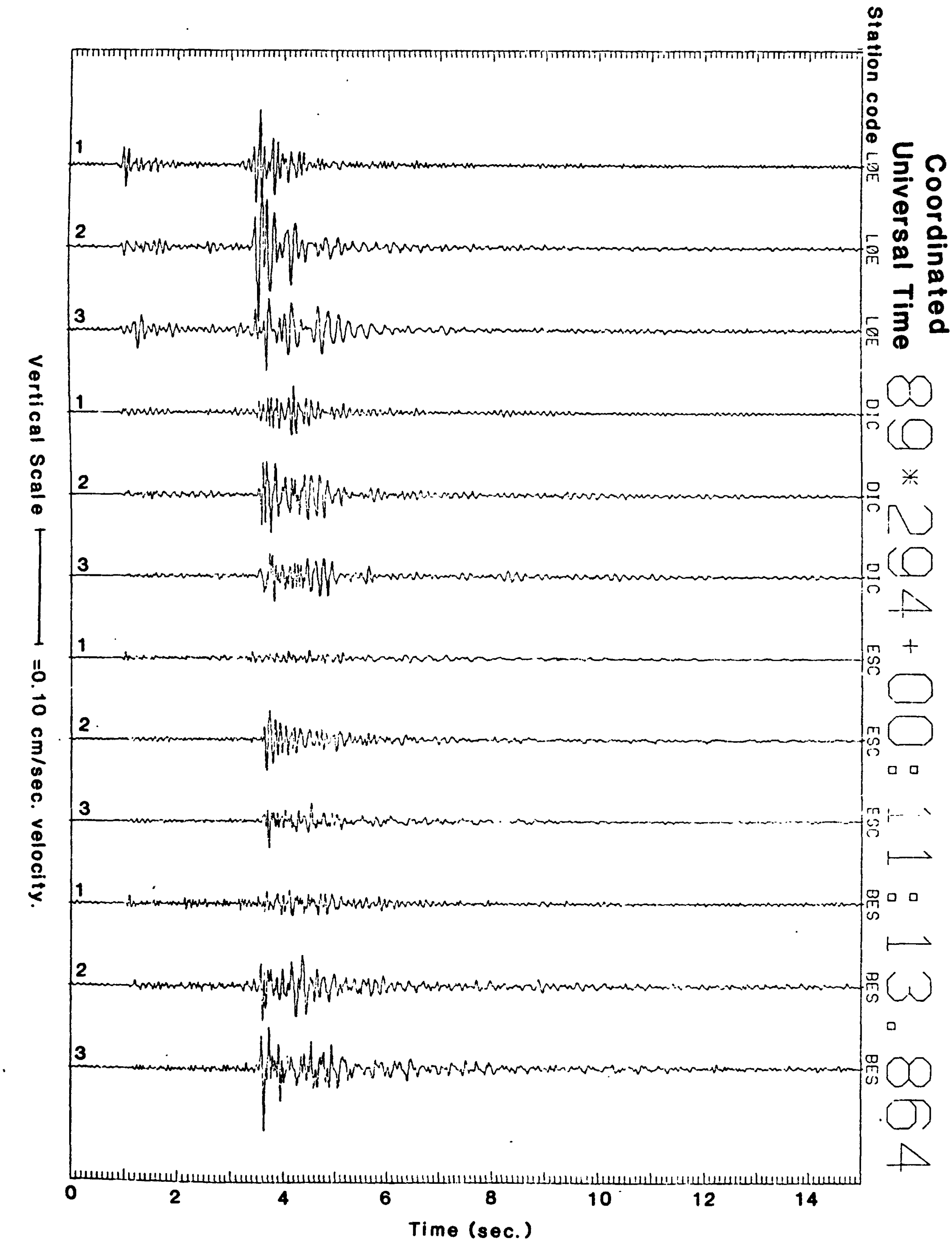

Figure 6.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 13 km North of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

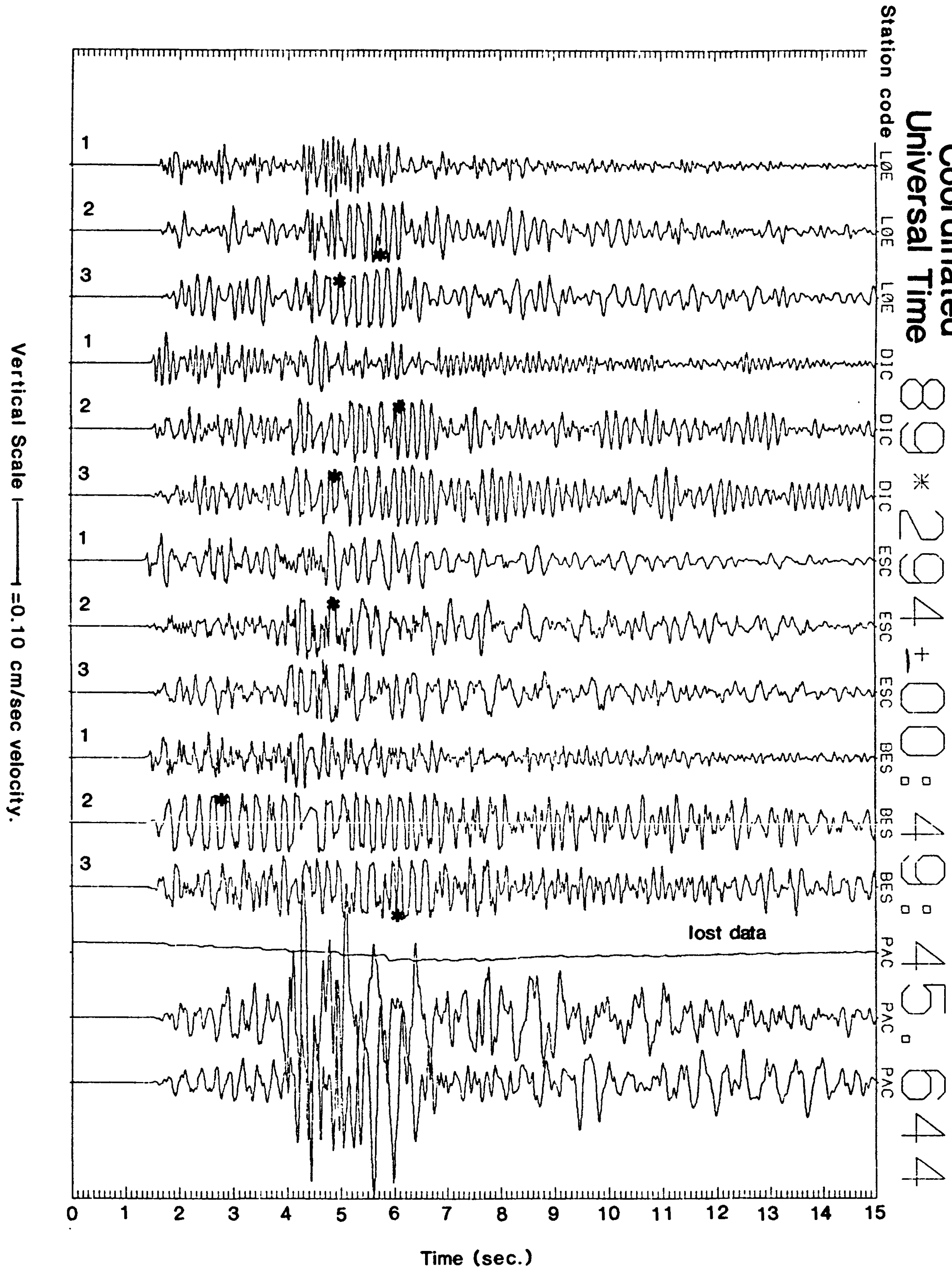

Figure 7.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

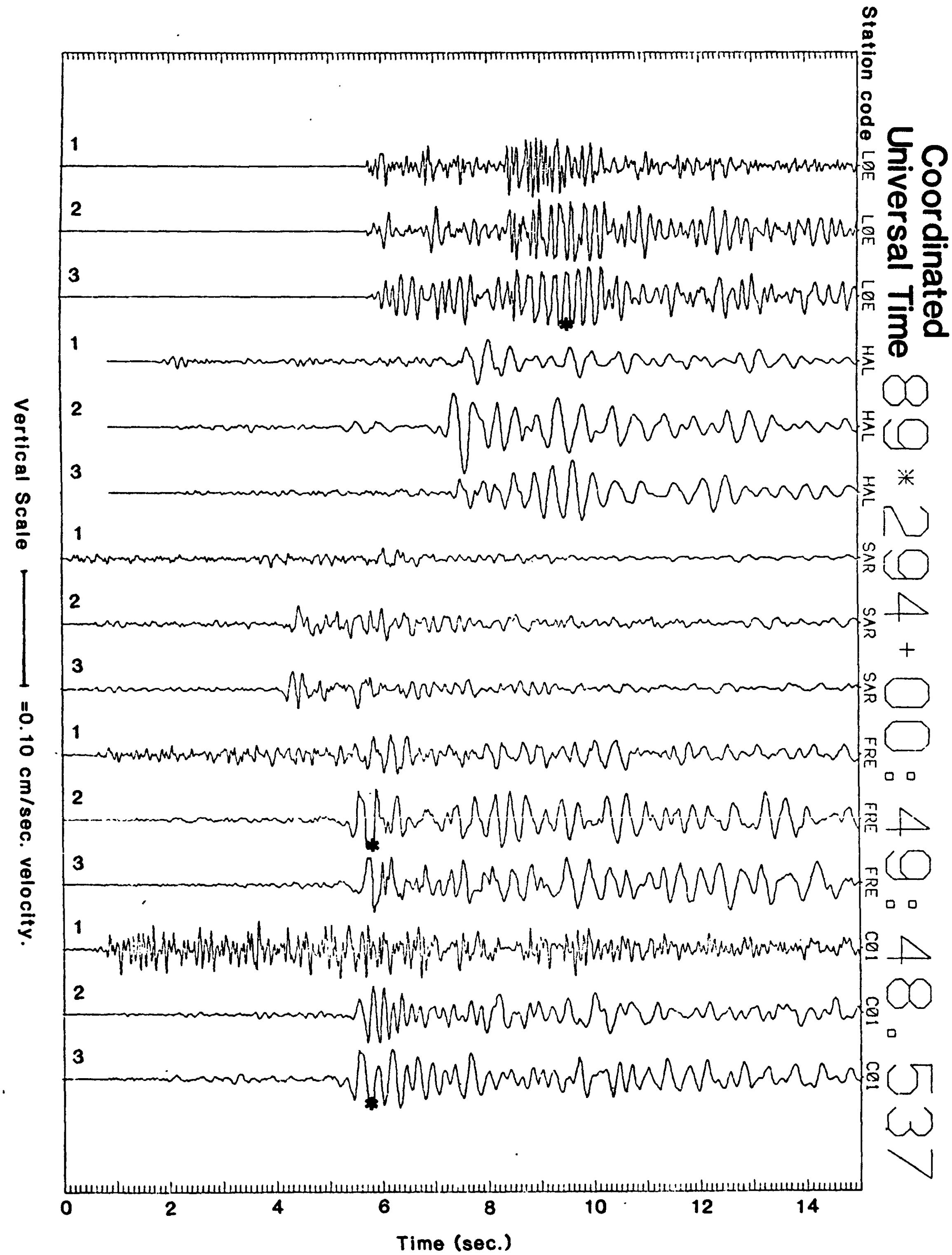

Figure 8.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Strong motion comparisons sites.

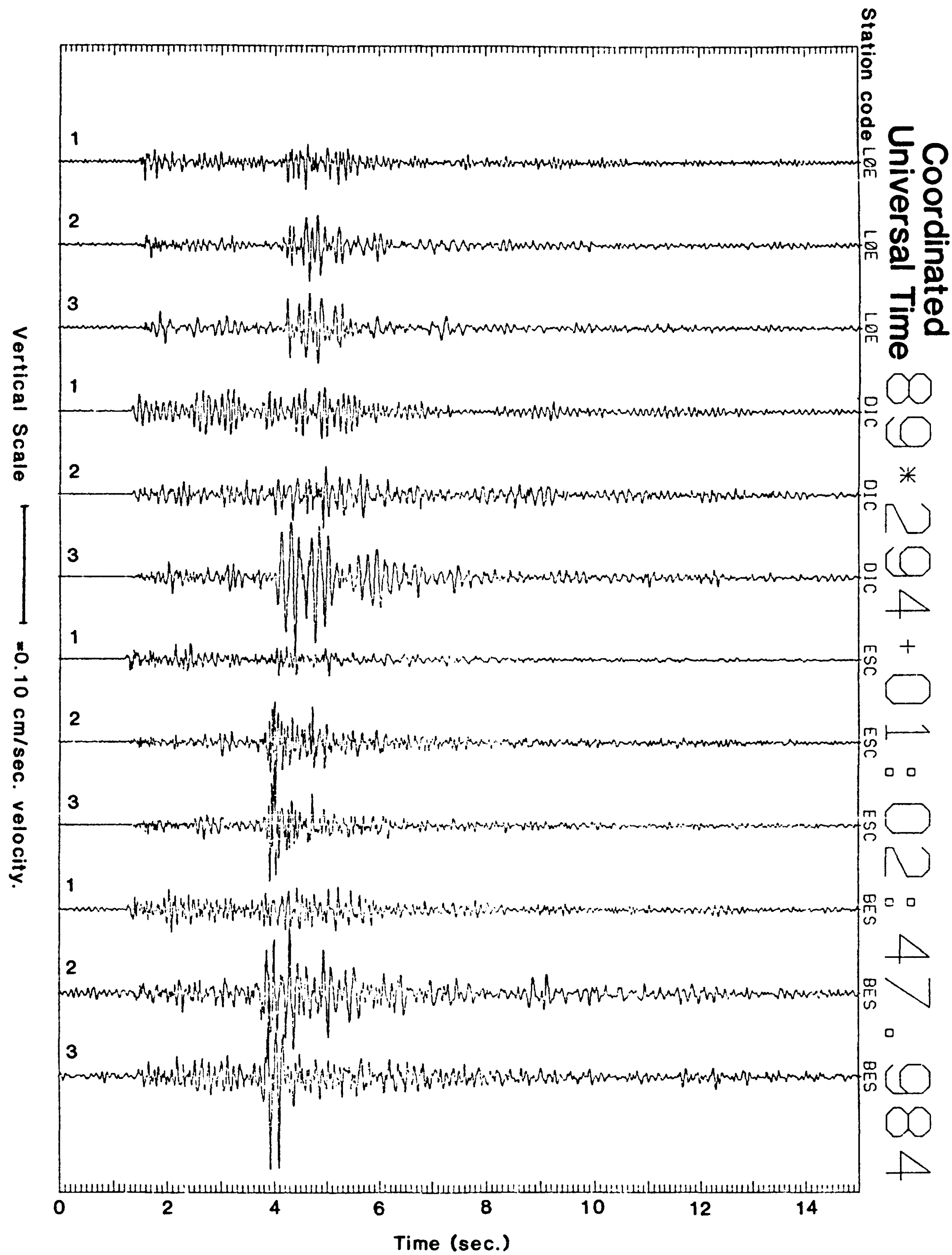

Figure 9.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

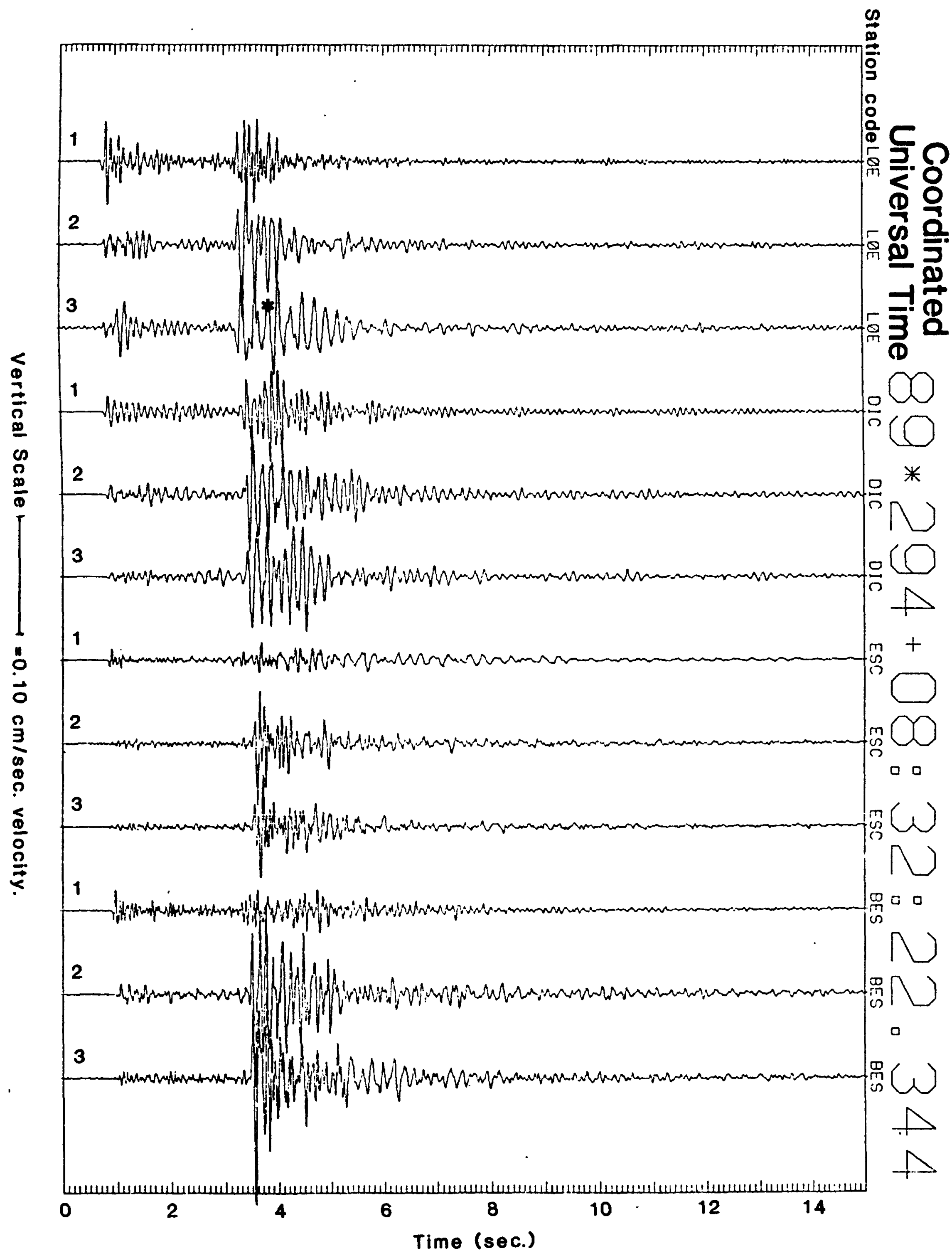

Figure 10.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km North of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

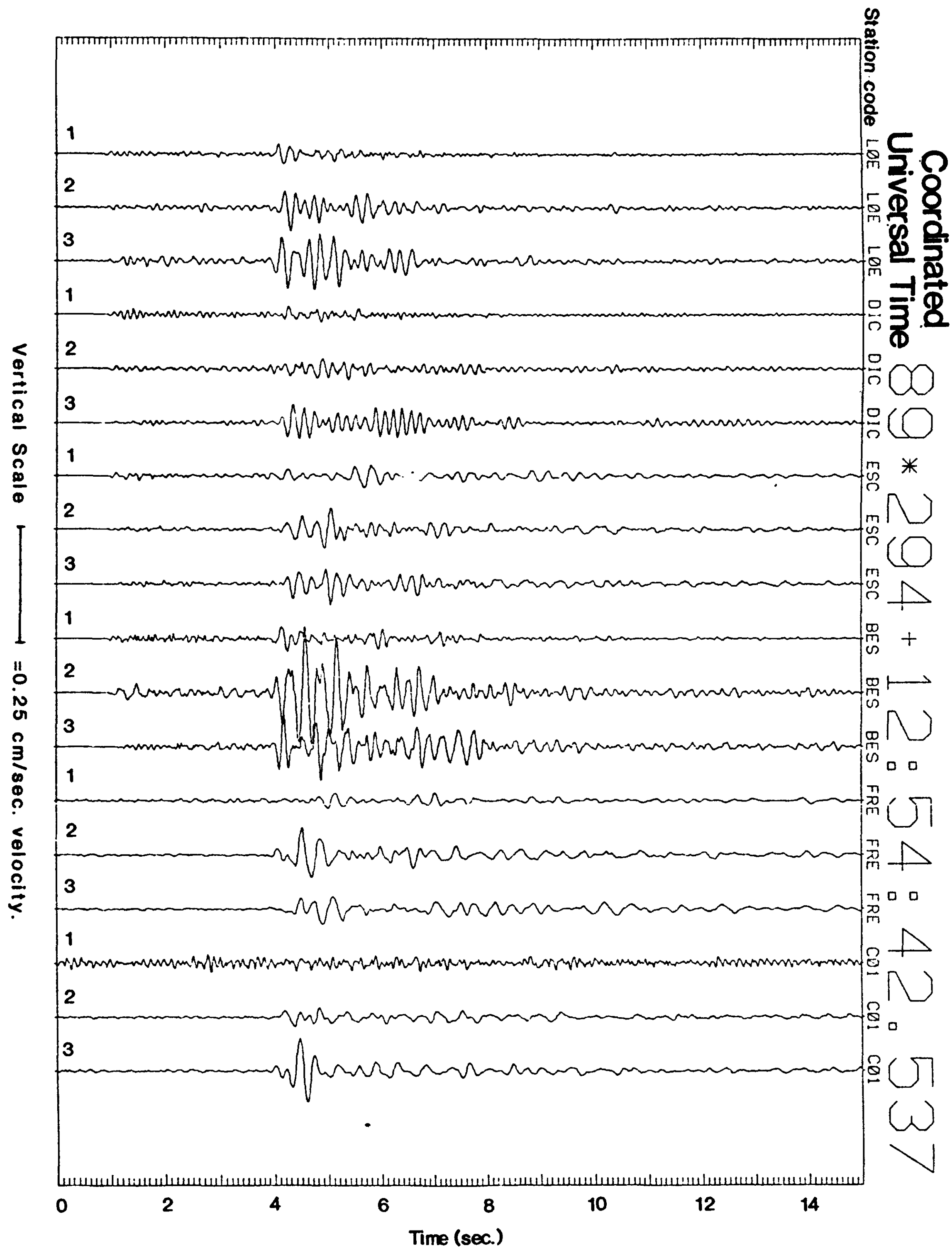

Figure 11.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 18 km North of central Santa Cruz. Sites in areas of low to high damage in Santa Cruz and at the Moss Landing thermal electric plant.

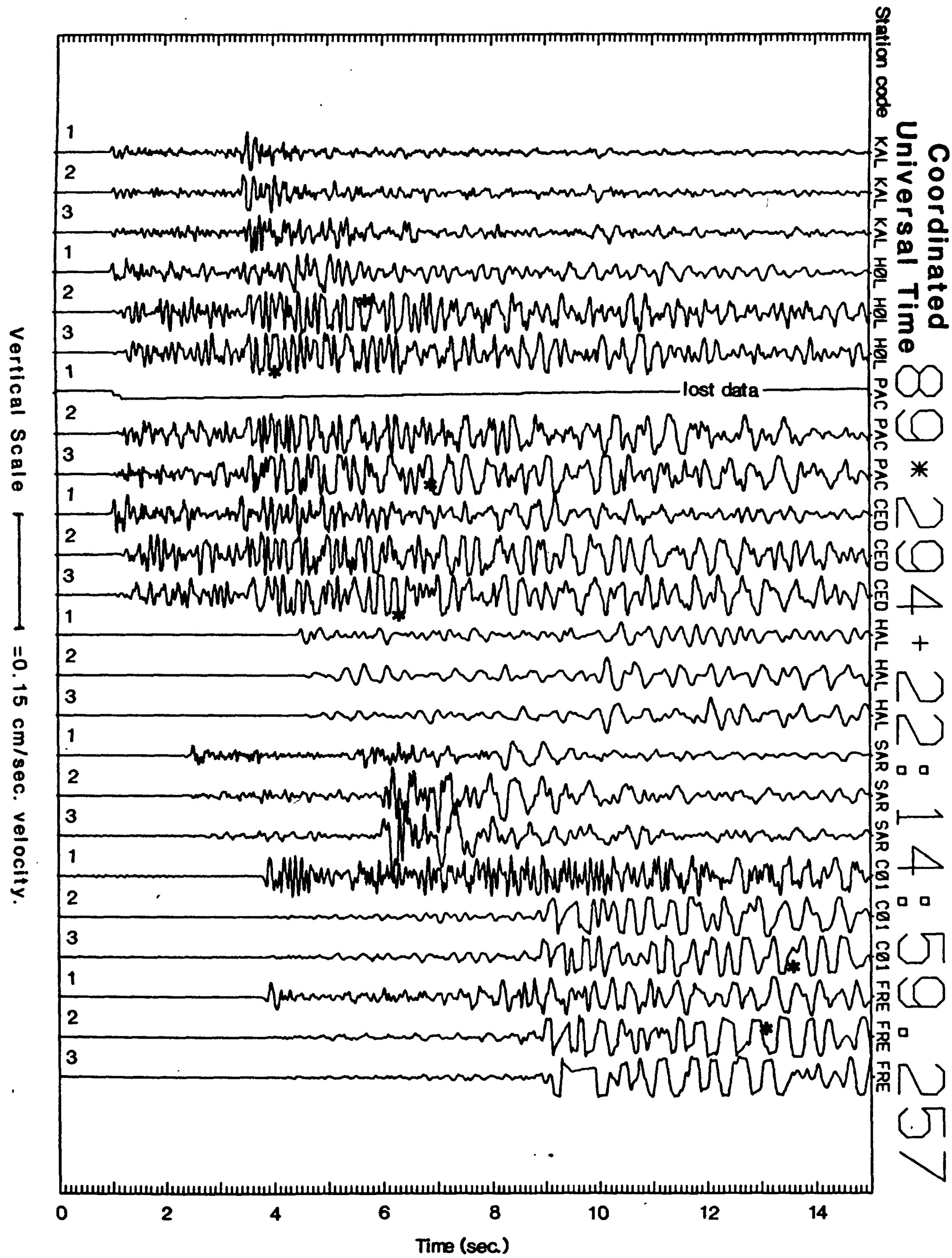

Figure 12.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

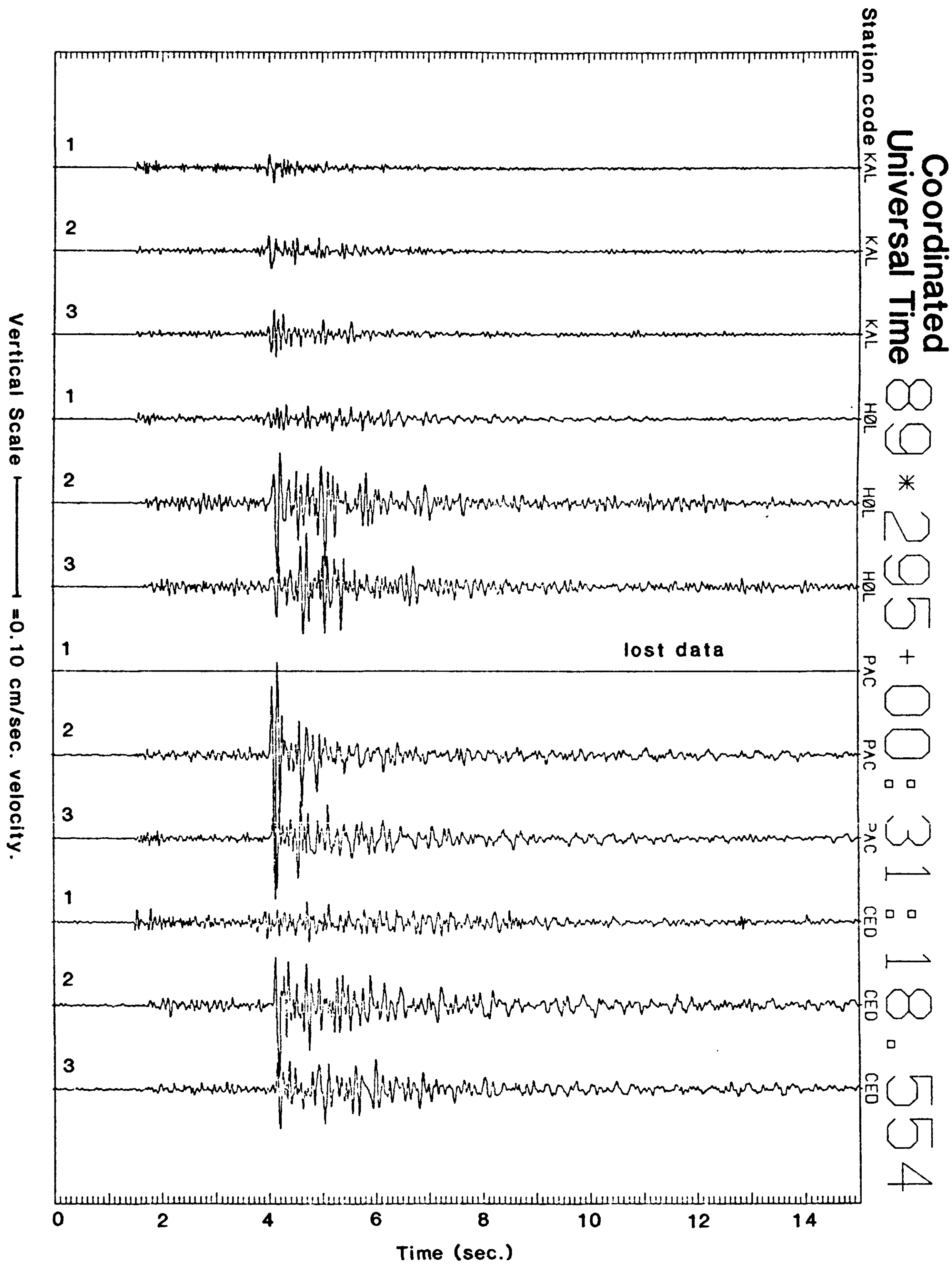

Figure 13.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

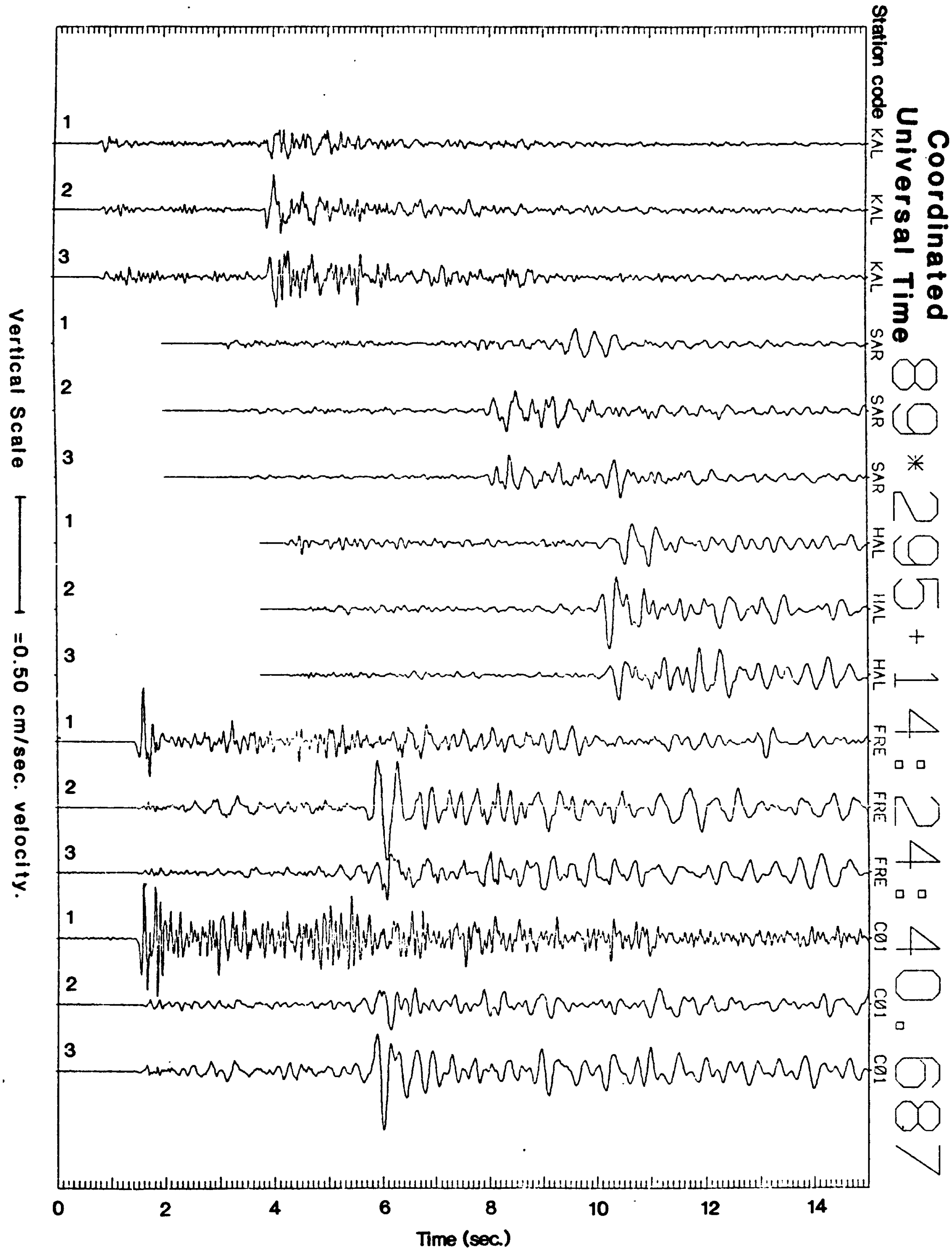

Figure 14.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 17 km East of central Santa Cruz. Sites in areas of strong motion instruments that recorded the Loma Prieta earthquake.

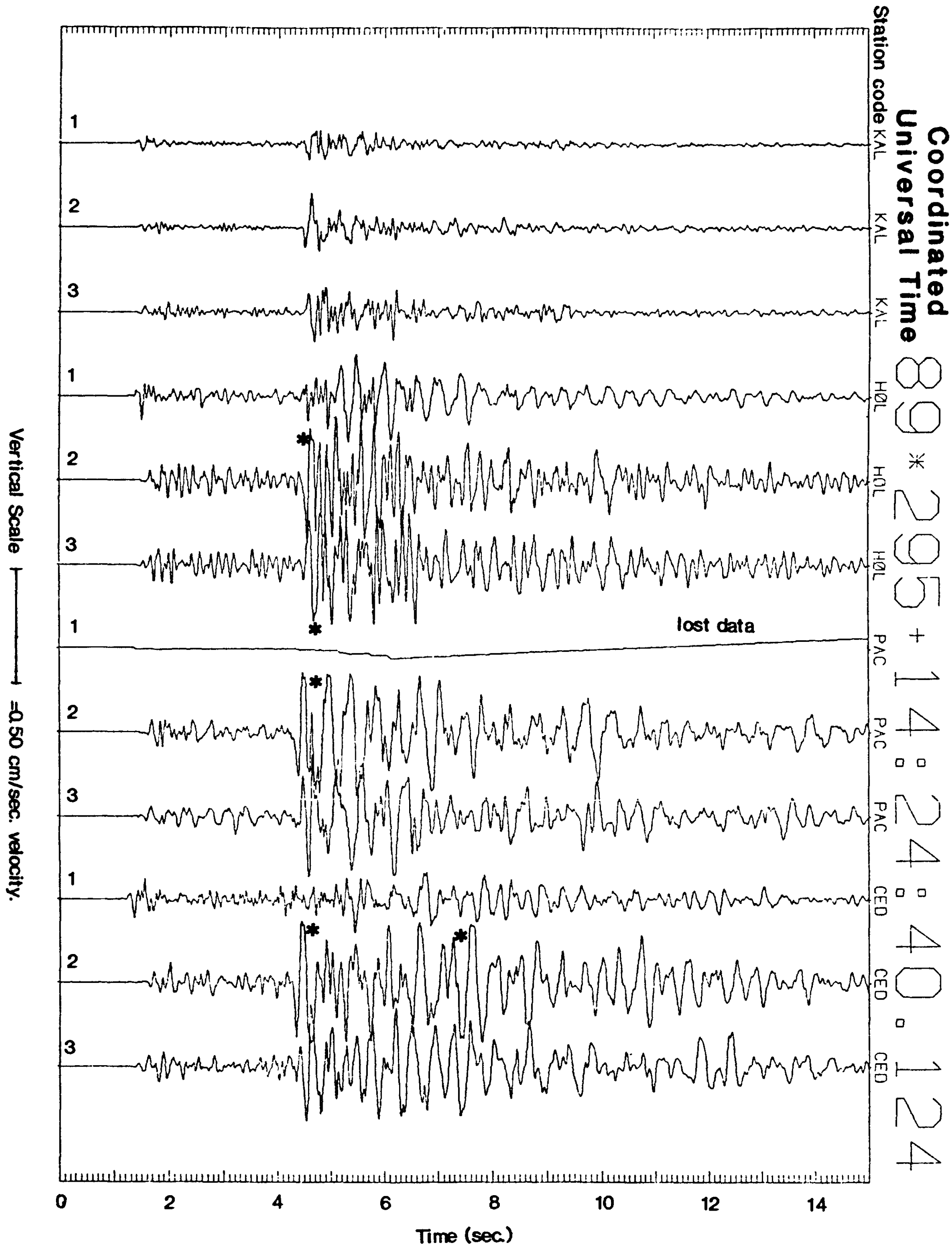

Figure 15.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 17 km East of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

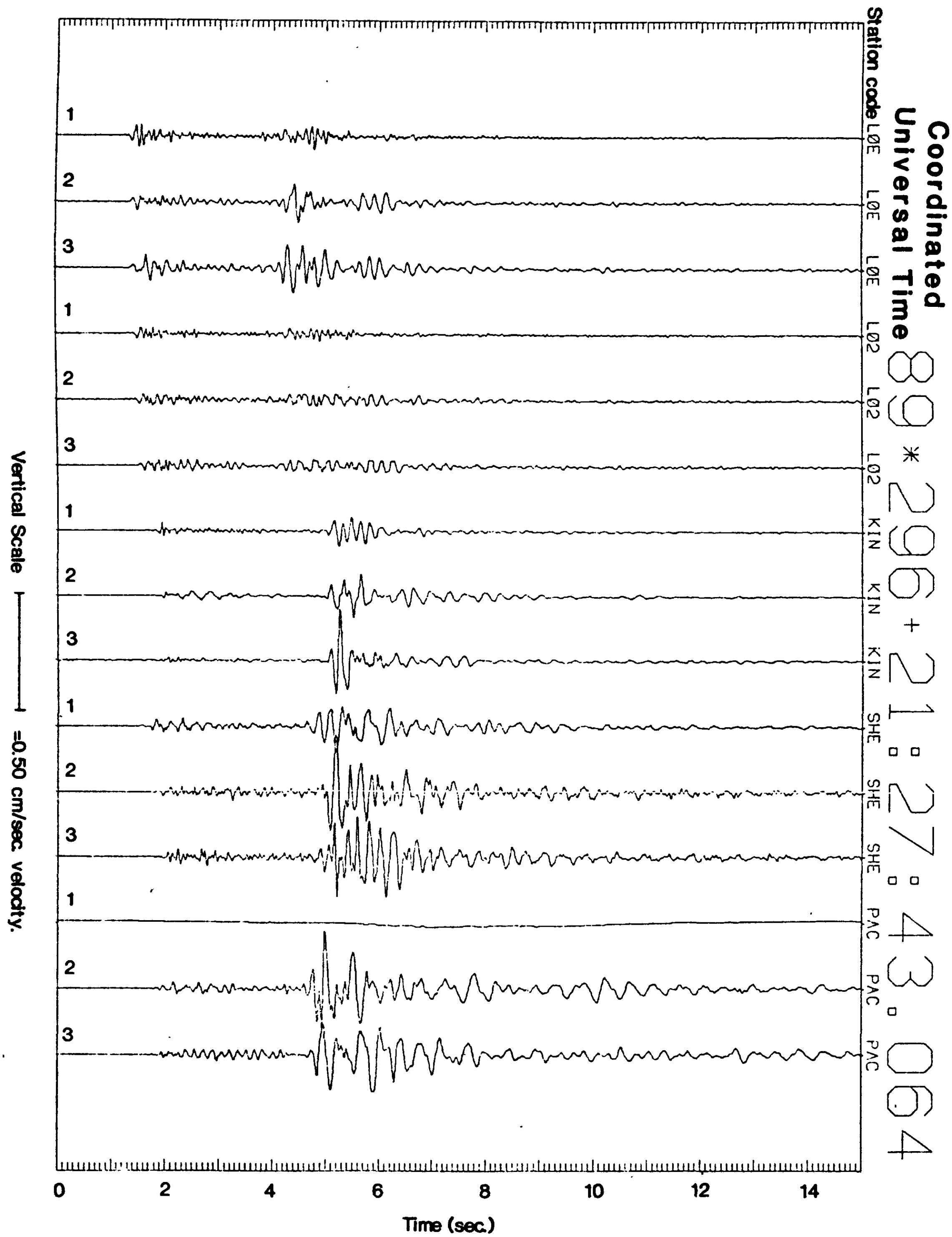

Figure 16.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 17 km North of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

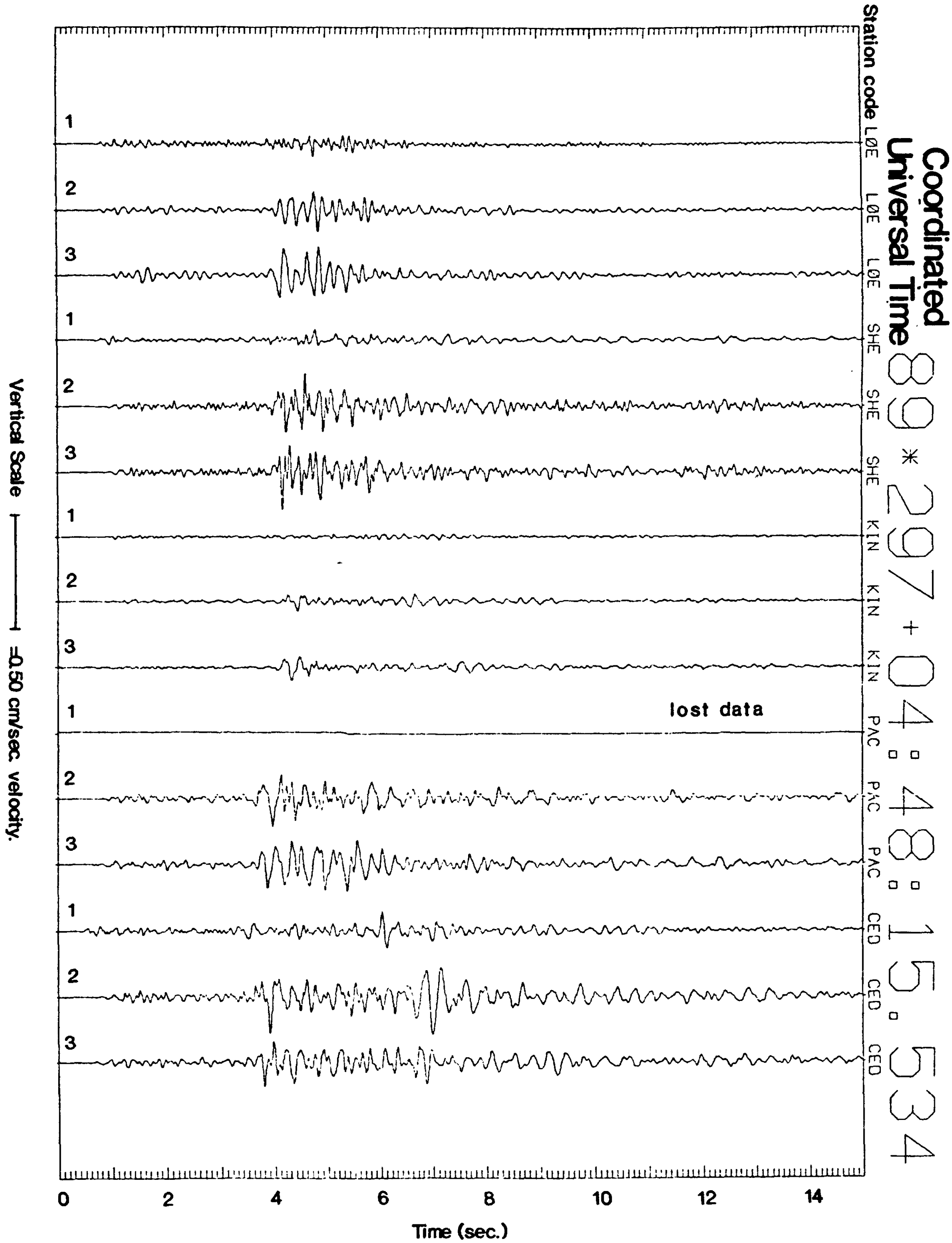

Figure 17.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 20 km Northeast of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

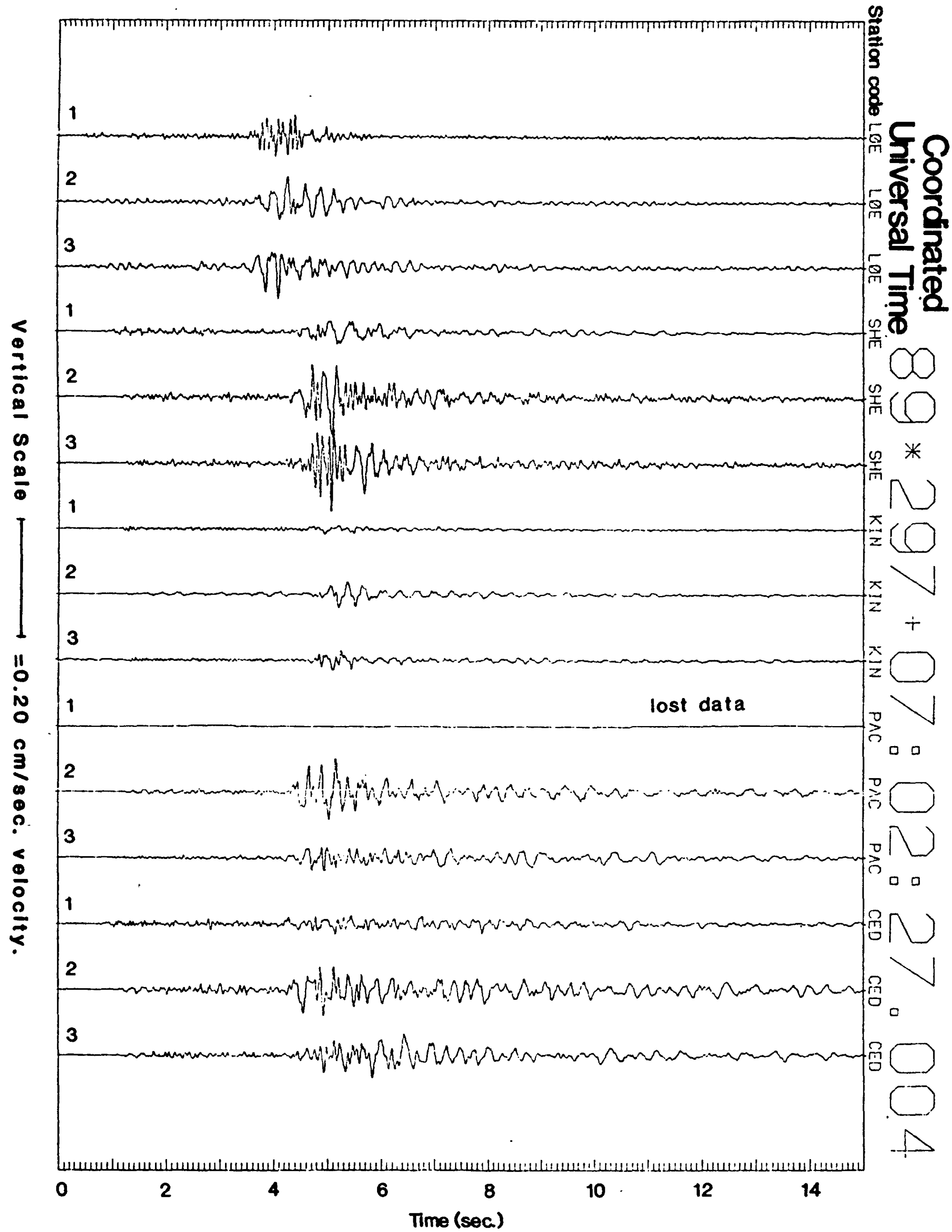

Figure 18.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 21 km North of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

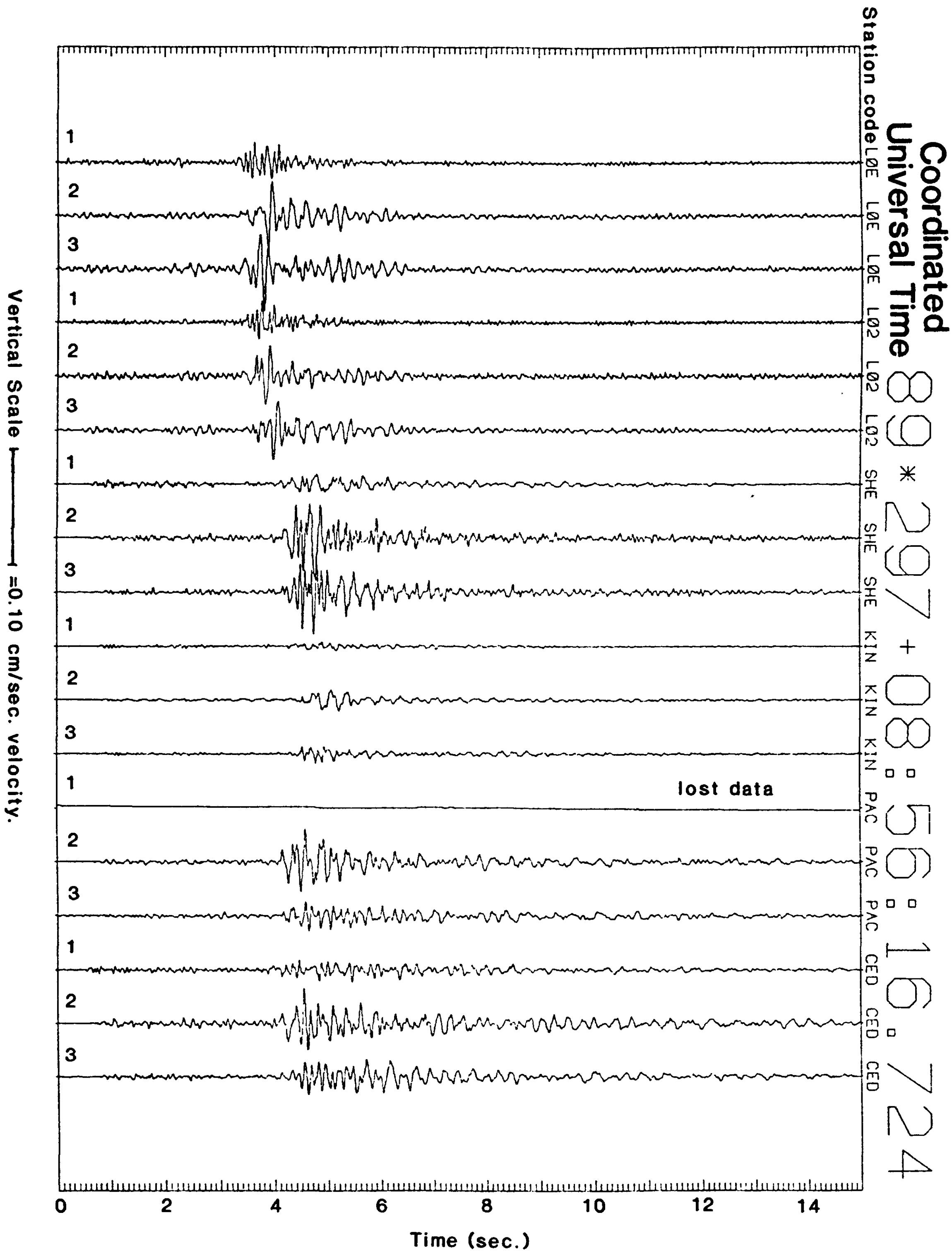

Figure 19.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 21 km North of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

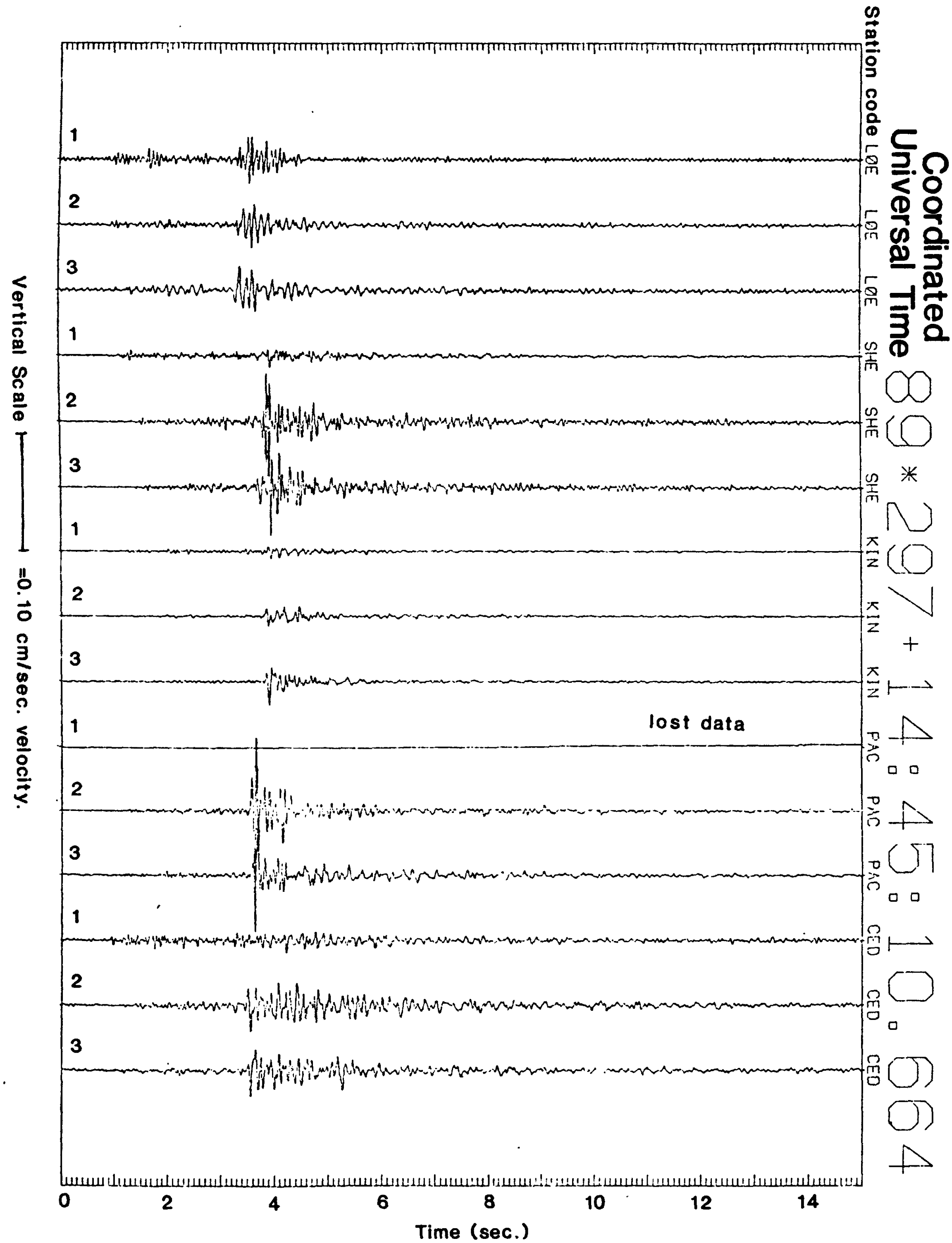

Figure 20.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km Northeast of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

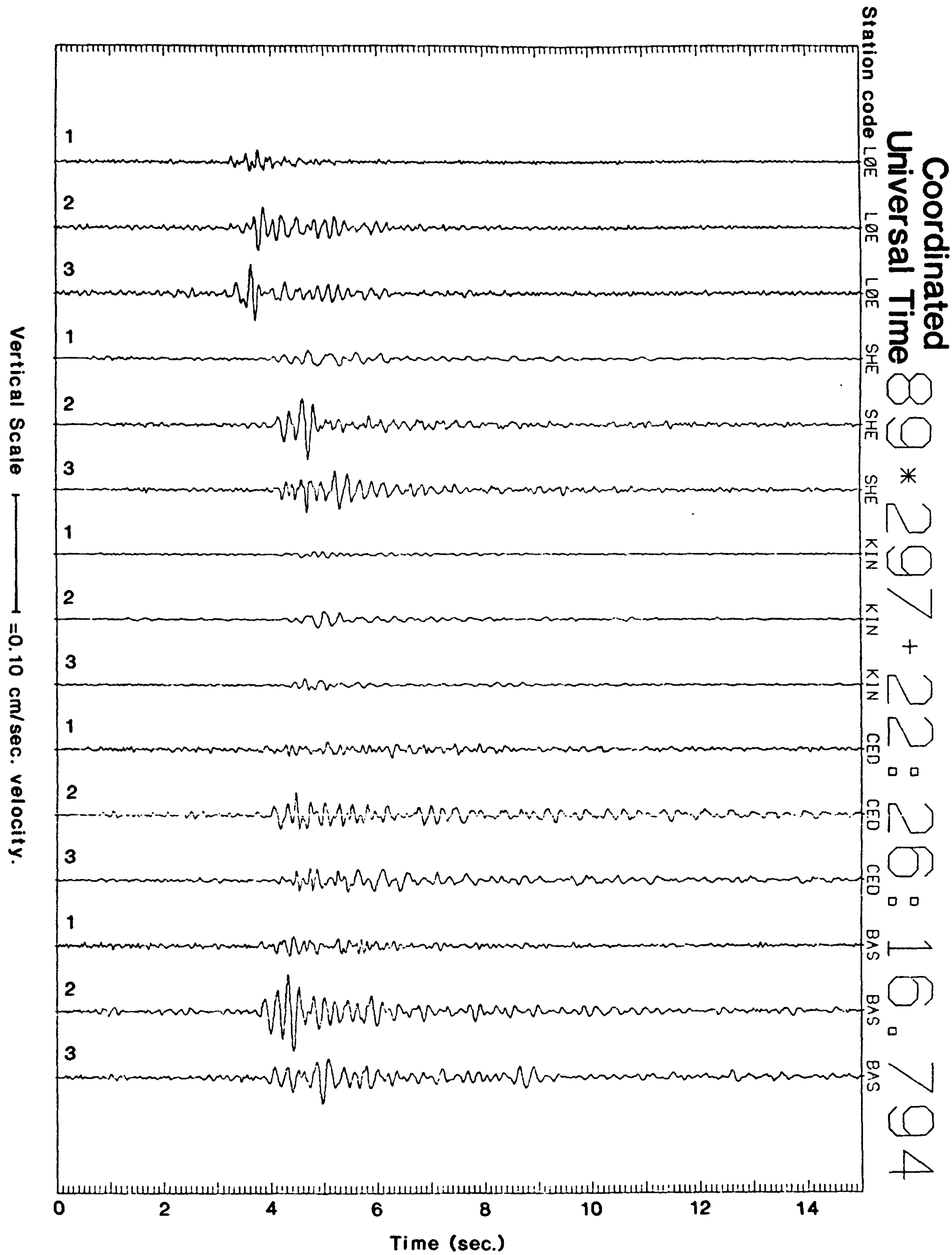

Figure 21.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 21 km North of central Santa Cruz. Sites in areas of low to high damage from the Loma Prieta earthquake.

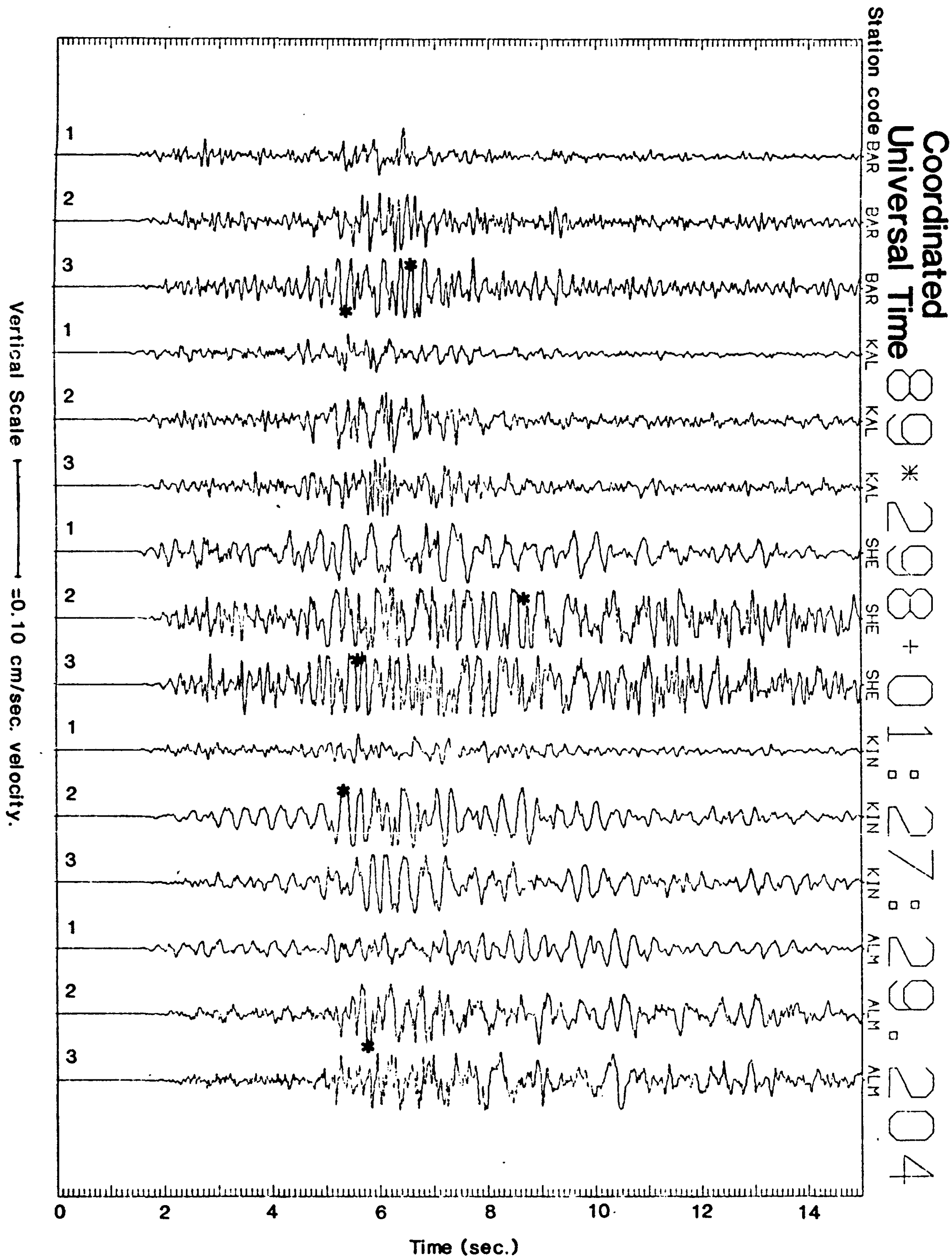

Figure 22.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 18 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

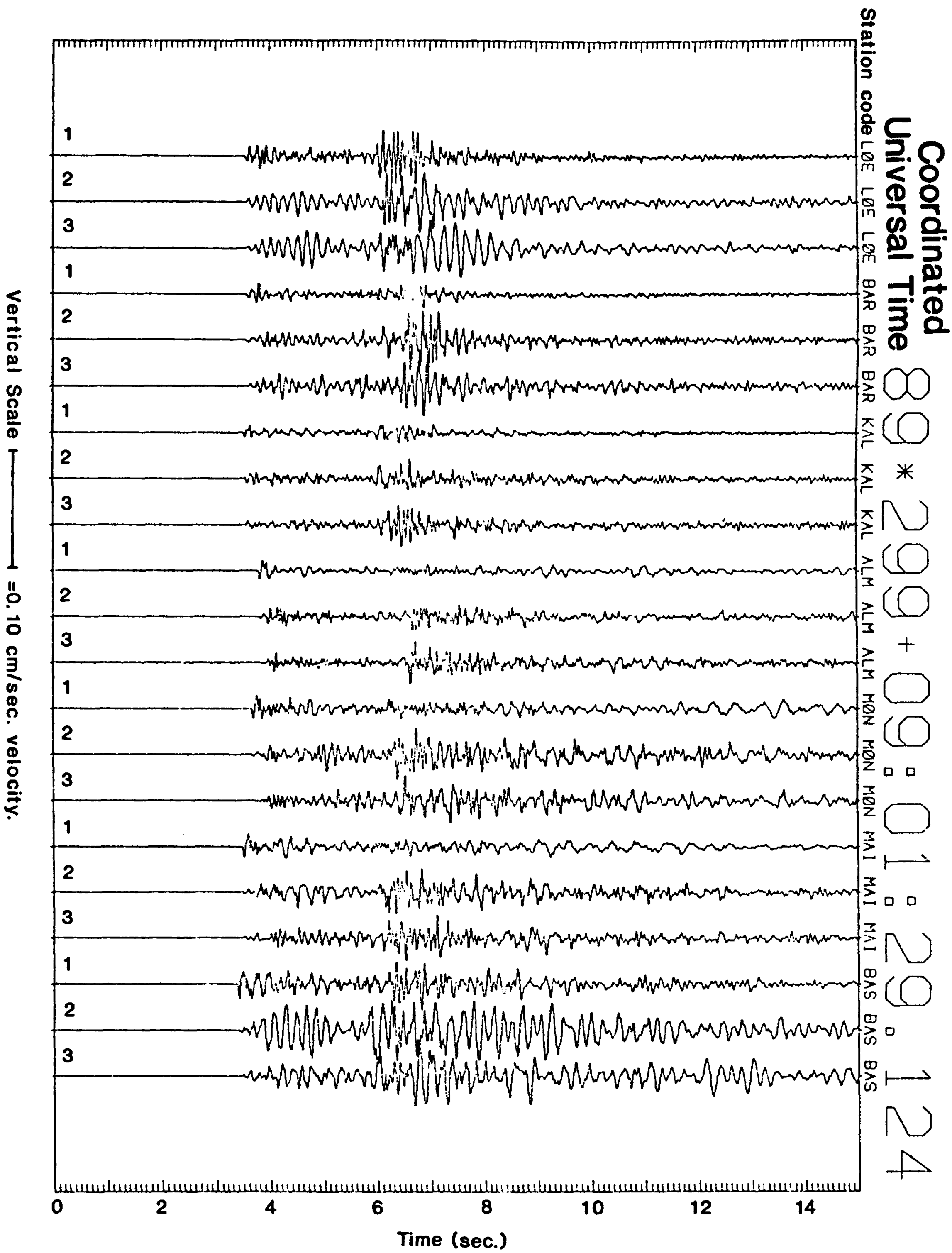

Figure 23.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 12 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

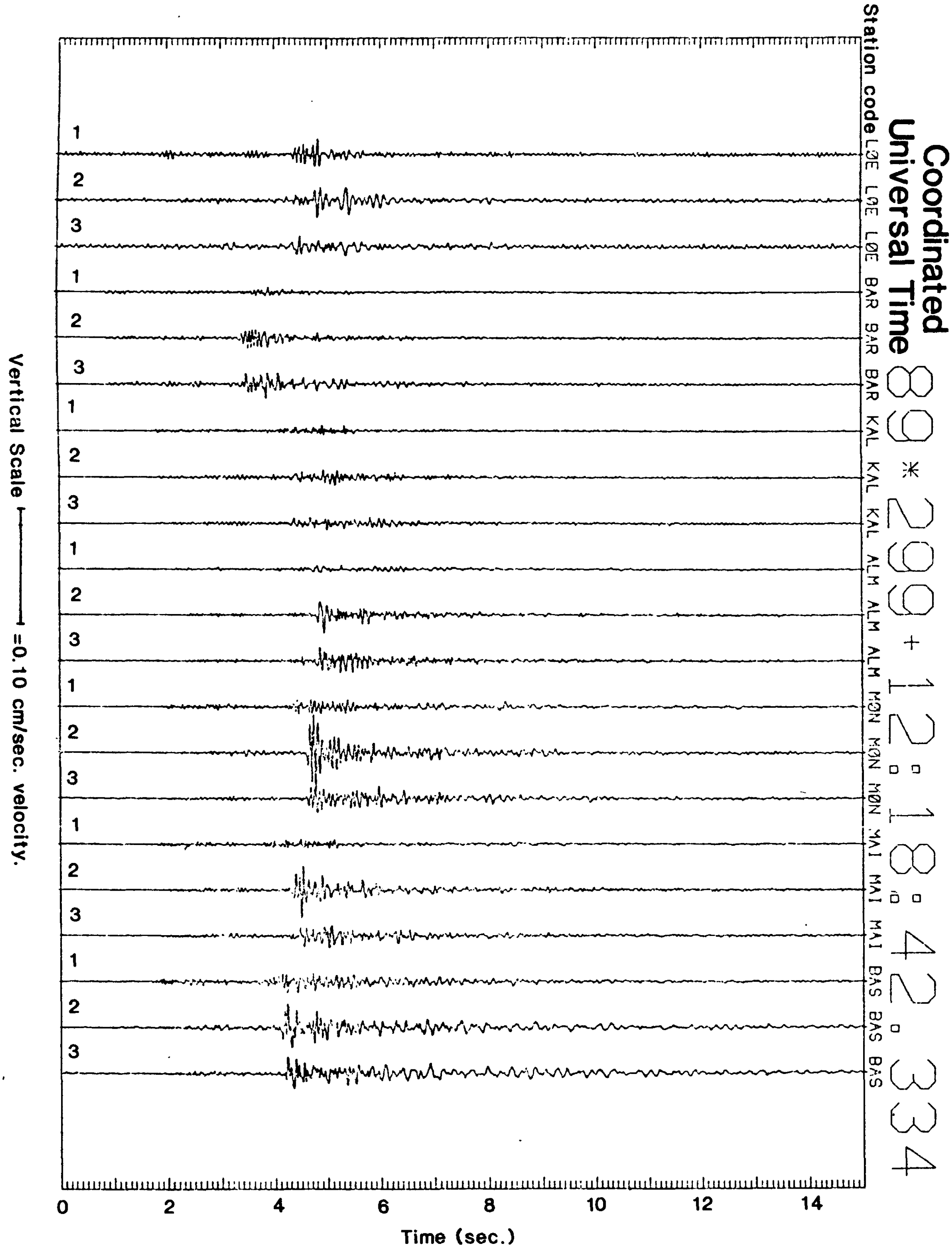

Figure 24.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake. Gain comparison with Figure 25.

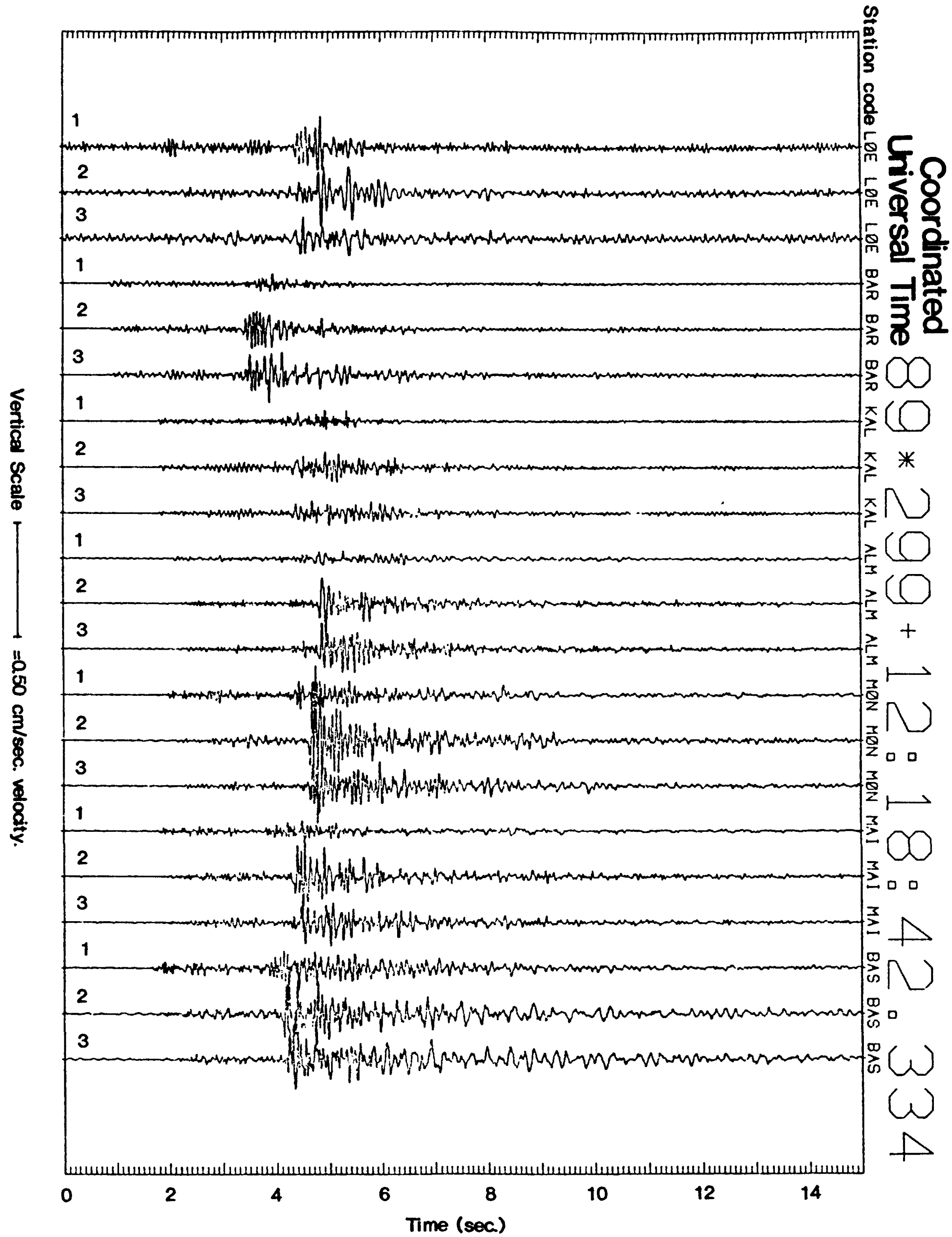

Figure 25.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake. Gain comparison with Figure 24.

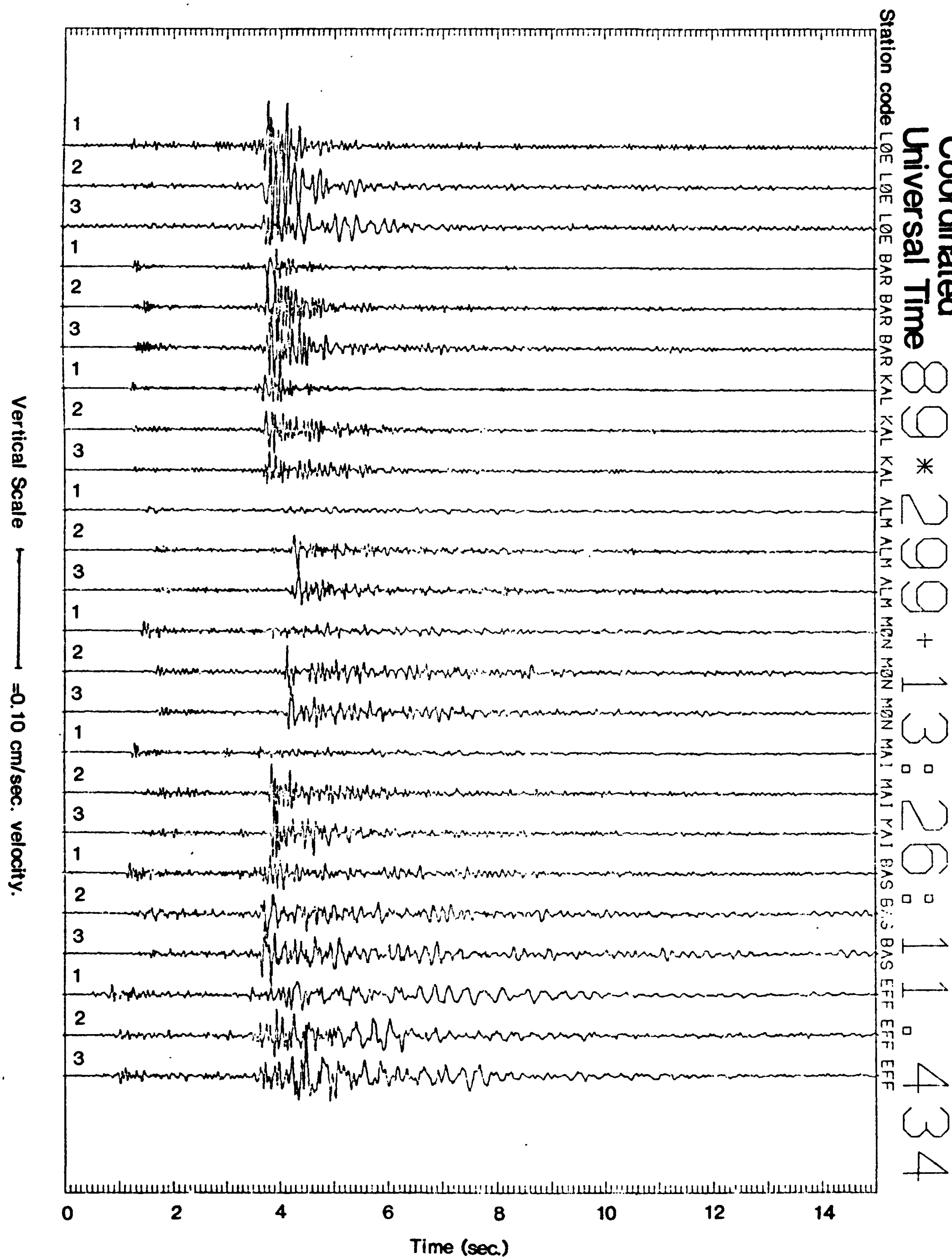

Figure 26.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 11 km Northeast of central Santa Cruz. Sites in areas of low to moderate damage from the Loma Prieta earthquake.

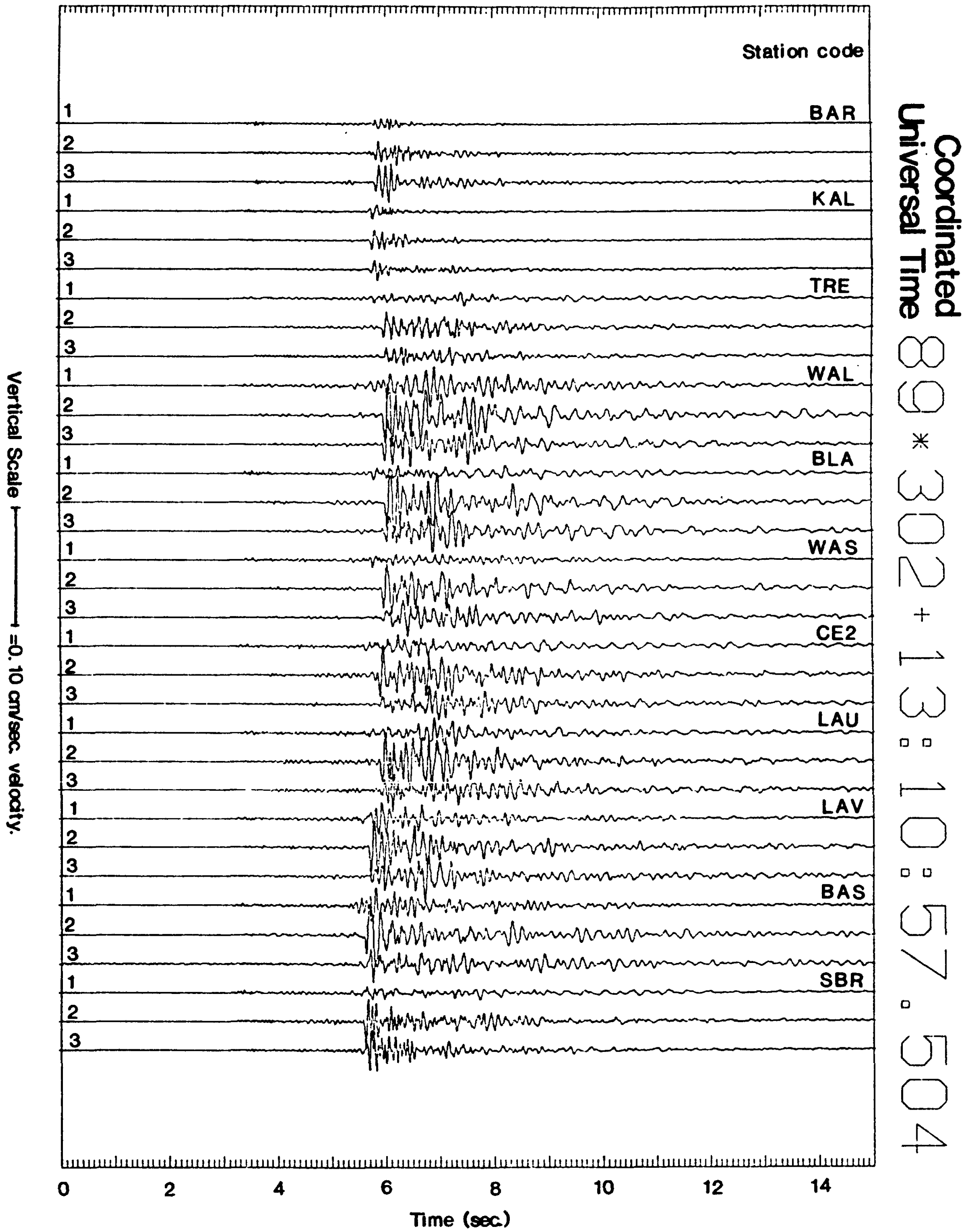

Figure 27.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 12 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

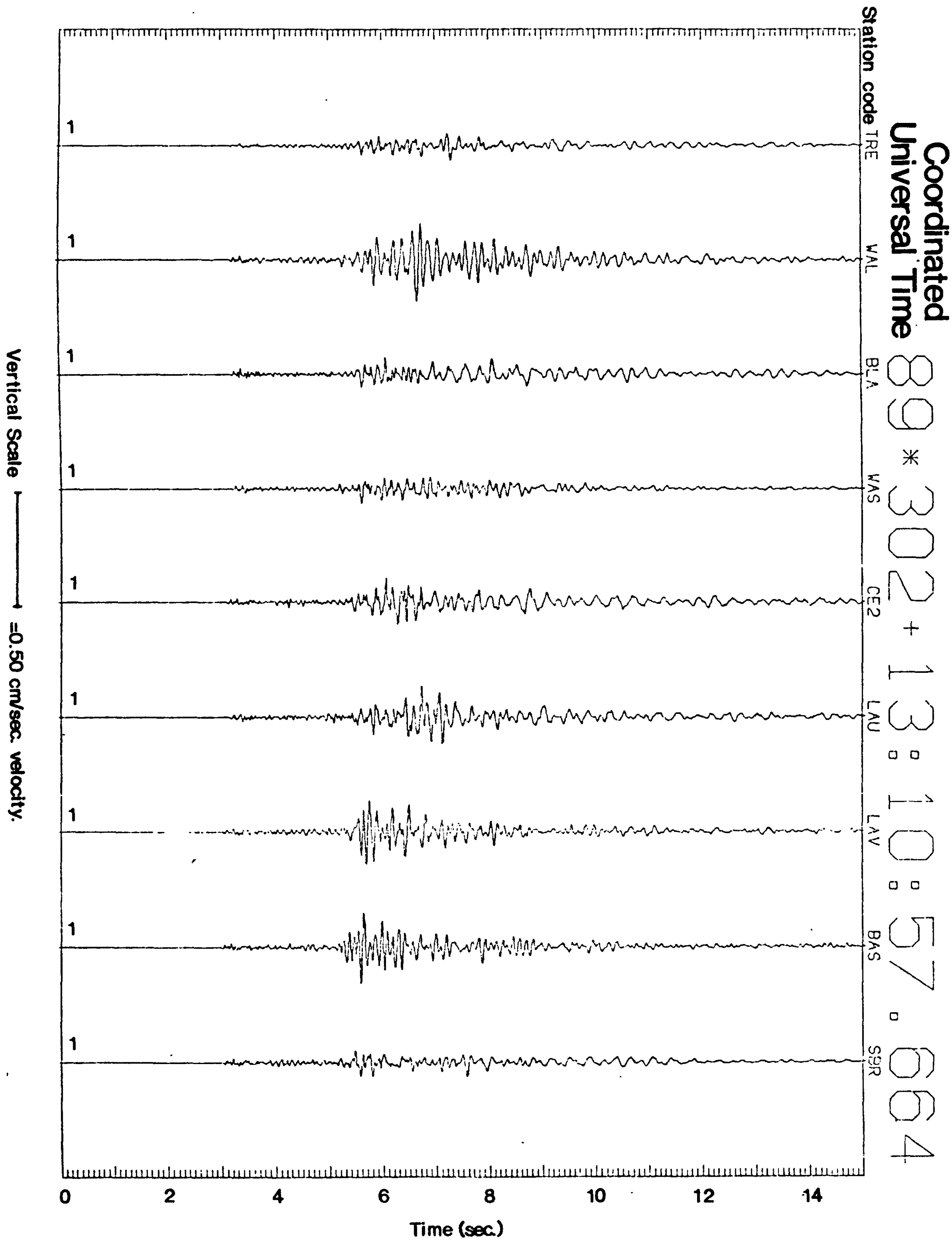

Figure 28.-- Earthquake time-history. Vertical component. *=clipped data. Epicenter is approximately 12 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

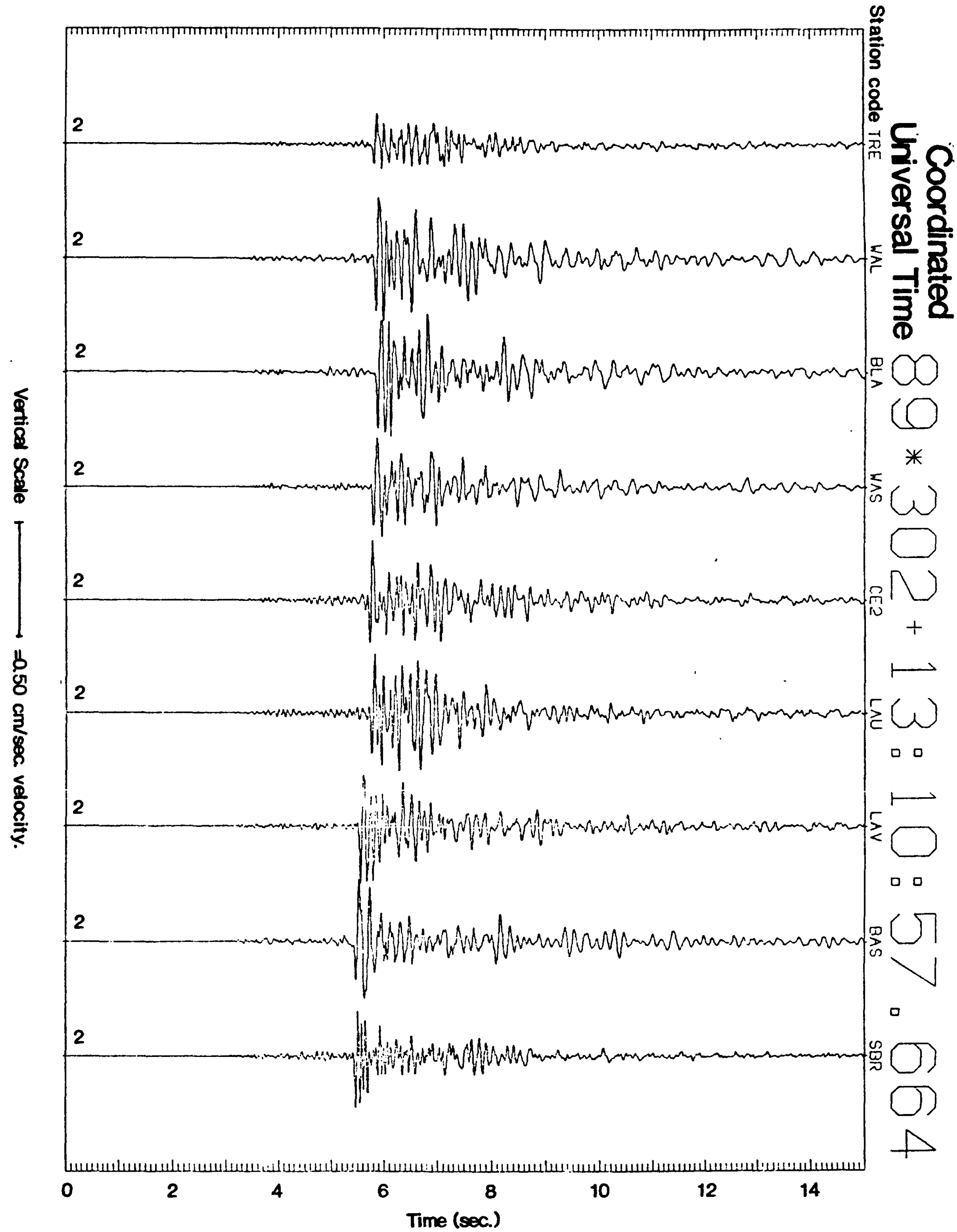

Figure 29.-- Earthquake time-history. Horizontal (NS) component. *=clipped data. Epicenter is approximately 12 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

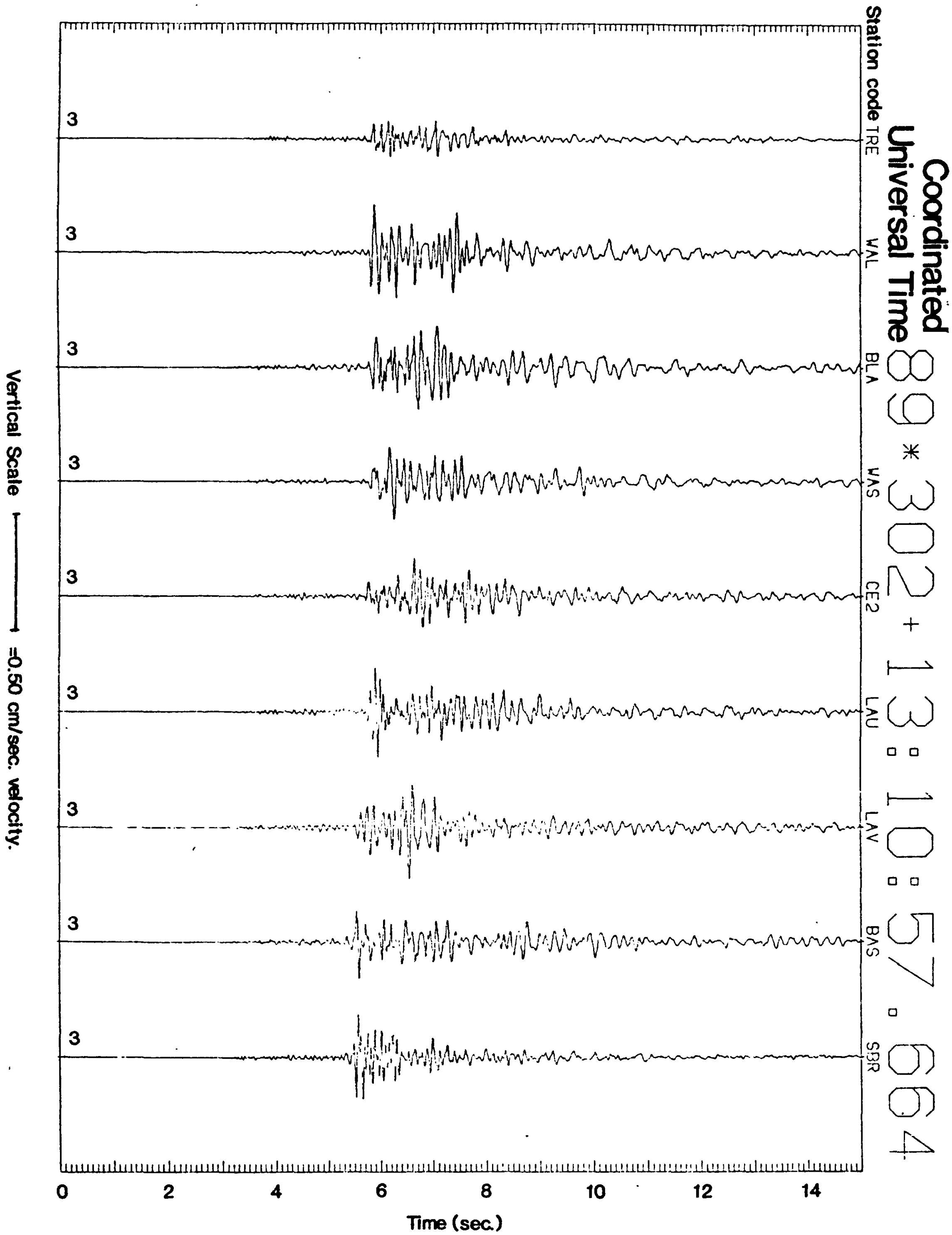

Figure 30.-- Earthquake time-history. Horizontal (EW) component. *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

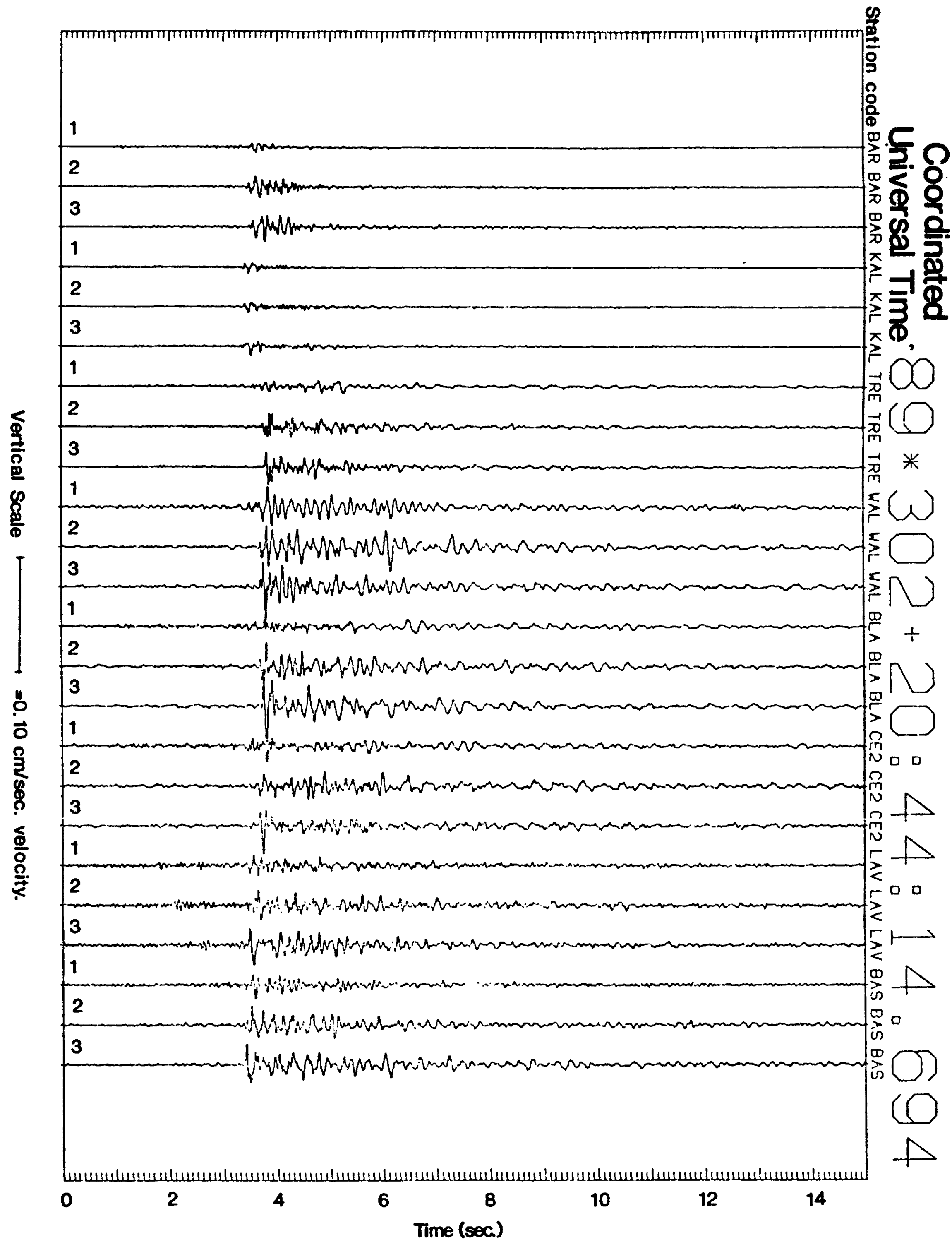

Figure 31.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

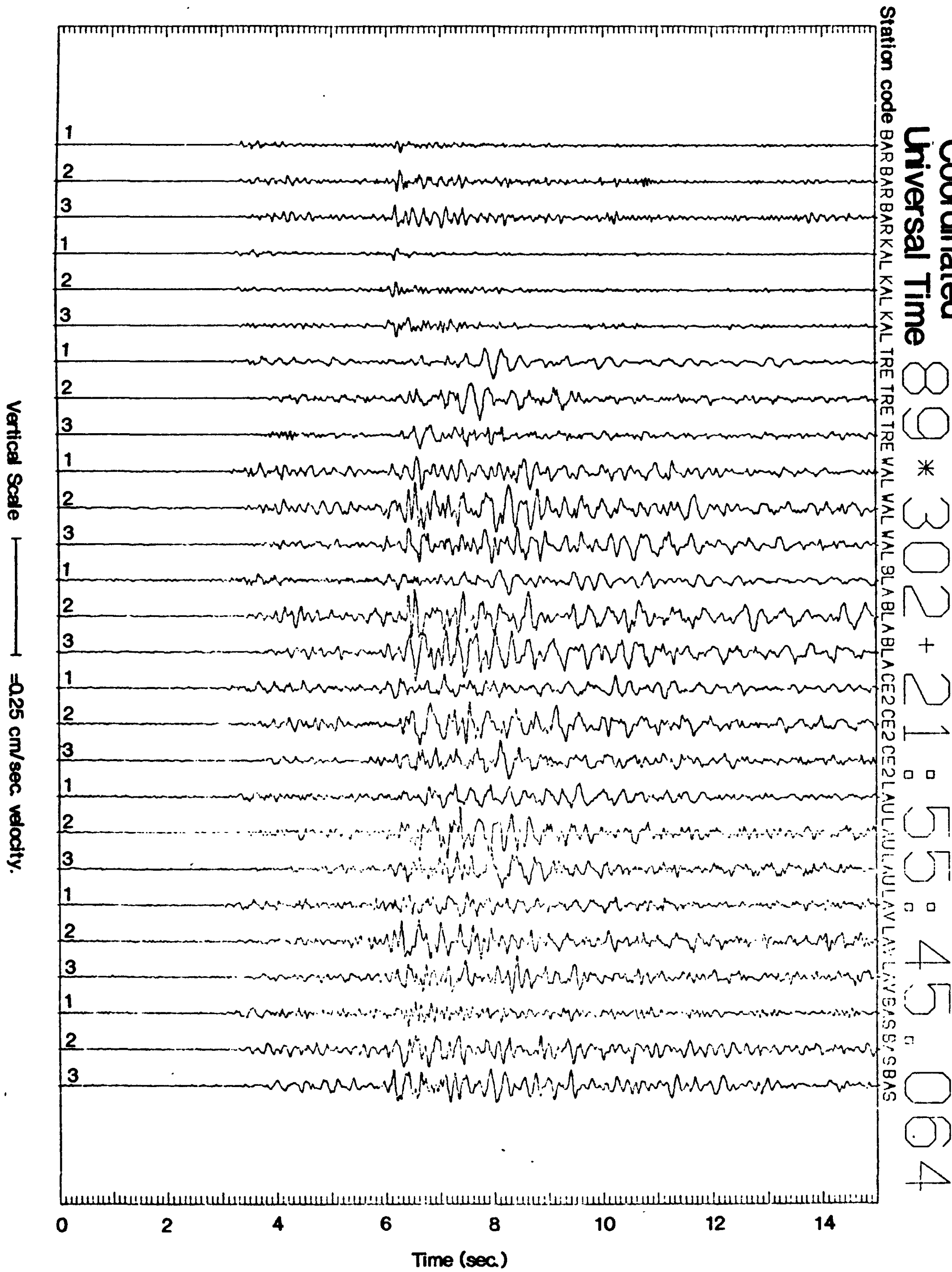

Figure 32.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

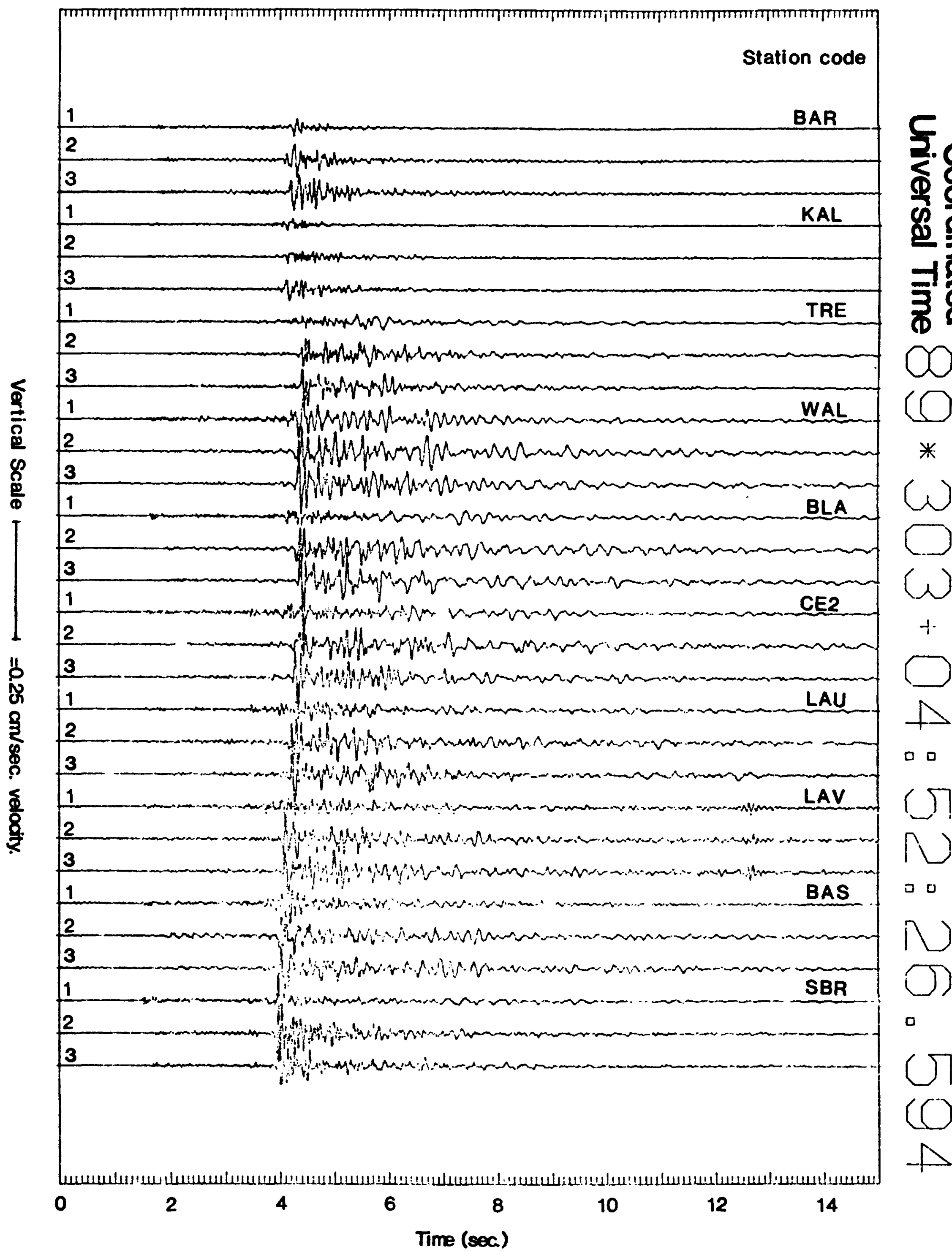

Figure 33.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 14 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

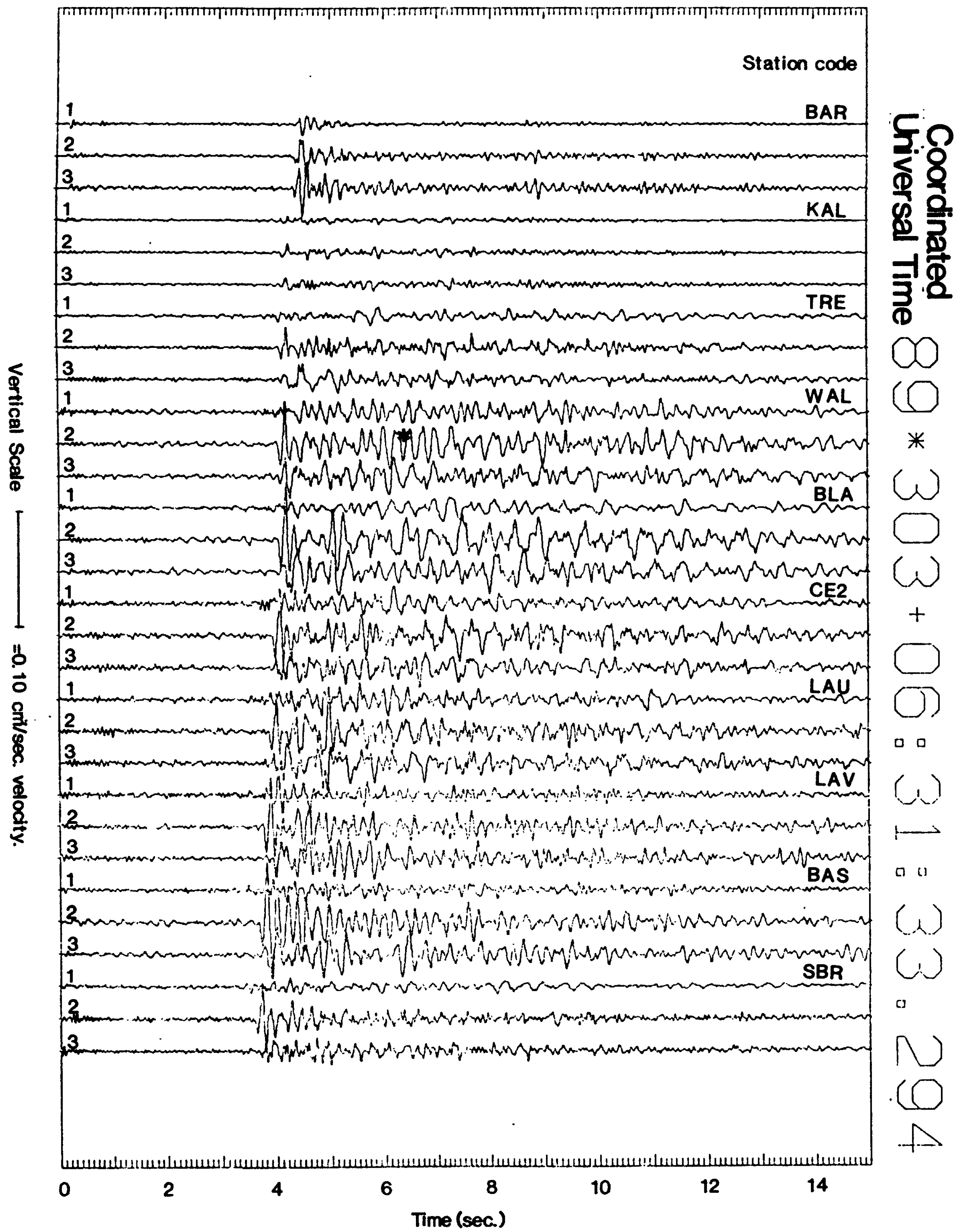

Figure 34.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 30 km East of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

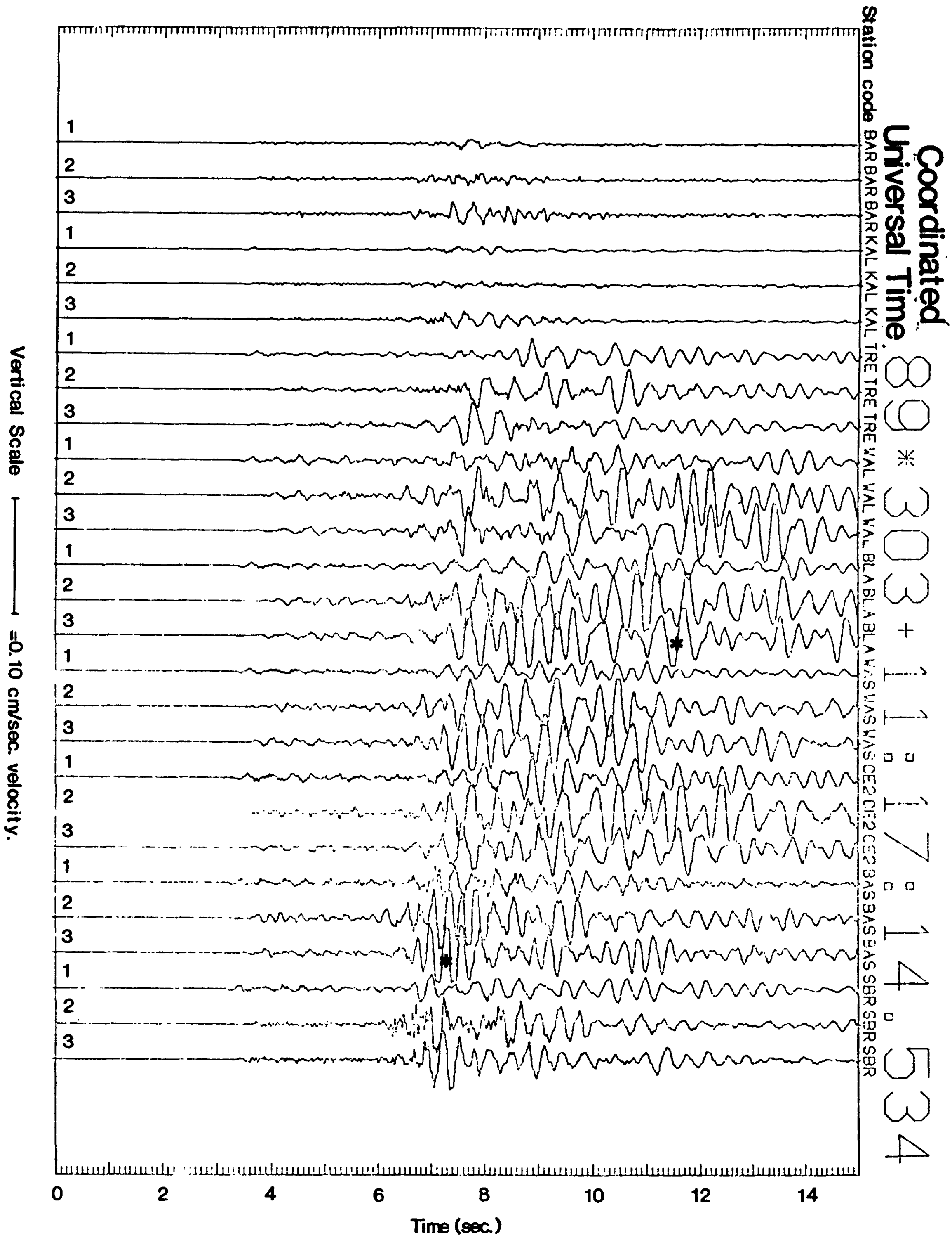

Figure 35.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 20 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

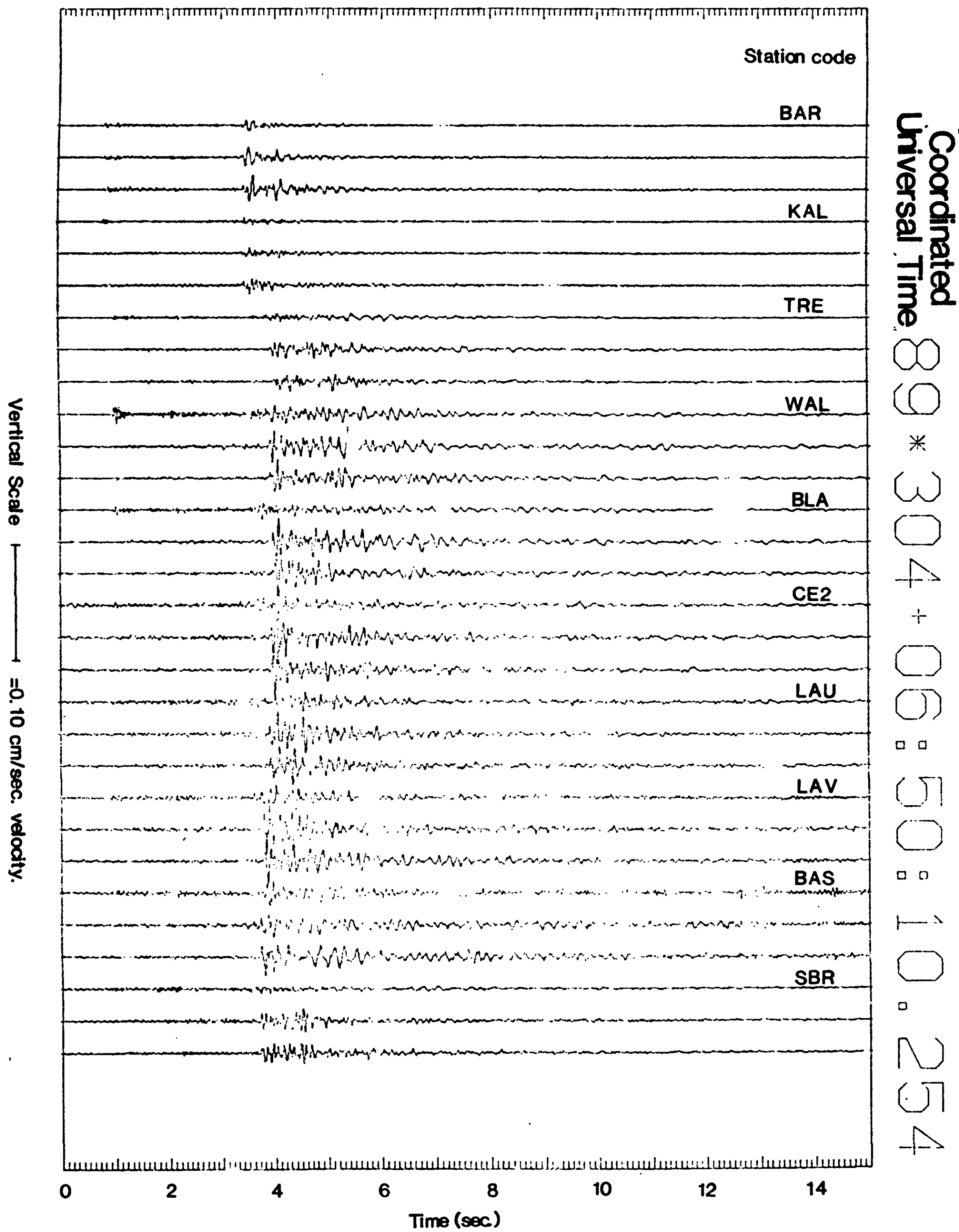

Figure 36.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 16 km North of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

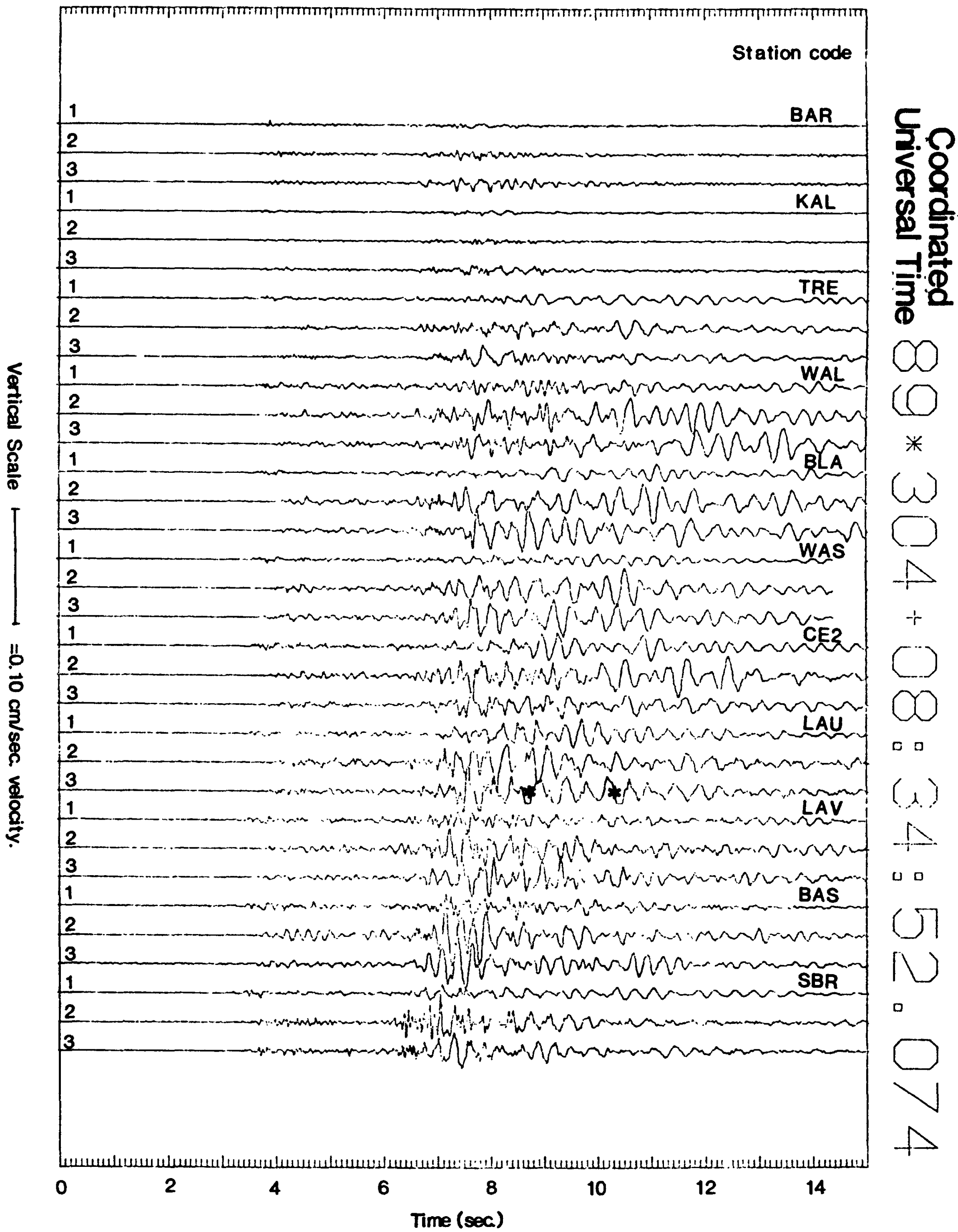

Figure 37.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 21 km Northeast of central Santa Cruz. Sites located on an E-W line across Santa Cruz alluvium basin.

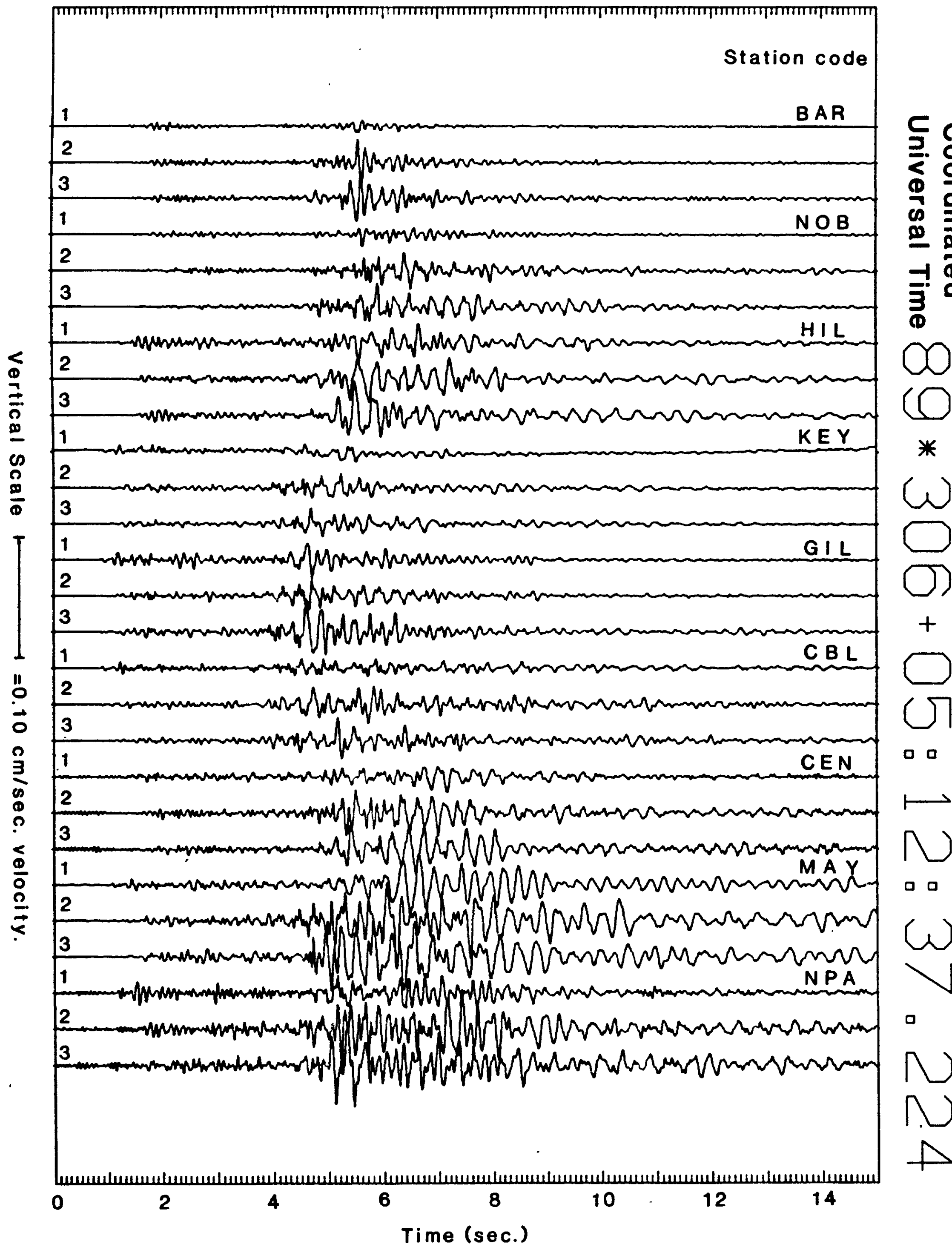

Figure 38.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 21 km Northeast of central Santa Cruz. Sites located on the East side of Santa Cruz.

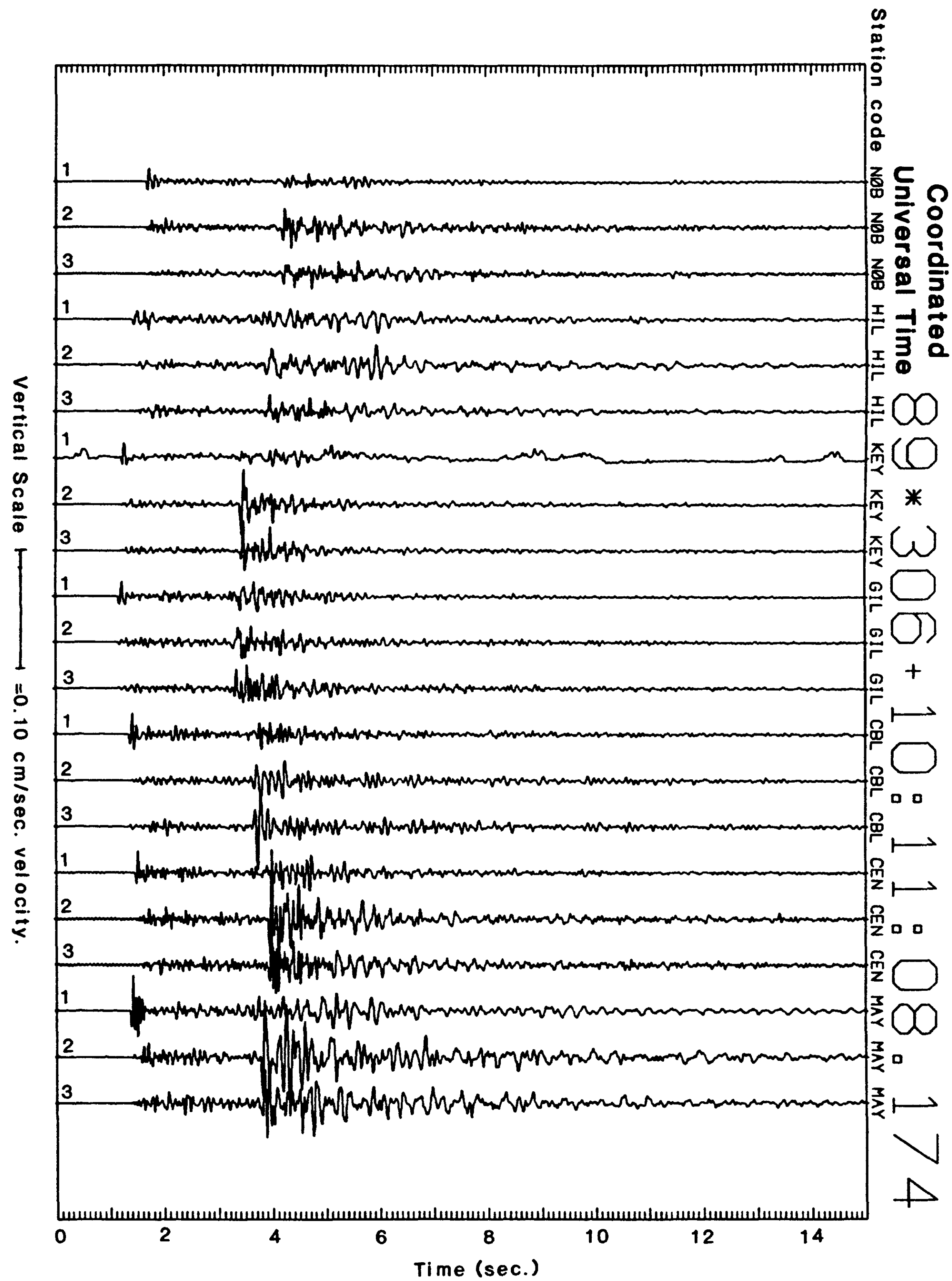

Figure 39.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 13 km Northeast of central Santa Cruz. Sites on the East areas of Santa Cruz.

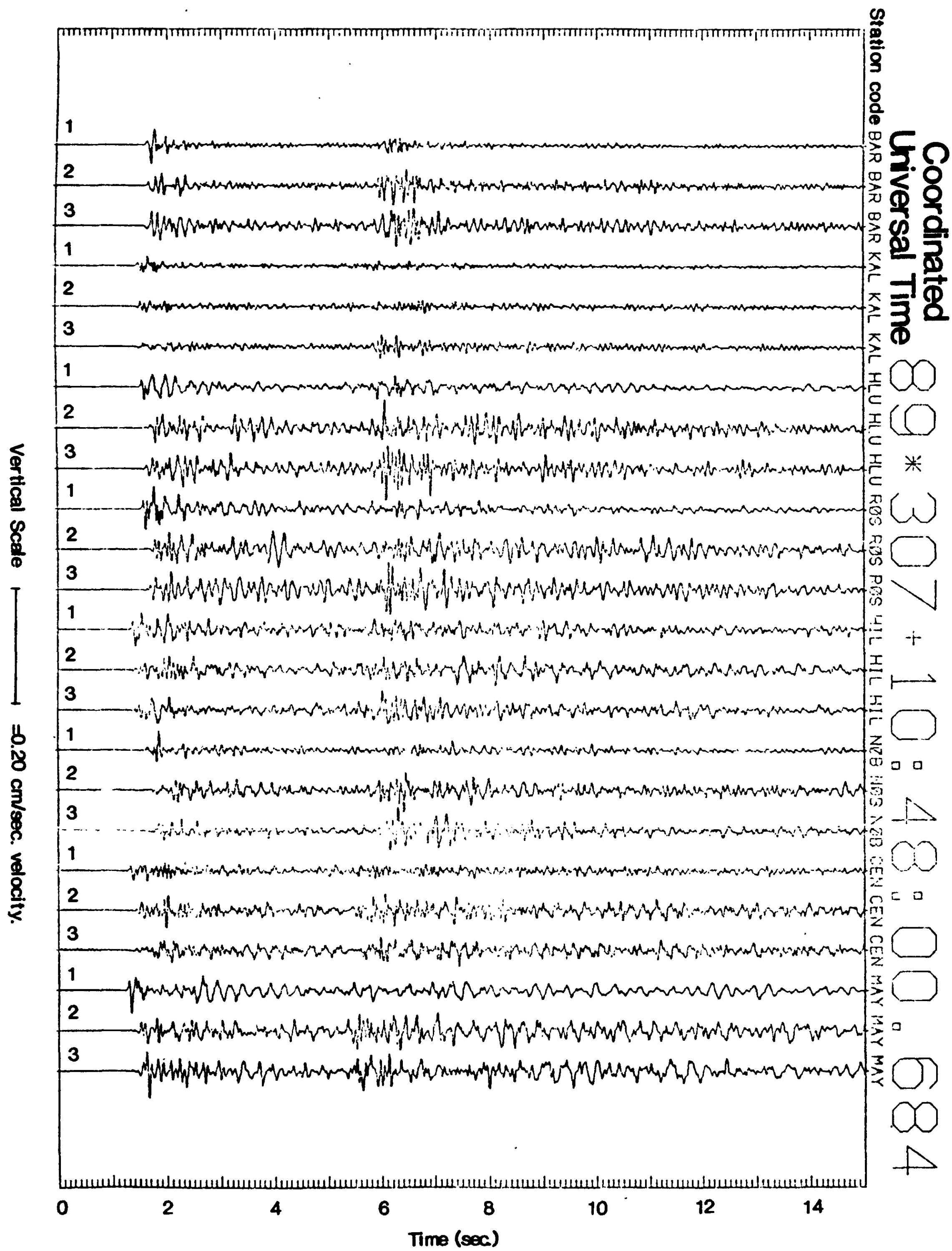

Figure 40.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 26 km East of central Santa Cruz. Sites located on an East-West topographic edge line.

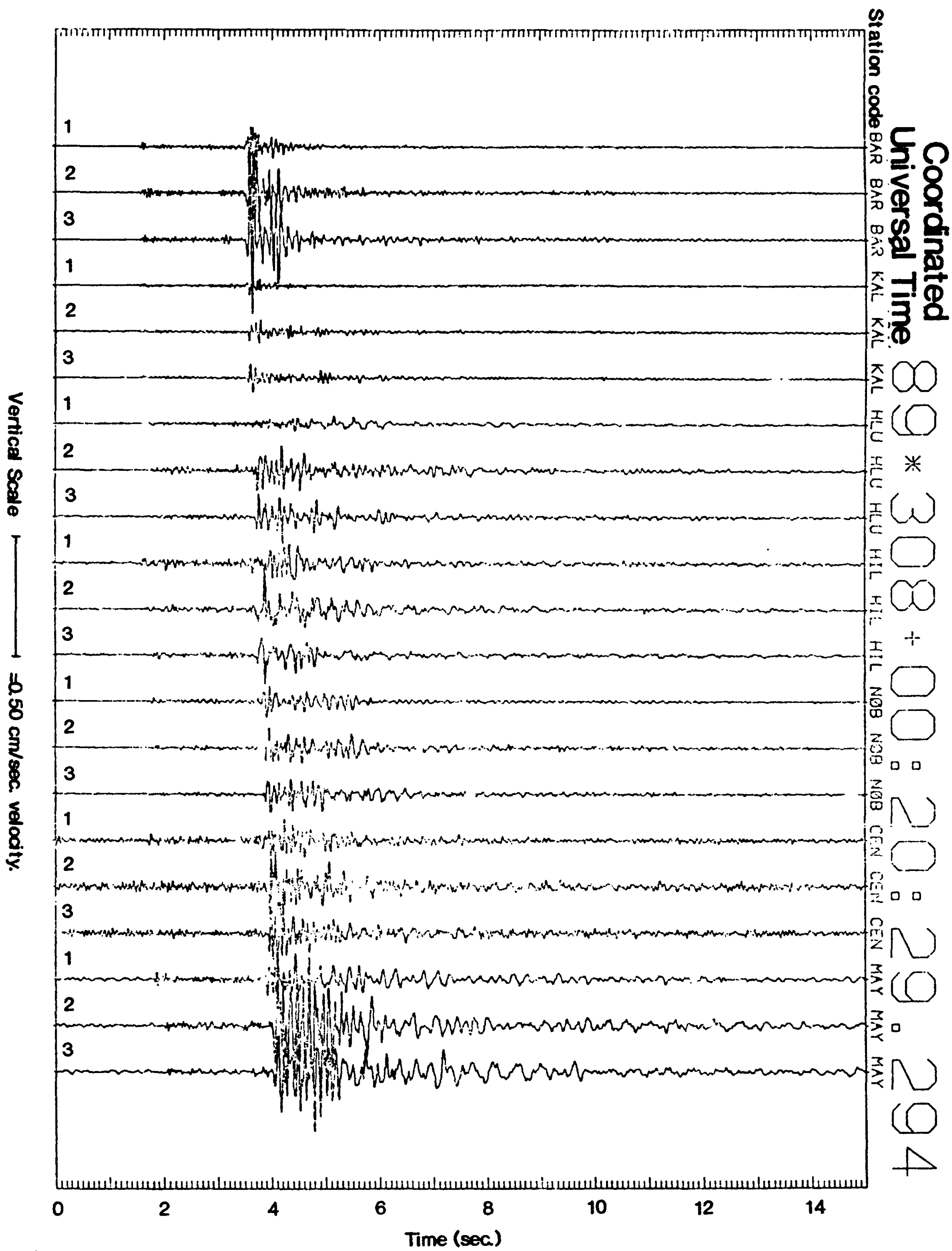

Figure 41.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 15 km North of central Santa Cruz. Sites located on an East-West topographic edge line.

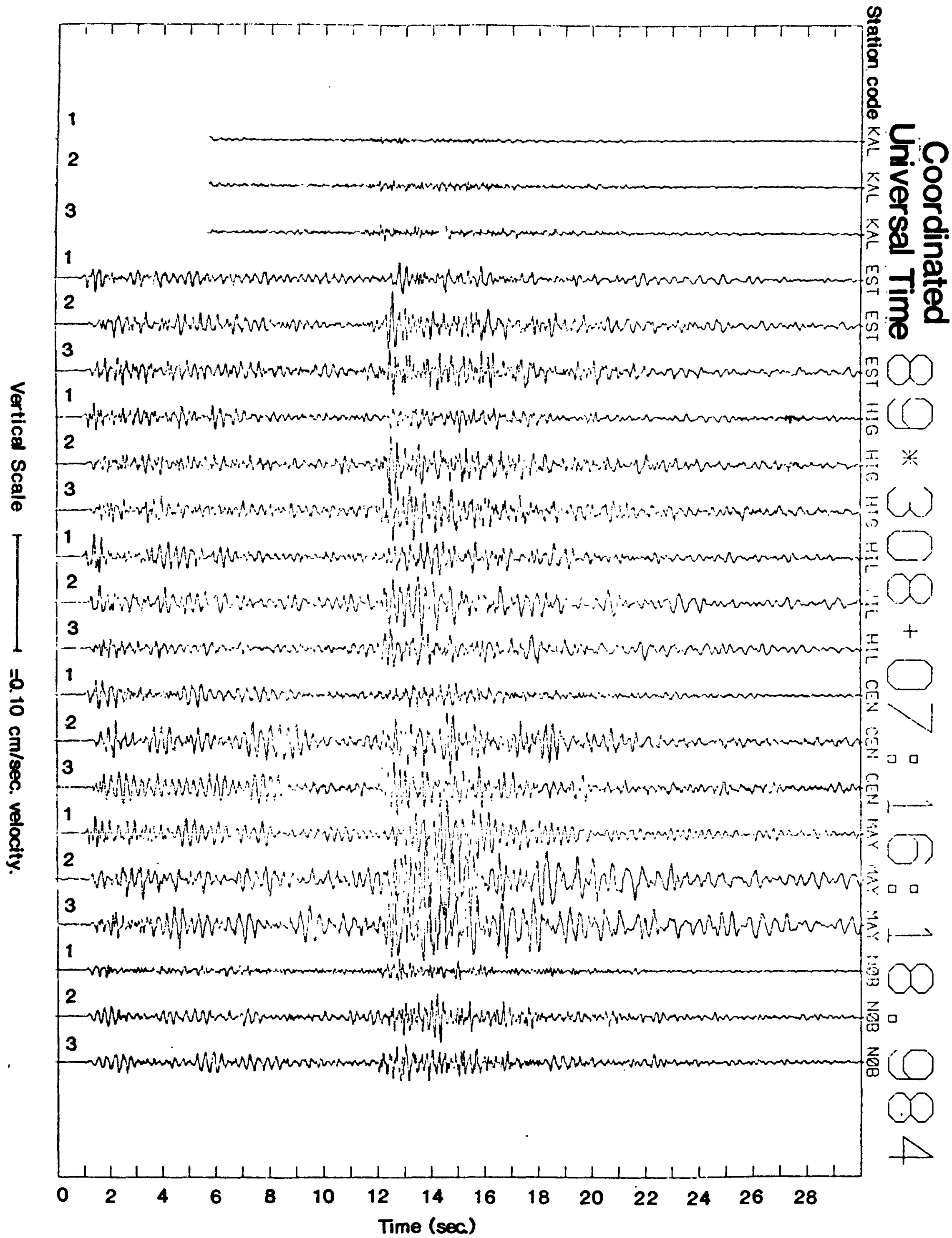

Figure 42.-- Earthquake time-history. 1=vertical component; 2=horizontal (NS) component; 3=horizontal (EW) component; *=clipped data. Epicenter is approximately 50 km Northwest (Hayward fault ?) of central Santa Cruz. Sites located on an East-West topographic edge line.

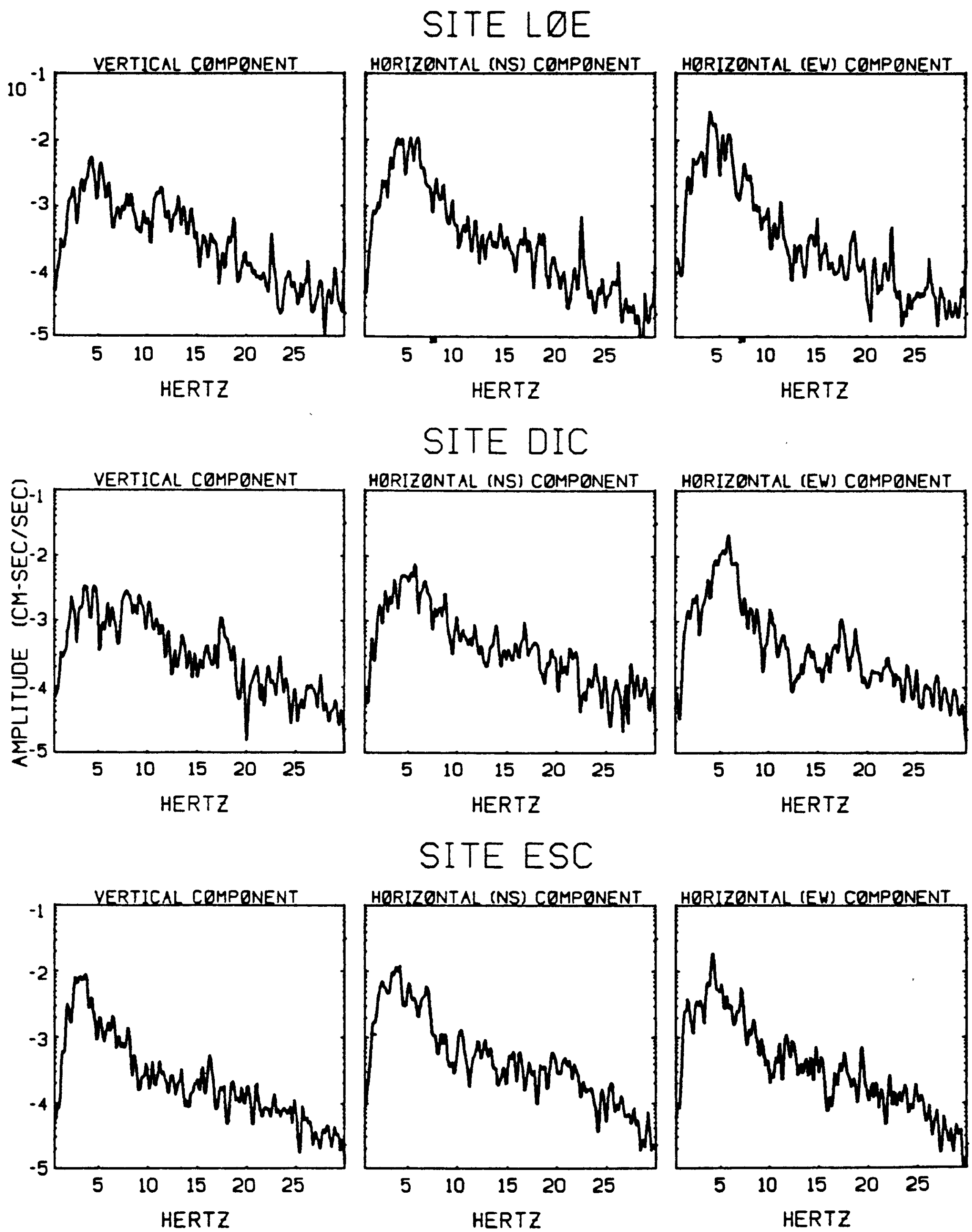

Figure 43.-- Event universal time 294:12:54 spectra.

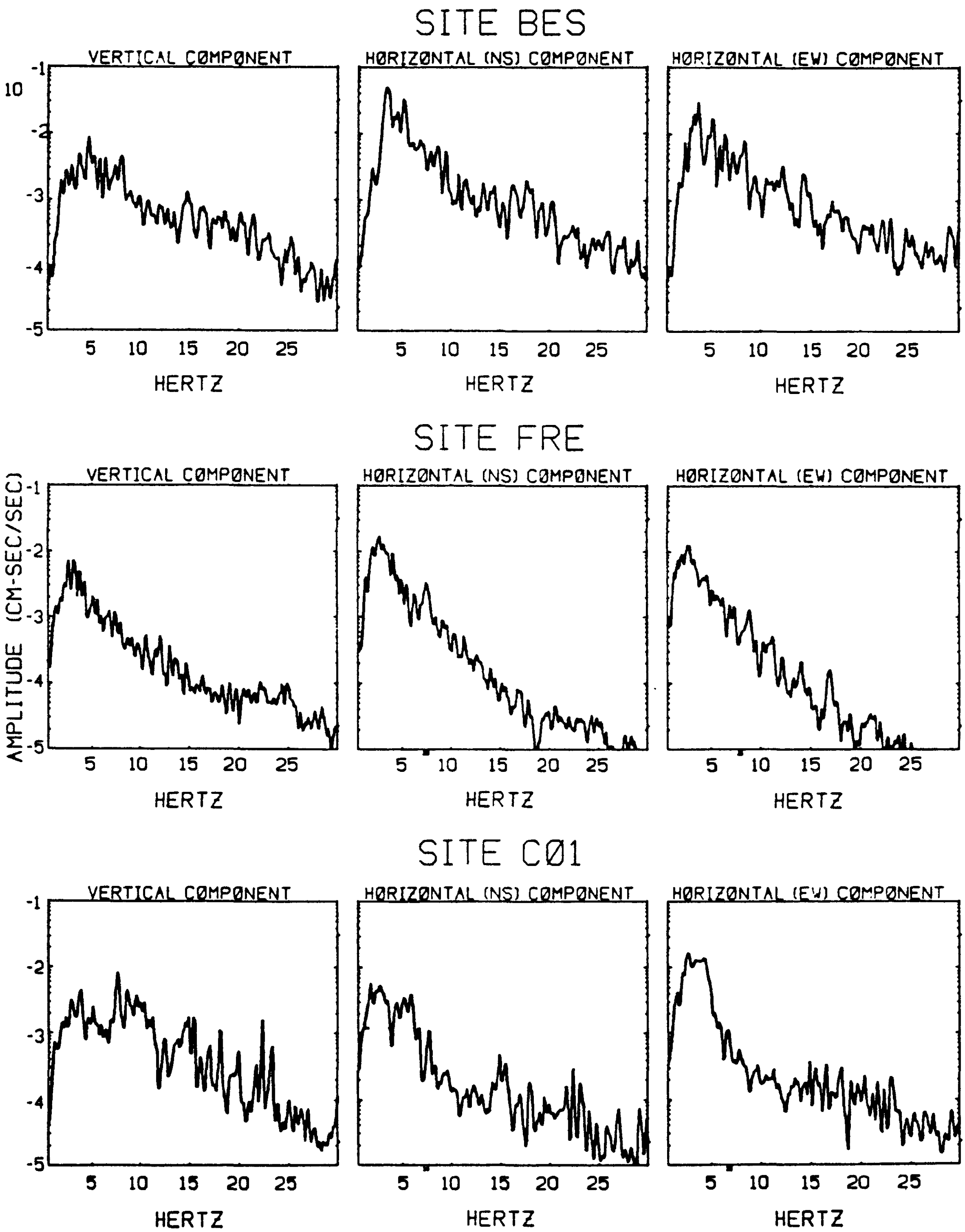

Figure 44.-- Event universal time 294:12:54 spectra.

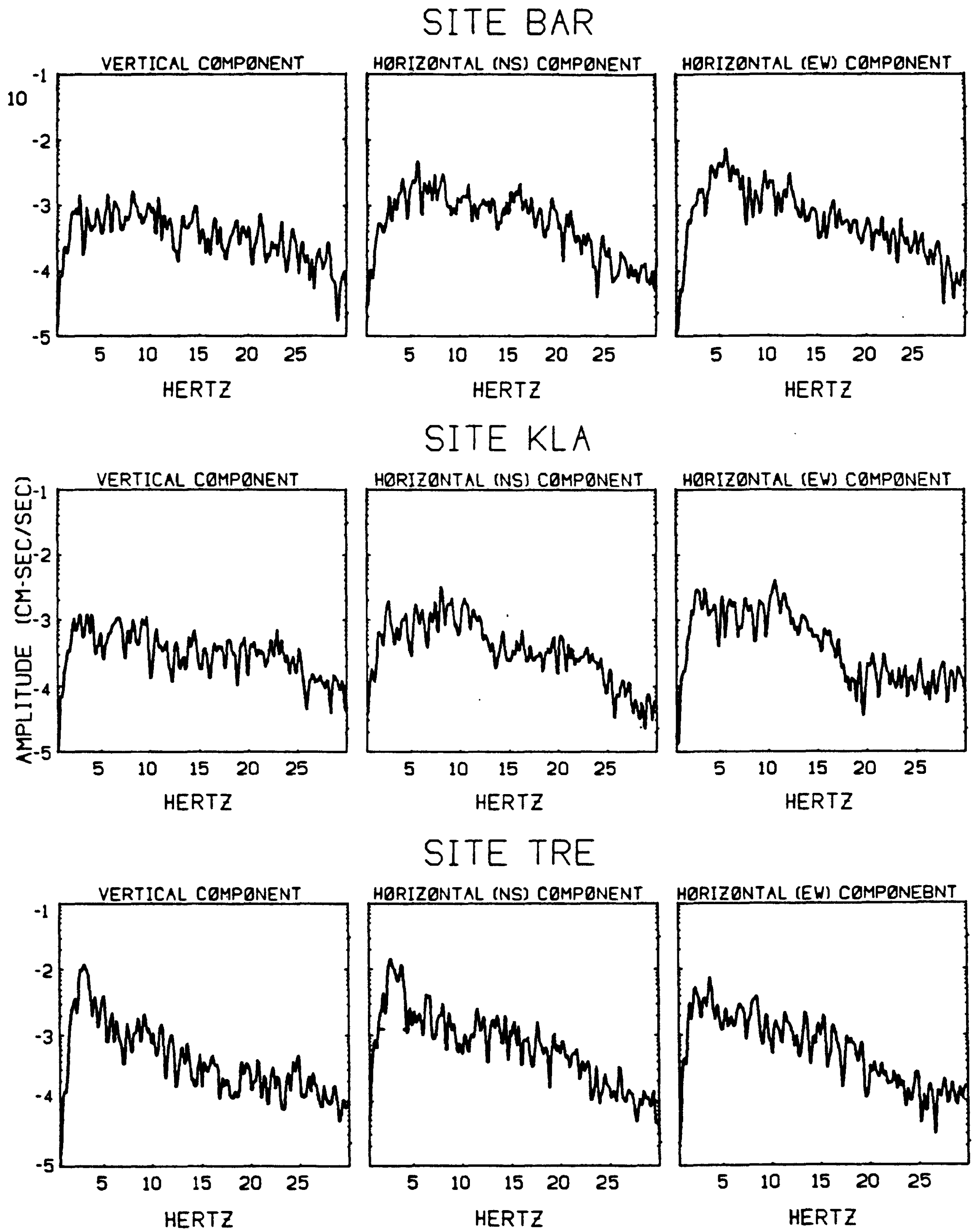

Figure 45.-- Event universal time 302:21:55 spectra.

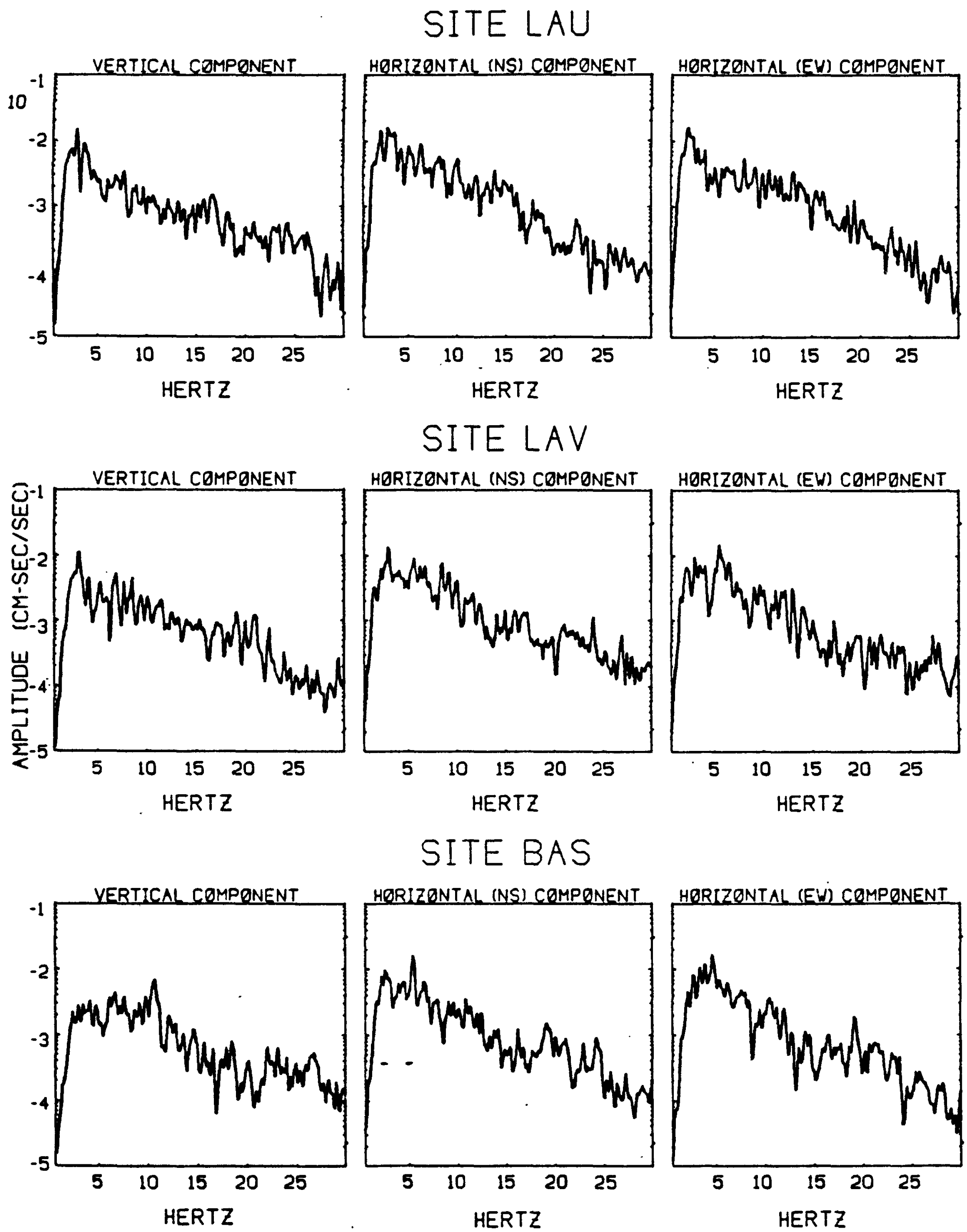

Figure 46.-- Event universal time 302:21:55 spectra.

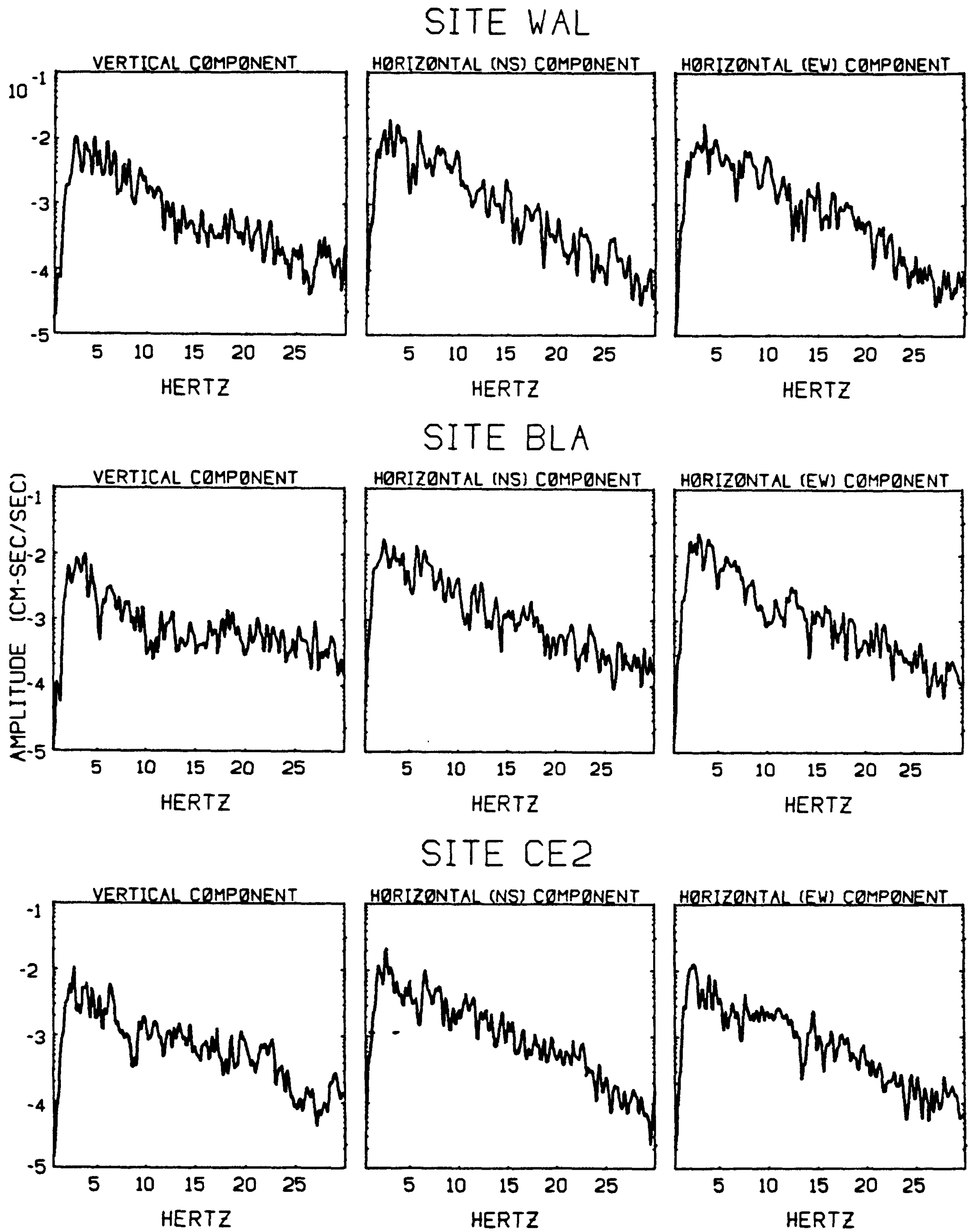

Figure 47.-- Event universal time 302:21:55 spectra.

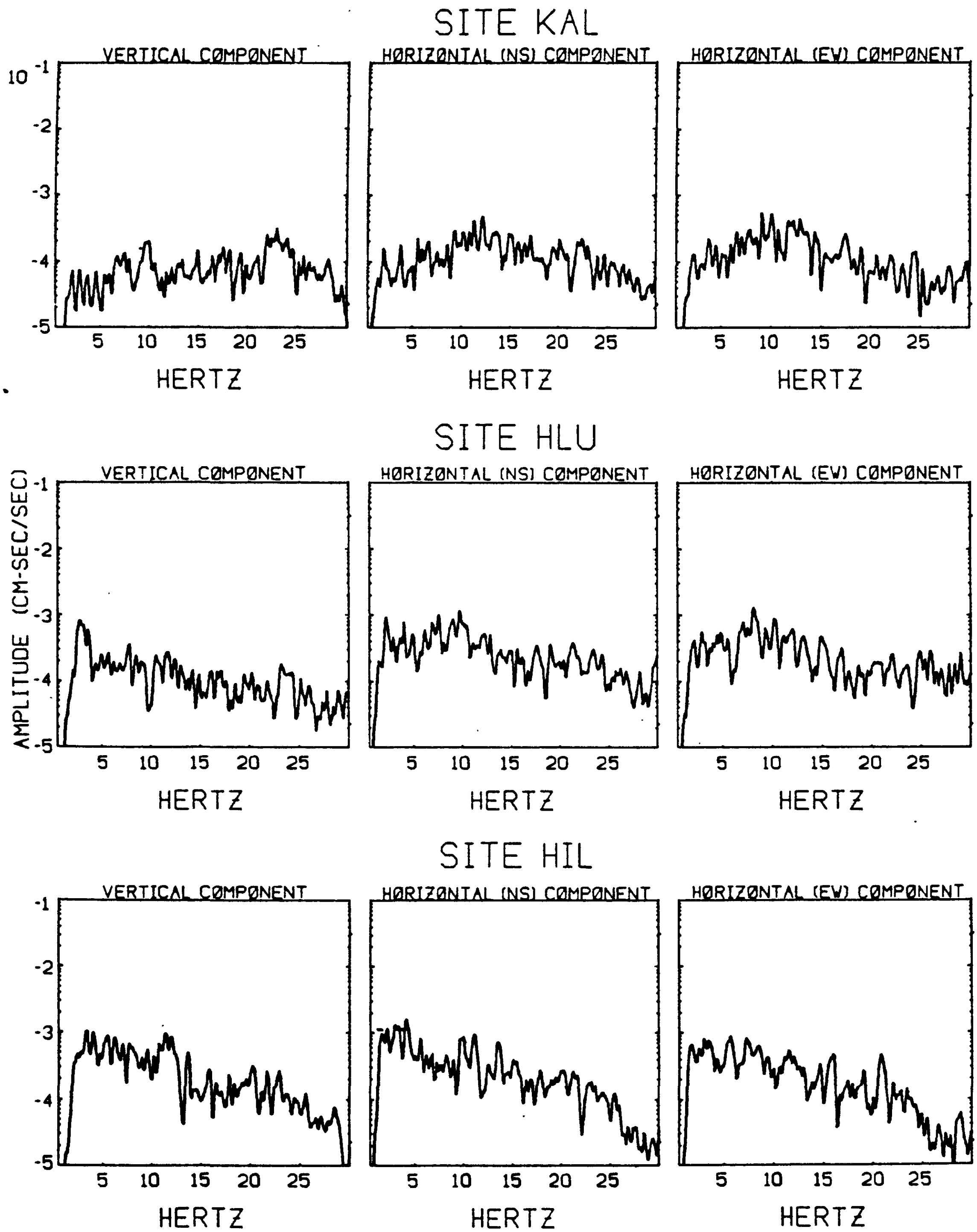

Figure 48.-- Event universal time 308:00:20 spectra.

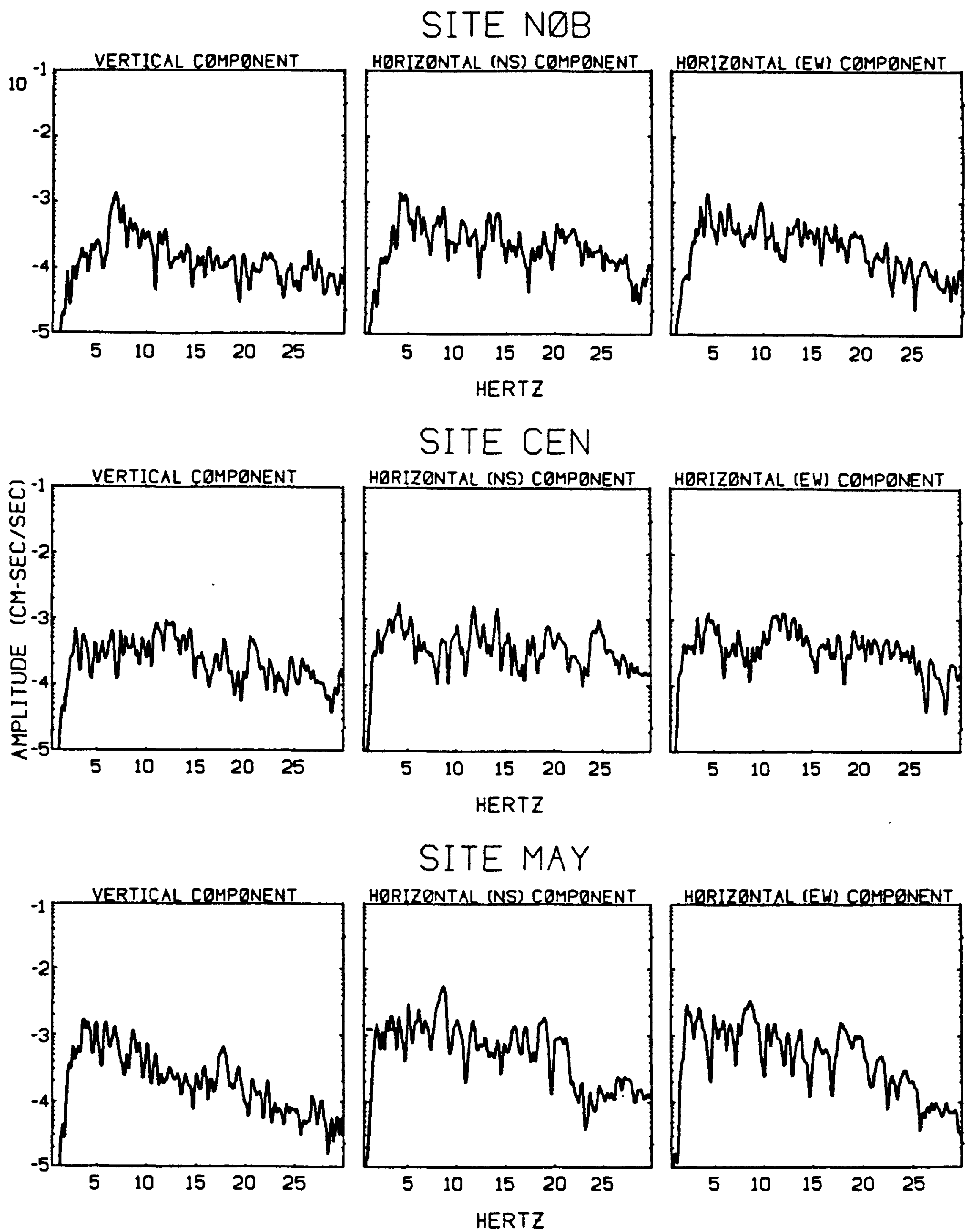

Figure 49.-- Event universal time 308:00:20 spectra.