Digital Strong Ground Motion Recordings of the June 1997, Strait of Georgia Earthquake

John F. Cassidy[1], Garry C. Rogers[1], Dieter H. Weichert[1], and Tim E. Little[2]

[1]Geological Survey of Canada
Pacific Division
Pacific Geoscience Centre
P.O. Box 6000, Sidney B.C. V8L 4B2
e.mail: cassidy@pgc.nrcan.gc.ca

[2]B.C. Hydro
Power Supply
6911 Southpoint Drive,
Burnaby B.C. V3N 4X8

Geological Survey of Canada
Open File 3599

March 1998
39 pp. 25 figs.

B.C. Hydro
Report No. MEP 481

ABSTRACT

An earthquake of M_W=4.3 [M_L=4.6] occurred on 24 June 1997 beneath the Strait of Georgia about midway between Vancouver, on the British Columbia mainland, and Nanaimo on Vancouver Island. This was a shallow thrust earthquake (3 km focal depth) that occurred along an approximately E-W striking fault. This earthquake triggered strong motion instruments at 19 sites in southwestern British Columbia, thus providing the largest single strong motion data set collected in this region to date. Peak ground accelerations ranged from 0.2%g to 2.4%g (2-24 $cm.s^{-2}$), at epicentral distances of 33-87 km. This data set is significant because it includes the first bedrock recordings made in the greater Vancouver area. These reference bedrock waveforms will allow for more accurate estimates of the site response at the Fraser River delta sites. In this Open File we present time series plots of the unprocessed digital data, as well as a comparison of the waveforms and spectra of select bedrock and soil recordings. Tabulated station parameters and peak accelerations are given together with maps of the network configurations showing the locations of triggered and untriggered instruments.

RÉSUMÉ

Un tremblement de terre de magnitude (Mw) 4.3 (ML 4.6) s'est produit le 24 juin 1997 sous le détroit de Géorgie à mi-chemin entre Vancouver sur la côte ouest de la Colombie britannique et Nanaimo sur l'Ile de Vancouver. C'était un tremblement de terre peu profond (profondeur de 3 km) qui s'est produit le long d'un chevauchement d'orientation approximative est-ouest. Ce séisme a déclenché des accélérographes à 19 sites dans le sud-ouest de la Colombie britannique et par conséquent, nous a fourni la plus grande collection d'accélérogrammes enregistrés jusqu'ici. Il y a un écart de 0,2% à 2,4% (2-24 cm/s^2) d'accélération maximale aux distances de 33-87 km de l'épicentre. Cette collection de données est importante parce que ça constitue les premiers enregistrements sur roc faits dans la région métropolitaine de Vancouver. Ces traces séismiques enregistréés sur roc nous permettront d'estimer avec précision les réponses de sites sur le delta de la rivière Fraser. Nous fournissons dans ce Dossier public les traces séismiques des données numériques et une comparaison des traces séismiques et des spectres enregistrés à quelques sites sur roc et quelques sites sur sol meuble. Nous fournissons aussi les caractéristiques des stations, les accélérations maximales et des cartes indiquant quels instruments ont été déclenchés et ceux qui n'ont pas été déclenchés.

Introduction

An earthquake of magnitude M_L= 4.6 (Geological Survey of Canada) [M_W=4.3, based on the moment tensor solution of Oregon State University] occurred on 24 June 1997 at 14:40 UT. The earthquake was located about 3 km beneath the Strait of Georgia at 49.62°N and 123.62°W. This is midway between Nanaimo, on Vancouver Island (30 km WSW), and Vancouver, on the Lower Mainland (30 km E). The rupture was thrust faulting along an approximately E-W striking fault (Figure 1). There were reports of slight damage resulting from this earthquake: glass breakage in Vancouver; and a broken water pipe in North Vancouver. Power was lost in parts of Port Alberni and Sechelt as protective relay switches were tripped at BC Hydro substations near these communities. This earthquake was felt on Vancouver Island from Campbell River in the north to Victoria on the southern tip of the island, and on the mainland as far to the east as Abbotsford. This earthquake is at the same location as a M_L= 4.9 event that occurred in November, 1975. That earthquake failed to trigger any of the strong motion instruments operating in southwest British Columbia (at that time all were SMA-1's set at a trigger level of 1%g, or RFT-250 and AR-240 instruments with displacement triggers set at 0.5mm).

The June 1997 Georgia Strait earthquake triggered strong ground motion instruments at 19 sites in southwestern British Columbia (Figures 1 and 2); 14 on the Lower Mainland, three on southern Vancouver Island, and two on central Vancouver Island. This is the largest single strong motion data set in this region to date, and the second significant data set in less than two years [In May, 1996, the Duvall Washington earthquake triggered nine strong motion instruments in southwest BC (Weichert et al., 1996; Cassidy et al., 1997; Rogers et al., 1998)].

Despite the low magnitude of this earthquake, it is significant for two important reasons:
1) For the first time, strong motion instruments situated on bedrock in the greater Vancouver area triggered. These "reference site waveforms" can be used to compute spectral ratios, and hence the site response for soil sites on and near the Fraser River delta.
2) These records can be compared with those of the 1996 Duvall, Washington M_W 5.1 earthquake (Weichert et al., 1996) - to verify the observations (see Cassidy et al., 1997) that amplification on the Fraser River delta is frequency dependent, and occurs in a narrow frequency band of about 1-5 Hz, with amplifications of up to 6-8 (relative to bedrock). The Georgia Strait earthquake is similar to the Duvall earthquake in that they are both shallow crustal events. It is different in that it is much closer to Vancouver (about 30 km rather than 180 km), and samples a very different azimuth (due west rather than southeast). The Georgia Strait earthquake is at a similar distance as the 1976 Pender Island earthquake (about 50 km south of Vancouver). That earthquake, of M_W 5.3 [m_b=5.2 (GSC), M_L=5.4 (GSC)] was a deep (62 km) event in the subducting oceanic plate. It triggered a number of strong motion recorders on southern Vancouver Island and the Lower Mainland (see Weichert and Milne, 1980; Rogers et al., 1998).

The Strong Motion Networks

Geological Survey of Canada The Geological Survey of Canada (GSC) operates a network of 33 strong motion seismographs in western Canada. For details of the history of this network and a description of the available data sets, see Milne and Rogers, (1971), Weichert et al. (1996), Rogers (1976) and Weichert and Munro (1987). The most significant prior data sets, are seven records of the 1976 Pender Island M_L=5.4 earthquake (Weichert & Milne, 1980; Rogers et al., 1997), and nine records of the 1996 Duvall, Washington earthquake (Weichert et al., 1996). The June 1997 Georgia Strait earthquake triggered strong motion instruments at 19 sites (8 GSC sites). At the time of the Georgia Strait earthquake, most GSC stations in the greater Vancouver area used Kinemetrics SSA-2 accelerographs, all 1g full-scale sensors, with trigger thresholds of ranging from 0.2%g to 1% g. Thresholds of 0.2%g were used for most bedrock sites, and a threshold of 0.4%g was used for many soil sites. These trigger levels were lowered from 1%g based on the successful analysis of low-amplitude recordings of the 1996 Duvall earthquake. This resulted in triggers at two GSC sites (ANN and BLO) that would not have triggered at the 1%g level. This change also resulted in the loss of data at two sites that likely would have triggered - Roberts Bank (ROB) and UBC - instruments at these sites were filled with noise triggers due to the low thresholds of 0.4%g, and 0.2%g, respectively. As a result, the trigger thresholds at ROB has been increased to 1%g, and the trigger at UBC to 0.4%g. On Vancouver Island most accelerographs are still Kinemetrics SMA-1 instruments with trigger thresholds of 1% g. The exceptions are an SSA-2 (1 g; 1%g) and an SSA-1 (2g sensor, gain 2, 0.1%g threshold) in the vault at the Pacific Geoscience Centre. Digital instruments (Kinemetrics ETNA's) have recently been purchased for deployment at six sites on Vancouver Island.

Table 1 lists the location and instrumentation details of the GSC network in the Greater Vancouver and southern and central Vancouver Island regions. The locations of strong ground motion recording sites in this region are shown in Figures 1 and 2. Three-letter location abbreviations and maximum peak horizontal accelerations recorded for the 1997 Georgia Strait earthquake are given for each of the triggered stations. Only one of these sites (CTL - a station on southern Vancouver Island that is operated by the GSC for Teleglobe Canada) had analogue records. These analogue data have not yet been digitized, and are not presented in this report. The peak accelerations recorded at this site are 1.7%g, 1.1%g, and 1.9%g (for the L, V, T components, respectively) at 4.5-6 Hz. For those stations that did not trigger (Figure 1), the trigger level is given - this represents the upper limit for peak ground acceleration at these sites.

BC Hydro B.C. Hydro (BCH) operates strong motion instruments at key hydroelectric projects and electrical substations across British Columbia. These instruments have been installed as part of the permanent monitoring of important dams, to verify design assumptions about the dynamic behaviour of structures when they are subjected to earthquakes, and to contribute to expanding the meagre strong motion data base for Western Canada. The BCH network includes Kinemetrics SMA-1's (all with a trigger threshold of 1.0 %g), SSA-2 instruments and ETNA's at electrical substation sites in greater Vancouver and on Vancouver Island. All of the SSA-2's and ETNA's are 2-g full scale, and are set to trigger at thresholds of either 0.4%g or 0.6%g. Unfortunately, the downhole instrument at Kidd No.2 in Richmond was not operational at the time of the Georgia Strait earthquake. One BCH station on the Fraser Delta at Canoe Pass Terminal was filled with noise triggers (the trigger level was set at 0.4%g) and did not record the earthquake. Table 2 shows details of the BCH network in the greater Vancouver and southern/central Vancouver Island regions. Figures 1 and 2 show the location, trigger status, and peak horizontal accelerations recorded for the combined GSC and BCH accelerograph networks.

BC Hydro - Anomalous activation of seismic triggers at John Hart Dam At John Hart Dam near Campbell River, there are two SMA-1's that did not trigger (Figure 1). At this site there are also nine Kinemetrics EST-2W seismic triggers which are used in an automatic shutoff system that will close penstock intake gates in the event of seismic shaking greater than a threshold level. The seismic triggers are installed in sets of three, in three different locations. Triggers in at least two of the three locations must be activated in order for the shutoff system to be activated.

During the June 24 earthquake, two of the three triggers located on a rock outcrop were activated. Triggers at the other two locations did not activate. The three triggers on the rock outcrop were removed and were tested on a shake table. The two which activated during the earthquake were found to be set at trigger levels of about 6%g and 7%g. The trigger which did not activate was found to have a sticky coil which prevented it from operating properly.

The acceleration that was apparently experienced at the rock outcrop is significantly higher than would be expected at this distance from the epicentre (130 km), and apparently was also significantly higher than experienced at other locations at this dam site - given that the SMA-1's (with a 1%g threshold) did not trigger. Perhaps there is subsurface focussing, or a bedrock topographic effect that has contributed to the high accelerations at this outcrop.

BC Ministry of Transportation and Highways The B.C. Ministry of Transportation and Highways, in collaboration with the University of British Columbia Department of Civil Engineering, operates strong motion instruments at three locations in southwestern British Columbia (Figures 1 and 2, Table 3). The main goal of this effort is to obtain information about ground motions and structural responses of bridges and tunnels in southwestern British Columbia, for use in seismic design and the retrofit of highway structures. For details on the instrumentation see Latendresse and Ventura (1997).

Data Processing

Timing Absolute timing is not available for any of the stations, and is therefore omitted from all plots.

Sensor orientations. Throughout this report, we present the unrotated three components as recorded by each instrument, using the notation L, V, T as defined by the manufacturer. The instrument orientation is given in Tables 1, 2 and 3. Note that ground motion in the positive L, V, and T directions yields a negative signal output from the instruments.

Base Lines. All records that were obtained are digital. Figures 1 and 2 show the location of these instruments and their trigger thresholds. Most instruments triggered on the S-phase, only stations KID, CLE and MUR triggered on the P-wave. The 'pre-event time' ranged from 2.5 s (most instruments) to 10.2 s. The initial processing step was subtraction of the total record average. A few traces were offset from their zero positions by amounts equal to or larger than the signal amplitudes.

Scaled instrument response. The Kinemetrics SSA2ASC utility was used for the SSA records to obtain ascii files in units of volts. These were then converted into $cm.s^{-2}$ using the known gain setting and instrument full-scale. The BCH ETNA records were retrieved using the ETNA software and converted into units of $cm.s^{-2}$. The resulting three component waveforms (in units of $cm.s^{-2}$, and with the baseline removed as described above) for each station are shown in Figures 3.1 to 3.20.

Instrument calibrations are not included as they typically show only a few tenths of percent deviation from the nominal values. Removal of the instrument response was not considered necessary; signal frequencies range to about 20 Hz, while accelerograph eigen-frequencies are 600 Hz for the SSA-2's and ETNA's, and 50 Hz for the PGC SSA-1.

Tabulated peak ground accelerations for all stations are given in Table 4.

Discussion

This Open File report documents the largest strong ground motion data set ever collected in southwestern British Columbia, and the first set that includes bedrock recordings in the greater Vancouver area. Strong ground motion acceleration records of a M_W=4.3 earthquake have been collected at 19 locations; 14 on the lower mainland, three on southern Vancouver Island, and two on central Vancouver Island. In the greater Vancouver area, six of the triggered sites are thick soil sites on the Fraser Delta; two are firm soil sites on upland areas north of the river, one is on landfill in False Creek, and three are bedrock recordings, including one less than 3 km from the Fraser River Delta.

The amplification at soil sites at frequencies near 1-3 Hz described by Cassidy et al. (1997) for the 1996 Duvall Washington earthquake is clearly visible in these data as well. In Figure 4 we compare recordings of the Georgia Strait earthquake made at BLO (the closest bedrock site to the Fraser River delta - only 3 km north of the delta), CSQ (a bedrock site beneath downtown Vancouver, 8 km north of the delta), MNY (at the north edge of the delta), and RHA and DEA (both thick soil sites near the middle of the delta). The recordings made at the soil sites are clearly amplified relative to the bedrock recordings BLO and CSQ. Note that CSQ has an amplitude about double that of BLO, this is likely due to the instrument at CSQ being located on soft sandstone. Note the similarity of the waveform shape for the rock sites and the soil sites. A close-up of the S-wave at BLO and MNY is shown in Figure 4 (right). The key difference between these waveforms is that the MNY amplitude is about 7 times greater than that of the BLO waveform.

The Fourier amplitude spectra for the waveforms shown in Figure 4 are given in Figure 5. The spectra have been smoothed using an 11-point running-mean filter with a width of 0.48 Hz. The rock sites have the lowest amplitude, as expected. The MNY spectra has the highest peak (as was the case for the Duvall earthquake), but for this earthquake it is only slightly larger than for the delta centre site RHA. Both of the deep soil sites RHA and DEA have a broader peak than MNY. As was observed for the Duvall earthquake, most of the amplification occurs between about 1 and 5 Hz. Note that the BLO recording is of very low amplitude (just above the bit level noise). The low-frequency (<1.5 Hz) shoulder in the BLO spectra (Figure 5, 6) is likely an artifact of this low signal level; energy in the 1.5-15 Hz range is well-defined, even at low signal levels. This was demonstrated by comparing coincident well-recorded broadband records with bit-level strong motion records (Cassidy, 1998).

All three of the Ministry of Transportation and Highways strong motion instruments at the George Massey Tunnel were triggered by this earthquake. It is noteworthy that the strongest shaking was recorded by the surface instrument at the south end of the tunnel (Fig. 3.15) with a peak acceleration of 0.9%g. The two instruments at depth (near the middle of the tunnel) recorded a peak acceleration of 0.5%g, and lacked the high-frequency energy observed in the surface recording (Fig. 3.16, Fig. 3.17).

Another observation in this data set is the significant variation in frequency content of some recordings. For example, compare waveforms for the stations CLE, PGC, BLO, and MNY (Figure 6). The CLE record is clearly dominated by high frequency energy. Note that the peak horizontal acceleration of 1.8%g recorded at the bedrock site CLE is anomalously high compared to other rock sites (0.2%g for BLO, 0.2%g for PGC, and 0.5%g for CSQ - see Figures 1 and 2). The spectra (Figure 6 - right) show that the CLE waveform is dominated by 15-20 Hz energy, compared to about 2-3 Hz for MNY. This is most likely a site effect at CLE - the instrument here is located on a concrete floor on the shoulder of the Cleveland dam. The PGC spectra reveals a peak near 9-10 Hz. This peak is also observed in the 1996 Duvall recording and also is likely a site effect at PGC. The differences between the three bedrock spectra shown here serve to remind that care must be used in the choice of a reference "rock" spectra for use in calculating the response of the Fraser Delta soil sites. Note that crystalline rock sometimes exhibits high-frequency amplification; this is most likely due to weathering and fracturing in the near-surface (see Steidl et al., 1996).

The June 1997 Strait of Georgia earthquake has provided the largest single strong-motion data set in southwestern British Columbia to date, and the first bedrock recordings in the greater Vancouver area. Analyses of these records will provide for improved estimates of site response on the Fraser River delta. In addition, a comparison of the recordings of this earthquake to those of the 1996 Duvall Washington, and 1976 Pender Island earthquakes will provide valuable insight into the variation of site response with earthquake type (deep oceanic plate vs shallow crustal earthquakes) and direction of approach.

Acknowledgements

We thank Ken Beverley, Richard Baldwin, John Carter, and Taimi Mulder for their assistance in collecting, and processing these strong motion data. We thank the B.C. Ministry of Transportation and Highways for allowing us to include their data in this report. A thorough review of this manuscript by John Adams is gratefully acknowledged. Figure 1 was generated using Generic Mapping Tools (GMT, Wessel and Smith, 1995). Thanks to Robert Kung for preparing Figure 2.

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Table 1 - Geological Survey of Canada Strong Motion Seismograph Sites

	ABBV.	DISTANCE (km)	AZIMUTH	COORD	INSTR	SENS	TRIGGER	LAXIS	TAXIS	BUILDING	FOUNDATION
Lower Mainland											
Matsqui Clearbrook Public Library		96.8	102	49.0618 122.3257	SSA-2	1 g	0.004 g	338	68	Two-storey reinforced concrete. Instrument on concrete floor slab.	Sand and gravel at surface. At least 100m to bedrock.
Langley Langley Municipal Hall		74.4	102	49.0959 122.6223	SSA-2	1 g	0.004 g	23	113	One-storey wood frame. Instrument on reinforced concrete basement floor slab.	Clay at surface. At least 150m to bedrock.
Delta Roberts Bank Sea Port		41.0	127	49.0181 123.1699	SSA-2	1 g	0.004 g	48	138	Small Hut. Instument on concrete slab.	Silt fill on 100m alluvium. 500m to bedrock.
Annacis Island Industrial Estates	ANN	50.7	97	49.1811 122.9291	SSA-2	1 g	0.004 g	203	293	One-storey building. Instrument on concrete slab.	100m of alluvium. 250m to bedrock.
Richmond Deas Dock	DEA	41.2	108	49.1257 123.0816	SSA-2	1 g	0.01 g	72	162	Two-storey wood frame. Instrument on concrete floor slab.	150m of alluvium. 600m to bedrock.
Haney UBC Forestry Research Center		61.0	83	49.3226 122.5126	SMA-1	1 g	0.01 g			Small vault. Instrument on bedrock outcrop.	Bedrock
Richmond Richmond City Hall	RHA	36.2	103	49.1636 123.1363	SSA-2	1 g	0.004 g	280	10	Two-storey structure. Instrument on concrete floor slab.	300m of alluvium. 800m to bedrock.
Vancouver Manitoba City Yard	MNY	37.2	95	49.2097 123.1103	SSA-2	1 g	0.004 g	188	278	Two-storey steel frame, masonry walls. Instrument on concrete floor slab over pile foundation.	2-3m of alluvium over 10m of till over sand. 200m to bedrock.
Vancouver Bloedel Conservatory	BLO	36.9	90	49.2414 123.1123	SSA-2	1 g	0.002 g	195	285	Triodetic dome structure 15m high and 43m in diameter. Instrument on concrete foundation.	Bedrock
Vancouver UBC Metals and Materials Lab		27.2	84	49.2631 123.2473	SSA-2	1 g	0.004 g	156	246	Two-storey. Instrument on concrete floor slab.	Sand. 100m to bedrock.
Vancouver Cleveland Dam	CLE	40.8	71	49.3606 123.1089	SSA-2	1 g	0.002 g	21	111	Concrete gravity dam 91m high. Instument at end of gallery on concrete floor directly above bedrock.	Bedrock
Sechelt		57.6	338	49.7200 123.9200	SMA-1	1 g	0.01 g				
Southern / Central Vancouver Island											
Victoria University of Victoria		89.4	165	48.4636 123.3066	SMA-1	1g	0.01 g	11	281	Three-storey reinforced concrete. Foundation part reinforced concrete footings, part 'Franki' piles.	Gravelly sand
Victoria Law Courts Building		93.2	166	48.4200 123.3600	SMA-1	1g	0.009 g	285	195	Five-storey reinforced concrete. Instrument on concrete basement floor slab.	Bedrock
Sidney Pacific Geoscience Center	PGC	66.8	169	48.6509 123.4486	SSA-1	2 g	0.001 g	0	90	Buried concrete seismic vault. Instrument on concrete pier.	Bedrock
Saturna Island		60.8	147	48.7800 123.1700	SMA-1	1 g	0.009 g			Instrument in small vault.	Bedrock
Duncan Cowichan District Hospital		53.9	188	48.7860 123.7226	SMA-1	1 g	0.01 g	11	281	Varying from one to six storeys, reinforced concrete. Instrument on pier on concrete footing at basement level.	Sand and gravel at surface. At least 25m to bedrock.
Cowichan Lake Teleglobe Canada	CTL	55.2	217	48.8432 124.0740	SMA-1	1 g	0.01 g	180	270	One-storey structure next to earth station antenna. Instrument on concrete floor slab.	At least 20m of dense sandy gravelly till.
Nanaimo		24.6	252	49.1700 123.9400	SMA-1	1 g	0.009 g	85	355	One-storey wood frame. Instrument on concrete floor slab.	Bedrock
Port Alberni Pulp and Paper Mill		86.5	271	49.2400 124.8100	SMA-1	1 g	0.008 g	271	181	Two-storey reinforced concrete. Instrument on concrete floor over a stiff cellular substructure built on wood piles.	Sand and gravel at surface.
Port Alberni Maquinna Elementary School		86.1	270	49.2300 124.7900	SMA-1	1 g	0.009 g	91	1	One-storey wood frame. Instrument on concrete basement floor slab.	Bedrock
Comox St. Joseph's School		106.8	297	49.6700 124.9400	SMA-1	1 g	0.009 g	181	91	Four-storey reinforced concrete. Instrument on concrete pier at ground level.	Glacial till

Table 2 - B.C. Hydro Strong Motion Seismograph Sites

	ABBV.	DISTANCE (km)	AZIMUTH	COORD	INSTR	SENS	TRIGGER	LAXIS	TAXIS	BUILDING	FOUNDATION
Lower Mainland											
Tsawwassen English Bluff Terminal		46.6	123	49.006 123.09	SSA-2	2 g	0.004g	0	90	On concrete floor slab of one-storey building.	Till at surface. 600m to bedrock.
Vancouver Cathedral Square Substation	CSQ	37.1	82	49.283 123.114	SSA-2	2 g	0.004g	46	136	On lowest level of a three-storey underground substation (17m underground).	Tertiary sandstone and shale.
Vancouver Murrin Substation	MUR	38.0	83	49.2783 123.1018	ETNA	2g	0.004g	180	270	On concrete pad within electrical switchyard	Reclaimed tidal flats - several metres of sandy deposits over dense till
Ladner Arnott Substation	ARN	46.2	111	49.091 123.042	SSA-2	2 g	0.004g	90	180	On concrete floor slab of one-storey building.	250m of alluvium. 750m to bedrock.
Delta Canoe Pass Terminal		38.9	116	49.052 123.121	ETNA	2g	0.004g	225	315	On concrete pad within electrical switchyard (Out of service at time of earthquake)	100m of deltaic deposits over dense till
Surrey Ingledow Substation		66	99	49.158 122.874	SSA-2	2 g	0.004g	90	180	On spare concrete equipment footing within electric switchyard.	At least 2m of very dense silt, sand and gravel till. 400m to bedrock.
Maple Ridge Alouette Dam		82.6	96	49.287 122.486	SMA-1	1 g	0.01g			On concrete pad on crest of earth fill dam.	Earth fill dam
Coquitlam Meridian Substation	MDN	87.1	84	49.309 122.906	SSA-2	2 g	0.004g	305	35	On concrete footing within electrical switchyard.	At least 7m of very dense silty sandy till.
Burnaby Barnard Substation	BND	52.4	87	49.263 122.899	SSA-2	2 g	0.004g	180	270	On spare concrete equipment footing within electrical switchyard	Very dense sandy till.
Richmond Kidd#2 Substation	KID	37.0	97	49.199 123.114	SSA-2 SSA-2	2 g 2 g	0.004g 0.004g	0 0	90 90	1) On concrete pad in electric switchyard 2)In drillhole about 20m deep (Out of service at time of earthquake.)	40m of alluvium. At least 200m to bedrock.
Coquitlam Coquitlam Dam		62.7	78	49.364 122.776	SMA-1	1 g	0.01g			1) On concrete pad on crest of earth fill dam. 2) On concrete pad on dam abutment.	Earth fill dam Bedrock
Sechelt Malaspina Substation		40.0	336	49.670 123.960	ETNA	2g	0.004g	180	270	On concrete floor slab of one-storey building. (Out of service at time of earthquake)	About 4m of sand and gravel over bedrock
Squamish Cheekeye Substation	CKY	69.9	26	49.7916 123.157	ETNA	2g	0.004g	90	180	On concrete pad within electrical switchyard	Dense sand and gravel
Southern/Central Vancouver Island											
Victoria Esquimalt Substation		91.1	169	48.436 123.394	SSA-2	2 g	0.006g	0	90	On spare concrete equipment footing within electric switchyard.	Up to 8m of clay over bedrock.
Victoria George Tripp Substation	GTP	87.3	167	48.474 123.368	SSA-2	2 g	0.006g	79	169	On spare concrete equipment footing within electric switchyard.	20m of silty clay over till. Bedrock outcrops nearby.
Victoria Goward Substation		84.3	170	48.494 123.419	SSA-2	2 g	0.006g	92	182	On spare concrete equipment footing within electric switchyard.	Several metres of silt or clay overlying bedrock.
Victoria Pike Lake Substation		84.0	172	48.492 123.458	SSA-2	2 g	0.006g	0	90	On concrete floor slab of one-storey building.	Up to 3m of silt overlying bedrock.
Victoria Horsey Substation				48.443 123.366	ETNA	2g	0.006g			On spare concrete equipment footing within electric switchyard. (Out of service at time of earthquake).	Up to 15m of clay overlying bedrock
Jordon River Dam		96.6	199	48.430 124.061	SMA-1	1 g	0.01g			1) On concrete pad at toe of dam. 2) On buttress of dam.	1) Bedrock 2) Concrete buttress dam
Duncan Vancouver Island Terminal		46.5	188.6	48.827 123.716	SSA-2	2 g	0.006g	0	90	On concrete floor slab of small one-storey building.	Up to 3m of dense sandy, gravelly till overlying bedrock.
Nanaimo Lantzville Substation	LTZ	33.1	266	49.227 124.074	SSA-2	2g	0.006g	230	320	On concrete pad within electrical switchyard	about 1m of gravelly sand overlying very dense sandy silty till
Bowser Dunsmuir Substation	DMR	78.4	283	49.3936 124.6719	SSA-2	2g	0.006g	326	56	On concrete floor slab of one-storey building.	about 3m of dense sand overlying bedrock
Campbell River John Hart Dam		131.9	291	50.0399 125.337	SSA-1	1g	0.01g	296	206	On concrete pad and within steel housing on earth fill dam	earth fill dam
Campbell River John Hart Dam		131.9	291	50.0399 125.337	SSA-1	1g	0.01g	297	207	Instrument in spillway of concrete dam	bedrock

Table 3 - B.C. Ministry of Highways and Transportation Strong Motion Seismograph Sites

	ABBV.	DISTANCE (km)	AZIMUTH	COORD	INSTR	SENS	TRIGGER	LAXIS	TAXIS	BUILDING	FOUNDATION
Lower Mainland											
Richmond George Massey Tunnel	MT1	41	109	49.117 123.083	K2	2 g	0.01g	270	0	South end of tunnel ground level.	30m sand fill, 150m of alluvium 600m to bedrock
Richmond George Massey Tunnel	MT2	41	109	49.118 123.083	FBA-2	2 g	0.01g	180	270	Near 1/3 length of tunnel (30m N of the joint between the south-most and next segment)	sand fill, 150m alluvium 600m to bedrock
Richmond George Massey Tunnel	MT3	41	109	49.119 123.083	FBA-2	2g	0.01g	180	270	Near mid-tunnel (0.3m n of the centre joint)	sand fill, 150m alluvium 600m to bedrock
New Westminster Queensborough Bridge		49	96	49.197 122.946	K2	2 g	0.03g	55	145	Ground level sensor	~6m of loose silty sand till at about 30m
New Westminster Queensborough Bridge		49	96	49.197 122.946	FBA-2	2 g	0.005g	55	145	12 m below ground level	till at about 30m
New Westminster Queensborough Bridge		49	96	49.197 122.946	FBA-2	2g	0.03g	145	55	mounted on column at base of pier S3	~6m of loose silty sand till at about 30m
Central Vancouver Island											
Parksville French Creek Bridge		62	280	49.317 124.317	K2	2 g	0.015g	217	307	South abutment	2m firm-hard silty clay over 16-19m dense/very dense sand/gravel
Parksville French Creek Bridge		62	280	49.317 124.317	FBA-2	2 g	0.015g	127	217	Base of Pier No. 3	
Parksville French Creek Bridge		62	280	49.317 124.317	FBA-2	2g	0.015g	217	307	North abutment	7m firm silt and compact sand over dense/very dense soil
Parksville French Creek Bridge		62	280	49.317 124.317	FBA-2	2g	0.015g	307	217	outermost girder close to north abutment	7m firm silt and compact sand over dense/very dense soil

Table 4 Peak Acceleration

Site	Soil Type	Distance	Azimuth	Unfiltered Acceleration		
		km	degrees	cm.s^{-2}		
				L	V	T
ANN	90 m of alluvium 200 m to bedrock	51	97	-8.6	-2.8	4.9
ARN	250m of alluvium. 750m to bedrock.	45	111	-6.5	dead	-17.2
BLO	Tertiary bedrock	37	90	-2.1	-1.5	2.3
BND	Very dense sandy till.	52	87	-3.9	-2.0	5.2
CKY	dense sand and gravel	70	28	13.2	10.0	11.5
CLE	bedrock	41	71	-18.1	14.4	-12.1
CSQ	tertiary sandstone and shale 17 m underground	37	82	-4.5	2.6	-4.6
CTL	>20 m dense sandy gravelly till	55	217	16.7	10.8	18.6
DEA	150 m of alluvium 500 m to bedrock	41	108	8.8	-2.5	-14.4
DMR	about 3 m of dense sand overlying bedrock	78	283	-8.6	-2.4	7
GTP	20m of silty clay over till. Bedrock outcrops nearby.	87	167	7.6	-5.8	-8.6
KID	40m of alluvium. 200m to bedrock.	37	97	22.9	4.9	13
LTZ	about 1 m of gravelly sand over very dense sandy till	33	268	-20.9	10.0	-20.1
MDN	At least 7m of very dense silty	87	84	9	3.5	3.4
MNY	sandy till. 2-3 m of alluvium over 10 m of till	37	95	-13.5	-5.2	8.6
MT1	Sand fill on 150m of alluvium 600 m to bedrock instrument at south end of tunnel	41	109	-8.7	-2.7	8.2
MT2	Sand fill on 150 m alluvium 600 m to bedrock instrument at 1/3 length tunnel	41	109	-4.3	-0.8	-4.9
MT3	Sand fill on 150 m of alluvium 600 m to bedrock instrument at mid-tunnel	41	109	-4.1	-0.8	-3.9
MUR	reclaimed tidal flats several m of sandy deposits overlying dense till	38	83	23.8	12.6	23.9
PGC	granitic bedrock	67	169	-1.9	1.0	-1.2
RHA	300m of alluvium. 800m to bedrock	36	103	7.7	-2.9	15.9

Figure Captions

Figure 1: Map showing the location (star) and focal mechanism of the M_W=4.3 Georgia Strait earthquake, and the locations of the strong ground motion sites in this region operated by the Geological Survey of Canada (squares), B.C. Hydro (circles), and the B.C. Ministry of Transportation and Highways (triangles). Solid symbols denote stations that triggered, open symbols indicate stations that did not trigger, and shaded symbols are stations that were not operational at the time of the earthquake (the memory had filled with noise triggers). Station codes and peak horizontal acceleration (in units of cm.s^{-2}) is given for each station that triggered. The trigger threshold is given for those stations that did not trigger - as this represents the upper limit on peak acceleration at these sites. The box indicates the area shown in Figure 2. Epicentral distances of 50 km and 100 km are denoted by the dotted circles.

Figure 2: The Lower Mainland region showing station locations. The hatched area indicates the Fraser River Delta. Solid symbols with station names are those sites which triggered, and data are presented in this report. For those stations that triggered, the peak horizontal acceleration is given (in cm.s^{-2}); the trigger threshold is given for those stations that did not trigger. Shaded symbols denote stations that were not operational at the time of the earthquake due to noise triggers.

Figures 3.1-3.20: Unfiltered acceleration records in units of cm.s^{-2}, listed in alphabetical order of 3-letter station code. L and T are orientations listed in Tables 1, 2, and 3.

Figure 4: Comparison of strong motion records for the granitic bedrock site BLO to the bedrock (sandstone) site CSQ, and the soil site recordings at MNY (north edge of the delta), RHA and DEA (both thick soil sites near the centre of the delta). These records are the "L" components at each site except RHA - which is the "T" component - all of these components are oriented approximately N-S. Note that the bedrock recording at BLO is very similar to the soil recording at MNY - but has an amplitude about one seventh that at MNY (right). The bit level noise is clearly visible in the low-amplitude BLO recording.

Figure 5: Acceleration Fourier spectra of the waveforms shown in Figure 4. The spectra have been smoothed with a 0.48 Hz width running mean filter. The MNY spectra is slightly narrower than the other two soil sites, and has a slightly higher peak.

Figure 6: Strong motion "L" component recordings in units of cm.s^{-2} (left), and corresponding Fourier amplitude spectra (right) showing the variation in frequency content of the waveforms at three rock sites (CLE, PGC, and BLO) and a soil site (MNY) at the edge of the Fraser River Delta. The CLE recording has a very high peak horizontal acceleration of 1.8%g compared to the other bedrock sites, however the spectra here clearly show that this is dominated by high-frequencies that likely represent a site effect. At PGC, the peak in the spectra is near 10 Hz. A similar peak in the Duvall earthquake spectra suggest that this also is a local site response. The frequency content of the recording at the rock site BLO is similar to that of the soil site MNY (and other soil sites, not shown).

Figure 1 - STRONG GROUND MOTION SITES

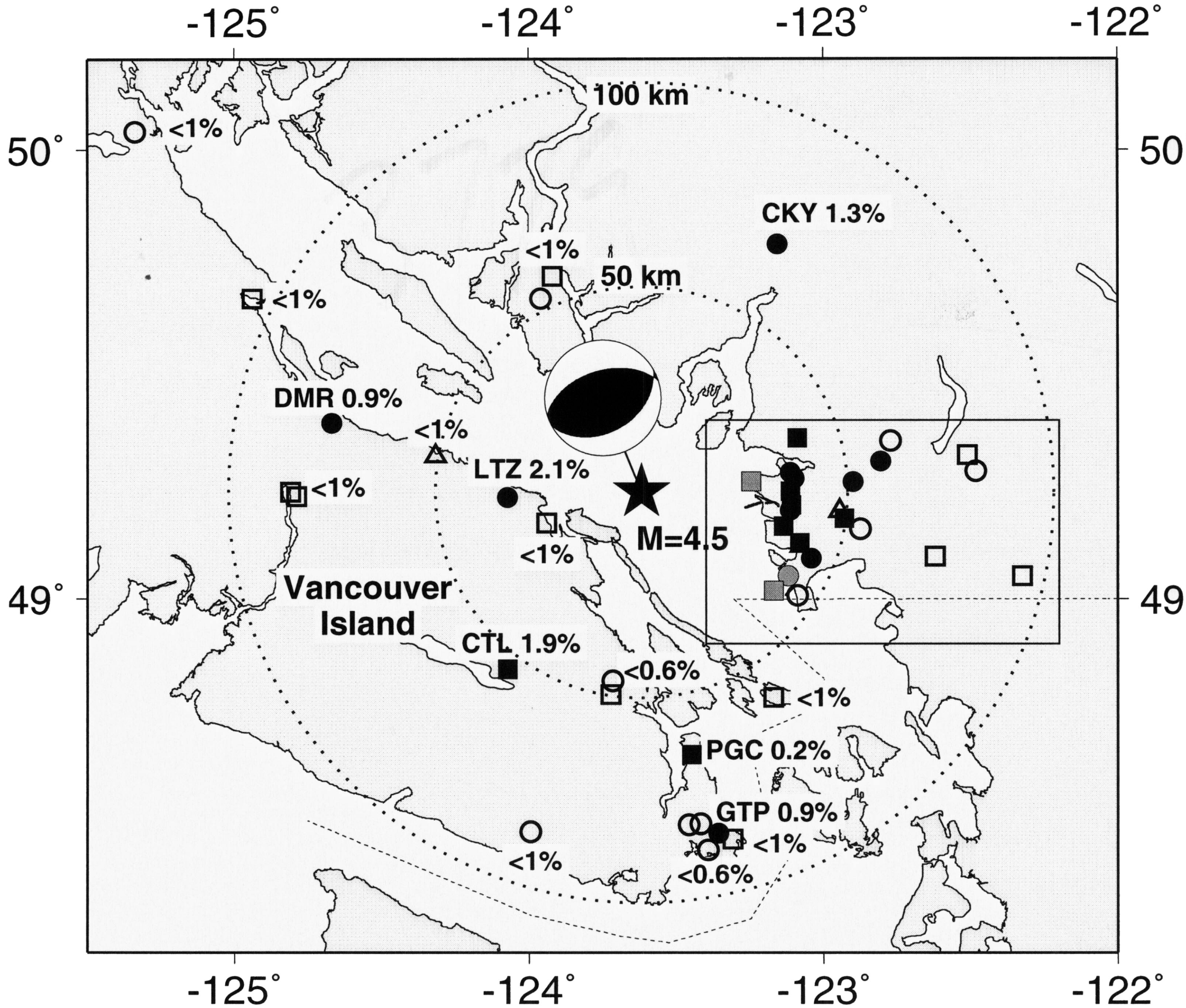


Fig 2

FIGURE 2

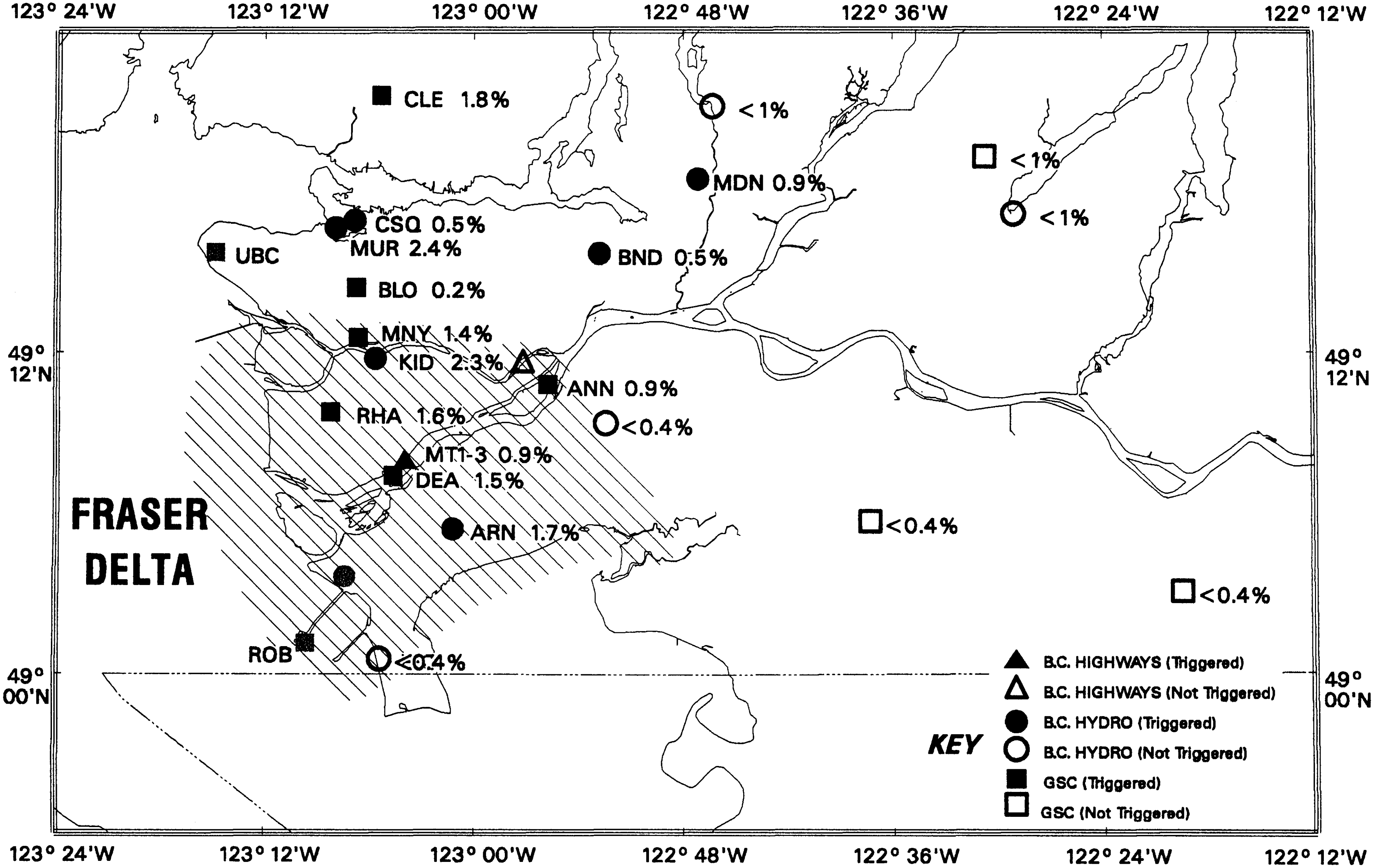


Fig. 3.1 ANN Unfiltered Acceleration Waveforms

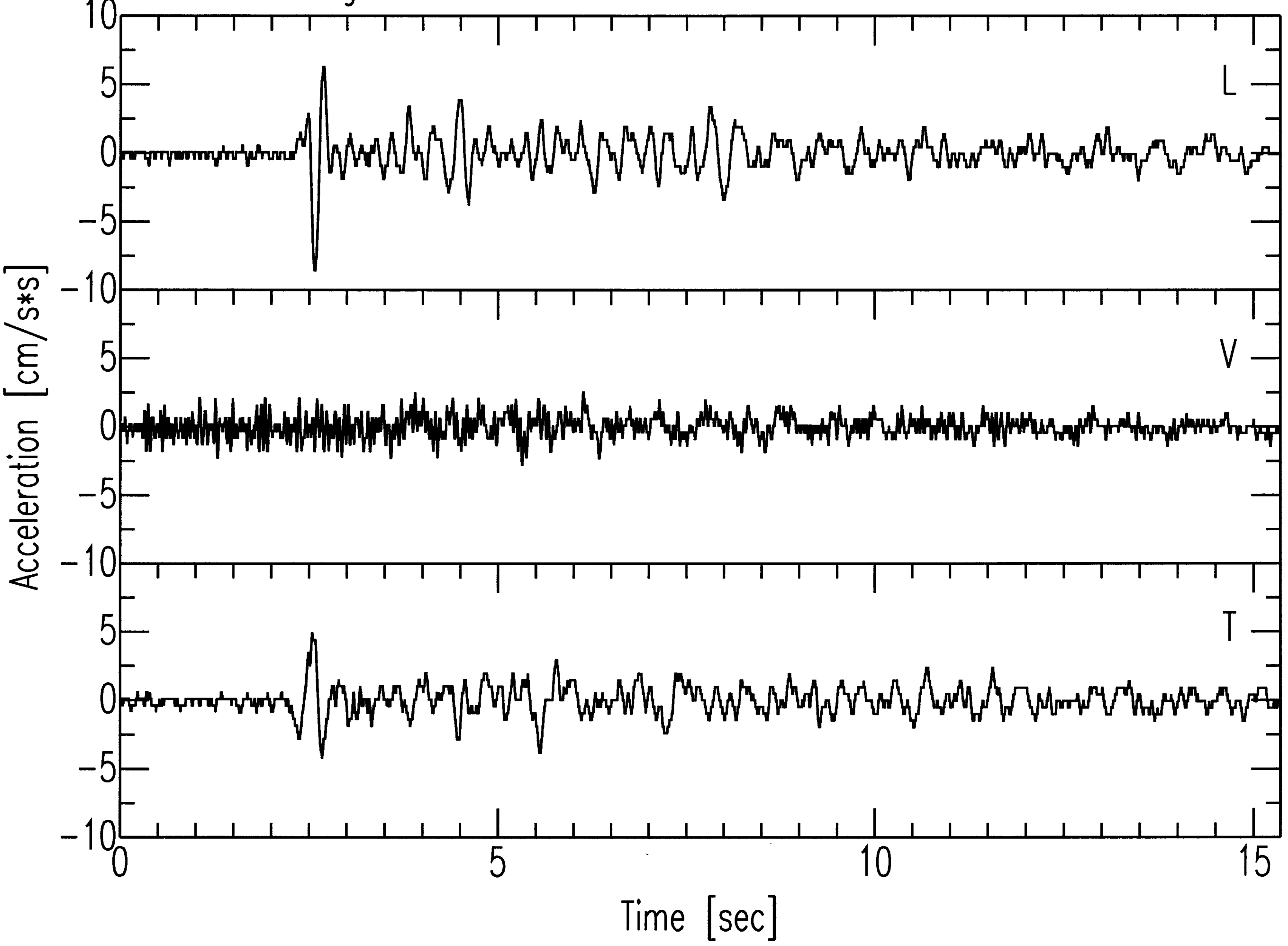


Fig. 3.2 ARN Unfiltered Acceleration Waveforms

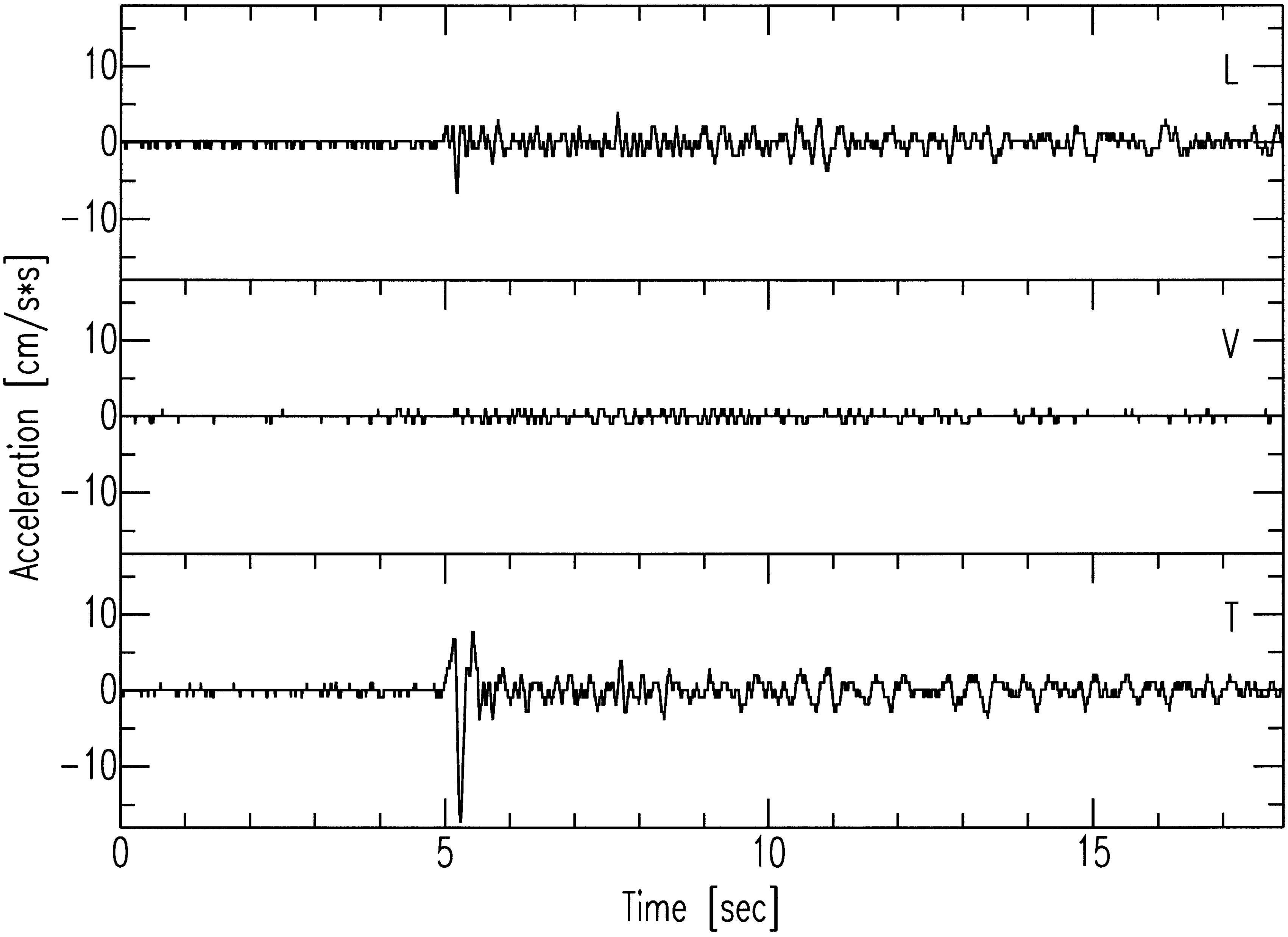


Fig. 3.3 BLO Unfiltered Acceleration Waveforms

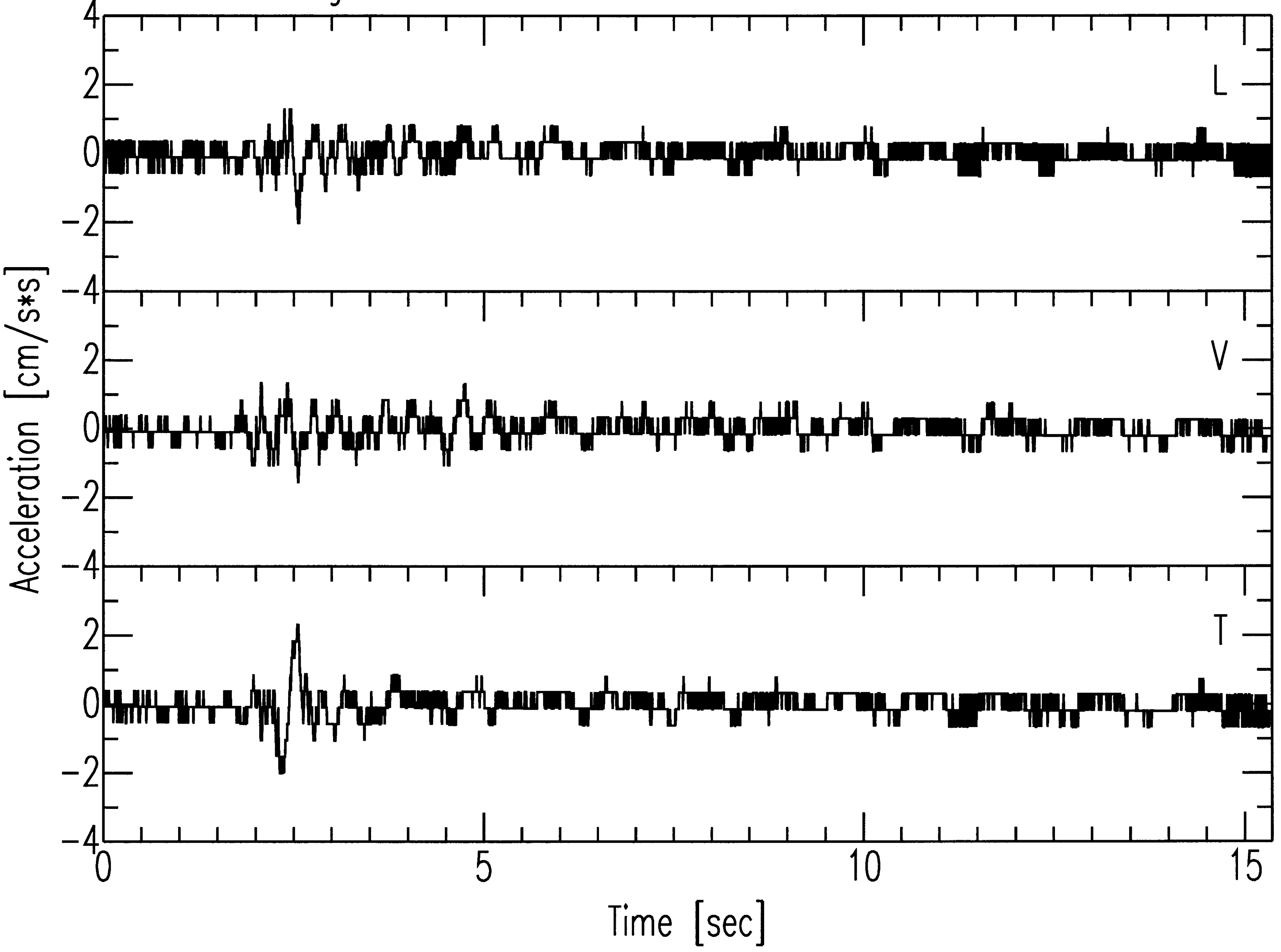


Fig. 3.4 BND Unfiltered Acceleration Waveforms

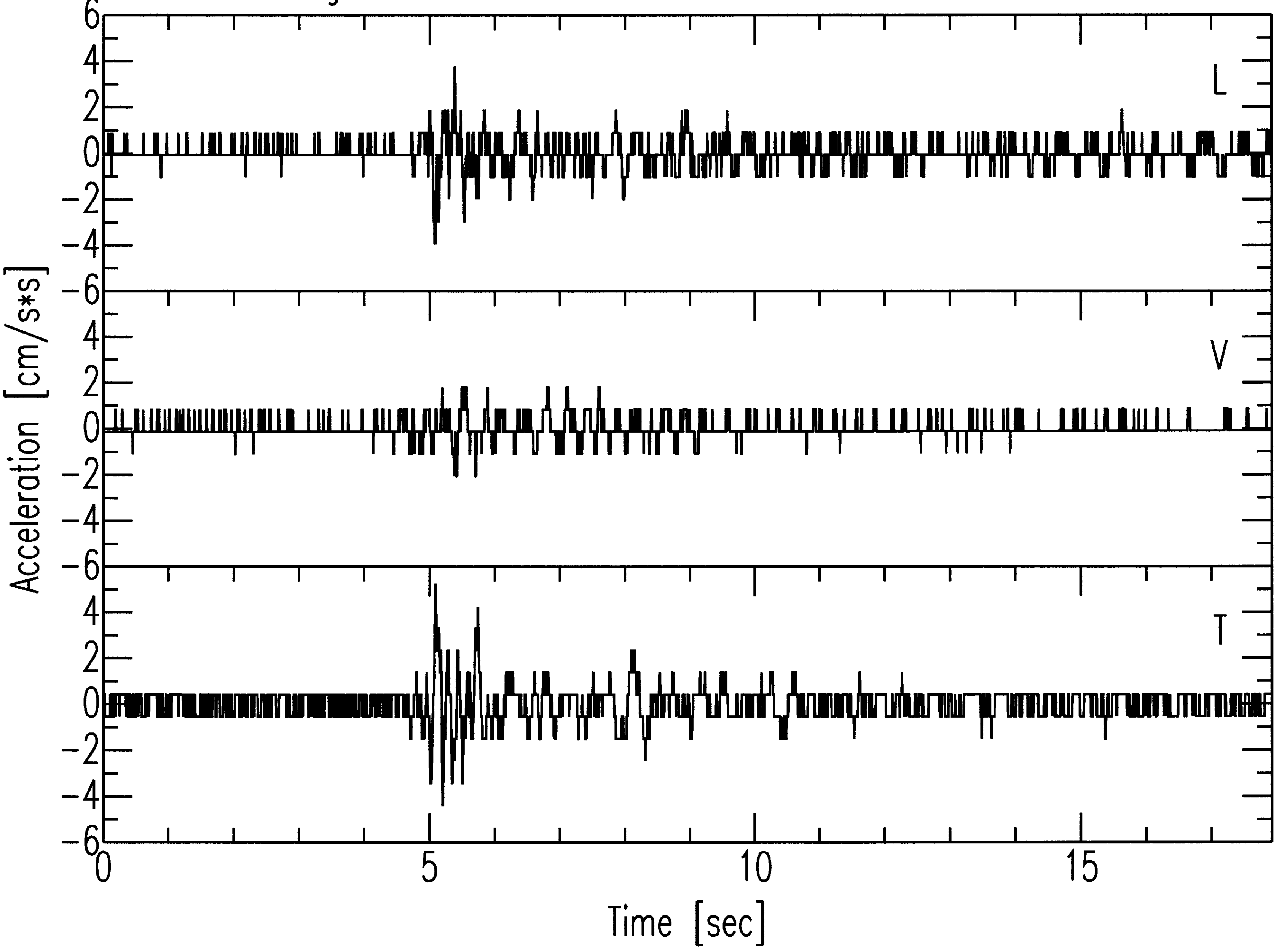


Fig. 3.5 CKY Unfiltered Acceleration Waveforms

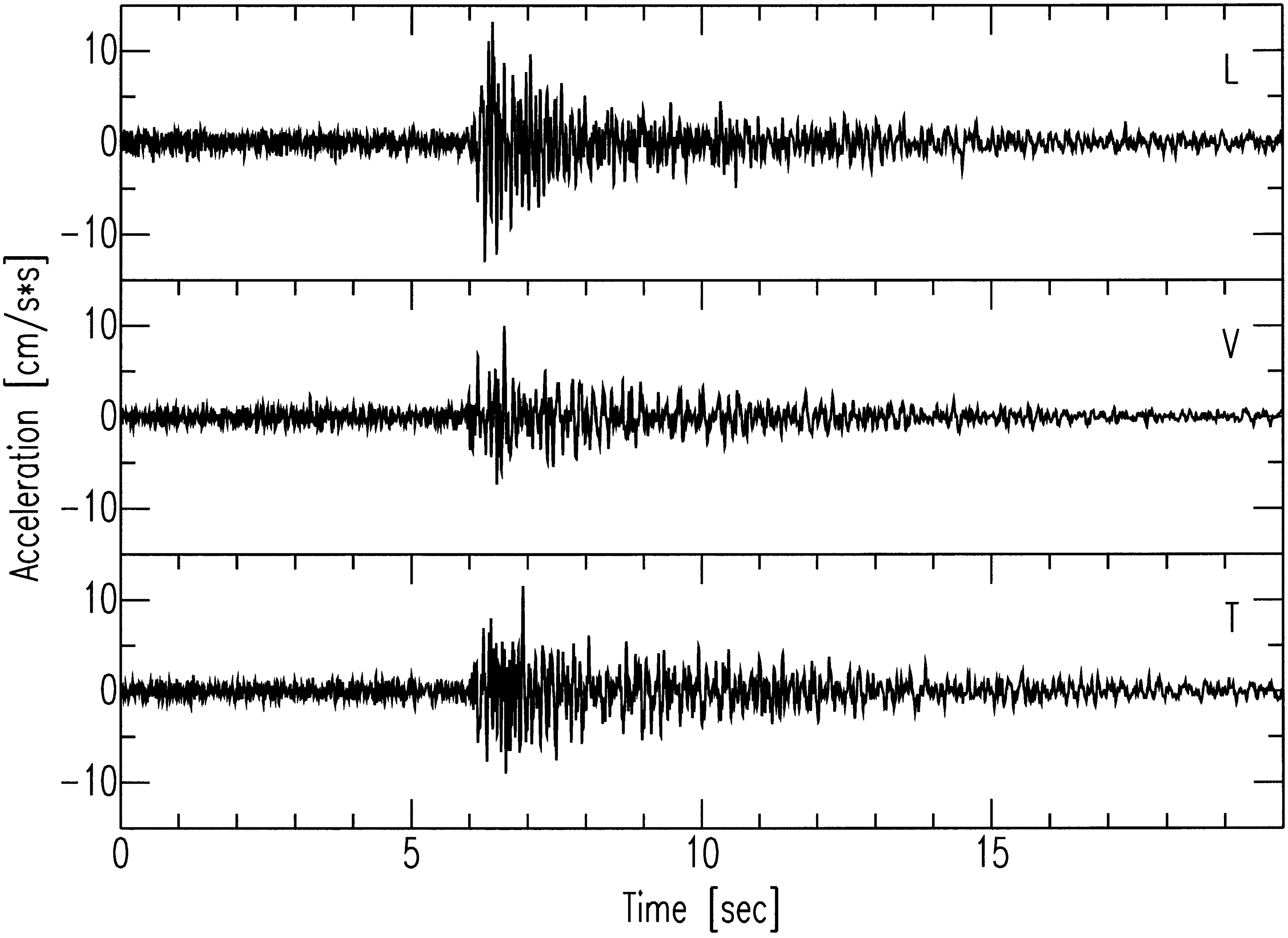


Fig. 3.6 CLE Unfiltered Acceleration Waveforms

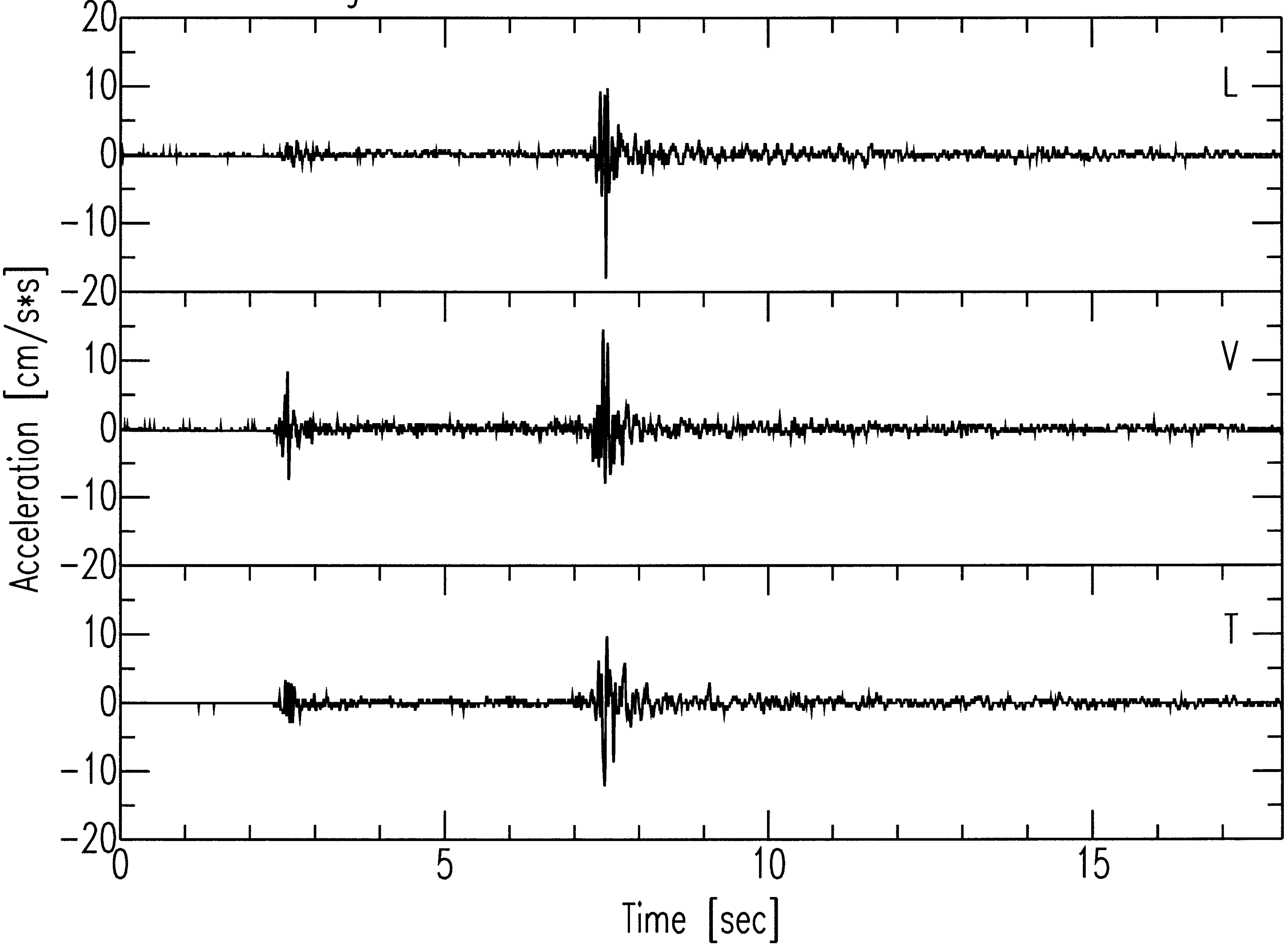


Fig. 3.7 CSQ Unfiltered Acceleration Waveforms

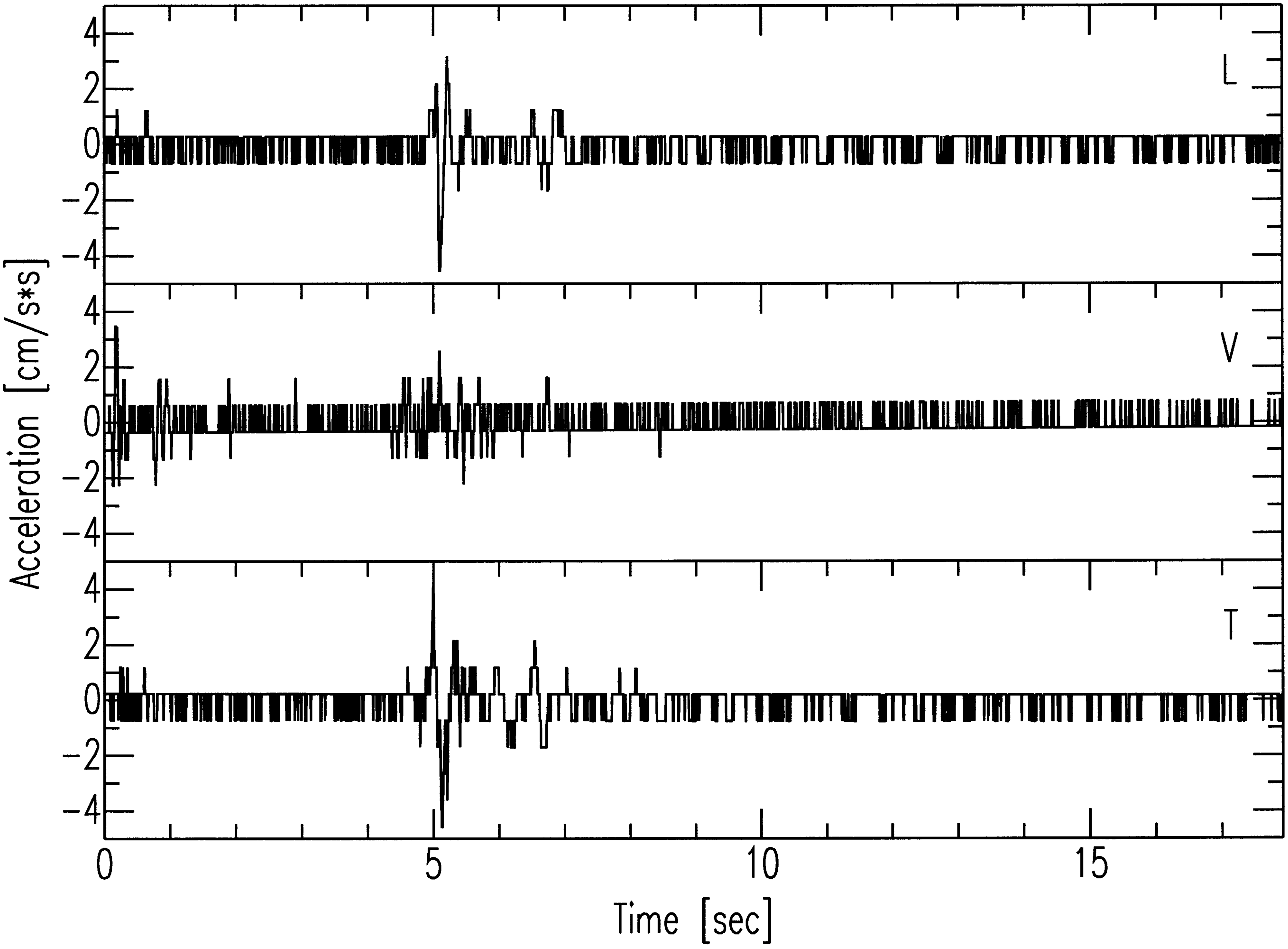


Fig. 3.8 DEA Unfiltered Acceleration Waveforms

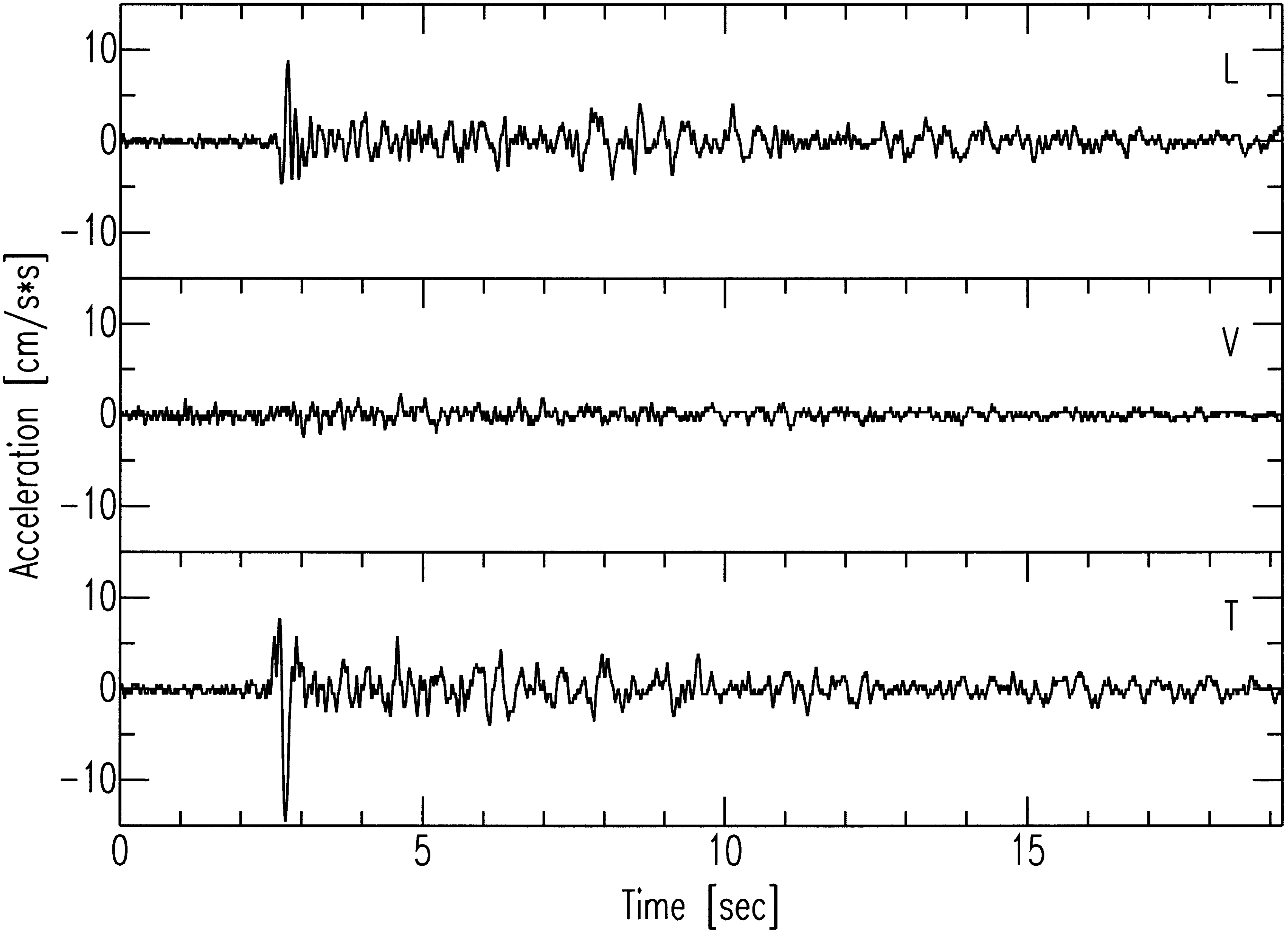


Fig. 3.9 DMR Unfiltered Acceleration Waveforms

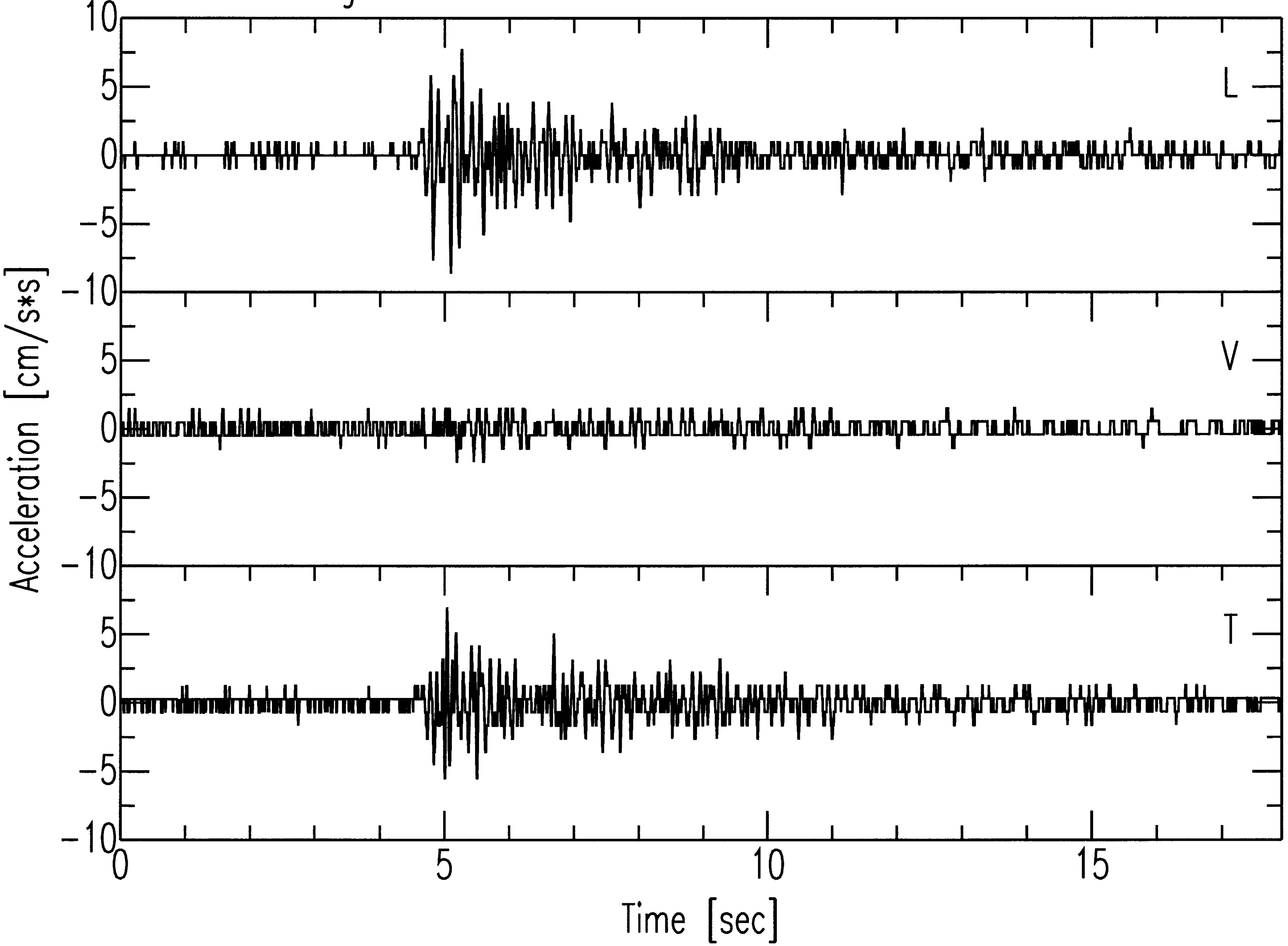


Fig. 3.10 GTP Unfiltered Acceleration Waveforms

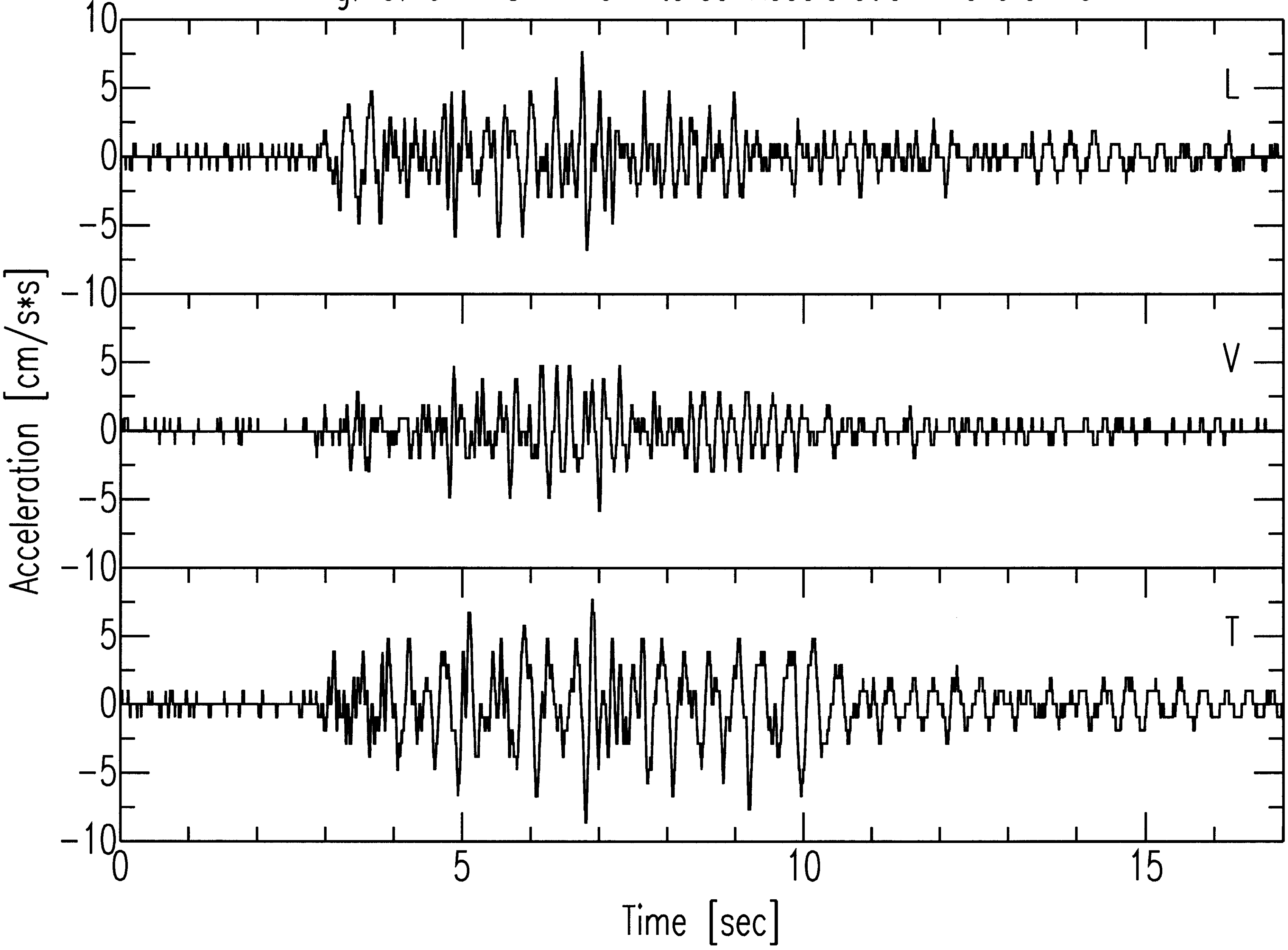


Fig. 3.11 KID Unfiltered Acceleration Waveforms

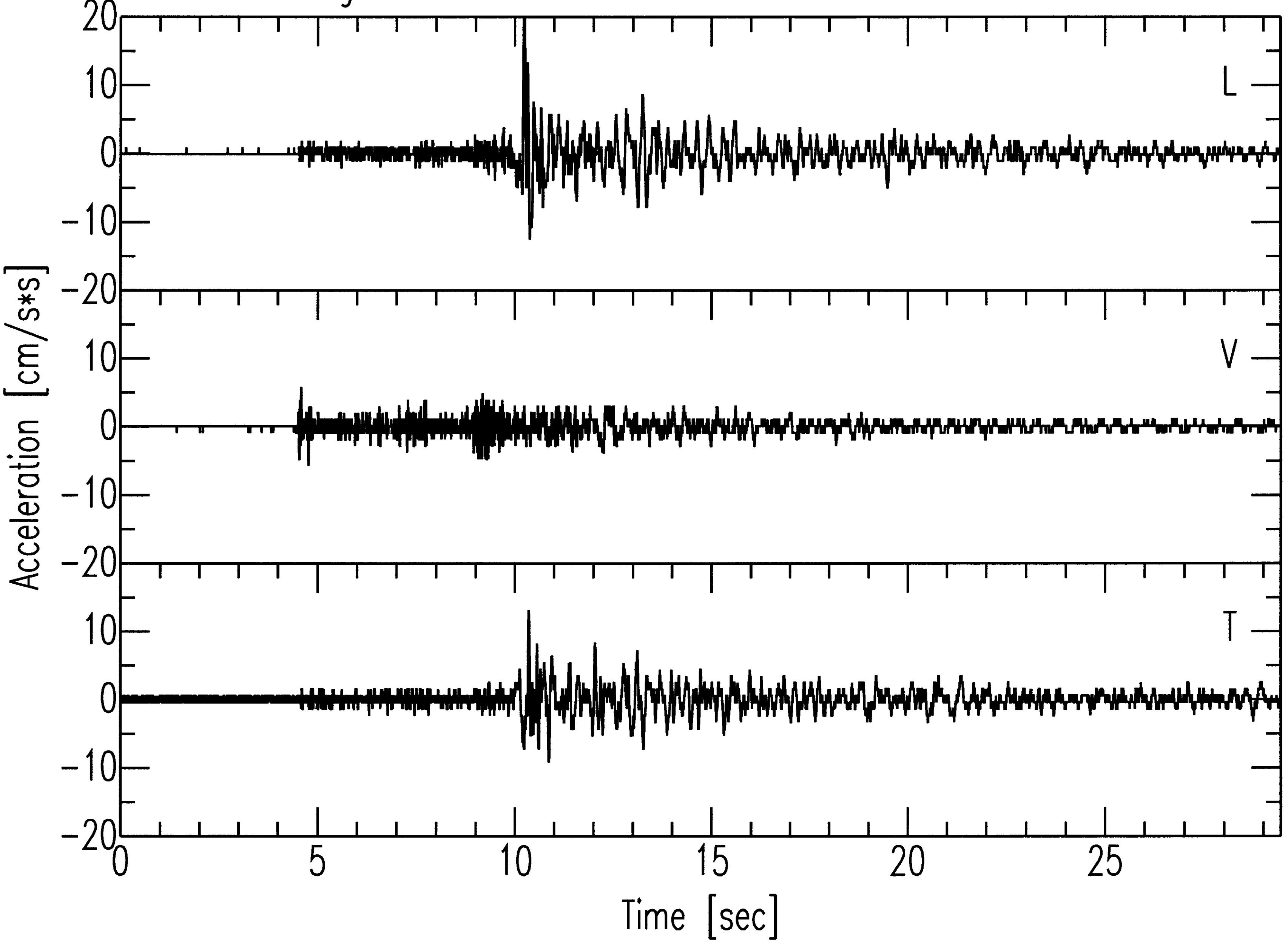


Fig. 3.12 LTZ Unfiltered Acceleration Waveforms

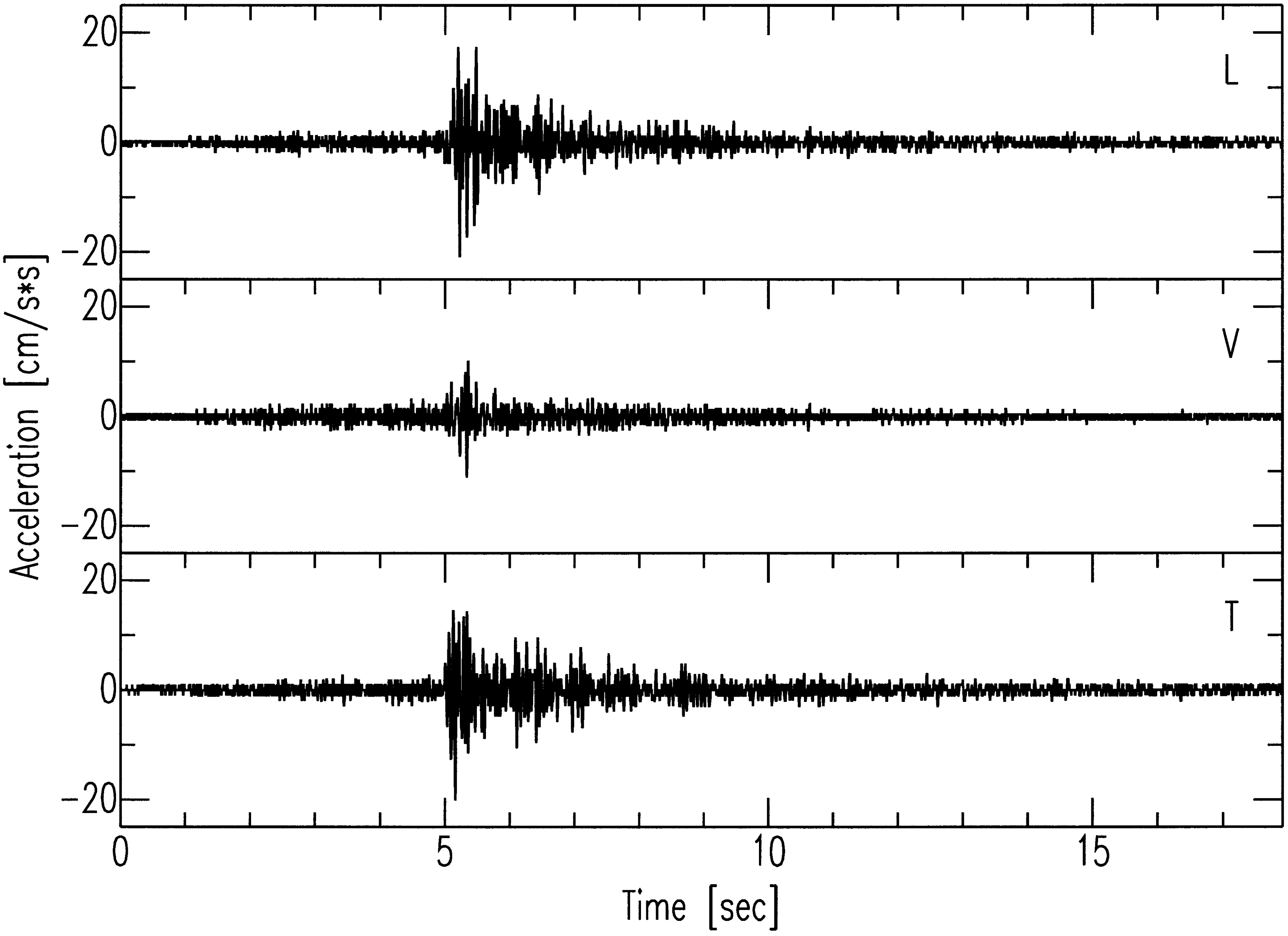


Fig. 3.13 MDN Unfiltered Acceleration Waveforms

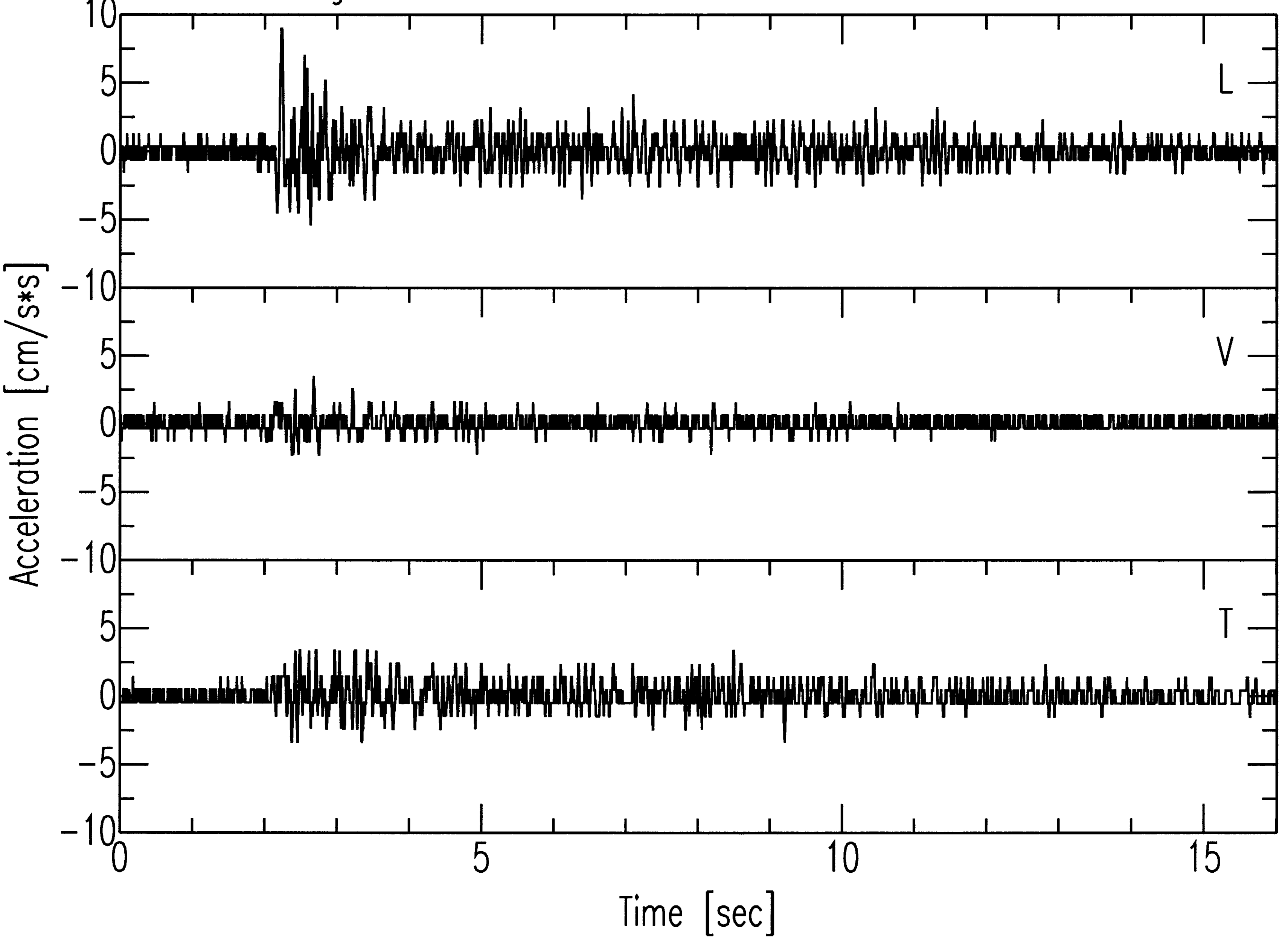


Fig. 3.14 MNY Unfiltered Acceleration Waveforms

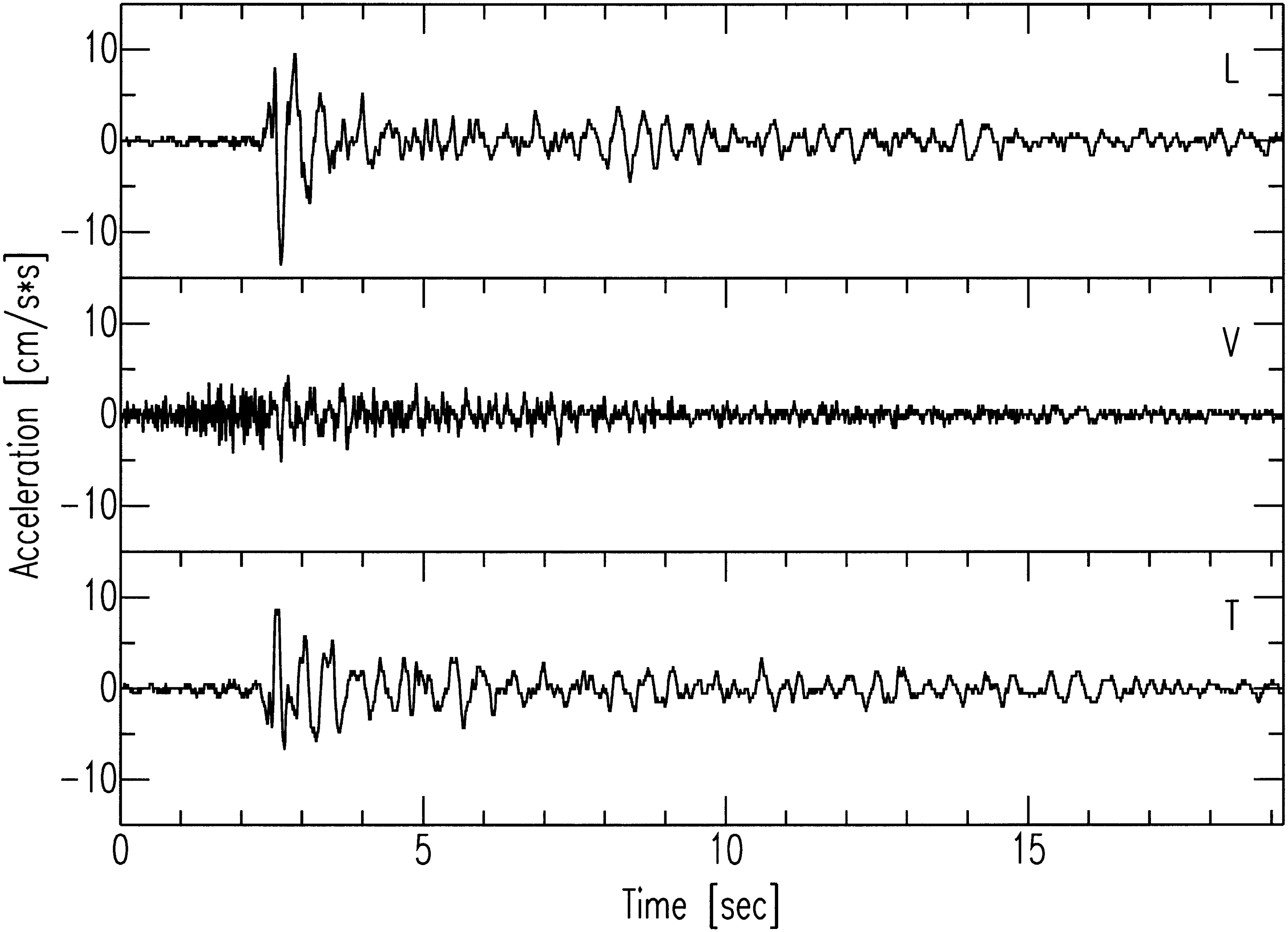


Fig. 3.15 MT1 Unfiltered Acceleration Waveforms

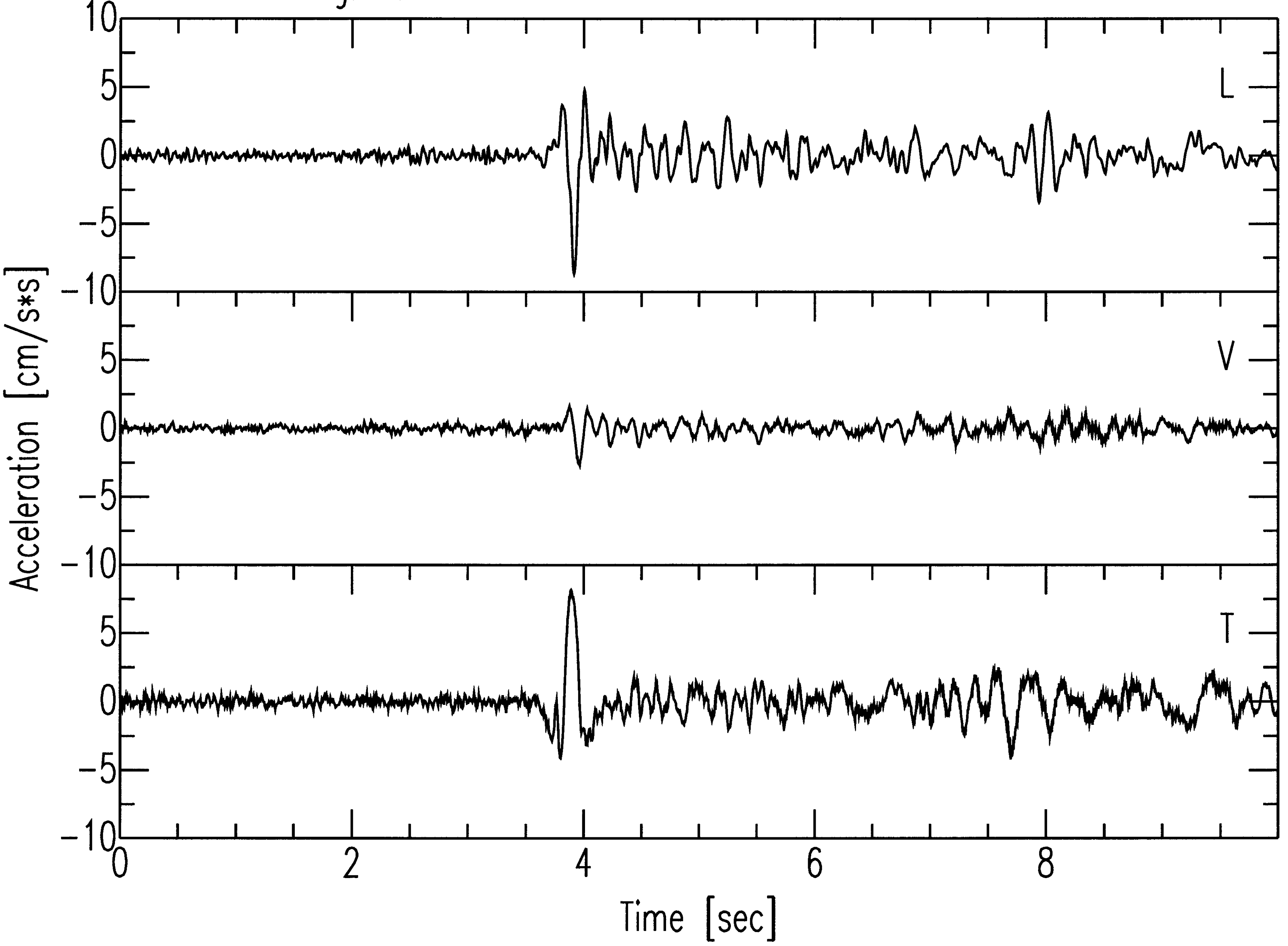


Fig. 3.16 MT2 Unfiltered Acceleration Waveforms

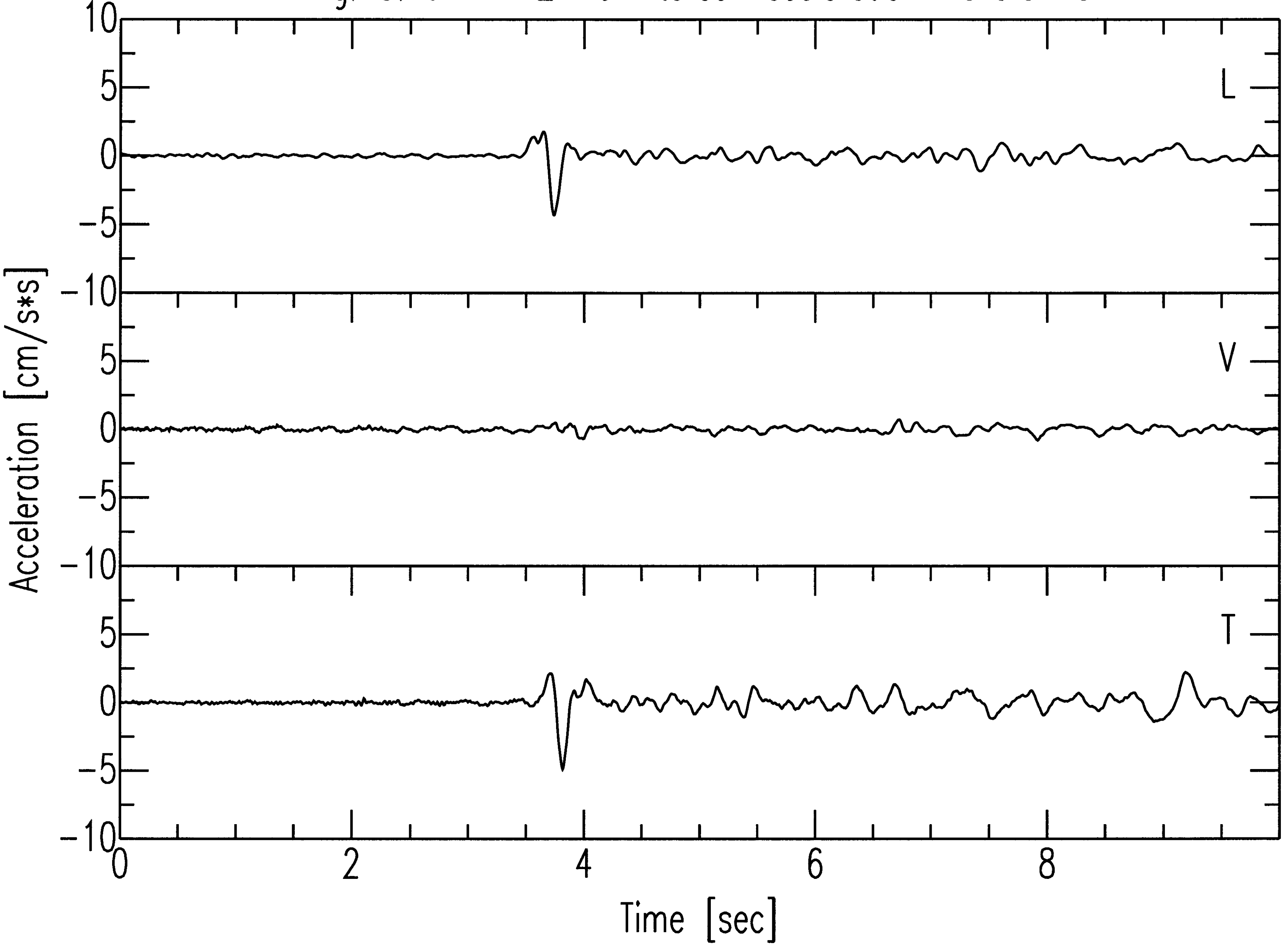


Fig. 3.17 MT3 Unfiltered Acceleration Waveforms

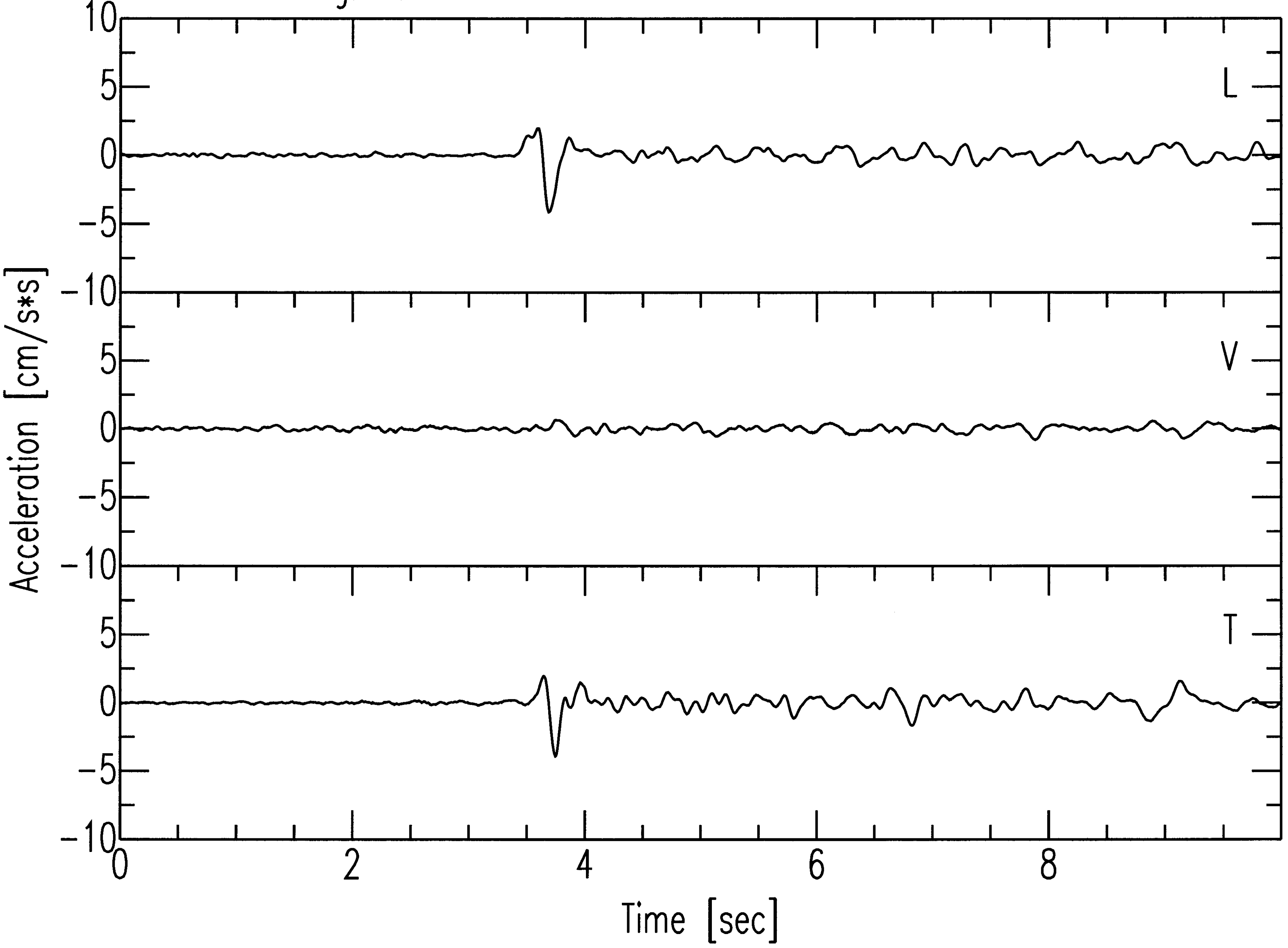


Fig. 3.18 MUR Unfiltered Acceleration Waveforms

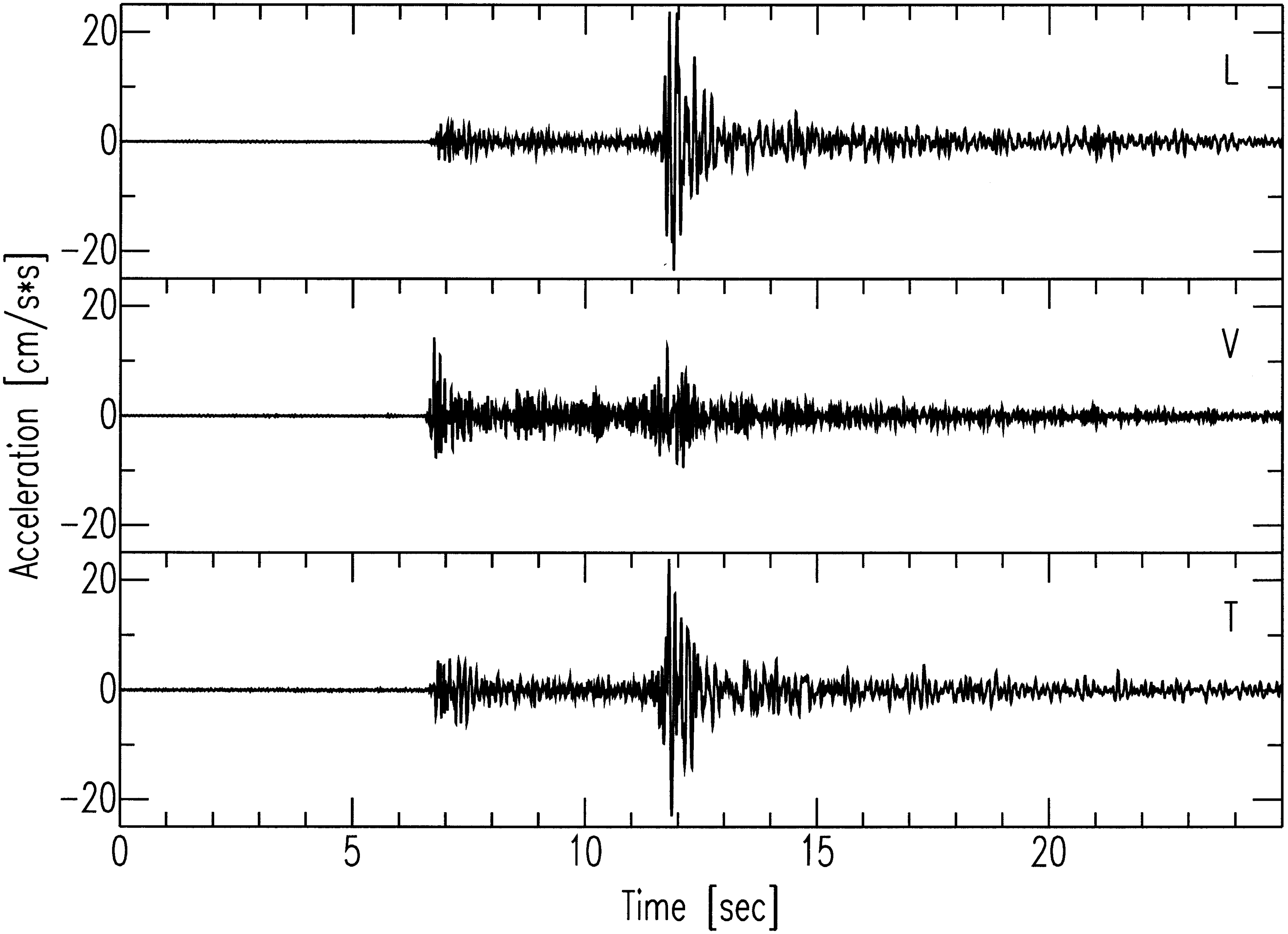


Fig. 3.19 PGC Unfiltered Acceleration Waveforms

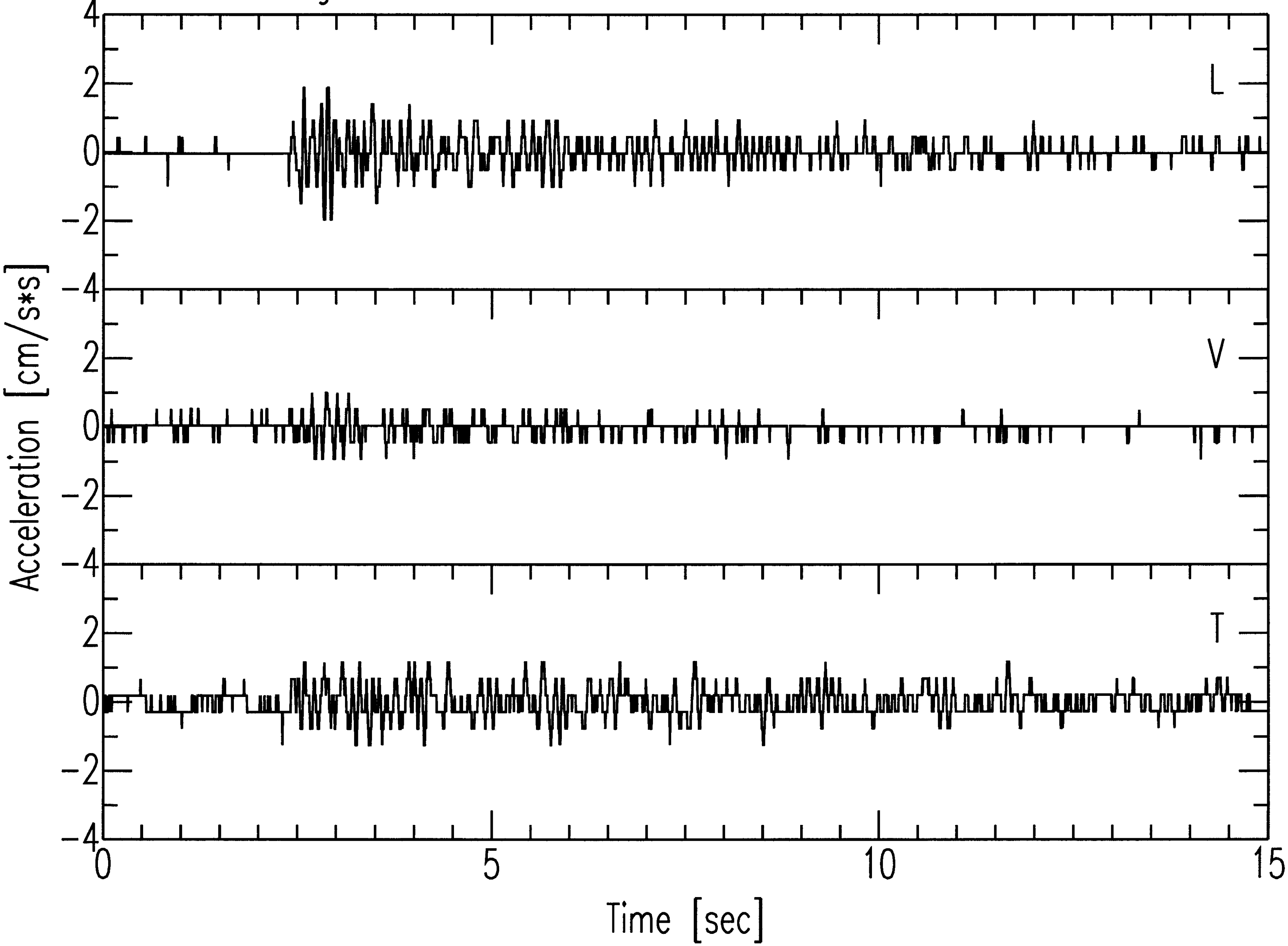


Fig. 3.20 RHA Unfiltered Acceleration Waveforms

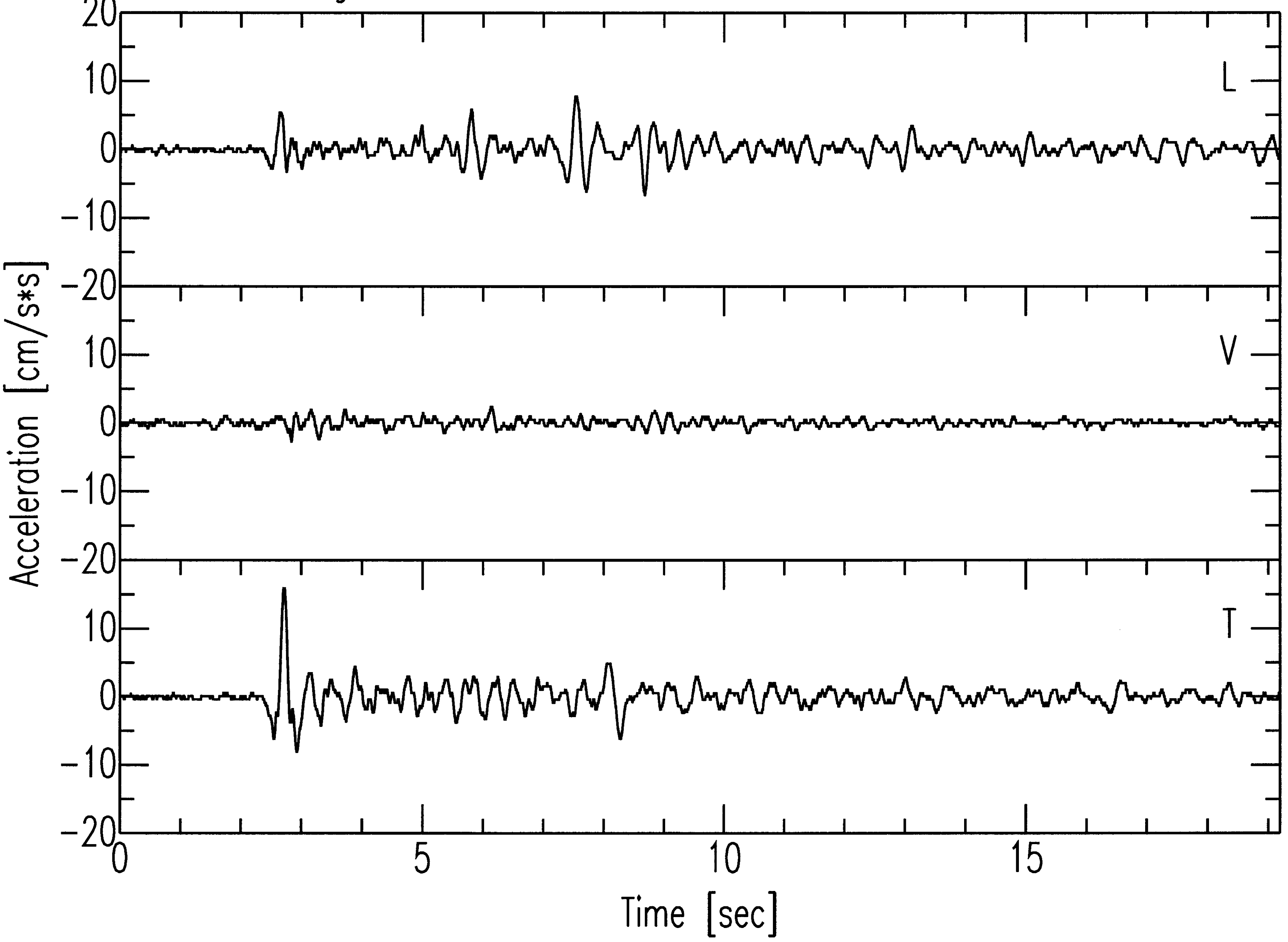


Figure 4

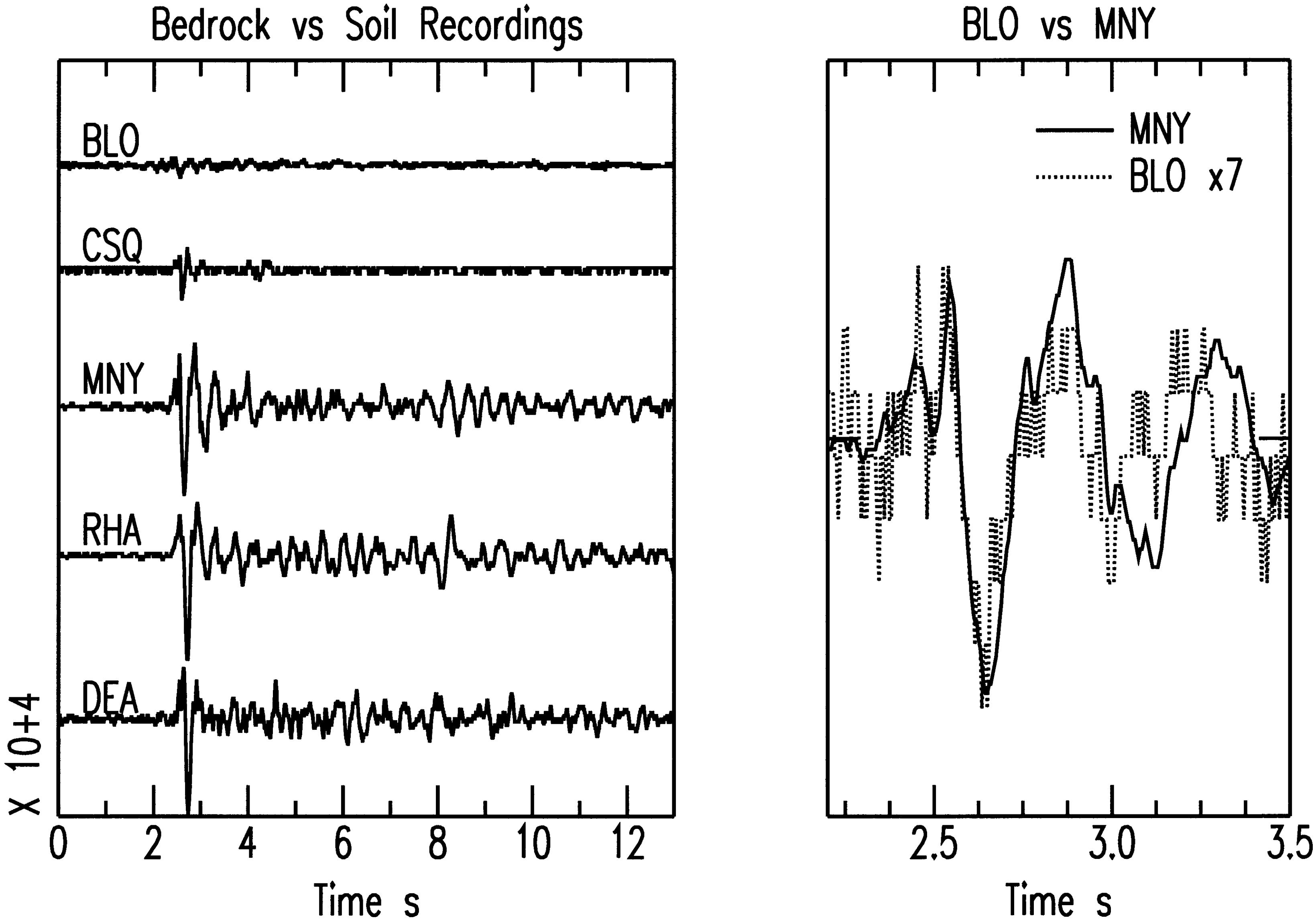

Bedrock vs Soil Recordings
BLO
CSQ
MNY
RHA
DEA
X 10+4
0
2
4
6
8
10
12
Time s
BLO vs MNY
MNY
BLO x7
2.5
3.0
3.5
Time s

Figure 5 - Acceleration Spectra

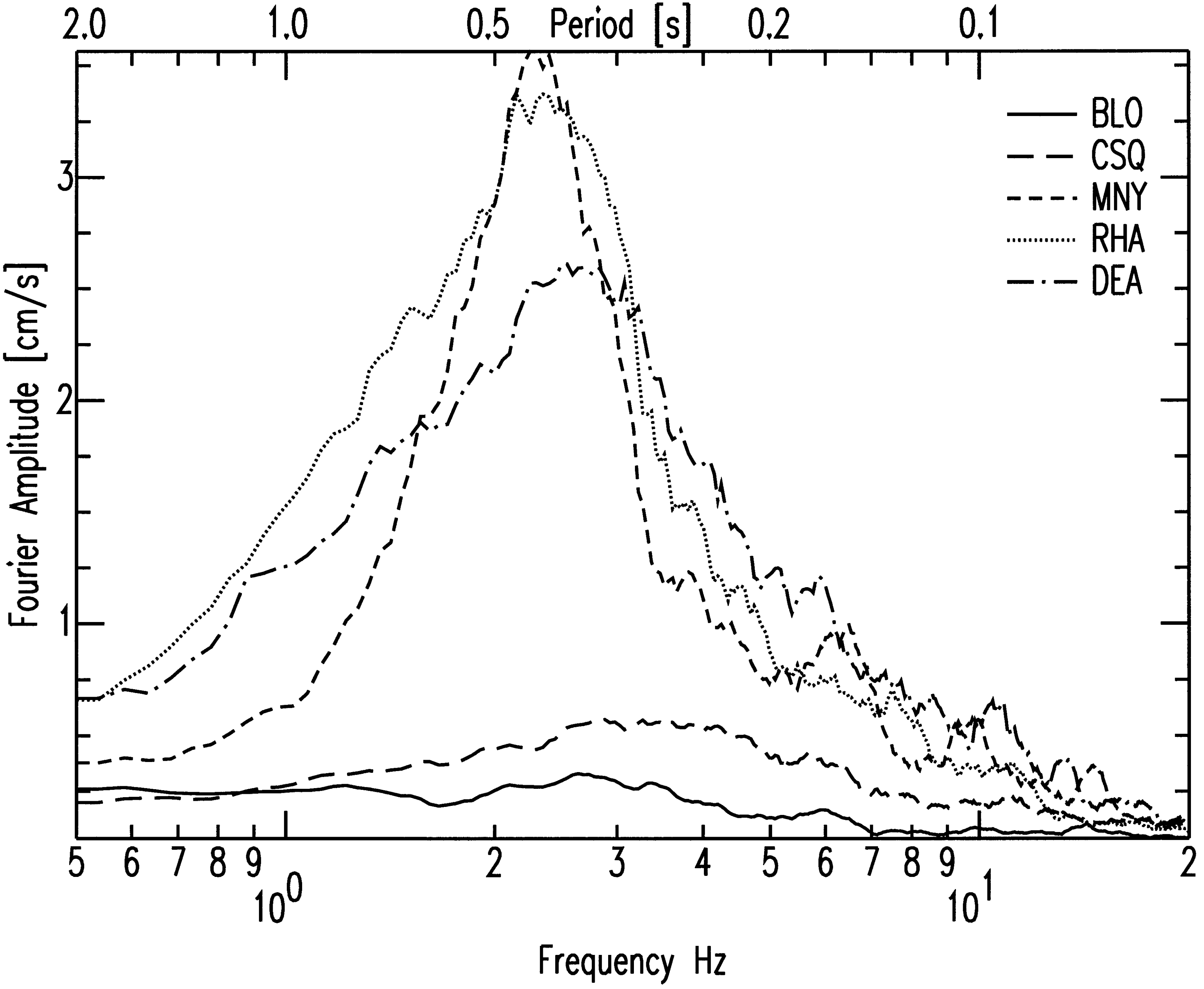
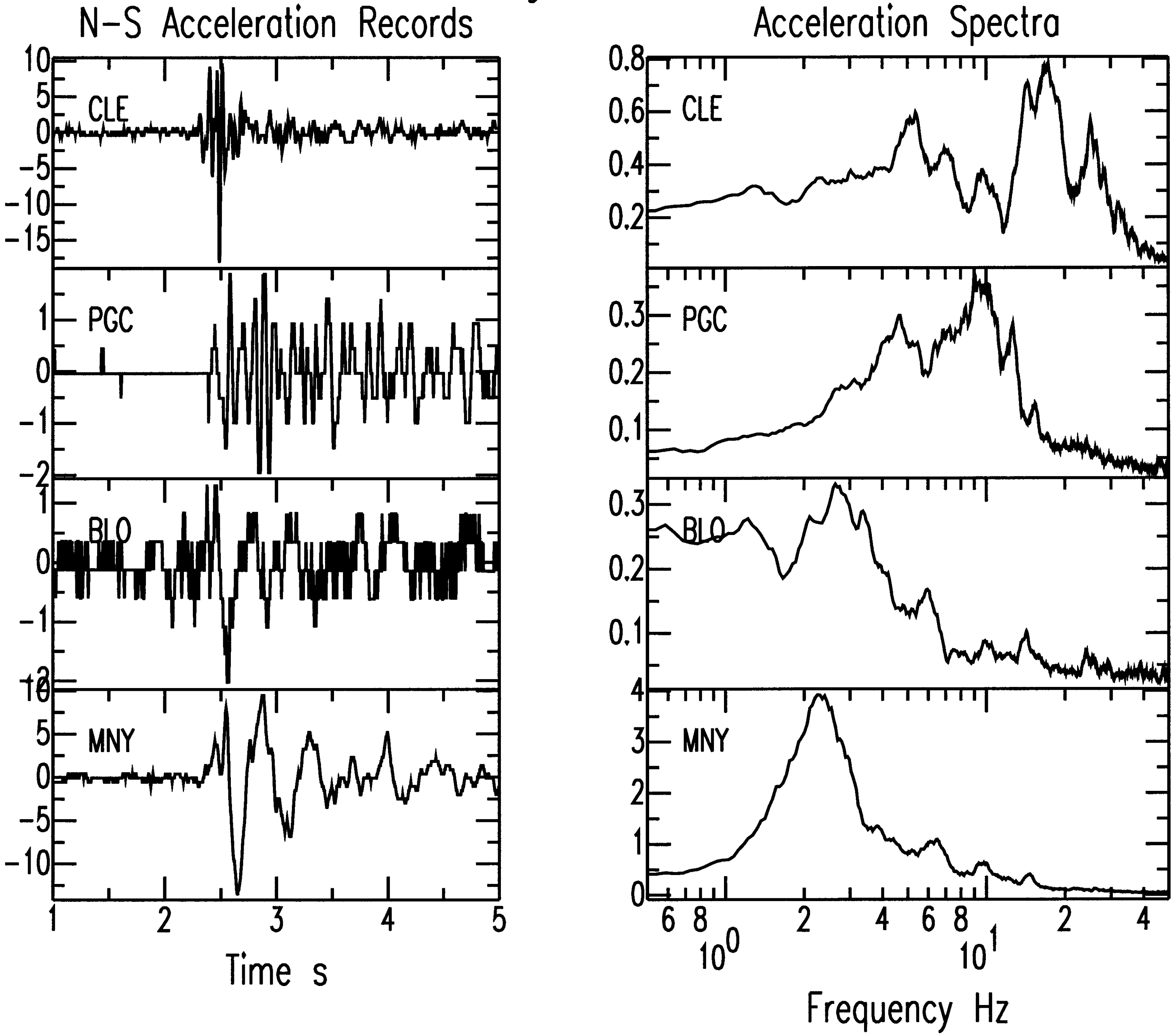


Figure 6


N-S Acceleration Records
CLE
PGC
BLO
MNY
10
5
0
-5
-10
-15
1
0
-1
-2
1
0
-1
-2
10
5
0
-5
-10
1
2
3
4
5
Time s
Acceleration Spectra
CLE
PGC
BLO
MNY
0.8
0.6
0.4
0.2
0.3
0.2
0.1
0.3
0.2
0.1
4
3
2
1
0
6
8
10^0
2
4
6
8
10^1
2
4
Frequency Hz