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Digital Seismograms of Selected Aftershocks of the Northridge Earthquake Recorded by a Dense Seismic Array on February 11, 1994 at Cedar Hill Nursery in Tarzana, California.

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Introduction

The January 17, 1994 Northridge, California earthquake ($M_W = 6.7$) produced unexpectedly large ground accelerations at some sites in the epicentral region. In particular, the CDMG SMA-1 accelerograph (number 24436) at Cedar Hill Nursery in Tarzana, California recorded a peak horizontal acceleration of 1.8 g and a peak vertical acceleration of 1.2 g (Shakal et al., 1994). Because this accelerograph also recorded one of the largest accelerations observed during the 1987 Whittier Narrows earthquake (Shakal et al., 1987), at an epicentral distance of 45 km, it is likely that some sort of unusual site conditions are amplifying motions at this site. Given the large Northridge earthquake motions, it is important to determine the cause and the spatial extent of the local zone of amplified motion.

To address this question, we deployed 21 three-component velocity sensors at 50-200 feet intervals in an cross pattern centered roughly on the CDMG accelerograph at the Cedar Hill site. Using a 16-bit digital recording system, we recorded aftershocks of the Northridge earthquake and seismic signals generated on-site by small explosive sources and a portable shear-wave generator. In this report, we present digital data for 29 selected aftershocks recorded on February 11, 1994 by the array. It is the first of a series of three reports in which we present the data recorded during three days of the deployment. A poster session paper presenting some preliminary results of this deployment was given by Spudich et al. (1994) at the 89th Annual Meeting of the Seismological Society of America.

The Cedar Hill Site and Observed Damage

The Cedar Hill site is located on the northern flanks of the Santa Monica mountains. The CDMG accelerograph is near the crest of a low, nearly east-west-trending ridge with a maximum relief of about 60 feet. Damage observed at this site due to the Northridge earthquake main shock is puzzling. Fifty feet west from the CDMG accelerograph is a single story wood-frame house that was hardly damaged (see Figure 1). However, the main house, a 2-story mansion about 250 feet west of the accelerograph, was damaged with broken windows, collapsed chimney, and cracked columns. Trailer offices located about 100 feet east to the CDMG accelerograph were hardly damaged – – windows were not broken; only one of doors became stuck and needed repair. Figure 2 is a photograph taken on February 3, 1994, about 500 feet east of the CDMG accelerograph, at the Cedar Hill Nursery where stacks of flower pots were only slightly disrupted by the Northridge earthquake. It was verified from employees at the Nursery that the flower pots were there before the Northridge earthquake and had not been re-arranged since. A few broken pots were picked up and are seen in the foreground of Figure 2.

Figure 3 is a site map showing the locations of the CDMG accelerograph and the 3-component velocity seismometers used in this study. Station sites, except S06 which is located about 280 m south of the CDMG accelerograph, were surveyed by John Hamilton and Cris Garvin using a Wild T2000/2002 Total Station, which is a combined electronic distance measurer and a theodolite. We have reduced the surveyed data such that the CDMG accelerograph is the center of the local coordinates (0, 0, 0). According to Shakal et al. (1994), the location of the CDMG Cedar Hill accelerograph is 34.160° N, 118.534° W, with no elevation given. We determined the coordinates and elevation of the CDMG accelerograph from the "Canoga Park, California" USGS topographic sheet to be: 34.1606° N, 118.5340° W, 890 ft (271 m). Similarly, the values for S06 are: 34.1580° N, 118.5348° W, 850 ft (259 m). Station coordinates for our stations are given in local coordinates in Table 1.

According to a geotechnical report by GeoSoils, Inc. (1992), the natural ridge top was graded to form a level pad at some time in the past, and at several test pits around the site, artificial fill materials were found. Depth to "bedrock" is generally shallow (a few meters), and the "bedrock" is marine sedimentary rock of the Modelo Formation. Fumal et al. (1981) conducted in-situ measurements of the near-surface velocity at Cedar Hill, and presented a velocity model as shown in Figure 4. Jim Gibbs and Willie Lee noted that the location map given by Fumal et al. (1981) was in error. Tom Fumal returned to the site and identified that their drill hole was located about 500 feet northeast from the CDMG accelerograph (see Figure 3).

Instrumentation and Calibration

The seismic array deployed at the Cedar Hill site consisted of 21 three-component L22 seismometers connected by cables to a 64-channel, 16-bit PC-based seismic recording system (Lee, 1989; Lee and Dodge, 1992). Seismometer spacing varied from approximately 50 feet to 200 feet, with the densest spacing near the CDMG accelerograph. Each seismometer was buried in a small hole to a depth of about one foot. The N-S direction of the seismometer was aligned to the geographical north using a compass and the seismometer was leveled using its build-in leveling bubble. Timing for the system was achieved by a Truetime/Kinemetrics clock synchronized to a GOES satellite time source. The amplifier gain was set to 1,000, and the analog signals passed through a 30-Hz high-cut filter. The maximum/minimum output from the amplifier/filter was ± 5 volts, corresponding to $\pm 16,384$ digital counts for a 16-bit A/D converter with ± 10 volts full scale. In practice, any voltage that has a digital count above about 15,000 may have been clipped.

The digitization rate for the February 11 events was set to 200 samples per sec. The actual sampling rate was determined from digitizing IRIG-E time signal generated by the Truetime/Kinemetrics clock synchronized to a GOES satellite, and is written in the data files. The Data Translation DT2827 A/D board has a throughput of 100,000 samples per second, so that the channel skew is about 10 micro-second from channel-to-channel. Allowing for some delays in multiplexing, the maximum time delay between channel 0 and channel 63 is about 1 msec, which is small in comparison with the 5 msec sampling interval for digitization.

Although we used the same made of seismometers, amplifiers, etc. for our seismic array, instrument calibrations are required to ensure that the instrument response of all stations of the seismic array is the same for a given ground motion. This was difficult to achieve in practice owing to limited manpower and budget.

Instrument calibrations were performed in two steps. First, each seismometer was connected to a GEOS unit (Borcherdt et al., 1985) and a calibration voltage was applied to the seismometer coil and then released. The calibration pulse output signal from the GEOS unit was recorded on a 16-bit PC-based system (Lee and Dodge, 1992). The seismometer was also tapped by the handle of a screw driver in vertical, north-south, and east-west directions, respectively, and the polarity of seismometer response was observed on an oscilloscope connected to the monitoring channel of the GEOS unit. Positive digital values correspond to north, east, and upward ground velocity. The recorded peak sensor output and polarity, along with the seismometer serial number and name of the station that used the seismometer, is given in Table 2.

The second step in calibration was to correct for variations of overall sensitivity in the amplifier/filter units with gain setting at 1,000, using the same PC-based seismic recording system (digitizing at 200 samples per second). The DC level of each channel of the 64-channel amplifier was first adjusted so that the DC average over 256 samples produced an output digital count of less than 100 when connected to an L22 seismometer sitting on the basement floor of our Menlo Park office. Then the DC average over 256 samples of the amplified output signal was recorded for a 0-millivolt and a 3-millivolt DC input source (using a Datel voltage calibrator). The results of these tests are given in Table 3.

From data listed in Tables 2 and 3, we computed the adjustment factors to be applied to the observed raw data with the following assumptions: (1) ± 10 volts corresponds to $\pm 32,768$ digital counts in the PC-based recording system, (2) the response of a "standard"

L22 seismometer to the GEOS calibration voltage produces 1024 digital counts, and (3) the difference in digital counts observed for 0- and 3-millivolt input signals corresponds to a 3 V output signal for a "standard" amplifier that is set to a gain of 1,000. Station C00 used the in-situ L22 seismometer of the station TAG installed by Wennerberg et al. (1994). Their GEOS calibration data for the TAG station seismometer was used.

The actual adjustment factors applied to the recorded data are given in Table 4; their values are in general within several percents of unity. However, since the calibrations were not performed in situ, we expect a few percent variation in the recorded amplitudes for the stations in our array for the same input ground motion, even after our adjustments are applied. Furthermore, at present we lack the proper equipment to do a thorough calibration of our seismometer in the field. We realized that to confirm the assumptions we used in calibration would also require much more work.

Digital Seismograms for the Selected Events

Recording of the Northridge aftershocks was carried out at night, because active source experiments were conducted during the day time. From 02:00 to 16:00 UTC on February 11, 1994, 48 earthquake events and 10 questionable events were recorded by our array. The earthquake list by the Caltech-USGS Southern California Seismic Network for the same time period contains 85 earthquake events, of which 23 are distant small events. We found 38 events in common, i.e., recorded by both the regional network and our array. Of these 38 events, 29 earthquakes were selected for this report.

In this report, we selected 29 of the "better" recorded aftershocks. Their hypocenter parameters as reported by Caltech-USGS Southern California Seismic Network are listed in Table 5, and their locations are plotted in Figure 5. After the recorded data were adjusted according to Table 4, all digital seismograms were trimmed to begin approximately 10 seconds before the P-wave onset and end several seconds or more after the coda had decayed to the noise level. There are a few exceptions owing to either multiple events or the maximum duration of recording permitted by the auto-triggering algorithm.

Intermittent problems with a faulty power supply and oscillator noise in the amplifier/filter unit, caused glitches in the recorded data. Many of the glitches are single-points and were removed using a moving-spline algorithm. Two channels (E01N and E03E) had faulty data because the cables were chewed by sheep. These two traces will not be plotted in the figures; however, their data are in the digital data files on the network computer.

To help readers browse through the recorded data, we plot the seismograms in record-section format for the east-west and north-south lines of the array (Figures 6 through 34). They are plotted three-components to a page, two pages for each selected aftershock. The amplitude scale varies from page to page, but does not vary within a page. Owing to the page-size limitation, only portions of the significant parts of the seismograms were displayed. The distance axis is not "true" distance, but rather the x-coordinates of the stations along the east-west line, or the y-coordinates of the stations along the north-south line. Note that the east-west and north-south lines are not "true" east-west and north-south (see the North arrow in Figure 3). These east-west line follows the approximate trend of Cedar Hill, and the north-south line is approximately perpendicular to the east-west line.

Magnitudes for the 29 selected aftershocks range from 1.5 to 3.7. Some aftershocks produced clipped records for one or more stations, and in particular, the records for the magnitude 3.7 aftershocks are all clipped. As noted before, any amplitude values exceeding about 15,000 digital counts represent clipped values.

The digital seismograms of the 29 selected aftershocks have been placed on the hard disk of the USGS computer called "andreas.wr.usgs.gov". They can be accessed by the "anonymous ftp" protocol via the Internet. These data are in ASCII format, using the SUDS structures (Ward, 1989; Banfill, 1993), and are more or less self-explanatory. However, some parameters in the SUDS structures have not been implemented and thus contain the default values instead of the actual values. Users should use only the "tracedata" structure, and the relevant parameters are: (1) station name, (2) component, (3) initial time, (4) sampling rate, and (5) digitized data values of ground velocity.

Discussion

The purpose of this report is to present some of the digital seismograms of Northridge aftershocks recorded by our dense seismic array at the Cedar Hill site, where CDMG has recorded very large ground motions for the Northridge earthquake, and to make the seismograms available to anyone wishing to carry out further studies.

Observed damage at Cedar Hill suggests large variations of ground motion during the Northridge earthquake over a scale of 100 meters or less. Our data (Figures 6-34) and the analysis by Spudich et al. (1994) also suggest large variations of ground motion at Cedar Hill for small aftershocks. As pointed out by Spudich et al. (1994), "observed peak velocities are generally correlated with elevation above the base of the hill and peak velocities observed at the CDMG site on top of the hill are a factor of 2 or 3 larger than those observed only 50 m away on the flanks of the hill" (see for example, Figure 20).

If the above is correct, then large spatial variations of ground motion may be an important factor contributing to the large variations in building damage observed over distances as short as a city block in some large earthquakes, e.g., at Tangshan (Seismological Press, 1982), and Armenia (New Zealand Herald, 1988).

Acknowledgments

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Table 1: Station Locations in Local Coordinates (in meters)

The center of the local coordinates is the CDMG acclerograph location at: 34.1606° N, 118.5340° W, 890 ft (or 271 m). The location for S06 station is: 34.1580° N, 118.5348° W, 850 ft (or 259 m). Relative location of stations listed below is accurate to 0.1 m.

Station	X (m)	Y (m)	Z (m)
CDMG	0.00	0.00	0.00
C00	-2.45	-0.62	0.05
N01	-3.23	16.53	-0.18
N02	-7.70	46.92	-7.88
N03	-9.23	85.65	-17.83
S01	1.93	-16.36	-1.32
S02	3.90	-48.24	-8.11
S03	5.84	-80.39	-11.72
S04	7.41	-113.40	-12.96
S05	8.26	-134.52	-13.07
E01	17.05	3.73	-1.46
E02	45.06	13.42	-5.93
E03	72.15	26.92	-8.56
E04	102.54	41.79	-9.18
E05	161.93	64.76	-10.90
E06	227.38	140.96	-15.39
W01	-13.37	-12.65	0.03
W02	-40.85	-25.49	-0.32
W03	-71.33	-29.78	-1.53
W04	-113.31	-44.83	-4.94
W05	-154.17	-69.34	-11.29
W06	-184.21	-70.14	-16.35

Table 2: L22 Seismometer Polarities and Calibration Outputs (in digital counts)

L22 #	Station	Vert-comp	NS-comp	EW-comp
523	E01	−1038	+1036	+1031
524	E02	+1065	+1054	+1013
525	E03	+0963	+0888	+1021
526	E04	−1058	+1027	+0983
527	E05	+1006	+0986	+1059
529	E06	+1016	+0960	+1072
530	S06	+0845	+0865	+0954
532	S01	+1045	+0983	+1047
533	S02	−1048	+0944	+1057
534	S03	−1016	+0991	+1043
535	S05	+1039	+1071	+1029
536	N01	+1118	+1023	+1119
537	N02	+1113	+1063	+1173
538	N03	+0996	+0991	+0879
539	W01	+0878	+0846	+0824
541	W06	−0950	+0972	+0987
557	W02	−1060	+1071	−1056
558	W03	−0787	+0815	−0866
559	W04	−1011	+0976	−1016
560	W05	−1061	+0969	−0974
561	S04	+1166	+1056	−1112
302	C00	+1031	+1071	+0938

Table 3: Amplifier Calibration Outputs (in digital counts)

Station	V: 0mV	V: 30mV	NS: 0mV	NS: 30mV	EW: 0mV	EW: 30mV
C00	56	9768	10	9794	−8	9684
N01	55	9793	58	9779	−111	9702
N02	68	9772	97	9821	16	9736
N03	123	9843	60	9809	15	9783
S06	18	9799	118	9963	−7	9712
S01	70	9936	120	9998	25	9845
S02	102	9936	60	9911	91	9958
S03	61	9814	80	9806	−55	9675
S04	112	9858	100	9828	−13	9691
S05	18	9799	118	9963	−7	9712
E01	61	9825	60	9873	87	9867
E02	124	9935	104	9925	57	9844
E03	−22	9778	27	9827	2	9791
E04	44	9744	101	9795	90	9816
E05	96	9820	116	9859	30	9763
E06	82	9815	24	9743	−21	9715
W01	50	9809	61	9802	43	9841
W02	89	9837	103	9960	101	9936
W03	97	9850	50	9820	−42	9783
W04	41	9770	85	9869	−42	9673
W05	−33	9698	38	9827	46	9812
W06	66	9930	32	9827	51	9815

Table 4: Instrument Adjustment Factors Applied to Recorded Data

Station	Vert-comp	NS-comp	EW-comp
C00	1.005	0.961	1.106
N01	0.926	1.011	0.919
N02	0.929	0.972	0.880
N03	1.043	1.040	1.170
S01	0.976	1.037	0.981
S02	-0.980	1.085	0.967
S03	-1.018	1.042	0.990
S04	0.885	0.981	-0.929
S05	0.995	0.951	1.011
S06	1.211	1.188	1.087
E01	-0.997	0.992	0.995
E02	0.964	0.972	1.014
E03	1.067	1.153	1.004
E04	-0.984	1.014	1.053
E05	1.031	1.051	0.981
E06	1.020	1.076	0.961
W01	1.171	1.216	1.254
W02	-0.970	0.949	-0.971
W03	-1.309	1.258	-1.177
W04	-1.020	1.058	-1.022
W05	-0.972	1.057	-1.060
W06	-1.071	1.057	1.049

Table 5: Hypocenter Information for the Selected Aftershocks

The "Symbol" column indicates the symbol used in plotting the aftershocks in Figure 5, and the "Figure" column indicates the figure number for the record-sections.

Time (Hr:Mn:Sec)	Latitude, N	Longitude, W	Depth	M_L	Symbol	Figure
2 : 31 : 07.10	34° 12.56'	118° 35.51'	1.79	2.0	0	6
3 : 33 : 05.74	34° 15.03'	118° 27.70'	9.46	2.3	1	7
5 : 29 : 03.29	34° 15.12'	118° 31.93'	14.01	2.0	2	8
5 : 57 : 50.10	34° 17.73'	118° 26.72'	9.20	2.1	3	9
6 : 10 : 22.74	34° 17.19'	118° 35.75'	16.29	2.4	4	10
6 : 41 : 13.88	34° 18.74'	118° 26.82'	5.32	2.8	5	11
6 : 41 : 30.86	34° 18.40'	118° 26.81'	6.85	2.9	6	12
7 : 23 : 45.83	34° 18.01'	118° 27.08'	7.18	1.5	7	13
7 : 28 : 32.97	34° 18.32'	118° 25.03'	9.70	1.9	8	14
7 : 28 : 44.21	34° 17.78'	118° 24.04'	5.72	1.9	9	15
7 : 30 : 57.43	34° 18.16'	118° 24.74'	8.90	1.8	A	16
7 : 32 : 33.74	34° 18.37'	118° 24.35'	9.11	1.4	B	17
7 : 47 : 29.66	34° 12.85'	118° 35.77'	19.75	1.7	C	18
8 : 02 : 21.91	34° 22.54'	118° 38.79'	13.72	2.3	D	19
8 : 36 : 59.24	34° 21.82'	118° 34.69'	6.01	2.1	E	20
10 : 36 : 16.96	34° 22.64'	118° 39.11'	14.55	1.5	F	21
10 : 37 : 40.18	34° 14.39'	118° 29.87'	9.11	1.6	G	22
12 : 19 : 21.52	34° 15.50'	118° 37.54'	1.42	2.0	H	23
12 : 56 : 07.66	34° 16.05'	118° 27.59'	6.10	1.9	I	24
13 : 29 : 45.02	34° 16.53'	118° 32.39'	10.22	1.7	J	25
13 : 39 : 51.01	34° 11.88'	118° 31.33'	9.48	1.5	K	26
13 : 56 : 18.89	34° 18.56'	118° 25.58'	8.05	1.5	L	27
14 : 01 : 01.84	34° 19.81'	118° 28.64'	4.49	2.2	M	28
14 : 07 : 53.06	34° 20.07'	118° 29.05'	4.98	3.7	N	29
14 : 23 : 10.47	34° 21.66'	118° 34.45'	6.37	2.5	O	30
14 : 35 : 44.93	34° 13.81'	118° 28.35'	13.16	1.9	P	31
15 : 12 : 48.45	34° 16.51'	118° 28.14'	10.26	2.1	Q	32
15 : 15 : 14.08	34° 16.91'	118° 27.79'	8.69	2.4	R	33
15 : 52 : 49.18	34° 24.05'	118° 46.52'	10.65	3.1	S	34

Figure 1. A photo taken at the CDMG accelerograph site. The CDMG instrument is shown at left. Leif Wennerberg was servicing the GEOS TAR instrument at the foreground. A one-story house (undamaged) is shown in the background.

Figure 2. A photo taken on Feb. 3, 1994 at the Cedar Hill Nursery (about 500 feet east of the CDMG Accelerograph). Note the slightly disturbed stacks of flower pots, suggesting low ground motion during the Northridge earthquake.

TOPOGRAPHIC MAP SHOWING LOCATION OF CDMG TARZANA SMA
AND TRIGGERED DIGITAL AFTERSHOCK GEOPHONE ARRAY
FEBRUARY 11, 1994

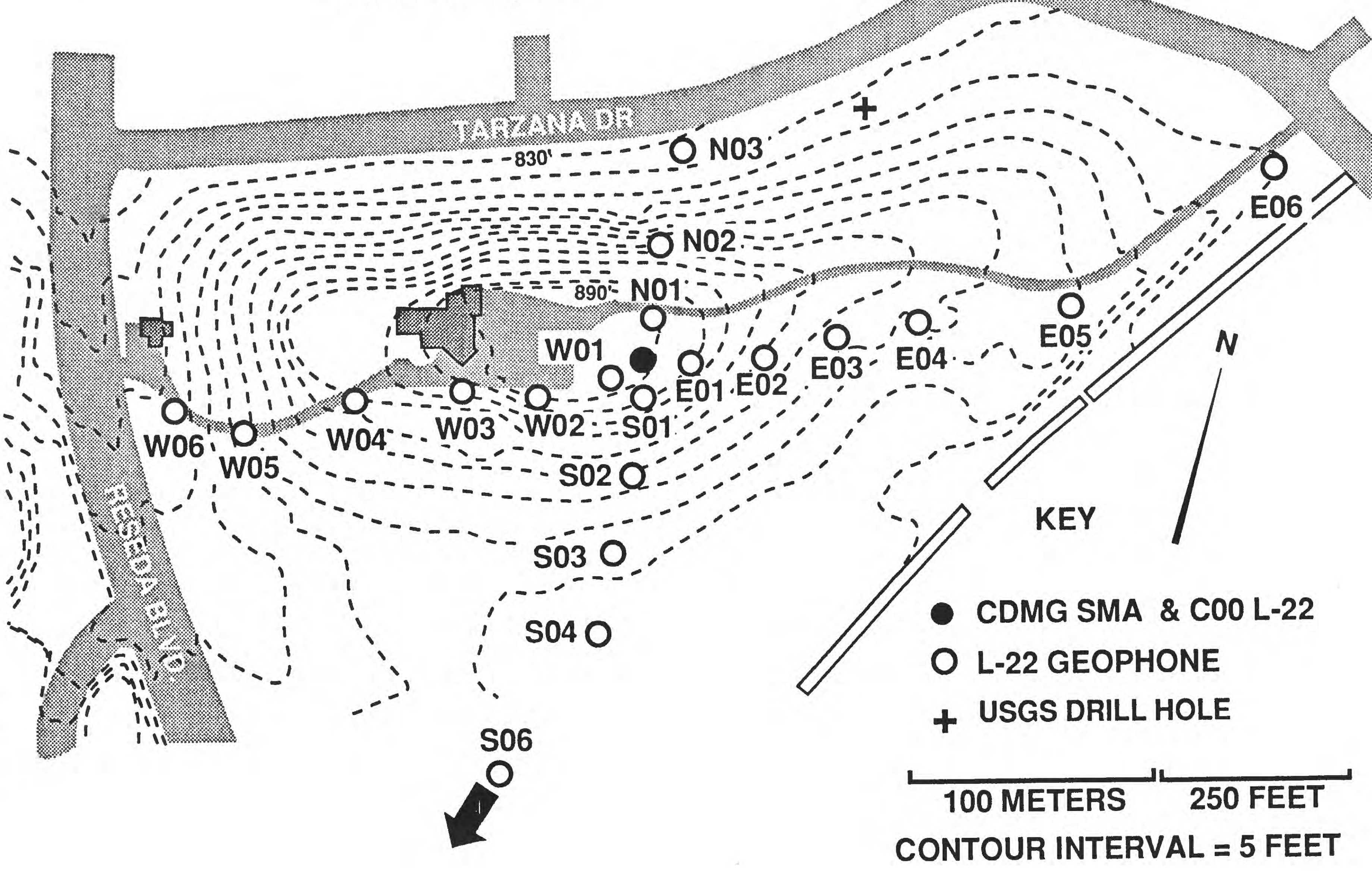


Figure 3. Station Map

CEDAR HILLS NURSERY SITE NO. 45

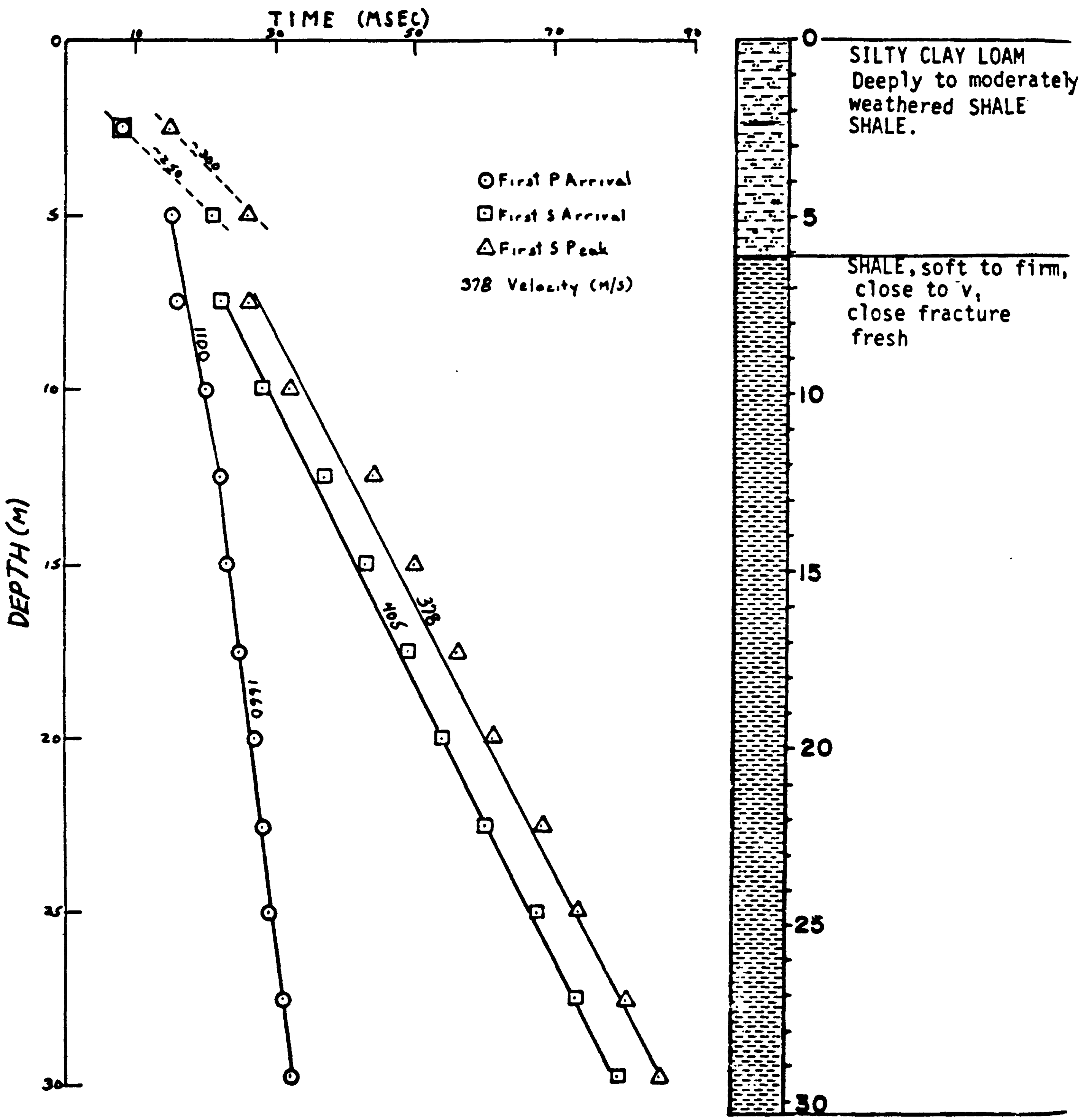


Figure 4. In-situ, downhole measurements of P- and S-velocity by Fumal et al. (1981) at the Cedar Hill site.

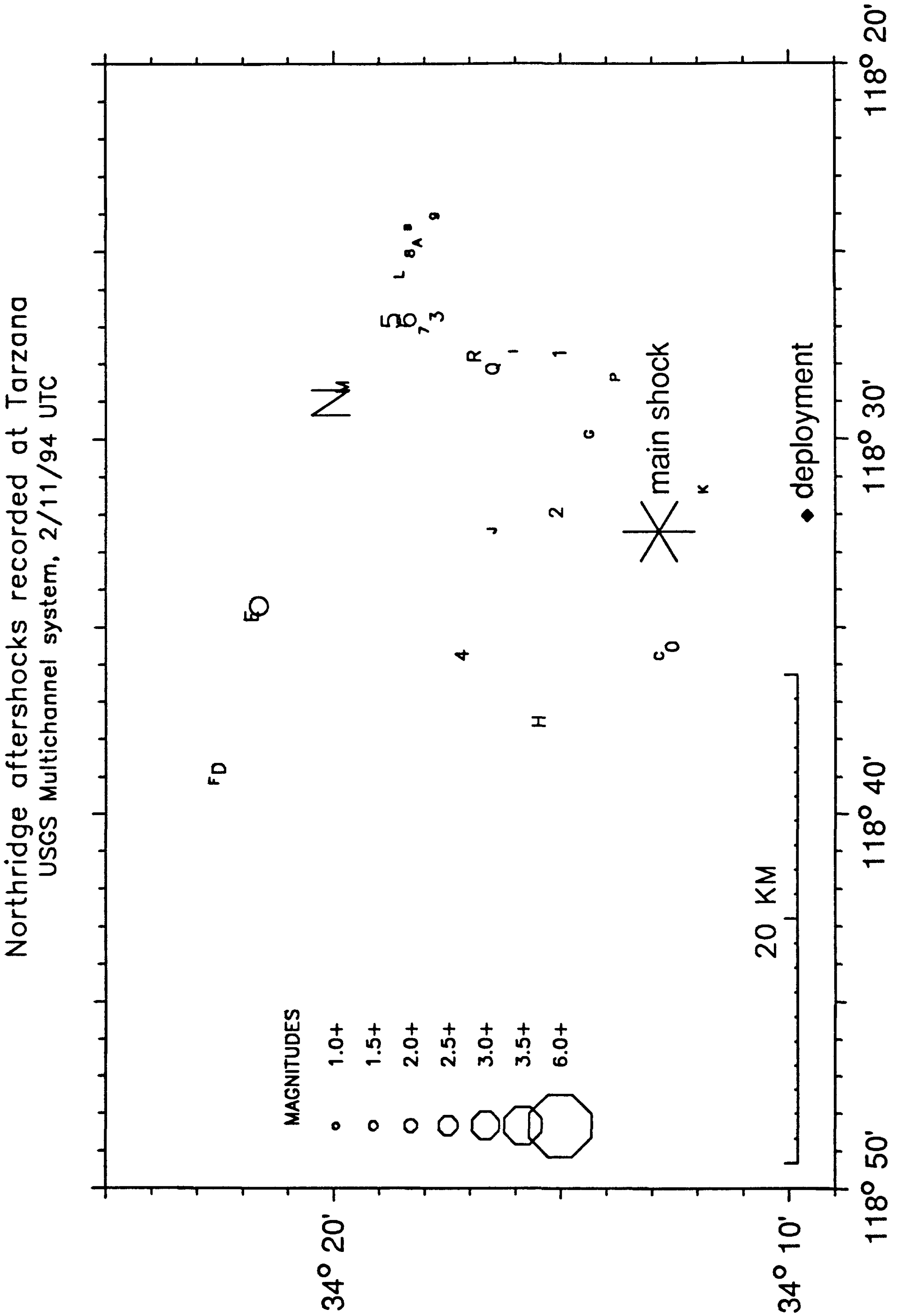


Figure 5. Location of Selected Aftershocks for 2/11/94.

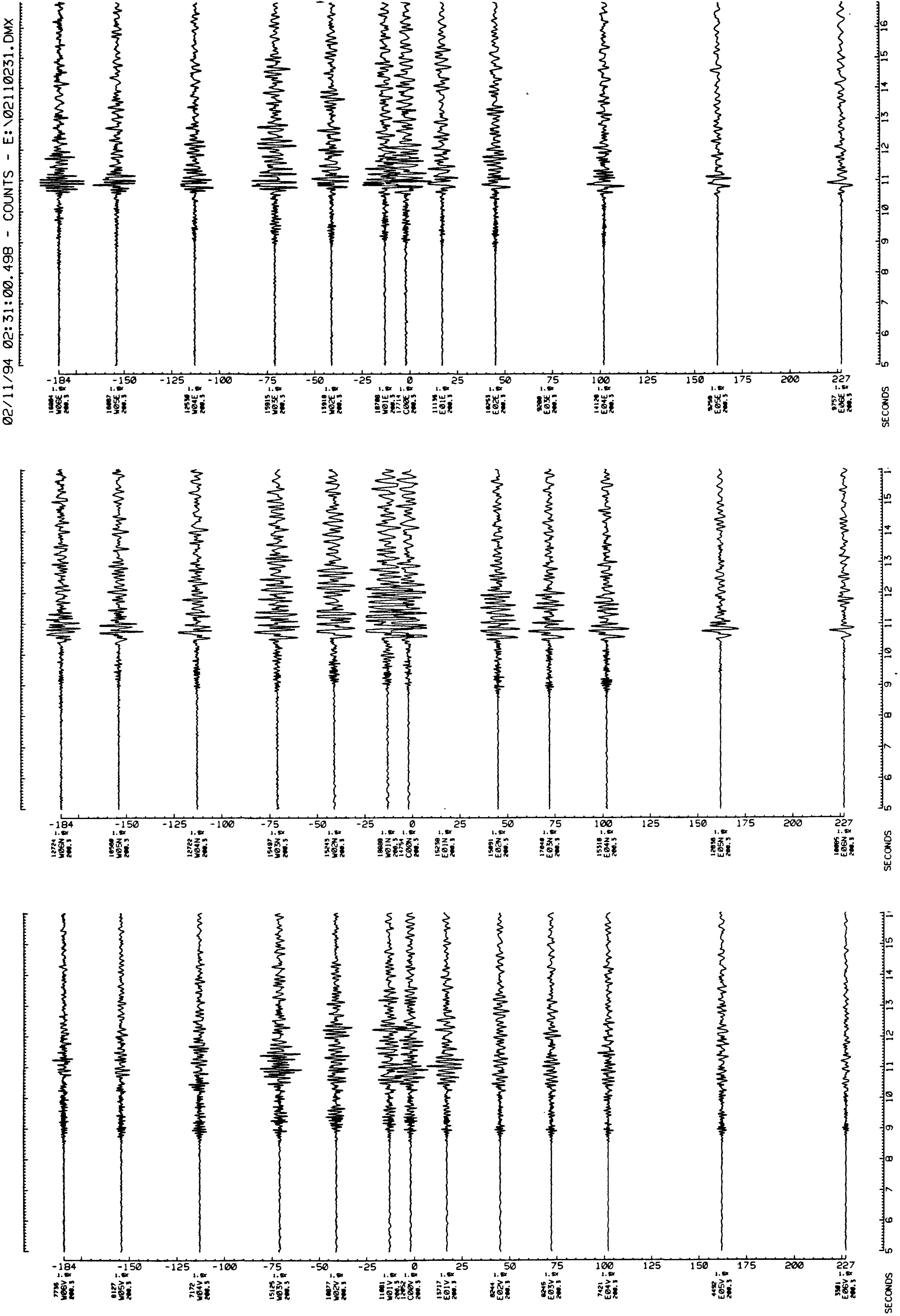


Figure 6(a)

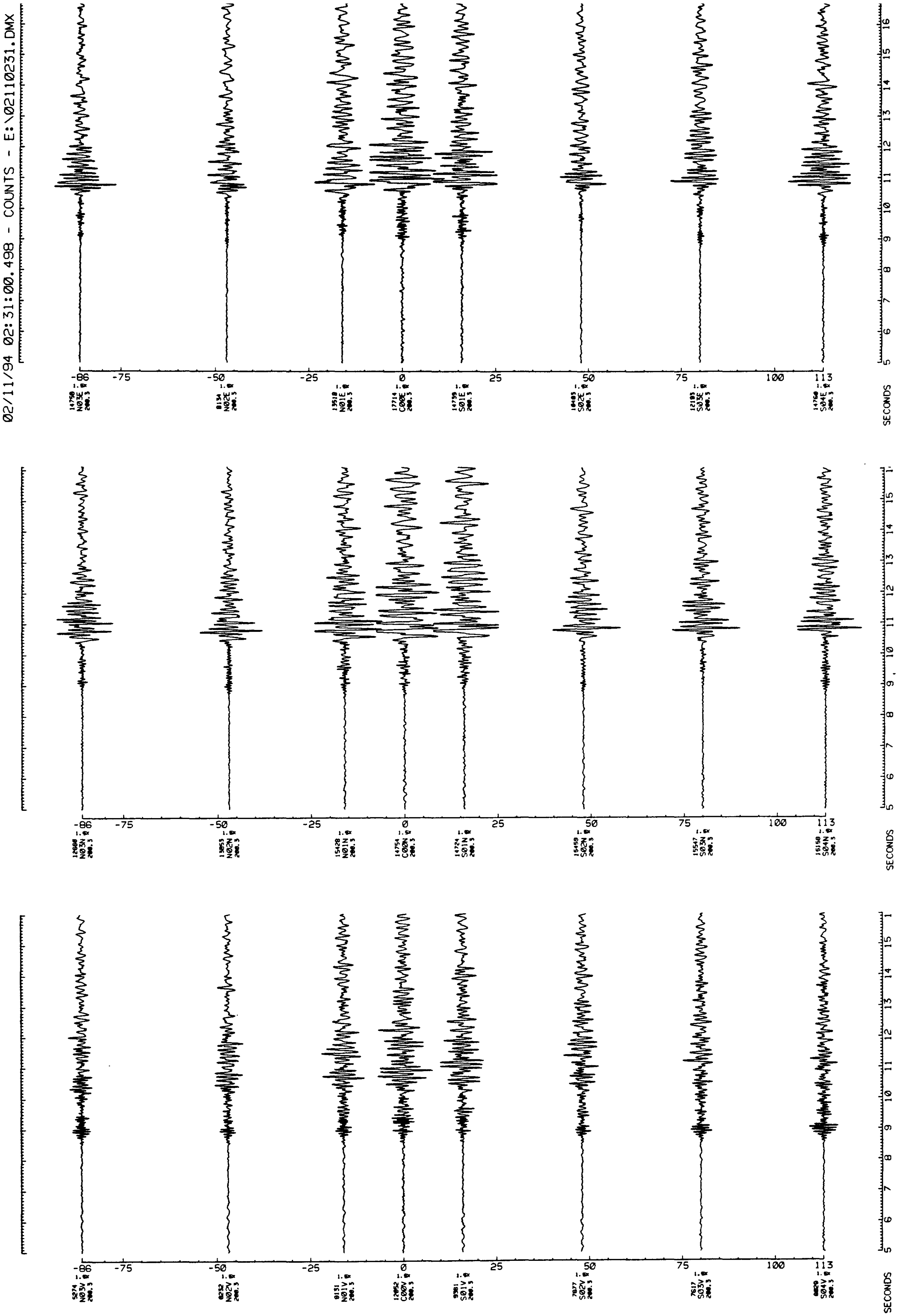


Figure 6(b)

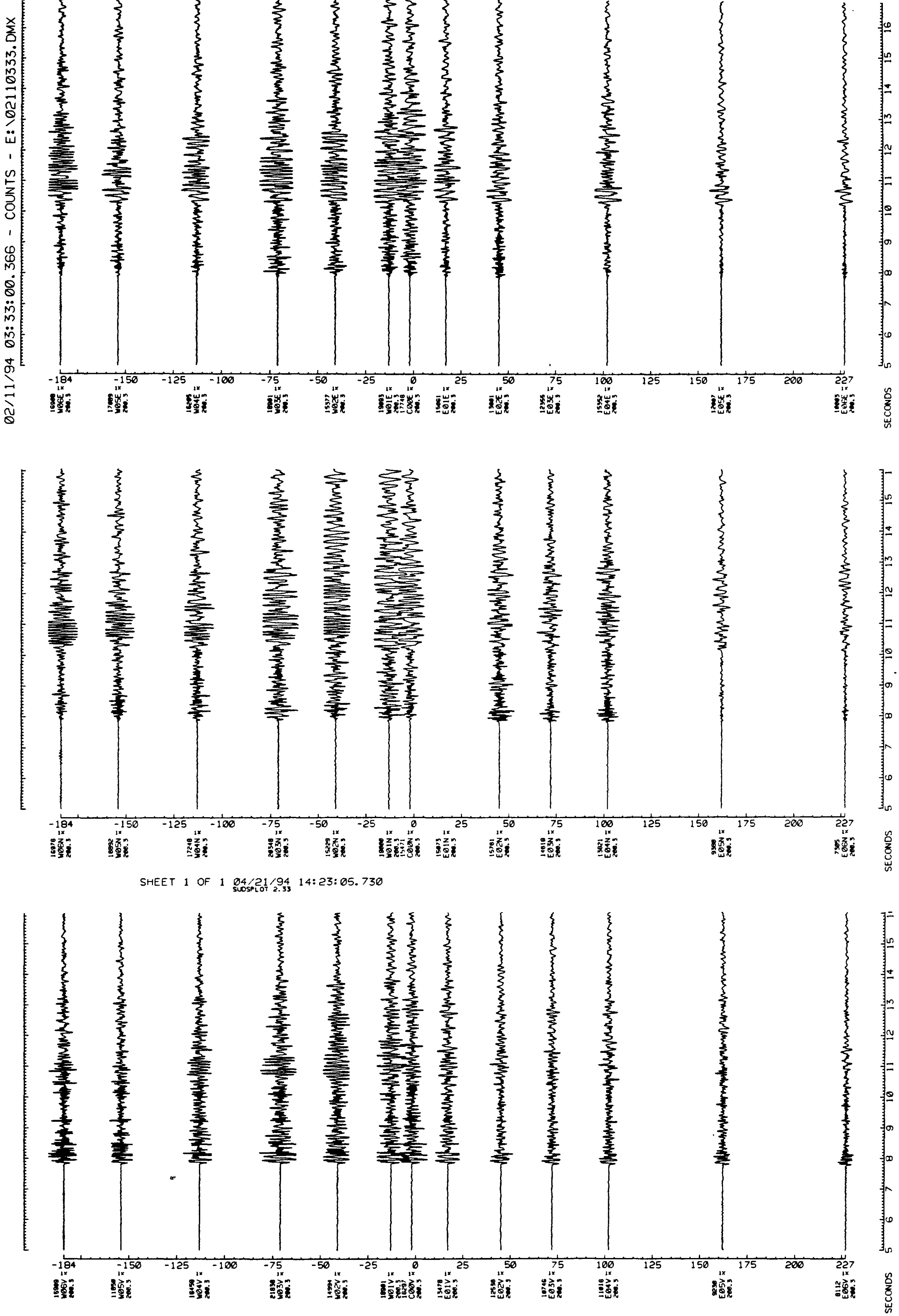
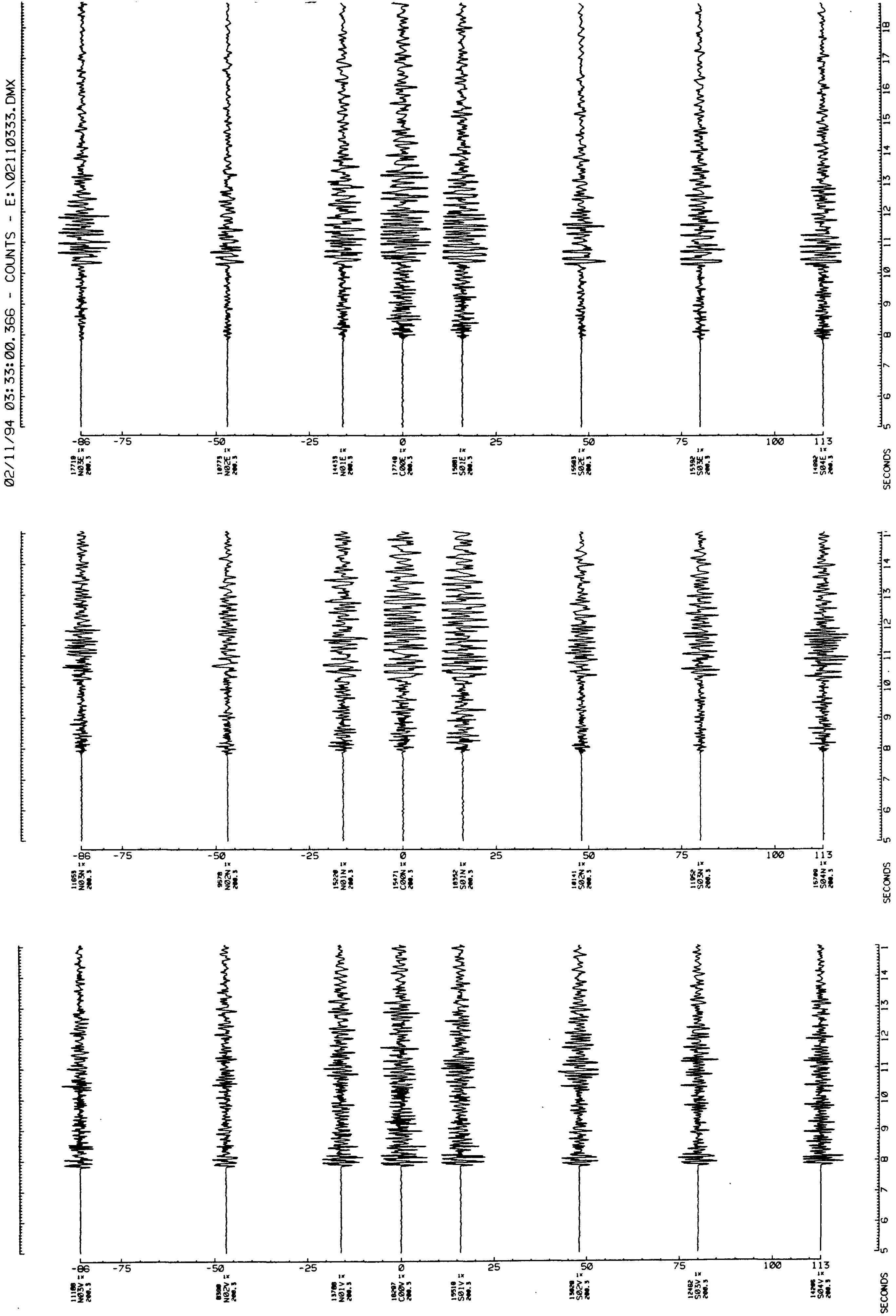

02/11/94 03:33:00.366 - COUNTS - E:\02110333.DMX
SHEET 1 OF 1 04/21/94 14:23:05.730
SUDSPLOT 2.33
SECONDS

Figure 7(a)


02/11/94 03:33:00.366 - COUNTS - E:\02110333.DMX
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S04V
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Figure 7(b)

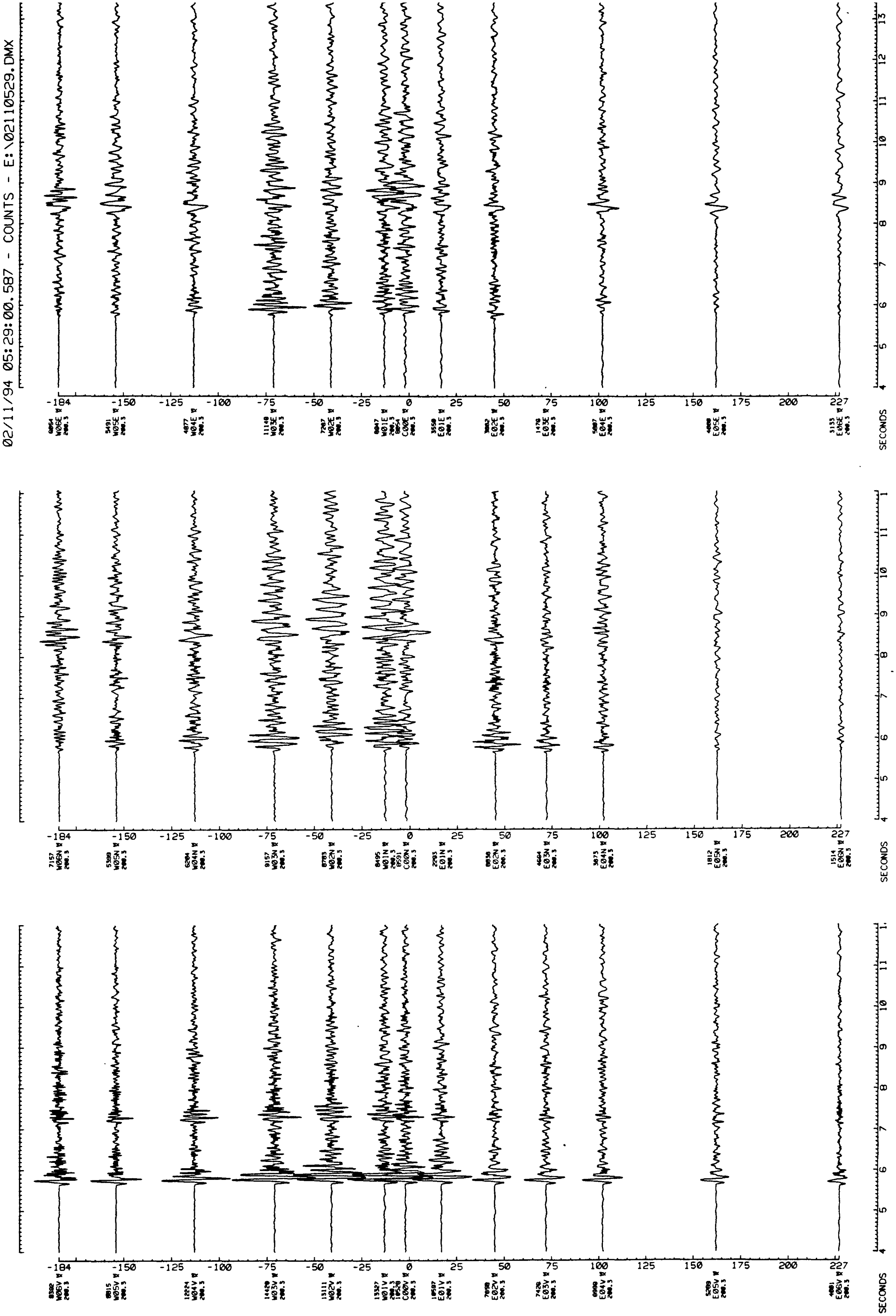
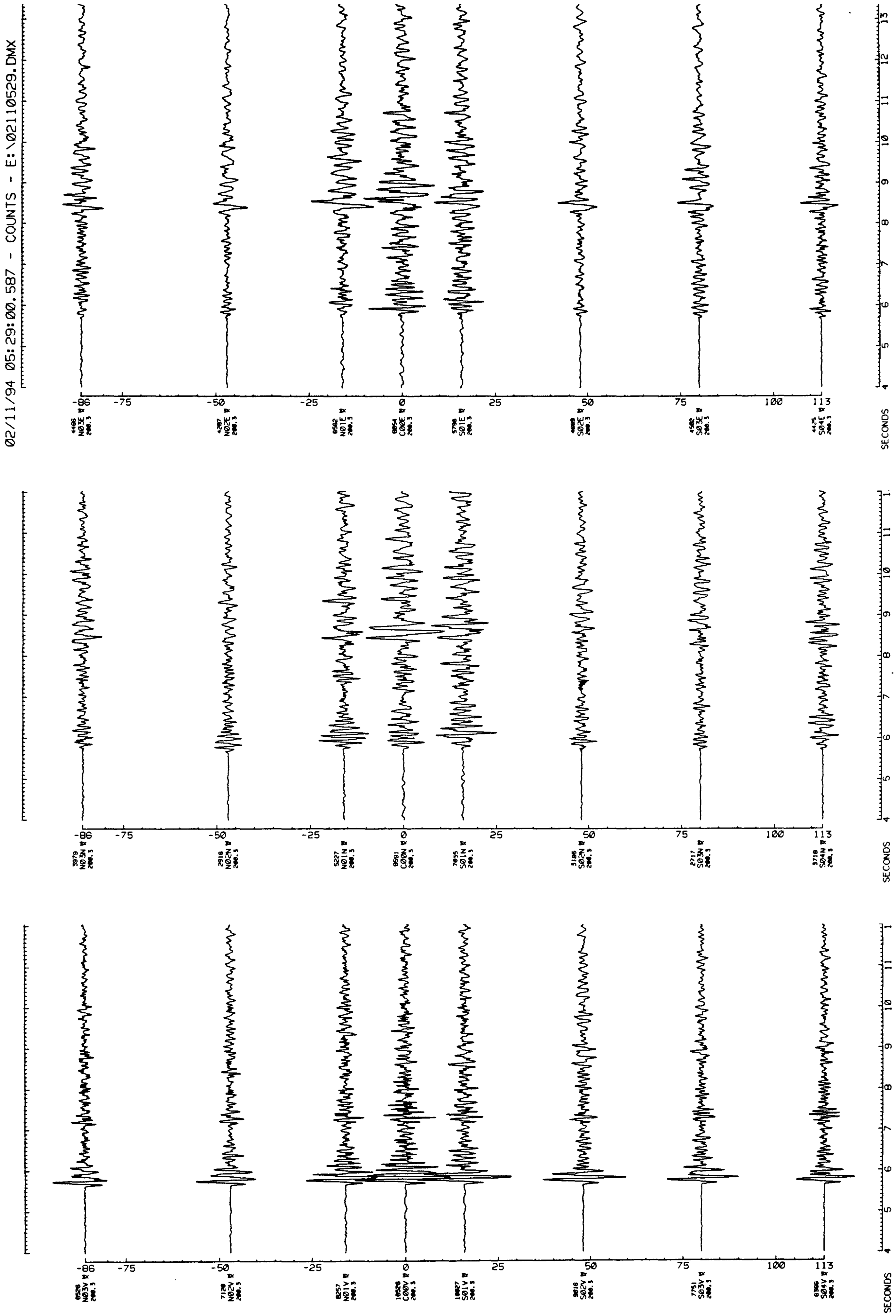


Figure 8(a)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SECONDS

Figure 8(b)

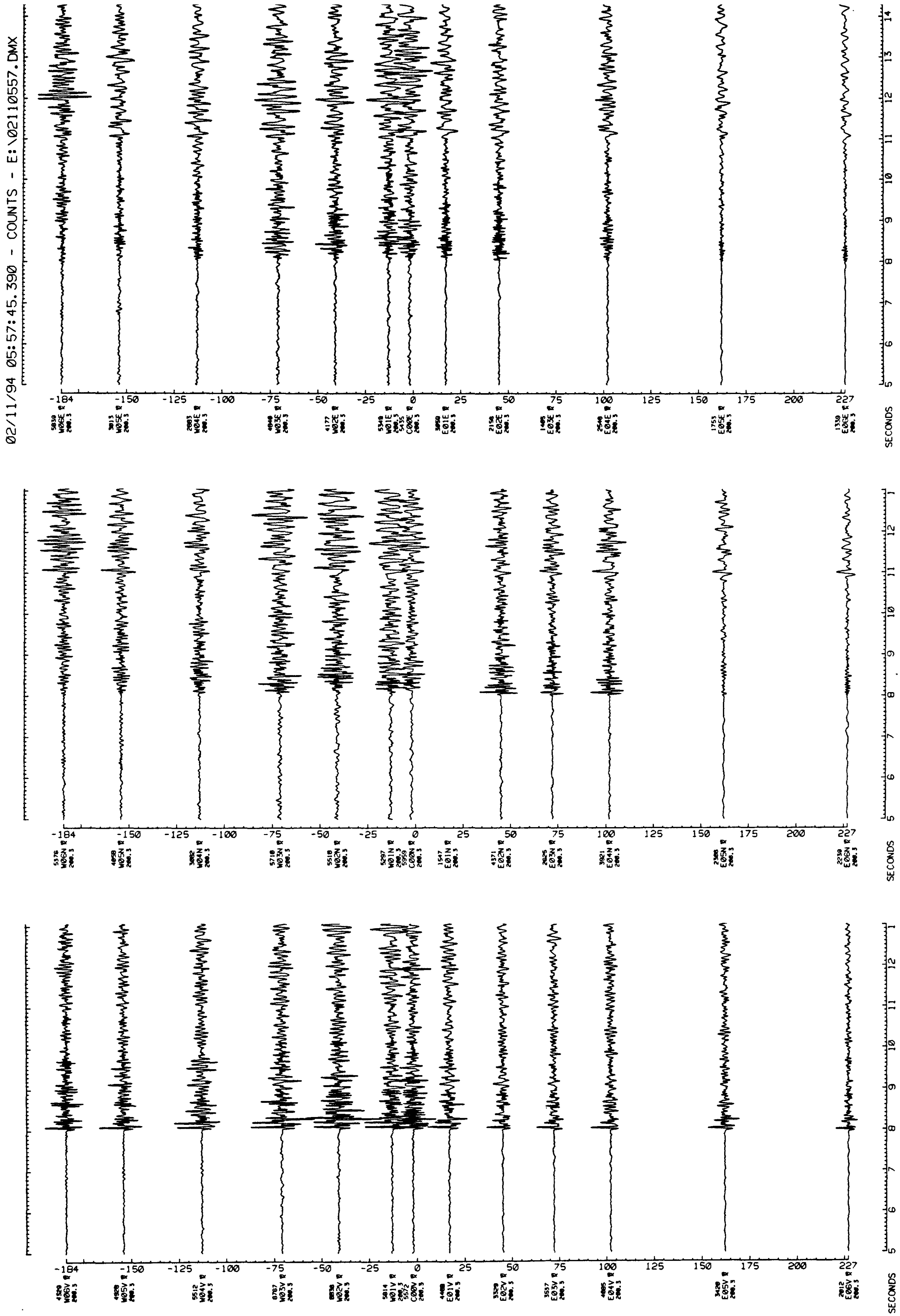


Figure 9(a)

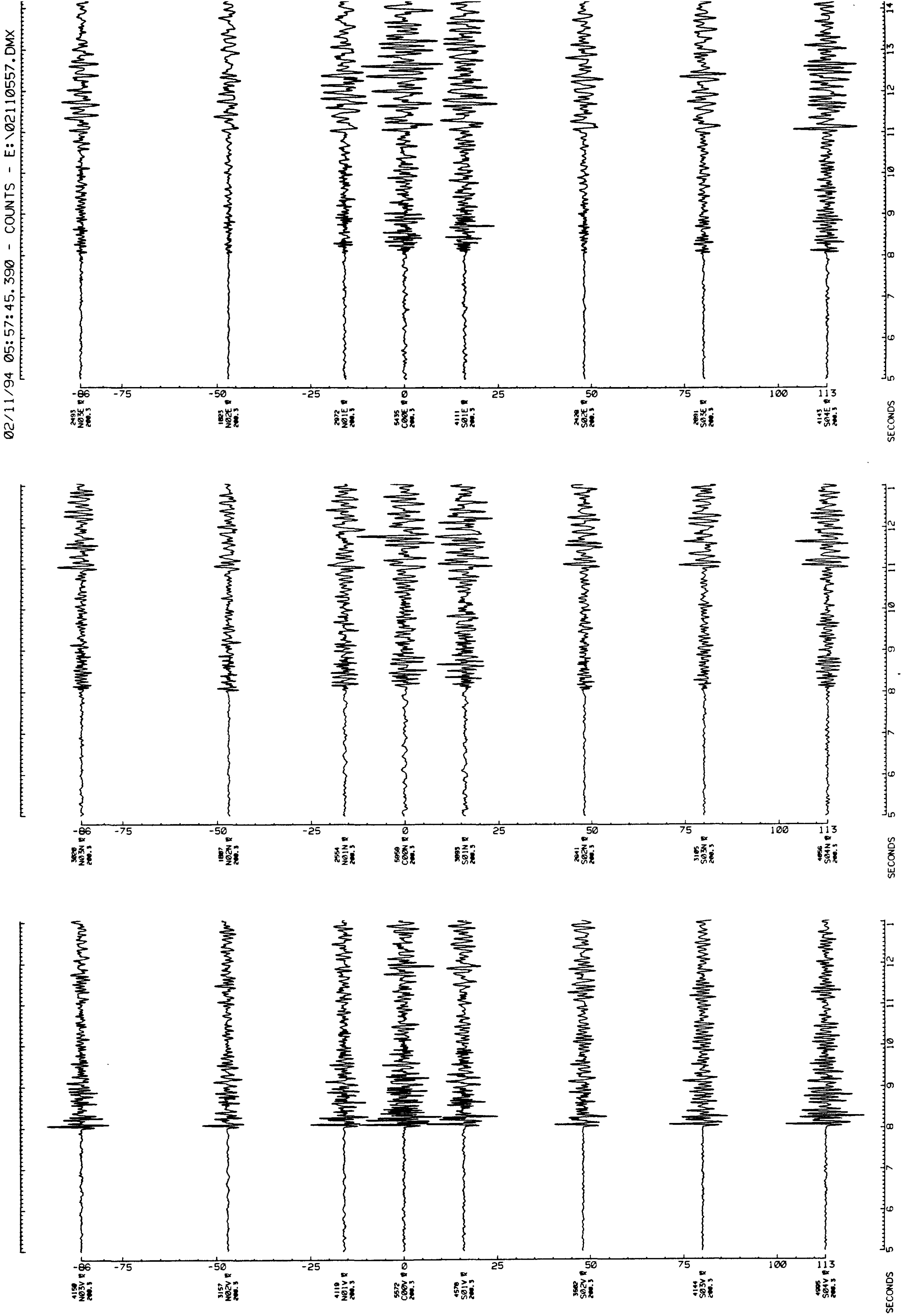


Figure 9(b)

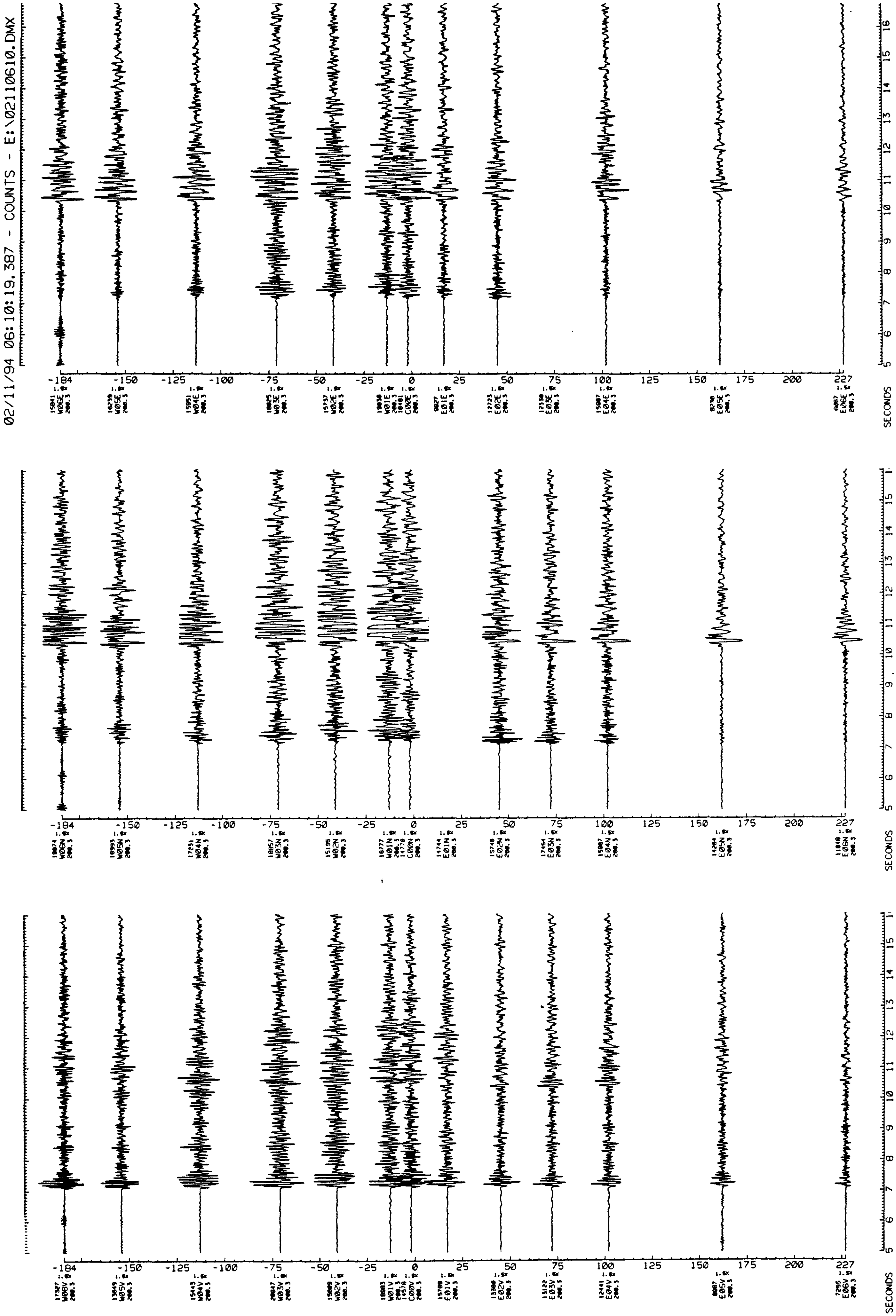


Figure 10(a)

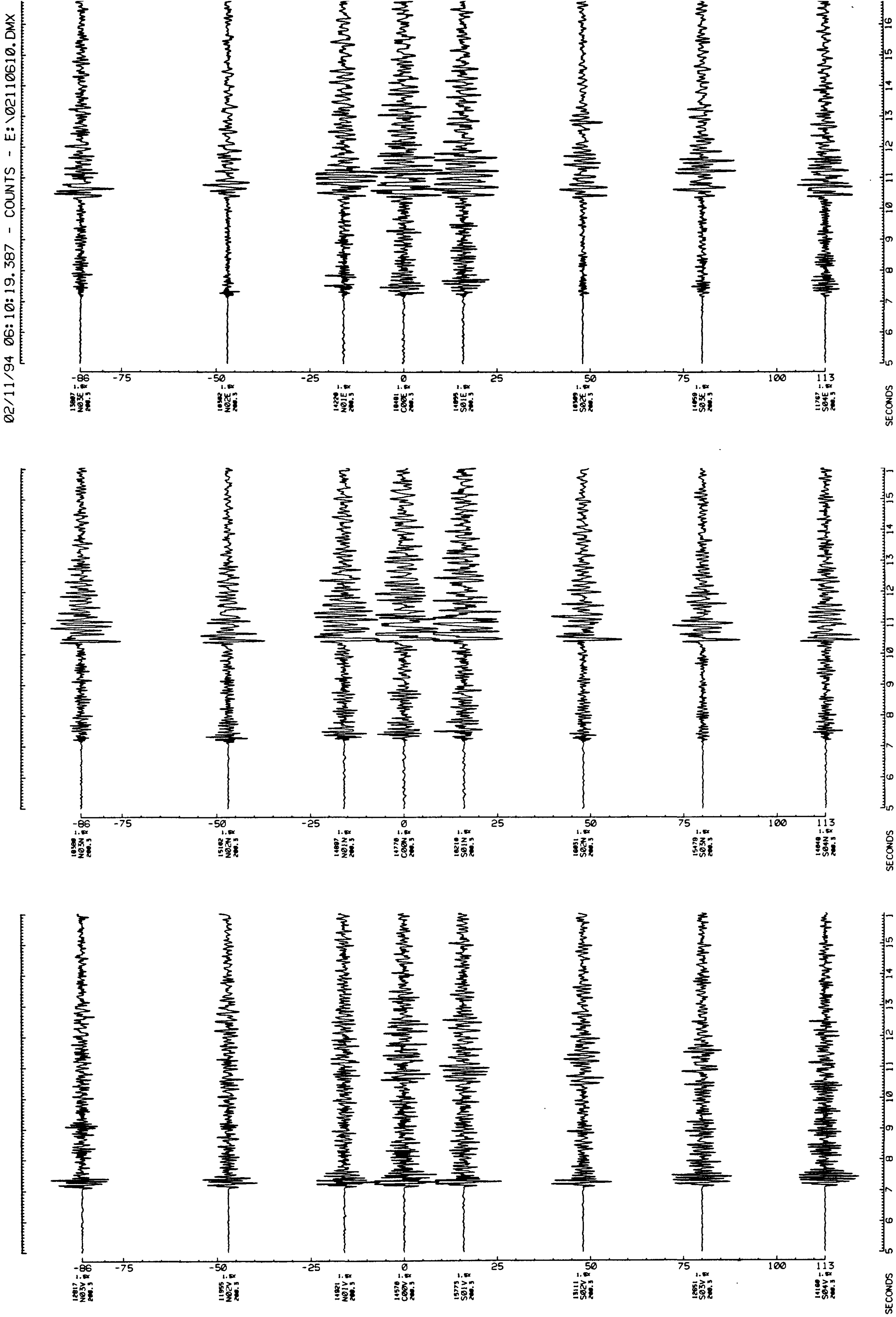


Figure 10(b)

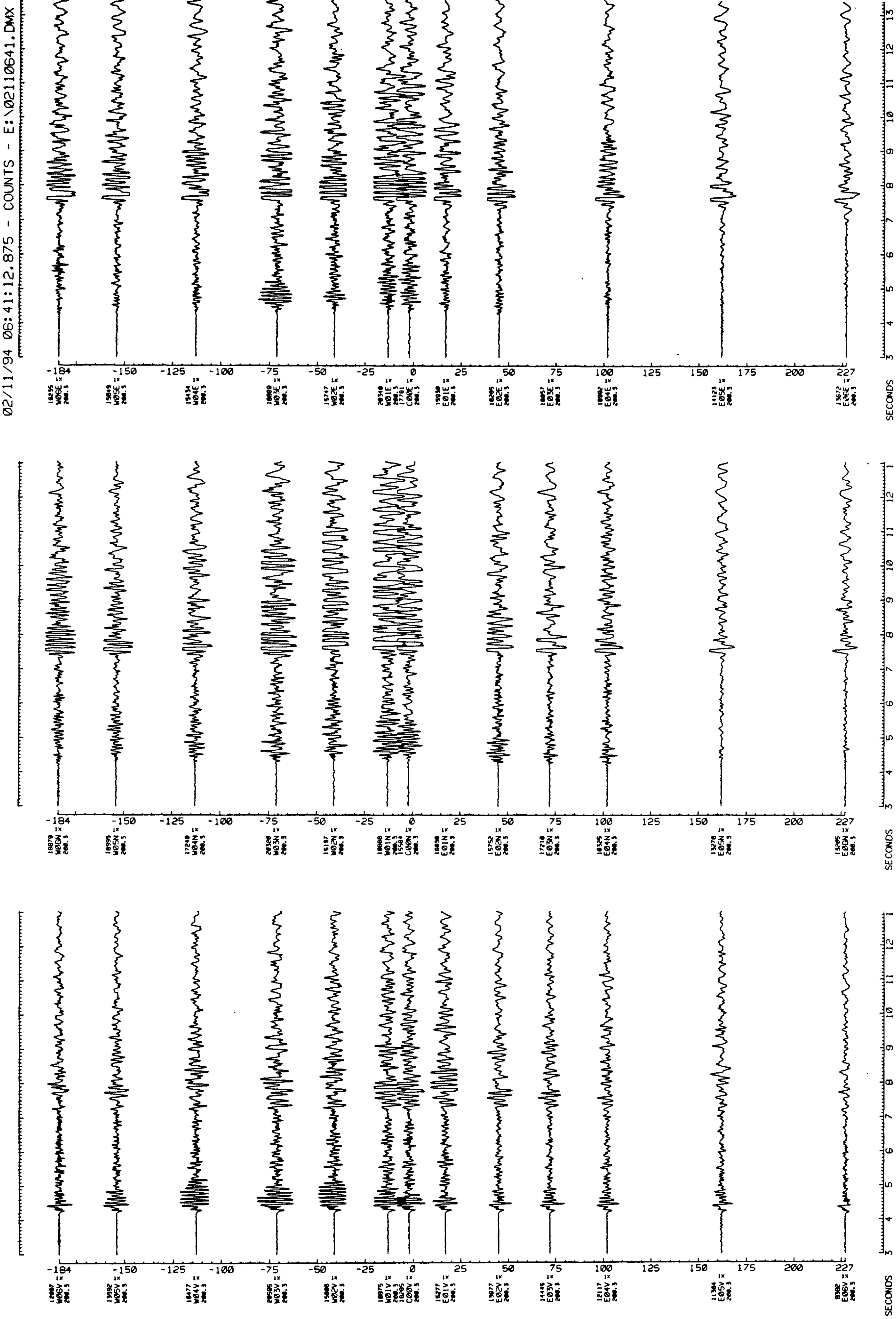


Figure 11(a)

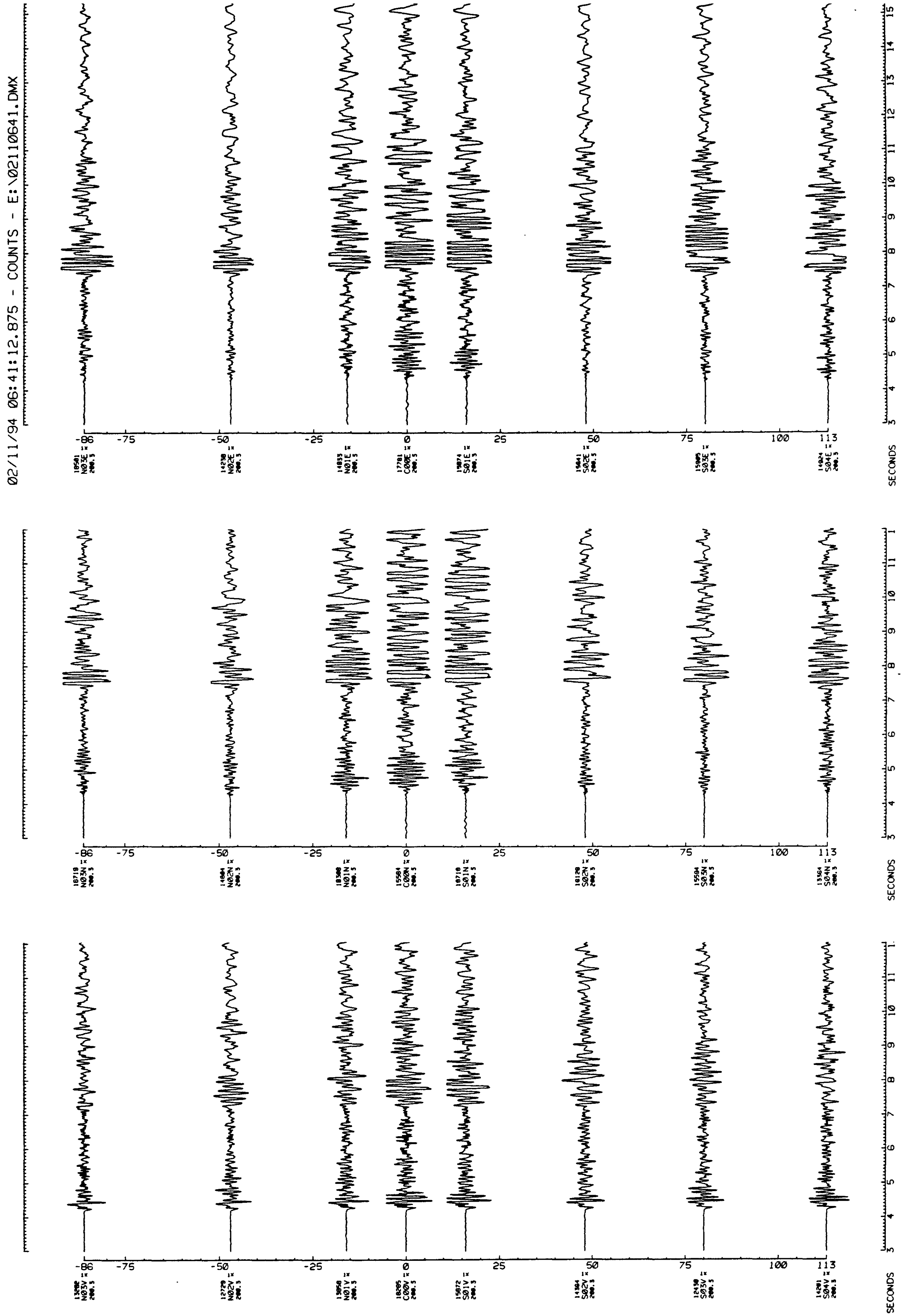


Figure 11(b)

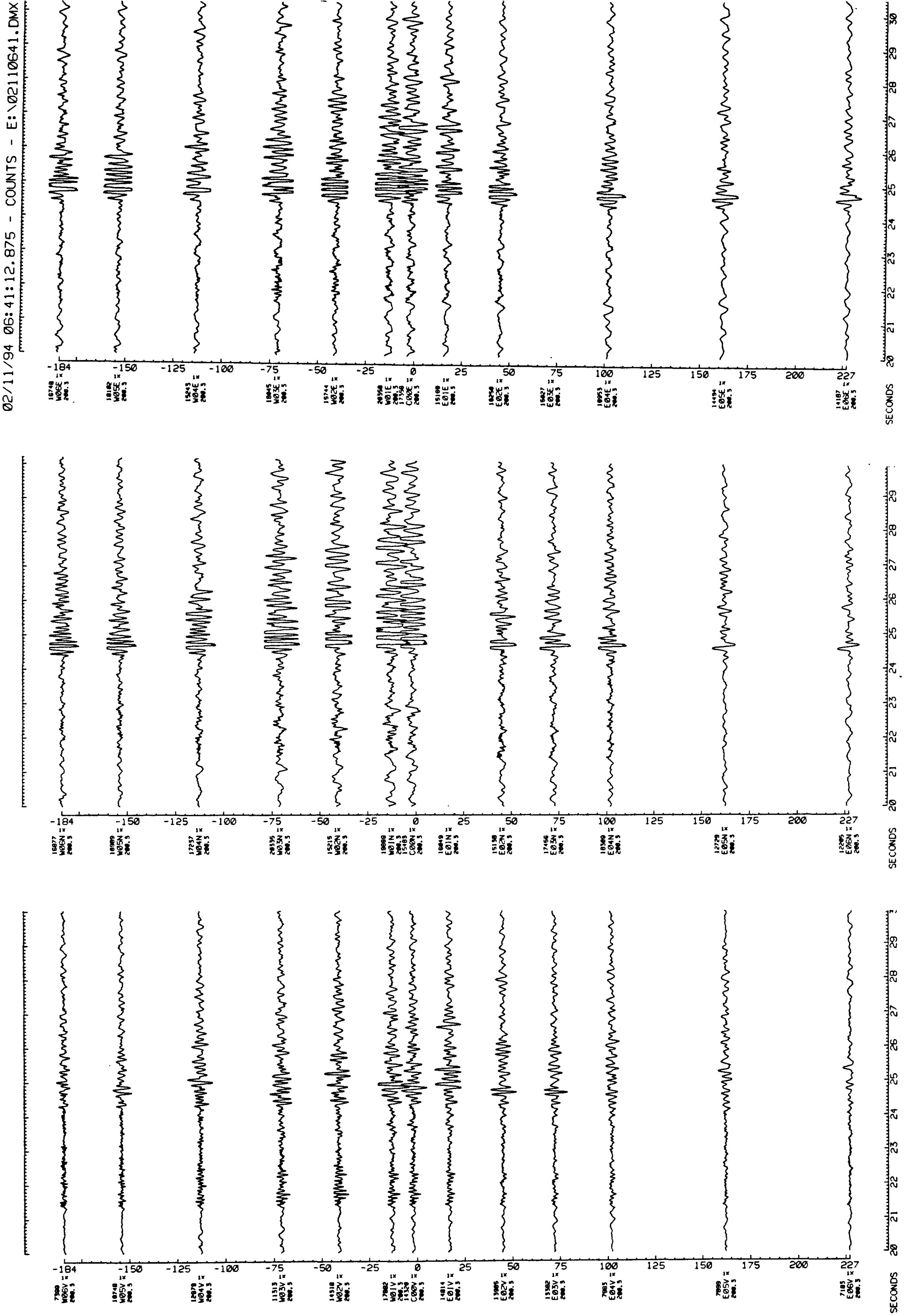
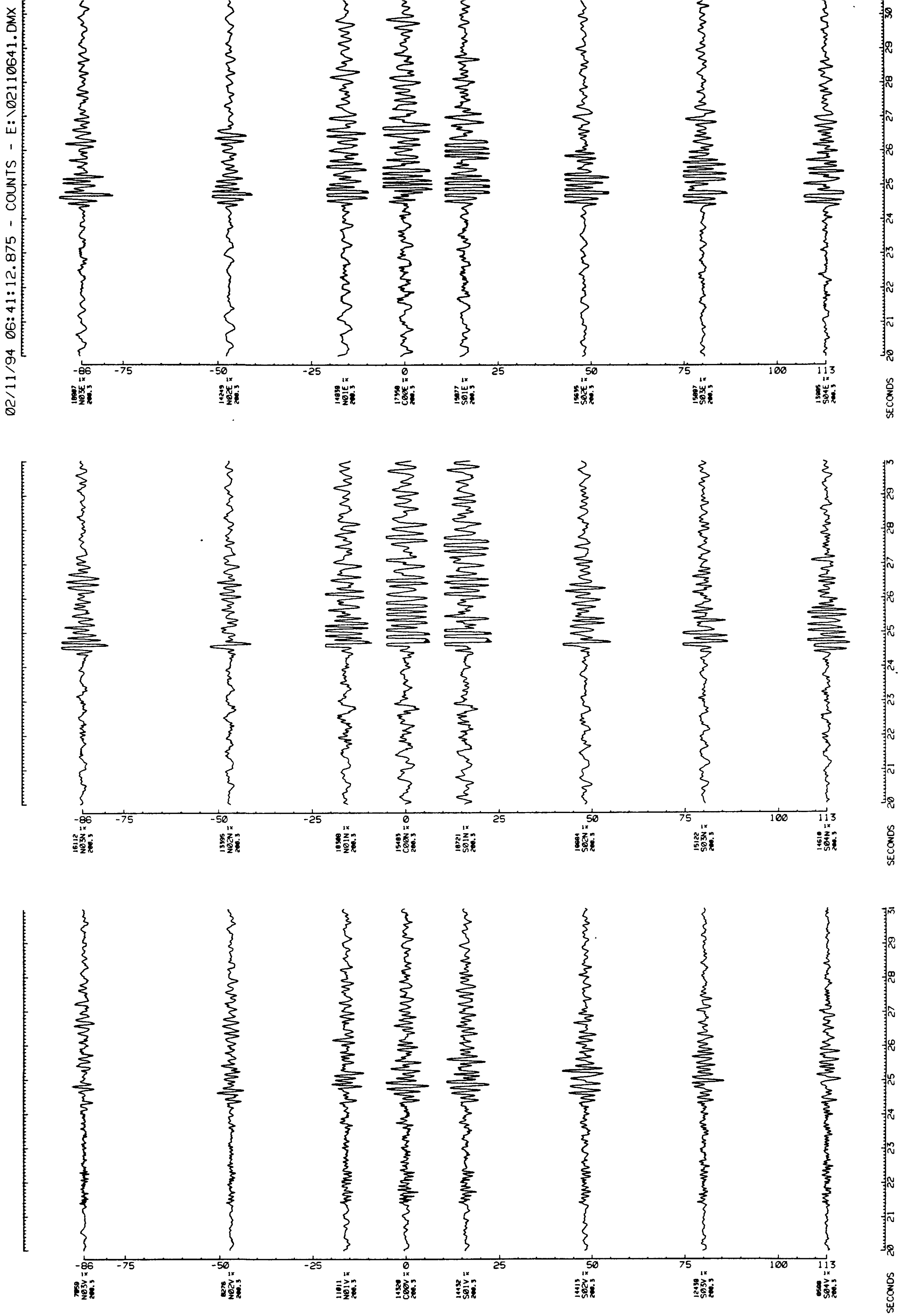


Figure 12(a)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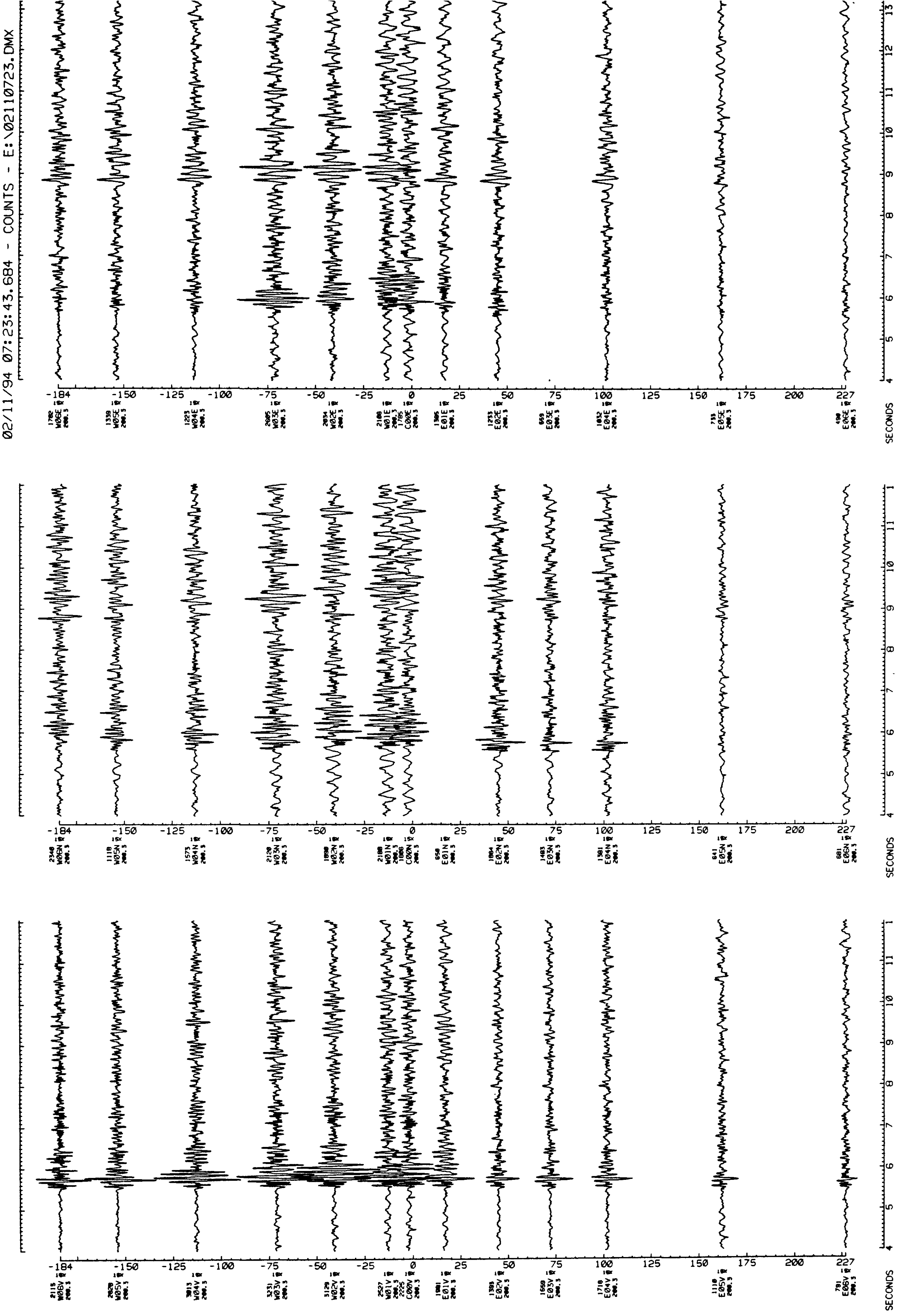
S02V
S03V
S04V
SECONDS

Figure 12(b)



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SECONDS

Figure 13(a)

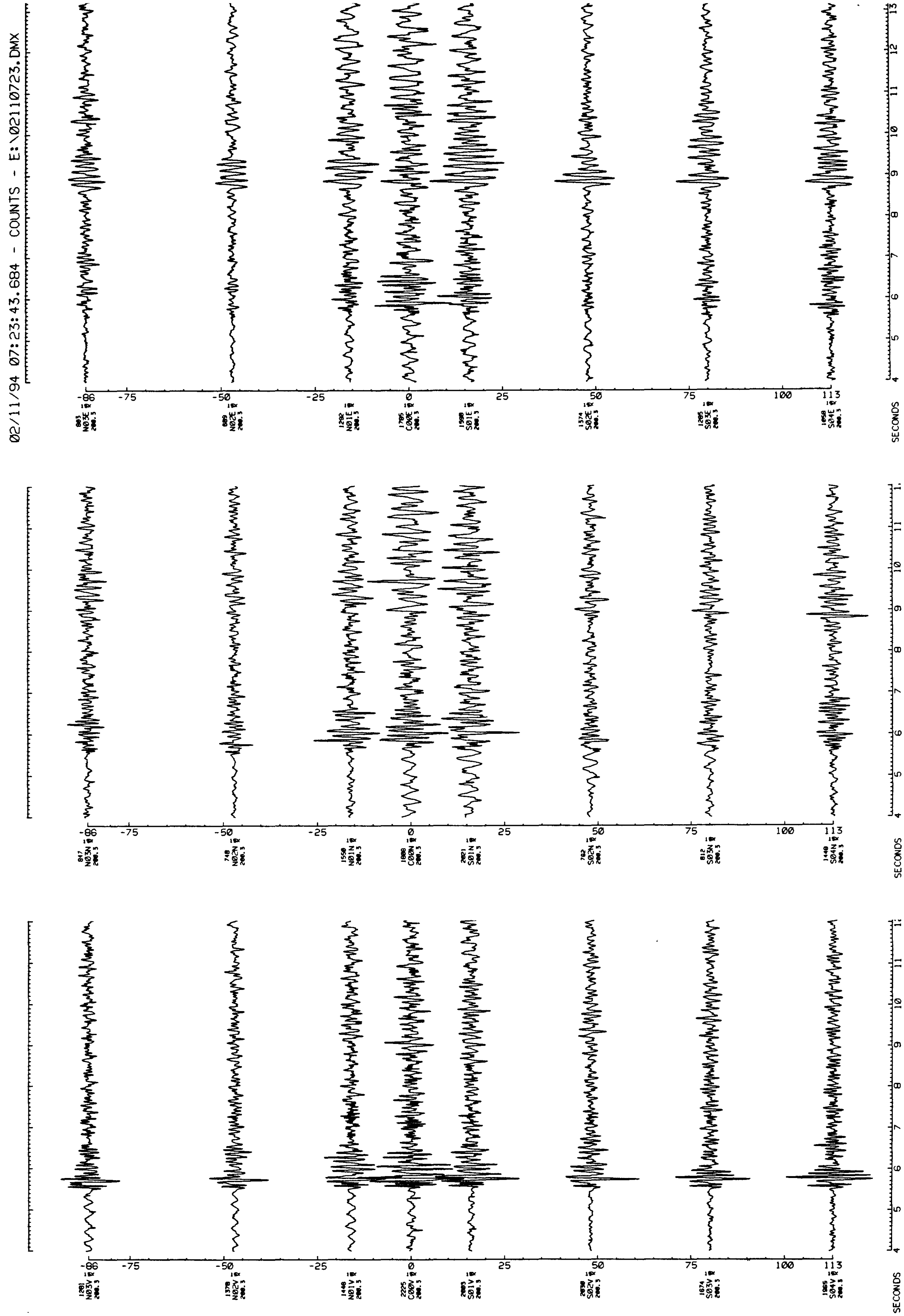
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Figure 13(b)

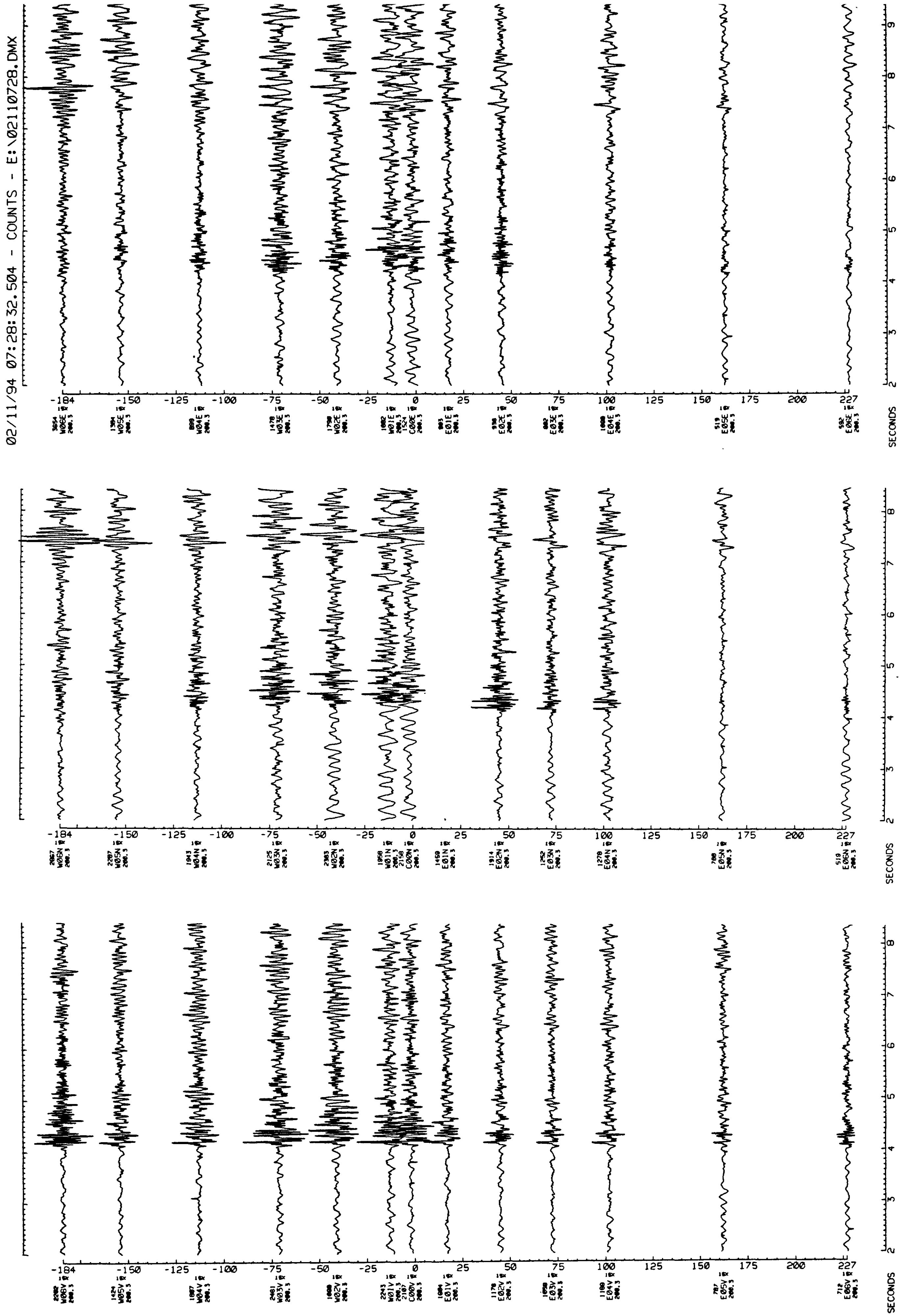


Figure 14(a)

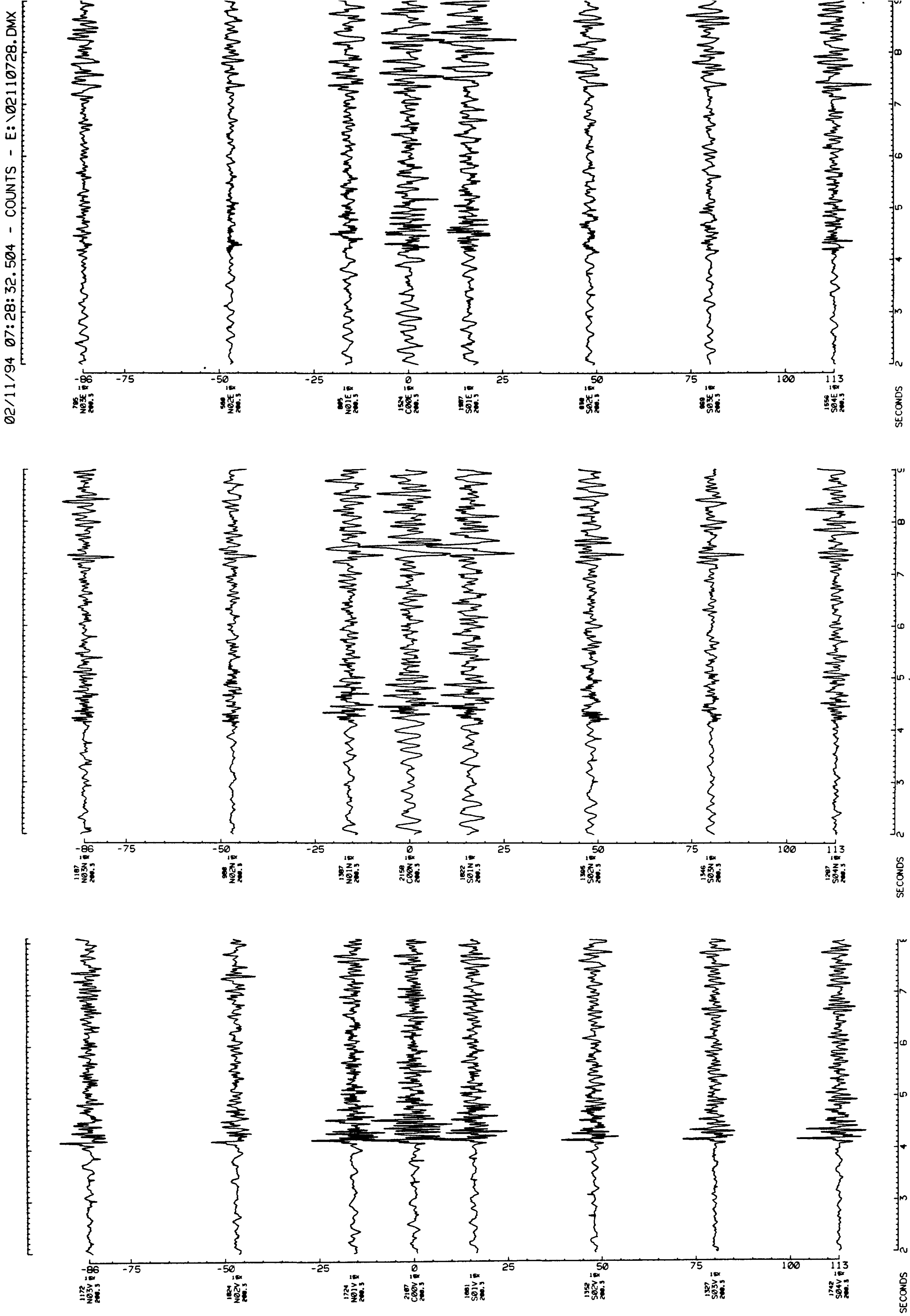


Figure 14(b)

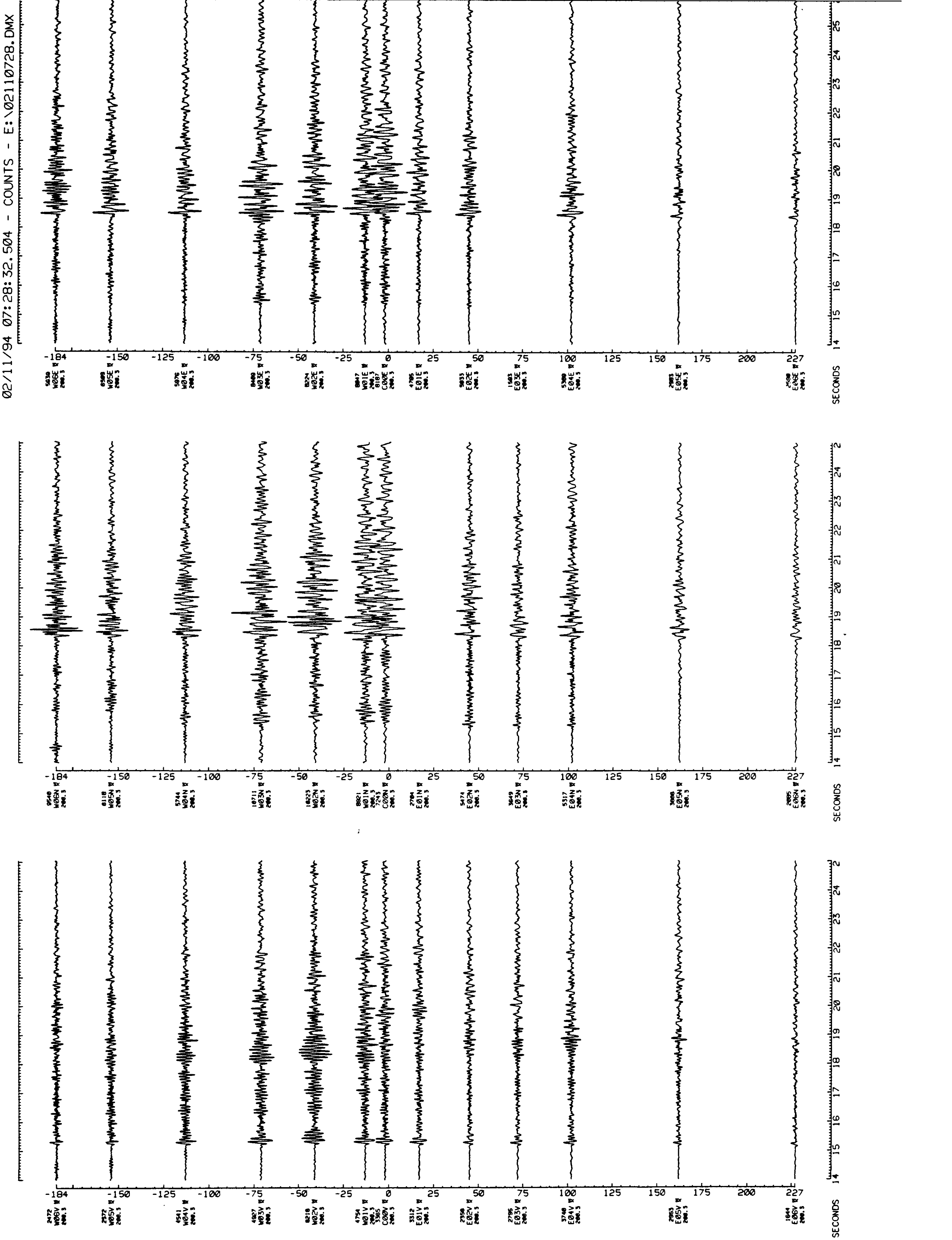


Figure 15(a)

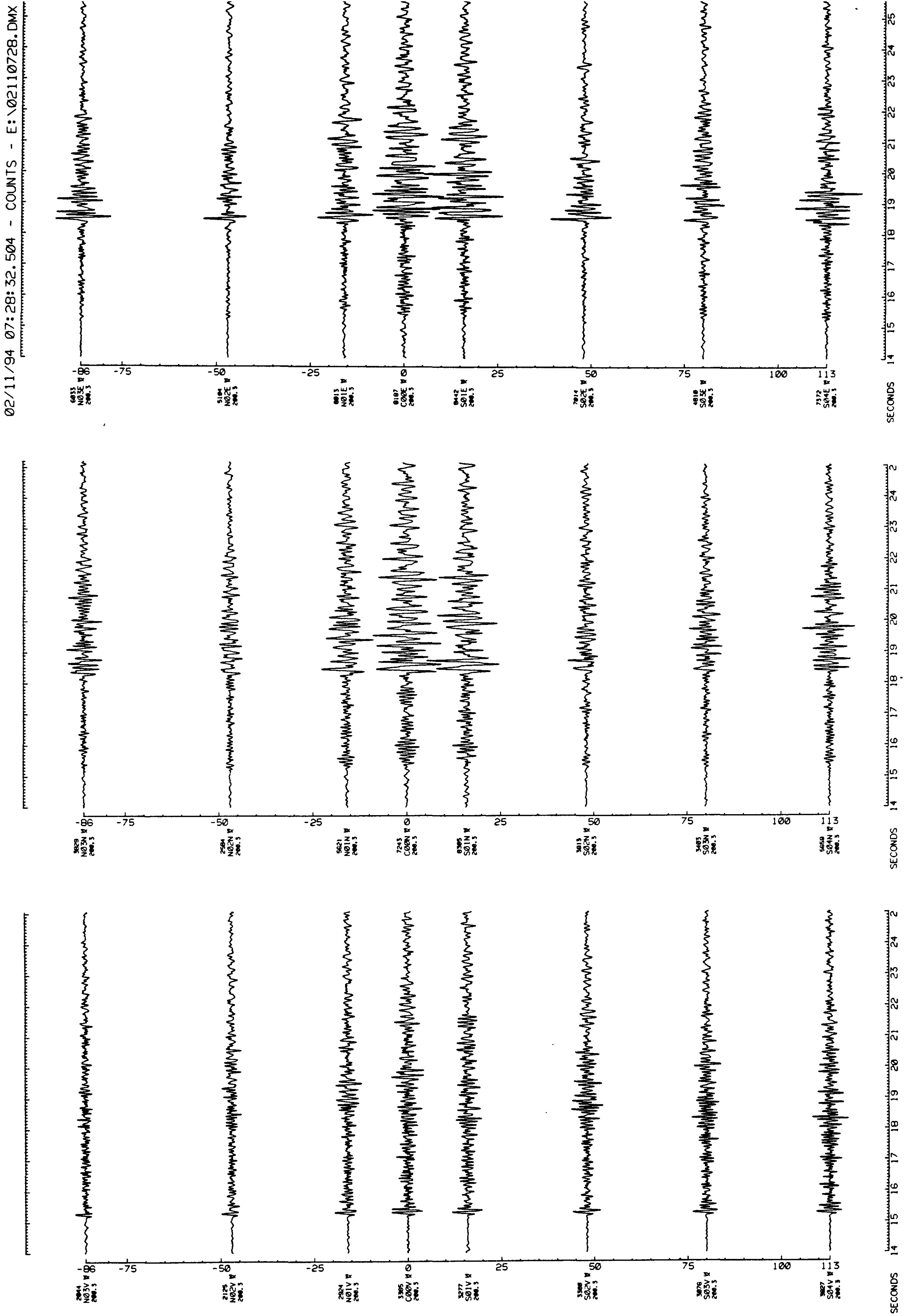


Figure 15(b)

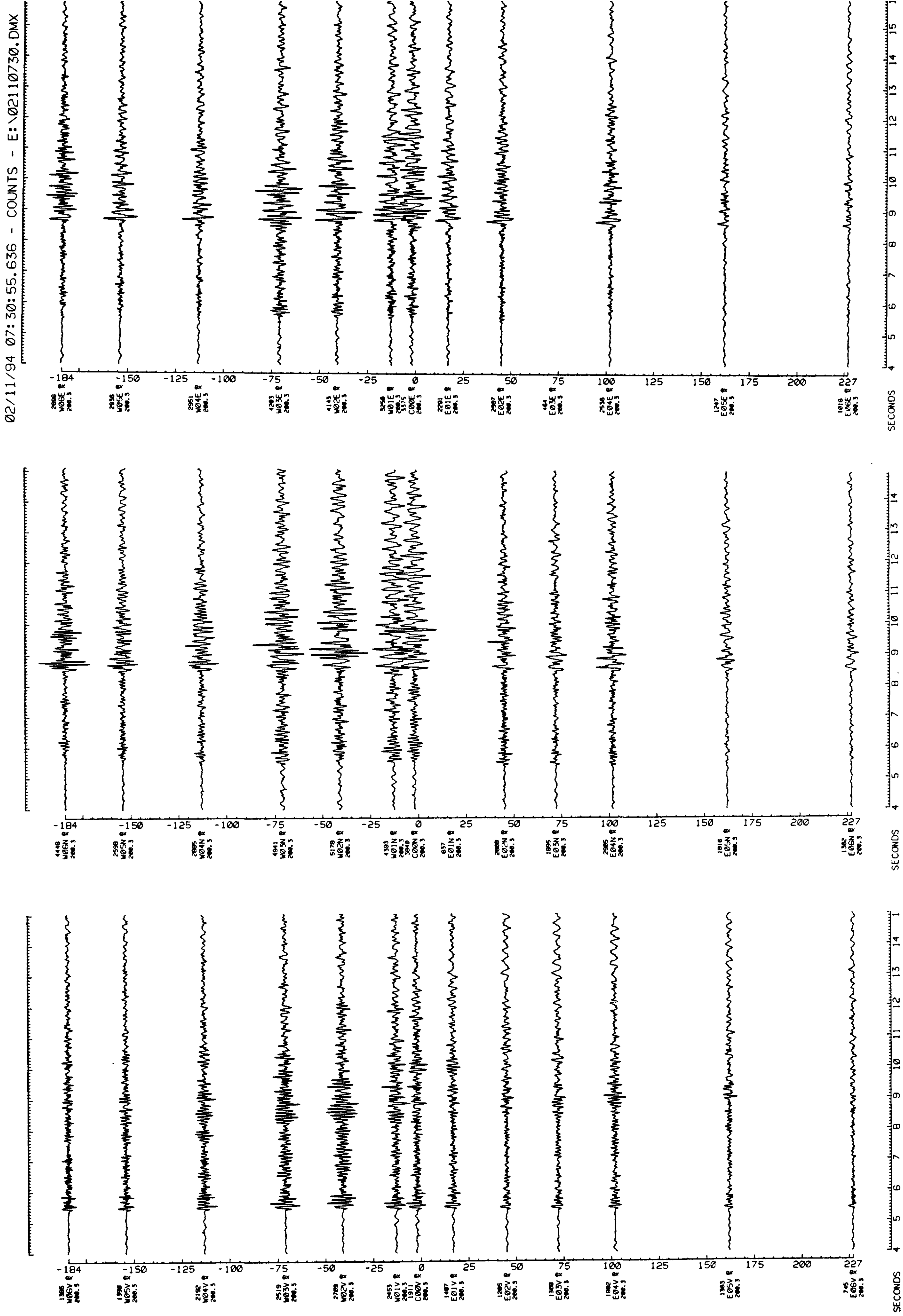


Figure 16(a)

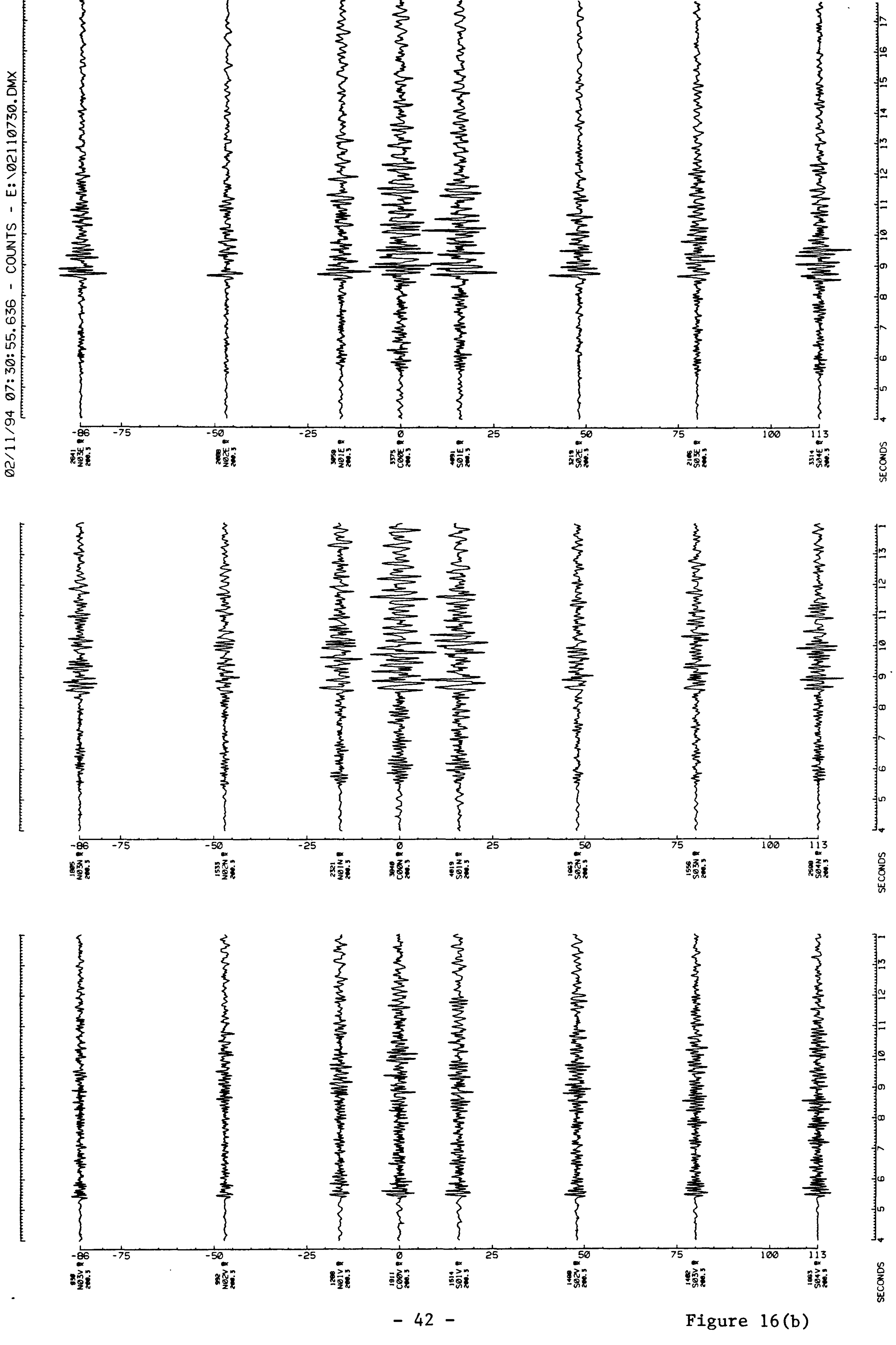


Figure 16(b)

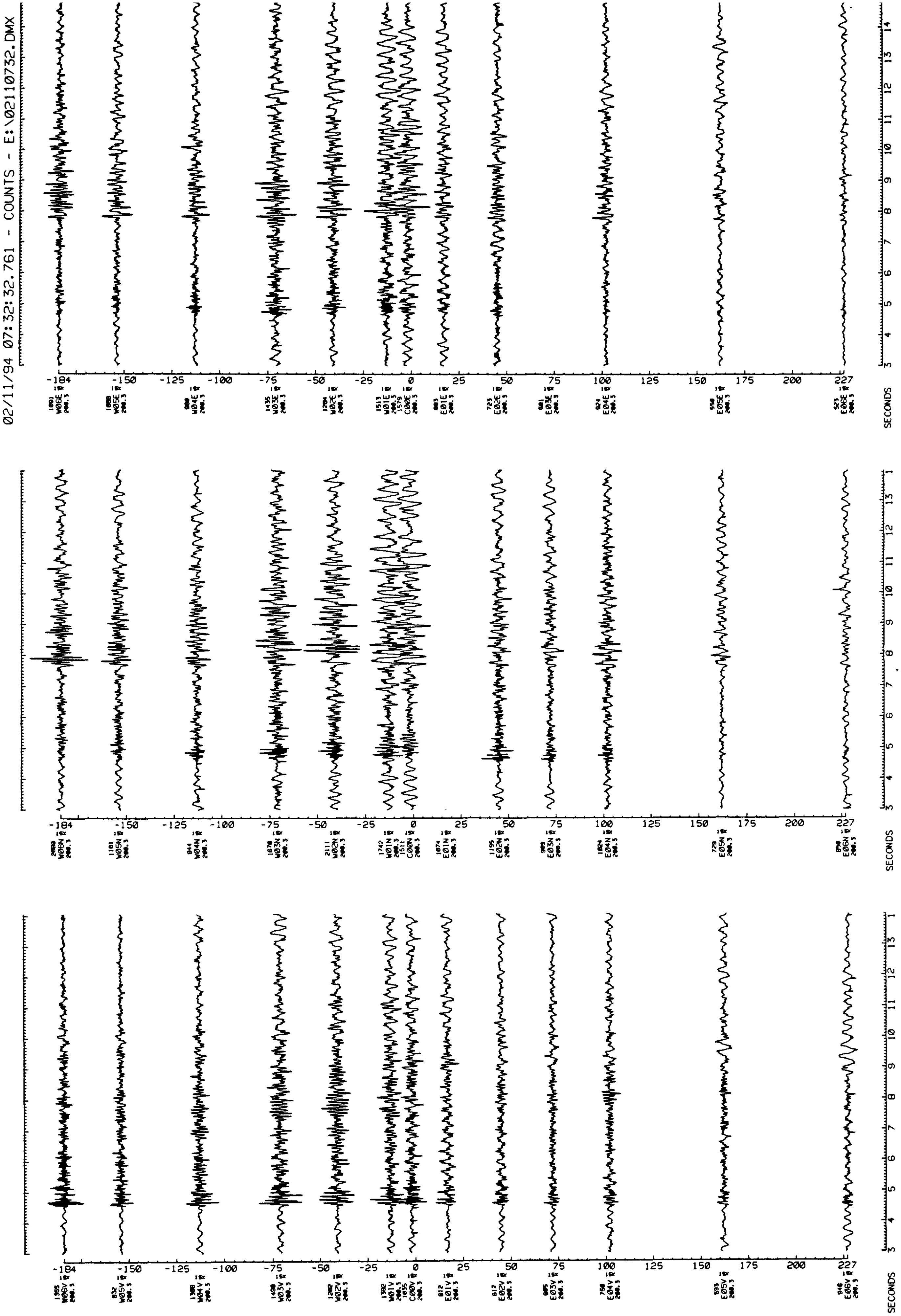
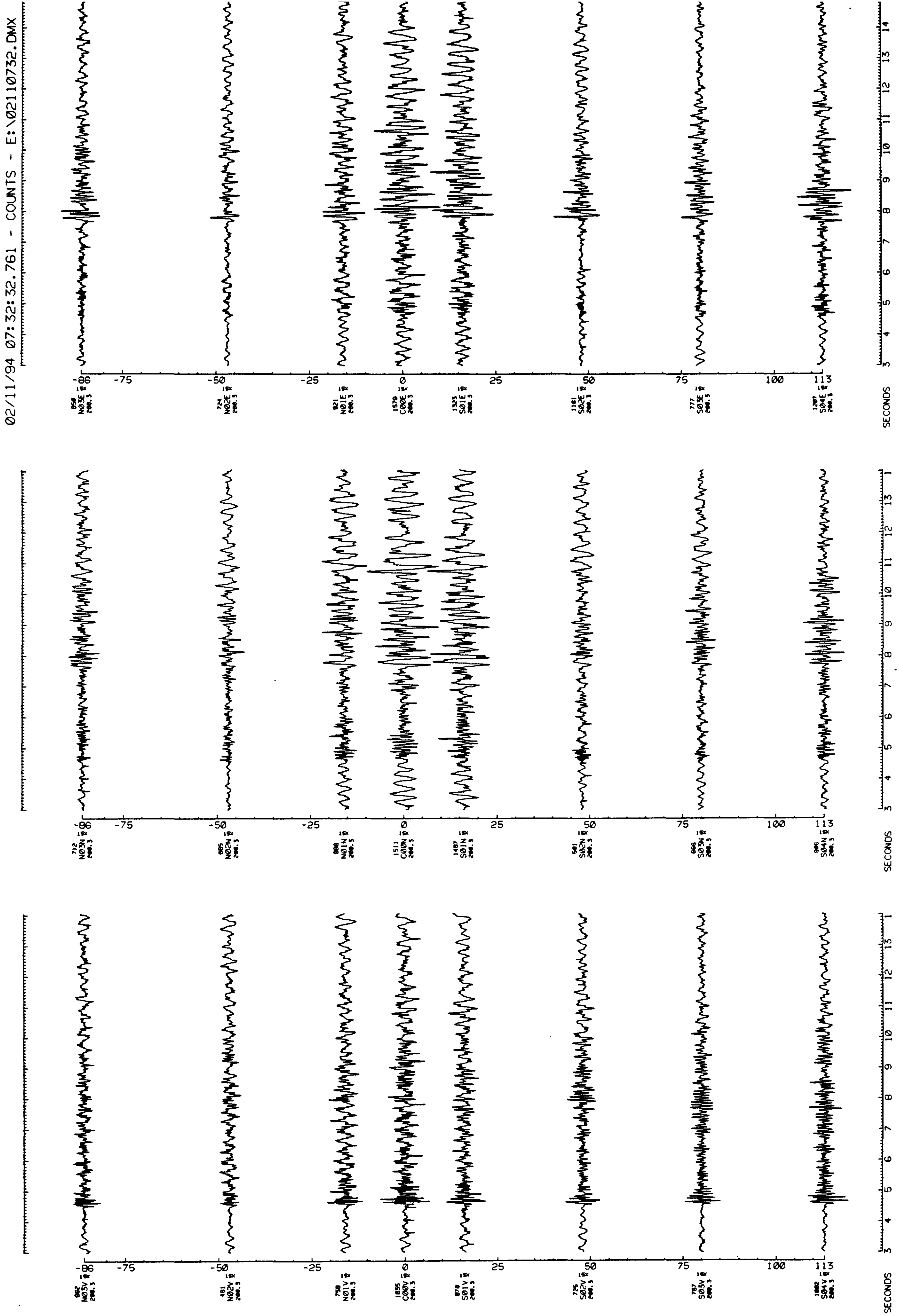


Figure 17(a)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75
100
113
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Figure 17(b)

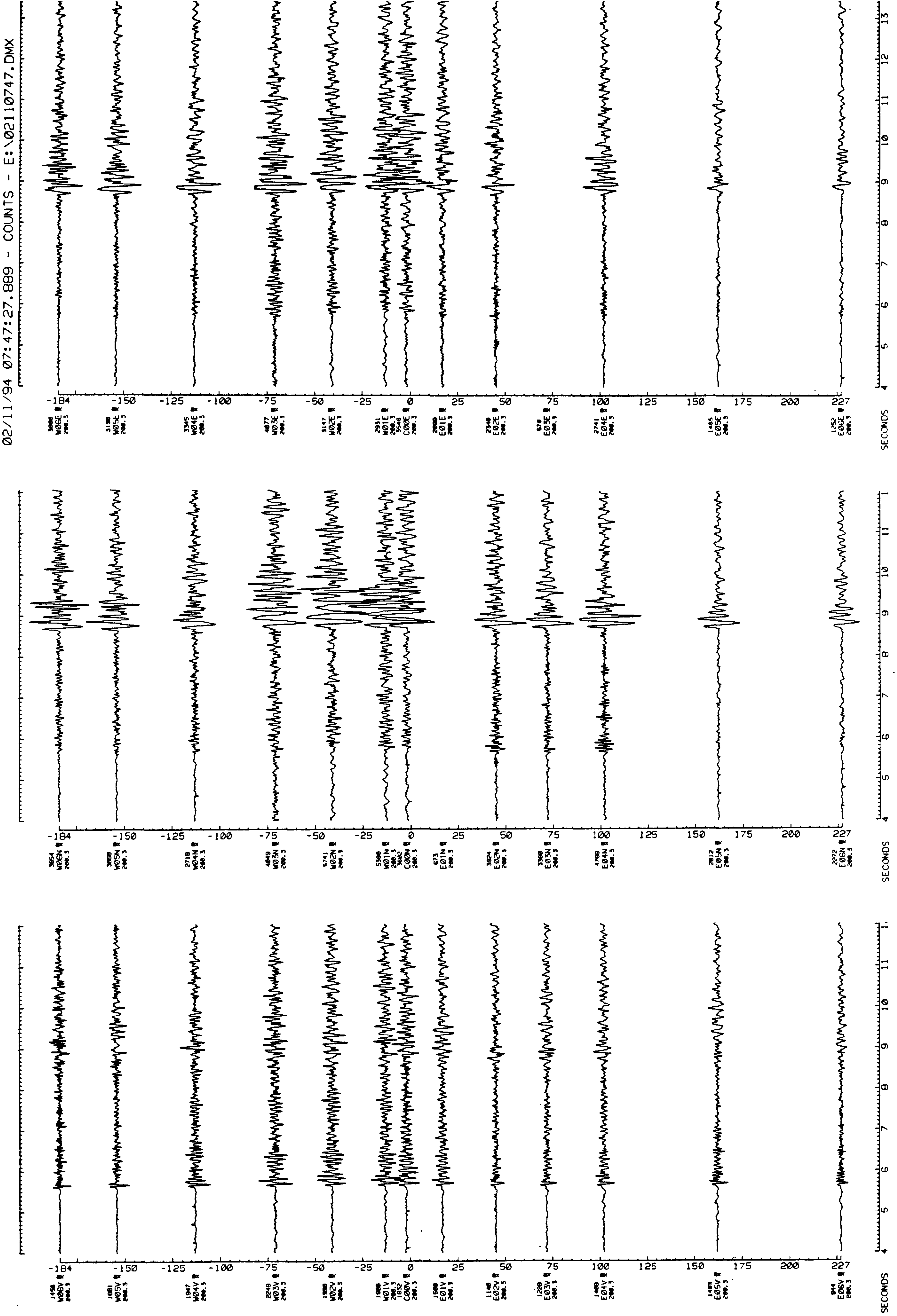

Figure 18(a)

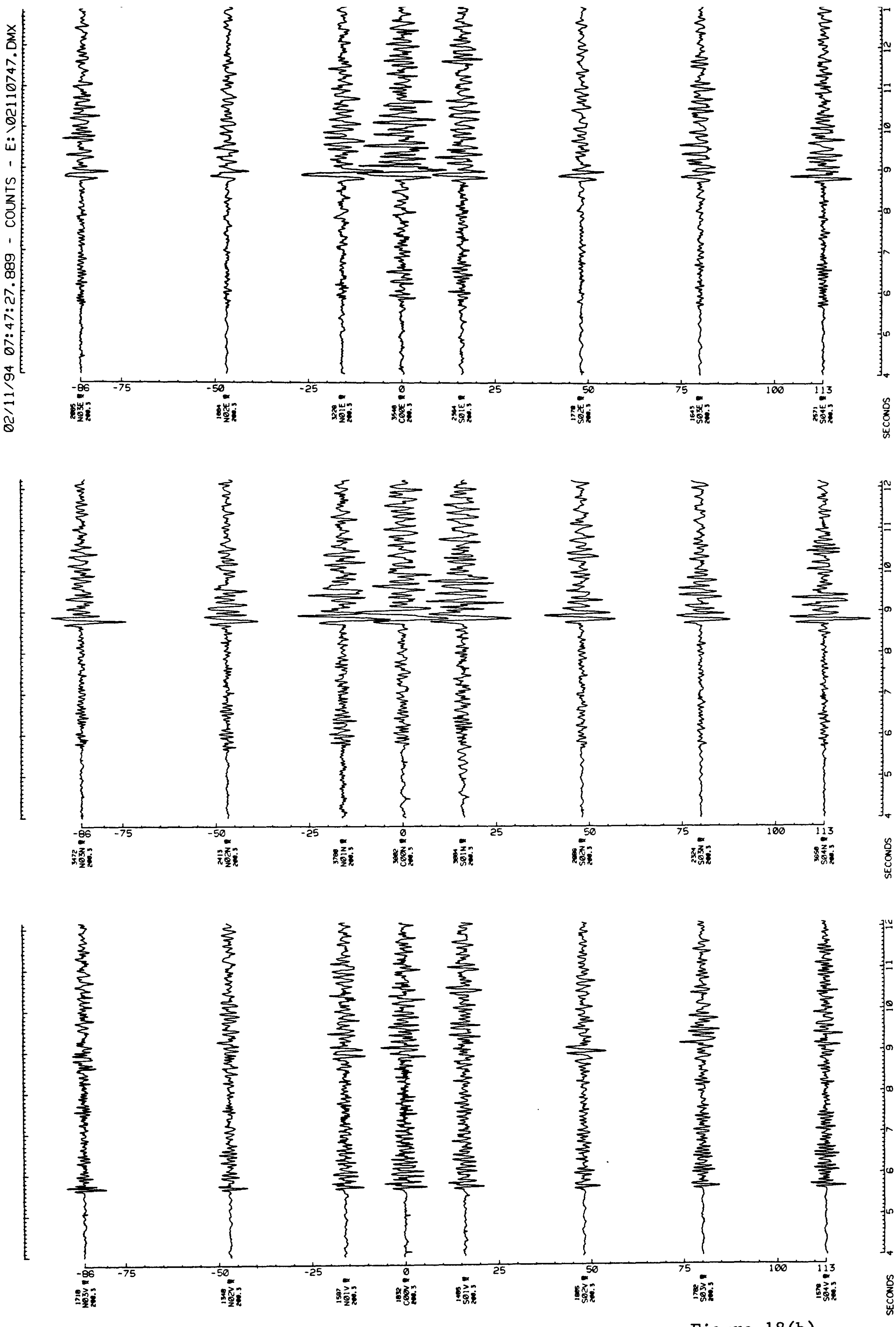
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Figure 18(b)

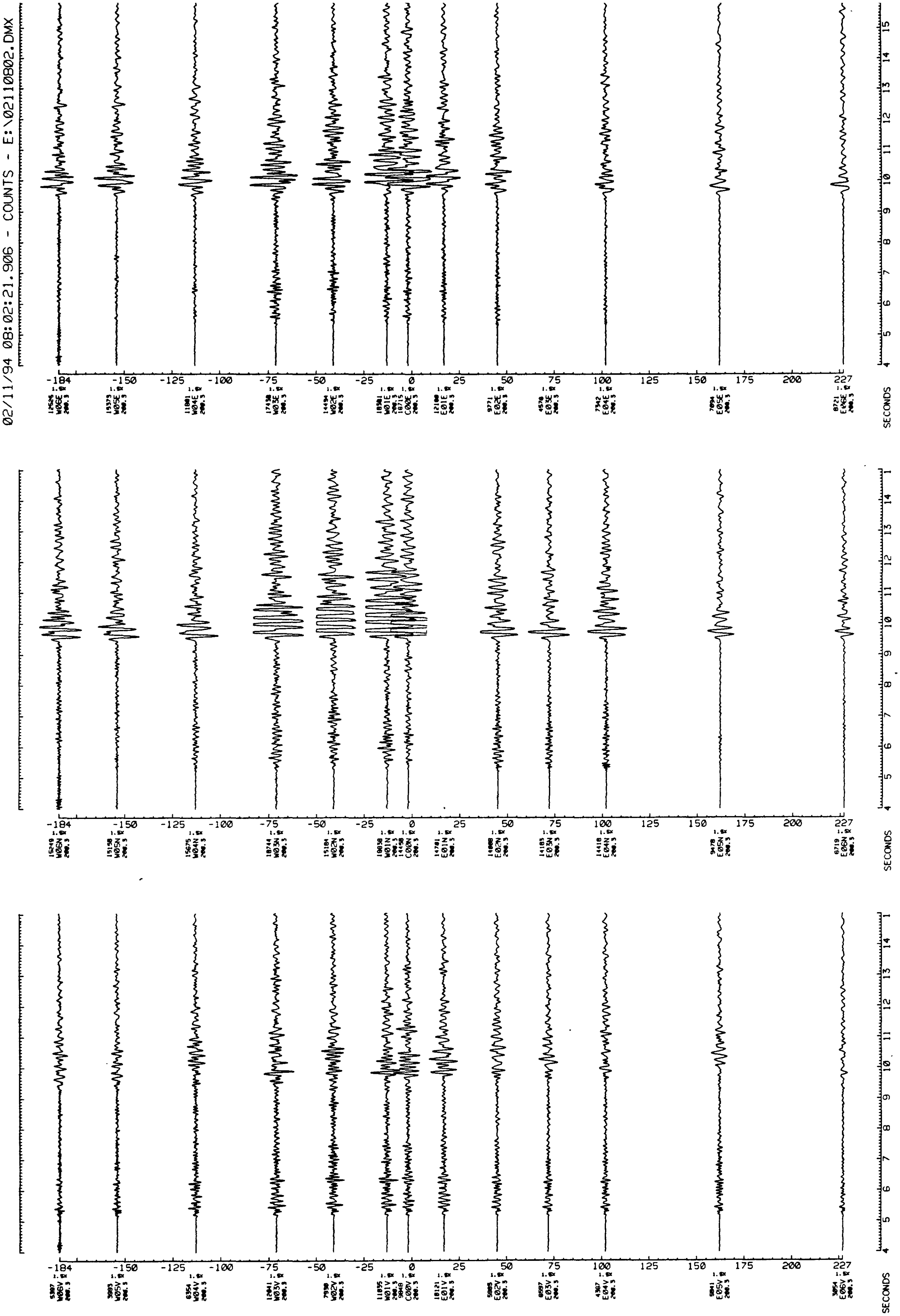

Figure 19(a)

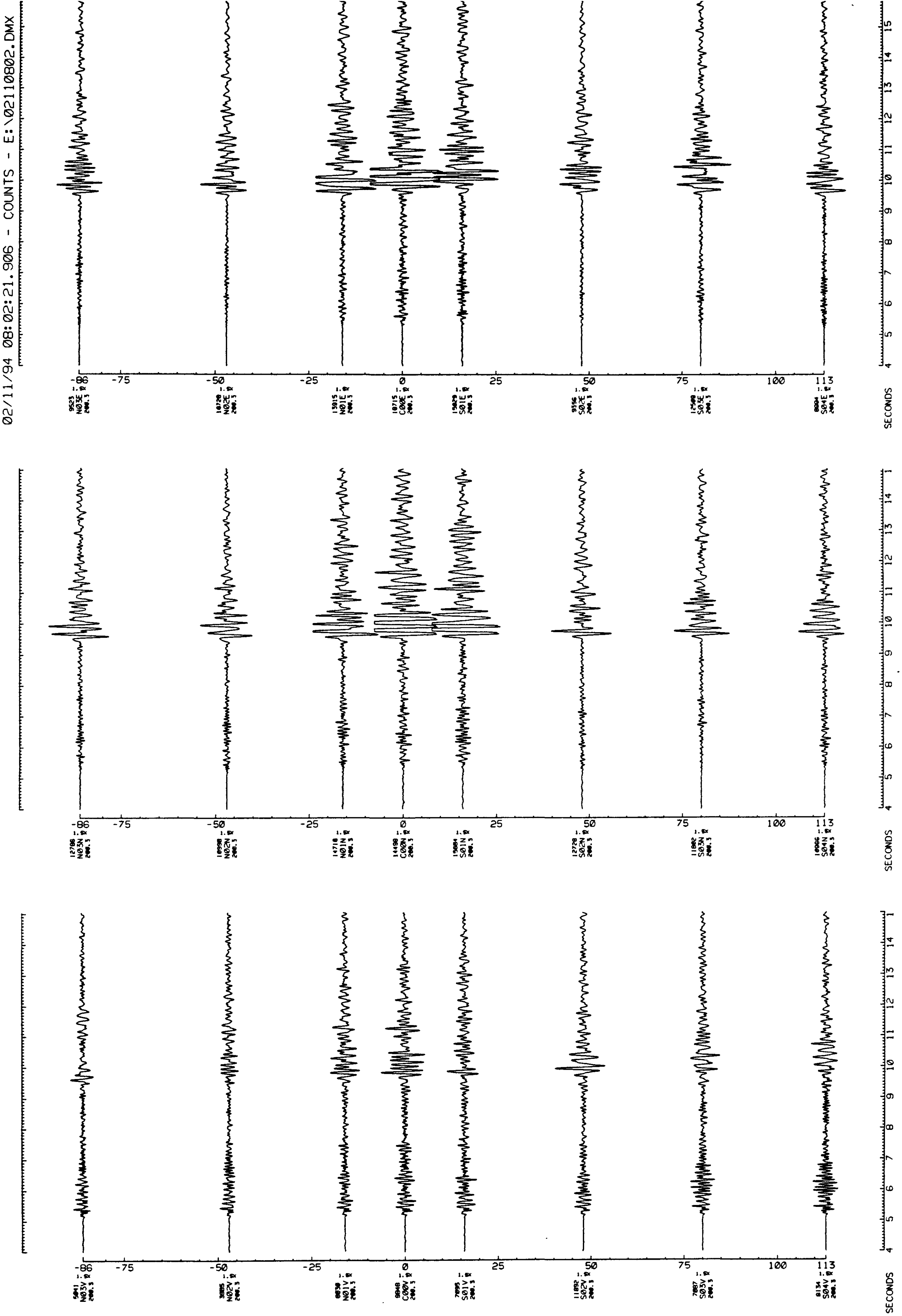
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Figure 19(b)

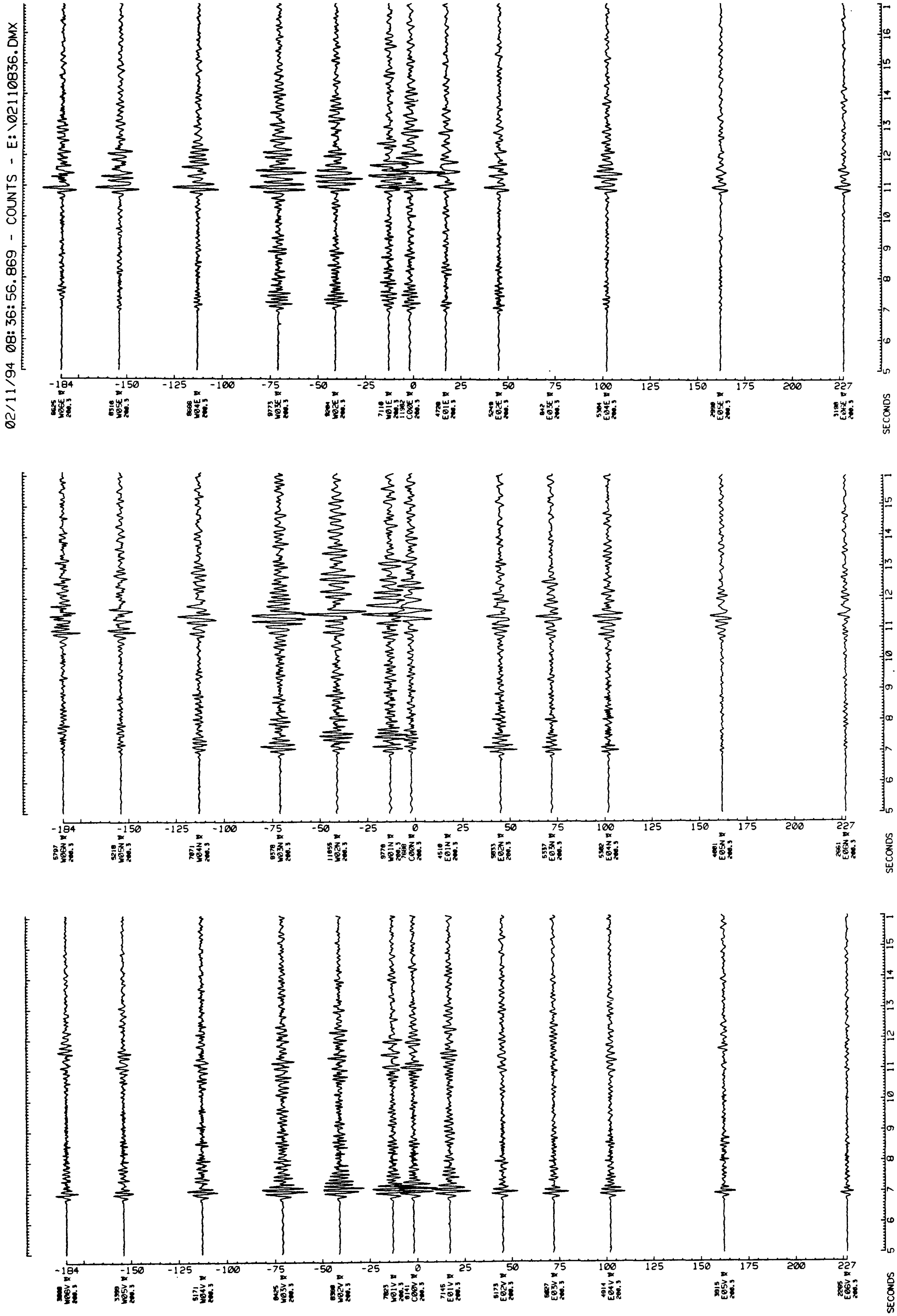
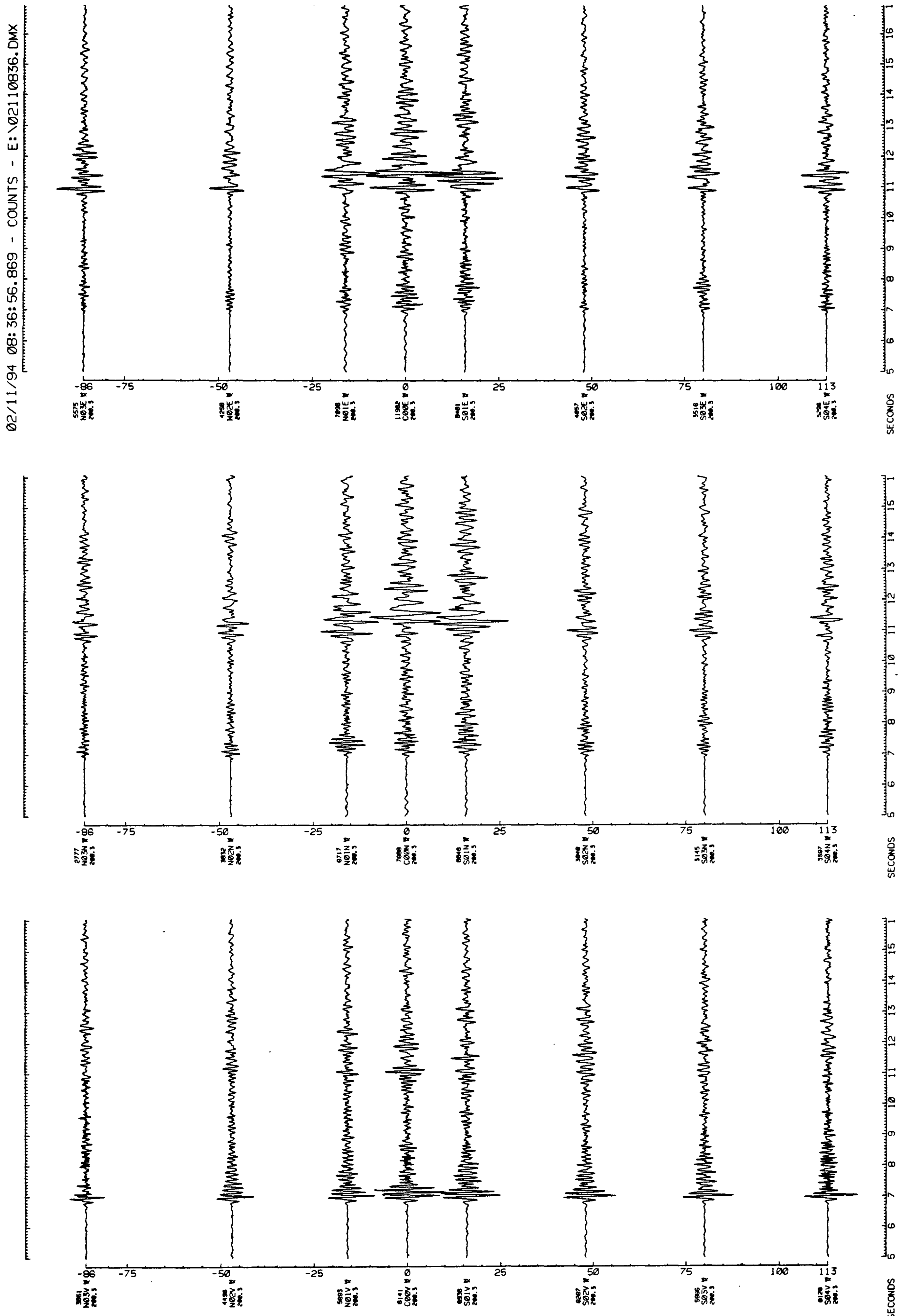


Figure 20(a)



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N01V
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75
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113
SECONDS

Figure 20(b)

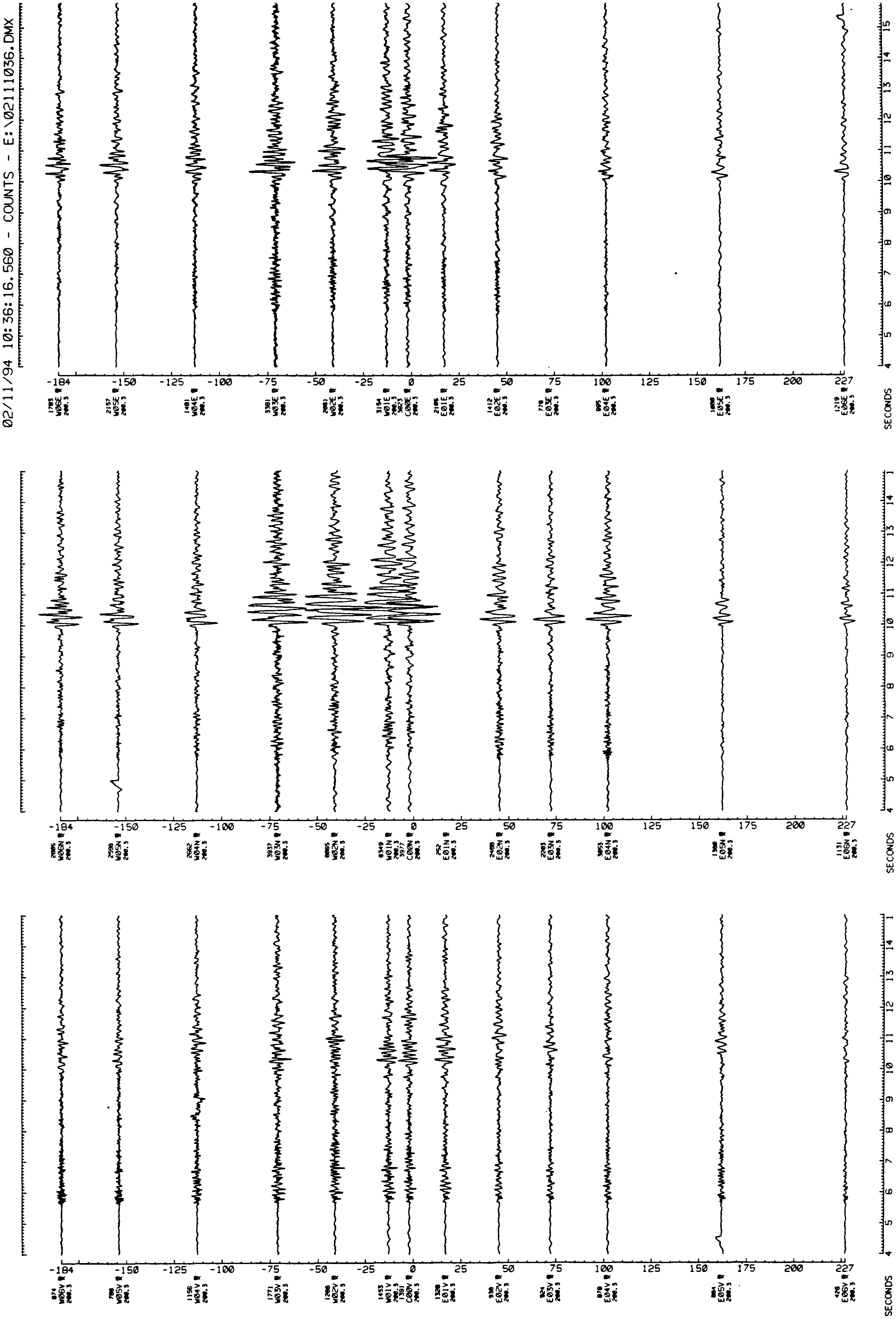

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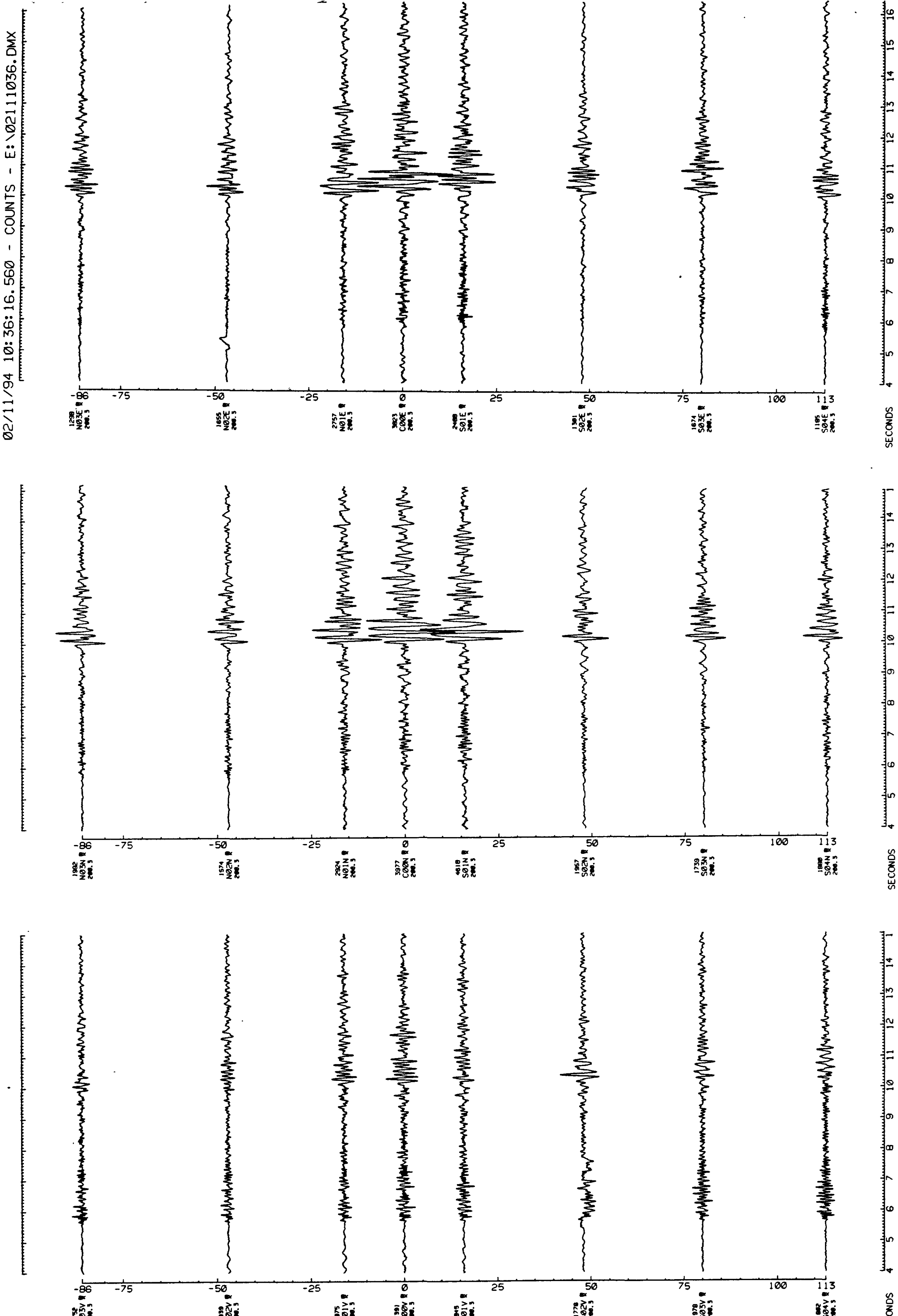
Figure 21(a)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C00N
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S02V
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S04V
SECONDS

Figure 21(b)

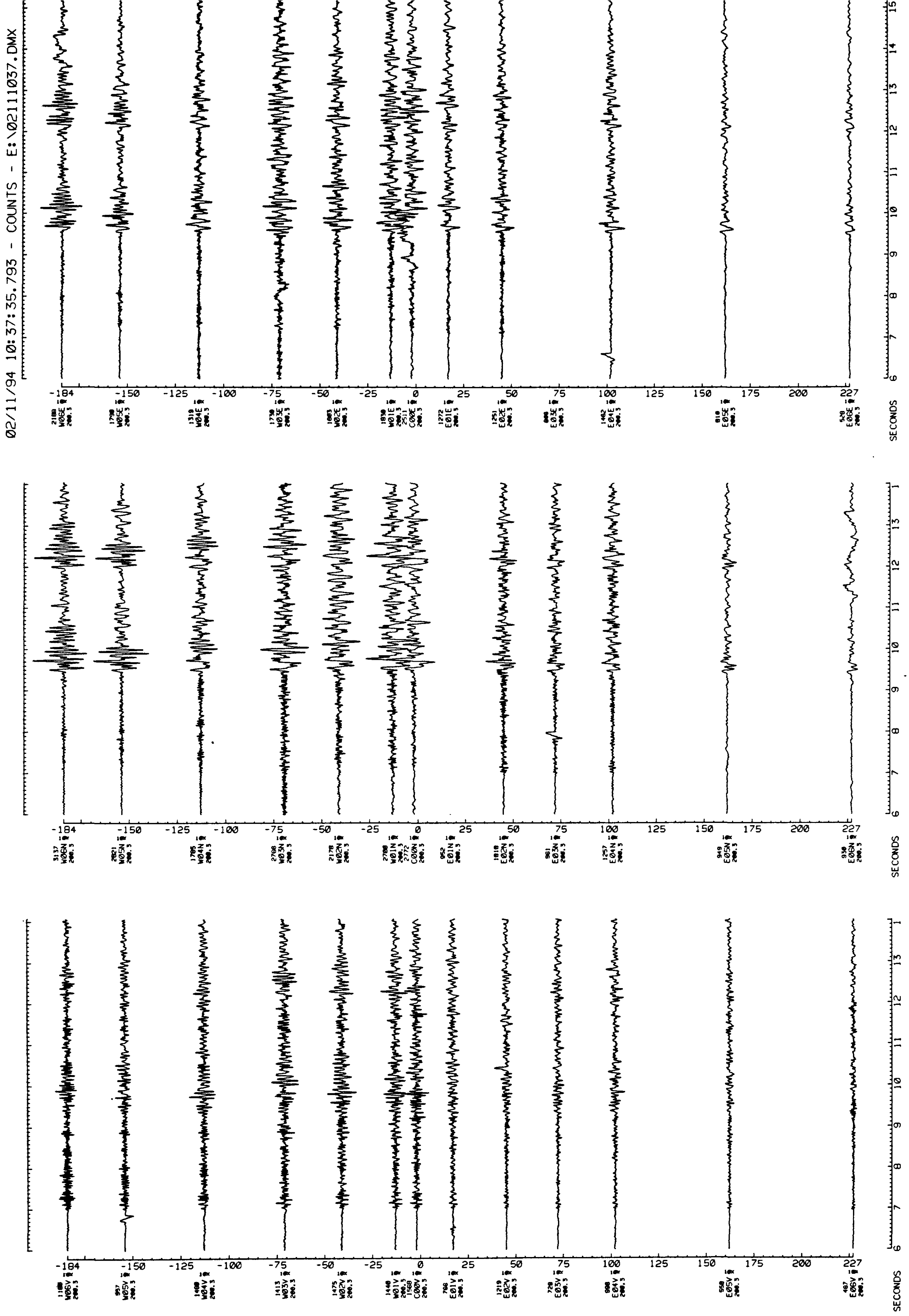
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Figure 22(a)

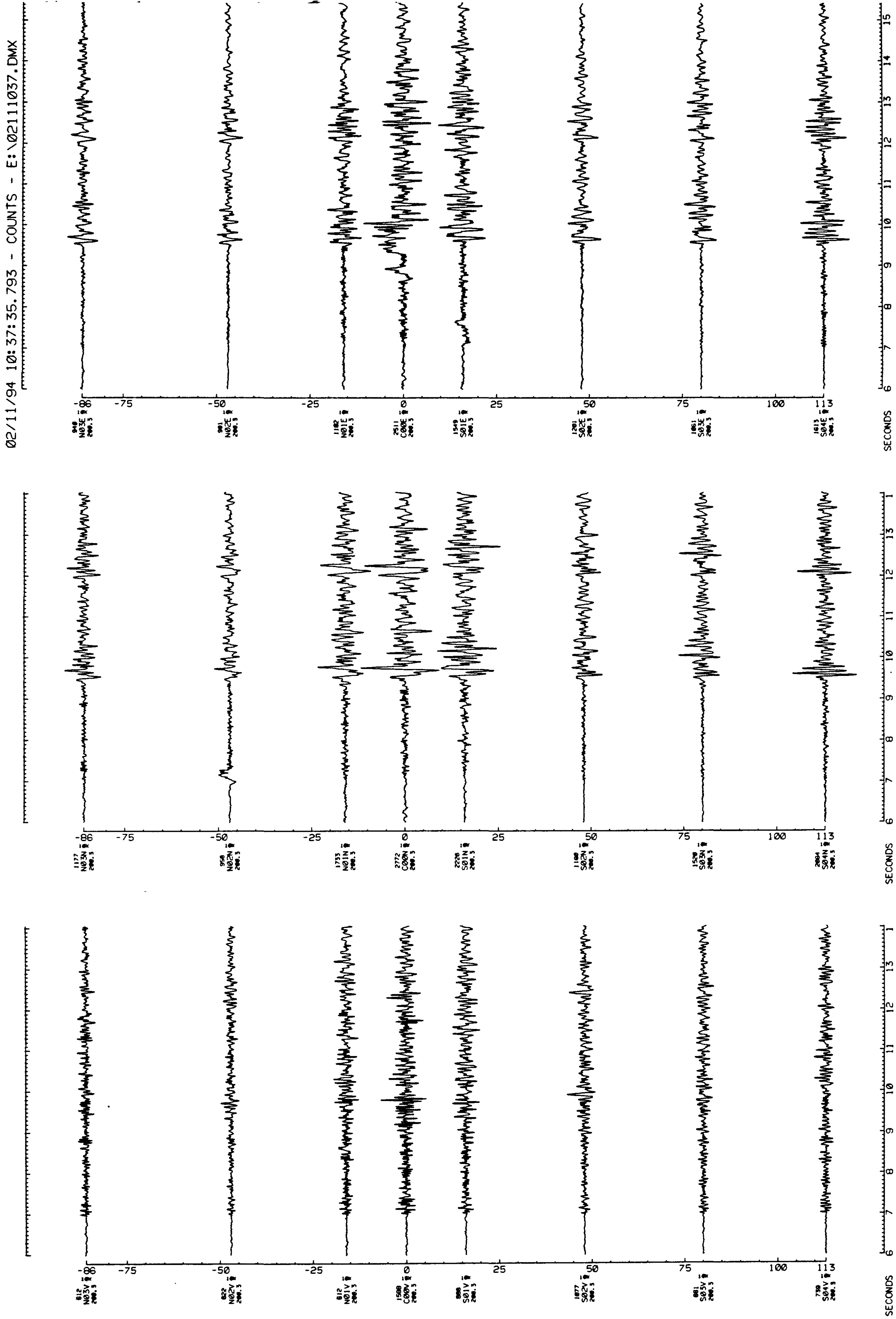
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Figure 22(b)

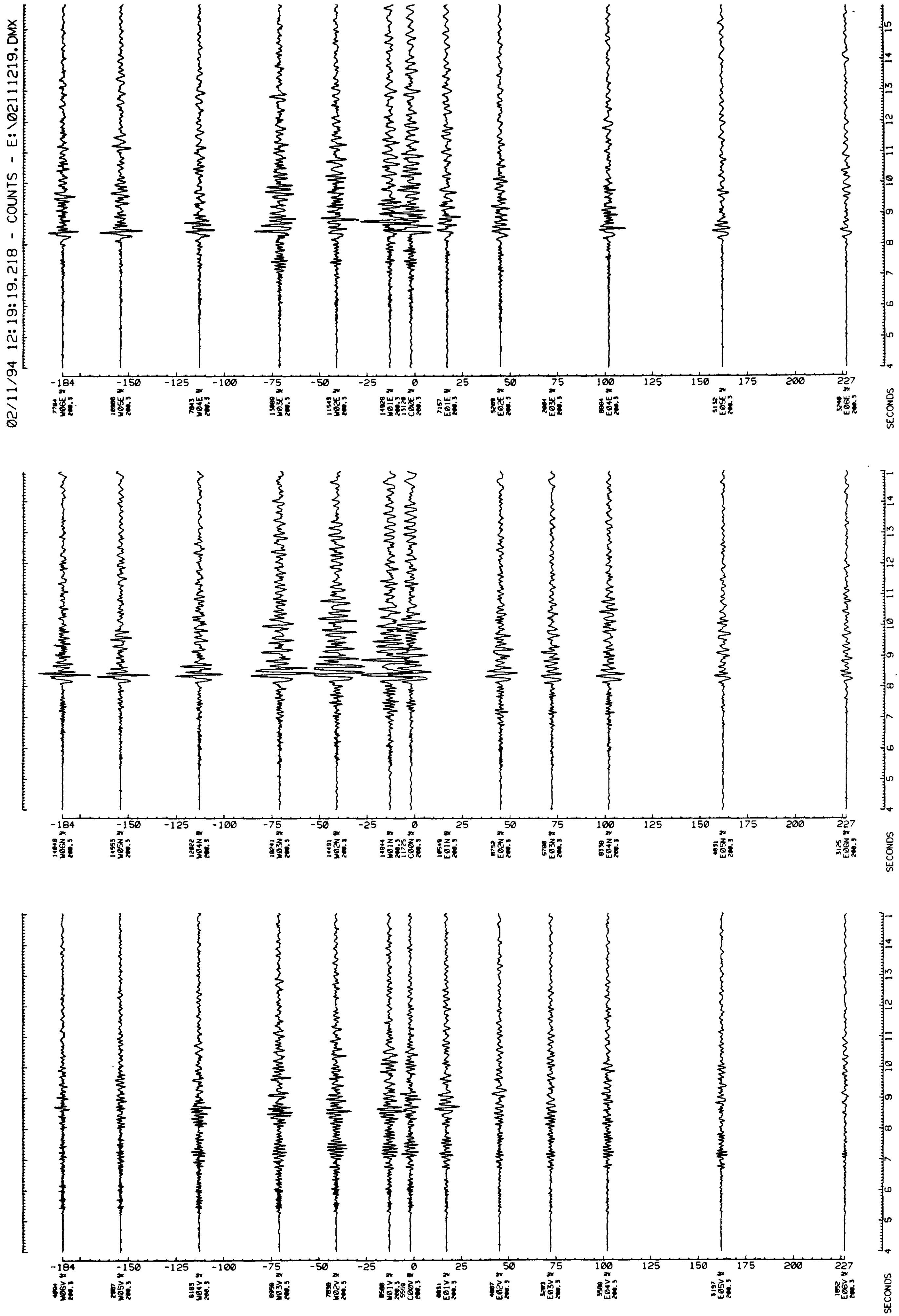
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Figure 23(a)

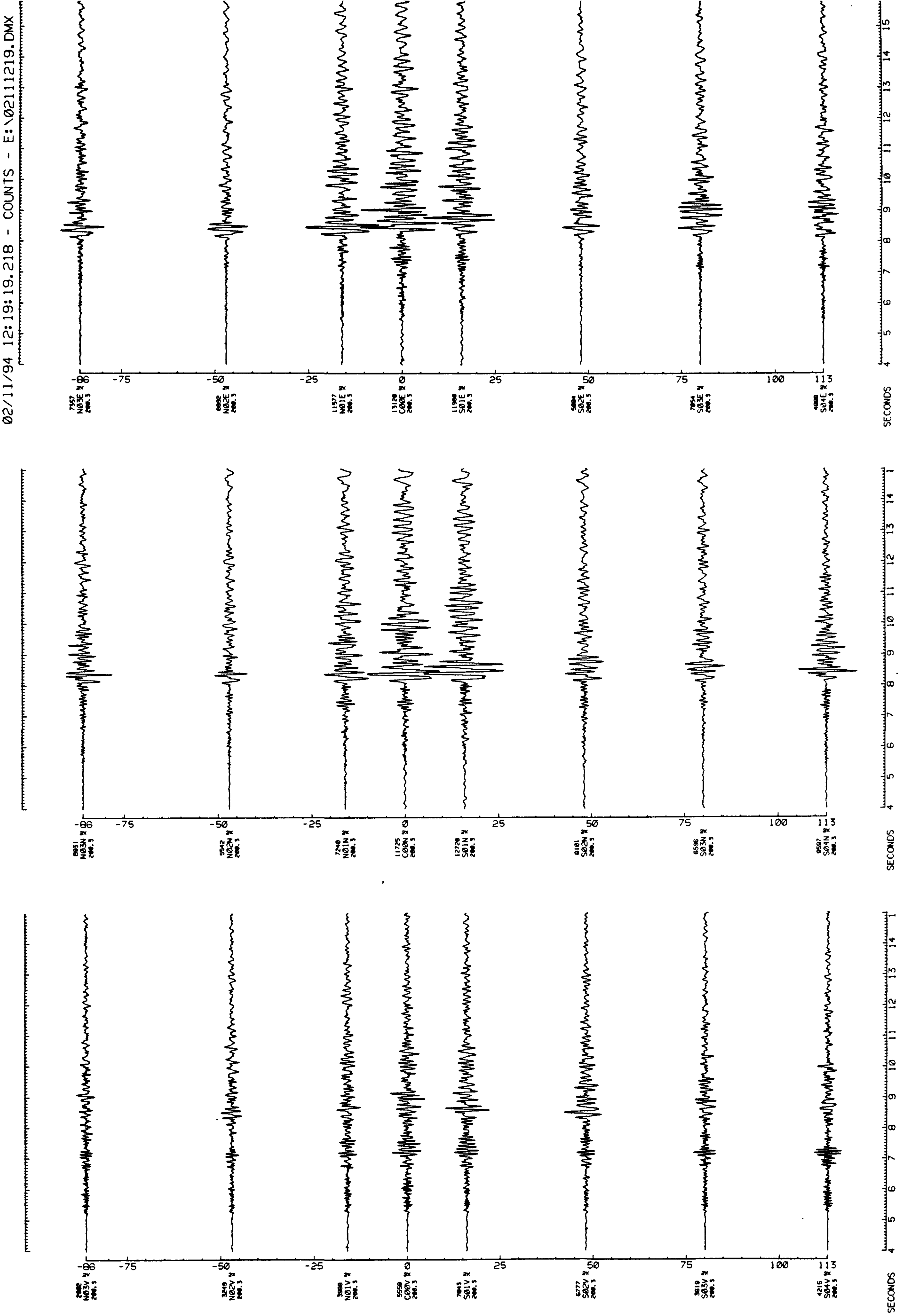

Figure 23(b)

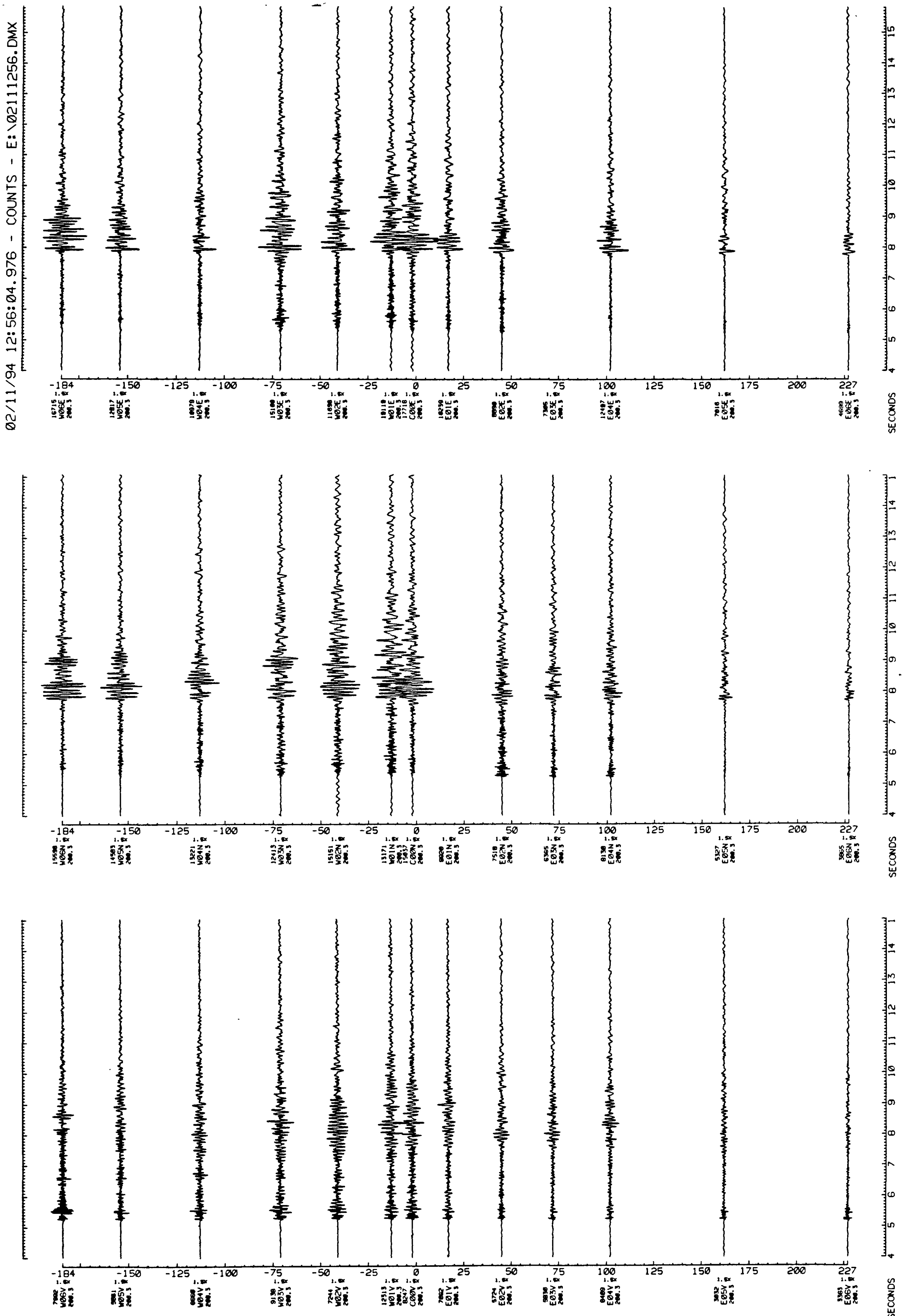

Figure 24(a)

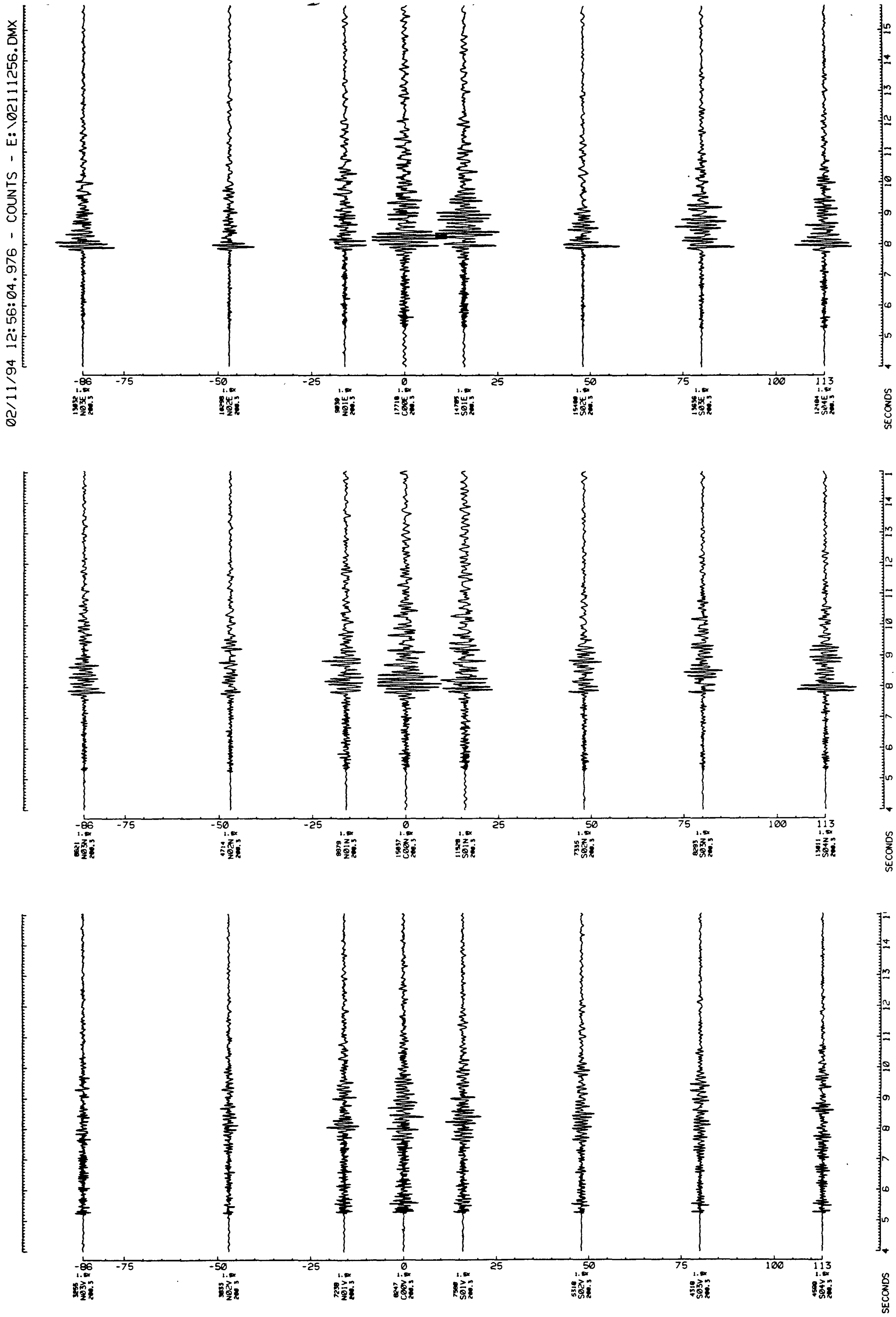
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Figure 24(b)

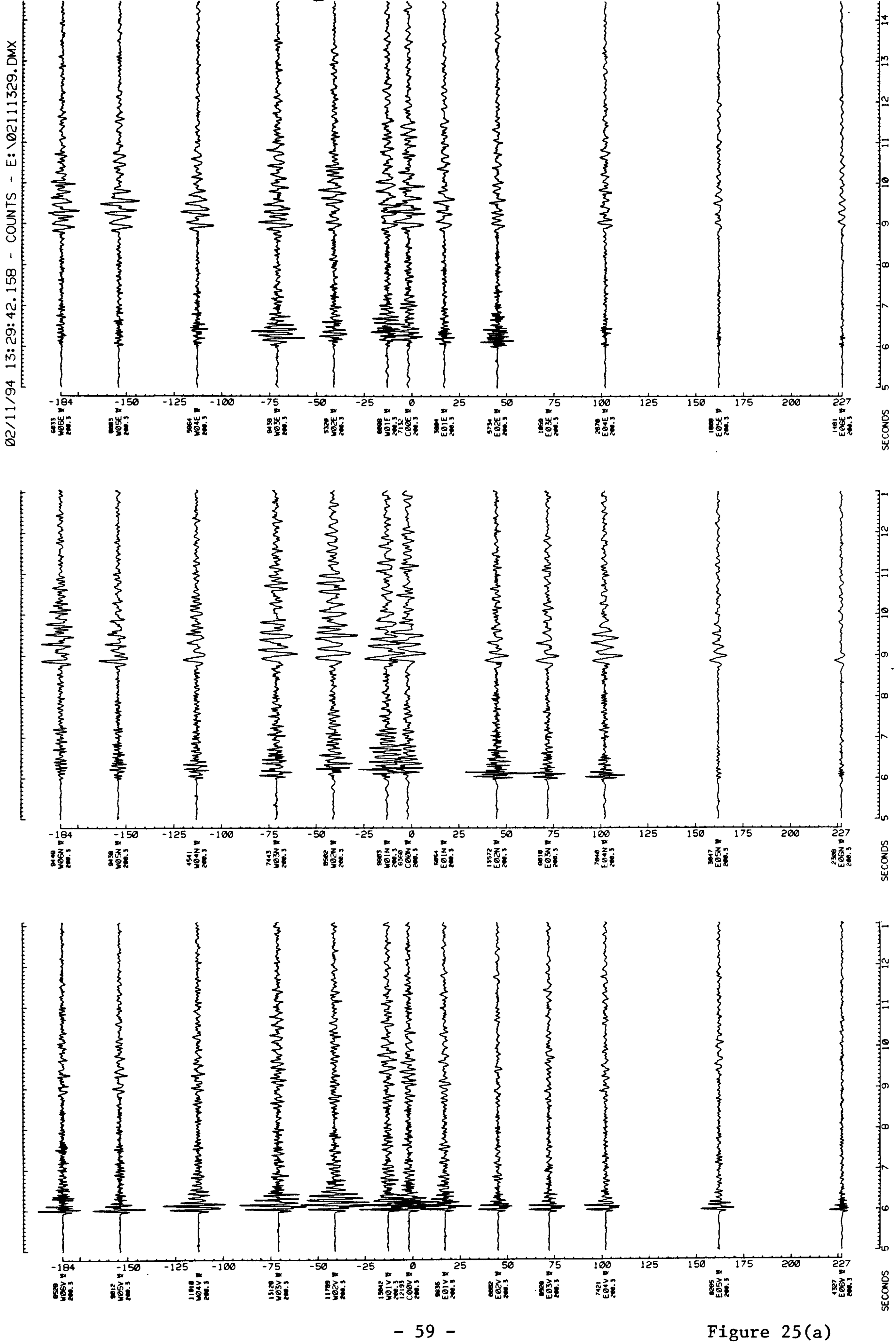


Figure 25(a)

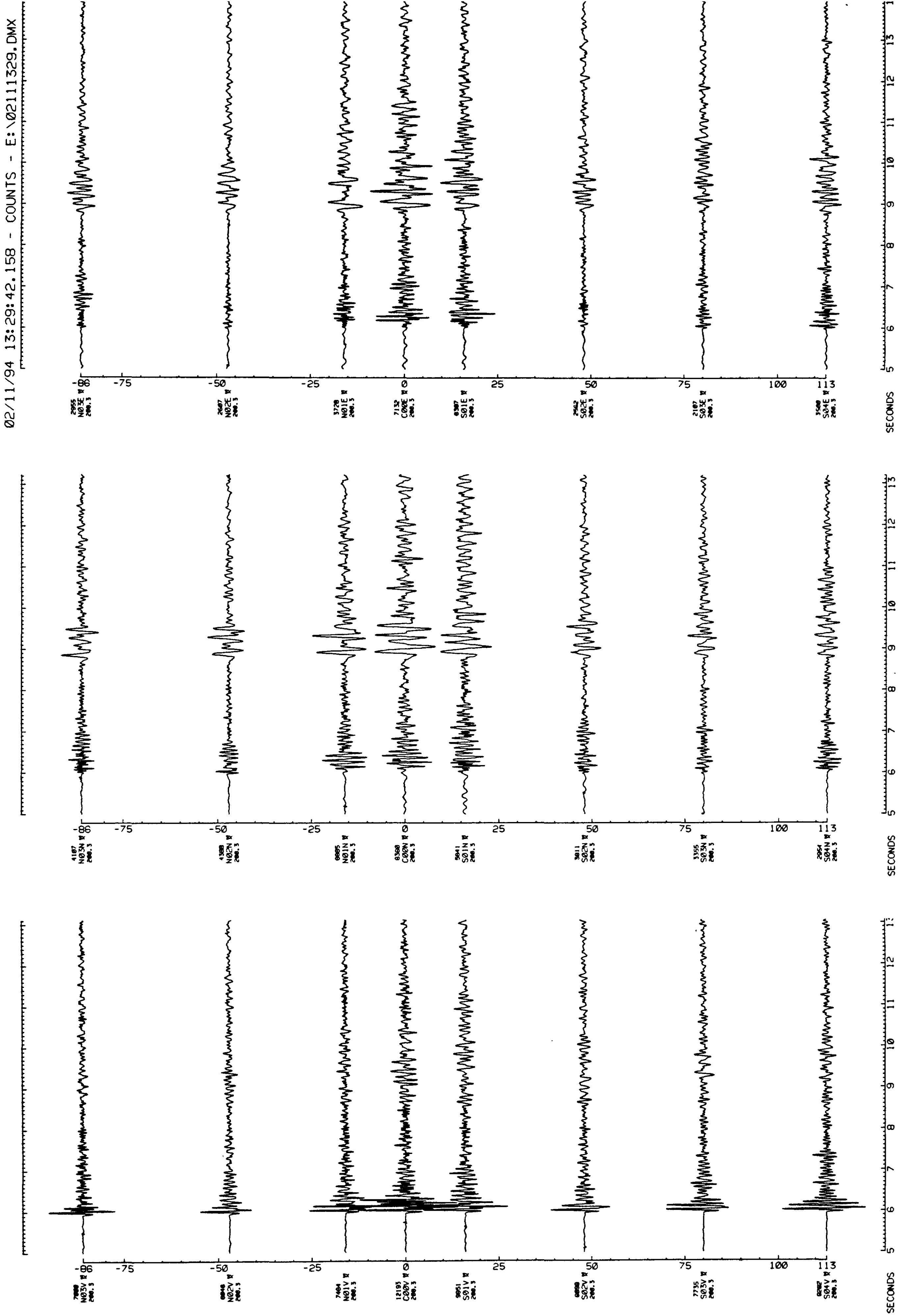


Figure 25(b)

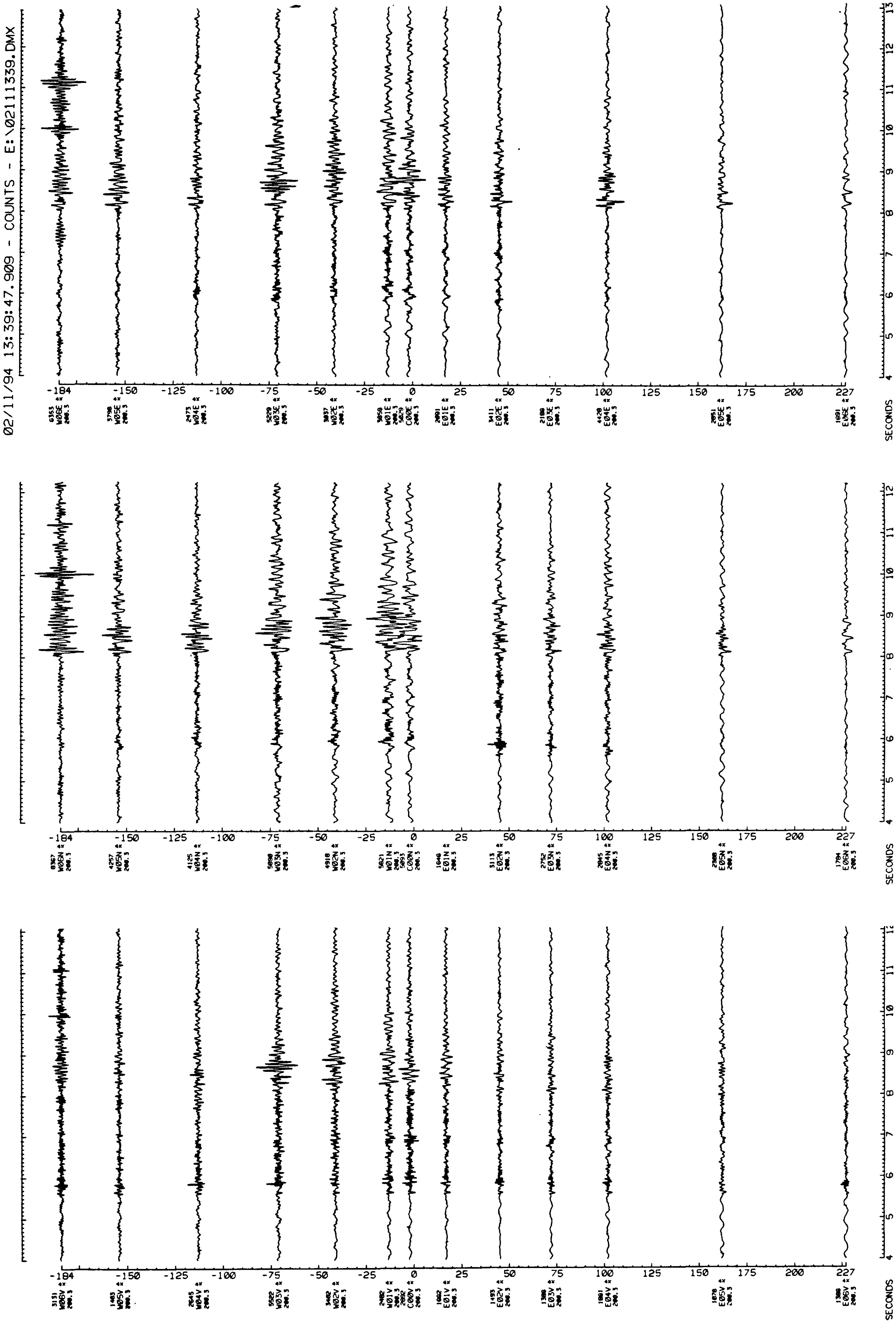
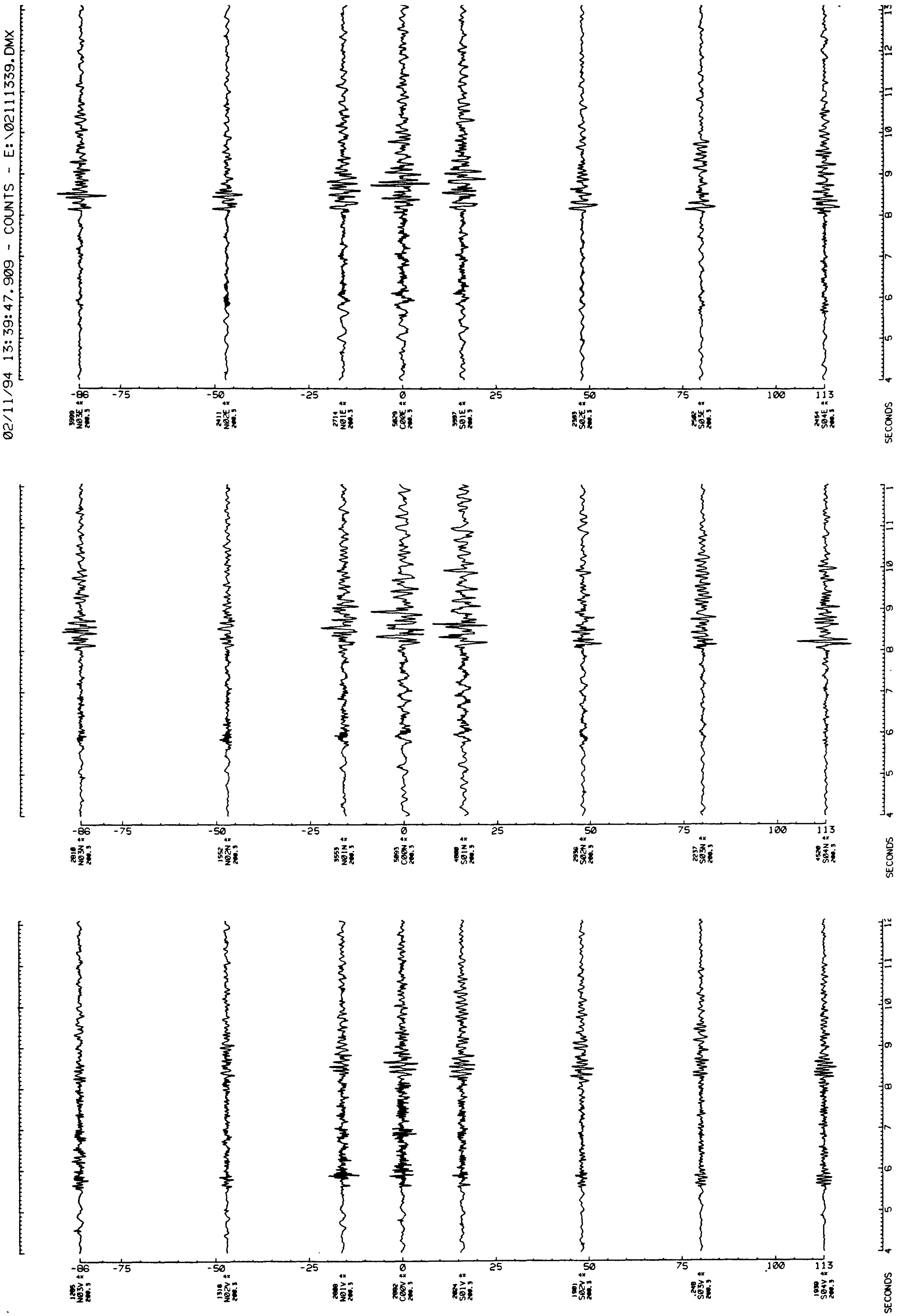


Figure 26(a)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S01N
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C00V
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S03V
S04V
SECONDS

Figure 26(b)

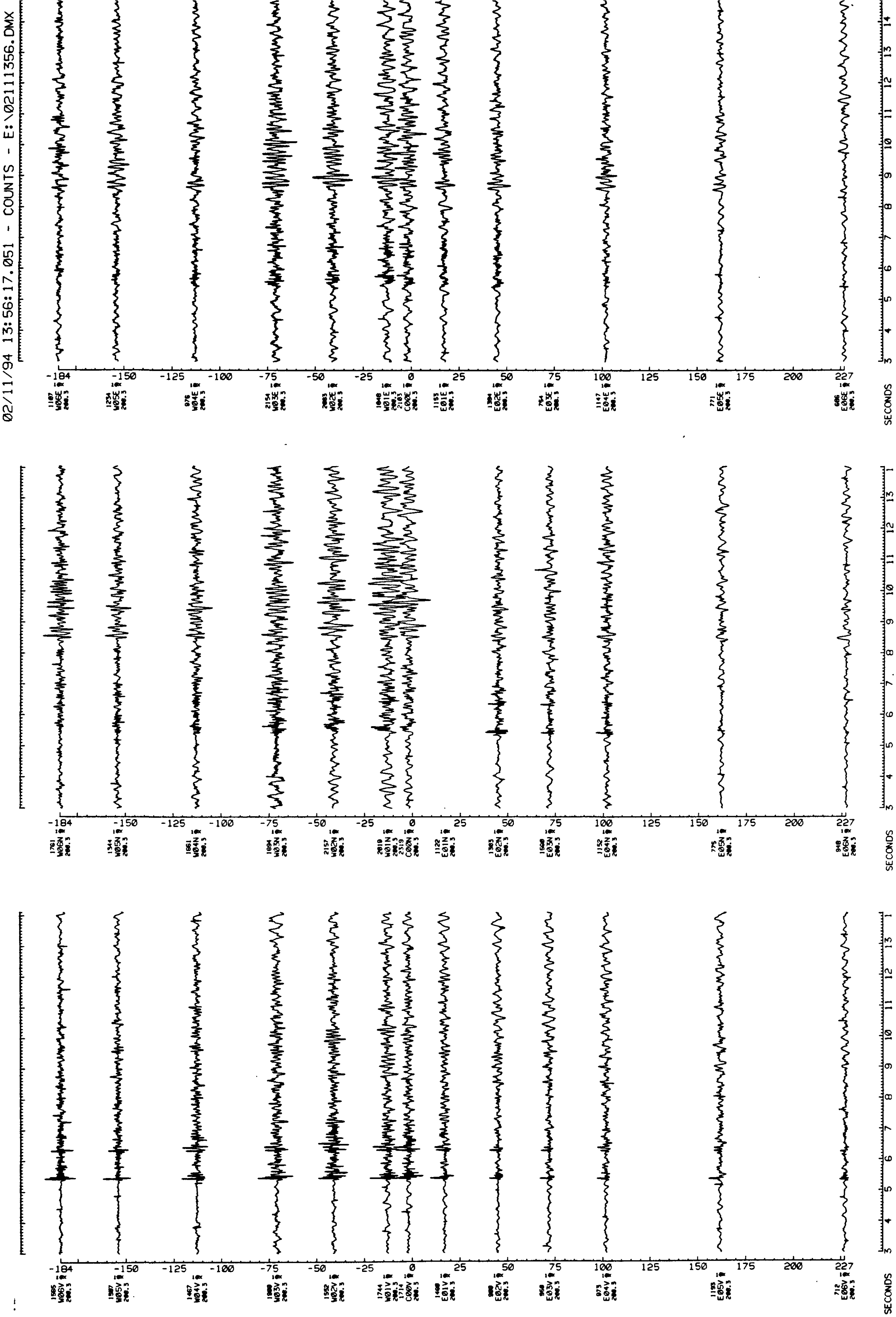
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Figure 27(a)

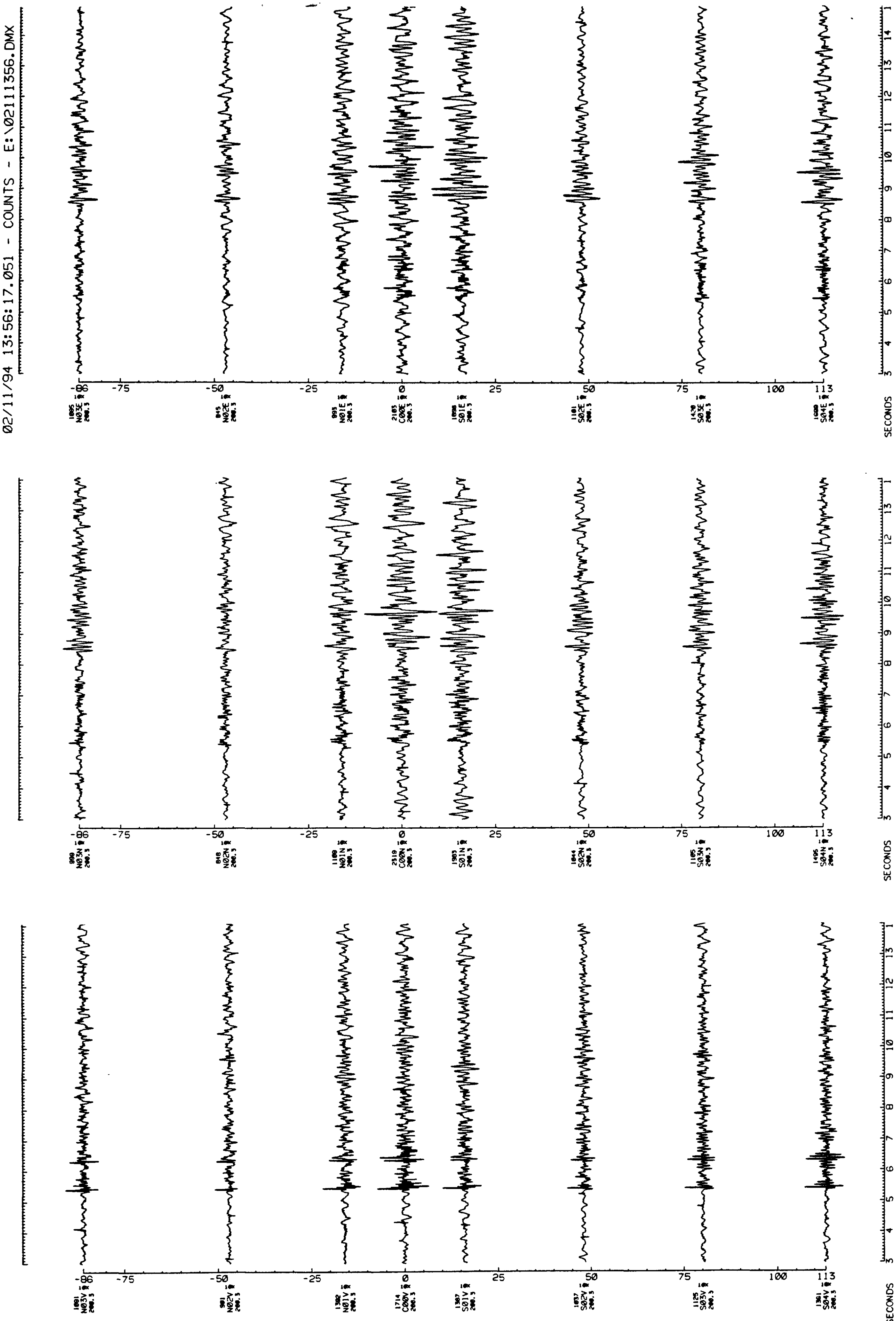


Figure 27(b)

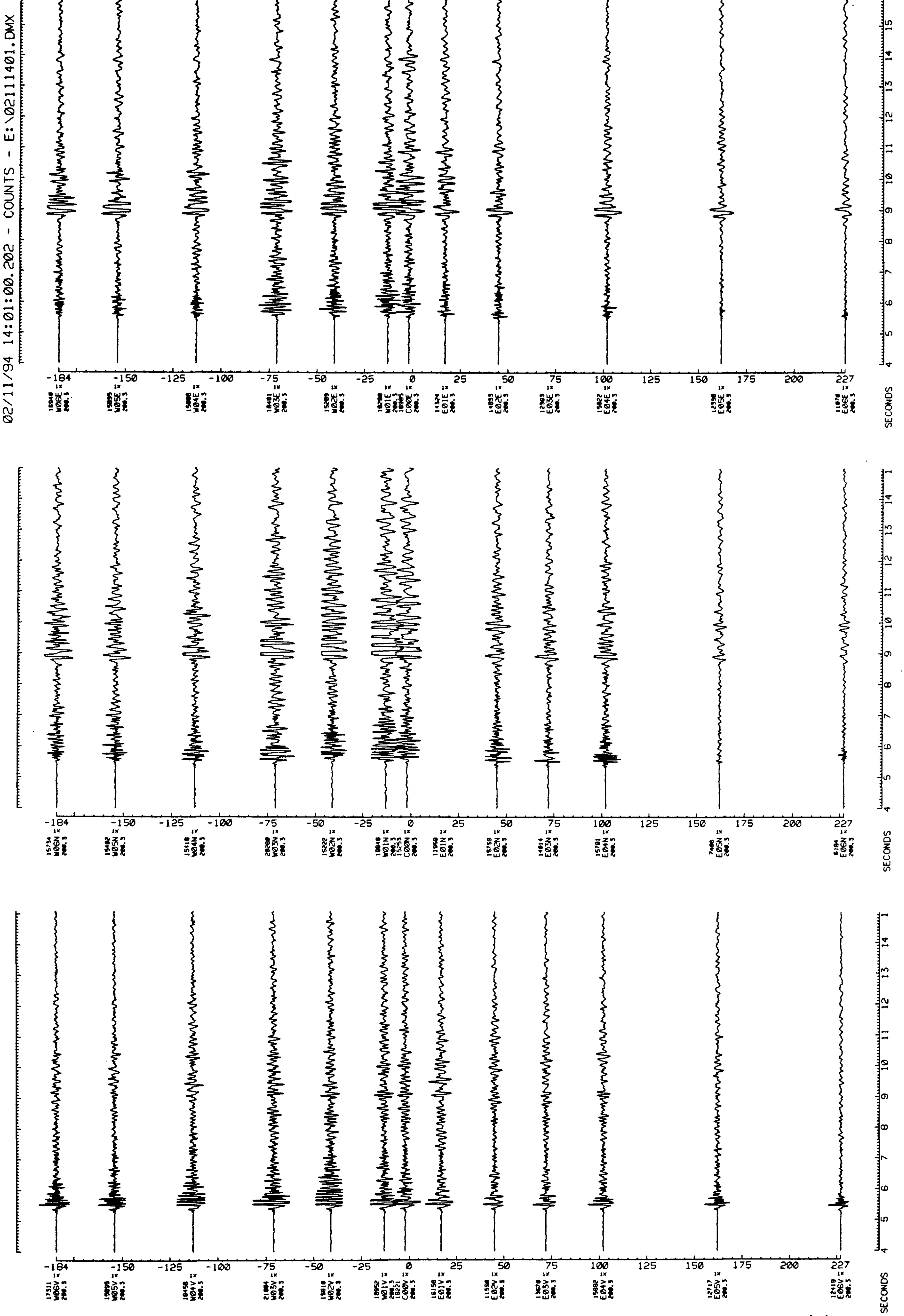
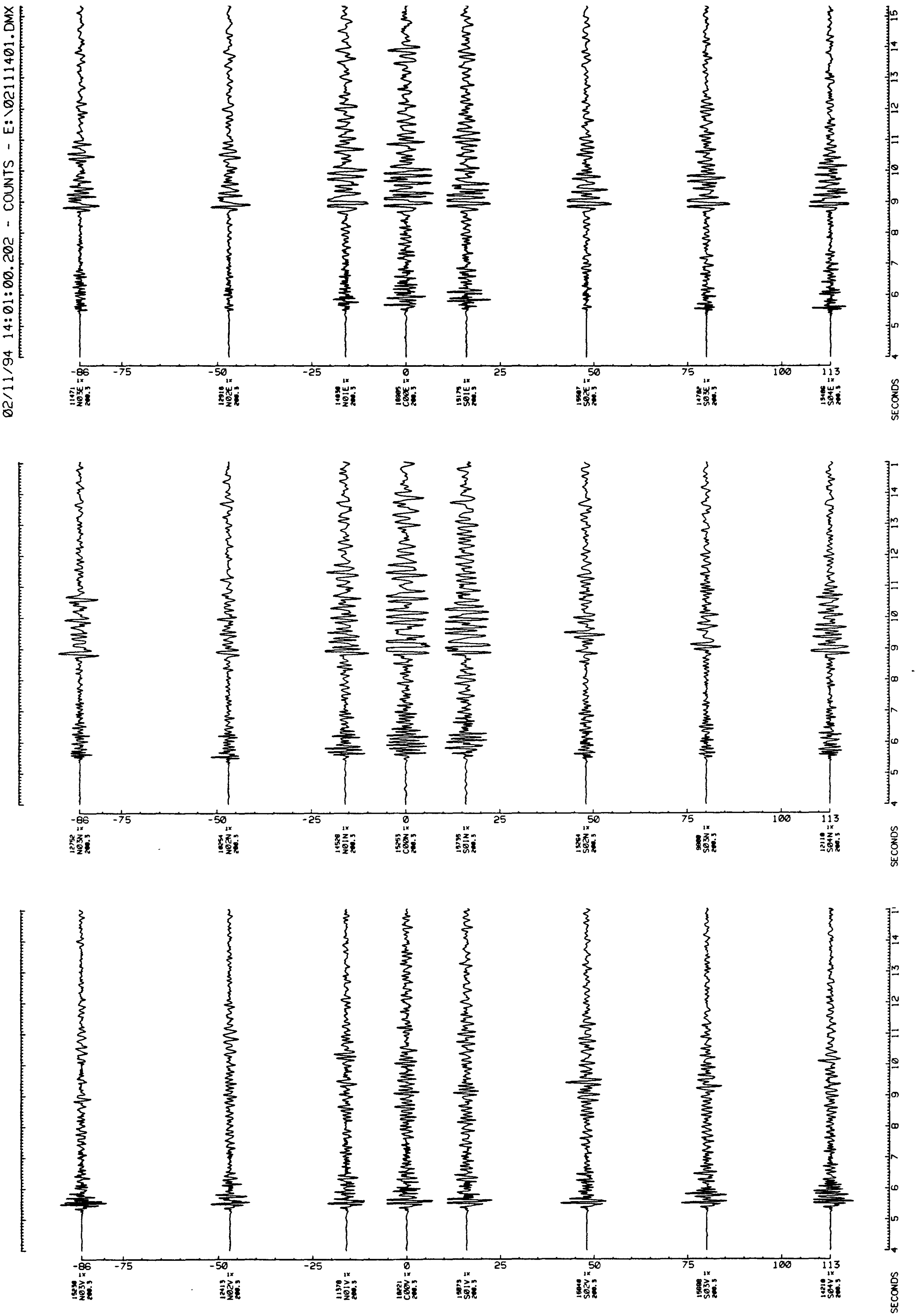


Figure 28(a)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S02V
S03V
S04V
SECONDS

Figure 28(b)

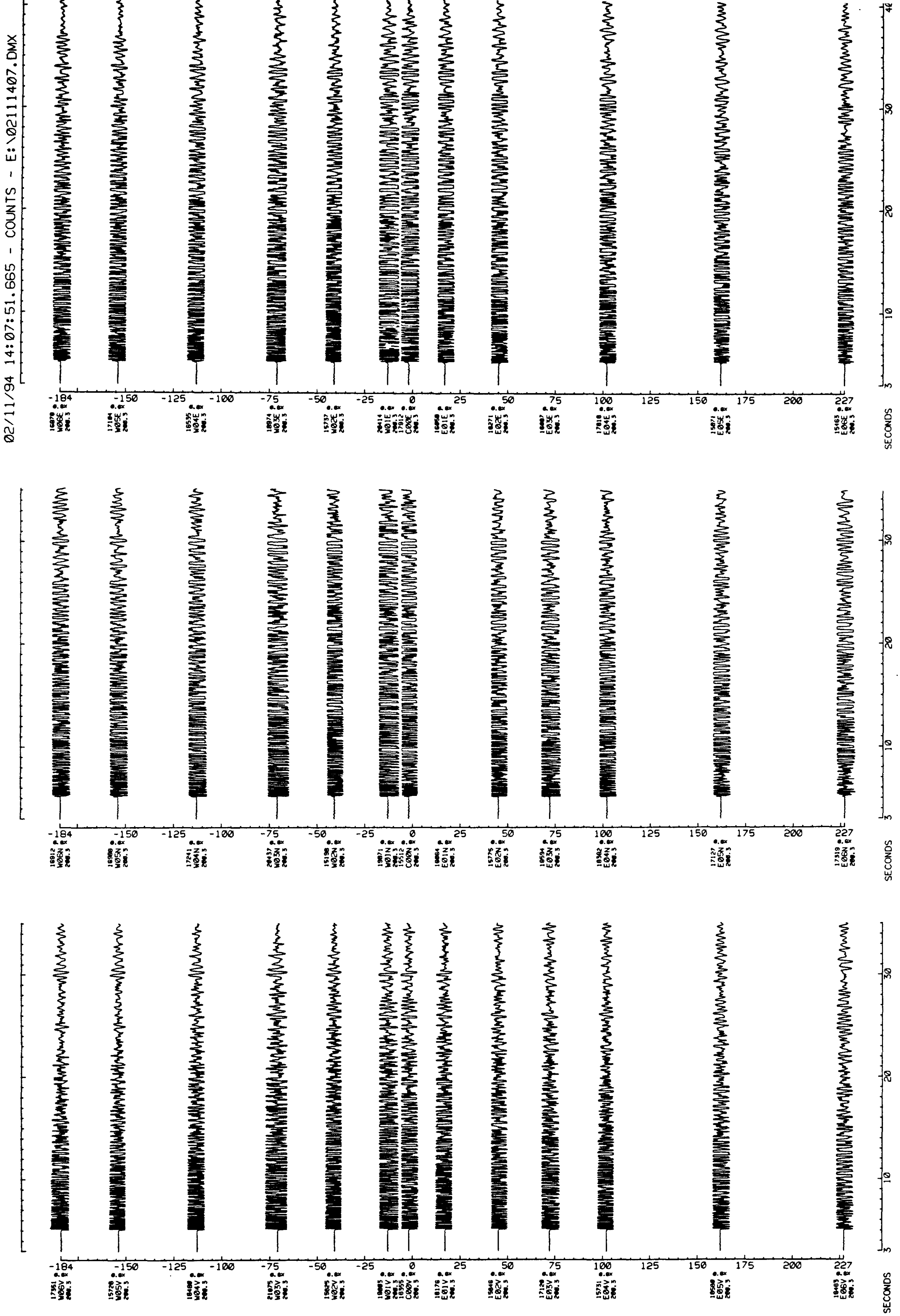
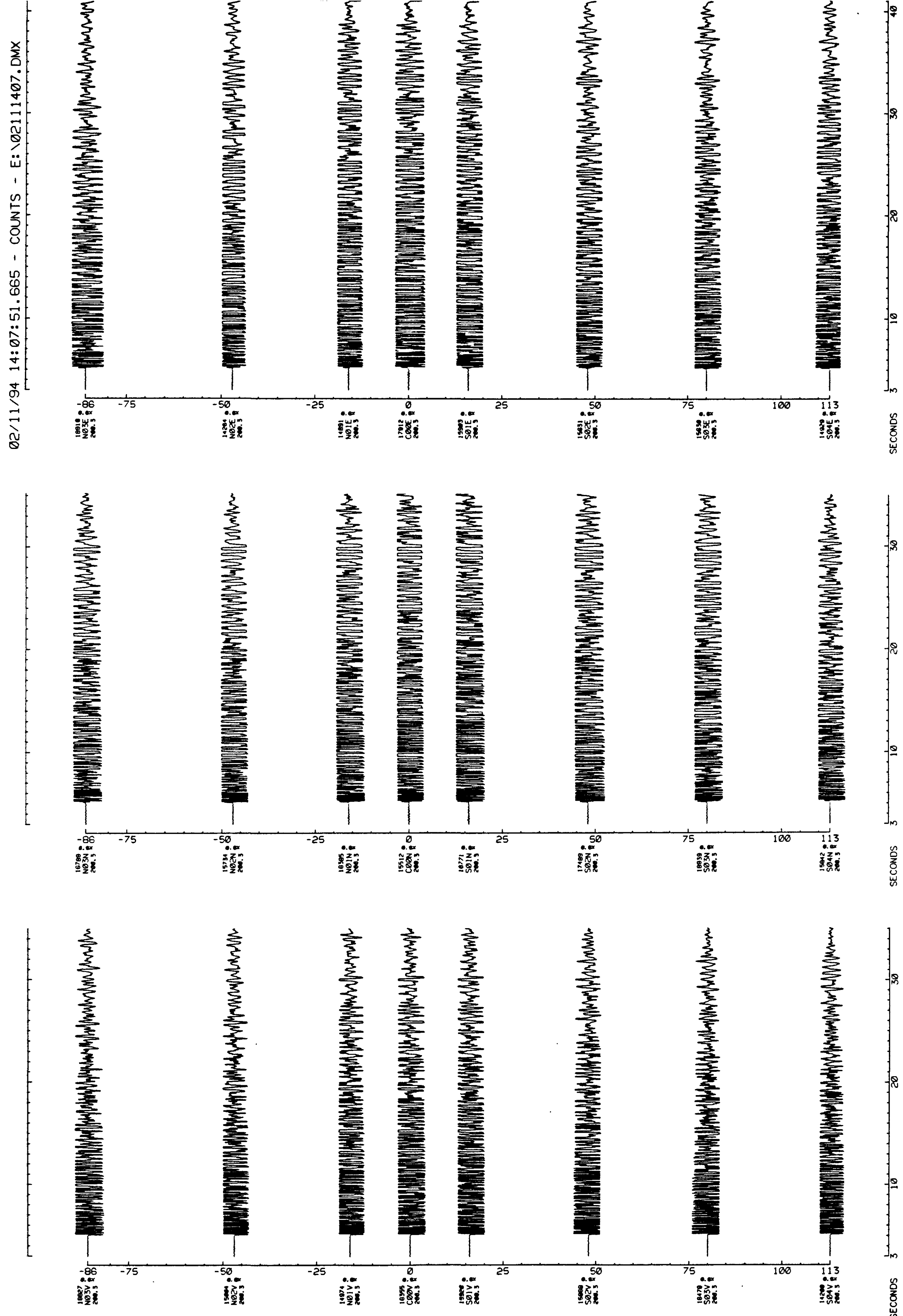


Figure 29(a)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SØ4V
SECONDS

Figure 29(b)

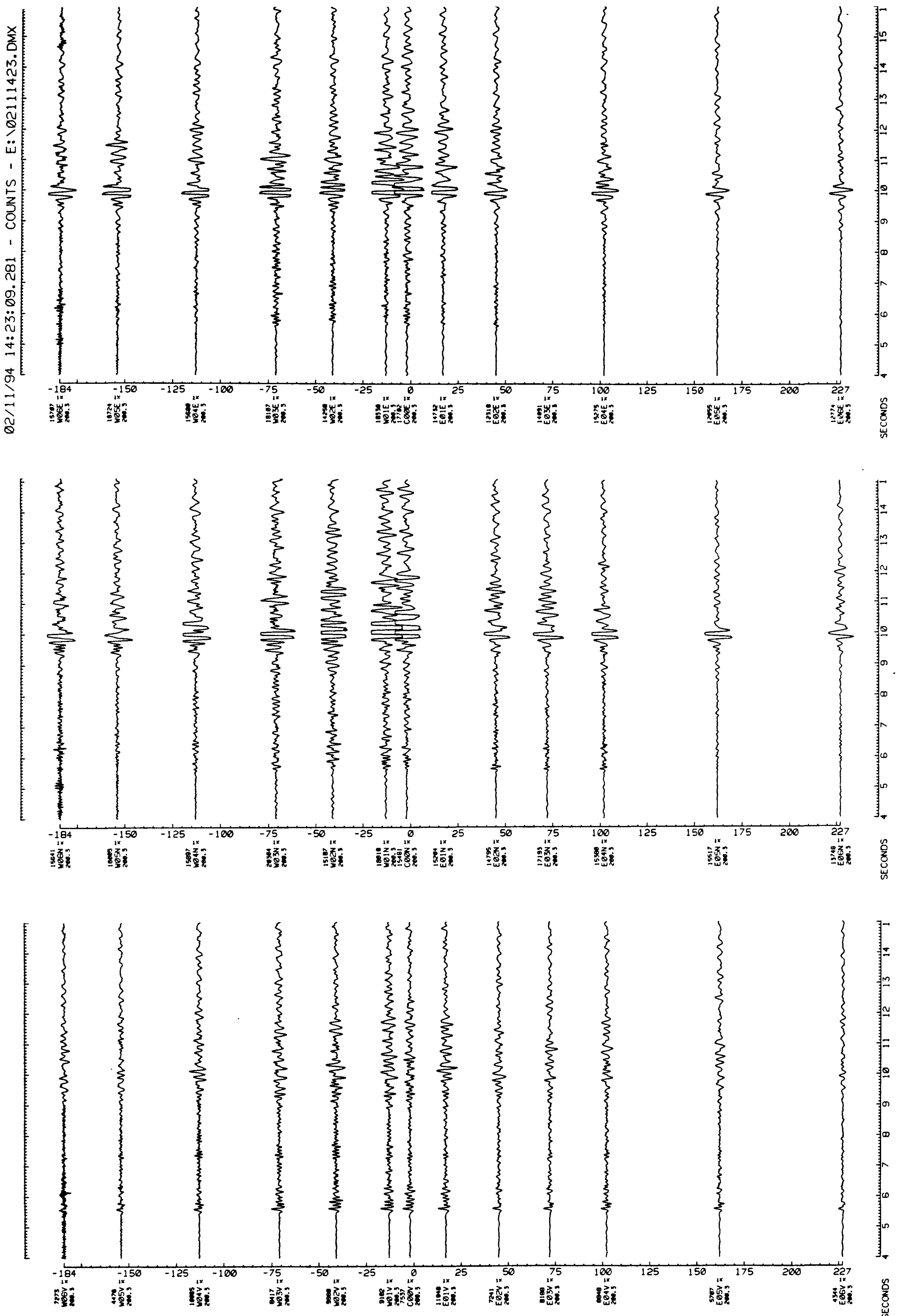

Figure 30(a)

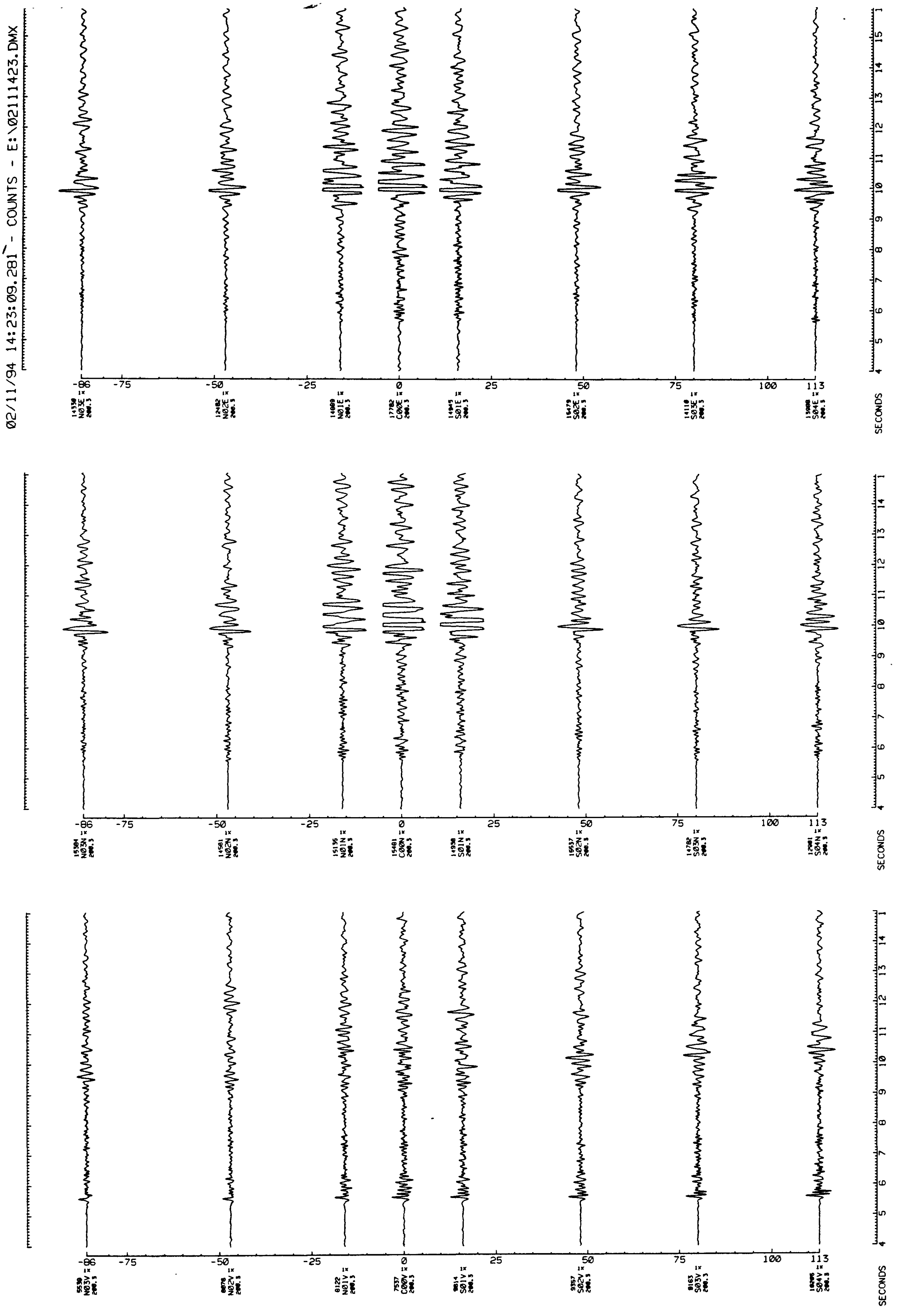
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Figure 30(b)

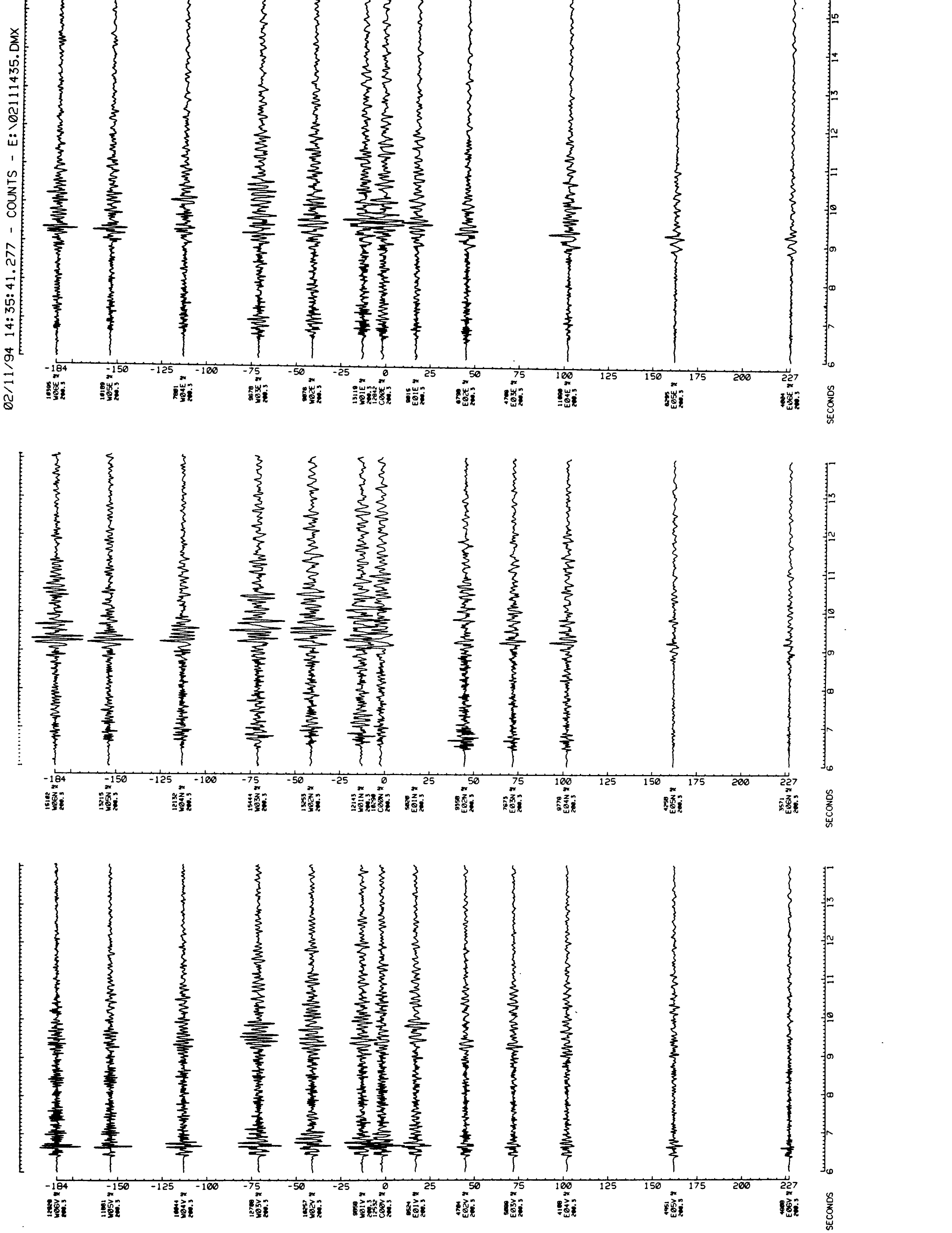
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Figure 31(a)

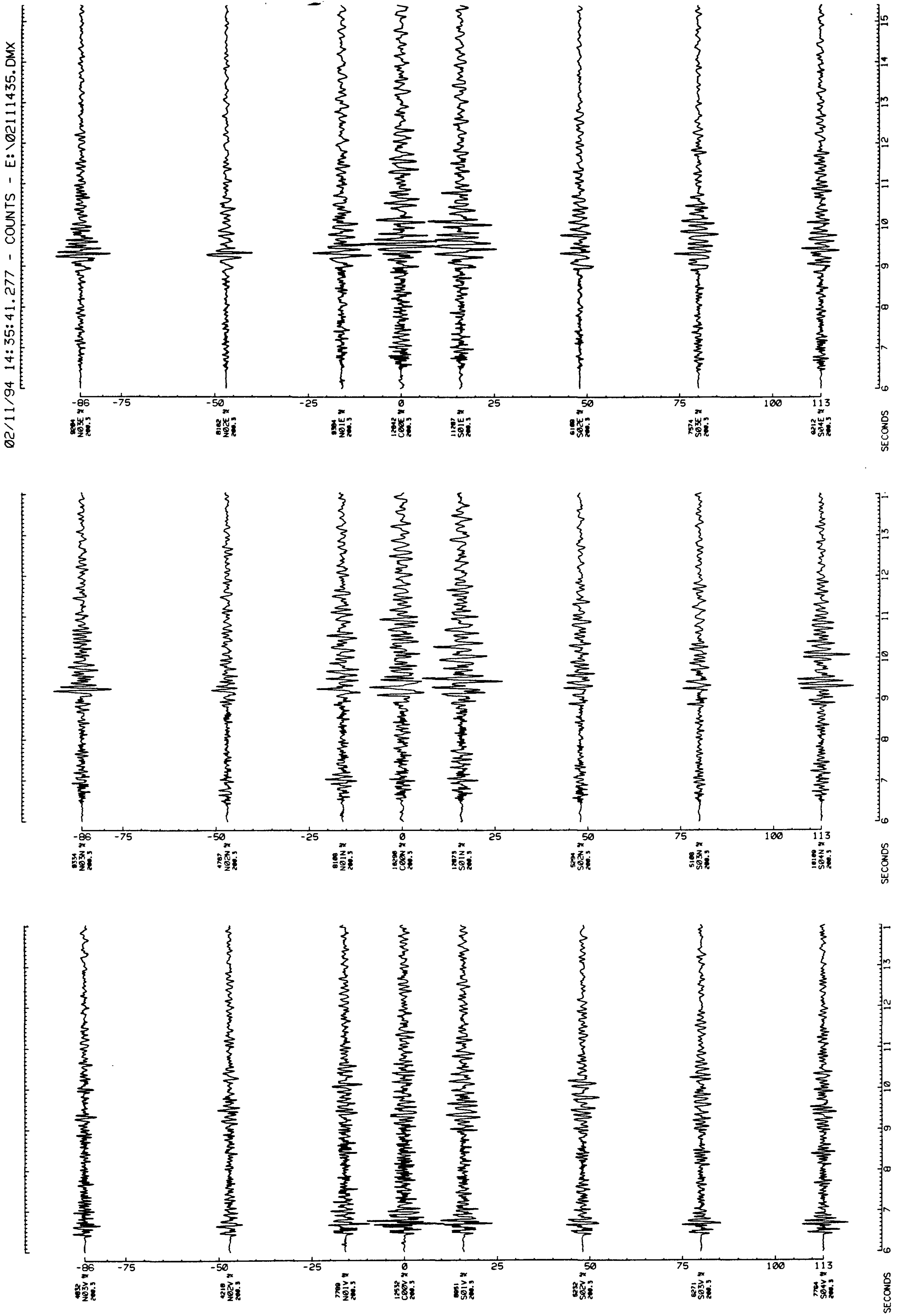
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Figure 31(b)

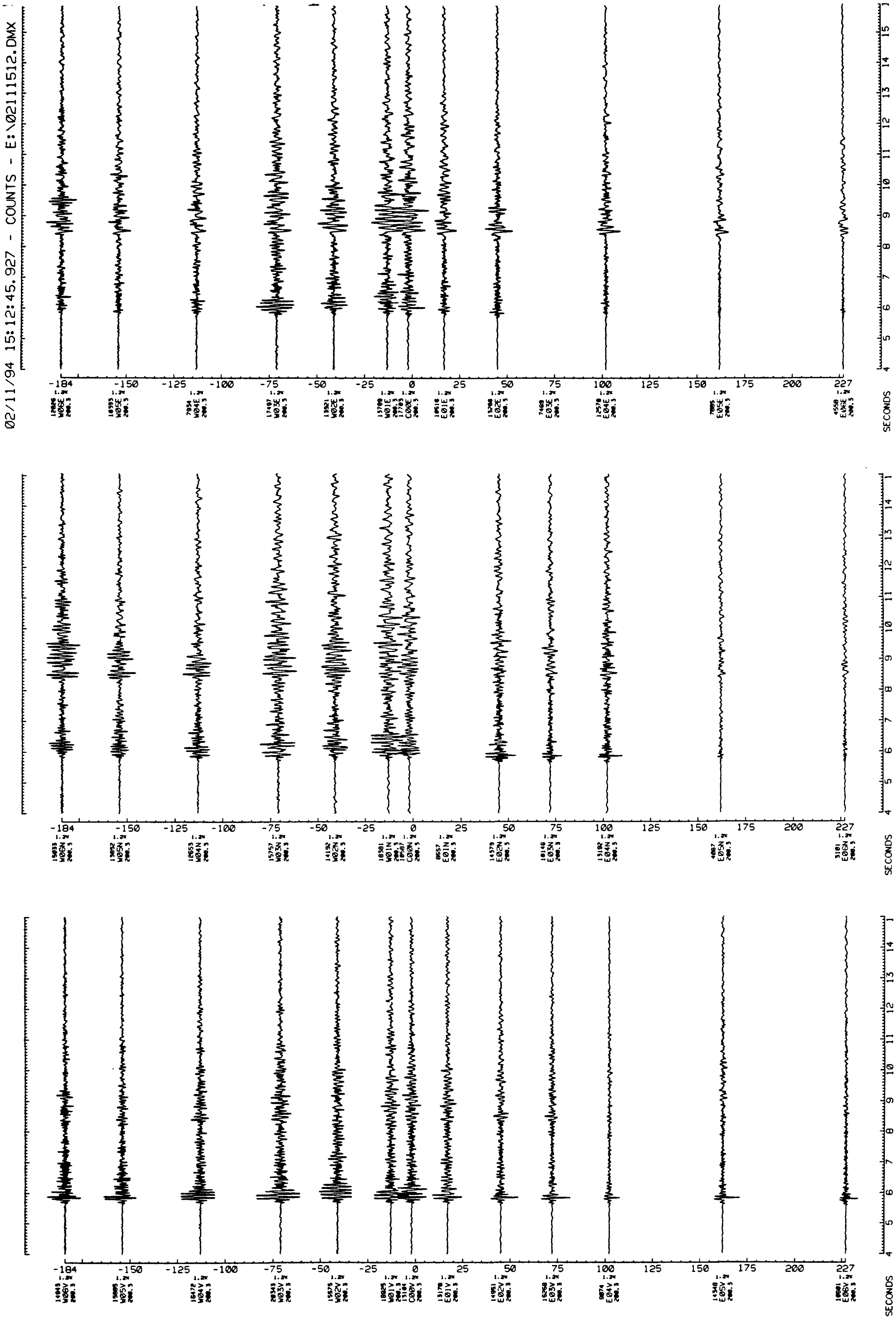

Figure 32(a)

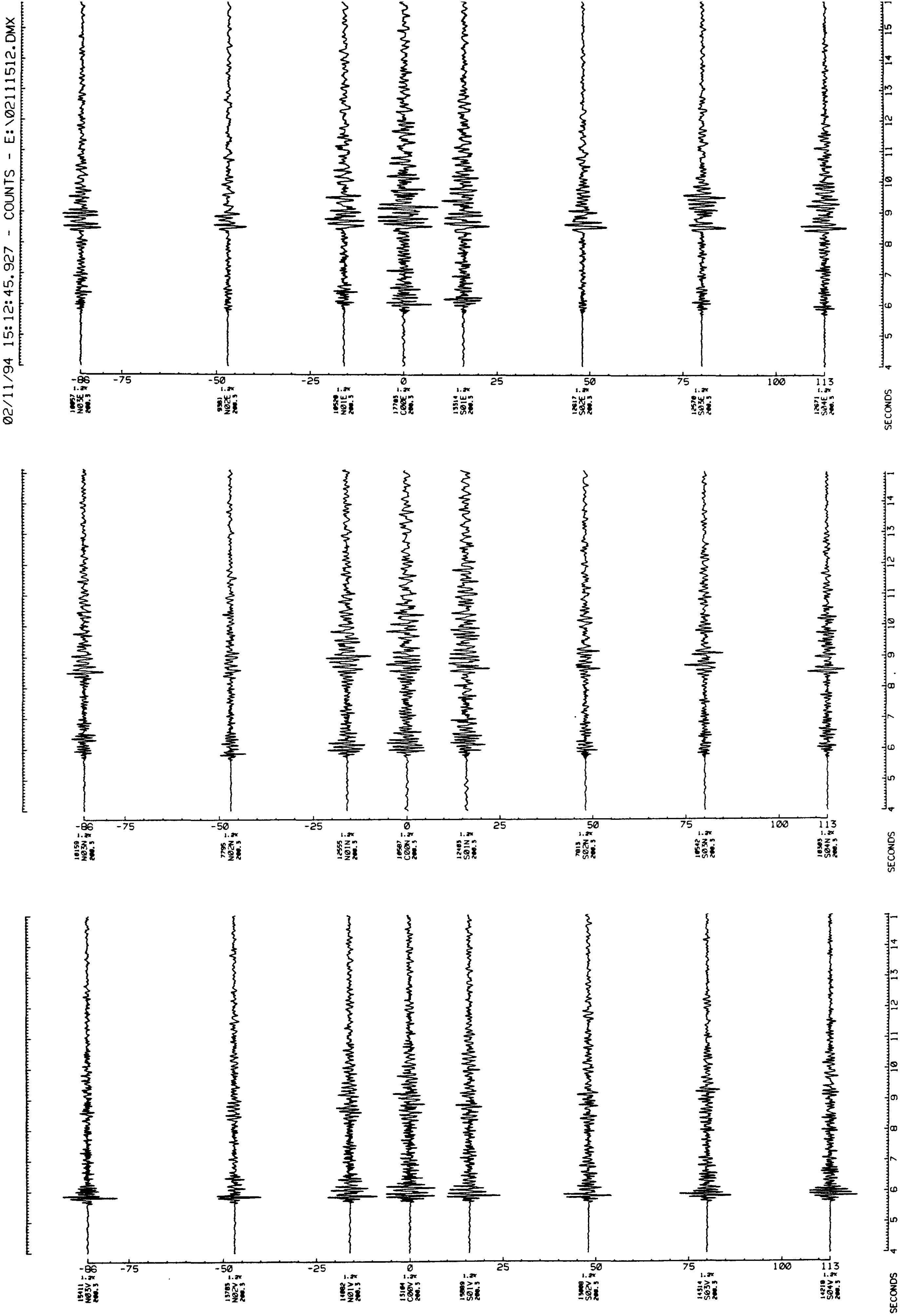
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Figure 32(b)

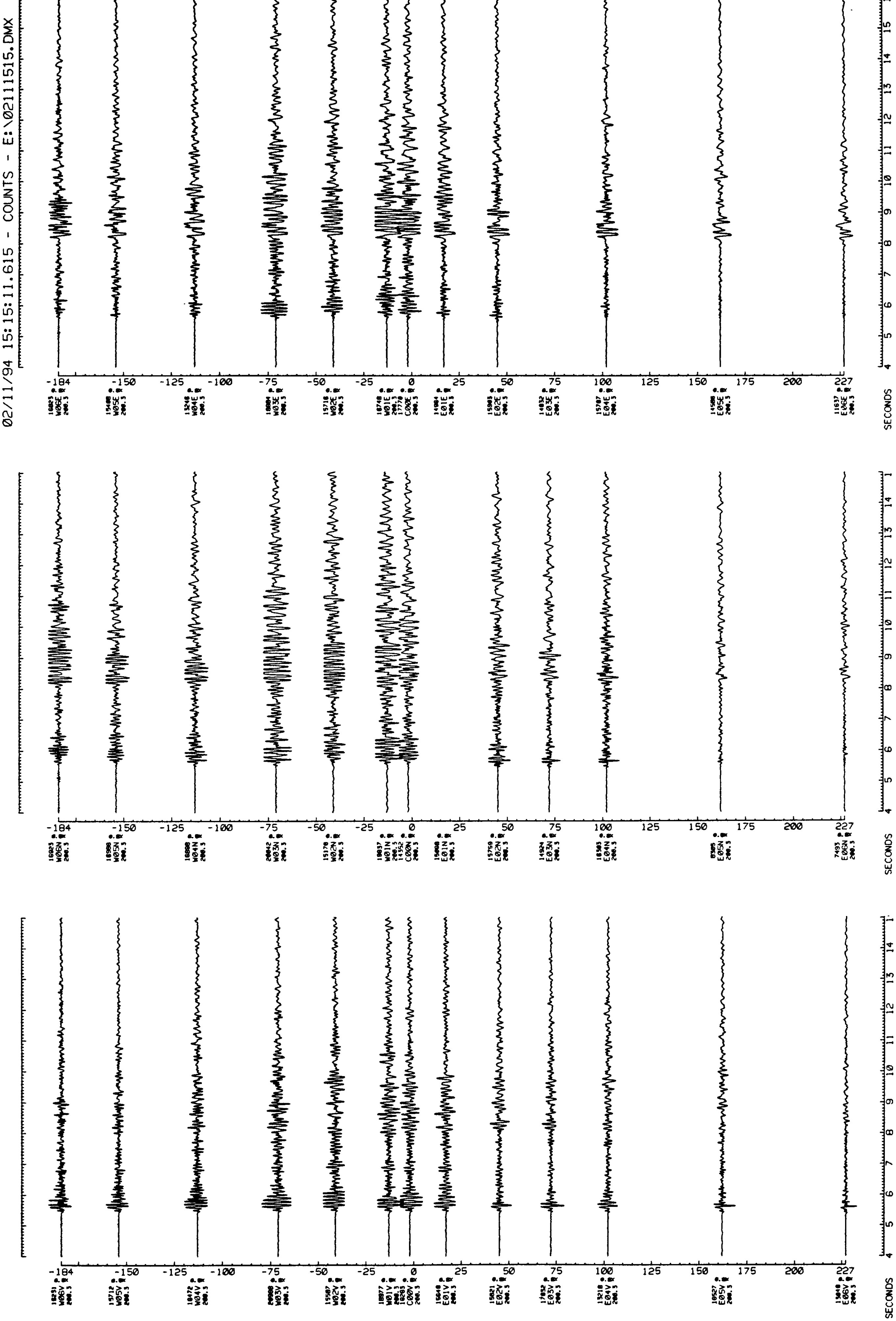
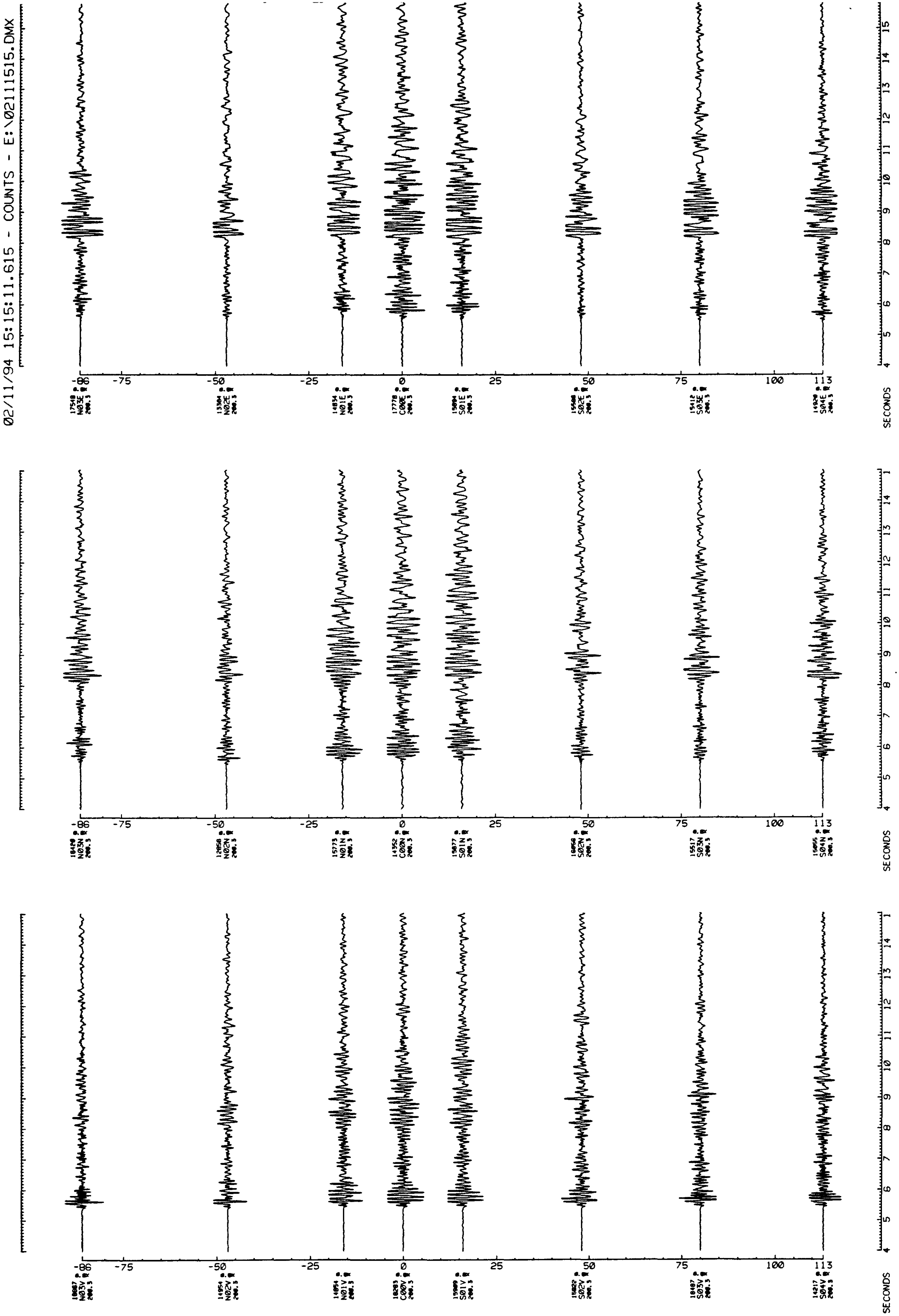


Figure 33(a)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S02N
S03N
S04N
N03V
N02V
N01V
C00V
S01V
S02V
S03V
S04V

Figure 33(b)

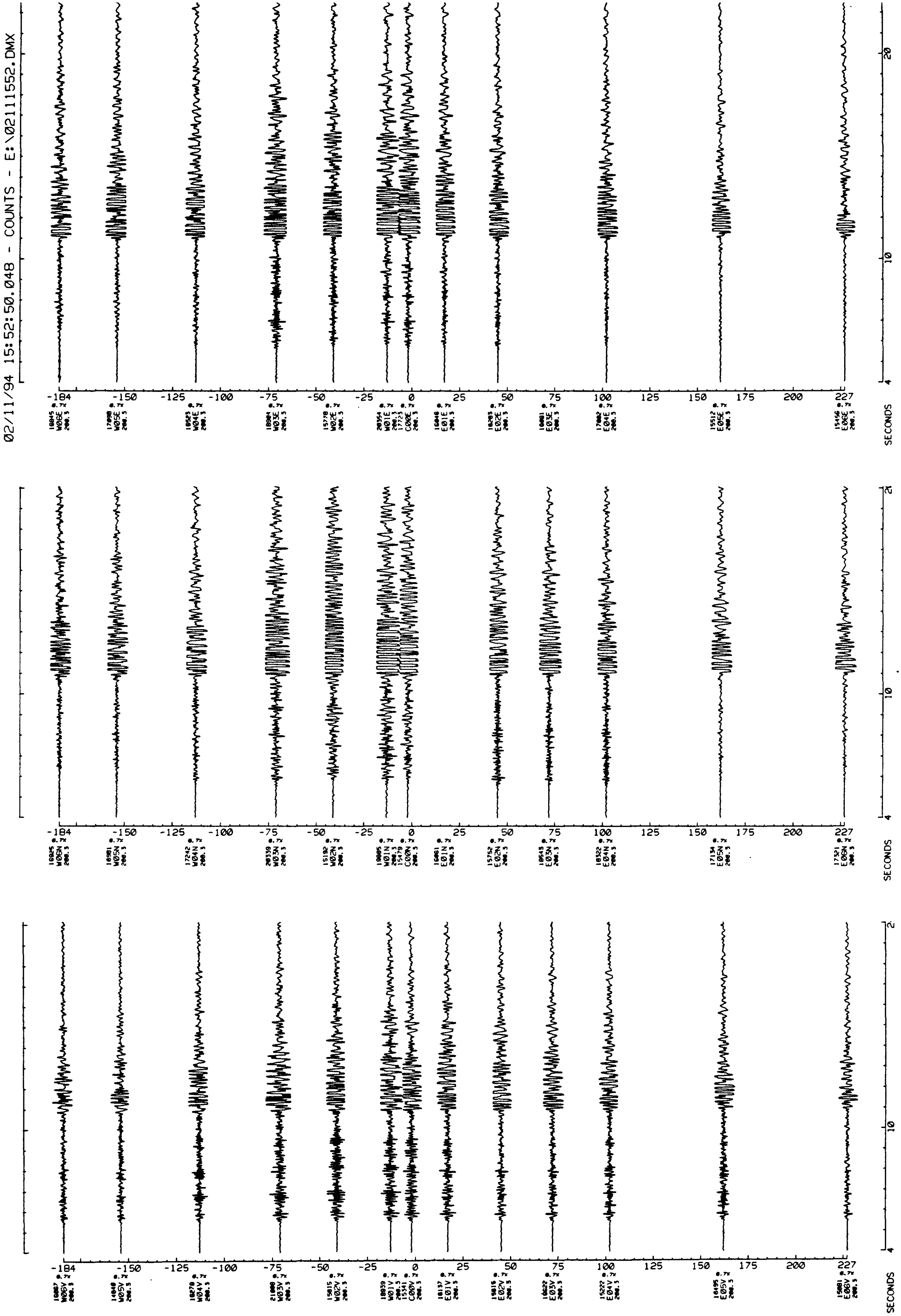
02/11/94 15:52:50.048 - COUNTS - E:\02111552.DMX
SECONDS
SECONDS
SECONDS

Figure 34(a)

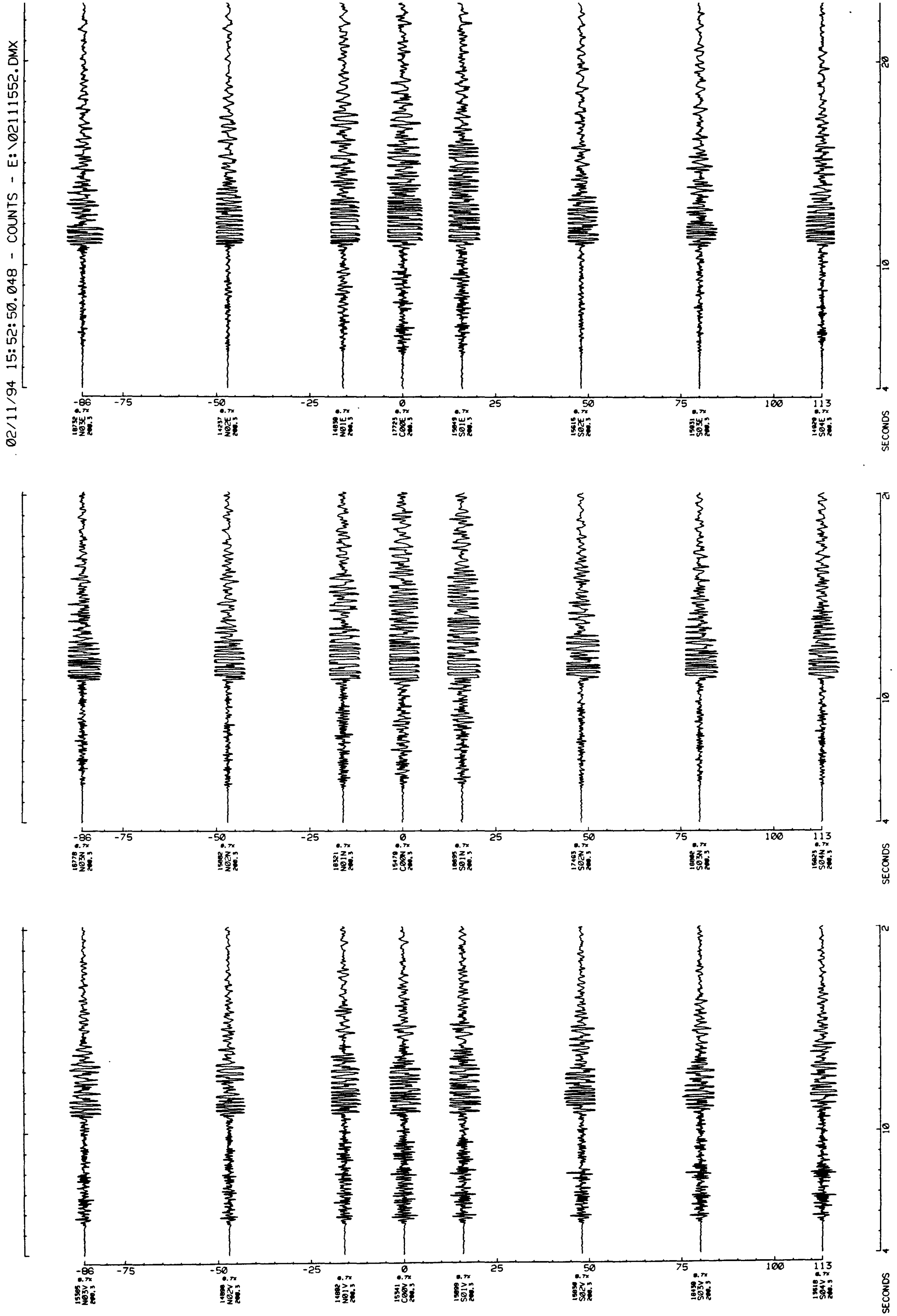

Figure 34(b)