Project PROBES
(Puerto Rico Ocean Bottom Earthquake Survey)

By

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U.S. Department of the Interior
U.S. Geological Survey

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EXECUTIVE SUMMARY

Puerto Rico and the Virgin Islands are located at an active tectonic plate boundary between the North American plate and the northeast corner of the Caribbean plate. 3.7 million U.S. citizens live on the islands and the population density, 392 people per square kilometer, is one of the highest in the western hemisphere. Large magnitude earthquakes and devastating tsunamis have occurred in historical times in and around the island. Lack of geological understanding of the tectonic movements in this part of the Caribbean has hampered our ability to assess the seismic and tsunami hazard. Puerto Rico and the Virgin Islands are unique among the seismically-active regions of the United States in being mostly covered by water, which presents both opportunities and challenges for geological and geophysical studies.

In 2000, the U.S. Geological Survey (USGS) Coastal and Marine Program, Woods Hole, Massachusetts, and the Puerto Rico Seismic Network (PRSN) of the Department of Geology of the University of Puerto Rico at Mayagüez (UPRM), began a program to better assess the hazards from earthquakes, submarine slides, and tsunamis to Puerto Rico and the Virgin Islands. The University of Puerto Rico, Mayagüez, maintains a permanent network of seismographs on Puerto Rico and several surrounding islands. To augment this array and fill in gaps in spatial coverage, the U.S. Geological Survey deployed three temporary land stations and 12 ocean bottom seismometers (OBS) in and around western Puerto Rico. This deployment, which is one of a series of studies planned, recorded local and regional earthquakes for 45 days during May and June 2000. It was the largest single deployment to date of the U.S. Geological Survey's OBS, the longest deployment, and the first time, where a joint onshore/offshore USGS OBS array was deployed in conjunction with land seismometers to record earthquakes.

The combined data from the USGS and PRSN arrays will be used to locate earthquakes more accurately than is presently possible, because the accuracy of an earthquake location depends on the distance from the earthquake to the seismometers and on the geographical distribution of the seismometers. A better relocation of earthquakes may reveal the locations of active faults. The data from these arrays will be used to construct seismic velocity maps of the Earth's crust under the arrays. Seismic velocity can be a good proxy for the types of rocks at depth. We also hope to learn about the attenuation of seismic energy from the earthquakes at particular seismic stations to better understand the thermal structure beneath Puerto Rico and help predict the degree of ground shaking.

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This report primarily describes the data acquisition and depicts the data from the USGS OBS array. Plots of seismographs from the experiment can be found in Appendices A and B. Information about the USGS temporary land seismometers can be found in Appendix C and information about the PRSN stations active during the OBS deployment in Appendix D.

DESCRIPTION OF THE ARRAY

The University of Puerto Rico, Mayagüez, maintains a network of permanent short-period and broadband one- and three-component land seismographs that extend along the length of the main island of Puerto Rico and several surrounding islands (Figures 1 and 5). The USGS augmented the permanent land stations with three temporary land stations and 12 ocean bottom seismometers to form two perpendicular arrays: one along a 150-km-long north-south line crossing the Puerto Rico platform along the western side of Puerto Rico, and one along a 250-km-long east-west line through the southern part of Puerto Rico to Isla Mona. Stations were roughly spaced 15 to 25 km apart.

Instrumentation

Each OBS was equipped with a hydrophone and a three-component geophone package. The OBS were housed in a 27 inch aluminum sphere making them portable and easy to deploy from small vessels. Table 1 describes in more detail the technical specifications of the OBS.

In most previous refraction and reflection experiments where active sources are used, we have been primarily concerned with picking arrival times, thus waveform quality has not been of great importance. While we are continuing to use the instruments for active source seismology, we have also begun to analyze earthquakes. For this experiment, we decided it was necessary to redesign the OBS configuration to enhance waveform quality. Unlike in earlier OBS designs, the geophone package was placed external to the sphere so that it rests directly on the ocean floor (Figures 2 and 3). Prior to deployment, the geophone package is attached with a pressure release pin to a 1-meter-long arm that extends from the sphere. The arm is held by another pin in an upright position. As the OBS sinks, upon reaching the ocean floor, the pins are released by the ambient pressure, the arm is lowered and the geophone package is released from the arm. The only connection to the central unit is a flexible cable that transmits the data to the data logger, which is housed in the sphere.

The purpose of the new design was to decouple the instrument package from the higher profile sphere and flotation aids, while improving seafloor coupling. Higher profile OBS are more susceptible to noise generated by ocean currents. Having the geophone package separate from the sphere and lower to the ground reduces the amount of ambient ocean noise. To improve coupling, the geophone package is enclosed in a bag of sand designed to mimic the burial of the geophones in sediment. The new OBS design has led to improved recovery of waveform shape for use in phase identification and in studies of attenuation, focal mechanisms, and crustal structure.

Extensive testing of the new design was performed in Woods Hole and Los Angeles in 1999, yielding a cutoff magnitude of 2.5 for local event detection. The PROBES experiment marks the first complete deployment of all external sensor OBS.

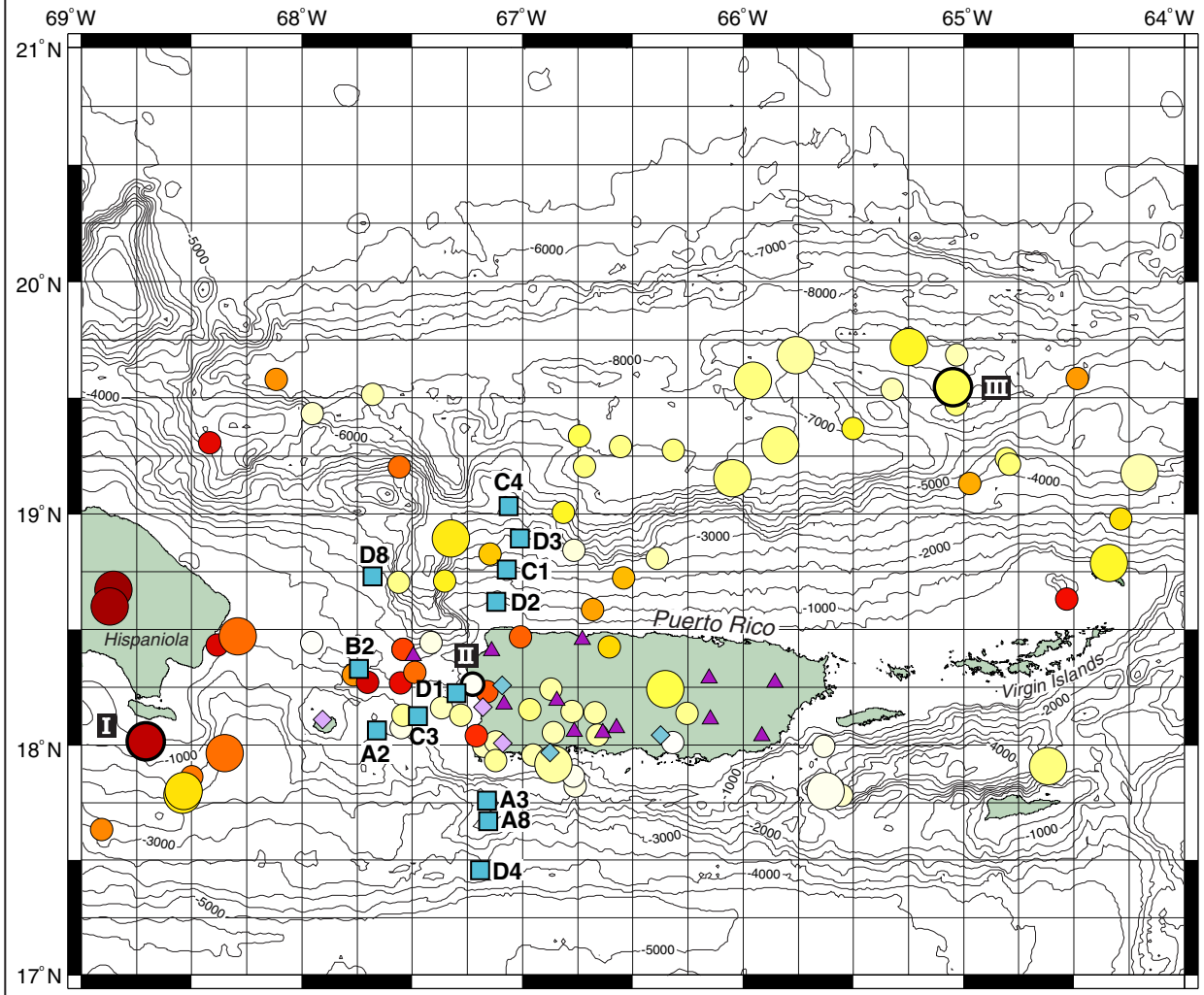


Figure 1. Map of the Puerto Rico region showing stations that were active during the Puerto Rico Ocean Bottom Earthquake Survey as well as all local events that occurred during the deployment. USGS OBS stations are the blue boxes, the USGS temporary land stations are the blue diamonds, the University of Puerto Rico's short-period and broadband seismometers are the purple triangles and diamonds, respectively. Local events are indicated as circles. The events with the heavy borders labeled I, II, and III were used to compare each event's arrival across the OBS array.

Table 1. OBS Instrument Specifications.

Sensors:	three 4.5 hertz L15B geophones OAS E-2S hydrophone Capable of recording continuously for 6 weeks
Sample Interval:	Continuous recording at 100 samples/second
Dynamic Range:	72 dB plus a 30 dB step gain range
Clock Accuracy:	~1 millisecond/day drift
Power:	Standard alkaline batteries
Maximum Depth:	5,000 meters
OBS Design:	External geophone package with sandbag
Arm Length:	1 meter
Arm Deployment:	Pressure-induced release mechanism
Anchor Type:	100 pound forged anchor
Flotation:	Aluminum sphere & attached syntactic foam
Release Mechanism:	Acoustic, with ranging capabilities
Recovery Aids:	Strobe, VHF radio beacon, acoustic transponder
Total Bottom Deployment Time:	45 days

Figure 2. Configuration of the ocean bottom seismometers (OBS). (a) OBS with arm deployed. (b) Expanded view of inset showing the external geophone package enclosed in the sandbag.

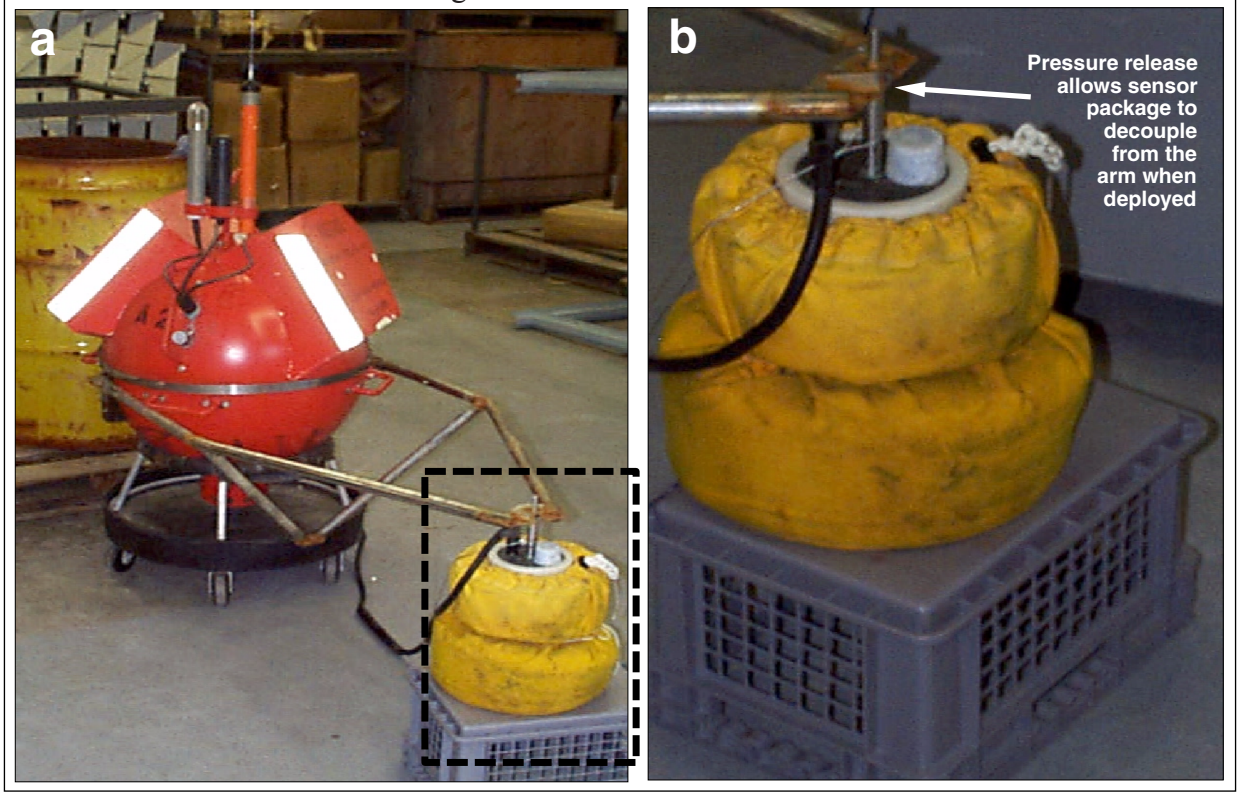
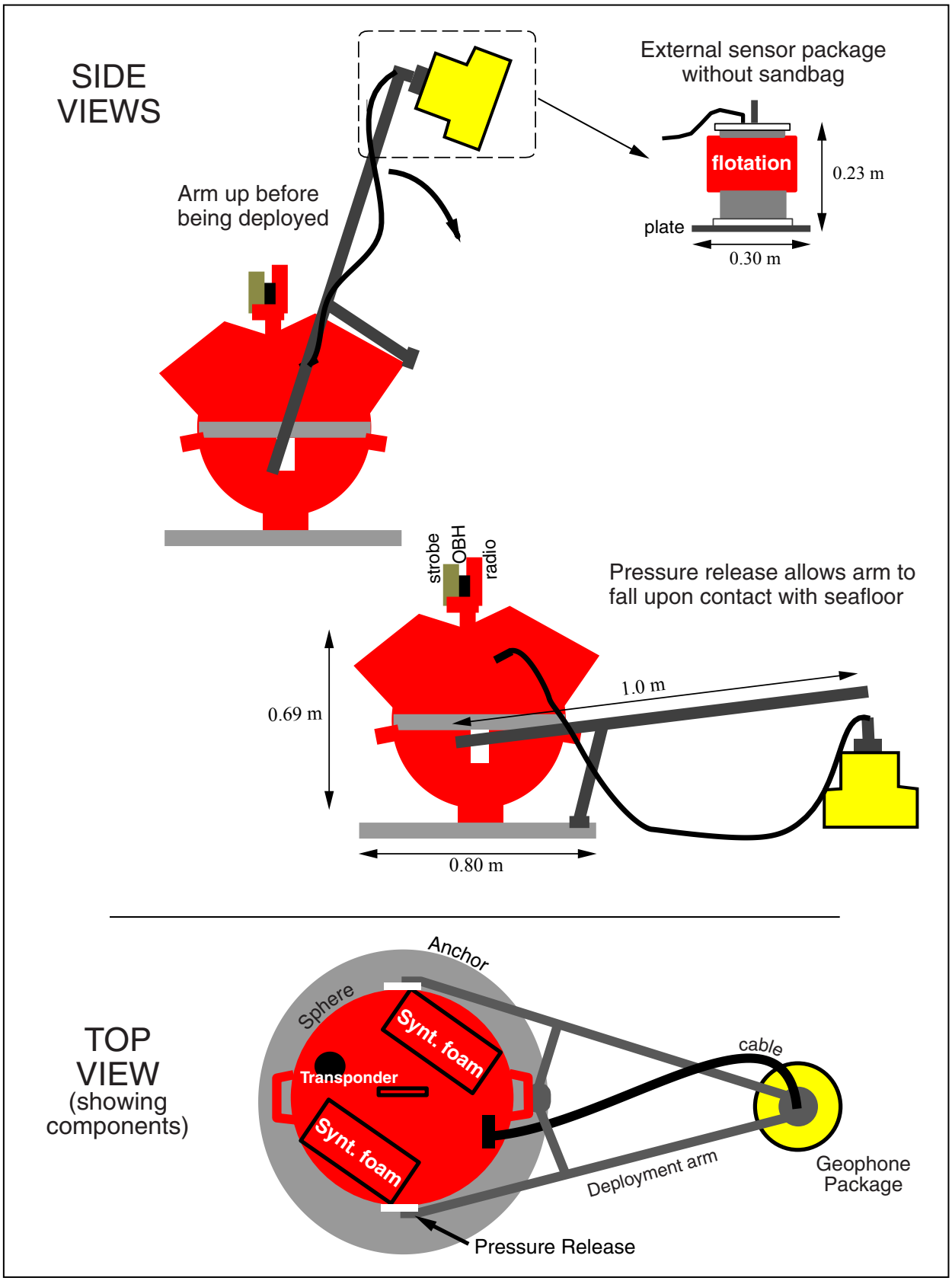


Figure 3. Schematic views of ocean bottom seismometer (OBS) configuration.



CRUISE REPORT

OBS deployment

The offshore deployment of the OBS took place aboard the University of Puerto Rico's R/V *Isla Magueyez* during May 2-4, 2000. The *Isla Magueyez* departed Mayagüez harbor on May 2, 2000, at 18:47 local time (123:22:47 UT). The *Isla Magueyez* is a 72-ft.-long vessel with a beam of 22 ft. and a draft of 11 ft. A news conference took place in the harbor prior to the ship's departure. The OBS deployment was uneventful and proceeded quickly and efficiently around the clock. The *Isla Magueyez* arrived at the University of Puerto Rico's Marine Lab on Isla Magueyez on May 4, 2000, at 11:30 local time (125:15:30 UT).

The instruments were programmed to start recording on May 4, 2000 at 21:00 UT. Table 3 lists information about both the deployment and recovery of the OBS.

Table 2. OBS Deployment Personnel.

Crew of the R/V *Isla Magueyez*
Captain Jose Montablo 4 seamen, 1 cook
Scientific party
Dr. Uri ten Brink - Chief Scientist, USGS Rafael Abreu, Puerto Rico Seismic Network, UPRM Prof. Jorge Capella, Marine Sciences Dept., UPRM Robert Iuliucci, Contractor Greg Miller, USGS Philipp Molzer, USGS Dr. Erich Roth, USGS

OBS recovery

Recovery of the OBS took place aboard the University of Puerto Rico's R/V *Chapman* during June 13-15, 2000. The R/V *Chapman* departed Mayagüez harbor on June 13, 2000, at 16:08 local time (165:20:08 UT). The R/V *Chapman* is a 110-ft.-long fisheries research vessel, built in 1979 with 384 gross tonne. OBS recovery was uneventful and proceeded quickly and efficiently around the clock. All instruments responded immediately and arrived at the sea surface, where expected. Drift through the water column was surprisingly low, generally less than 0.1°. Drift for station B2 was 0.374 km and for station A3 was 0.238 km, but these OBS drifted on the surface for a few minutes before being found. The only significant drift was for A2, 1.187 km. The rise speed

Table 4. OBS Recovery Personnel.

Crew of the R/V *Chapman*
Captain Hector (Cabrilla) Pagan 4 seamen, 1 cook
Scientific party
Dr. Uri ten Brink - Chief Scientist, USGS Rafael Abreu, Puerto Rico Seismic Network, UPRM Sr. Ramon Alonso, Dept. de Recursos Naturales, Commonwealth of Puerto Rico Kurt Grove, Sea Grant Program, UPRM Robert Iuliucci, Contractor David Martinez, Dept. of Geology, UPRM Greg Miller, USGS Jeffrey Nealon, USGS Dr. Erich Roth, USGS Rusell Sell, USGS Samuel Vega Figueroa, Red Sismica, UPRM

Table 3. OBS Station Information.

Station	Latitude (N) (on deploy-ment)	Longitude (W) (on deploy-ment)	Water depth[1] (m) (on deploy-ment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
D1	18°13.629'	67°17.849'	398	18°13.575'	67°17.898'	391	0.98	36.4	1423	4	
C4	19°01.991'	67°03.780'	~4200	19°02.037'	67°03.853'	4139	0.94	138	1422	4	
D3	18°53.660'	67°00.696'	~2900	18°53.69'	67°00.722'	2947	0.94	52.4	1421	3	No data for vertical geophone.
C1	18°45.695'	67°04.169'	~1850	18°45.708'	67°04.220'	1849	0.88	unknown	1155	4	The 24 volt battery pack was completely dead on recovery, so no checks were possible. The Seascan clock drift could not be recovered. 1155 tracks were written by the data logger before it died. The cause is unknown.
D2	18°37.134'	67°07.028'	449	18°37.190'	67°07.127'	447	0.74	92.8	1419	4	Sensor connector leaked. There was no vacuum and a lot of salt water intrusion. Arm was bent and got stuck in horizontal position, but geophone package released from arm.
D8	18°43.848'	67°40.749'	~1380	18°43.802'	67°40.852'	1373-82	0.85	62.8	1420	4	Arm released, but sensor package didn't deploy from arm. The piston was bent from the violent twisting of the sensor pack.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.

[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

Table 3. OBS Station Information, cont'd.

Station	Latitude (N) (on deploy-ment)	Longitude (W) (on deploy-ment)	Water depth[1] (m) (on deploy-ment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
B2	18°19.878'	67°44.259'	~400	18°19.825'	67°44.464'	385	unknown	unknown	0	0	Sensor connector leaked. There was no vacuum and heavy salt water intrusion. The data logger and Seascan clock boards were both destroyed by the flooding. Data logger failed before the start of data, so no data were recorded. Instrument drifted a few minutes before being found so no rise time could be calculated.
A2	18°03.171'	67°39.653'	1015	18°03.804'	67°39.531'	1009	0.99	48	1414	4	Sensor connector leaked. There was no vacuum and some salt water intrusion. Data indicate only the vertical and hydrophone worked. 4 channels were recorded, but there was no data for either of the horizontals. Sensor package and wiring check OK on the surface. Believe problem is in the mating of the sensor package cable.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.

[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

Table 3. OBS Station Information, cont'd.

Station	Latitude (N) (on deploy-ment)	Longitude (W) (on deploy-ment)	Water depth[1] (m) (on deploy-ment)	Latitude (N) (on recovery)	Longitude (W) (on recovery)	Water depth[2] (m) (on recovery)	Rise speed (m/s)	Clock Drift (ms)	# tracks recorded	# channels w/data	Comments
C3	18°07.487'	67°28.514'	203	18°07.528'	67°28.502'	198	1.32	unknown	100	4	The 24 volt battery pack was completely dead on recovery, so no checks were possible. The Seascan clock drift could not be recovered. Flooding of the sensor connector resulted in only ~100 tracks of data even though 1100 tracks were written by the data logger before it died.
D4	17°27.473'	67°11.419'	~3500	17°27.488'	67°11.494'	3490	1	53.6	1422	4	Arm released, but sensor package didn't deploy from arm. The piston was pulled too far out, so there was no air space behind it.
A8	17°40.237'	67°09.465'	~1900	17°40.189'	67°09.390'	1841	0.88	93.6	1421	4	
A3	17°45.588'	67°09.798'	~2150	17°45.519'	67°09.684'	2136	unknown	22.2	1423	4	The negative 12 volt connection on the 24 volt battery was dead. On recovery, instrument drifted on surface for a while before being found so no rise time could be calculated.

[1]Estimated water depths are for points beyond fathometer range and were taken from the bathymetry map.

[2]Water depth was determined by ship's echo sounder for stations D1, D2, D8, B2, A2, and C3. For stations C4, D3, C1, D4, A8, and A3, water depth was determined by direct distance between transducer and OBS transponder. This is a maximum distance because the transducer may not have been vertically above the transponder.

for the OBS through the water column was 1±0.3 m/s. Rise speed is the average speed at which the OBS rises through the water column. The R/V *Chapman* arrived at Mayagüez harbor on June 15, 2000, at 09:00 local time (167:13:00 UT). A small news conference took place at the harbor afterwards.

DATA PROCESSING AND ANALYSIS

During the time the array was deployed, 88 local events (Figure 1) were detected by the University of Puerto Rico's permanent network of seismometers, the Puerto Rico Seismic Network (PRSN). UPRM defines these local events as events which occur within 17°N to 20°N latitude and 63.5°W to 69°W longitude. This list of local events is based on previous detection thresholds. If it is found that additional lower magnitude regional and global events can be seen in the data, the working event catalog will be augmented.

Data from the OBS were written both in raw format and as 120-second-long SEGY traces. The traces were then written into day-long SEGY files for each component of each station. For some analyses, the list of local events was used to extract a subset of data into 120-second-long SEGY traces whose start corresponds with the start of the known event.

Each SEGY file contains 17.5 megabytes of data. There are four components for each station and 12 stations, resulting in 840 Mb per day and 37.8 gigabytes for the entire deployment. The raw OBS data traces for each station are 1.403 Gb, resulting in 16.836 Gb total.

Two methods were used to check the quality of the data. In the first method, the arrivals for four known regional and teleseismic events were compared across stations. Plots derived from this analysis are in Appendix A. The second method compared the expected arrival time with the actual arrival time for 20 known events located within the permanent network. The locations of the 20 events, which are within or near the Puerto Rico Seismic Network, are considered reliable. Plots for this method are in Appendix B.

For the first method, three local events plus one teleseismic event were used (Table A1). The events are labeled I through IV on Figures 1 and 4. All three of the local events were recorded by PRSN. The teleseismic event was located under the Andes at the northwestern tip of Argentina some 4,853 km (41.5°) away from our array.

Figures A1-A4 depict each of the four events at the OBS stations. All data are unfiltered. The times for station D1 have been shifted to match the times of the other instruments because of a delay in station D1's clock. Events I through IV were shifted by -60.5 sec., -73.7 sec., -61.3 sec., and -60.4 sec., respectively.

The second method, which compared predicted and actual arrival times, used a

Figure 4. Location of Event IV, the teleseismic event used to compare arrivals across the OBS array.

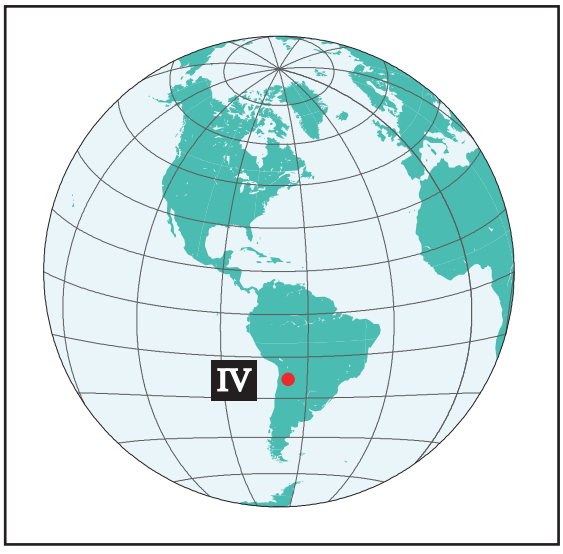
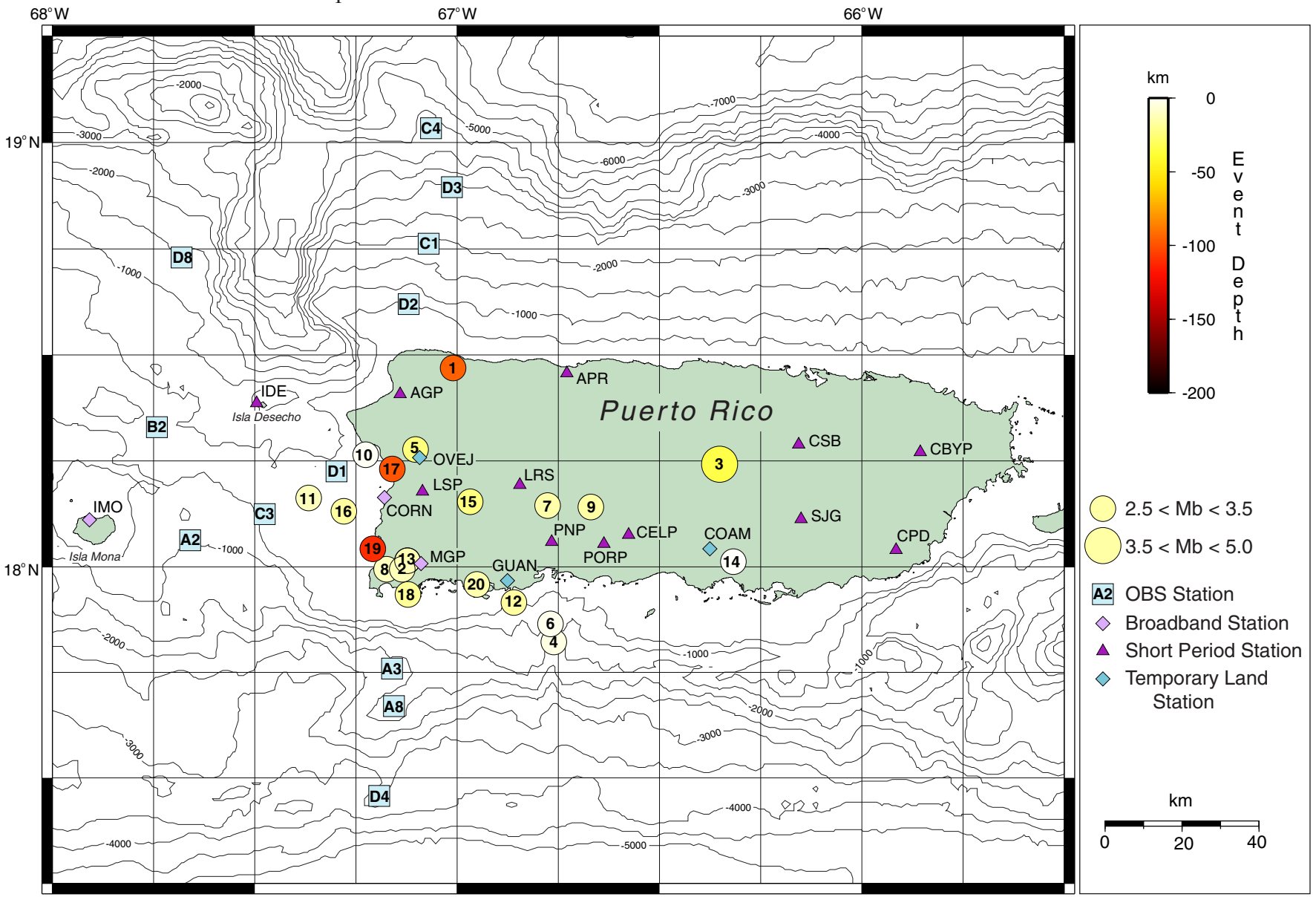


Figure 5. Map of the Puerto Rico region showing the 20 local events used to compare predicted and actual arrival times. Numbers correspond to the event numbers in Table B1.



regional velocity model prepared by Robert Sohn at the Woods Hole Oceanographic Institute to calculate the predicted P-wave arrival times for 20 events at all stations. Figure 5 shows the locations of these events and Table B1 lists the important information for each event. Note that Event II used in the previous method was used in this analysis as well, now labeled Event 10. Tables B2-B10 and Figures B1-B9 compare the difference between the predicted and actual arrival times of the 20 events at each station. Rough estimates of observed arrival time errors were calculated by subtracting the next best pick times before and after the chosen arrival time. Not all events were seen clearly enough at each station to choose an arrival, so only those events which were resolvable at a particular station were included in the analysis. None of the 20 events had clear arrivals at station D2, so D2 was not included in this analysis.

Plots of each event at each station can be found in Appendix B (Figs. B10-B102). The predicted arrival times are marked on each plot with a red vertical line. The plots marked "filtered" have been filtered using an Ormsby bandpass filter. Filter frequency values used were generally 1.0-2.0-12.0-13.0 Hz. Time is in milliseconds after the start of the event. All traces shown are of the vertical component unless otherwise noted.

ACKNOWLEDGMENTS

We would like to thank the Puerto Rico Port Authority of Mayagüez, the President's office of the University of Puerto Rico, and the staff of the Puerto Rico Seismic Network, whose generous help were central to the success of the experiment. We would also like to thank the crews of the R/V *Isla Magueyez* and R/V *Chapman*. The field work was funded by the USGS Coastal and Marine Geology Program, by the Puerto Rico Department of Natural and Environmental Resources, by the Sea Grant Office at the University of Puerto Rico, Mayagüez, and by the President's Office of the University of Puerto Rico.

APPENDIX A:

Plots for the Comparison of Four Events Across Stations

Table A1. Events used to compare arrivals across stations.

Event No.	Date	Time (UTC)	Latitude	Longitude	Depth (km)	Magnitude
I	5/26/2000	04:37:22.17	18° 0.98' N	68° 42.36' W	143.9	4.0 local Mb
II	6/2/2000	08:32:26.16	18° 15.88' N	67° 13.50' W	1.7	3.3 local Mb
III	6/1/2000	21:02:53.83	19° 32.76' N	65° 02.88' W	33.0	4.5 Mb
IV	5/12/2000	18:43:23.82	22° 59.40' S	66° 44.40' W	243.0	7.20 Mw

Figure A1a: Event I, one of the subset of three local events, recorded at stations D8, A2, and C4. Time is seconds after start of event.

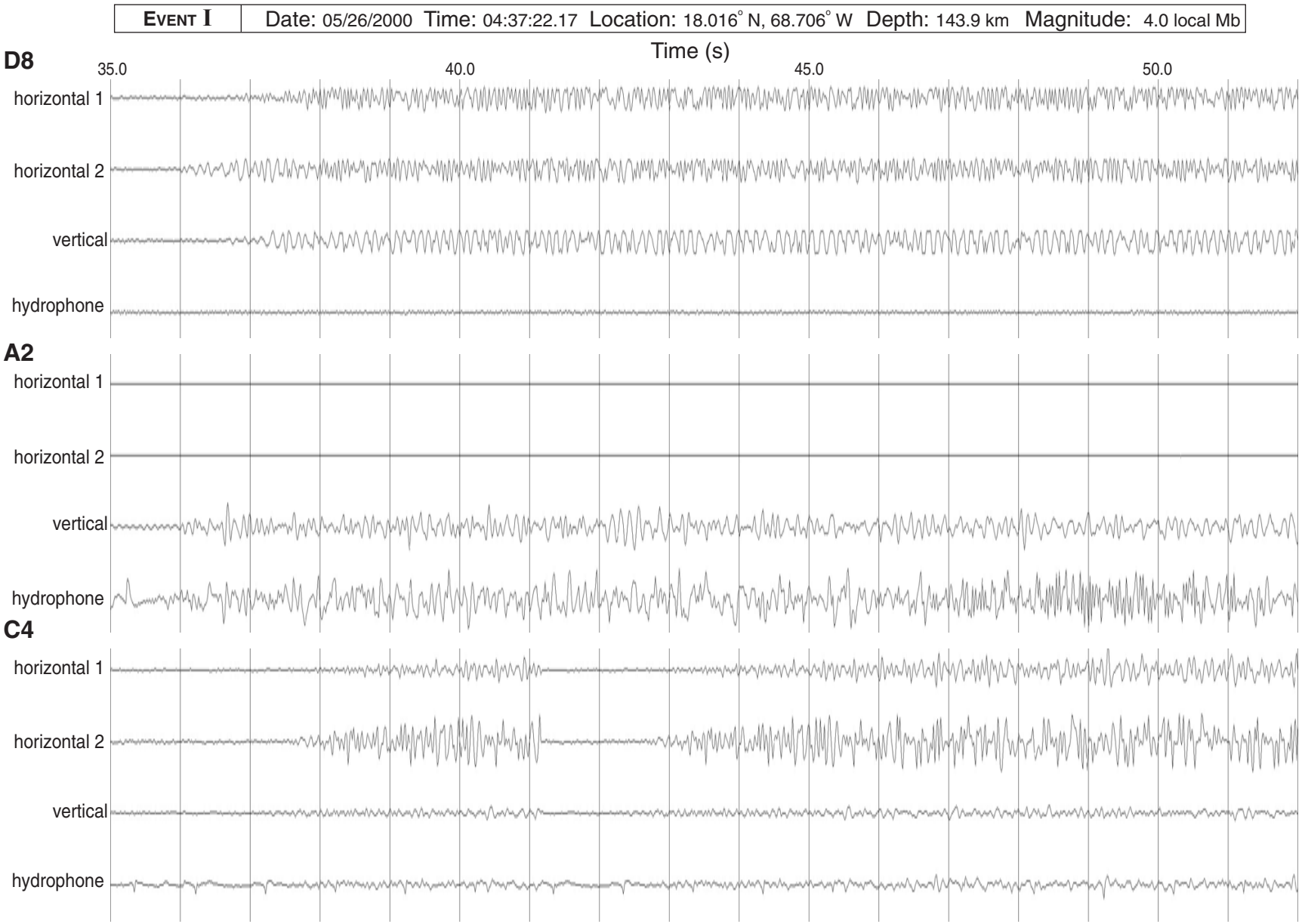


Figure A1b: Event I, one of the subset of three local events, recorded at stations A3, A8, and D3. Time is seconds after start of event.

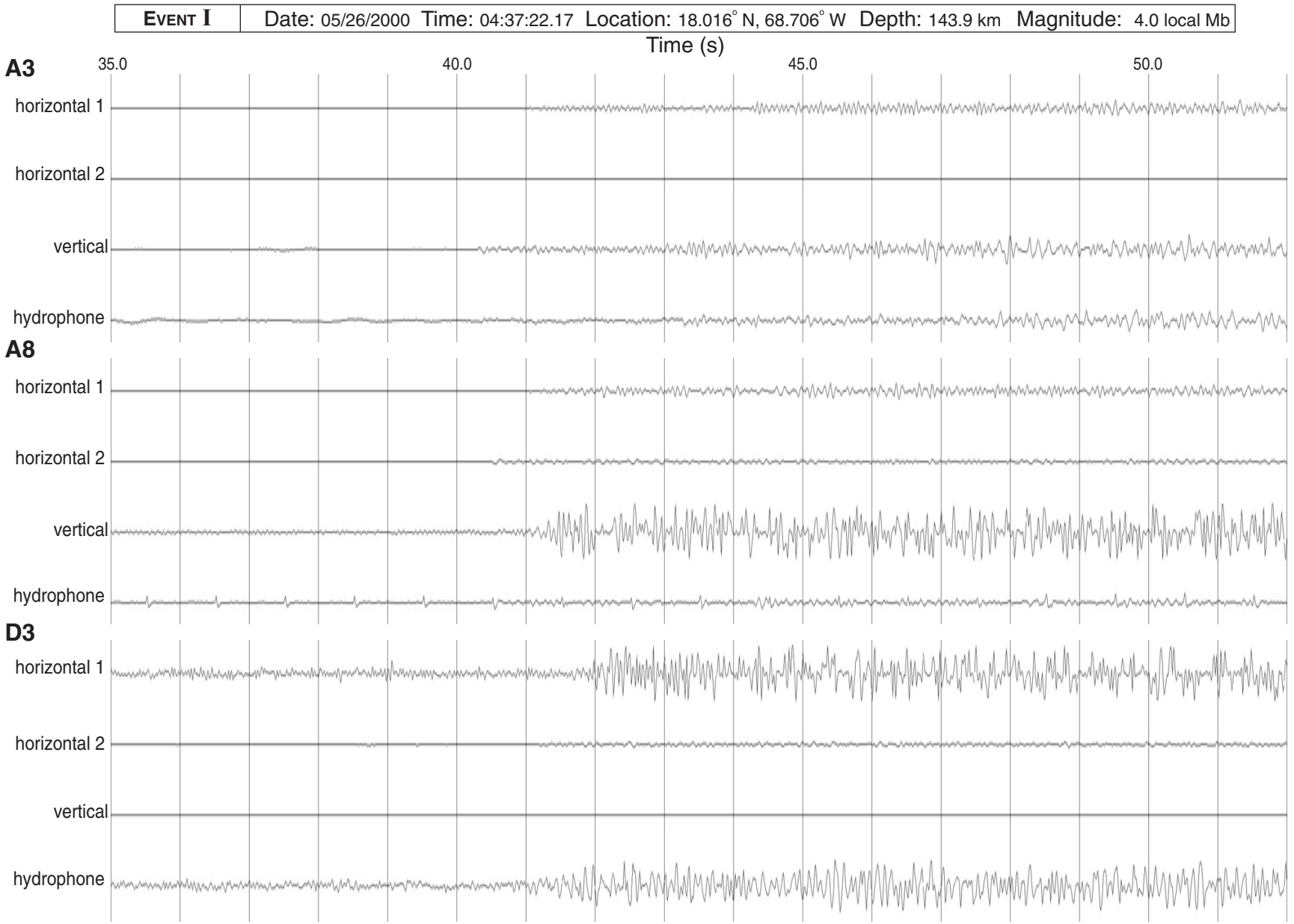
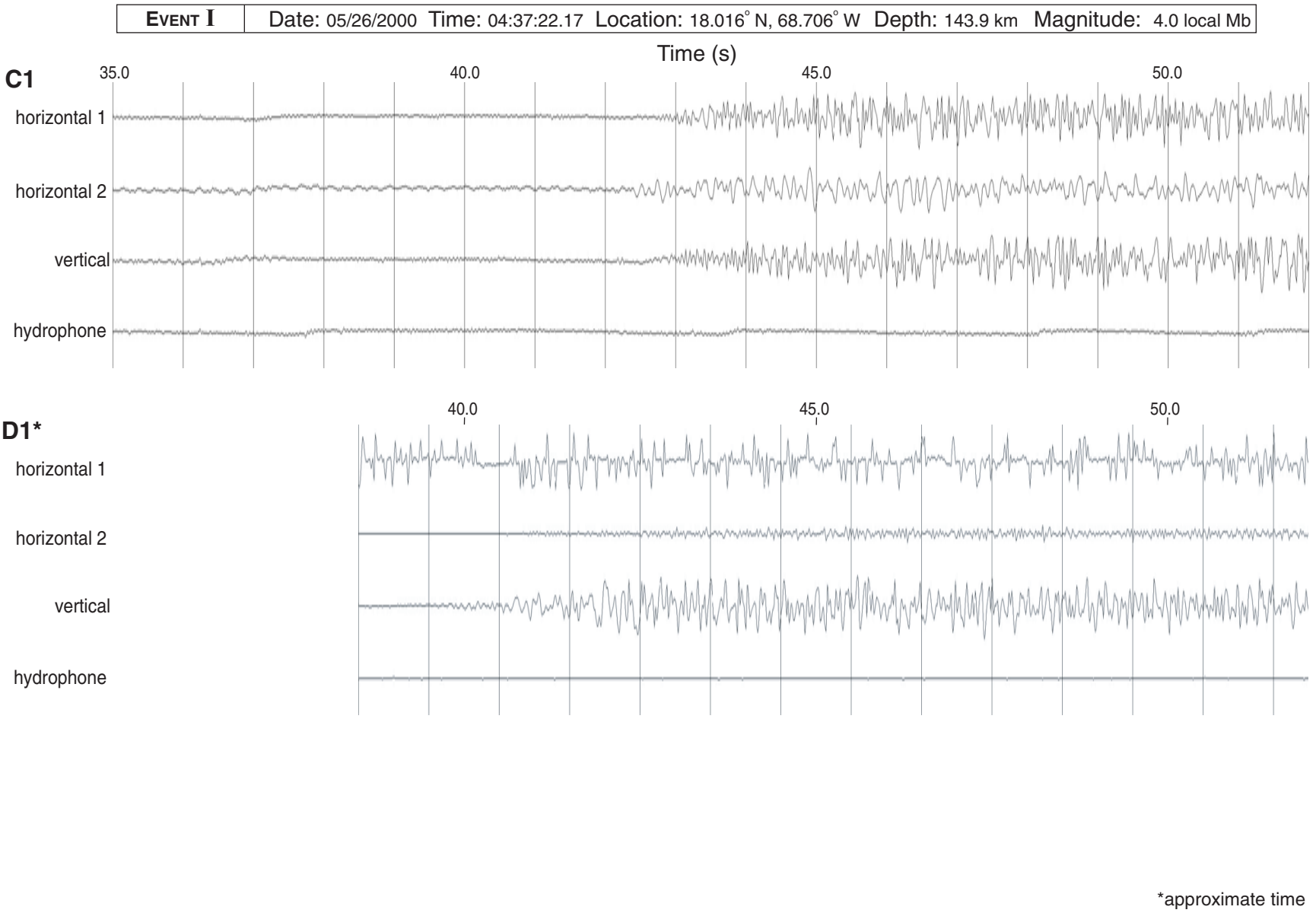


Figure A1c: Event I, one of the subset of three local events, recorded at stations C1 and D1. Time is seconds after start of event.



*approximate time

Figure A2a: Event II, one of the subset of three local events, recorded at stations A2, A3, and D8. Time is seconds after start of event.

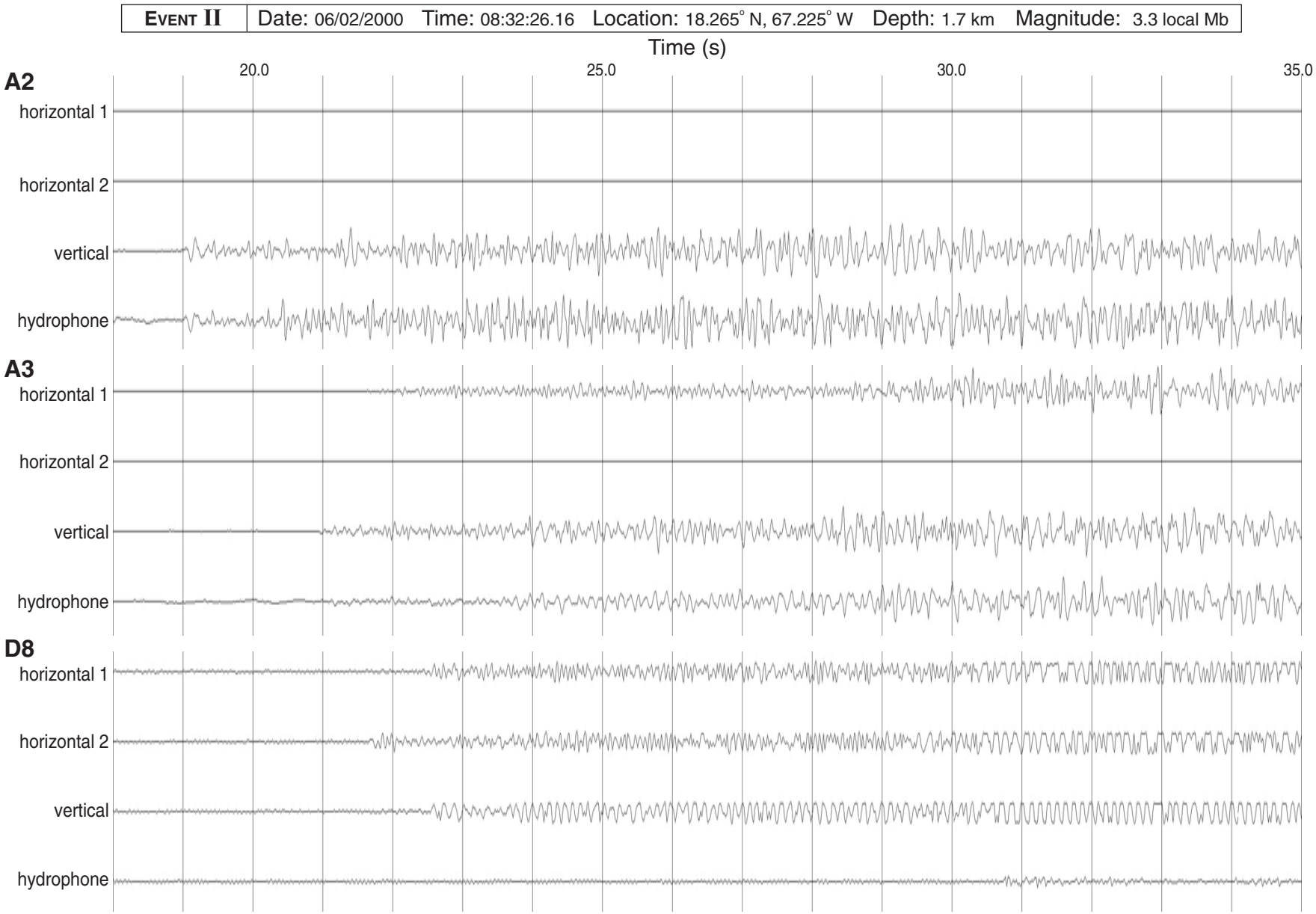


Figure A2b: Event II, one of the subset of three local events, recorded at stations D3, A8, and C4. Time is seconds after start of event.

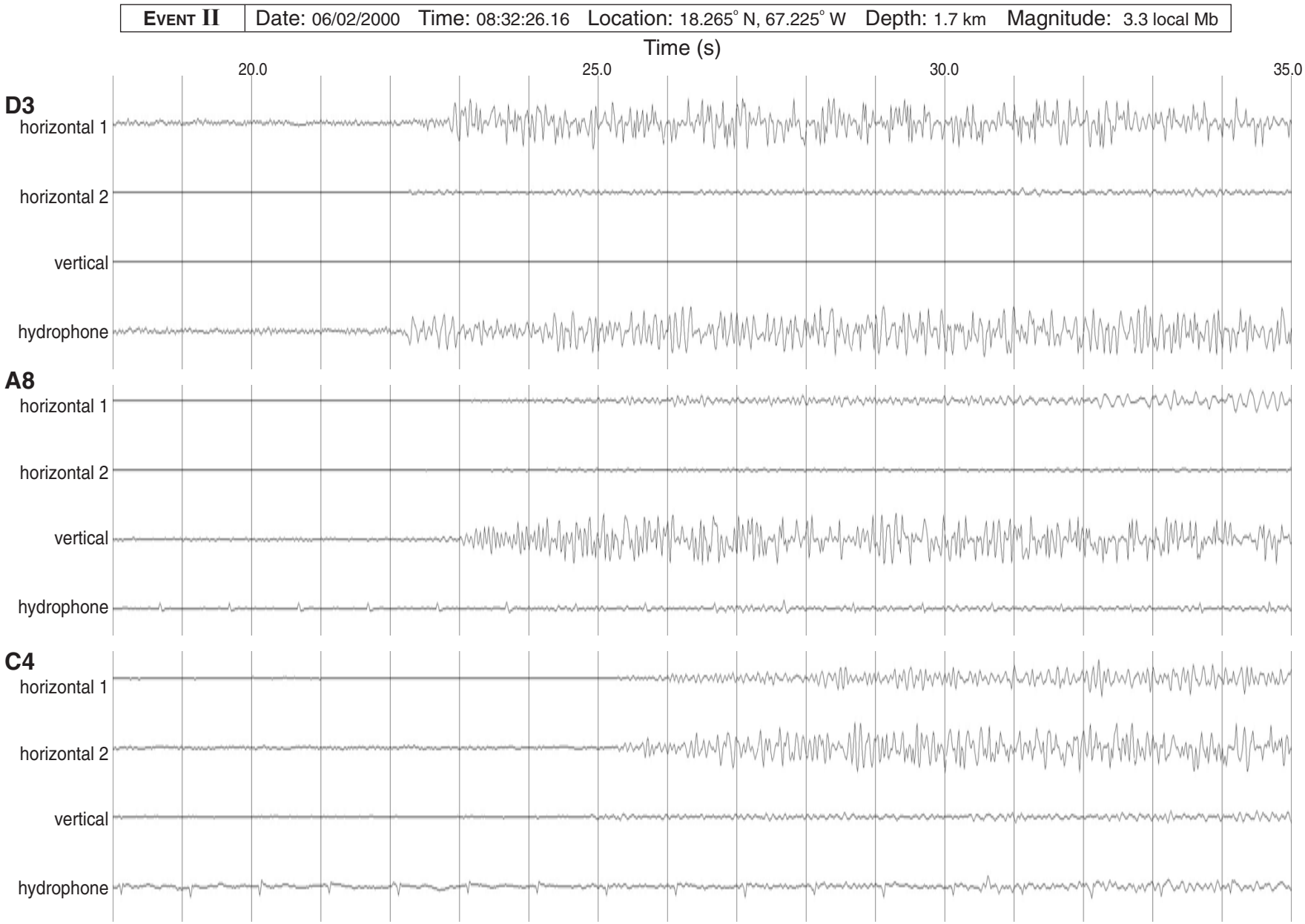
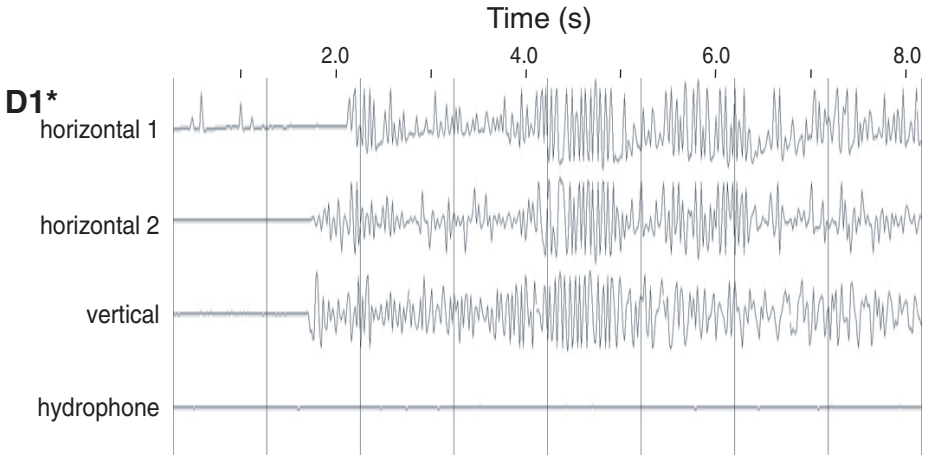


Figure A2c: Event II, one of the subset of three local events, recorded at station D1. Time is seconds after start of event.

EVENT II	Date: 06/02/2000 Time: 08:32:26.16 Location: 18.265° N, 67.225° W Depth: 1.7 km Magnitude: 3.3 local Mb



*approximate time using an average crustal velocity of 5 km/s

Figure A3a: Event III, one of the subset of three local events, recorded at stations C4 and D3. Time is seconds after start of event.

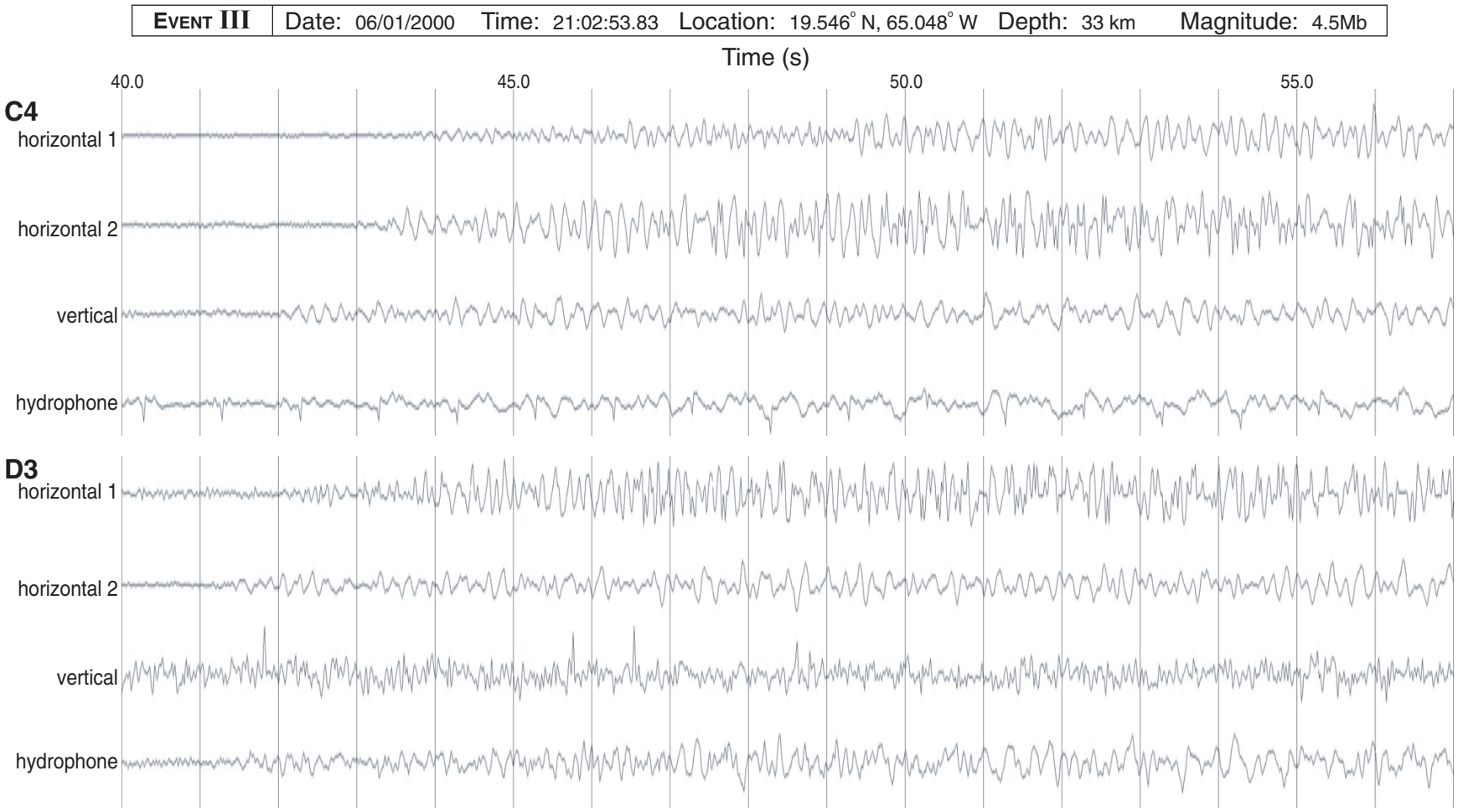
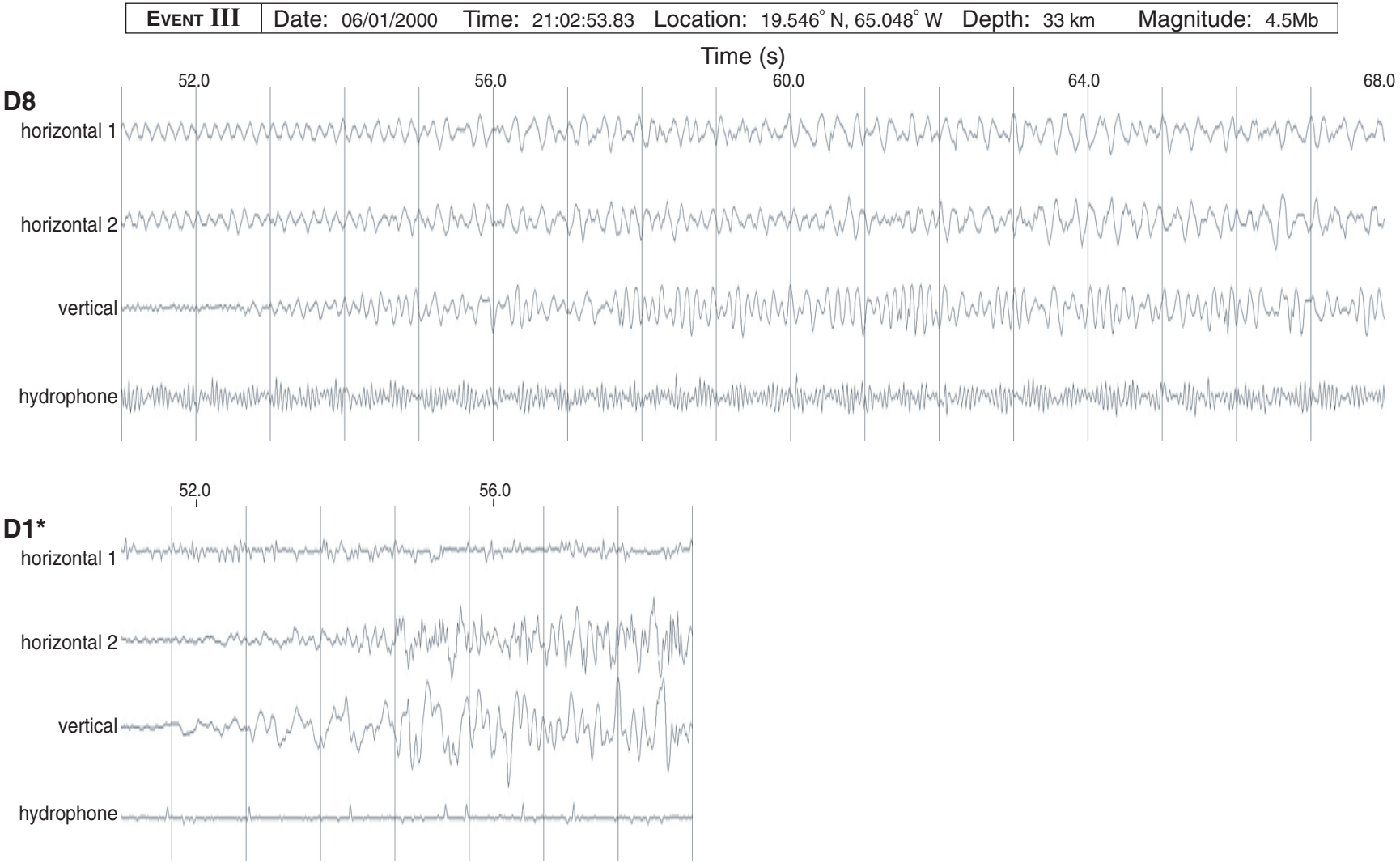


Figure A3b: Event III, one of the subset of three local events, recorded at stations D8 and D1. Time is seconds after start of event.



*approximate time

Figure A3c: Event III, one of the subset of three local events, recorded at stations A2, A3, and A8. Time is seconds after start of event.

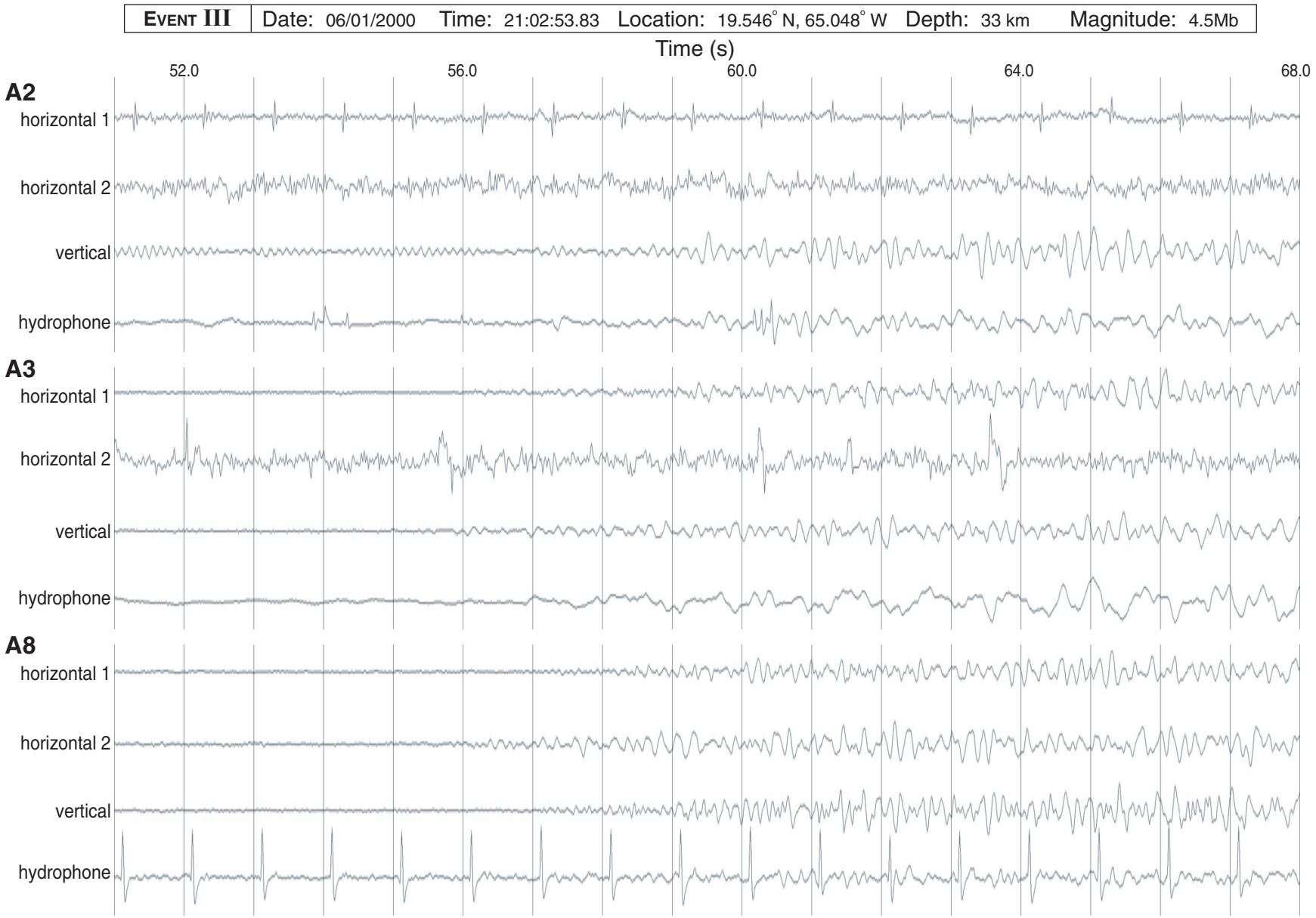


Figure A4a: Event IV, the teleseismic event, at stations C4, D3, and C1. Time is seconds after start of the event.

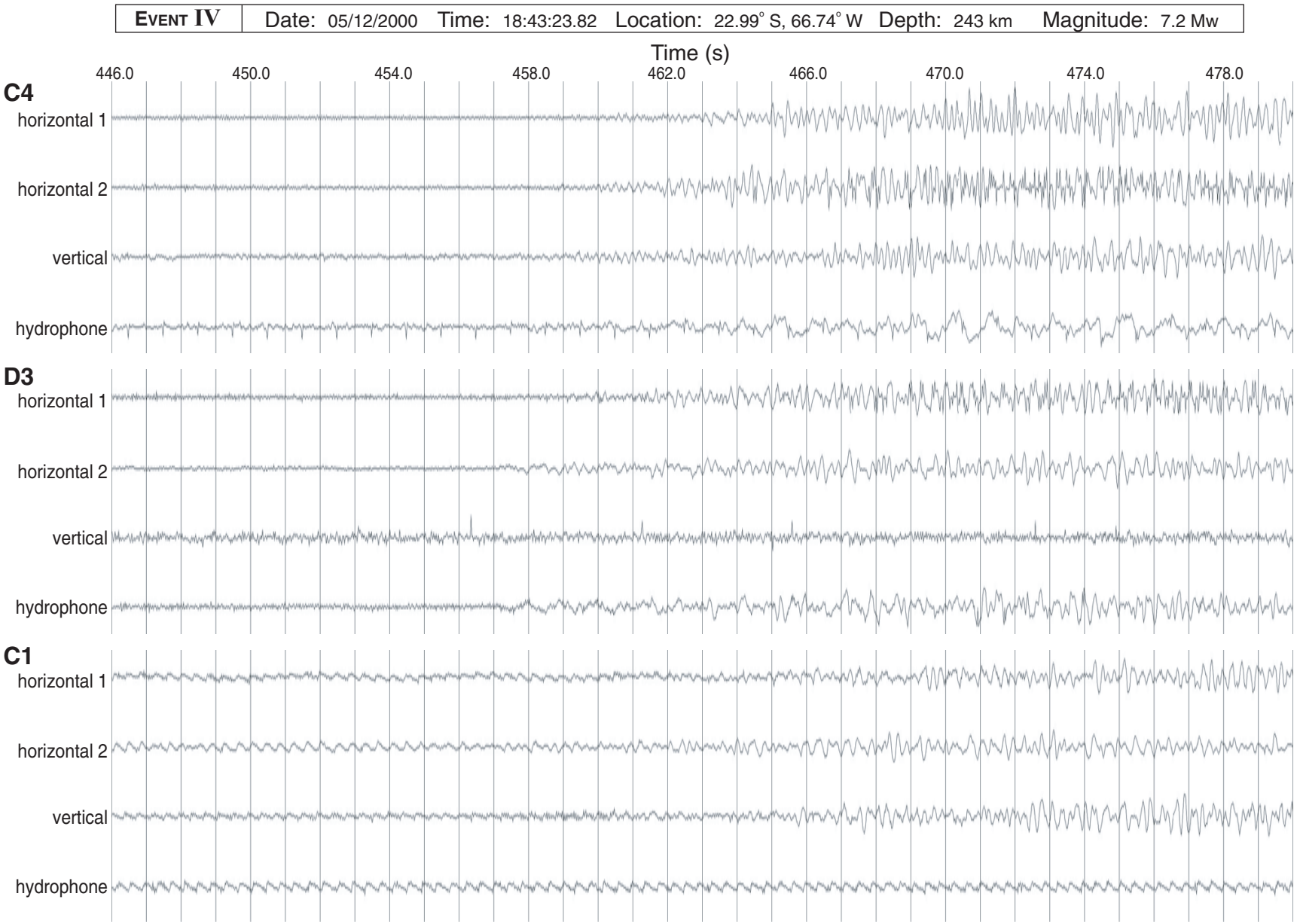


Figure A4b: Event IV, the teleseismic event, at stations A2, A3, and A8. Time is seconds after start of the event.

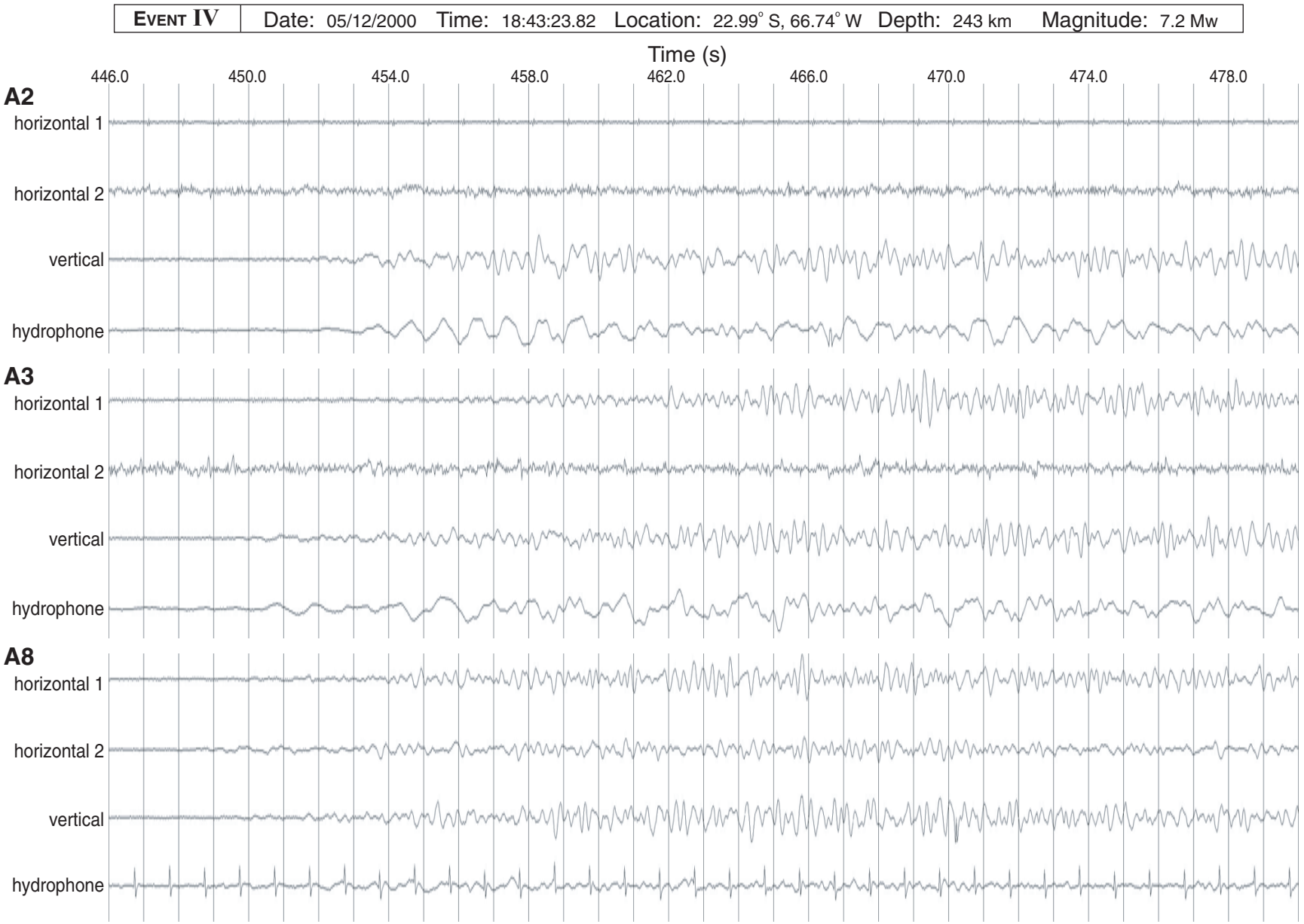
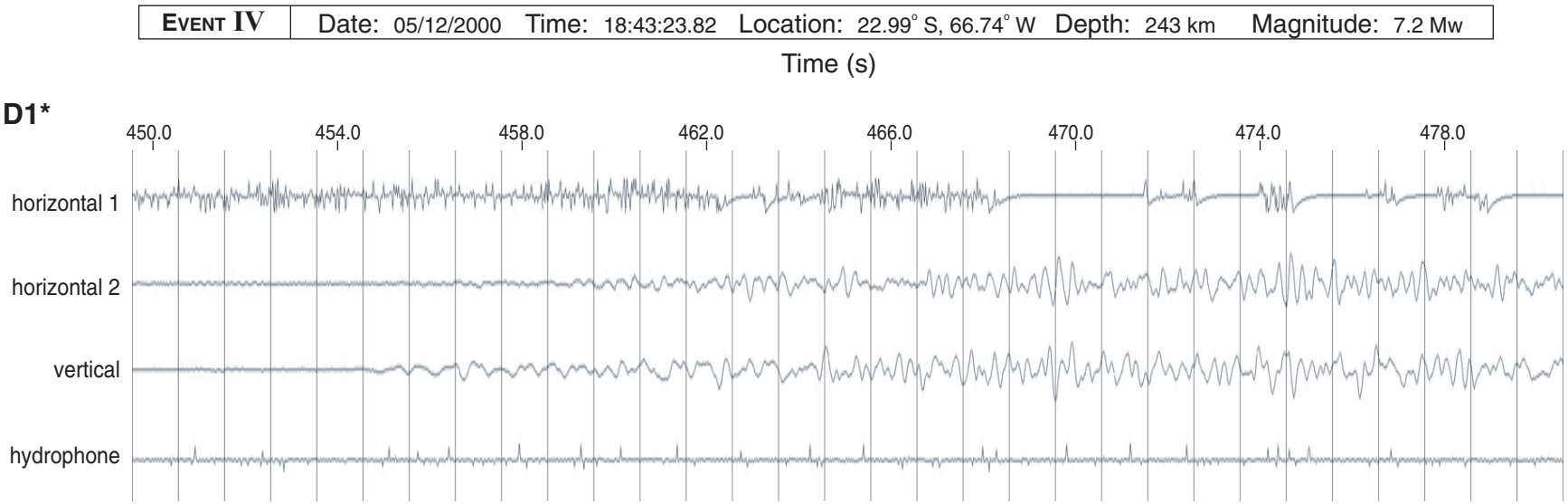


Figure A4c: Event IV, the teleseismic event, at station D1. Time is seconds after start of the event.



*approximate time

APPENDIX B:

Tables and Plots for the Comparison of 20 Local Events at Each Station

Table B1. The 20 local events used to compare predicted and actual arrivals.

Event No.	Date	Time (UTC)	Latitude	Longitude	Depth (km)	Magnitude (local Mb)
1	5/12/2000	11:34:52.53	18° 28.20' N	67° 00.54' W	96.4	2.7
2	5/15/2000	04:48:46.73	17° 59.64' N	67° 08.10' W	13.7	2.8
3	5/15/2000	05:20:06.10	18° 14.52' N	66° 21.06' W	35.7	3.5
4	5/21/2000	06:33:34.39	17° 49.32' N	66° 45.60' W	5.5	2.1
5	5/21/2000	17:05:0 .90	18° 16.62' N	67° 06.12' W	25.3	3.1
6	5/22/2000	07:26:54.14	17° 51.90' N	66° 46.14' W	3.4	3.0
7	5/23/2000	11:32:46.55	18° 08.70' N	66° 46.50' W	16.8	2.5
8	5/23/2000	21:03:08.58	17° 59.64' N	67° 10.38' W	12.8	2.5
9	5/31/2000	07:00:30.01	18° 08.46' N	66° 40.14' W	17.4	2.2
10	6/2/2000	08:32:26.16	18° 15.90' N	67° 13.50' W	1.7	3.3
11	6/3/2000	04:11:33.12	18° 09.78' N	67° 21.96' W	12.9	3.0
12	6/7/2000	10:51:53.94	17° 54.96' N	66° 51.54' W	18.3	2.9
13	6/8/2000	06:26:31.65	18° 00.84' N	67° 07.32' W	14.8	3.0
14	6/8/2000	16:58:25.71	18° 00.72' N	66° 19.02' W	0.5	2.7
15	6/10/2000	01:26:34.13	18° 09.24' N	66° 58.02' W	24.9	2.2
16	6/11/2000	18:42:13.91	18° 07.86' N	67° 16.74' W	18.4	2.6
17	6/12/2000	01:25:33.96	18° 13.86' N	67° 09.54' W	100.3	2.9
18	6/12/2000	04:20:33.33	17° 56.04' N	67° 07.26' W	20.3	2.6
19	6/12/2000	11:11:34.60	18° 25.50' N	66° 36.30' W	61.9	2.6
20	6/13/2000	05:45:21.15	17° 57.48' N	66° 57.06' W	15.8	2.3

Table B2. Comparison of predicted and actual arrivals across events for Station C1.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
C1	1	13.30	24.94	11.64		3.68
C1	3	13.65	26.84	13.19		1.2
C1	5	8.51	21.06	12.55		0.12
C1	7	11.30	25.24	13.94		0.76

Figure B1. Difference between predicted and actual P-wave arrival times at Station C1.

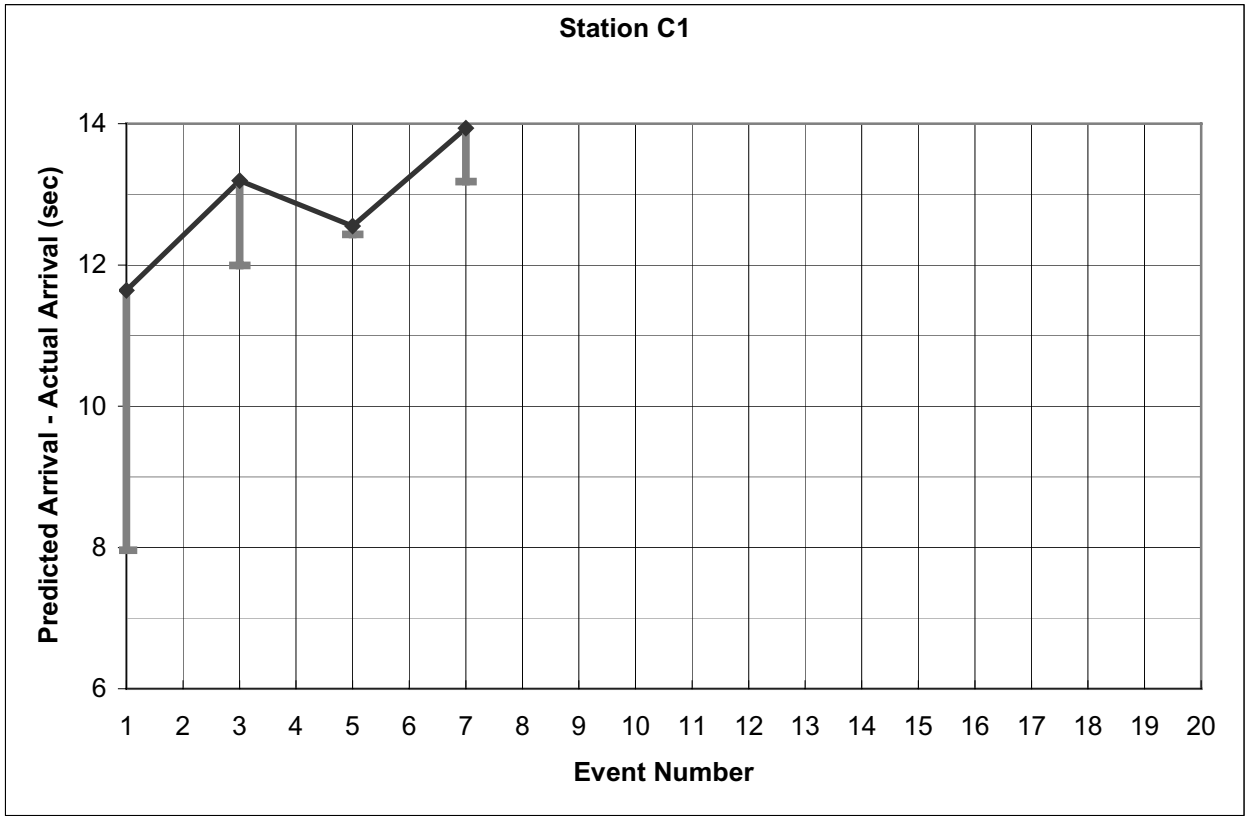


Table B3. Comparison of predicted and actual arrivals across events for Station C4.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
C4	3	16.24	28.50**	12.26	0.84	0.48
C4	5	12.34	24.26	11.92	0.28	0.06
C4	7	14.88	39.50*	24.62		10.4
C4	8	16.71	28.34	11.63	0.06	0.82
C4	10	14.19	24.86	10.67	0.02	0.02
C4	11	14.93	26.82	11.89	0.46	
C4	12	17.64	34.18**	16.54	0.04	0.98
C4	15	14.10	48.90*	34.80		11.6
C4	17	17.54	40.36	22.82	0.06	0.02

*used horizontal component 1 to pick arrival time; vertical component was unclear or bad
**used horizontal component 2 to pick arrival time; vertical component was unclear or bad

Figure B2. Difference between predicted and actual P-wave arrival times at Station C4.

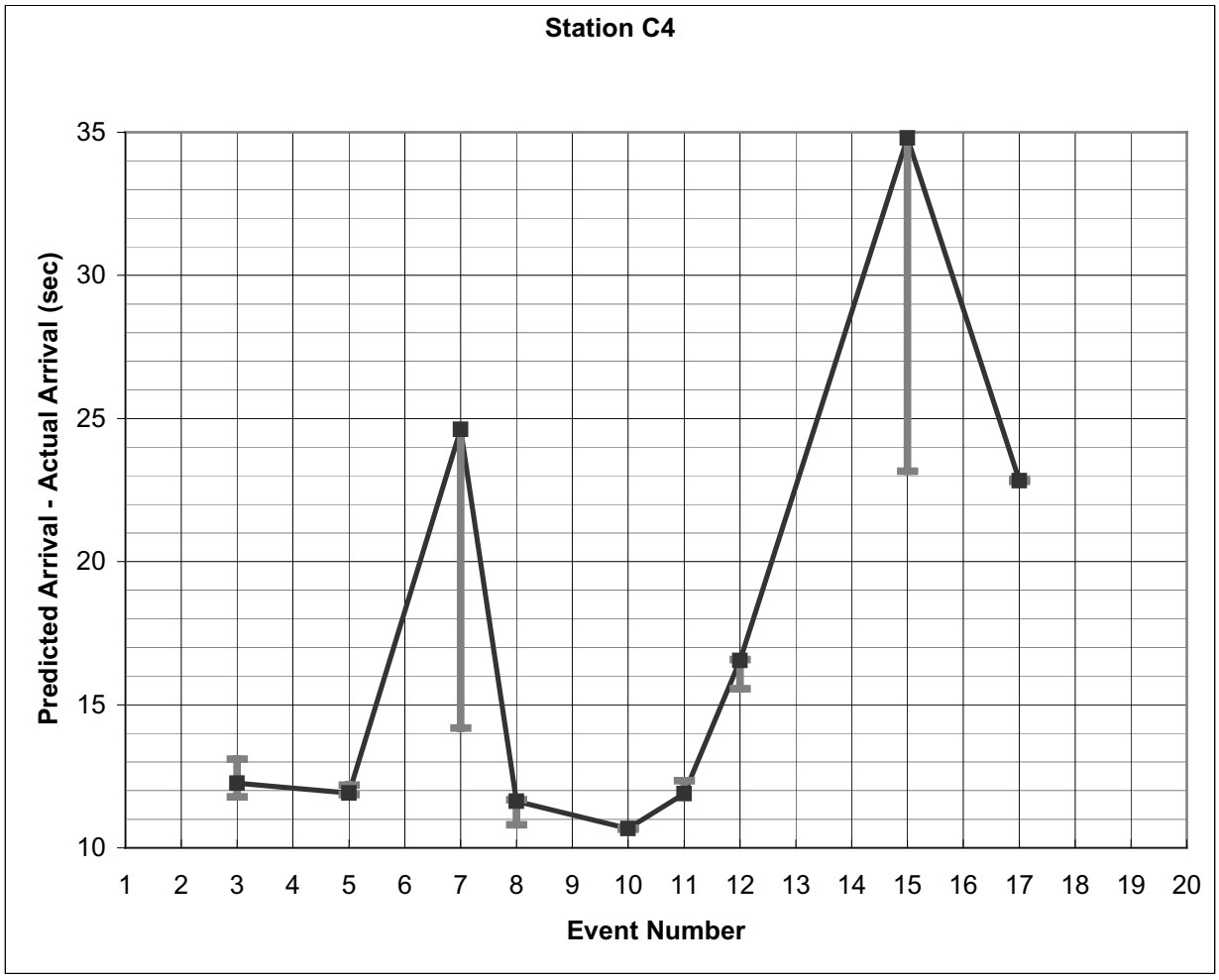


Table B4. Comparison of predicted and actual arrivals across events for Station D1.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
D1	2	5.46	79.80	74.34		0.14
D1	3	14.23	89.44	75.21	0.16	0.12
D1	4	11.73	85.82	74.09	0.04	0.06
D1	5	4.91	79.02	74.11		0.04
D1	6	11.41	85.20	73.79	0.04	0.14
D1	7	8.85	83.14	74.29	0.28	0.02
D1	9	10.25	83.88	73.63	0.08	0.34
D1	10	1.84	75.44	73.60		0.04
D1	11	2.71	76.52	73.81	0.02	0.08
D1	13	5.35	83.68	78.33	0.64	2.78
D1	14	16.73	91.70	74.97	0.02	0.52
D1	16	3.35	88.64	85.29	0.02	
D1	17	13.21	97.98	84.77	0.04	0.12

Figure B3. Difference between predicted and actual P-wave arrival times at Station D1.

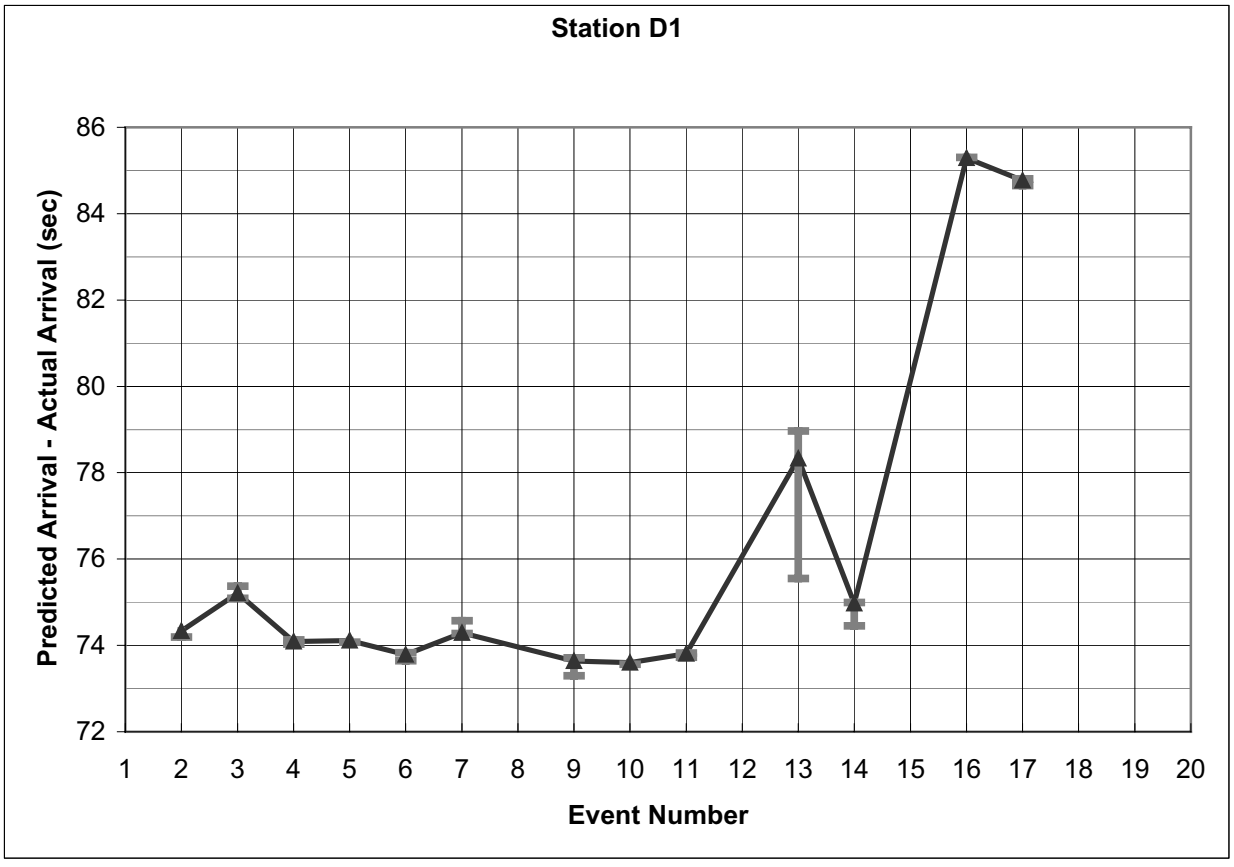


Table B5. Comparison of predicted and actual arrivals across events for Station D3.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
D3	3	14.30	28.00*	13.70	1.84	2.58
D3	10	12.28	22.24*	9.96	0.02	0.04
D3	17	16.31	37.82*	21.51	0.04	0.3

*used hydrophone to pick arrival time; vertical component was bad

Figure B4. Difference between predicted and actual P-wave arrival times at Station D3.

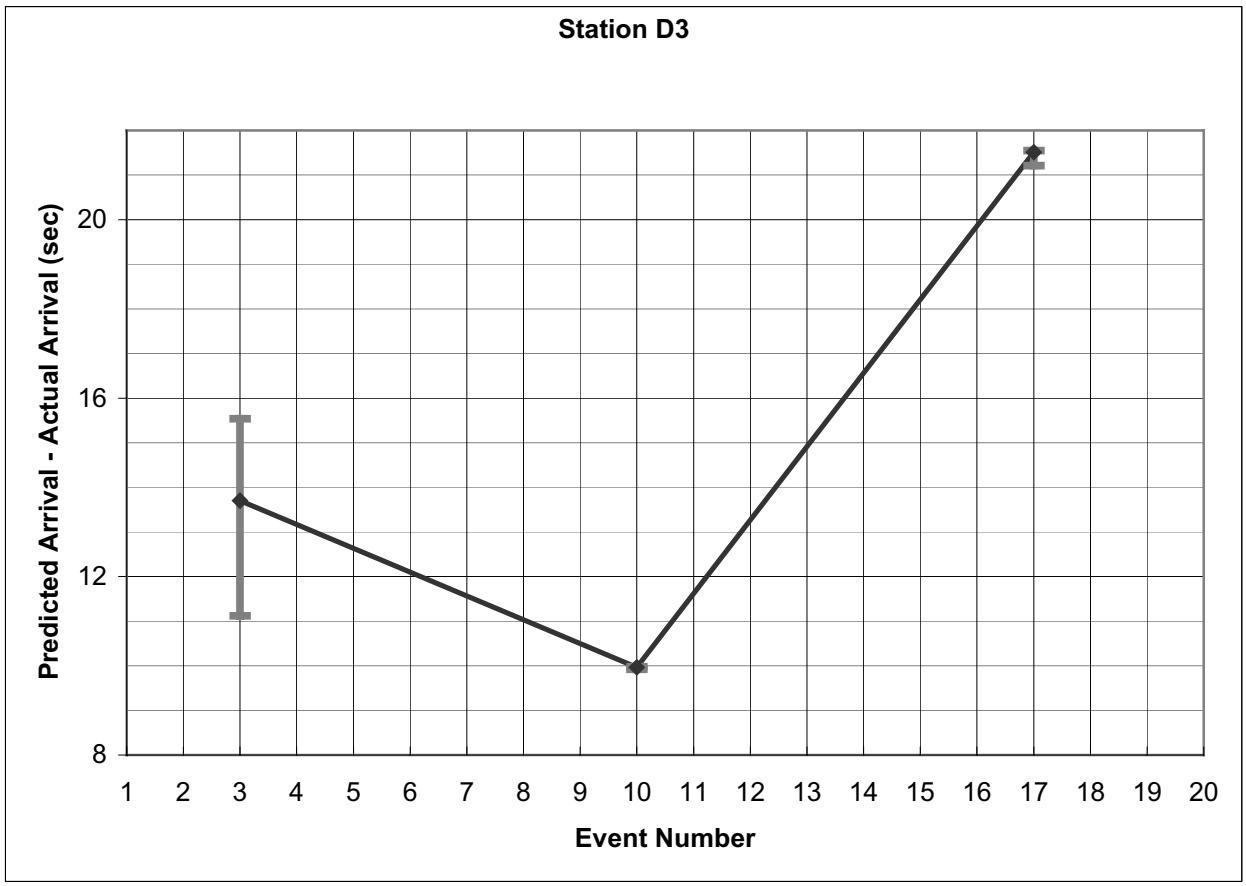


Table B6. Comparison of predicted and actual arrivals across events for Station D8.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
D8	1	16.02	7.30	-8.72	0.28	0.2
D8	2	14.57	40.08	25.51	0.02	0.06
D8	3	20.48	34.68	14.20	0.06	0.14
D8	5	11.63	27.44	15.81	0.18	0.1
D8	6	19.99	51.08	31.09	0.62	7.36
D8	8	14.35	39.78	25.43	0.02	0.1
D8	10	11.85	21.84	9.99	0.7	
D8	11	11.01	27.84	16.83	0.02	2.94
D8	13	14.37	40.08	25.71	0.02	0.16
D8	16	11.69	37.64	25.95	0.1	1.72
D8	17	16.52	42.02	25.50	0.8	1.04
D8	19	18.71	57.64	38.93		4.84
D8	20	16.34	35.00	18.66	3.76	0.68

Figure B5. Difference between predicted and actual P-wave arrival times at Station D8.

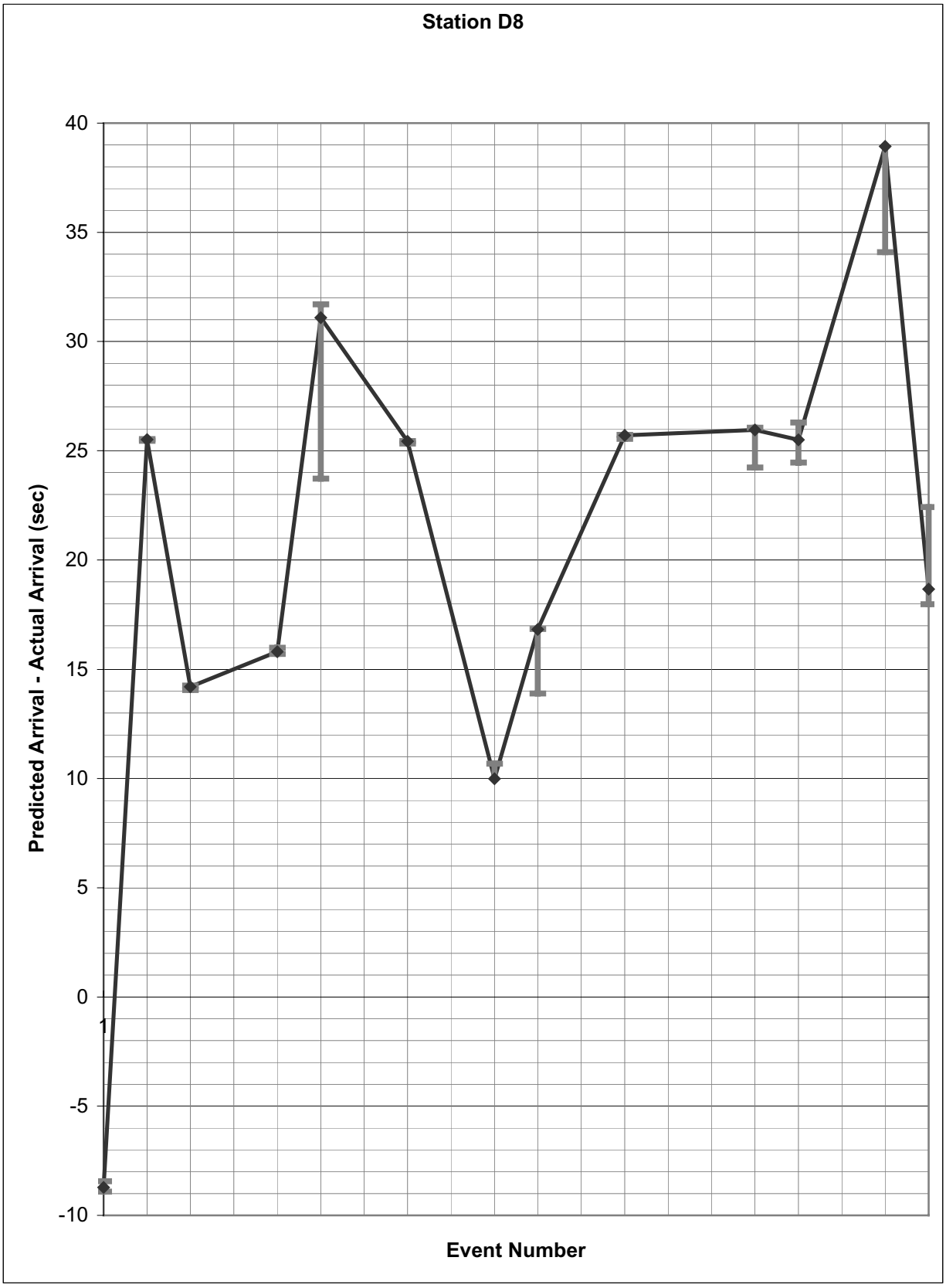


Table B7. Comparison of predicted and actual arrivals across events for Station A2.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
A2	2	8.95	22.08	13.13	0.58	
A2	3	19.14	32.82	13.68	0.18	0.32
A2	5	9.68	22.44	12.76	0.06	0.06
A2	6	15.09	27.98	12.89	0.16	
A2	10	8.94	18.98	10.04	0.04	0.02
A2	11	5.71	19.68	13.97	0.04	1.14
A2	12	12.59	26.72	14.13	0.1	0.3
A2	13	9.05	17.50	8.45	4.76	

Figure B6. Difference between predicted and actual P-wave arrival times at Station A2.

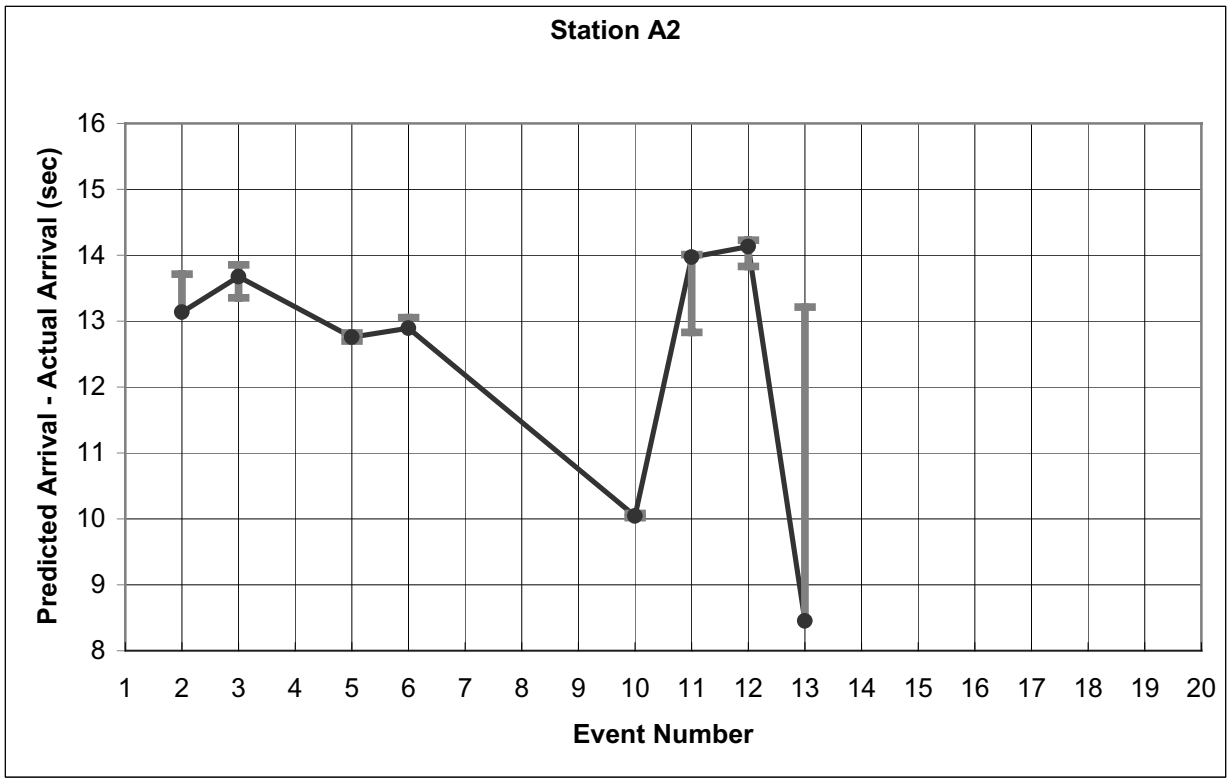


Table B8. Comparison of predicted and actual arrivals across events for Station A3.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
A3	1	16.36	30.74	14.38	0.48	
A3	2	4.80	16.80	12.00	0.08	
A3	3	14.37	28.32	13.95	0.12	
A3	4	7.39	19.58	12.19	0.56	
A3	5	9.00	22.34	13.34	0.04	
A3	6	7.57	19.16	11.59	0.22	0.02
A3	7	9.27	22.00	12.73	0.22	
A3	8	4.76	16.48	11.72	0.02	0.16
A3	10	9.80	20.92	11.12	0.04	
A3	11	8.14	20.38	12.24	0.34	
A3	12	6.27	18.58	12.31	0.02	0.02
A3	13	5.16	16.42	11.26	0.02	0.02
A3	14	15.13	28.80	13.67	1.86	
A3	17	14.73	37.38	22.65		0.04
A3	18	4.37	27.36	22.99	0.04	0.02
A3	19	15.12	39.16	24.04	2.76	0.52
A3	20	5.56	17.42	11.86	0.04	0.08

Figure B7. Difference between predicted and actual P-wave arrival times at Station A3.

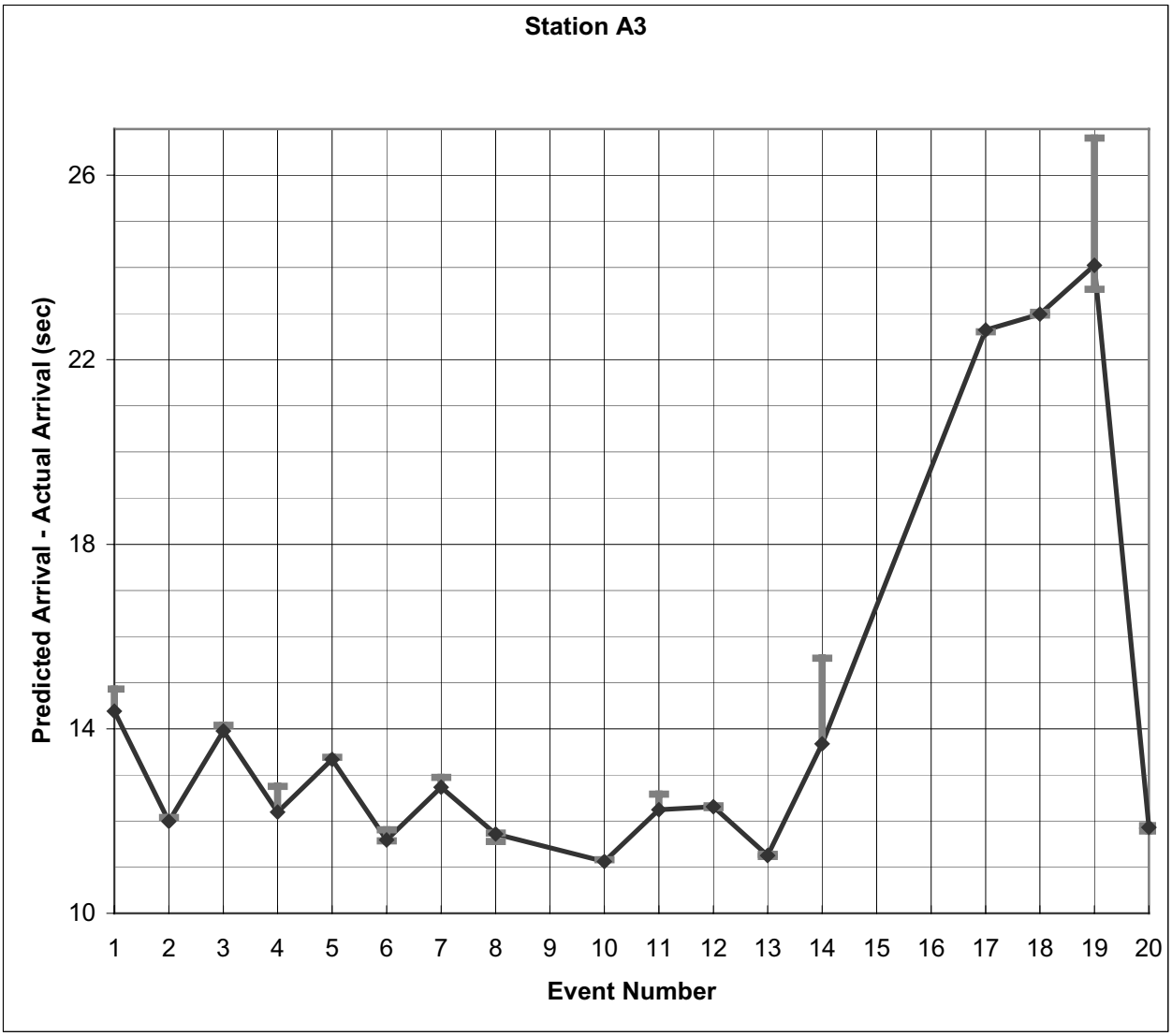


Table B9. Comparison of predicted and actual arrivals across events for Station A8.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
A8	1	17.18	32.42	15.24	0.18	
A8	2	6.17	18.74	12.57	0.04	0.46
A8	3	15.01	49.12	34.11		1.12
A8	4	7.72	21.72	14.00	0.2	0.7
A8	5	10.22	25.24	15.02	0.46	0.48
A8	6	8.06	21.08	13.02	0.36	0.06
A8	7	10.19	24.70	14.51	0.08	0.86
A8	8	6.17	17.92	11.75	0.74	
A8	10	11.27	22.74	11.47		0.6
A8	11	9.42	22.82	13.40	0.04	0.36
A8	12	6.95	20.12	13.17	0.88	
A8	13	6.51	20.66	14.15		0.78
A8	14	15.50	29.52	14.02	0.04	1.1
A8	15	8.94	35.82	26.88		1.04
A8	16	8.40	33.60	25.20	0.04	0.76
A8	17	15.37	39.36	23.99		0.42
A8	18	5.47	29.42	23.95	0.24	0.42
A8	19	15.51	40.50	24.99		0.84
A8	20	6.55	20.84	14.29	0.24	2.6

Figure B8. Difference between predicted and actual P-wave arrival times at Station A8.

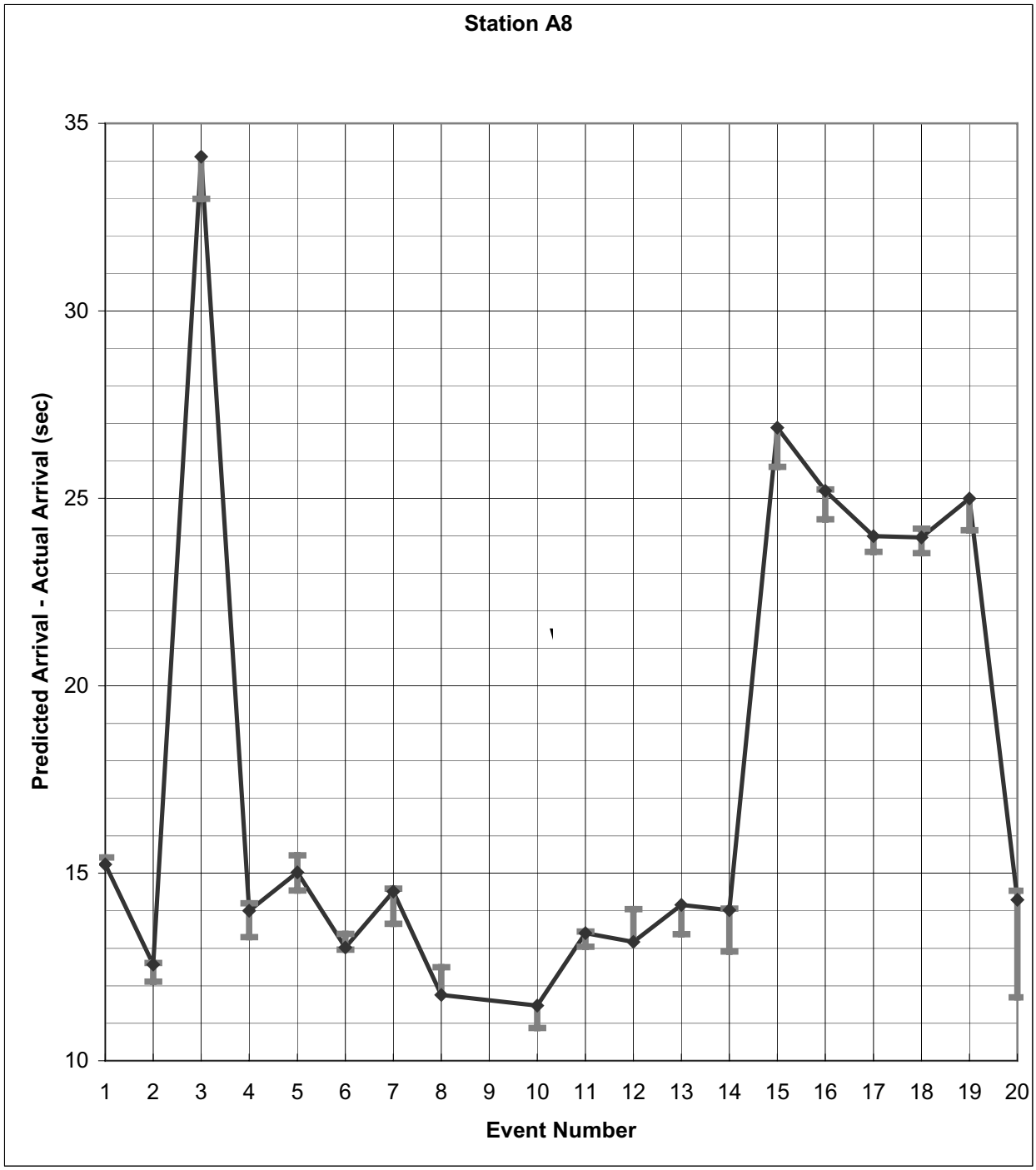


Table B10. Comparison of predicted and actual arrivals across events for Station D4.

Station	Event No.	Predicted Arrival (s)	Actual Arrival (s)	Difference (s)	Picking Error + (s)	Picking Error - (s)
D4	2	9.48	23.98	14.50		0.72
D4	3	17.27	32.38	15.11		0.9
D4	4	10.08	23.74	13.66	0.08	0.76
D4	5	13.17	28.04	14.87		1
D4	6	10.65	23.16	12.51	0.06	0.6
D4	7	12.91	27.58	14.67	0.08	1.2
D4	8	9.48	23.24	13.76	0.04	0.16

Figure B9. Difference between predicted and actual P-wave arrival times at Station D4.

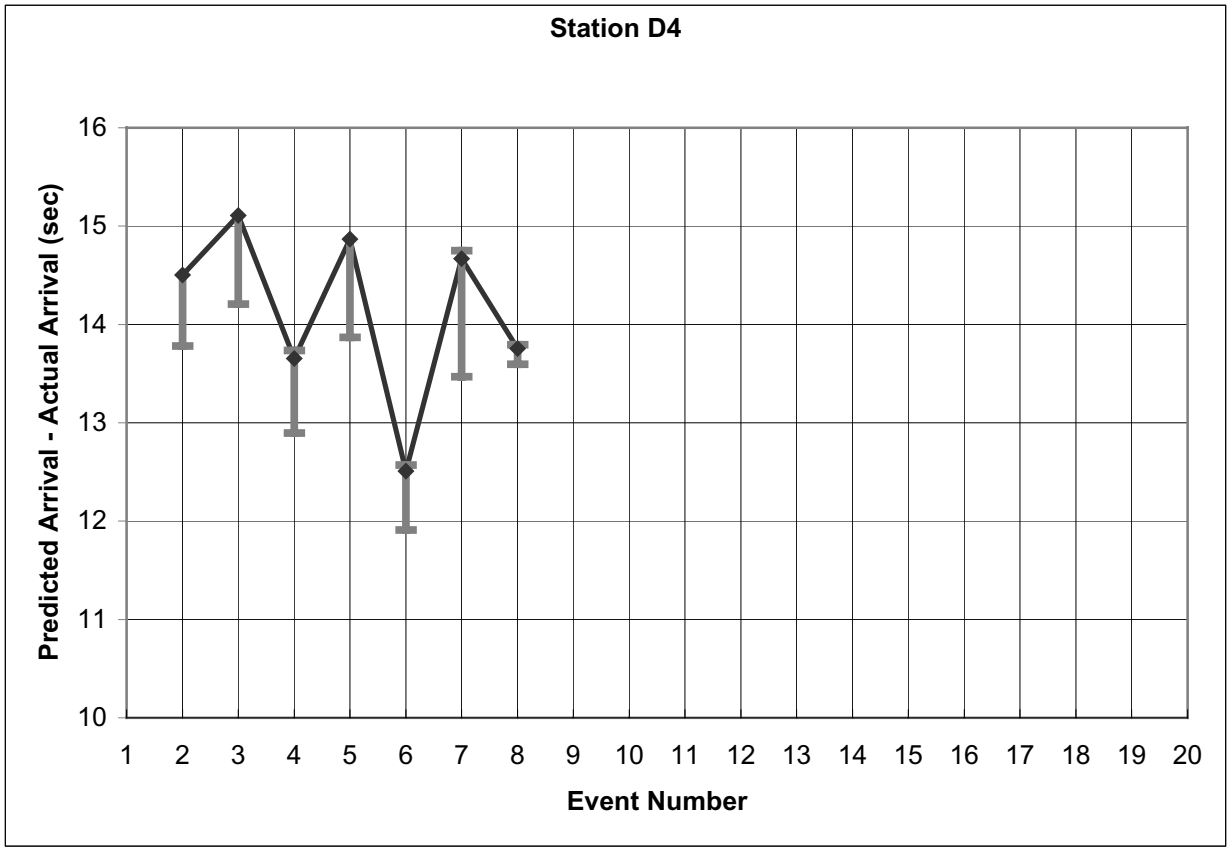


Figure B10. Event 1, from the list of 20 local events, at station C1.

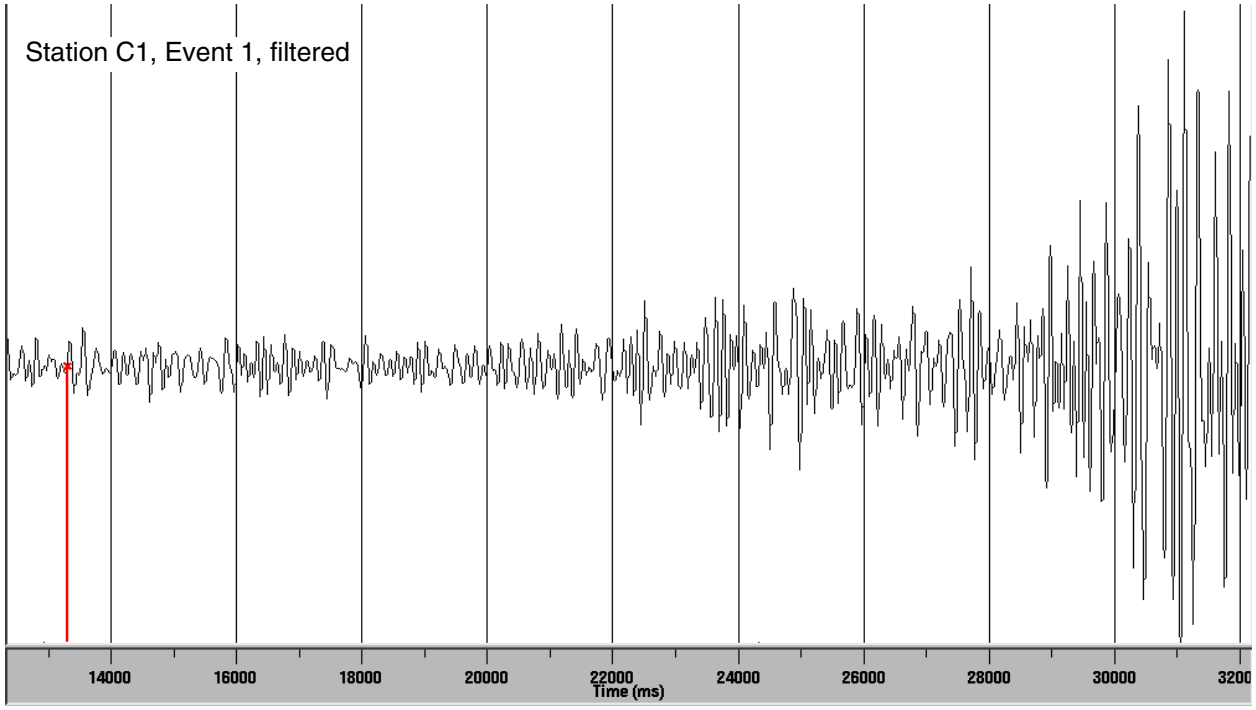


Figure B11. Event 3, from the list of 20 local events, at station C1.

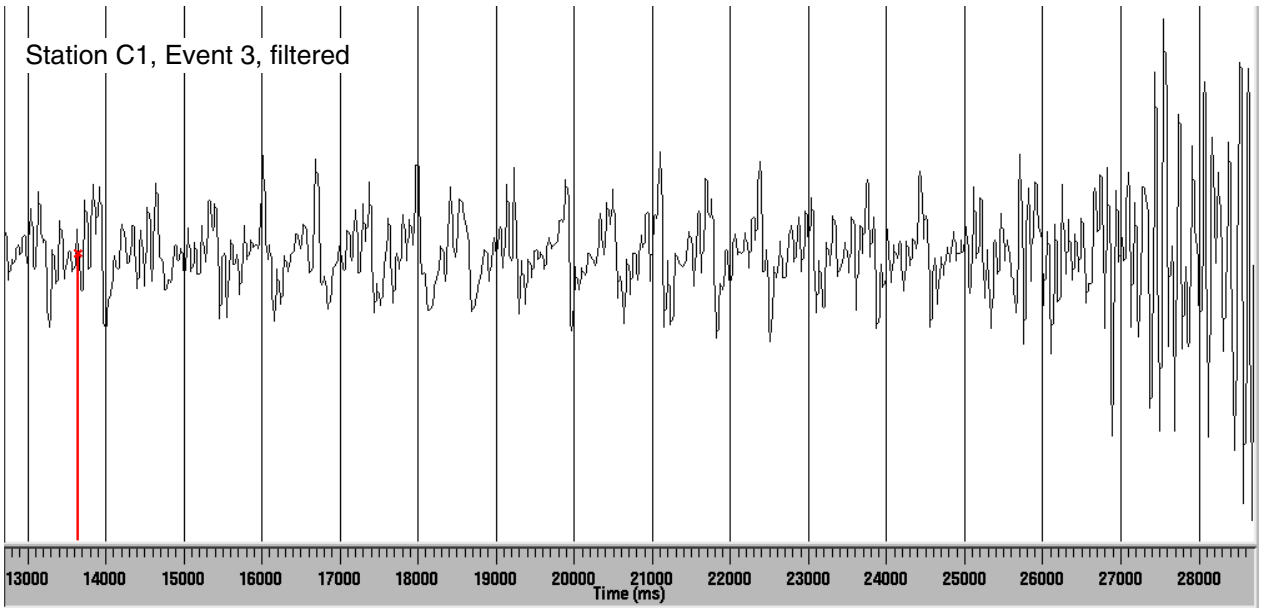


Figure B12. Event 5, from the list of 20 local events, at station C1.

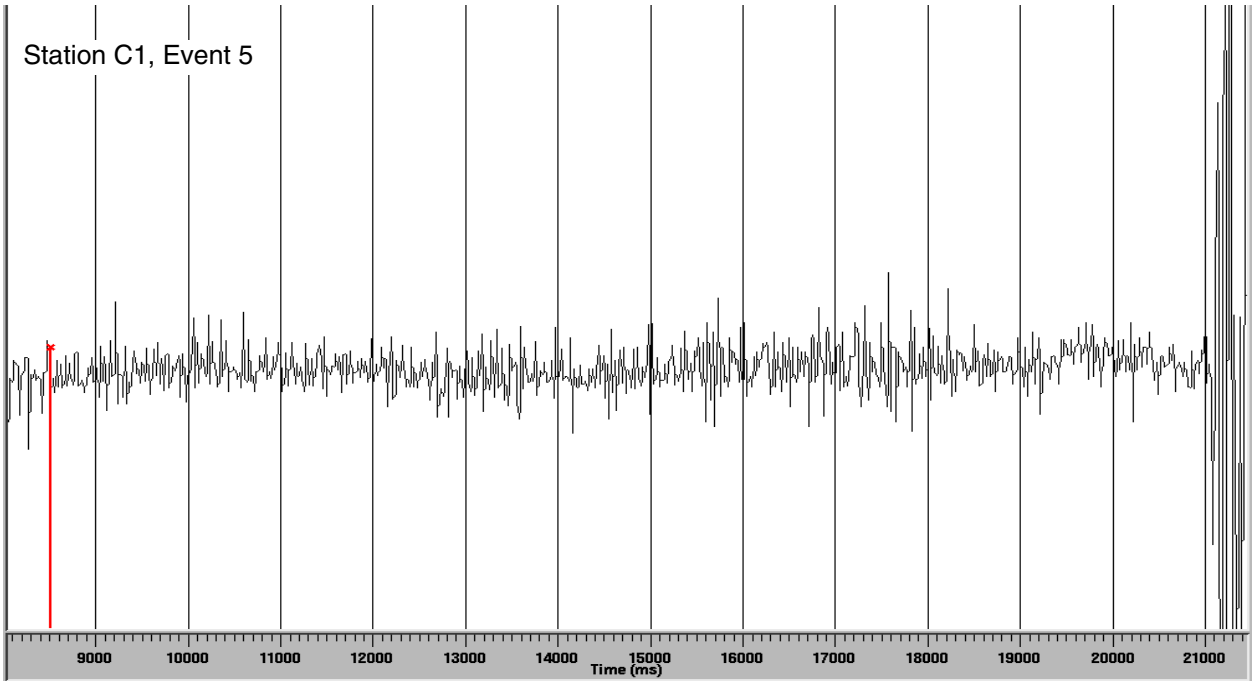


Figure B13. Event 7, from the list of 20 local events, at station C1.

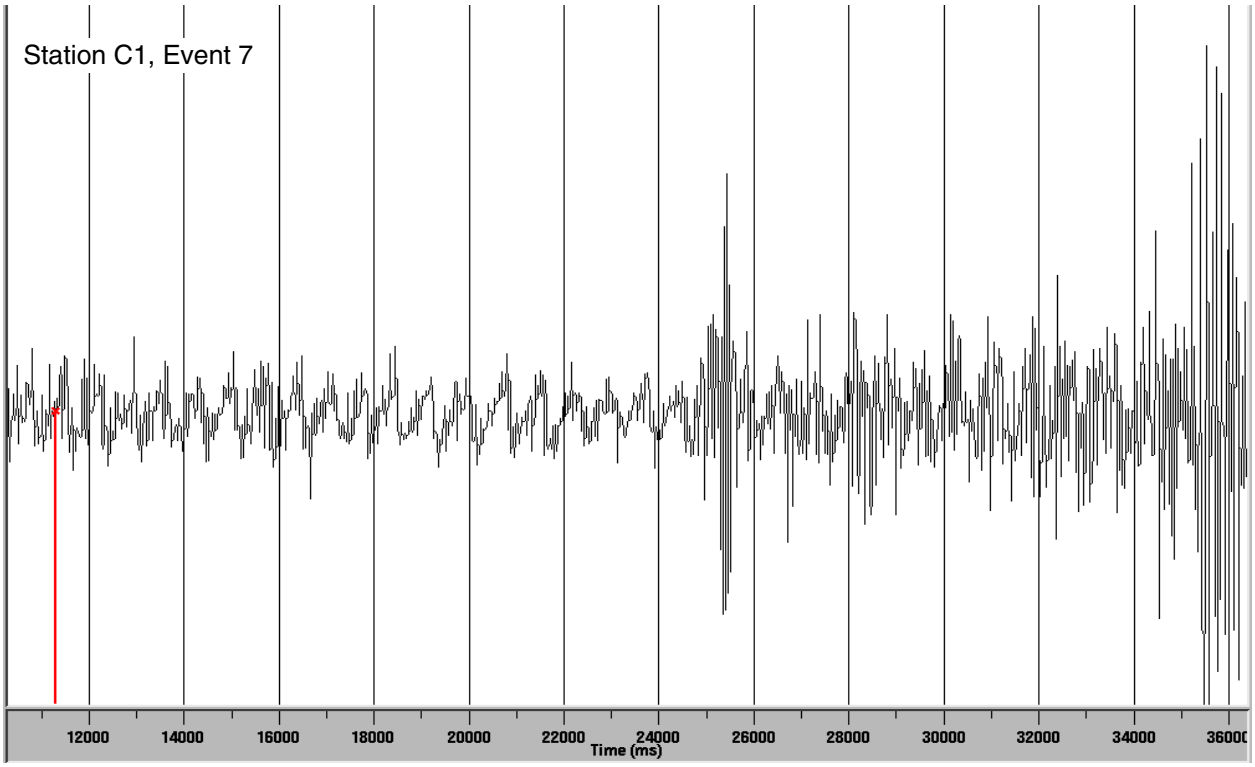


Figure B14. Event 3, from the list of 20 local events, at station C4.

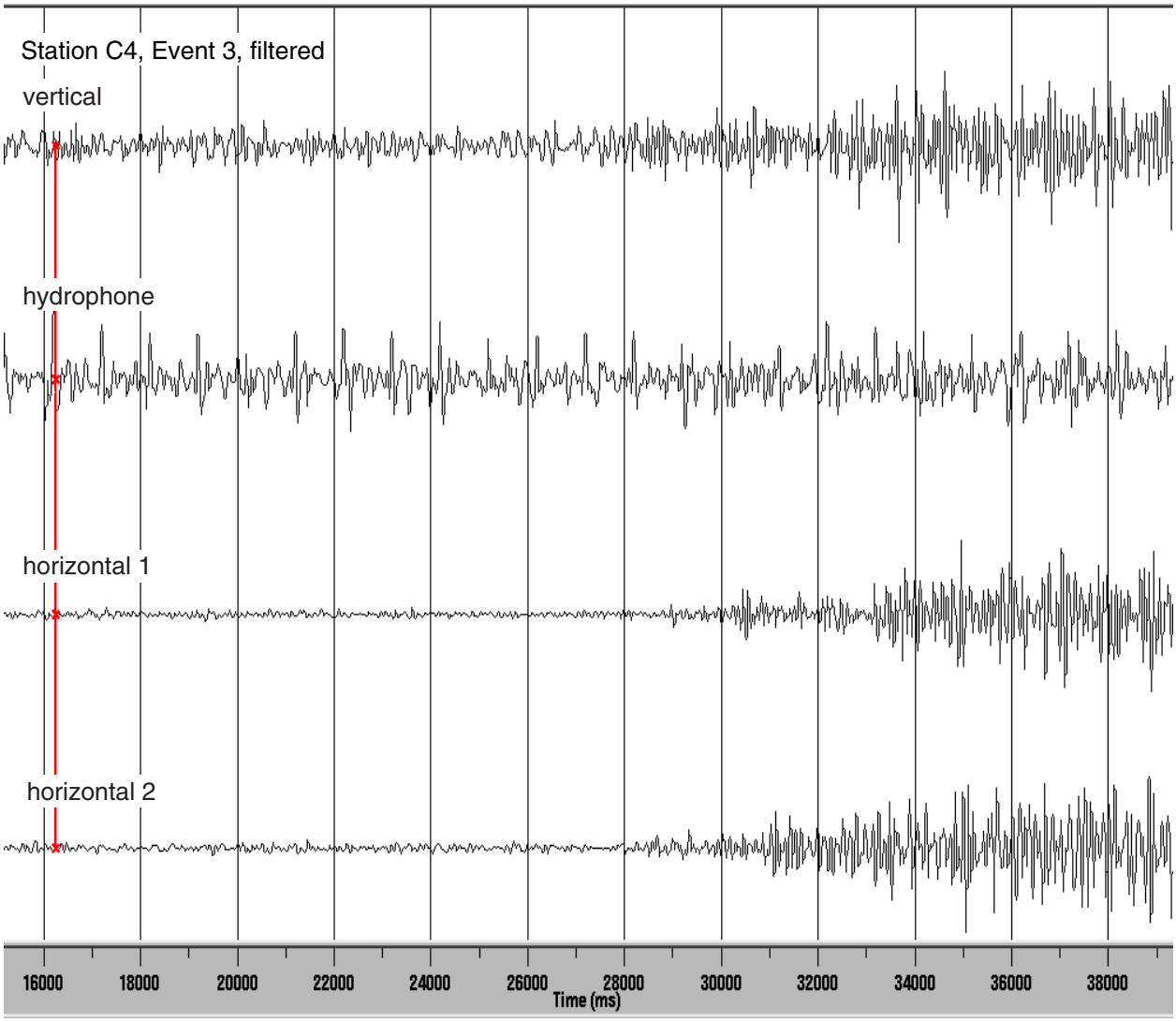


Figure B15. Event 5, from the list of 20 local events, at station C4.

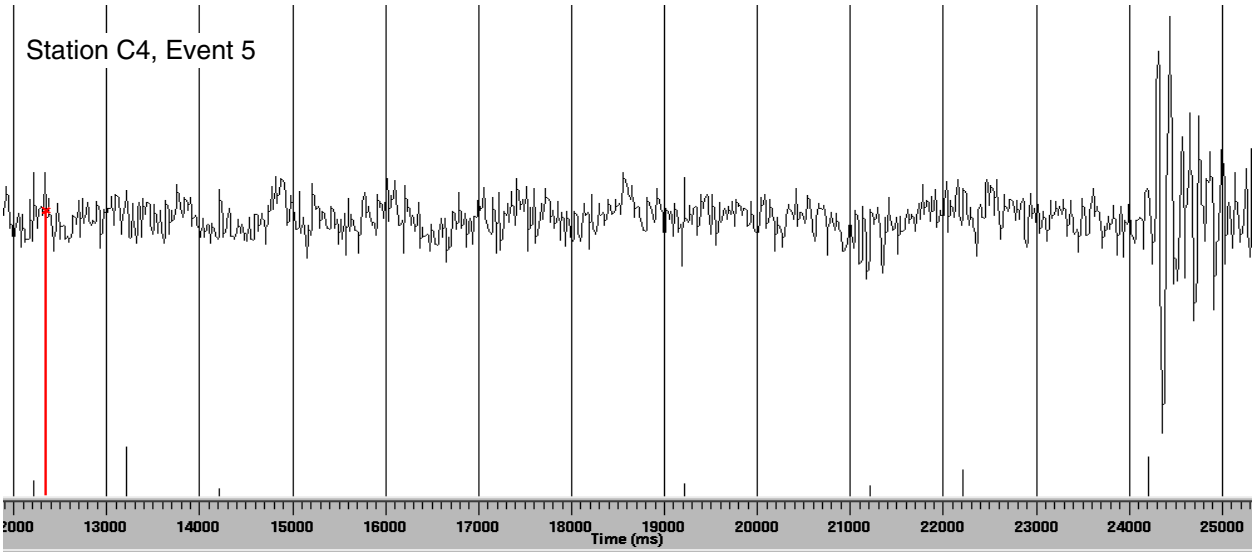


Figure B16. Event 7, from the list of 20 local events, at station C4.

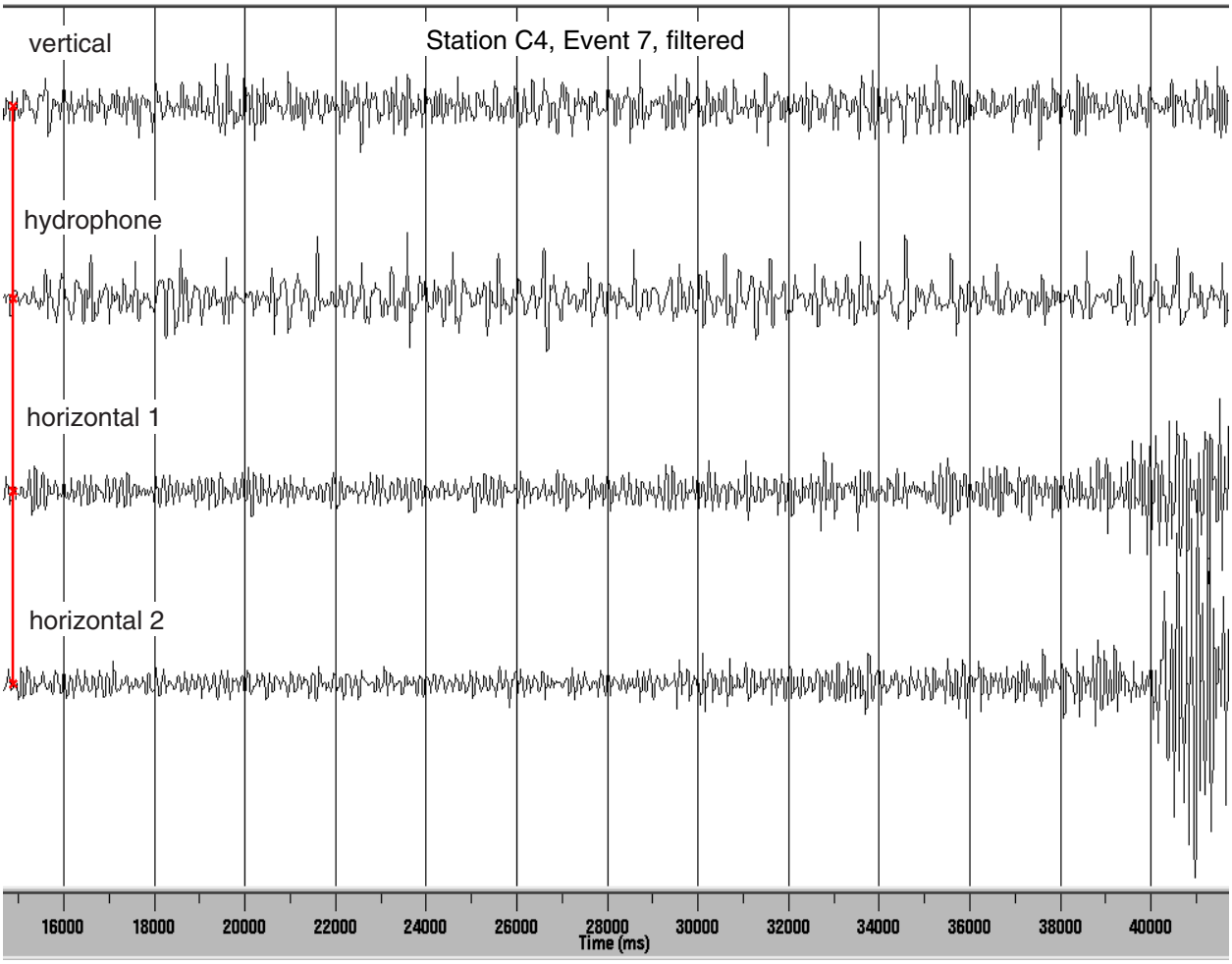


Figure B17. Event 8, from the list of 20 local events, at station C4.

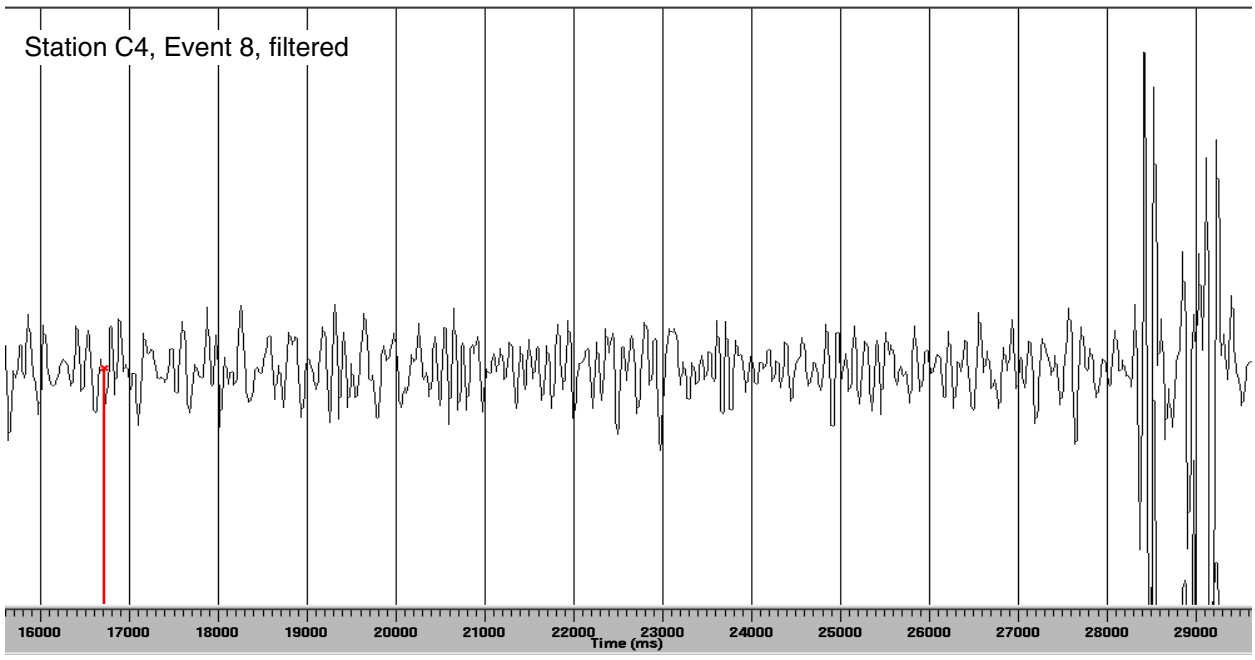


Figure B18. Event 10, from the list of 20 local events, at station C4.

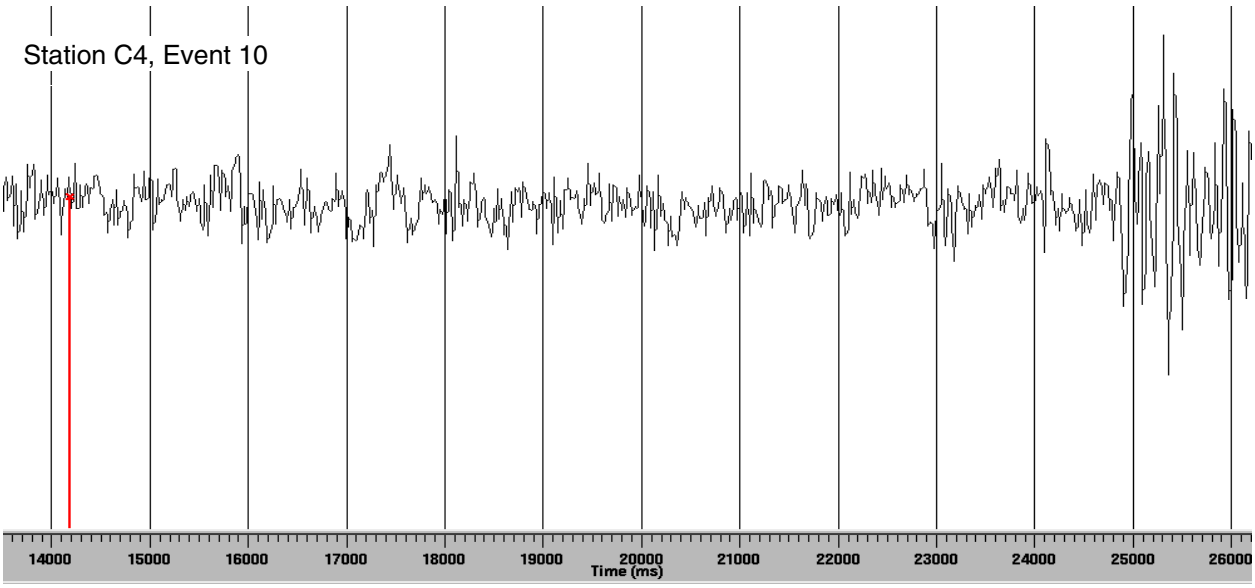


Figure B19. Event 11, from the list of 20 local events, at station C4.

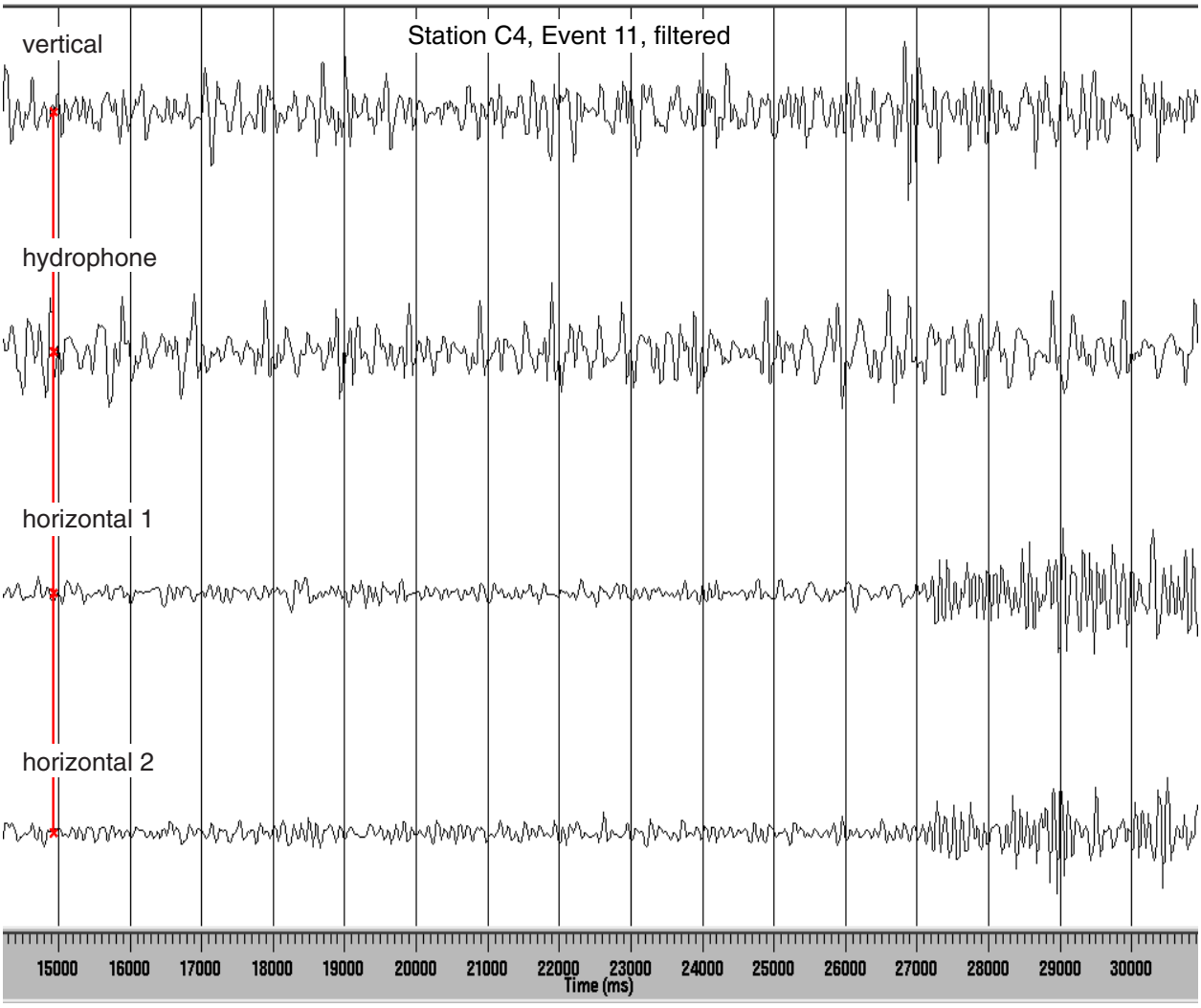


Figure B20. Event 12, from the list of 20 local events, at station C4.

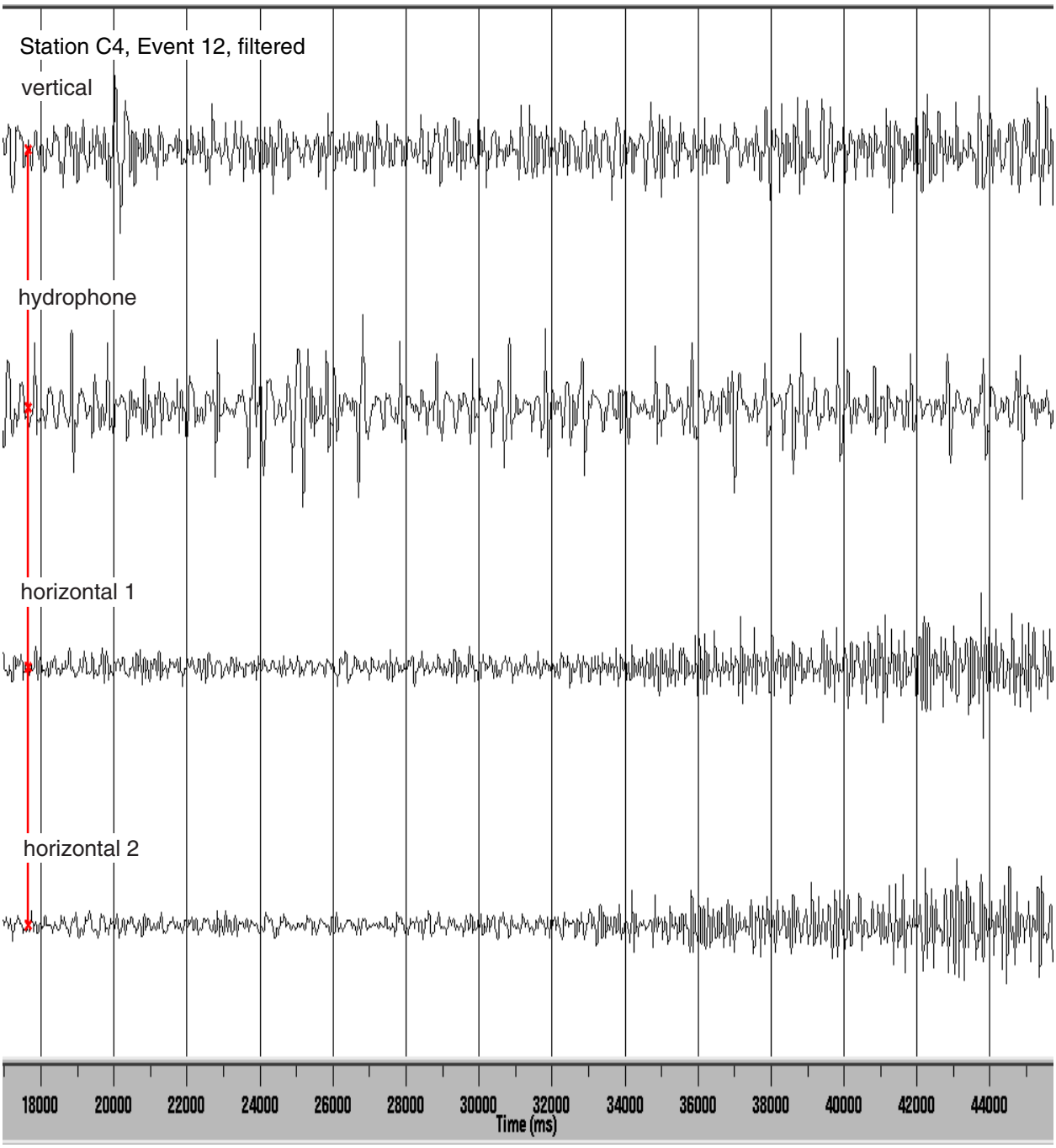


Figure B21. Event 15, from the list of 20 local events, at station C4.

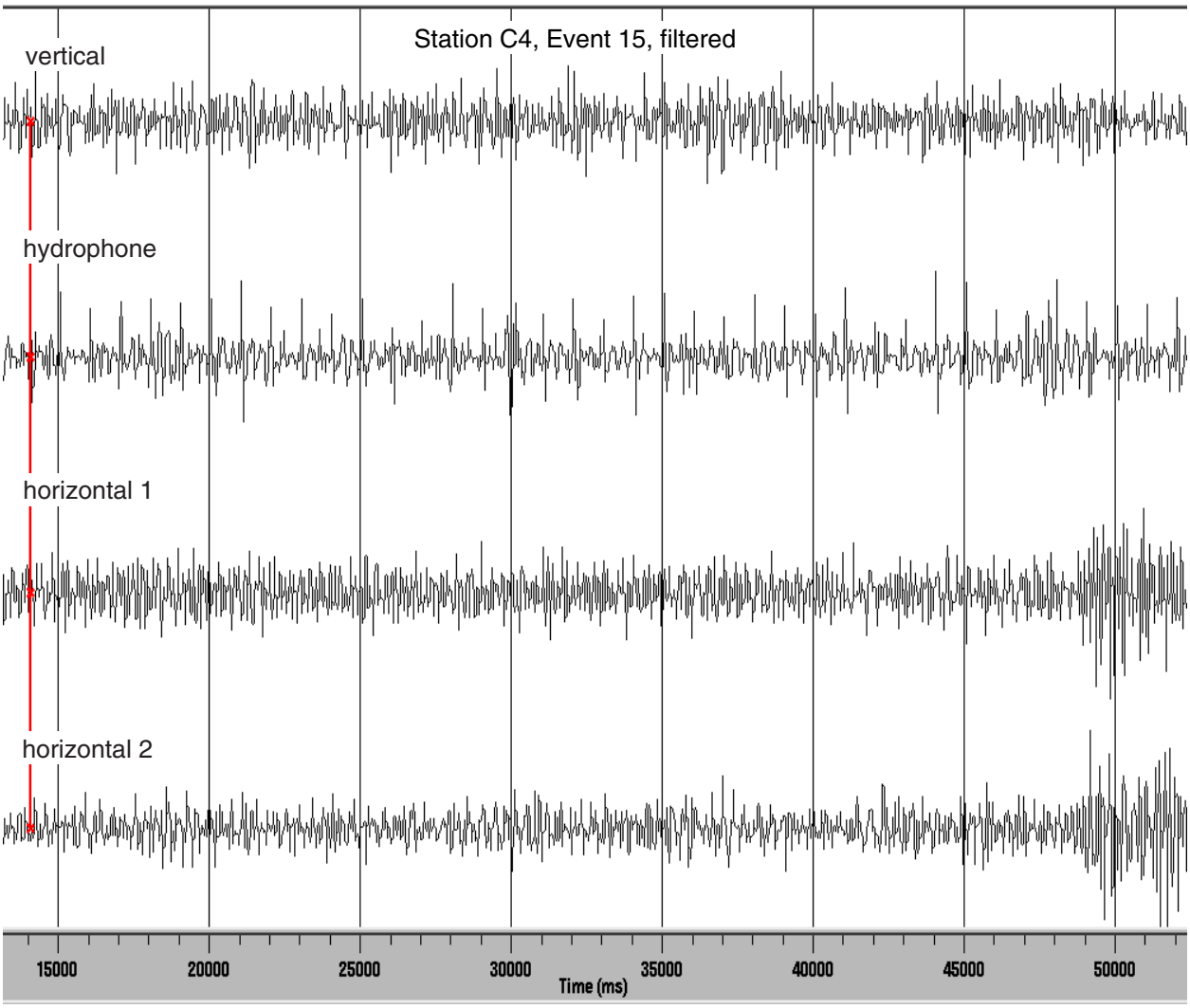


Figure B22. Event 17, from the list of 20 local events, at station C4.

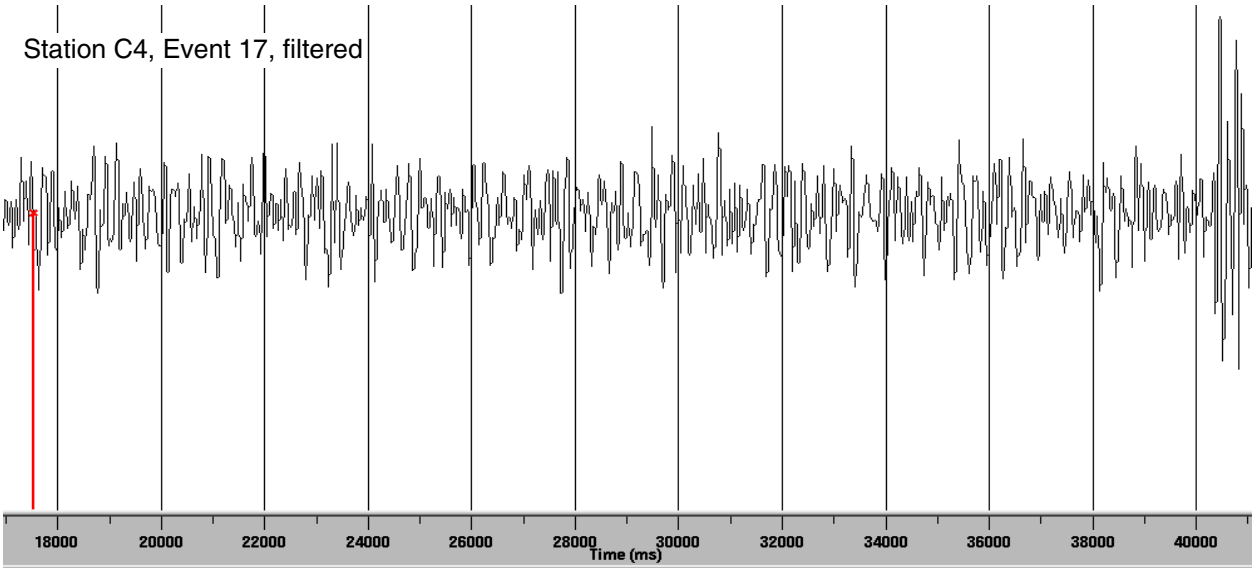


Figure B23. Event 2, from the list of 20 local events, at station D1.

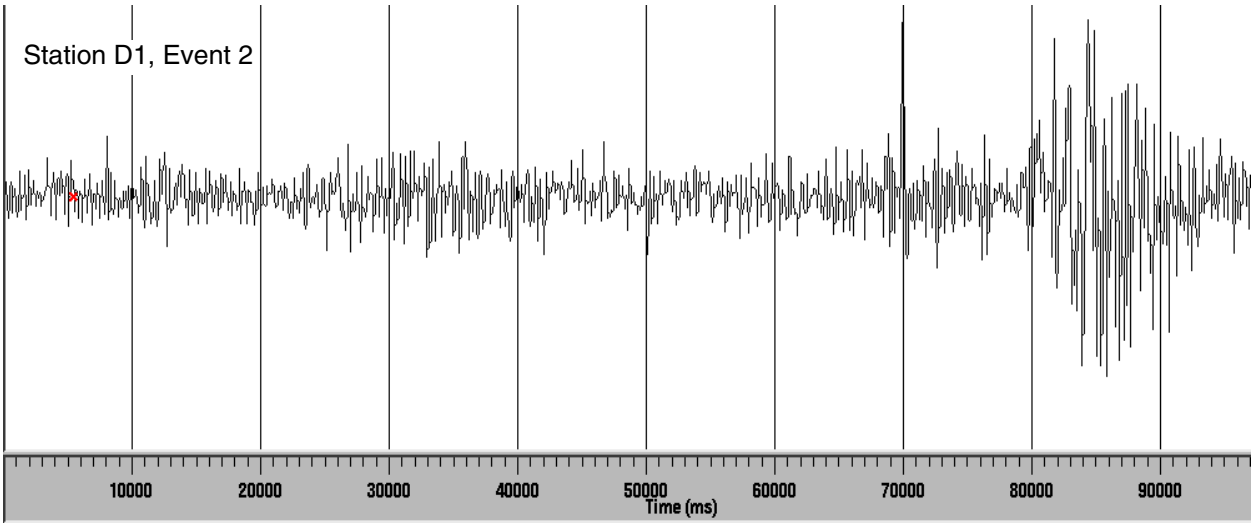


Figure B24. Event 3, from the list of 20 local events, at station D1.

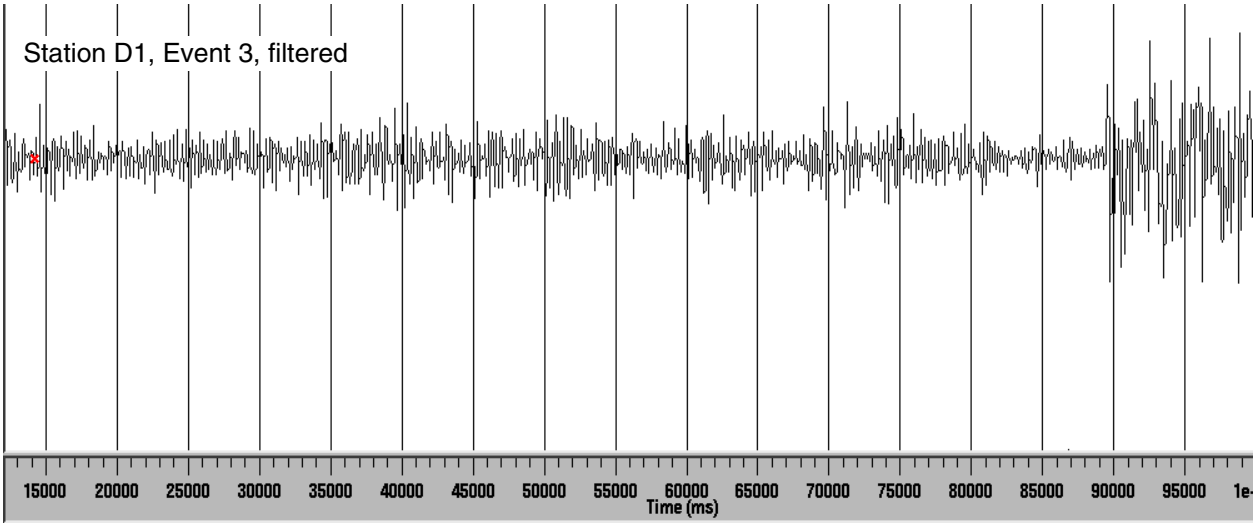


Figure B25. Event 4, from the list of 20 local events, at station D1.

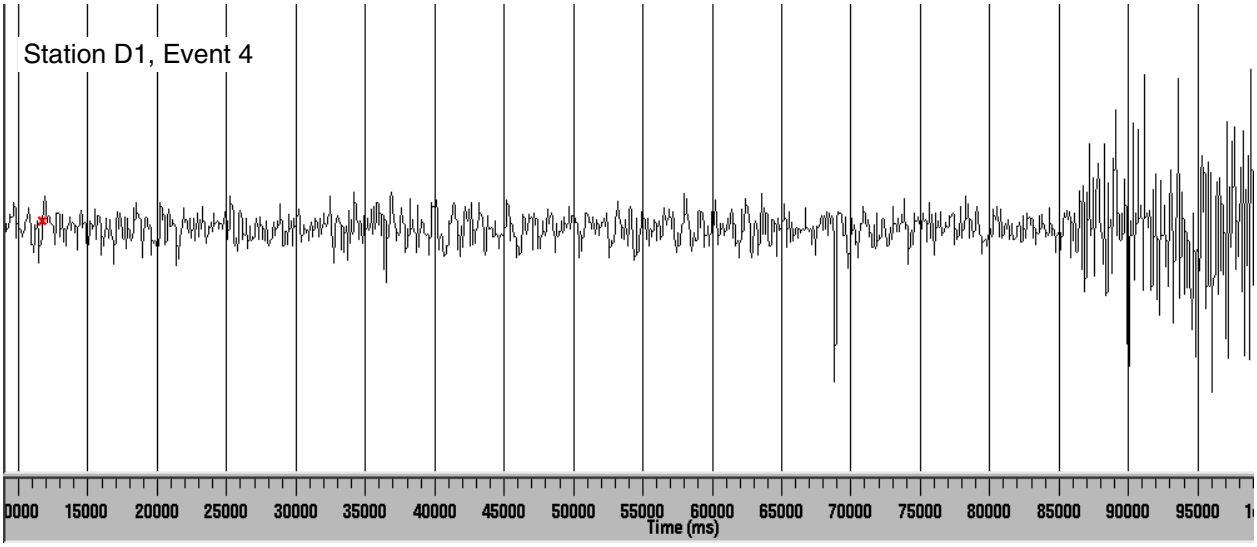


Figure B26. Event 5, from the list of 20 local events, at station D1.

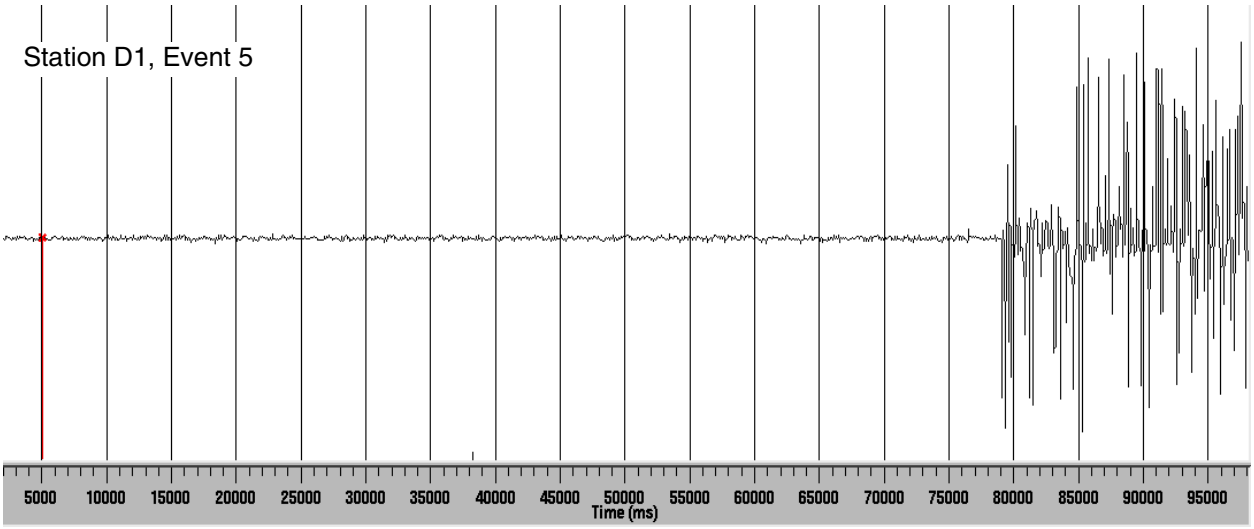


Figure B27. Event 6, from the list of 20 local events, at station D1.

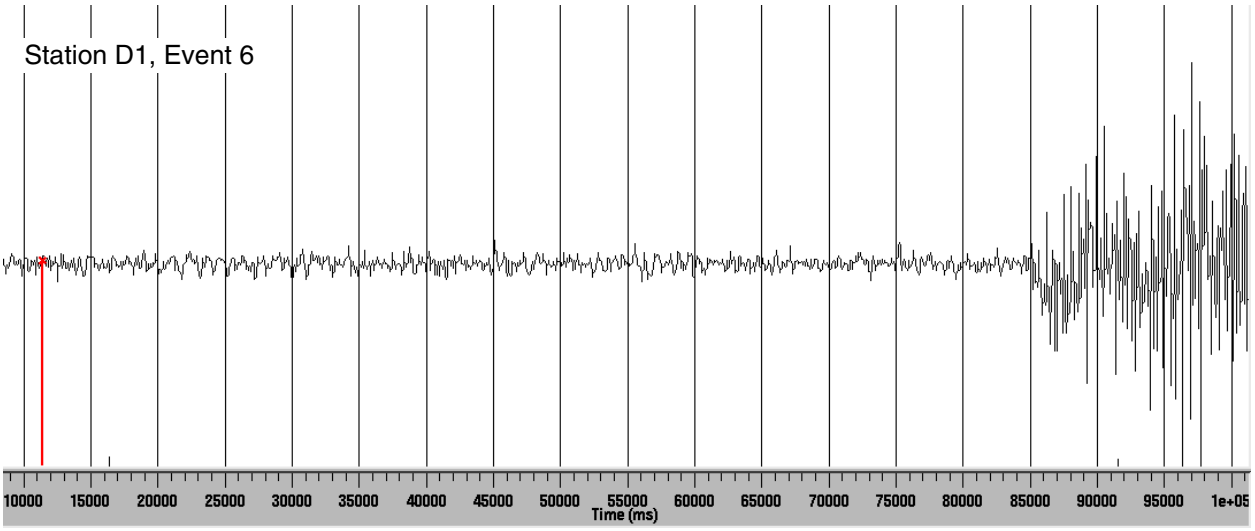


Figure B28. Event 7, from the list of 20 local events, at station D1.

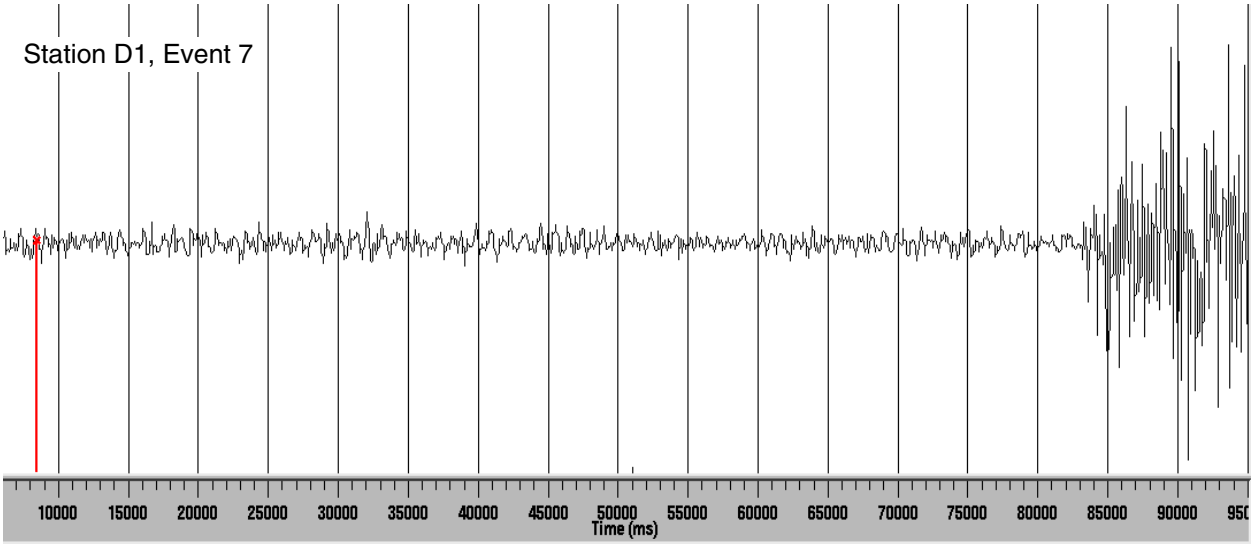


Figure B29. Event 9, from the list of 20 local events, at station D1.

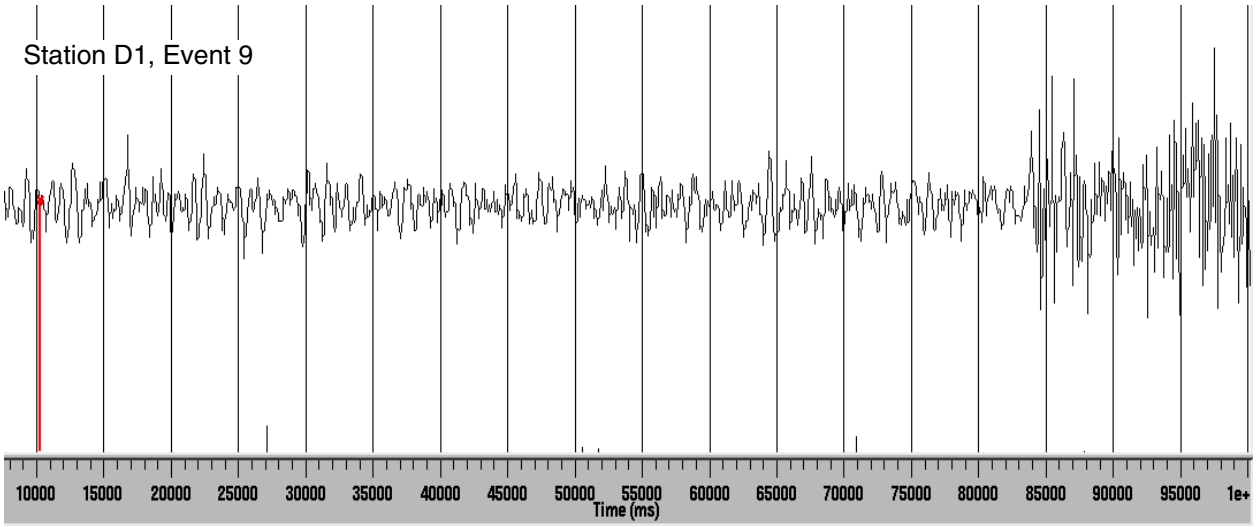


Figure B30. Event 10, from the list of 20 local events, at station D1.

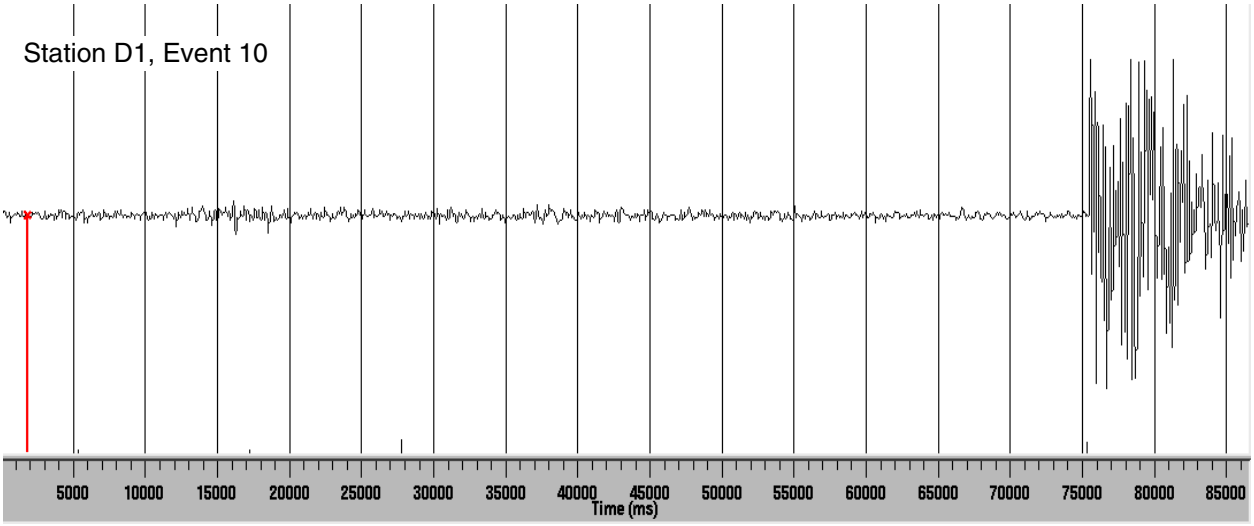


Figure B31. Event 11, from the list of 20 local events, at station D1.

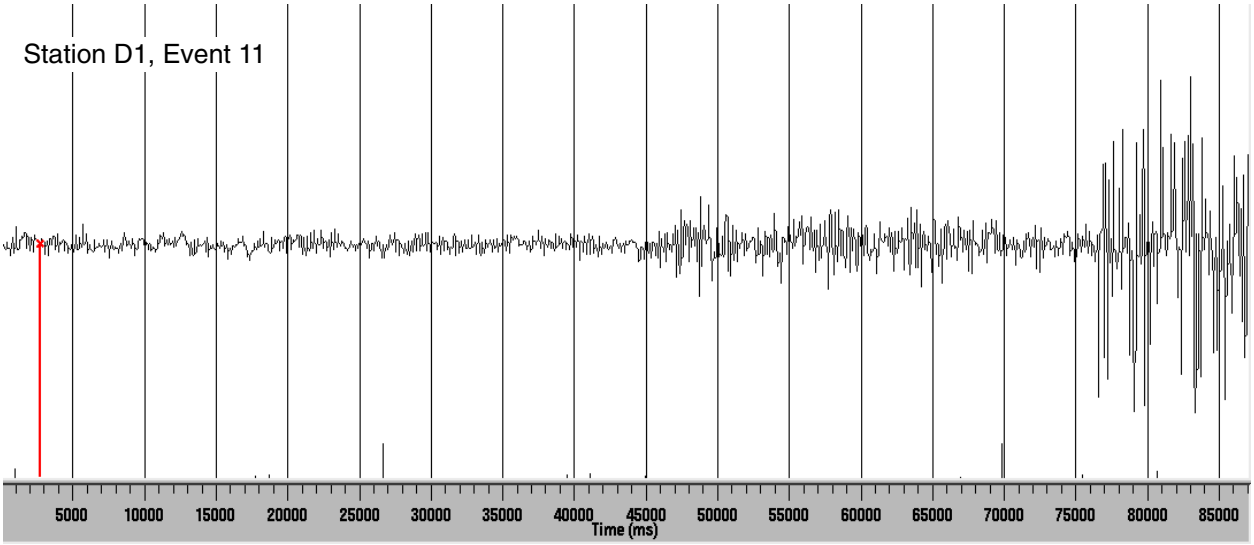


Figure B32. Event 13, from the list of 20 local events, at station D1.

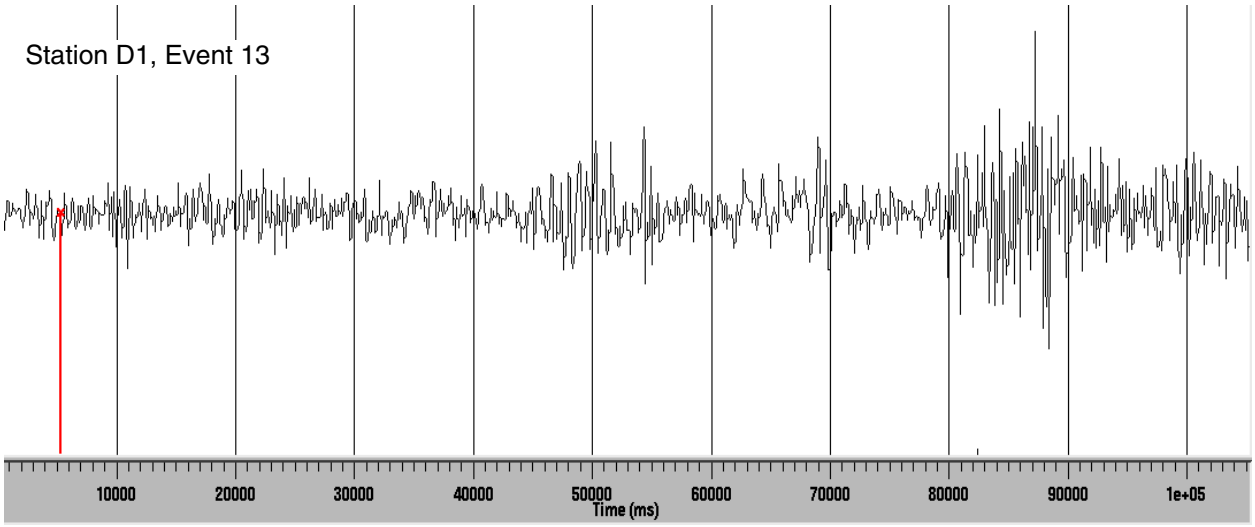


Figure B33. Event 14, from the list of 20 local events, at station D1.

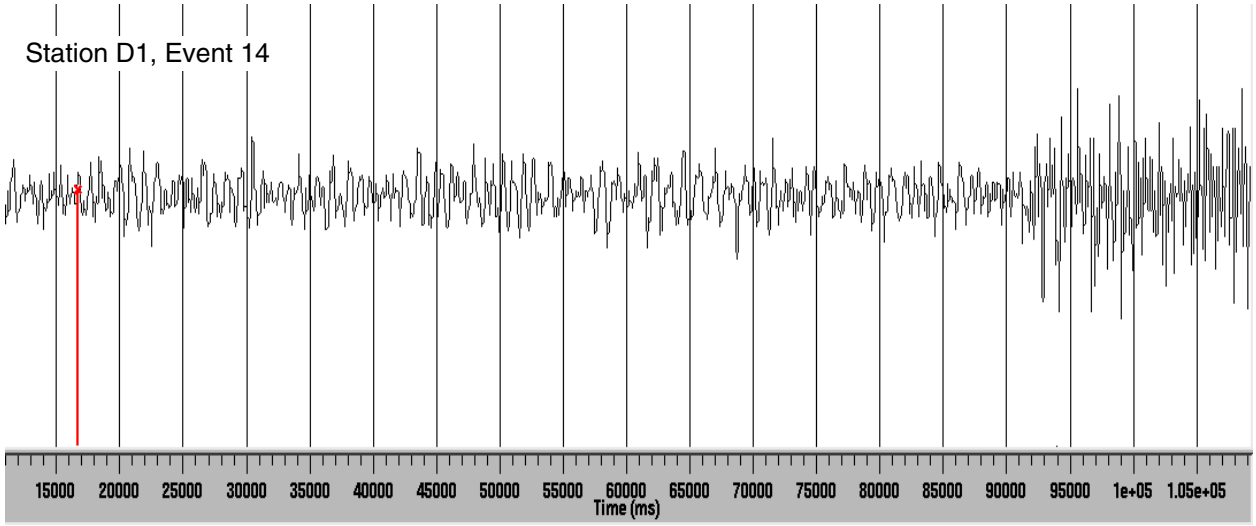


Figure B34. Event 16, from the list of 20 local events, at station D1.

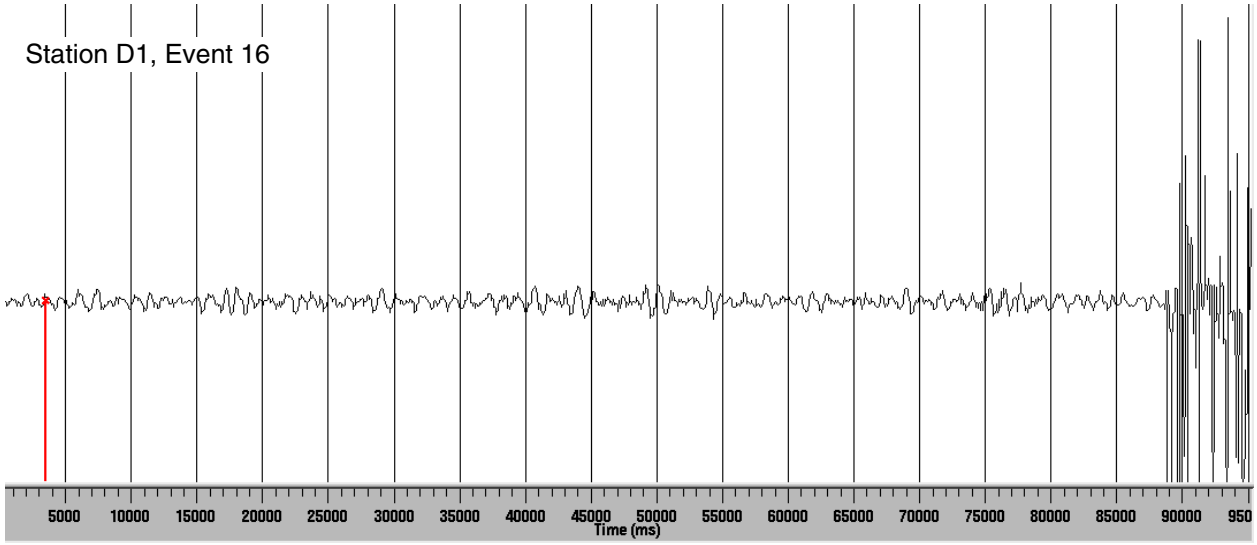


Figure B35. Event 17, from the list of 20 local events, at station D1.

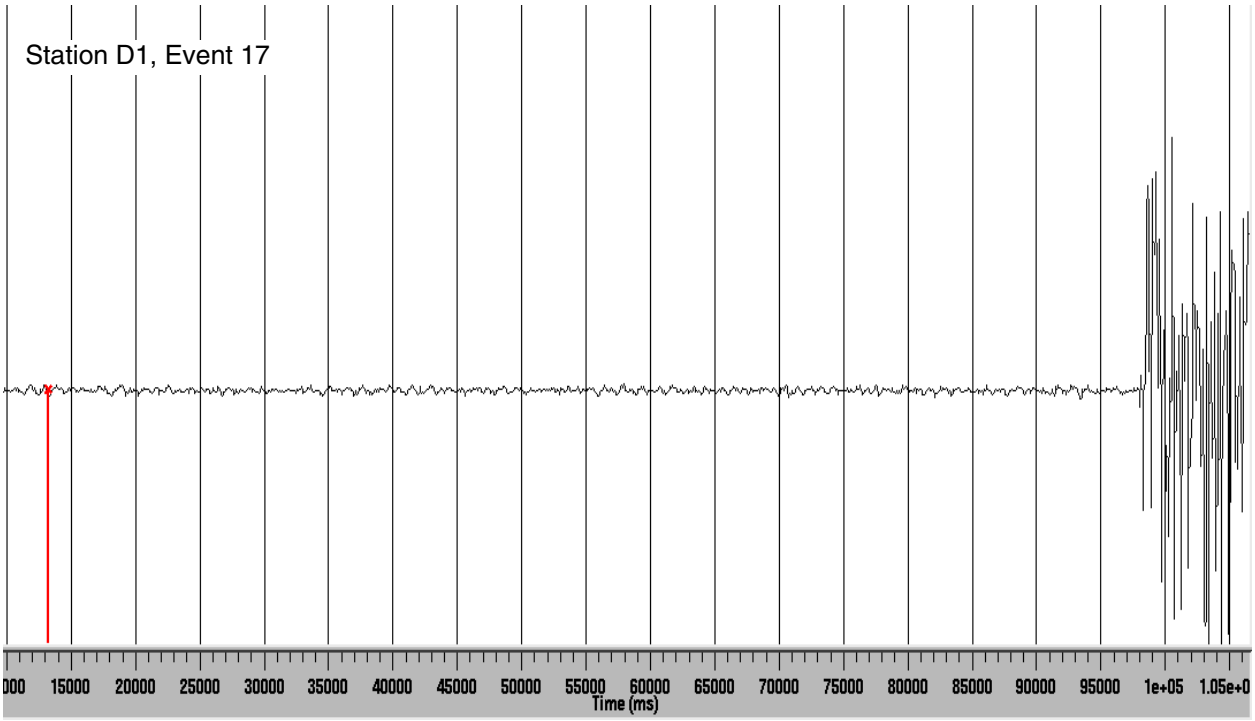


Figure B36. Event 3, from the list of 20 local events, at station D3.

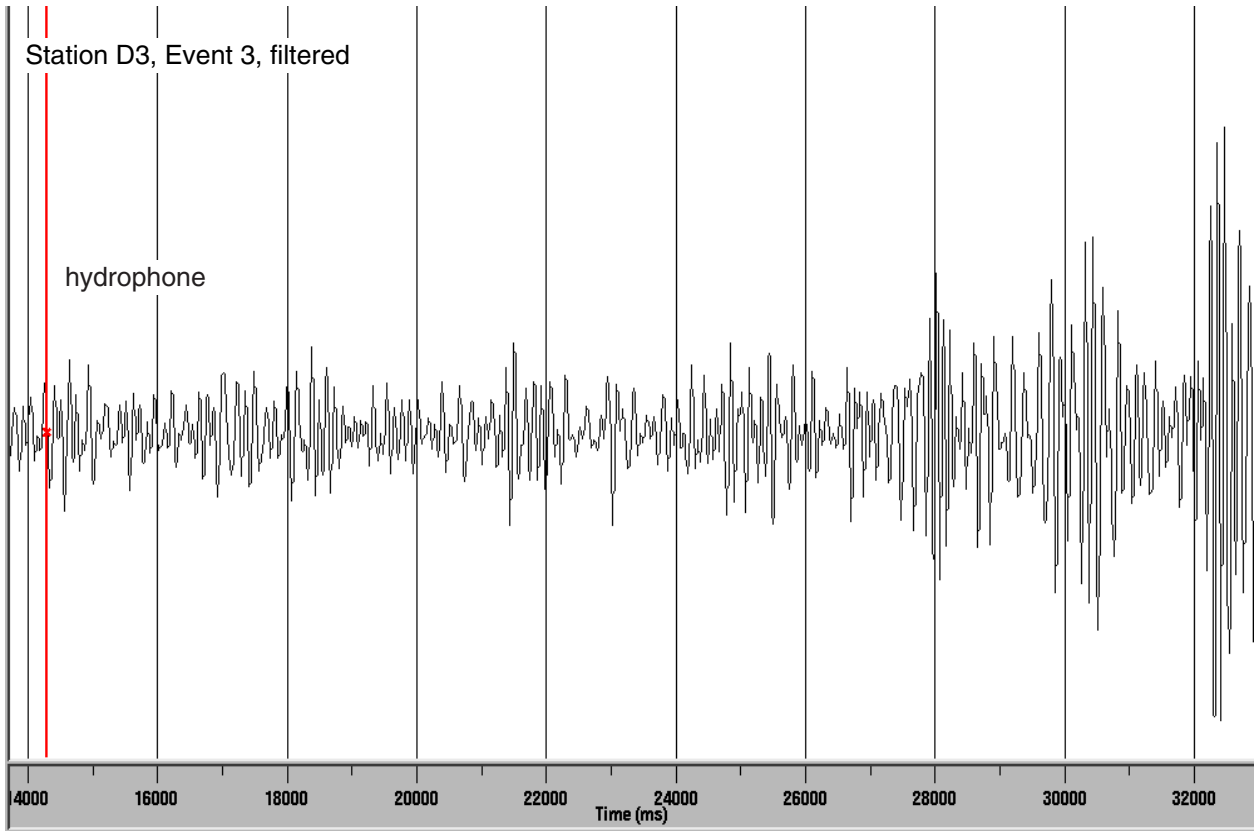


Figure B37. Event 10, from the list of 20 local events, at station D3.

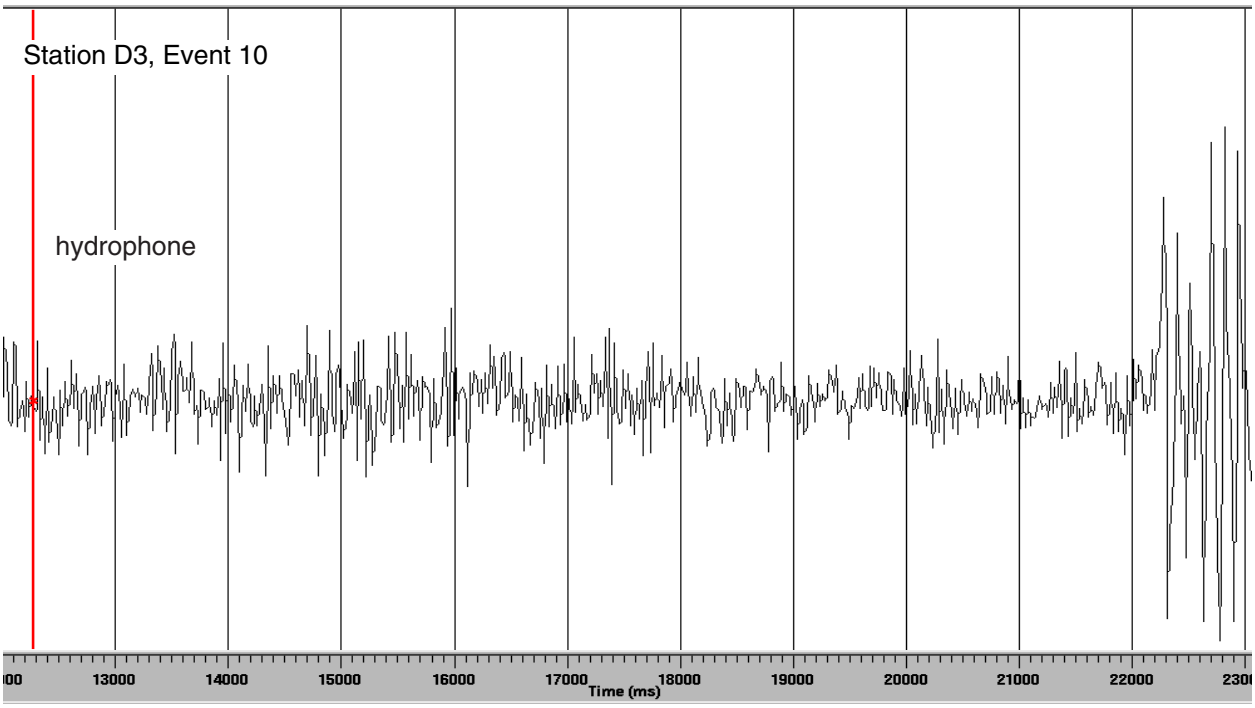


Figure B38. Event 17, from the list of 20 local events, at station D3.

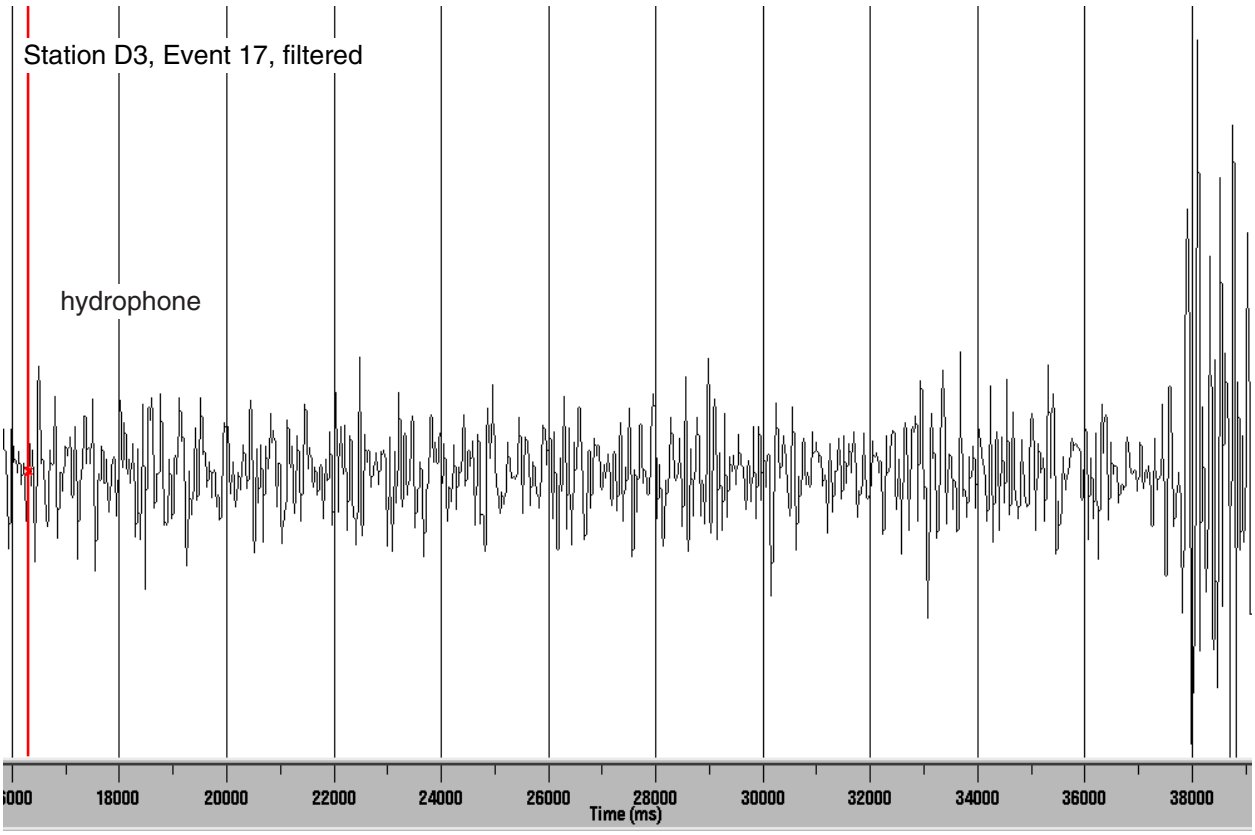


Figure B39. Event 1, from the list of 20 local events, at station D8.

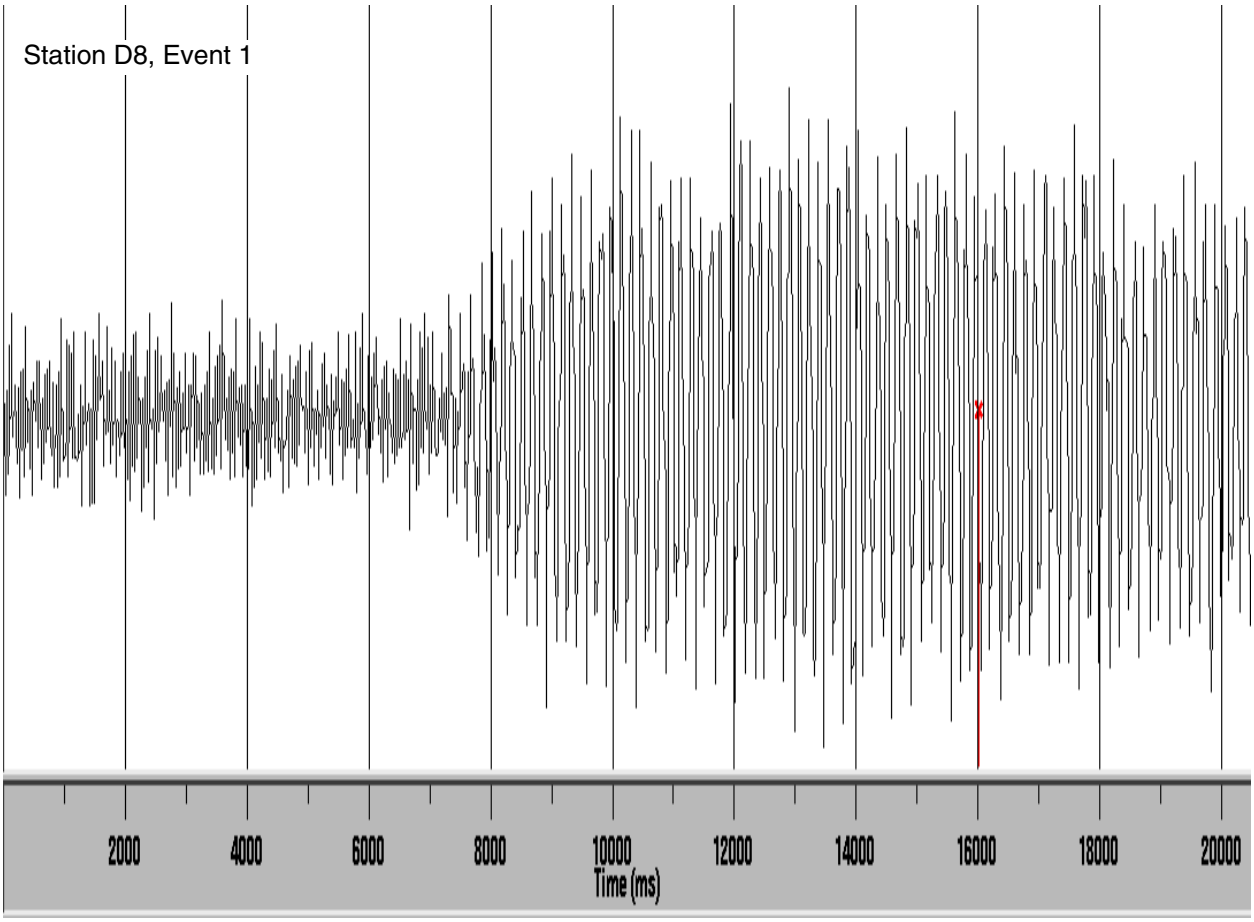


Figure B40. Event 2, from the list of 20 local events, at station D8.

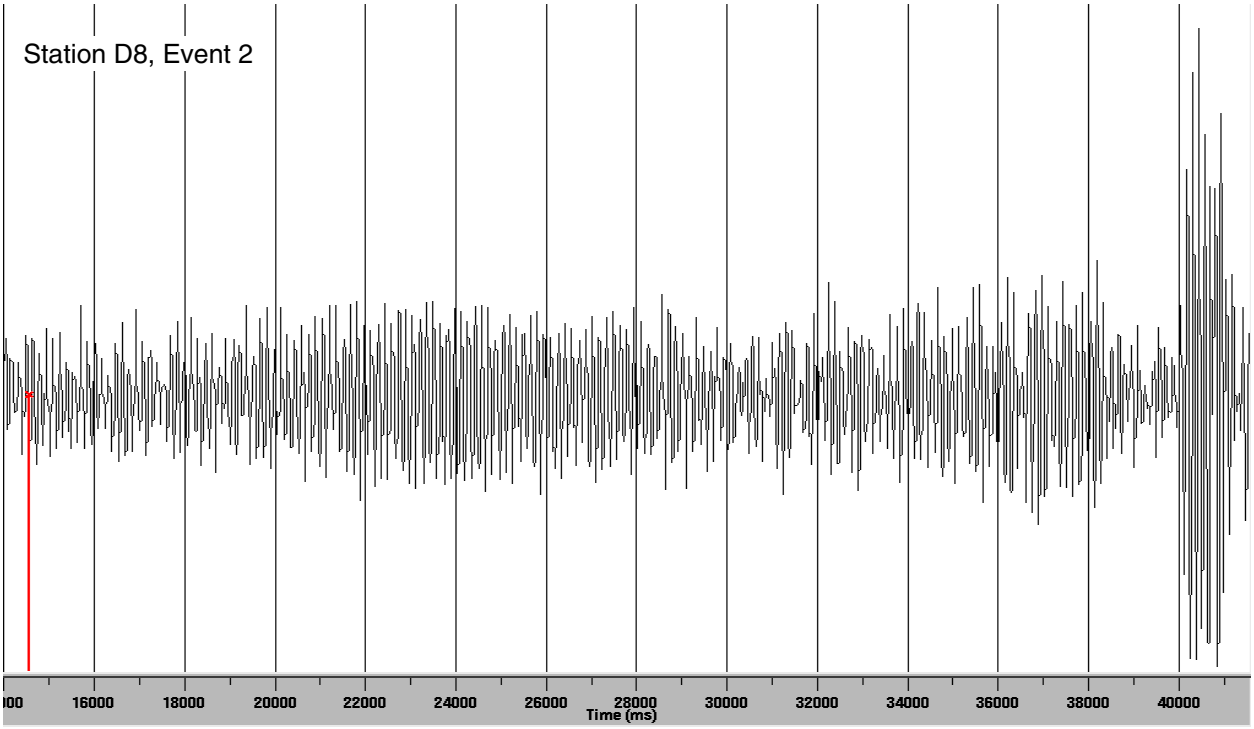


Figure B41. Event 3, from the list of 20 local events, at station D8.

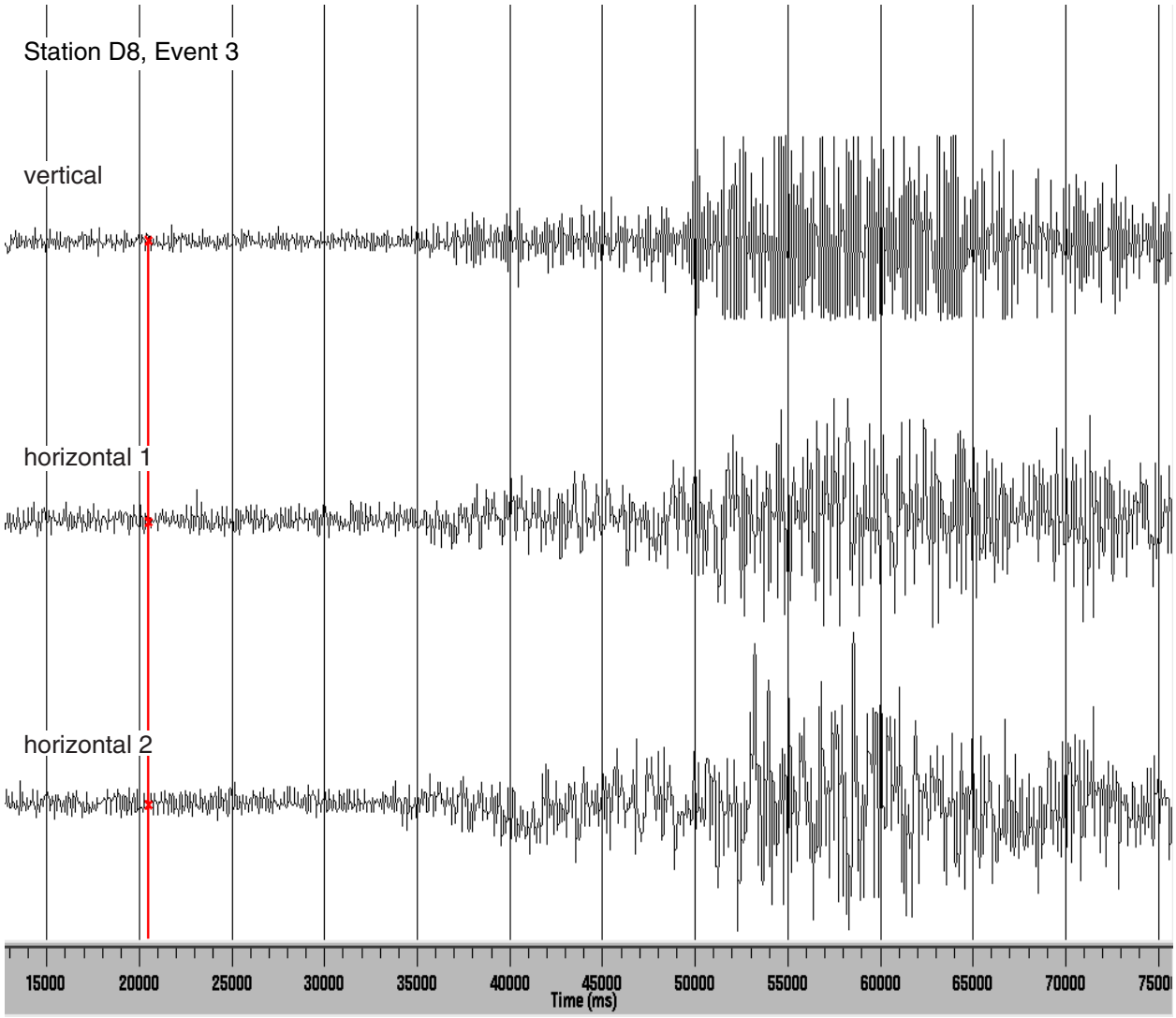


Figure B42. Event 5, from the list of 20 local events, at station D8.

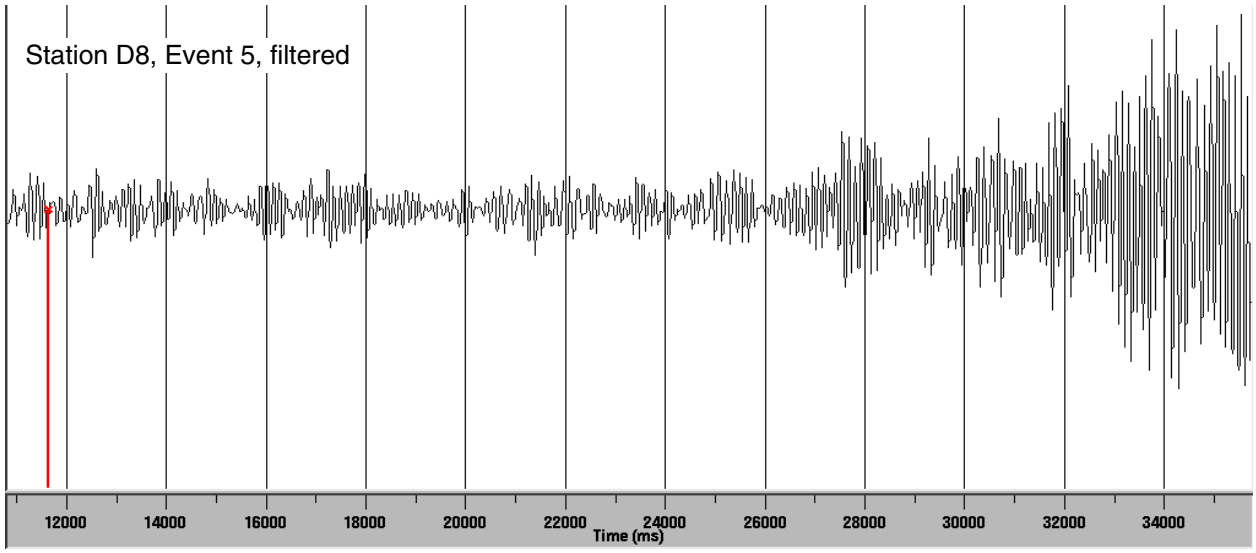


Figure B43. Event 6, from the list of 20 local events, at station D8.

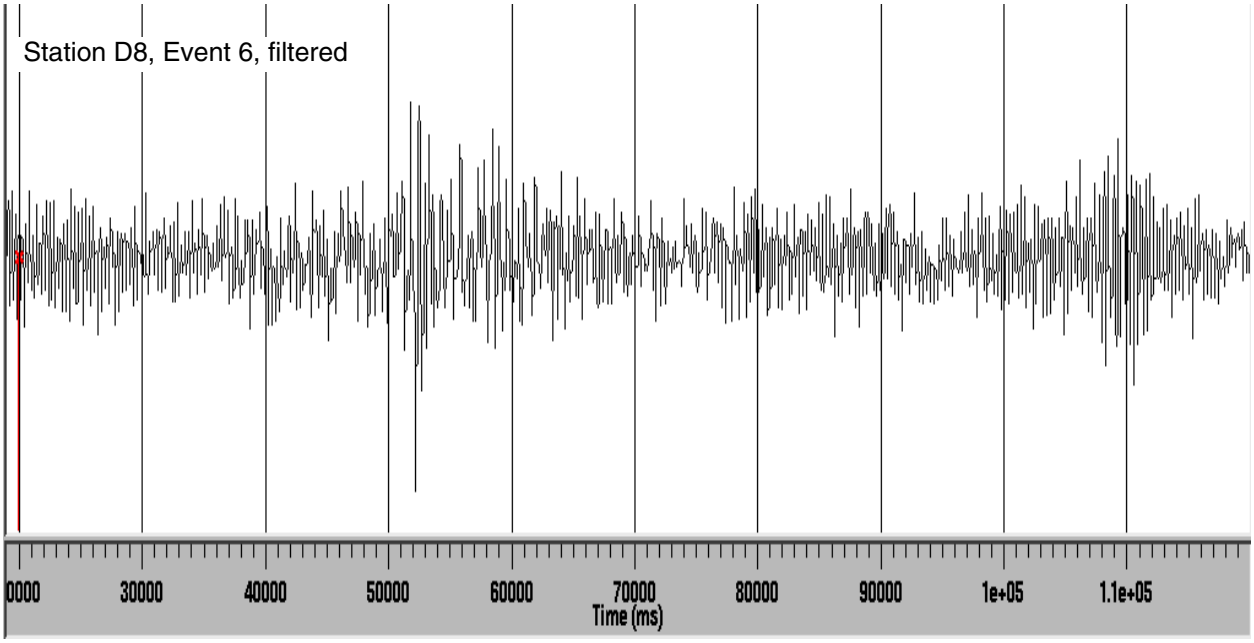


Figure B44. Event 8, from the list of 20 local events, at station D8.

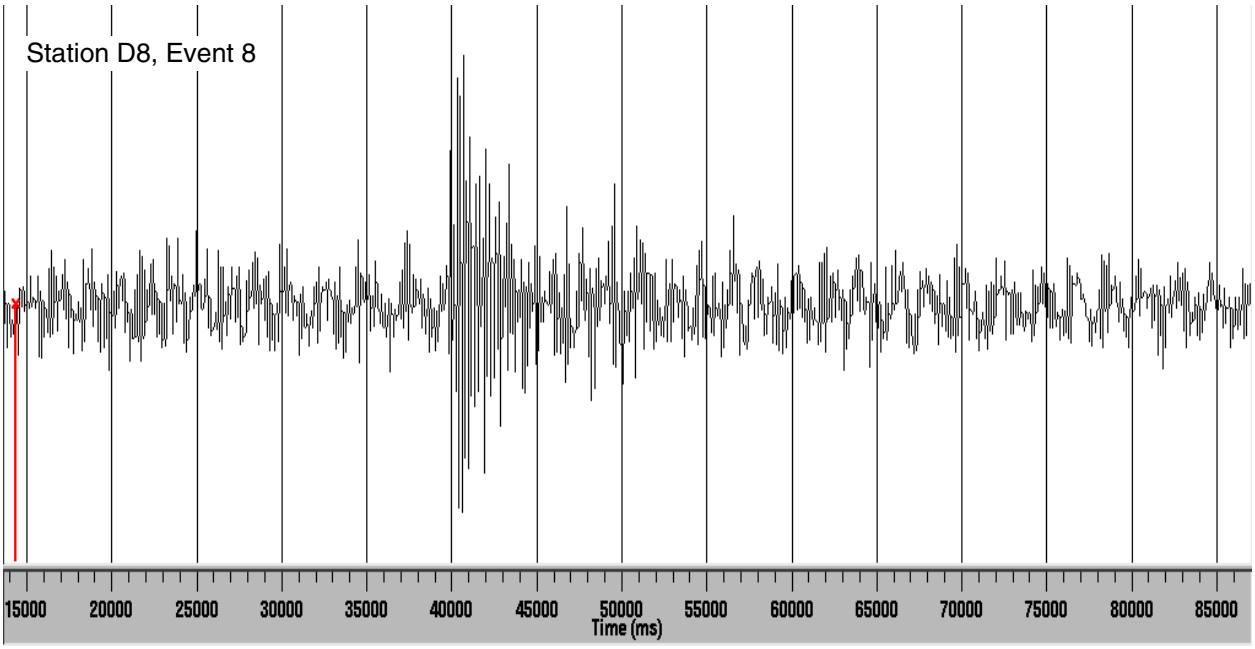


Figure B45. Event 10, from the list of 20 local events, at station D8.

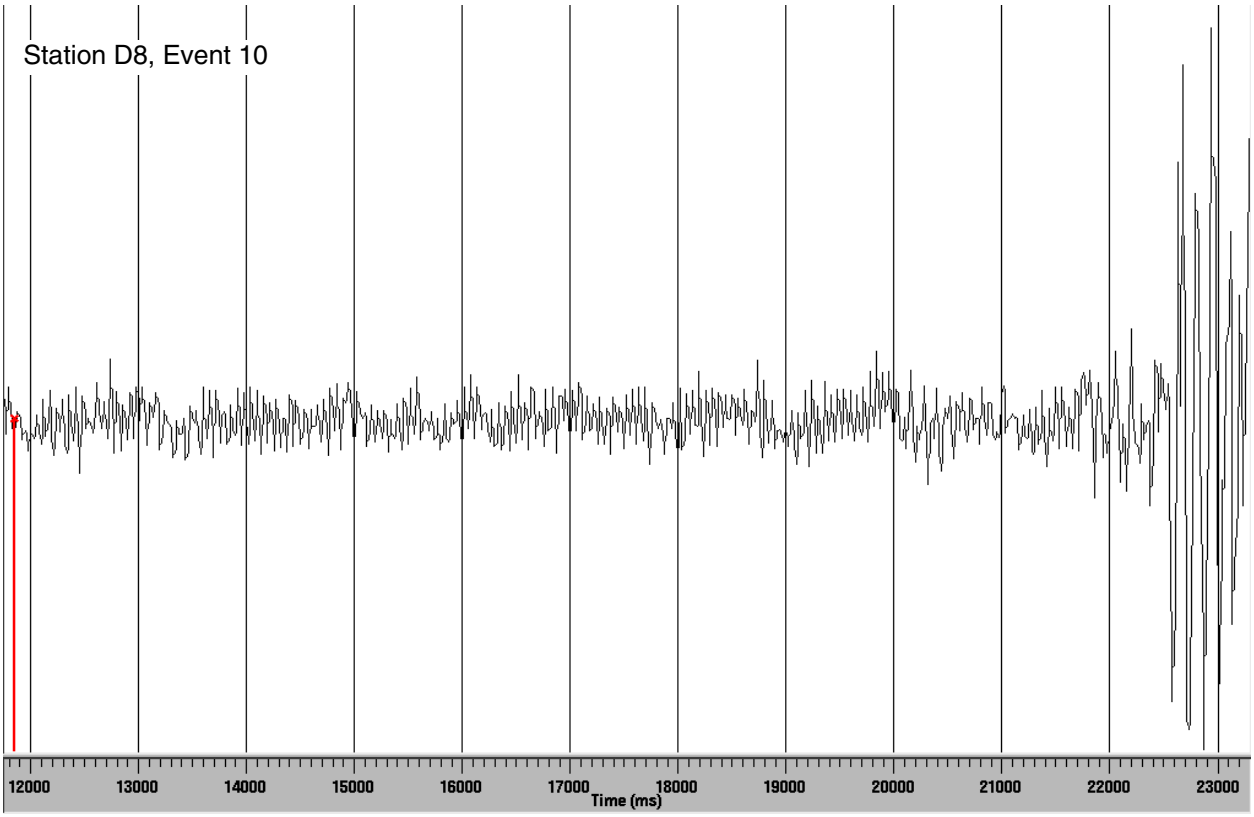


Figure B46. Event 11, from the list of 20 local events, at station D8.

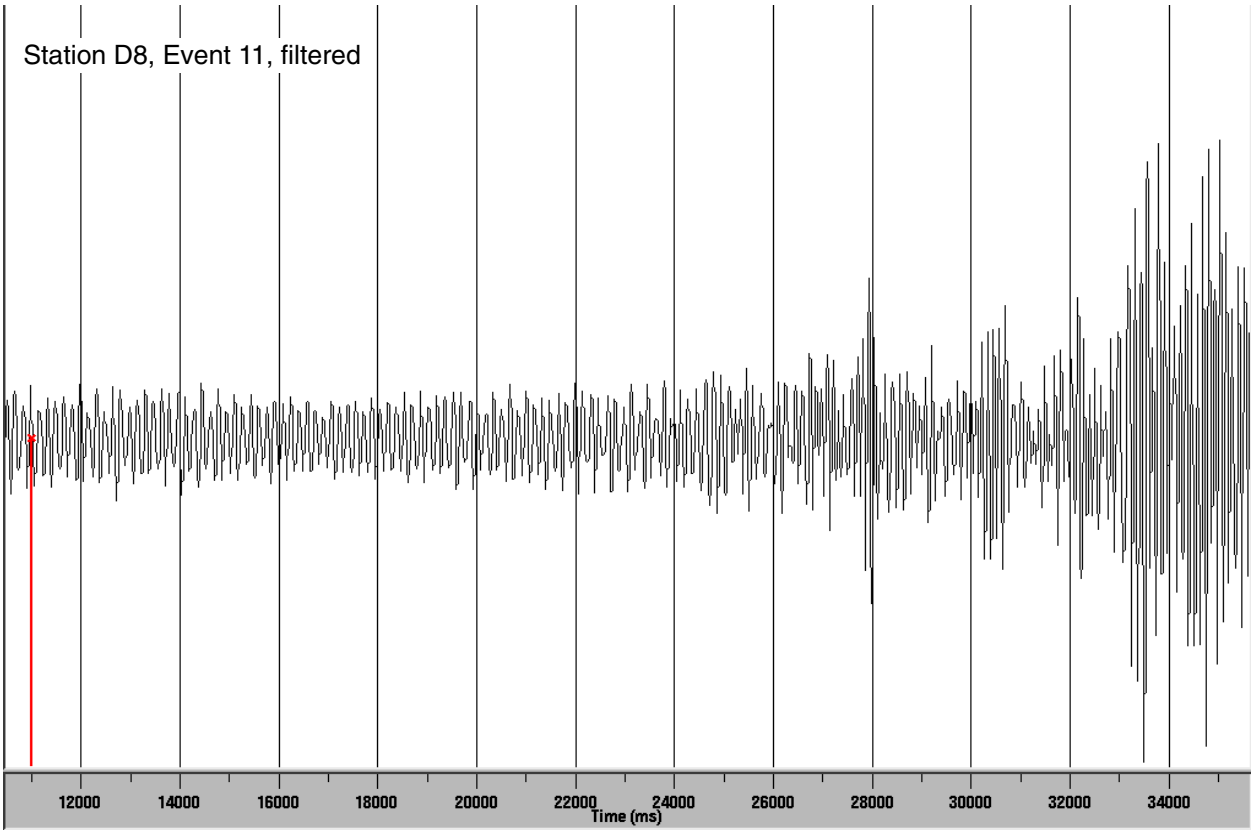


Figure B47. Event 13, from the list of 20 local events, at station D8.

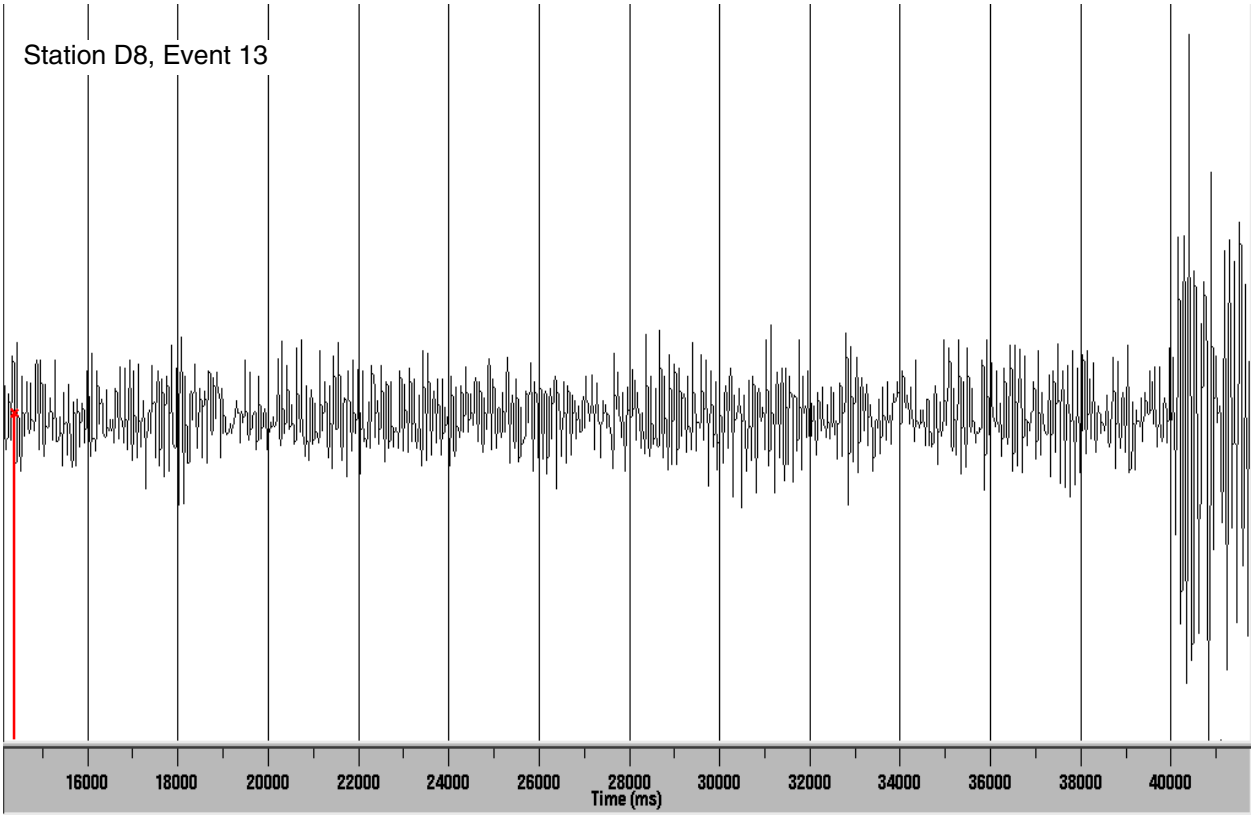


Figure B48. Event 16, from the list of 20 local events, at station D8.

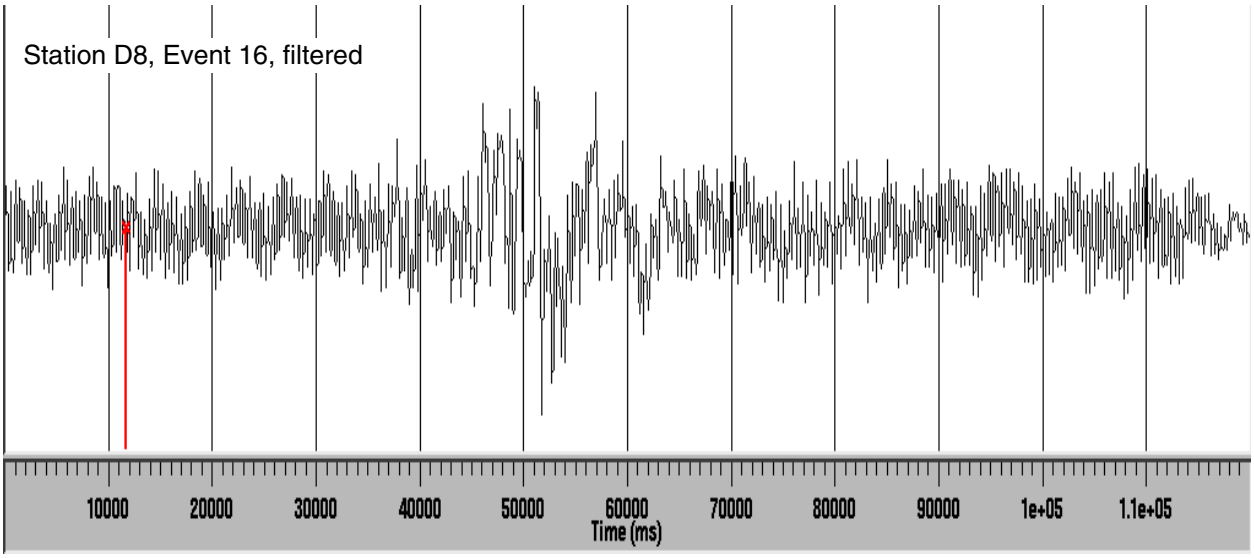


Figure B49. Event 17, from the list of 20 local events, at station D8.

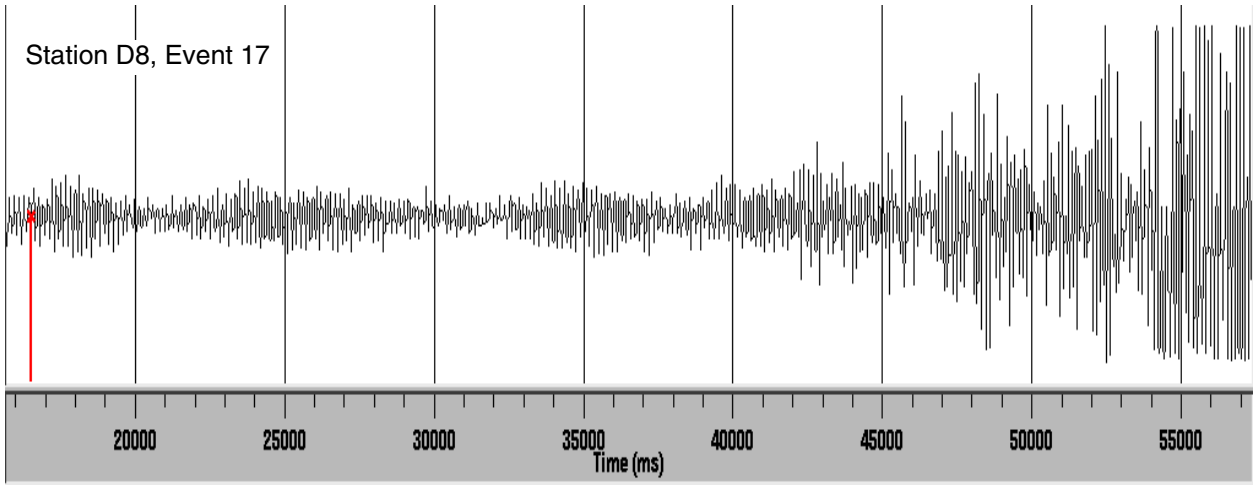


Figure B50. Event 19, from the list of 20 local events, at station D8.

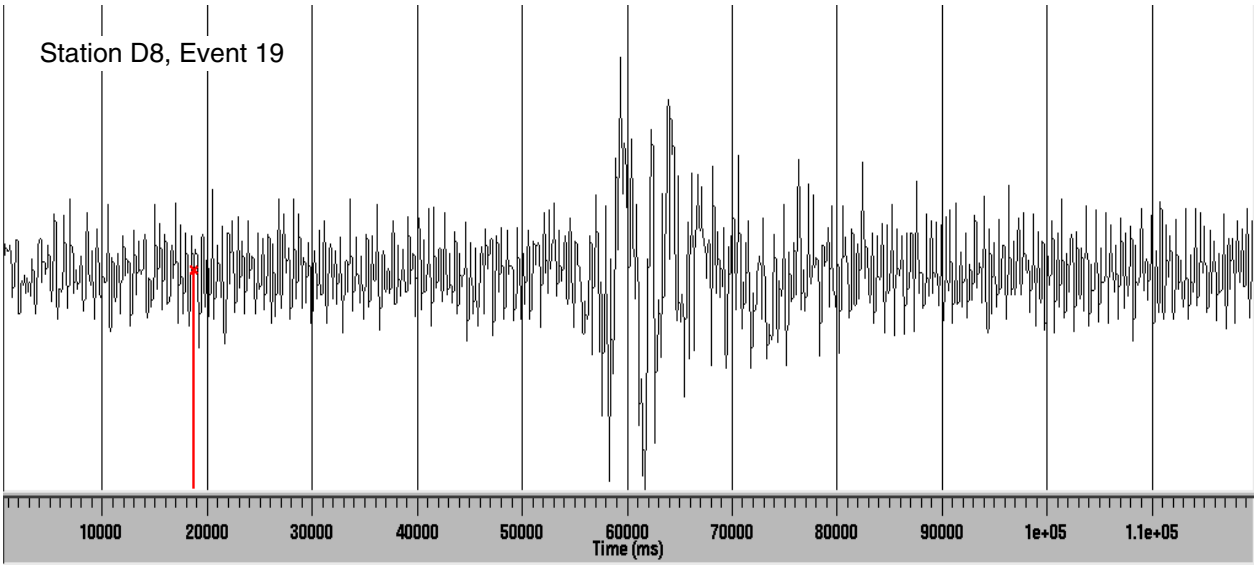


Figure B51. Event 20, from the list of 20 local events, at station D8.

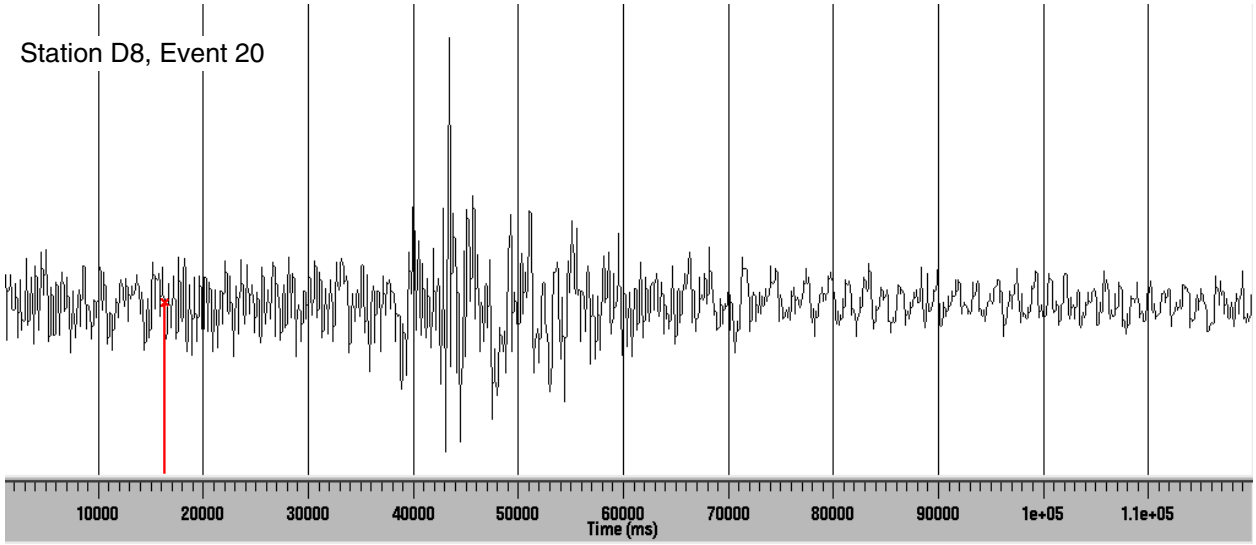


Figure B52. Event 2, from the list of 20 local events, at station A2.

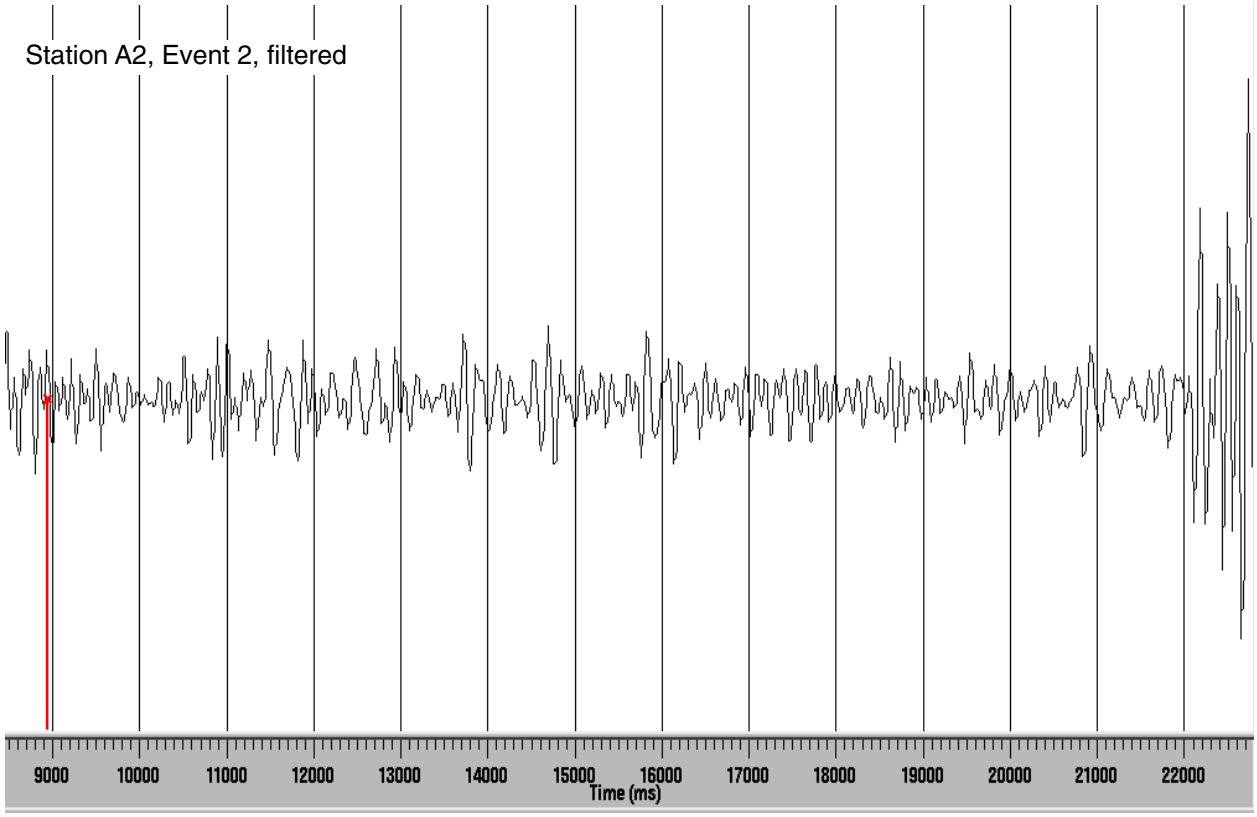


Figure B53. Event 3, from the list of 20 local events, at station A2.

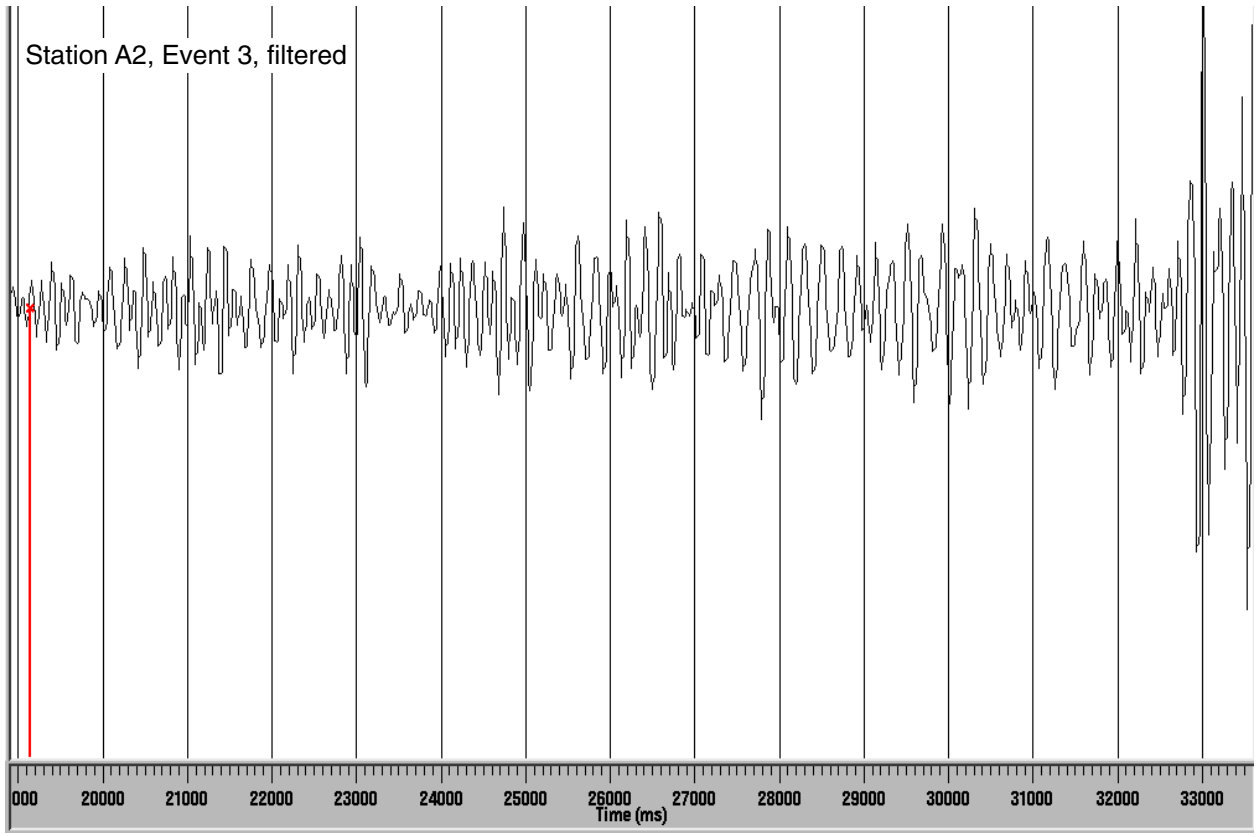


Figure B54. Event 5, from the list of 20 local events, at station A2.

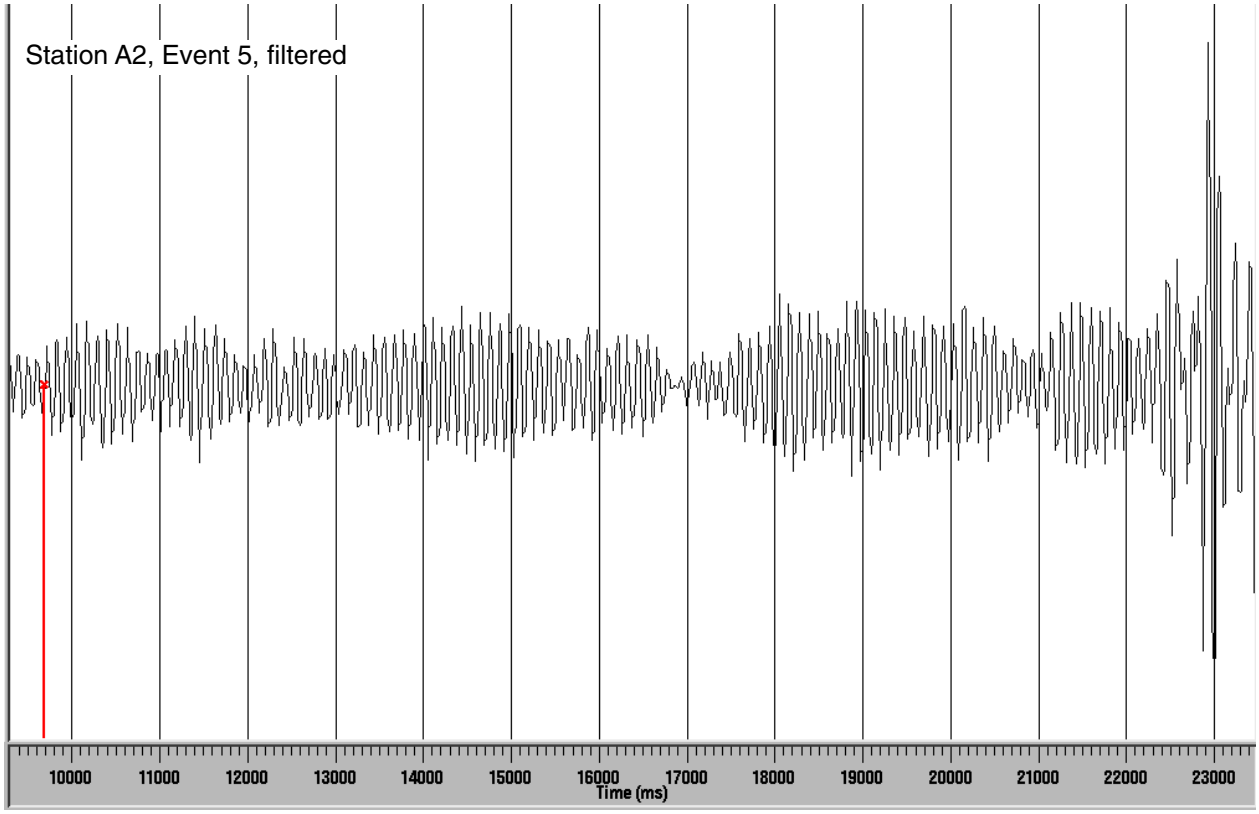


Figure B55. Event 6, from the list of 20 local events, at station A2.

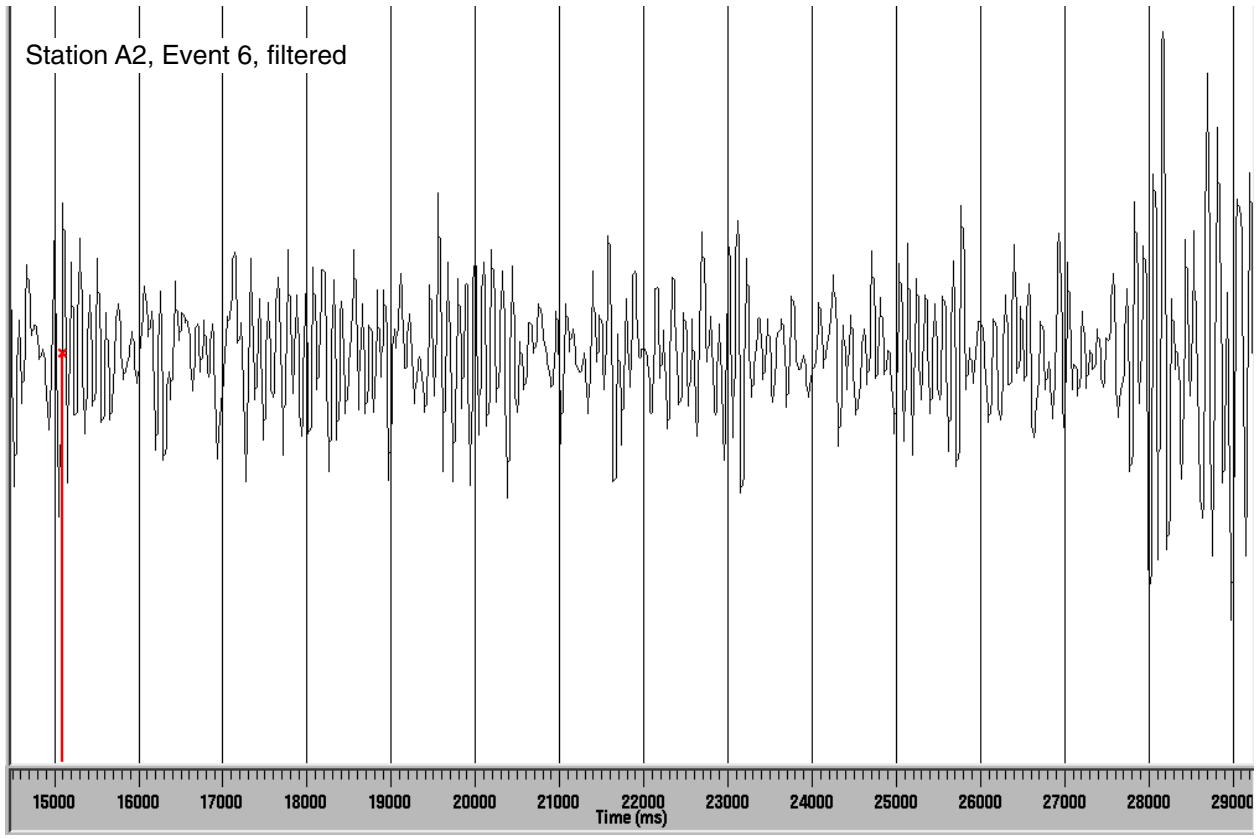


Figure B56. Event 10, from the list of 20 local events, at station A2.

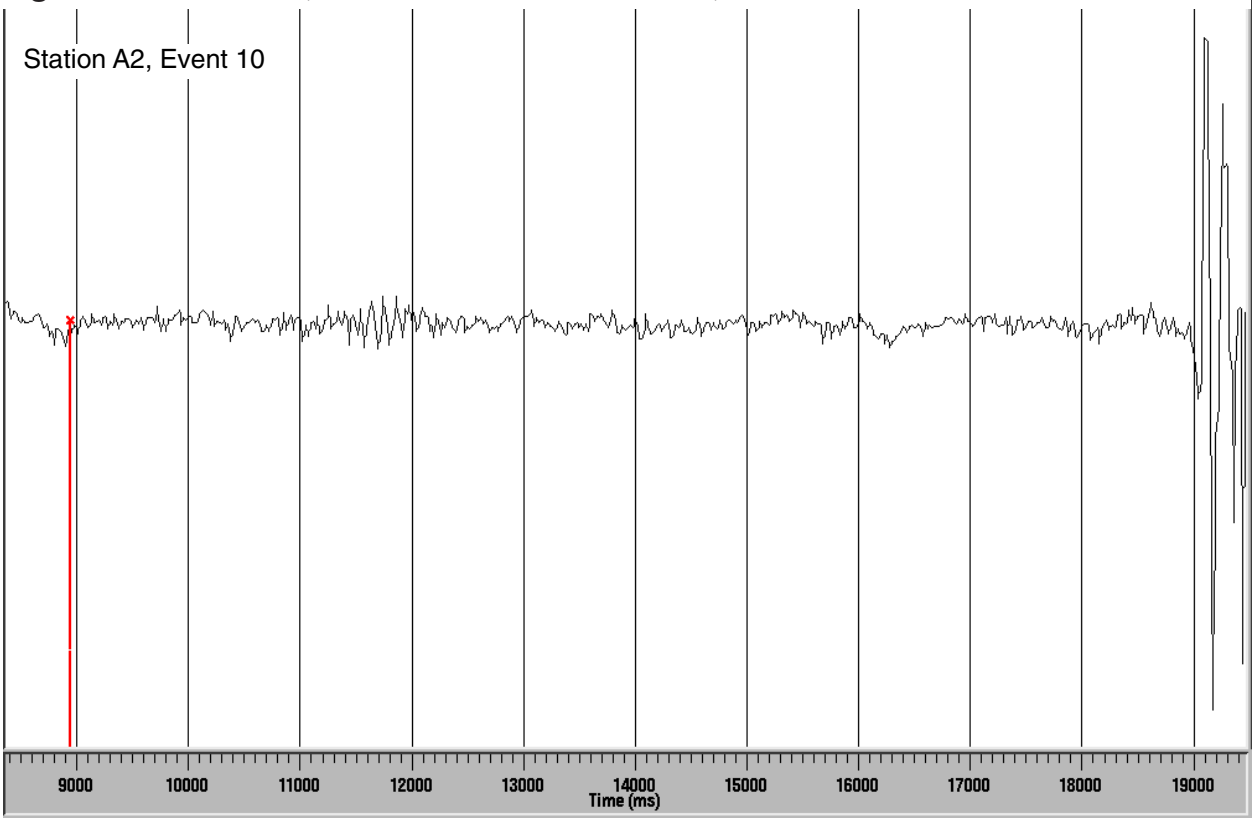


Figure B57. Event 11, from the list of 20 local events, at station A2.

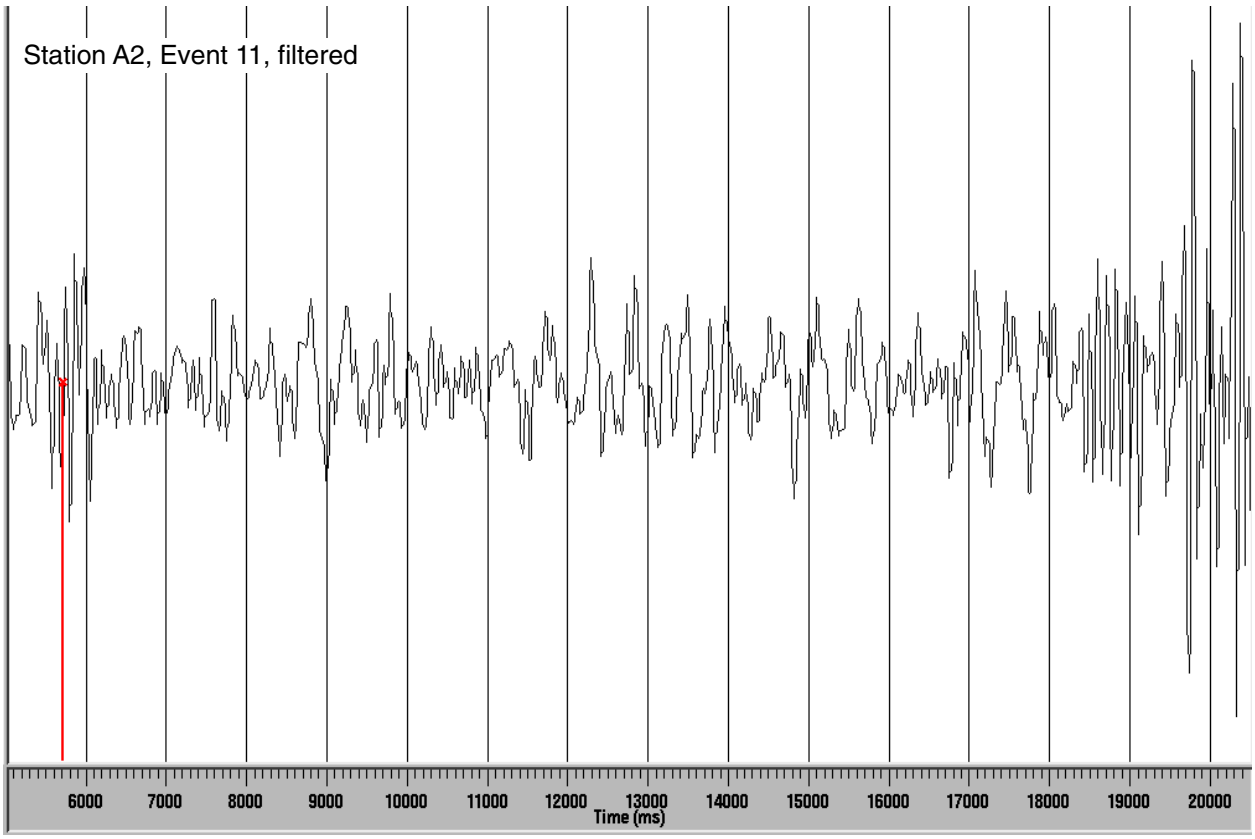


Figure B58. Event 12, from the list of 20 local events, at station A2.

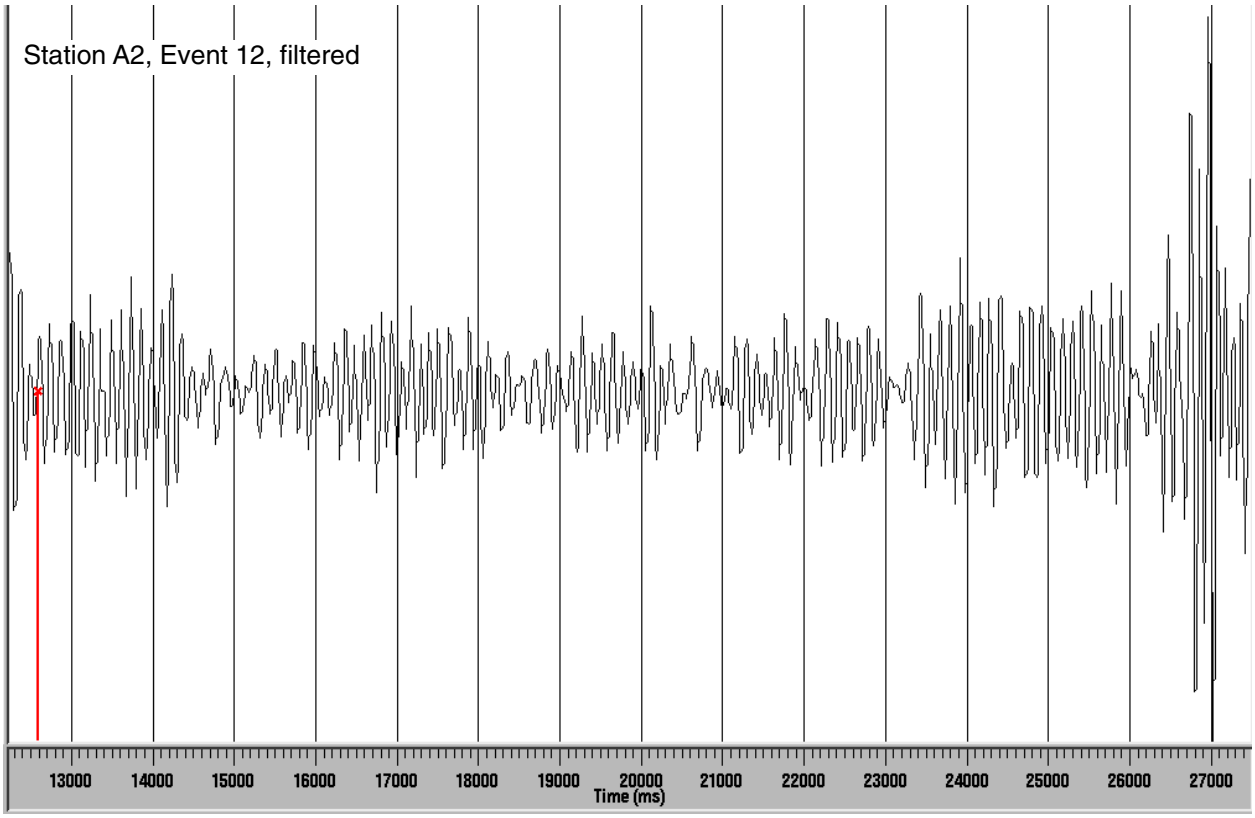


Figure B59. Event 13, from the list of 20 local events, at station A2.

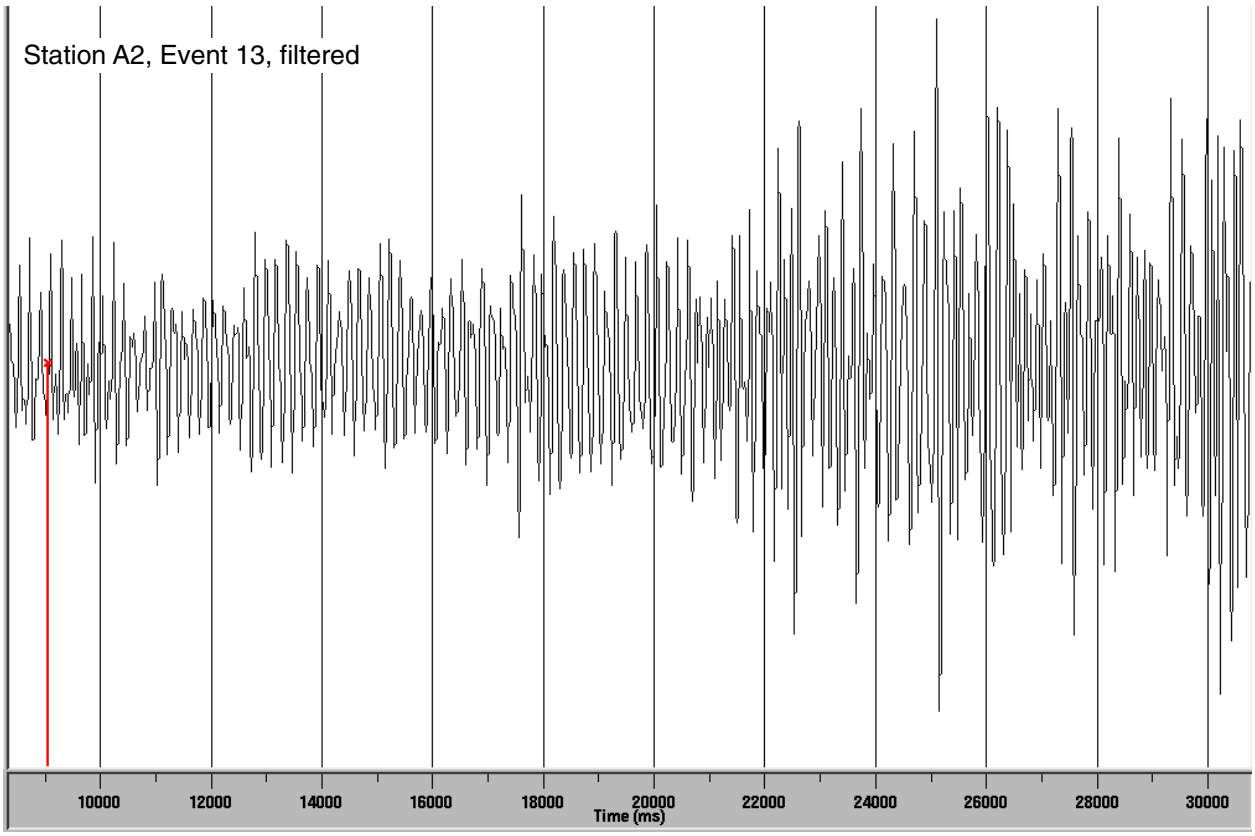


Figure B60. Event 1, from the list of 20 local events, at station A3.

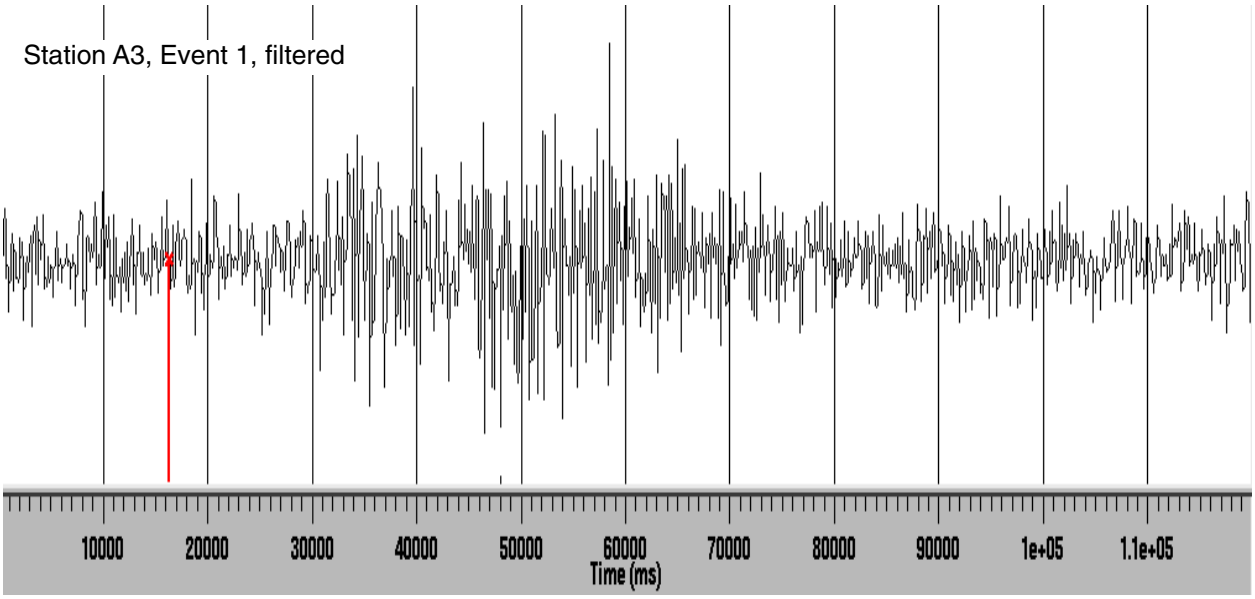


Figure B61. Event 2, from the list of 20 local events, at station A3.

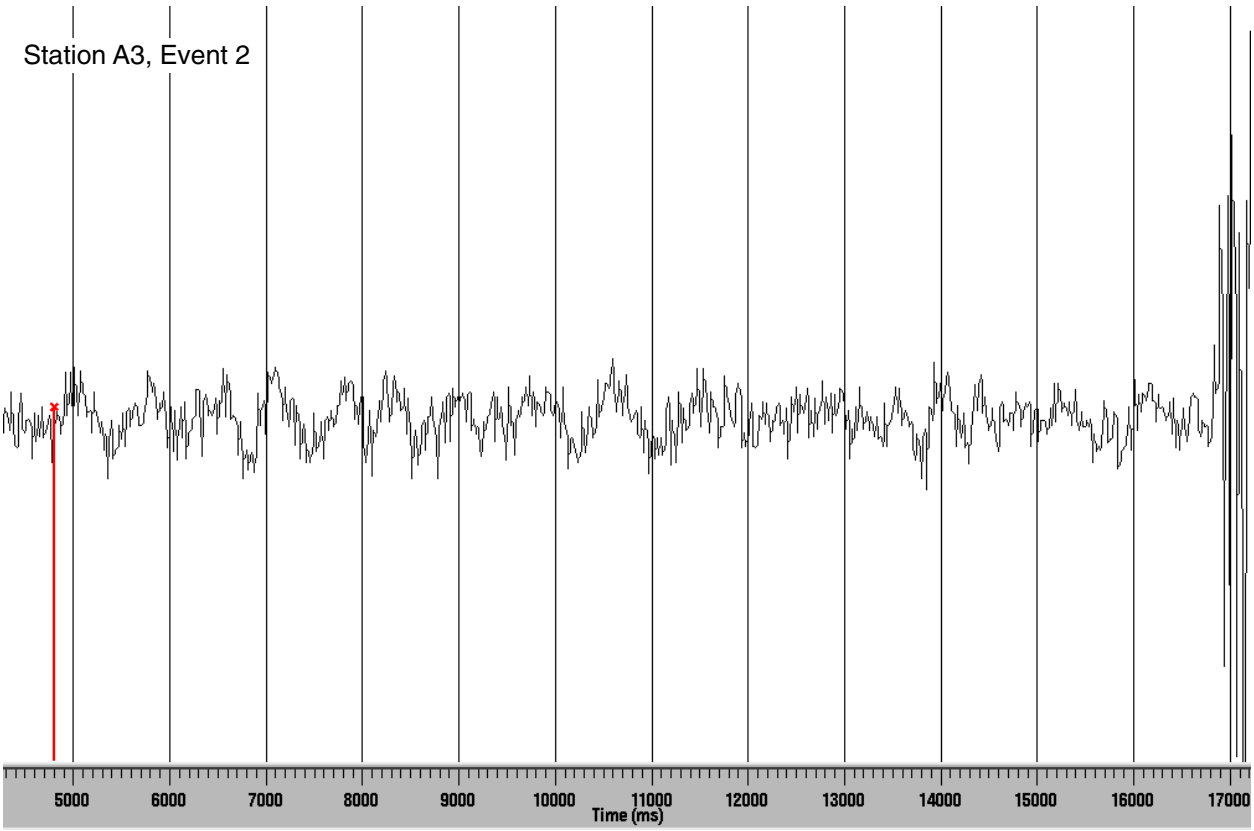


Figure B62. Event 3, from the list of 20 local events, at station A3.

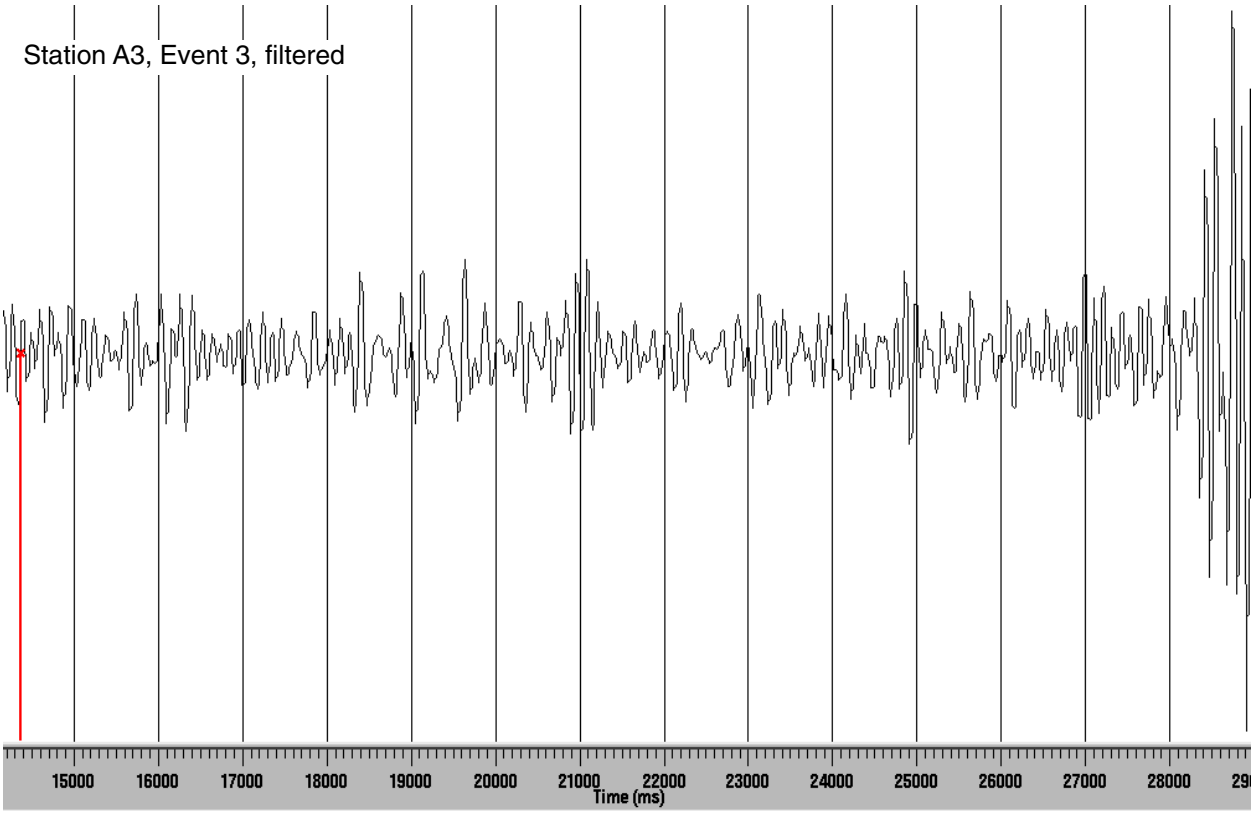


Figure B63. Event 4, from the list of 20 local events, at station A3.

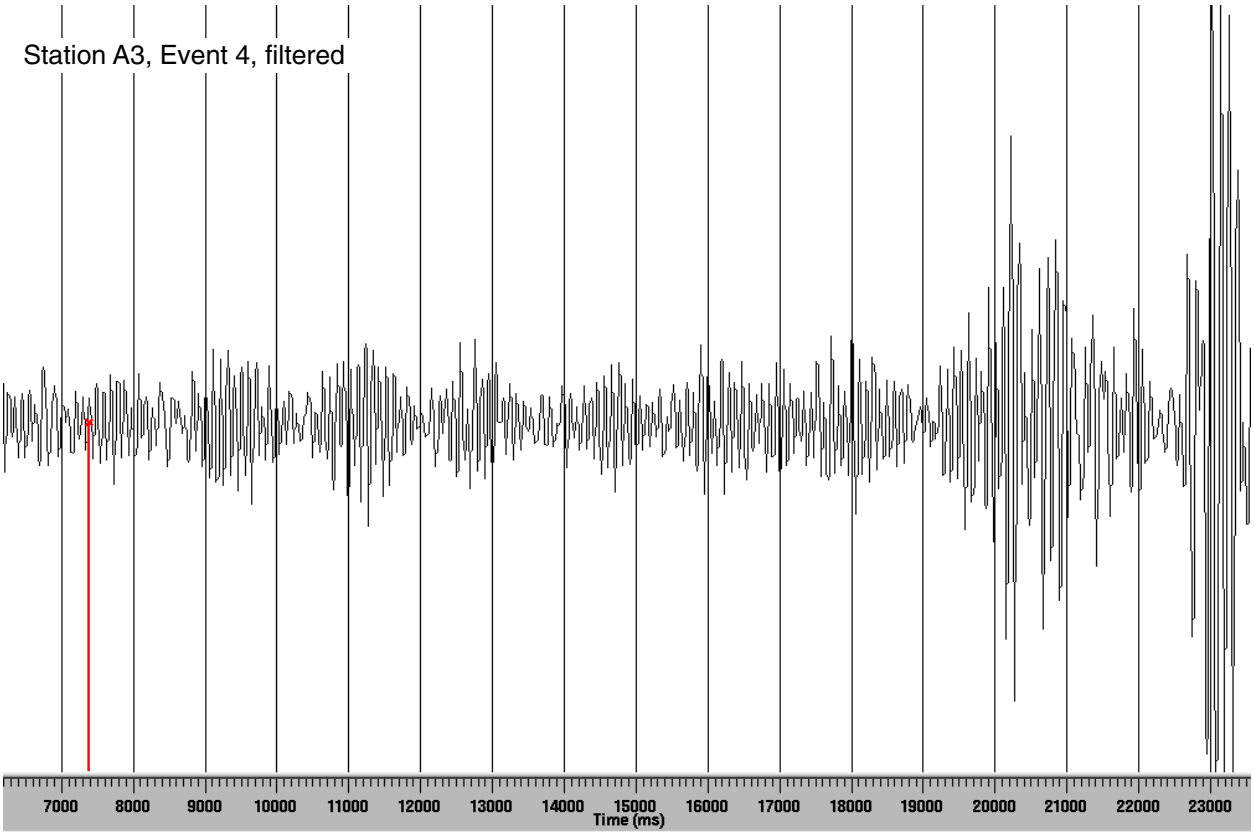


Figure B64. Event 5, from the list of 20 local events, at station A3.

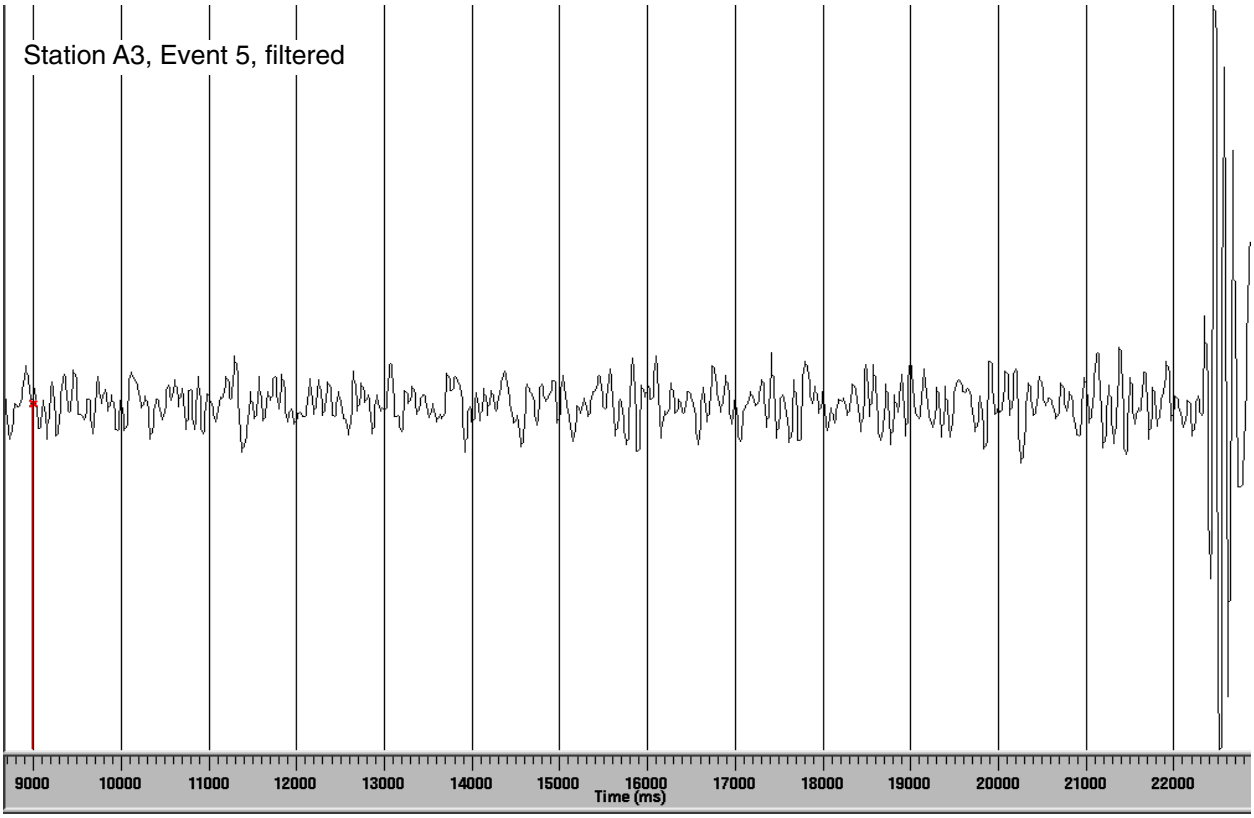


Figure B65. Event 6, from the list of 20 local events, at station A3.

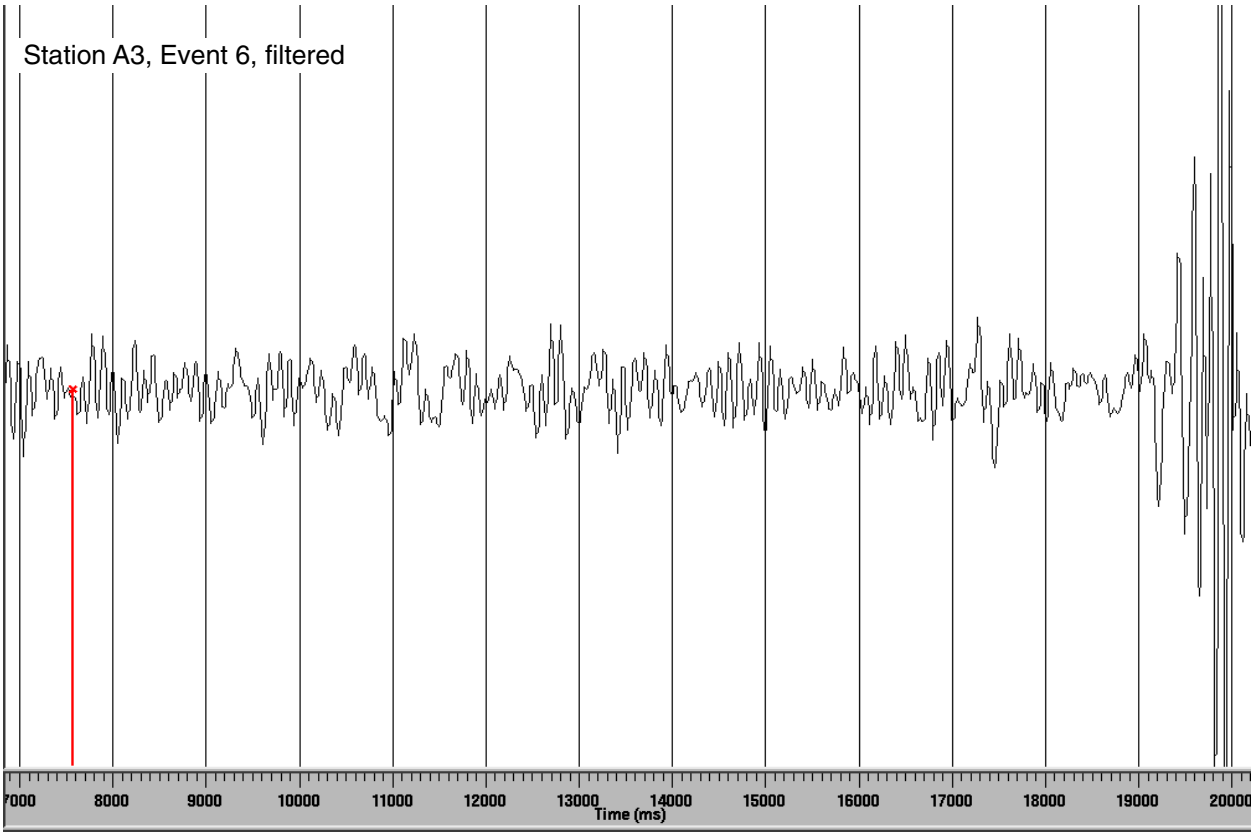


Figure B66. Event 7, from the list of 20 local events, at station A3.

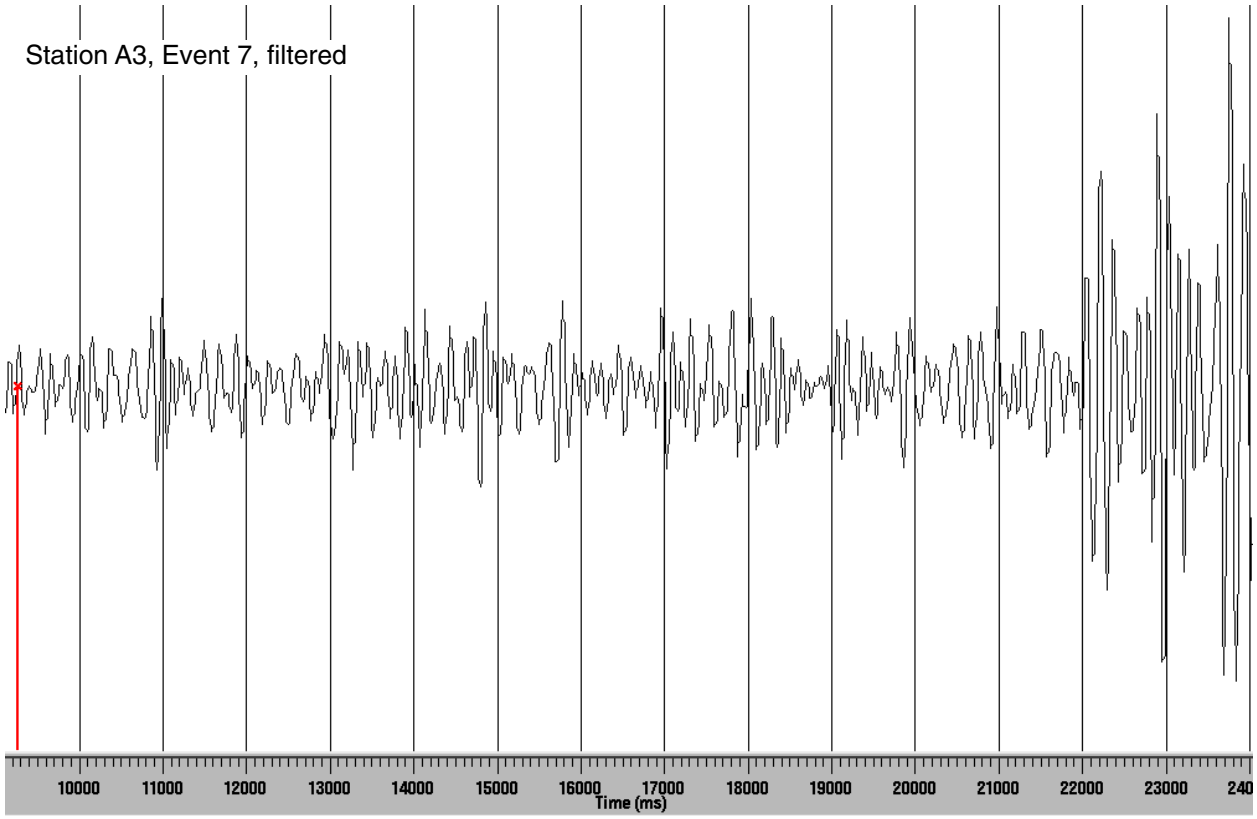


Figure B67. Event 8, from the list of 20 local events, at station A3.

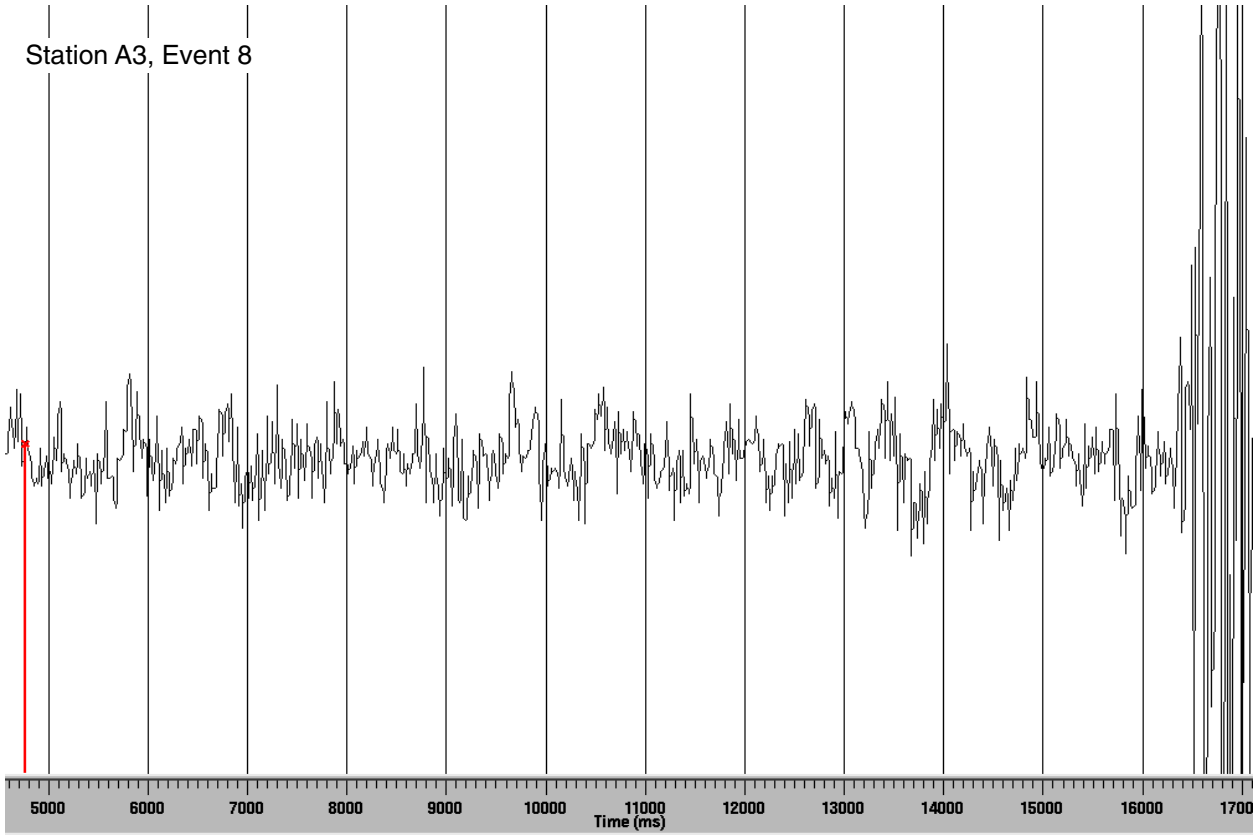


Figure B68. Event 10, from the list of 20 local events, at station A3.

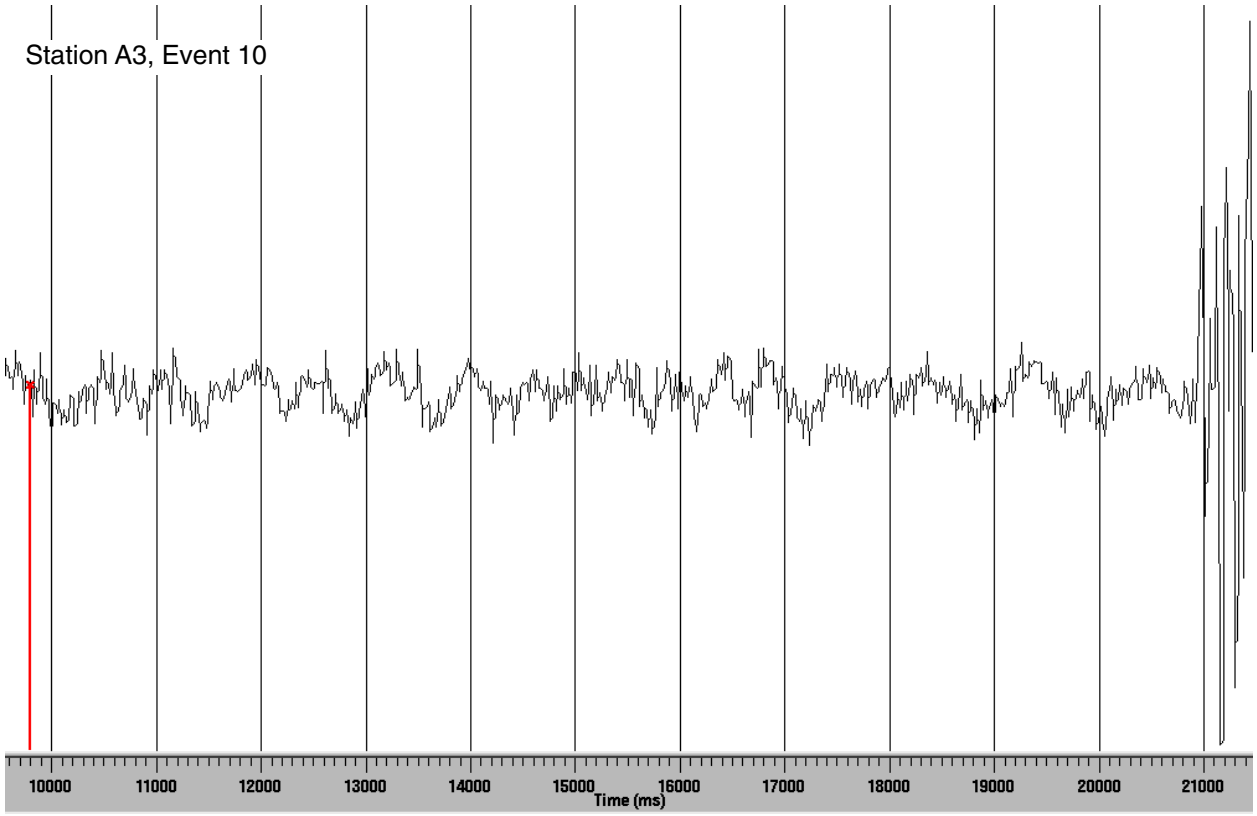


Figure B69. Event 11, from the list of 20 local events, at station A3.

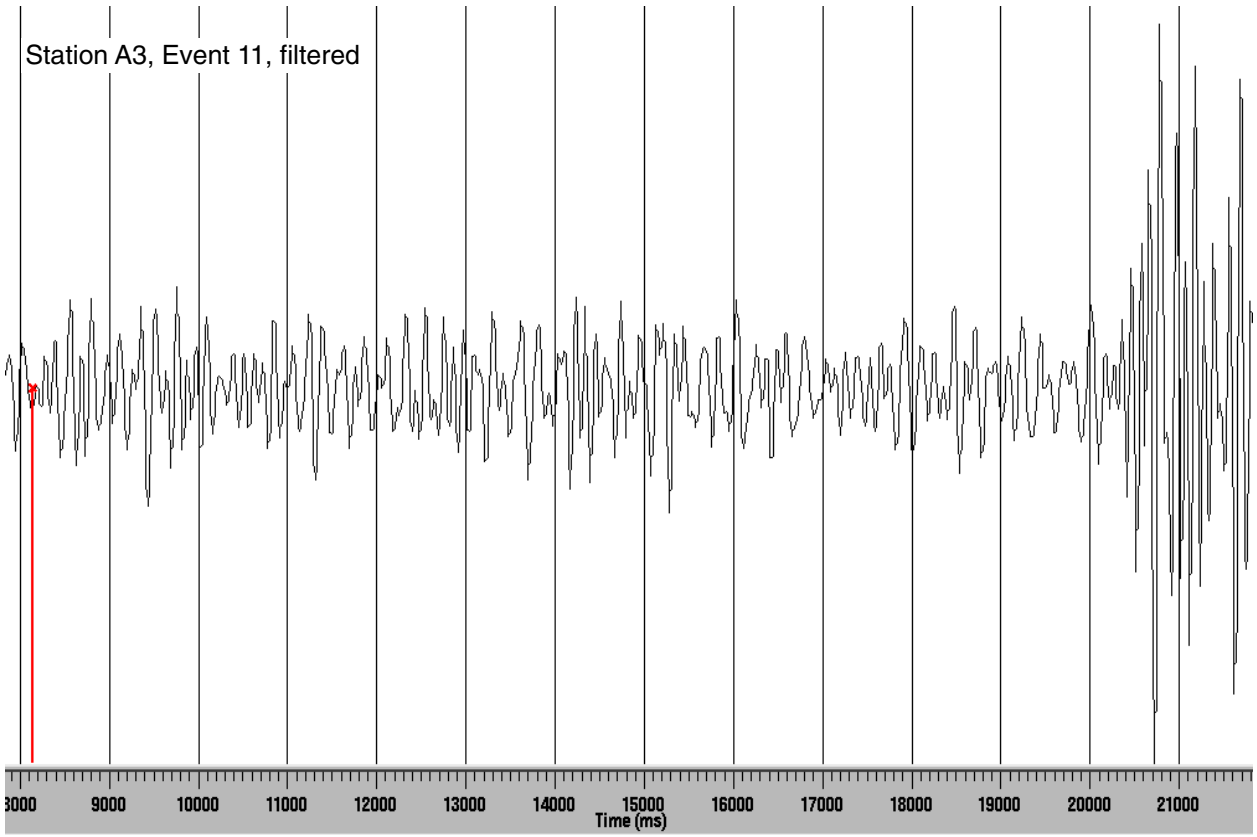


Figure B70. Event 12, from the list of 20 local events, at station A3.

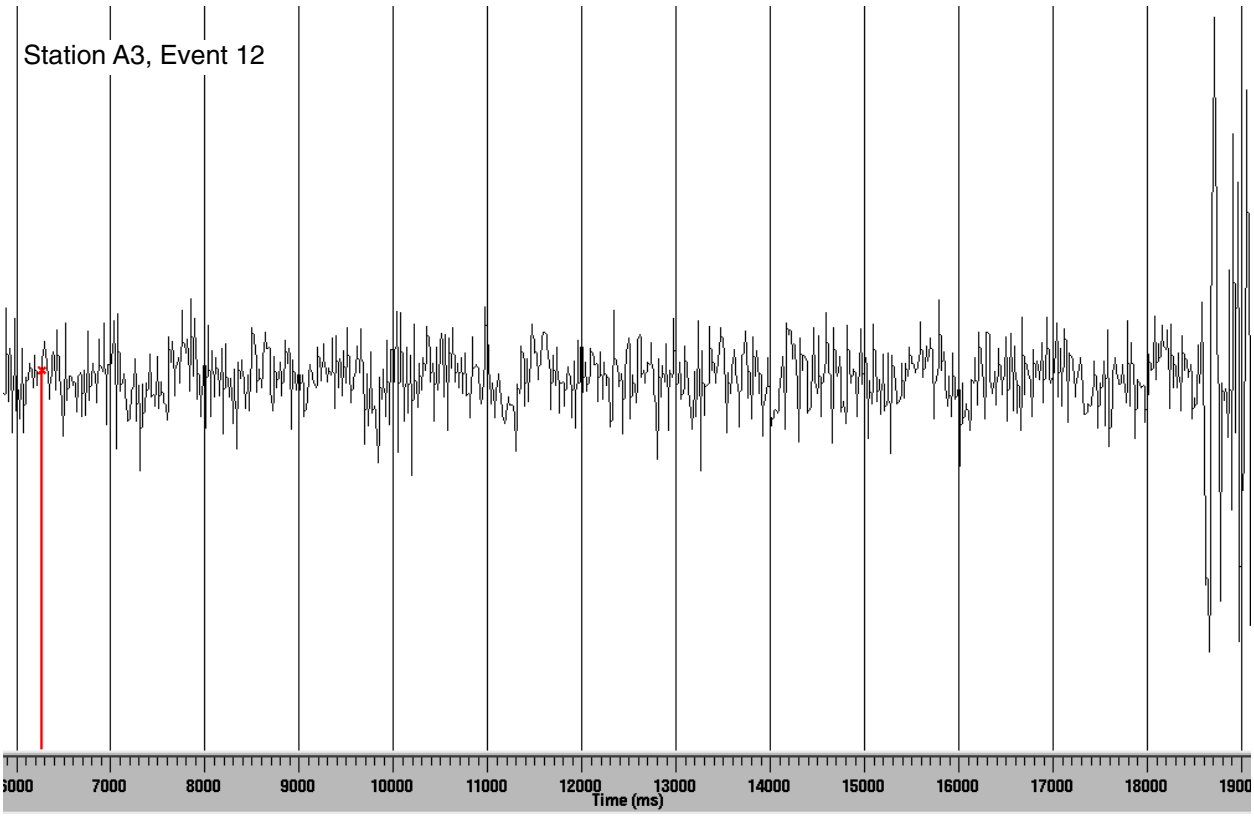


Figure B71. Event 13, from the list of 20 local events, at station A3.

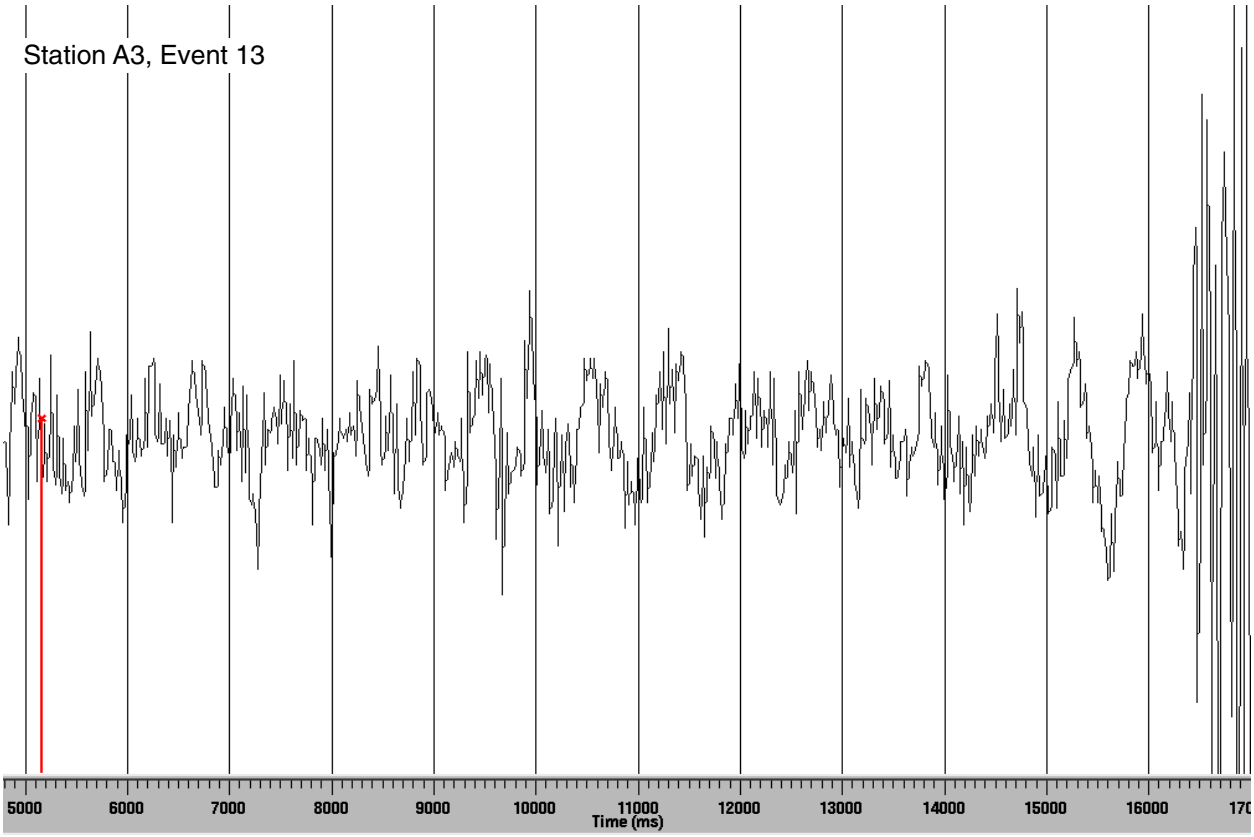


Figure B72. Event 14, from the list of 20 local events, at station A3.

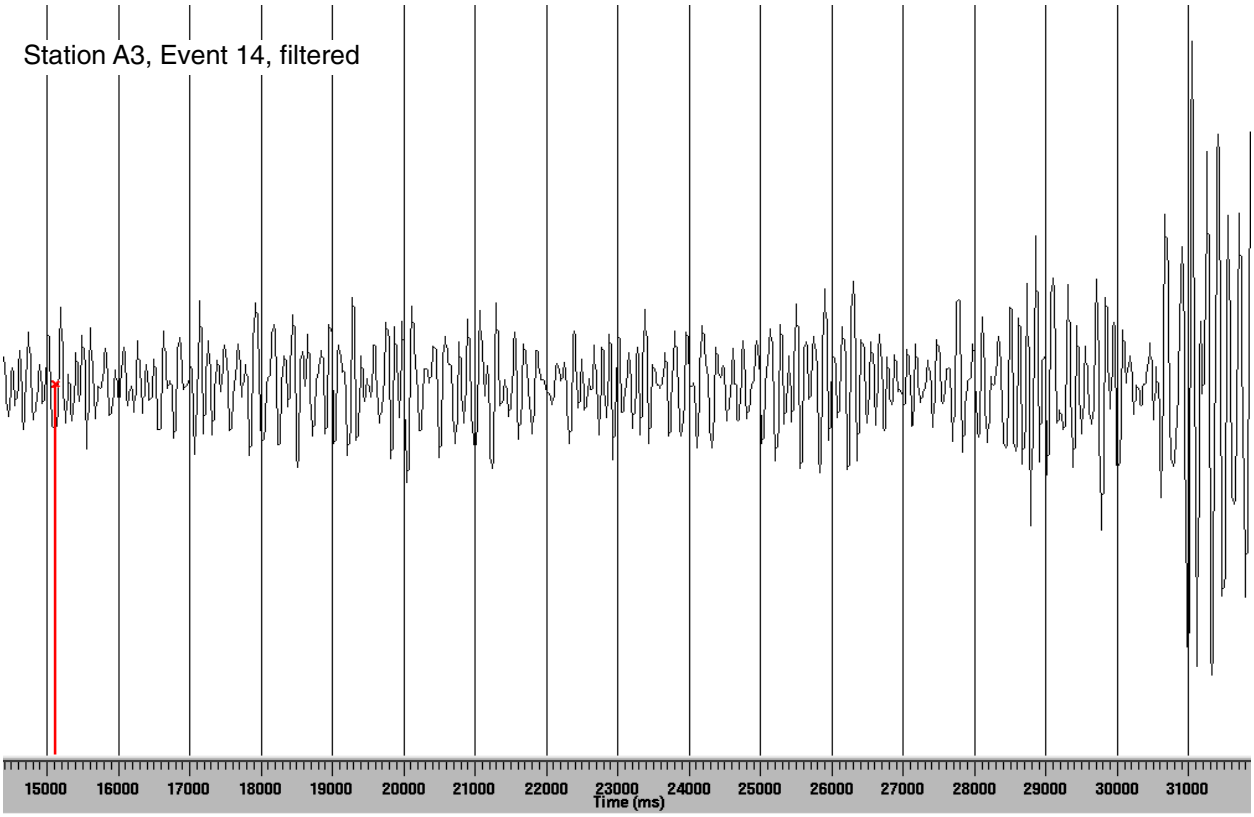


Figure B73. Event 17, from the list of 20 local events, at station A3.

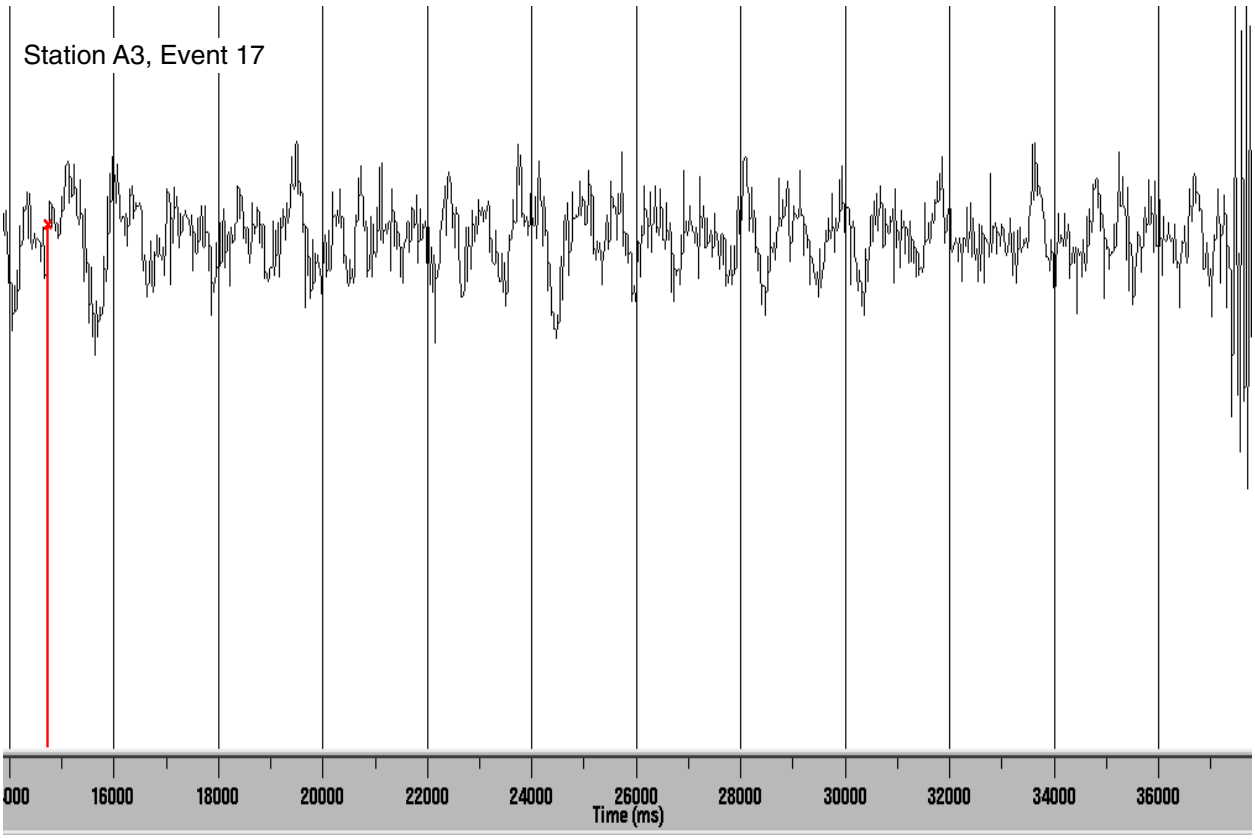


Figure B74. Event 18, from the list of 20 local events, at station A3.

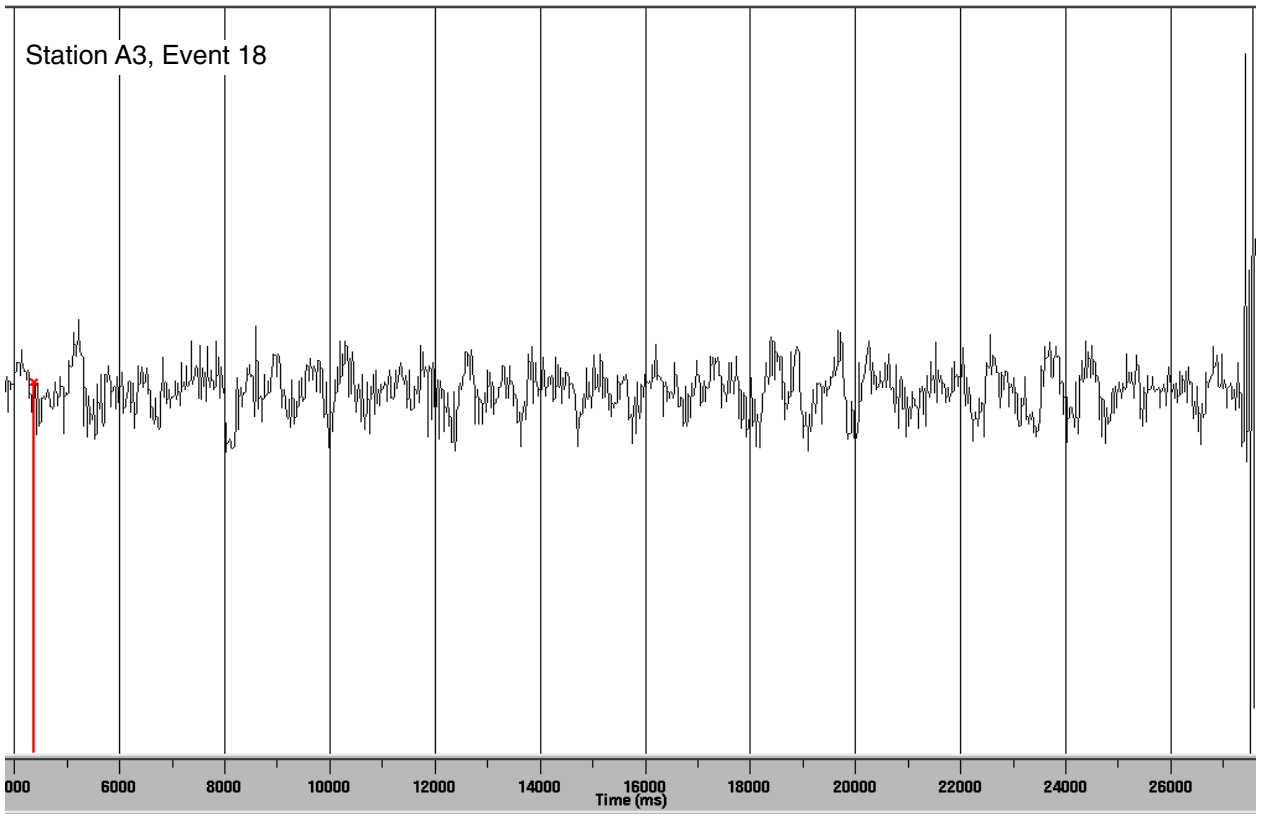


Figure B75. Event 19, from the list of 20 local events, at station A3.

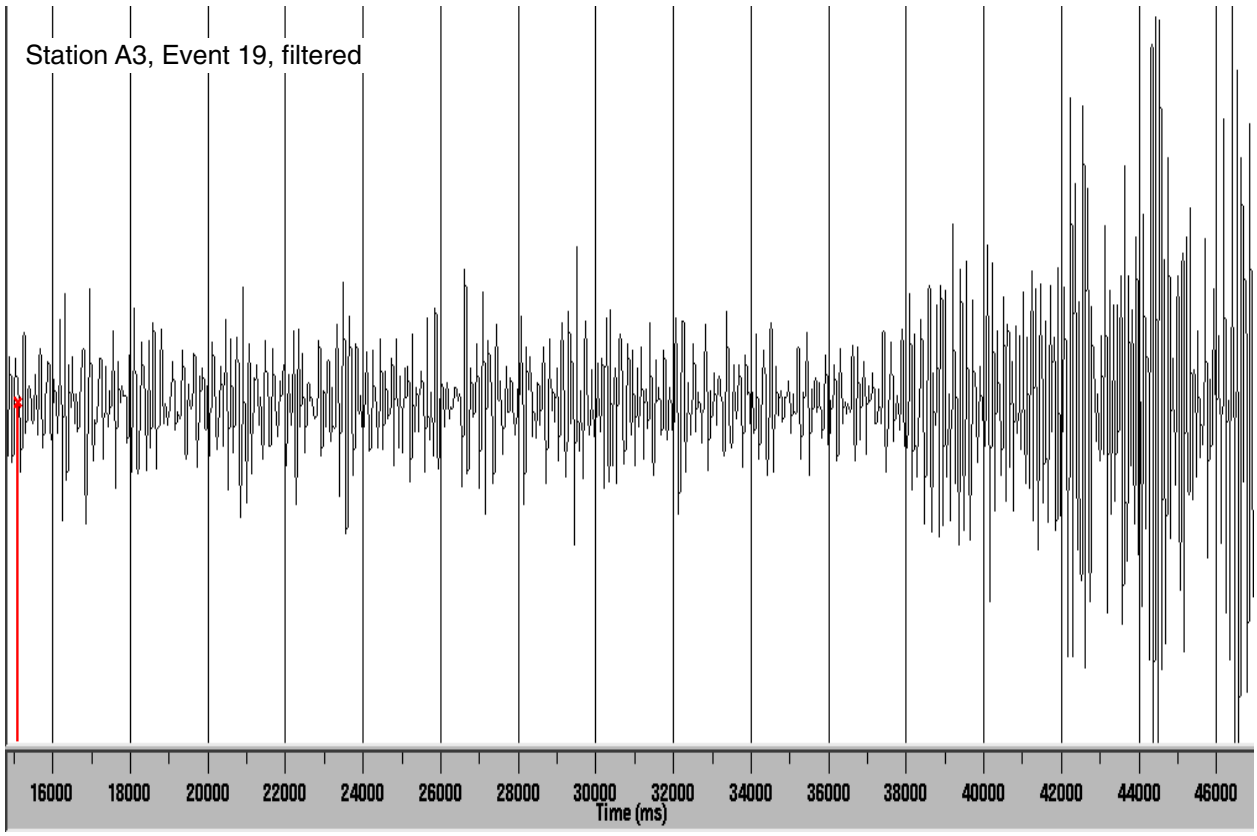


Figure B76. Event 20, from the list of 20 local events, at station A3.

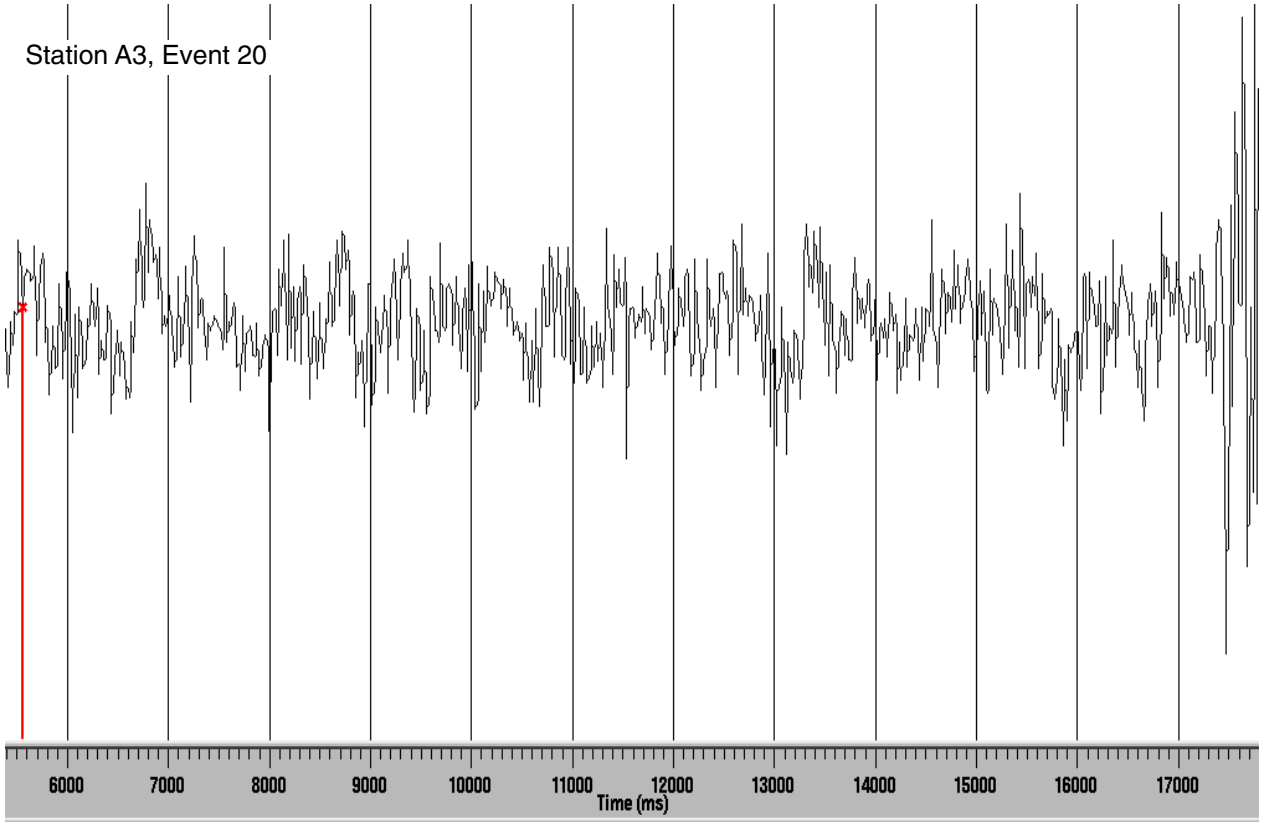


Figure B77. Event 1, from the list of 20 local events, at station A8.

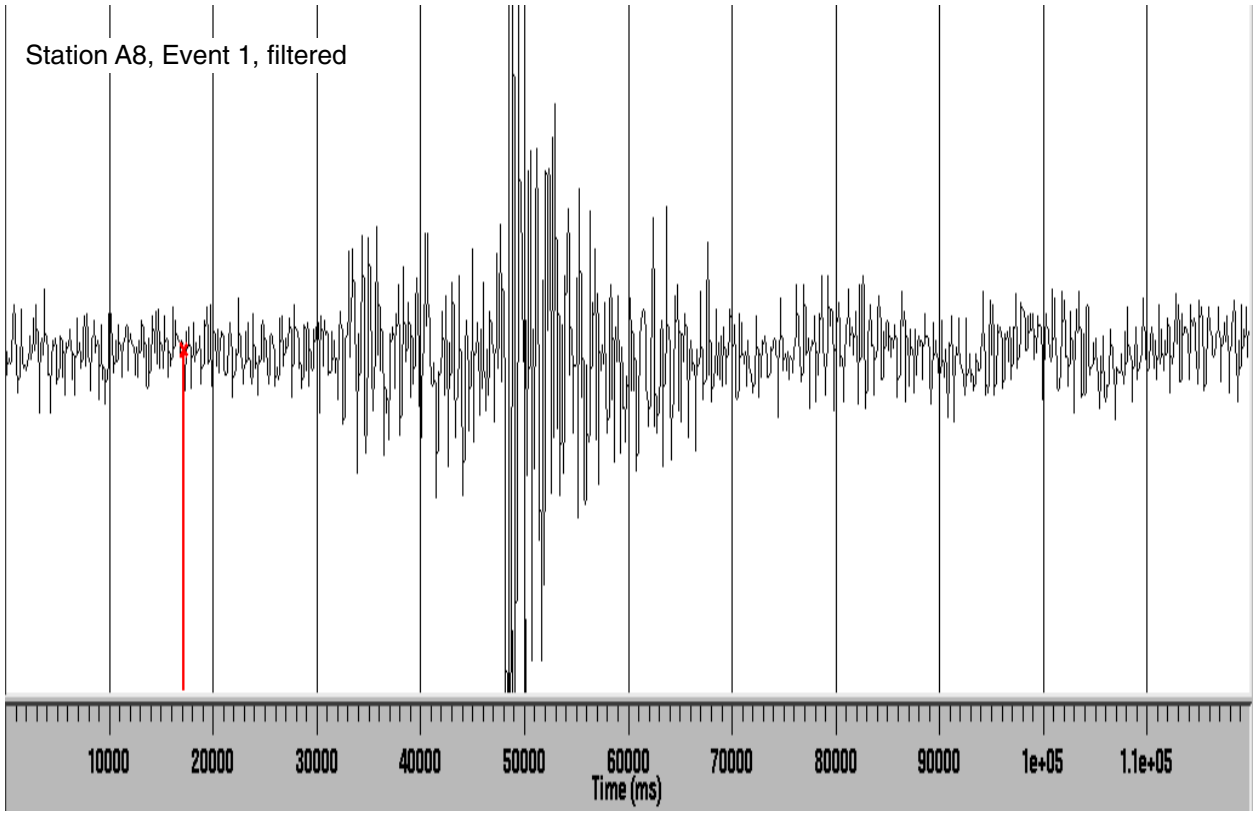


Figure B78. Event 2, from the list of 20 local events, at station A8.

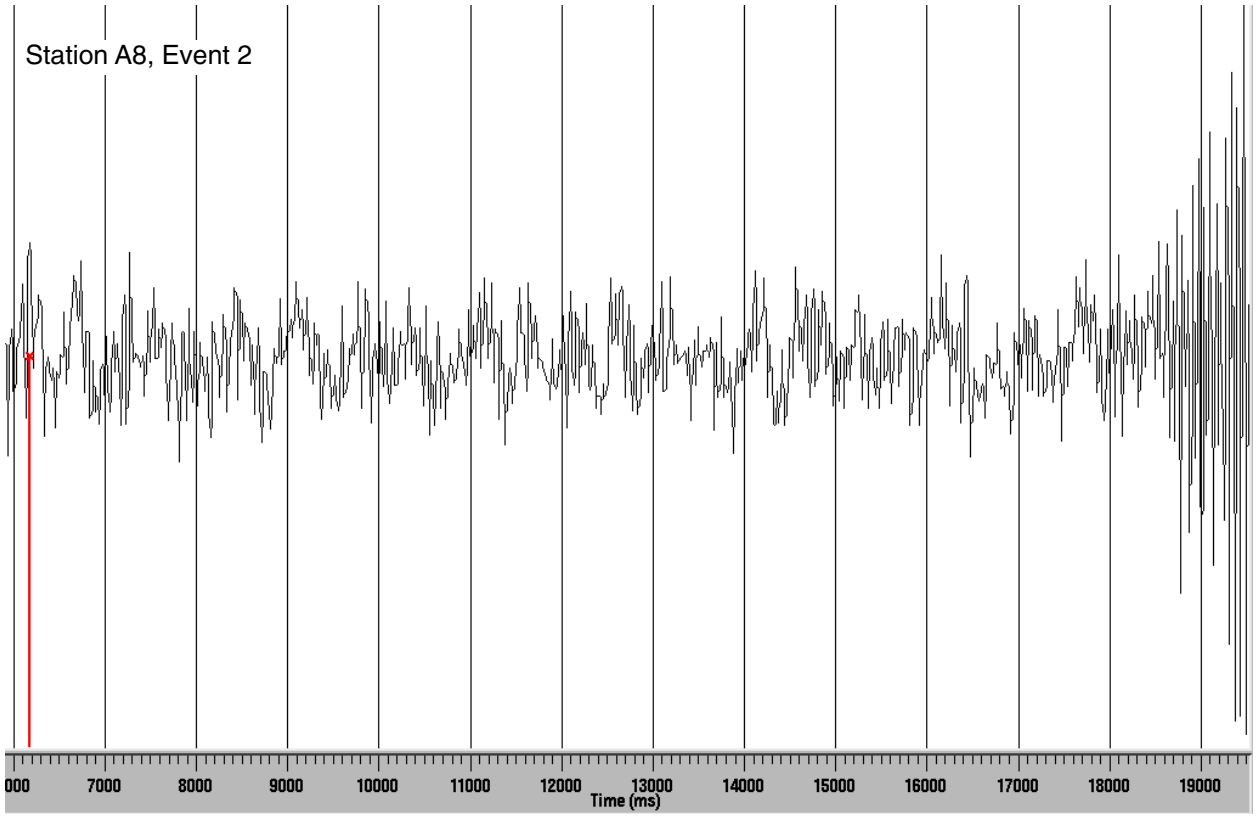


Figure B79. Event 3, from the list of 20 local events, at station A8.

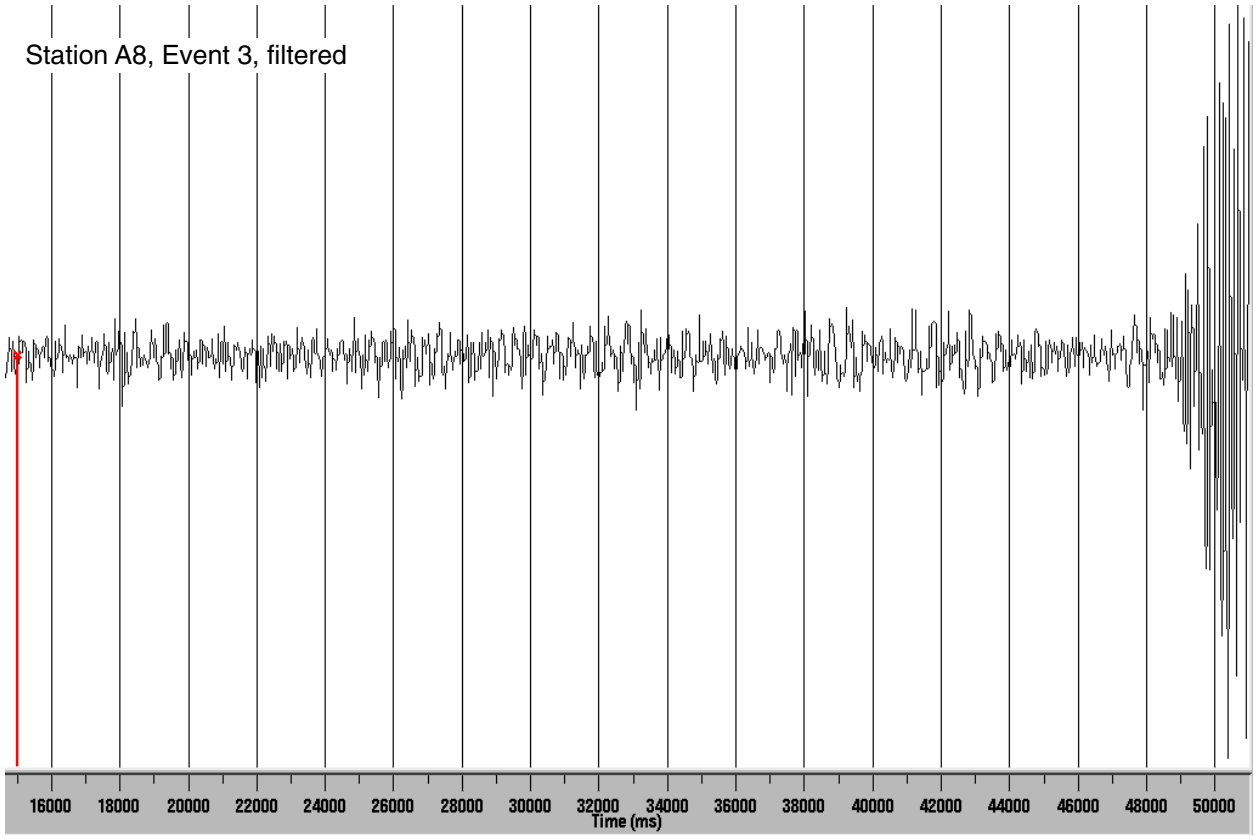


Figure B80. Event 4, from the list of 20 local events, at station A8.

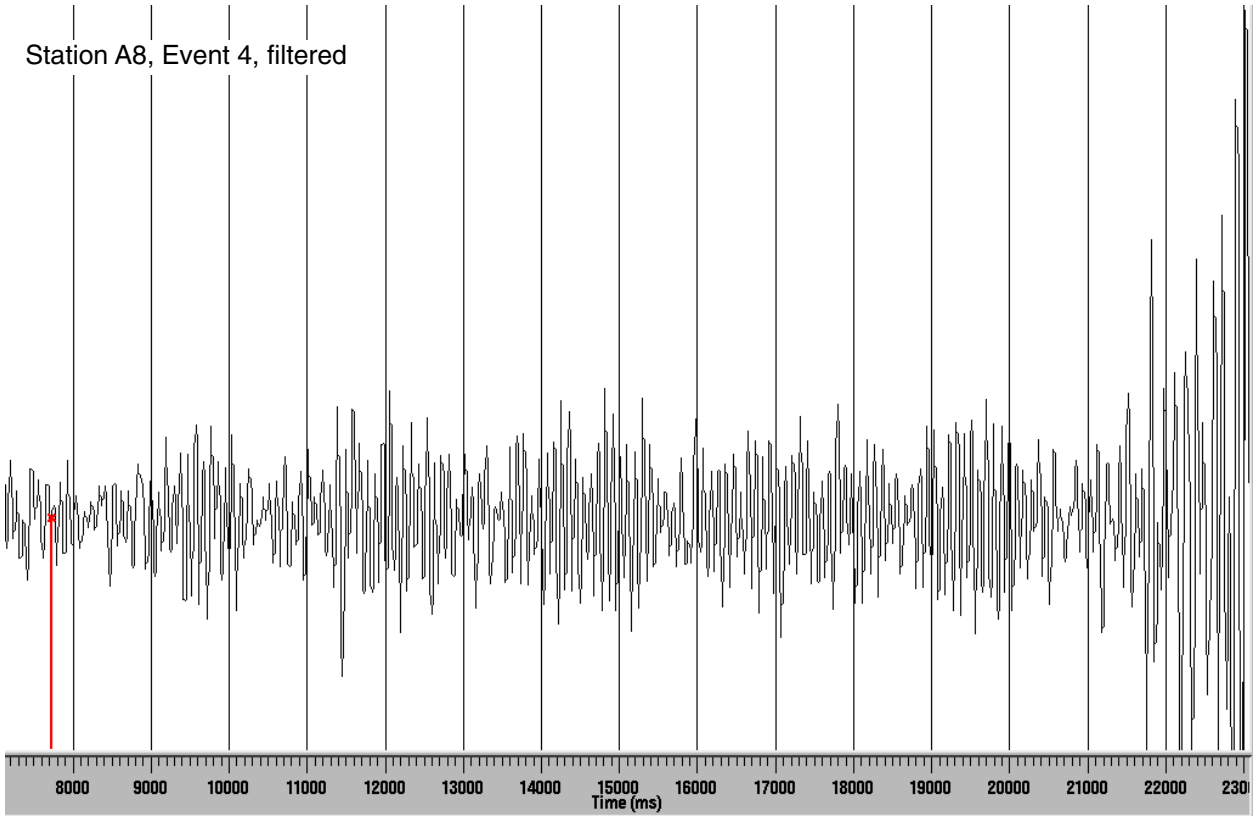


Figure B81. Event 5, from the list of 20 local events, at station A8.

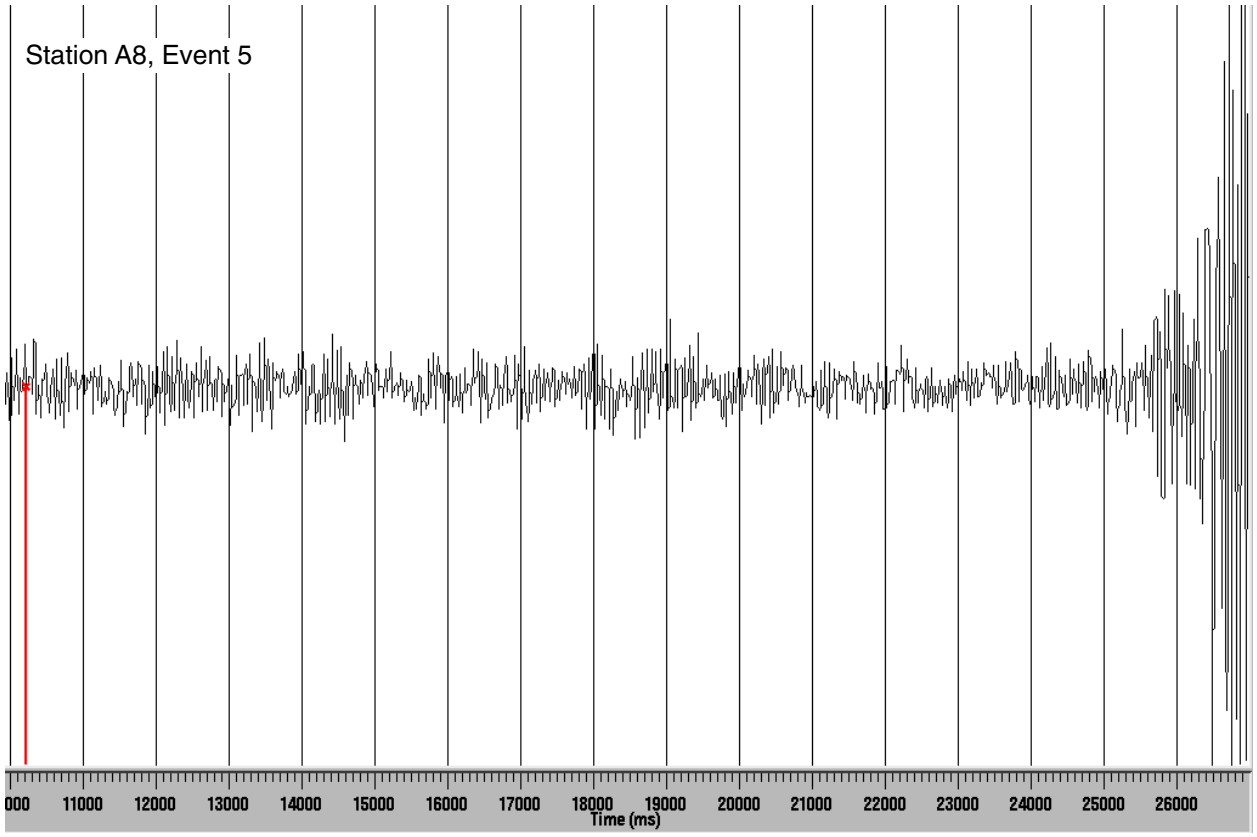


Figure B82. Event 6, from the list of 20 local events, at station A8.

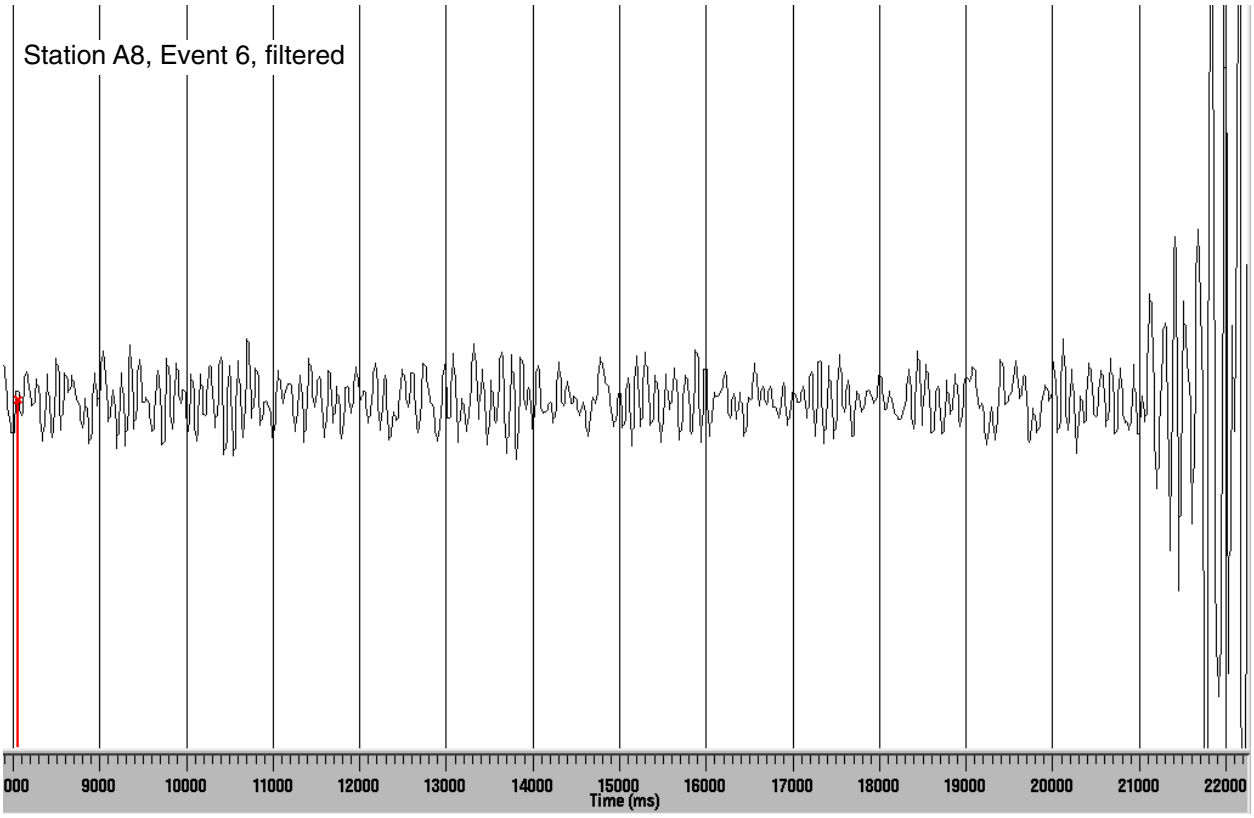


Figure B83. Event 7, from the list of 20 local events, at station A8.

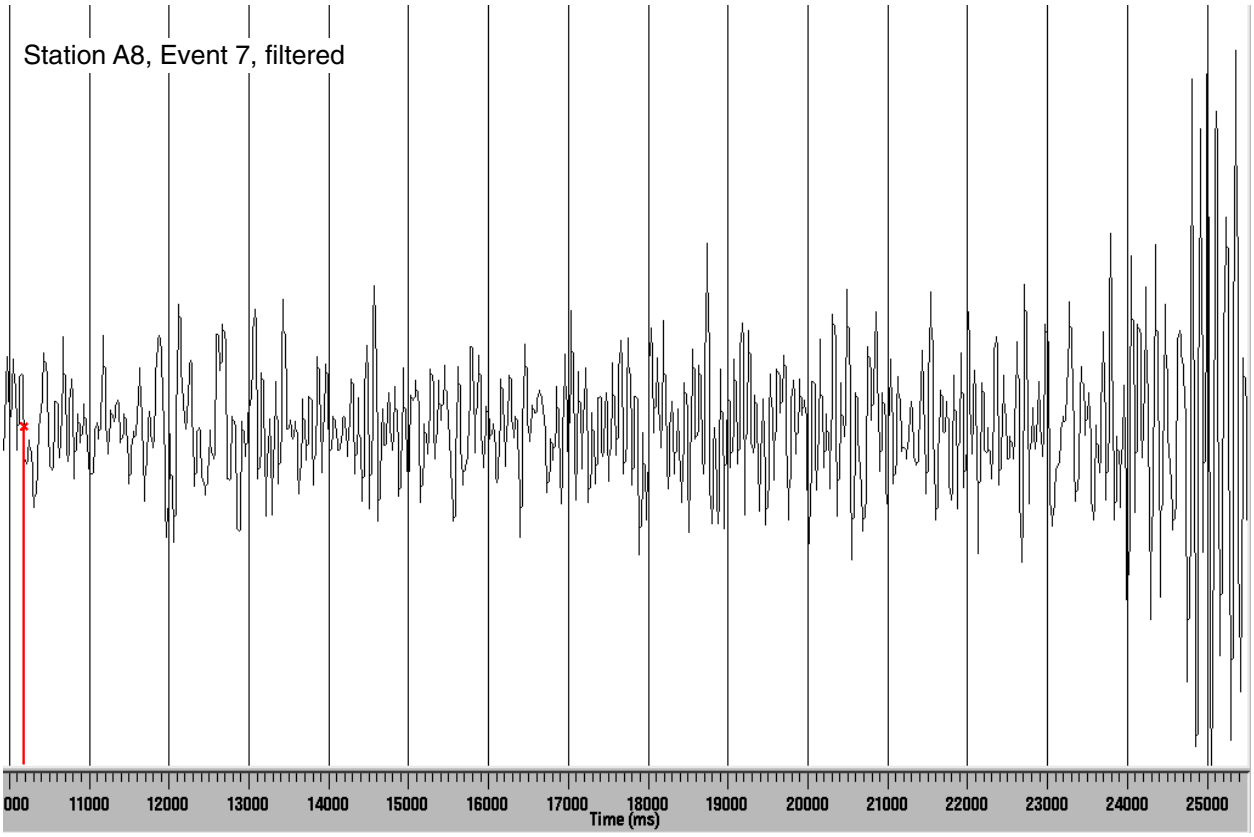


Figure B84. Event 8, from the list of 20 local events, at station A8.

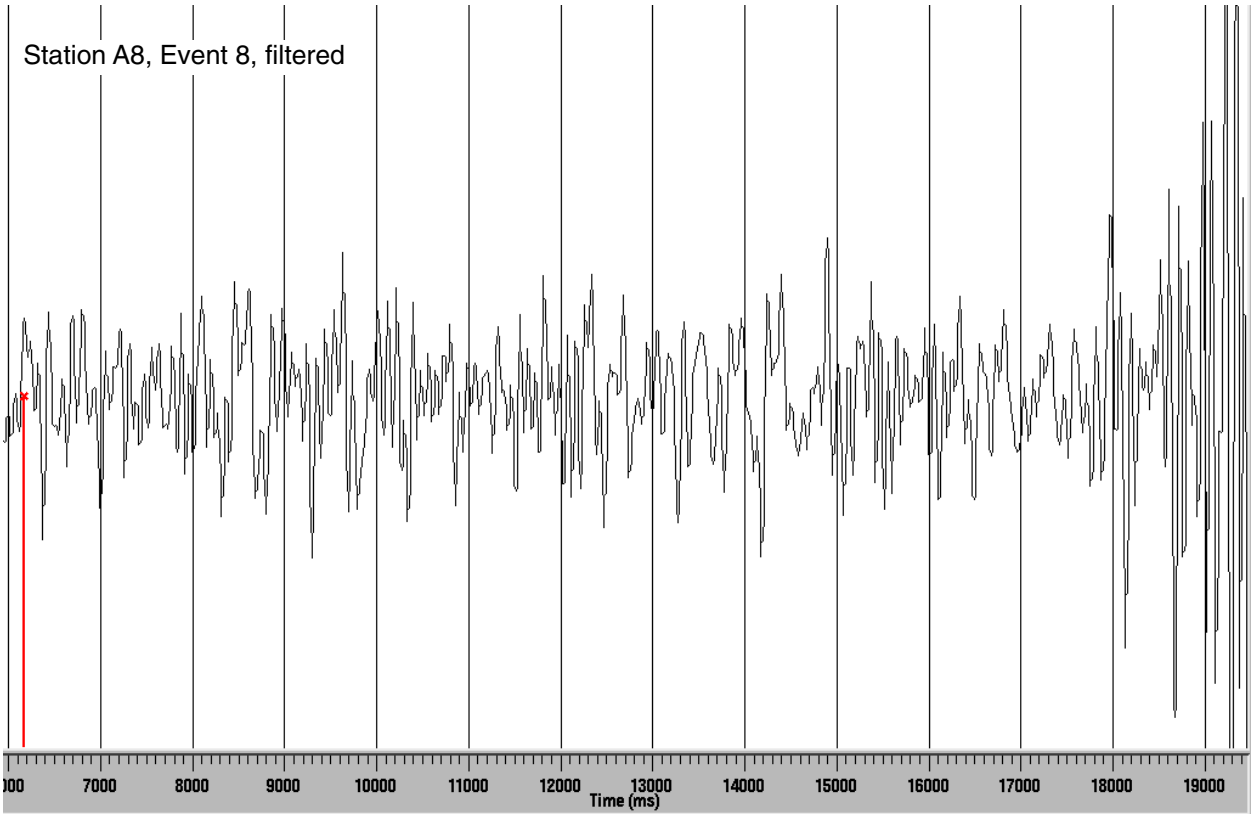


Figure B85. Event 10, from the list of 20 local events, at station A8.

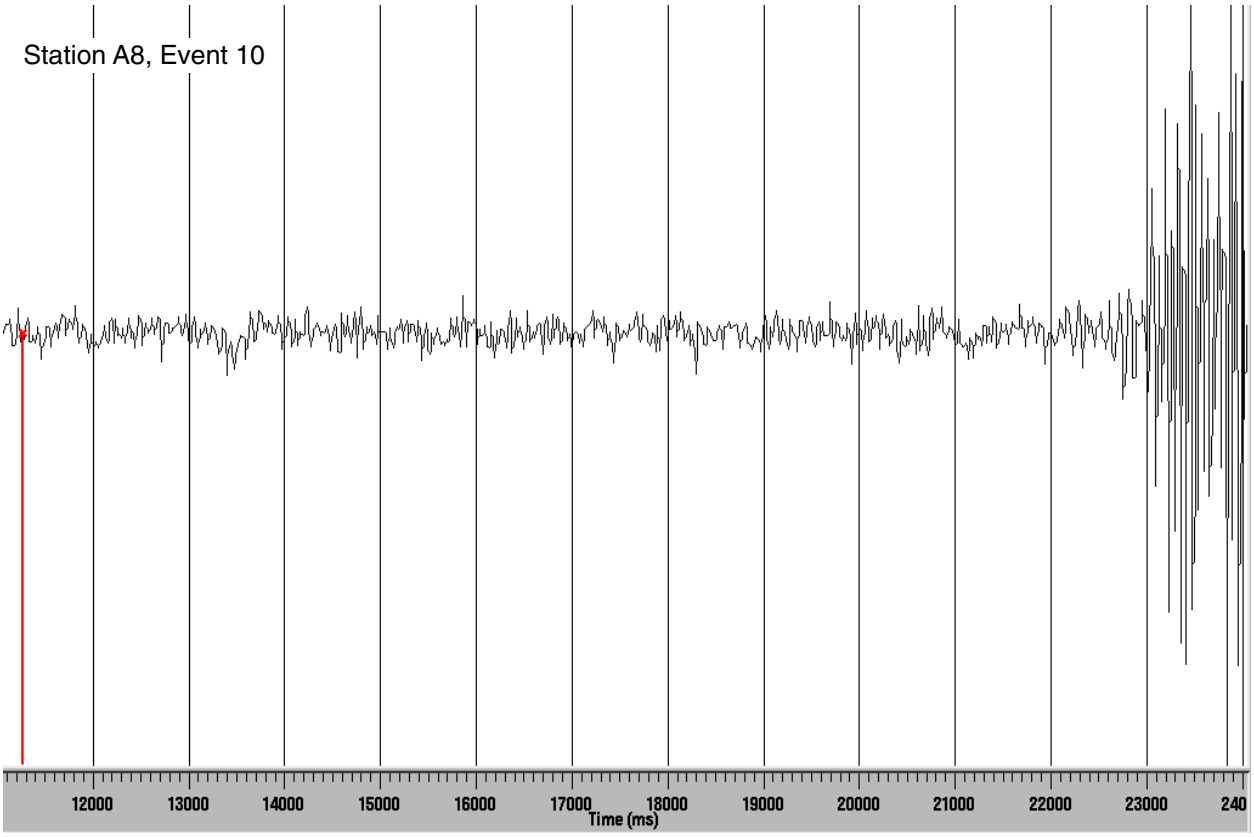


Figure B86. Event 11, from the list of 20 local events, at station A8.

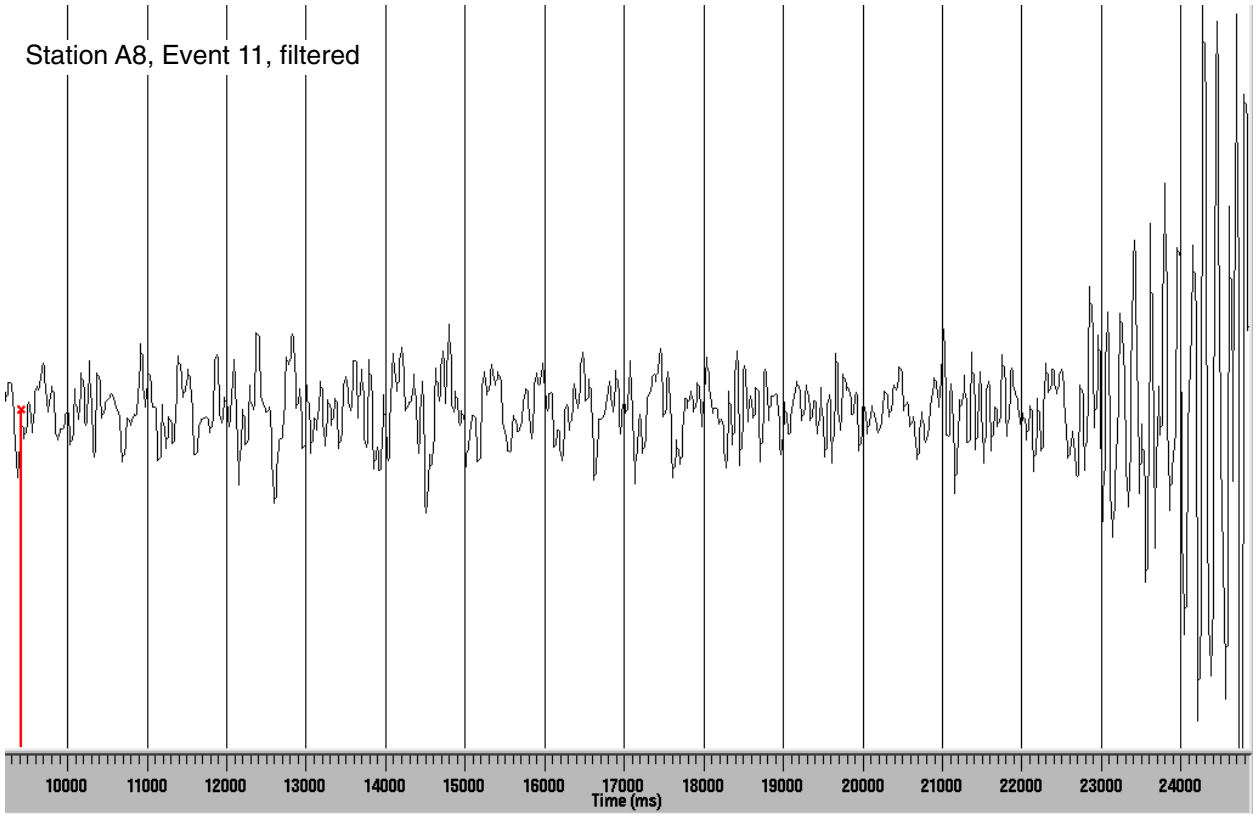


Figure B87. Event 12, from the list of 20 local events, at station A8.

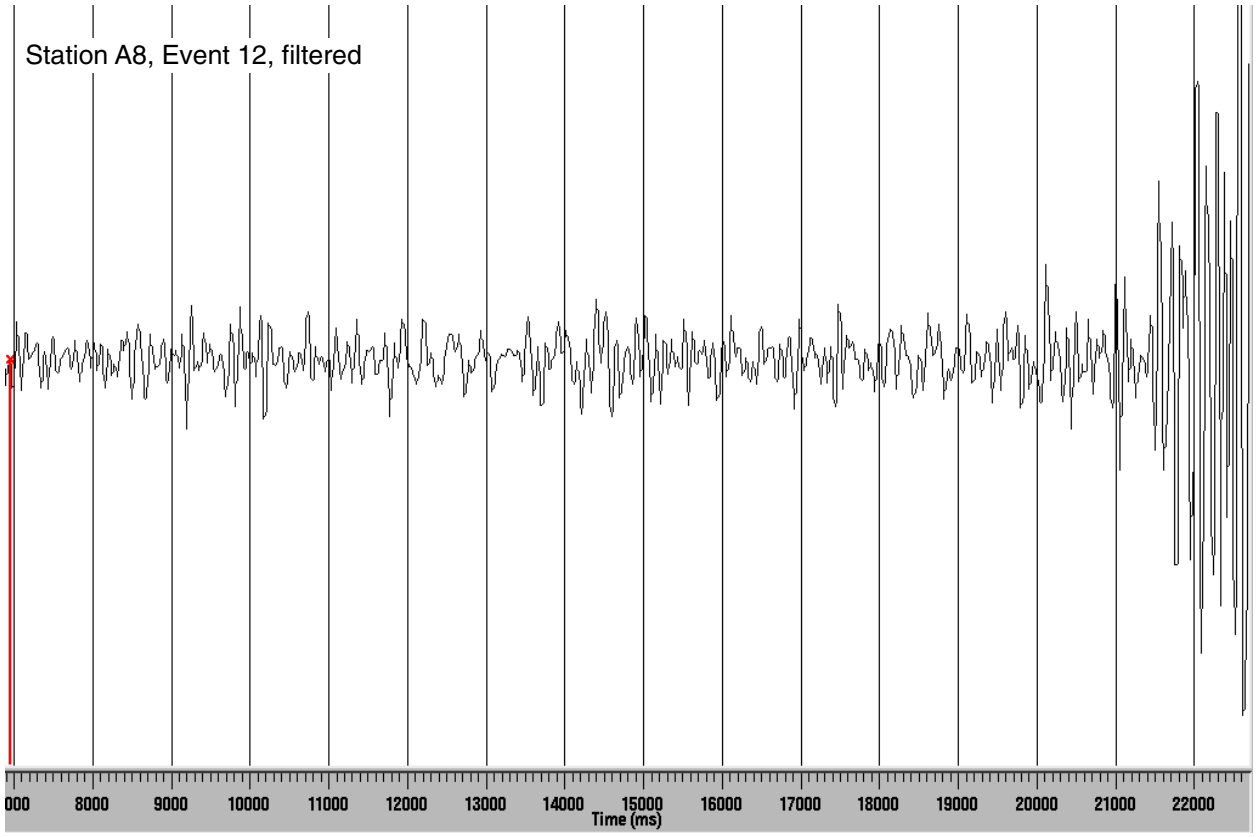


Figure B88. Event 13, from the list of 20 local events, at station A8.

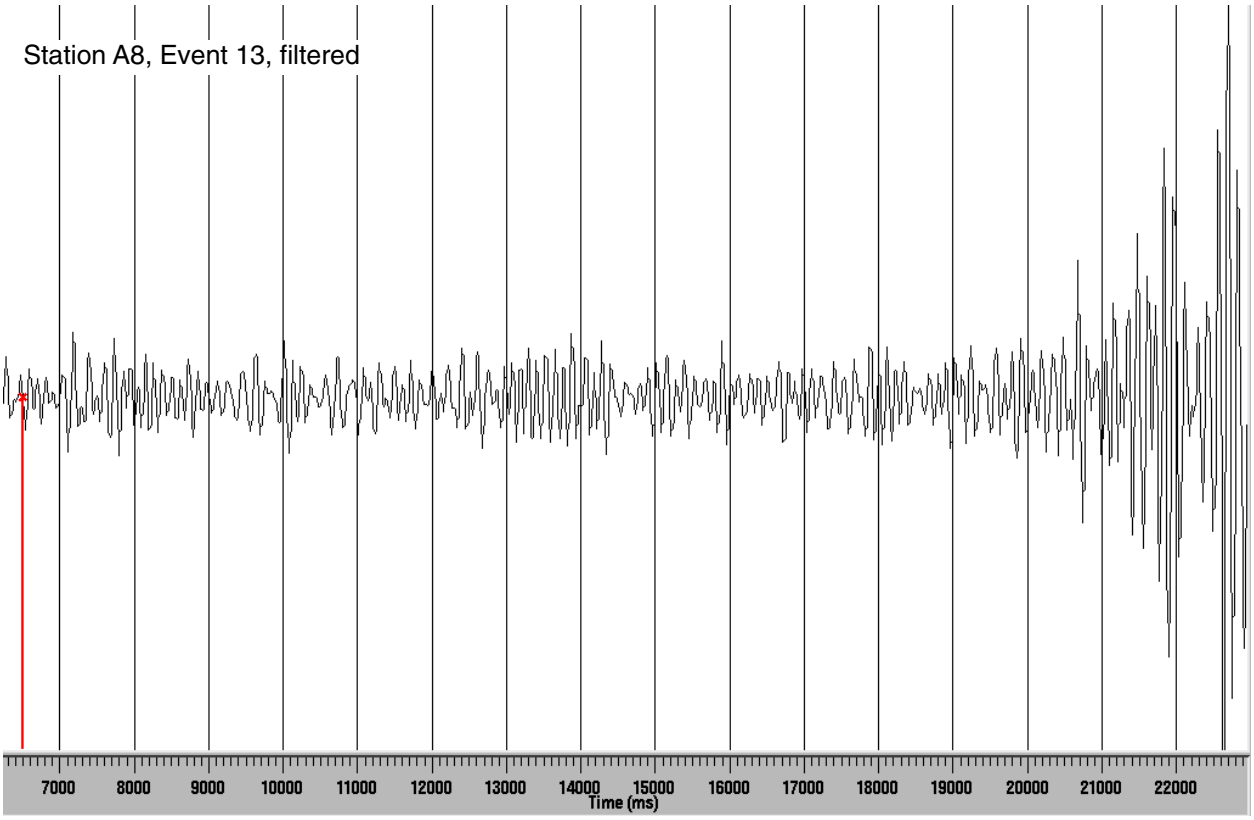


Figure B89. Event 14, from the list of 20 local events, at station A8.

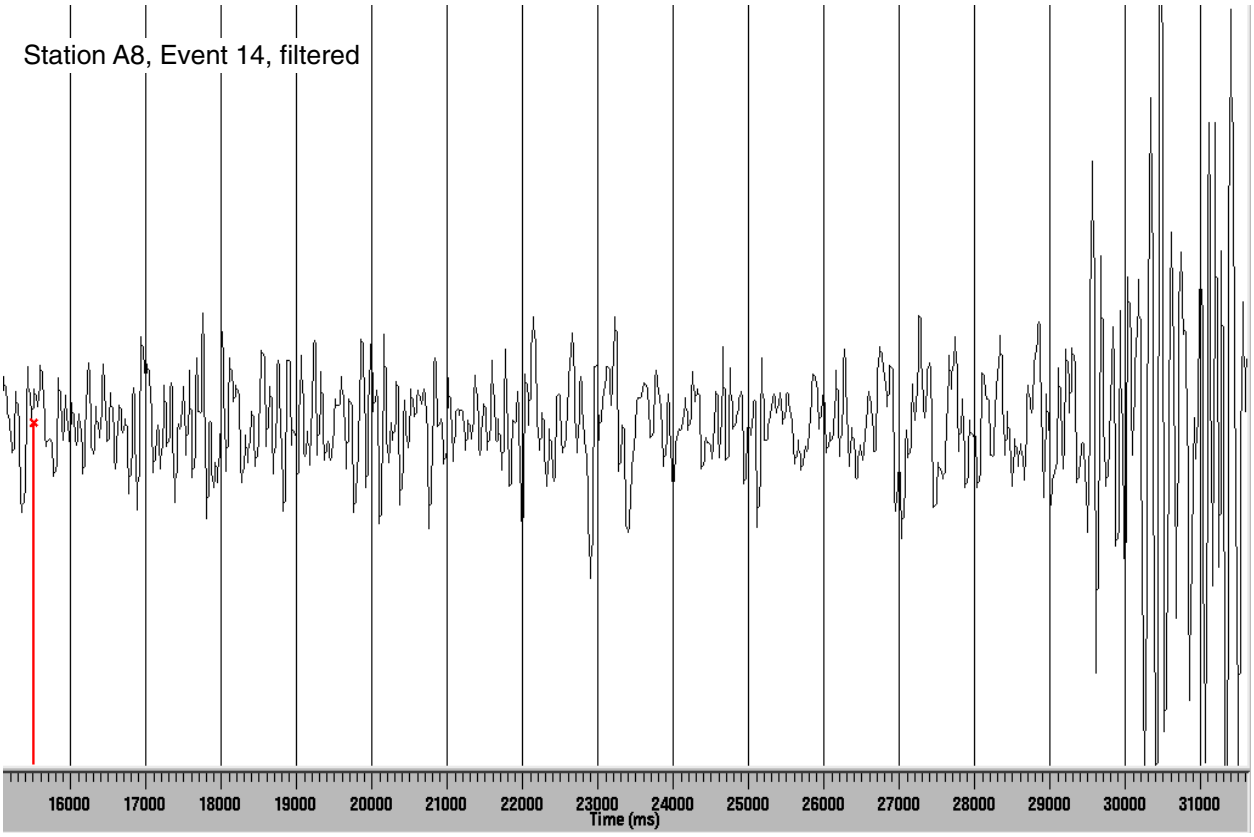


Figure B90. Event 15, from the list of 20 local events, at station A8.

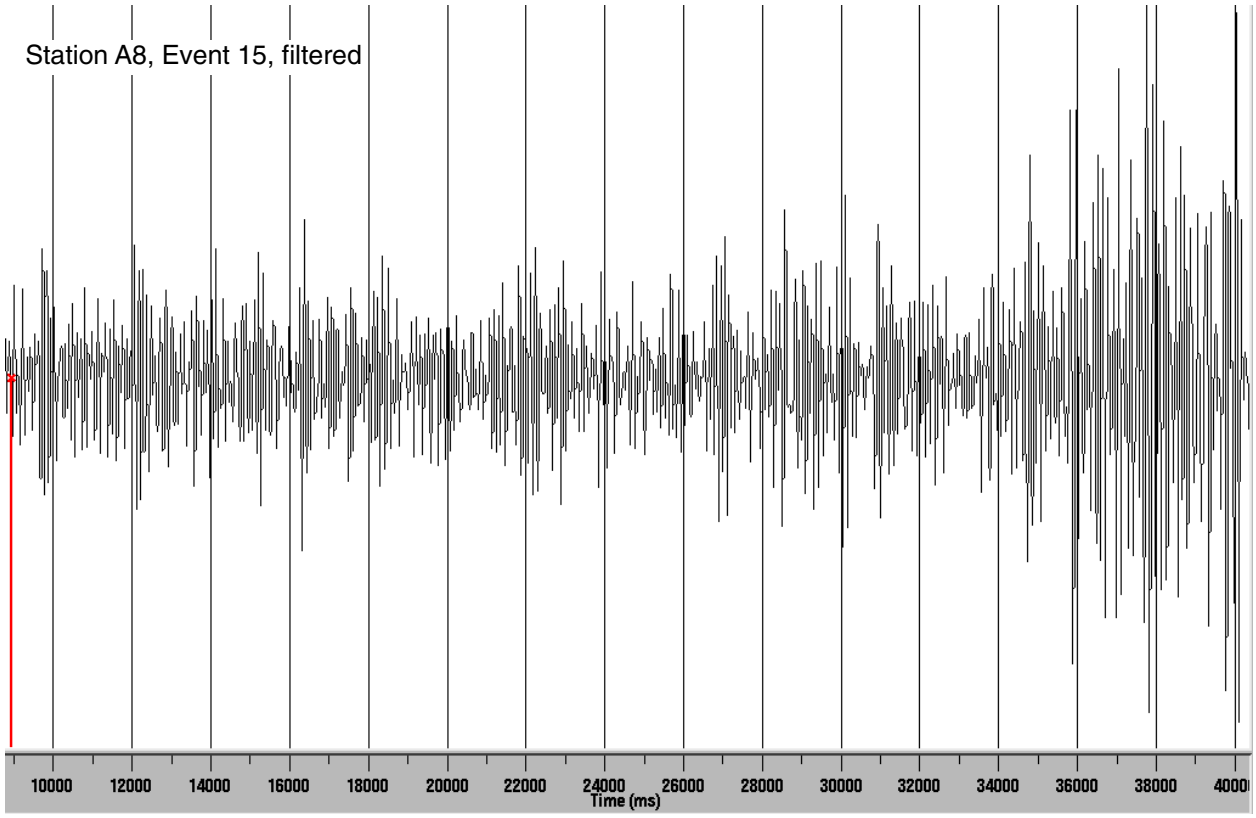


Figure B91. Event 16, from the list of 20 local events, at station A8.

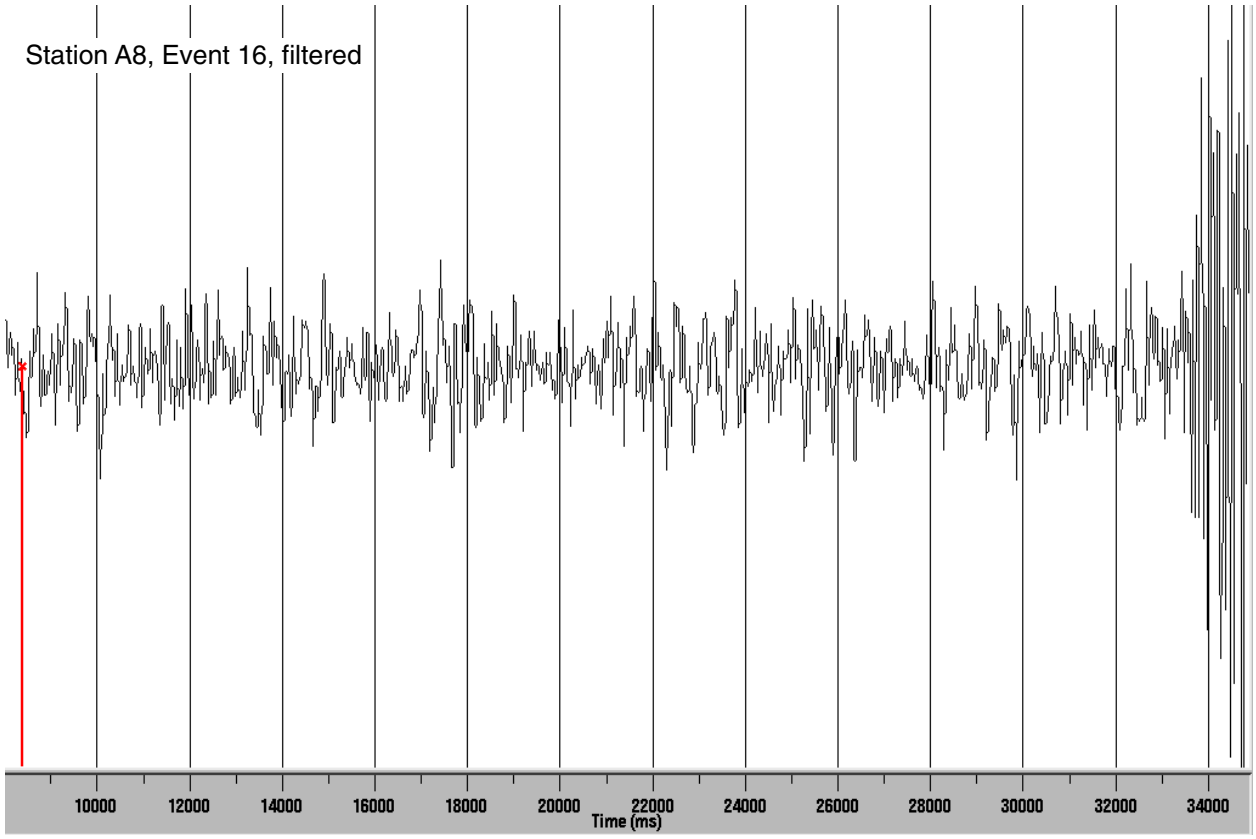


Figure B92. Event 17, from the list of 20 local events, at station A8.

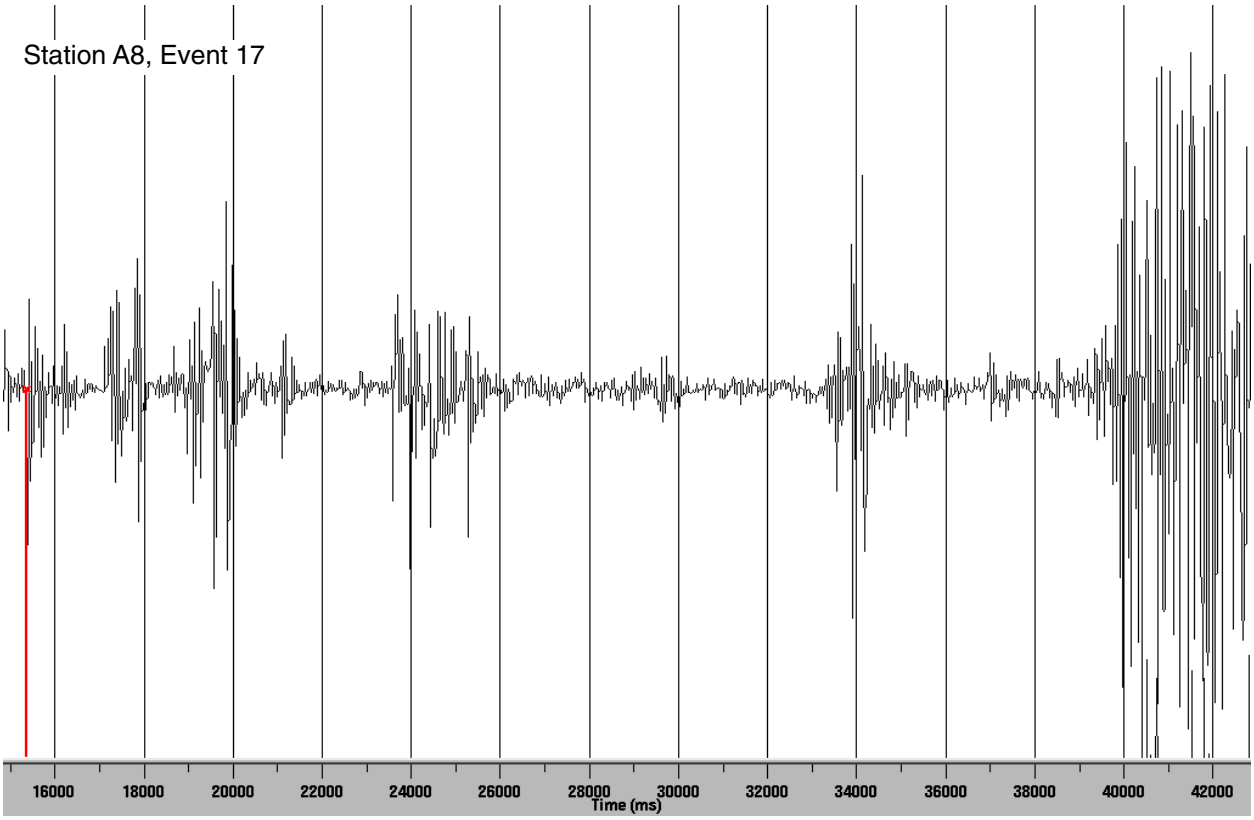


Figure B93. Event 18, from the list of 20 local events, at station A8.

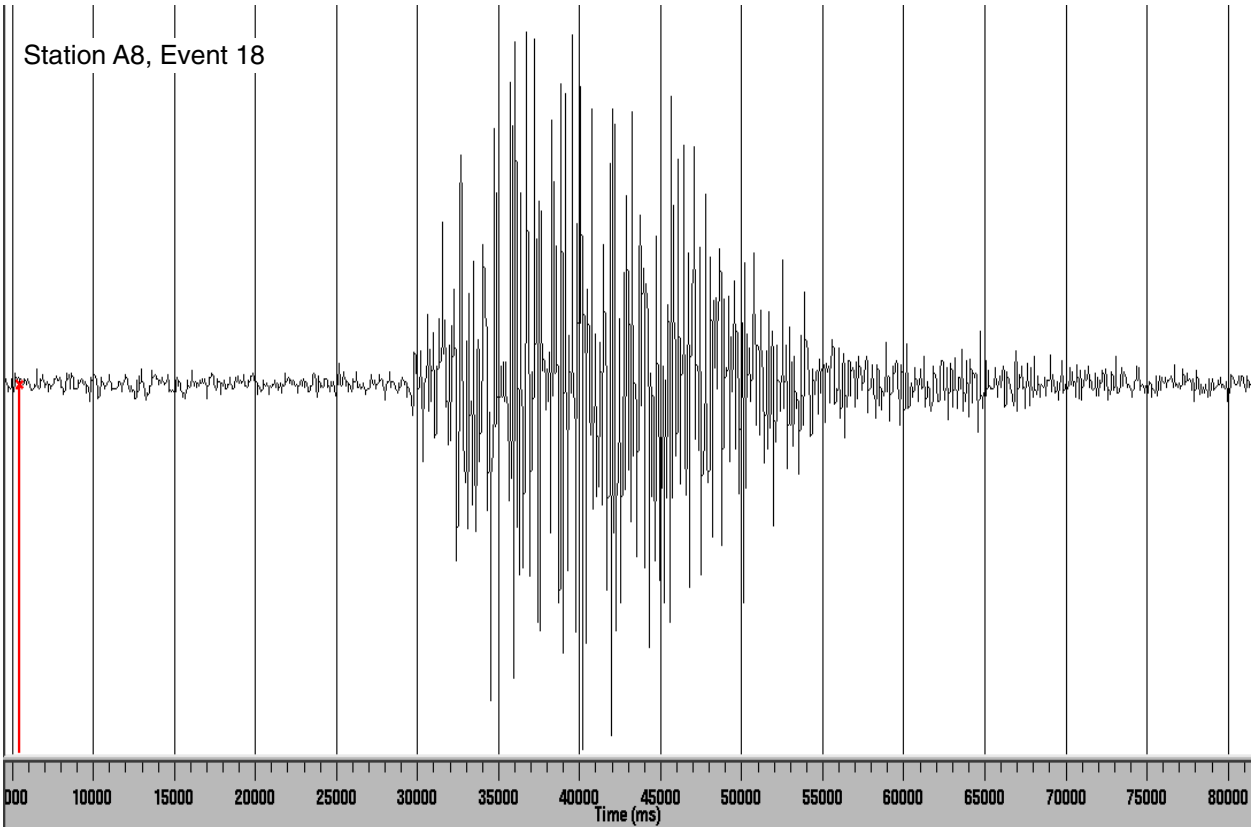


Figure B94. Event 19, from the list of 20 local events, at station A8.

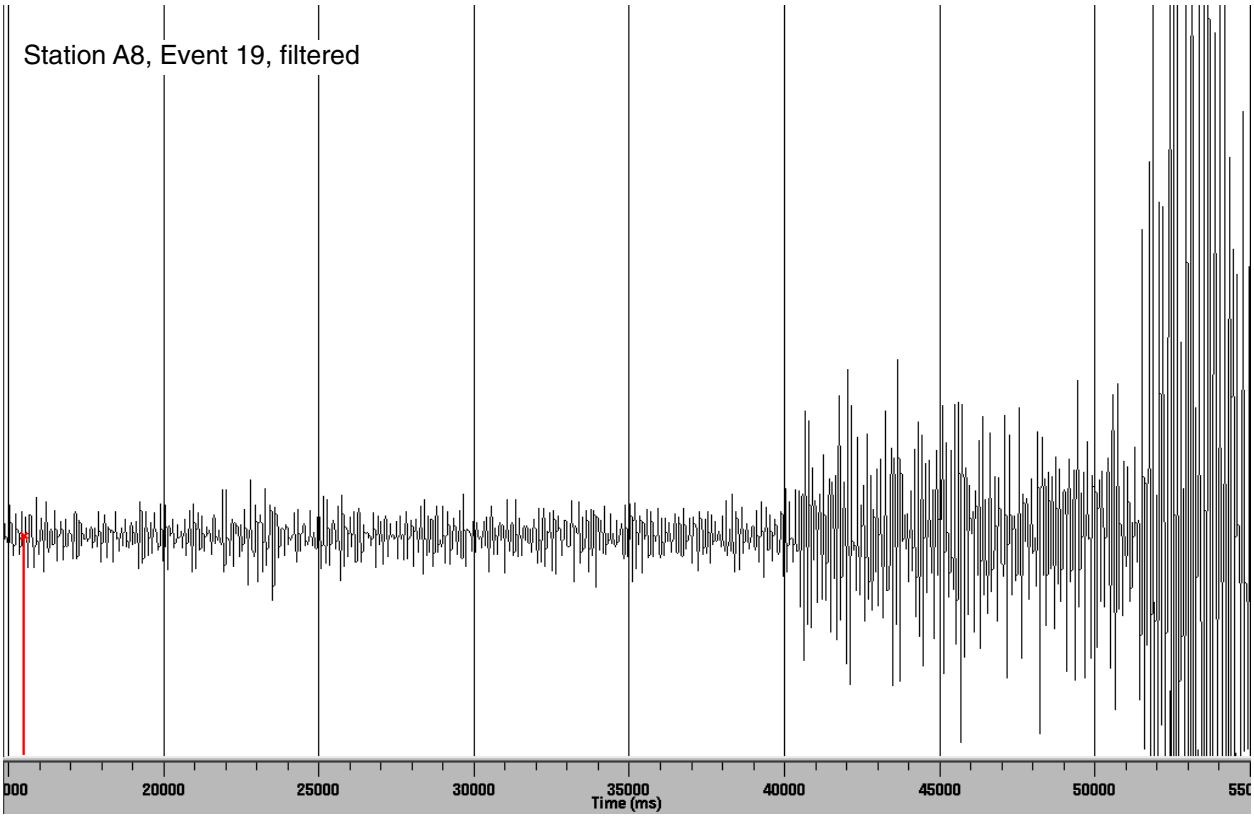


Figure B95. Event 20, from the list of 20 local events, at station A8.

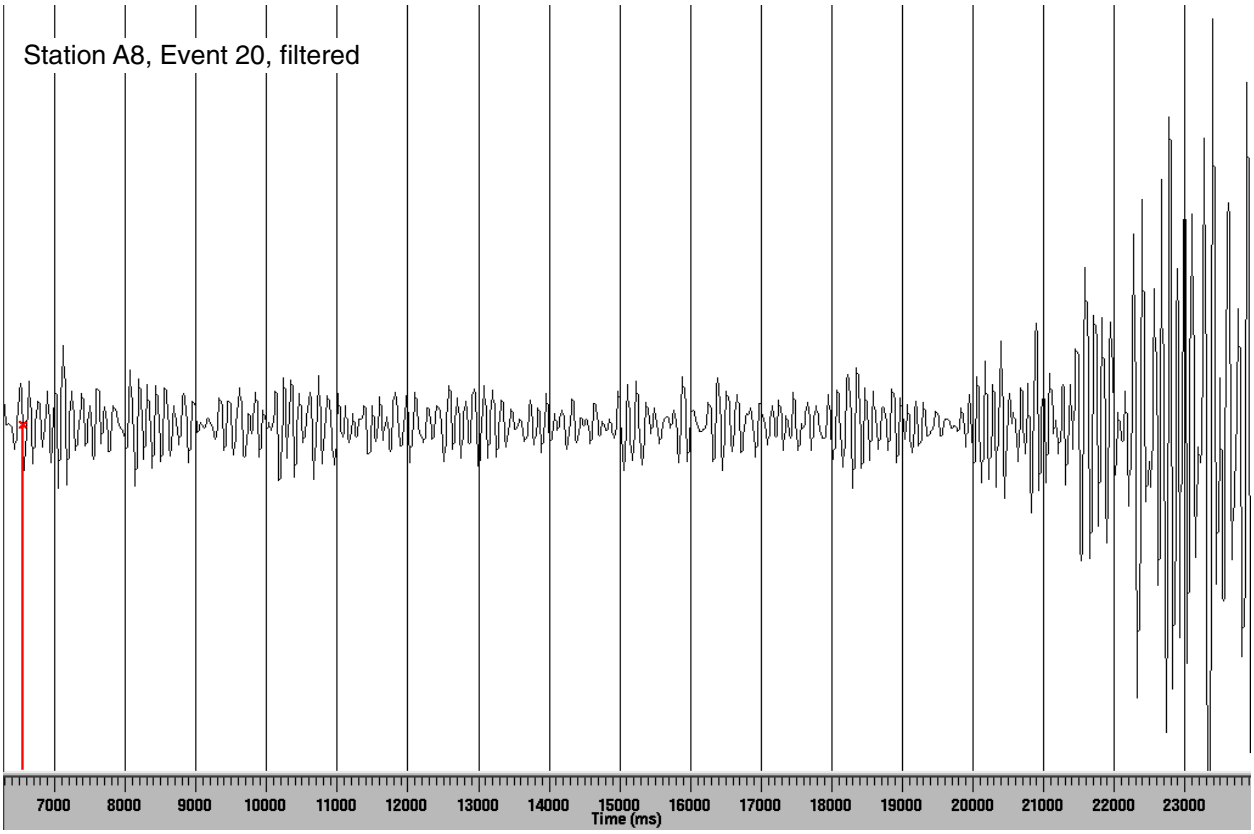


Figure B96. Event 2, from the list of 20 local events, at station D4.

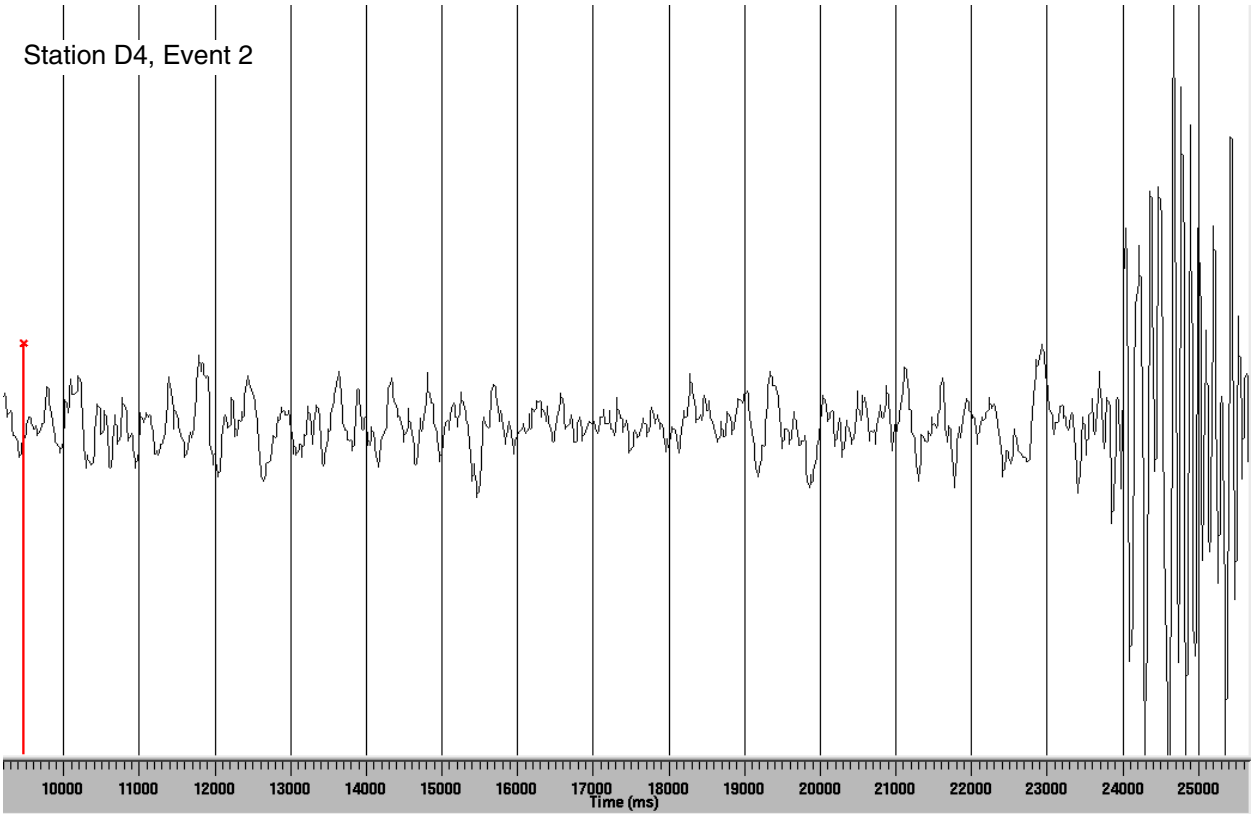


Figure B97. Event 3, from the list of 20 local events, at station D4.

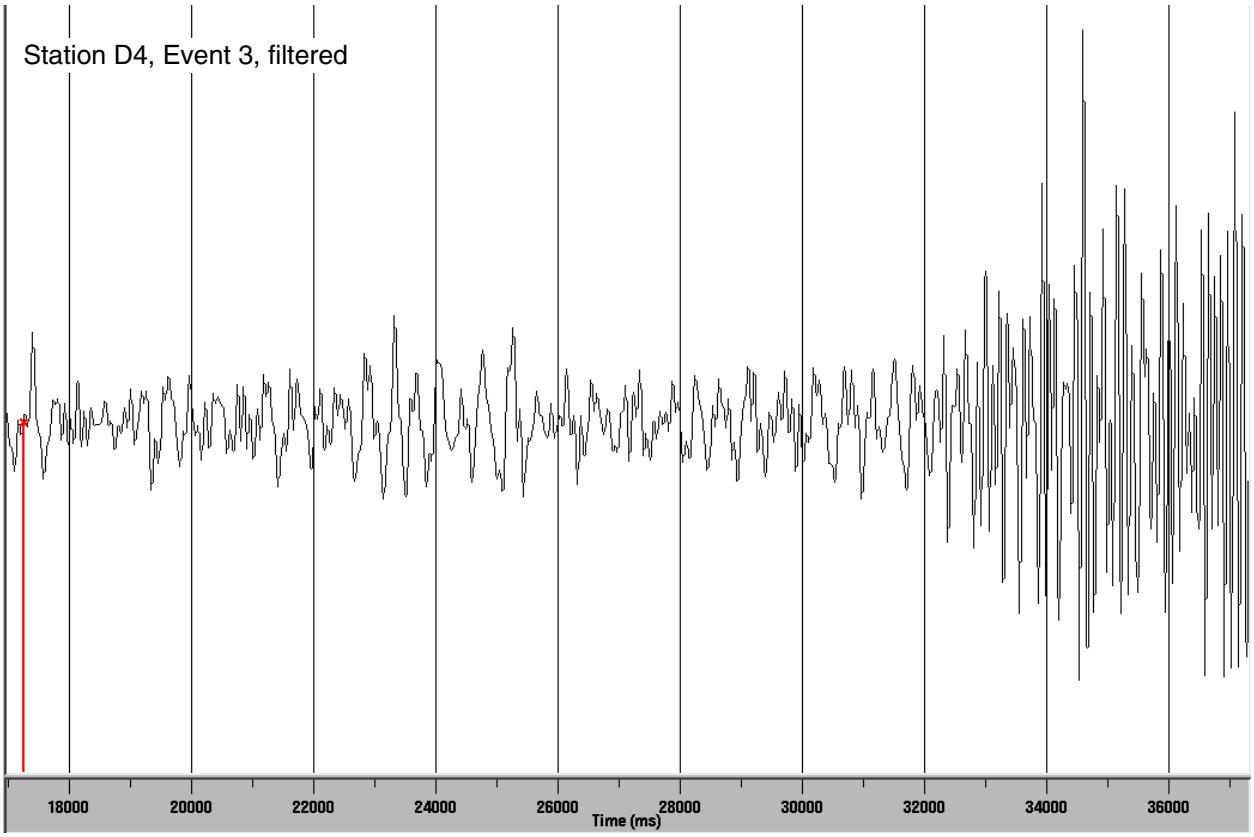


Figure B98. Event 4, from the list of 20 local events, at station D4.

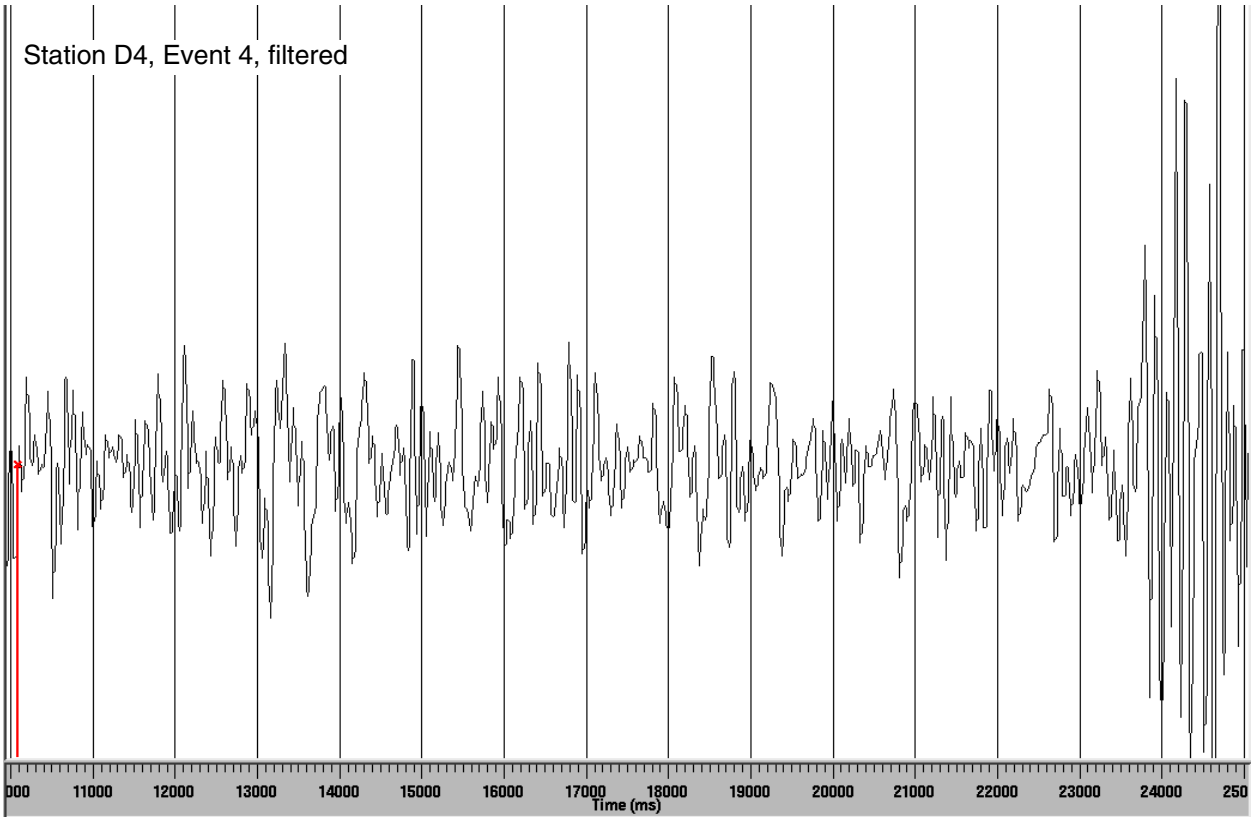


Figure B99. Event 5, from the list of 20 local events, at station D4.

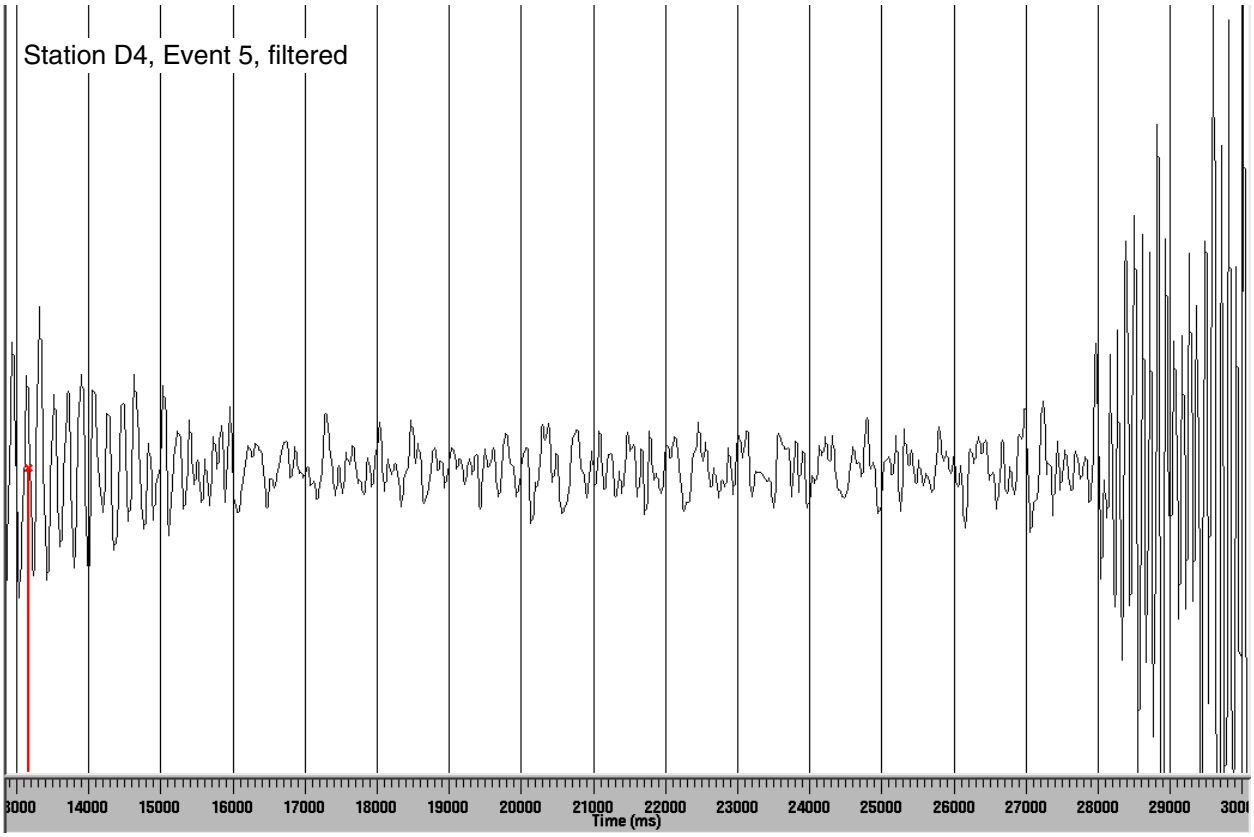


Figure B100. Event 6, from the list of 20 local events, at station D4.

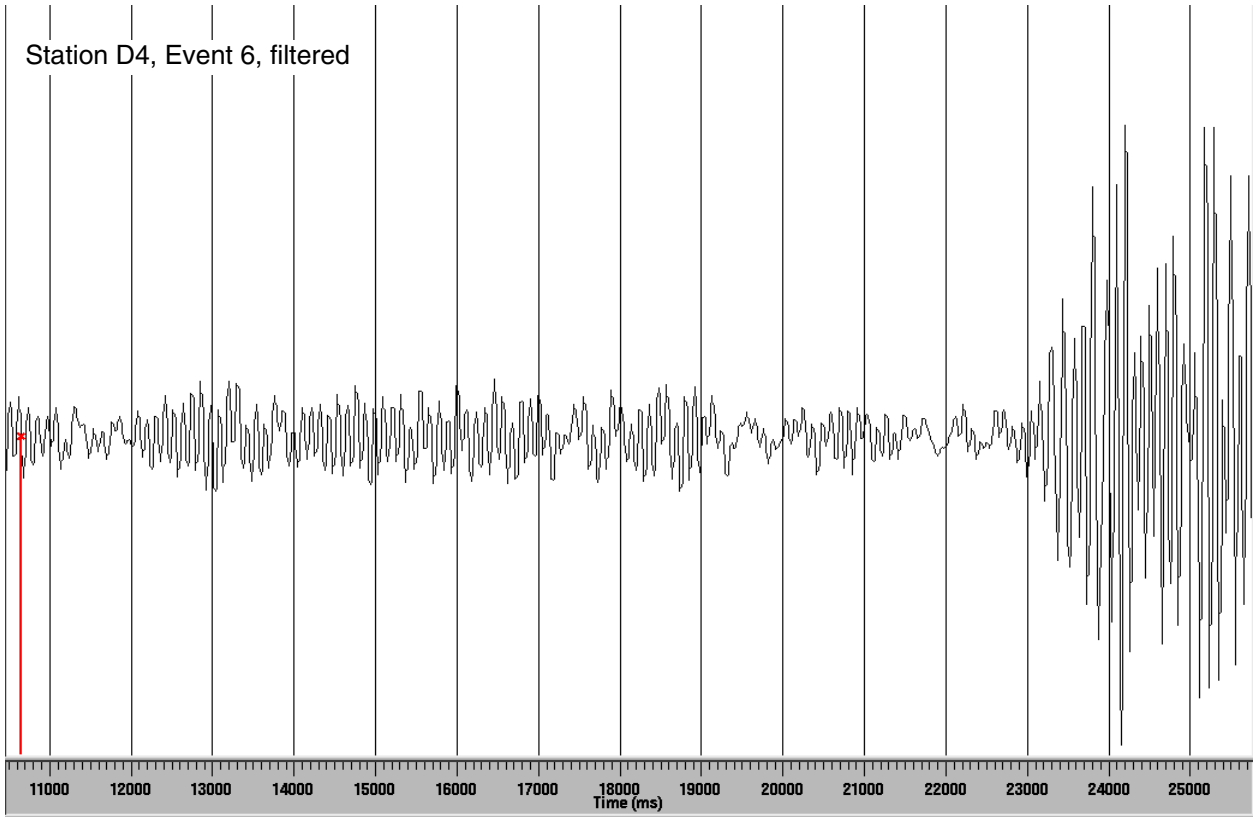


Figure B101. Event 7, from the list of 20 local events, at station D4.

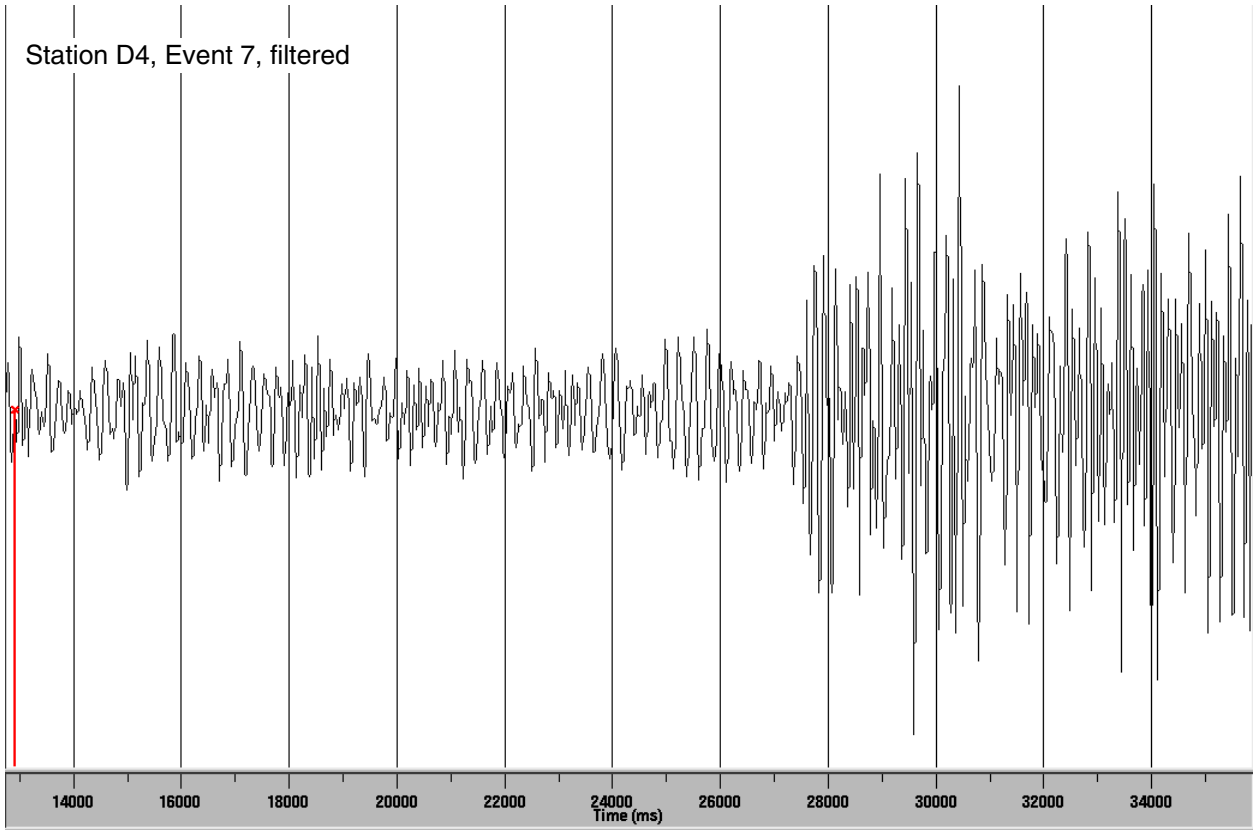
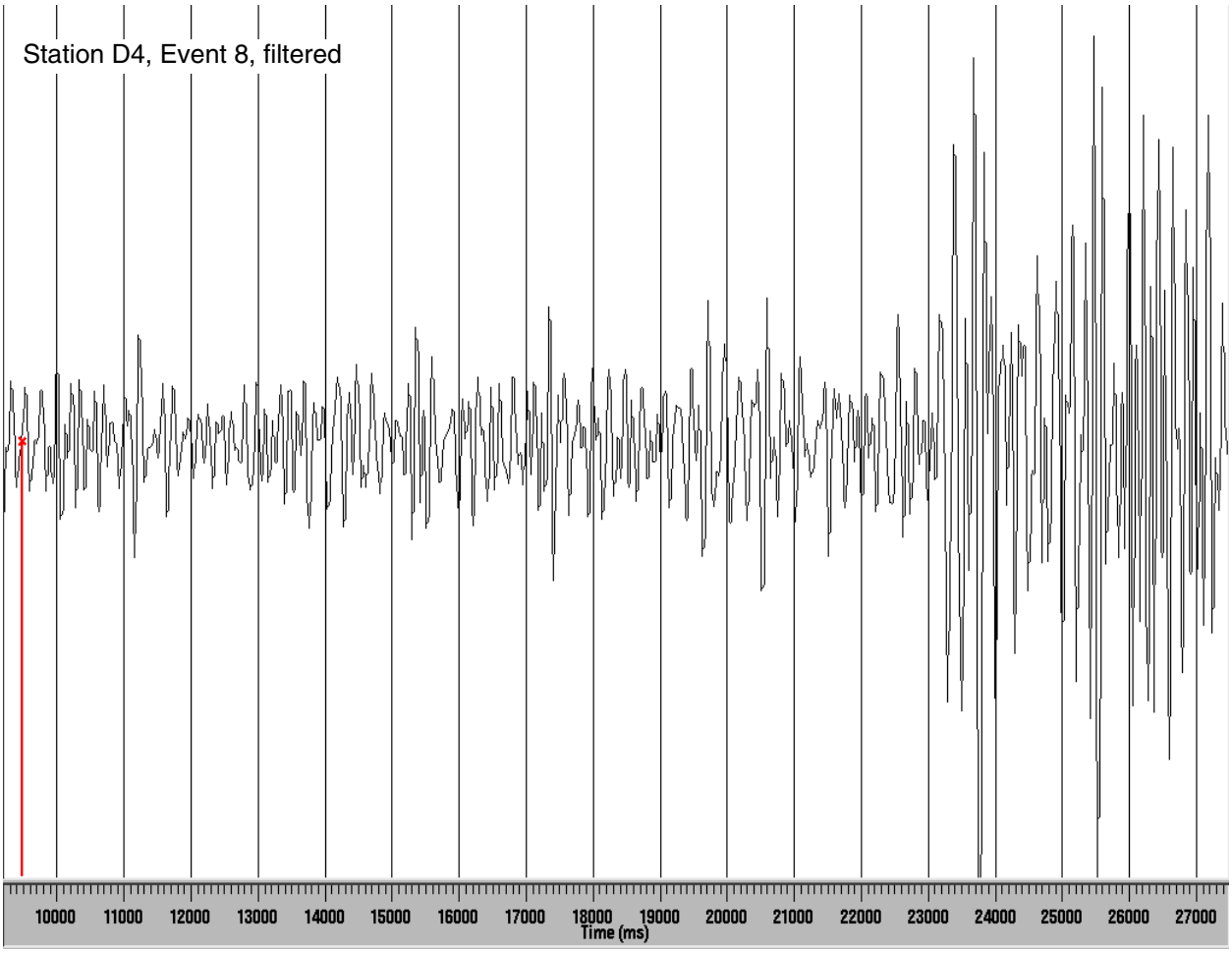


Figure B102. Event 8, from the list of 20 local events, at station D4.



APPENDIX C:

USGS TEMPORARY LAND STATION INFORMATION

On April 24-25, 2000, three temporary land stations were deployed for 1.5 months along the western side of Puerto Rico (Figures 1 and 5, and Table C1). These stations fill in the gaps in the north-south and east-west lines of ocean bottom seismometers. The sites were also chosen so as to augment the current coverage of PRSN land stations. While these three stations will not provide locations of new events, they will help reduce the relocation errors for most onshore or near-shore events.

Three short-period three-component land seismographs were provided by the USGS Menlo Park, CA, office. Table C3 describes the technical specifications for the temporary land seismographs. During the 45-day deployment, each station was serviced twice to download data to tape. Continuous data was saved in Reftek format and later written as SEGY files.

Table C2. USGS temporary land station deployment personnel.

Deployment Personnel
Russell Sell, USGS
Dr. Erich Roth, USGS
Rafael Abreu, Puerto Rico Seismic Network, UPRM
Samuel Vega Figueroa, Puerto Rico Seismic Network, UPRM

Table C1. USGS temporary land station information.

Station	Location	Latitude	Longitude	Installed (UTC)	Removed	Comments
OVEJ	North of Mayagüez	18° 15.5' N	67° 5.5' W	4/25/2000 16:21	6/13/2000	
GUAN	Guanica State Forest	17° 58.0' N	66° 52.5' W	4/25/2000 20:54	6/13/2000	
COAM	Banjo de Coamo	18° 02.5' N	66° 22.5' W	4/26/2000 15:53	6/14/2000	A bad disk was swapped out on 6/15/2000. This resulted in the loss of data for 6/13/2000 through 6/15/2000.

Table C3. USGS temporary land seismometer specifications.

Instrument:	Mark Products L-22 seismometer
Type:	3-component Short-period 2 Hz natural frequency
Data Recorder:	Reftek Data Acquisition System Model 72A-07/6
Sample Interval:	100 samples per second
Clock Accuracy:	Clock synchronized with REFTEK Model 111A GPS clock Time errors less than 10 milliseconds
Power:	1 Standard 12-volt deep-cycle auto battery Continuously recharged with a trickle charger

APPENDIX D:

PUERTO RICO SEISMIC NETWORK INFORMATION

At the time of the OBS experiment the University of Puerto Rico, Mayagüez, maintained a network of 15 short-period and broadband one- and three-component land seismographs on the main island of Puerto Rico and several surrounding islands (Figures 1 and 5, and Table D1). The data from the network is either saved to disk and retrieved manually or telemetered back to UPRM through a repeater in central Puerto Rico. For the broadband stations the format is RT raw (steim-1) format, and for the short-period network the format is 16-bit multiplexed binary data. This network is used to routinely locate all local Puerto Rico events.

Table D1. Permanent land stations active during USGS deployment.

Name	Station Type	Components	Latitude	Longitude	Elevation (m)
AGP	short period	vertical	18.4075° N	67.141° W	220
LSP	short period	vertical	18.177° N	67.086° W	390
IDE	short period	3-component	18.386° N	67.496° W	140
LRS	short period	vertical	18.193° N	66.845° W	460
CBYP	short period	vertical	18.271° N	65.856° W	140
APR	short period	vertical	18.457° N	66.729° W	550
PNP	short period	vertical	18.059° N	66.766° W	53
PORP	short period	vertical	18.054° N	66.637° W	165
CELP	short period	vertical	18.075° N	66.576° W	195
CSB	short period	vertical	18.289° N	66.156° W	430
CPD	short period	vertical	18.039° N	65.915° W	370
SJG	short period	vertical	18.112° N	66.150° W	457
CORN	broadband	3-component	18.163° N	67.179° W	100
MGP	broadband	3-component	18.007° N	67.089° W	60
IMO	broadband	3-component	18.111° N	67.908° W	50