Earthquake on the Hussar low-frequency experiment

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ABSTRACT

On the last day of acquisition on the Hussar low-frequency line, a magnitude 6.3 earthquake occurred offshore of Vancouver Island, British Columbia, Canada. The low-frequency seismic line included 10 Hz 3-C geophones at 10 meter station spacing, VectorSeis 3-C accelerometers at 10 meter spacing, 4.5 Hz geophones at 20 meter spacing, a partial line of high-sensitivity 10 Hz geophones at 10 Hz spacing and Nanometrics compact seismometers at 200 meter spacing. Earthquake arrivals were recorded during acquisition of source line 6, which had a Failing vibe running two 1-100 Hz low-dwell sweeps per vibe point. The earthquake was successfully recorded by all sensors that were part of the low-frequency experiment, at a distance of about 1050 kilometers from the epicenter. The earthquake arrivals have an apparent velocity of about 4500 m/s across the 4.5 km seismic line. Inverse filtering of the 10 Hz and 4.5 Hz geophone data to correct for geophone response at low frequencies is shown to be succesfull, based on visual inspection, at enhancing data with frequencies of less than one Hertz.

INTRODUCTION

On the last day of acquisition on the Hussar low-frequency line, a magnitude 6.3 earthquake occurred offshore of Vancouver Island, British Columbia, Canada. The low-frequency seismic line included 10 Hz 3-C geophones at 10 meter station spacing, VectorSeis 3-C accelerometers at 10 meter spacing, 4.5 Hz geophones at 20 meter spacing, a partial line of high-sensitivity 10 Hz geophones at 10 Hz spacing and Nanometrics compact seismometers at 200 meter spacing. Earthquake arrivals were recorded during acquisition of source line 6, which had a Failing vibe running two 1-100 Hertz low-dwell sweeps per vibe point. The earthquake was recorded by all sensors that were part of the low-frequency experiment, at a distance of about 1050 kilometers from the epicenter (Figure 1).

Table 1 is a merged version of the observer's notes from the two Aries (SPML271 and SPML295, run by CREWES) and one Scorpion recorder (run by Geokinetics) that were on site. The observer in the Scorpion recorder required that VP 209 be repeated due to earthquake 'noise' on his noise monitor during the first try. The repeated VP 209 was not recorded by either of the Aries systems. Data compared in this report is highlighted in yellow (Table 1). Note that vibe points 210-217 were not acquired due to a highway crossing. We will be comparing single-fold uncorrelated data for this report, with the exception of Scorpion/VectorSeis data, for which the two uncorrelated source gathers were vertically stacked in the field.

Seismometer data

Figure 2 shows the vertical component of the seismometer data for the earthquake arrivals after being normalized by dividing each trace by the maximum amplitude on that trace. The east and north components look similar (not shown). The traces in this figure are 11.5 minutes long. Red lines delineate the start time of the first vibe sweep of two (Table 1; Hall and Margrave, 2011), and a black line shows the time of the earthquake (Natural Resources Canada, 2011; Appendix A). Primary arrivals can be seen about halfway between VP 218 and VP 209 times, and the secondary arrivals begin just before VP 209 starts. At the time of VP 208, the highest amplitude secondary arrivals have passed, but the background noise has clearly not yet returned to the levels seen for VP 218.

The Nanometrics compact seismometers have a flat response to velocity from 120 s (0.008 Hz) to 100 Hz (Nanometrics, 2011). The first five Hertz of the average amplitude spectra for the thirteen traces of Figure 2 are shown in Figure 3. Most of the earthquake energy is below 1 Hz. We would normally expect data of these frequencies to be attenuated by recording system hardware and software, geophone response to the velocity of ground motion below 4.5 Hz and 10 Hz, and by correlation with the 1-100 Hz low-dwell sweep that was being used for acquisition. The Aries recorders were run without a low-cut filter during acquisition. The Scorpion recorder purportedly had a low-cut filter in place that could not be turned off.

Other sensors

Figures 4 through 7 allow a visual comparison of uncorrelated source gathers for vibe points 218, 209 and 208 for the vertical components of all receivers on the line. Each source gather covers 4.5 km, repeated three times for a figure width of 13.5 km by 34 seconds. Three things are immediately apparent: 1) We have recorded data of 1 Hz or less on all of the sensors that were deployed for the low-frequency experiment, regardless of recording system low-cut filters (if present) or geophone response to the velocity of low-frequency ground motion. 2) As we would expect from known geophone and accelerometer characteristics, the low-frequency earthquake arrivals are least prominent on the 10 Hz geophone data, better on the 4.5 Hz geophones, and best on the accelerometer data. 3) The earthquake arrivals have an apparent velocity across the seismic line of about 4500 m/s (ie. 4.5 km of seismic line in about one second). As we would expect, they are first seen on the end of the seismic line closest to Vancouver Island (Station 564).

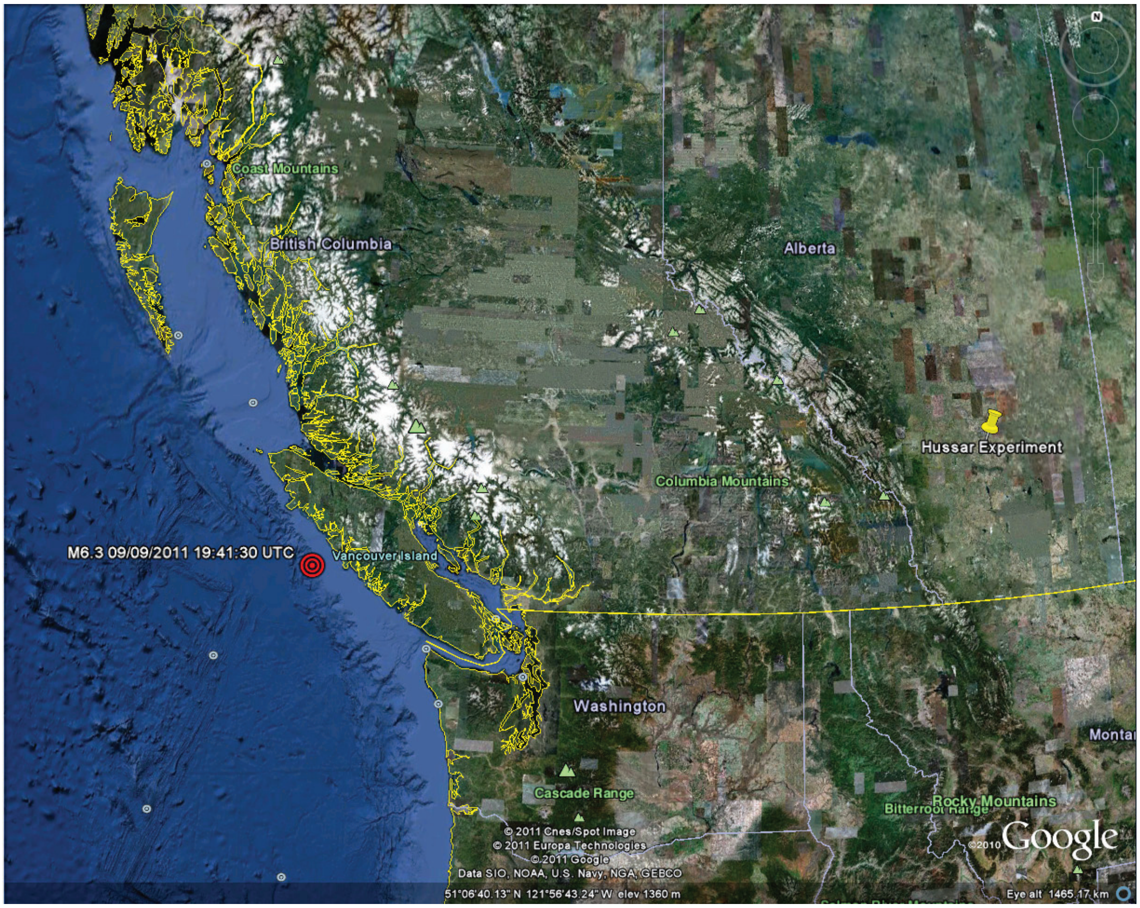

FIG. 1. Earthquake (red bulls-eye) and Hussar low-frequency experiment (yellow push-pin) locations. © 2011 Cnes/Spot Image and © 2011 Europa Technologies and © 2011 Google, Data SIO, NOAA, U.S. Navy, NGA, GEBCO (Google Earth, 2011 and Natural Resources Canada, 2011).

Table 1. Merged and edited observer's notes. Shots compared in this report are high-lighted in yellow (Uncorrelated data, first sweep of two per vibe point).

SPML273 Flag	SPML273 File	SPML295 File	Scorpion SHOT ID	Scorpion TIME (UTC)	Scorpion COMMENTS
Flag	File	File	SHOT ID	TIME	COMMENTS
218	2142	2230	1315593673	9/9/2011 19:41:14	35M S.E.
218	2143	2231			
209	2145	2233	1315593998	9/9/2011 19:46:43	Void File Earthquake
209	2146	2234			
209			1315594116	9/9/2011 19:48:38	
208	2148	2236	1315594204	9/9/2011 19:50:05	
208	2149	2237			

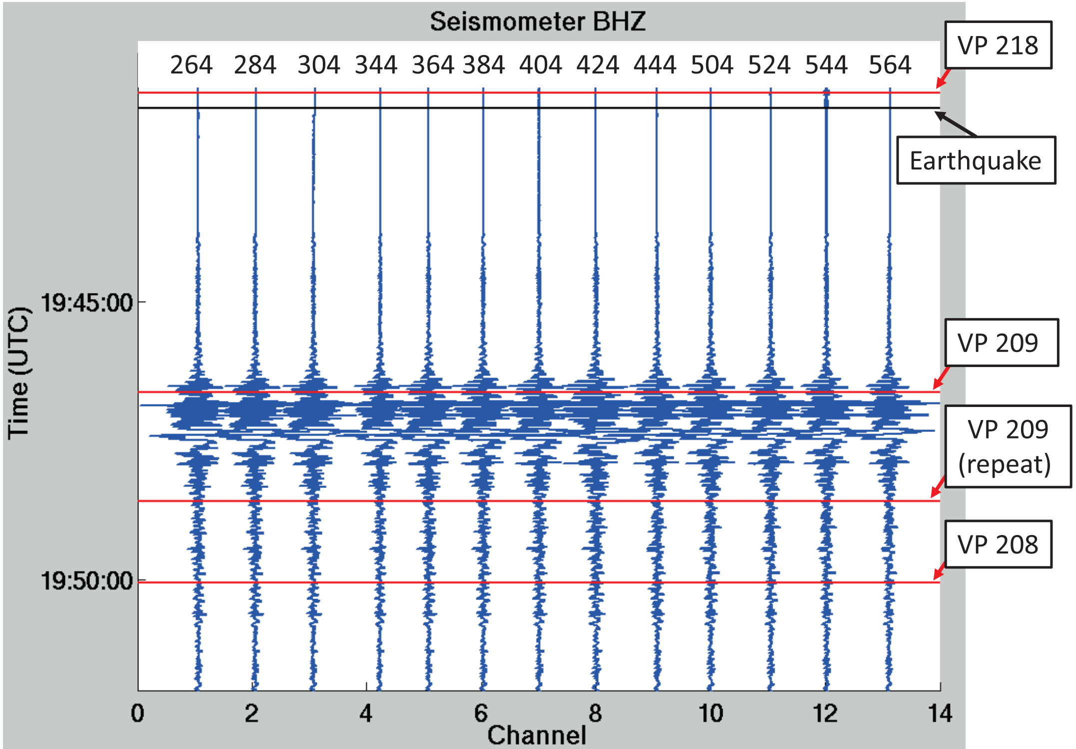

FIG. 2. Vertical component of uncorrelated data from seismometers. Trace length is 11.5 minutes. The time of the first sweep (of two sweeps per vibe point) is shown as red lines. The time of the earthquake is shown as a black line (see Appendix A).

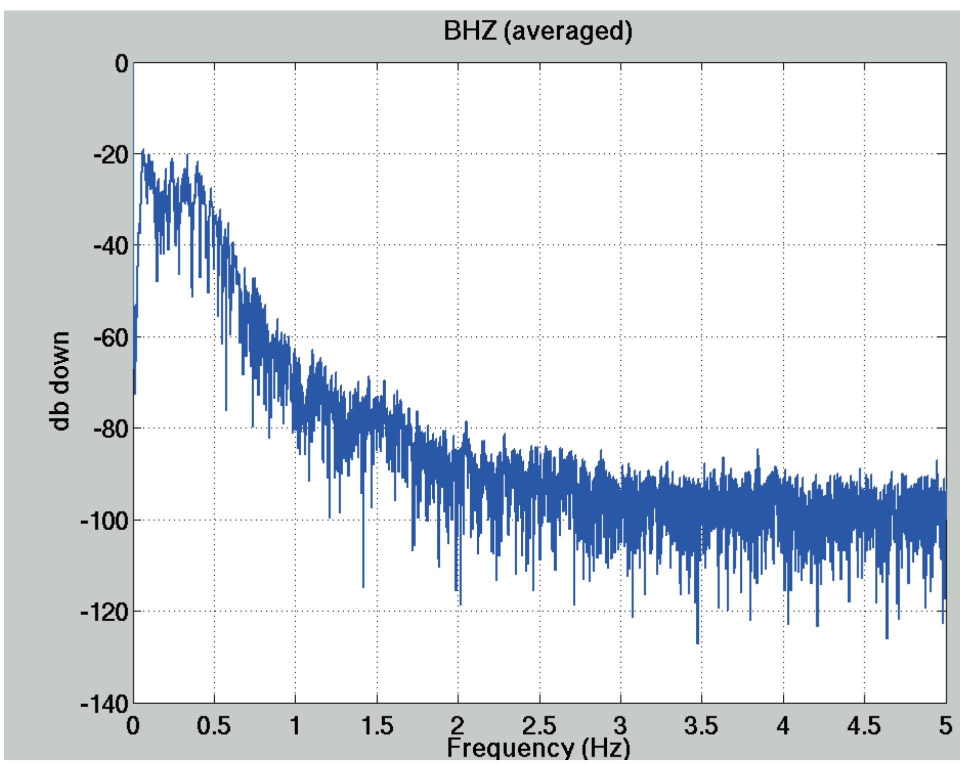

FIG. 3. First 5 Hz of the amplitude spectra for the traces shown in Figure 1. There is an apparent DC bias in this figure. Earthquake energy is primarily below 2 Hertz.

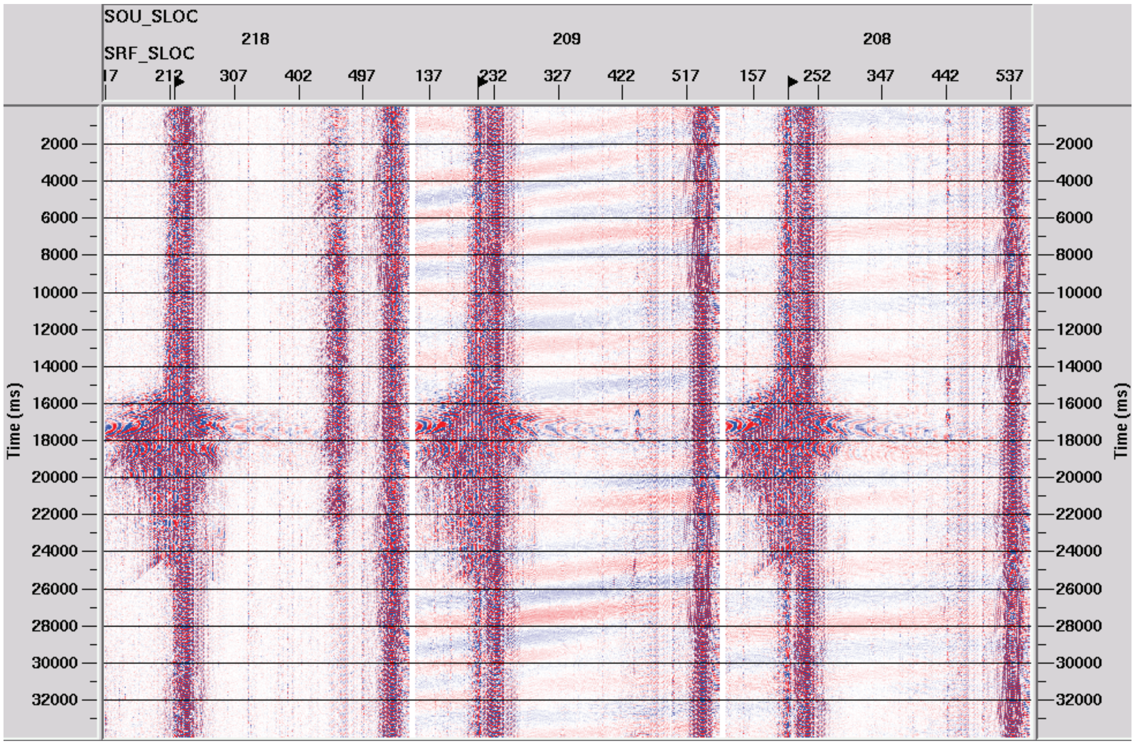

FIG. 4. Vertical component of uncorrelated data from 10 Hz 3-C geophones for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to fifteen. Vertical fold is one.

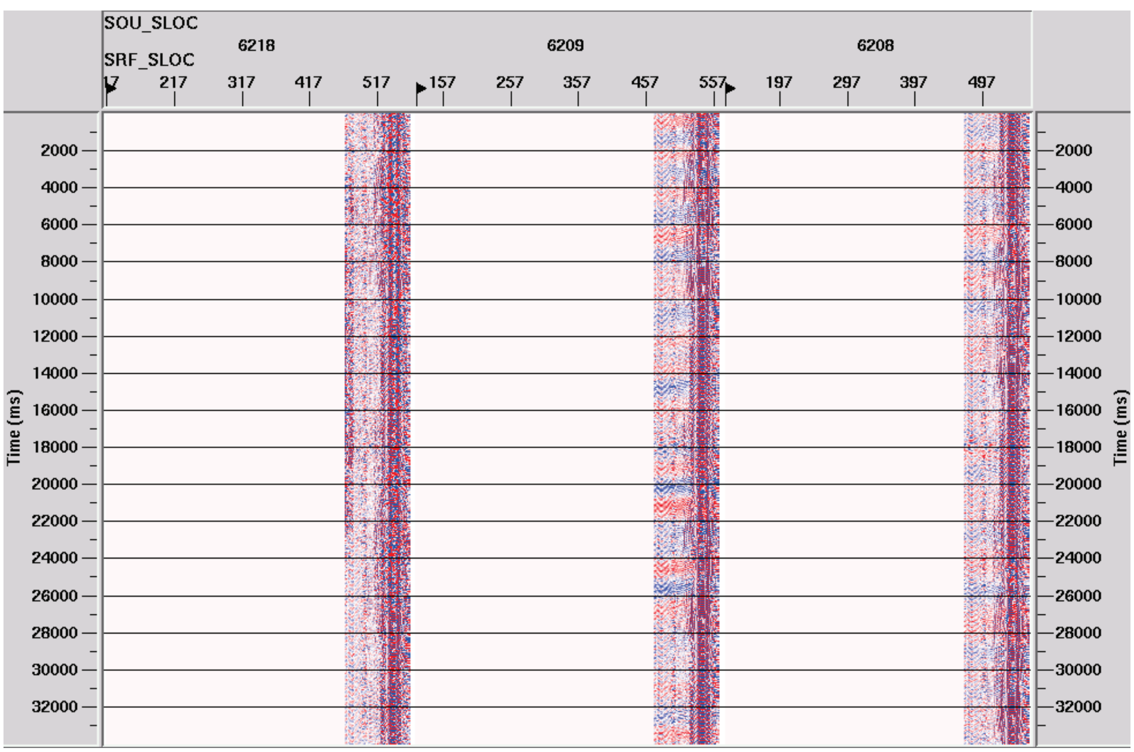

FIG. 5. Uncorrelated data from 10 Hz high-sensitivity geophones for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to five. Vertical fold is one.

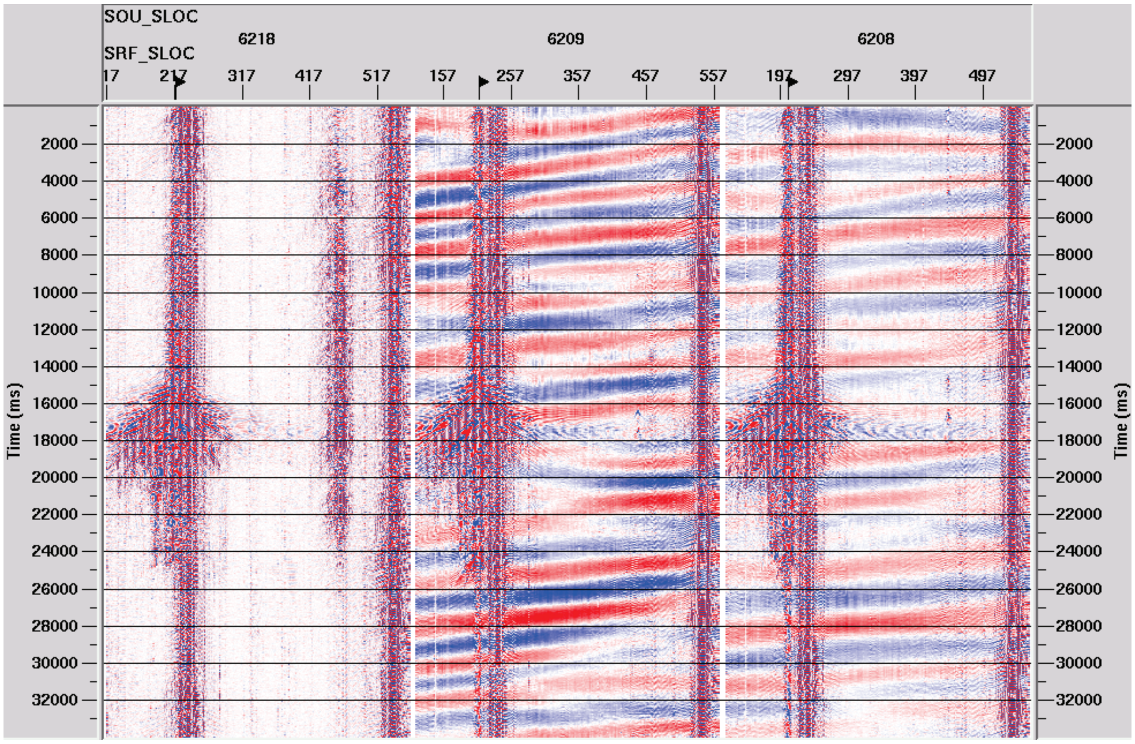

FIG. 6. Uncorrelated data from 4.5 Hz 1-C geophones for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to fifteen. Vertical fold is one.

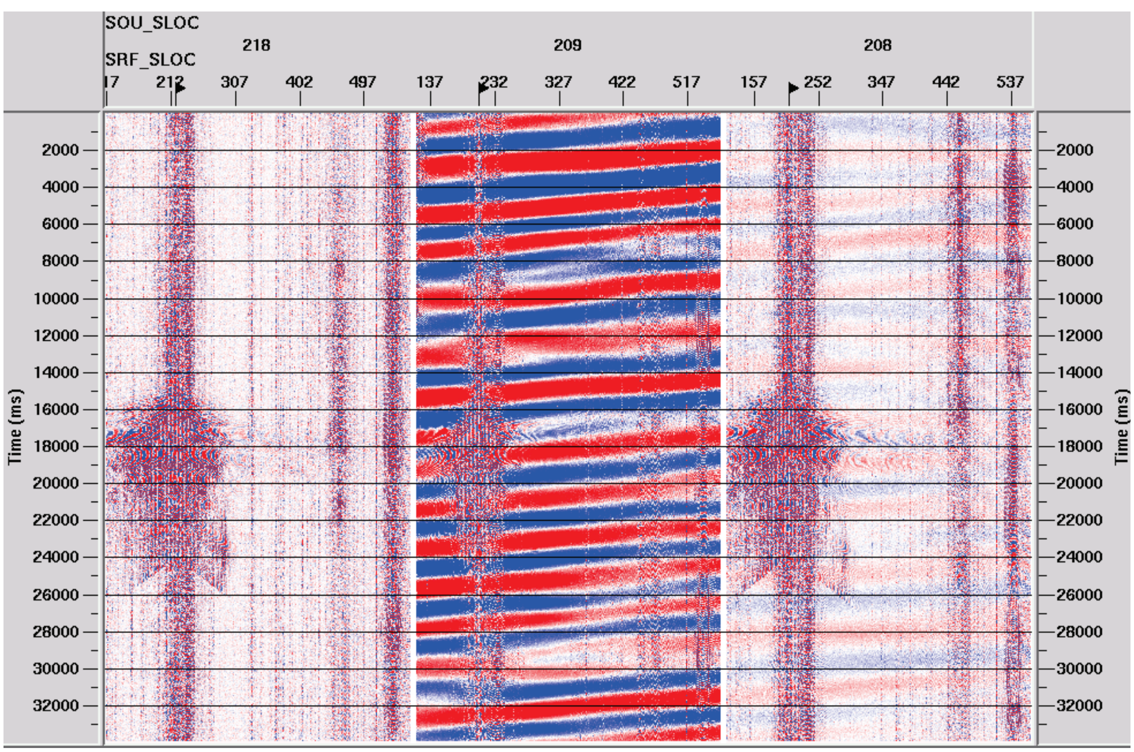

FIG. 7. Uncorrelated data from the vertical component of VectorSeis accelerometers for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to fifteen. Vertical fold is two.

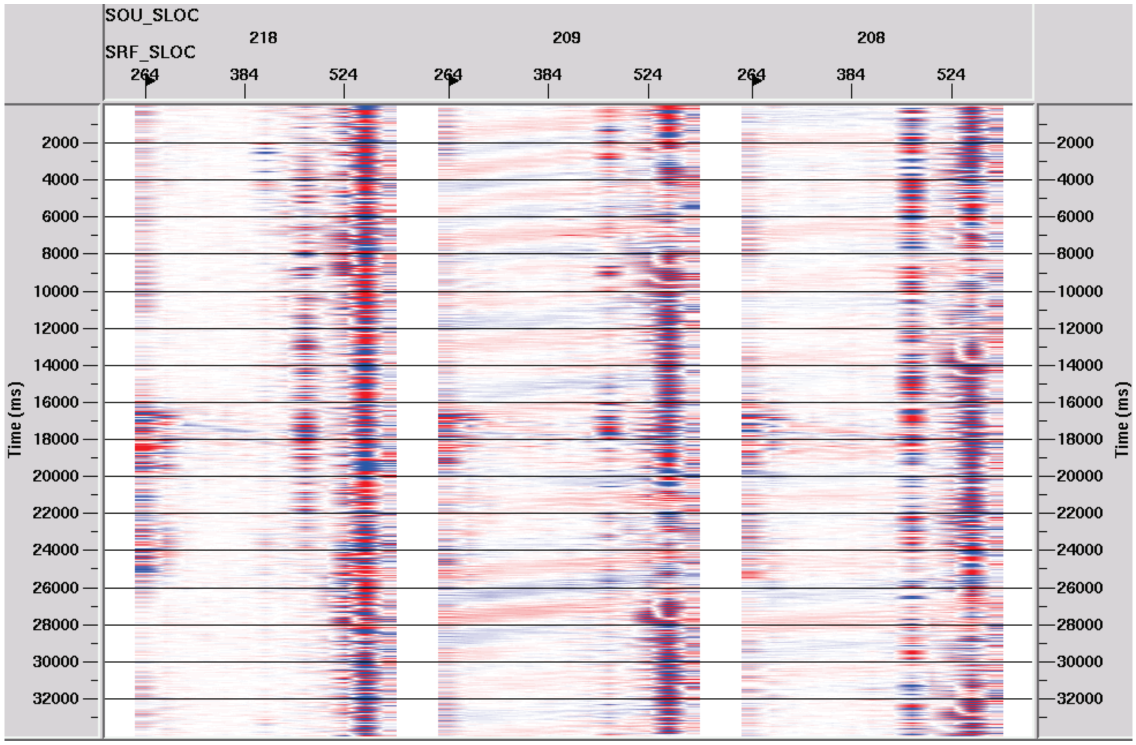

FIG. 8. Vertical component of uncorrelated data from 10 Hz 3-C geophones at thirteen seismometer stations for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is one.

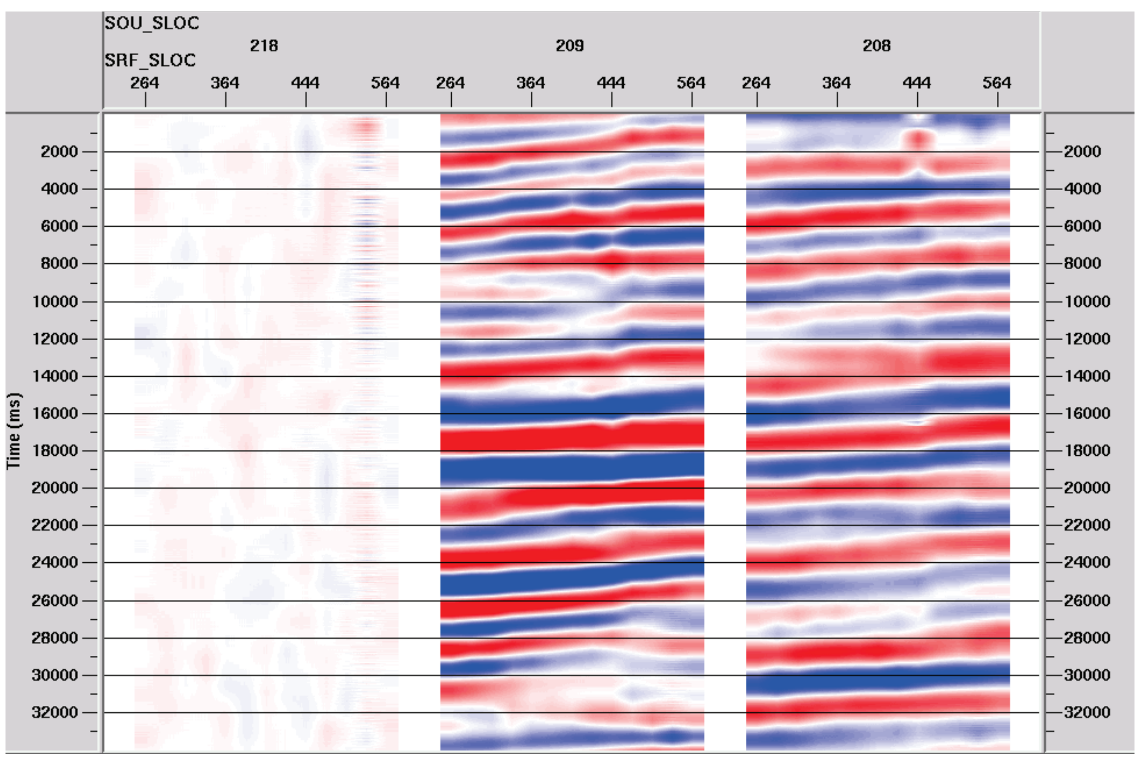

FIG. 9. Figure 8 after correcting for geophone response below 10 Hz. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is one.

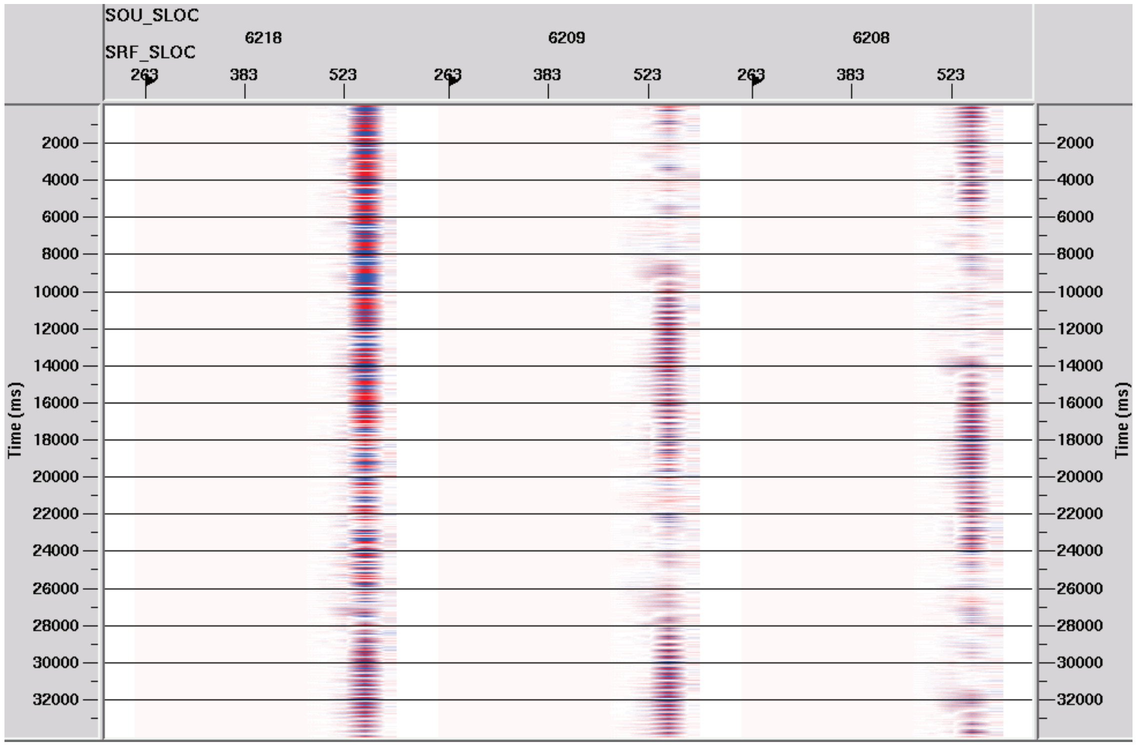

FIG. 10. Uncorrelated data from four 10 Hz high-sensitivity geophones one flag east of seismometer stations for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is one.

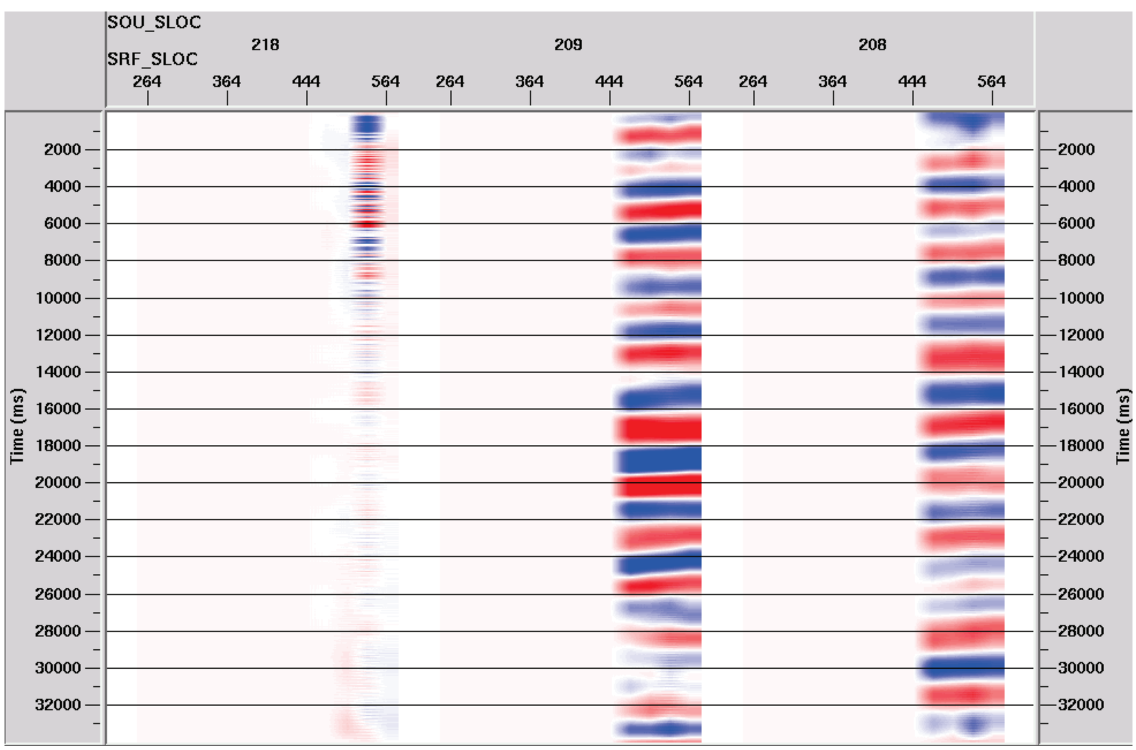

FIG. 11. Figure 10 after correcting for geophone response below 10 Hz. Trace length is 34 seconds. ProMAX trace display scaling: entire screeen with gain set to one. Vertical fold is one.

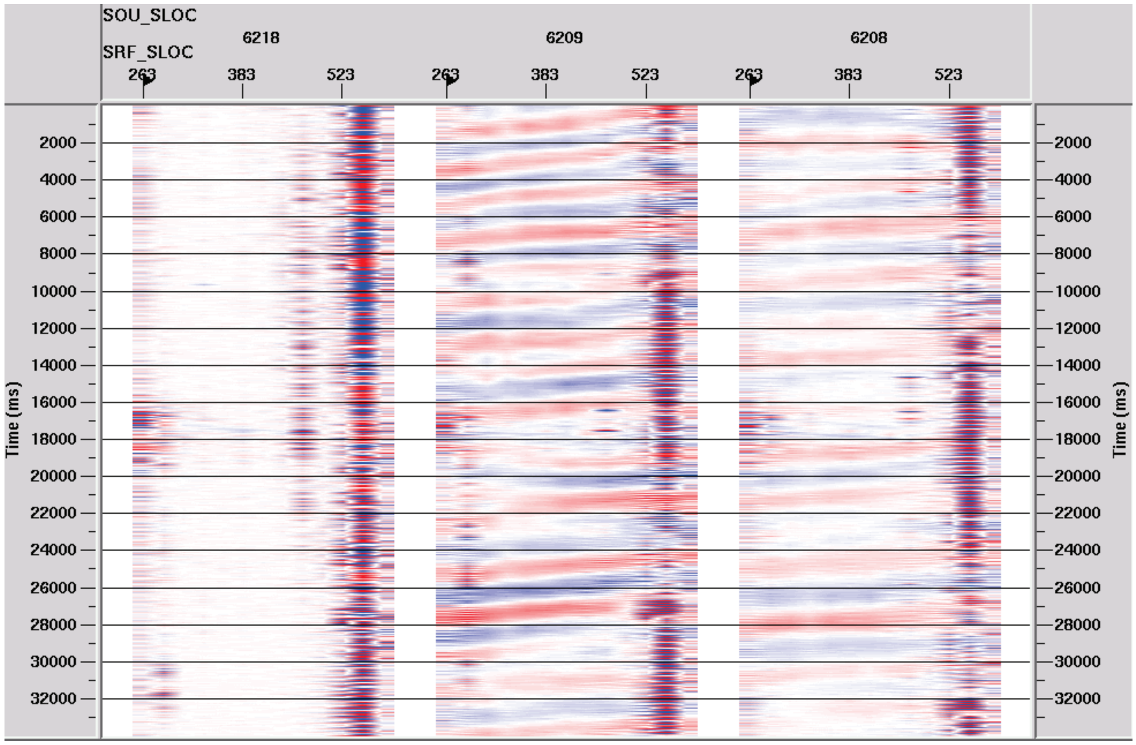

FIG. 12. Uncorrelated data from 4.5 Hz 1-C geophones one flag east of seismometer stations for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is one.

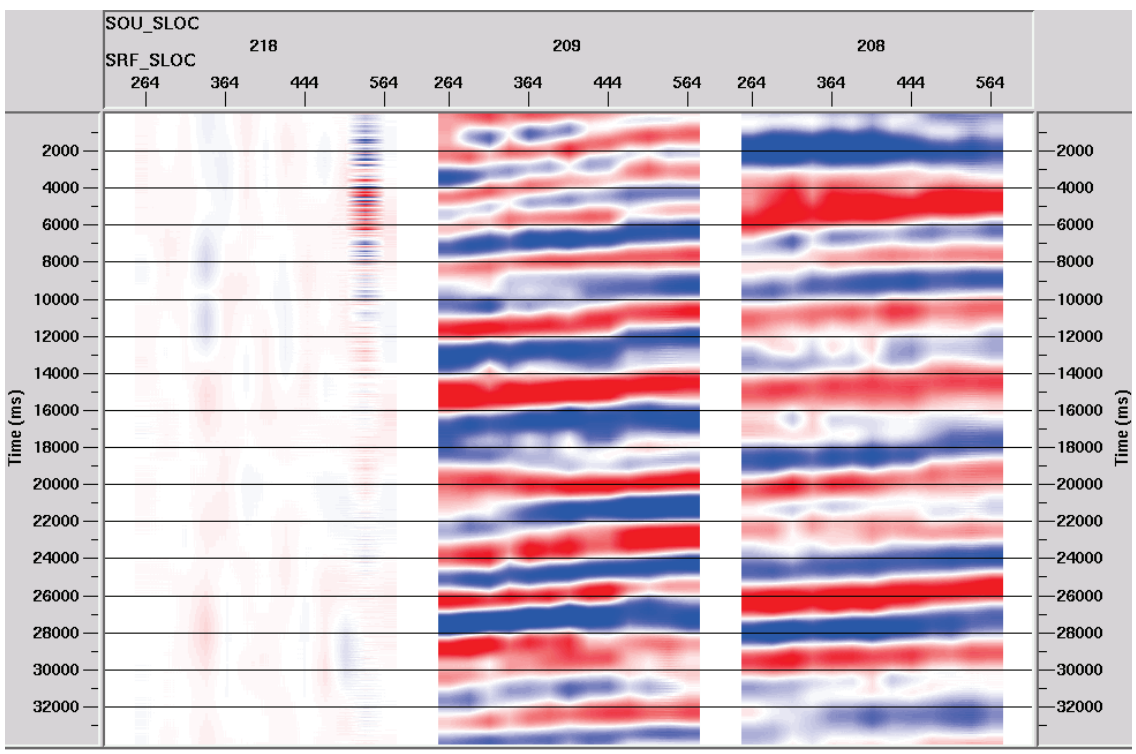

FIG. 13. Figure 12 after correcting for geophone response below 4.5 Hz. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is one.

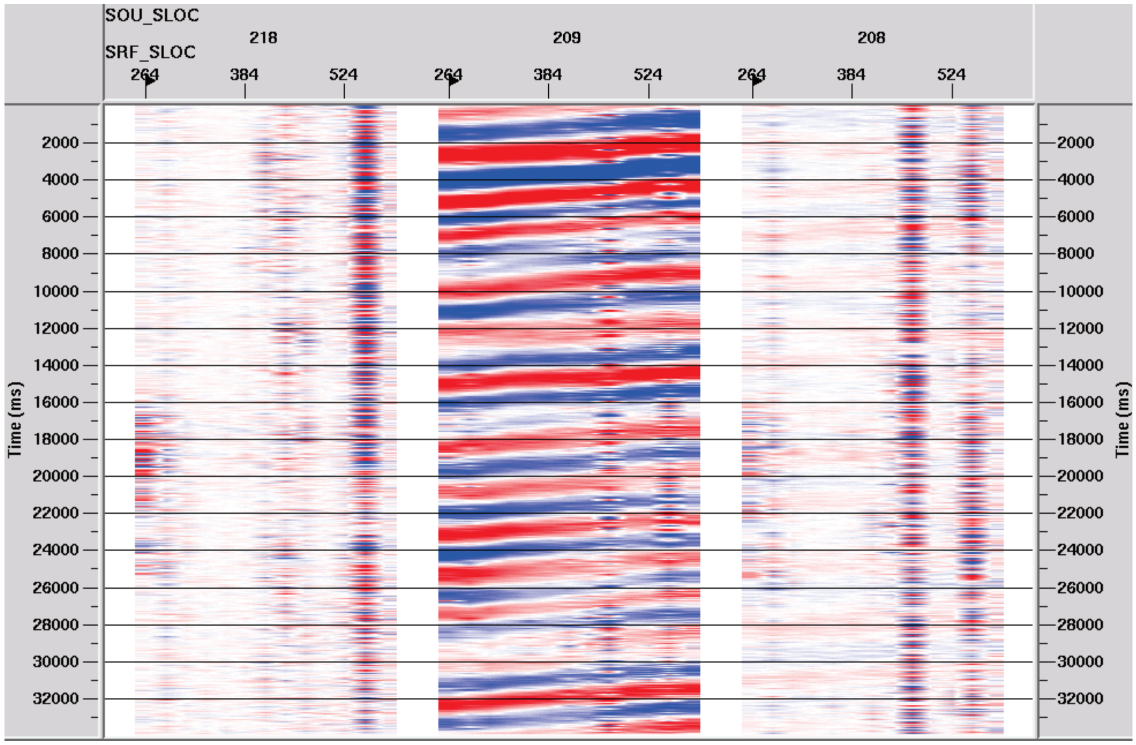

FIG. 14. Uncorrelated data from the vertical component of VectorSeis accelerometers at thirteen seismometer stations for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Vertical fold is two.

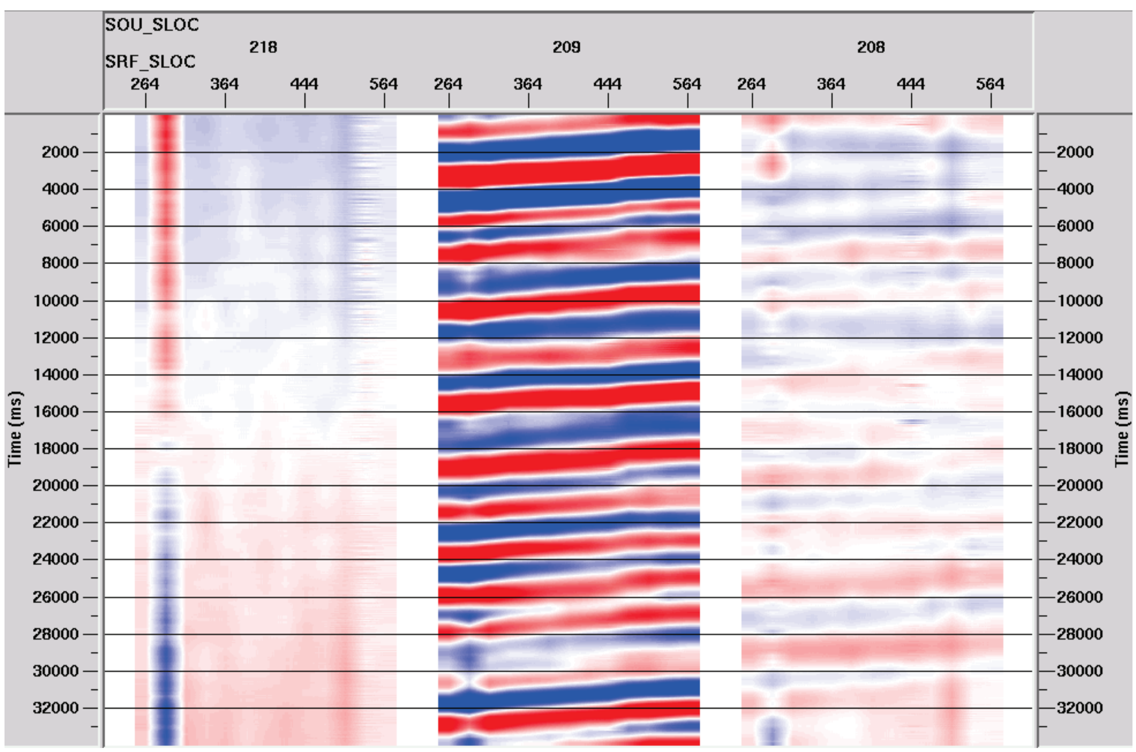

FIG. 15. Figure 14 integrated, Apparent trace dc bias removed for display. Integration has introduced low-frequency noise (eg. VP 218, left-hand side), as expected.

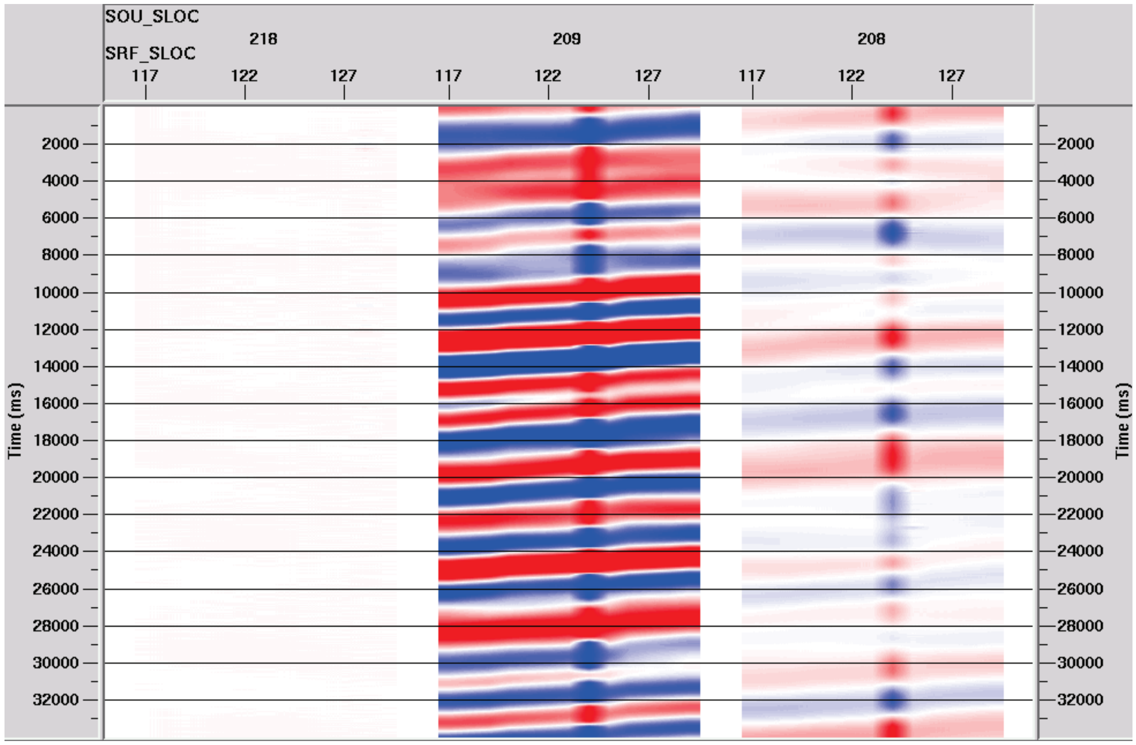

FIG. 16. Uncorrelated data from the vertical component of seismometers for VPs 218, 209, and 208. Trace length is 34 seconds. ProMAX trace display scaling: entire screen with gain set to one. Trace fold is one.

Comparisons

Figures 8, 10, 12, 14 and 16 show visual comparisons of traces extracted from the full shot gathers to match seismometer stations (10 Hz 3C geophones, and VectorSeis), or one flag (10 m) northeast of the seismometers (4.5 Hz and 10 Hz high-sensitivity geophones were at odd numbered flags, while the seismometers were at even numbered flags). Figures 9, 10 and 13 show the same gathers as in Figurew 8,10 and 12 after they have been corrected for geophone response at low frequencies by inverse filtering, using the method described by Bertram and Margrave (2010). Figure 15 shows integrated accelerometer data (cf. Figure 14) with dc bias removal applied by subtracting the mean, but with no filters of any kind. Integration has introduced long-wavelength noise, as expected (eg. background transition from blue to red for VP 218 over the 34 second traces).

Figures 17-19 show the first five Hertz of the averaged amplitude spectra for the gathers shown in Figures 8-16 (top), as well as for the north and east components of the 3C sensors. The left side shows amplitude spectra for raw geophone data, and integrated VectorSeis data. The right side is the same, except it shows the amplitude spectra of geophone traces after inverse filtering to correct for geophone response. Improvements in the geophone amplitude spectra (defined as a closer visual match to the seismometer amplitude spectra) can be seen to almost zero Hertz for all geophones, all components and all vibe points. All traces were de-biased and normalized before the amplitude spectra were calculated.

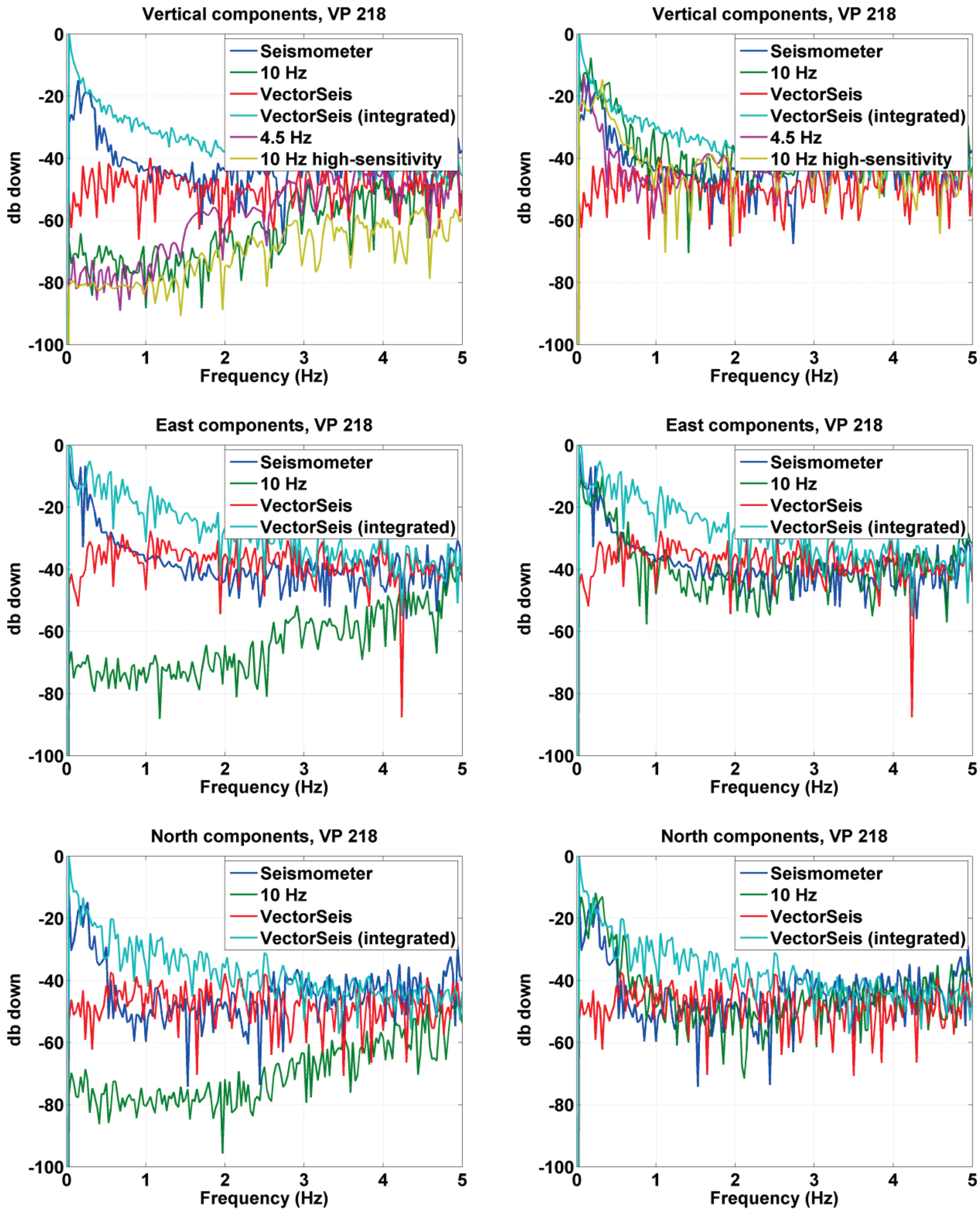

FIG. 17. The first five Hertz of amplitude spectra for uncorrelated data from VP 218, prior to any arrivals from the Vancouver Island earthquake. Left; Before correcting for geophone response. Right; After correcting for geophone response.

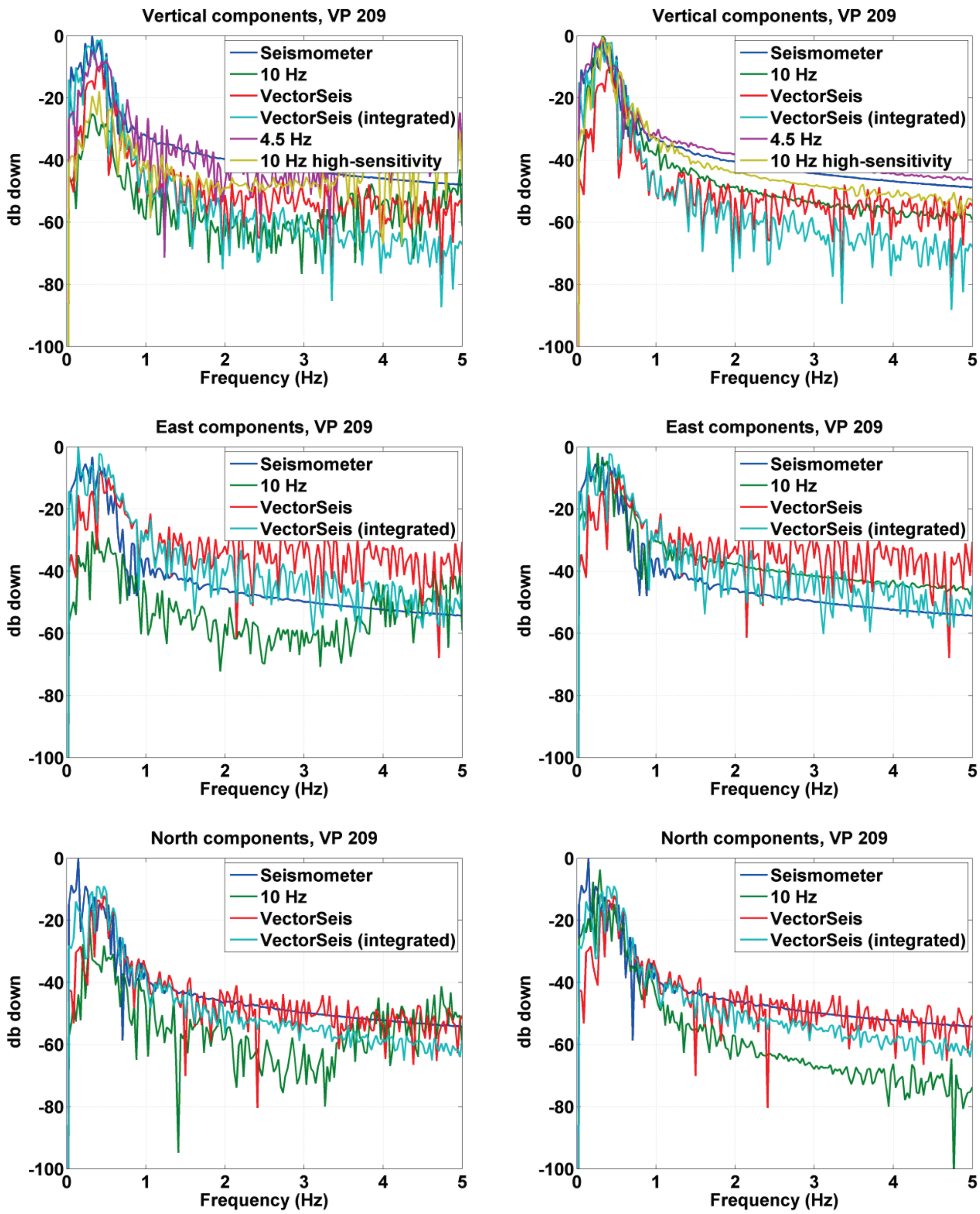

FIG. 18. The first five Hertz of amplitude spectra for uncorrelated data from VP 209, during high-amplitude secondary arrivals from the Vancouver Island earthquake. Left; Before correcting for geophone response. Right; After correcting for geophone response.

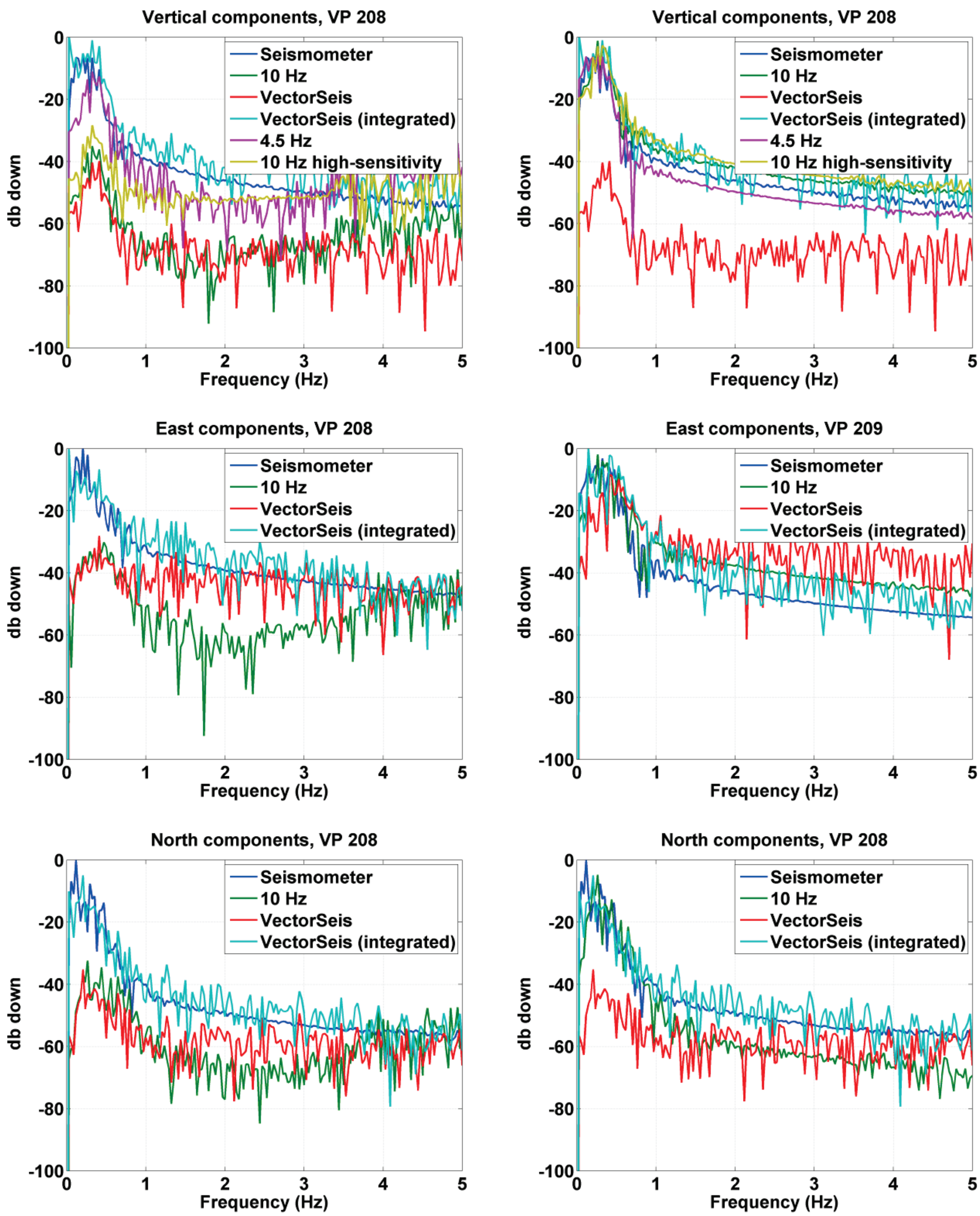

FIG. 19. The first five Hertz of amplitude spectra for uncorrelated data from VP 208, during secondary arrivals from the Vancouver Island earthquake. Left; Before correcting for geophone response. Right; After correcting for geophone response.

SUMMARY

The earthquake provided the best low-frequency source we could have asked for during a low-frequency experiment. That it happened while our sensors were on the ground is very fortunate, as the last large earthquake on the west coast was about ten years ago. To our surprise, the less than 1 Hz earthquake arrivals were recorded on all of our sensors, and after inverse filtering to correct for geophone response at low-frequencies, the geophone data is surprisingly similar to the accelerometer and seismometer data.

ACKNOWLEDGEMENTS

We would like to thank all participants in the low-frequency experiment, Husky, INOVA, Geokinetics and Nanometrics, as well as Landmark Graphics for the use of donated software.

REFERENCES

Bertram, M. B. and Margrave, G. F., 2011, Recovery of low frequency data from 10Hz geophones, CREWES Research Report, **22**.

Google Earth, 2011, Google Earth version 6.0.3.2197 software downloaded and installed from http://www.google.com/earth/index.html, images accessed October 17, 2011.

Hall, K. W. and Margrave, G. F., 2011, Timing issues on the Hussar low-frequency experiment, CREWES Research Report, **23**.

Nanometrics, 2011, http://www.nanometrics.ca/ckfinder/userfiles/files/NMX-TrilliumCompact-brochure.pdf, Accessed October 30, 2011.

Natural Resources Canada, 2011, http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php, accessed October 31, 2011.

APPENDIX A

The following is the Natural Resources Canada (2011) listing for the Vancouver Island earthquake of September 9, 2011:

```
Date     Time(UT)     Lat      Long  Depth  Mag   Region and Comment
----     --------     ---      ----  -----  ---   ------------------
2011/09/09  19:41:30  49.35  -127.22  35.5*  6.3Mw 88 km WSW of Gold R.
A total of 1 events found.
```