PNNL-16678
GR07-10
Volume II

Pacific Northwest National Laboratory
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Deep Downhole Seismic Testing at the Waste Treatment Plant Site, Hanford, WA

Volume II
P-Wave Measurements in Borehole C4996 Seismic Records, Wave-Arrival Identifications and Interpreted P-Wave Velocity Profile

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June 2007

Prepared by The University of Texas at Austin
for the Pacific Northwest National Laboratory
under Contract DE-AC05-76RL01830
with the U.S. Department of Energy

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Deep Downhole Seismic Testing at the Waste Treatment Plant Site, Hanford, WA

Volume II of VI

P-Wave Measurements in Borehole C4996
Seismic Records, Wave-Arrival Identifications and Interpreted P-Wave Velocity Profile

for

Pacific Northwest National Laboratory
Richland, WA

by

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June 28, 2007

Geotechnical Engineering Report GR07-10
Geotechnical Engineering Center
Civil Engineering Department
The University of Texas at Austin

Volume II: P-Wave Measurements in Borehole C4996
Seismic Records, Wave-Arrival Identifications and Interpreted
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Table of Contents

Volume II: P-Wave Measurements in Borehole C4996 Seismic Records, Wave-Arrival Identifications and Interpreted P-Wave Velocity Profile

Section 1: Introduction

The U.S. Department of Energy (DOE) and the Pacific Northwest National Laboratory (PNNL) installed three boreholes to a depth of approximately 1400 feet below ground surface (bgs) in 2006 at the Waste Treatment and Immobilization Plant (WTP) construction site on the Hanford Site in southeastern Washington State. The purpose of the new boreholes was to obtain direct shear (S) and compressional (P) wave velocity measurements in the subsurface for use in reducing the uncertainty in the seismic response spectra and design basis for the WTP. The University of Texas at Austin (UTA) was contracted by PNNL to collect S- and P-wave measurements in each of the three new boreholes identified as C4993, C4996 and C4997 (Barnett et al. 2007; Gardner and Price 2007).

Velocity measurements in shallow sediments from the ground surface to approximately 370 to 400 feet bgs were collected by Redpath Geophysics using impulsive S- and P-wave seismic sources (Redpath 2007). Measurements below this depth within basalt and sedimentary interbeds were made by UTA between October and December 2006 using the T-Rex vibratory seismic source (Stokoe et al. 2004) in each of the three boreholes. Results of these measurements including seismic records, wave-arrival identifications and interpreted velocity profiles are presented in the following six volumes:

I. P-Wave Measurements in Borehole C4993,

II. P-Wave Measurements in Borehole C4996,

III. P-Wave Measurements in Borehole C4997,

IV. S-Wave Measurements in Borehole C4993,

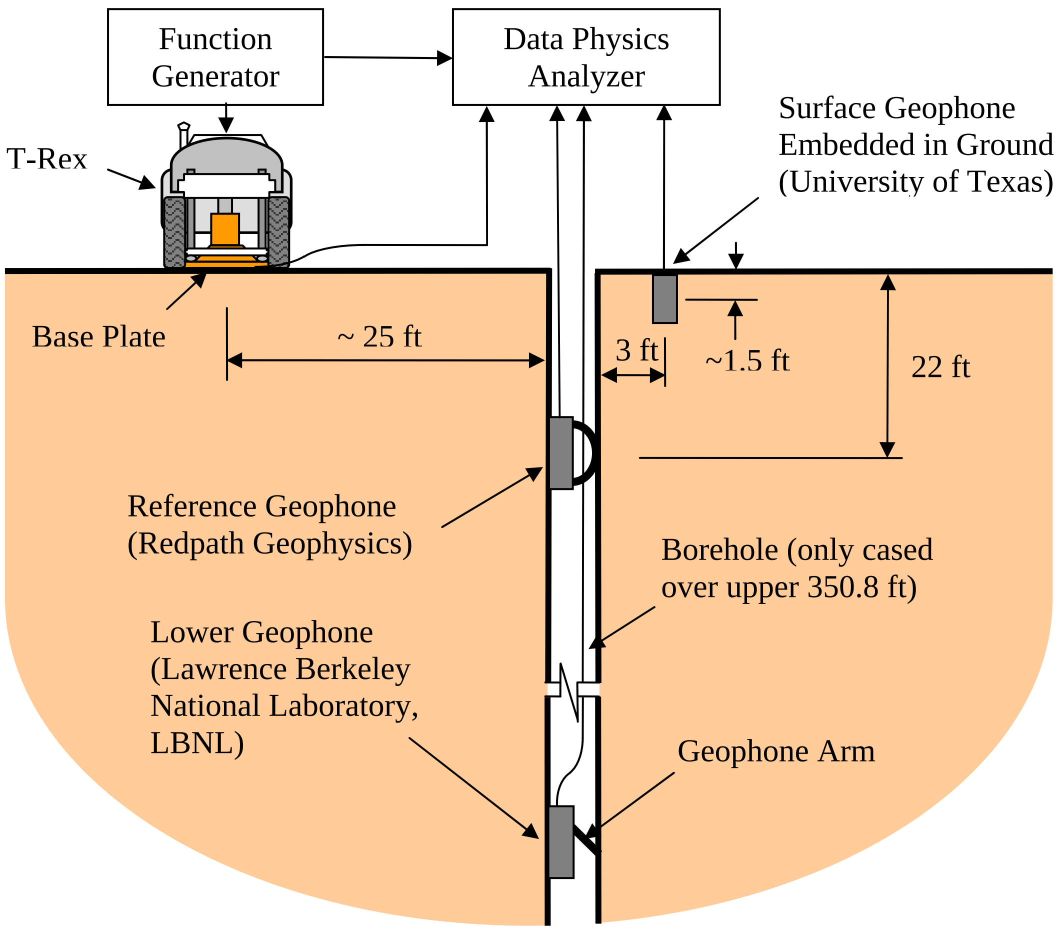
V. S-Wave Measurements in Borehole C4996, and

VI. S-Wave Measurements in Borehole C4997.

In this volume (II), all P-wave measurements are presented that were performed in Borehole C4996 at the WTP with T-Rex as the seismic source and the Lawrence Berkeley National Laboratory (LBNL) 3-D wireline geophone as the at-depth borehole receiver. P-wave measurements were performed over the depth range of 360 to 1400 ft, typically in 10-ft intervals.

However, in some interbeds, 5-ft depth intervals were used, while below about 1180 ft, depth intervals of 20 ft were used. The field setup is illustrated in Figure 1.1.

Figure 1.1 Field Setup for P- and S-Wave Measurement in Borehole C4996



Compression (P) waves were generated by moving the base plate of T-Rex for a given number of cycles at a fixed frequency as discussed in Section 2. This process was repeated so that signal averaging in the time domain was performed using 3 to about 15 averages, with 5 averages typically used.

In addition to the LBNL 3-D geophone, called the lower receiver herein, a 3-D geophone from Redpath Geophysics was fixed at a depth of 22 ft in Borehole C4996, and a 3-D geophone from the University of Texas was embedded near the borehole at about 1.5 ft below the ground surface.

This volume is organized into 13 sections as follows:

Section 1: Introduction,

Section 2: Explanation of Terminology,

Section 3: Vp Profile at Borehole C4996,

Sections 4 to 6: Unfiltered P-wave records of lower vertical receiver, reaction mass, and reference receiver, respectively,

Sections 7 to 9: Filtered P-wave signals of lower vertical receiver, reaction mass and reference receiver, respectively,

Section 10: Expanded and filtered P-wave signals of lower vertical receiver,

Sections 11 and 12: Waterfall plots of unfiltered and filtered lower vertical receiver signals, respectively, and

Section 13: References.

Section 2: Explanation of Terminology

1. Record or Signal

The recorded and sampled time series of analog voltage from a geophone or an accelerometer is called a record. A signal can generally be a raw record, a processed record or any designed or generated (as by function generator) time series.

The magnitude of any signals related to this test is by default in voltage. All signal amplitudes (y-axis for time series, both axes for hodograph) in figures of this report, if not otherwise explicitly labeled, have a unit of volt.

All figures for time series have the y axis scaled independently for legibility for each trace (gain-normalized). This makes them legible when the amplitude varies from trace to trace (large close to the surface, small at depth).

2. Input Signal or Drive Signal

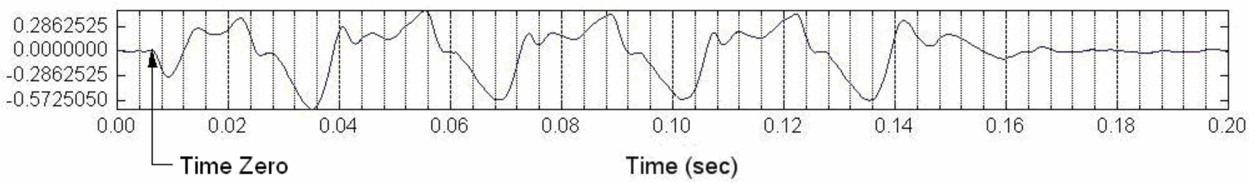
At each measurement depth, an independent fixed sine wave with a frequency of 50 Hz, 20 Hz or 30 Hz was sent from a function generator to T-Rex. This signal is called the Input Signal to T-Rex, or the T-Rex Drive Signal. The input signal was a perfect sine wave, with 5 cycles of 50 Hz, 4 cycles of 20 Hz or 4 cycles of 30 Hz. Input signals of all measurements were aligned so that they all began at the same instant, which is called time zero, and was marked as time zero (at t = 0) on all recorded signals.

In addition, the given input signal was sent to T-Rex anywhere from 3 to about 15 times to allow signal averaging of the P-wave to be performed in the time domain.

3. Reaction Mass Acceleration or T-Rex Output Signal

The vertical output force of T-Rex was transmitted to the ground surface by a square base plate located on the bottom of T-Rex. The base plate directly contacted the ground surface. The acceleration of the reaction mass that loads the base plate, also called T-Rex Output Signal, was recorded by a vertical accelerometer on the reaction mass. An example of the reaction mass output signal is presented in Figure 2.1.

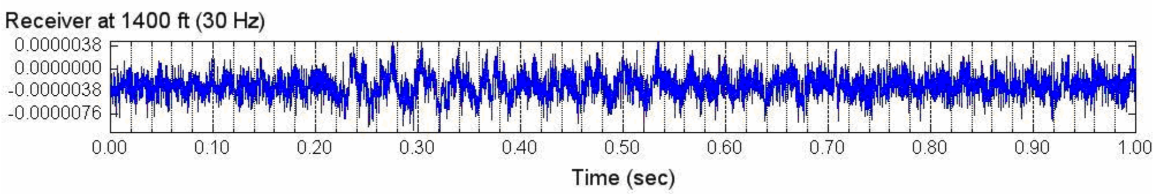
Figure 2.1 Unfiltered Vertical (P-Wave) Acceleration of the Reaction Mass
Input Signal: 4 Cycles of 30-Hz Sine Wave



4. Unfiltered Signals

Unfiltered signals are the original time series directly recorded with the Data Physics Analyzer[1]. They are the outputs of the reaction mass accelerometer or the receiver geophones due to the 50-Hz, 20-Hz or 30-Hz input signal. The average amplitudes of these unfiltered signals may not be zero due to the non-zero initial voltage. Figure 2.2 shows that the average amplitude of the unfiltered signal of the lower receiver at a depth of 1400 ft is less than zero. If an unfiltered signal is not stationary, its average value may have a trend or vary with time. Only the fluctuation of the waves is our concern. The trend of each signal was removed to get a zero average, so that in waterfall plots showing signal fluctuations versus scaled depth intervals, the center line (average) of each signal is located exactly at each depth location.

Figure 2.2 Unfiltered Lower Vertical Receiver (P-Wave) Signal
Input Signal: 4 Cycles of 30-Hz Sine Wave



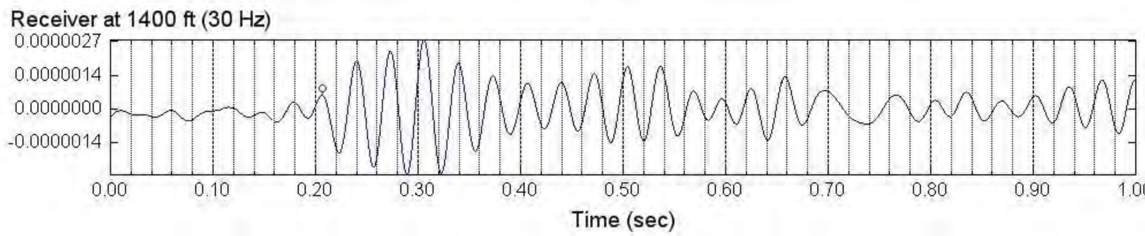
5. Filters and Filtered Signals

Filters were used in processing the unfiltered signals. A filter is a transfer function that can modify magnitudes and phases of the signal. A low-pass filter is a filter that attenuates or removes undesired high frequencies. The filtered signal is then smoother, and the input signal transmitted through the geologic column is easier to identify. Unfiltered signals in the time domain were transformed into the frequency domain using the discrete Fast Fourier Transform

[1] System No. 70270 Mobilyzer II – 16C2S – HS, Data Physics Corporation, San Jose, California

(FFT), where a low-pass filter was applied by multiplying filter coefficients with both the real and imaginary parts of the frequency magnitudes to get a modified frequency response. Then the inverse FFT was performed on the modified frequency response to obtain a filtered signal in the time domain. Figure 2.3 is the filtered version of the recorded signal in Figure 2.2.

Figure 2.3 Filtered Lower Vertical Receiver (P-Wave) Signal
Input Signal: 4 Cycles of 30-Hz Sine Wave; Filter Pass Band: 0 to 40 Hz

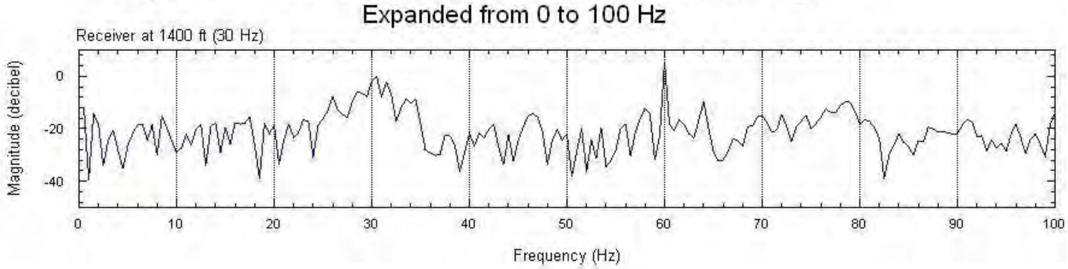


The exact same filtering was performed on all signals with a given fixed frequency. Therefore, any minor shifting in the time domain due to the filtering was the same for each fixed-frequency signal. As a result, the relative travel times determined herein are unaffected by this filtering. Also, the wave-arrival identification on the filtered waveform is denoted by a symbol added to the waveform (the small circle at t~0.205 sec in Figure 2.3) as discussed below in item "Relative Travel Times".

6. Pass Band or Low Pass

By signal-processing convention, the "pass band" of a filter is the band of frequencies that lie within 3 decibels of the peak magnitude. The "stop band" or "reject band" is all other frequencies. The word "band" refers to a frequency range. The frequency corresponding to 3 decibels of the peak value is called the "cut-off" frequency. If a pass band of a filter is the frequency range between zero and the cut-off frequency, it is called a "low pass" filter.

Figure 2.4 Power Spectrum of Unfiltered P-Wave Signal
Expanded from 0 to 100 Hz

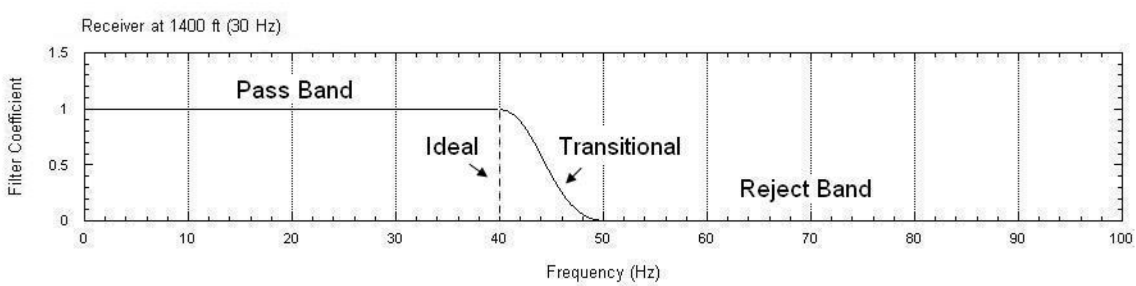


Unfiltered signals are all digital discrete time series, whose frequency domain is also discrete, as shown in Figure 2.4, where the input signal is a 30-Hz sine wave. As demonstrated in the figure, except for the 60-Hz noise, the largest magnitude in the spectrum is the frequency near 30 Hz. Because the 60-Hz noise has a dominant contribution in the unfiltered signal, it must be filtered or removed to retrieve and view the desired measurement of the 30-Hz input signal.

A discrete filter in the frequency domain, shown in Figure 2.5, is applicable to these discrete time series. The pass band is 0 to 40 Hz, the reject band is 50 Hz to the Nyquist frequency (not shown), and there is a transitional band between 40 Hz and 50 Hz, which is a cubic spline curve in this work.

A transitional band is preferred if the magnitude of the reject band is not negligible compared with the magnitude of the desired dominant frequency. For example, in Figure 2.4, if the pass band is 0 to 32 Hz, a transitional band of 32 to 40 Hz would make the filtered signal better. If the contribution of the reject band to the spectrum (or energy) is negligible, an ideal filter makes little difference compared to a transitional filter. For example, if the pass band is 0 to 40 Hz, there is no significant difference between a transitional filter and an ideal filter. If there was a general trough (near 39 Hz) following the peak of the signal energy (near 30 Hz), a cut-off frequency (40 Hz) was chosen near the trough, and an ideal filter was used. Otherwise, a transitional filter was used.

Figure 2.5 Filter Pass Band and Stop Band Coefficient



7. Time Shift

The input signal to the ground, represented by the acceleration of the reaction mass, is not a perfect sine wave, as shown in Figure 2.6. It can be distorted when the initial state of the T-Rex mass is not consistently the same, or the soil below the reaction mass is loaded nonlinearly. Therefore, even if the drive signal is always aligned to zero time, the reaction mass initial response may be shifted from zero time, which is called a time shift. In Figure 2.6, the denoted first arrival is the best point for wave-arrival identification. However, it is not reliable because of the nonlinear initial response of the reaction mass, which may produce different first arrival times for reaction mass and receivers even if the drive signals are exactly aligned. This effect is demonstrated by the first cycle right after the first arrival that shows a transient amplitude and frequency.

Figure 2.6 P-Wave Initial Response of the Reaction Mass

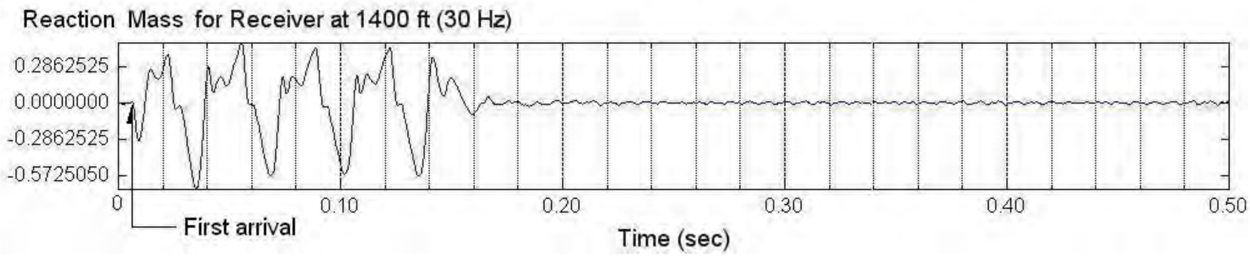
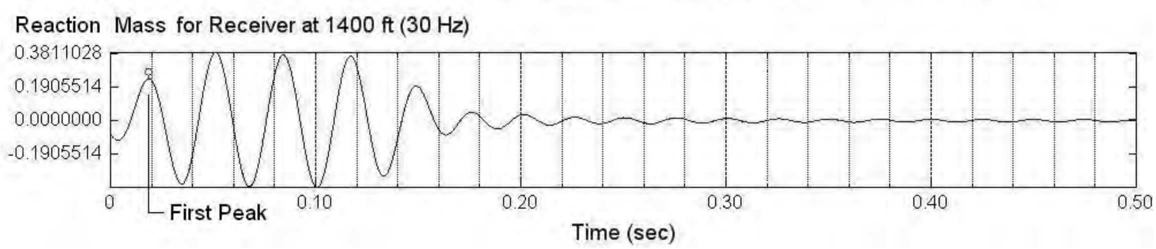


Figure 2.7 is used to further explain the unreliability of the first arrival (or first movement of the reaction mass) and the transient effect on both frequency and magnitude. The filter is a 40-Hz low pass (Figure 2.5) that removed all frequencies higher than 40 Hz. The first arrival point (or "first break") in Figure 2.6 no longer exists in Figure 2.7 because it contains transient frequencies that are higher than 30 Hz. On the other hand, the amplitude of the first peak denoted by a small circle is smaller than that of other peaks because the reaction mass is beginning to move at 30 Hz. The first peak is the correct point to use in evaluating the relative travel times of a 30-Hz P wave.

Figure 2.7 First Peak of the Filtered Acceleration Signal of The Reaction Mass



Further analysis confirmed that, different non-causal low pass filters for the 30-Hz signal in Figure 2.6 will shift the first arrival and first trough, but only slightly shift the first peak if the transient state extends to it, while other peaks and troughs that are in steady state stay unchanged and perfectly aligned. The shift of the first arrival is systematically backward (time is less) and stable because the desired 30-Hz signal remains dominant. Steady-state peaks of output signals have no time shift if the input signals have no time shift. An FFT low-pass filter can do an excellent job in tracking the desired fixed frequencies.

Nevertheless, steady state peaks and troughs are not a perfect reference for wave-arrival identification because of reflection waves that come into the direct signal and distort the steady state peaks and troughs.

As a compromise and for convenience, the first-arrival wave identification method is replaced with the first peak or first trough of the waveform for the reaction mass acceleration and other receiver signals. There is little shifting from the steady state of the desired signal frequency (for example 30 Hz), and less interference from the reflections.

As an alternative for the non-causal filter, a Butterworth filter may secure the first arrival stationary, but it falls short if the frequency of the dominant noise (60-Hz noise in Figure 2.4 has greater magnitude than the desired signal at 30 Hz) is very close to that of the signal, and even worse for the filtering of the 60-Hz noise from the 50-Hz signal, which was used in all three boreholes. If the noise can not be significantly attenuated or removed, it will shift not only the first arrival, but also the steady-state peaks and troughs, and the shift is irregular because it is controlled by the noise. While the FFT low-pass filter, which is non-causal, can remove undesired 60-Hz noise completely and track the desired frequency effectively. Therefore, the FFT low-pass filter was used herein.

8. Relative Travel Times

Relative travel times are the time intervals between the same points on the waveforms of the reaction mass and receivers (lower receiver or reference receiver). The time on each filtered waveform that is used to determine the relative travel time is denoted by a small symbol that has been added to all waveforms. Examples are shown in Figures 2.3 and 2.7 by the small circles. These points (representing times) are not the wave arrivals but are the same point on the waveform from one measurement depth to the next. These points are called “wave-arrival identifications” herein.

9. Long Lever Arm and Short Lever Arm

The lower borehole geophone from Lawrence Berkeley National Laboratory (LBNL) was fixed to the borehole wall at a depth by rotating the pivoting lever arm that was attached to the geophone case. As the lever arm rotated outward, the geophone case was pushed into contact with the borehole wall. Two lengths of lever arms were used, the longer one called a long lever arm and the shorter one called a short lever arm. Because of irregularities in the borehole diameter (Gardner and Price 2007), the long lever arm was used to avoid inadequate contact with the borehole wall in regions where washouts may have substantially increased the borehole diameter. Both long and short arms were used at depths 1240 and 1260 ft in Borehole C4993, only the long arm was used for all depths in Borehole C4996.

10. Reference Receiver

The reference receiver is the vertical (geophone) receiver in the 3-D reference geophone (see Figure 1.1) that was fixed at a depth of 22 ft in Borehole C4996 while the lower vertical (geophone) receiver was moved downward along the borehole. The reference receiver was always at a depth of 22 ft

11. Lower Vertical Receiver

The lower vertical receiver is the vertical (geophone) component of the LBNL 3-D geophone (see Figure 1.1). It is positioned at the deeper depth or below the location of the reference receiver. It is one component in the only 3-D geophone that was moved during testing in the borehole.

Section 3: Vp Profile at Borehole C4996

Section 3 contains the geologic profile, interpreted Vp profile and relative P-wave travel times.

1. Figure 3.1 presents the geologic profile.
2. Figure 3.2 shows all relative P-wave travel times and the interpreted Vp profile at Borehole C4996.
3. Figures 3.3 to 3.5 are the expanded relative P-wave travel times and the interpreted Vp profile at Borehole C4996.
4. Tables 3.1 to 3.4 list the relative P-wave travel times at Borehole C4996, including the times of the wave-arrival identifications for the peaks or troughs of the reaction-mass acceleration, reference receiver and lower receiver signals.

Figure 3.1 General Stratigraphy of Borehole C4996

(Depths source: Barnett et al. 2007; Rohay and Brouns 2007)

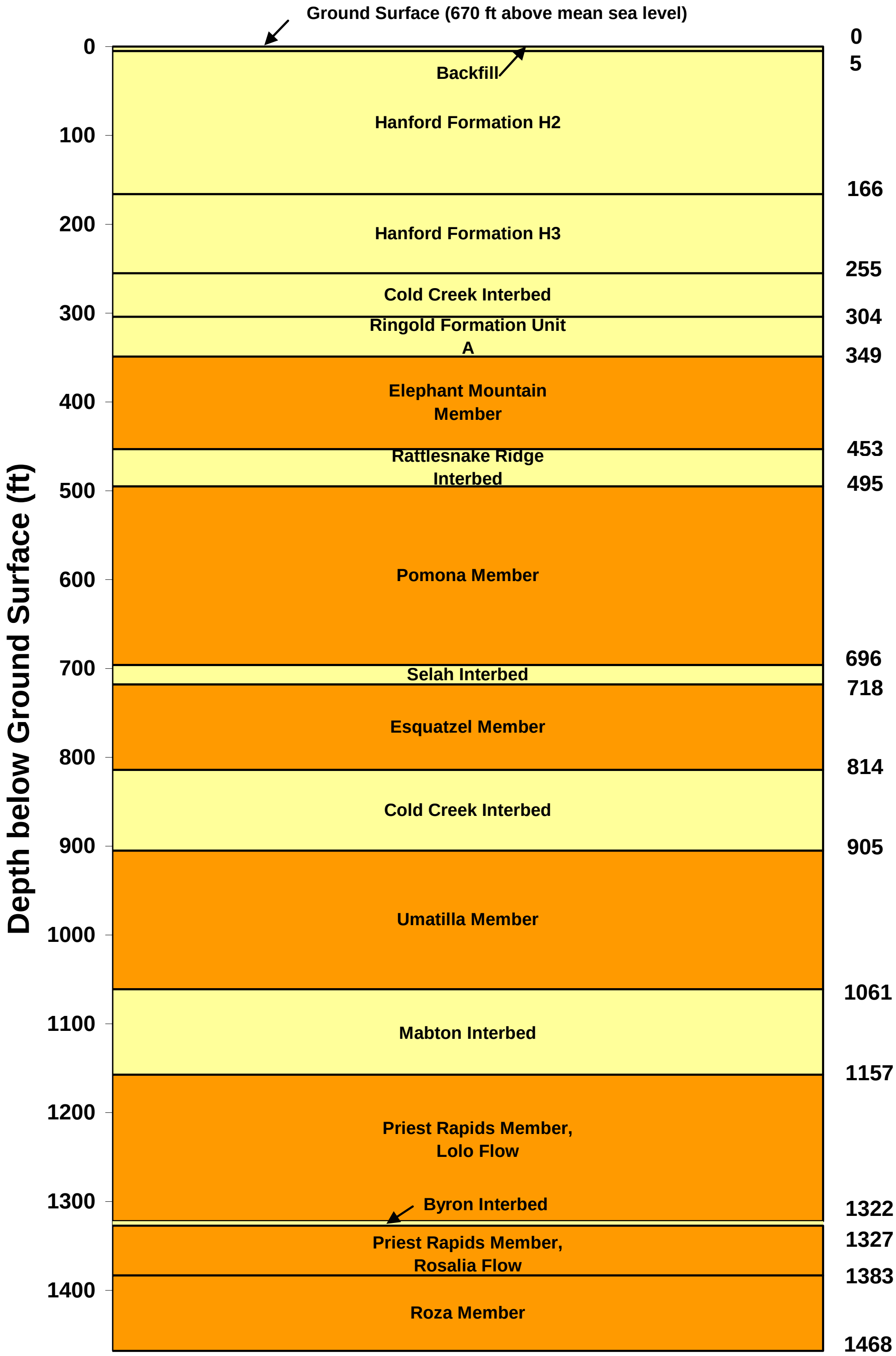


Figure 3.2 Relative P-Wave Travel Times and Interpreted Vp Profile at Borehole C4996

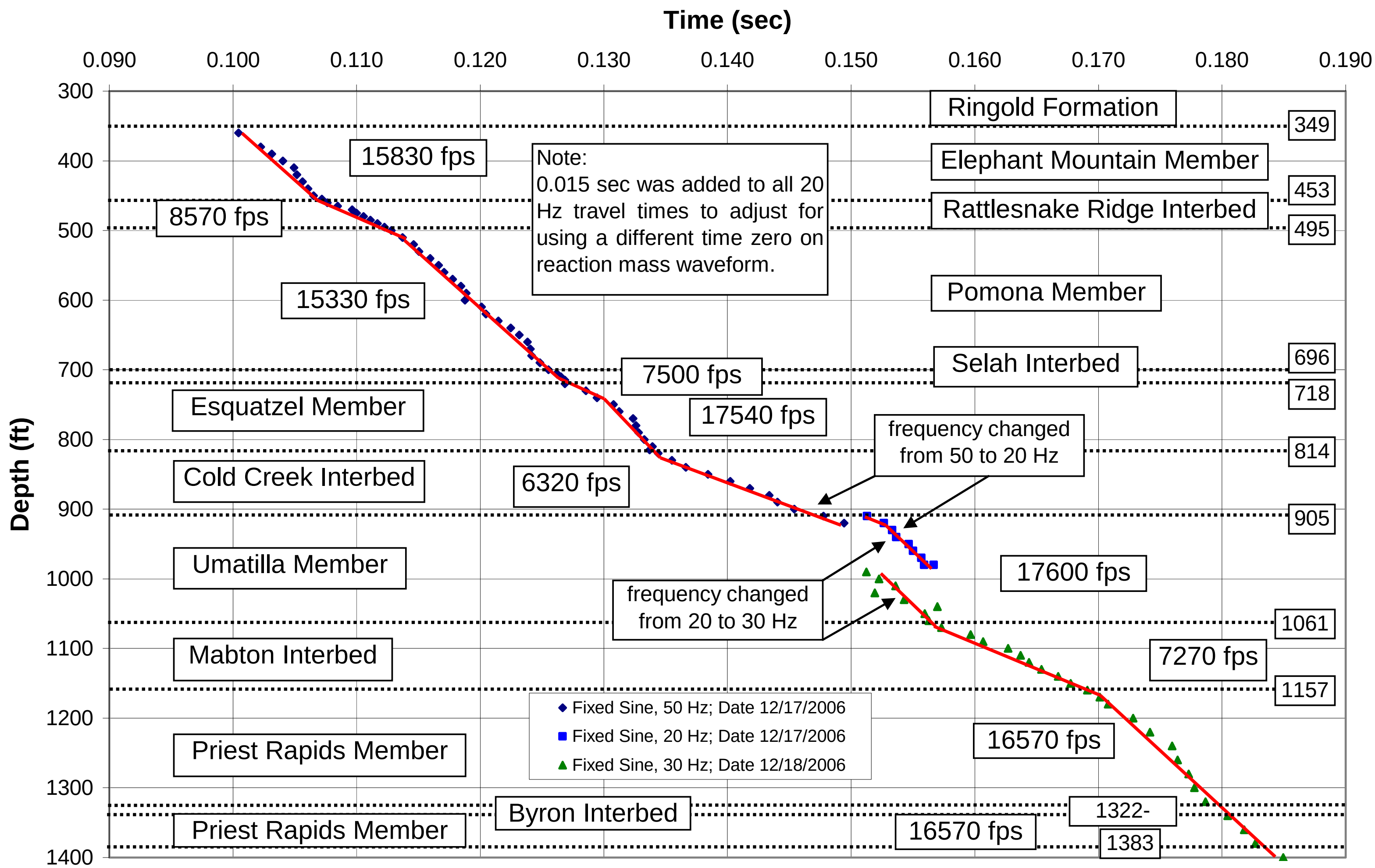


Figure 3.3 Expanded Relative P-Wave Travel Times and Interpreted Vp Profile at Borehole C4996, Depths 300 to 800 ft

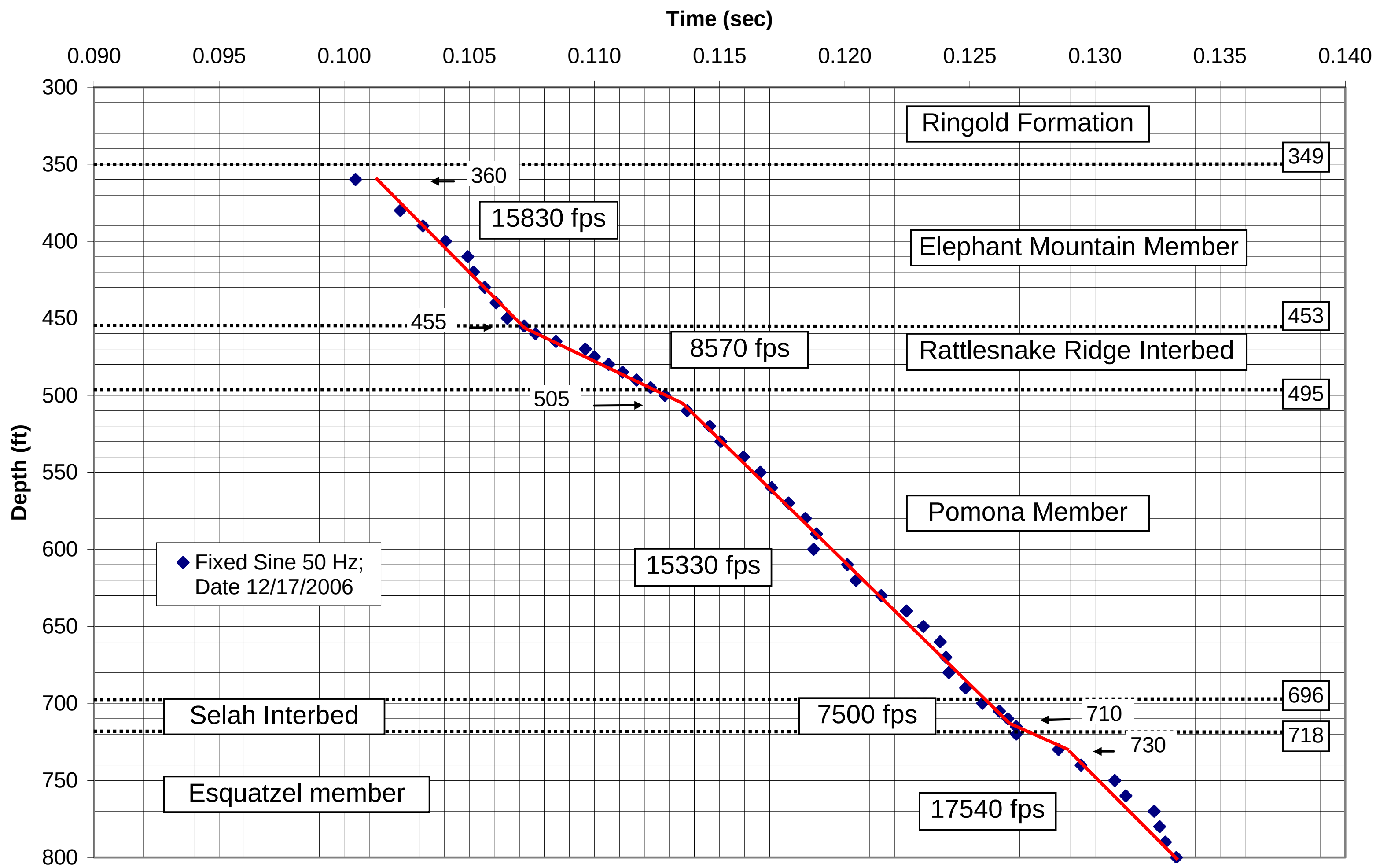


Figure 3.4 Expanded Relative P-Wave Travel Times and Interpreted Vp Profile at Borehole C4996, Depths 600 to 1100 ft

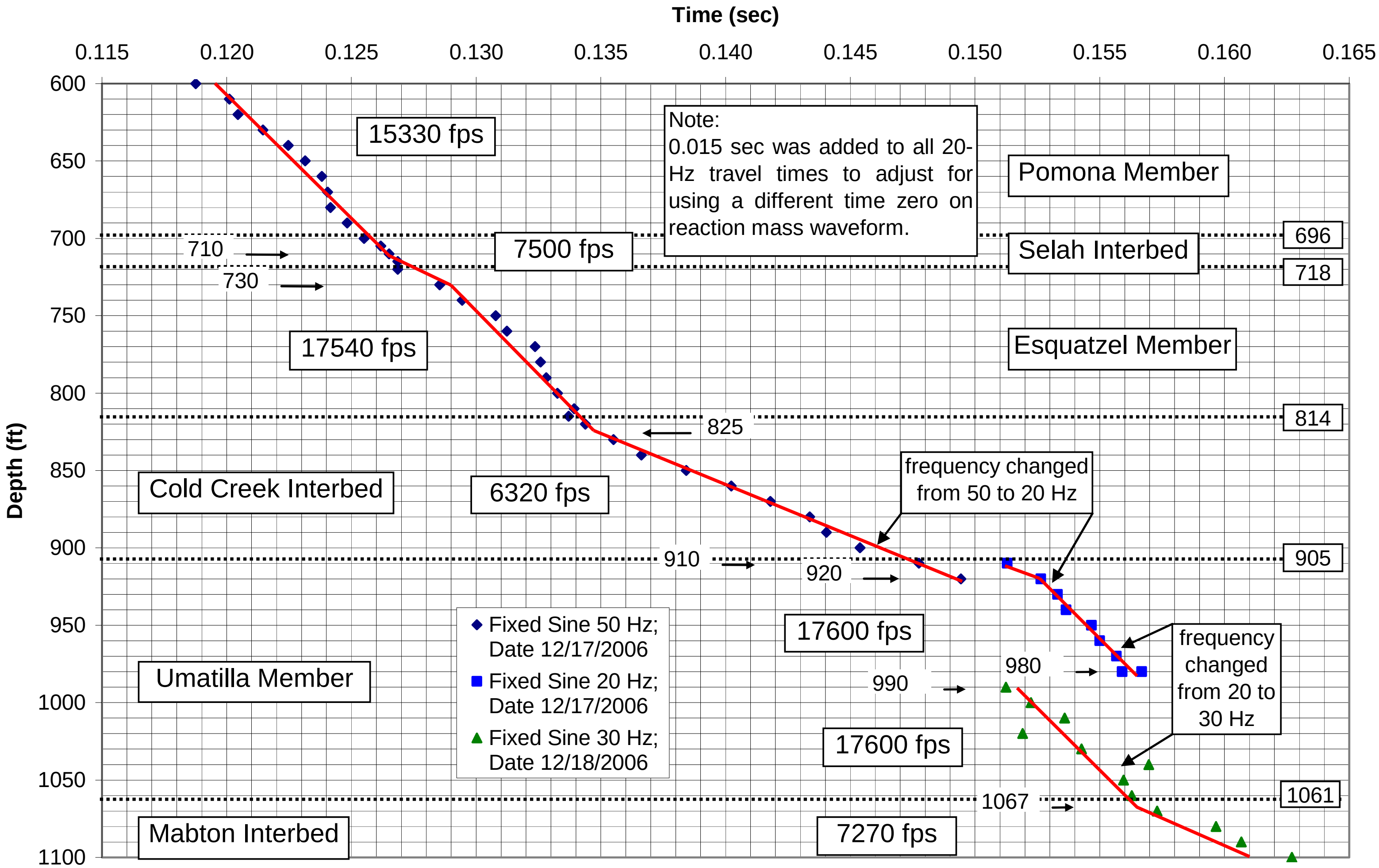


Figure 3.5 Expanded Relative P-Wave Travel Times and Interpreted Vp Profile at Borehole C4996, Depths 900 to 1400 ft

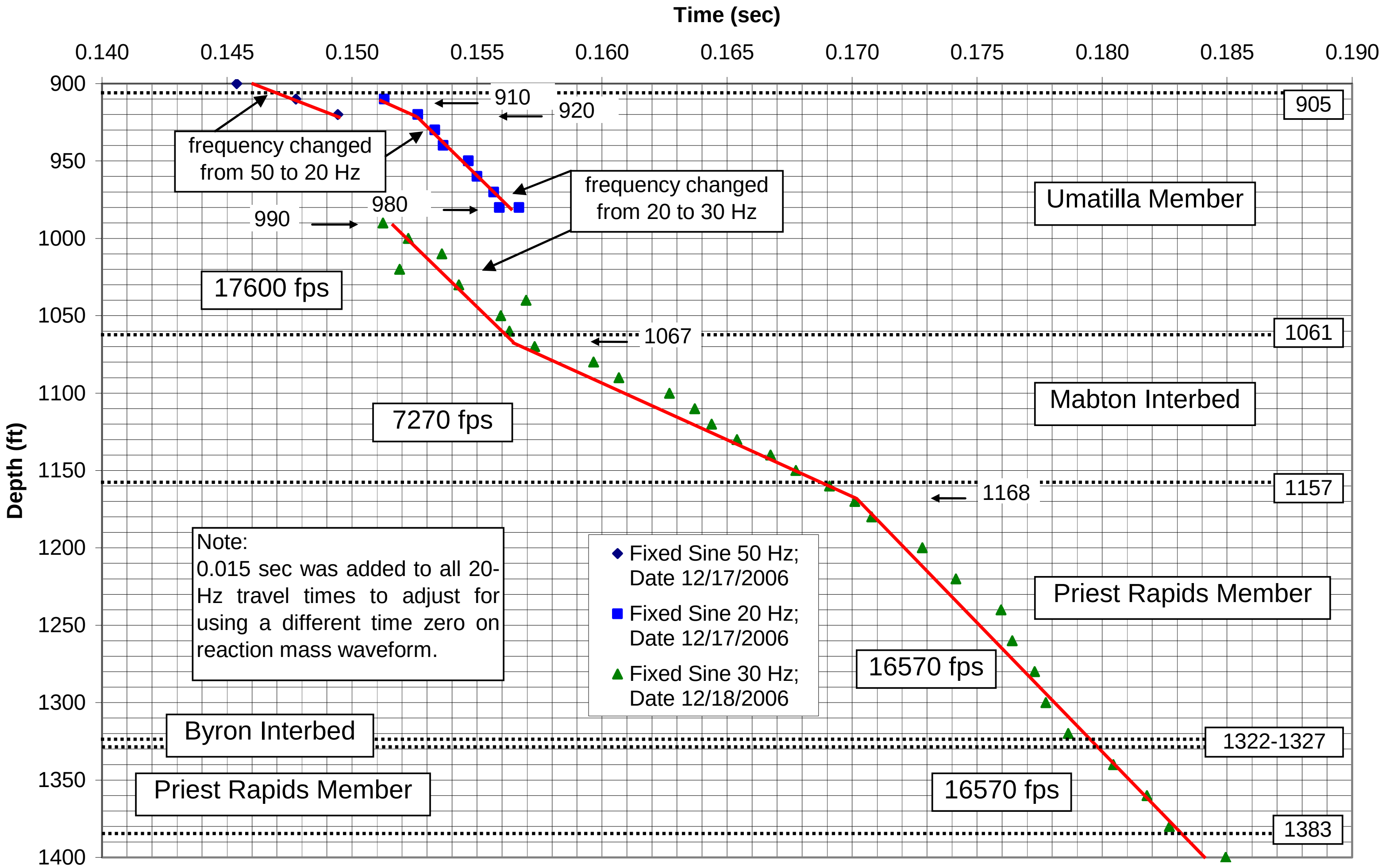


Table 3.1 Relative P-Wave Travel Times at Borehole C4996

Lower Receiver Depth (ft)	Reference Receiver Depth (ft)	T-Rex Drive Freq./ No. of Cycles (Hz/No.)	T-Rex Excitation Direction	Time: Peak or Trough at Reaction Mass (sec)	Time: Peak or Trough at Ref. Receiver (sec)	Time: Peak or Trough at Lower Receiver (sec)	Travel Time Relative to Ref. Receiver (sec)	Travel Time* Relative to Reaction Mass (sec)
360	22	50/5	Vertical	0.01528	0.06065	0.11573	0.05508	0.10045
370	22	50/5	Vertical	0.01528	0.06061	**	-	-
380	22	50/5	Vertical	0.01528	0.06109	0.11753	0.05644	0.10225
390	22	50/5	Vertical	0.01528	0.06109	0.11843	0.05734	0.10315
400	22	50/5	Vertical	0.01528	0.06109	0.11933	0.05823	0.10404
410	22	50/5	Vertical	0.01528	0.06109	0.12022	0.05913	0.10494
420	22	50/5	Vertical	0.01528	0.06109	0.12045	0.05936	0.10517
430	22	50/5	Vertical	0.01528	0.06109	0.12090	0.05981	0.10562
440	22	50/5	Vertical	0.01528	0.06109	0.12135	0.06026	0.10607
450	22	50/5	Vertical	0.01528	0.06109	0.12180	0.06071	0.10652
455	22	50/5	Vertical	0.01528	0.06109	0.12247	0.06138	0.10719
460	22	50/5	Vertical	0.01528	0.06109	0.12292	0.06183	0.10764
465	22	50/5	Vertical	0.01528	0.06109	0.12374	0.06265	0.10846
470	22	50/5	Vertical	0.01528	0.06109	0.12491	0.06382	0.10963
475	22	50/5	Vertical	0.01528	0.06109	0.12528	0.06419	0.11000
480	22	50/5	Vertical	0.01528	0.06109	0.12584	0.06475	0.11056
485	22	50/5	Vertical	0.01528	0.06109	0.12640	0.06531	0.11112
490	22	50/5	Vertical	0.01528	0.06109	0.12697	0.06588	0.11169
495	22	50/5	Vertical	0.01528	0.06109	0.12753	0.06644	0.11225
500	22	50/5	Vertical	0.01528	0.06109	0.12809	0.06700	0.11281
510	22	50/5	Vertical	0.01528	0.06109	0.12899	0.06790	0.11371
520	22	50/5	Vertical	0.01528	0.06109	0.12989	0.06880	0.11461
530	22	50/5	Vertical	0.01528	0.06109	0.13034	0.06925	0.11506
540	22	50/5	Vertical	0.01528	0.06109	0.13124	0.07015	0.11596
550	22	50/5	Vertical	0.01528	0.06109	0.13191	0.07082	0.11663
560	22	50/5	Vertical	0.01528	0.06109	0.13236	0.07127	0.11708
570	22	50/5	Vertical	0.01528	0.06109	0.13303	0.07194	0.11775

* Use of the reaction mass as a reference for calculating relative travel times exhibited less scatter than using the reference receiver.
** Waveform was distorted making arrival time unidentifiable.

Table 3.2 Relative P-Wave Travel Times at Borehole C4996

Lower Receiver Depth (ft)	Reference Receiver Depth (ft)	T-Rex Drive Freq./ No. of Cycles (Hz/No.)	T-Rex Excitation Direction	Time: Peak or Trough at Reaction Mass (sec)	Time: Peak or Trough at Ref. Receiver (sec)	Time: Peak or Trough at Lower Receiver (sec)	Travel Time Relative to Ref. Receiver (sec)	Travel Time* Relative to Reaction Mass (sec)
580	22	50/5	Vertical	0.01528	0.06109	0.13371	0.07262	0.11843
590	22	50/5	Vertical	0.01528	0.06109	0.13416	0.07307	0.11888
600	22	50/5	Vertical	0.01528	0.06109	0.13404	0.07295	0.11876
610	22	50/5	Vertical	0.01528	0.06109	0.13539	0.07430	0.12011
620	22	50/5	Vertical	0.01528	0.06109	0.13573	0.07464	0.12045
630	22	50/5	Vertical	0.01528	0.06109	0.13674	0.07565	0.12146
640	22	50/5	Vertical	0.01528	0.06152	0.13775	0.07623	0.12247
650	22	50/5	Vertical	0.01528	0.06152	0.13843	0.07691	0.12315
660	22	50/5	Vertical	0.01528	0.06152	0.13910	0.07758	0.12382
670	22	50/5	Vertical	0.01528	0.06152	0.13933	0.07781	0.12404
680	22	50/5	Vertical	0.01528	0.06152	0.13944	0.07792	0.12416
690	22	50/5	Vertical	0.01528	0.06152	0.14011	0.07859	0.12483
700	22	50/5	Vertical	0.01528	0.06152	0.14079	0.07927	0.12551
705	22	50/5	Vertical	0.01528	0.06152	0.14146	0.07994	0.12618
710	22	50/5	Vertical	0.01528	0.06152	0.14180	0.08028	0.12652
715	22	50/5	Vertical	0.01528	0.06152	0.14213	0.08062	0.12685
720	22	50/5	Vertical	0.01528	0.06152	0.14213	0.08062	0.12685
730	22	50/5	Vertical	0.01528	0.06152	0.14382	0.08230	0.12854
740	22	50/5	Vertical	0.01528	0.06152	0.14472	0.08320	0.12944
750	22	50/5	Vertical	0.01528	0.06152	0.14607	0.08455	0.13079
760	22	50/5	Vertical	0.01528	0.06152	0.14652	0.08500	0.13124
770	22	50/5	Vertical	0.01528	0.06152	0.14764	0.08612	0.13236
780	22	50/5	Vertical	0.01528	0.06152	0.14787	0.08635	0.13258
790	22	50/5	Vertical	0.01528	0.06152	0.14809	0.08657	0.13281
800	22	50/5	Vertical	0.01528	0.06152	0.14854	0.08702	0.13326
810	22	50/5	Vertical	0.01528	0.06152	0.14921	0.08770	0.13393
815	22	50/5	Vertical	0.01528	0.06206	0.14899	0.08693	0.13371

* Use of the reaction mass as a reference for calculating relative travel times exhibited less scatter than using the reference receiver.

Table 3.3 Relative P-Wave Travel Times at Borehole C4996

Lower Receiver Depth (ft)	Reference Receiver Depth (ft)	T-Rex Drive Freq./ No. of Cycles (Hz/No.)	T-Rex Excitation Direction	Time: Peak or Trough at Reaction Mass (sec)	Time: Peak or Trough at Ref. Receiver (sec)	Time: Peak or Trough at Lower Receiver (sec)	Travel Time Relative to Ref. Receiver (sec)	Travel Time* Relative to Reaction Mass (sec)
820	22	50/5	Vertical	0.01528	0.06206	0.14966	0.08760	0.13438
830	22	50/5	Vertical	0.01528	0.06206	0.15079	0.08873	0.13551
840	22	50/5	Vertical	0.01528	0.06206	0.15191	0.08985	0.13663
850	22	50/5	Vertical	0.01528	0.06206	0.15371	0.09165	0.13843
860	22	50/5	Vertical	0.01528	0.06206	0.15551	0.09344	0.14022
870	22	50/5	Vertical	0.01528	0.06206	0.15708	0.09502	0.14180
880	22	50/5	Vertical	0.01528	0.06206	0.15865	0.09659	0.14337
890	22	50/5	Vertical	0.01528	0.06206	0.15933	0.09727	0.14405
900	22	50/5	Vertical	0.01528	0.06206	0.16067	0.09861	0.14539
910	22	50/5	Vertical	0.01528	0.06206	0.16303	0.10097	0.14775
920	22	50/5	Vertical	0.01528	0.06206	0.16472	0.10266	0.14944
910	22	20/4	Vertical	0.02067	0.06400	0.15697	0.09297	0.13629
920	22	20/4	Vertical	0.02067	0.06400	0.15831	0.09431	0.13764
930	22	20/4	Vertical	0.02067	0.06400	0.15899	0.09499	0.13831
940	22	20/4	Vertical	0.02067	0.06400	0.15933	0.09533	0.13865
950	22	20/4	Vertical	0.02067	0.06400	0.16034	0.09634	0.13966
960	22	20/4	Vertical	0.02067	0.06400	0.16067	0.09667	0.14000
970	22	20/4	Vertical	0.02067	0.06400	0.16135	0.09735	0.14067
980	22	20/4	Vertical	0.02067	0.06400	0.16236	0.09836	0.14169
980	22	20/4	Vertical	0.02067	**	0.16157	-	0.14090
990	22	30/4	Vertical	0.01888	0.06206	0.17011	0.10805	0.15124
1000	22	30/4	Vertical	0.01888	0.06206	0.17112	0.10906	0.15225
1010	22	30/4	Vertical	0.01888	0.06206	0.17247	0.11041	0.15360
1020	22	30/4	Vertical	0.01888	0.06206	0.17079	0.10873	0.15191
1030	22	30/4	Vertical	0.01888	0.06206	0.17315	0.11109	0.15427
1040	22	30/4	Vertical	0.01888	0.06206	0.17584	0.11378	0.15697
1050	22	30/4	Vertical	0.01888	0.06206	0.17483	0.11277	0.15596

* Use of the reaction mass as a reference for calculating relative travel times exhibited less scatter than using the reference receiver.
** Waveform was distorted making arrival time unidentifiable.

Table 3.4 Relative P-Wave Travel Times at Borehole C4996

Lower Receiver Depth (ft)	Reference Receiver Depth (ft)	T-Rex Drive Freq./ No. of Cycles (Hz/No.)	T-Rex Excitation Direction	Time: Peak or Trough at Reaction Mass (sec)	Time: Peak or Trough at Ref. Receiver (sec)	Time: Peak or Trough at Lower Receiver (sec)	Travel Time Relative to Ref. Receiver (sec)	Travel Time* Relative to Reaction Mass (sec)
1060	22	30/4	Vertical	0.01888	0.06206	0.17517	0.11311	0.15629
1070	22	30/4	Vertical	0.01888	0.06206	0.17618	0.11412	0.15730
1080	22	30/4	Vertical	0.01888	0.06206	0.17854	0.11648	0.15966
1090	22	30/4	Vertical	0.01888	0.06206	0.17955	0.11749	0.16067
1100	22	30/4	Vertical	0.01888	0.06206	0.18157	0.11951	0.16270
1110	22	30/4	Vertical	0.01888	0.06206	0.18258	0.12052	0.16371
1120	22	30/4	Vertical	0.01888	0.06206	0.18326	0.12120	0.16438
1130	22	30/4	Vertical	0.01888	0.06206	0.18427	0.12221	0.16539
1140	22	30/4	Vertical	0.01888	0.06206	0.18562	0.12356	0.16674
1150	22	30/4	Vertical	0.01888	0.06206	0.18663	0.12457	0.16775
1160	22	30/4	Vertical	0.01888	0.06206	0.18798	0.12592	0.16910
1170	22	30/4	Vertical	0.01888	0.06206	0.18899	0.12693	0.17011
1180	22	30/4	Vertical	0.01888	0.06206	0.18966	0.12760	0.17079
1200	22	30/4	Vertical	0.01888	0.06206	0.19169	0.12962	0.17281
1220	22	30/4	Vertical	0.01888	0.06206	0.19303	0.13097	0.17416
1240	22	30/4	Vertical	0.01888	0.06206	0.19483	0.13277	0.17596
1260	22	30/4	Vertical	0.01888	0.06206	0.19528	0.13322	0.17640
1280	22	30/4	Vertical	0.01888	0.06206	0.19618	0.13412	0.17730
1300	22	30/4	Vertical	0.01888	0.06206	0.19663	0.13457	0.17775
1320	22	30/4	Vertical	0.01888	0.06206	0.19753	0.13547	0.17865
1340	22	30/4	Vertical	0.01888	0.06206	0.19933	0.13727	0.18045
1360	22	30/4	Vertical	0.01888	0.06206	0.20067	0.13861	0.18180
1380	22	30/4	Vertical	0.01888	0.06206	0.20157	0.13951	0.18270
1400	22	30/4	Vertical	0.01888	0.06206	0.20382	0.14176	0.18494

* Use of the reaction mass as a reference for calculating relative travel times exhibited less scatter than using the reference receiver.

Section 4: Unfiltered P-Wave Records at Lower Receiver

Section 4 includes all unfiltered P-wave records at the lower vertical receiver.

1. Figures 4.1 through 4.6 present unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 4.7 presents unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 4.8 through 4.10 present unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; input signal: 4 cycles of 30-Hz sine wave.

Figure 4.1 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

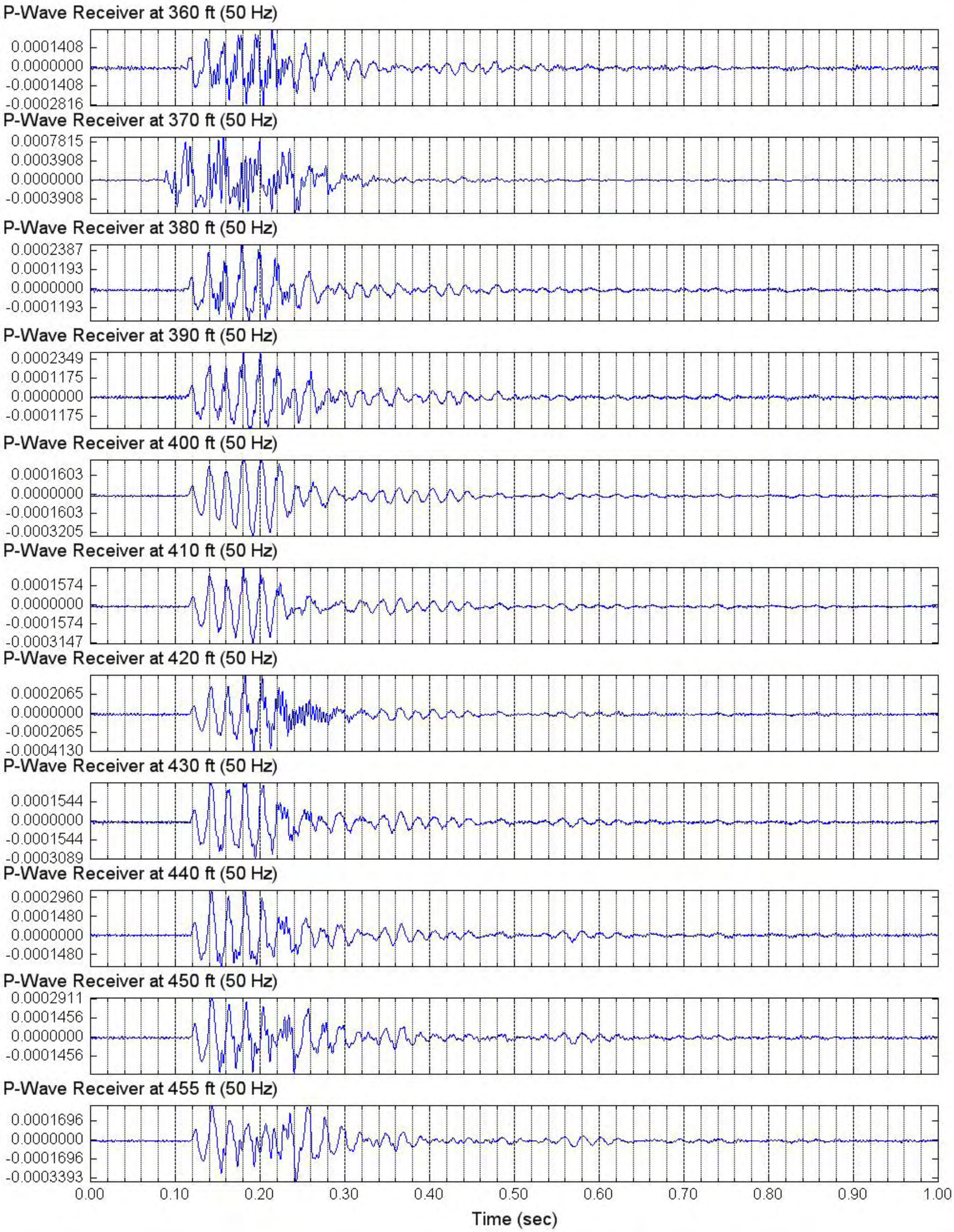


Figure 4.2 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

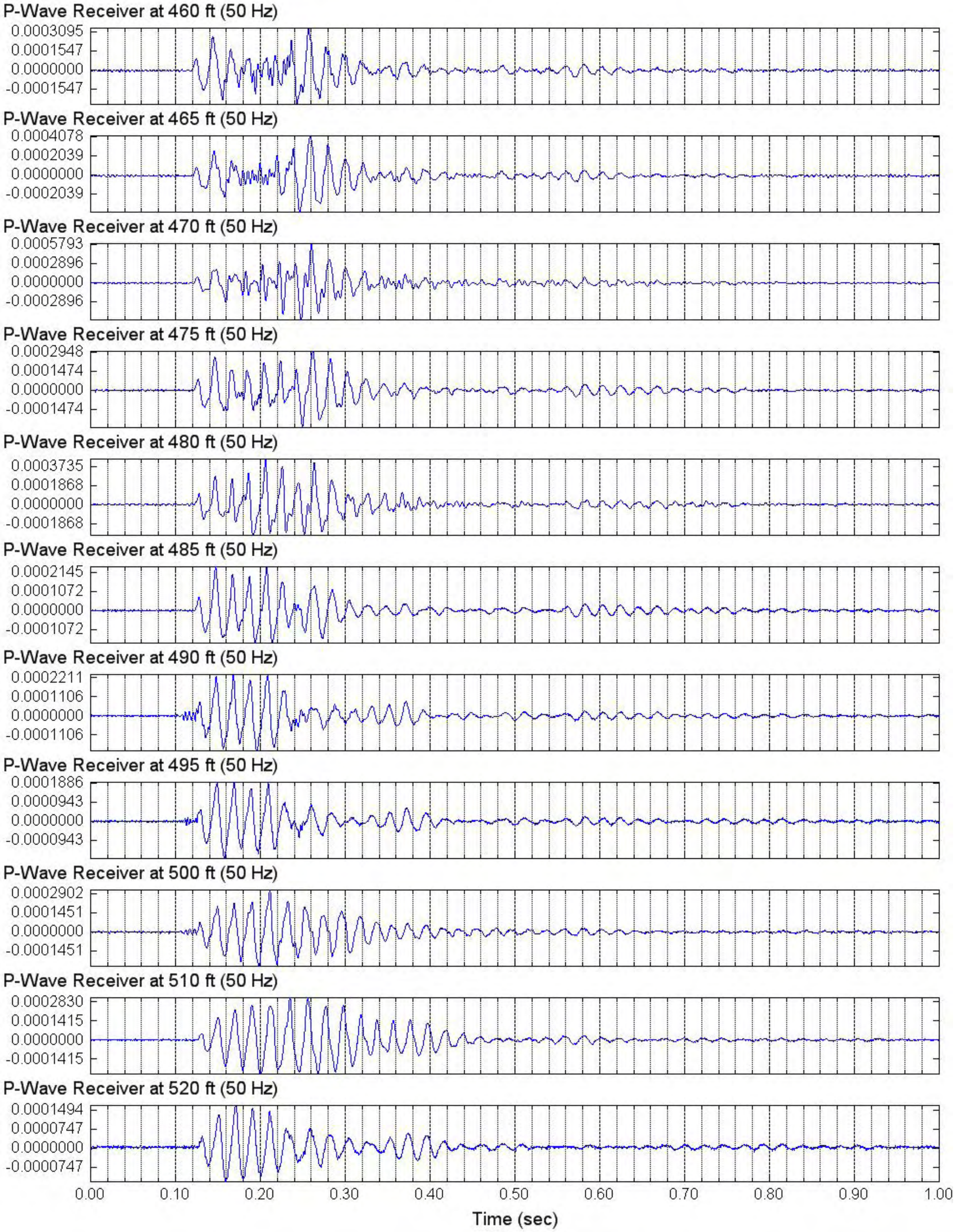


Figure 4.3 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

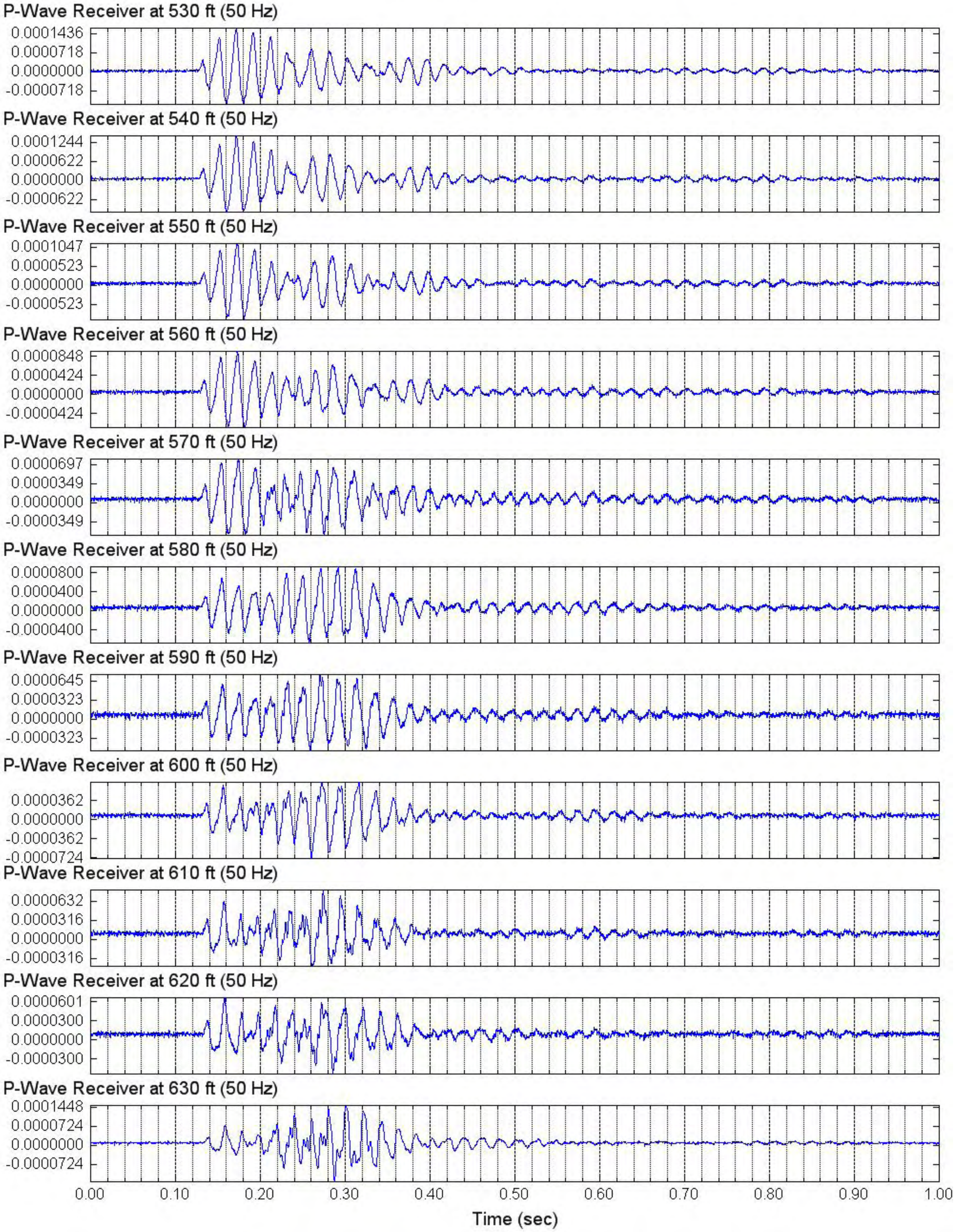


Figure 4.4 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

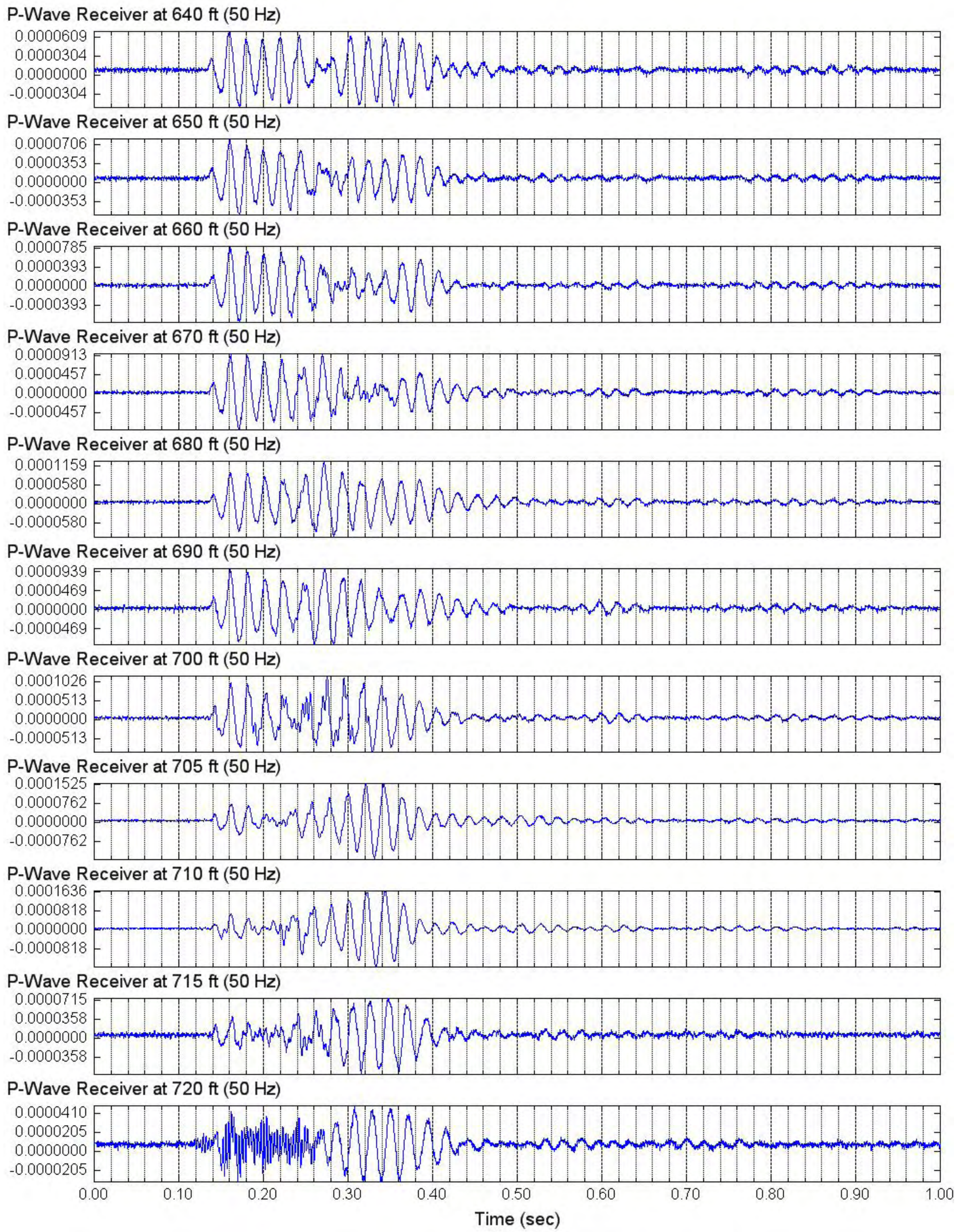


Figure 4.5 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

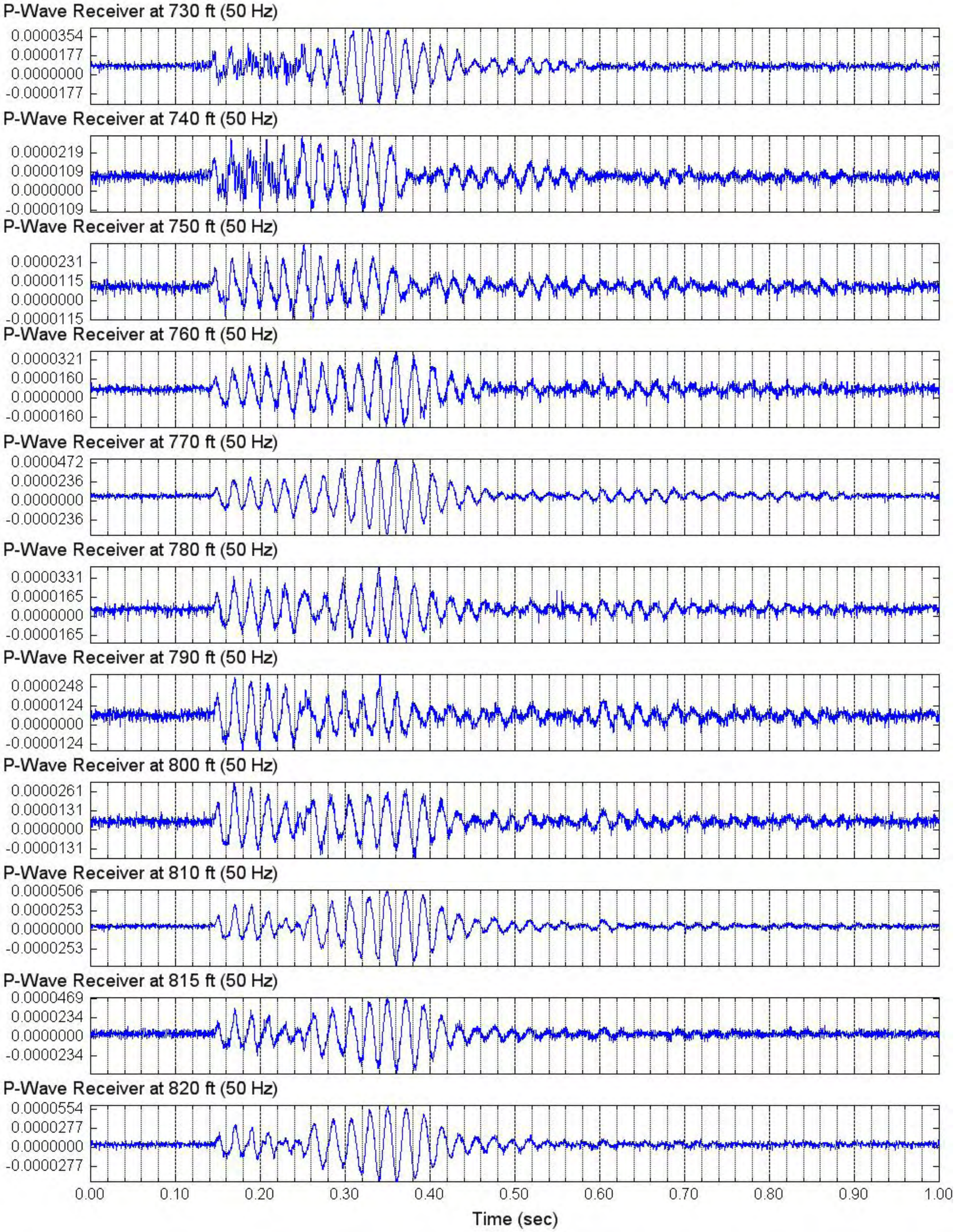


Figure 4.6 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

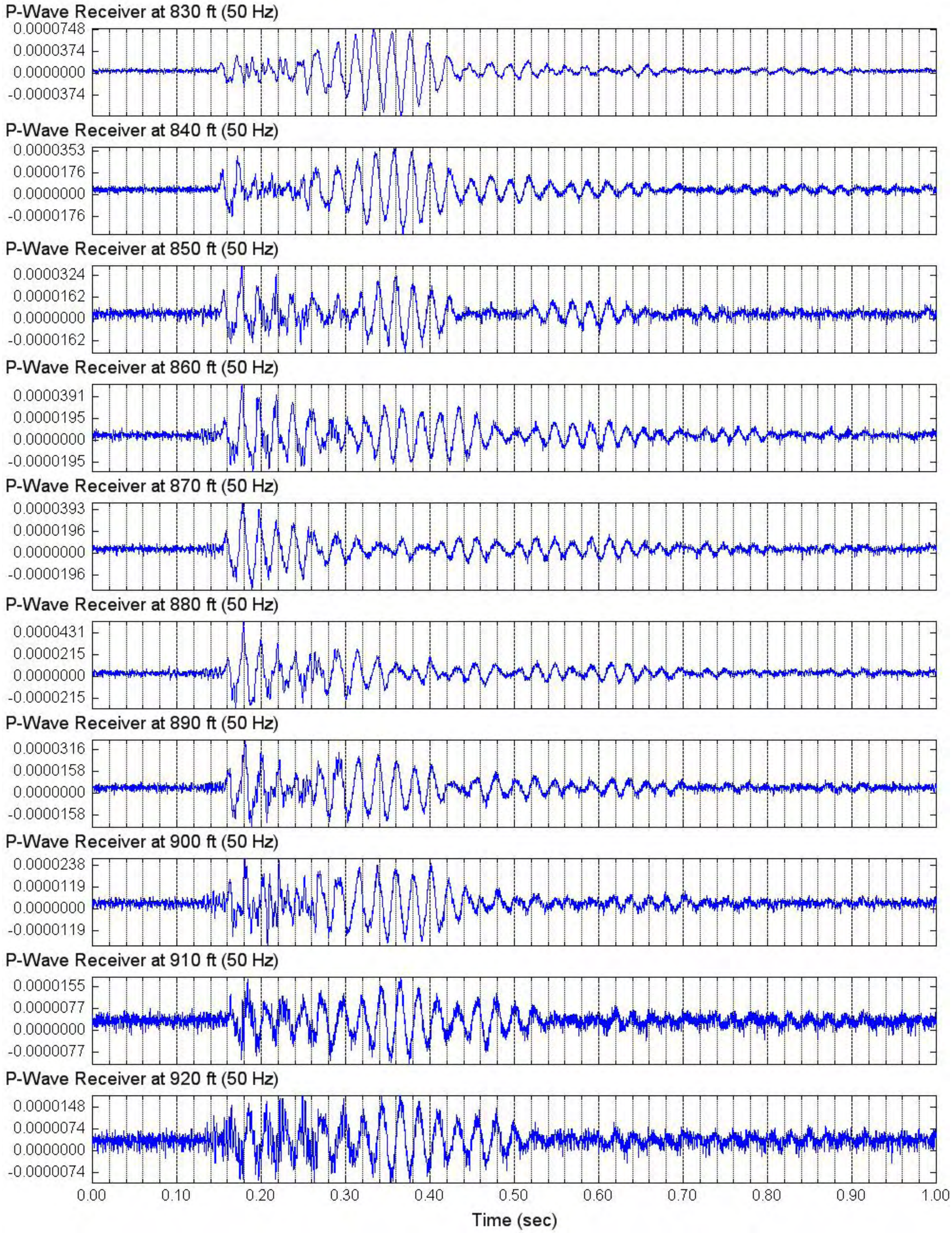


Figure 4.7 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave

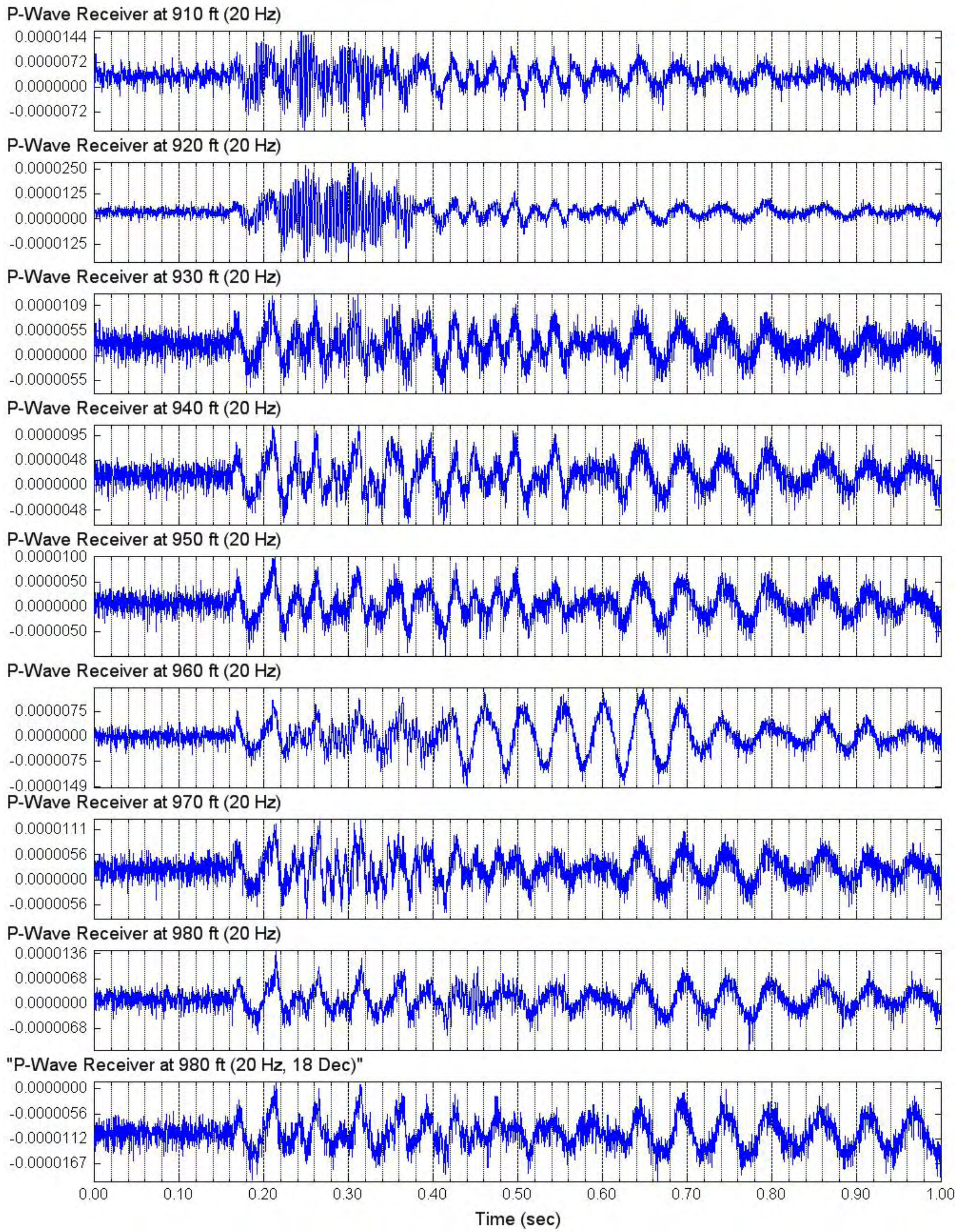


Figure 4.8 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

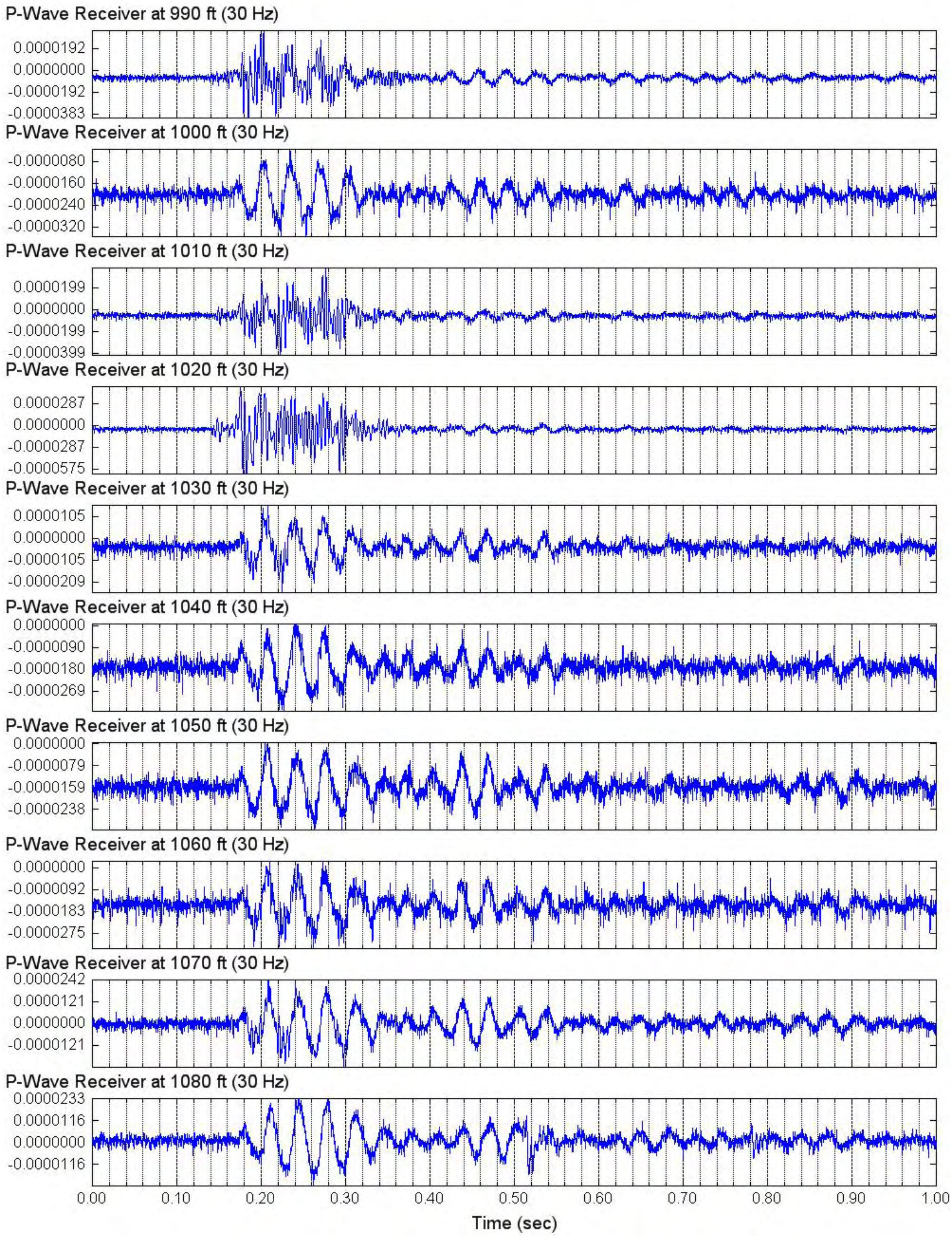


Figure 4.9 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

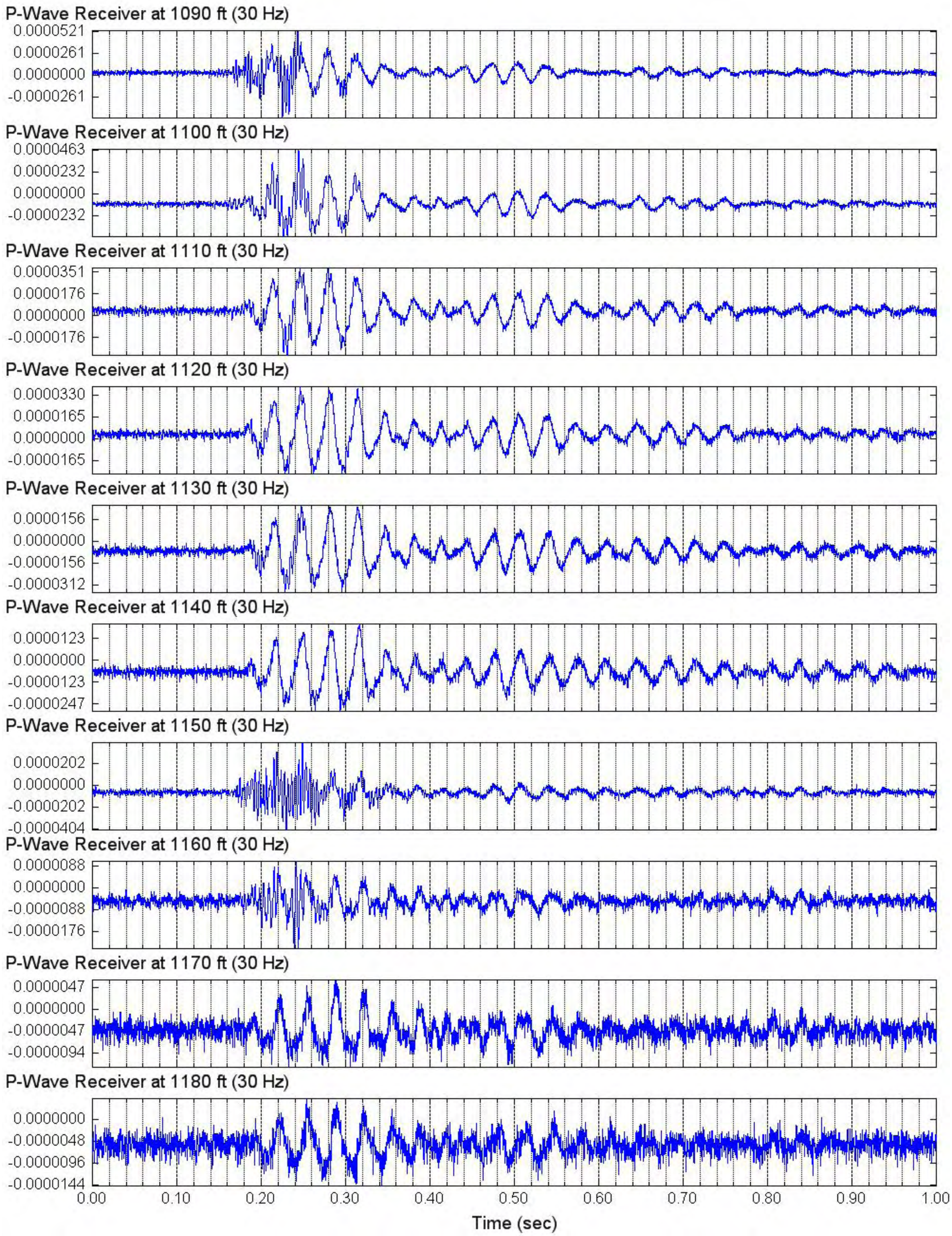
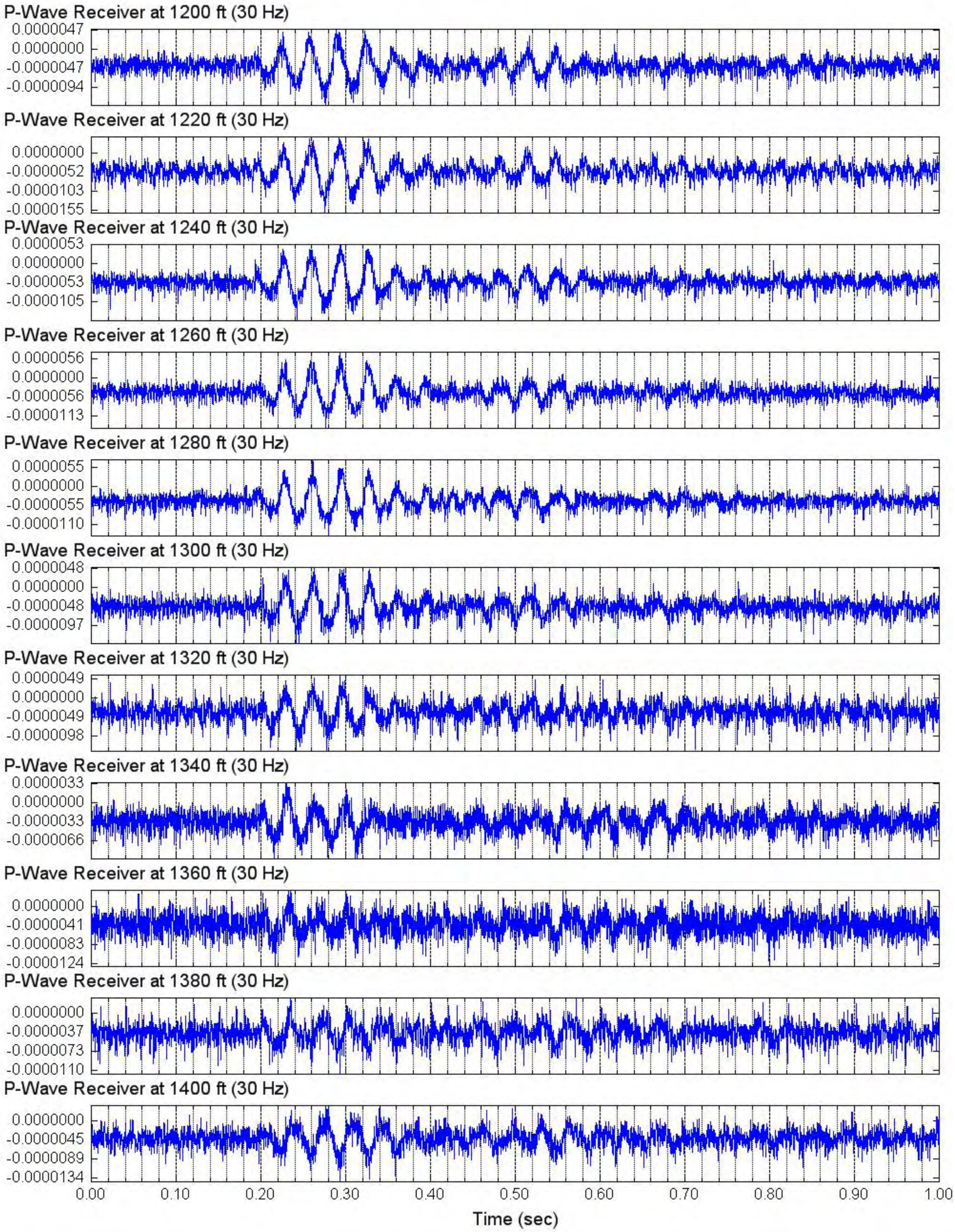


Figure 4.10 Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave



Section 5: Unfiltered P-Wave Records of Reaction Mass

Section 5 includes all unfiltered P-wave signals of the reaction mass accelerometer.

1. Figures 5.1 to 5.6 present unfiltered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 360 to 920 ft; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 5.7 presents unfiltered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 910 to 980 ft; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 5.8 to 5.10 present unfiltered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 990 to 1400 ft; input signal: 4 cycles of 30-Hz sine wave.

Figure 5.1 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

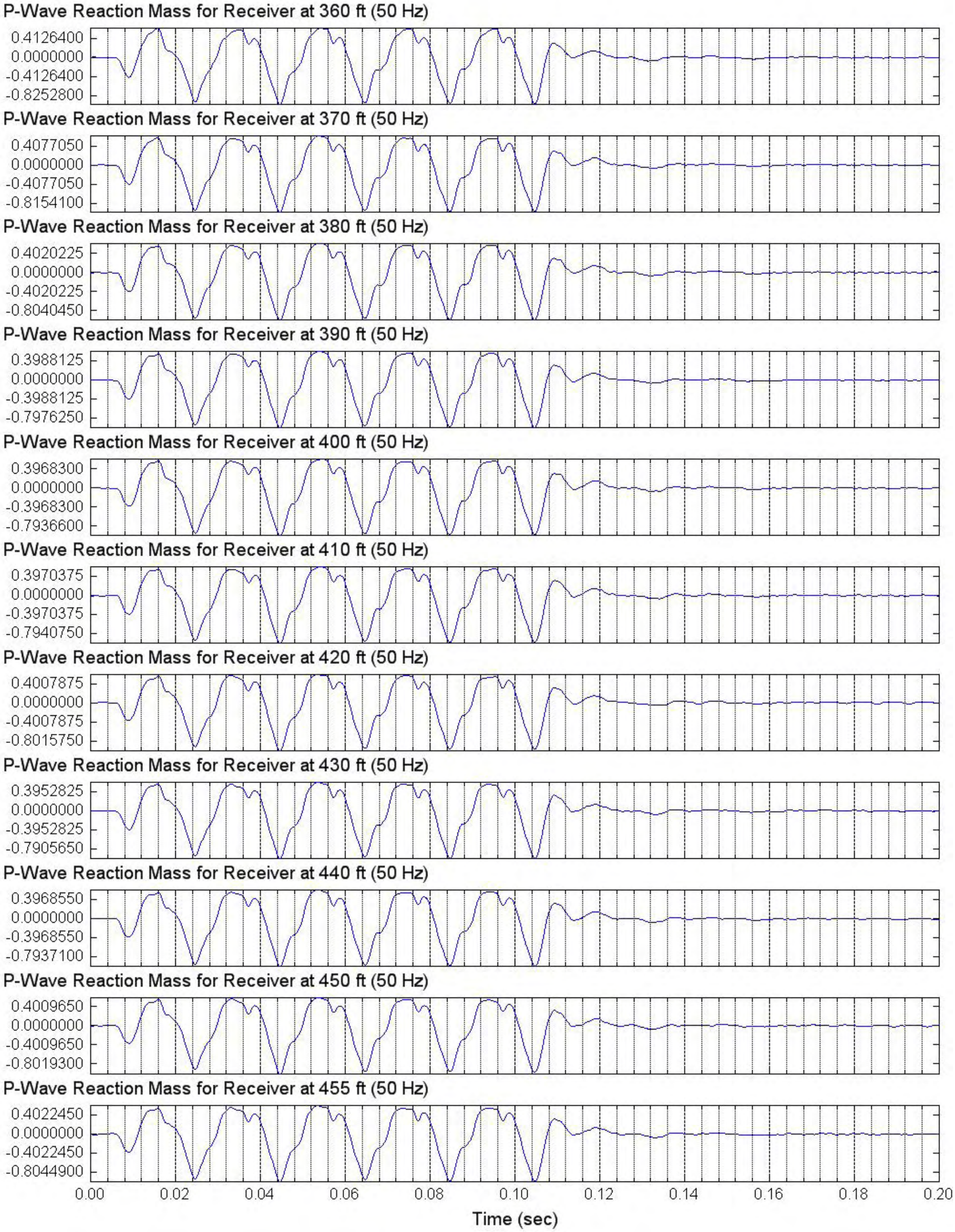


Figure 5.2 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

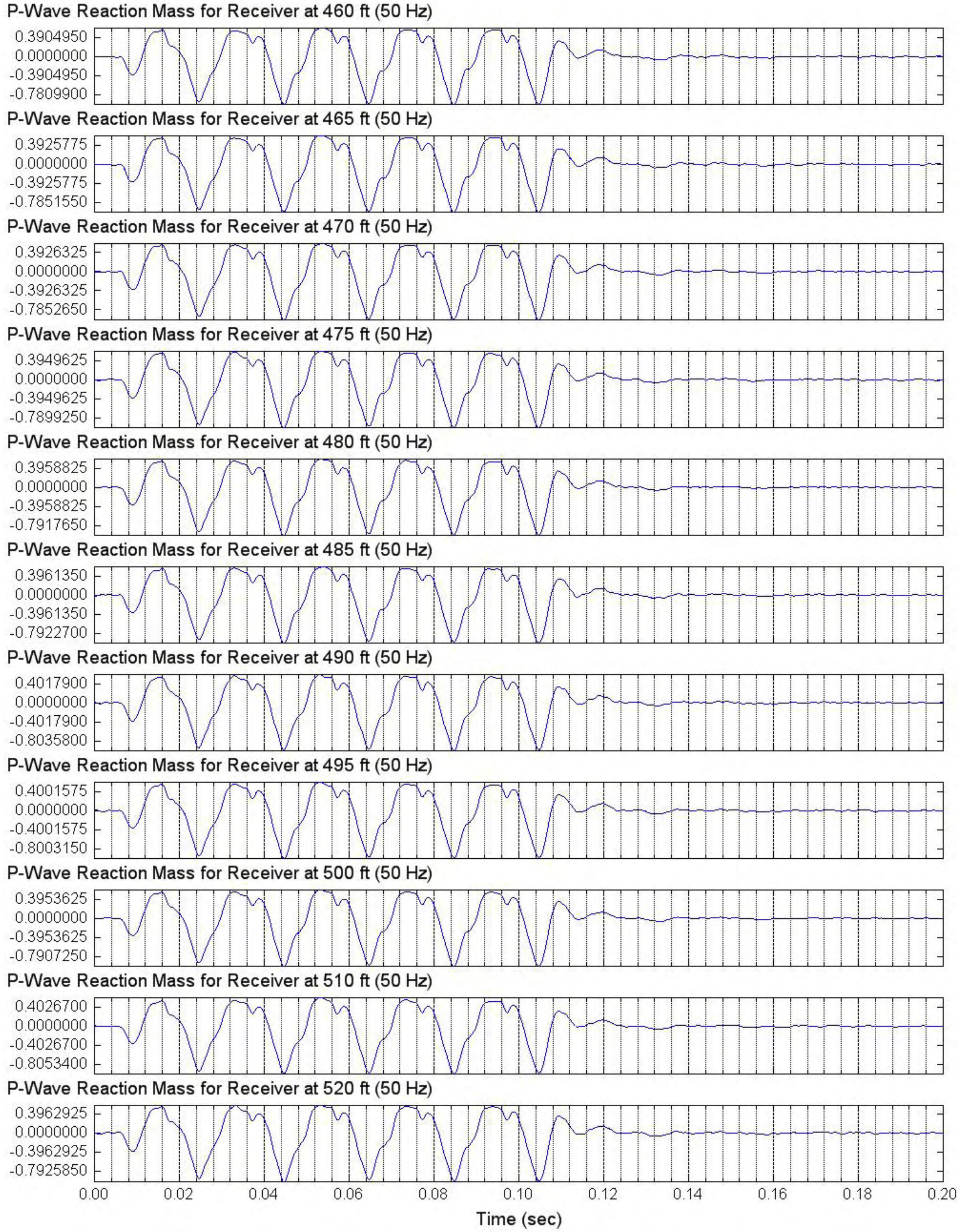


Figure 5.3 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

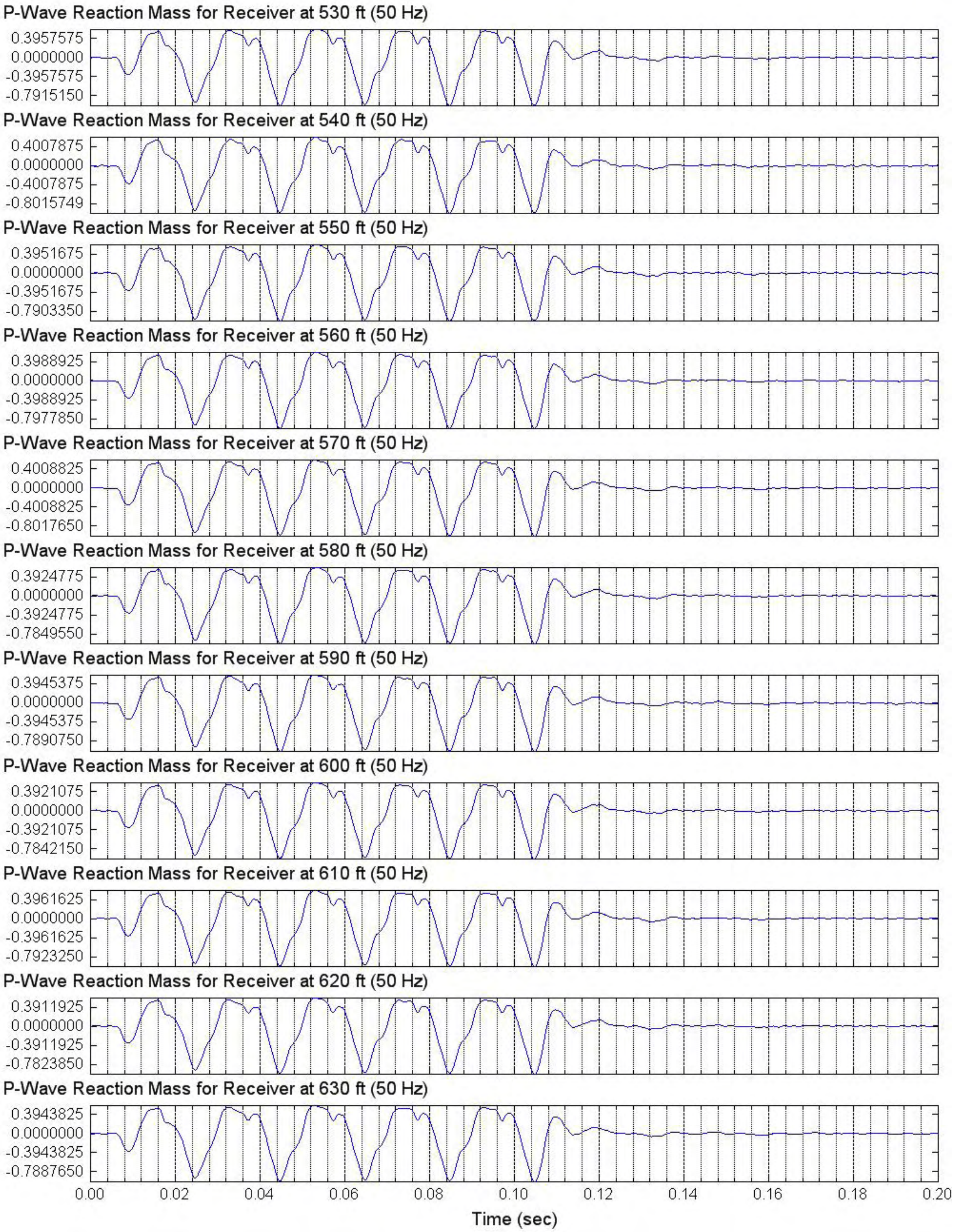


Figure 5.4 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

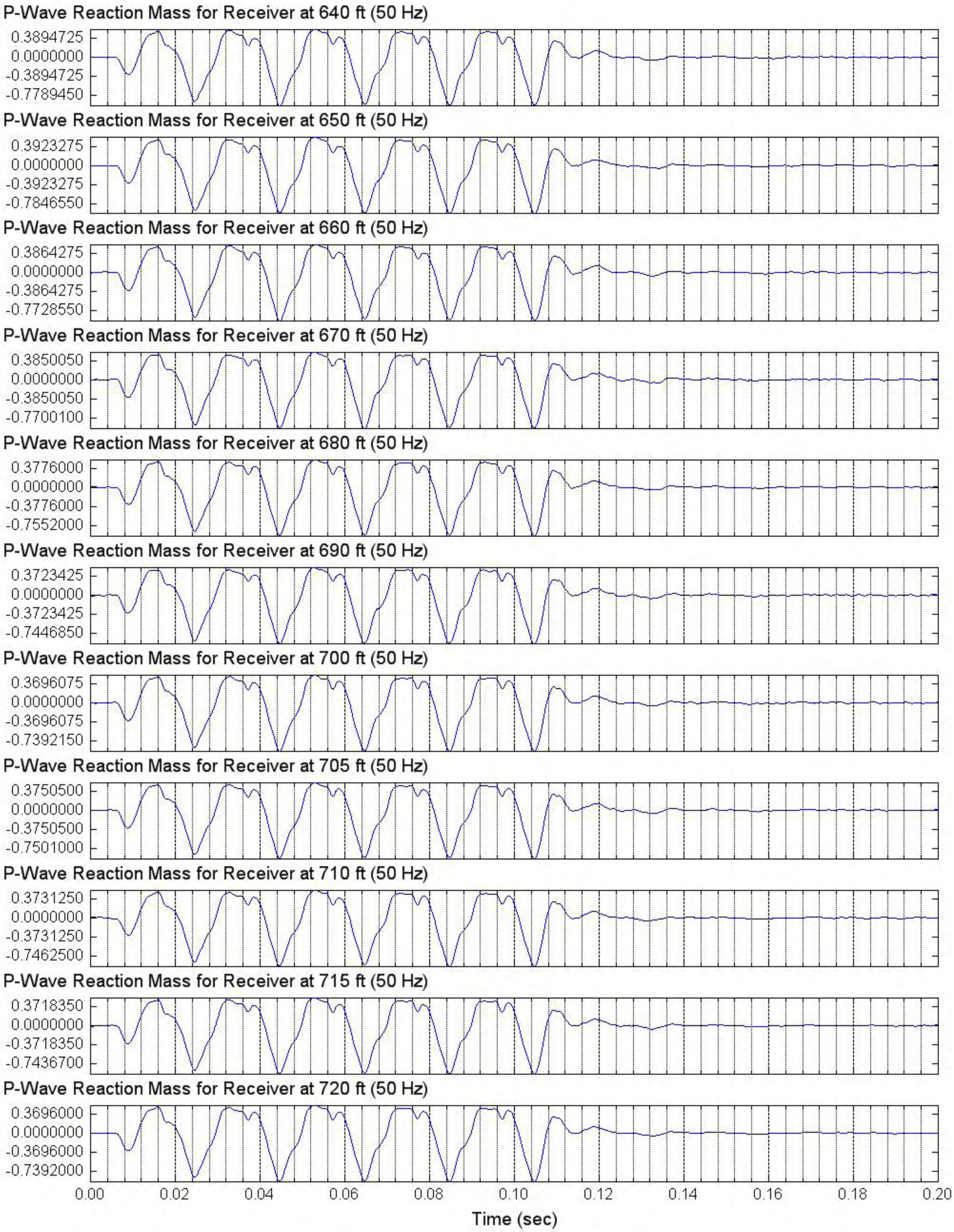


Figure 5.5 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

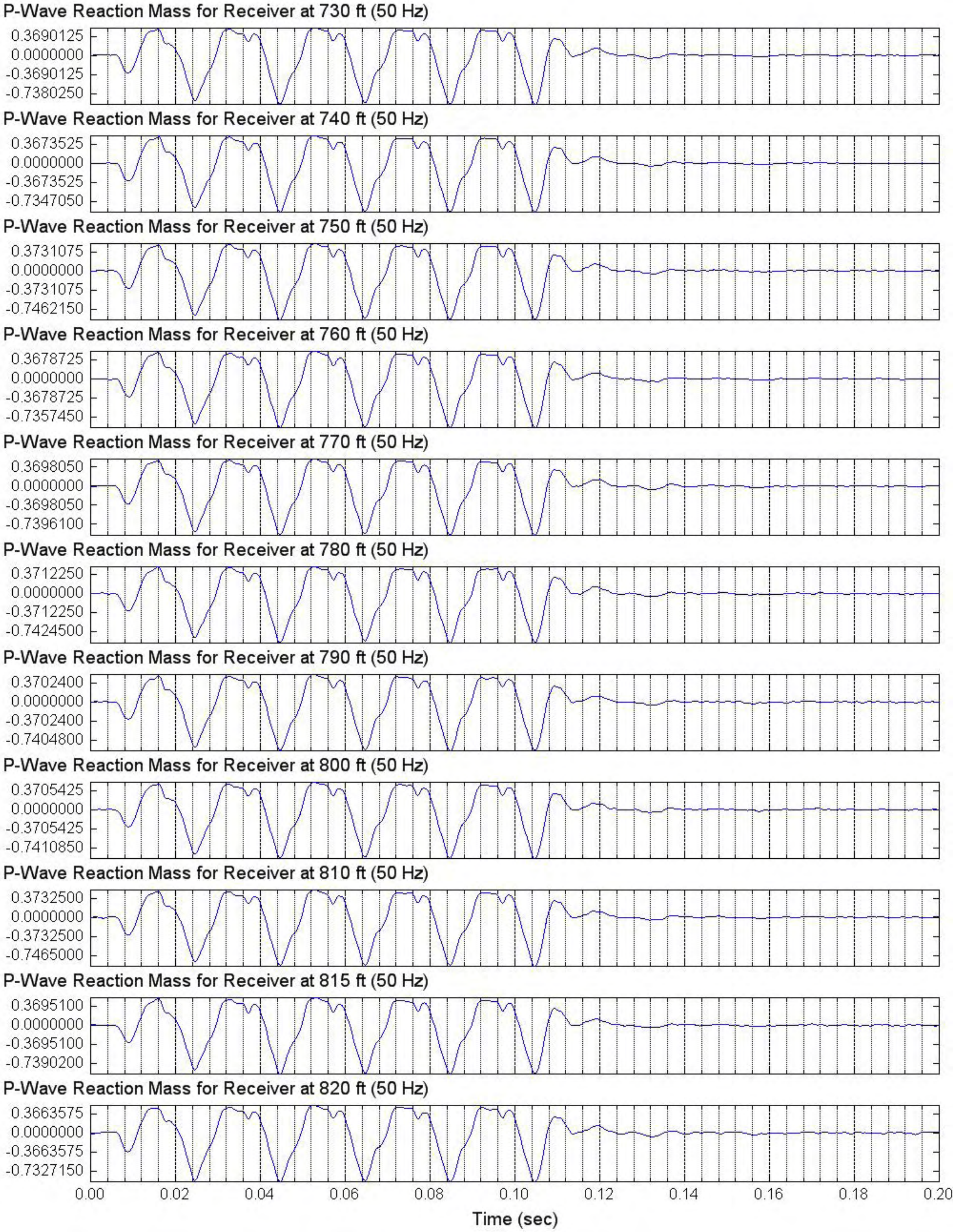


Figure 5.6 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

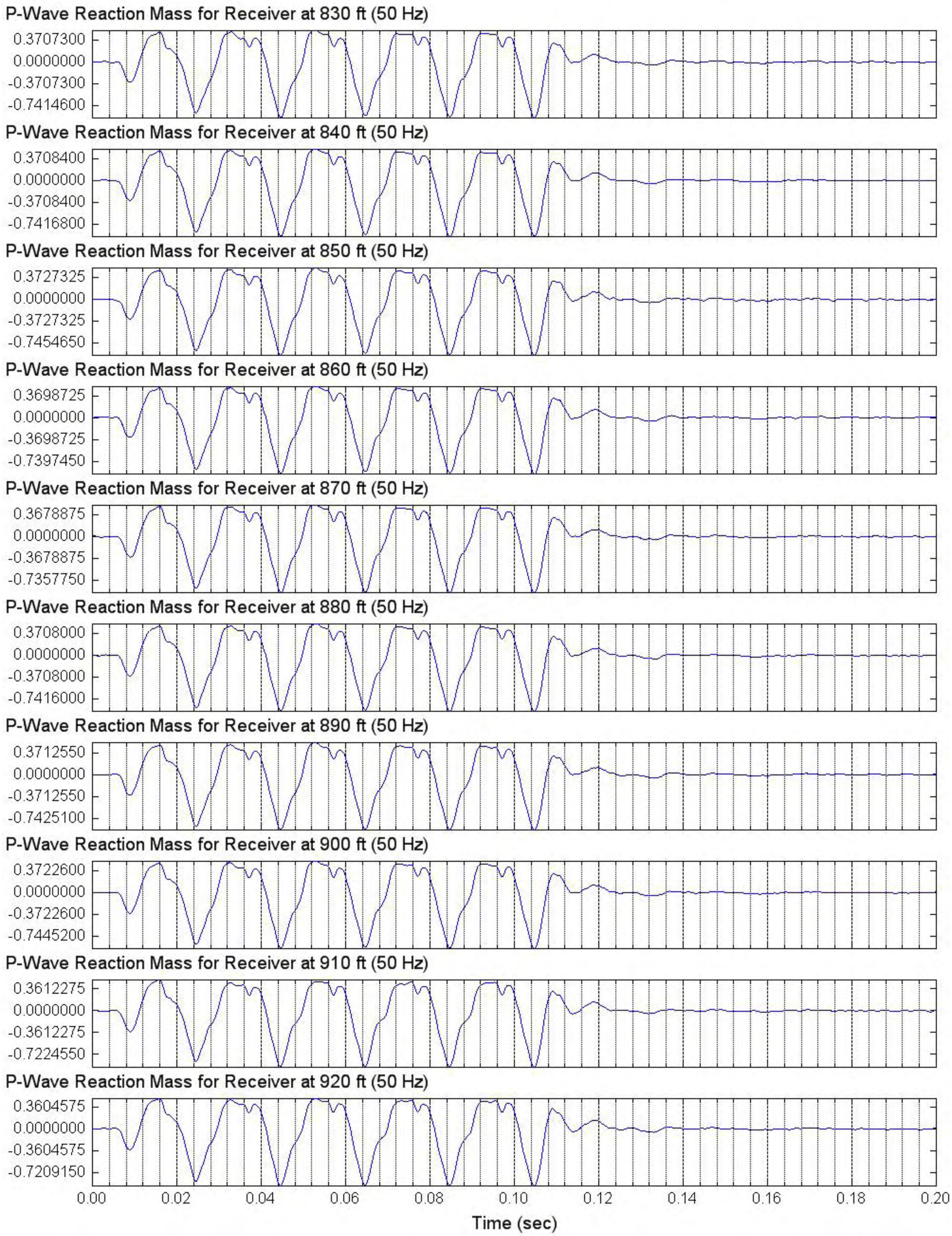


Figure 5.7 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave

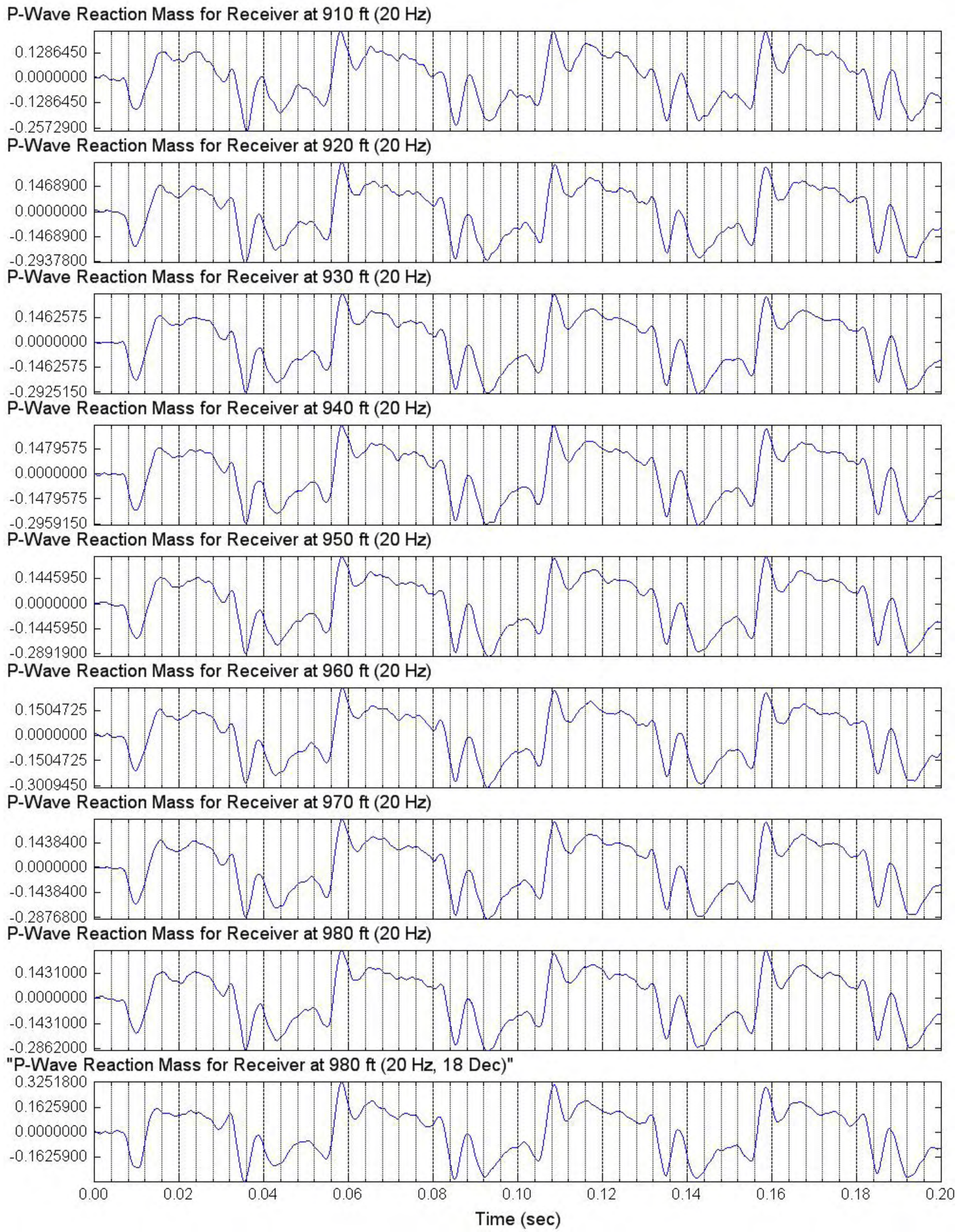


Figure 5.8 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

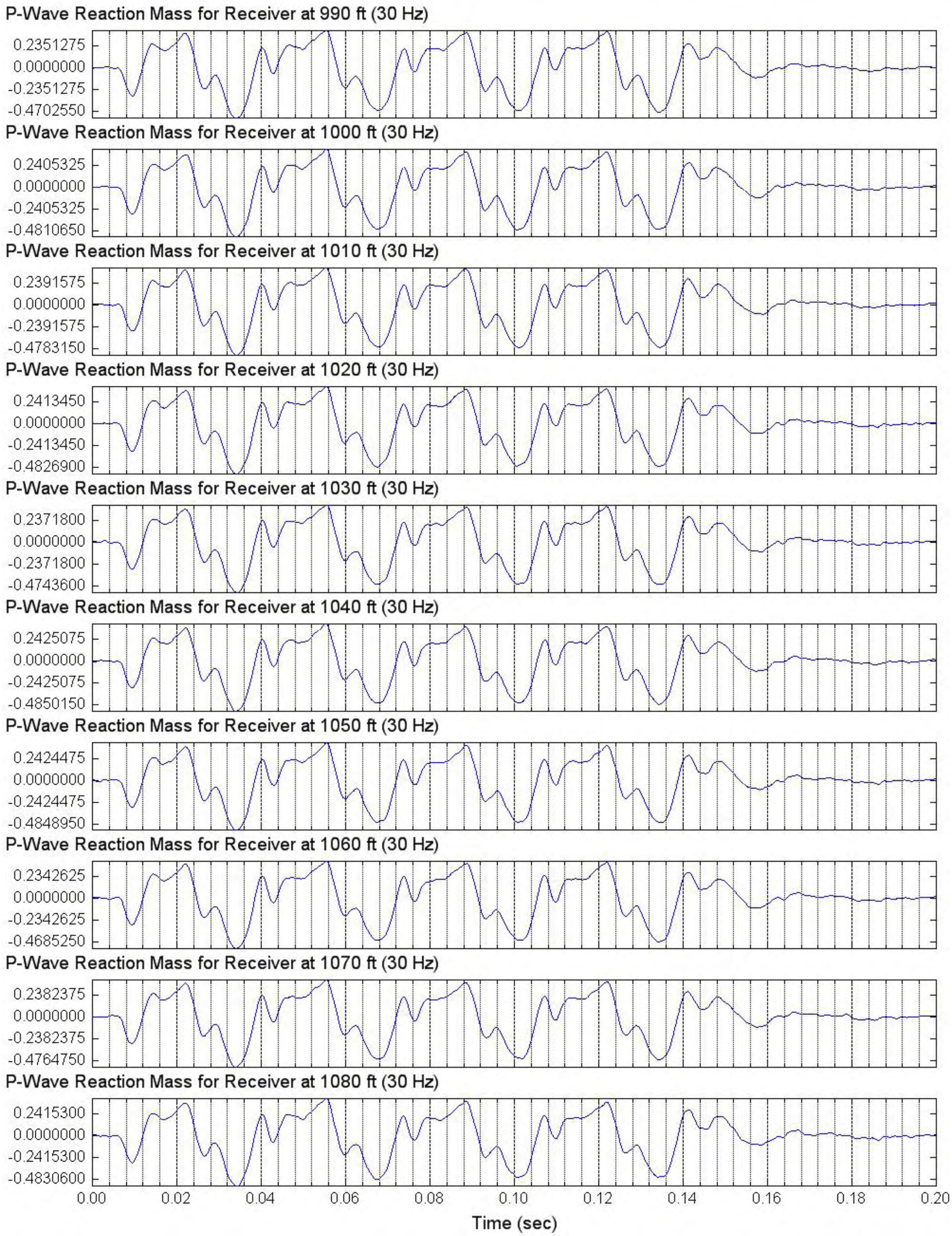


Figure 5.9 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

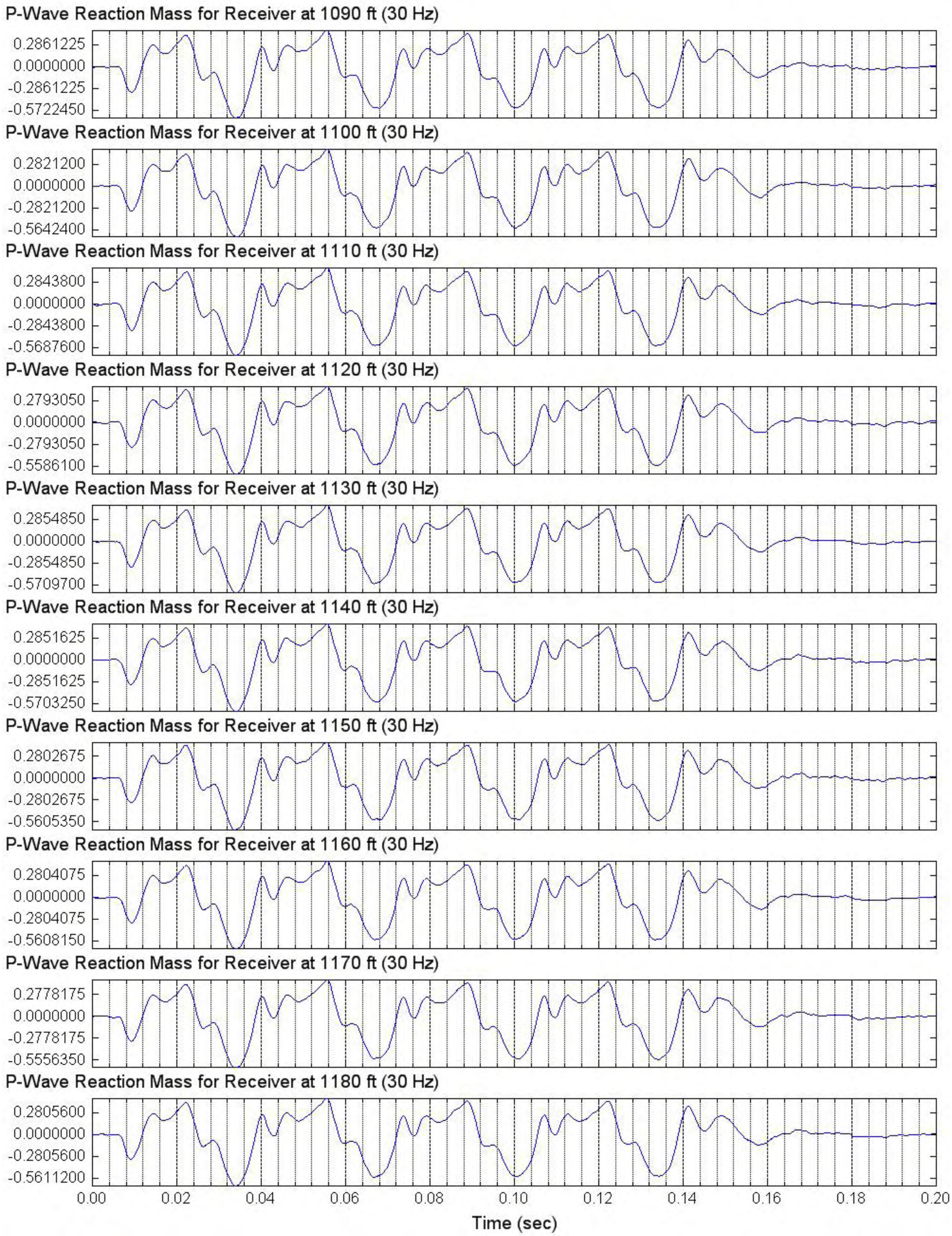
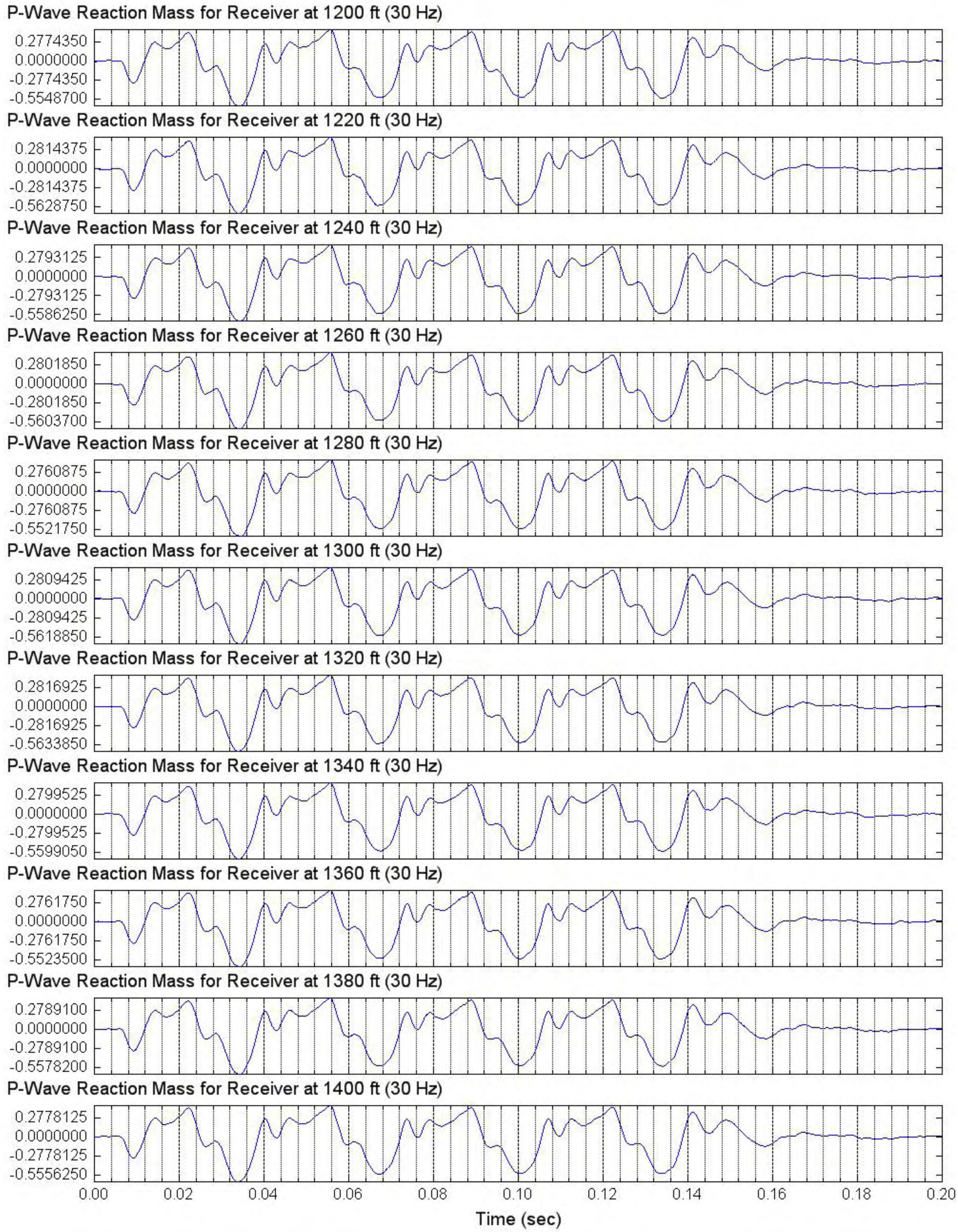


Figure 5.10 Unfiltered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave



Section 6: Unfiltered P-Wave Records of Reference Receiver

Section 6 includes all unfiltered P-wave signals at the reference receiver.

1. Figures 6.1 to 6.6 present unfiltered reference vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 6.7 presents unfiltered reference vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 6.8 to 6.10 present unfiltered reference vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; input signal: 4 cycles of 30-Hz sine wave.

Figure 6.1 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

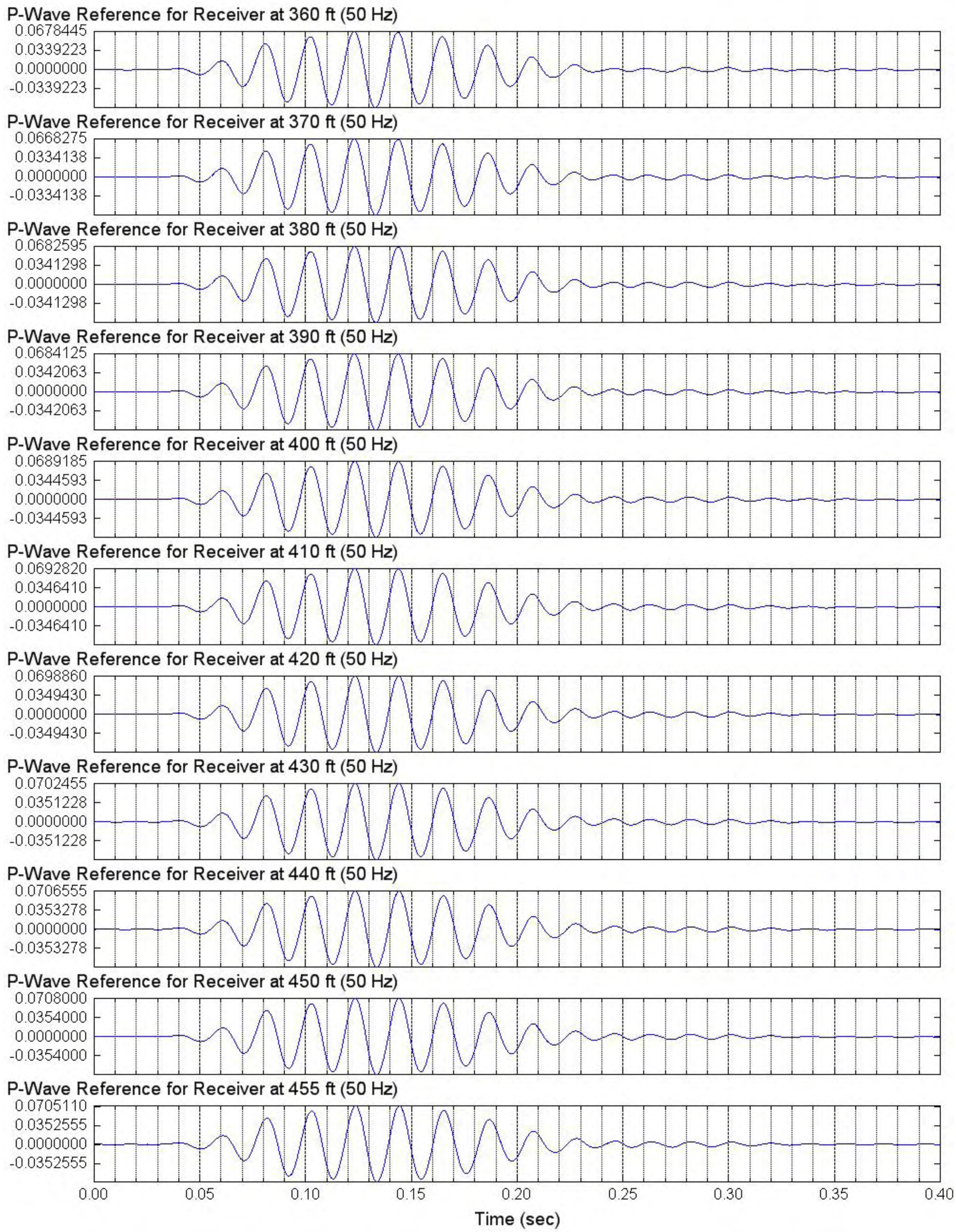


Figure 6.2 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

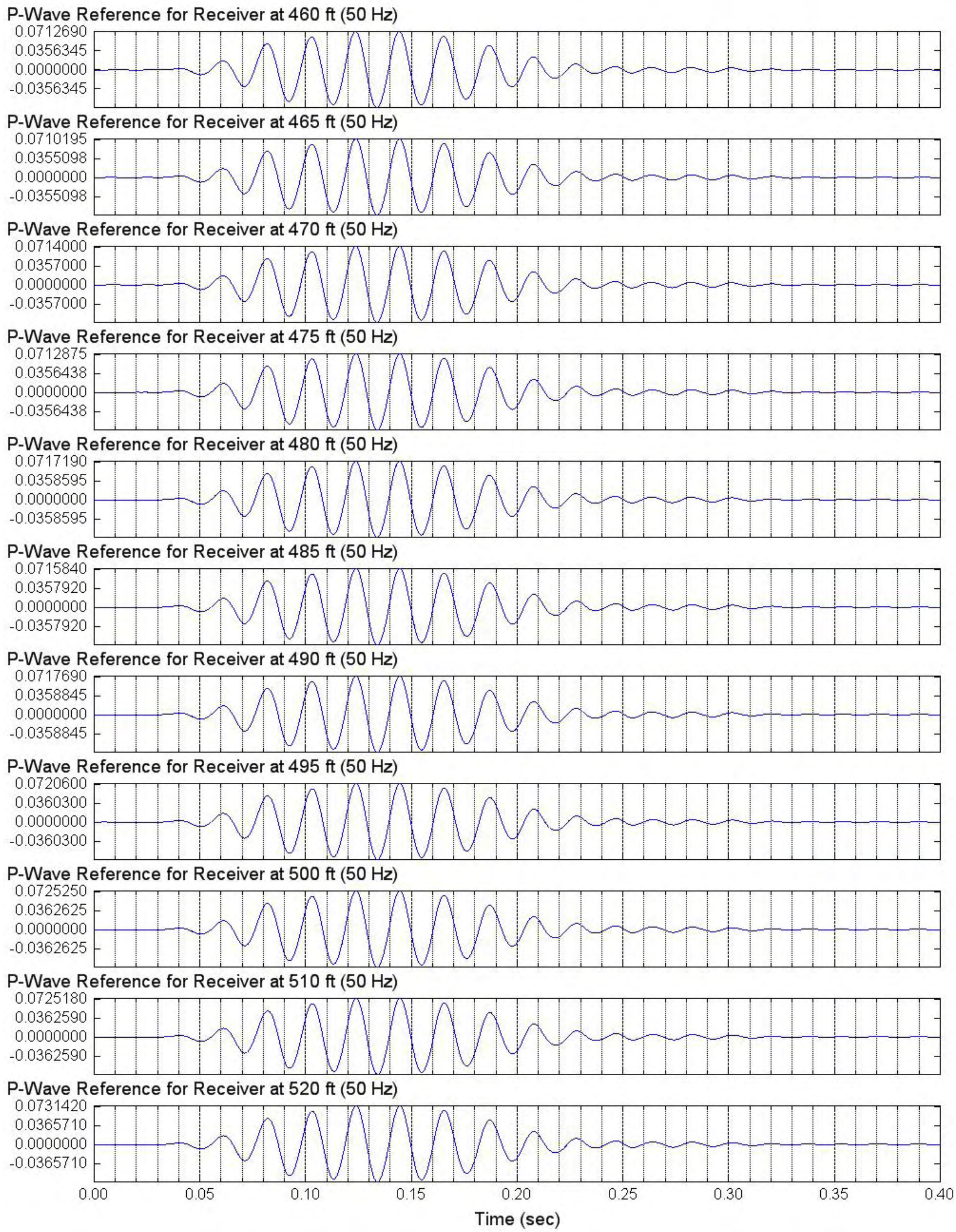


Figure 6.3 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

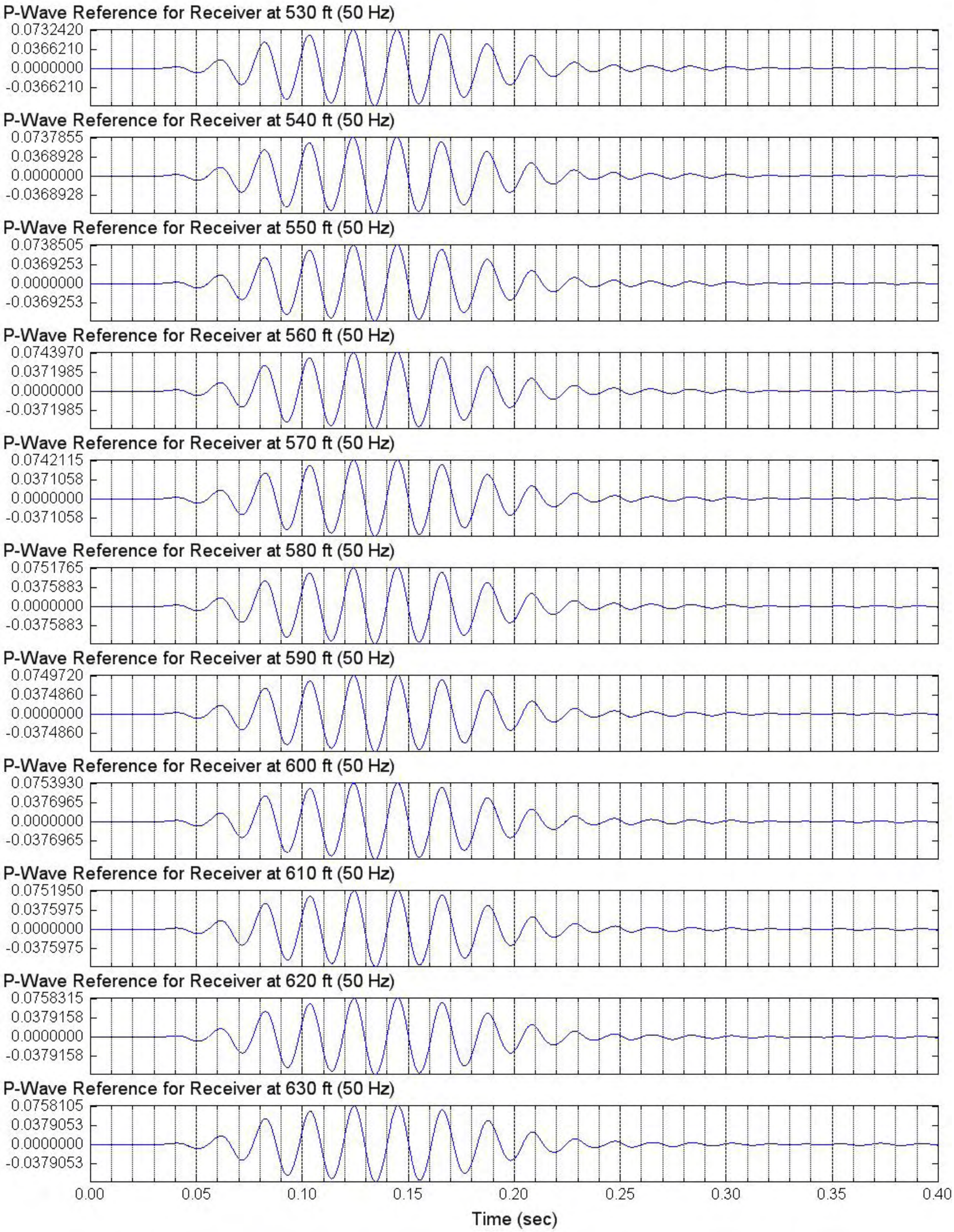


Figure 6.4 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

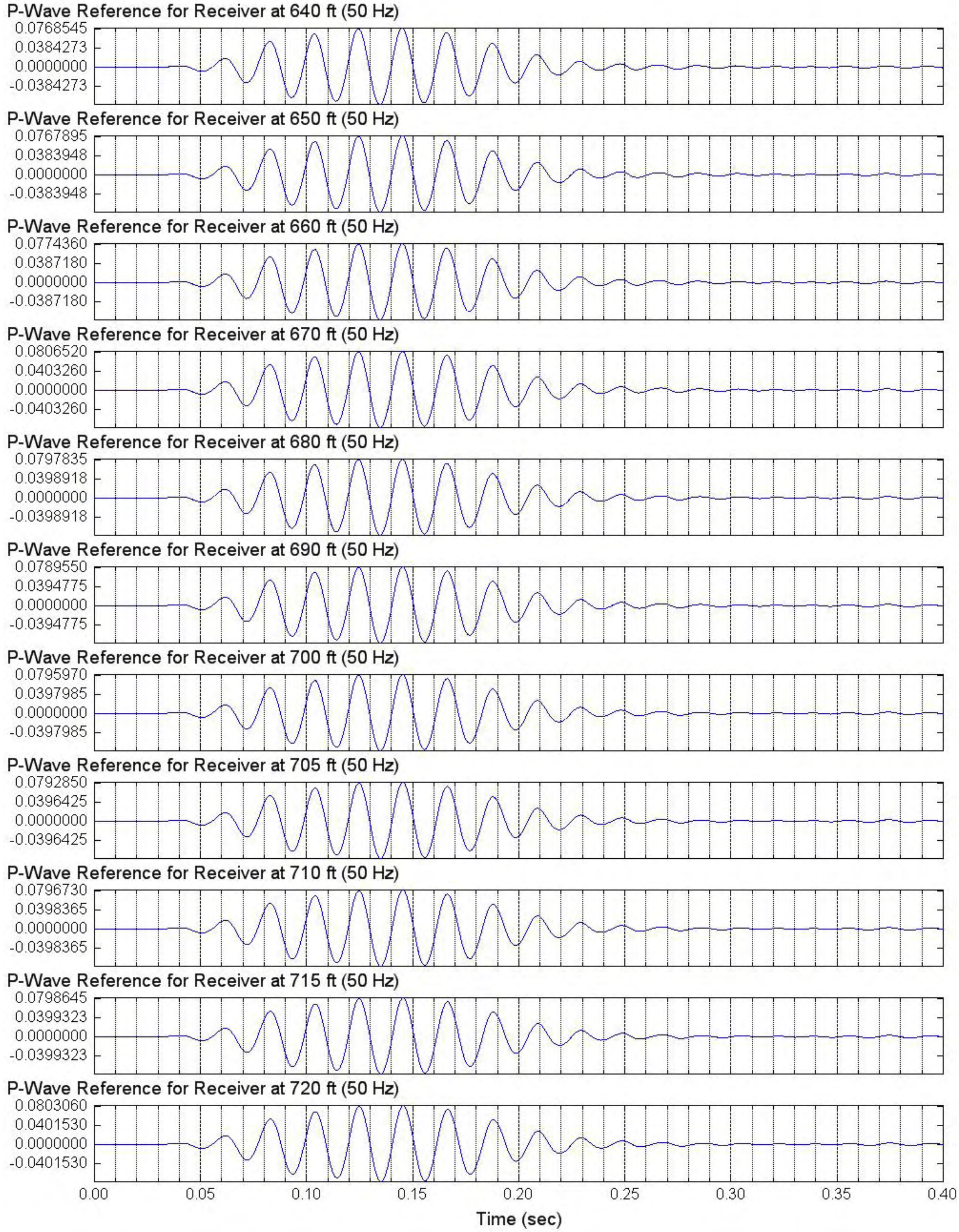


Figure 6.5 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

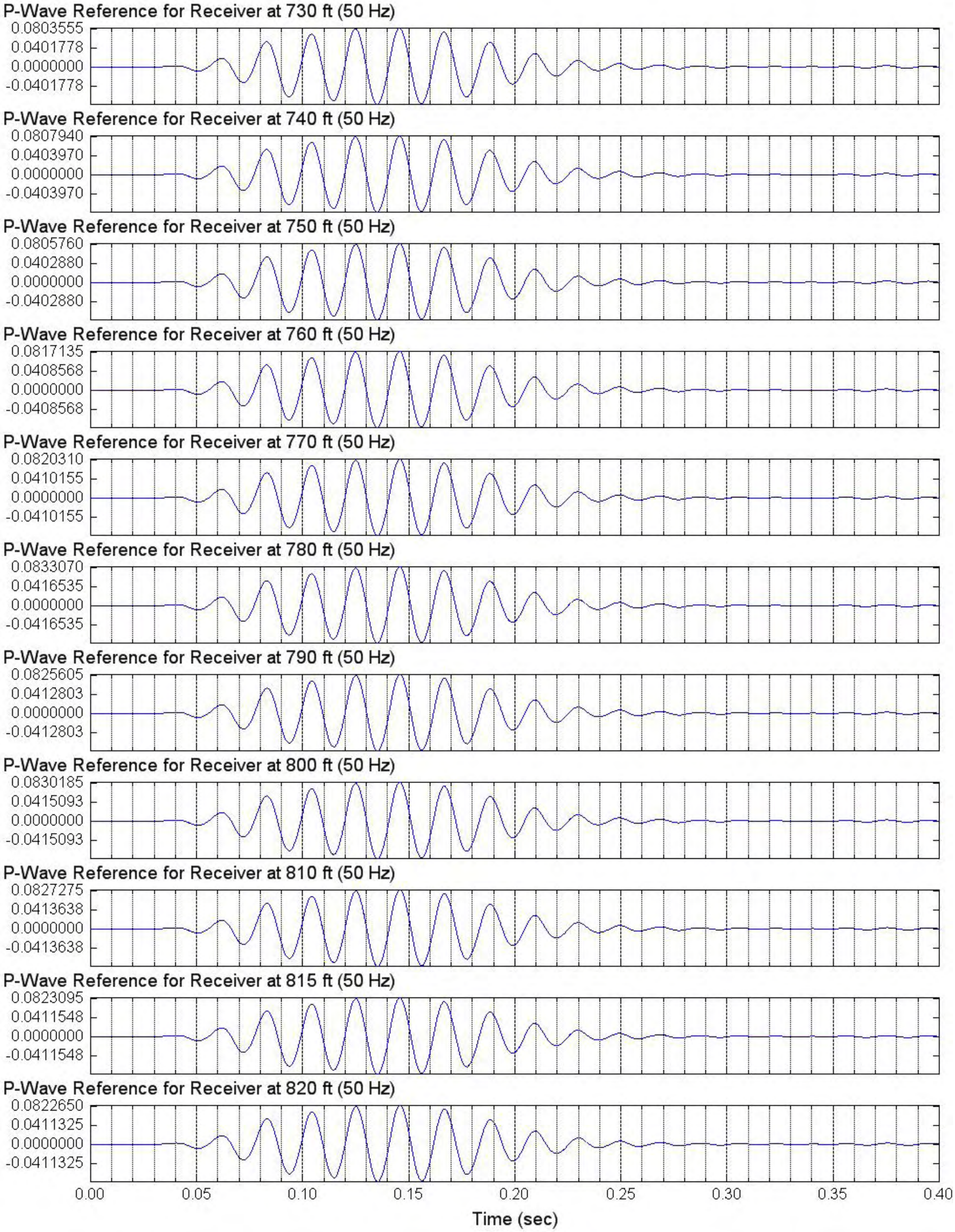


Figure 6.6 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave

Figure 6.7 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave

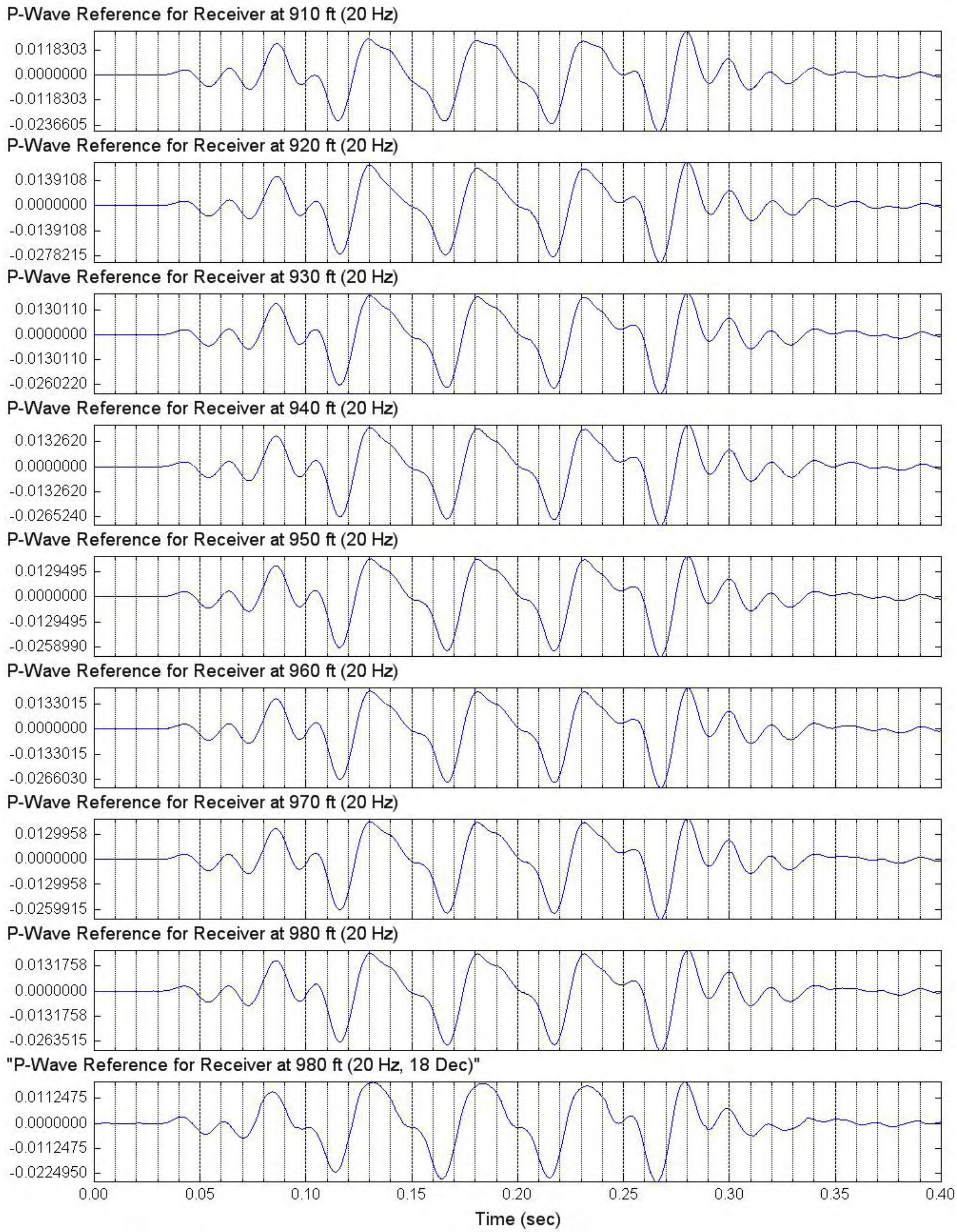


Figure 6.8 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

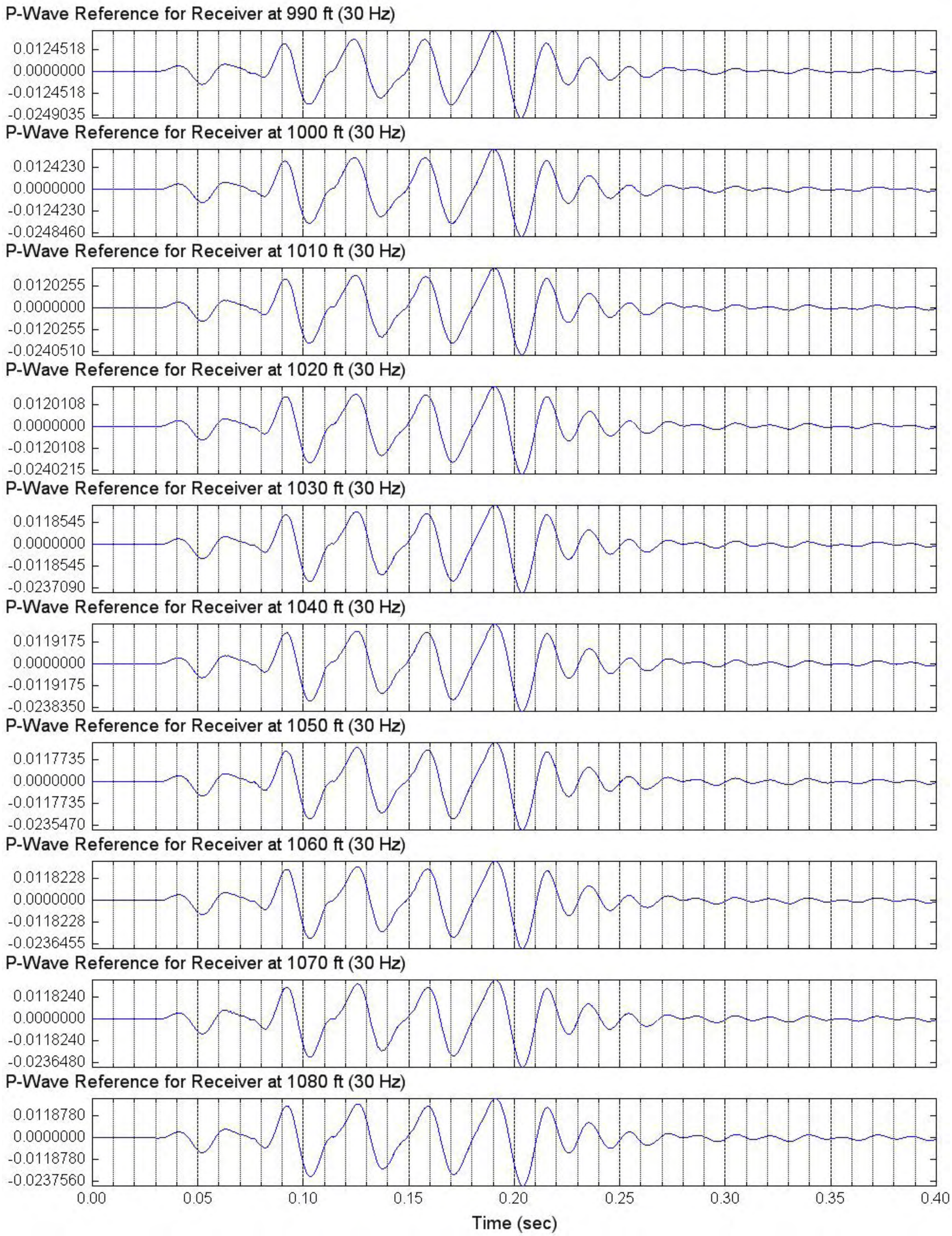
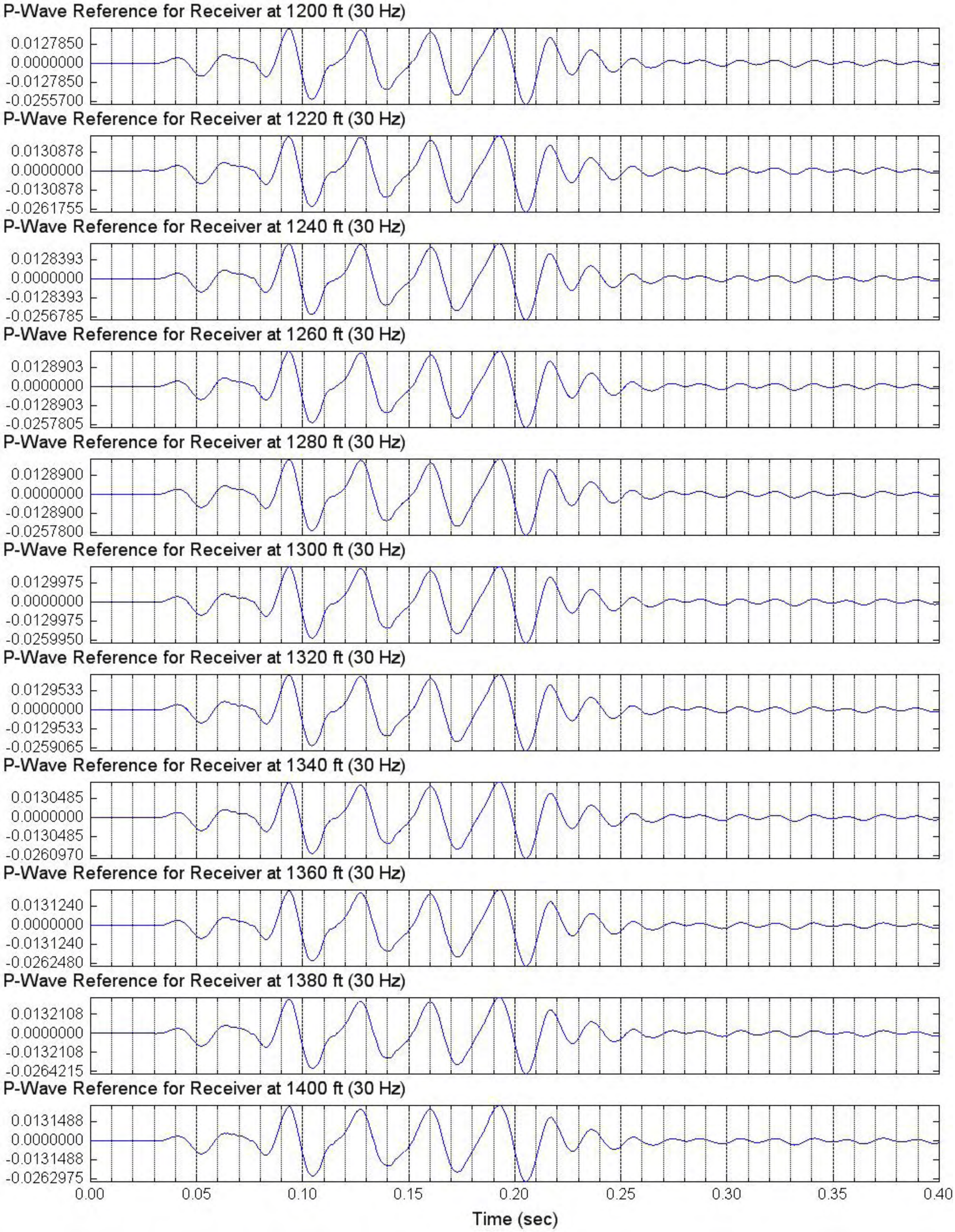


Figure 6.9 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave

Figure 6.10 Unfiltered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave



Section 7: Filtered P-Wave Signals of Lower Vertical Receiver

Section 7 includes all filtered P-wave signals at the lower vertical receiver.

1. Figures 7.1 to 7.6 present filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; FFT low pass 60 Hz; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 7.7 presents filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; FFT low pass 25 Hz; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 7.8 to 7.10 present filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; FFT low pass 40 Hz; input signal: 4 cycles of 30-Hz sine wave.

Figure 7.1 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

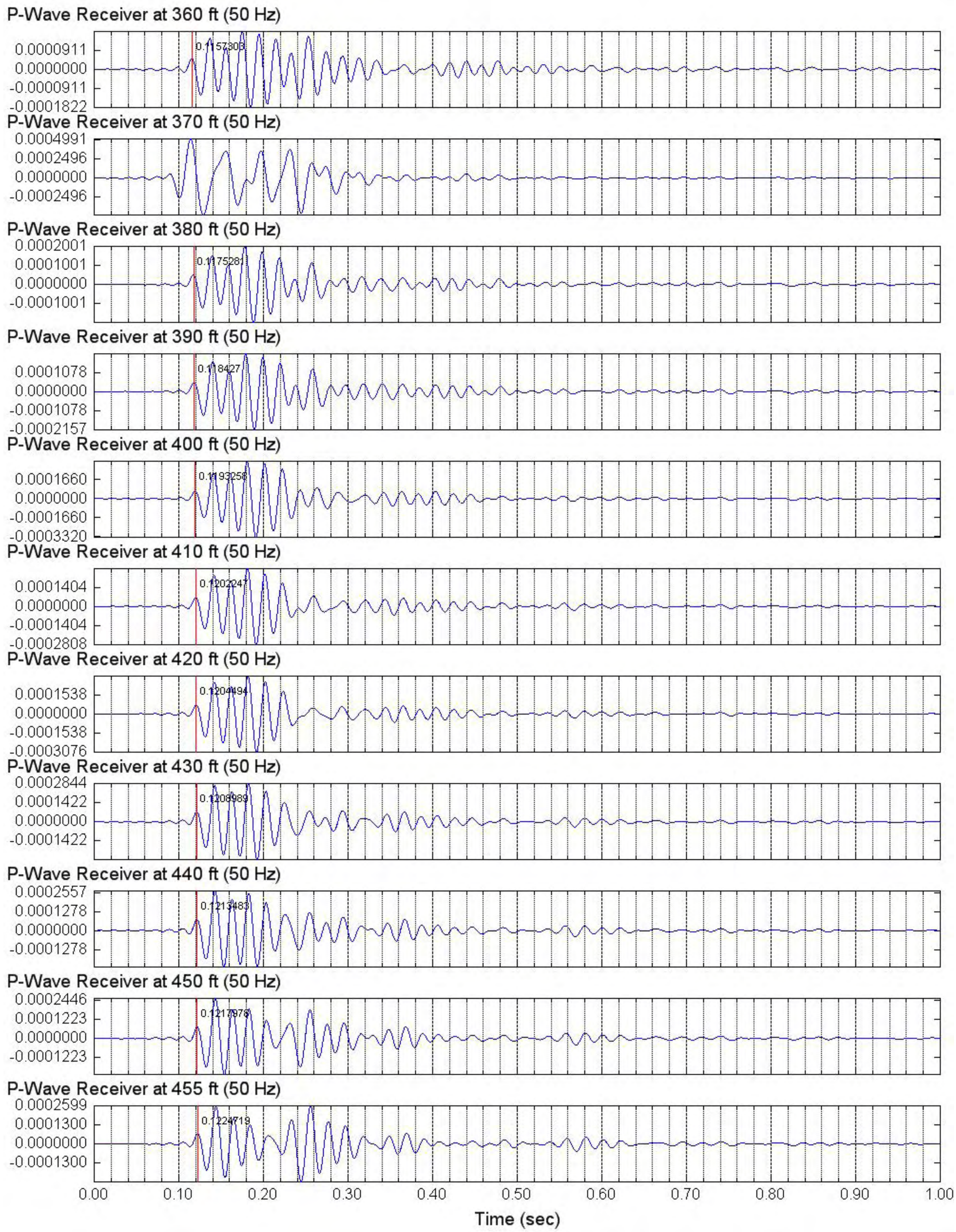


Figure 7.2 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

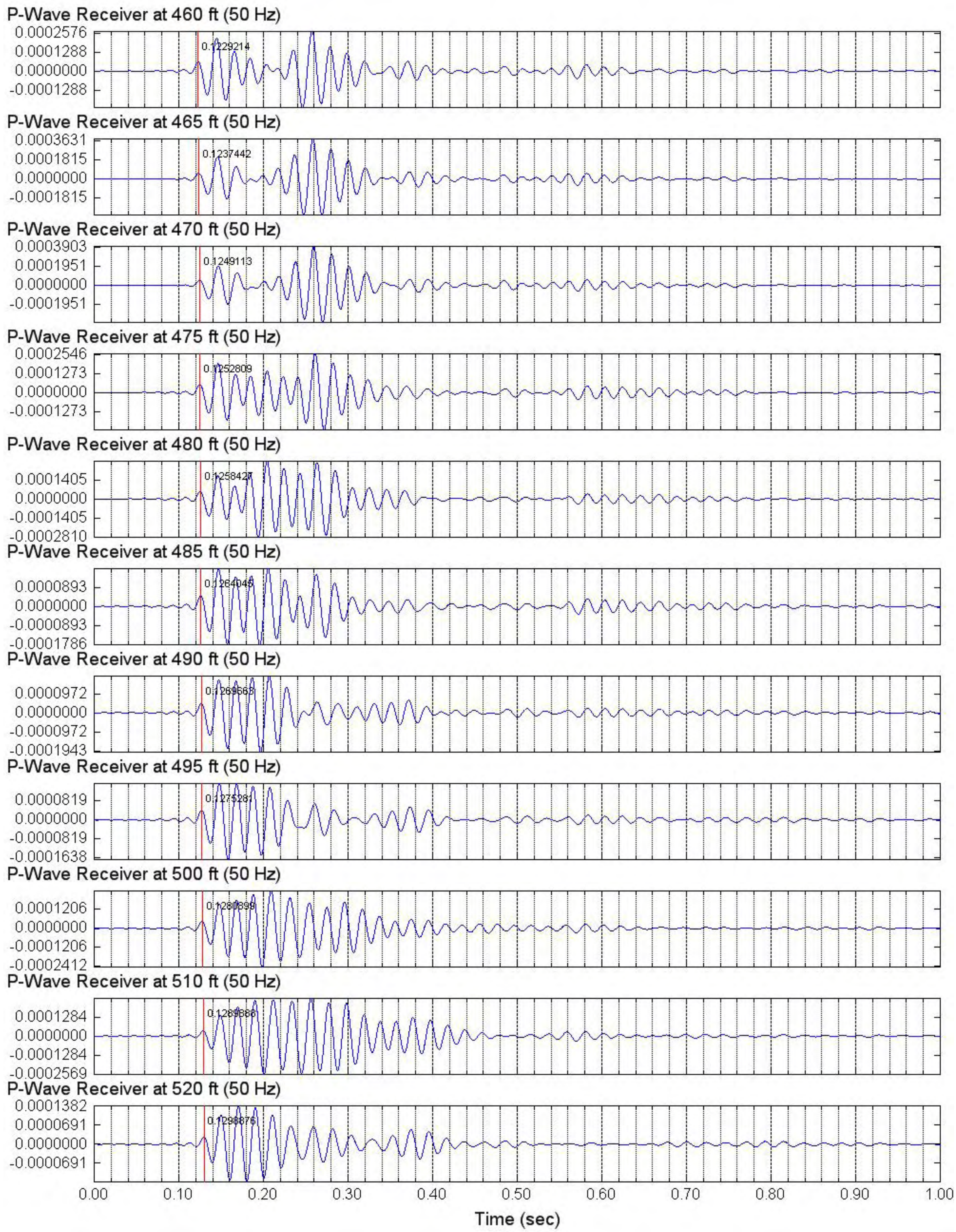


Figure 7.3 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

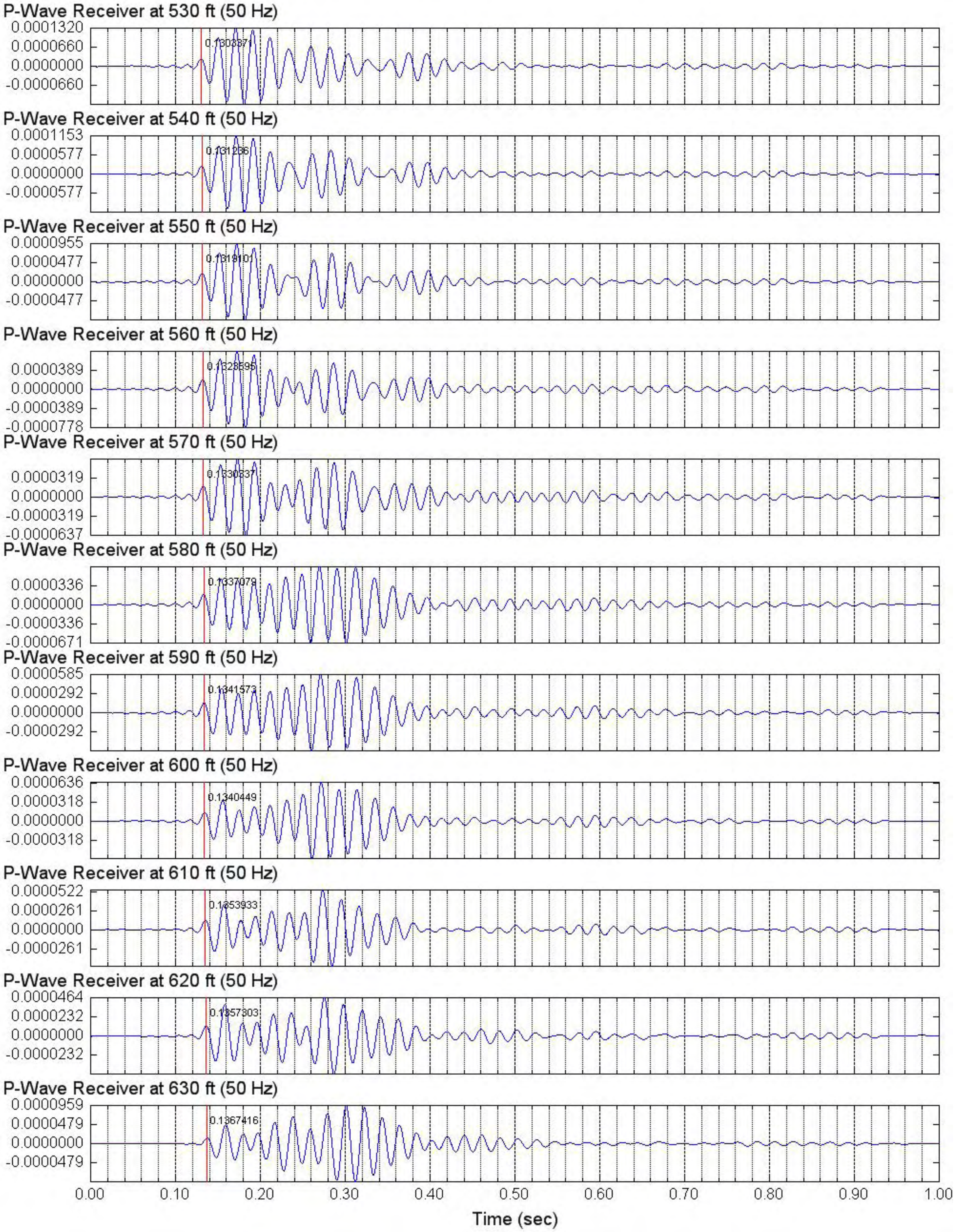


Figure 7.4 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

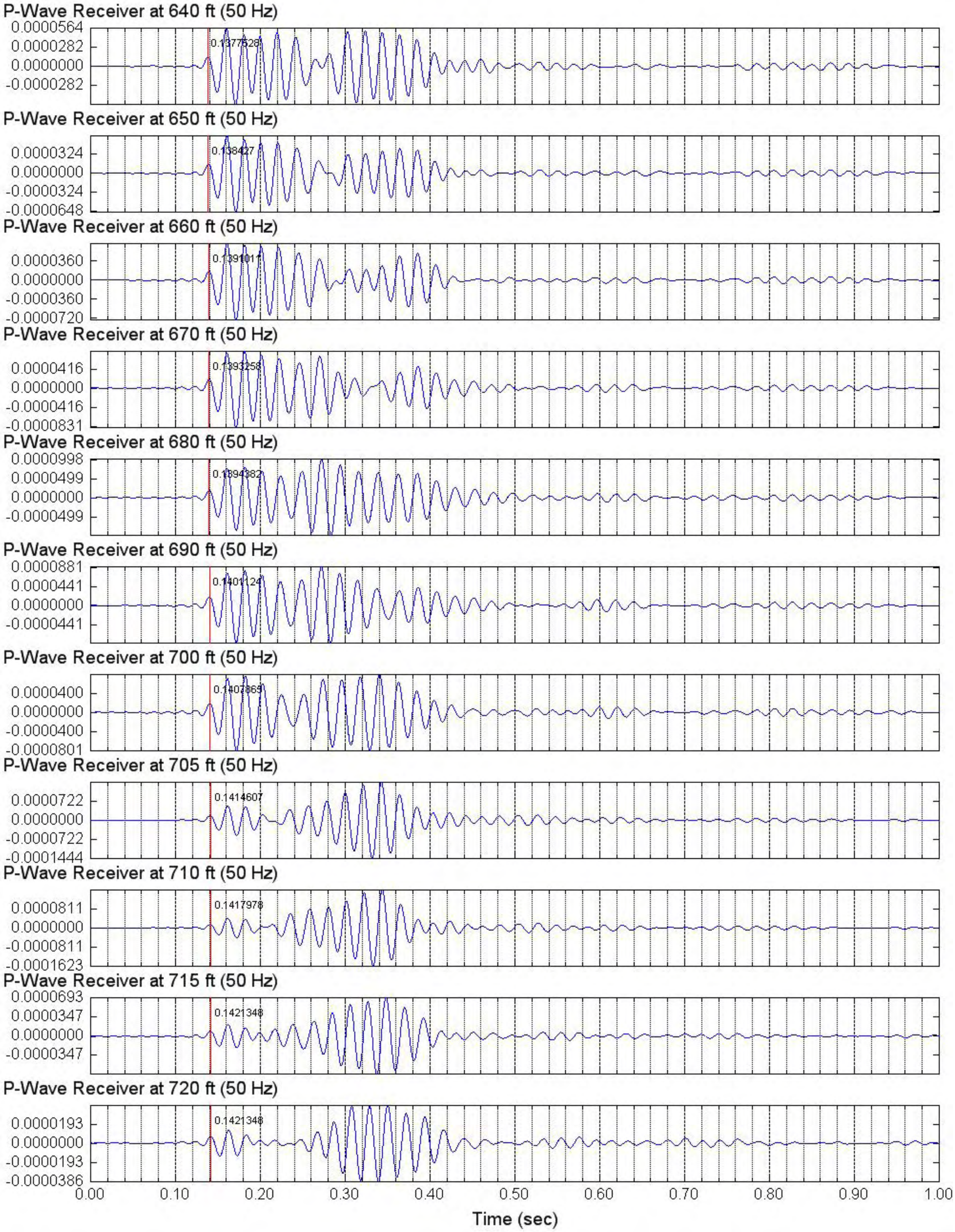


Figure 7.5 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

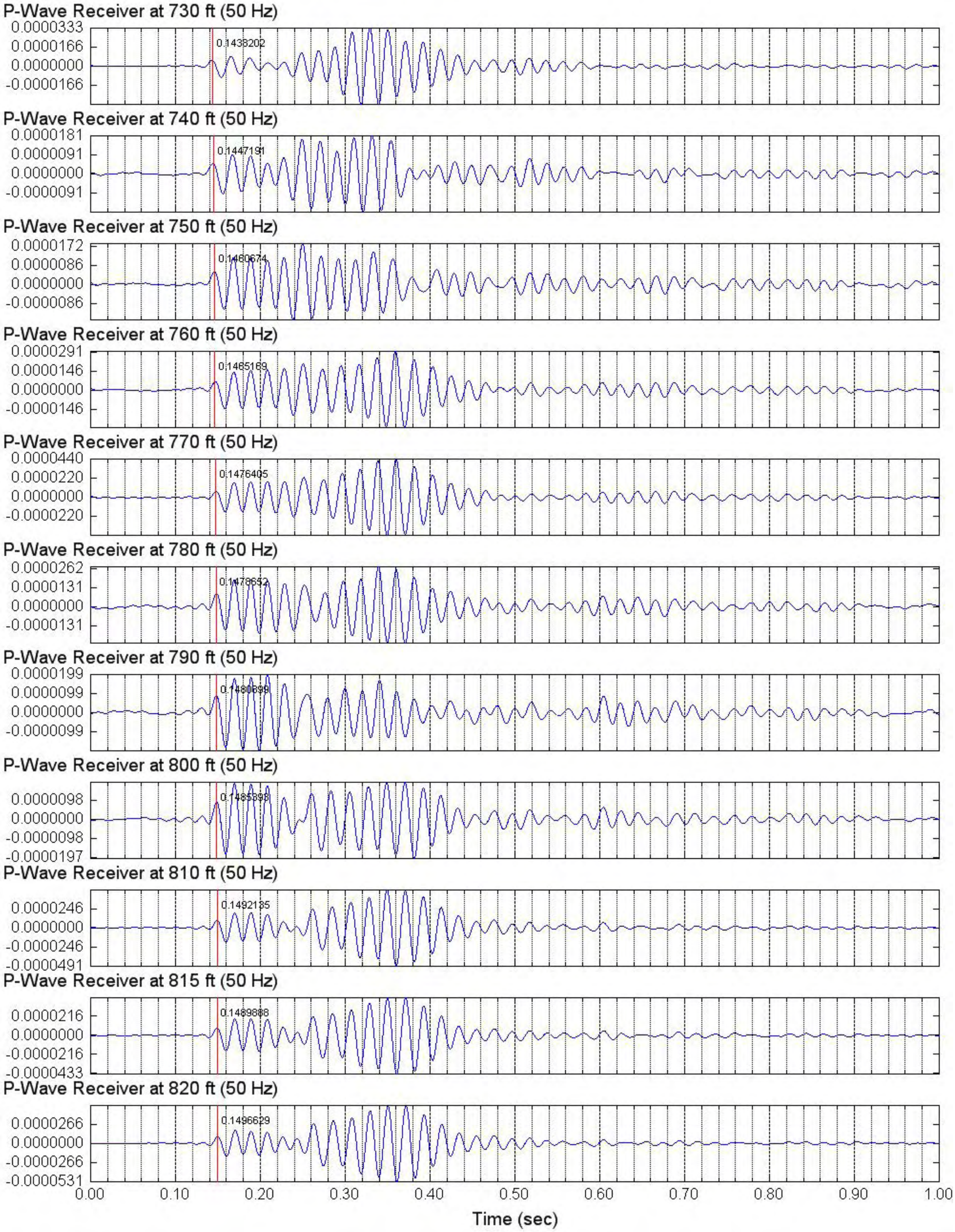


Figure 7.6 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

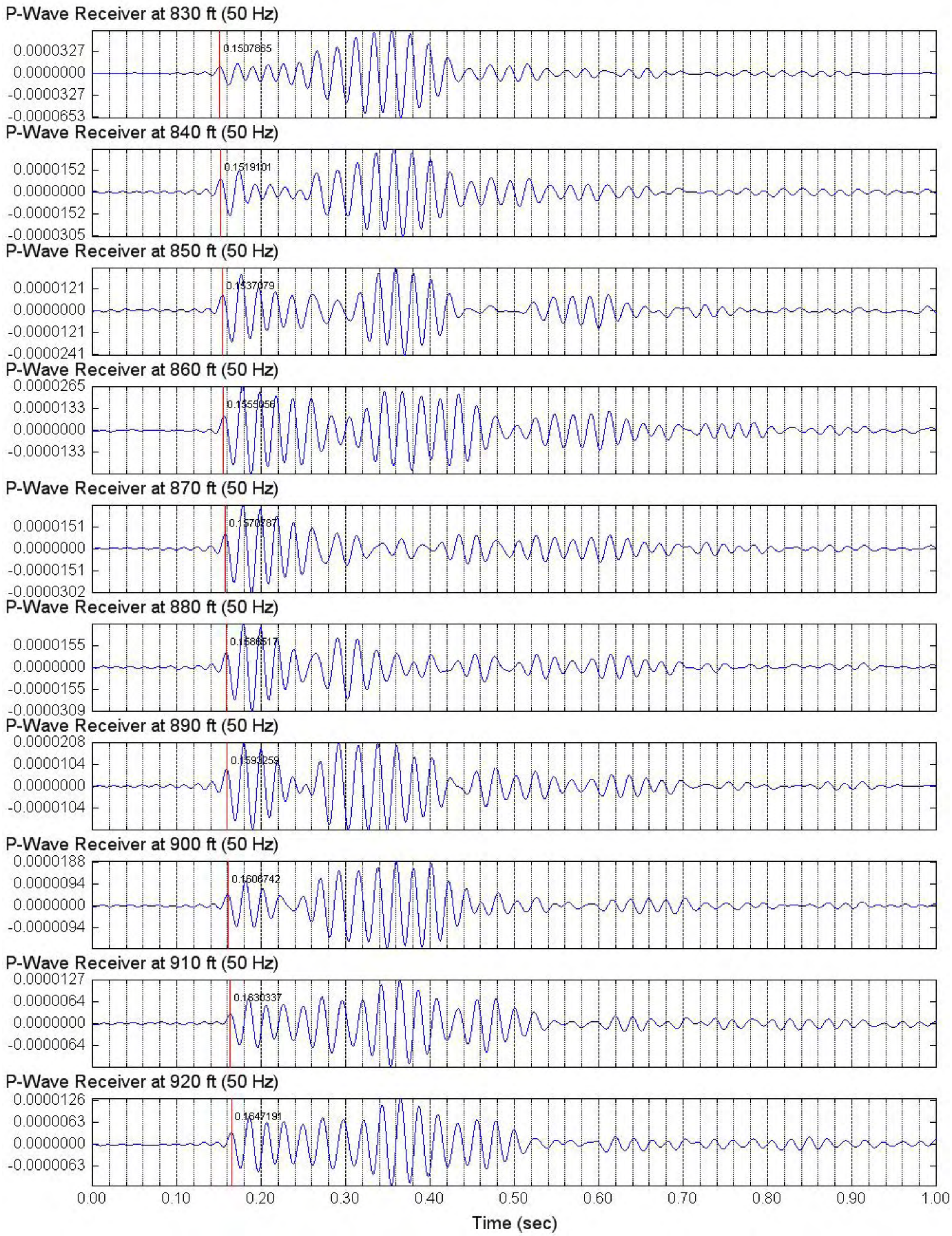


Figure 7.7 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Low Pass 25 Hz

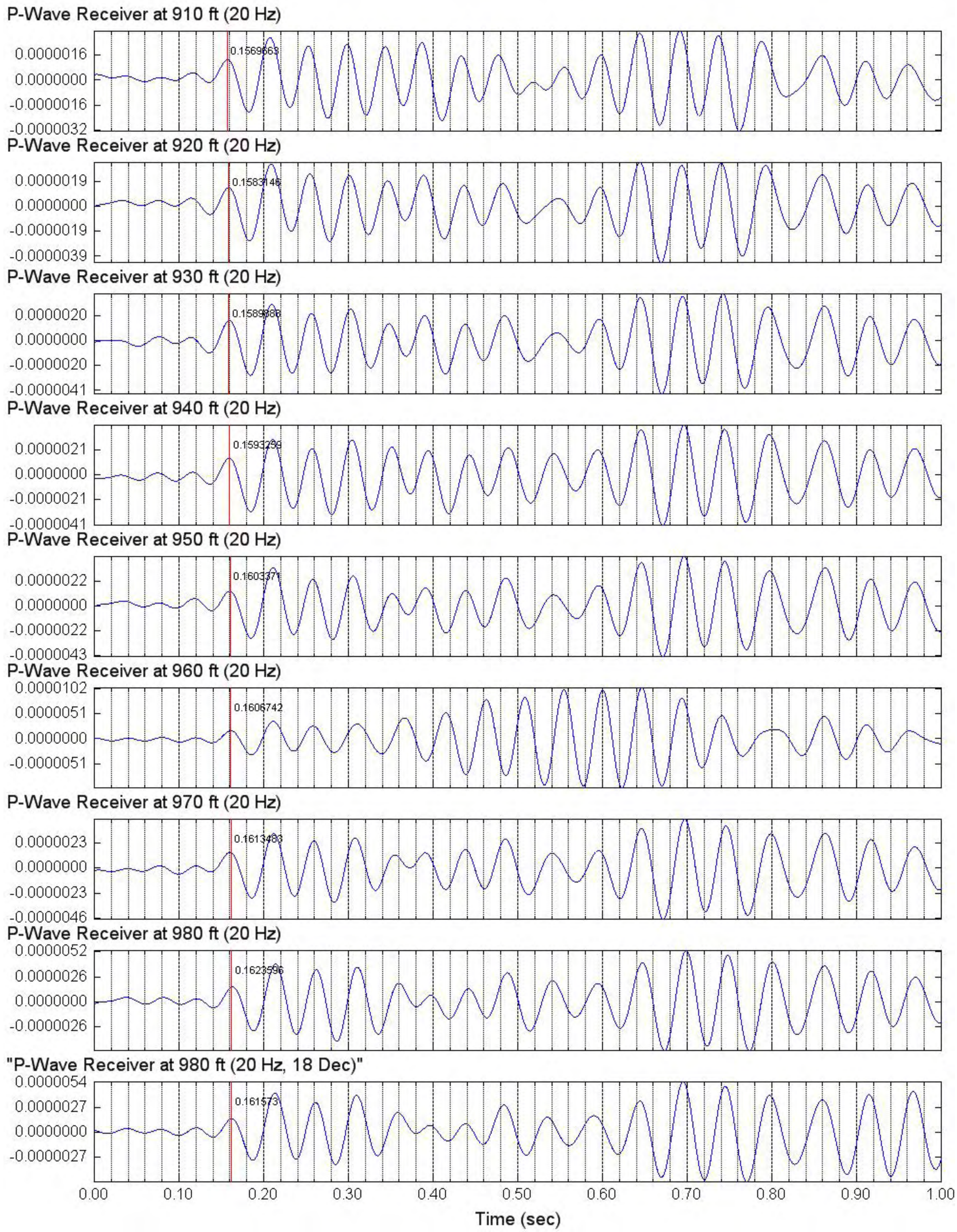


Figure 7.8 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

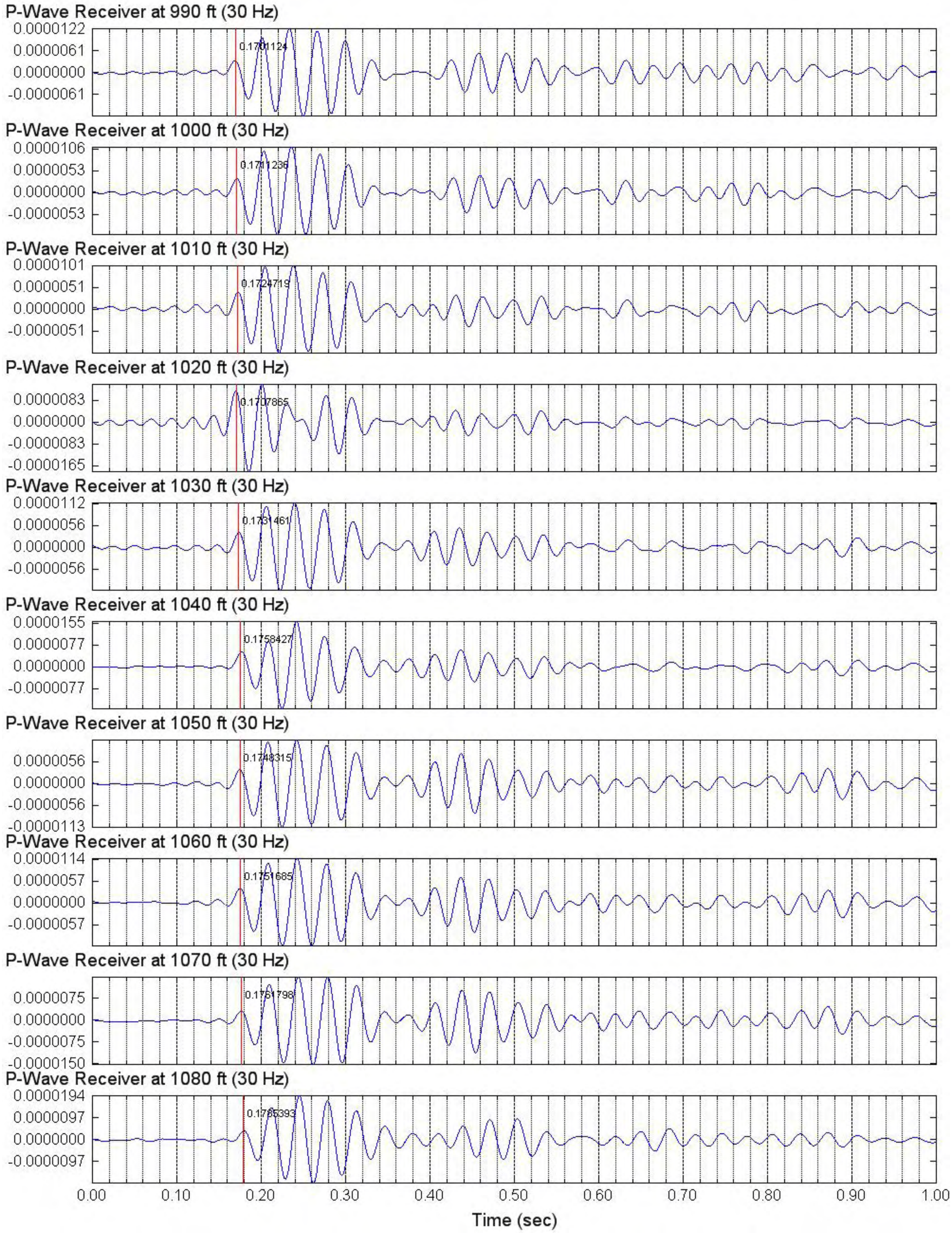


Figure 7.9 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

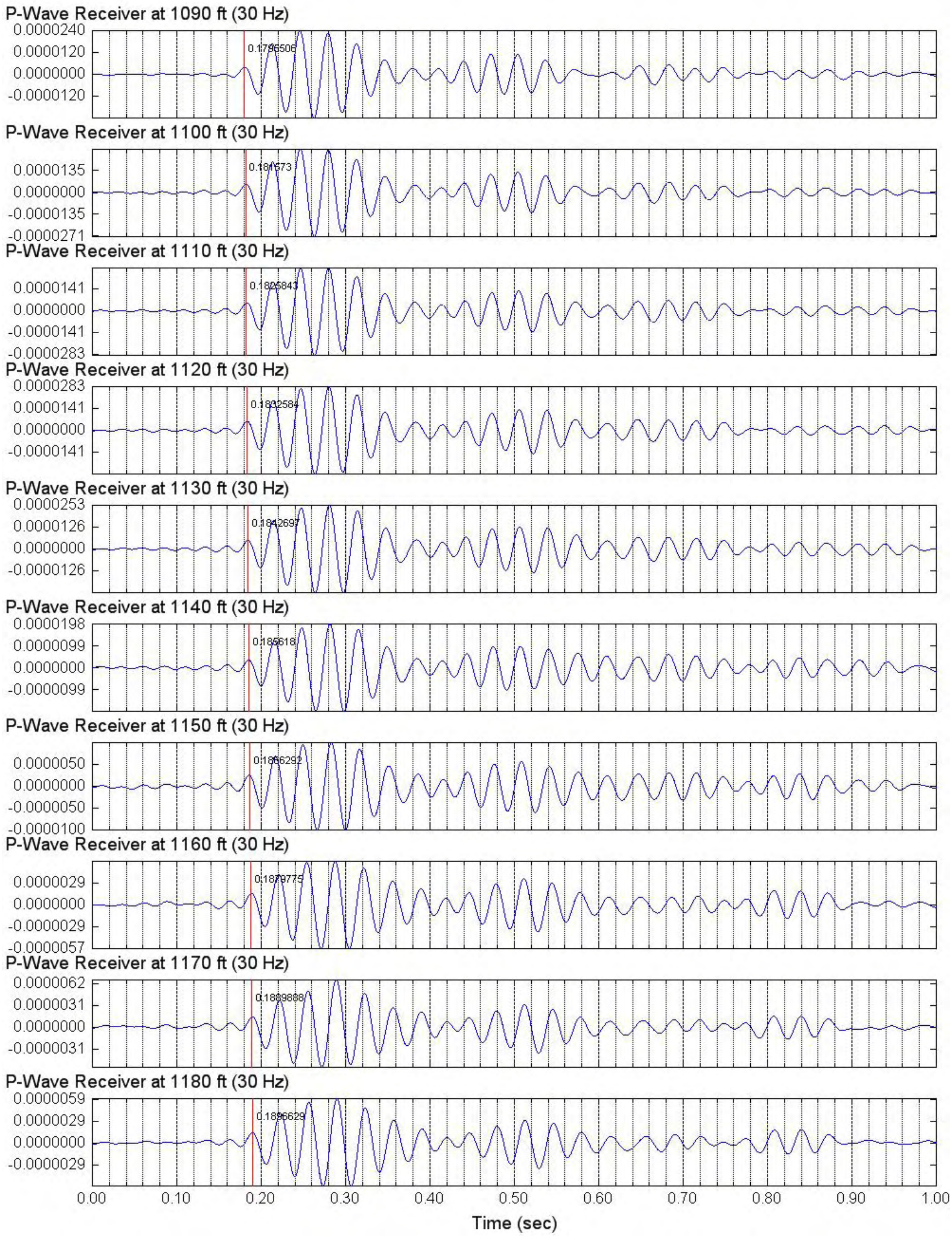
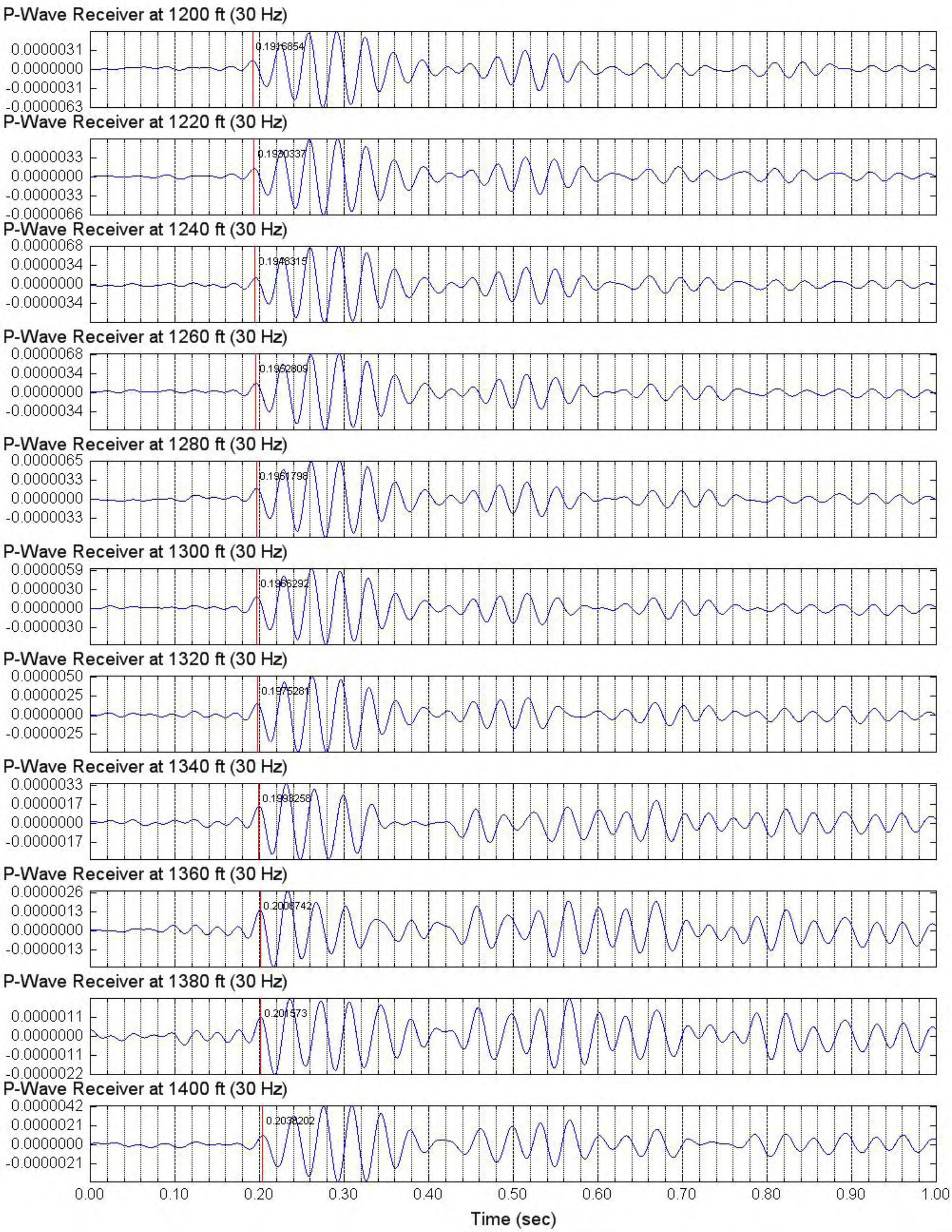


Figure 7.10 Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz



Section 8: Filtered P-Wave Signals of Reaction Mass Acceleration

1. Figures 8.1 to 8.6 present filtered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 360 to 920 ft; FFT low pass 60 Hz; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 8.7 presents filtered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 910 to 980 ft; FFT low pass 25 Hz; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 8.8 to 8.10 present filtered reaction mass vertical (P-wave) acceleration at Borehole C4996, depths 990 to 1400 ft; FFT low pass 40 Hz; input signal: 4 cycles of 30-Hz sine wave.

Figure 8.1 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

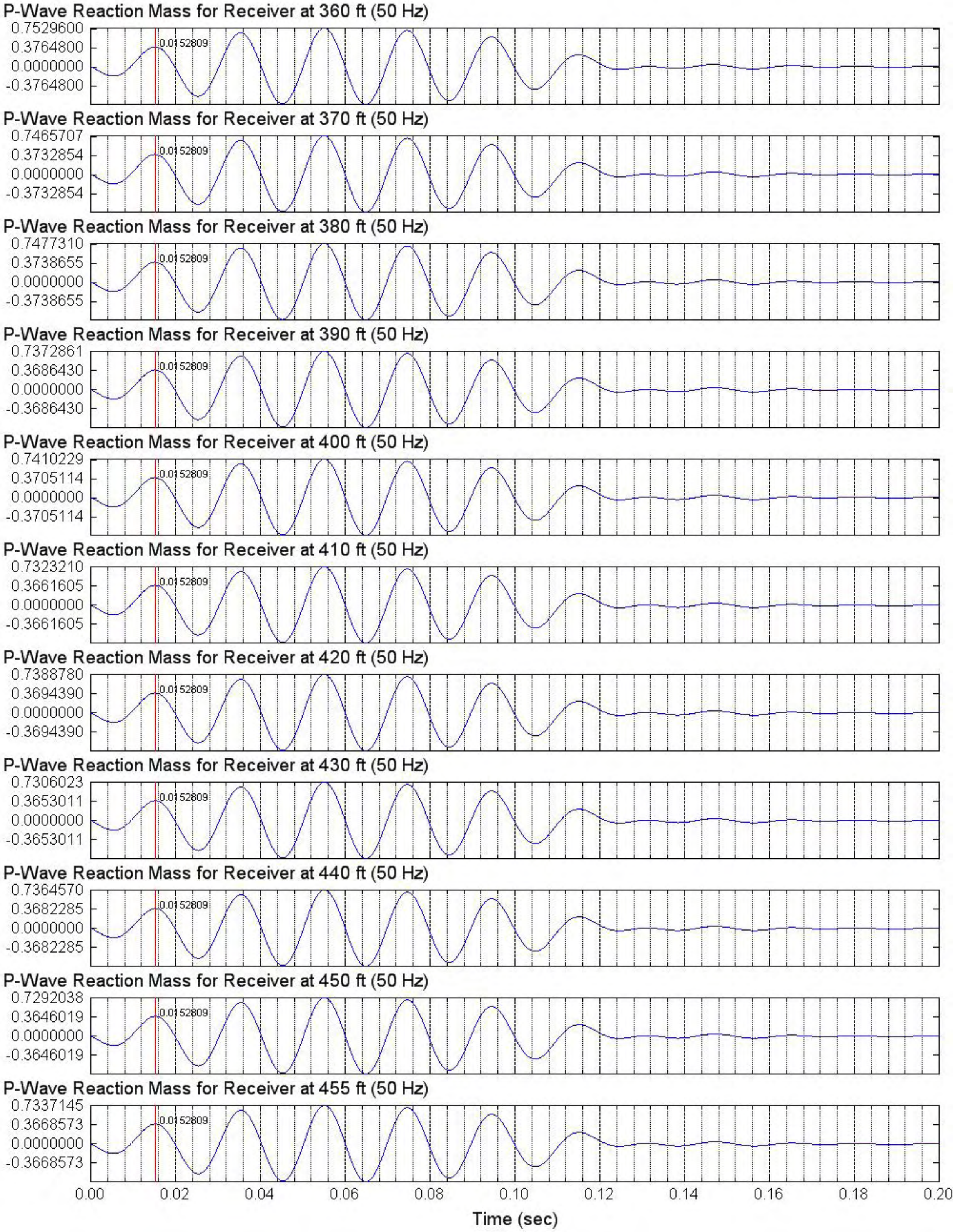


Figure 8.2 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

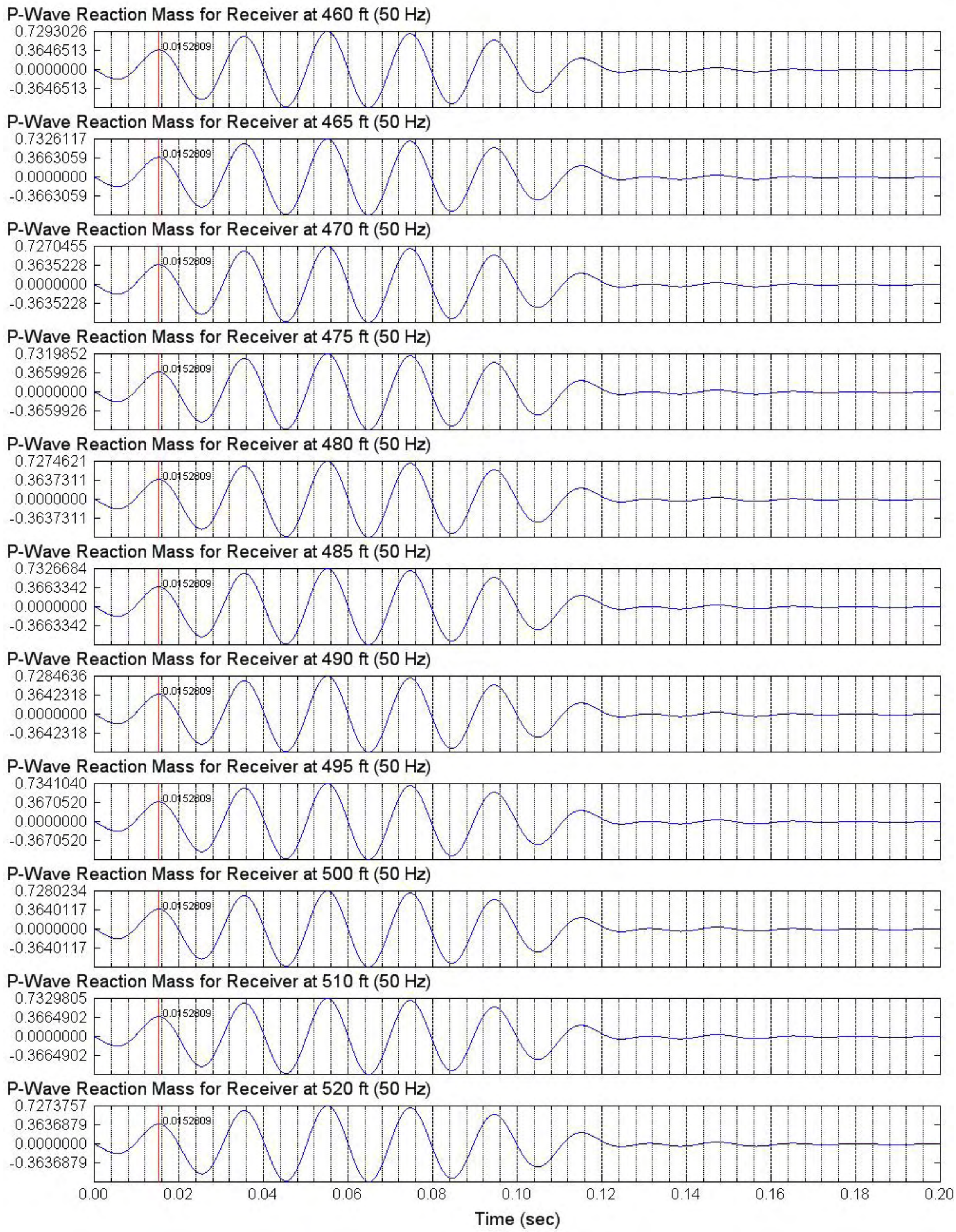


Figure 8.3 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

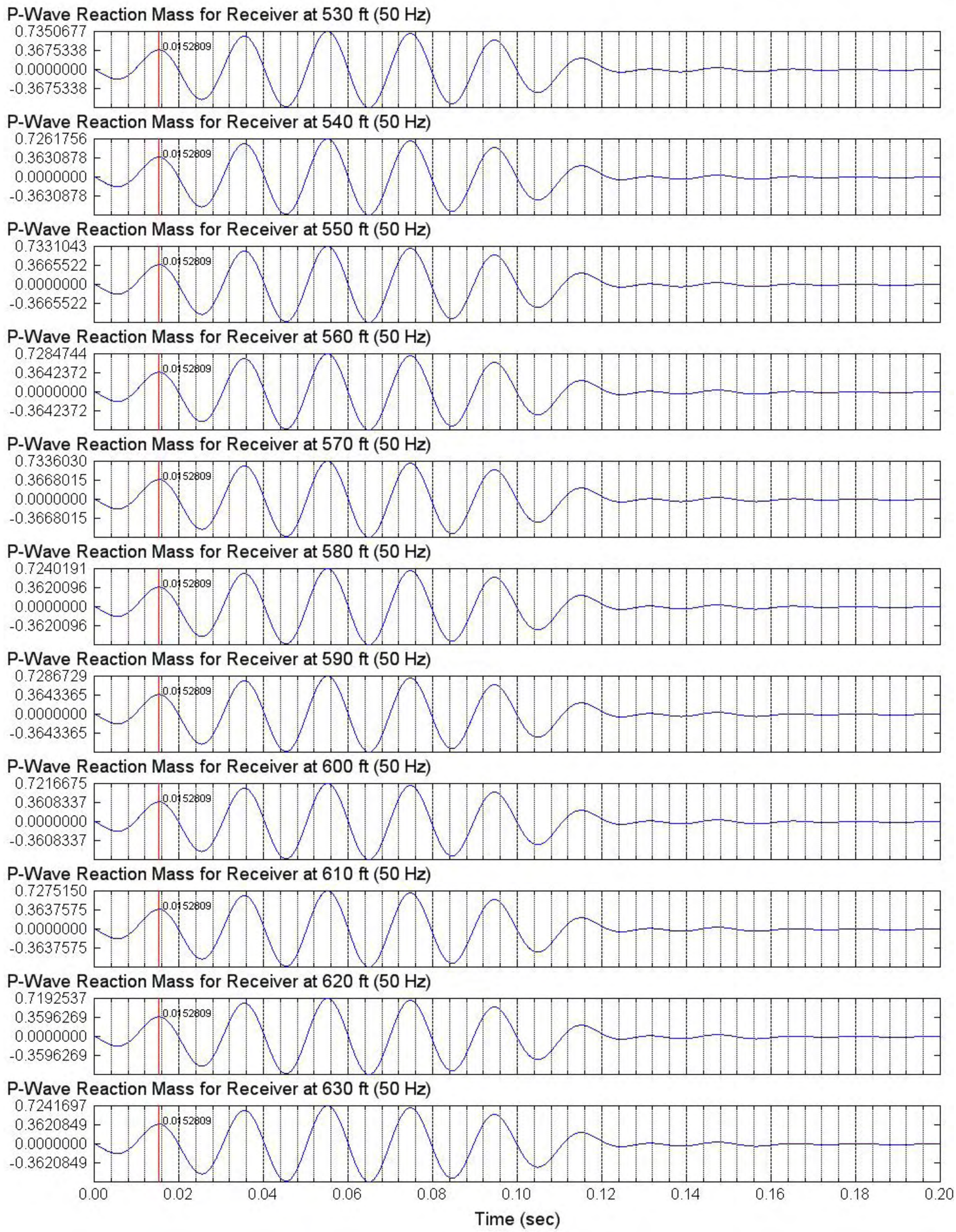


Figure 8.4 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

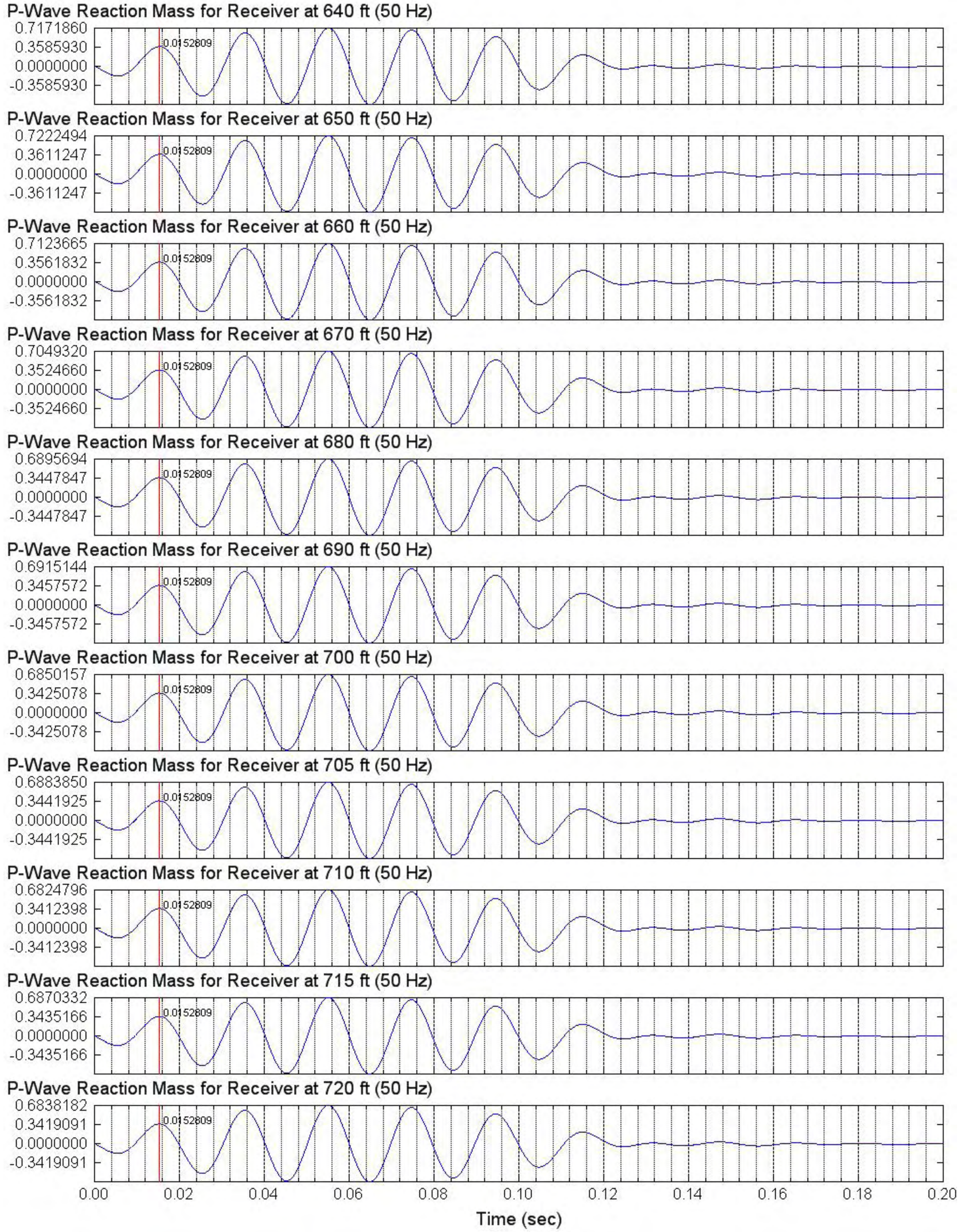


Figure 8.5 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

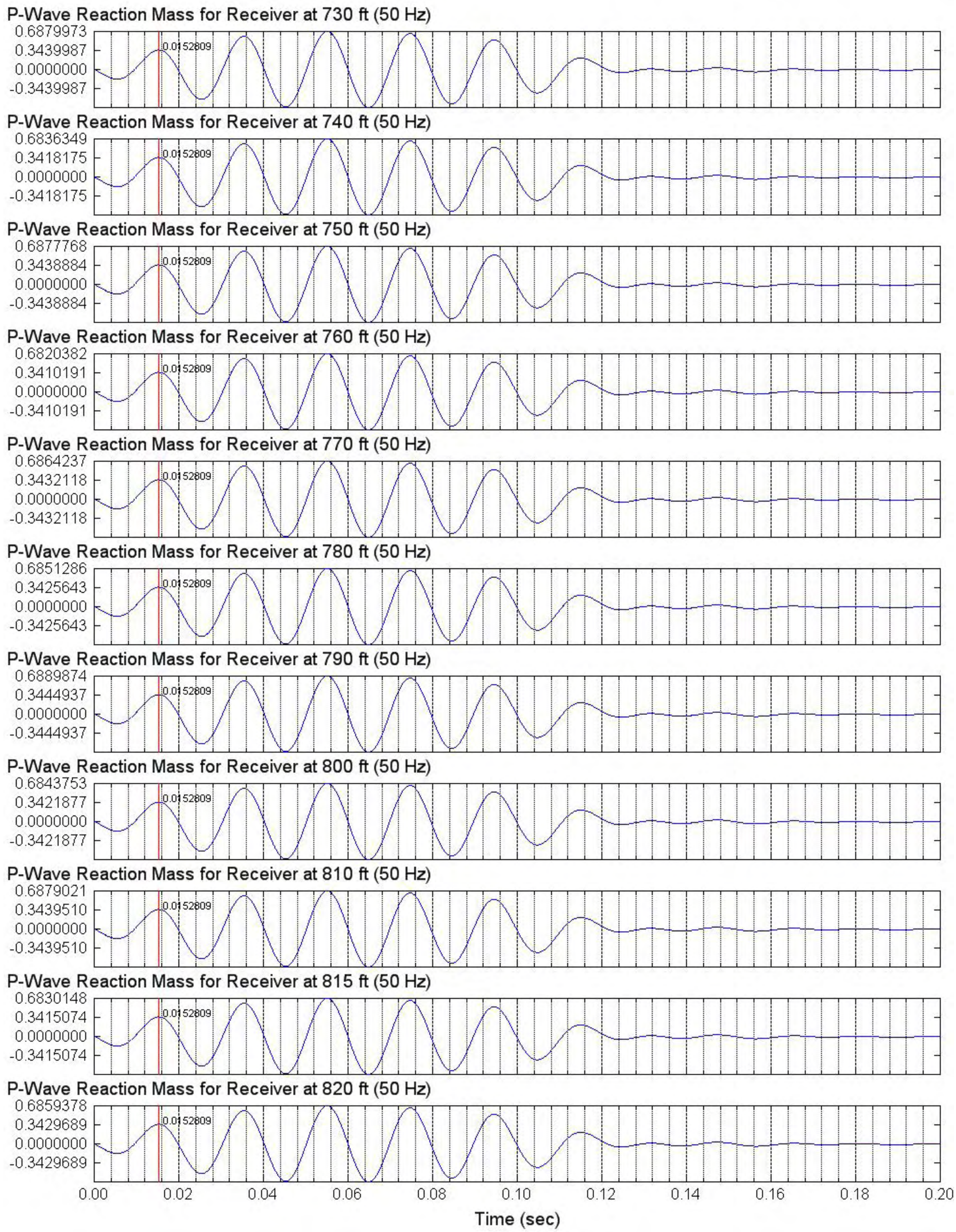


Figure 8.6 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

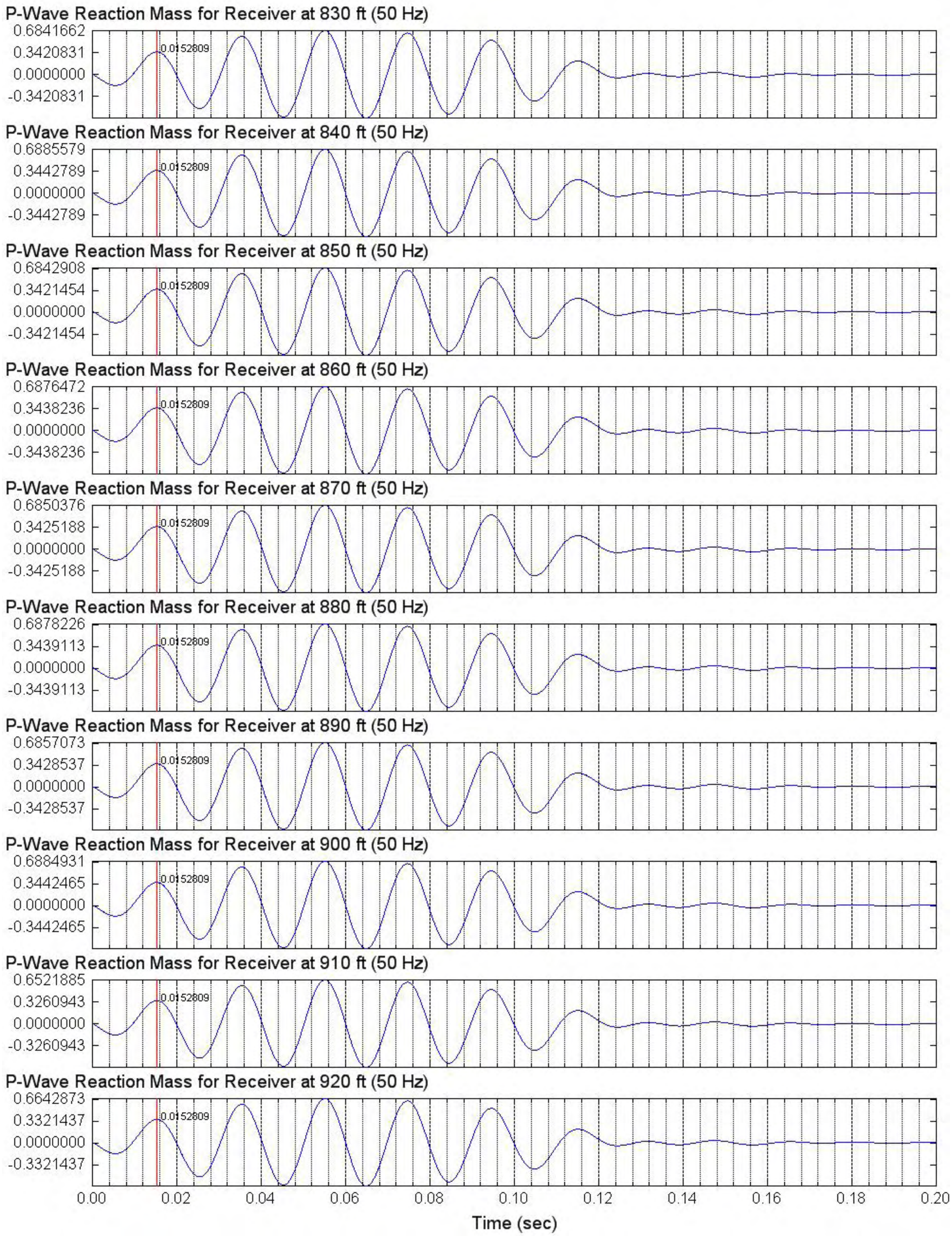


Figure 8.7 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Low Pass 25 Hz

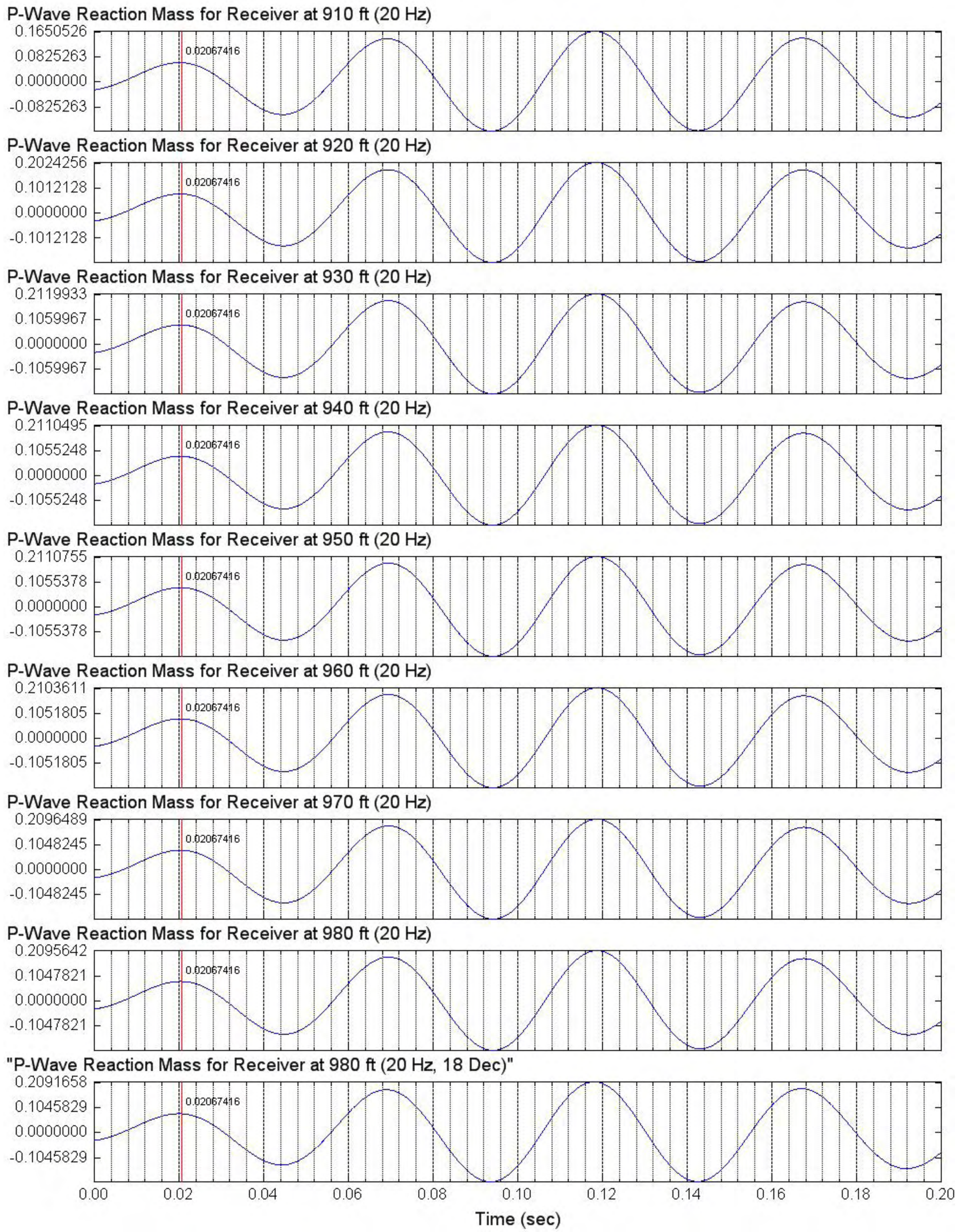


Figure 8.8 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

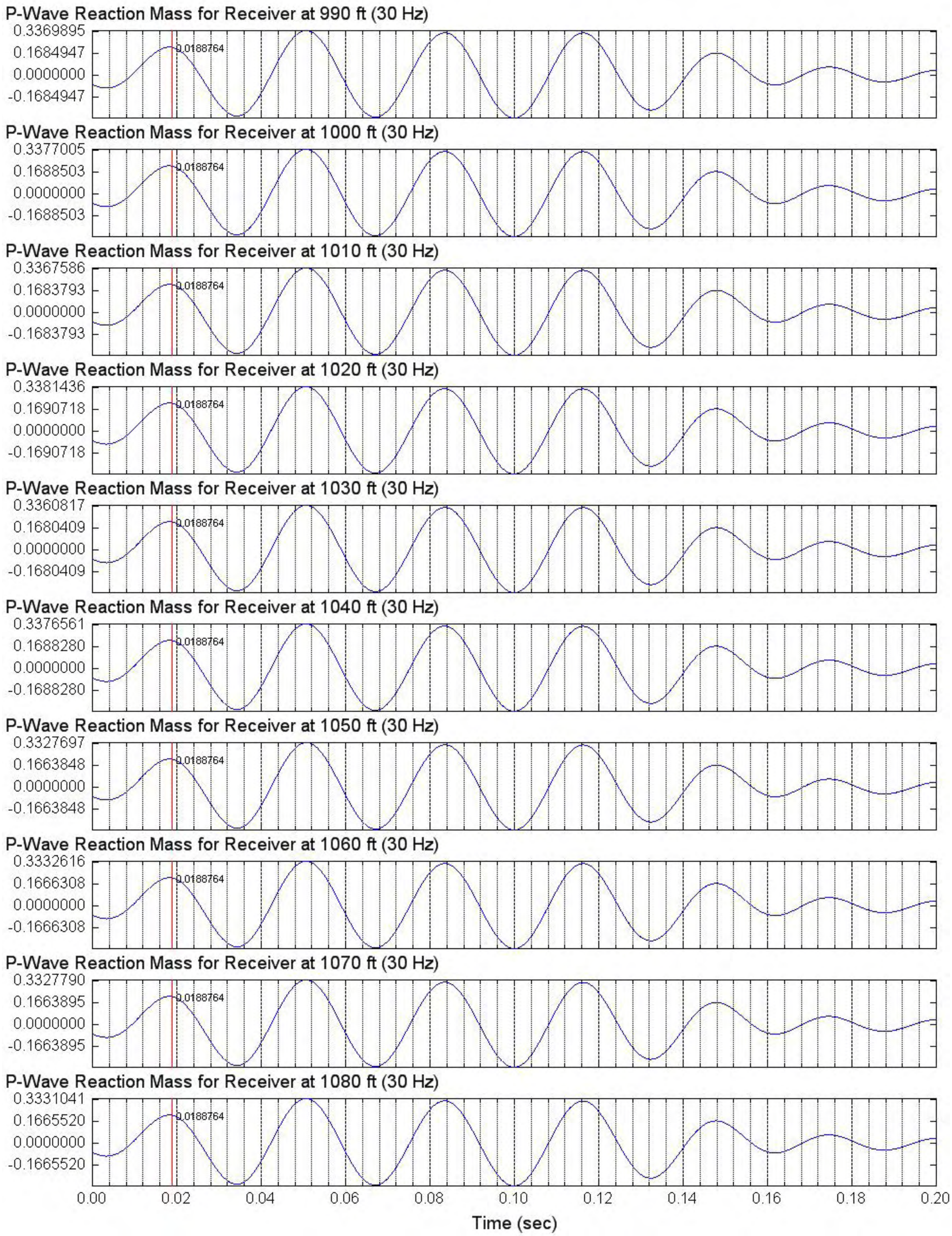


Figure 8.9 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

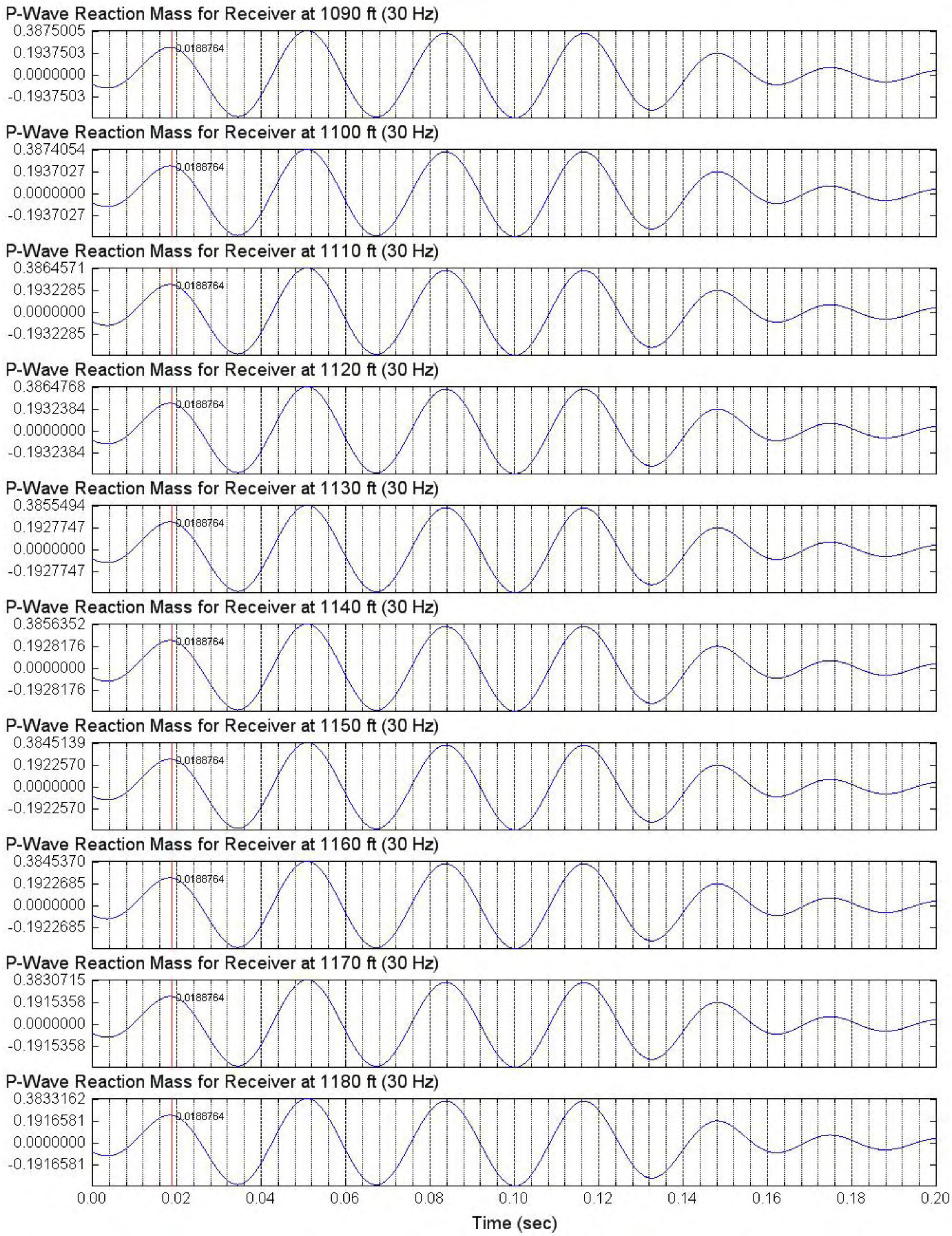
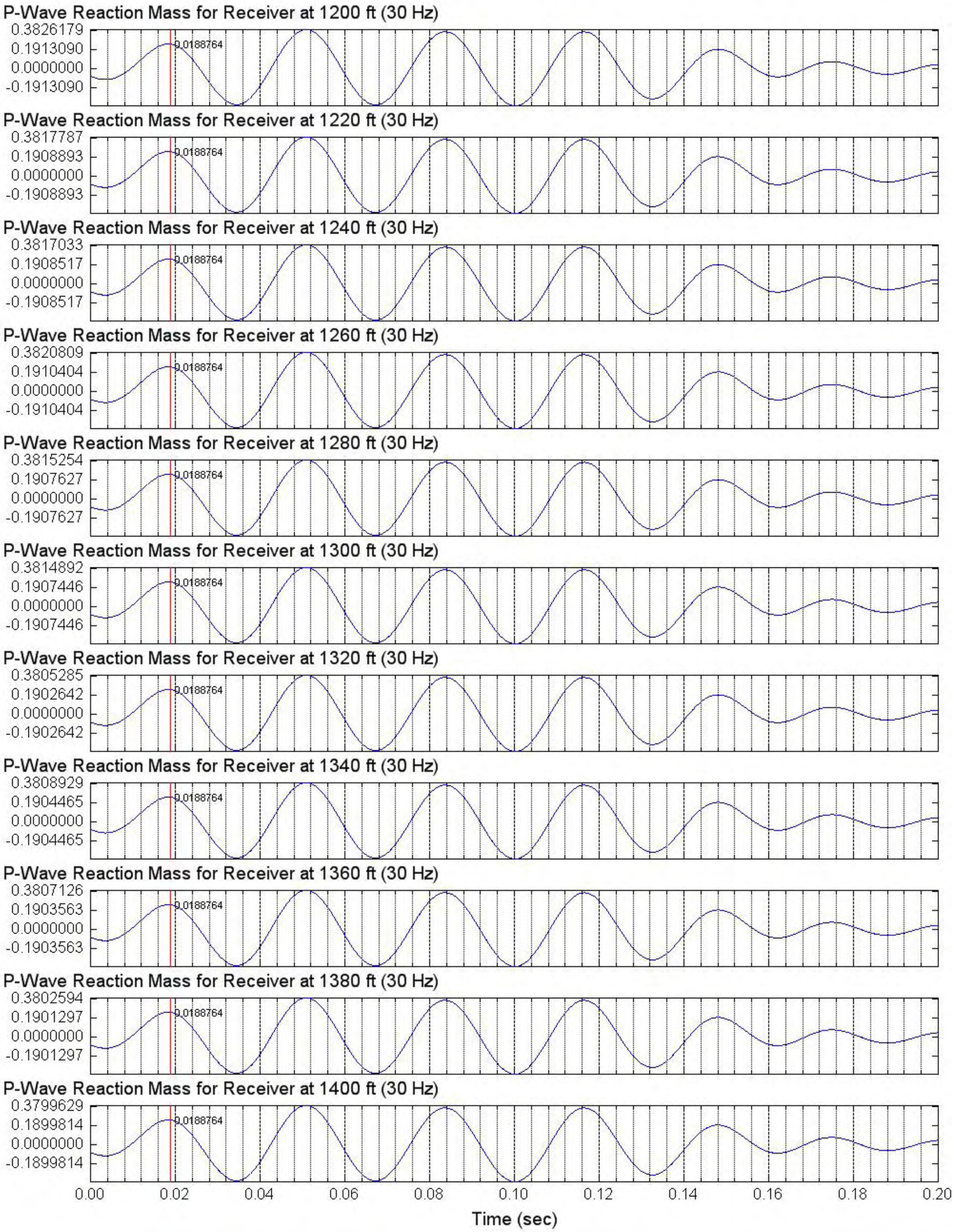


Figure 8.10 Filtered Reaction Mass Vertical (P-Wave) Acceleration at Borehole C4996

Lower Receiver Depth 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz



Section 9: Filtered P-Wave Signals of Reference Receiver

1. Figures 9.1 to 9.6 present filtered reference vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; FFT low pass 60 Hz; input signal: 5 cycles of 50-Hz sine wave.
2. Figure 9.7 presents filtered reference vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; FFT low pass 25 Hz; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 9.8 to 9.10 present filtered reference vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; FFT low pass 40 Hz; input signal: 4 cycles of 30-Hz sine wave.

Figure 9.1 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

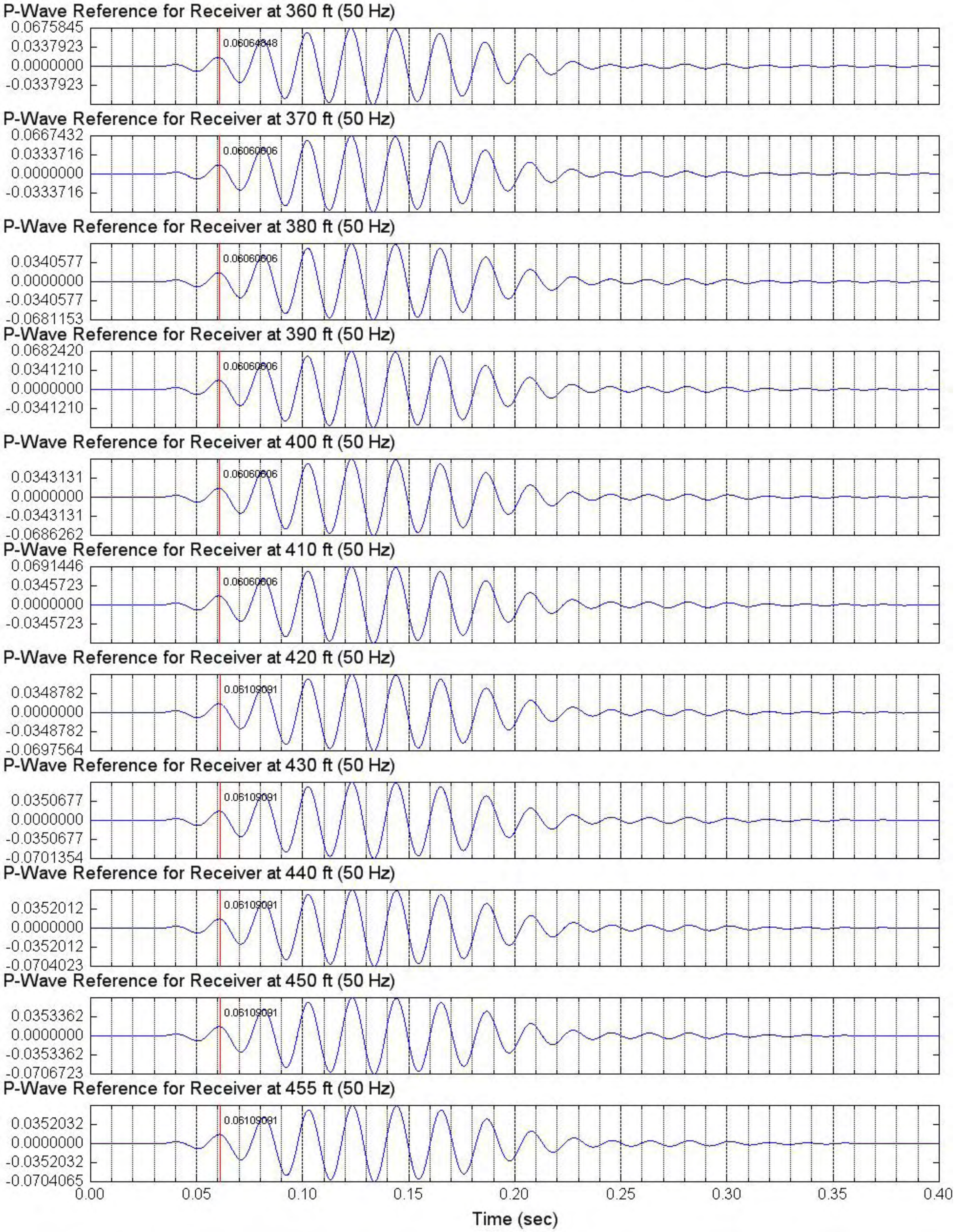


Figure 9.2 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

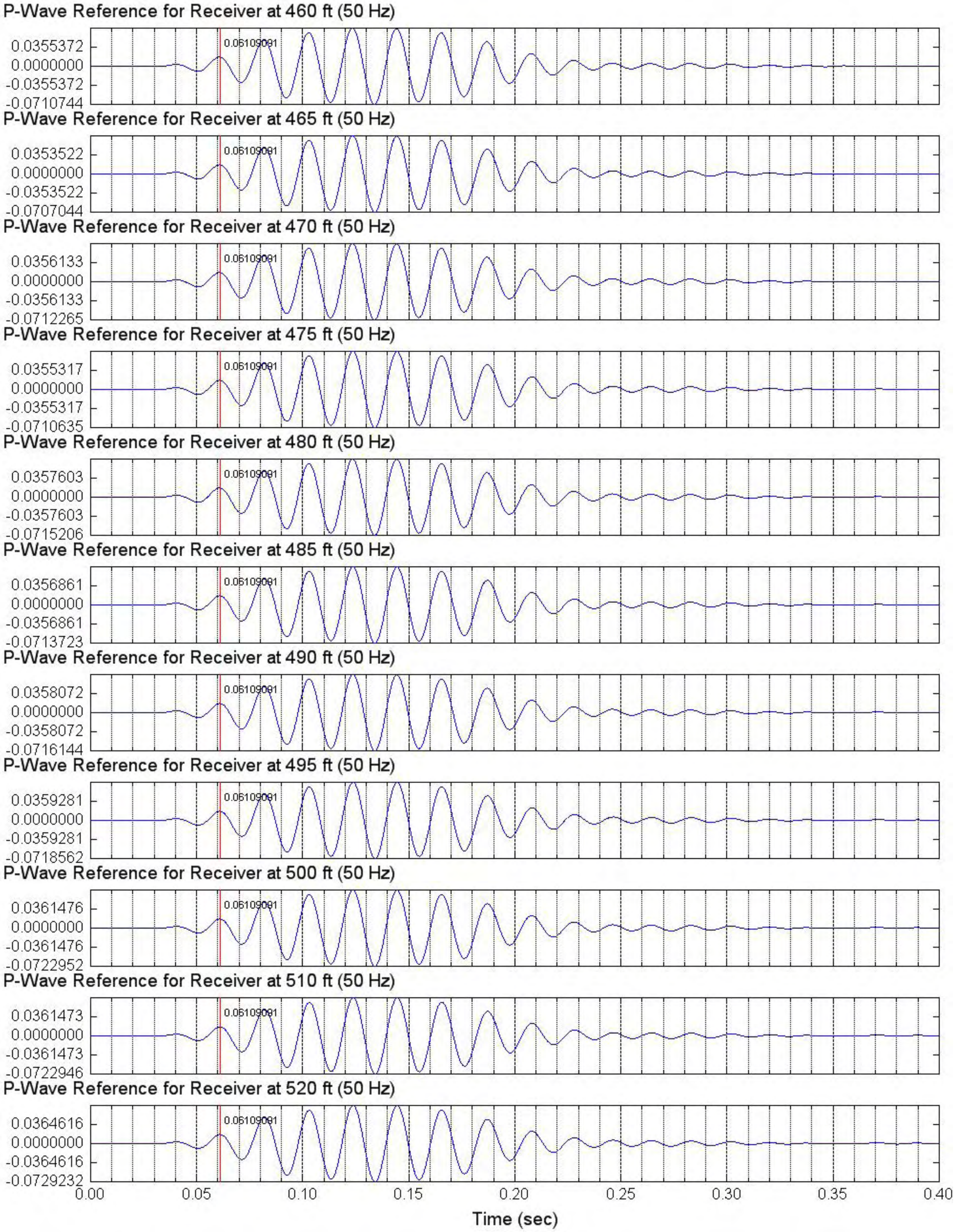


Figure 9.3 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

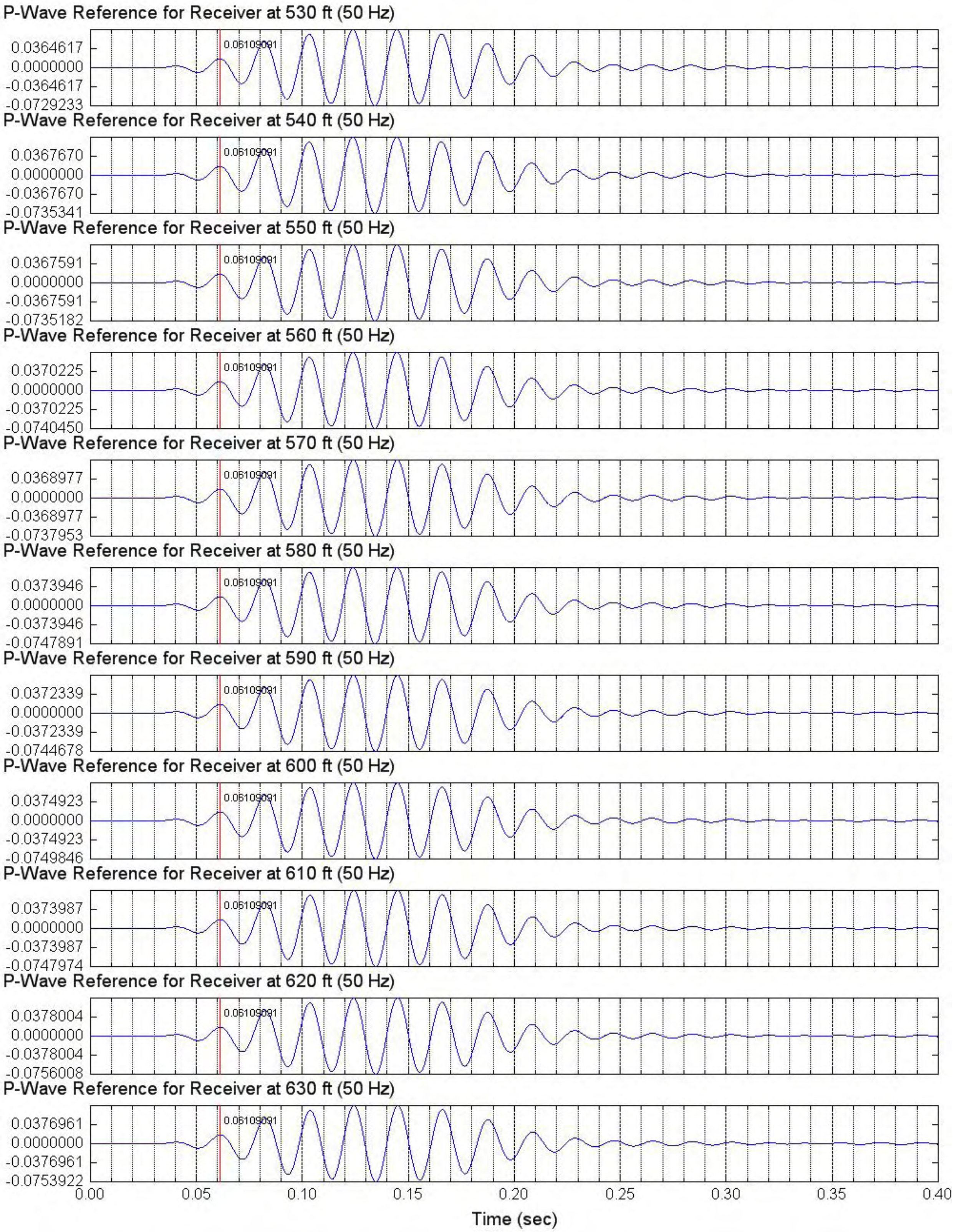


Figure 9.4 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

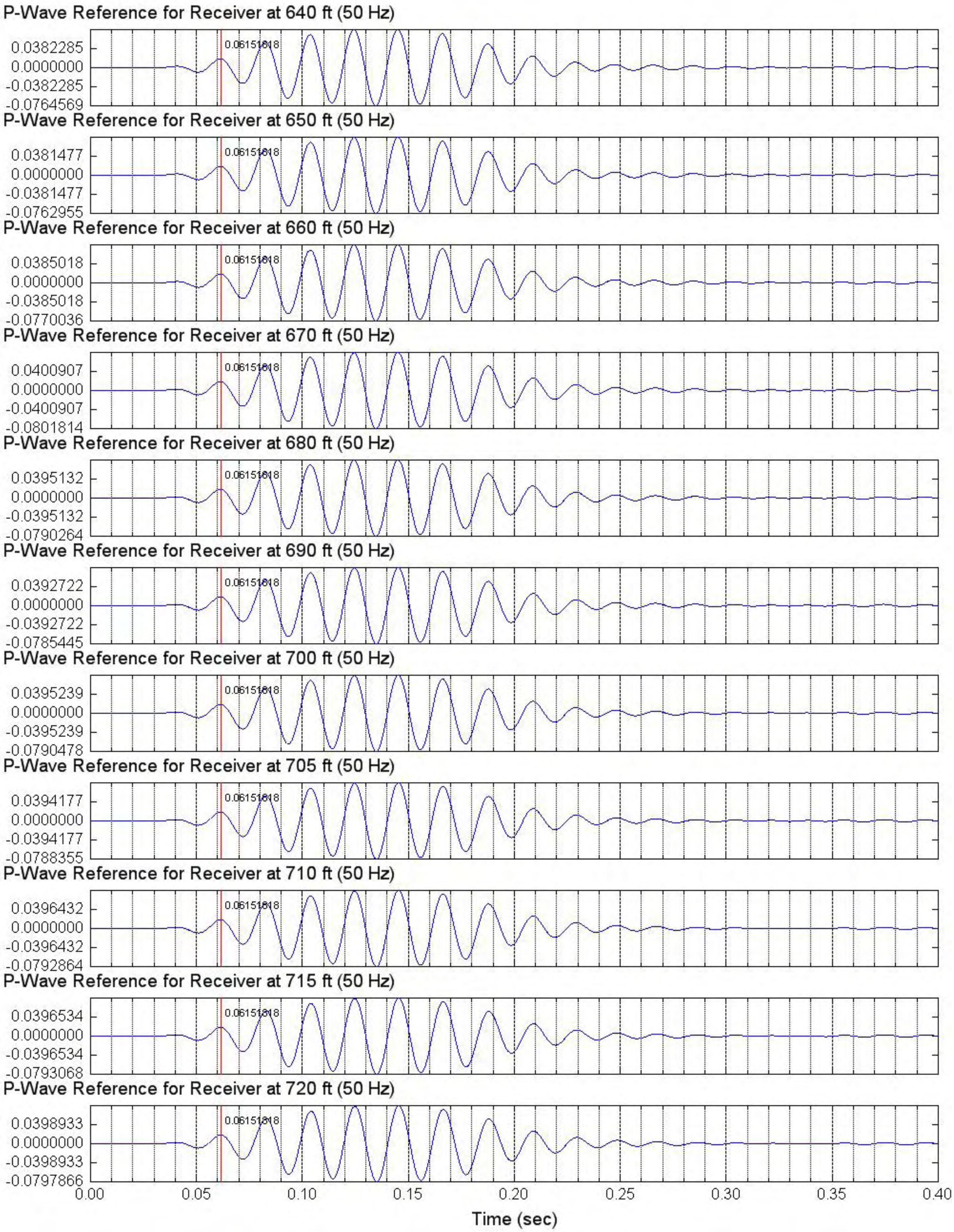


Figure 9.5 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

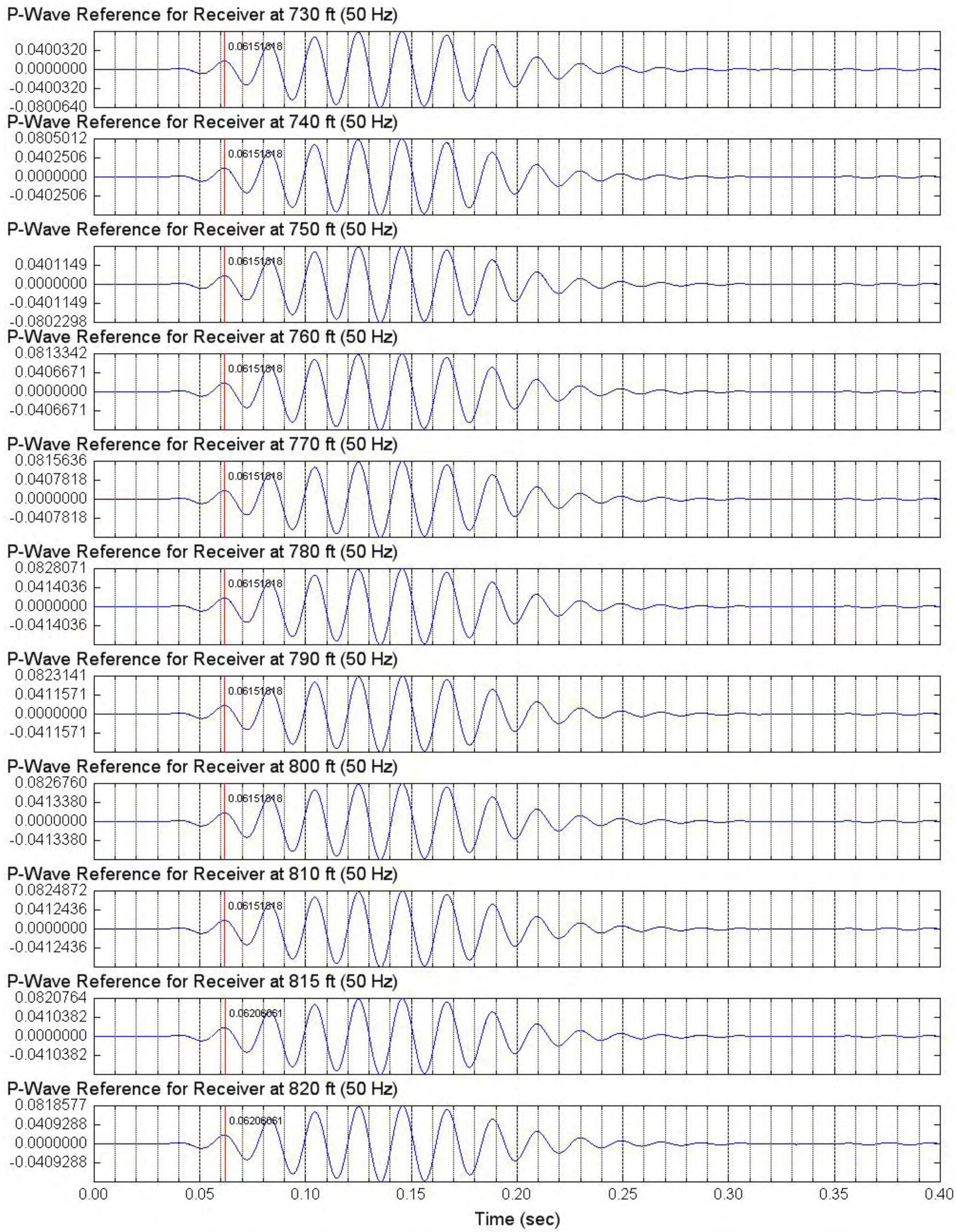


Figure 9.6 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

Figure 9.7 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Low Pass 25 Hz

Figure 9.8 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

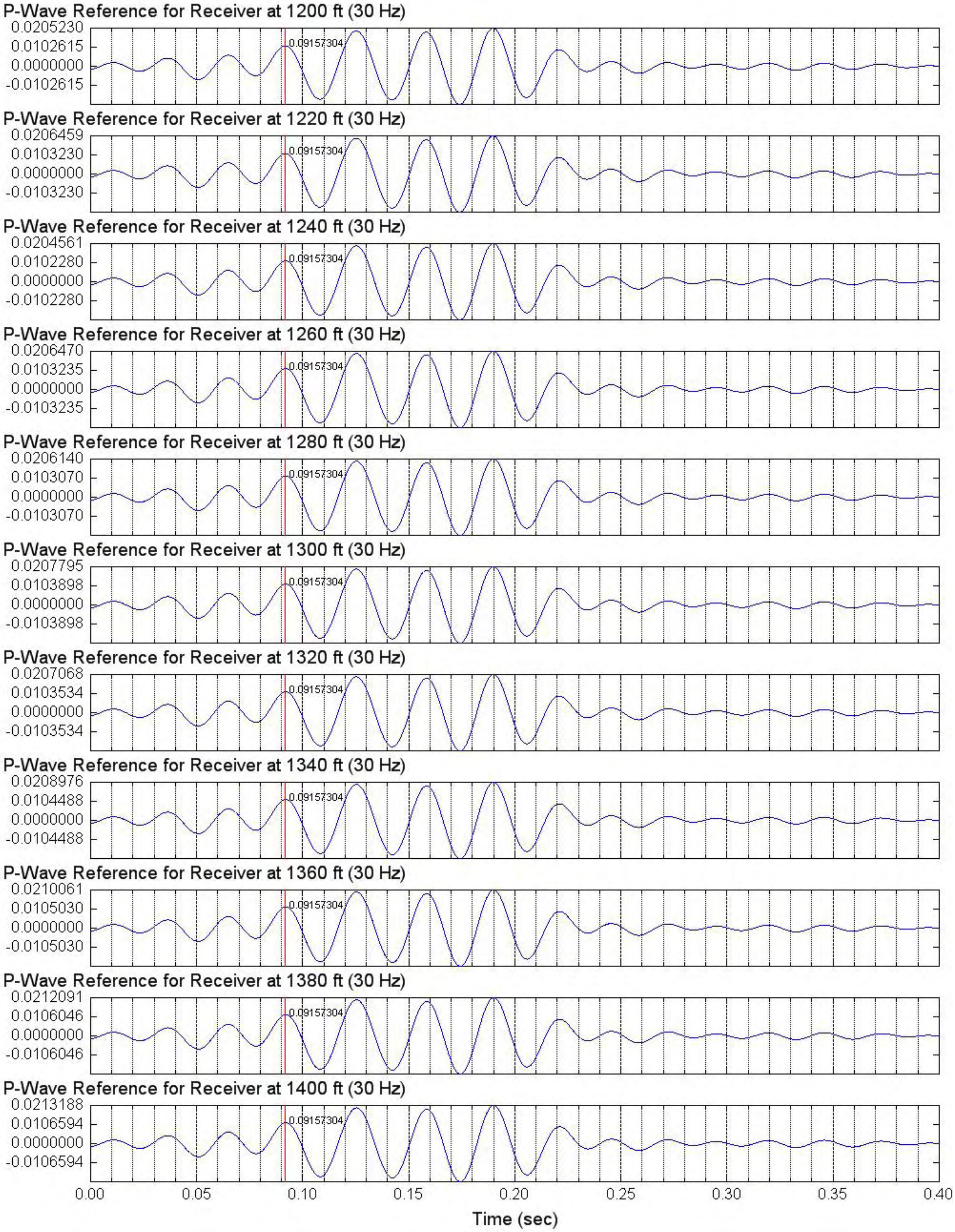
Lower Receiver Depths 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

Figure 9.9 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

Figure 9.10 Filtered Reference Vertical Receiver (P-Wave) Signals in Borehole C4996

Lower Receiver Depths 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz



Section 10: Expanded and Filtered P-Wave Signals of Lower Vertical Receiver

1. Figures 10.1 to 10.6 present expanded lower vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; FFT low pass 60 Hz; input signal: 5 cycles of 50-Hz sine wave.
2. Figures 10.7 presents expanded lower vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; FFT low pass 25 Hz; input signal: 4 cycles of 20-Hz sine wave.
3. Figures 10.8 to 10.10 present expanded lower vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; FFT low pass 40 Hz; input signal: 4 cycles of 30-Hz sine wave.

Figure 10.1 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 360 to 455 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

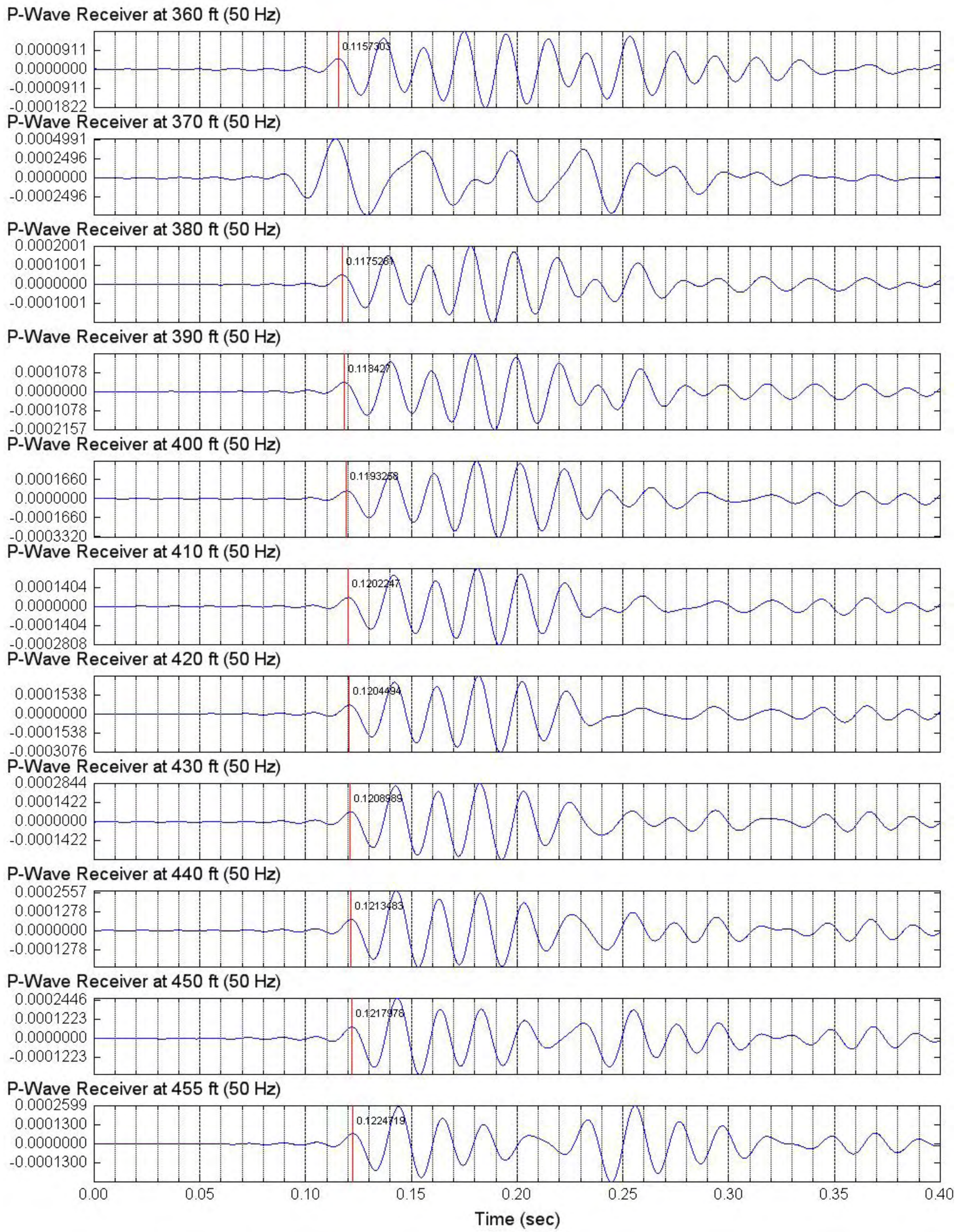


Figure 10.2 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 460 to 520 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

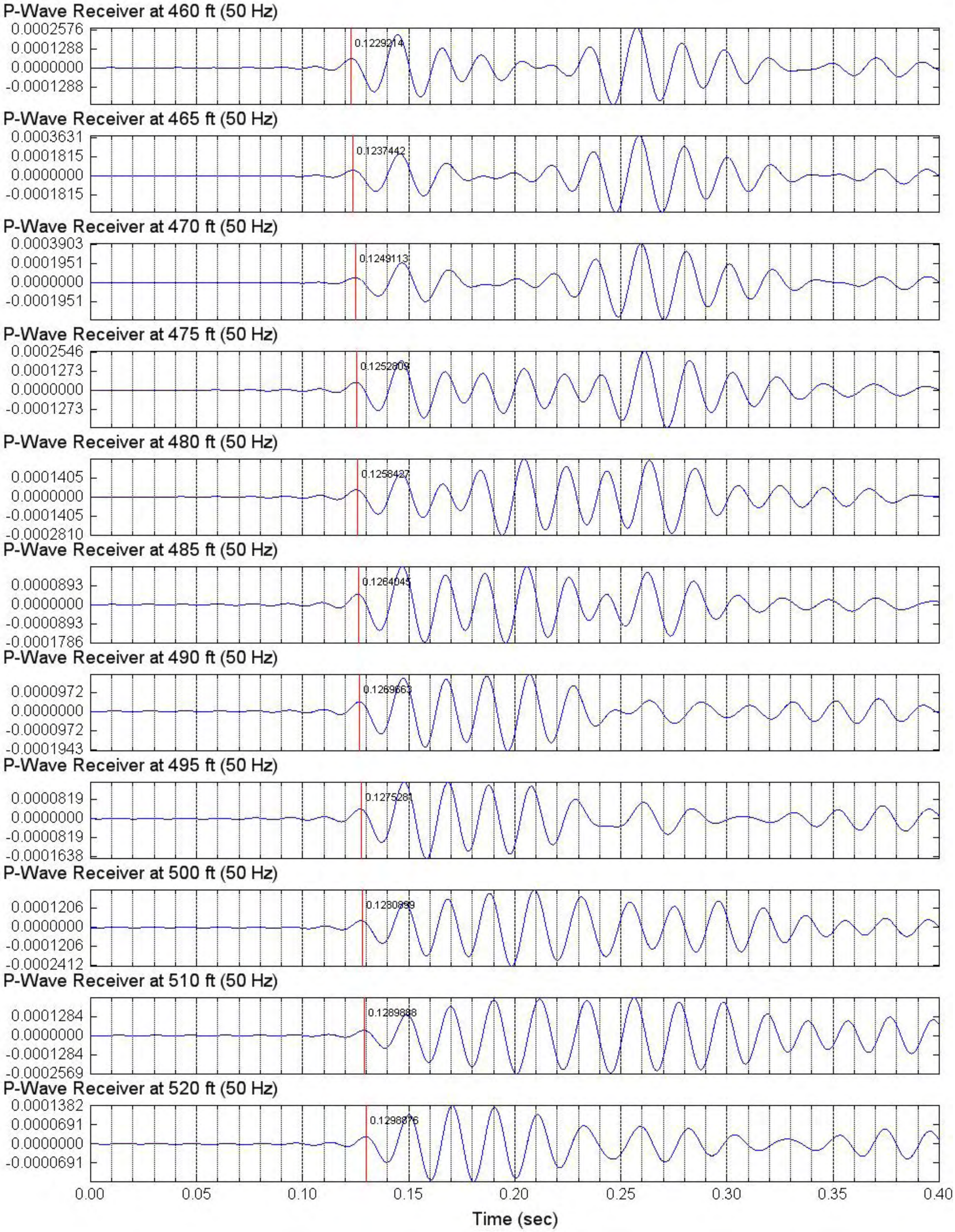


Figure 10.3 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 530 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

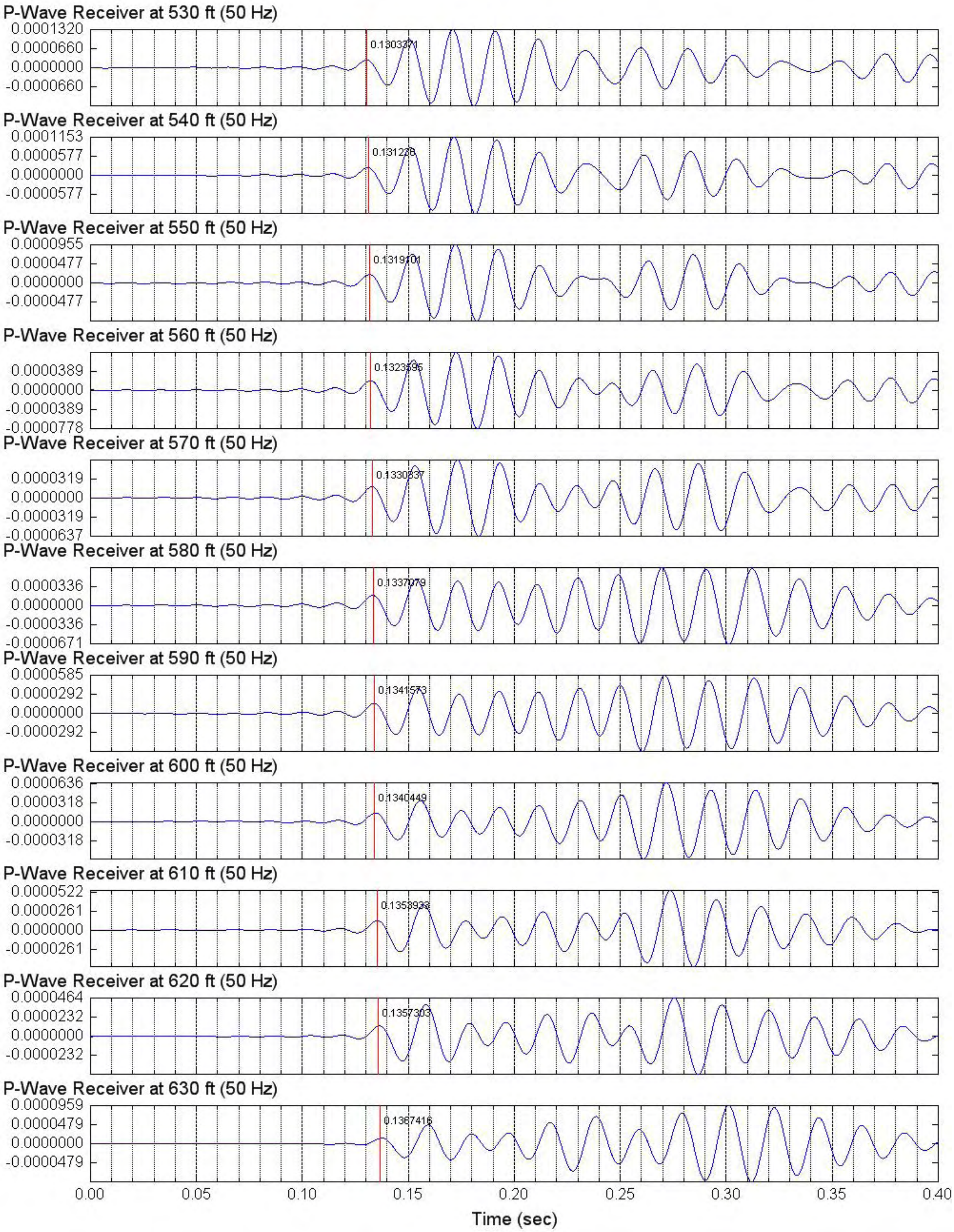


Figure 10.4 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 640 to 720 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

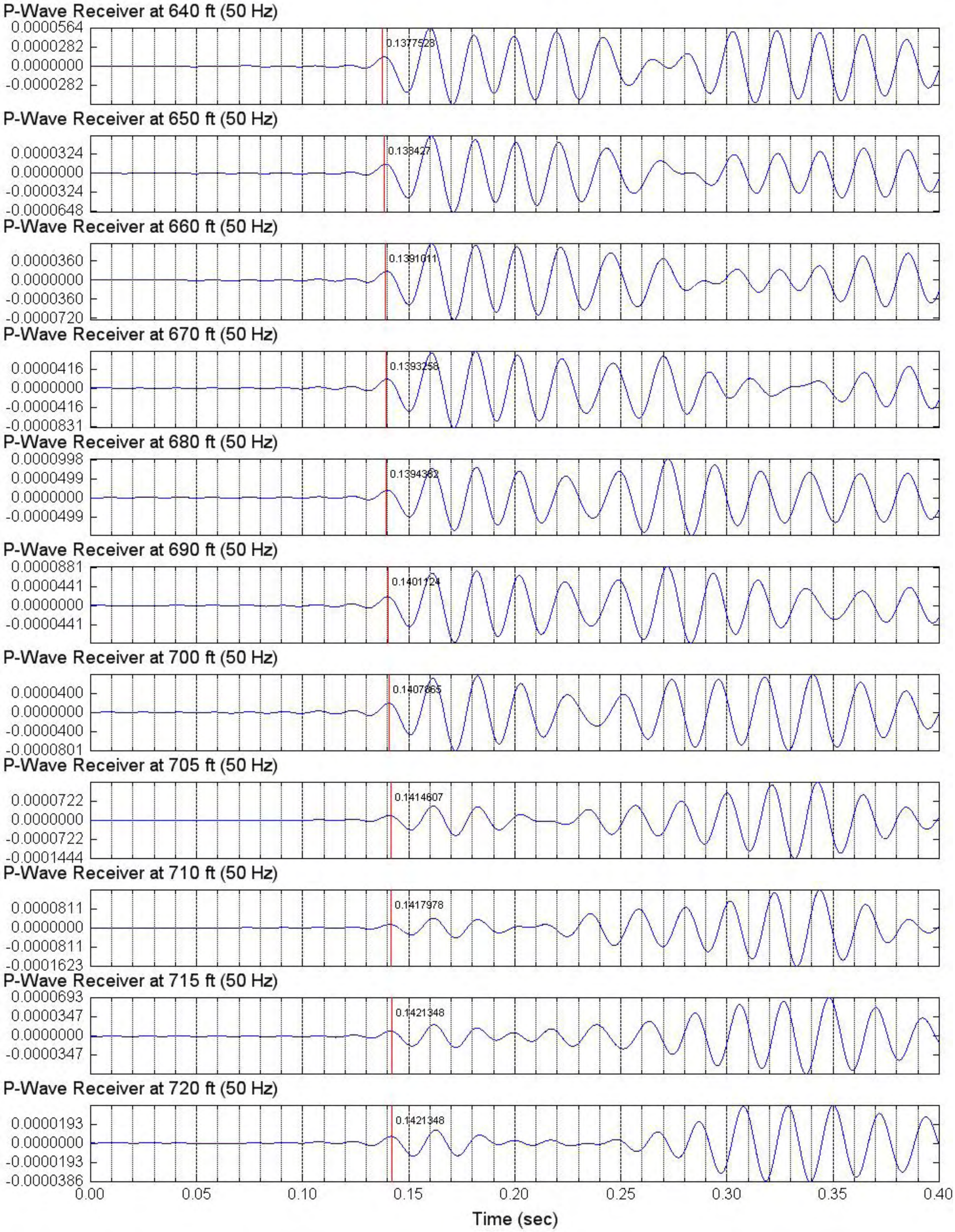


Figure 10.5 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 730 to 820 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

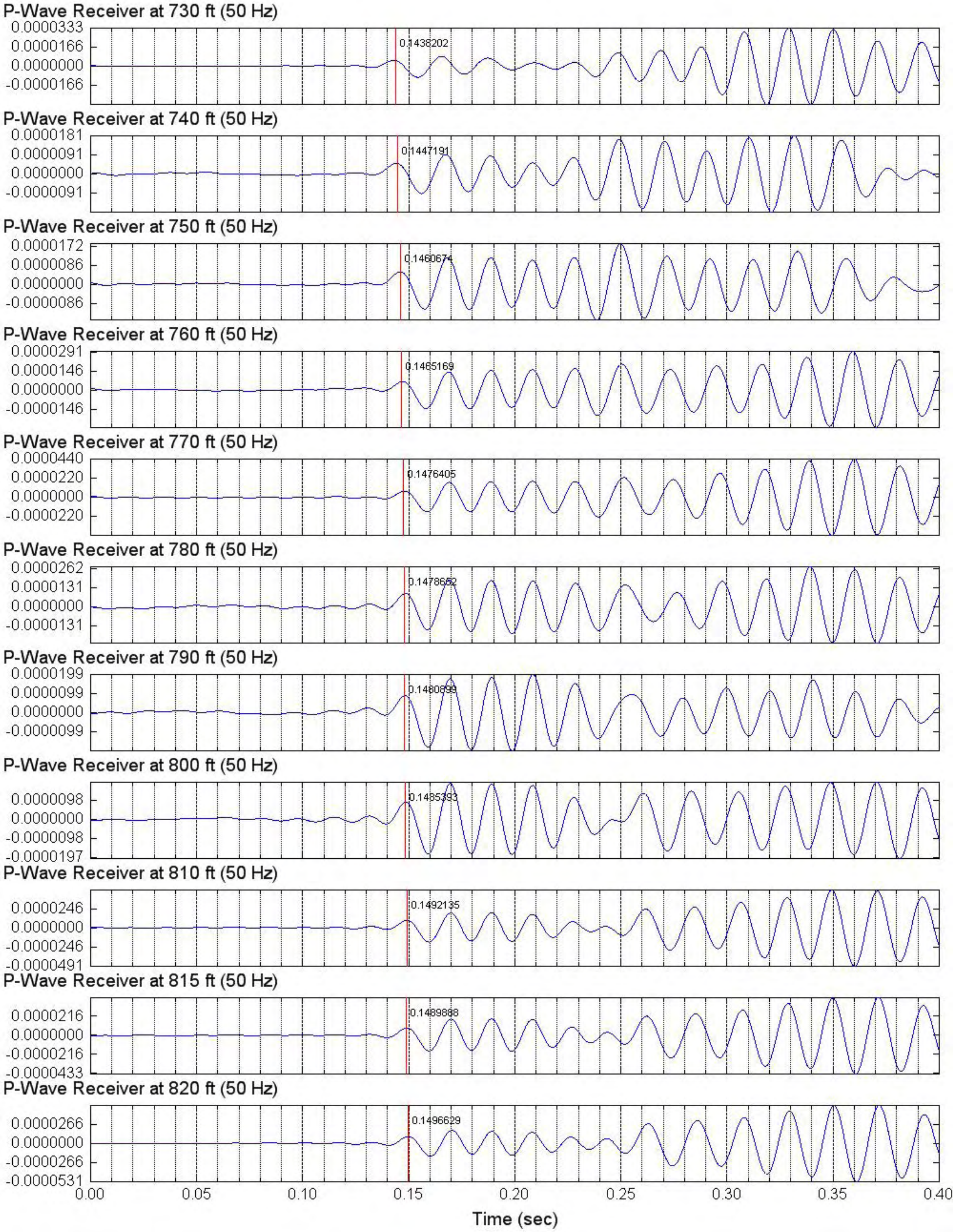


Figure 10.6 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 830 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Low Pass 60 Hz

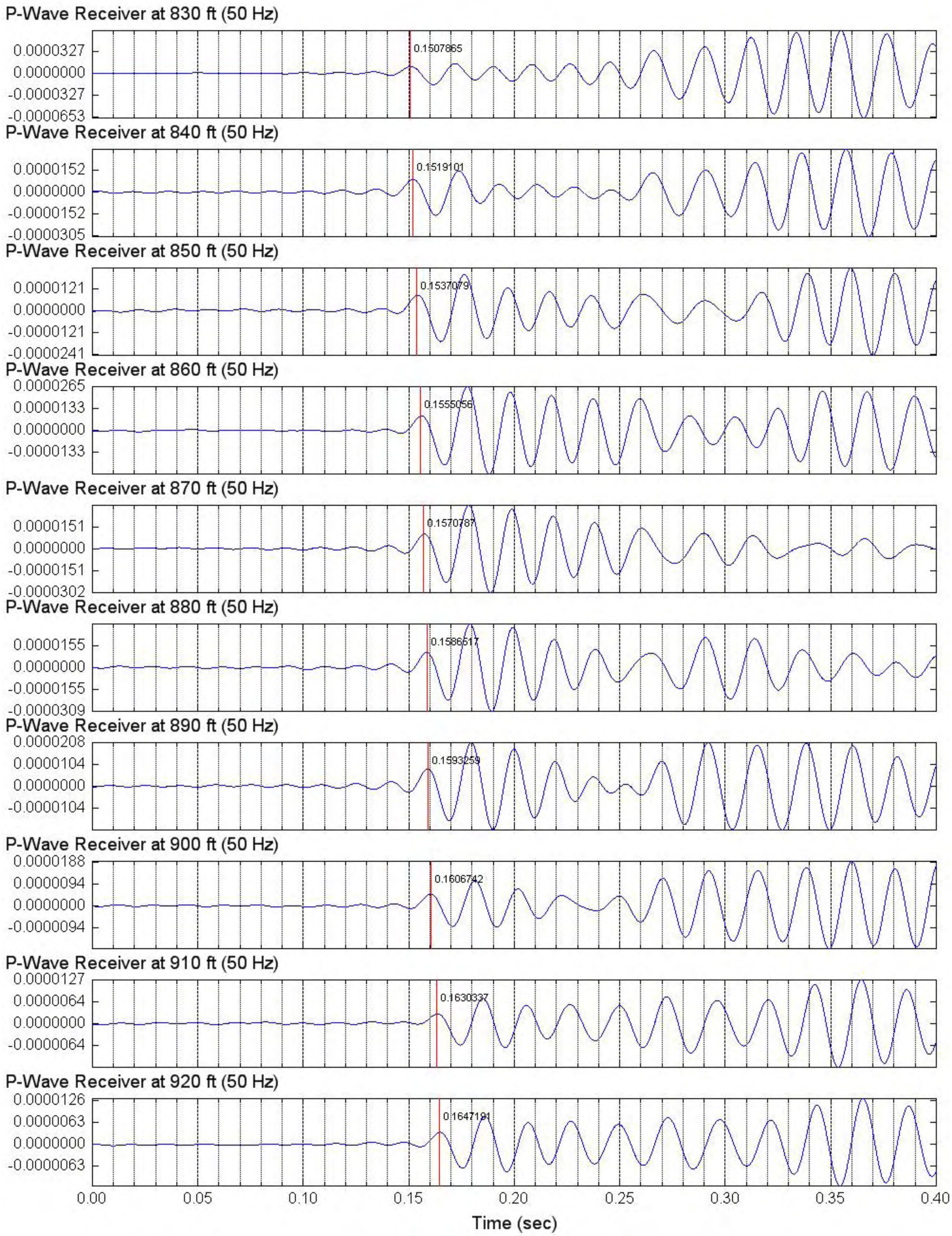


Figure 10.7 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Low Pass 25 Hz

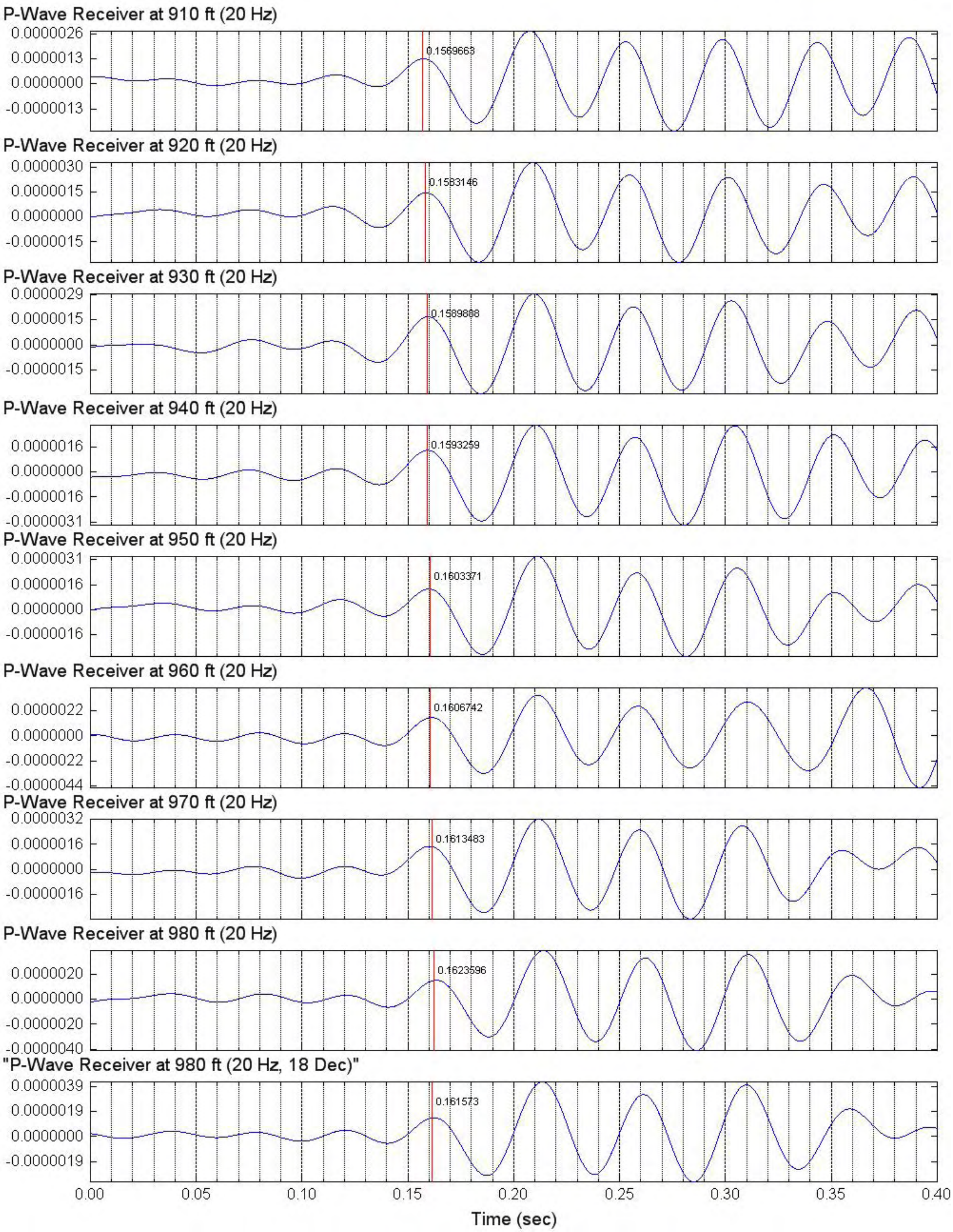


Figure 10.8 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 990 to 1080 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

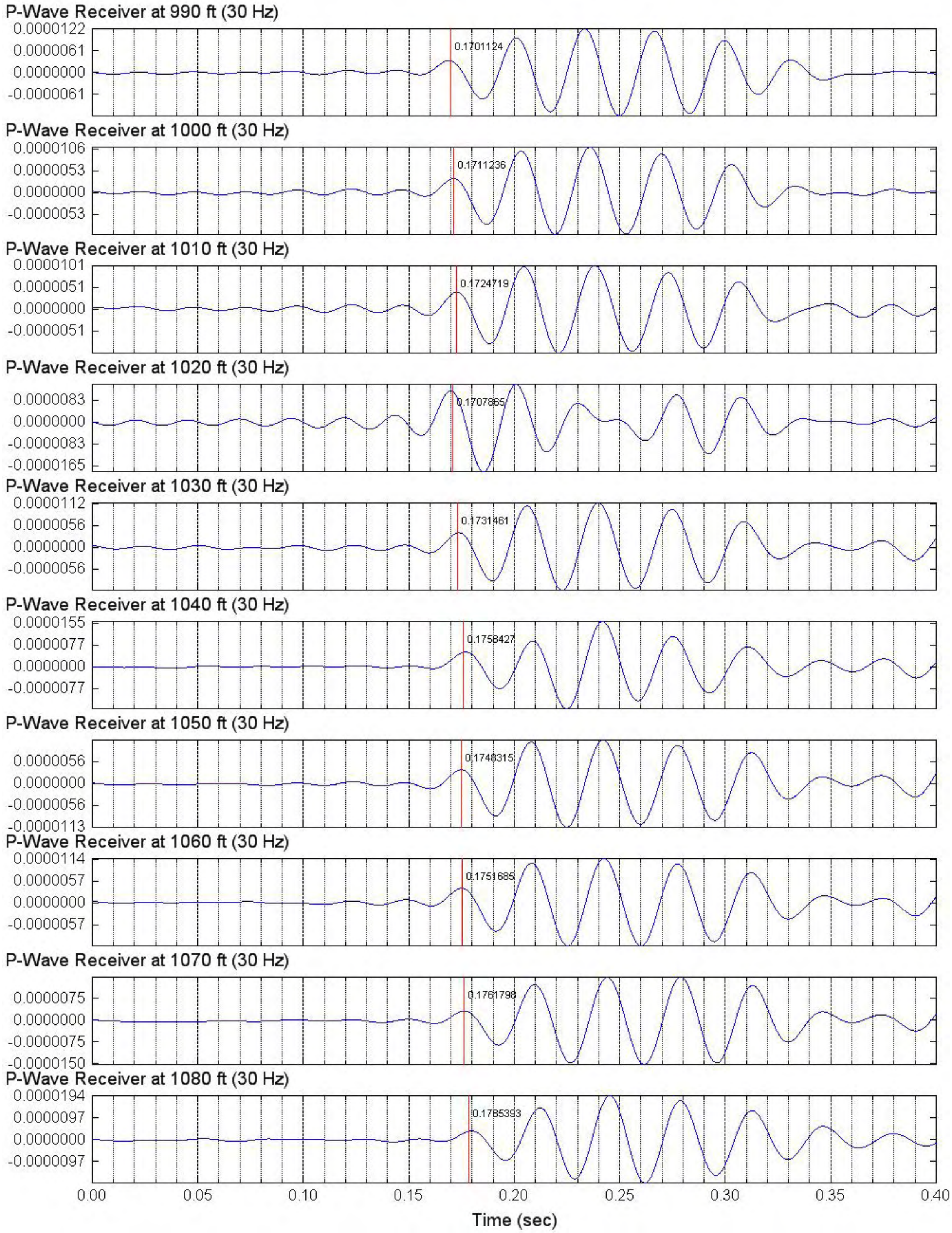


Figure 10.9 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1090 to 1180 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz

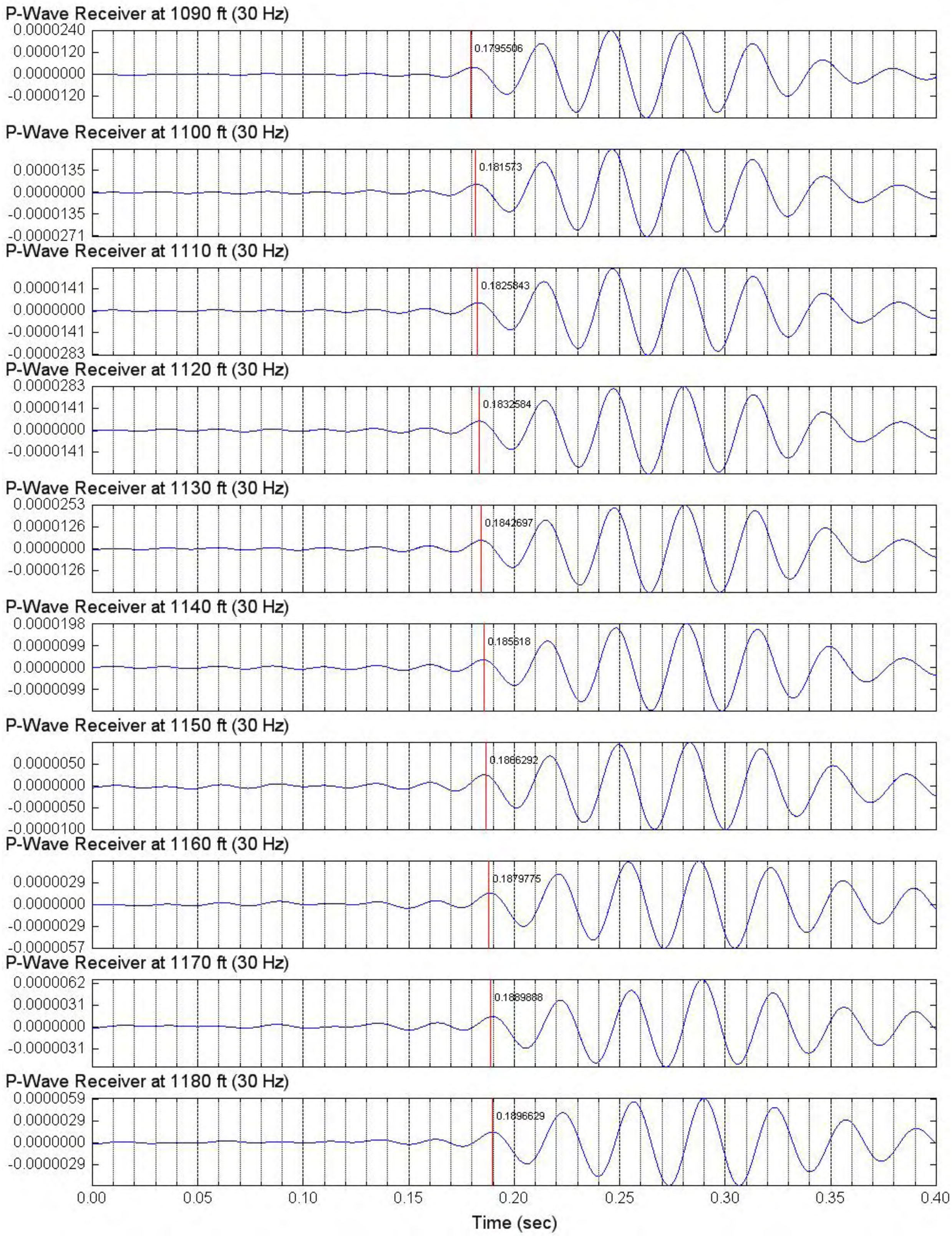
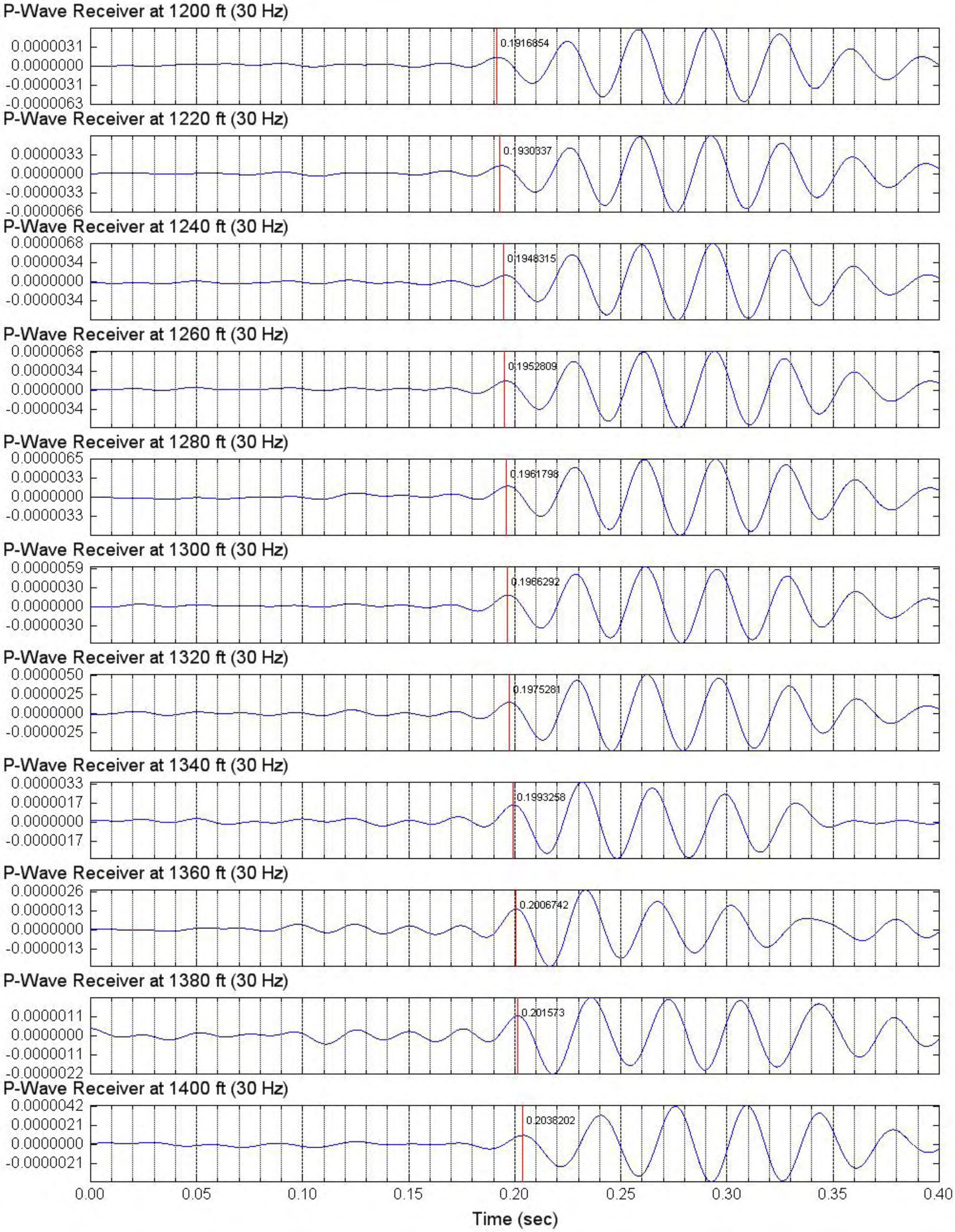


Figure 10.10 Expanded Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depth 1200 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Low Pass 40 Hz



Section 11: Waterfall Plots of Unfiltered P-Wave Signals of Lower Vertical Receiver

1. Figures 11.1 to 11.2 present waterfall plots of unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; input signal is 5 cycles of 50-Hz sine wave; time shifted by reaction mass acceleration.
2. Figure 11.3 presents the waterfall plot of unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; input signal is 4 cycles of 20-Hz sine wave; time shifted by reaction mass acceleration.
3. Figure 11.4 presents the waterfall plot of unfiltered lower vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; input signal is 4 cycles of 30-Hz sine wave; time shifted by reaction mass acceleration.

Figure 11.1 Waterfall Plot of Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 360 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration

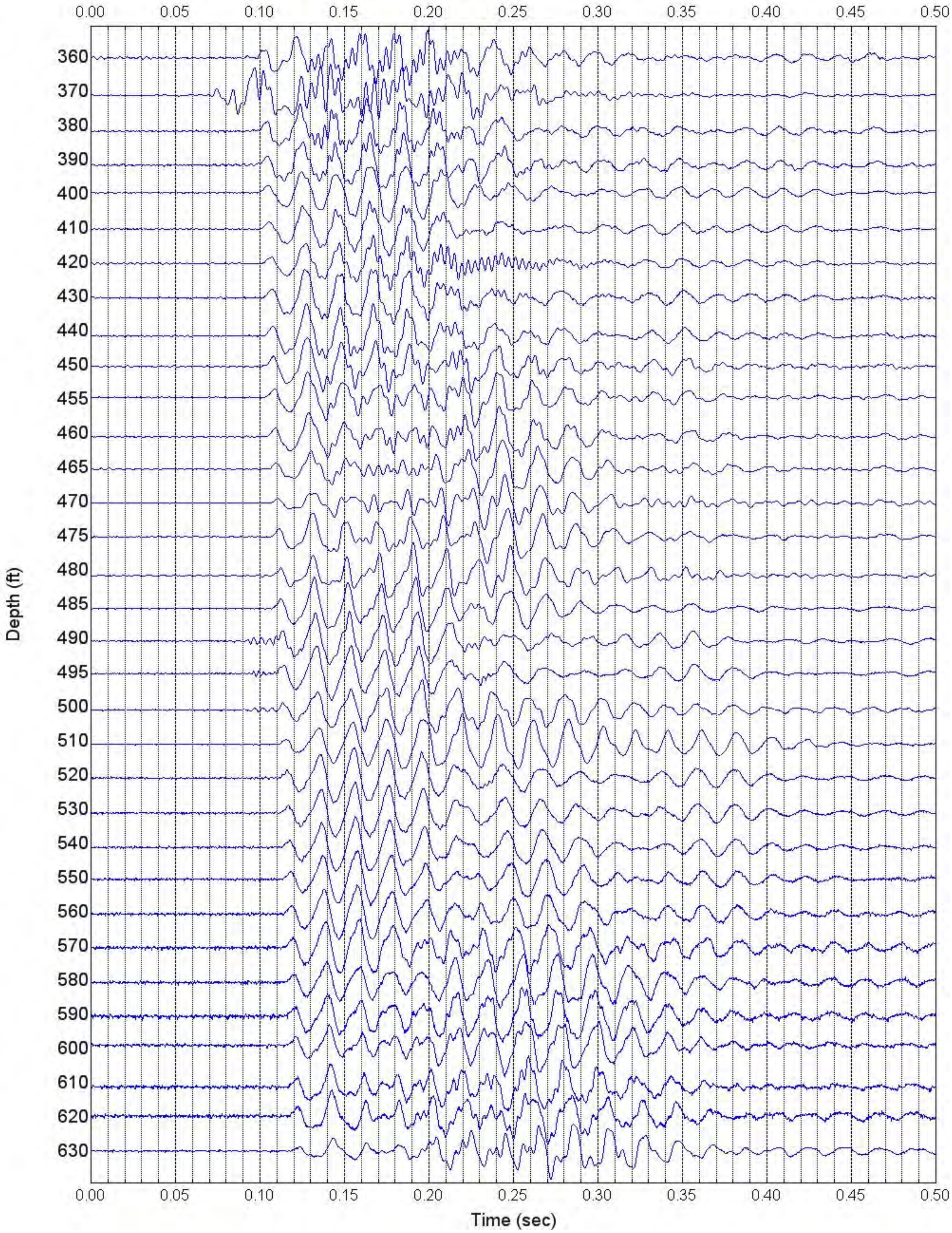


Figure 11.2 Waterfall Plot of Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 640 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration

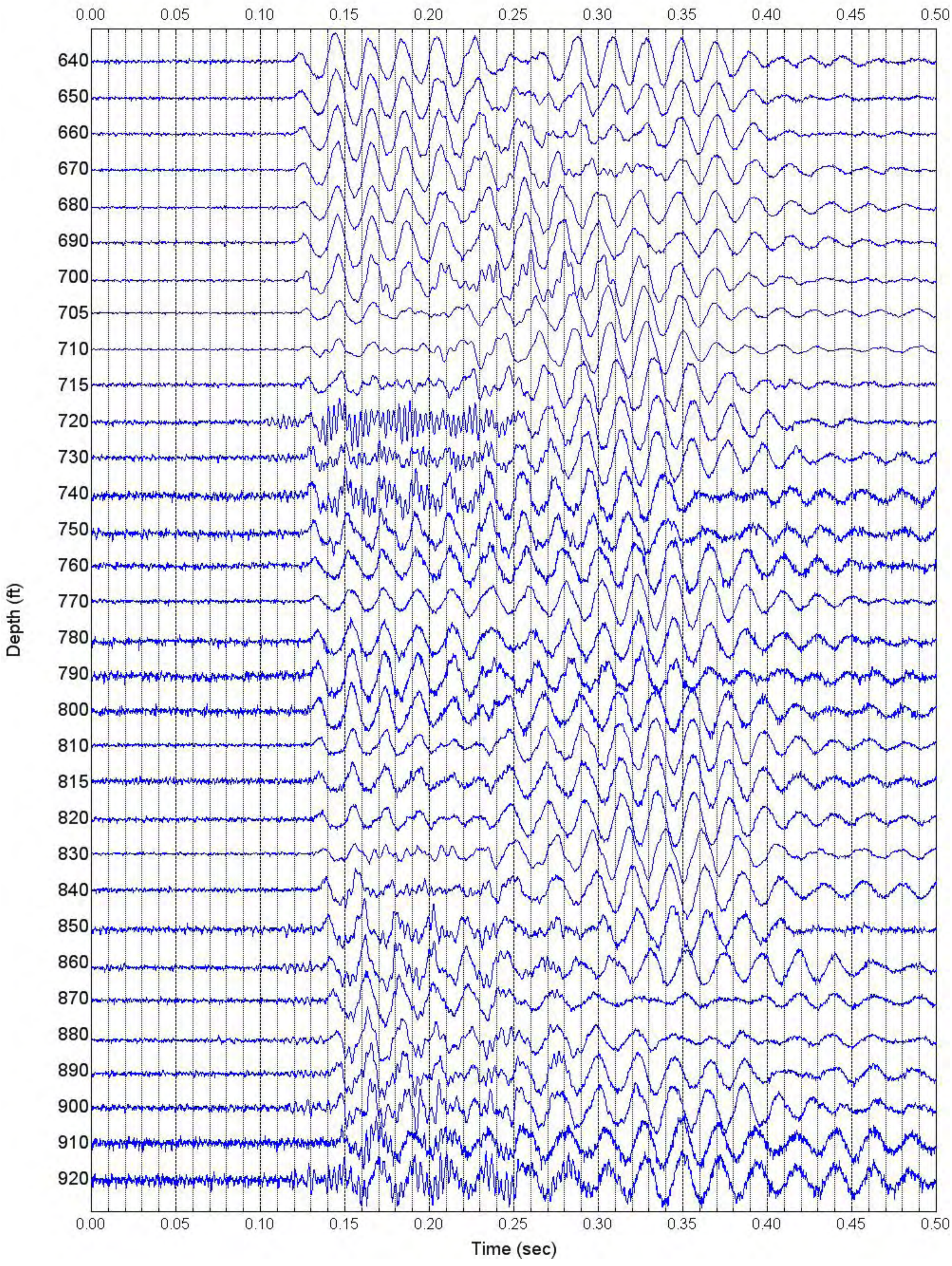


Figure 11.3 Waterfall Plot of Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration

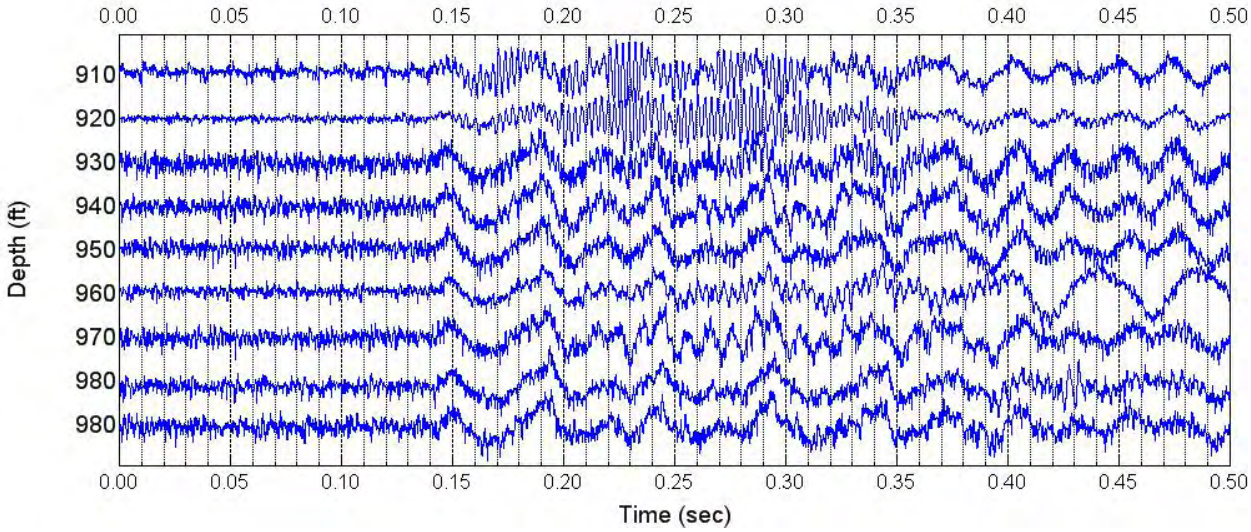
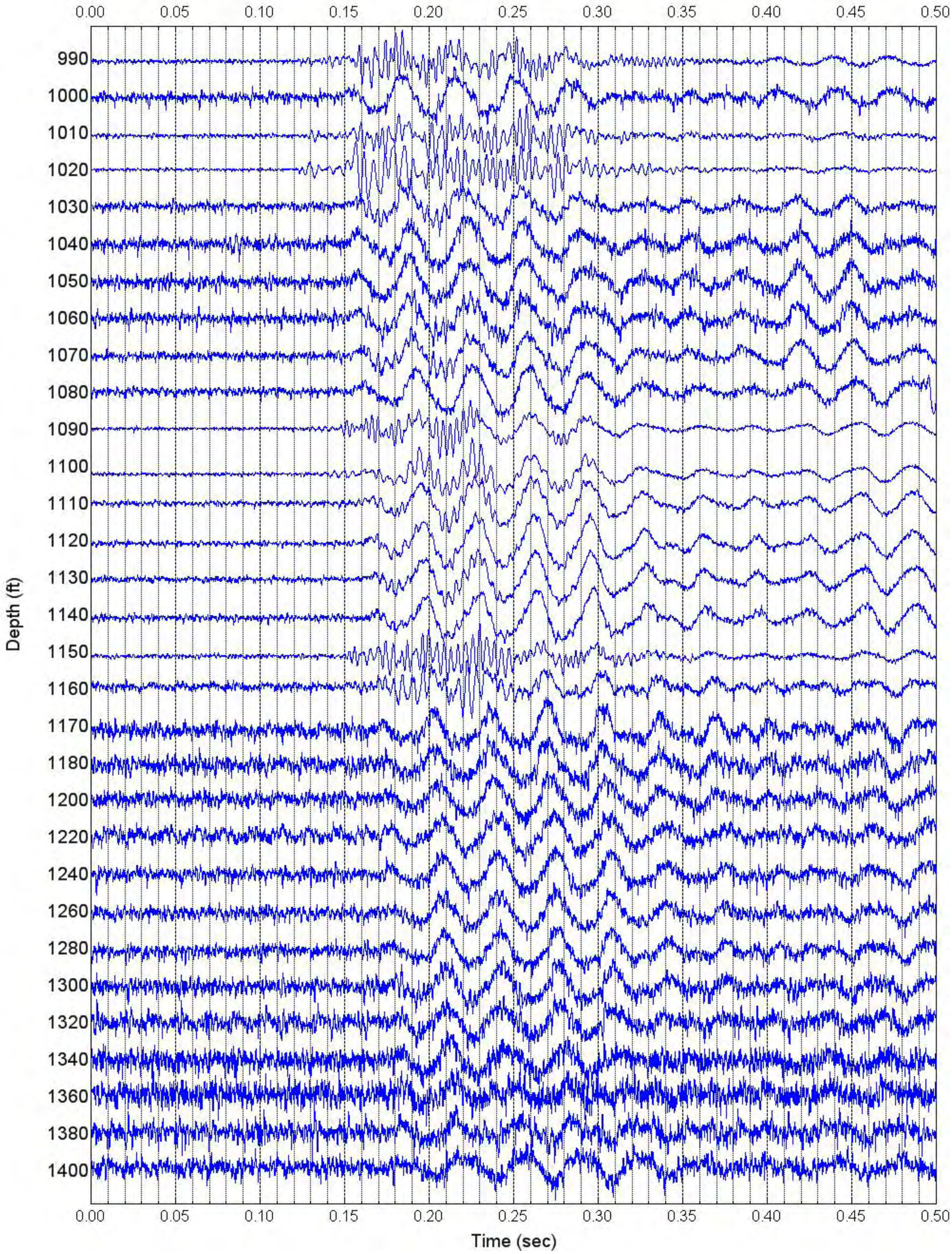


Figure 11.4 Waterfall Plot of Unfiltered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 990 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration



Section 12: Waterfall Plot of Filtered P-Wave Signals of Lower Vertical Receiver

1. Figures 12.1 to 12.2 present waterfall plots of filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 360 to 920 ft; input signal is 5 cycles of 50-Hz sine wave; time shifted by reaction mass acceleration, and depth scaled.
2. Figure 12.3 presents waterfall plots of filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 910 to 980 ft; input signal is 4 cycles of 20-Hz sine wave; time shifted by reaction mass acceleration, and depth scaled.
3. Figure 12.4 presents the waterfall plot of filtered lower vertical receiver (P-wave) signals in Borehole C4996, depths 990 to 1400 ft; input signal is 4 cycles of 30-Hz sine wave; time shifted by reaction mass acceleration, and depth scaled.

Figure 12.1 Waterfall Plot of Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 360 to 630 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration; Depth Scaled

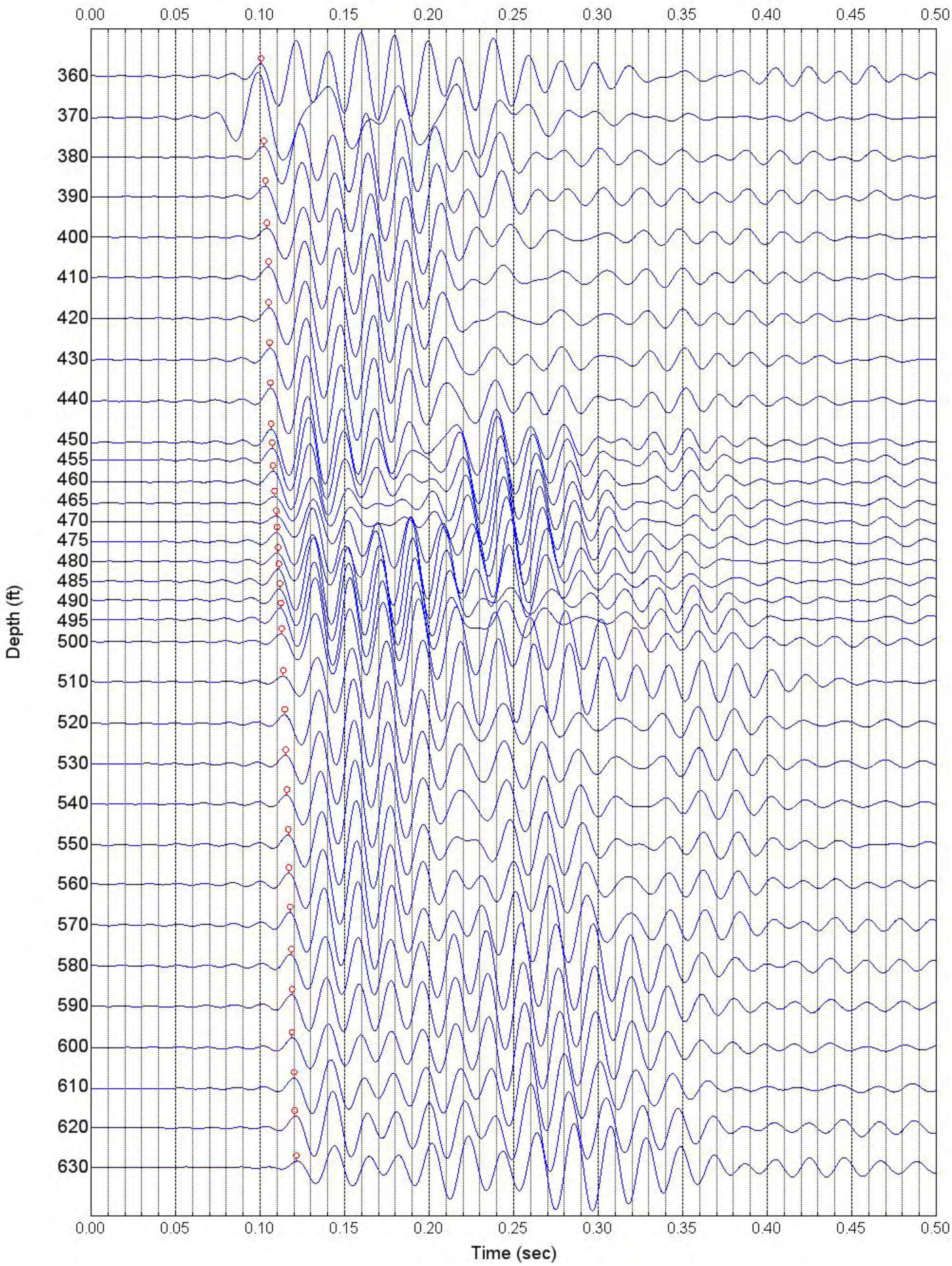


Figure 12.2 Waterfall Plot of Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 640 to 920 ft; Input Signal: 5 Cycles of 50-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration; Depth Scaled

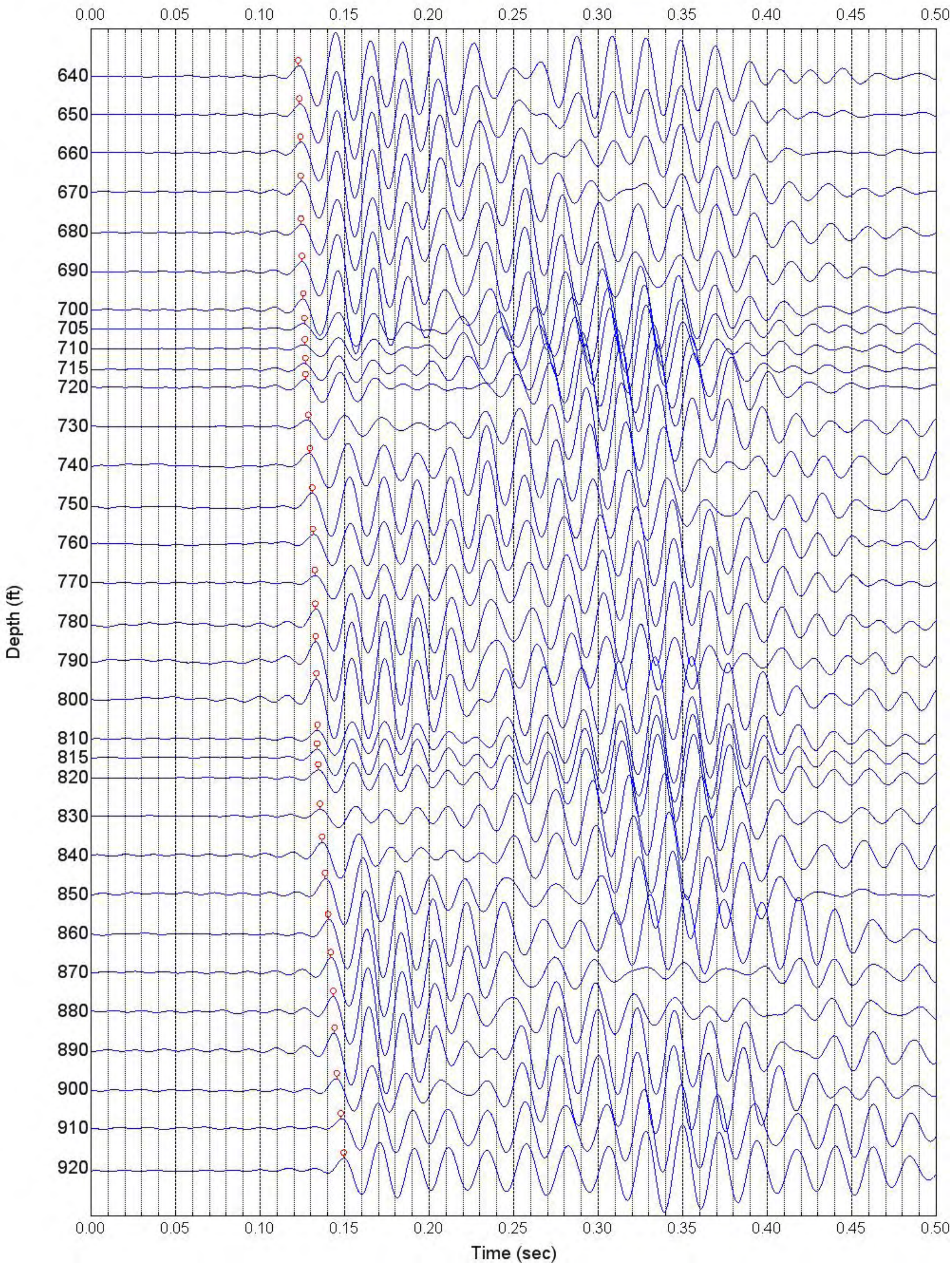


Figure 12.3 Waterfall Plot of Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 910 to 980 ft; Input Signal: 4 Cycles of 20-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration; Depth Scaled

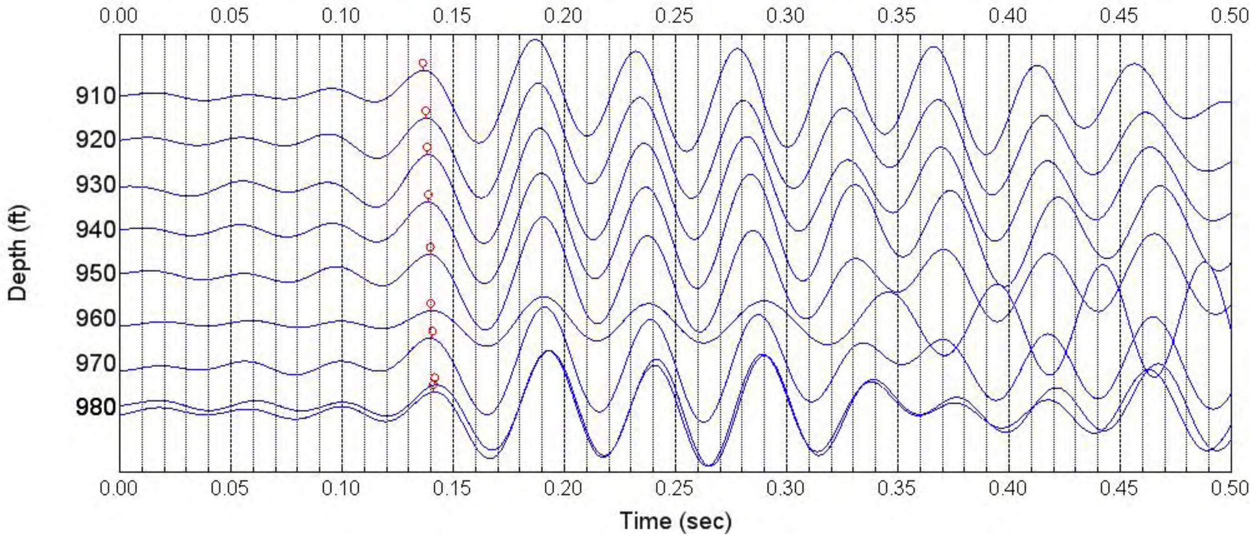
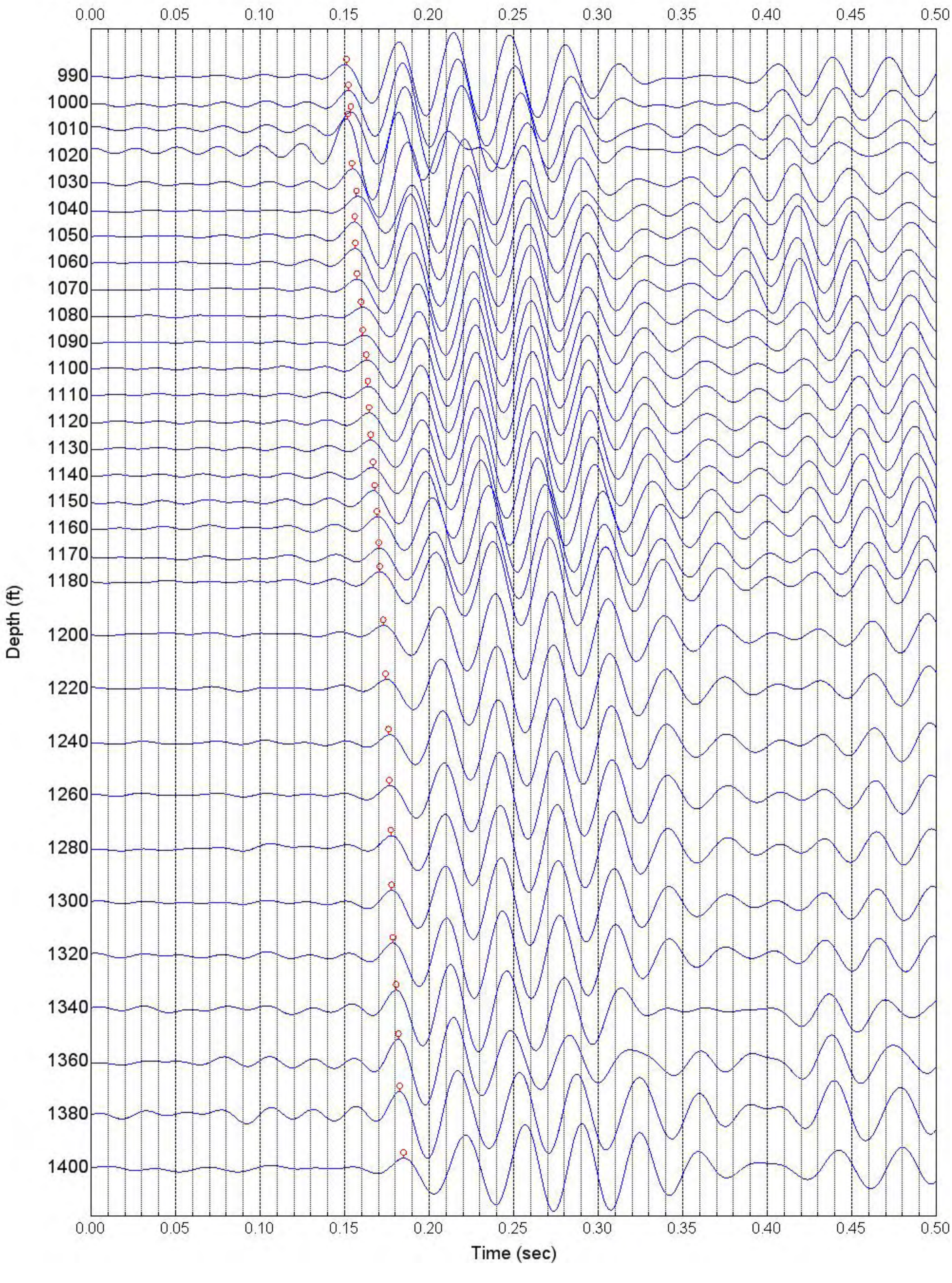


Figure 12.4 Waterfall Plot of Filtered Lower Vertical Receiver (P-Wave) Signals in Borehole C4996

Depths 990 to 1400 ft; Input Signal: 4 Cycles of 30-Hz Sine Wave; Time Shifted by Reaction Mass Acceleration; Depth Scaled



Section 13 References

1. Barnett, D.B., K.R. Fecht, S.P. Reidel, B.N. Bjornstad, D.C. Lanigan and C.F. Rust. 2007. "*Geology of the Waste Treatment Plant Seismic Boreholes"*. PNNL-16407, Rev. 1. Pacific Northwest National Laboratory, Richland, Washington.
2. Gardner, M.G. and R.K. Price. 2007. "*Summary Report of Geophysical Logging for the Seismic Boreholes Project at the Hanford Site Waste Treatment Plant"*. DTS-RPT-090 / PNNL-16395. Energy*Solutions* and Pacific Northwest Geophysics, Richland, Washington.
3. Redpath, B.B. 2007. "*Downhole Measurements of Shear- and Compression- Wave Velocities in Boreholes C4993, C4997, C4997 and C4998 at the Waste Treatment Plant DOE Hanford Site"*. PNNL-16559. Redpath Geophysics, Murphys, California.
4. Stokoe, K.H., II, Rathje, E.M., Wilson, C. and Rosenblad, B., 2004. *"Development of Large-Scale Mobile Shakers and Associated Instrumentation for In Situ Evaluation of Nonlinear Characteristics and Liquefaction Resistance of Soils,"* 13th World Conference on Earthquake Engineering, Vancouver, B.C. Canada , August 1-6.
5. Rohay, A.C. and T.M. Brouns. 2007. "*Site-Specific Velocity and Density Model for the Waste Treatment Plant, Hanford, Washington"*. PNNL-16652. Pacific Northwest National Laboratory, Richland, Washington.