FINAL TECHNICAL REPORT: 1996

Name of Contractor:	University of Washington
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Government Technical Officer:	Dr. John Sims MS 905 U.S. Geological Survey 12201 Sunrise Valley Drive Reston, VA 20192
Short Title:	Broad-Band Array Analysis of the Puget Sound Region
Program objective number:	II-1
Effective Date:	March 1, 1995
Amount:	$57,309. (3/1/95-12/31/96)
Time Period Covered in Report:	3/1/95 - 12/31/96
Date Report Submitted:	Oct. 14, 1998

Research supported by the
U.S. Geological Survey (USGS), Department of the Interior,
under USGS award number 1434-95-G-2605

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FINAL TECHNICAL REPORT
USGS Grant # 1434-95-G-2605
BROAD-BAND ARRAY ANALYSIS OF THE PUGET SOUND REGION

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NON-TECHNICAL ABSTRACT

We collected nearly three months of continuous data from sixteen broadband seismometers in a 100-km long, east-west array stretching from the Olympic Mountains through North Seattle to the Cascade Mountains. Analysis of these data indicate that the 5-10 km deep Seattle basin extends west to Hood Canal and east to about 20 km east of Lake Sammamish. The basin ends abruptly at both sides, suggesting it may be bounded by active or inactive faults. The basin amplifies shear waves by a factor of two and causes long-period waves to reverberate. This has important consequences for bridges and large buildings.

TECHNICAL ABSTRACT

We received one year of funding for this project. We collected nearly three months of continuous data from sixteen three-component, broadband seismometers in a linear, 100 km long, east-west array stretching from the Olympic Mountains through Seattle to the Cascade Mountains. All of these data were converted to SEED format and are freely available through the IRIS Data Management Center. Our primary analysis tool is modeling receiver functions to image crustal structure and the geometry of the subducted slab. This technique takes advantage of P to S converted waves from teleseismic earthquakes to determine the depth, orientation and impedance contrast of discontinuities in the crust and uppermost mantle. Two features in the data stand out as being very prominent and consistent across the array. Forward modeling of these observations using 3-D ray tracing through simple models associated with one or two dipping layers indicate that one of the prominent features is associated with conversions off the top of the south-dipping Crescent Basalts at a depth of 5 or more km, and the other is the east-dipping slab at depths of 40 to 60 km. The Seattle Basin, which sits on top of the Crescent Basalts is very deep, there is no obvious east-west dip to the basin, and the basin is sharply bounded to the west by the Hood Canal Fault as well as to the east, possibly by a southward extension of the South Whidbey Island fault. Long-period (5-15s) S waves are amplified by a factor of 2 in the basin, and large-amplitude reverberations continue for at least two minutes. This has important implications for damage to bridges and the largest buildings in Seattle and Bellevue from large subduction zone earthquakes. The Moho of the subducted slab produces a clear arrival on long-period receiver functions that appears at systematically greater times for stations from west to east. These features can be explained by a slab dipping at 16° to the east from depths of 40 to 60 km across the array.

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Program Element: II.1

Introduction

In 1994 we deployed sixteen three-component, broad-band seismometers in a linear, 100 km long, east-west array stretching from the Olympic Mountains through Seattle to the Cascade Mountains (Figure 1). These stations recorded continuous data at 20 samples per second and at 1 sample per second for about two and a half to three months.

This project only received funding for one year. The accomplishments during that year are outlined below.

Data availability

We have converted the continuous data to the standard SEED format and they are available to the community for further processing at the IRIS Data Management Center in Seattle. Data are available by calling (206) 547-0393 or using any of the standard data request mechanisms through the WEB at http://www.iris.washington.edu/

This was one of the first PASSCAL data sets to be converted to SEED format using the IRIS-PASSCAL software. Because we did this while the software was still being developed, this was a significant effort.

Preliminary Results

Our primary modeling work is analyzing the receiver functions calculated for these data. A receiver function is the deconvolution of the vertical component of a teleseismic P wave and its coda from the radial component. In principle, the structure of the P-waveform caused by the source complexity and by wave interactions near the source are the same for both components and are therefore removed by the deconvolution, leaving a waveform that depends primarily on structure near the receivers. These waveforms are modeled by comparing them with similarly deconvolved synthetic seismograms. An advantage of analyzing receiver functions of closely-spaced seismometers is that several features of the receiver function are correlated across the array, facilitating their interpretation.

Two features in the observed receiver functions that are very clear across the array are apparently caused by impedance contrasts associated with the eastward dipping subducted slab, and with the southward dipping base to the Seattle Basin.

The Seattle Basin: We have focused on forward modeling of the entire array using simple 3-D models with one or two dipping interfaces. A striking feature of the first 5 seconds of 1-Hz receiver functions is a pronounced positive peak at about 2 s and the absence of a peak at zero lag for stations that lie within the Seattle Basin: east of the Hood Canal fault and west of the Cascade foothills (Figure 2). The peak at 2 s disappears entirely and the zero-second-lag arrival appears for stations to the west of Hood Canal (distance <12 km), and in the Cascades (distance > 80). Both of these features can be readily explained by synthetics (waveform at distance = 44 km) calculated from a model inferred from a north-south reflection profile taken along Puget Sound. The reflection line shows a very strong reflector at 3.5 s two-way travel time, which has been interpreted as a sharp boundary between the Crescent Basalts below and sedimentary rocks above. This boundary is dipping 15 degrees down to the south. Synthetics calculated from a 3-D model consistent with this interpretation, and with a large impedance contrast, explain the main features in the first few seconds of the observed receiver functions. It is especially interesting to note that the Seattle Basin does not appear to have any significant east-west dip, and seems to continue at about the same depth all the way to Hood Canal where the basin disappears abruptly. The Seattle Basin appears to be fault-bounded to the east, perhaps by an extension of the Whidbey Island fault (Figure 1).

Broad-band, transverse-component seismograms from an intermediate-focus earthquake in Mexico, 40 degrees away, display large-amplitude reverberations after body-wave phases such as S, sS, and SS for stations within the basin (Figure 3). The reverberations are peaked at a period of about 10 s, and are often larger in amplitude than the direct body waves. We model this part of the seismogram using the Direct Solution Method [Cummins et al., 1994] which calculates complete synthetic seismograms in a spherical geometry at periods of 4 s and larger. The qualitative features of the SH seismograms can be modeled with a simple low-S velocity basin below Seattle, but a detailed waveform match may require a 2-D calculation.

Slab Structure: The M_w 7.6 deep-focus Fiji earthquake of 9 March 1994 was recorded by each of our seismometers, and provides a source with good signal-to-noise at long periods. We analyze long-period receiver functions from this event to image the crust-mantle boundary of the subducting slab, which lies at a depth of 40-60 km along our array (Figure 4). A prominent arrival, which can be traced across our entire array, and varies systematically in time from 15 to 25 s, is consistent with synthetics calculated from a discontinuity dipping at 16° to the east, and is interpreted as the Moho of the subducted oceanic lithosphere. We hope to model this arrival in more detail to be able to determine the precise depth of the subducted Moho relative to the seismicity so we can determine whether the seismicity is in the subducted crust or subducted mantle, a question with important implications regarding the physical mechanisms for intermediate-focus earthquakes. Before this question can be answered, however, we must improve the model of the upper crust (Seattle Basin) because the large S-wave velocity anomalies associated with this basin significantly affect the travel times of phases used to image the depth to the slab. The SHIPS experiment will provide a high resolution image of the P-wave velocities for this purpose, though it is not yet clear how well we will be able to resolve the S-wave velocities.

References

Cummins, P.R., R.J. Geller, T. Hatori, and N. Takeuchi, DSM complete synthetic seismograms: SH, spherically symmetric, case , Geophys. Res. Lett., 21, 533-556, 1994.

Johnson, S. Y., C. J. Potter, and J. M. Armentrout, Origin and evolution of the Seattle fault and Seattle basin, Washington, Geology, 22, 71-74, 1994.

Publications

Two AGU abstracts resulted from this research:

Pullen, J., K. C. Creager and S. Malone, Receiver function array study in the Puget Sound Region, Washington *EOS, 75(44),* 485, 1994

Pullen, J., K. C. Creager and S. Malone, Broadband array study in the Puget Sound Region, Washington *EOS, 76(46),* F416, 1995

S52B-20 1330h POSTER

Receiver Function Array Study in the Puget Sound Region, Washington

James L Pullen, K.C. Creager and S.D. Malone (Geophysics Program AK-50, University of Washington, Seattle WA 98195)

Sixteen three-component, broadband seismometers paired with high dynamic range digital recorders were deployed in a linear, 100 km, east-west array stretching from the Olympic Mountains through the central Puget Basin to the Cascade Mountains. These stations recorded at 20 sps for two and a half months (mid-February-late April, 1994).

Structural features of the subducting Juan de Fuca plate and continental crust are modelled by comparing synthetic receiver functions and receiver functions derived from the array data. At long periods (8-25s) there are several persistent features of the observed receiver functions. Two of the most prominent features can be replicated with a simple model, consisting of a deep sedimentary basin (Seattle basin) and a dipping slab over a half space. Earthquakes with backazimuths of 187 to 300 degrees show a prominent converted phase moving out from 15 s in the west to 25 s in the east. This is the direct P phase that has reflected from the surface and converted to a S wave at the slab's top (PPPmS). The moveout is consistent with a slab dipping at approximately 15 degrees. Also, the first pulse in the receiver functions, near zero lag, is delayed by 1-2 s for stations above the Seattle basin. This can be explained by the interference of the zero lag pulse with a P-to-S converted phase from a large, shallow velocity discontinuity. We have reproduced this effect with a deep (5-10 km), low velocity basin. Teleseismic P and S travel times are delayed by 1-2 and 2-4 seconds, respectively, for stations within the basin relative to stations outside, indicating a very low S wave velocity in the basin.

S41E-4 0930h

Broadband Array Study in the Puget Sound Region, Washington

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Sixteen three-component, broadband seismometers paired with high dynamic range digital recorders were deployed in a linear, 100 km, east-west array stretching from the Olympic Mountains through the central Puget Basin to the Cascade Mountains. These stations recorded at 20 sps for two and one-half months (mid-February-late April, 1994).

Structural features of the subducting Juan de Fuca plate and continental crust are modelled by comparing synthetic receiver functions and receiver functions derived from the array data. At long periods (8-25s) there are several persistent features of the observed receiver functions. Two of the most prominent features can be replicated with a simple model, consisting of a deep sedimentary basin (Seattle basin) and a dipping slab over a half space. Earthquakes with backazimuths of 187 to 300 degrees show a prominent converted phase moving out from 15 s in the west to 25 s in the east. This is the direct P phase that has reflected from the surface and converted to a S wave at the slab's top (PPPmS). The moveout is consistent with a slab dipping at approximately 15 degrees. Another prominent feature of the receiver functions is the absence or reduction of the phase at zero lag (the deconvolved direct P phase), followed by a prominent phase at 2-5 seconds, for stations in the Seattle basin. This phenomena may be due to a dip in the basin and/or the interference of a large converted phase with the zero lag phase. Both of these possibilites can be modelled by a deep (5-10 km), dipping basin, and we are using teleseisms at more back- azimuths to constrain the parameters (e.g., dip, depth, impedence contrast).

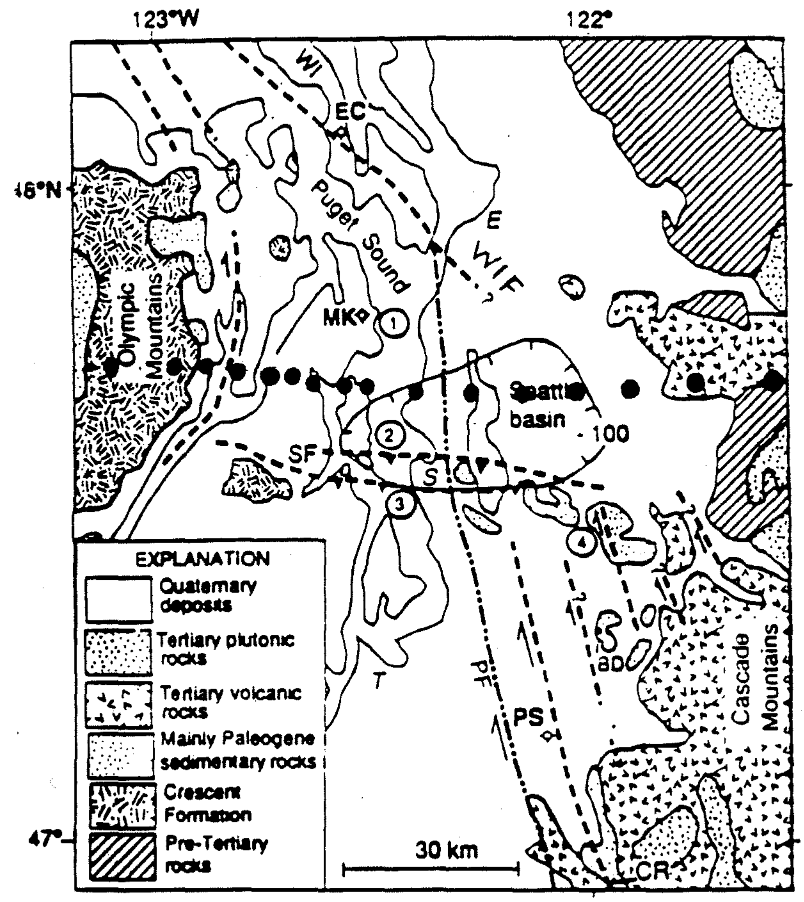

Figure 1. Crustal geology of the Puget Lowlands [after Johnson et al., 1994], and station locations of our temporary array.

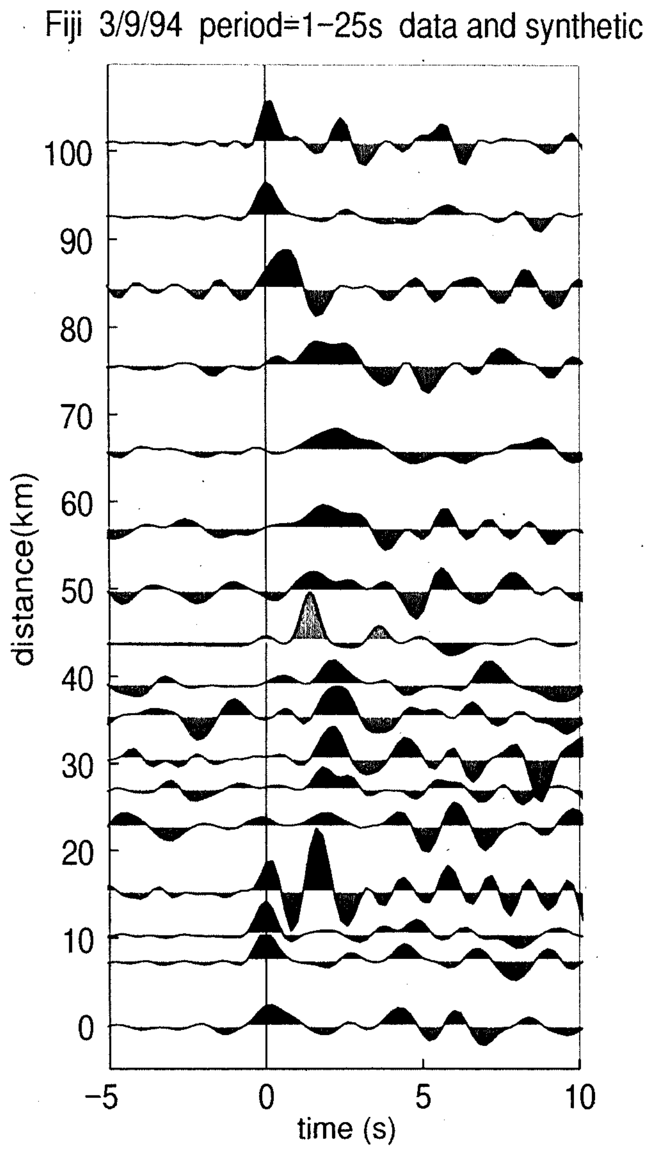

Figure 2. Observed (every trace except the one at distance=44 km) and synthetic (trace at distance =44 km) receiver functions filtered at 1-25 s periods. Positive peak normally observed at zero time is missing from stations in the Seattle Basin (20-80 km) and is replaced by a peak at about 2 s. This behavior is predicted by the synthetic receiver function (44 km) for a southward dipping crustal layer interpreted to be the top of the Crescent Basalts.

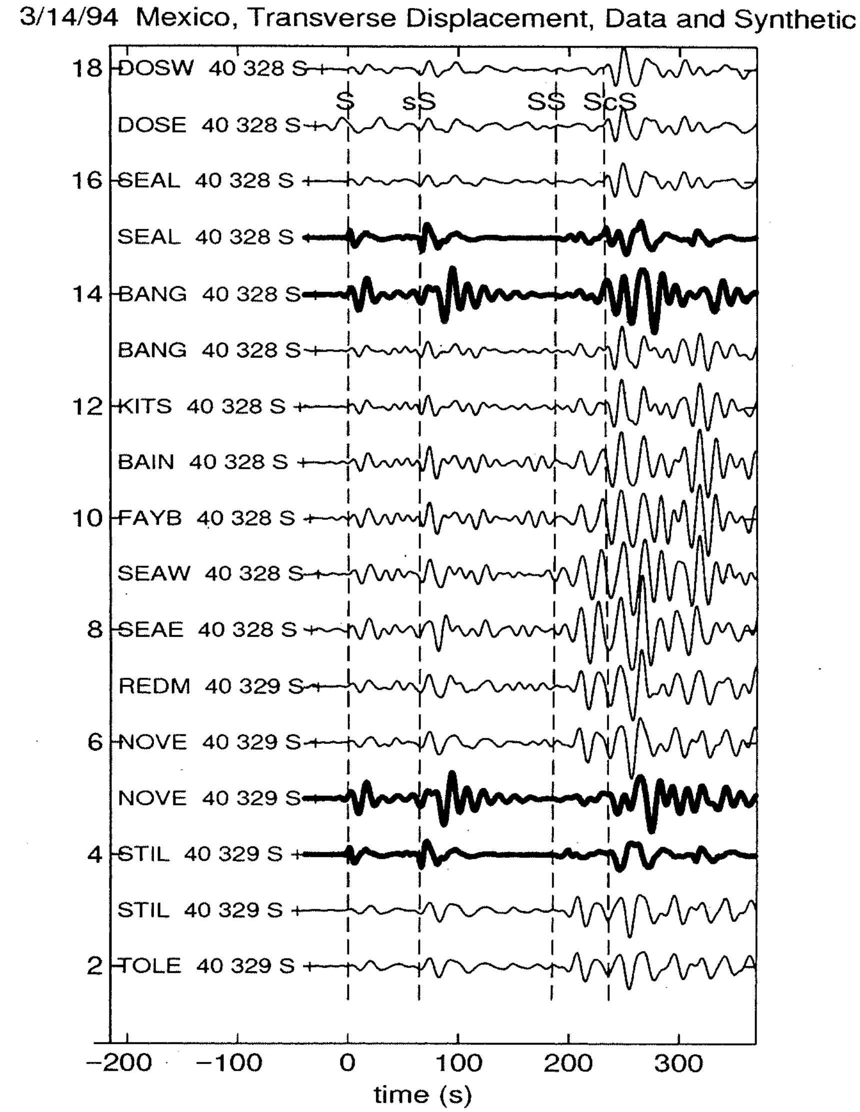

Figure 3. Transverse component, observed (thin lines) and synthetic (bold), displacement seismograms from the 160 km deep, 3/14/94, earthquake near Mexico. True amplitudes are shown. Stations are ordered from east (bottom) to west (top). Predicted times of S, sS, SS, and ScS are shown. SSS also arrives at about the same times as ScS. The coda following S and sS is markedly larger for Puget Lowland stations (stations 4-11) than for the other stations which sit over volcanic rocks of the Olympic and Cascade foothills. Synthetics are calculated with a deep sedimentary basin for NOVE and BANG, and without a basin (STIL and SEAL).

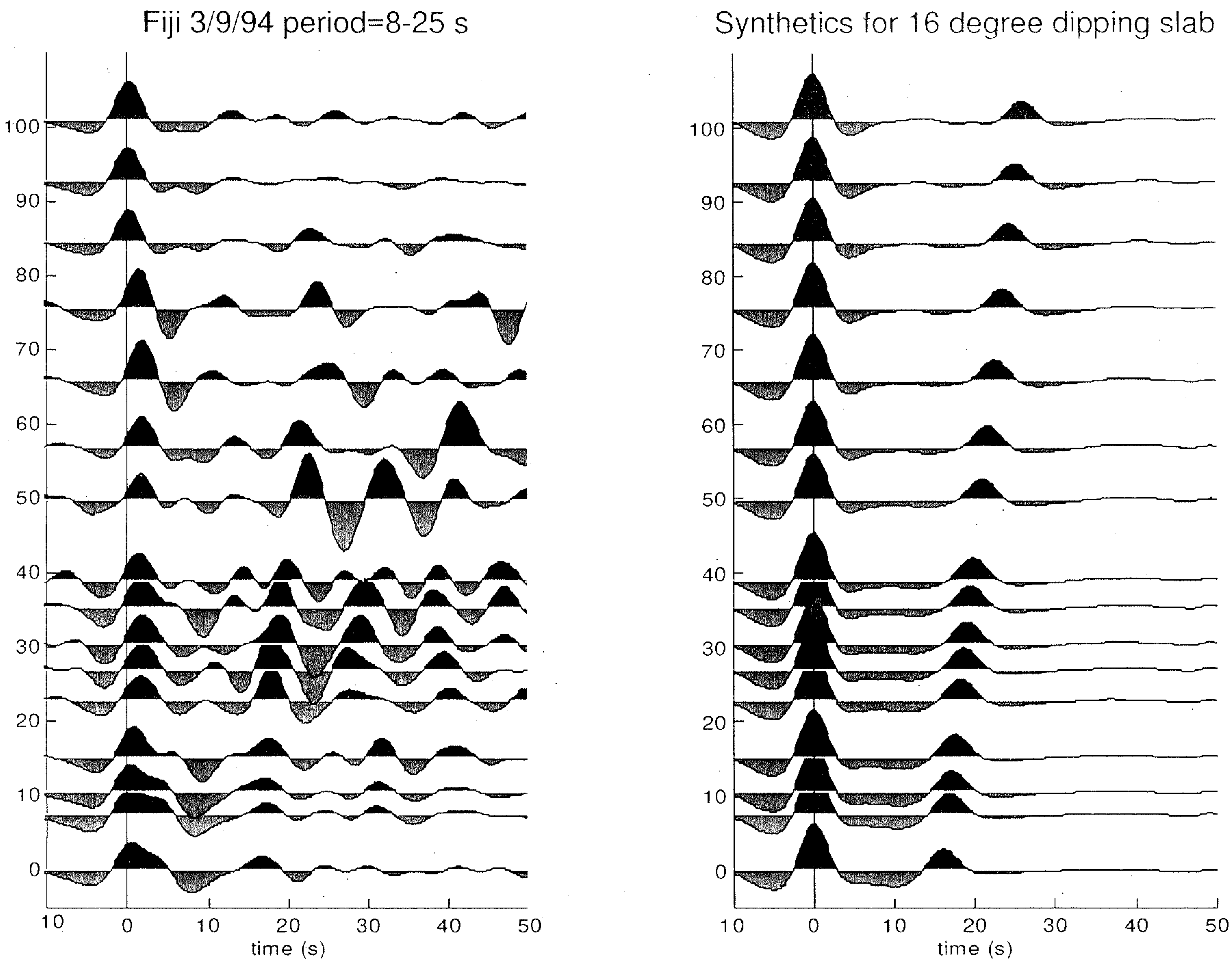

Figure 4. Observed (left) and synthetic (right) radial receiver functions for a deep earthquake in Fiji, filtered at 8 to 25 s periods. The model is a 16 degree dipping layer (Moho of subducted oceanic plate) over a half space. Stations lie on an east-west line (Figure 1) with distance from the westernmost station indicated.