vspiso: A VSP ray synthetic seismogram program for *P-S$_V$* wave propagation in an isotropic, homogeneous, plane layered medium

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ABSTRACT

This user manual describes the meaning of terms, approximations made, and output obtained from ***vspiso***, a simple but fast VSP ray synthetic seismogram program for P-S$_V$ wave propagation in an isotropic, homogeneous, plane layered medium.

INTRODUCTION

Seismic modeling programs can be useful data processing tools provided they are fast, reasonably accurate, and require minimal user interaction in the form of data preparation. Also, the results should be in a form that makes their display as uncomplicated as possible and in a form that allows for a straightforward interpretation of events of interest. A general program type often used for this purpose is a plane parallel layered model for the coupled PS_V wave propagation vertical seismic profile (VSP) analysis of a geological structure. Although far from realistic, programs in this class provide a means of obtaining at least a general trend of the seismic response of a specified subsurface geology and as a consequence, an indication of how accurately a data processor may be interpreting field data.

As mentioned, a determining factor in the usefulness of this program type is that its run time be in the range of seconds or at the most minutes for models with large number of layers and receivers. This allows a user to compute synthetics for a series of models in an attempt to iterate to the optimal solution of the problem being considered in a time efficient manner. Past experience has shown that this, together with ease of use, determines whether or not the software is used as an interpretation or modeling tool.

Programs also exist for more complicated geological structures in both two and three dimensions. This, however, introduces the not insignificant process of model building, which is almost a science unto itself. Efficient use of these program types often requires a person dedicated solely to the task of building models, model databases and computing the synthetics, as the complexity of the model translates into a comparable complexity in the synthetic seismogram program with respect to data input, as well as significant increases in run time and turn around time. This takes control of the modeling aspect away from the primary user who, again from past experience, will not be inclined to use this service.

The program described here is of the first type described above, a plane parallel layered geometry is assumed with the source located on the surface and receivers at user specified depths in the vertical borehole. The principal output from this program consists of four files containing the synthetic traces for the vertical and horizontal, generally complex, amplitude components of particle displacement written (at present) in both *SU* (Seismic Unix) and *SEGY* format.

A very select subset of rays is used in the computation of the synthetic traces, allowing for a large number of layers to be considered. The specification of the model with large number of layers usually consists of *P*-wave and *S*-wave velocity and density logs together with the depth indication of these parameters. A blocked model is probably preferable, but this task can be time consuming as well as an unwanted hindrance for the primary user. From a program developer's perspective, the use of logs stretches the range of applicability for the use of asymptotic ray theory (ART) to its limits, (Hron and Kanasewich., 1972; Červený and Ravindra, 1970; Červený et al., 1976; Červený, 2001).

RAY GENERATION

At present, the program includes only the direct down-going *P* ray, the reflected *P*-primary (*PP*) (*P* down to reflector, *P* up to the borehole receiver) and the once converted reflected PS_V ray (*P* down to reflector, S_V up to the borehole receiver). Several orders of unconverted multiples and primary type converted rays, with only one mode conversion along the ray, are the next level of rays that can be introduced. The same situation, assuming the source emits *S* waves, may also be included in the program. Currently the above extensions to the basic rays have been disabled or are undergoing rewrites. The addition of an extremely small subset of the partial ray expansion (Hron, 1971 and Hron et al., 1974) dramatically increases run time, even if the concepts of kinematic and dynamic groups (Hron, 1972) are employed to reduce the number of computations required. In addition to the ray types listed above, a user specified ray file can be added either alone or in conjunction with the rays generated in this program.

PROGRAM INPUT

Input to the program follows a pattern used in other related programs of this type (Daley, 2005). Upon initiation of the program the user is prompted for the following information, which is usually done on a UNIX type platform, by putting the required information in a file, say *input*, and issuing the command: " ***vspiso*** < *input* & "

1. Input a ***rootname***. This name is used to create and/or open the files:

    a. ***rootname*.data** – a file which exists and contains the velocity/density – depth data. If the model consists of *mlay* layers over a halfspace there are *mlay+1* lines in this file. The depth to interface field in the *mlay+1* layer description is the depth to the halfspace. A check is made to see that the file exists and that the number of layers in the model does not exceed the maximum allocated number. Each line in this file describes a single layer of the model in a sequential manner. A line field includes the *P* - wave velocity, S_V - wave velocity, density and the layer thickness, in consistent units. The depth to interface field on the line describing the halfspace is set equal to zero. A sample **.data** file is shown in Figure 1 based on the model in Table 1.

    b. ***rootname*.info** – an output file which contains information relevant to the current job being run.

    c. ***rootname*.vert** – an output file containing the vertical component of the synthetic traces computed for the depths and time window specified in *SU* format.

    d. ***rootname*.horz** – an output file containing the horizontal component of the synthetic traces computed for the depths and time window specified in *SU* format.

    e. ***rootname*_v.segy** – an output file containing the vertical component of the synthetic traces computed for the depths and time window specified in *SEGY* format.

    f. ***rootname*_h.segy** – an output file containing the horizontal component of the synthetic traces computed for the depths and time window specified in *SEGY* format.

2. Input the number of layers in the model $(mlay)$. Do not include the halfspace in this count. The *mlay+1* layer parameters are read from the file ***rootname*.data**.

3. Input the sampling interval (nsi) in milliseconds. If the sampling interval is specified as greater than 20, the sampling interval is taken to be in microseconds.

4. Input the predominant frequency, f_0, of the source wavelet together with its dimensionless damping factor γ $(4 \leq \gamma \leq 5)$, which controls the side lobes. Default is the Gabor wavelet:

$$f(t) = \sin[2\pi f_0 t] \exp\left[-\left(\frac{2\pi f_0 t}{\gamma} \right)^2 \right]$$

5. Input the maximum length of the trace in seconds, t_{MAX}.

6. Direct *P* ray to be computed? **t** or **f**

7. *PP* ray reflected primaries to be computed? **t** or **f**

8. *PS$_V$* ray reflected primaries to be computed? **t** or **f**

9. Number of receivers? Depth of first offset? Receiver spacing? This is given by the number of receiver depths *ndepth* on a line followed by *ndepth* lines specifying the depths of the receivers in the borehole. All values are to be in consistent units with those contained in the input model file *rootname*.data. An alternate method of accomplishing the above has been disabled. It entails entering the answers to the three questions above on one line.

NUMERICAL RESULTS

A simple 14 layer isotropic homogeneous model has been constructed for computing test results for the program module ***vspiso***. The current default wavelet is of the Gabor type. A wavelet of this type with a predominant frequency of $f_0 = 60Hz$ and a dimensionless damping factor of $\gamma = 4$ is used for computing synthetic traces. A $60Hz$ Gabor wavelet with $\gamma = 4$ does not differ significantly from a $60Hz$ Ricker wavelet. The time sampling rate in all programs is $1ms$. A check is made in the program that the time sampling rate is such that there are a sufficient number of time domain points describing the wavelet. An error message is generated and the program is terminated if the test fails.

Three runs of the program were made and the vertical and horizontal components of displacement displayed. The three different runs consisted of:

(I).   Direct downgoing *P* rays together with the upward propagating (reflected) *PP* and PS_V arrivals, vertical (*V*) and horizontal (*H*) components.

(II).   Upward propagating (reflected) *PP* and PS_V, vertical (*V*) and horizontal (*H*) components.

For a receiver in layer *n*, the single arrival at the receiver in case (I) above was the direct *P* arrival. In case (II), for a receiver in layer *n* with *mlay* being the total number of layers in the model, the number of arrivals is $\left[2\left(mlay - n + 1\right) : mlay \geq n \right]$, the factor 2 being a result of the two different reflected ray types included. For $\left(n > mlay \right)$ the only possible arrival is the direct *P* arrival.

The receiver depth range was 1600 to 2850*ft* at steps of 10*ft* for a total of 126 receivers. The source is located at a lateral distance of 2000*ft* from the borehole.

Both pre- and post-critical reflections for some arrivals are present in the synthetic sections. This was done to check for a smooth transition in the wavelet between the two regions. As previously indicated, critically refracted arrival computations are not included in the program, but the theory and computer code exist to facilitate this if required. The zero order asymptotic ray theory (ART) formulae employed to compute amplitudes in this region is somewhat inaccurate due to the fact that it is based on the assumption of a simple saddle point solution of an integral, when in fact, what should be considered is a saddle point in the vicinity of a branch point. However, taken in perspective, this is a minor matter when compared with all of the other approximations incorporated in this genre of synthetic seismogram program.

The computed results are shown in Figures (2) and (3) with annotations in the figure captions.

Table 1. Model specification that will be used in this report for ***vspiso***. Velocities are in *m/s*, depths in *m*, and densities in *g/cm^3*. The corresponding file **rootname.*data*** is shown in Table 2.

Layer	P Velocity	S$_V$ Velocity	Density	Layer Thickness
1	4000	2400	1.76	100
2	8700	5020	2.15	220
3	12100	6980	2.33	180
4	10400	6000	2.24	250
5	12300	7100	2.34	250
6	15000	8660	2.46	50
7	14200	8200	2.43	250
8	13700	7910	2.40	350
9	14000	8080	2.41	190
10	21500	12413	2.65	30
11	15000	8660	2.45	20
12	21000	12120	2.67	360
13	13000	7505	2.37	100
14	12700	7330	2.34	225
Hspace	14000	8080	2.41	0

CONCLUSIONS

VSP synthetic seismograms were produced for a plane layered medium for an extremely simple ray generation scheme in that only a fundamental subset of rays comprising a partial ray expansion are considered in the production of the synthetic traces. On a more positive note this program requires a minimum of interaction by the user and can produce at least a gross estimate of the total seismic response in a timely manner. Also, as a result of the fast execution of this program, even for models with

numerous layers and receivers, it may be incorporated into an iterative scheme for a linearized inverse problem.

This pared down type of program is often more useful than a "one size fits all" type that may overwhelm a user due to the complexity of the required input. If users require some specialization of the basic program they may be accommodated with minimal effort by enabling some code that is currently available, adding plug and play procedures from a database of existing code, or by having a customized procedure written.

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Table 2. Sample **test1.***data* input file.

P-wave Velocity (ft/s)	S_v - wave Velocity (ft/s)	Volume Density g/cm^3	Layer Thickness ft
4000	2400	1.76	100
8700	5020	2.15	220
12100	6980	2.33	180
10400	6000	2.24	250
12300	7100	2.34	250
15000	8660	2.46	50
14200	8200	2.43	250
13700	7910	2.40	350
14000	8080	2.41	190
21500	12413	2.65	30
15000	8660	2.45	20
21000	12120	2.67	360
13000	7505	2.37	100
12700	7330	2.34	225
14000	8080	2.41	0

APPENDIX

Ongoing updates in order of precedence:

1. FORTRAN90 (SUN FORTRAN77 – SC3.0.1 or higher) wrapper to dynamically allocate arrays at execution time.

2. Introduce an interface to MATLAB Seismic Processing Package so that upon completion of a run the two components of the particle displacement are automatically displayed, if requested by a user.

3. C wrapper to do the same as above, plus provide provisions for a GUI using Motif (LessTif).

An incomplete list of possible extensions:

1. Allow the source to lie anywhere in the first layer, which may be liquid.

2. Inclusion of all possible *P* primaries with 2 additional ray segments.

3. Inclusion of all possible *P* primaries with 4 additional ray segments.

4. Third order *P* multiples which includes all *P*-primary rays with all combinations of six additional ray segments per ray. (Both kinematic and dynamic groups.)

5. Extend the PS_V primary such that all once converted $P \rightarrow S_V$ rays are generated and considered in the construction of the synthetic trace. (A special case of this is included in the synthetic - (PS_V) reflected rays.)

6. If it is assumed that the source emits S_V energy, some or all of the above ray types for a *P* wave source may be included.
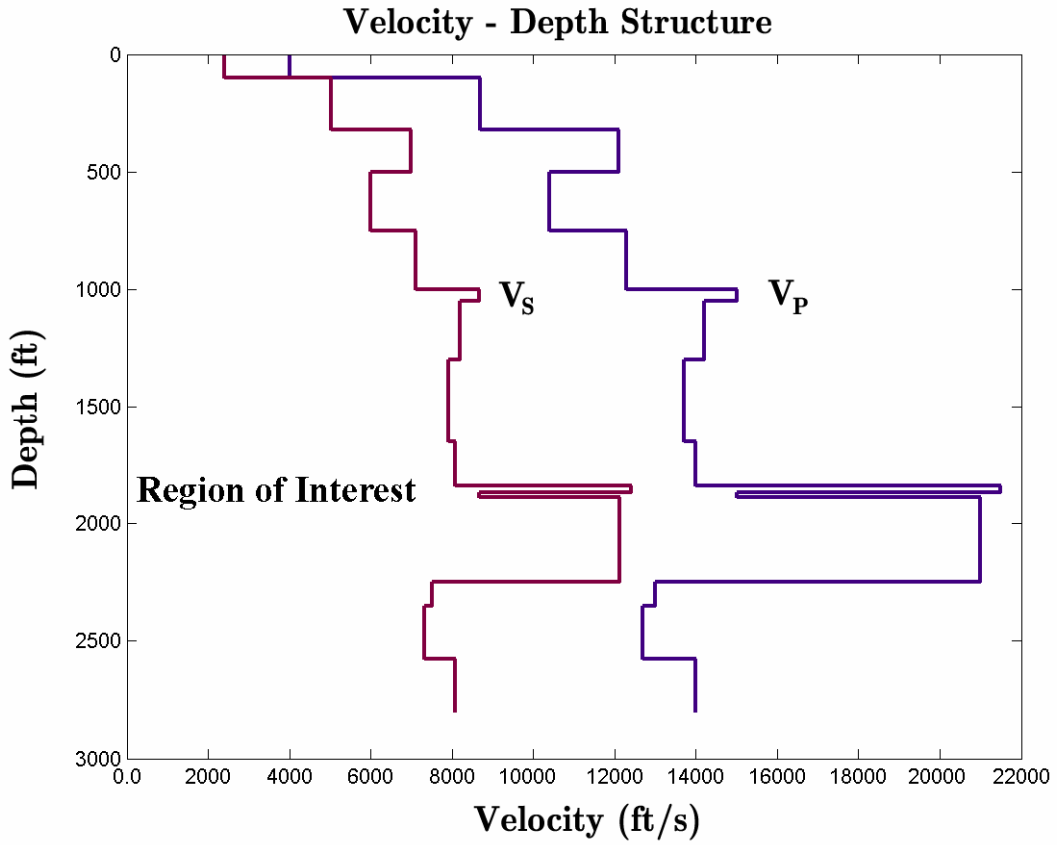
7. Read specific rays from a file.

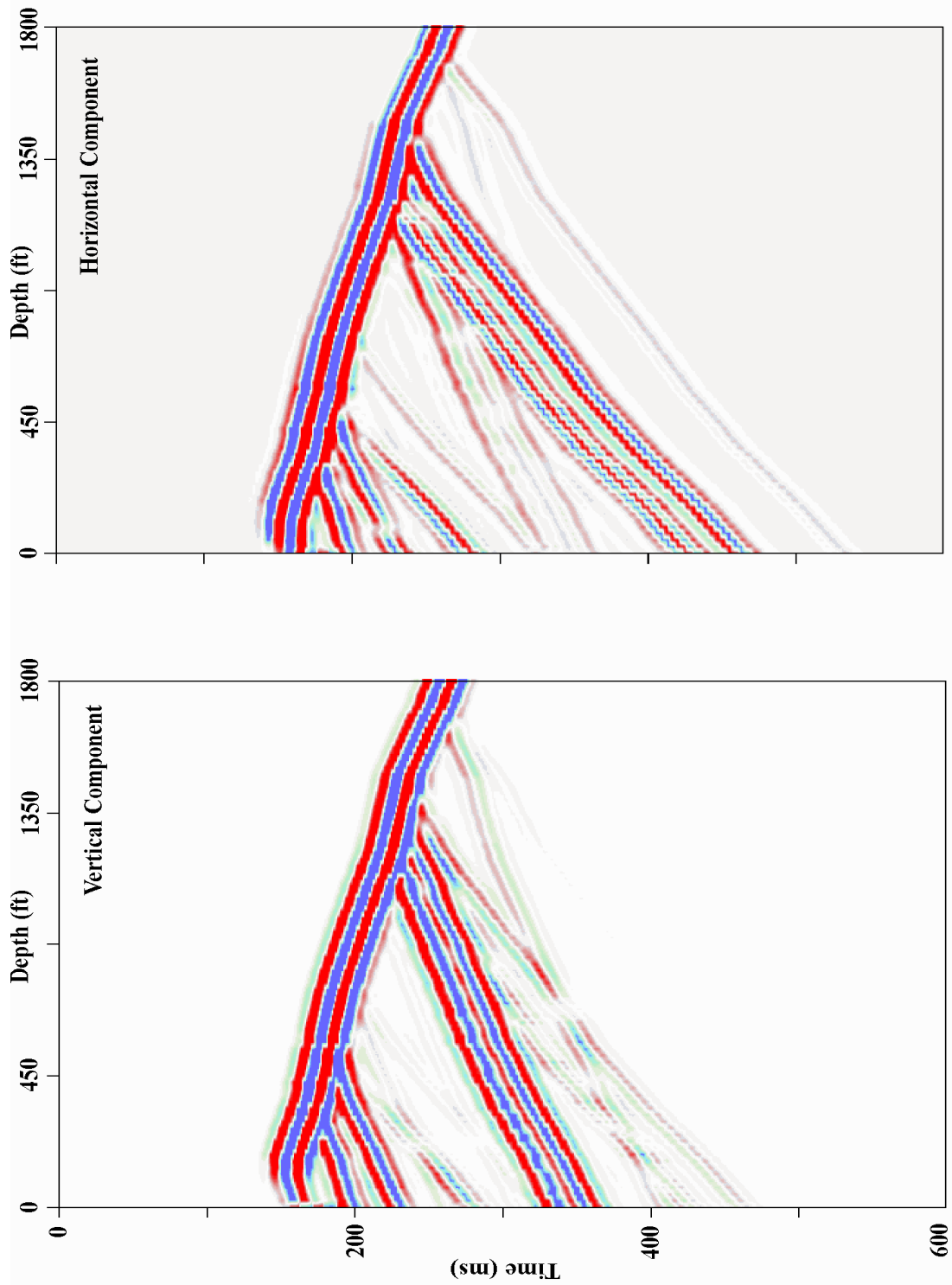FIG. 1. Velocity – depth structure: Depths and offsets are in *ft* and velocities are in *ft/s*

FIG. 2. Vertical and horizontal components of displacement for the 14 layer model shown in Figure 1. Both the downgoing P rays and reflected PP and PS$_V$ rays are included in the traces shown.
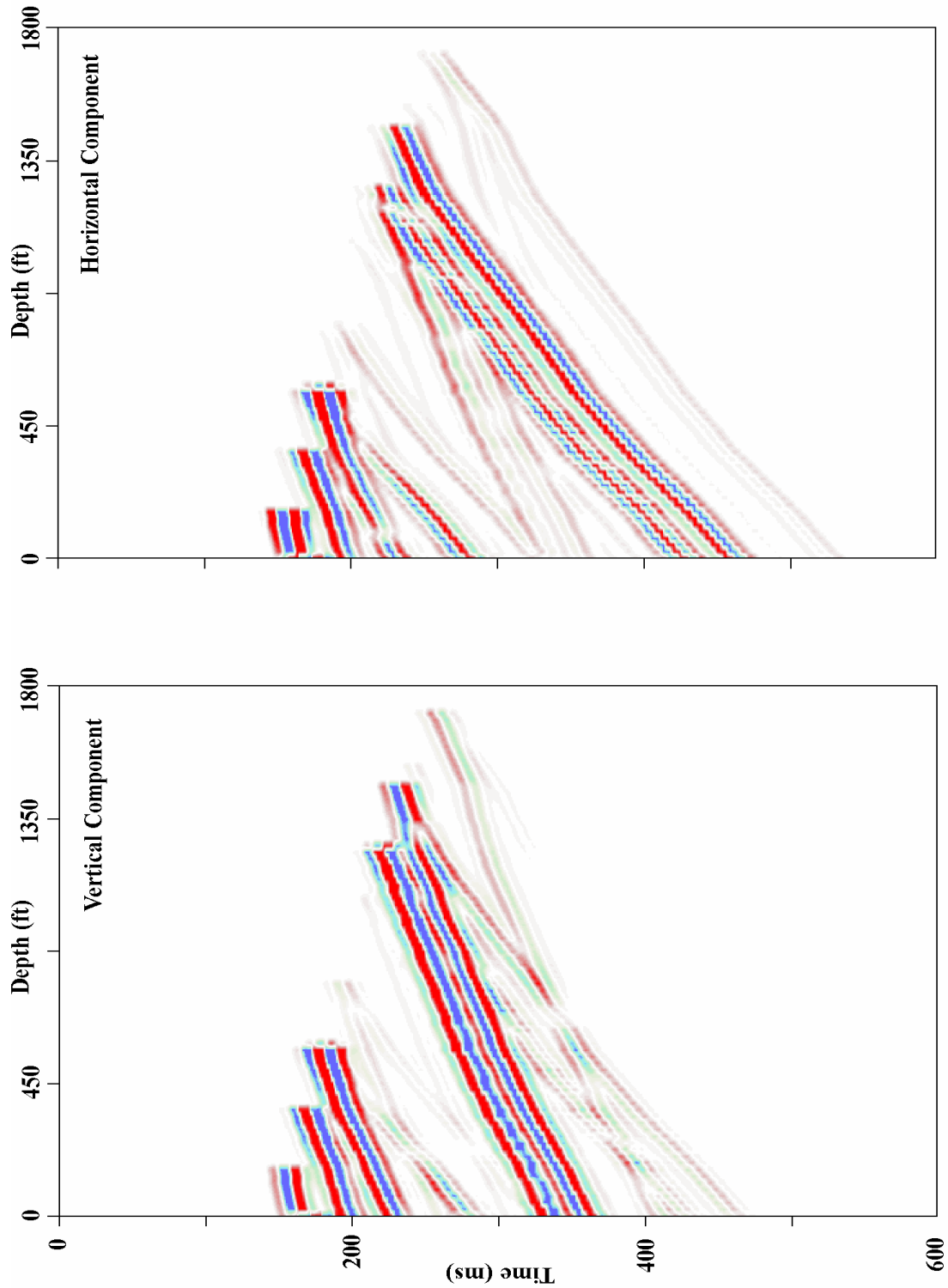
FIG. 3. Vertical and horizontal components of displacement for the 14 layer model shown in Figure 1. Only the reflected PP and PS_V rays (upward propagating) are included in the traces shown.