

Stable finite-difference modelling of sedimentary basins ¹

I. Opršal, J. Zahradník

Department of Geophysics,
Faculty of Mathematics and Physics,
Charles University, Prague,
V Holešovičkách 2,
180 00 Praha 8, Czech Republic
tel.: +420-2-2191 2535
fax.: +420-2-2191 2555
Email: io@karel.troja.mff.cuni.cz

1 Abstract

FD modelling of the two-dimensional P-SV seismic response is performed for the Volvi Lake sedimentary basin at EURO-SEISTEST site. The basin is 6 km long and 200 m deep. Viscoelastic linear rheology, with the attenuation described by Q proportional to frequency is used. The FD synthetics are accurate up to $4Hz$. The site is characterized by complex structure, with high velocity contrasts between individual blocks, ($v_S = 2600$ m/s)/($v_S = 425$ m/s); also the v_P/v_S velocity ratio is up to 5. Numeric instabilities have been found at contacts between blocks with high and low v_P/v_S ratios. A simple trick to stabilize the calculations for long FD runs (e.g. 20 000 time levels, or more) has been suggested. It consists of a special algorithmic treatment of the material discontinuities, preventing mixing of very large and very low values of the so-called effective material parameters within a grid cell. Discussed are also various possible ways of numerical evaluating the effective parameters in inhomogeneous media, some of which may yield incorrect results. Appendix provides a comparison of the present FD method with an independent method for a model with non-planar topography and several v_P/v_S ratios.

2 Introduction

Earthquake ground motion predictions of site effects profit mainly from test sites at which geotechnical parameters are measured in great detail, and numerous seismic records are accumulated. These two data sets enable testing of computational codes through comparisons of the numerically simulated ground motions with the recorded ones. So far, the interest was focused first of all on questions like: How 1D predictions differ from the 2D and 3D ones, what is the role of material non-linearities, how the finite-difference simulations compare with the finite-element ones, etc. For instance, the Ashigara test site, Japan (Midorikawa, 1992) indicated, rather surprisingly, that different modelling methods

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provide very similar results. On the other hand, Riepl (1997) found considerable differences between various simulations results, and different degree of their agreement with seismograms. Her study was for Volvi Lake site, close to the epicentre of the damaging Thessaloniki earthquake of June 20th, 1978 (M=6.5). The Volvi Lake has been intensively studied as an international test site, EURO-SEISTEST, since 1997 (Jongmans et al, 1998; Riepl et.al. 1998). Our intention was to contribute to the Volvi Lake studies by the elastic finite-difference (FD) simulations. However, in the initial stage, serious numerical problems (instabilities) were encountered. Therefore, the aim of this paper is to explain from where the instabilities come, and how they can be prevented. Finally, a few examples of the Volvi simulated ground motions are presented. The comparisons with other methods, as well as a detailed physical discussion of the Volvi seismic response will be later published jointly with the other Euroseistest participants.

3 Data and method

Structural data of the test site are shown in Figure 1a and Table 1. It is a 2D model with flat surface topography. The sedimentary valley structure consists of blocks with constant velocities (v_P and v_S), densities (ρ), and quality factors (Q_P and Q_S). Our model is purely linear. The intention is to simulate the response of the valley with respect to the plane wave vertically incident from below. Both analytic (formal) and numeric (realistic) excitation time histories will be considered.

The simulation is performed for two cases: SH, and P-SV. It is based on the FD method, consisting basically of the PS2 scheme (Zahradník, 1995) with some modifications described below. The PS2 is a scheme in displacement components, 2nd order accurate inside the medium, employing heterogeneous formulation of the elastodynamic equation on a regular square grid. The free surface is treated by vacuum formalism with 1st order accuracy. The attenuation, described for simplicity by $Q_P=Q_S$, proportional to frequency, is included in the equations of motion by a term proportional to velocity. The quality factor is spatially variable. The prescribed Q values are assumed to be valid at 2Hz.

The modeling consists of two steps, *A* and *B*. Step *A* is calculation of the pseudoimpulse response (*PIR*) with respect to the vertically incident plane wave excitation, whose time history is a Ricker wavelet of a short duration, $t_p = 0.25$ seconds. Step *B* is calculation of the response with respect to the prescribed excitation represented by an earthquake record. Step *B* is similar to convolution, but it includes also some special features, like deconvolution of the Ricker wavelet used in step *A*, treatment of different time steps inevitably used in steps *A* and *B*, and the low-pass filtration. The filtration is needed for two reasons: It stabilizes the mentioned deconvolution, and it eliminates higher frequencies, inaccurately calculated by the FD method.

Numerical parameters of our modeling are summarized in Table 2. The simulation of the pseudoimpulse response 15 seconds long took about 750 minutes on HP 735/125 workstation (step *A*). Each realistic earthquake P-SV excitation (step *B*) (total length of 80 seconds) calculated for 135 valley sites required about 40 minutes on Pentium II/266, using repeatedly the same *PIR* from step *A*.

Table 1: *Model parameters corresponding to Figure 1.: v_P, v_S - P, S wave velocities (m/s); ρ -density (kg/m³); $Q = Q_P = Q_S$ -the quality factor*

<i>blockNo.</i>	1	2	3	4	5
v_P	460	1500	1800	2600	4200
v_S	230	300	425	700	2600
ρ	1700	2000	2200	2300	2600
Q	15	30	40	60	200

Table 2: *Numerical parameters of the finite-difference method: $dx = dz$ =spatial step (m), dt =time step (s), f_{ac} =frequency (Hz) up to which the numerical method is accurate, and N_x, N_z, N_t , representing the size of the model in terms of the multiples of dx, dz, dt respectively.*

$dx = dz$	dt	f_{ac}	N_x	N_z	N_t
5.0	0.0007	4.0	1350	150	21500

4 Algorithmic and numeric problems

Any numeric simulation inherently includes a trade-off between two opposite requirements: an easy data preparation, and possibility to treat various complex structural models without any code change. In our code the two requirements are met by the polygonal (rectangular) representation of the model. Neither nodes of the polygonal blocks, nor their sides coincide with gridlines, in general. The distance of the gridpoints from the block boundaries is calculated automatically, and it determines the so-called effective material parameters. Figure 1a well illustrates how the effective parameters vary along the block boundaries in a complex way (e.g., see the interface between blocks 2 and 3, or 3 and 4). In a very early stage of this work a numerical instability of the P-SV simulation was found, that could not be removed by any decrease of the steps dx, dt . (Let us note that SH case was completely free of any instability.) As easily found from snapshots, the problem was spatially localized to the edges of the basin; see details marked in the sections of the model in Figures 1b,c. As already reported in Zahradník (1995), the PS2 scheme requires that gently sloping interfaces outcropping at the surface are locally transformed into short vertical segments coinciding with a grid line. We used this trick in the model of Figure 1, too, but it only postponed the catastrophic instability by tens of timelevels (i.e. by 0.01 s).

Therefore, as a next step, a detailed numerical analysis of the so-called effective parameters was performed. The effective parameters (*EPR*), that represent a key feature of the PS2 method, are geometric averages of the true elastic parameters along so-called grid legs between two neighbouring grid lines. In our code, two sets of *EPR* are directly calculated: $(\lambda + 2\mu)_{ef}$, and $(\mu)_{ef}$. The term "directly" means calculation after definition formulas, e.g. equation (2) of Zahradník (1995). Then, using these two, the effective λ is

indirectly calculated as $(\lambda + 2\mu)_{ef} - 2(\mu)_{ef}$. This, of course, **is not** the same as the directly calculated $(\lambda)_{ef}$. We hypothesized that the mentioned instabilities could be just of this reason. Therefore, in an auxiliary code, we directly calculated all the three: $(\lambda + 2\mu)_{ef}$, $(\lambda)_{ef}$, $(\mu)_{ef}$. And, as an additional experiment, we also correctly determined $(\lambda)_{ef}$ and $(\mu)_{ef}$ from which the effective $\lambda + 2\mu$ was (indirectly) calculated as $(\lambda)_{ef} + 2(\mu)_{ef}$. All these parameters have been compared in Figures 2a,b,c for a suite of a few typical velocity values. Taking the direct calculation of all the three *EPR* as a reference, we see that both indirect calculations, in which one *EPR* is being found indirectly from the two directly calculated *EPR*'s, yield significant deviations. In particular, for high contrasts of μ (1 : 10), the error in evaluating $(\lambda)_{ef}$ may be greater than 200%, see Figures 2a,b. (Let us stress that this contrast in μ doesn't necessarily mean contrast in v_s between the neighbouring blocks as the density also plays a role.) Even the evaluation of $(\lambda)_{ef}$ at very weakly contrasting blocks in contact leads an error of more than 300% (Figure 2c). On the other hand, the incorrectly computed $(\lambda + 2\mu)_{ef}$ do not suffer too much. This explains why the *EPR* calculated in our main code (that one using direct *EPR* for $\lambda + 2\mu$ and μ , but indirect one for λ) display some 'overshoots' marked by the narrow bright spots along certain boundaries; see a detail of the model λ values in Figure 3.

However, in spite of the fact that, the FD code was modified so as to all the three effective parameters $(\lambda + 2\mu)_{ef}$, $(\lambda)_{ef}$, $(\mu)_{ef}$ were calculated directly, the instabilities mentioned above were not removed.

5 Stabilization

Next we concentrated on the stabilization through a model modifications similar to those introduced for the first time in Opršal & Zahradník (*in press*). As found in that paper (for nonplanar topography) serious problems occur in the grid cells crossed by legs with mixed zero and non-zero *EPR* values. In the present model (flat topography) the legs with zero *EPR*'s under the surface gridline do not exist, but we experimentally verified that the instabilities have a very similar reason, i.e. mixing of a small (non-zero) and a large value of *EPR* within a grid cell. Therefore, the following stabilization approach was adopted (see also Figure 4a): As an example, let A and B are *EPR* values very different from one another. The large difference between A and B comes from the geometrical averaging of two contrasting media parameters (A value), while B is equal to parameter value of block under the interface, see Figure 4a. The stabilization trick is as follows: For $A \ll B$, we substitute $A \rightarrow A'$ and $B \rightarrow B'$, while $A < A' \equiv B' < B$. The other parameters in the gridcell are treated in the same way as described in Zahradník (1995). This trick is equivalent to surrounding the blocks with one-gridstep thick belt of varying parameters whose values are still in the range given by the parameters of the neighbouring blocks, see Figures 4b,c. This creates a 1-gridcell-thick block with varying parameters supplying the original interface blurring it, compare Figures 4b and 4c. The same stabilization process is sometimes also needed in other cases (e.g. in the random medium, Opršal & Zahradník, 1997).

A general-purpose subroutine has been written, such that *EPR* routinely calculated in the original FD program are automatically modified and re-entered in the FD code, thus substituting the parameters causing instabilities. All the results shown below were stabilized by this method.

It is interesting to note that many other stabilization tricks (several dozens of experiments !) were attempted with absolutely no success. For example, we artificially substituted velocities in the upper left and right parts of block 4 with parameters of block 2 and/or 3 (Figure 1) in order to decrease the v_P/v_S velocity contrast, etc. Compared to these trials, an appreciable fact is that the successful stabilization introduced above allowed calculations with the very high v_P , v_S contrasts, as well as very high v_P/v_S ratio contrasts, prescribed in the original model (Figure 1, Table 1), without any necessity to change these values in the whole blocks.

Although a minor modification of the interfaces is (locally) introduced by the stabilization, the traction continuity is not violated (Opršal & Zahradník (*in press*)). Thus the overall effect of the curved material discontinuities is modelled satisfactorily. To show this, at least for a particular model, we have tested the method at the most contrasting discontinuity, i.e. the non-planar free surface, by comparison with the finite-element method; see appendix.

6 Results

The pseudoimpulse response, *PIR*, for the vertical incidence of pure SH, and pure SV waves, is shown in Figures 5a,b,c for u, v, w components respectively. The u, w components refer to the $P - SV$ case, while v is the SH component. The notable features are as follows: a) the edge effects, including fast spatial changes of the wavefield, as well as the edge-generated surface waves, b) large durations inside the valley (dependent, of course, on the adopted attenuation model), c) combined effects of the deep valley structure and the localized shallow layers, and d) the mode conversion (seen on the vertical component of the $P - SV$ case), whose maximum amplitude, however, is only of the order of about $\frac{1}{3}$ of that in the horizontal components; there is only very weak conversion in the central part of the basin.

The earthquake response of the valley, in form of the surface ground motion corresponding to the excitation represented by two formally selected records, "Kozani earthquake" and "June 25, 1995 earthquake" (Figure 6), used as a pure SV incidence wavefield, is shown in Figures 7 and 8. The entire earthquake records were formally used as the time variation of the incidence wave without any previous deconvolution of the free surface effect at their original recording sites. Such an approach is permitted here because we are not interested in the true ground motion prediction, but rather in a relative analysis of the response for different excitation time histories. The Kozani EQ ($e - w$) and June 25, 1995 EQ ($n - s$) were acceleration and velocity records, thus also the calculated surface motion is acceleration and velocity, respectively. Physical parameters of the two earthquakes, as well as comparisons of synthetics with ground motions recorded at the Volvi Lake site will be addressed in a separate paper. The time steps of the excitations (and also of the resulting surface motions) were 0.005 and 0.01 seconds for Kozani EQ and June 25/1994 EQ, respectively. The low pass filter flat(= 1) from 0 to 3Hz, with a cosine taper between 3 and 4 Hz, was used.

As seen from the results in Figures 7 and 8, the surface motions vary significantly along the valley as regards their peak values, spectral content and durations. Moreover, the ground motion pattern changes also from one excitation time history to the other. This important conclusion has been obtained in spite of the fact that the excitation was only a

simple plane wave. That is why, in parallel to this study, we concentrate on more realistic excitations due to point sources. The distant point sources would extremely increase the FD model size, thus they are treated indirectly by hybrid methods (e.g., Zahradník & Moczo, 1996).

7 Conclusion

Numerical simulation of the sedimentary valley near Volvi Lake in the Thessaloniki area, EURO-SEISTEST, was performed by the finite-difference method. This is a part of benchmark aimed at comparison of various simulation techniques with each other prior systematic modelling of the earthquake records. In contrast to very easy SH calculations, serious problems with the P-SV response modelling were encountered due to the extremely high v_P/v_S ratios, and v_P and v_S contrasts close to the free surface, in particular close to the valley edges. Several attempts to stabilize the calculations failed. For instance, that was the case of the improved effective parameters, and/or the case of the model modifications consisting of the lowering the velocity contrast, or changing the shape of the blocks. The successful stabilization is based on equalizing the 'crossing' parameters inside the gridcell as described above and shown in Figure 4. That, in fact, is equivalent to surrounding the blocks by one-gridstep thick belt of varying parameters, but at the same time it doesn't mean blurring the interface or corrupting it's sharpness. However, no changes in the v_P/v_S ratio are needed during this trick. A general purpose subroutine has been written that automatically modifies the calculated effective parameters into the form allowing stable calculation, and re-enters them into the FD code. In other words, it is now possible to run the previously unstable models with the 'old' code. The stabilization trick is usable also in 3D codes.

Saving of computer time when modelling the earthquake valley response is possible thanks to splitting the calculations into two steps: the time-consuming FD calculation of the pseudoimpulse response, and the fast calculation of the earthquake response. The second step repeatedly employs the same pseudoimpulse response, saved from the first step. Interesting features of the studied response included fast spatial variations along the valley surface resulting from the effects of the valley deep and shallow structures, the valley edges, and attenuation. The two studied earthquake excitations provided different surface ground motion patterns.

All results presented in Figures 5-8 are available in a numerical form (as ASCII files) on the WWW server <http://karel.troja.mff.cuni.cz/students/oprsal/geophys/ismod/ismod.htm> to stimulate comparisons with other independent methods.

8 Appendix

The behaviour of the *PS2* scheme for a ridge model was compared with the hybrid *FDFE* method of Moczo et. al. (1997) in which the topography is treated by finite elements, here taken as a reference solution. The model is depicted in Figure 9. The source is a vertical force applied at the base, in the centre of the hill, its time function is defined as: $f(t) = (b - 0.5)\exp(-b)$, $b = [\pi(t - t_s)/t_p]^2$, with $t_p = 0.4875s$, $t_s = 0.4875s$. The time window was $t \in (0s, 4.0s)$ The surface shape is (Gaffet and Bouchon, 1989):

$s(x) = h(1.0 - a)\exp(-3a) a = (x/l)^2$, with $h = 375$ m, $l = 1000$ m, where h and l denote the height and the half-width of the hill; $x \in (0, l)$, while $s(x) = 0$ for $x > l$.

Receivers $R1..R13$ are located on a free surface with a constant horizontal spacing of 166.66 m, the $R1$ receiver is on the top of the ridge (see Figure 9). Receivers $R14..R19$ are located in depth $z = 615.6$ m, the horizontal distance of these receivers is as follows: $R14 = 0.0$ m, $R15 = 11.165$ m, $R16 = 166.667$ m, $R17 = 333.333$ m, $R18 = 500.0$ m, $R19 = 1000.0$ m. There are no artificial reflections arriving to any of the receivers during the defined time window. Computation was done for a series of cases with $v_P = 2000$ m/s and $v_S = 1400, 1000, 750, 500, 300, 200, 0.01$ m/s (the last one being just formal).

The results (w component) are presented for two cases: $v_S = 0.01$ m/s, and $v_S = 500$ m/s ($v_P/v_S = 4$) in Figure 10. The good agreement visible in these two cases was also found in all trials with $v_S \geq 500$ m/s, while the two models with $v_S = 300$ and, 200 m/s had worse agreement between FD and FEFD synthetics in receivers $R15..R19$.

Because the 'liquid ridge' case with the formal value of $v_S = 0.01$ m/s does not suffer of this disagreement, it is probable that the differences come from different behaviour of the methods in treating the surface computations for high v_P/v_S ratios, larger than 4.

The *FDFE* synthetics were kindly provided by J. Kristek, SAVBA Bratislava, Slovakia. The comparison in GIF and EPS formats for other v_P/v_S ratios is available at http://karel.troja.mff.cuni.cz/students/oprsal/geophys/fd_fdf/fd_fdf.htm.

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Figure captions

FIG. 1. The computational model. (a) The model constitution of blocks indicated by numbers (see Table 1), and the corresponding $(\lambda)_{ef}$ along vertical gridlegs. (b-c) Details of the upper part of the model with free surface: left upper part at (b) and right upper part at (c). The arrows point at the contacts of the blocks that produced instabilities.

FIG. 2. The effective parameters $(\mu)_{ef}$ (dashed-dotted), $(\lambda)_{ef}$ (thin firm), $(\lambda + 2\mu)_{ef}$ (thick firm) computed correctly by geometric averaging of each of these three values separately. The dashed thick and thin lines show the value of $(\lambda + 2\mu)_{ef}$ and $(\lambda)_{ef}$ indirectly computed from the known effective parameters $(\mu)_{ef}$, $(\lambda)_{ef}$ and/or $(\lambda + 2\mu)_{ef}$ respectively. The (a,b,c) cases are for different velocity values.

FIG. 3. Detail of the lower-right part of the basin - the model parameter $(\lambda)_{ef}$ affected by the incorrect indirect computation (see Figure 2a,c). The 'overshoots' are visible as the narrow bright spots along certain boundaries (between blocks 4 and 5 depicted in Figure 1). Shown is the vertical parameter, corresponding to *A* in Figure 4.

FIG. 4. The model parameters treatment for stabilization purposes. (a) Shows that in case of contrast of parameters in blocks *I* and *II*, and when the effective parameters are $A \ll B$, we substitute $A \rightarrow A'$ and $B \rightarrow B'$, while $A < A' \equiv B' < B$. (b,c) Are details of the model for vertical (b) and horizontal (c) parameters along the slightly dipping interface between two blocks. After the stabilization trick, the new effective parameters are looking like in (c) for **both** vertical and horizontal parameters ((a) right).

FIG. 5. The pseudoimpulse response for the Volvi Lake with respect to a horizontally incident plane S wave for the $P-SV$ case (a,c) and SH case (b). It is accurate up to $3Hz$, with a cosine taper from $3Hz$ to $4Hz$. The $P-SV$ case has weaker w-component compared to the u-component. It is because the vertical (w-component) motion in this case appears purely due to the $S-to-P$ (and $P-to-S$) conversion of the S wave. This conversion is weaker at the horizontal interfaces, thus the lack of the scattering in the central part of the profile, and topmost part of the profile mirrored at the time section. The SH case (b) is similar to the u-component of the $P-SV$ case (a), but features a strong phase in the middle of the profile (at about 2 seconds). Both cases also exhibit very slow strong surface waves locked up at the basin, with a very weak, but visible, propagation to the sides.

FIG. 6. The input earthquake excitation time histories to be convolved with the impulse response. The East-West acceleration component for the Kozani EQ is in the upper graph, the North-South velocity component for June 25/1994 EQ is plotted in the lower graph.

FIG. 7. The basin response to the S wave excitation represented by the time history (Kozani EQ) of Figure 6a. The resulting signal is low-pass filtered between 0 and $5.5Hz$ while cosine-tapered from $4Hz$ to $5.5Hz$. The $P-SV$ case in (a,c), the SH case in (b). The basin edge effects and different predominant frequency in different parts of the profile and also in different times are visible.

FIG. 8. The basin response to the S wave excitation represented by the time history (June 25,1994 EQ) of Figure 6b. The resulting signal is low-pass filtered between 0 and $5.5Hz$ while cosine-tapered from $4Hz$ to $5.5Hz$. The $P-SV$ case in (a,c), the SH case in (b). The basin edge effects and different predominant frequency in different parts of the profile and also in different times are visible.

FIG. 9. The ridge model. The model is symmetrical (Gaffet and Bouchon, 1989). The receivers $R1..R19$ are depicted by crosses; receivers $R1..R13$ are located on a free surface with a constant horizontal spacing of 166.66 m, $R1$ is on the top of the ridge ($h = 375$ m), $R14..R19$ are located in depth $z = 615.6$ m ($R15$ is not displayed here because it would be partially coinciding with $R14$ in this scale), the horizontal distance of these receivers is as follows: $R14 = 0.0$ m, $R15 = 11.165$ m, $R16 = 166.667$ m, $R17 = 333.333$ m, $R18 = 500.0$ m, $R19 = 1000.0$ m.

FIG. 10. The comparison between the method of the present paper, and $FDFE$ hybrid method of Moczo et al (1997) for the ridge model described in Figure 9. $R1..R19$ are the receivers. The results are presented for $v_P = 2000$ m/s and two values of v_S : formal $v_S = 0.01$ m/s (left), and $v_S = 500$ m/s (right). ($v_P/v_S = 4$). The $FDFE$ synthetics were computed and provided by J. Kristek, SAVBA Bratislava, Slovakia.

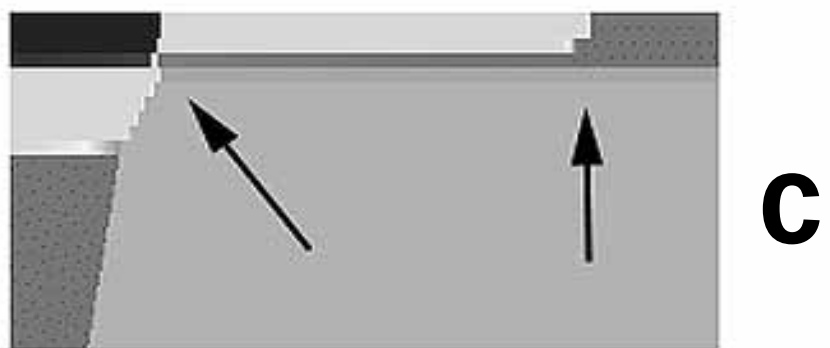
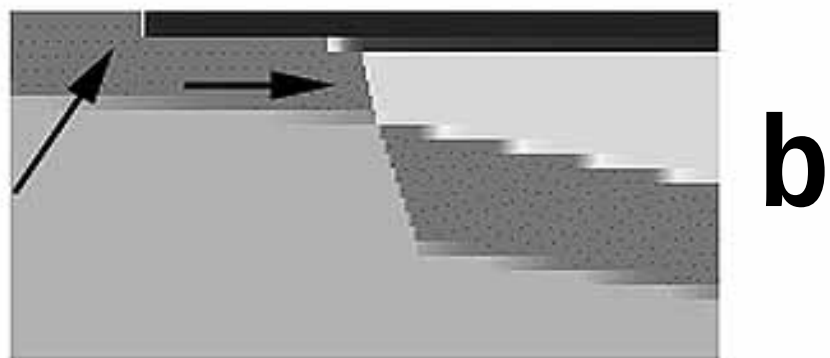
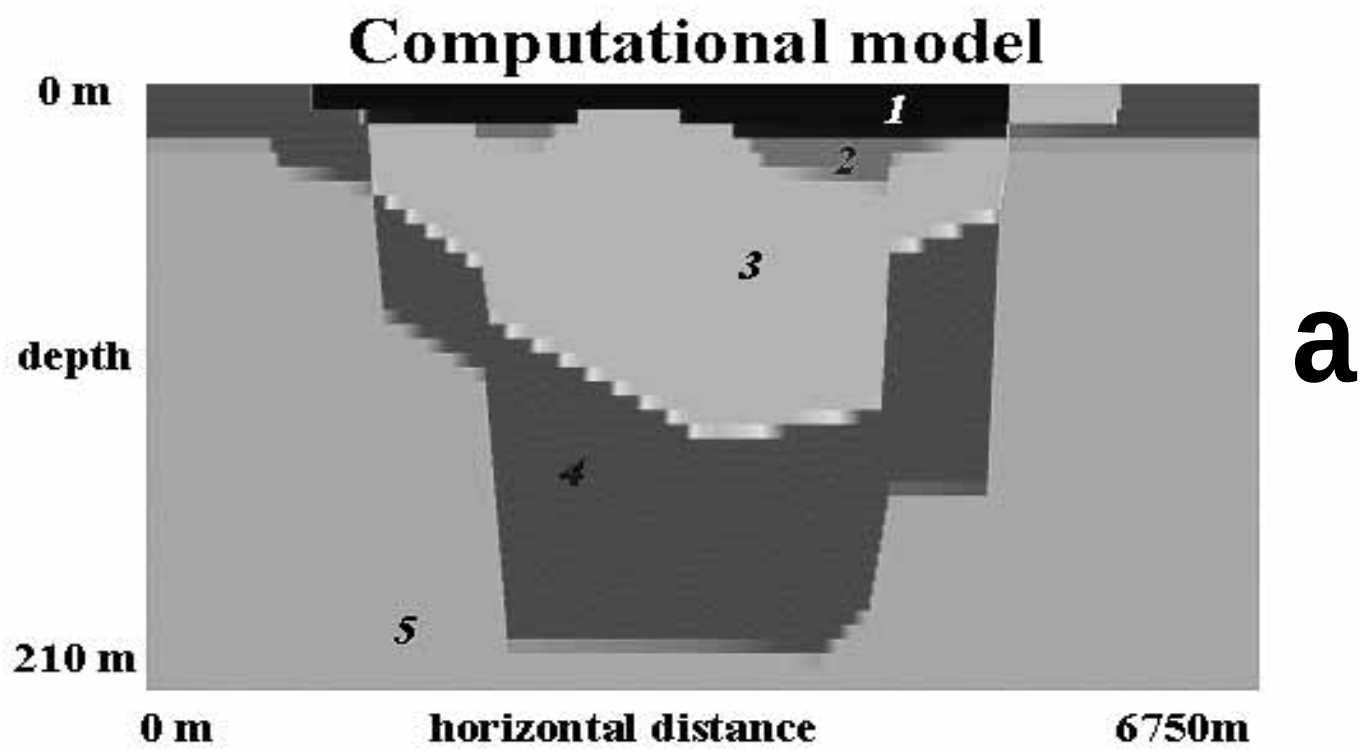


fig. 1

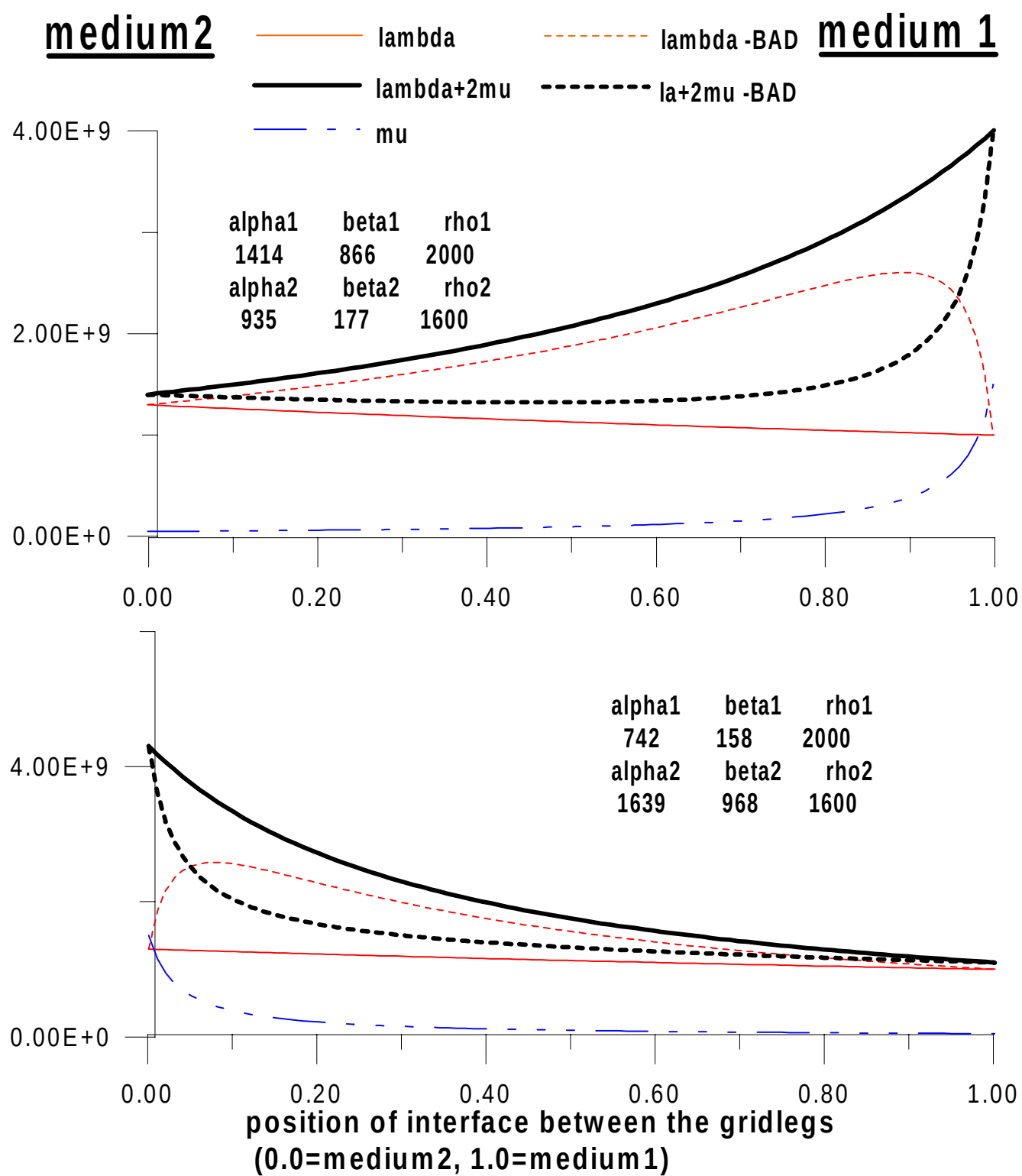


fig. 2a

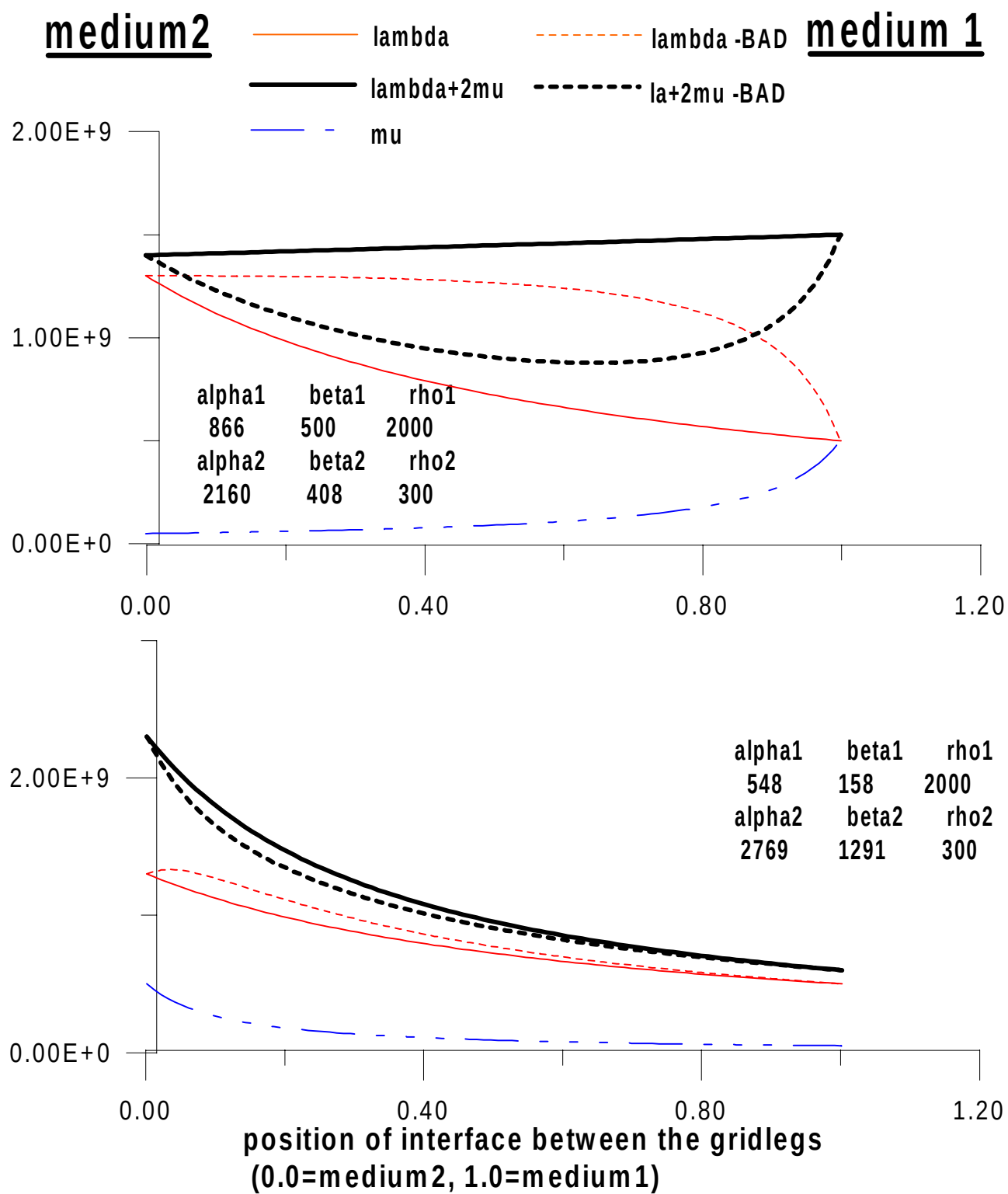


fig. 2b

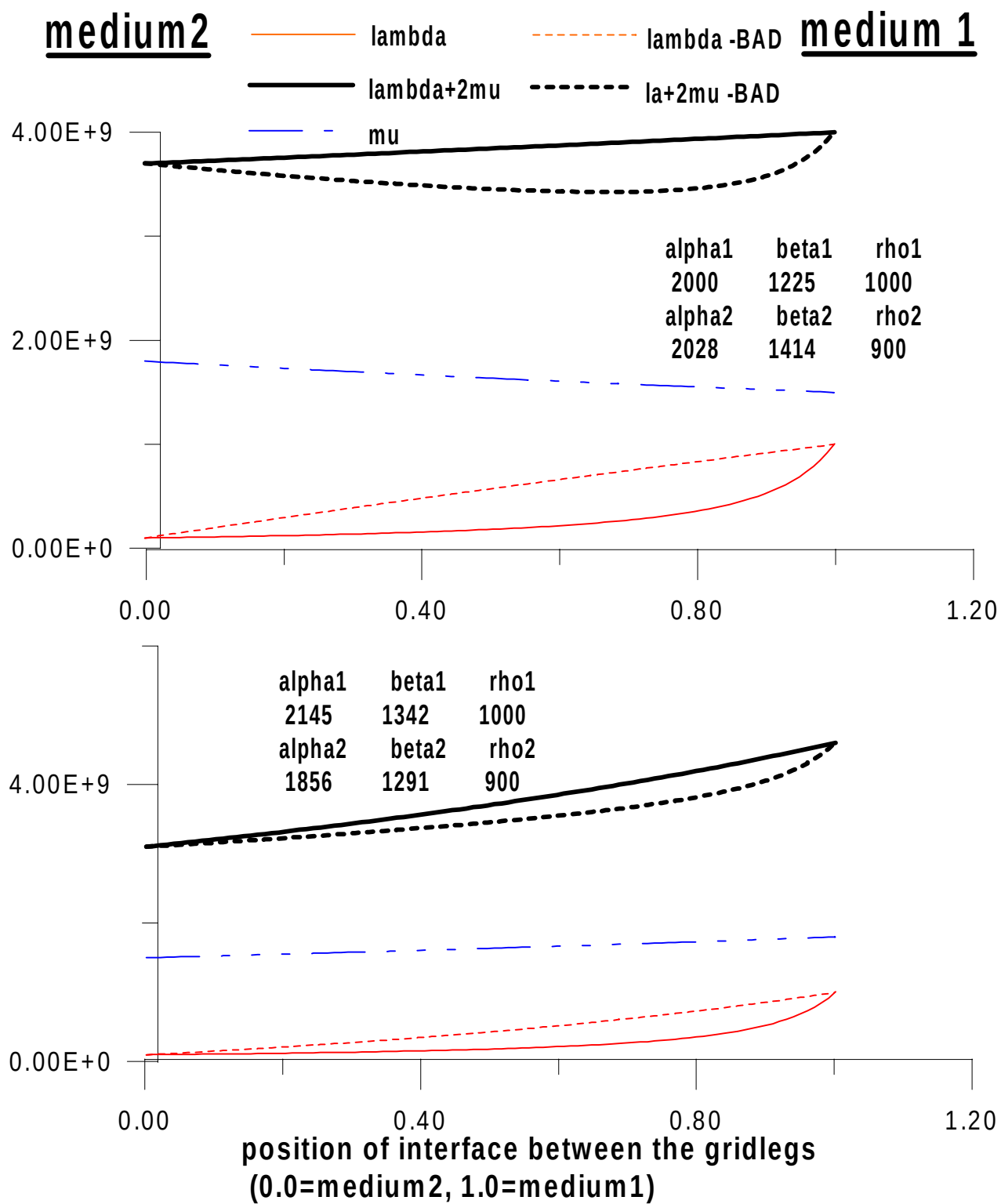


fig. 2c

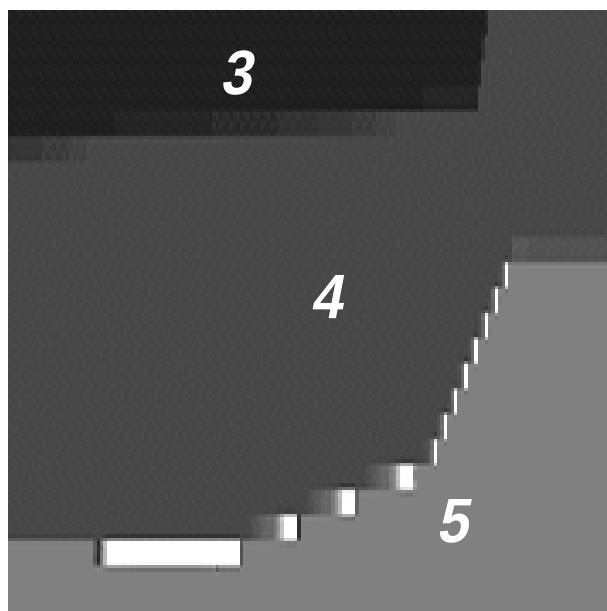
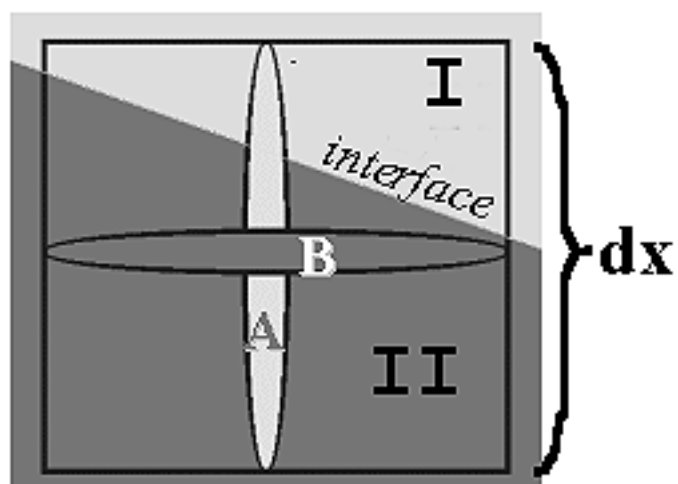


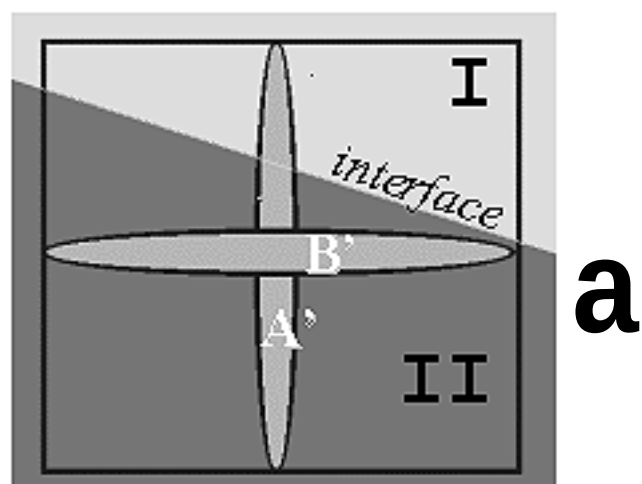
fig. 3

Unstable



$$\underline{A \ll B}$$

STABLE



$$\underline{A < A' = B' < B}$$



b



c

fig 4.

Volvi - pseudoimpulse response; P-SV case; U comp(max=45.6)

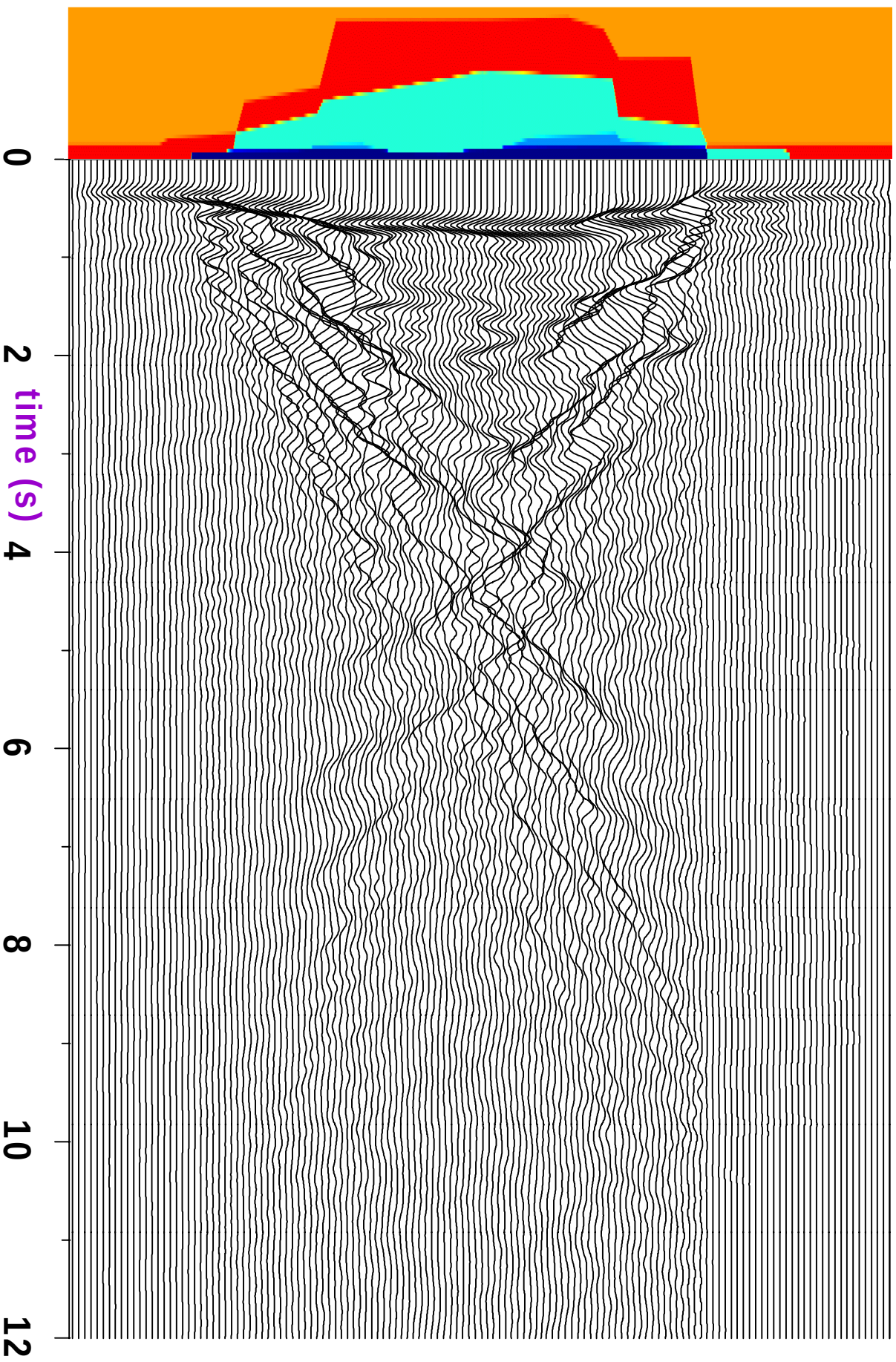


fig. 5a

Volvi - pseudoimpulse response; SH case; V comp(max=47.9)

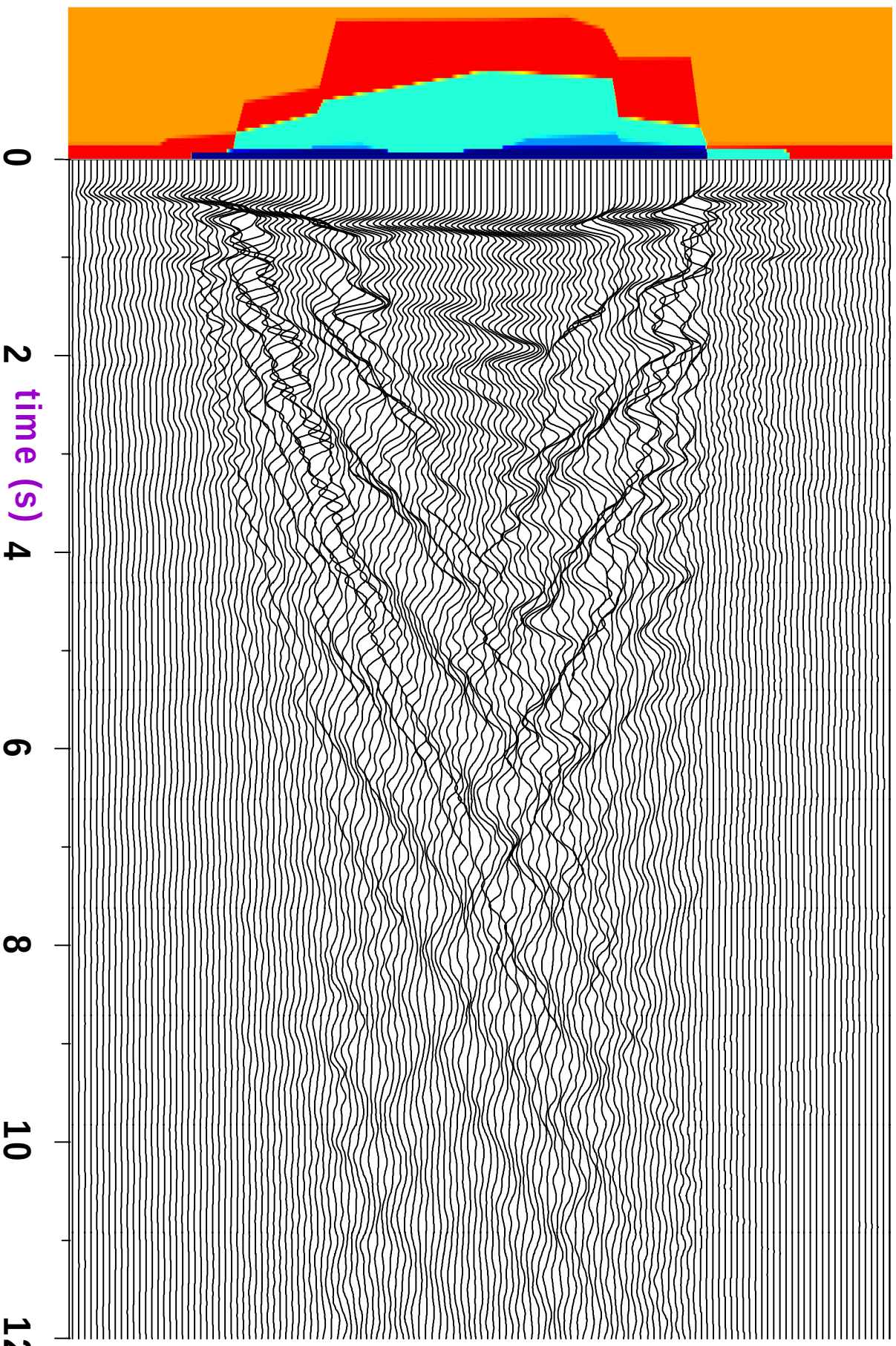


fig. 56

Volvi - pseudoimpulse response; P-SV case; W comp(max=17.3)

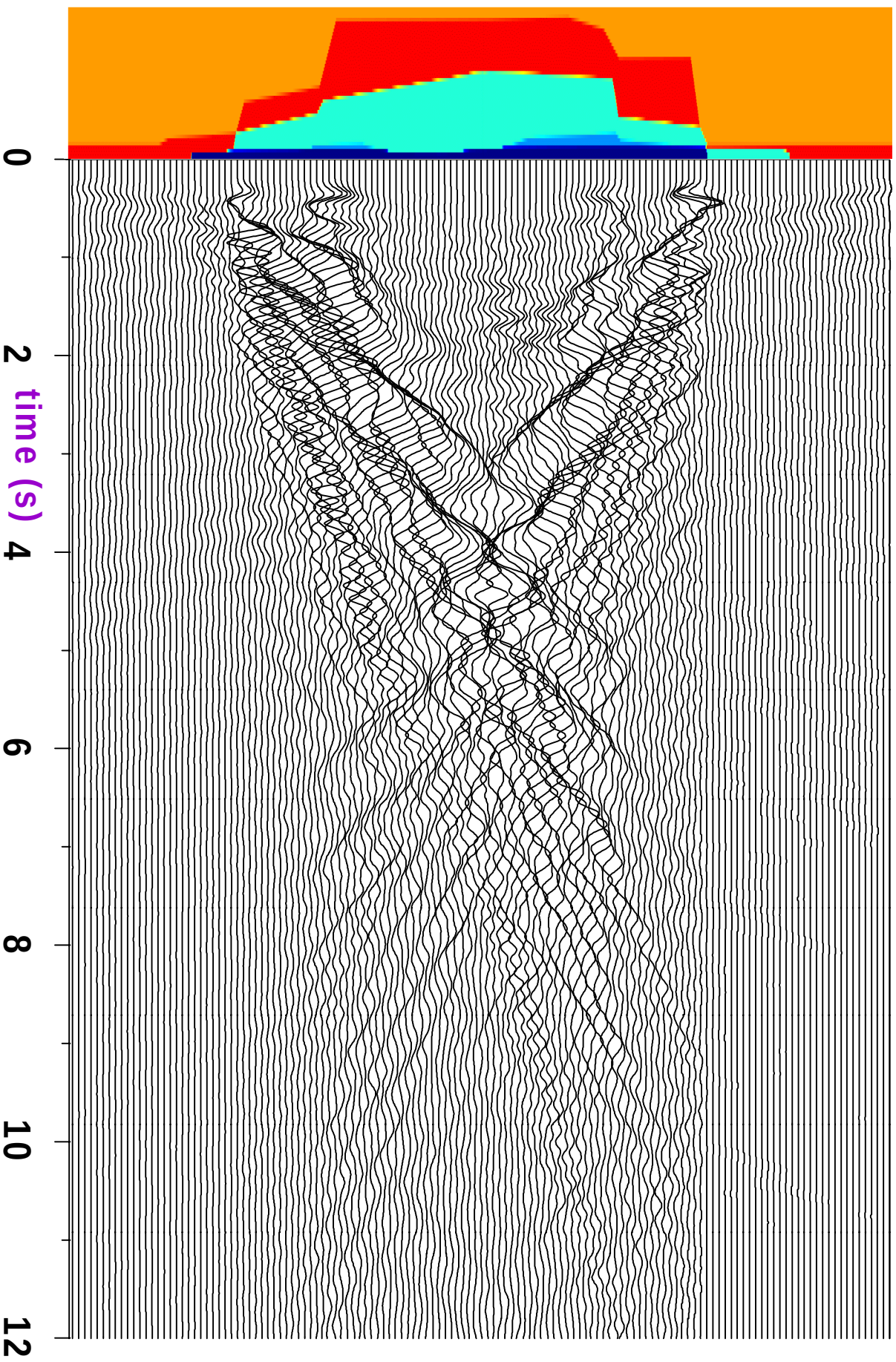


fig. 5c

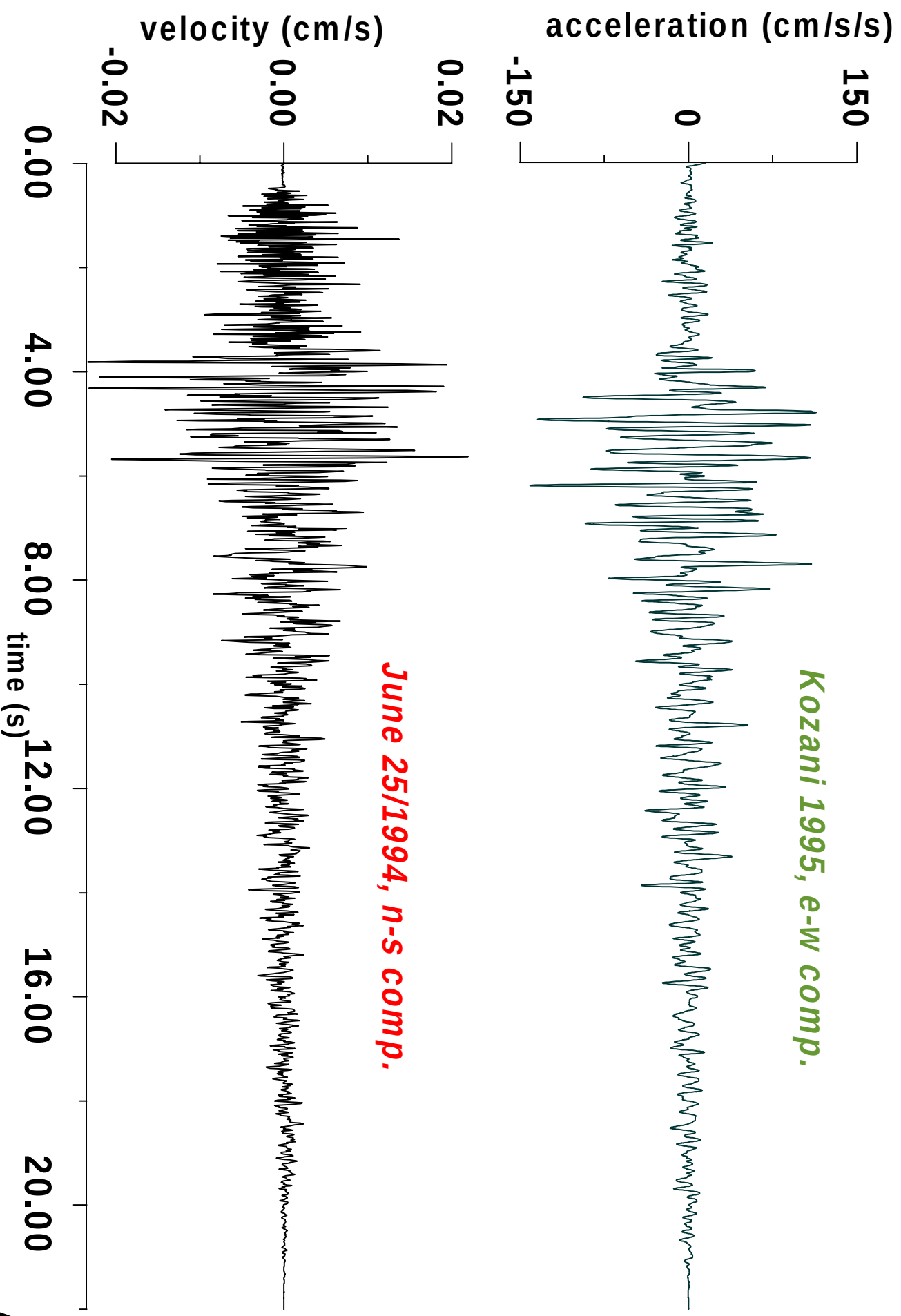


fig. 6

Volvi - response; to Kozani EQ (acc), P-SV case; U comp, (max=1193)

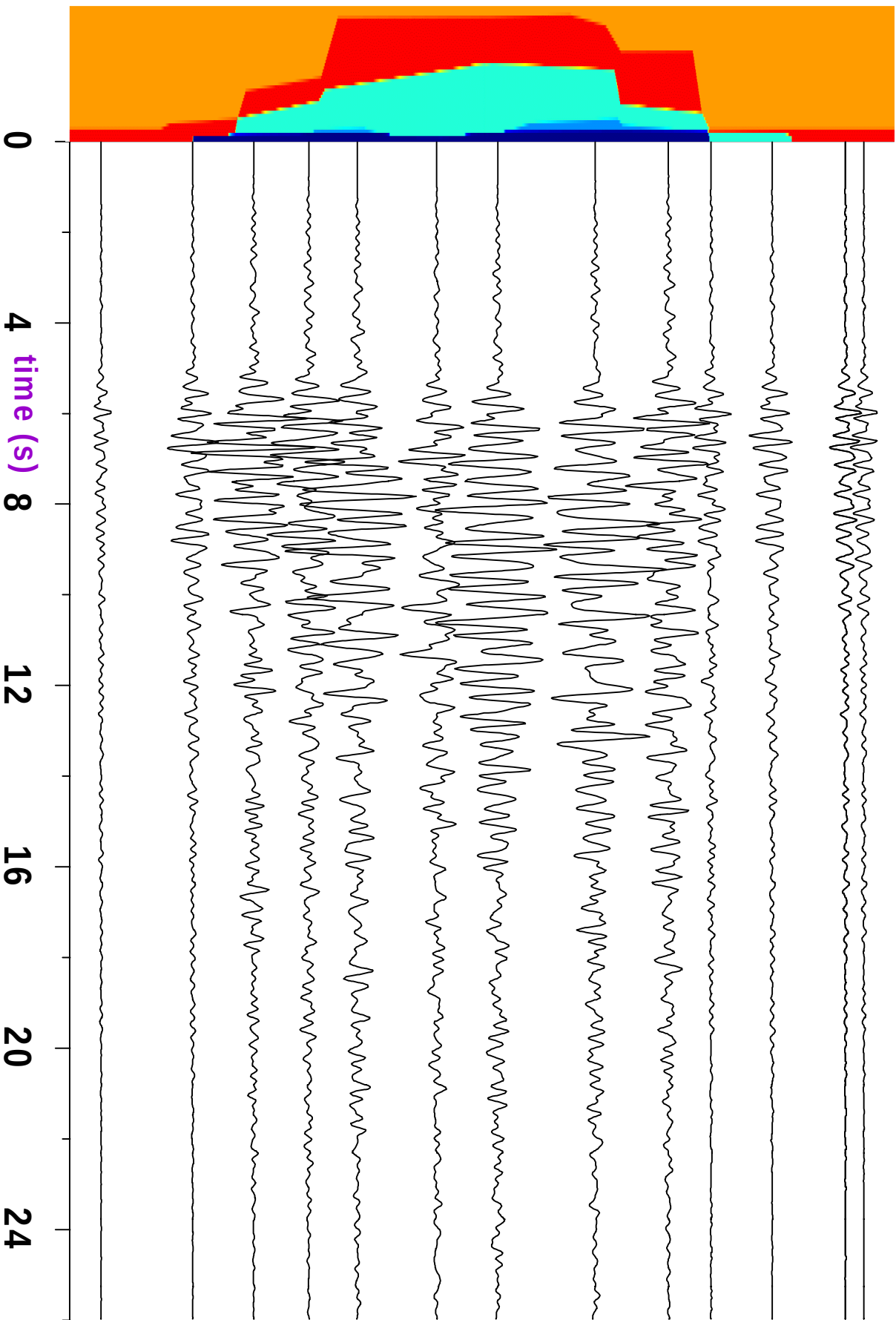


fig. 7a

Volvi - response; to Kozani EQ (acc), SH case; V comp, (max=1230)

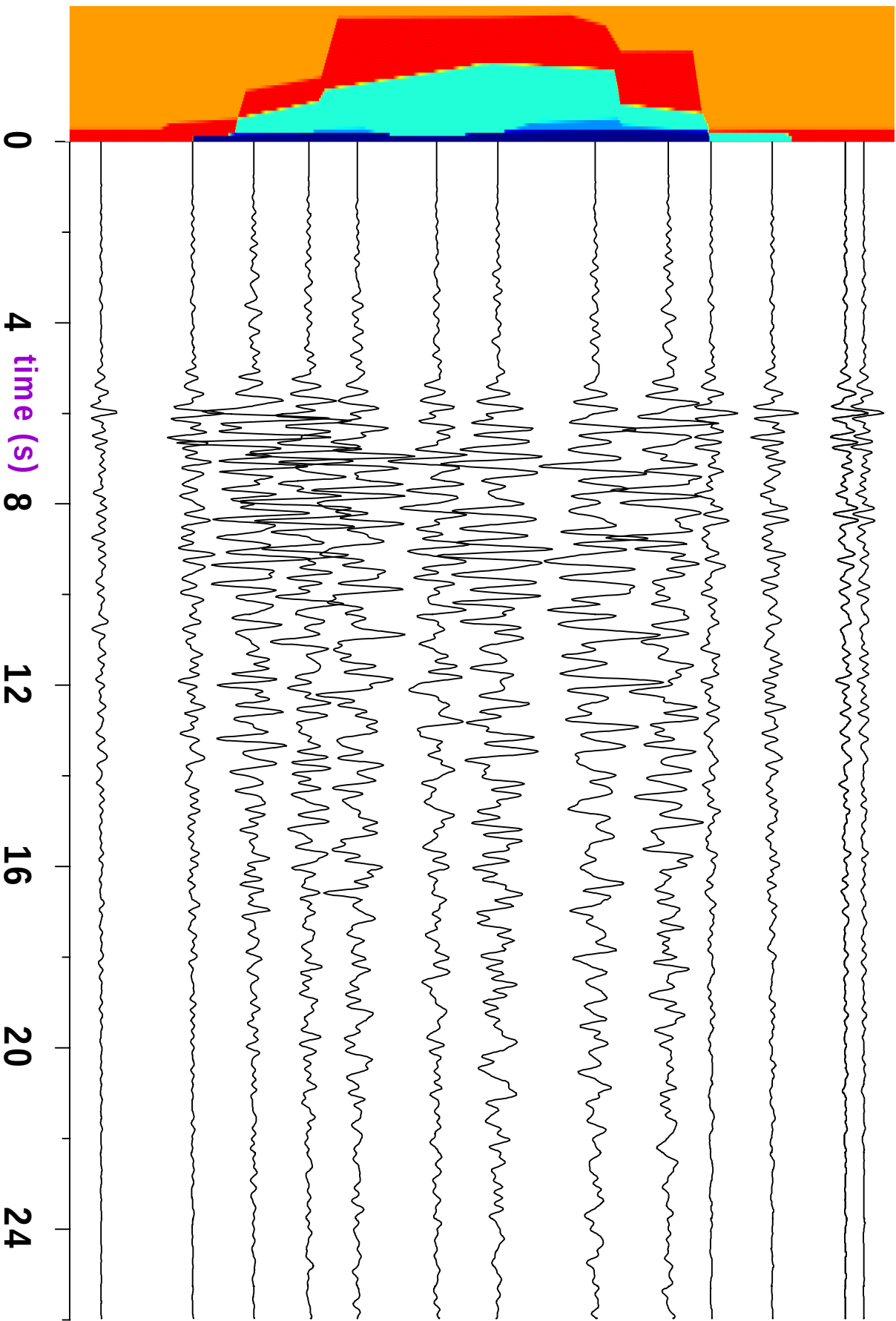


fig. 76

Volvi - response; to Kozani EQ (acc), P-SV case; W comp,(max=514)

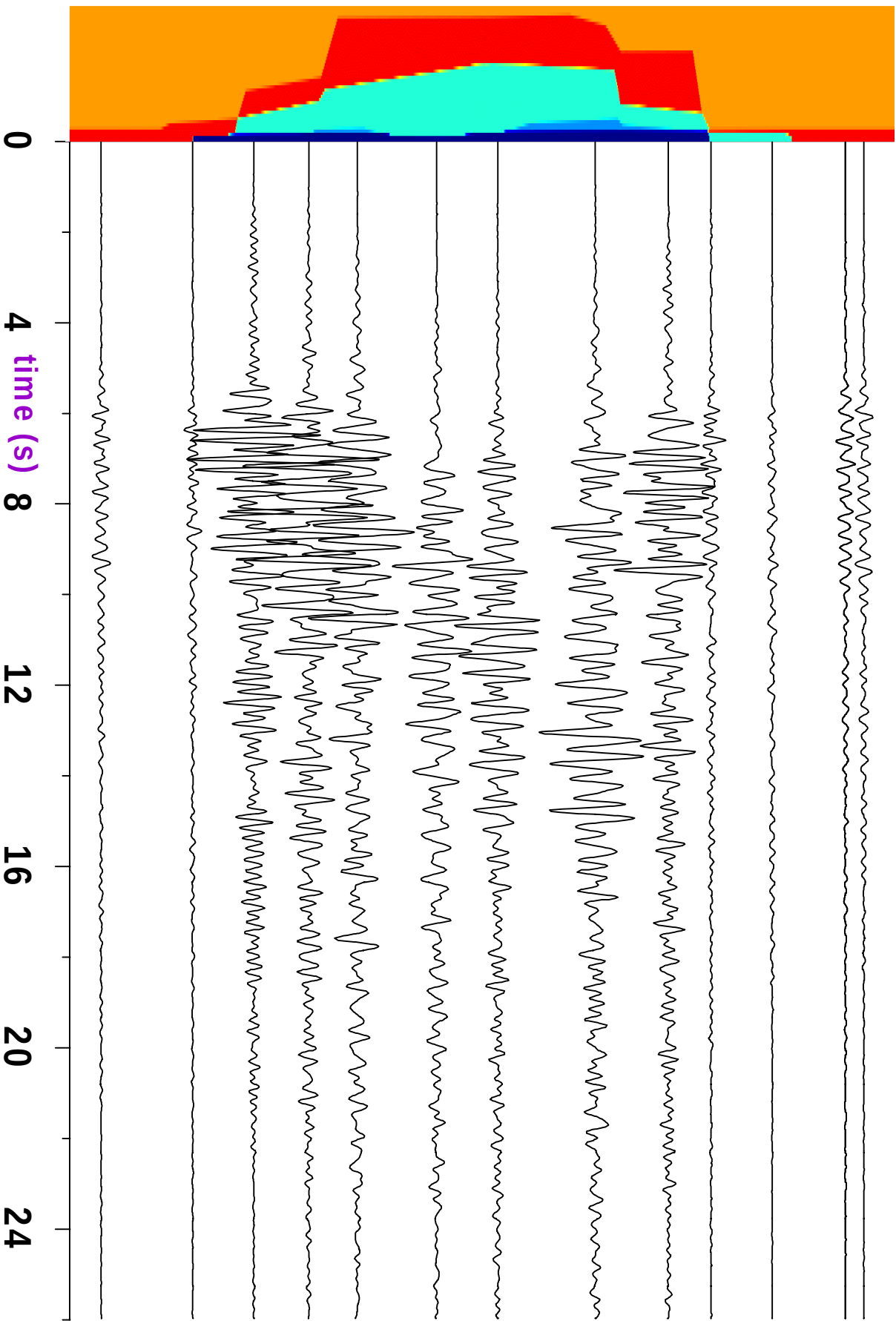


fig. 7c

Volvi - response; to June 1994 EQ (vel), P-SV case; U comp, (max=0.111)

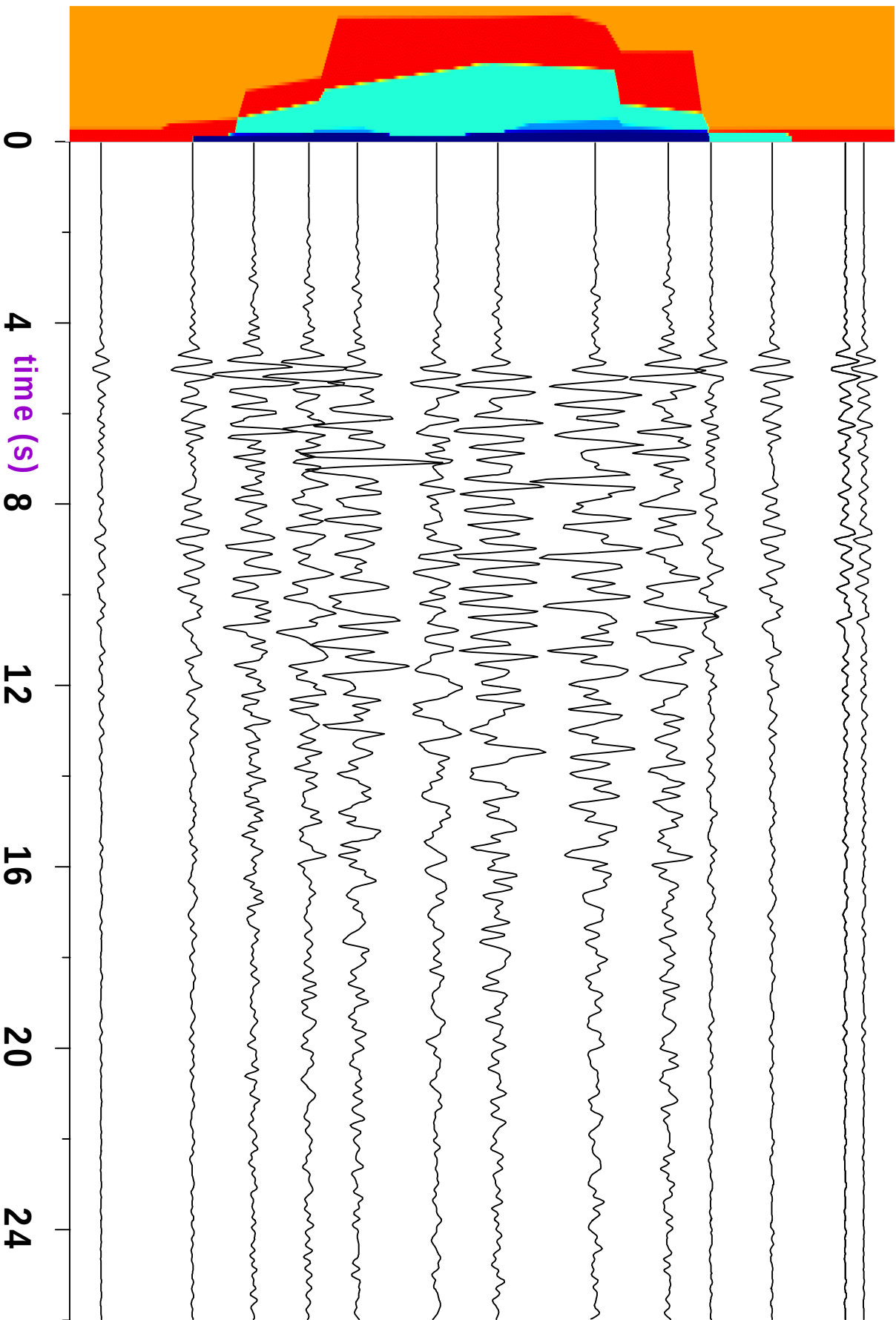


fig. 8a

Volvi - response; to June 1994 EQ (vel), SH case; V comp, (max=0.103)

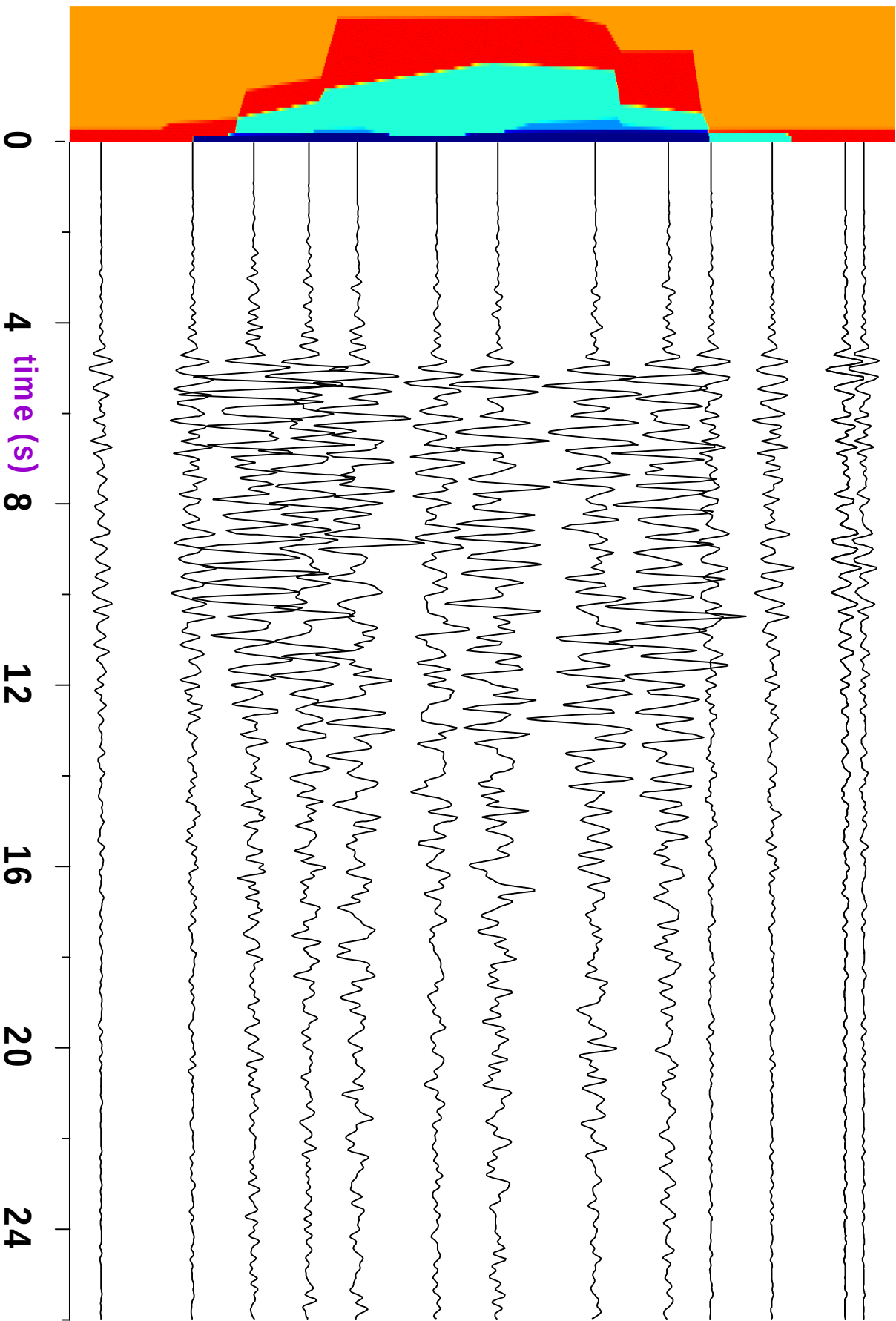


Fig. 86

Volvi - response; to June 1994 EQ (vel), P-SV case; W comp, (max=0.0527)

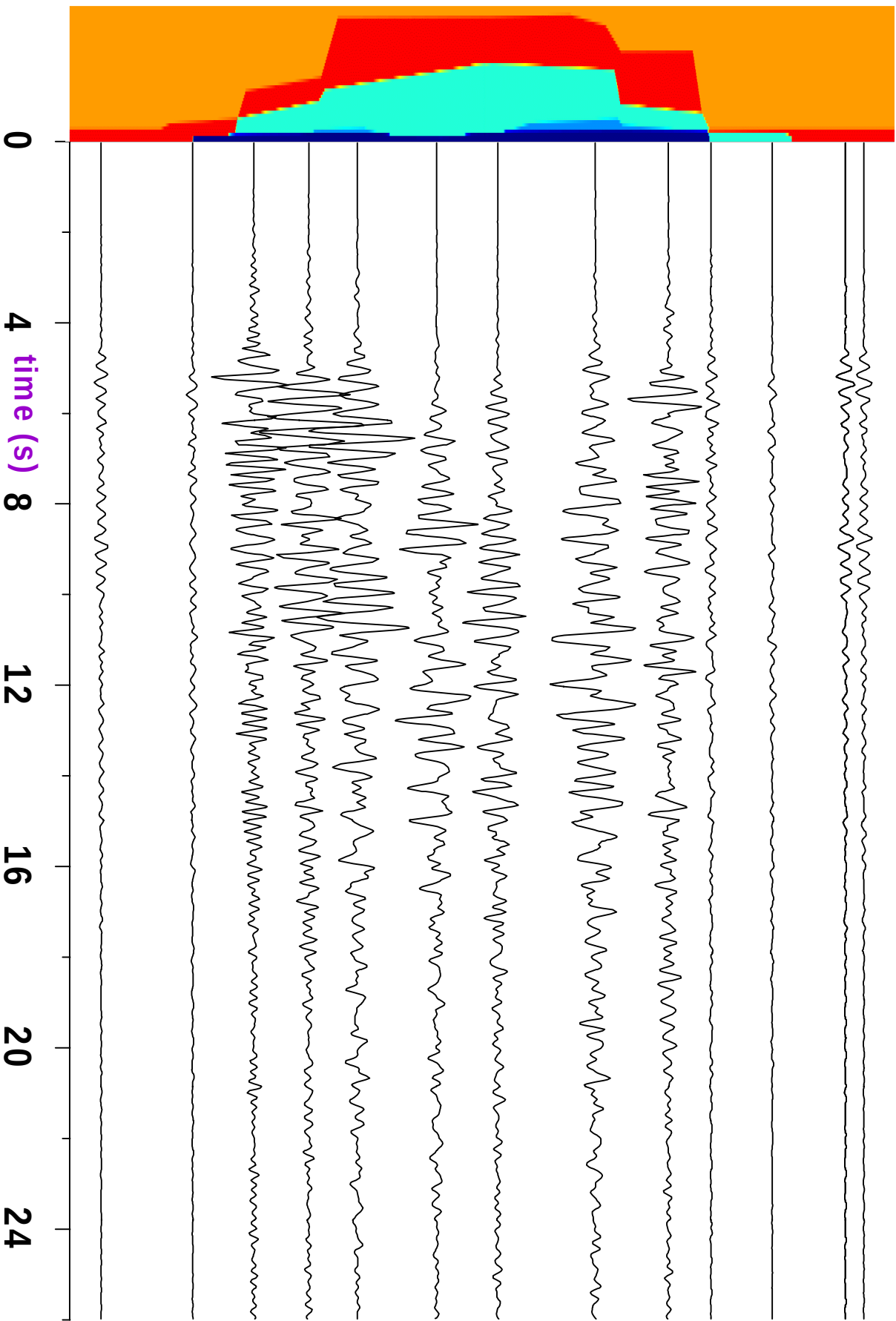


Fig. 8c

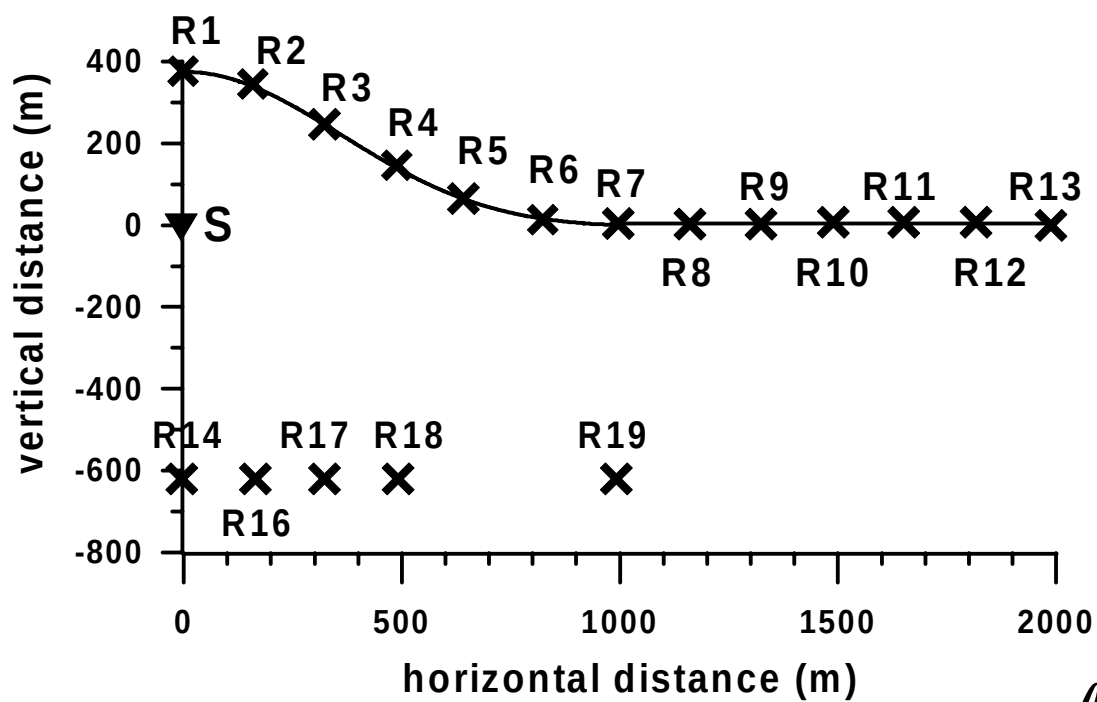


fig. 9

Ridge model:

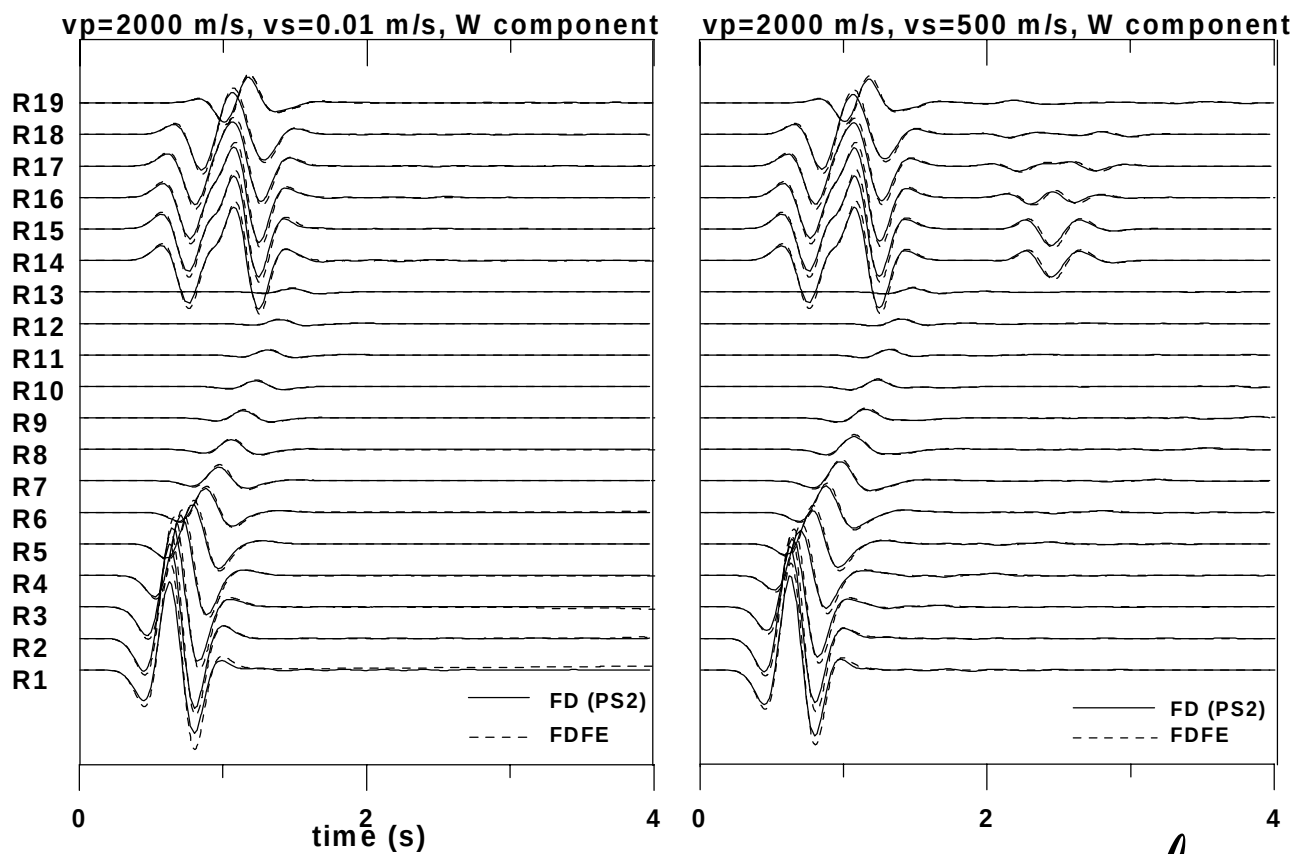


fig. 10