LA-UR-03- 2356.

Approved for public release;
distribution is unlimited.

Title: ELASTIC MODELING AND STEEP DIPS: UNRAVELING THE REFLECTED WAVEFIELD

Author(s): Cory J. Hoelting, EES-11 and University of Houston
Mariana Gherasim, University of Houston
Leigh S. House, EES-11
Kurt Marfurt, University of Houston

Submitted to: Annual meeting of the Society of Exploration Geophysicists, Dallas, Texas, October 26-31, 2003

47

Los Alamos
NATIONAL LABORATORY

Elastic modeling and steep dips: unraveling the reflected wavefield

Cory Hoelting, Los Alamos National Laboratory/Allied Geophysical Laboratories, Univ. of Houston, Mariana Gherasim, Allied Geophysical Laboratories, Univ. of Houston, Leigh House, Los Alamos National Laboratory, and Kurt Marfurt, Allied Geophysical Laboratories, Univ. of Houston*

Summary

As part of a larger elastic numerical modeling project, we have been investigating how energy reflected from steeply dipping interfaces is recorded using typical multicomponent acquisition geometries. Specifically, we have been interpreting how reflection events from the flanks of salt dome structures are distributed on 3C and 4C phones for vertical seismic profiles (VSPs) and ocean bottom seismic (OBS) or land surface surveys. The ultimate goal of this investigation is to improve the structural imaging of steeply dipping interfaces and eventually to evaluate the use of the recorded elastic wavefield for fluid description near these interfaces. In the current work, we focus on a common assumption used when processing converted wave reflection seismic data that most PP energy is recorded on the vertical geophone and/or the hydrophone and that most PS energy is recorded on the horizontal geophones. This is a useful assumption when it is valid, because it eliminates the need for separation of the recorded wavefield into P and S wavetypes. Using two elastic models and different acquisition geometries, we examine the validity of this assumption in the presence of steeply dipping interfaces and discuss the implications for converted-wave and vector imaging of salt flanks.

Introduction

Recent advances in multicomponent acquisition, especially OBS, have created interest in processing converted-wave data. As evidence of this interest, a recent tutorial published in Geophysics examined many applications of converted-wave exploration seismology (Stewart *et al.*, 2003). Two of the application categories discussed in this tutorial are structural imaging and fluid description. The combination of these two categories is potentially useful in locating hydrocarbon reservoirs on the flanks of salt structures. Such hydrocarbon reservoirs are common in the Gulf of Mexico and Gulf Coast region. Our modeling study currently focuses on structural models of salt bodies typical of the Gulf of Mexico and Gulf Coast region.

First, let us consider the structural imaging of steeply dipping reflectors, such as salt flanks. Using streamer data, the best images of steeply dipping salt flanks seem to be produced when using a large (often greater than 10 km) migration aperture. This is because energy reflected from the salt flank, which is predominantly propagating laterally, must have 'time to turn' (via refraction in the gradient velocity structure that is typical of Gulf of Mexico sediments) and be recorded near the water's surface. The same situation exists for vertical component land surface surveys. A schematic representation of this is shown in Figure 1.

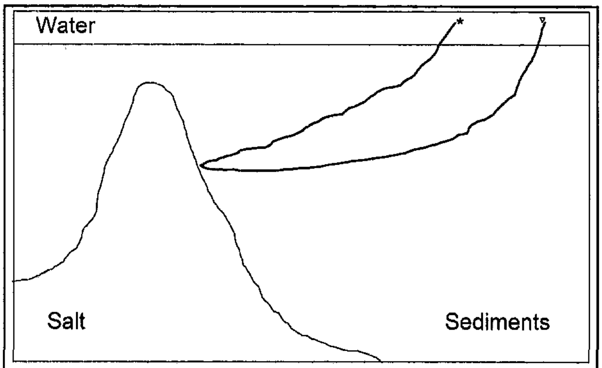


Figure 1: Schematic of salt flank imaging using streamer/surface data.

At least two situations can prevent us from migrating the flank reflection energy represented in Figure 1. One, we are unable to acquire data with sufficient recording aperture to capture the flank reflection events due to economic constraints or restricted property access on land. Two, we are unable to use a sufficiently large migration aperture due to computational constraints. What options exist for salt flank imaging in these situations? Two alternatives that have appeared in the literature are: (1) using a VSP survey to record the salt flank reflection while it is still propagating laterally, and more recently (2) using PS reflected energy from a steeply dipping interface (in this case a salt flank) that may be more readily captured using smaller recording apertures in multicomponent OBS or multicompent land surface surveys. In our modeling study we will examine both of these options.

Second, let us anticipate the use of converted-wave energy for fluid description of potential hydrocarbon reservoirs on salt flanks. This application of convert-wave seismology will only be possible if we can produce a high fidelity (a.k.a. 'true amplitude') image of the salt flank. This image could take the form of a pair of PP and PS images or a 'vector reflectivity' image.

Elastic modeling and steep dips

Our current modeling results were generated using structural models. These models are most applicable to studying the structural imaging of steeply dipping reflectors. However, we will describe other efforts in the larger elastic modeling project that are considering the topic of fluid description. We will also briefly discuss our plans to extend one of the salt body structural models for use in studying fluid description.

Structural Imaging of Steep Reflectors

As mentioned briefly above, two alternatives for imaging steep reflectors have been proposed when recording aperture or migration aperture are limited. One alternative is using a VSP survey. A second option is using PS energy which, due to ray path differences, may be captured using a smaller recording aperture. For both of these alternatives, we will review some previous results. In the next section, we will interpret our elastic modeling results to evaluate these alternatives.

Several studies using VSP surveys to image steeply dipping salt flanks have appeared in the literature. We will briefly review several of these studies. We make no claim that this is an exhaustive review of published work about VSP salt flank imaging.

Whitmore and Lines (1985,1986) discussed using a VSP survey for salt flank imaging. They used acoustic finite difference forward modeling, tomography, and reverse time depth migration to evaluate the feasibility of VSP salt flank imaging, design the acquisition, build an interval velocity model, and perform depth imaging. Their main goal was to produce a structural image of the salt flank. Therefore, they processed the 3C VSP field data to emphasize P mode energy and to attenuate S mode energy. Using reverse time migration (based on a two way wave equation) they eliminated any algorithmic dip limitations during the imaging of the salt flank.

Algorithmic limitations on the dip range are a concern when using wavefield migration based on an approximation of a one way wave equation. One method for using 'dip limited' one way wavefield migration algorithms to image steep dips is to modify the algorithm so the central angle of the dip range is not zero (Higginbotham *et al.*, 1985). Higginbotham *et al.* refer to this technique as directional migration. A post-stack application of this type of technique for steep dip migration of VSP data was presented by Berg (1992). Higginbotham (1993) anticipated the availability of walk-away and 3D VSP surveys for use in steep dip imaging via directional one way wavefield migration. More recently, Brandsberg-Dahl *et al.* (2003) have applied lateral continuation (central angle of dip range set to 90°) to a 3D VSP survey to image a salt flank. Hoelting *et al.* (2002) evaluated the feasibility of a similar approach using synthetic acoustic finite difference data.

Most of these studies have only been concerned with generating structural images of a salt flank. Thus, they have only used P mode energy to generate a PP image. Our eventual goal is to combine high fidelity structural imaging with converted-wave fluid description. Therefore, we are concerned with generating PP and PS images (or a vector reflectivity image). In support of this goal, we will interpret how PP and PS energy reflect from steep dips is recorded on a VSP survey in the next section.

Using PS reflected energy is a second option for imaging steeply dipping salt flanks when recording aperture or migration aperture is limited. Several researchers have mentioned the possibility of using PS reflections for imaging steep dips with limited aperture. Recently, Stewart *et al.* (2003) presented an example from Cary and Couzens (2000) where steeply dipping fault planes are much clearer on the PS section than on the PP section. Stewart *et al.* state that the reason for the sharper fault plane reflections on the PS section is not exactly known. They offer several explanations, one of which is that PS ray paths from steeply dipping reflectors are more readily captured using 'limited' recording aperture (Stewart *et al.*, 2003). We will investigate this possibility in the context of salt flank reflections in the next section.

Interpretation of Modeling Results

We have generated elastic synthetic seismograms over two structural models of salt bodies. These synthetics were computed using an elastic finite difference code (Larsen and Grieger, 1998). We have recorded data using both VSP and OBC/surface acquisition geometries. These seismograms and 'snapshots' of the P and S wavefields were used to evaluate the two imaging alternatives discussed in the previous section.

The first model is an elastic version of the 2D salt diapir model from (Hoelting *et al.*, 2002). The Vp section of this model is shown in Figure 2. Figure 3 shows vertical and horizontal particle velocity component common shot gathers for the VSP well and shot location shown in Figure 2. The PP salt flank reflection is actually recorded on the horizontal component and the PS salt flank reflection is recorded on the vertical component. This is 'opposite' of the common assumption used when imaging C-wave data from structurally simple areas. Using the P and S snapshots from this model, we found that the PS salt flank reflection does not emerge at the surface before it propagates 'out of the side of the model'. Thus, it was not recorded on the multicomponent surface survey.

The second model was a 2D cross section from the elastic version of the 3D SEG/EAGE salt structure (House *et al.*, 2000). We extracted the 2D cross section from the 3D SEG/EAGE salt structure because it allowed us to generated P and S mode snapshots which were finely sampled in both space and time. These snapshots proved quite valuable during interpretation of the seismograms.

Figure 4 contains the Vp section of this second model; please note the VSP well location and the shot location. The VSP vertical and horizontal particle velocity component common shot gathers are displayed in Figure 5. With the aid of the P and S snapshots, we once again find that the PP salt flank reflection is recorded on the horizontal component and the PS salt flank reflection is recorded on the vertical component. Using the P and S snapshots, we again found that the PS salt flank reflection was not recorded on the OBC survey. Finally, please note that similar calculations are being carried out using the full 3D SEG/EAGE salt model.

Conclusions

Given the results of the previous section, it appears that using a VSP survey for salt flank imaging is more feasible that using PS energy recorded at the surface or ocean bottom. We note that this conclusion is only valid for areas with a velocity structure similar to our models and for surveys with offsets comparable to our model surveys.

The results of our modeling study contain two important implications for converted-wave/vector salt flank imaging. One, the salt flank reflection, especially in the 2D SEG/EAGE salt structure, is quite subtle and contains both upgoing and downgoing energy. Therefore, we must take great care not to remove this reflected energy in preprocessing before migration. Two, the PP reflections are recorded on the horizontal component for vertical interfaces and on the vertical component for horizontal interfaces and vice versa for PS reflections. Therefore, reverse time vector migration might be the most effective way of producing an image of the elastic wavefield suitable for fluid description. To test this hypothesis, we plan to introduce hydrocarbon traps into to 2D salt diapir model like those described in by Martin *et al.* (2002) and migrate these data.

References

Berg, L. E., 1992, Steep dip migration by replacing vertical with horizontal propagation, 54th EAGE Conference.

Brandsberg-Dahl, S., Van Gestel, J. P., Etgen, J. T., and Hornby, B., 2003, VSP salt flank imaging through wavefield continuation, *to appear at the* 65th EAGE Conference.

Cary, P. W., and Couzens, R. A., 2000, Processing 4-C data from Mahogany Field, Gulf of Mexico: Presented at the SEG/EAGE Summer Research Workshop, Boise, Idaho.

Higginbotham, J. H., Shin, Y. and Sukup, D. V., 1985, Directional depth migration (short note): Geophysics, **50**, 1784-1796.

Higginbotham, J. H., 1993, Shot record directional migration for VSP imaging, 63rd Annual SEG Meeting Extended Abstracts, 122-124.

Hoelting, C., Duncan, W., Gherasim, M., Marfurt, K., and Zhou, H., 2002, A preliminary study of salt flank illumination at Vinton Dome, Louisiana: do we need lateral wavefield continuation?, 72nd Annual SEG Meeting Extended Abstracts, 1368-1371.

House, L., Larsen, S., and Bednar, J., 2000, 3-D elastic numerical modeling of a complex salt structure, 70th Annual SEG Meeting, 2201-2204.

Larsen, S., and Grieger, J., 1998, Elastic modeling initiative, part III: 3-D computational modeling, 68th Annual SEG Meeting Extended Abstracts, 1803-1806.

Martin, G., Marfurt, K., and Larsen, S., 2002, Marmousi-2: an updated model for the investigation of AVO in structurally complex areas, 72nd Annual SEG Meeting Extended Abstracts, 1979-1982.

Stewart, R. R., Gaiser, J. E., Brown, R. J., and Lawton, D. C., 2003, Converted-wave seismic exploration: applications: Geophyscis, **68**, 40-57.

Whitmore, N. D. and Lines, L. R., 1985, VSP depth migration of a salt dome flank, 55th Annual SEG Meeting Extended Abstracts, Session:BHG1.3.

Whitmore, N. D. and Lines, L. R., 1986, Vertical seismic profiling depth migration of a salt dome flank: Geophysics, **51**, 1087-1109.

Acknowledgements

We would like to thank Shawn Larsen for discussions about the E3D elastic finite difference modeling code.

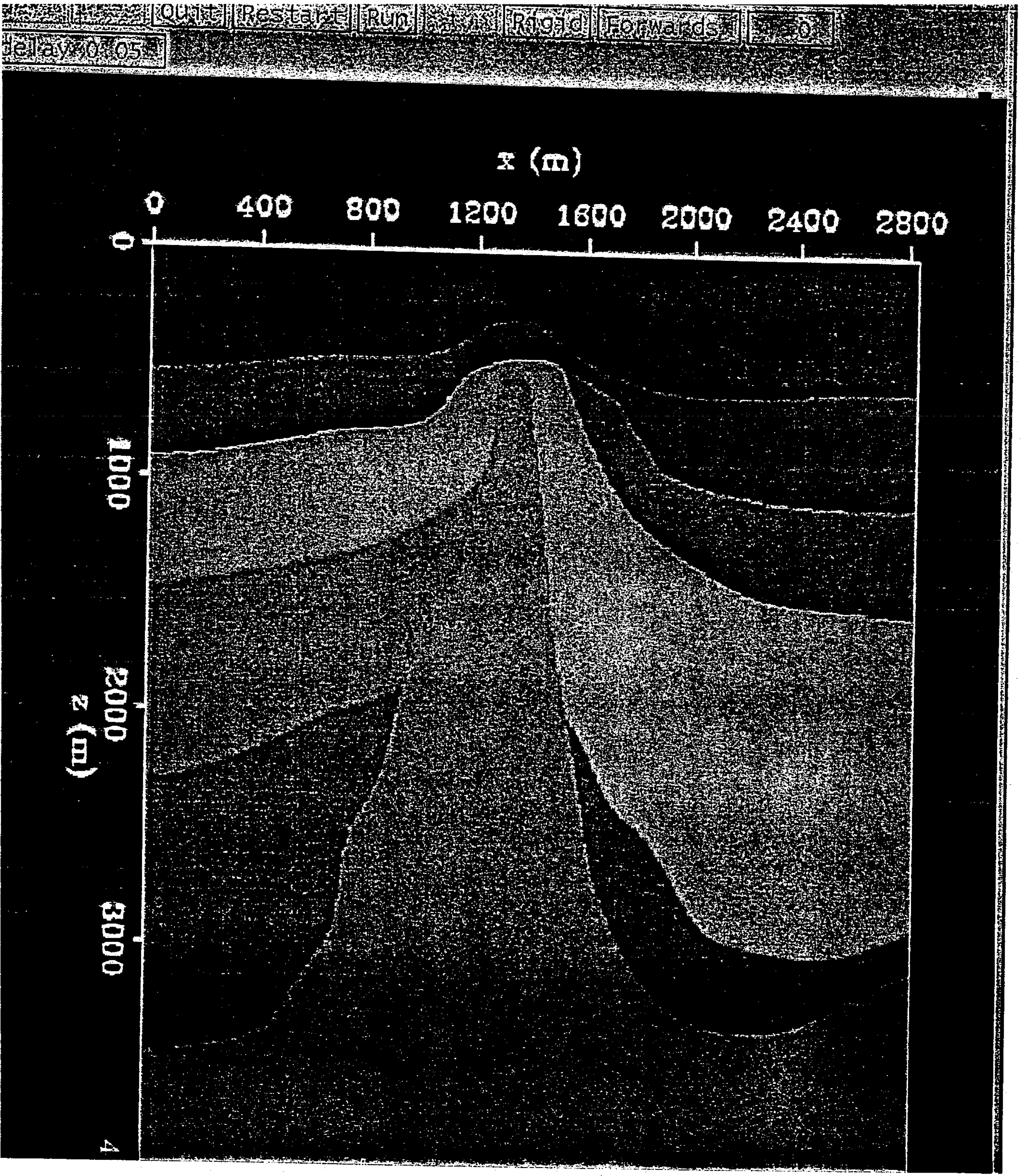
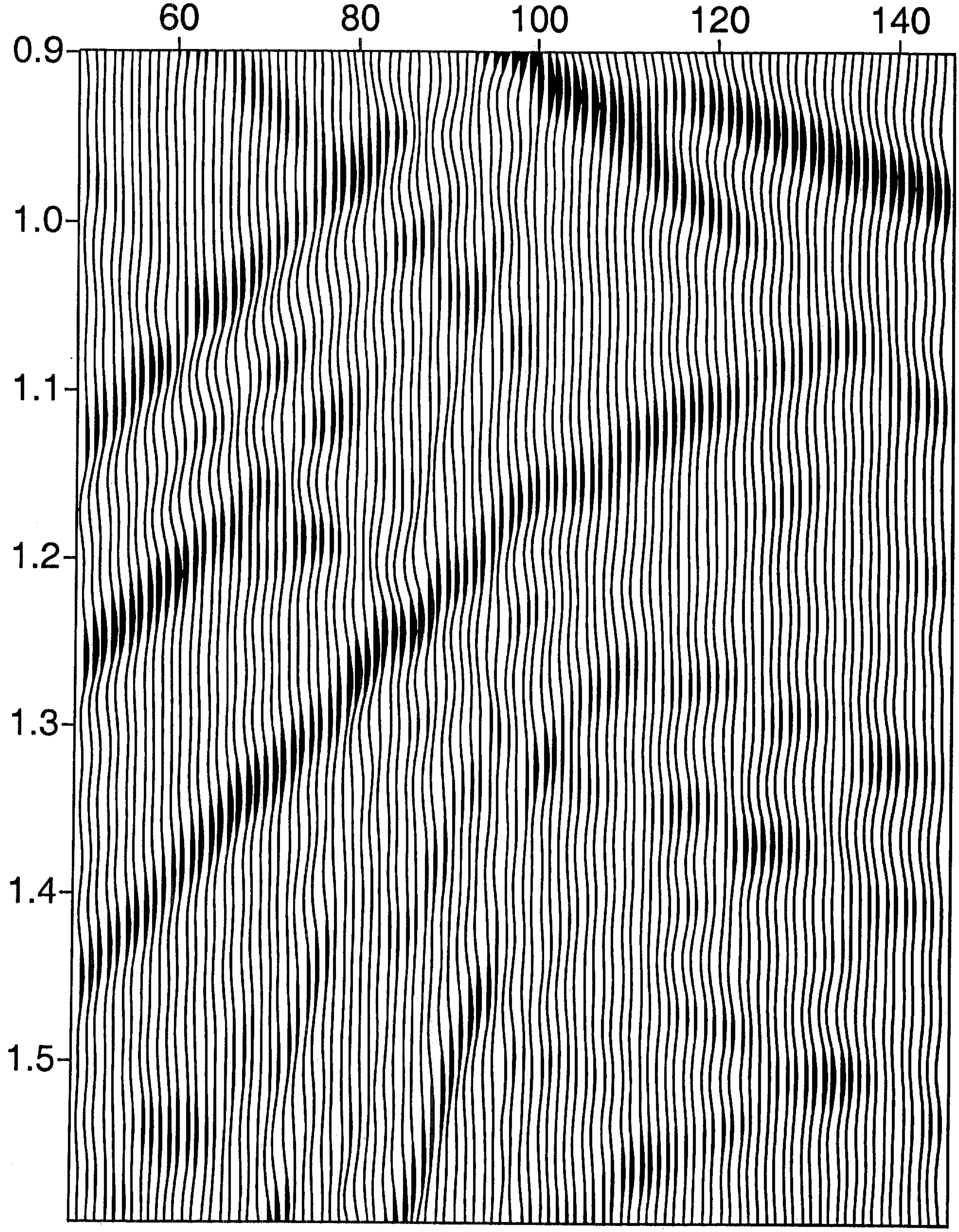
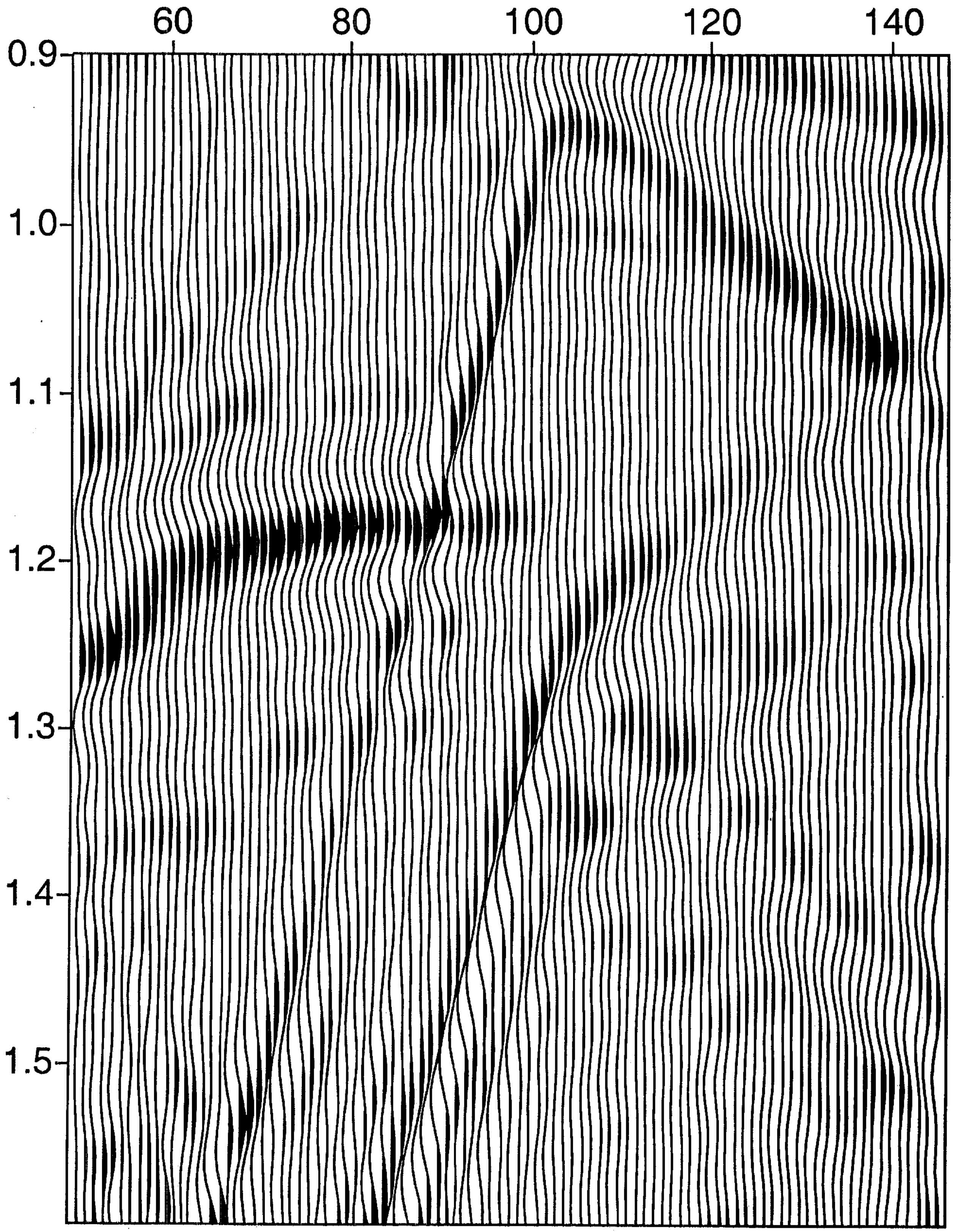

Quit
Restart
Run
Rigid
Forwards
x (m)
0
400
800
1200
1600
2000
2400
2800
0
1000
2000
3000
z (m)

Figure 2



s142_2d_vsp_5.TVz.su -- agc

Figure 3 (a)



s142_2d_vsp_5.TVx.su -- agc

Figure 3 (b)

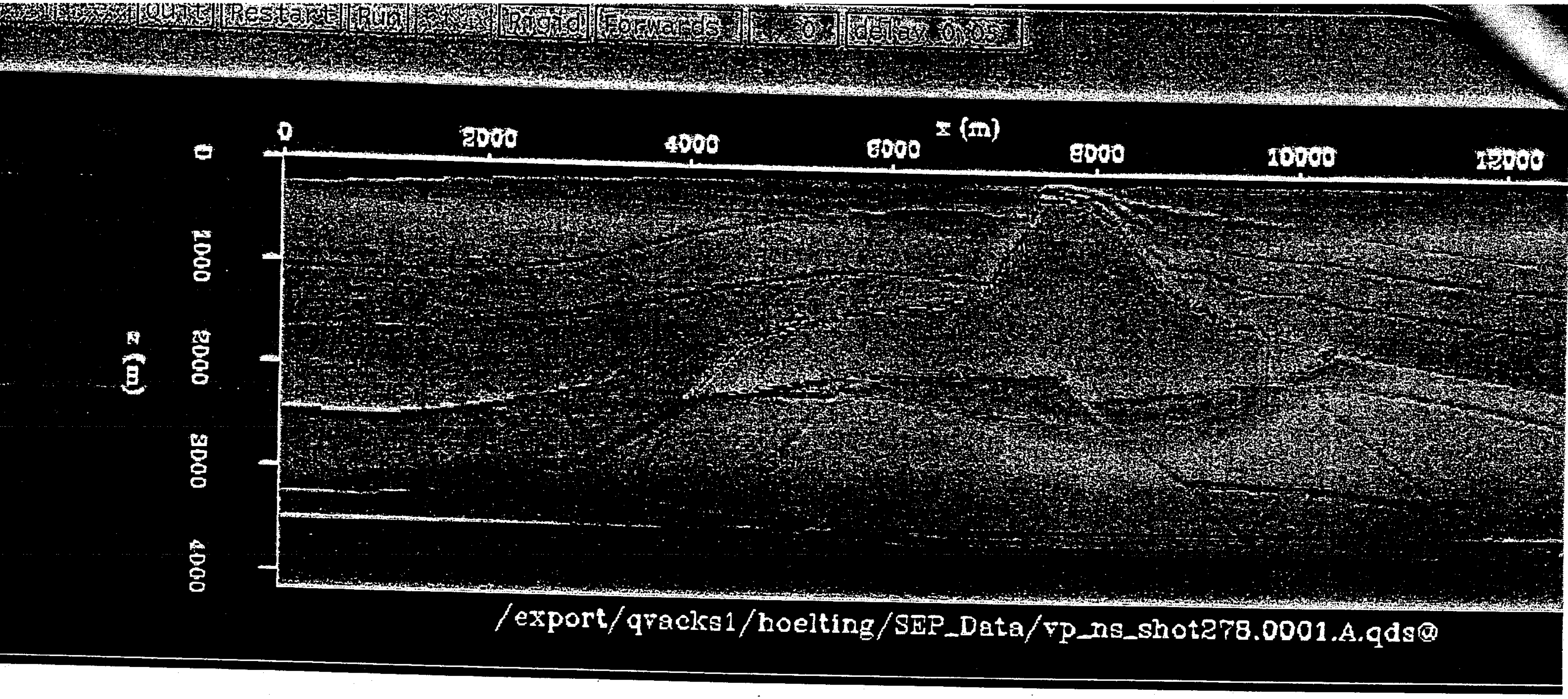
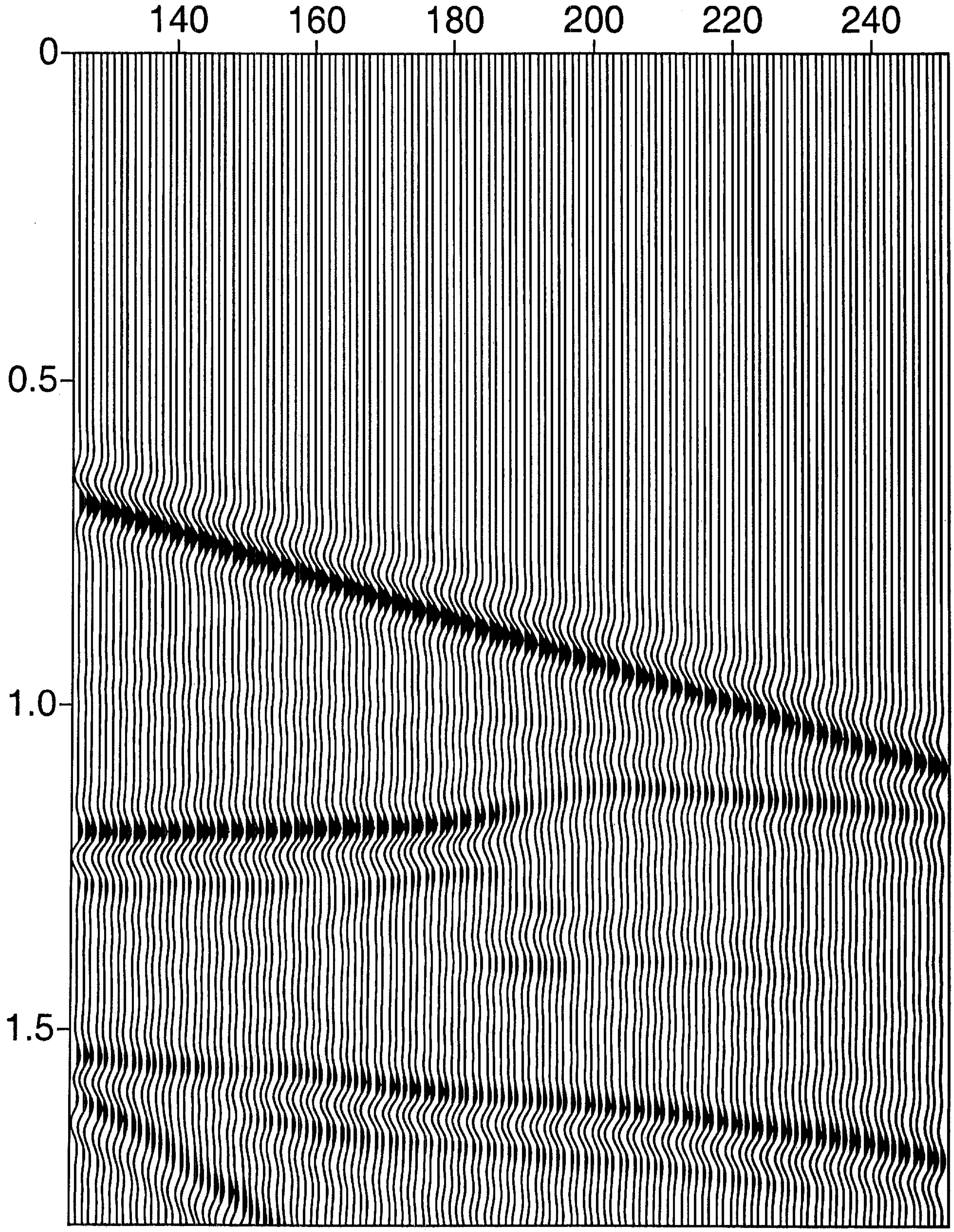
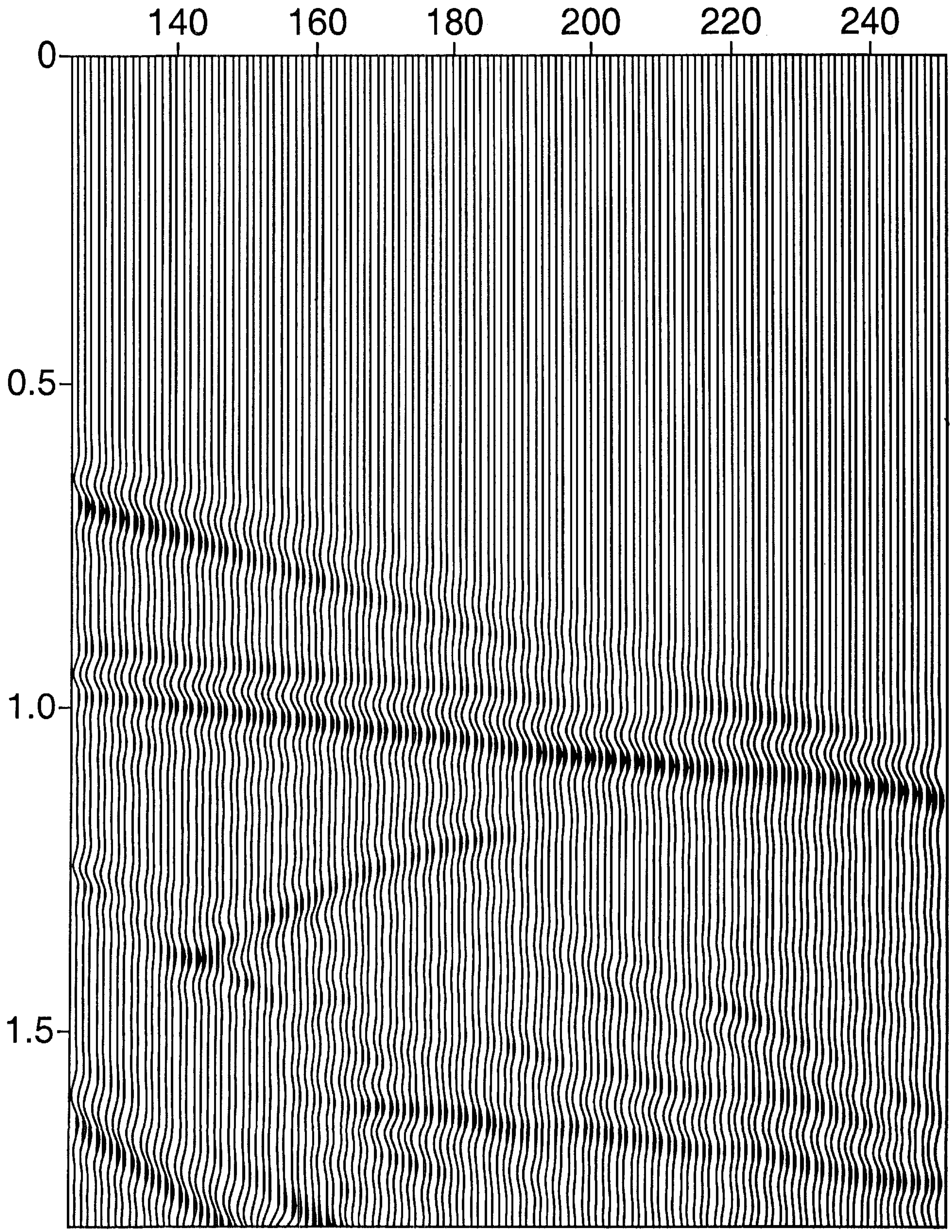

Quit
Restart
Run
Rigid
Forwards
delay 0.05
x (m)
0
2000
4000
6000
8000
10000
12000
z (m)
1000
2000
3000
4000
/export/qvacks1/hoelting/SEP_Data/vp_ns_shot278.0001.A.qds@

Figure 4



vsp1_8hz_7.5dh_1.5vs.TVz.su -- agc

Figure 5 (a)



vsp1_8hz_7.5dh_1.5vs.TVx.su -- agc

Figure 5(b)