Phase-shift migration of passive seismic data

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ABSTRACT

Can passive seismic data be used to image subsurface structure? From a processing standpoint, it seems possible. There is only one difference between passive data and conventional reflection seismic data that will require modification of existing wave-equation based imaging methods. That difference is that in a passive survey, structures may be illuminated by a variety of ambient noise sources over time, rather than a single source whose position and excitation time are known. There is no "time zero" at which our reflectors explode. This constraint is not difficult to accommodate. In phase shift migration, for example, the downward continuation step is unaffected; it is only the imaging step that requires changes. I bypass the imaging step of phase shift migration and obtain a picture of subsurface scatterer strength as a function of time. Integrating the power in this image over time gives an image of the subsurface. In tests, this technique gives a consistent result when applied to passive data recorded during different time intervals. While these results are preliminary, their success suggests that imaging with passive data is a viable technique.

INTRODUCTION

In SEP–57 I presented a passive seismic dataset that I had recently acquired. In that report, I discussed two approaches to processing the data. First I used beam steering to examine the energy incident on the receiver array as a function of arrival direction, hoping to see vertically incident energy that would correspond to reflections from subsurface layers, rather than horizontally travelling energy that was more likely due to nearby cultural noise sources. Not surprisingly, beam steering found plenty of energy travelling nearly horizontally. Vertically incident energy, if present, was effectively hidden.

In a second paper, I used trace to trace crosscorrelation to look for vertically incident energy. If there were vertically incident energy present, it should arrive at the same time on all 1023 traces, or perhaps with small, consistent time shifts due to receiver station statics. I crosscorrelated over long time intervals in an attempt to see these consistent trace to trace time shifts, the presence of which would indicate the presence of vertically-incident energy in the data. The receiver station statics that I solved for were inconsistent, illustrating again that near-horizontally incident energy, with its own arrival time differences from trace to trace, overwhelmed any vertically incident energy present.

That surface-travelling noise was strong was not surprising, given the recording geometry of this survey, which is illustrated in Figure 1. The survey contained three parallel lines of receivers, with an approximate spacing of one-half mile between lines. Each line had 341 receiver stations, with a 55 foot spacing between stations. An inline array of six geophones was used at each station. Thus there was almost no noise-cancelling ability in the crossline direction. For a conventional survey, with a strong energy source, this approach is fine. For a passive survey, however, we need areal arrays to be able to attack surface noise travelling in all directions if we are to see vertically incident energy. This has been a motivating factor in the design of an upcoming SEP passive seismic experiment (Claerbout et al., this report).

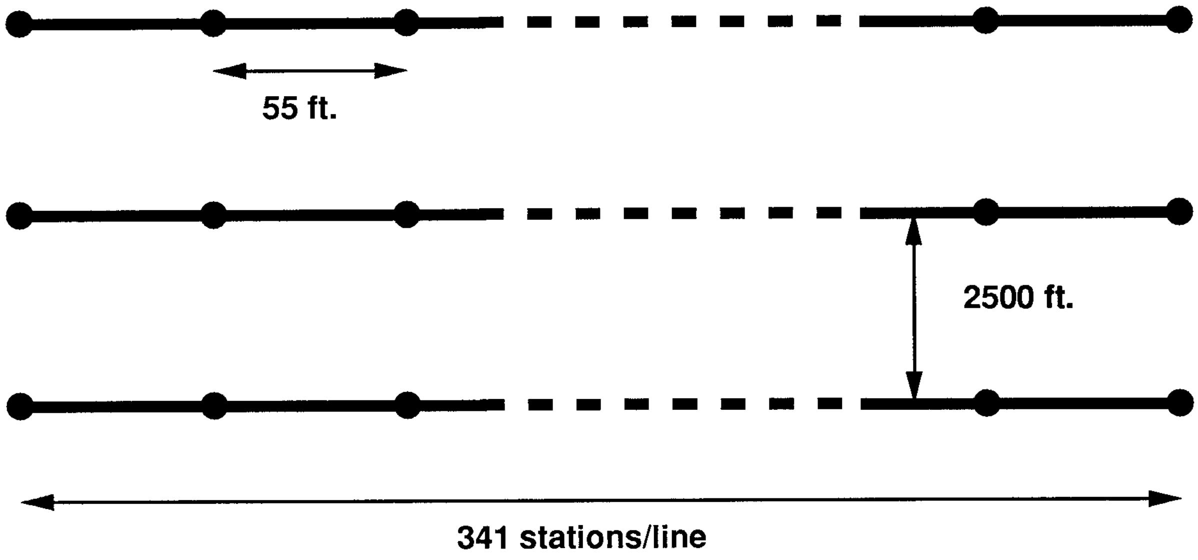


FIG. 1. Recording geometry for a passive seismic experiment. Each of the three lines contains 341 receiver stations, with a station spacing of 55 feet. An inline array of six geophones is used for each station, which is undesirable from the standpoint of attenuating surface noise.

Migrating passive data

Given that vertically incident energy corresponding to reflections from deep in the earth was difficult to find in this dataset, I looked for techniques that could be applied to the data that didn't rely on finding a subsurface reflection in the midst of the near-horizontally travelling energy. Downward continuation, a fundamental element in wave equation based migration methods such as the phase shift and Stolt methods, was such a process. Given the data recorded at the earth's surface, application of a frequency-domain operator can give the wavefield that would have been recorded had our receivers been buried at a given depth in the earth. If a scatterer is present at some depth, downward continuing to this depth should focus energy diffracted off this scatterer, allowing us to see it.

Phase-shift migration consists of downward continuing the surface data to a series of depths, and at each depth, extracting the image at time t=0, the time at which the reflectors at that depth "exploded". With passive data, there is no one time at a subsurface scatterer would necessarily be illuminated. After downward continuation, then, we are left with a time-varying picture of the subsurface. Integrating this picture over time gives a composite picture of subsurface scatterers. Thus with minor modifications, phase shift migration is a tool that, in principle, can be used to image the subsurface from passive seismic data.

In this paper, I will first illustrate how phase shift migration can be modified to handle passive seismic data. A brief synthetic example will illustrate the processing sequence and why the method works. Then I will apply the method to some actual passive data, in two and three dimensions. The measure of success of the method will be consistency. If processing data recorded during two separate time intervals gives a consistent picture, we can conclude that we are actually imaging a real primary or secondary energy source.

THEORETICAL DEVELOPMENT

Downward continuation

Given data recorded at the earth's surface $z = 0$, downward continuation is a frequency-domain operation that produces the data that would be recorded at some depth z. This technique will be the basis for our passive data imaging scheme. Downward continuation is simply multiplication by a complex exponential in the frequency-wavenumber domain, as shown by Claerbout (1985):

$$P(\omega, k_x, z) = P(\omega, k_x, 0)\, e^{ik_z(\omega,k_x)z} \tag{1}$$

where k_z is given by the dispersion relation:

$$k_z = \sqrt{\frac{\omega^2}{v^2} - k_x^2} \tag{2}$$

Phase shift migration

After downward continuation, the (t, x) domain wavefield that would be recorded at depth z could be recovered by a two-dimensional inverse Fourier transform:

$$p(t,x,z) = \int\int e^{ik_x x - i\omega t + ik_z z}\, P(\omega, k_x, 0)\, d\omega\, dk_x \tag{3}$$

According to the exploding reflectors model, however, we are only interested in the image at the single time value $t = 0$, when the reflectors explode, since we are trying to image the reflectors. This simplifies equation 3 to the following:

$$p(x,z) = \int\int e^{ik_x x + ik_z z}\, P(\omega, k_x, 0)\, d\omega\, dk_x \tag{4}$$

Instead of inverse Fourier transforming in the frequency direction, we simply sum over frequency before inverse transforming over k_x.

With passive seismic data, downward continuation can be performed without modification. The imaging condition of phase-shift migration, however, requires some changes. The fundamental difference between passive data and conventional reflection seismic data is, in this context, that in passive seismic survey a reflector or scatterer may be illuminated by a variety of energy sources over time. There is no single source with a well-defined location and excitation time. So we cannot sum over frequency to extract the subsurface image at any one time; we need to look at this image as a function of time.

We still want to produce a single subsurface image rather than having to look at an image for every time sample. If we start with the downward continued, time-varying image of equation 3:

$$p(t,x,z) = \int\int e^{ik_x x - i\omega t + ik_z z}\, P(\omega, k_x, 0)\, d\omega\, dk_x \tag{5}$$

and sum the power in this image over time:

$$p(x,z) = \sum_t \left[\int\int e^{ik_x x - i\omega t + ik_z z}\, P(\omega, k_x, 0)\, d\omega\, dk_x\right]^2 \tag{6}$$

we get a composite image that shows the strength of subsurface scatterers as a function of x and z. The summation is done in terms of power rather than amplitude to prevent having the positive and negative parts of a source pulse cancel one another out.

Besides reducing the data volume to a single subsurface image, this summation has another benefit. If the energy sources illuminating a scatterer are due to a number of different sources, the source waveforms may be quite different. Summation of power removes any need on our part to identify these different waveforms.

Extension to three dimensions

Thus far, the method is two-dimensional. It returns an image of the subsurface as a function of x and z. A scatterer that is located on the surface a distance r away from the receiver line will appear to be at depth r with this method. For passive data, it is important to resolve this ambiguity. If we see a strong scatterer in our two-dimensional result, there is no way to know if this is a scatterer at depth (a secondary source) or an energy source on the surface (a primary source) such as a pump, or a moving vehicle. Therefore it is necessary to extend the method to three dimensions. Fortunately this is quite easy to do. The dispersion relation in 3D is:

$$k_z = \sqrt{\frac{\omega^2}{v^2} - k_x^2 - k_y^2} \tag{7}$$

Thus after summation over time the final three-dimension image of the subsurface is given by:

$$p(x,y,z) = \sum_t [\int\int\int e^{ik_x x + ik_y y - i\omega t + ik_z z}\, P(\omega, k_x, k_y, 0)\, d\omega\, dk_x\, dk_y]^2 \tag{8}$$

What about Stolt migration?

Stolt migration is similar to phase shift migration, but has a trick at the end that makes it much faster. Can a similar trick be used to speed up the imaging scheme proposed here? Since passive seismology typically involves recording for long time periods, computational speed may be essential if we are to be able to process such large data volumes. In the present case, the passive dataset contains 1023 traces, and for each of those 960,000 time samples!

Recall the expression from equation 4 for phase shift migration:

$$p(x,z) = \int\int e^{ik_x x + ik_z z}\, P(\omega, k_x, 0)\, d\omega\, dk_x \tag{9}$$

Solving the dispersion relation for the frequency ω gives:

$$\omega = -sgn(k_z)\, v\, \sqrt{k_x^2 + k_z^2} \tag{10}$$

Taking a derivative with respect to k_z:

$$\frac{d\omega}{dk_z} = \frac{-v|k_z|}{\sqrt{k_x^2 + k_z^2}} \tag{11}$$

If we substitute:

$$d\omega = \frac{d\omega}{dk_z} dk_z \tag{12}$$

in equation 9, this gives:

$$p(x,z) = \int\int e^{ik_x x + ik_z z}\, \{P(\omega, k_x, 0)\, \frac{v|k_z|}{\sqrt{k_x^2 + k_z^2}}\}\, dk_z\, dk_x \tag{13}$$

Notice that this equation is just a 2D inverse Fourier transform with an added multiplicative factor. A single two-dimensional integration gives the entire $p(x,z)$

image. In equation 9, the extra factor of $e^{ik_z z}$ requires that a two-dimensional integration be performed for ***each z level.*** This trick makes Stolt migration much faster than phase shift.

Can a similar trick be performed in the passive seismic case? Recall the expression for the downward continued image given in equation 3:

$$p(t,x,z) = \int \int e^{ik_x x - i\omega t + ik_z z} \, P(\omega, k_x, 0) \, d\omega \, dk_x \tag{14}$$

substituting:

$$d\omega = \frac{d\omega}{dk_z} dk_z \tag{15}$$

would not help to reduce the complexity of this equation. As long as the terms e^{ik_x}, $e^{ik_z z}$, and $e^{-i\omega t}$ are present in the exponential, there is no way to reduce this to a two-dimensional Fourier transform using a substitution similar to equation 15. We must perform a 2D integration for each depth (or each time). The trick used to make Stolt migration fast discussed above depends on the imaging step where we sum over frequency. Since we are unable to perform that summation with passive seismic data, we are unable to use the same trick. However, there are undoubtedly other ways to improve computation speed.

RESULTS

A synthetic example

A simple synthetic example will illustrate the method described in the previous section and demonstrate the sort of results that we hope to obtain with passive data. Figure 2 shows a simple constant velocity earth model containing three point scatterers, two at one depth, and a third shallow scatterer at the same horizontal position as one of the deeper scatterers. Figure 3 shows a shot gather resulting from the application of a phase-shift modeling program to this model.

In Figure 4, the result of downward continuation is shown at several depths, and in Figure 5, the result of summing the power in each of these panels is displayed to form a composite (x, z) image of the subsurface. The large amplitudes produced by proper focusing of the events has allowed us to identify the depths and horizontal positions of all three scatterers. Even the fact the there were two scatterers at a single horizontal location was not a problem, since the two events exhibited different moveout patterns that were indicative of the scatterers' depths.

2D migration of passive data

A portion of a passive seismic record is shown in Figure 6. This data is from one of the three receiver lines, and displayed here is the data recorded during one second out of a total recording time of 64 minutes. A great deal of coherent energy

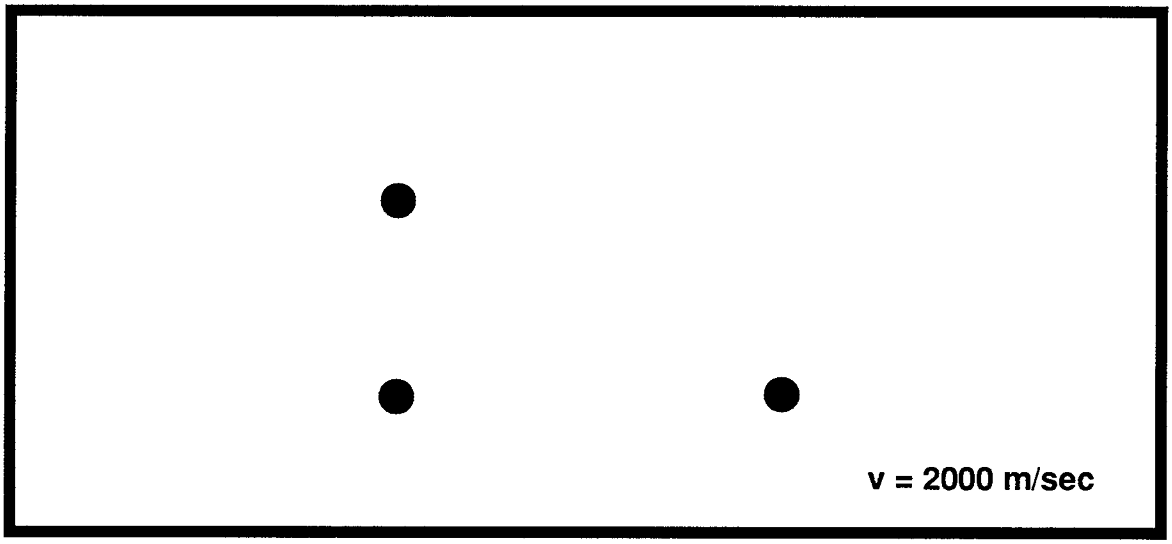


FIG. 2. A simple earth model containing three point scatterers buried in a constant-velocity medium.

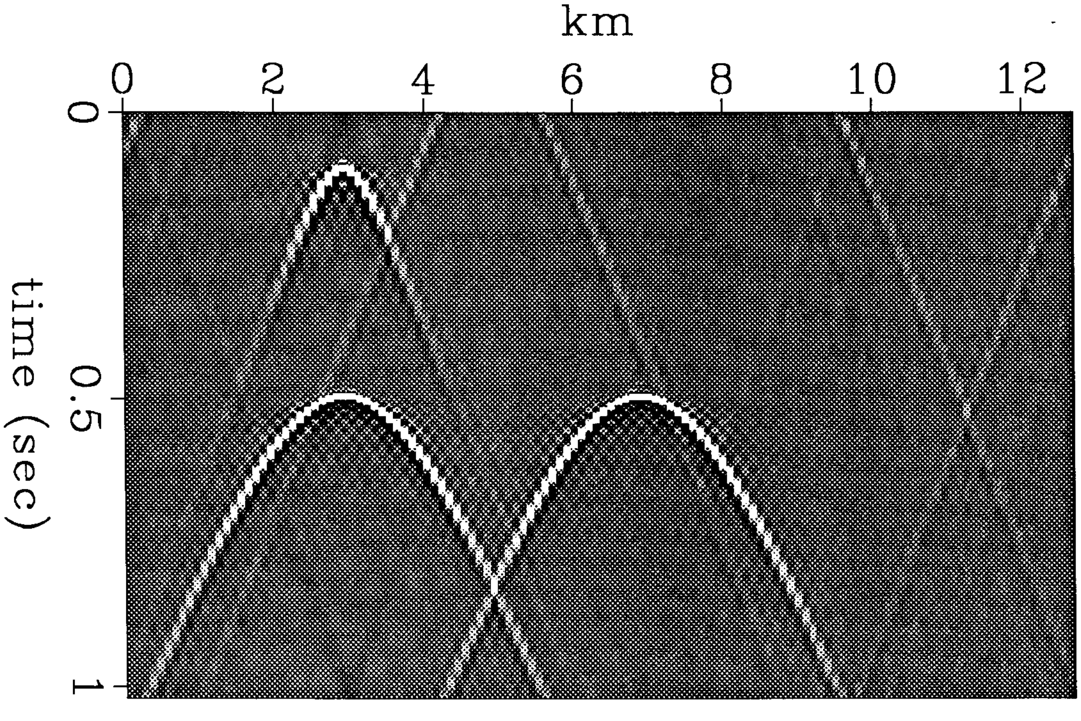


FIG. 3. Shot gather computed from model in Figure 2 using a phase-shift modeling scheme.

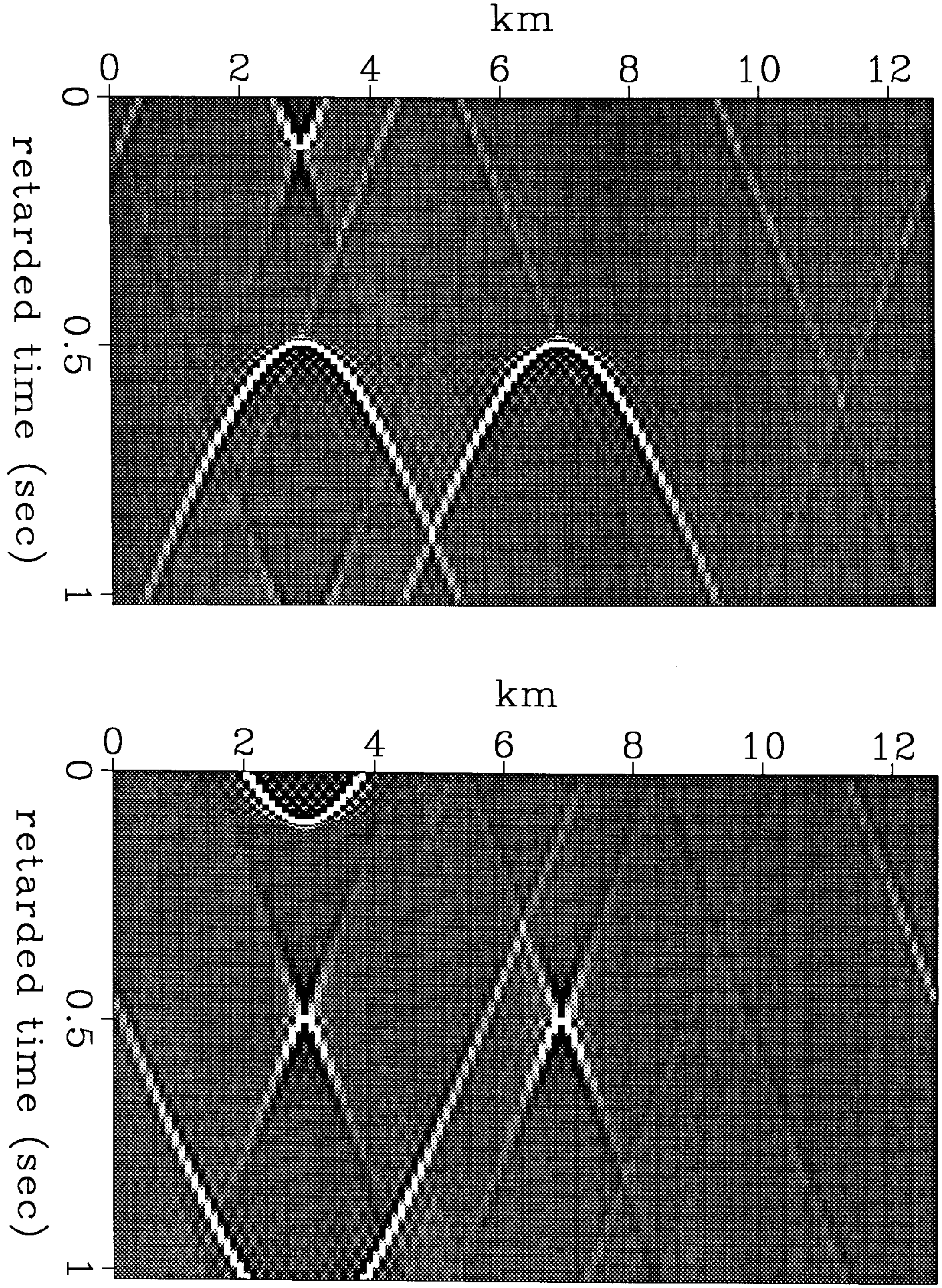


FIG. 4. Downward continuation of the data in Figure 3. (top) Data that would be recorded at the depth of the shallow scatterer; (bottom) At the deep scatterer.

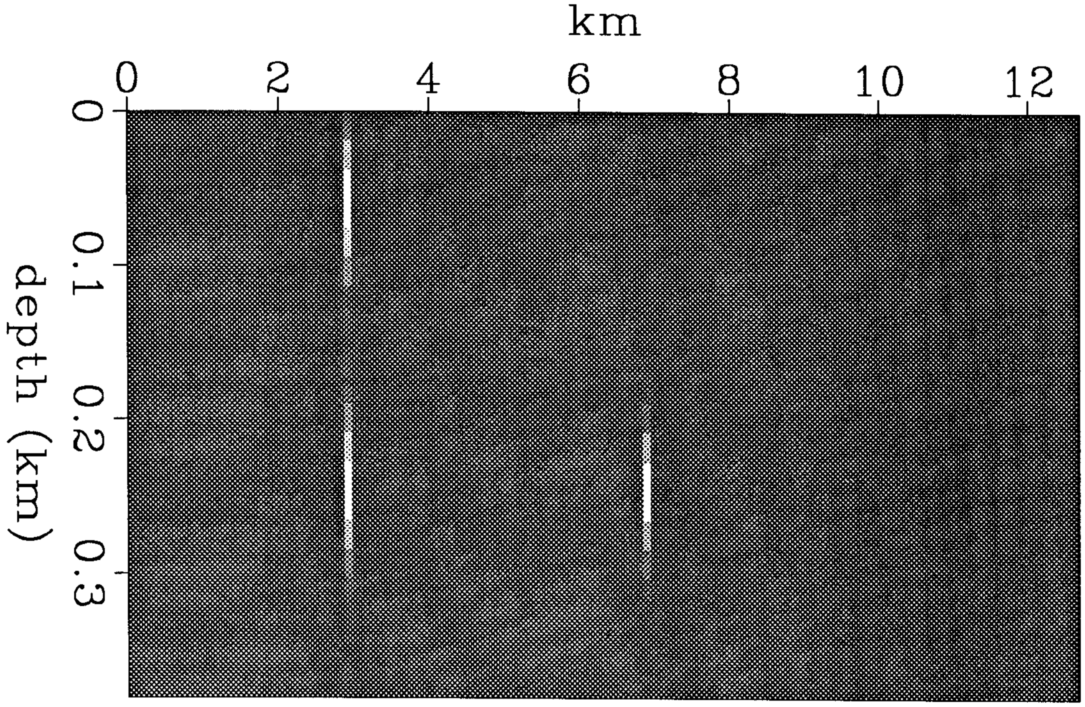


FIG. 5. Subsurface image computed by summing power along the time axis in each downward continuation step. The scatterers are easily located at their correct depths because proper focusing resulted in a large power value.

is visible on the record. Particularly interesting is the event exhibiting hyperbolic moveout whose apex is at roughly 4 kilometers. The event is visible throughout the record, and on many of the other records taken from this location. This could be an energy source on the surface, such as a pump, or a secondary source– a scatterer at some depth. Three-dimensional migration is needed to resolve this ambiguity.

This source is radiating over time. This is the reason why the imaging technique normally used in phase shift migration (summation over frequencies) will not work here. There is no one time at which we wish to image such sources. We have to obtain an image of the sources as a function of time, and look for consistency over time, indicating a source.

Figures 7 and 8 show the data downward continued to a number of different depth levels. A correction has been applied to keep the hyperbola tops stationary, otherwise events would move to earlier times with increasing depth. We can see the characteristic collapse of the hyperbola to a focus as we downward continue. There are other instances of focusing at different locations at various depths, but this is the clearest case in this record. In Figure 9, the power in each trace of each downward continued panel has been computed and displayed, giving an image of the subsurface. The source at 4 kilometers is the most prominent feature on this image, since it was consistently strong over time.

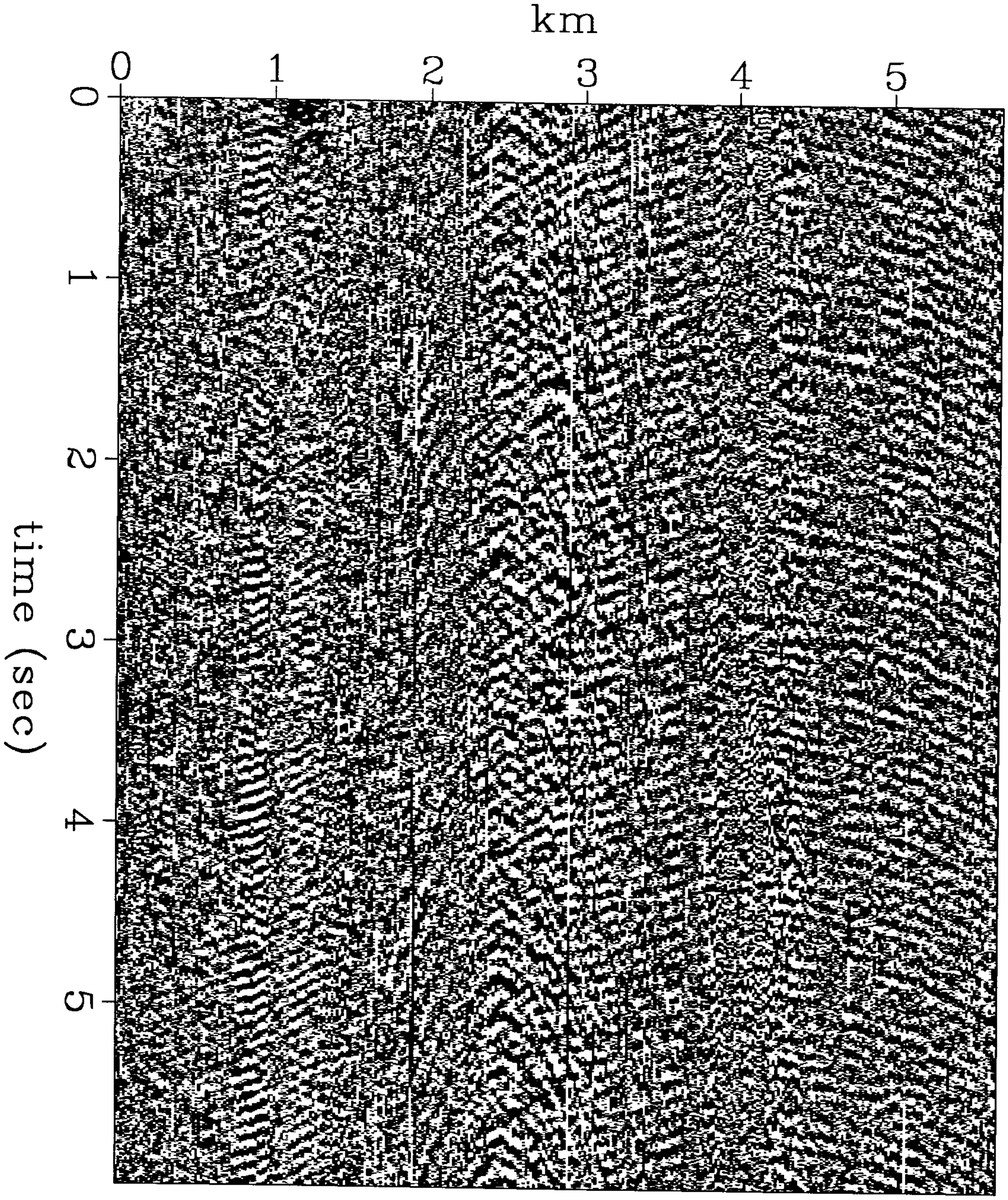


FIG. 6. A portion of a passive seismic record. Note the event with roughly hyperbolic moveout with its apex near 4 kilometers.

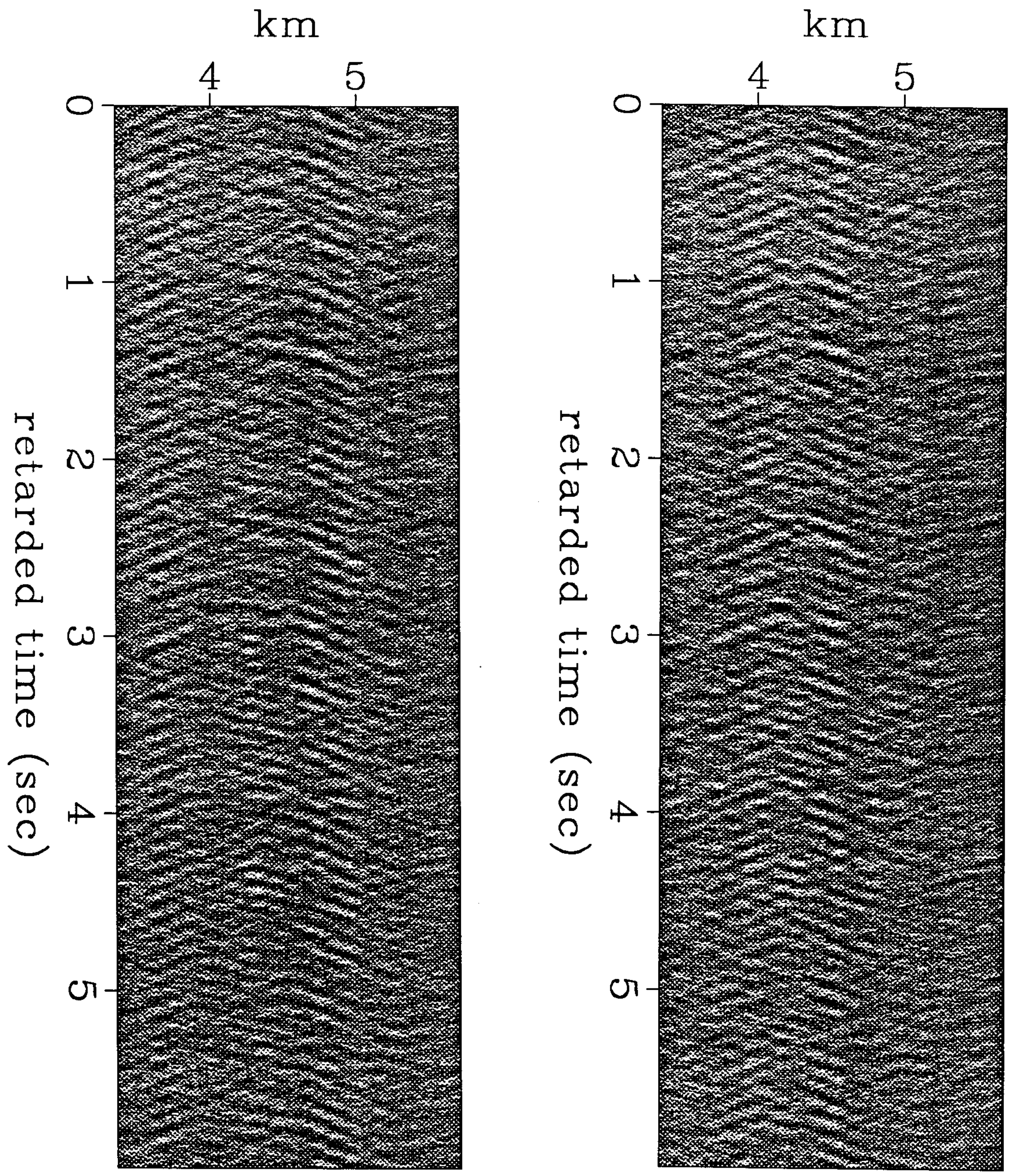


FIG. 7. The data in Figure 6 downward continued to depths of (left) 300 meters, and (right) 600 meters. Note the gradual collapse of the hyperbola centered near 4 kilometers.

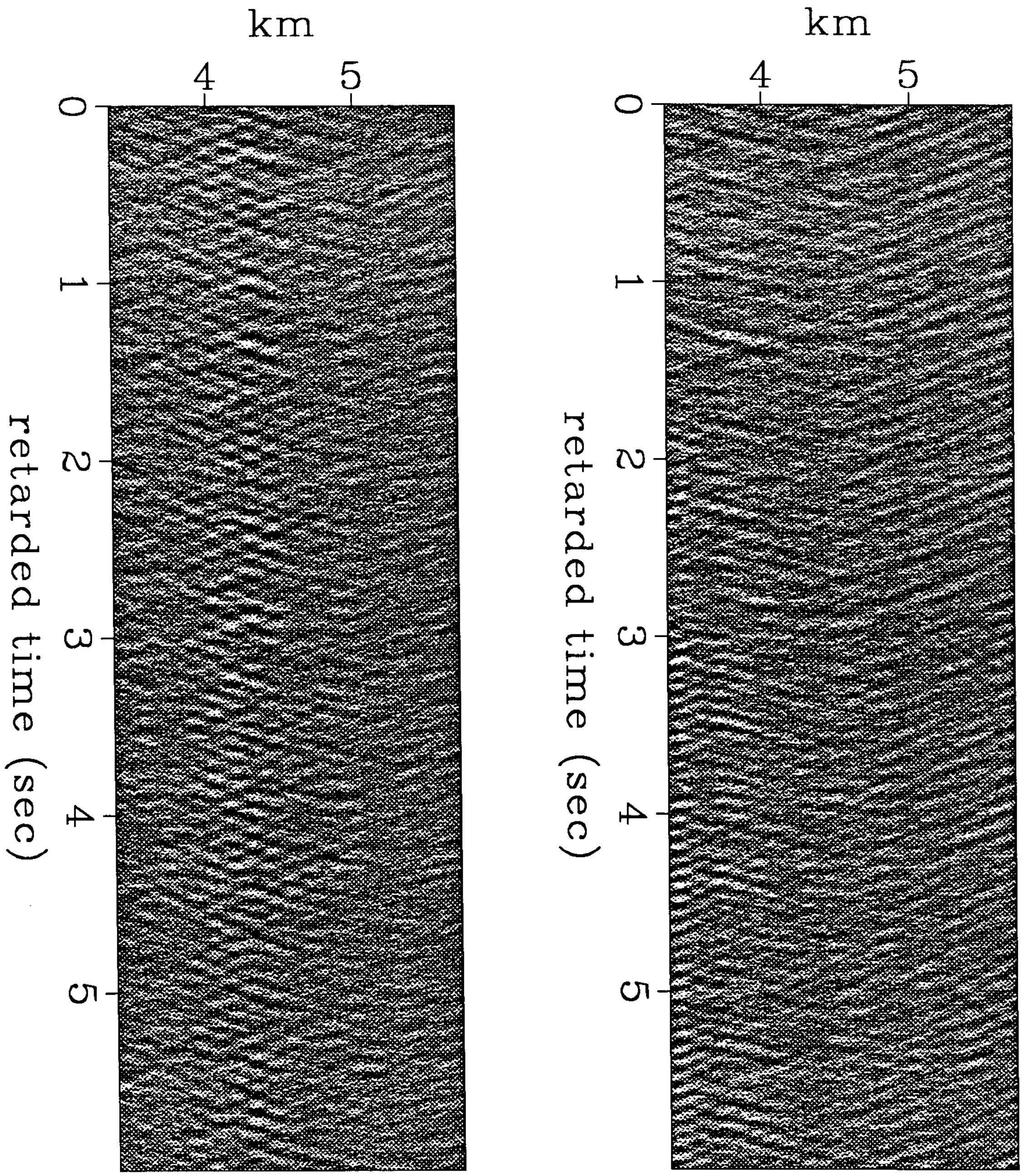


FIG. 8. The data in Figure 6 downward continued to depths of (left) 900 meters, and (right) 2100 meters. The hyperbola centered near 4 kilometers is best focused at 900 meters, indicating that this is the distance of the energy source from the line. By 2100 meters it is apparent that most of the energy in the figure is over-migrated.

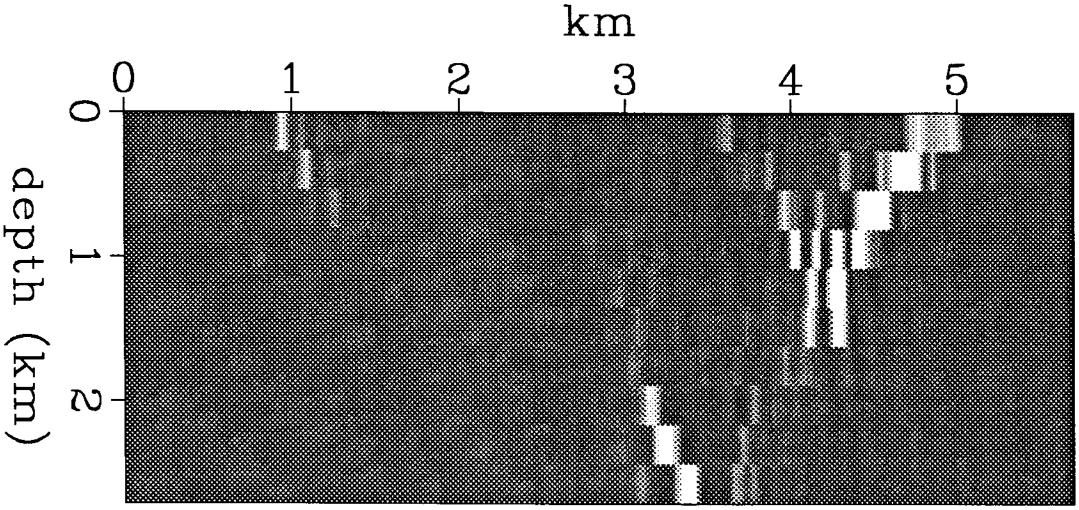


FIG. 9. A subsurface image formed by summing power along the time direction in each downward continuation step. Such a summation favors well-focused events that are consistent in time, thus the feature near 4 kilometers, which was clearly visible in the downward continuation panels and best focused at a depth of 900 meters, is the most prominent feature.

Consistency is a measure of the success of this technique. If the features of the image in Figure 9 are truly surface noise sources or subsurface scatterers, we expect them to be consistently visible over time. If we independently process data from different recording intervals, do we get the same picture? In Figures 10 and 11, the result of processing six different records from the passive survey are shown. These records were recorded over a two-hour period from roughly 7:30 to 9:30 in the evening in September. They represent only 1/60th of the total data volume. There is a fair amount of consistency from record to record. This indicates that we are seeing something, be it a surface noise source or subsurface scatterer. It is interesting to note that the picture seems clearer for later recording times. This agrees with our expectation that noise sources such as farming and irrigation equipment, vehicles, and thermal noise would be much stronger in the early part of the recording period, before sunset.

Given that we seem to be able to see some sources of energy with consistency, an obvious question is, are these subsurface scatterers being illuminated by ambient energy, or are they noise sources on the surface? Two-dimensional processing cannot answer this question. We need to extend the method to three dimensions, as discussed earlier.

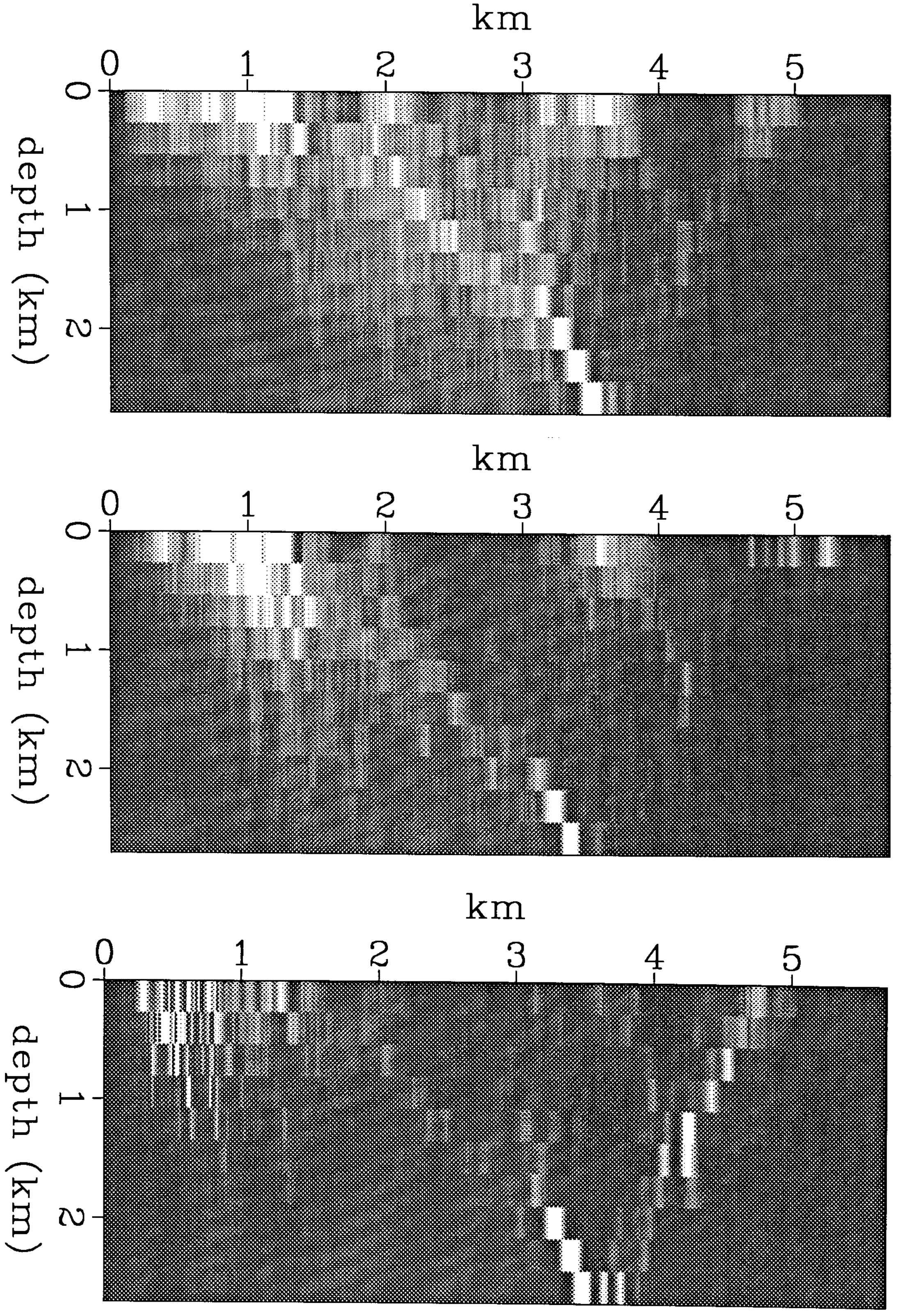


FIG. 10. Subsurface images generated for three different 32 second recording periods. (a) 7:48 P.M.; (b) 8:16 P.M.; (c) 8:37 P.M.

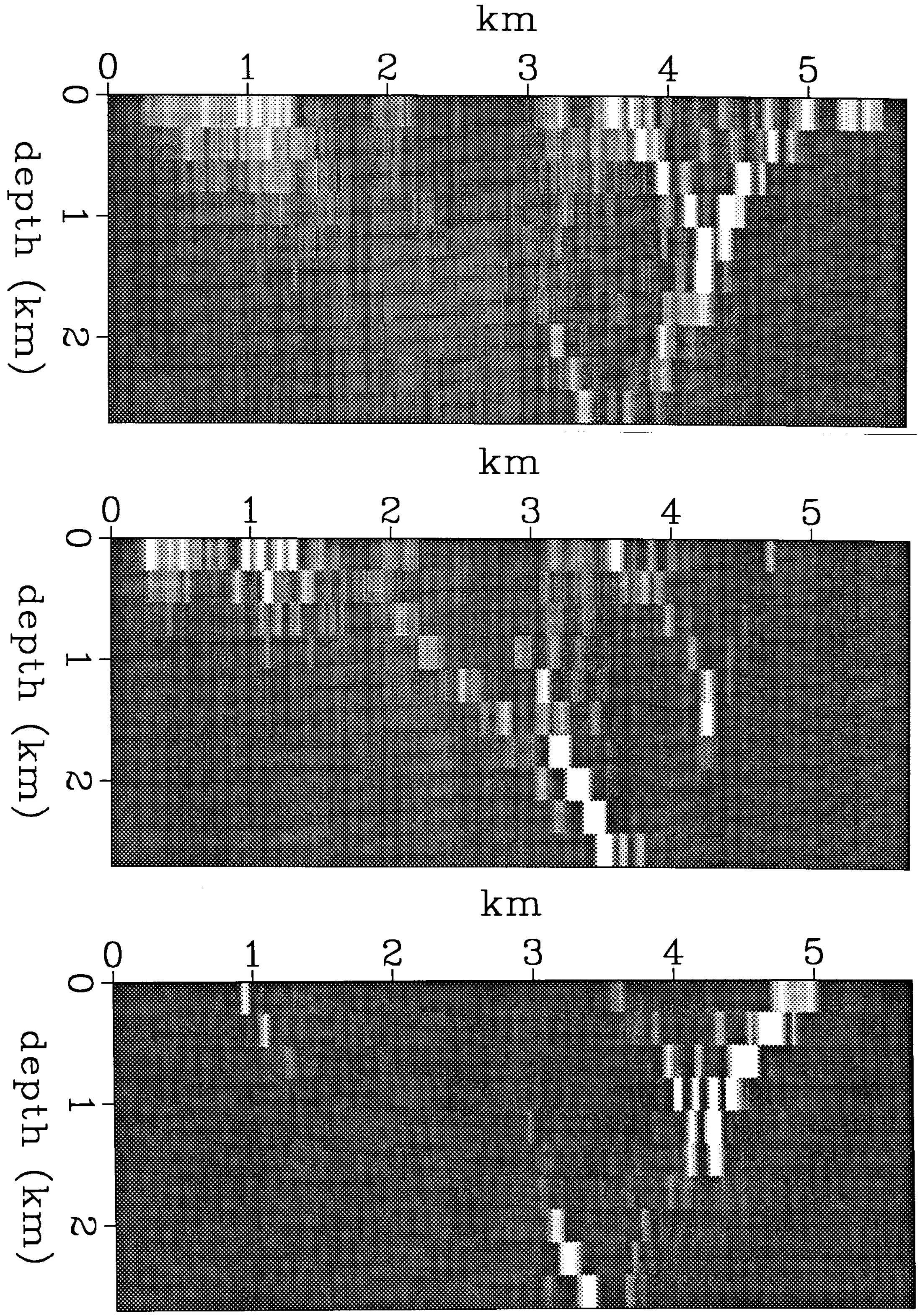


FIG. 11. Subsurface images generated for three different 32 second recording periods. (a) 8:56 P.M.; (b) 9:13 P.M.; (c) 9:30 P.M. The image appears to be cleaner for later recording times, agreeing with our expectation that many surface noise sources decrease in intensity after sunset.

3D migration of passive data

Figure 12 shows the data from the two remaining receiver lines collected along with the data from the first line shown in Figure 6. The data from all three lines were migrated in a three-dimensional scheme analogous to the two-dimensional processing in the previous section. Again, a constant velocity of 2000 meters/second was used. In Figures 13, three planes from the resulting three-dimensional migrated image (corresponding to the locations of the three lines) are shown. The result for the first line is very similar to the two-dimensional result shown in Figure 9. Little energy appears to migrate from line to line because of the large distance between lines. Data with a better sampling in the crossline direction would be needed to determine whether our imaged energy sources are on the surface or not.

CONCLUSIONS

The migration scheme described here yields fairly consistent results when applied to data recorded during different time intervals of a passive seismic survey, indicating that we are able to image energy sources. These could be sources of energy located on the surface, such as irrigation pumps, or secondary sources, scatterers located at some depth in the near-surface. Three-dimensional results fail to resolve this issue because sampling in the crossline direction is inadequate. But the consistency of the two-dimensional results suggests that this is a viable technique for processing passive seismic data.

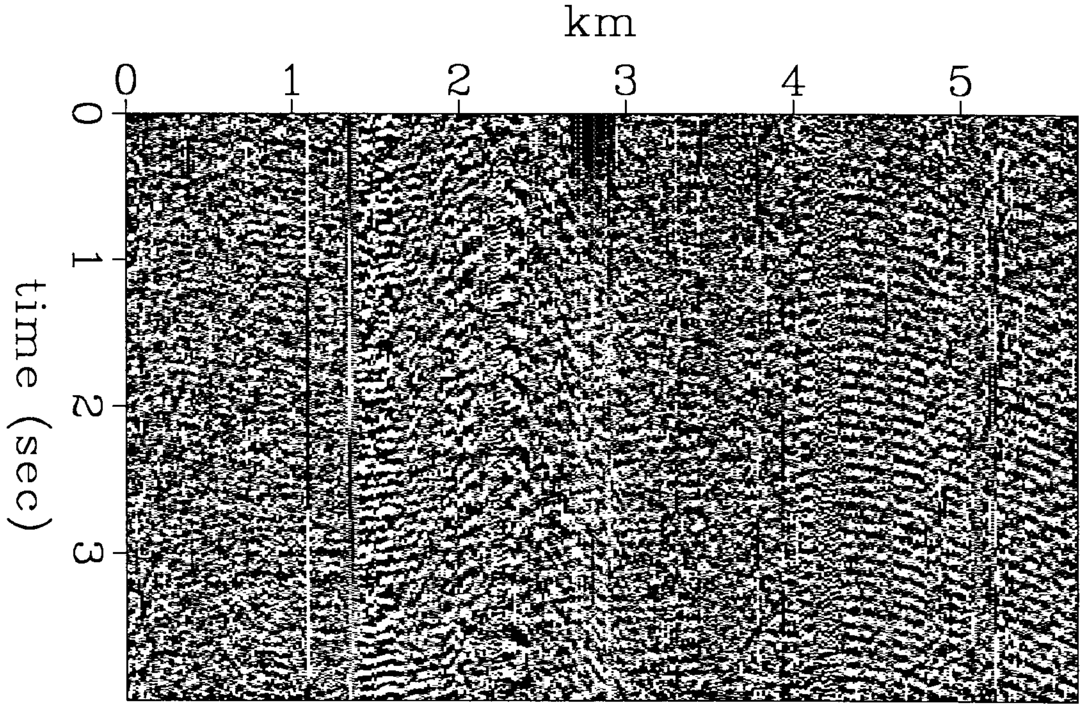
Directions for future work

A constant velocity of 2000 meters per second was used in all the migrations performed here, on the assumption that this was a reasonable guess at a near-surface velocity, and because most of the focusing seems to occur at shallow depths. Using a more realistic velocity function may reveal some focused energy at greater depths. Since the migration method used here is a phase-shift method, including vertical velocity variation is not difficult. Some sort of autofocusing scheme that determines the correct velocity would also be very useful.

A three-dimensional recording geometry with better sampling in the crossline direction is needed if we are to remove the ambiguity between energy sources on the surface and subsurface scatterers. In the upcoming SEP passive experiment, our two-dimensional grid of recorded channels should be an improvement.

The recording geometry of this survey does little to attenuate surface noise, since the geophone groups are simple inline arrays. Two-dimensional arrays will attack surface noise better and give us a better chance of seeing energy scattered off subsurface structures.

Finally, I would like to explore applications of these techniques to conventional seismic surveys. The method described here locates coherent noise sources. Just



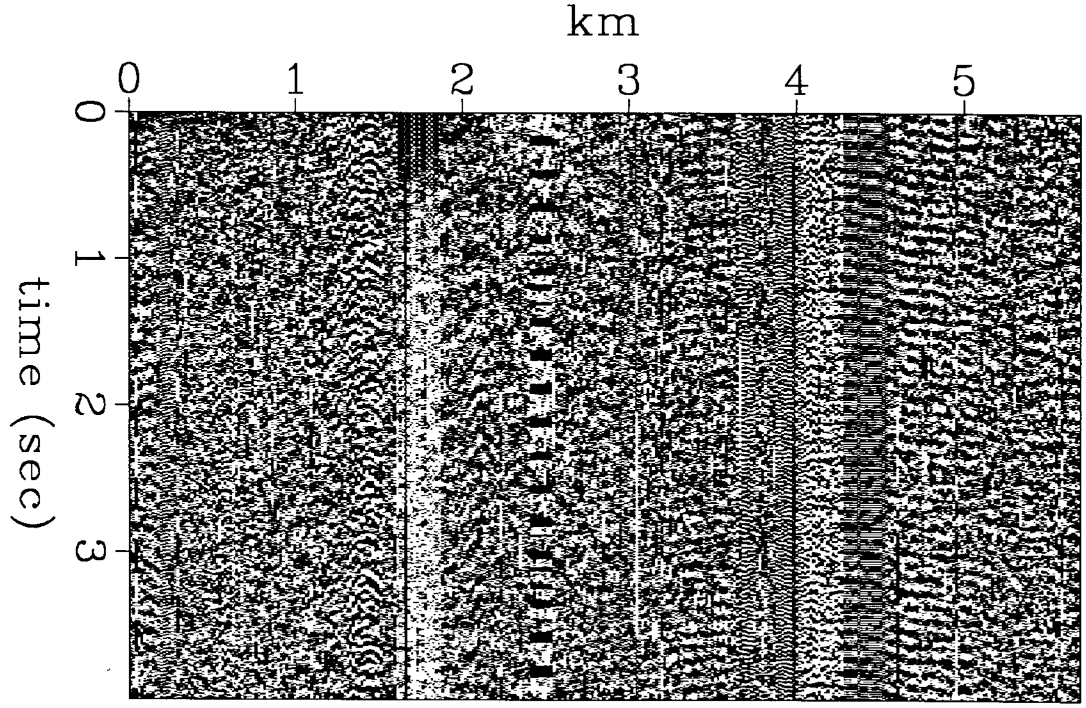


FIG. 12. Data from the two remaining receiver lines recorded at the same time as the data shown in Figure 6.

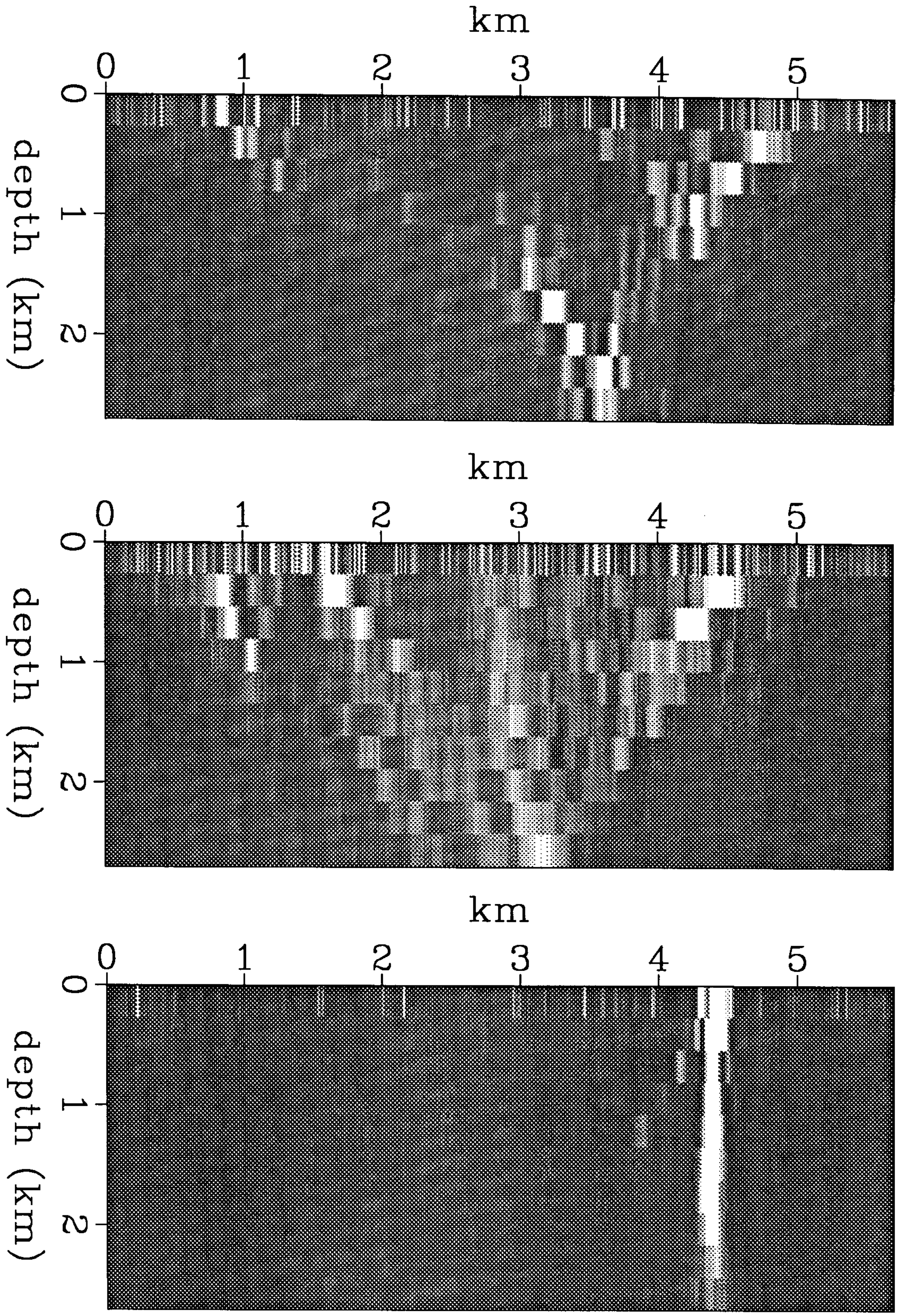


FIG. 13. Depth slices from the 3D migrated image corresponding to the receiver line locations. The image for the first line (top) is similar to the two-dimensional result in Figure 9. This suggests that the large distance between lines prevents energy from migrating between lines.

as we have used this method in this paper to locate these noise sources for use in imaging, we might locate coherent noise sources in conventional reflection seismic data, with the goal of removing such contaminating noise.

ACKNOWLEDGMENTS

Fabio Rocca first suggested that migration techniques could be applied to passive seismic data, and recognized that phase shift migration required only a modification of the imaging condition. I am indebted to Fabio for the many helpful discussions and suggestions that motivated this work. Dave Nichols and Lin Zhang also contributed ideas and suggestions on several occasions.

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The view from 300 miles above Dallas.