Location of a subsurface source using reverse-ray backpropagation

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ABSTRACT

A reverse-ray backpropagation algorithm is used to estimate the location of a subsurface source using the travel times from the source to a spread of surface geophones. The technique involves tracing rays from the receiver through a known geologic model until the time of the ray equals the observed travel time. The end point of each ray is a possible source position. The mode of all ray end points from many receivers is the source position.

Reverse-ray backpropagation of numerically modeled synthetic travel times resulted in the source position being accurate to +/- 1 m for the 2-D case of a buried source and a line of receivers. Picking travel times from acoustic physical model data resulted in a source estimation accurate to +/- 5 m for a similar geometry.

INTRODUCTION

Horizontal drilling is becoming a popular method of increasing oil and gas production from a borehole (Burgess and Van de Slijke, 1990). Drilling horizontally can increase the amount of pay thickness and thus production rates dramatically. If we assume that it is possible to put a seismic source in the downhole drilling string, it is an interesting problem to try and determine the position of the source using the travel times from the source to a spread of surface receivers. The accuracy of location will have implications into the feasibility of developing such a source.

This study considers using a reverse-ray backpropagation technique to locate a downhole seismic source. The algorithm is tested on synthetic computer generated data and physical model data.

THEORY

The geometry of the experiment is shown schematically in Figure 1. There is a source in the subsurface and a spread of receivers along the surface. The source-receiver ravel time for a homogeneous half space is

$$t_j = \frac{\sqrt{(x_s - R_j)^2 + z_s^2}}{V} .$$

For a layered medium this expression can be written as

$$t_j = \sum_{n=0}^{N} \frac{\sqrt{x_n^2 + z_n^2}}{V_n}$$

where

$$X_s = \sum_{n=0}^{N} x_n + R_j \quad ,$$

and

$$Z_s = \sum_{n=0}^{N} x_n \quad .$$

Where t_j are the observed travel times, R_j is the receiver offset, x_n and z_n are the horizontal and vertical distance in layer n and N is the number of layers. The unknowns in the problem are the coordinates of the source position (X_s,Z_s).

This study considers using a reverse-ray backpropagation technique similar to the reverse-time migration method for VSP migration (Chang and McMechan, 1986). The technique tries to determine the source position by backward propagating rays from each receiver by the observed travel time at each receiver. Thus for each receiver there is a set of points which are the possible source locations. Given two receivers the source position is the point unique to both receivers as shown in Figure 2. For a number of receivers, the source can be determined by the point with the greatest number of curves passing through it. Statistically, this is equivalent to the mode of all possible source positions.

The assumptions in this method are:

- an impulsive source is excited downhole;
- the excitation time (time zero) is known;
- the geology consists of flat homogeneous layers;
- there is a reasonably good estimate of the source position.

Although these assumptions may not be valid, they constrain the problem for initial tests of the reverse ray backpropagation technique.

ALOGORITHM DESIGN

Computer code has been written in the C language on a PC computer to test this method. Figure 3 shows the algorithm design schematically. A guess of the source position is made. Using the velocity model and receiver position a guide ray is traced from the receiver to the source using Newton's method to iteratively approximate the ray parameter P of the guide ray (Appendix A). A window of ray parameters is specified using the guide ray as the center of the window. Assuming a ray traveling to the real source position has a ray parameter within the window, using the guide ray means fewer rays need to be traced for each receiver which decreases the computation time. Rays are then traced from the receiver through the model until the travel time of the ray equals the observed travel time. The end point of each ray is a possible source position.

After the rays have been traced for all the receivers, the ray end-point data space is binned and the number of possible source positions in each bin is calculated. The bin with the largest number of possible source positions is the source position. The binned data are then output into a computer contouring package for a topographical display of the data space.

ALGORITHM TESTING - NUMERICAL SYNTHETIC DATA

The algorithm has been tested using synthetic travel times generated by ray tracing through the velocity model shown in Figure 4. The source is positioned at a depth of 1050 m and a horizontal distance of 500 m from the first receiver position. Travel times from 40 receivers, spaced at 25 m intervals from 0 m to 1000 m offset, were used in the algorithm. The travel times are accurate to 0.0001 s which is 20 times the sampling rate (0.002 s) of conventional surface seismic. So, testing the algorithm with these data will likely yield better results than can be expected with field data.

The results of applying the reverse-ray backpropagation algorithm to these data are shown in Figure 5. The possible source position data space has been binned at a 1 m interval. The bin with the largest number of source positions is easily identifiable in Figure 5, and corresponds to the bin with center at a depth of 1050.5 m and offset of 500.5 m. So the algorithm has determined the source position to +/- 1 m using these data.

The algorithm has been further tested using the same data rounded off to 0.001 s. The results of reverse-ray backpropagation are shown in Figure 6. The ray end points are again binned using a 1 m interval. The contour map (Figure 6) shows that there are three local highs, meaning that there are three possible source positions. The correct source position can be easily interpreted in this case as the middle high by assuming the source is the center of the "bow tie" in Figure 6. This high corresponds to the data bins (1050.5 m, 499.5 m), (1050.5 m, 500.5 m), and (1050.5 m, 500.5 m). Thus with synthetic data accurate to .001 s, the source position is estimated as 1050.5 m offset and at a 500 m depth +/- 1 m in either direction. However, this is after interpreting the contoured source position data space, and the mode of the ray end point is non-unique.

ALGORITHM TESTING - PHYSICAL MODEL DATA

The final test of the algorithm was on acoustic model data. The scaled acoustic model is shown in Figure 7. The data acquired for a spread of receivers spaced at 25 m intervals and a source positioned beneath the model are shown in Figure 8. The first breaks of the direct P-wave arrivals were picked by hand and input into the reverse-ray backpropagation algorithm. The result is shown in Figure 9. The data are binned at 2 m intervals. The contour map (Figure 9) shows the source position to be between a depth of 554 m and 558 m and an offset position of 1244 m and 1250 m. Thus the algorithm has determined the source position to be at a depth of 556 +/- 2 m and an offset position of 1247 +/-3 m . There was some uncertainty to the vertical position of the source under the model, as the distance of the source was measured hanging in air beneath the model. The source has some buoyancy, and it is likely that the source was closer to the model when immersed in water. The source was originally thought to be at a depth of 600 m. The horizontal location of the source is 1250 m. Thus the estimation of the vertical source location showed some discrepancy, but the method is consistent with the known horizontal source location.

DISCUSSION

The reverse-ray backpropagation algorithm has been tested using numerical synthetic data and physical model data. The results show that with noise free synthetic data, the source position can be determined within 1 m. Generally when horizontal wells are drilled Measurement While Drilling (MWD) measurements are made to determine the drill bit location so the bit can be steered while drilling. The accuracy of the inclination (the angle from vertical) of the MWD measurement is +/- 1.3° degrees at 5° inclination, +/- 0.9° at 10° inclination, and +/- 0.6° at 20° inclination (Burgess and Van de Slijke, 1990). Over 100 m, an error of +/- 1.3°corresponds to +/- 0.22 m vertically and +/- 2.25 m horizontally for an inclination of 5°. Thus the reverse-ray backpropagation technique may have some application in helping to locate the drill bit while a horizontal well is being drilled.

Another possible application of this type of geometry is to image beneath the borehole using seismic reflections. If it were important to determine the distance between the drill bit and a bed below the drill bit, the time difference between the direct arrival and the reflection from the bed could be used to calculate the distance. Thus there are several applications of the geometry of a downhole source in a horizontal well and a spread of receivers along the surface. This may help motivate the development of a downhole source.

There are several other sources of error which have not been tested using the reverse-ray backpropagation algorithm. How accurately can the travel time be picked with bandlimited data? It appears that errors associated with time picking are a factor, causing a decrease in the accuracy of the source estimation. As shown by the physical model data, travel times picked crudely by hand led to a vertical error of +/- 2 m and a horizontal error of +/- 3 m for the source location. Also, statics are likely to be a problem. For example, a near surface low velocity pod 50 m thick with a 500 m/s velocity contrast from laterally adjacent sediments would result in a .01 ms time shift. This is a considerable shift which will likely cause errors in the estimated source position. A possible solution to this problem is to detonate the source in the vertical portion of the well where the depth is known very accurately and use the travel times in a travel time inversion algorithm to determine the velocity structure.

CONCLUSIONS

The reverse-ray backpropagation a has been shown to have application to locating a down hole seismic source. The technique is accurate to +/- 1 m for synthetic data accurate to 0.0001 s. Decreasing the accuracy of the data to 0.001 s resulted in a scatter of possible source positions. The correct source position could easily be interpreted to within 3 m horizontally and +/- 1 m vertically. Using the algorithm on physical model data resulted in an estimate of the source location accurate to +/- 2 m vertically and +/- 3 m horizontally. Thus the reverse ray backpropagation can be used to locate a subsurface source position, however, the accuracy is limited to +/- 5 m for noise free physical model data.

REFERENCES

Anton, H., 1984, Calculus with analytic geometry: John Wiley and Sons.

Burgess, T. and Van de Slijke, P., 1990, Horizontal drilling comes of age: Oilfield Review, Vol 2, No 3, 22-33.

Chang, W. and McMechen, G.A., 1986, Reverse-time migration of offset vertical seismic profiling data using the excitation-time imaging condition: Geophysics, 51, 67-84.

APPENDIX A - NEWTON'S METHOD

Newton's method (Anton, 1984) can be written for the ray parameter as

$$P_{n+1} = P_n + \frac{F(P_n)}{F'(P_n)}. \qquad (1)$$

If we let $F(P_n)$ be the error term for the horizontal component of the source position
where

$$F(P_n) = X_s(P_n)-X_s\,, \qquad (2)$$

and

$$F'(P_n) = \frac{F(P_n+\varepsilon)-F(P_n)}{(P_n+\varepsilon)-P_n}\,, \qquad (3)$$

where ε is a small number,
so

$$\frac{F(P_n)}{F'(P_n)} = \frac{F(P_n)}{\frac{F(P_n+\varepsilon)-F(P_n)}{\varepsilon}}\,, \qquad (4)$$

or

$$\frac{F(P_n)}{F'(P_n)} = \frac{\varepsilon F(P_n)}{F(P_n+\varepsilon)-F(P_n)}\,,$$

so substituting into (1) yields

$$P_{n+1} = P_n + \frac{\varepsilon F(P_n)}{F(P_n+\varepsilon)-F(P_n)} \qquad (5).$$

Equation (5) can be solve numerically by using an initial guess for P_n from the geometry of the guessed source position, receiver position and average velocity through the model, where $P_n = \sin(\theta)/Vavg$, and $P_n + \varepsilon$ is used to find the slope of the error function curve. The new value for P_{n+1} is calculated and input back into equation (5). This process is continued until the error function is less than 5 m.

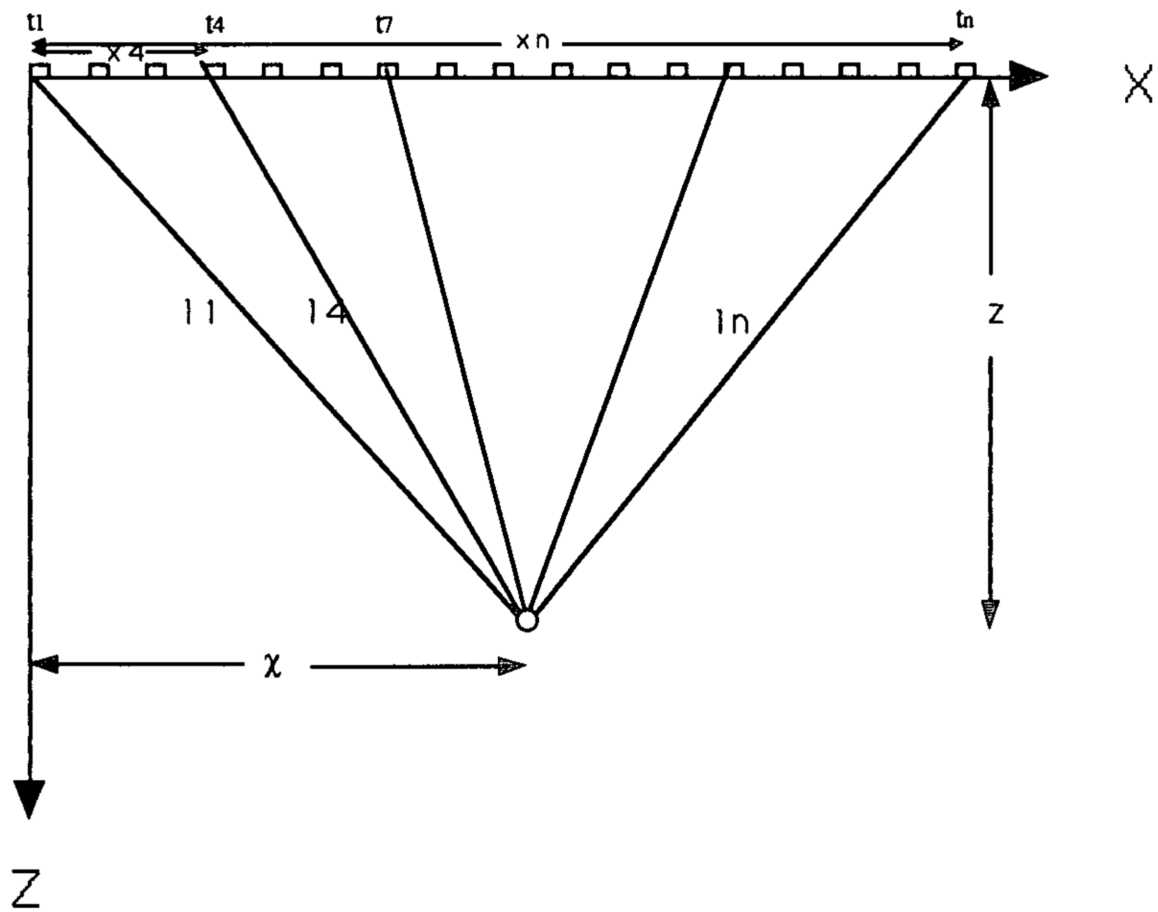

FIG. 1. Experiment geometry showing a source in the subsurface, and a 2-D line of receivers along the surface.

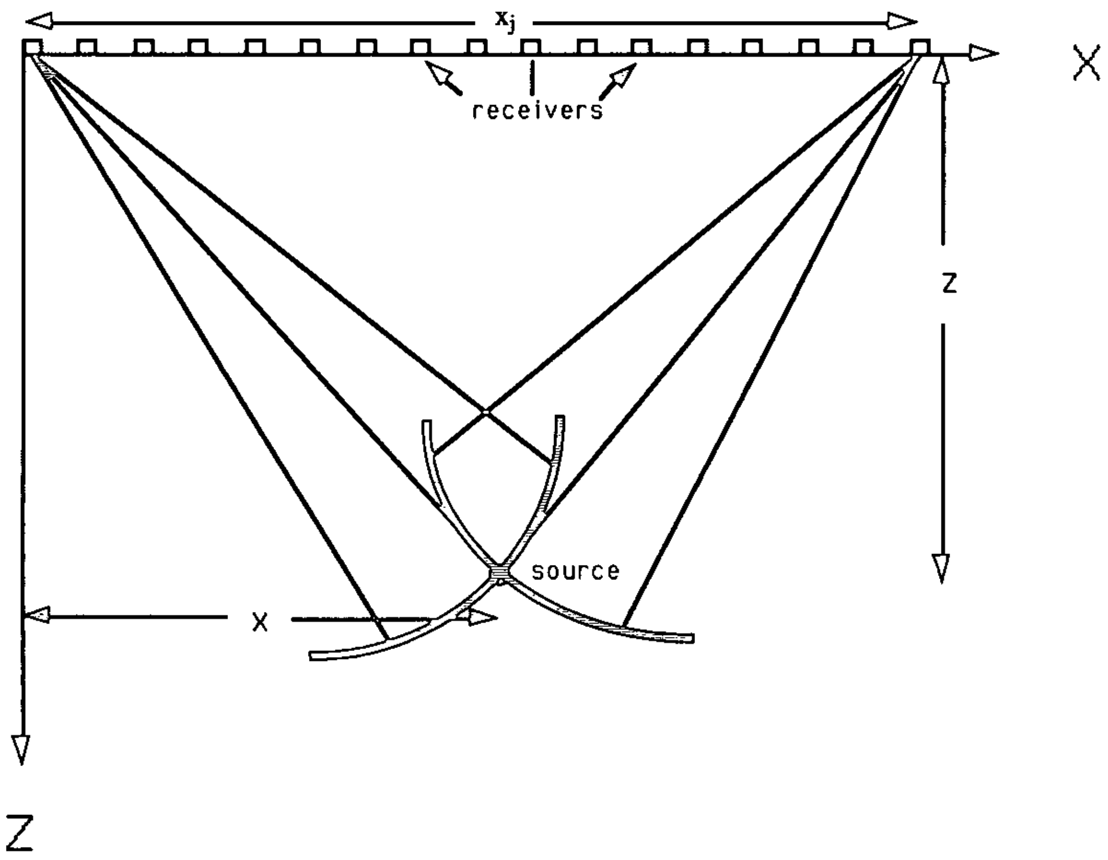

FIG. 2. Reverse-ray backpropagation for 2 receivers. Note that the end points of the rays cross at the source location.

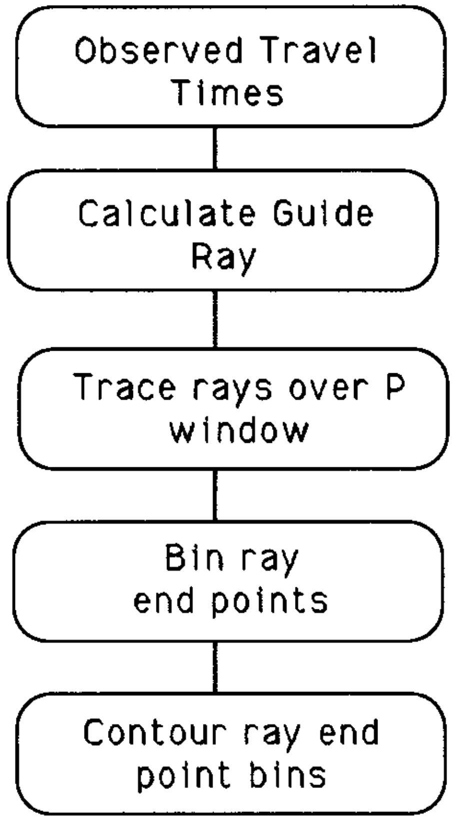

FIG. 3. Reverse-ray backpropagation algorithm design

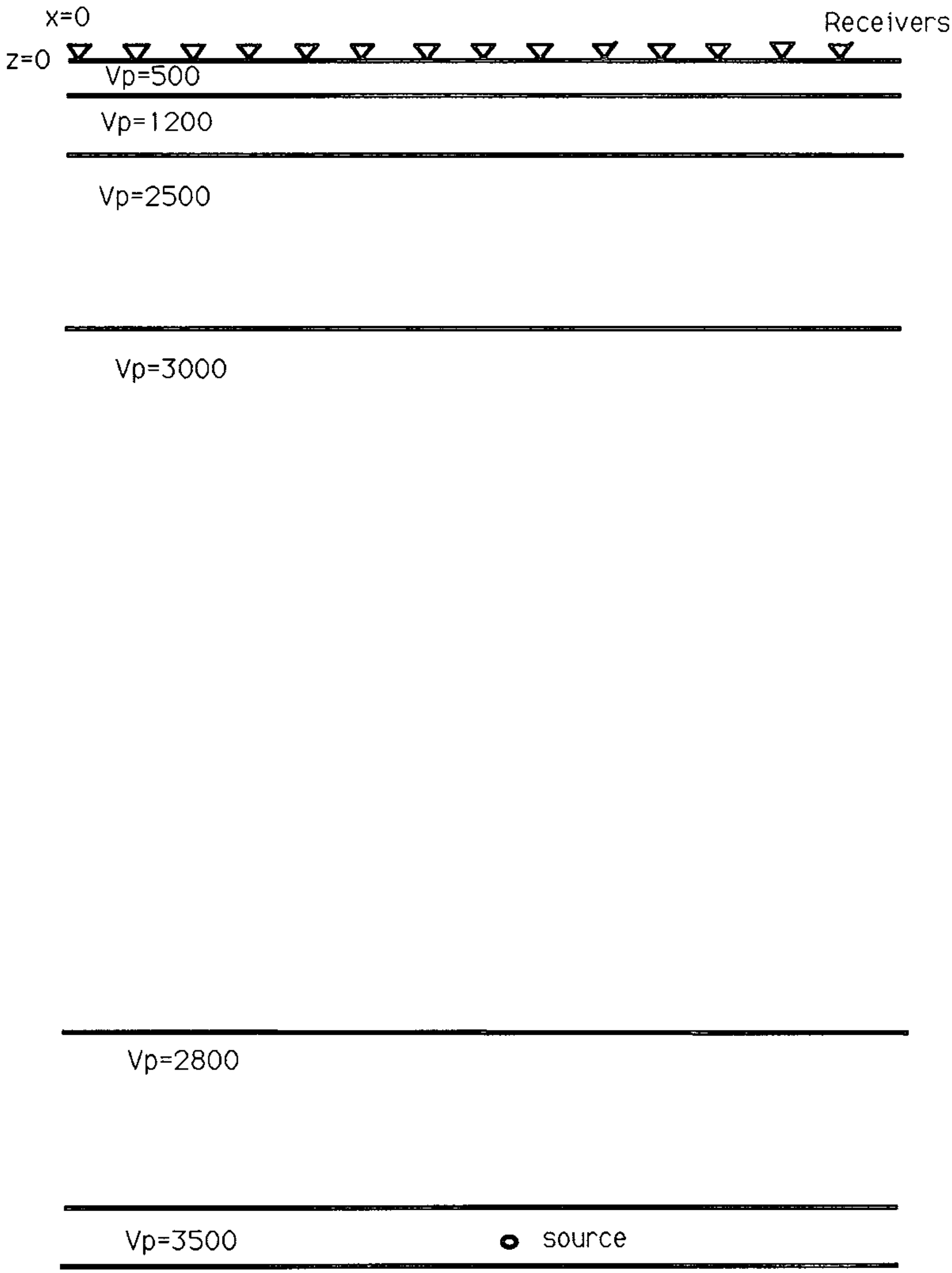

FIG. 4. Velocity model for synthetic data.

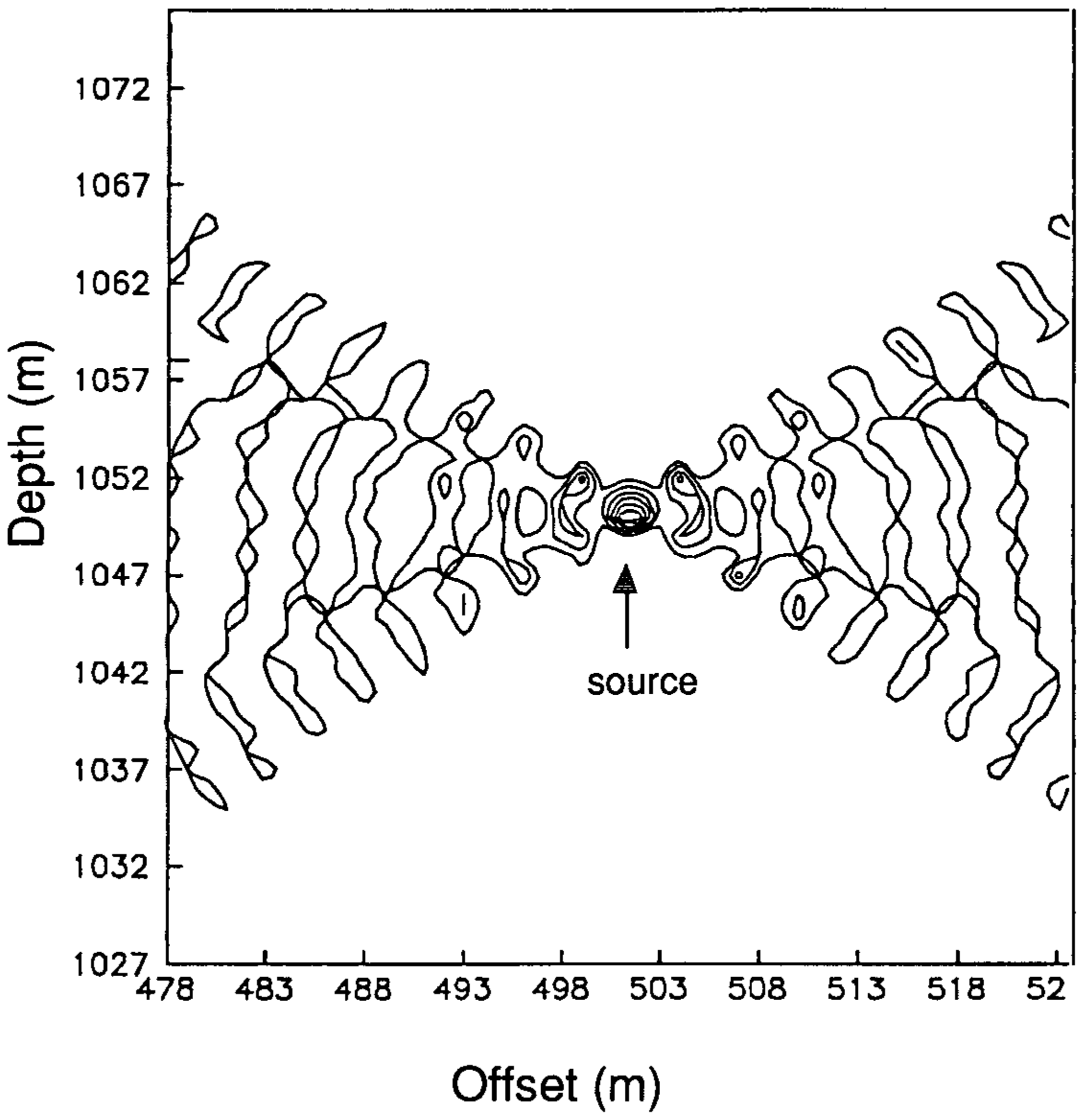

FIG. 5. Binned contour map of synthetic data accurate to .0001 s.

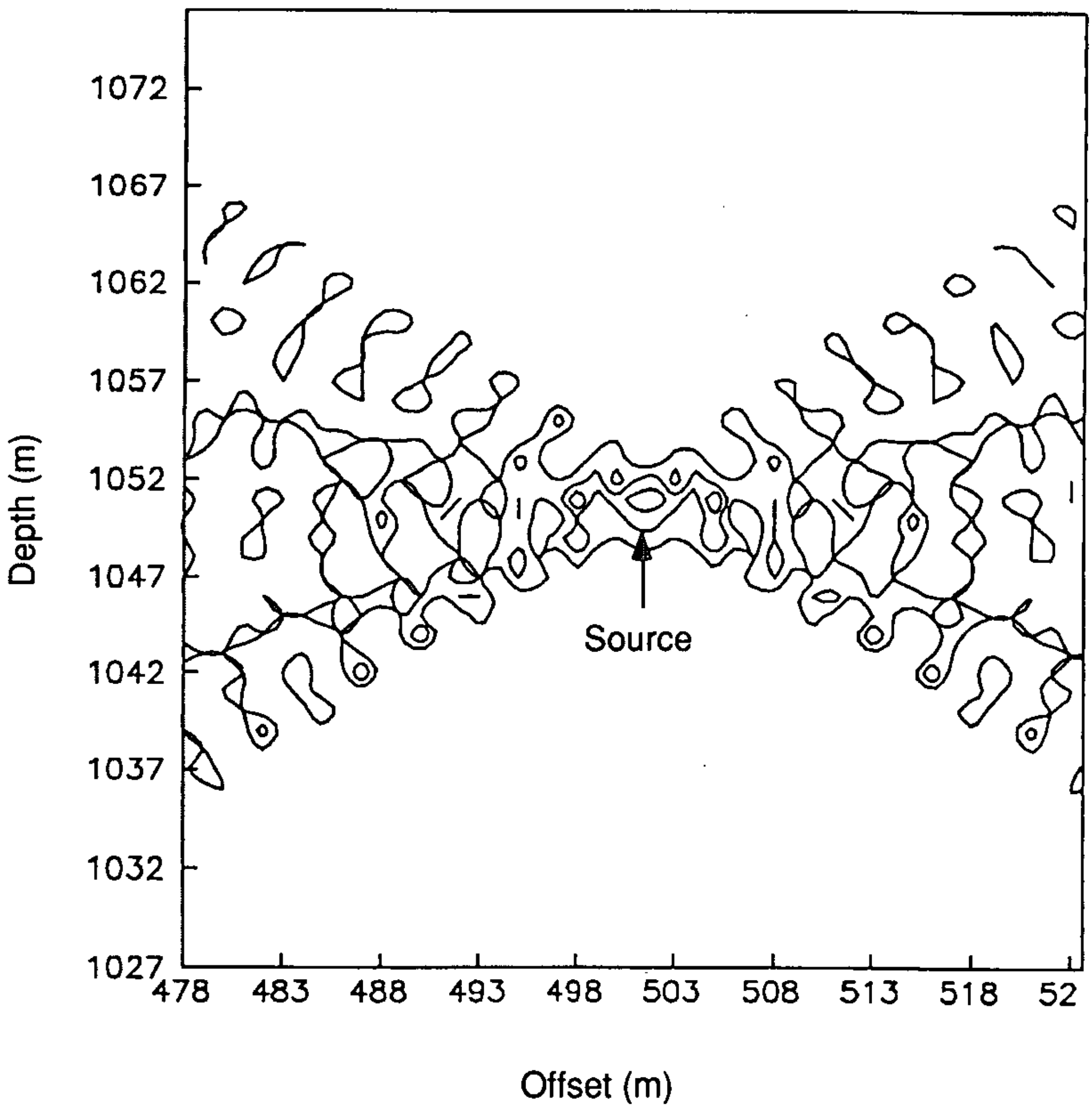

FIG. 6. Binned contour map of synthetic data accurate to 0.001 s.

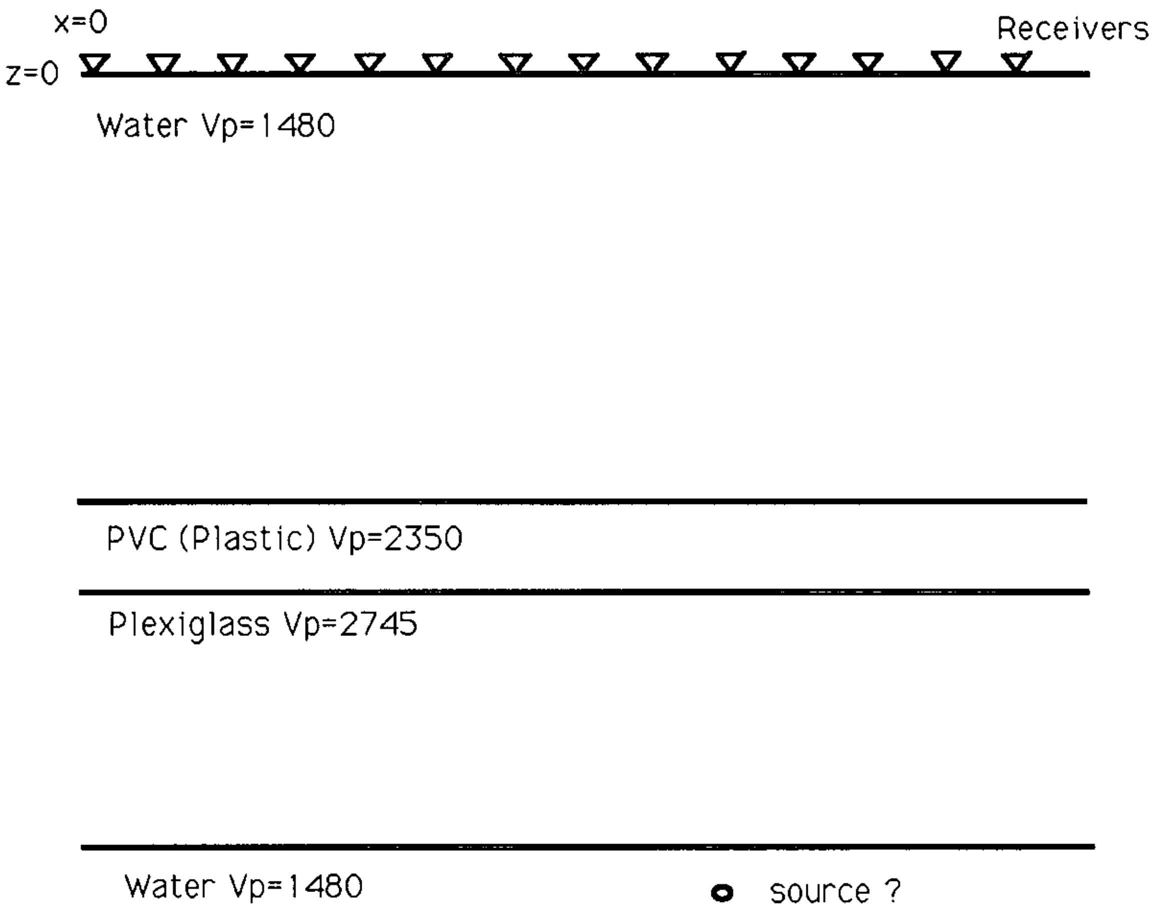

FIG. 7. Velocity model and geometry of the physical modeling tank experiment.

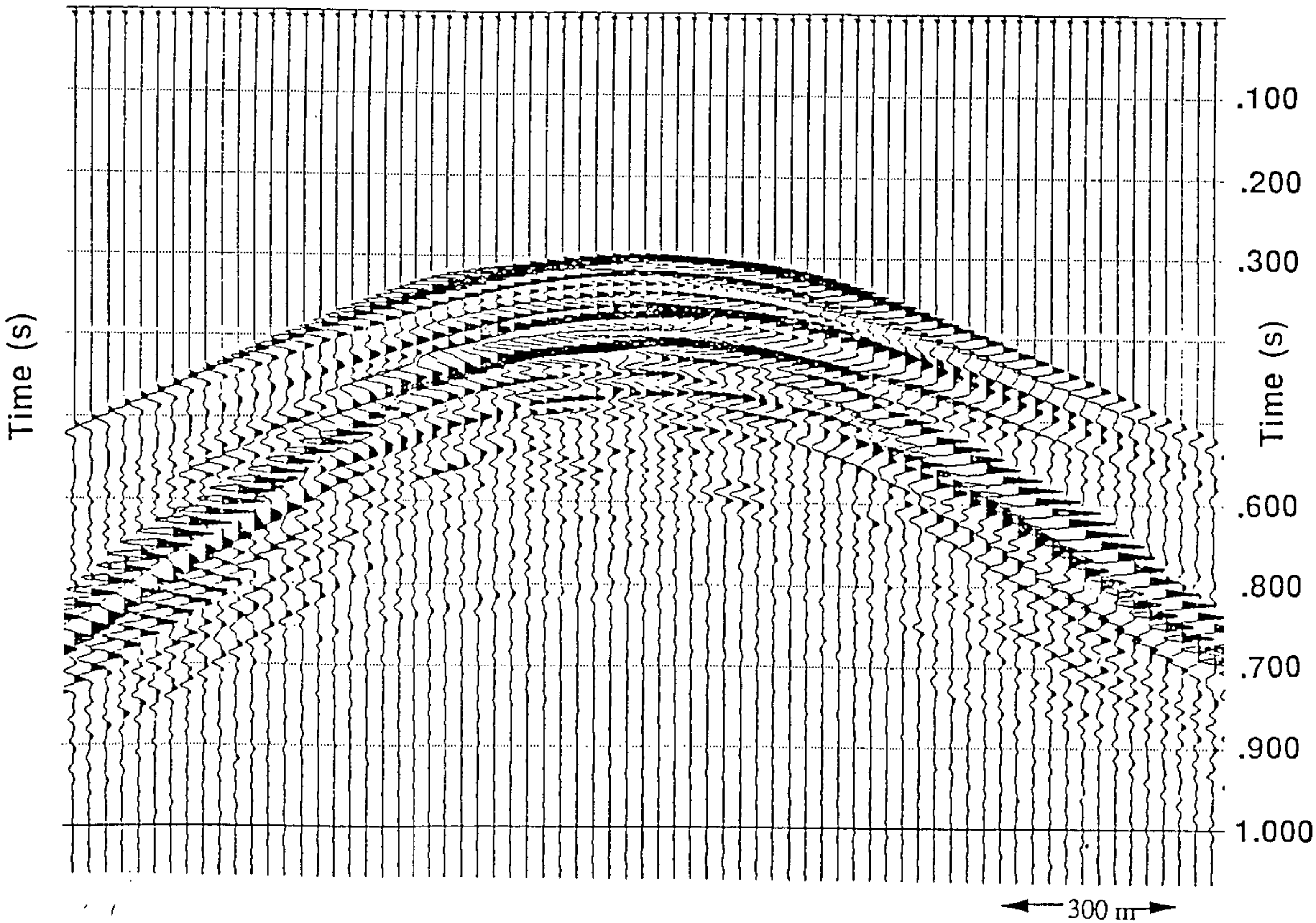

FIG. 8. Physical model data from acoustic modeling tank.

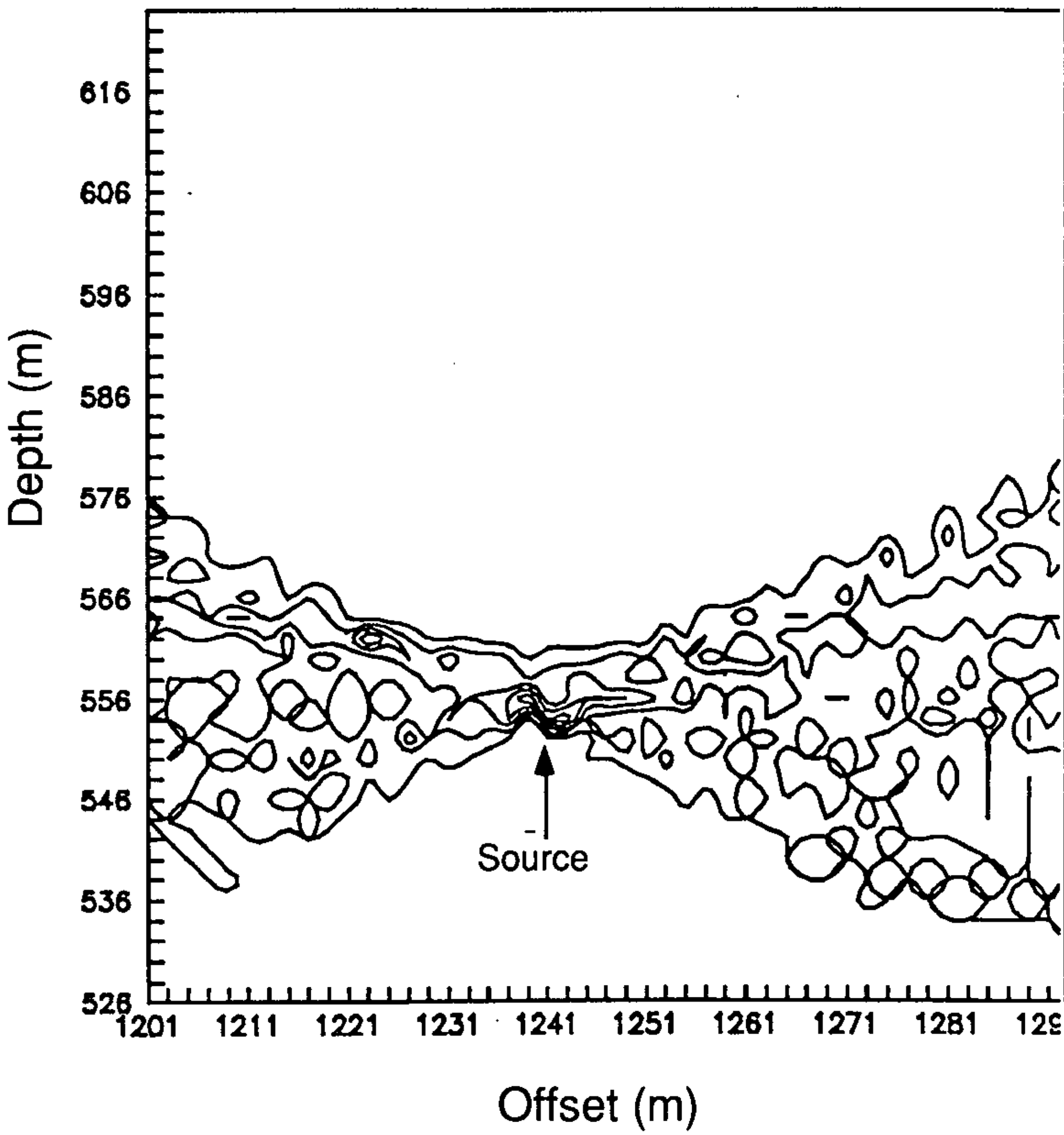

FIG. 9. Binned contour map of physical model data.