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A Vertical Array Method for Shallow Seismic Refraction Surveying of the Sea Floor

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INTRODUCTION

In recent years, specific requirements in offshore geotechnical site investigations, as well as detailed defense research studies, have stimulated research interest in methods of measuring seismic velocities of seafloor sediments on the continental shelves. Investigations have utilized wide-angle subbottom reflection measurements (McKay and McKay, 1982), bottom-laid refraction cables (Hunter et al., 1979), and towed refraction arrays, both on surface (Hunter and Hobson, 1974), and at depth (Fortin et al., 1987; Fagot, 1983).

This paper discusses the concept of a vertical array of hydrophones in the water column for the measurement of compressional velocities of waves refracted through the immediate sub-seabottom. The method is designed for use primarily in ice-covered waters of continental shelves, but it has potential applications in deep ice-covered rivers and lakes, and it may be possible to use the technique in open waters with a two-ship operation.

Until now, measurements of refraction velocities of bottom sediments in ice-covered waters have been carried out by deploying bottom-laid arrays through available open leads in sea-ice (Hunter et al., 1976), or by placing individual hydrophones of an array on the seabottom through holes in the ice, a technique used in shallow water only (Kurfurst and Pullan, 1985). The advantage of the vertical array concept lies in the relative ease in deploying the hydrophone array and sources, as well as in adjusting the array geometry to obtain the desired depth of penetration and resolution.

THEORY

Figure 1(a) illustrates the geometry of the field set-up for a vertical array experiment. The diagram shows the lowest receiver (hydrophone) to be at the water-bottom interface, although it need not be. Seismic impulsive sources (explosives, air or water-guns, sparker, etc.) can be placed either on the sea floor or in the water column at an offset from the vertical receiver array. In practice, several offsets may be required.

For a model consisting of a vertical array and a series of flat-lying subbottom refractors, the travel times of first arrival events can be expressed by simple mathematical formulas. The travel time of the direct wave through water from the source to one receiver of the array is:

$$t_o = \frac{\sqrt{x^2 + (h_r - h_s)^2}}{V_o} \tag{1}$$

where: V_o = velocity of water

x = source-array offset

h_s = height of source above bottom

h_r = height of receiver above bottom

The travel time of the refracted wave along the bottom is given by:

$$t_1 = \frac{x}{V_1} + (h_r + h_s)\frac{\sqrt{V_1^2 - V_o^2}}{V_1 V_o} \tag{2}$$

where h_r, h_s and V_o are as given above, and V_1 is the velocity of the immediate subbottom layer.

The travel time of a refracted wave along layer m is:

$$t_n = \frac{x}{V_n} + (h_r + h_s)\frac{\sqrt{V_n^2 - V_o^2}}{V_n V_o} + \sum_{m=1}^{n-1} 2\, Z_m \frac{\sqrt{V_n^2 - V_m^2}}{V_n V_m} \qquad (3)$$

where Zm is the thickness of layer m.

If the first arrival travel times are plotted as a function of the height of the receiver above the bottom (hr) as shown in Figure 1(b), the form of the data is similar to that of standard horizontal surface array refraction plots, at first glance. Refractors from bottom and subbottom layers appear as straight line segments having slopes given by:

$$S_n = \frac{\Delta t_n}{\Delta h_r} = \frac{\sqrt{V_n^2 - V_o^2}}{V_n V_o} \qquad (4)$$

Unlike the conventional T-X refraction plots, the slope Sn increases with increasing refractor velocity. Thus, the events arriving earliest in time at small hr are from the deepest subbottom refractor observable for the source offset x and the shot height hs.

From slope measurements (equation 4) and the intercept times of straight line segments (equation 3 for $h_r = 0$), layer thicknesses can be calculated in a straightforward manner for a model consisting of horizontal sub-seabottom layers and a vertical receiver array. Extending the analysis to a more realistic earth model and field situation, with dipping refractors and a non-vertical array, results in more cumbersome mathematical relationships (not shown here), which lend themselves to computer model fitting rather than analytic solutions. Such modelling requires arrival times from the direct water wave (later events) to be utilized in the analysis. However, experience has shown that convergence to a best-fitting model can easily be obtained.

Analyses of dipping refractor models have shown that apparent velocities of refractors for down-dip and up-dip shooting are similar to those encountered in conventional surface refraction work. Modelling suggests that field operations to test for dipping refractors can be accomplished by either shooting into the array from different directions (requiring the drilling of additional shot holes, if working through the ice), or, if dip in the vertical plane of the experiment only is required, by recording one shot with the source on the bottom (h_s=0), and recording a second shot using the same shot-hole, but with the source higher in the water column (h_s>0).

VERTICAL SENSITIVITY

Figure 2 shows. a plot of slope Sn (equation 4) with respect to Vn for a vertical array (solid line) assuming a water velocity V_o = 1460 m/s. Large charges in Sn occur for small charges in Vn for velocities less than about 2000 m/s; that is, for velocities associated with water-saturated unconsolidated materials (clays and sands).

The dashed lines indicate the apparent measured velocities assuming that the array is off-vertical by +/-10 degrees. Such deviation from vertical could occur in practise with a poorly-weighted array in the presence of a strong water current. Figure 2 indicates that the errors involved in estimating refractor velocities for V_n <2000 m/s are small even if the angle of the array is not detected by the water-break travel-time analysis and is not taken into account.

To compare the sensitivity of the vertical array with that of a horizontal array laid on the seabottom, Figure 3 shows a plot of the derivative of the slope of a straight line segment as a function of V_n, assuming a water velocity of V_o = 1460 m/s. This figure indicates that the sensitivity of the vertical array exceeds that of a horizontal array by a factor of 4 at very low refraction velocities. This advantage disappears at velocities above 2060 m/s where the horizontal array is more efficient. Hence, a vertical array should be employed if the objective of the survey is to obtain accurate velocities of subseabottom unconsolidated sediments; whereas a horizontal array would be a more accurate approach if the objective is to obtain velocities of subbottom bedrock.

To illustrate the practical effect of the higher sensitivity of a vertical array in measuring sediment velocities, a model consisting of a 10 m thick seabottom layer with a velocity of 1500 m/s (clay) overlying a semi-infinite layer with a velocity of 1600 m/s (sand) was examined. Seawater velocity was assumed to be 1460 m/s. For a vertical array, travel-time vs. receiver height off the bottom (h_r) for a shot offset of 150 m was plotted (Figure 4(a)). The corresponding plot of travel-time vs. source-receiver offset for a horizontal seabottom array is shown in Figure 4(b). Both plots have similar absissa and ordinate scales. For the horizontal array (Figure 4(b)) the plot is centered on the subtle breakover between 1500 m/s and 1600 m/s. However, the breakover between these layers when using a vertical array is, in comparison, a much more pronounced one. This suggests that less interpretation error in analyzing travel times and in the selection of segments corresponding to subbottom layers would result when using data obtained with a vertical array.

FIELD EXAMPLE

A field test of the vertical array was carried out on the ice-covered Ottawa River near Ottawa. The field geometry and layer interpretation are shown in Figure 5. A 12-channel array, with spacings of 3 meters between hydrophones, was deployed in 40 meters of water through a hole in the ice. At three shot hole locations, offset 50, 100 and 150 meters from the array, small dynamite charges were detonated on the river bottom. With this field set-up it was possible to obtain- velocity structure to depths in excess of 40 m subbottom. In differing field situations (for example, deeper water), it is possible to alter both shot offsets and vertical position of the array to obtain deeper subbottom penetration without substantial alteration of the design of the array.

Figure 6 shows a set of field seismograms recorded with an engineering seismograph at the site. Low amplitude, low frequency refractors can be observed as first arrivals on all records. Because of the limited dynamic range of the instrument, later arrivals are "clipped" due to amplifier saturation. The water wave arrival can be seen as a high frequency event superimposed on the clipped low frequency signal. Recording instruments with greater dynamic range would be necessary to preserve the precise onset of the water wave event. This is important because primary array positioning information is derived from the water wave arrivals.

An "ice-arrival", from waves which travel up through the water column and are then refracted through the surface ice, can be seen as an interfering event on near surface hydrophones. Water depth beneath the ice is thus a limiting factor in the use of this technique.

Figure 7 shows the travel-time vs. hydrophone height data obtained from the field records shown in Figure 6, along with the "best-fit" velocity model determined by computer analysis. The bottom sediment layers with velocities of 1640 m/s and 1740 m/s probably represent coarse-grained glacial till or till-derived materials, since tills occur on shore at the site. Two velocity layers were interpreted for bedrock. It is known that varying thicknesses of Paleozoic dolostone overlie Precambrian granite gneiss in the area, and the two derived velocities are consistent with an interpretation of both units existing at this site.

Since there is a current flowing in the Ottawa River, the hydrophone array was weighted at intervals over its active length so that it would stream in a straight line when deployed. The "best-fit" model from waterwave and refractor data indicated that the array was at an angle of 5.25 degrees off vertical.

As well, because of current drift while the shots were lowered to the bottom, the surface positions of the dynamite sources could only be used as a guide in the determination of the actual shot-array offset. This is not a serious problem in the iterations involved in model fitting, since the derived offset must fit both first arrival refractor velocity and water arrival events at $h_r=0$, while the refractor velocity is obtained through slope analysis.

CONCLUSIONS

The vertical array concept is a novel approach to seismic refraction surveying of seafloor sediments. It has potential applications in a number of engineering geophysics problems in ice-covered waters of northern latitudes, especially in deeper waters of continental shelves. The vertical array has a much better sensitivity or potential resolving power to discriminate velocity variations in low velocity sediments than does a horizontal bottom-laid array. Hence it might be advantageous to use this technique in open water areas, if the recording ship and the shooting ship can maintain station during deployment of both the array and the source.

To date, field experience has been limited to shallow water tests in the Ottawa River, but testing on ice-covered continental shelves is planned for the near future.

ACKNOWLEDGMENTS

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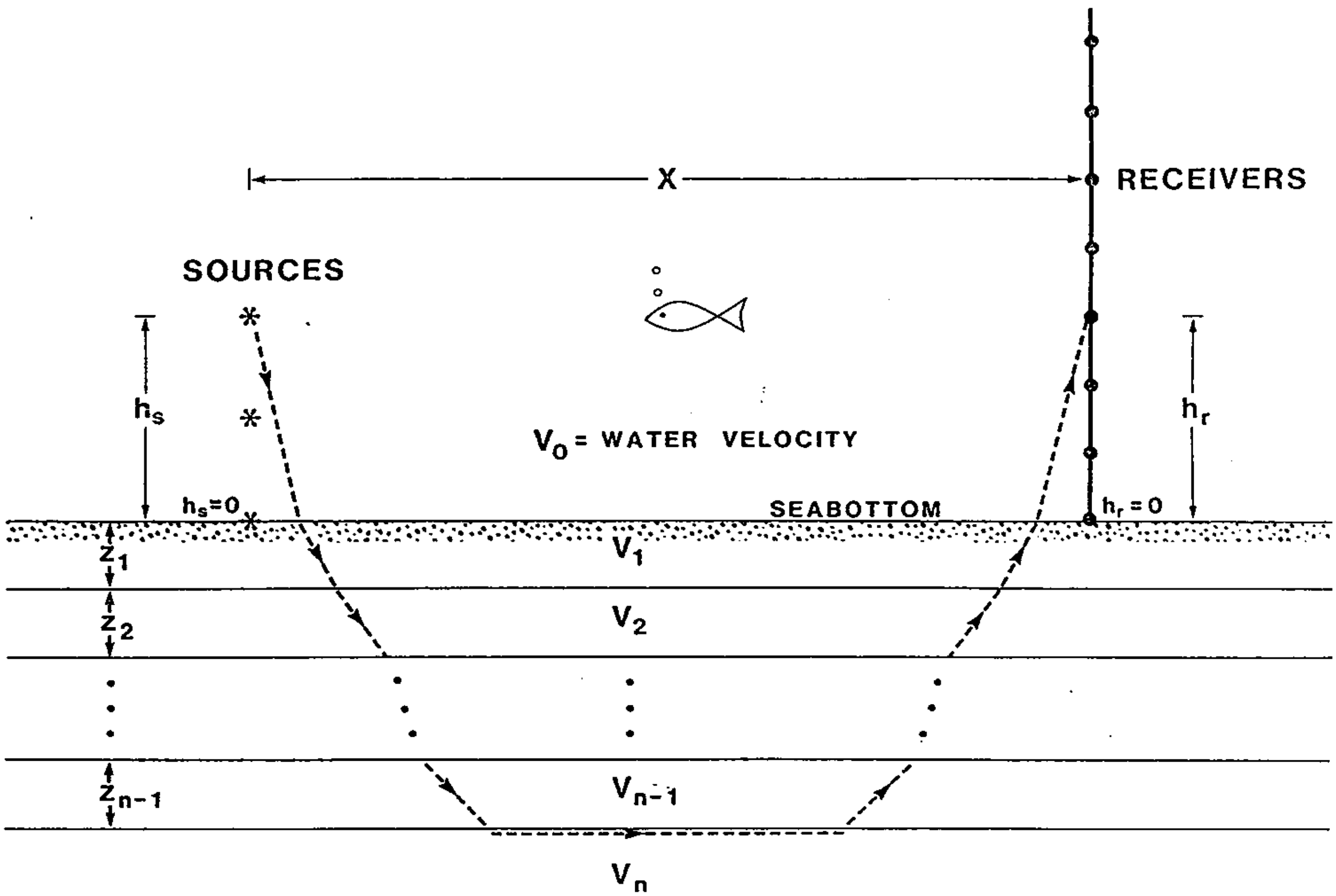

Figure 1(a): Geometry of a vertical array refraction experiment assuming flat-lying subbottom refractors.

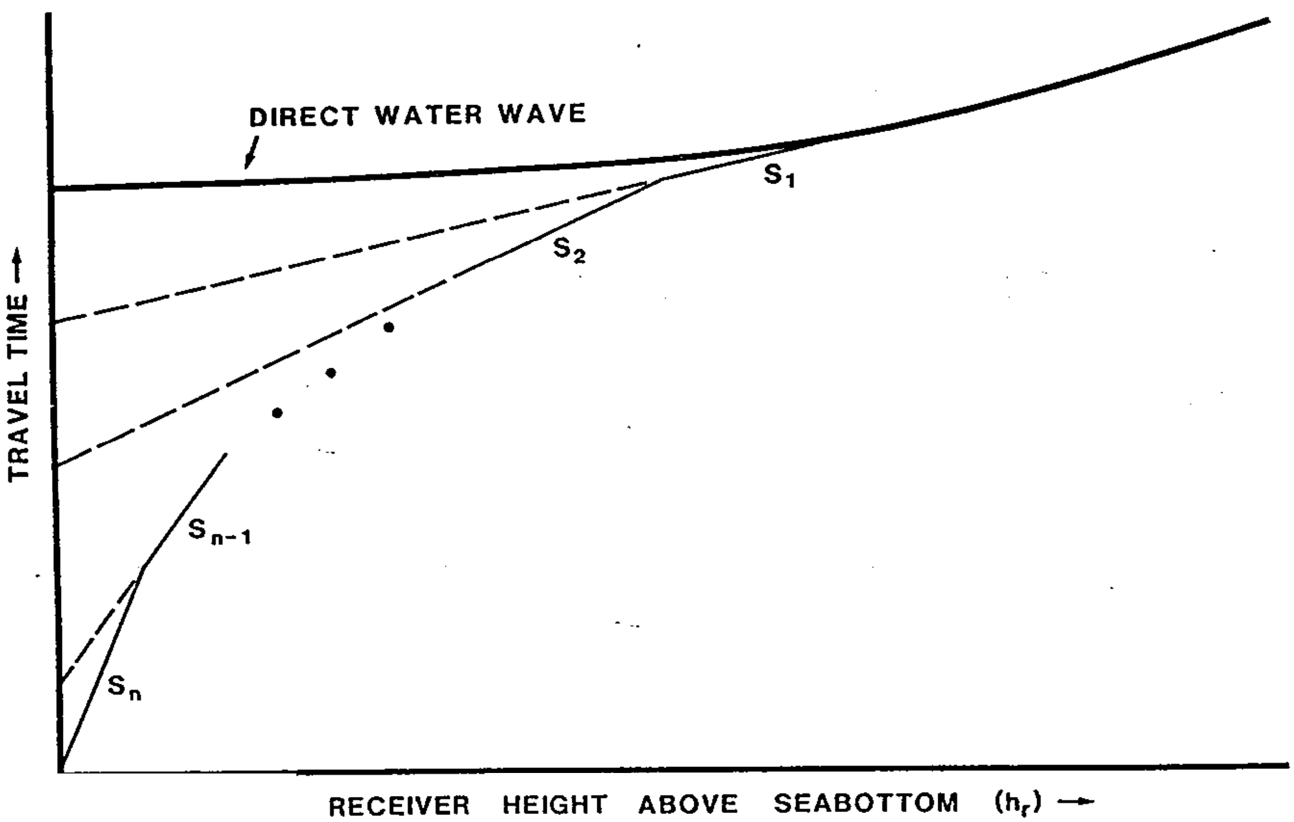

Figure 1(b): First arrival travel time plotted as a function of the height of the receiver above the bottom. Refracted arrivals from bottom and subbottom layers appear as straight line segments while the water wave arrival has a hyperbolic shape.

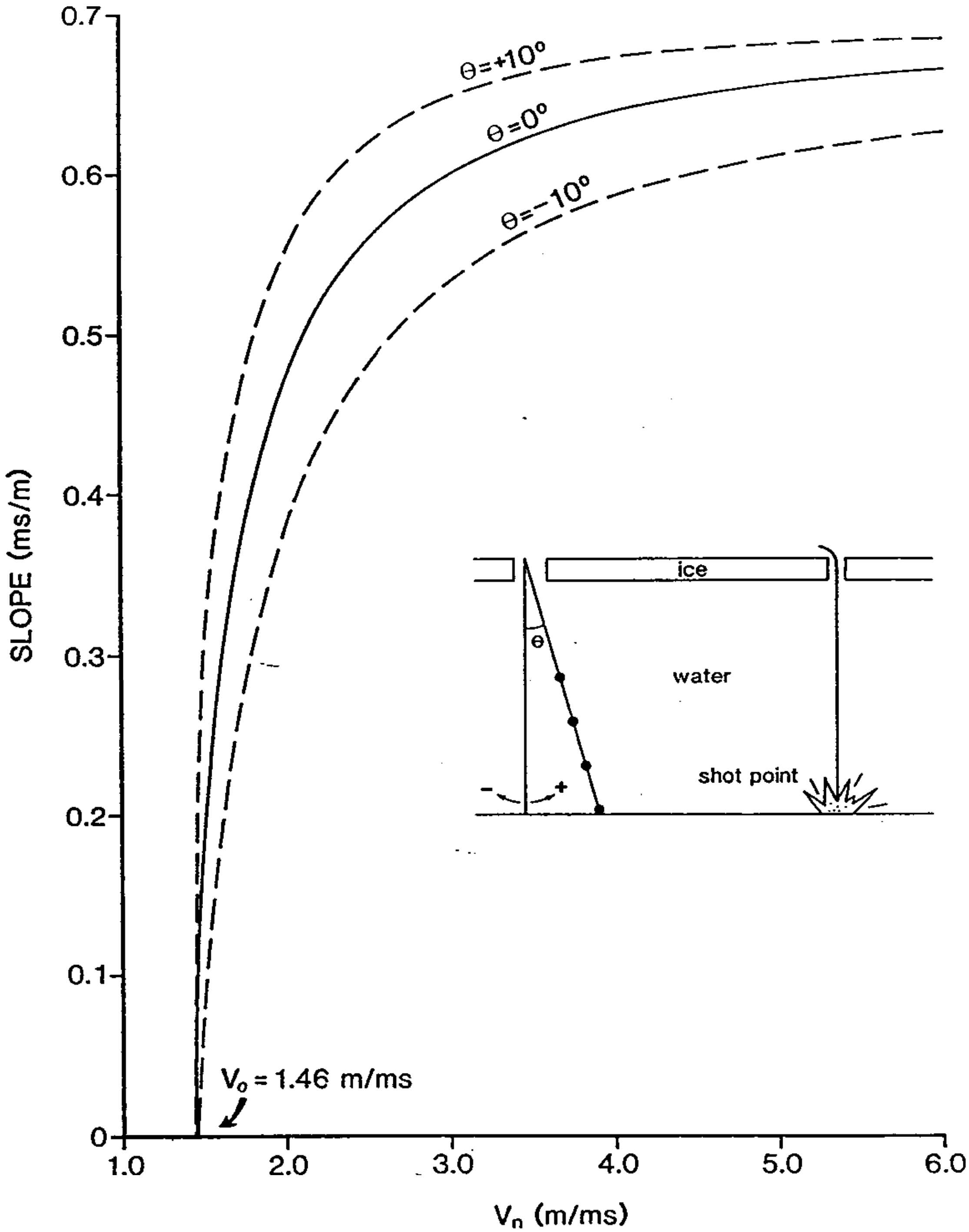

Figure 2: Plot of refractor slope versus refractor velocity showing the high sensitivity of the data to small changes in velocity for velocities below 2000 m/s. The dashed lines indicate the errors in measurement if an array that was deployed at angles of +/-10° was assumed to be vertical.

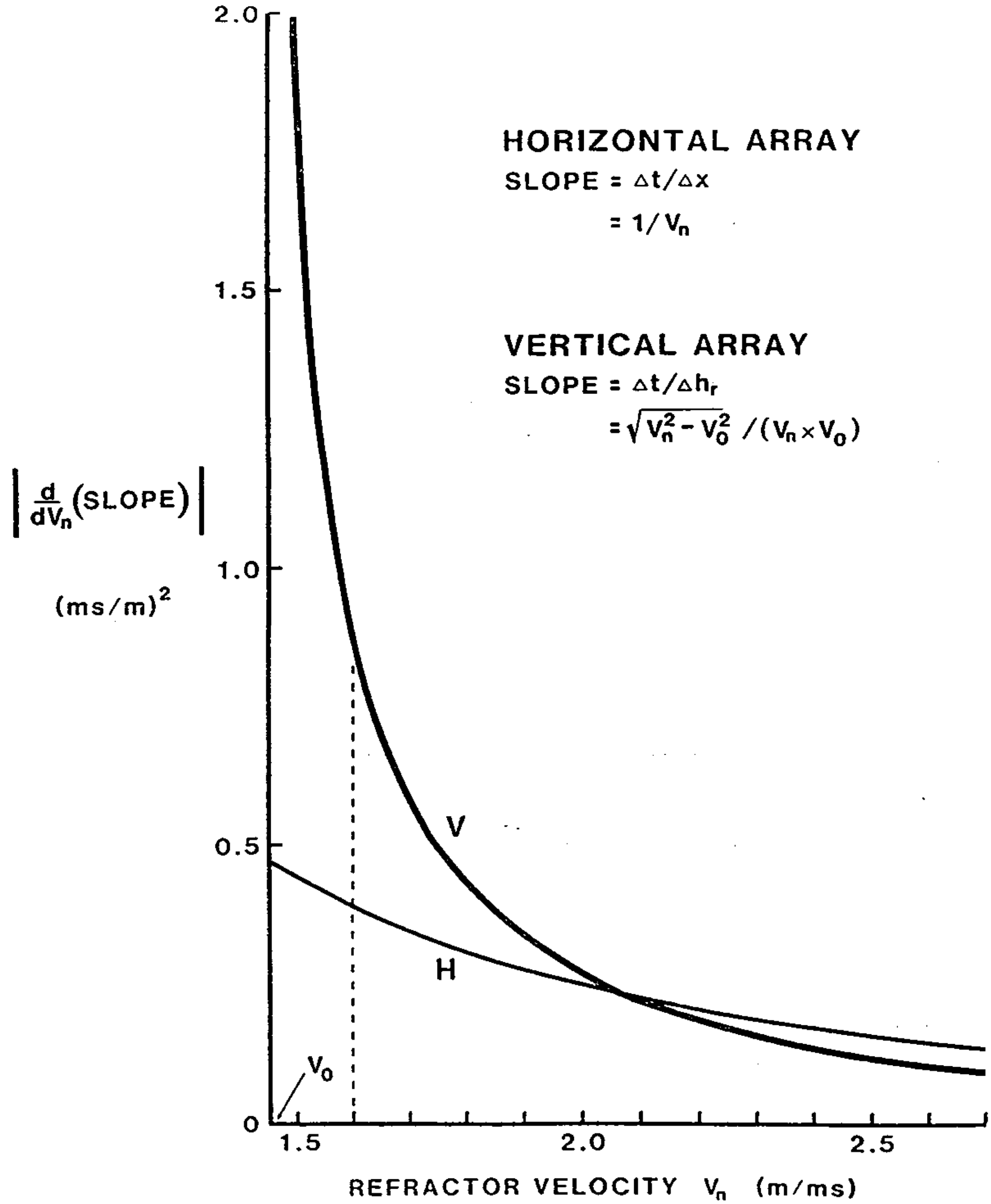

Figure 3: Plot of the derivative of the slope of refracted arrival line segments as a function of the refractor velocity for both the horizontal and vertical array. This shows the sensitivity of the vertical array in measuring refractor velocities exceeds that of the horizontal array for velocities below 2060 m/s.

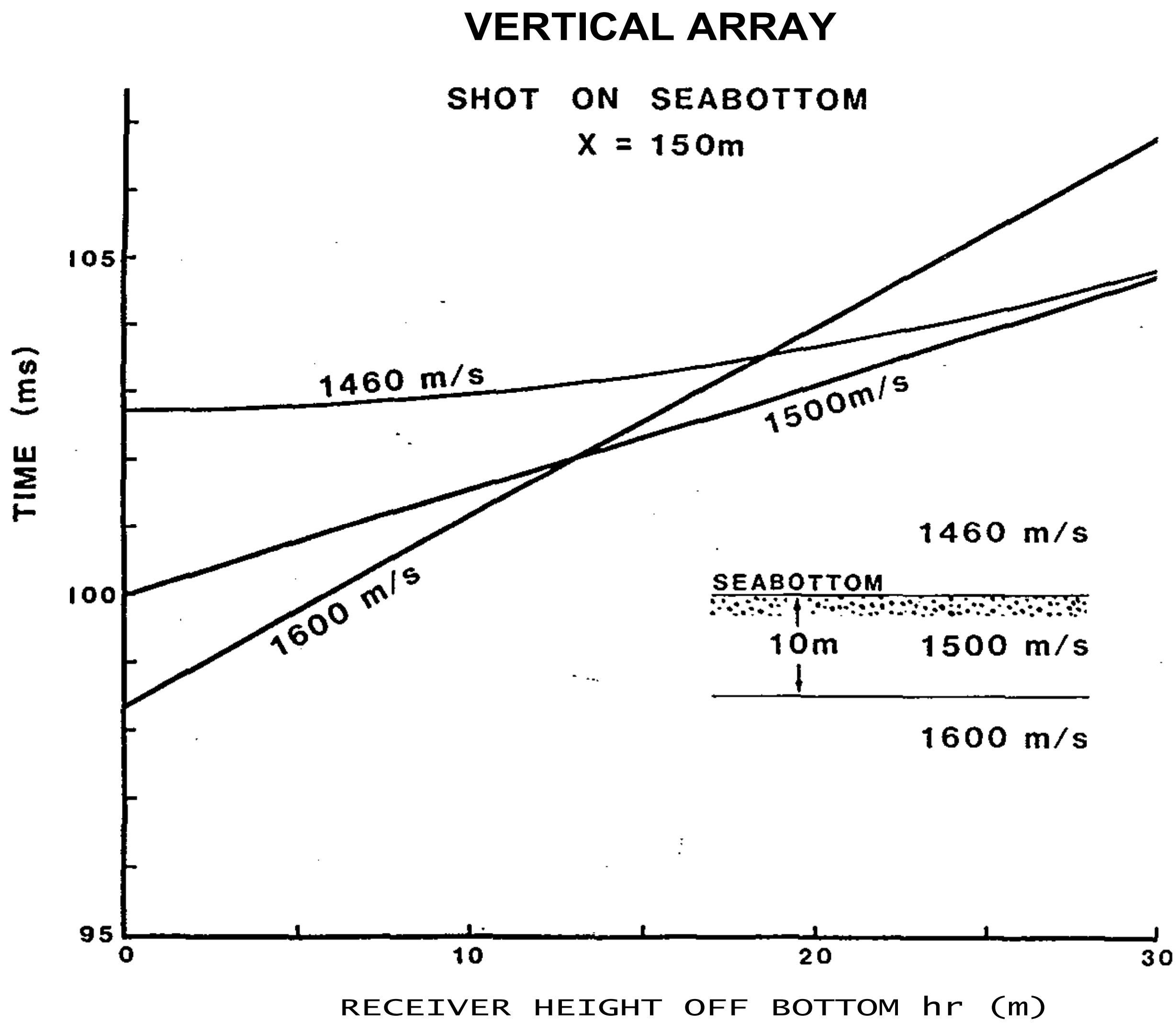

Figure 4(a): Calculated T-h_r plot for a vertical array in the water column and a source offset of 150 m, assuming the velocity model shown in the inset.

HORIZONTAL SEABOTTOM ARRAY

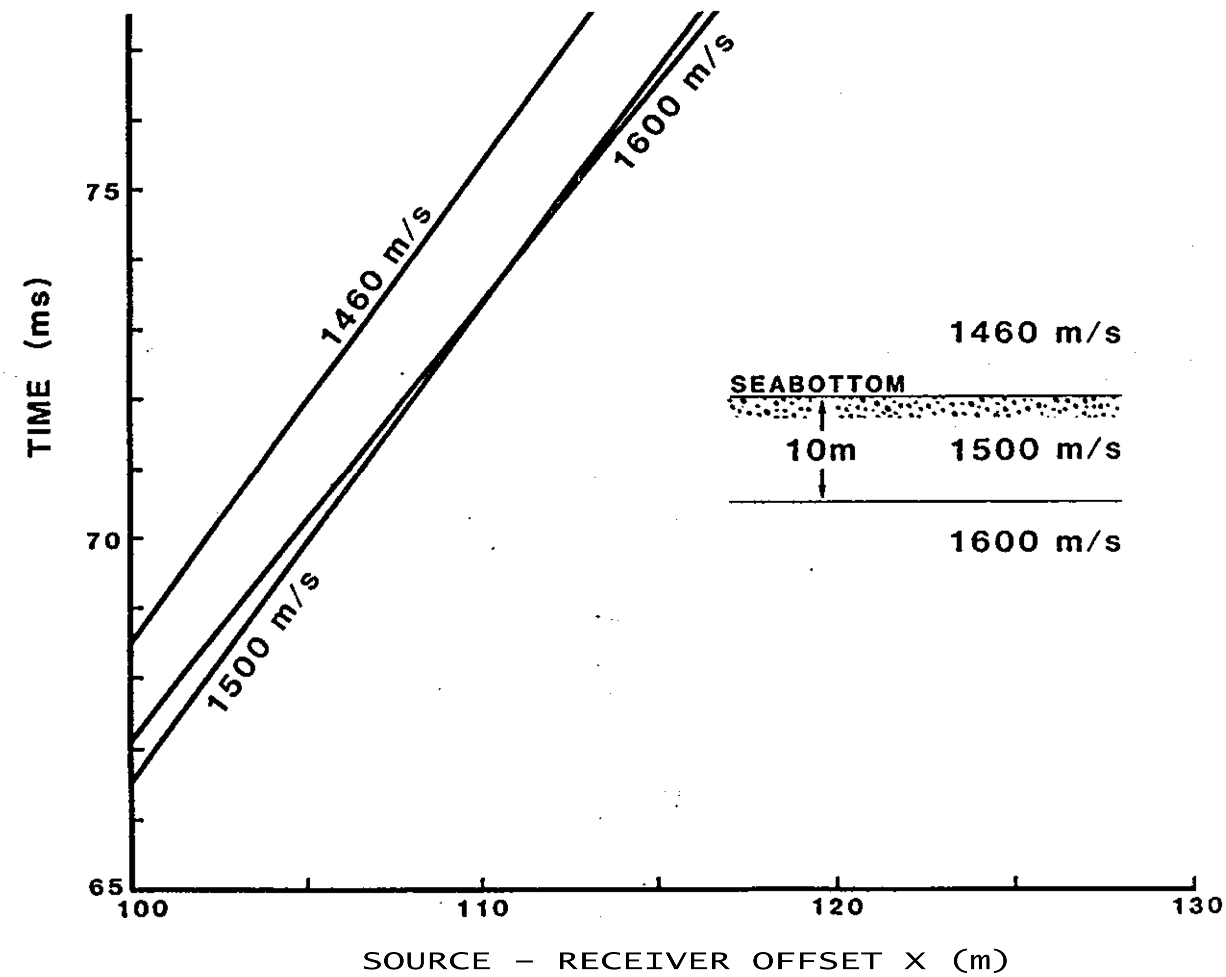

Figure 4(b): Calculated T-X plot for a horizontal seabottom array assuming the same velocity model. The breakover between the two straight line segments is much less pronounced than in the case of the vertical array.

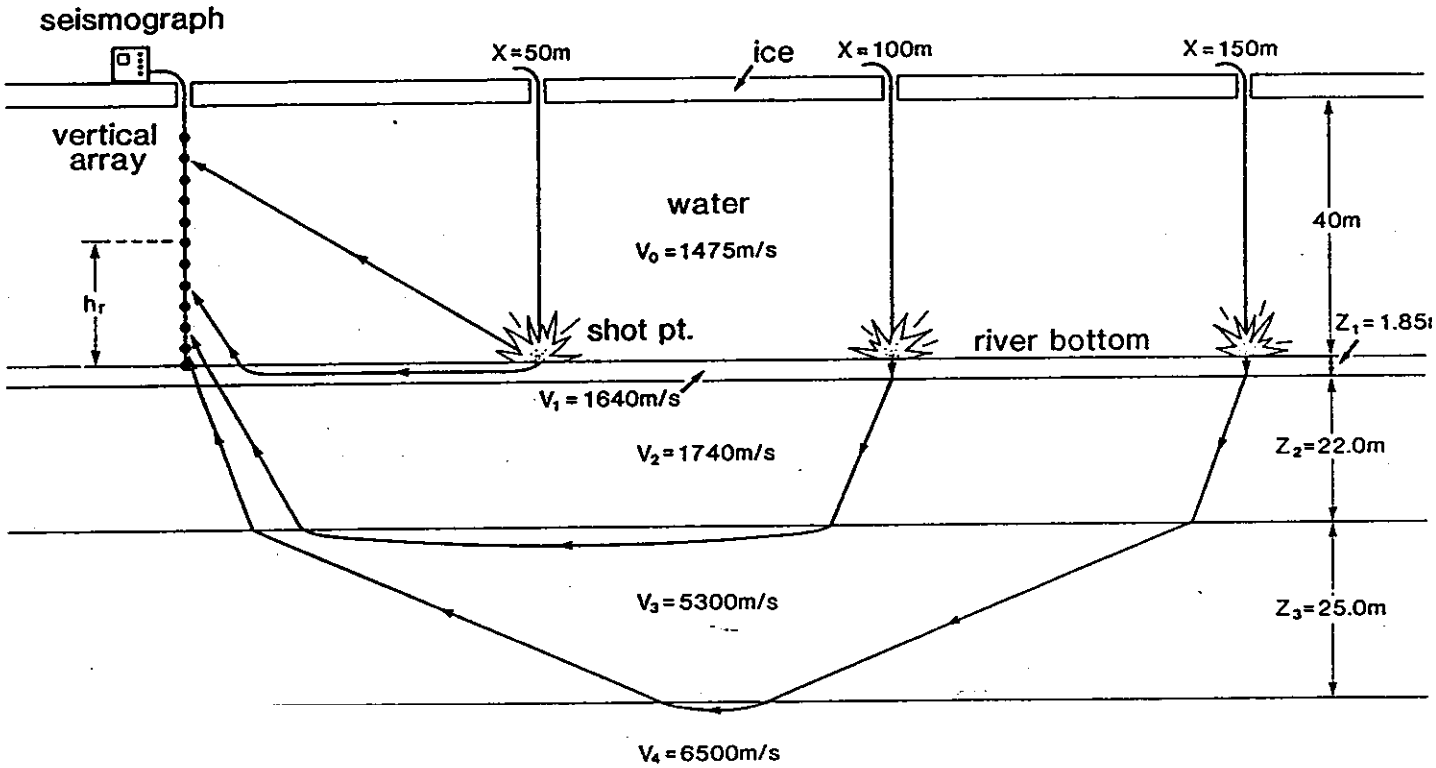

Figure 5: Field set-up for the Ottawa River vertical array experiment. The velocities and thicknesses of the subbottom layers were derived from an interpretation of the results obtained at this site.

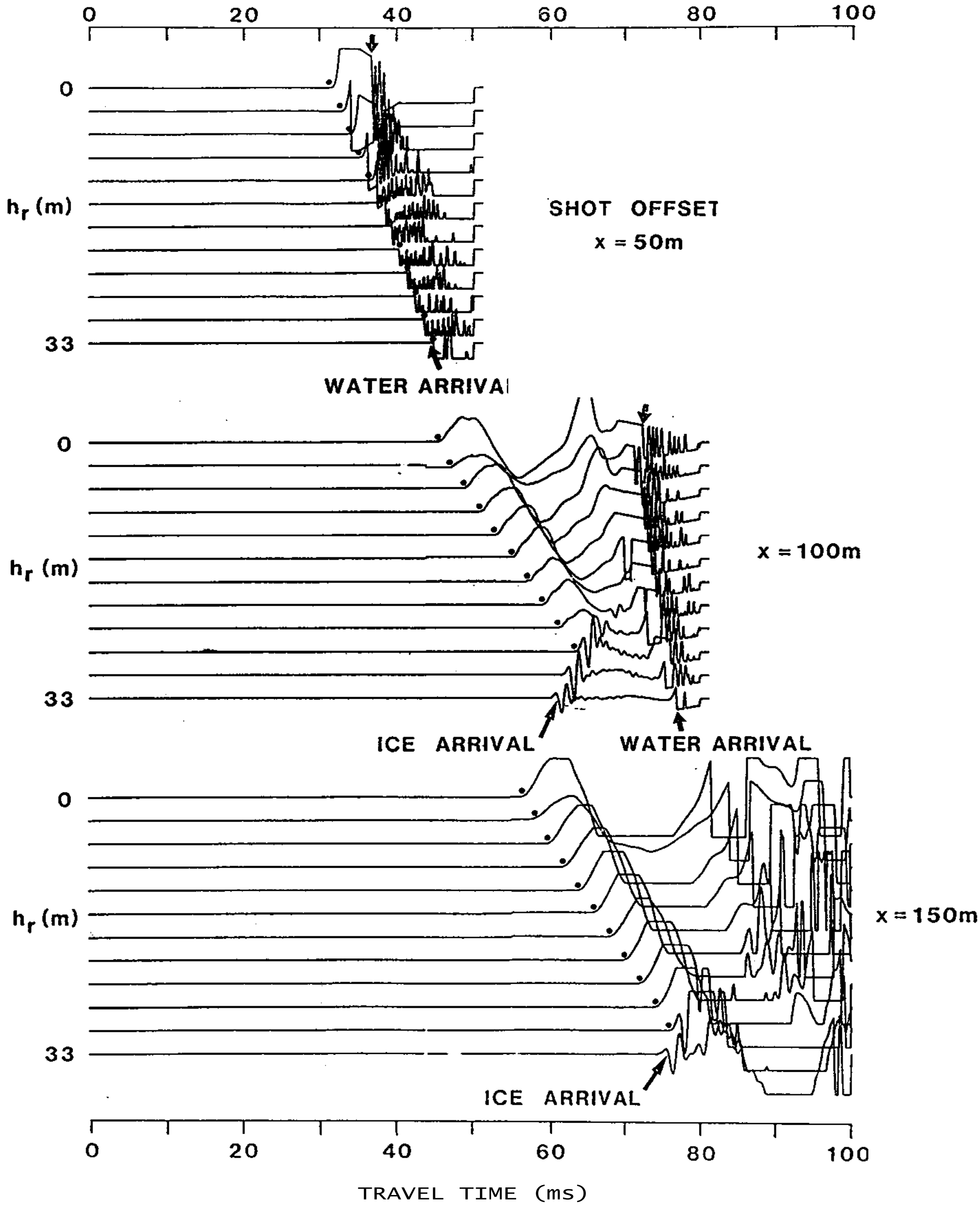

Figure 6: Three seismograms recorded with a vertical array at the Ottawa River site.

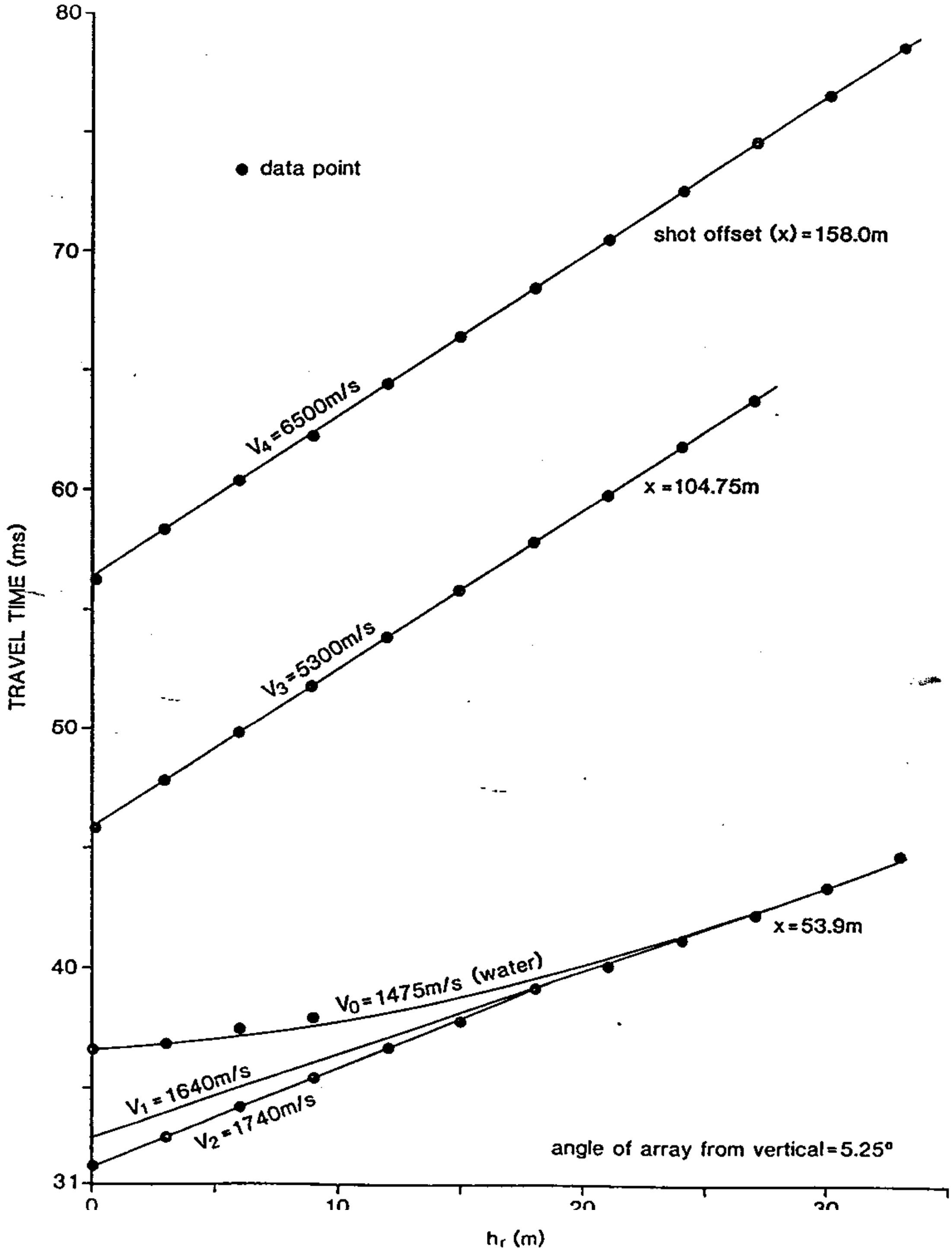

Figure 7: Traveltime vs. hydrophone height data from the records shown in Figure 6. The lines correspond to the model that "best fits" the data.