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VERTICAL SEISMIC PROFILING RECENT ADVANCES IN TECHNIQUES FOR DATA ACQUISITION PROCESSING AND INTERPRETATION

(Title)

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A B S T R A C T

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Since mid 1976 there has been a rapid increase in the number of exploration wells surveyed using Vertical Seismic Profiling methods. In some respects, the growth of these surveys at first outstripped the development of suitable field techniques and processing routines for dealing with the data acquired.

A variety of field techniques can now be employed in both Vertical and deviated wells, which include both fixed and variable offset source positions and both fixed and variable well geophone locations. This has necessitated the reconsideration of the type and suitability of the signal sources and recording instrumentation required for these well surveys.

Data processing techniques are now available which allow detailed studies to be made of the upward and downward travelling seismic waveforms which, in turn, enables primary and multiple reflection patterns and their mutual interaction to be evaluated. The origin and nature of particular reflection events, both from within the geologic section drilled and from beneath the well,can be analysed and used to determine precise stacking velocities and the amount and direction of true dip. Thus the reflection response and its dependence on lithology in the vicinity of the well is more clearly revealed.

Vertical Seismic Profiling techniques are considered to be an important new tool for the seismic data processor and interpreter and, when used in conjunction with other borehole derived data, forms the basis of a package of routines which helps to integrate surface and sub-surface geophysical observations. Close liaison between data processors and interpreters, between geophysicist and geologists is, however, essential if the optimum benefits from the techniques are to be realised.

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INTRODUCTION

For more than 15 years in the USSR, the Russians have been using and experimenting with Vertical Seismic Profiling methods in drilled boreholes in the effort to solve a wide variety of sub-surface problems. The work has been supported in the USSR by the oil industry and many of the research institutes there have contributed significantly to the study of such topics as wave dynamics, direction of particle motion and analysis of direct and converted shear waves. Much of this work has been published and is available in English language so that it is somewhat surprising that we, in the West, have been so slow in taking up these developments.

The reasons why these techniques have attracted so little attention in the West are by no means clear; perhaps the different economic structure of the industry, particularly as it relates to the cost of drilling, and the nature and magnitude of the geophysical problems are factors which need to be considered. It is the intention of this paper, therefore, to provide an overview of VSP techniques available at present in the West and to look at some of the ways they may be usefully employed.

THEORY IN TERMS OF SIMPLIFIED WAVE PATHS

First, we need to consider which seismic events we are concerned with and the way they propagate in the geologic section and then to look at three field methods currently being used, viz., the VSP in a vertical hole, and the moving offset source technique in both vertical and deviated holes.

Because the well geophone is buried somewhere in the sub-surface and, unlike a surface seismic spread, it records seismic events which travel upwards and downwards past the detector position. Figure 1 shows in diagrammatic form these two classes of events which have been separated for convenience into the right and left hand sides of the picture, although they both originate from the same source position close to the well. On the left are the upward travelling events which include the primary reflections and their multiples which have reflected an odd number of times - the last being from beneath the geophone. On the right are the downward travelling events including the first arrival and multiples that have reflected an even number of times - the last from above the detector. The downward travelling wave train is the waveform that illuminates the reflecting interfaces and will subsequently be reflected; its pattern will be added as a tail to all primary reflection events.

This is the simplest form of VSP, usually referred to as the zero offset, and is the one in most common use at present.

Figure 2 shows some of the primary reflections which will be recorded using a variation of the VSP in which the well geophone remains fixed at a particular depth and the source is moved along perpendicular lines such as the N - S and E - W traverses shown.

This is commonly referred to as the variable offset or moving source technique. For simplicity, only primary reflections from one dipping interface are shown, but as for the zero offset survey both upward and downward events, including the multiples, will arrive at the detector.

Figure 3 shows a deviated well in which a moving source is placed vertically above each geophone location in the well. Two such offset source positions are shown with a selection of the upward and downward travelling events, which will be detected at each geophone position.

FIELD TECHNIQUE AND INSTRUMENTATION

For the purpose of this discussion it is assumed that only wall clamped velocity sensitive well geophones and digital recording equipment is used.

The only significant difference between a zero offset VSP in a vertical well and a conventional check shot survey is that the source characteristics need to be much more carefully chosen and monitored, and many more geophone levels are used throughout the survey.

It is most important that for VSP work a good pressure peak to bubble ratio is obtained from the source and that the signature is maintained essentially constant throughout, if further data processing is to be kept to a minimum. This implies offshore that supply pressures and mixtures, and depth of source are held constant, and onshore that some repeatable surface input source should ideally be used.

On most marine well locations it simply is not practical to have large source arrays using many elements requiring large volumes of air or gas. The signature shown in Figure 4 is from a simple two air gun array and is about the best that can be achieved without more complex hardware. Also shown is the downhole version of this signature modified only by its passage through the earth and recording instrumentation.

The field technique begins to get more complicated when moving source surveys are undertaken. Offshore this presents a positioning problem which requires some sort of navigational aid referenced only to the rig, and remote firing of the energy source. Figure 5 illustrates one method that has been successfully used, employing bottom planted transducers that can be continuously interrogated by the shooting vessel. The method is particularly attractive in remote areas where no other suitable fixed positioning systems are available, in that the hardware is entirely portable and can be readily laid for use in about half a day, and is also quite easily recoverable. In the general case source positions need to be known with an accuracy of about 100 feet.

So far as instrumentation is concerned, the three most important factors in order to obtain distortion-free signals are the degree and constancy of the coupling of the well geophones to the borehole wall, which ideally should be observed and recorded at each check level, and the dynamic range and band width of the amplifier and digital tape system. In the shallow part of the hole the ratio of the largest to smallest signals, usually the ratio of first arrival amplitude to late reflection amplitude, may be of the order of 100 dB so that a resolution of not less than 110 dB is desirable.

Figure 6 is a schematic of the ideal instrumentation for borehole geophysical studies, which is under development. It provides for multiple signal inputs, which could be surface and/or downhole geophone data, a dynamic range of better than 110 dB, sampling rate down to $\frac{1}{2}$ ms, stacking of repeated shots at the same check level, and multiple outputs to monitor camera, digital tape recorder and some kind of section plotter.

This latter is required to provide on site some visual analysis of the events being recorded and their mutual relationship in time and depth. This system is to be built around micro-processors which will provide some degree of processing capability at least so far as the basic time and gain manipulations of the data are concerned.

Figure 7 shows a fairly typical zero offset VSP with the traces sorted sequentially in order of depth from top to bottom and with some gain recovery applied. Each trace represents one check level, and the check levels are equally spaced every 100 ft in the borehole so that approximately 7000 ft of section is shown. A line drawn from top left to bottom right through the first arrivals represents the time-depth curve for this particular velocity distribution. The events travelling across the section parallel to the time depth curve, labelled M, are downward travelling events which have been multiply reflected an even number of times; the events travelling across the section towards the time depth curve, labelled P, are primary reflections and their multiples which arrive at the geophone from below.

It can be shown by simple geometry that the point at which the time depth curve and a line through the primary reflections intersect defines the position in time and depth of the reflector, and that no multiple reflection associated with this reflector and travelling upwards can possibly intersect the time depth curve. Both the primary and the multiple reflection will terminate as soon as the geophone passes through the reflector.

Figure 8 shows the same data in which each trace has been statically time shifted by an amount related to the first arrival times so that primary reflections and their upward travelling multiples now appear as near horizontal alignments. The data has been further enhanced by a median picking routine. It is important not to confuse this display with a conventional seismic section which it may resemble. The display has the advantage of presenting the data to the same reflection time scale of a conventional seismic section which can be laid down the side for correlation purposes. The origin of the primary reflections can be located precisely within the section penetrated by the well by correlating the intercept points on the time depth curve with the acoustic impedance log shown on the left of the picture.

Figure 9 shows the same original data as before but time shifted in the opposite direction which has the effect of aligning the first arrivals and the downward travelling multiples, and illustrates in a real sense the pattern of multiple activity that is imposed on the conventional seismic data.

In Figure 10 the type of data obtained in a vertical well using a fixed geophone position and a variable offset source is illustrated. Each trace is the signal from one source position. A curve drawn through the first arrivals defines the NMO hyperbola for the particular velocity distribution above the well geophone position for the one way case; all the events following the first arrivals have undergone reflection from one or more horizons and could be travelling either upwards or downwards into this particular geophone location. No time shifting of traces is involved here. This display is therefore essentially a transposed single cover seismic record with a single buried detector.

Figure 11 illustrates the type of data that would be obtained in a deviated well with a variable geophone position and variable source offset to ensure near vertical travel paths to the well geophone. Each trace is the signal from one source position into one unique geophone position. The data has been time shifted and processed to enhance the primary reflectors and upward travelling multiples.

All the data shown so far was obtained offshore so for completeness Figure 12 has been included to demonstrate the onshore application - in this case using Vibroseis*as a source. It is from a conventional zero offset VSP in a vertical well. Many land VSP have been shot using air guns with satisfactory results, but particular care is needed to ensure a reasonably constant signature.

*Vibroseis is a trademark of the Continental Oil Company

ANALYSIS, INTERPRETATION AND USES

Figure 13 shows the relationship between primary and multiply reflected events and how these can be used to unravel and label the corresponding events on the seismic section at or near the same location. The figure shows the same data used in Figures 7 and 8 of a zero offset VSP in a vertical well, with the downward travelling multiples correlated with two different parts of the primary reflection sequence.

On the left of the figure the downward travelling events have been correlated with the upward travelling data with time zeros aligned. The correspondence of events on these displays and the continuity across all traces on the downward events demonstrates, as might be expected, that the sea surface is a major component in the multiple generating system, together with the primary reflectors seen for example at P1 and P2.

On the right of the figure the downward travelling display has been moved so that its time zero is aligned with the primary reflector P1. The event MP1 now clearly correlates with an event on the upward travelling data. Further, this event on the upward travelling display terminates at a point directly under the point at which P1 cuts the time-depth curve, marked X. This establishes without question that it is a multiple associated with the sea-surface and P1.

The position of the upper and lower components of any reverberant systems can be established by this technique of sliding the upward and downward event displays against each other in time, and also by noting the points at which events appear and terminate across the displays. Also the presence and position of near surface reflectors not adequately indicated by the upward travelling display can be inferred from the downward waveform.

Primary reflections from horizons below the TD of the well, or the deepest geophone level, will not intercept the time-depth curve, so that this criteria cannot be used to establish their origin. In order to determine whether an event below TD is primary or multiple one needs to apply a negative kind of reasoning. If the event of interest is a multiple, the primary at the base of the reverberant system with which it is associated must occur at a time intermediate between the first arrival on the deepest geophone position and the event in question. If no such event is apparent, then it is reasonable to assume that event is primary in origin.

The polarity of any event seen on this display is unambiguously demonstrated by reference to the observed polarity of the direct arrival; this can be used as a test of the origin of the reverberant system and in addition will establish the nature of any change of acoustic impedance beneath the deepest well geophone positions.

Spectral comparison between different events on the two displays e.g. P1 and MP1 involving the same primary reflector can provide some indication of the filtering properties associated with the various travel paths.

In this figure all the events appear horizontal indicating that there is little or no dip at the borehole location. The presence of dip on any reflector would be indicated by the time displacement of the event across the display of upward travelling events. For plane dipping reflectors the reflection point migrates up dip to shorter reflection times on the display as the geophone moves upwards away from the reflector. The true dip can be easily calculated but not the direction. To attempt to obtain any information with regard to dip azimuth the source position has to be varied.

The simulated offset source data shown in Figure 10 has an example of a primary event marked P1. The point at which P1 occurs on this display was established by reference to the zero-offset VSP data where one particular trace contains data obtained with the geophone at the same depth in the borehole.

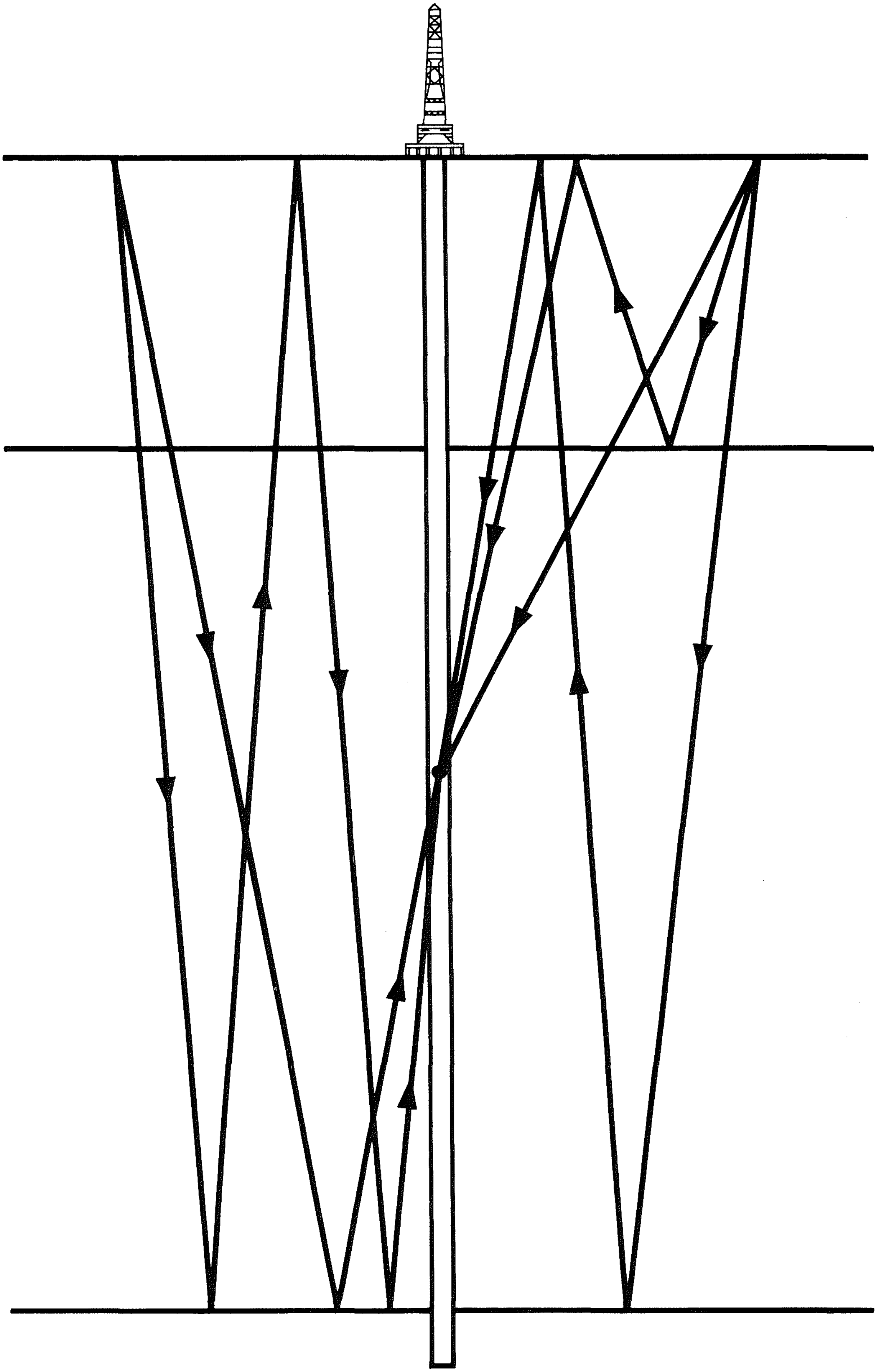
The offset survey data contains, as previously mentioned, both the upward and downward travelling waveforms. An advantage of this data is however, that by placing the detector below some of the near surface reverberant systems and above the primary events of interest, primary to multiple amplitude ratios can be improved by up to 12 dB. As the correlation of the offset source data with the zero offset VSP data is so important to interpretation it is recommended that the same source is used for both types of survey, and that this source should be as impulsive as possible. For the present we suggest that offset source surveys can only be justified economically, from the point of view of rig time costs, in areas so difficult seismically that primary reflections cannot be mapped beneath the cover of multiples.

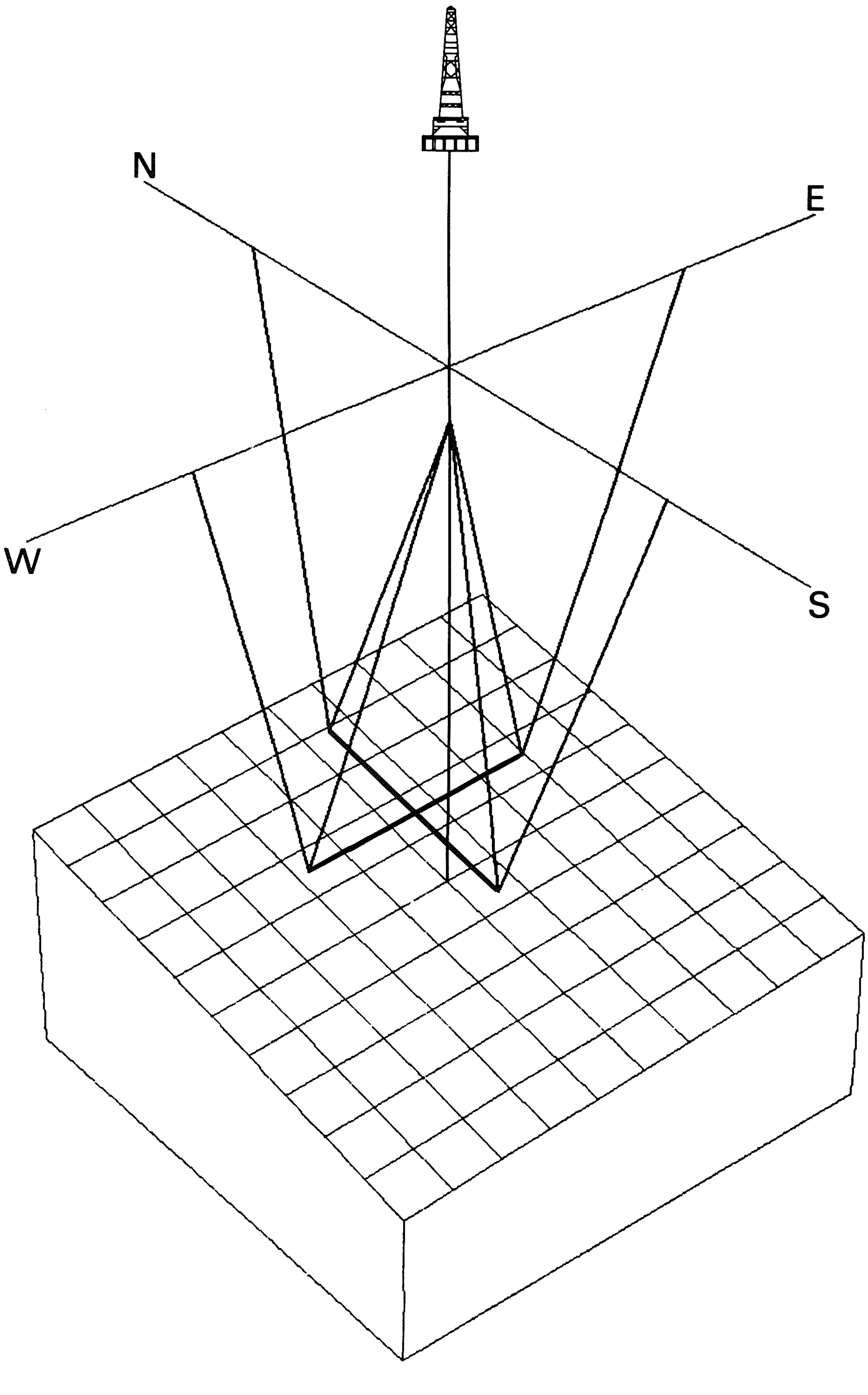
The moveout in the primary hyperbola obtained from these data can be used to compute dip angle and dip azimuth and the RMS velocity associated with any primary event. At this time certain simplifying assumptions have to be made and it is only fair to say that in areas of intense multiple activity and high primary energy loss the presence of and continuity of primary data is often difficult to establish. It is in such cases, where the identification of any primary activity is so difficult on the reflection seismic data, that determining stacking velocities is uncertain or impossible, or when the multiple and primary moveout functions do not obey simple rules, that the offset source technique would be utilised. The offset source technique in such areas should offer a better chance of establishing relevant stacking velocities when used in conjunction with the zero offset VSP; these stacking velocities may then be used to improve the seismic data. A potential advantage of this technique is the ability to look at structural change at lateral offsets from the axis of the borehole but the problems of interpretation are still many.

In Figure 11 a moving source/moving geophone in a deviated well was simulated. Two events labelled P1 and P2 are shown to illustrate the structural change that can be observed using this type of technique. The upper event P1 clearly converges towards P2 away from the well in a zone where all other arrivals are near horizontal.

CONCLUSION

Much of this work is still in the development stage but already a number of ideas and interesting questions have been raised as a result of what has been achieved so far. For example, to what extent are multiple geophone assemblies downhole either practical or desirable, what efforts should be made to detect shear wave transmission, to what extent can information contained in the downgoing signals be used to process other data? The potential applications for these techniques already seem to be considerable, for example better lithological correlation with the seismic data, a clearer understanding of the mechanisms affecting multiple generation and signal decay, structural mapping and reservoir studies, and we believe these to be the most immediate and practical benefits to be derived in closing the gap between the interpretation inferred from conventional seismic data and physical observations made in the well. Our overriding aim should be to make it possible to delineate structure and reservoirs with fewer wells, and these techniques used in conjunction with tailored synthetic seismograms and spectral analysis of the changing well geophone signals, together with improved surface to surface seismic acquisition and processing techniques, seems to us to be a step in the right direction.

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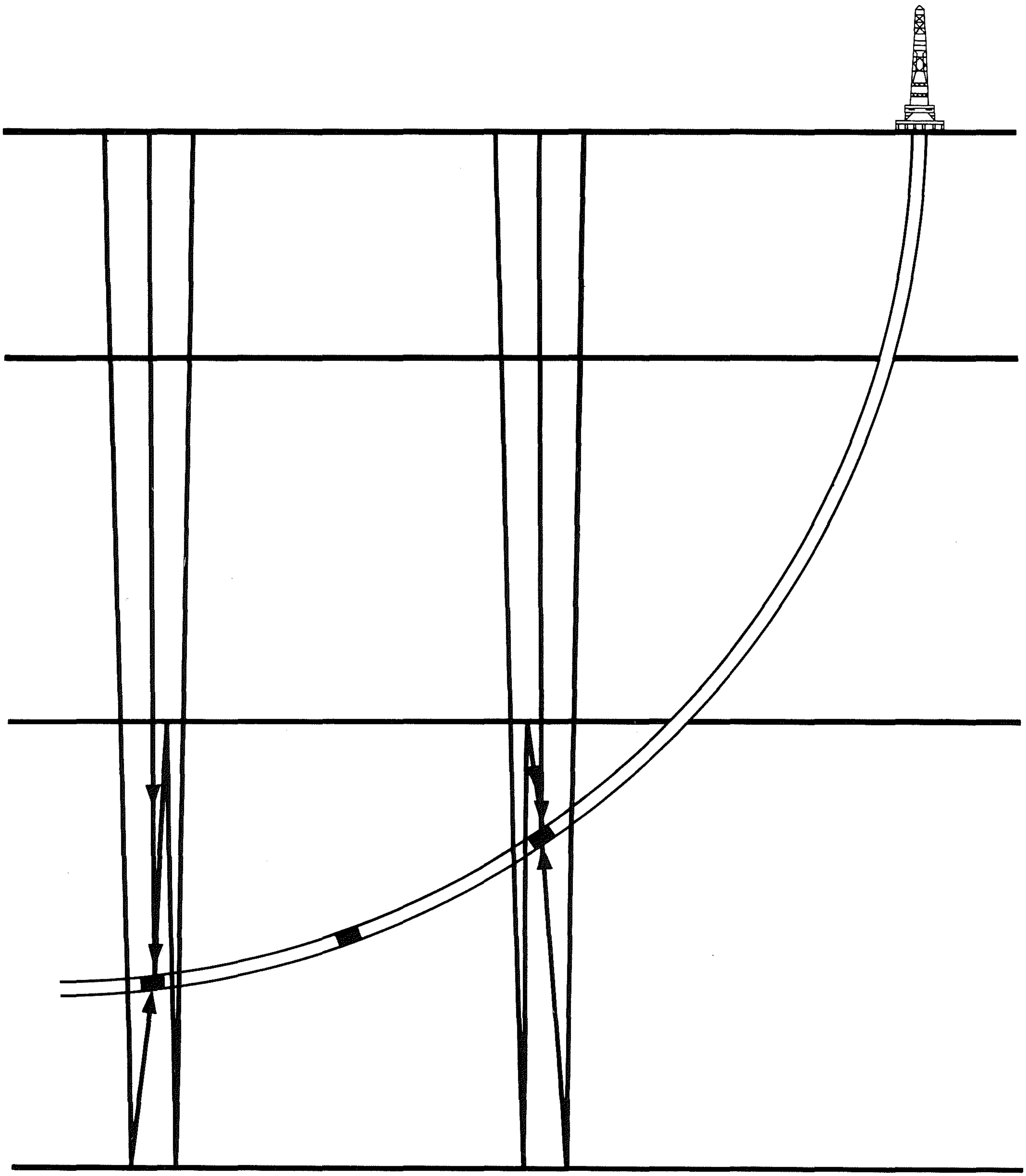

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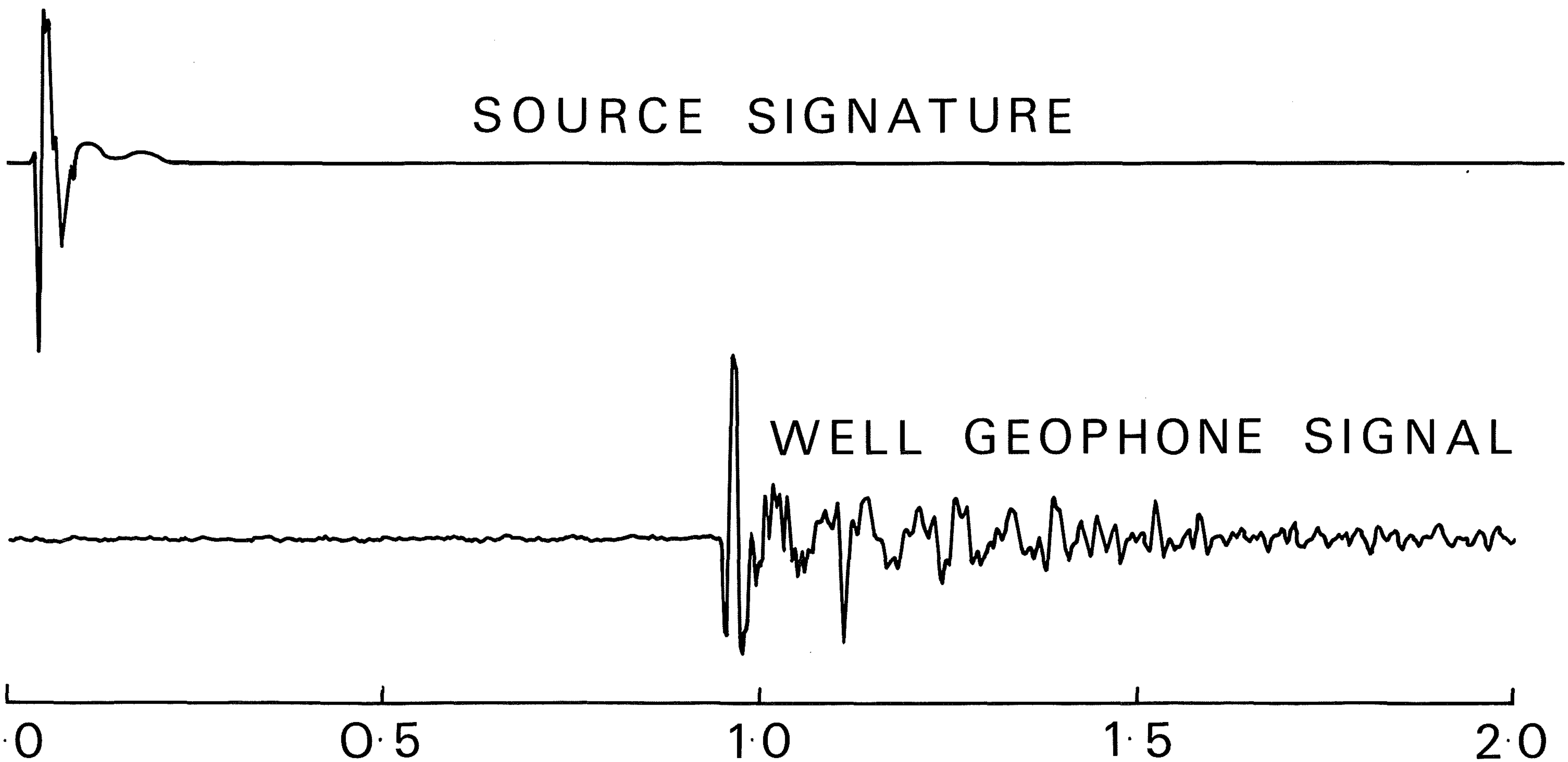


FIGURE 4

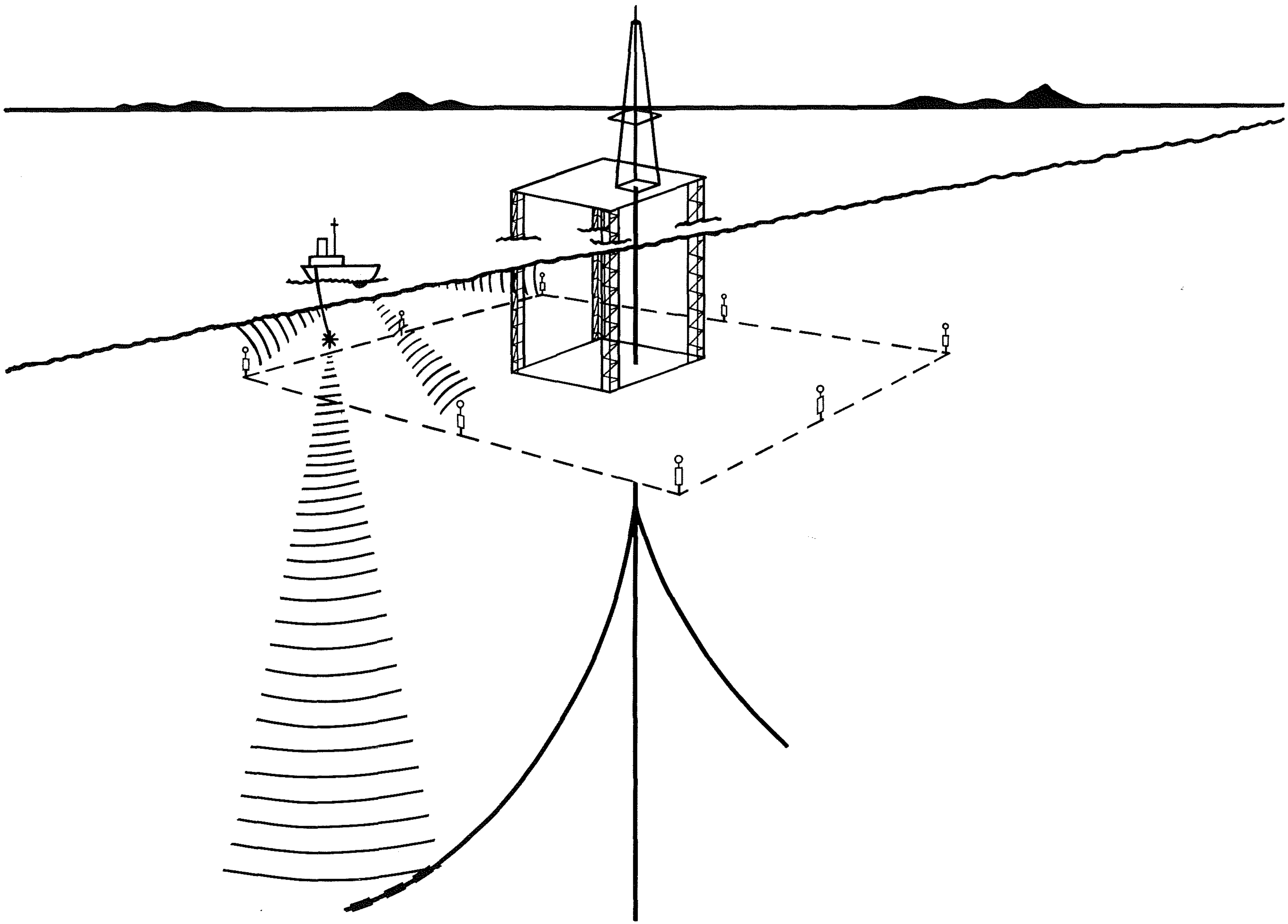


FIGURE 5

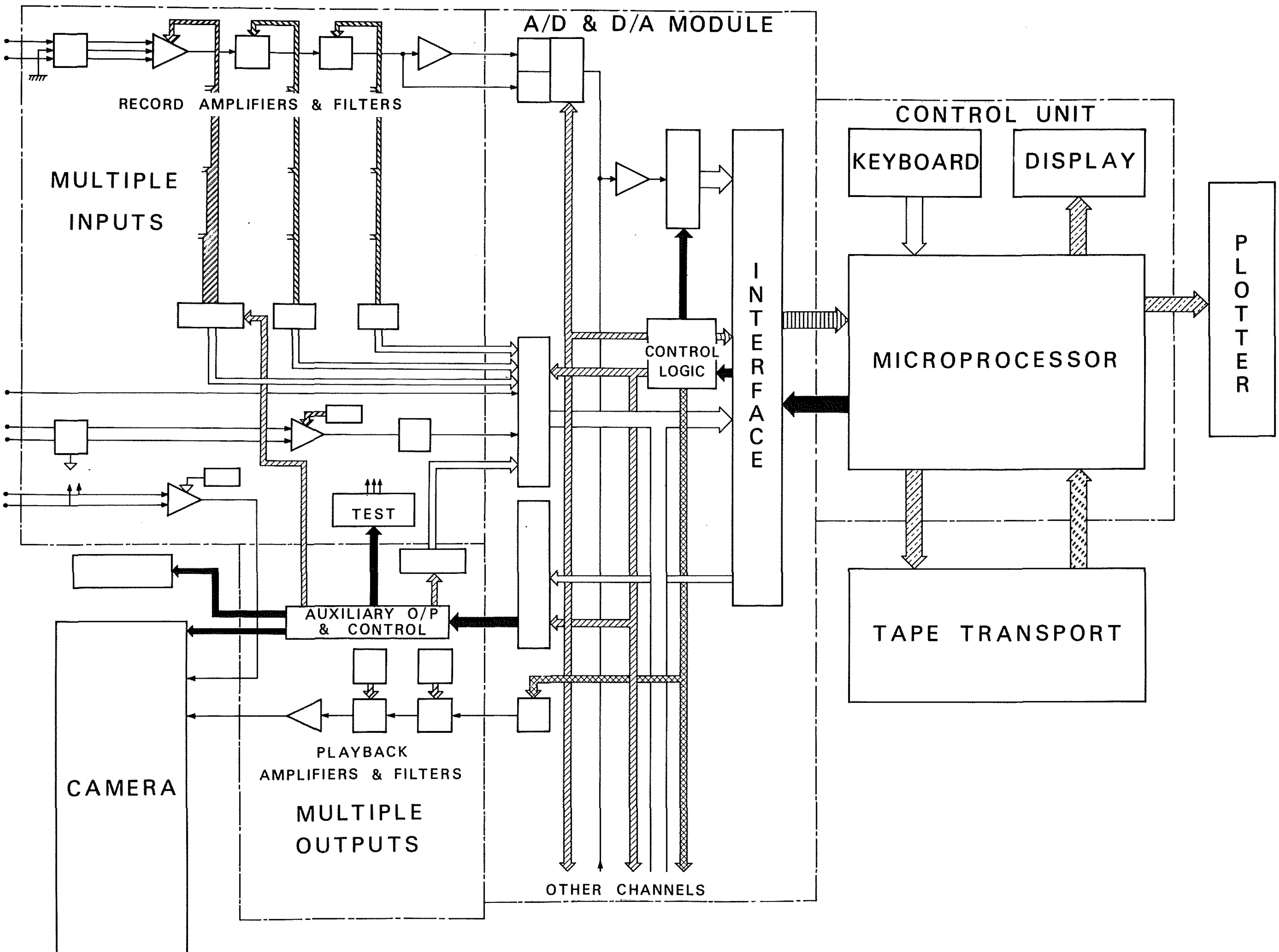

A/D & D/A MODULE
RECORD AMPLIFIERS & FILTERS
MULTIPLE INPUTS
CONTROL UNIT
KEYBOARD
DISPLAY
PLOTTER
INTERFACE
MICROPROCESSOR
CONTROL LOGIC
TEST
AUXILIARY O/P & CONTROL
TAPE TRANSPORT
CAMERA
PLAYBACK AMPLIFIERS & FILTERS
MULTIPLE OUTPUTS
OTHER CHANNELS

FIGURE 6

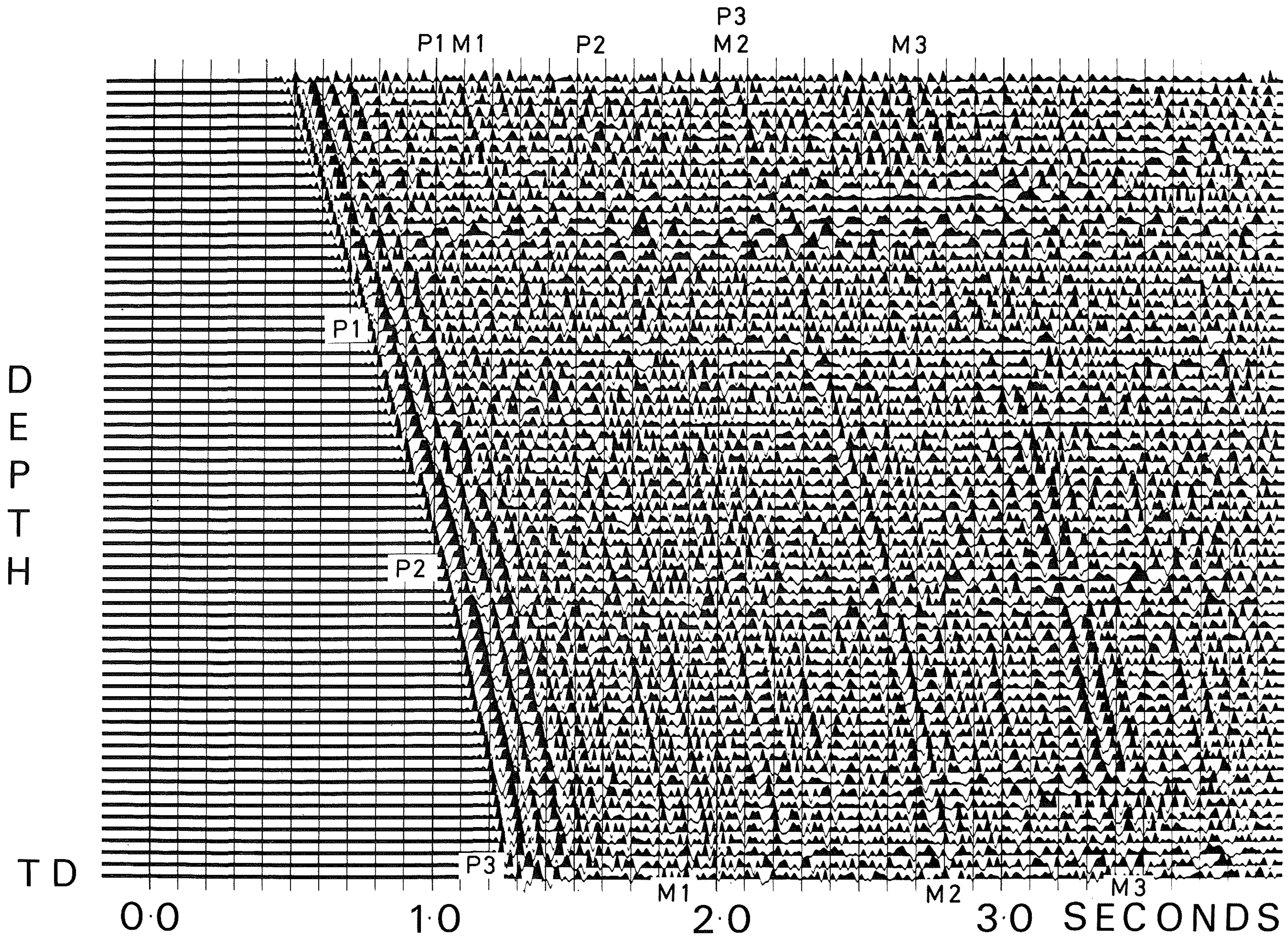


FIGURE 7

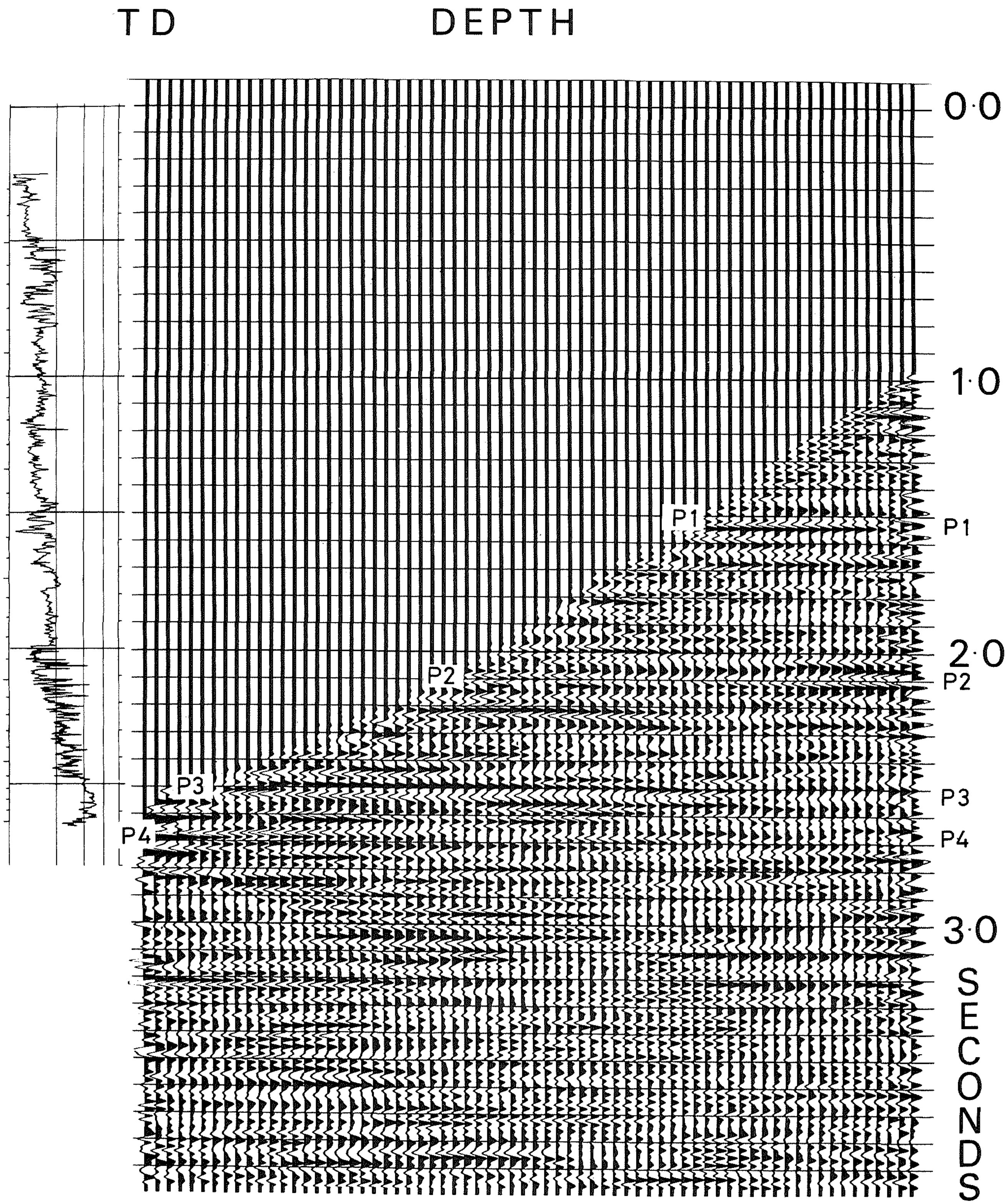


FIGURE 8

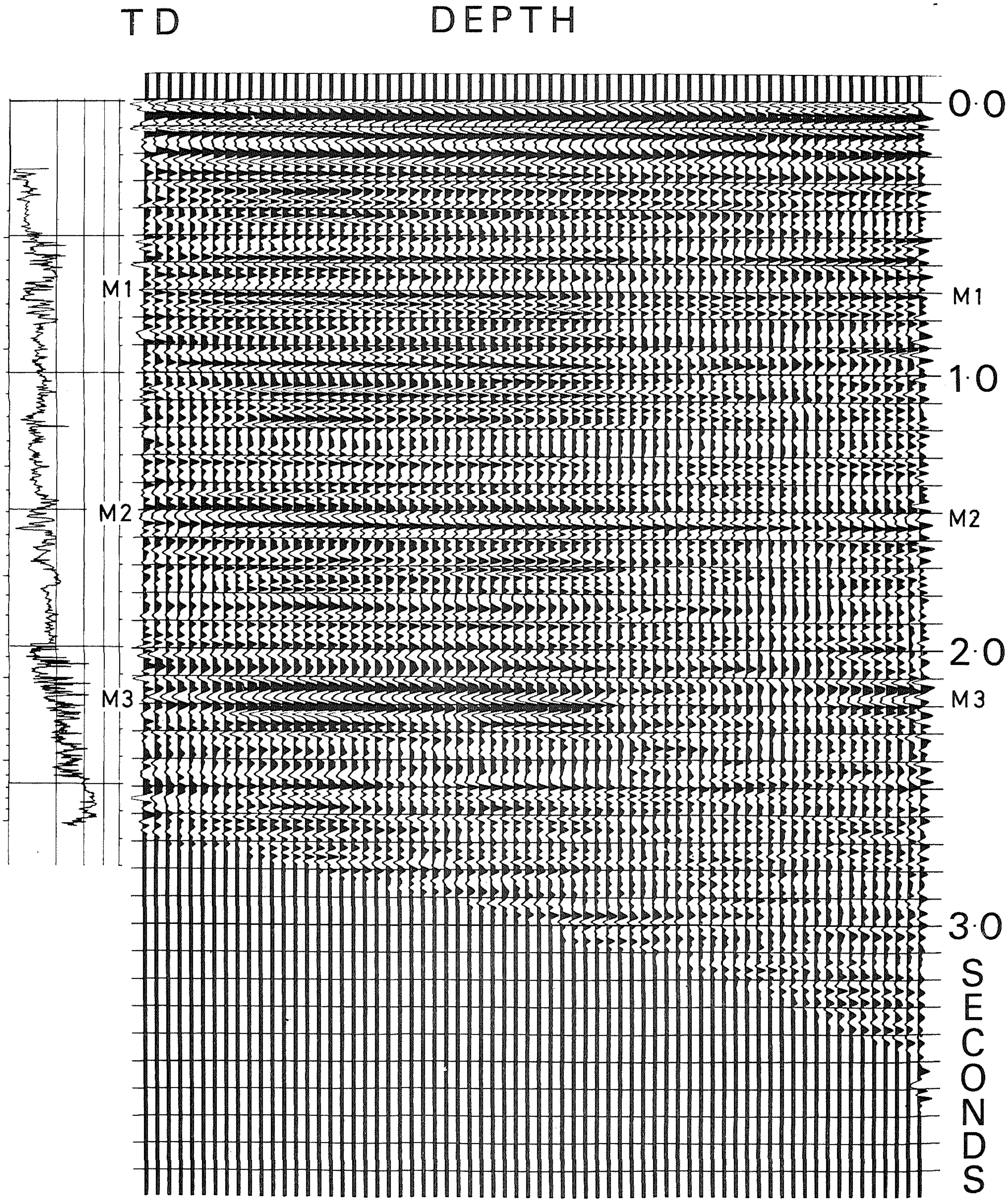
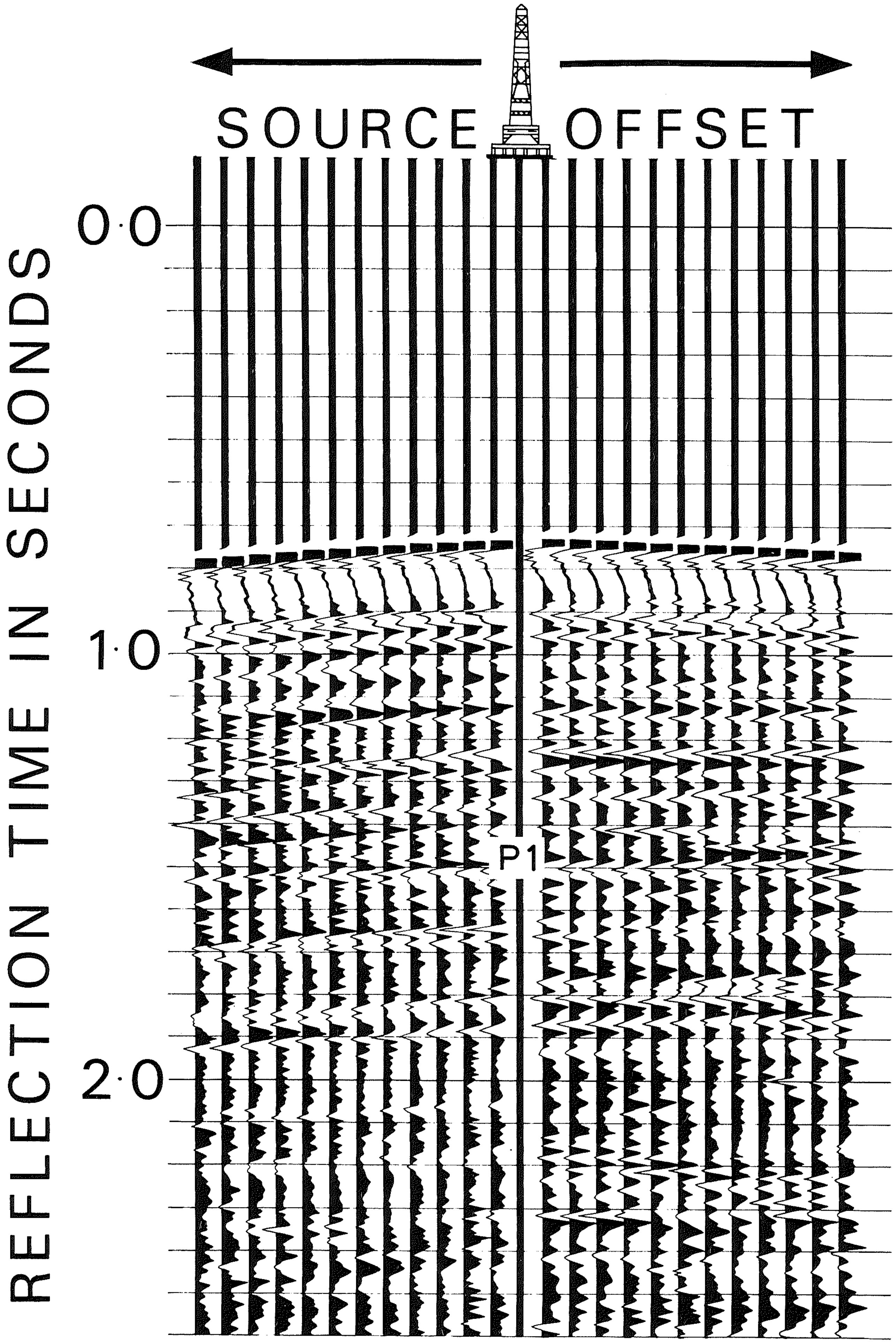


FIGURE 9


SOURCE
OFFSET
REFLECTION TIME IN SECONDS
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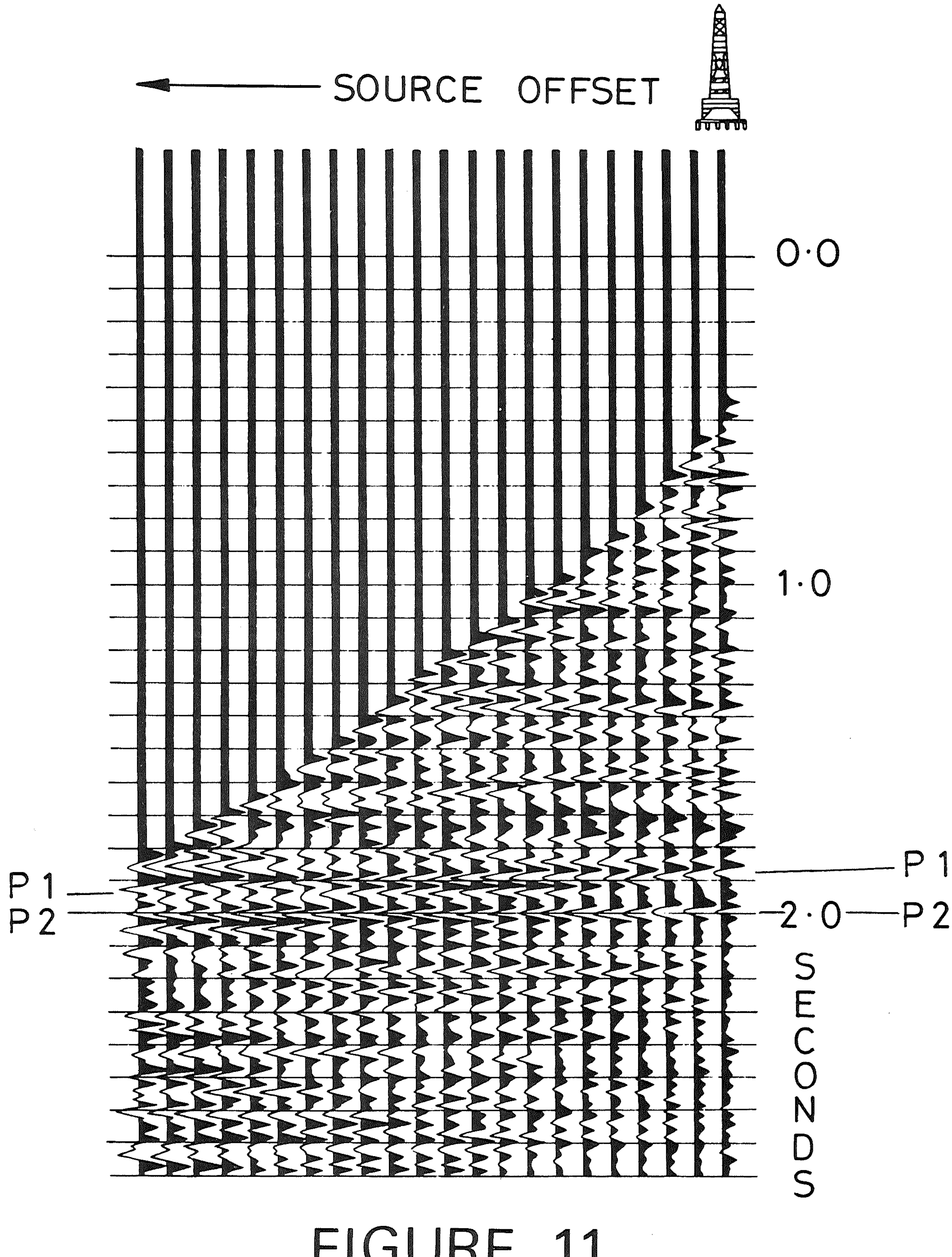

FIGURE 11

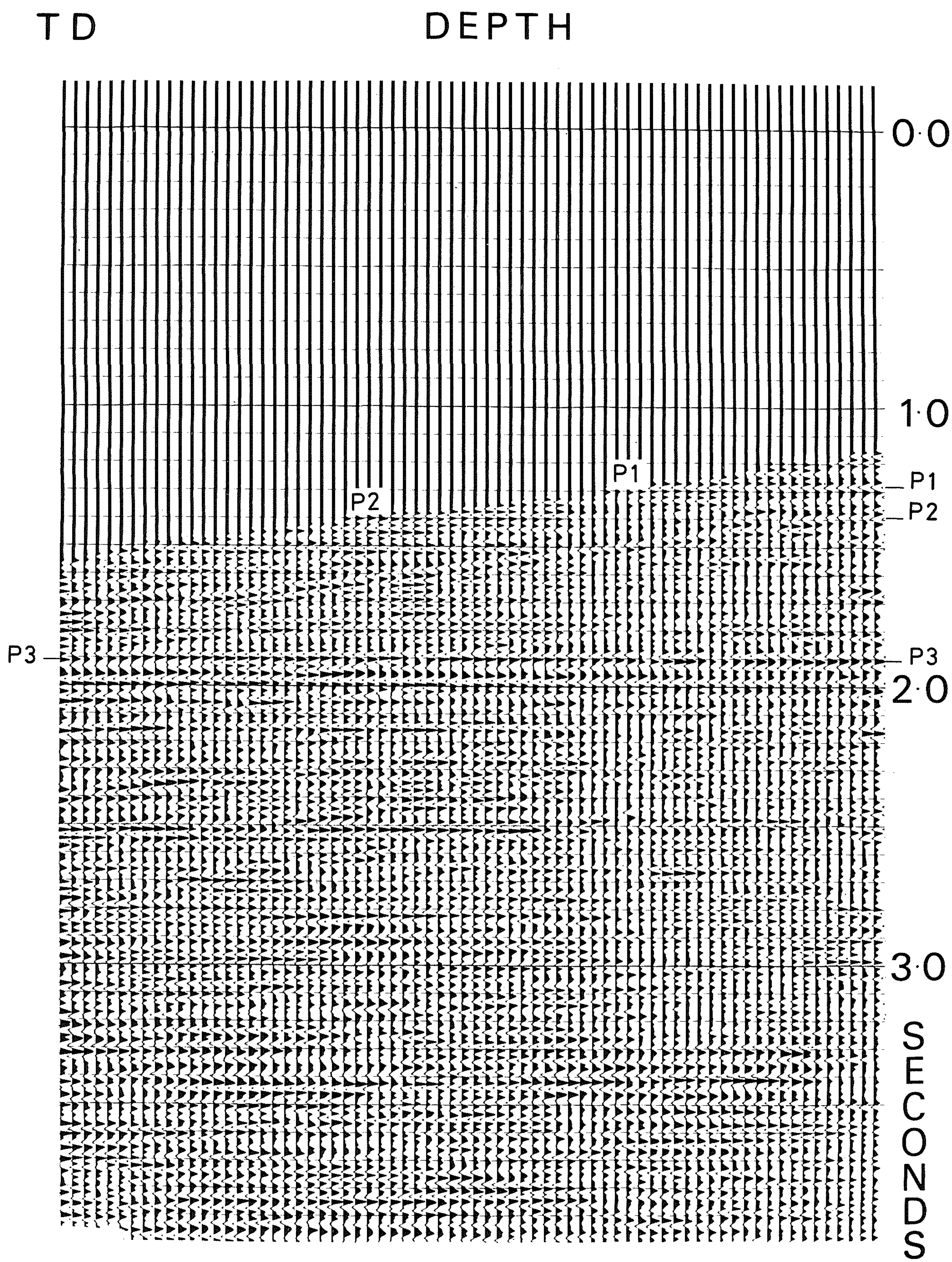

FIGURE 12

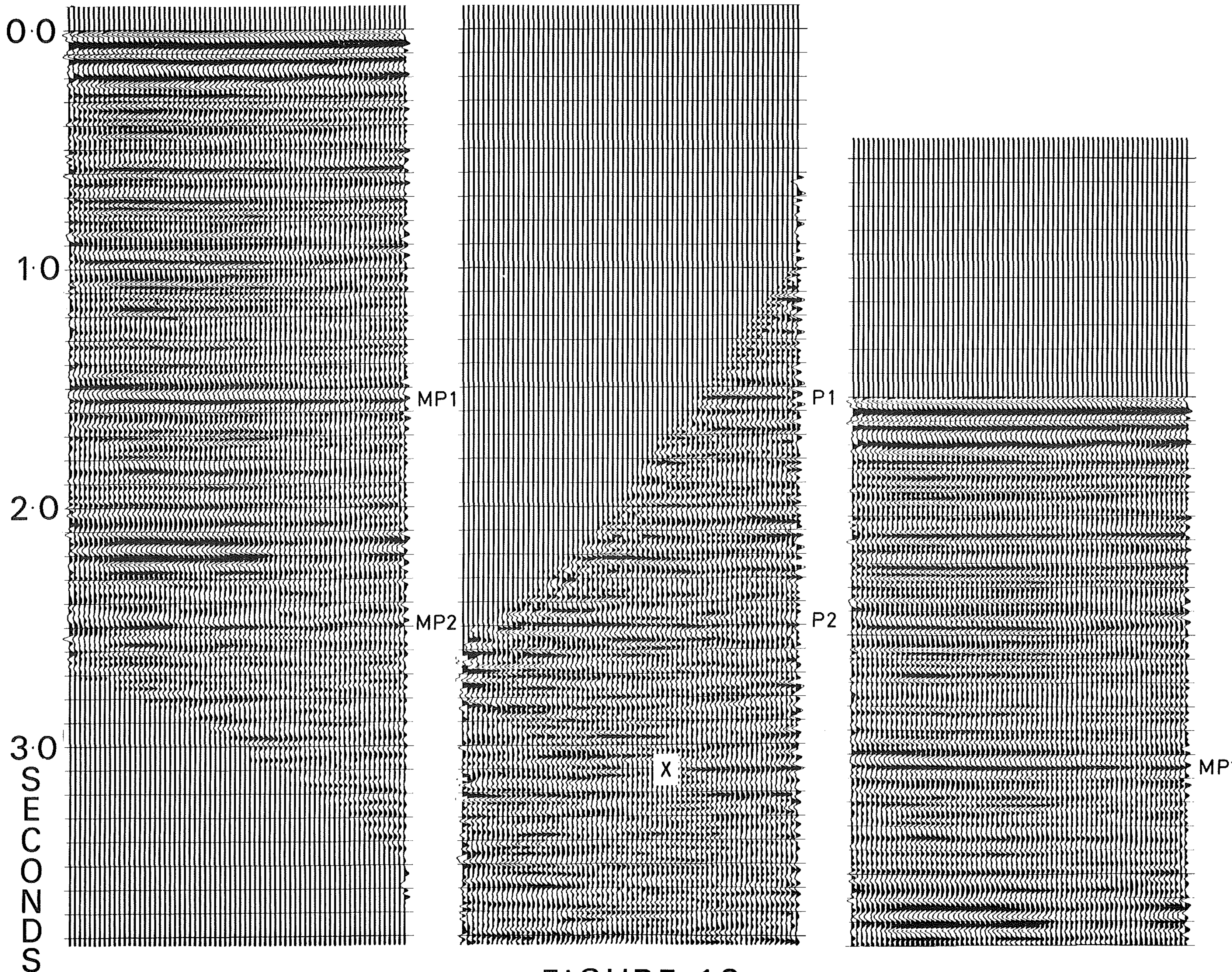

FIGURE 13