Cross-hole seismic reflection surveying in coal measures

Findlay, Michael John

Cross-hole Seismic Reflection Surveying in Coal Measures

by

Michael John Findlay

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Department of Geological Sciences
The University of Durham
1991

The research in this thesis has been carried out at the Department of Geological Sciences of the University of Durham between October 1987 and September 1990. It is the original work of the Author unless stated otherwise. None of this work has been submitted for any other degree.

Acknowledgements

There are a number of people whom I would like to mention for their contributions either directly or indirectly towards the work of this thesis.

Above all, I would like to thank Dr Neil Goulty for his supervision and encouragement throughout my research work.

I would also like to thank Ed Kragh for his comradeship and useful suggestions.

My thanks go to the other members of the borehole seismic research group who helped in fieldwork, i.e. Stefan Thatcher and Miles Leggett and also to the many British Coal Opencast geologists and drilling crews who were most helpful in providing access to boreholes and borehole logs.

I am grateful to the Department of Education for Northern Ireland for funding me.

Finally, I would like to thank my patient wife, Anita, for her encouragement over the past three years and especially so whilst this thesis was being written.

Abstract

This thesis is concerned with the development of the cross-hole seismic reflection surveying method with particular application to the shallow Coal Measures strata found in opencast coal mining prospects in the U.K.

A field acquisition technique developed for shallow boreholes utilising explosive sources and hydrophone receivers is described. Data have been acquired from several test sites in northern England.

Data-processing techniques including wavefield separation and waveshaping deconvolution have been developed for cross-hole data and the theories behind these techniques are discussed.

Methods of imaging cross-hole reflection data including the 'VSP-CDP' transformation and Generalised Kirchhoff migration are applied to computer-generated synthetic data and to real data in order to yield a depth section of the seismic reflectivity between the boreholes.

Finally, the data-processing and imaging techniques developed are applied to real data acquired at British Coal Opencast exploration sites in northern England between 1987 and 1990.

Table of Contents

Chapter I

Introduction

1.1 Synopsis

The purpose of this research work has been to develop the cross-hole reflection surveying method, and to consider its feasibility as an exploration technique for opencast coal prospects. The remainder of this chapter is concerned with opencast coal exploration in the U.K. in order to put the development of the cross-hole method into context. Chapter II deals with the acquisition of cross-hole seismic survey data and the problems associated with it. Chapter III is an overview of the data processing which is required for these surveys and chapter IV concentrates on the migration methods which may be used to image the data. Some trial surveys which were conducted at opencast prospects in the north of England are discussed in chapter V, and a comparison of different cross-hole migration operators is included in chapter VI. Conclusions of this work are drawn in chapter VII.

1.2 Opencast coal mining in the U.K.

In the modern era, opencast coal mining in the U.K. began in 1942, when it was introduced as a wartime measure to extract shallow coal reserves from the top few metres of the ground. Modern mines are now much deeper; a typical working site may be 100m deep. Pits are much smaller than in other parts of the world, simply because of the high population density in the U.K. Site boundaries are restricted by population centres and the communication networks between them as well as by natural boundaries.

Current estimates of shallow coal reserves in the U.K. suggest that there are around 300 million tonnes of coal which could be extracted by opencast mining. Although the total annual output (~15 Mtonnes) from opencast mines is less than 20% of the total U.K. production, opencast coal is more economical to produce and is often of an higher quality than deep-mined coal. Deep-mined coal often has opencast coal blended with it to improve its calorific value and bring it up to the required standard for a marketable product.

The responsibility for opencast coal developments lies with British Coal Opencast (BCO), which is a subsidiary of the British Coal Corporation. BCO provides a detailed specification of a prospect to civil engineering companies who tender for the contract to mine the site. BCO also uses the specification in applying for planning permission. As part of theit contract, the civil engineering companies must restore the pit area when the mining operation has been concluded.

1.3 Opencast coal exploration

Initial site assessments are based upon the currently available geological knowledge of the area. Additional information is also provided by the plans of old mineworkings (although these are usually too unreliable to help in site reserve estimates) as well as the data obtained from any nearby opencast sites. Once there is sufficient evidence to show that a proposed site may be profitable, the exploration stage begins.

BCO's present exploration strategy involves the drilling of a dense grid of shallow (typically with total depths less than 100m) boreholes. The boreholes have 14cm diameter steel casing from the surface down to rock head (typically 5-10 metres of casing), but below this depth they are left uncased. This drilling programme is a massive exploration effort with a total metreage of around 750,000m drilled each year. These are drilled using an air-flush system in which compressed air forces rock chippings from the drill bit to the surface, where they are logged by the driller. All the boreholes are subsequently geophysically logged by using natural gamma and density tools. The density log gives excellent responses to coal seams, whilst the natural gamma log identifies dirt bands and is used in correlations between boreholes. Approximately 20% of the boreholes are also cored. An ideal drilling strategy is initially to drill holes on a grid pattern with 120m spacing. This would then be reduced to 60m and then to 30m, or even less, in areas of particular interest where faulting or old mineworkings are believed to exist. However, permit difficulties and time limitations often dictate that the initial reconnaissance stage is omitted, and in some parts of the country only a single phase of drilling on, say, 50m centres is carried out. The interpreted logs from the boreholes are used to determine the overburden lithologies as well as the location and thicknesses of coal seams and the presence of fault zones which may lead to problems in the excavation of coal.

It is very important that BCO can provide as accurate an estimate as possible of the rippable coal reserves, since it will incur contractual penalties if the excavating civil engineering contractor finds less readily extractable coal in the site than was predicted, and also because any profits from excess coal reserves will chiefly benefit the contractor. The site must also be shown to be of primary economic importance to the appropriate planning authorities.

To date the drilling programme has proven to be an effective exploration strategy, but information coverage is disrupted where physical obstructions such as buildings and rivers are located. These gaps in the data might be filled by geophysical techniques which can provide information on the strata between the boreholes. It is barely possible to detect faults with throws of 2m or less from borehole levels, even if the boreholes were drilled only 2m apart. There is, therefore, great potential for a geophysical technique which can detect such small faults in critical areas such as site boundaries. In addition, suitable geophysical surveys combined with a 60m borehole spacing, might allow old workings and faults to be determined more accurately than would be possible by drilling boreholes with 30m separations. This could potentially eliminate the need for ~75% of the boreholes in these areas.

The pillar and stall type of old mineworkings are particularly prevalent in areas suitable for opencast mining because, naturally enough, the earliest old mineworkings were frequently located near outcrops. As many as five or six sets of old mineworkings may be present in different seams on the same site. Indeed, the greater part of the coal in an economically viable prospect may be in the form of pillars in the old mineworkings which were left behind to prevent collapse.

1.4 Seismic exploration for coal

Surface seismic reflection surveys have been used as an exploration tool for deep mines for almost twenty years. In these surveys target depths are of the order of hundreds of metres, and poor imaging is obtained in the upper 100m of the sections (see e.g. Ziolkowski, 1979). The surface reflection method has been applied specifically to opencast targets by Brabham (1986), but the results were poor with long wavelength (~20m) reflections being recorded, the higher frequencies having been absorbed by the weathered surface layers. A great problem for shallow seismic reflection surveys is interference from refracted waves and ground roll; this is very dependent on the shallow geology (Bredewout and Goulty, 1986).

In-seam seismic methods have also been used successfully in deep mines (Buchanan, 1983; Jackson, 1985). Deep mine hole-to-hole seam wave transmission experiments were carried out by Jackson et al. (1989), who observed arrivals with the dispersive character which one would expect for a low-velocity SH channel wave between holes where the seam was continuous. When old mineworkings or faulting exist between the boreholes, no such wave should be detected. The method has been applied to shallow Coal Measures strata (Goulty et al., 1990), but without success because of the strong attenuation of high-frequency shear waves in shallow strata. Vertical seismic profiling (VSP) methods have been applied to deeper coal seams by Suprajitno and Greenhalgh (1985) and Jackson et al. (1989) and to shallow Coal Measures strata by Kragh (1990).

It is hoped that cross-hole seismic reflection surveys may be used in conjunction with VSPs and borehole logs to provide a flexible, high-resolution tool for opencast coal exploration. In particular, they could fill in information where boreholes cannot be drilled and accurately determine the location of small faults and old mineworkings.

Chapter II

The cross-hole seismic reflection method

2.1 Borehole seismic techniques

The check shot survey is a long-established borehole seismic technique in the oil exploration industry which is used to calibrate velocity measurements obtained from borehole sonic logs. A natural progression from this was the vertical seismic profile (VSP). The VSP involves repeatedly firing rig-source shots while a geophone is located at successive depth levels in the borehole; see Balch et al. (1982) for a review. The seismic data recorded can then be processed to obtain a vertical profile of the seismic reflection response of the strata at the borehole. VSPs are useful for correlating conventional surface seismic reflection sections with well-log information.

Further developments in VSP data acquisition include offset VSPs, where the source is fired at a constant offset from the rig (see e.g. Dillon and Thomson, 1984) and walkaway VSPs, where the source is fired at several different offsets while the geophone position is kept constant (see e.g. Kohler and Koenig, 1986). These illuminate the geological structure over narrow cross-sections through the borehole in the azimuthal direction of the source locations. The most general case of such profiles utilises multiple geophone positions and source offsets in the same survey.

When the source is fired within the borehole and surface receivers are used the survey is known as a hole-to-surface seismic profile (Kragh, 1990), a simpler terminology for what has also become known as the inverse multi-offset VSP

(IMOVSP) (e.g. Jackson et al., 1989). These types of survey provide increased resolution of seismic reflectors compared with conventional surface seismic surveys because the acoustic signal only passes through the near-surface layer once, whereas two passes are needed for surface seismic reflection surveys. Thus the higher temporal frequencies in the signal are less attenuated by near-surface effects.

2.2 Cross-hole seismic techniques

Cross-hole seismic methods involve firing shots in one borehole and recording the transmitted and scattered wavefields on receivers positioned in a neighbouring borehole. By positioning both sources and receivers in the sub-surface, the frequency content of the data is higher than that of VSPs. The first applications of this recording geometry were in velocity surveys where the travel times of direct arrivals are used by tomographic inversion algorithms to generate a tomogram or slice of the velocity field between the boreholes (see e.g. Worthington, 1984; Dines and Lytle, 1979). The uses of this technique are principally in locating local velocity anomalies caused by intrusions and voids (e.g. Cottin et al., 1986; Bishop and Styles, 1990), and also in monitoring the changes in a velocity anomaly with time which may occur during fluid-injection enhanced oil recovery projects (Macrides et al., 1988 and Justice et al., 1989). Kragh (1990) applied the technique in trying to locate shallow old mineworkings in Coal Measures strata by looking for velocity anomalies in the collapsed zones immediately above the old mineworkings, but concluded that any such velocity anomalies were too small to be detectable by this method.

The basic type of tomographic survey uses only the direct arrival traveltime data. Obviously additional information is also present in the later scattered arrivals. Techniques to utilise scattered arrivals have been developed by Devaney (1984) and Pratt and Worthington (1988), amongst others. The diffraction tomography method may be applied to cross-hole data to provide velocity and attenuation tomograms. An alternative to this approach is to consider a cross-hole reflection survey as being composed of several offset VSPs where the sources and receivers are all below ground level. Data processing of the survey is then similar to, but more complicated than, processing a set of offset VSPs. This processing route has previously been applied to synthetic data by Hu et al. (1988) and to ultrasonic scale-model data by Zhu and McMechan (1988) and Balch et al. (1990). This is the processing method which has been adopted in this work.

2.3 Cross-hole seismic data acquisition

As in any type of seismic survey, the choice and deployment of acquisition equipment should be considered carefully. Of particular importance are the types of source and receiver and the recording device used.

2.3.1 The source

An explosive source was used in all the trial surveys of Chapter V. The explosive charge used consisted of an electrical (no.8 type) detonator which was sometimes boosted by 25g of dynamite. The dynamite was used to improve the signal-to-noise ratio in surveys where high background noise levels were observed, but it was generally avoided in order to minimise the risk of damage to the borehole walls. There was no noticeable change in the frequency content of data recorded using a dynamite source compared with that of data recorded using a detonator alone, suggesting that the charge scaling law proposed by Ziolkowski et al. (1980) does not hold for small-sized charges fired in boreholes.

The charge is positioned at the end of a 4cm diameter hollow steel tube which is 40cm long. The purpose of the tubing is to provide to provide sufficient weight to allow the source to be lowered and raised easily in the borehole and also to prevent the explosion from damaging the firing or triggering leads with which the source is connected to the surface. This source was found to give an adequate frequency range for the purposes of the trial surveys and also gave good shot repeatability.

2.3.2 The receivers

It was decided that, for reasons of practicality and speed, a string of receivers would be needed. The simplicity of utilising a ready-built hydrophone string greatly outweighed the complexity of constructing a string of (three-component) geophones. Hydrophones in a vertical fluid-filled borehole may be expected to detect SV body waves as well as P waves, but not SH waves (Schoenberg, 1986). However, the practical difficulties of accurately recording rock particle motion by a borehole geophone were recently demonstrated by Beattie (1990). She found that the geophone was much more sensitive to tube waves; a surprising result but explained by the effect of the pressure in the fluid due to the tube waves acting on the top and bottom of the geophone housing.

Two 12-channel hydrophone strings were used; the first (used in survey A of chapter V) had hydrophone spaced at 4m intervals and the second (used in the remainder of the trial surveys) had a 2m hydrophone spacing. The hydrophones were streamlined by enclosing each one in heat-shrink plastic to prevent snagging on the borehole wall. A weight is fastened to the bottom end of the string to facilitate lowering in the borehole. The 4m-spacing string was supported by a steel cable fed past each hydrophone and attached to the weight at the bottom. In the 2m-spacing prototype a nylon rope was used instead in order to reduce the overall weight of the string and make it easier to handle.

2.3.3 Recording equipment

Two recording devices were used in the field trials. The first was an EG&G Geometrics Nimbus 12-channel 10 bit enhancement seismograph with a dynamic range of 66dB. This was used in survey A of chapter V. In the remainder of the surveys an EG&G Geometrics ES-2401 24-channel enhancement seismograph was used. This equipment was a significant improvement on the earlier model with a much greater dynamic range and the additional benefit of storing data in SEG-DOS format on floppy disks instead of the tape reels (SEG-D format) used by the Nimbus. The advantage of 24-channel recording allowed the simultaneous acquisition of cross-hole and hole-to-surface surveys, with 12 channels allocated to the downhole hydrophones and the other 12 to a surface geophone spread. This led to a greatly improved rate of data acquisition, and reduced the risk of losing a survey due to explosive damage instigating collapses in the borehole wall.

2.3.4 Field equipment set-up

The typical equipment arrangement used in the field trials of chapter V is illustrated schematically in figure 2.1. The string of hydrophones is lowered into borehole B and the source is positioned in hole A. Shots are repeated at the same depth levels for different positions of the hydrophone string in order to extend the coverage of the receiver array. One hydrophone position is kept in common between the repeated shots to allow amplitude scaling and repeated shot deconvolution to be carried out (see section 3.2.1). In the trial surveys, the hydrophone string remained fixed while shots were fired successively at depth intervals of 2m (to make the coverage of reflectors between the boreholes as uniform as possible). The hydrophone string was then moved to a new position and the shot sequence was repeated.

A sampling interval of 200μs was used in all the trials and a data length of 1024 samples (204.8 ms) was recorded.

The deepest shot and receiver locations were usually limited by collapses in the boreholes, rather than the total depth actually drilled, and the shallowest shot and receiver positions were restricted by the level of the water table in each borehole. A hydrophone will simply not respond if it is not submerged, and there is insufficient coupling of the source energy to the surrounding rock unless the shot is also submerged. Shots fired 1-2m below the water table resulted in a noticeably lower frequency content in the recorded data; the dominant frequencies being approximately half those of the deeper shots. This was presumably due to an insufficient confining hydrostatic pressure to restrict the expansion of the exploding gas bubble.

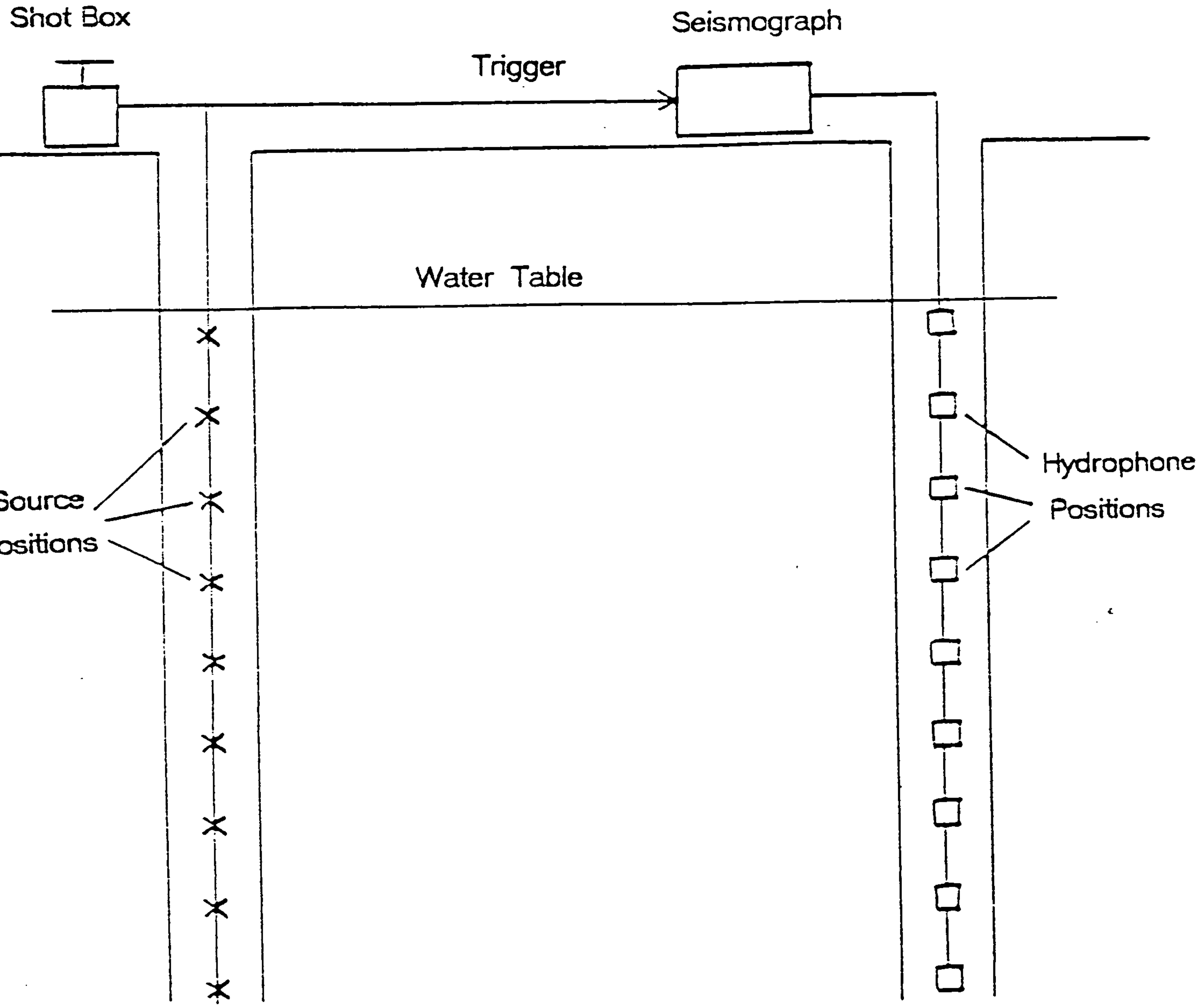


Figure 2.1 Typical cross-hole survey field set-up.

2.4 Data acquisition problems

Three distinct types of problem were encountered during data acquisition: timing errors, noise and borehole blockages.

2.4.1 Timing errors

Initial trials with the acquisition system used a Huntex shot box to fire the detonator and simultaneously send a trigger signal to the seismograph, but this was found to be insufficiently accurate, resulting in random timing errors of up to 1 ms in the recorded data. As an alternative to this, some wire was wrapped around the detonator and connected to a trigger lead above the steel tube of the source tool. The trigger lead ran up the borehole and was fed into the trigger input of the seismograph via a differentiating capacitor. The firing pulse was provided by a 12V car battery. When the detonator exploded, the wire around the detonator was broken causing a resistive change at the trigger input. This method was found to give very accurate timing breaks. Timing errors could be checked by inspecting the first break time of the common hydrophone channel between repeated shots. Occasionally random timing errors would still occur, and these were attributed to electrical pick-up between the firing and triggering lines.

2.4.2 Noise

There were two different categories of noise: shot-generated noise and background noise. The shot-generated noise consisted of tube-wave arrivals (equivalent to surface waves in conventional seismic surveys) which are low-velocity events travelling along the borehole wall. These are discussed in section 3.3.4. No suitable acquisition technique could be used to suppress these arrivals.

Background noise was both man-made and natural, including drilling-rig vibrations (because acquisition took place on active exploration sites), and factory-generated noise at one site. Water dripping into the boreholes from above the water table caused noise events on shallow receivers and low-frequency (~10 Hz) pipe resonances were detected in some surveys. Pipe resonances could be removed by the use of high-pass filters, but the presence of drilling crews frequently led to long delays between successive shots, until a lull in drilling operations took place.

2.4.3 Borehole blockages

Borehole blockages were the most serious problem encountered in data acquisition, and led to several trial surveys being abandoned. After drilling was finished, the borehole would gradually fill with mud and debris which fell from the borehole walls. This obviously reduced the maximum source and receiver depths as time passed. It was therefore essential for surface casing to be left in the boreholes so that the soft near-surface drift material would not simply fall down the boreholes. Ideally, surveys would also be carried out as soon as possible after the boreholes were drilled and logged.

Unfortunately, where old mineworkings and faulting occur in the boreholes (i.e. those areas of particular interest), the borehole walls are particularly susceptible to collapse. It was frequently the case that a borehole would be blocked just above the level of old mineworkings. Surveys in available boreholes where not attempted when the borehole walls were thought to be particularly unstable for fear of losing the hydrophone string.

2.5 Uphole shots and verticality

Two further sets of measurements were required to complete each survey: velocity readings within the boreholes and verticality readings. Unfortunately, in some cases these additional data were unobtainable due to borehole collapses.

2.5.1 Uphole velocity estimates

Interval velocity estimates are made in each borehole by firing a shot 2m below the hydrophone string. In this way approximate values of the vertical velocity field can be obtained. A sampling interval of 100μs is used and worst errors, Δv, in the interval velocities, v, can be estimated using the following equation (Stewart, 1984):

$$\Delta v = 2v\frac{\delta t}{\Delta t} \qquad (2.1)$$

where Δt is the travel time between two receiver positions, and δt is the timing error. To avoid the risk of losing the hydrophone string, it was sometimes necessary to estimate the interval velocities by recording the traveltimes to a surface geophone from several shot positions, but this resulted in less accurate first break picks and thus greater errors in the interval velocity field estimates.

2.5.2 Borehole verticality

The deviation of the borehole from the vertical and the azimuth of this deviation were measured by using a pendulum-type inclinometer. This tool could be run down the borehole within its own casing in two perpendicular directions, but had a depth limit of 60m. The dip readings were converted to borehole displacements using the program of Howson and Sides (1986). On the whole, borehole deviations were slight, particularly at shallow depths, and were rarely more than 3.0 metres at the bottom source and receiver depths. Neighbouring boreholes usually deviated in a similar manner.

Chapter III

Data processing

3.1 Introduction

The close resemblance of cross-hole seismic reflection common shot gathers to offset vertical seismic profiles (OVSPs) provides an obvious route for processing these surveys. Essentially, each common shot gather may be thought of as an individual OVSP, but with the additional complication of having some receiver positions at shallower depths than the level of the source. A typical data processing scheme for cross-hole data is shown in figure 3.1. The processing consists of several distinct stages: editing, wavefield separation, deconvolution, velocity field estimation and imaging. These are discussed below.

3.2 Editing

Following data acquisition, the field data are transferred from DOS-format floppy disks to the University of Durham Amdahl 470/V8 mainframe computer. Data from combined hole-to-surface and cross-hole surveys (see section 2.3.3) are then separated using utility software, and the cross-hole data are then sorted into common shot gathers.

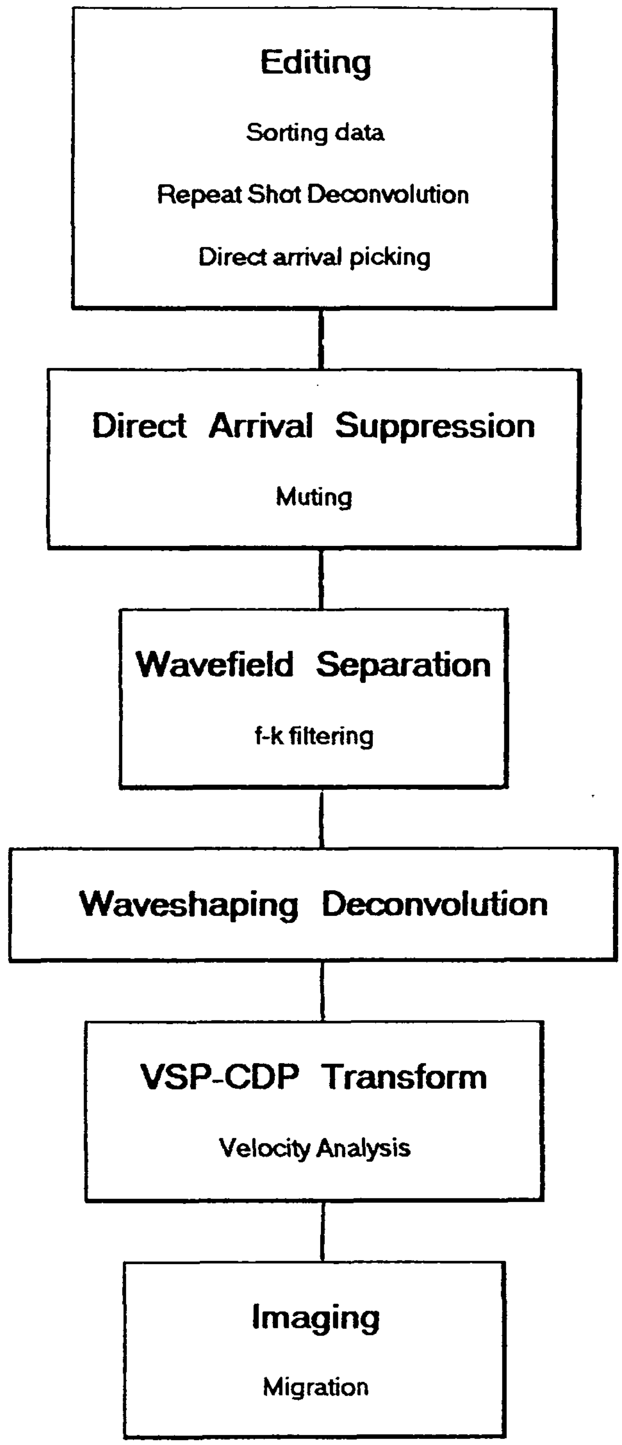


Figure 3.1 Outline of cross-hole reflection data-processing scheme.

3.2.1 Shot-matching deconvolution

Usually each common shot gather comprises two (or more) positions of the hydrophone string with at least one hydrophone position kept in common between adjacent string positions for the repeated shots. This is used as a precautionary measure to ensure that there are no time break errors in the survey and also to check for the repeatability of the source waveform. In cases where the common shot traces do not correspond, a waveshaping Wiener filter may be designed and applied to one set of hydrophone positions so that a match will occur on the common trace. An example of such a deconvolution is shown in figures 3.2-3.5 .

Figure 3.2 shows the raw recorded data for a particular common shot gather. In this case, data were recorded by firing a shot whilst the hydrophones were at depths (12-34 m) and then moving the hydrophones so that they lay at depths (34-56m) and firing a second shot at the same depth. Thus channels 12 and 13 correspond to the common channel for this common shot gather. There is a noticeable mismatch in the character of these traces and so a deconvolution operator was designed along the following lines. Firstly, a suitable time window (including the first arrivals and any dominant reflections) was chosen for the two traces and the segments of data within the window were tapered. A least-error-energy Wiener waveshaping filter was then calculated which, when convolved with the window from trace 13, would result in an output which approximated the window from trace 12. Figure 3.3 illustrates the windowed data, the deconvolution operator, and the filter output as time series. The respective amplitude spectra are plotted in figure 3.4. Figure 3.5 is a plot of the common shot gather following the application of the same waveshaping filter to traces 13-24.

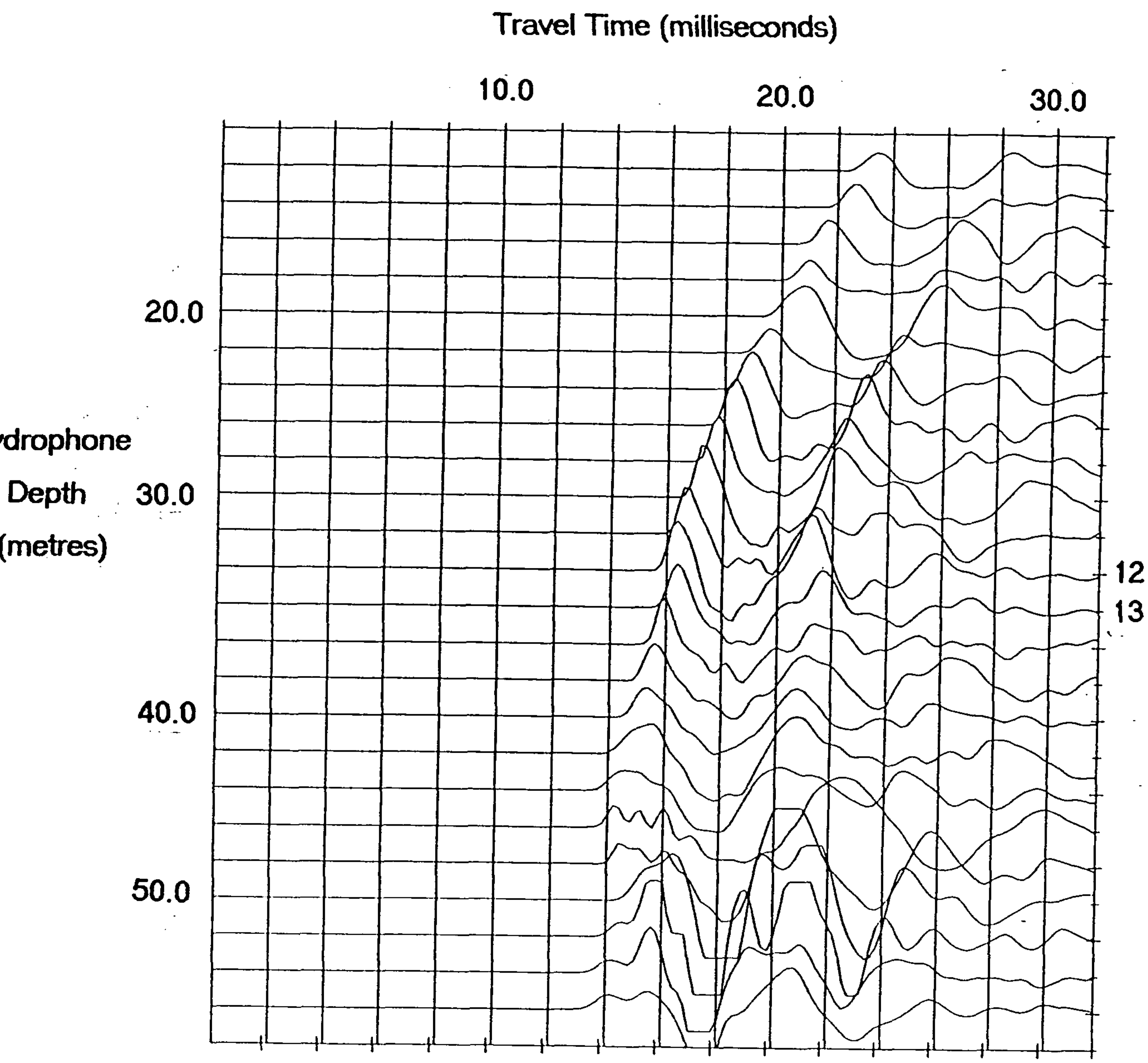


Figure 3.2 Unprocessed common shot gather. Channels 12 and 13 are repeat shot common receivers.

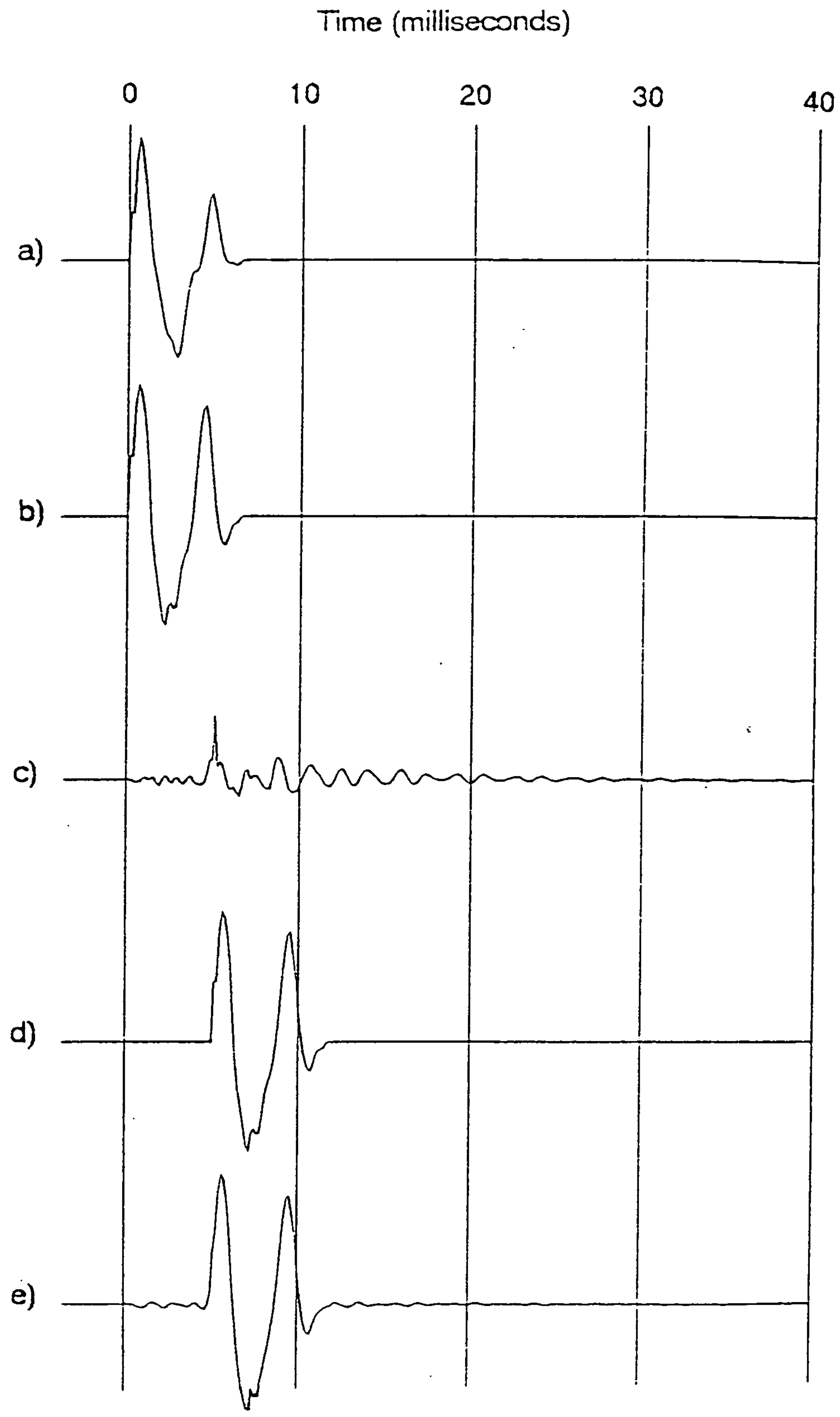


Figure 3.3 Repeat shot deconvolution: a) input signal, b) desired output signal, c) filter, d)lagged desired output signal, e) convolution of input signal and filter.

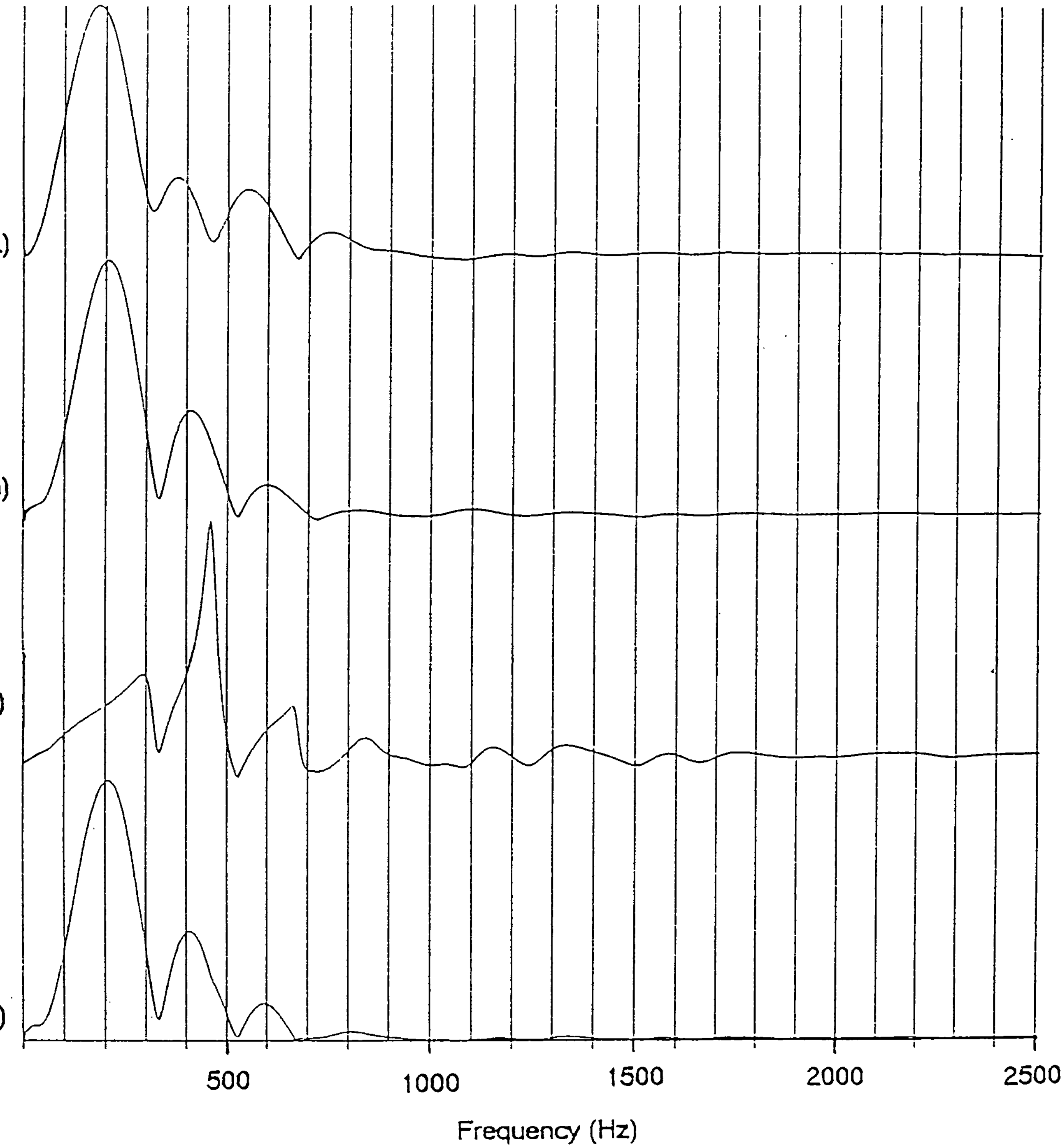


Figure 3.4 Repeat shot deconvolution - amplitude spectra: a) input signal, b) desired output, c) filter, d) filtered input.

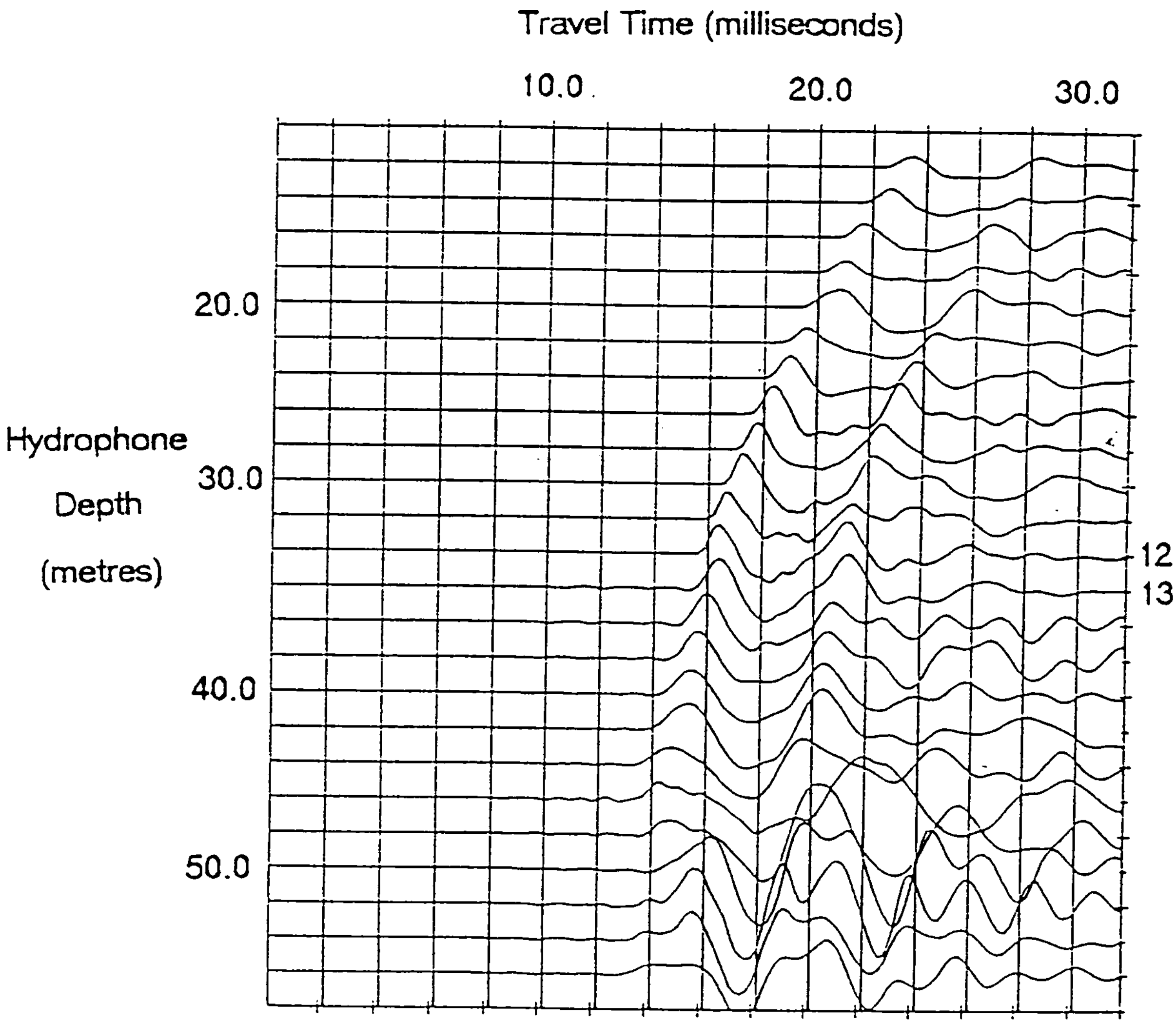


Figure 3.5 Common shot gather after repeat shot deconvolution.

After this preliminary deconvolution, an amplitude scaling factor is applied to equalise the shot energies for the two hydrophone positions. This is taken to be the ratio of the rms amplitudes of the common receiver traces.

3.2.2 First break estimation and direct arrival suppression

In order to mute out the large-amplitude direct arrivals, it is first necessary to estimate the direct arrival times at each hydrophone position. An automatic first-break picking program was found to give good results for cross-hole data provided the signal-to-noise ratio was sufficiently high (as is usually the case with cross-hole data). First breaks are picked on a statistical basis, by simply locating the time sample where the recorded signal amplitude rises sufficiently above the rms amplitude of the background noise. In addition, it was found to be necessary to check all first-break times manually to avoid the inclusion of "head wave" arrival picks.

Once direct arrival times have been picked from the data, it is a simple matter to mute the direct arrival energy by specifying a window for a cosine taper on each trace. Some reflected energy is undoubtedly lost by removing the direct arrivals in this way. Unfortunately this means that reflector coverage will be lost near the receiver borehole, but this method was found to be the most suitable for the field datasets discussed in chapter V.

An alternative scheme for direct arrival removal has been proposed by Pratt and Goulty (1991) who applied it to ultrasonic model data. This removes the direct arrival waveform of a particular trace by aligning the first breaks of those traces which correspond to nearest neighbour sources and receivers. These trace are then averaged to provide an estimate of the direct arrival waveform which may then be subtracted from the original trace to yield the scattered wavefield. This method was found to be unsuitable for the cross-hole datasets discussed later, because the direct arrival waveform was not sufficiently consistent between adjacent traces. This is probably due to peg-leg multiples which will be present in data acquired from the real earth with its small-scale layering, as opposed to that acquired from an ultrasonic modelling system where the model consists of relatively few homogeneous layers.

Direct arrival muting may be carried out either before or after wavefield separation. Inclusion of the direct arrivals in the wavefield separation can lead to ringing problems when frequency-wavenumber filters are applied to the data (see section 3.3), but on traces where the direct arrivals are downgoing and the interesting reflections are upgoing, it is preferable to mute after separation in order to preserve as much of the scattered wavefield as possible. This is the final stage of the editing procedure, and the processing sequence then continues with the application of wavefield separation filters.

3.3 Wavefield separation

The scattered wavefield recorded for each common shot gather may be classified as consisting of upgoing and downgoing components. These refer to waves which travel upwards or downwards, respectively, across the receiver array. The upgoing and downgoing scattered energies must be imaged independently because of the net cancellation effect which would result in combining their respective reflectivity amplitudes.

Clearly, for a particular reflecting interface, the signals which are recorded from shots above the interface on receivers above the interface (i.e. upgoing reflection events) will be of opposite polarity to those which are recorded from shots below the interface on receivers also below the interface (i.e. downgoing reflected events). Since the apparent velocities of these upgoing and downgoing events are of opposite sign ($\frac{dz}{dt} > 0$ for downgoing events; $\frac{dz}{dt} < 0$ for upgoing events) these events are readily separable by means of velocity filters.

For zero-offset VSP surveys, separation may be carried out by median filters which rely upon the linear moveout of reflection events (Hardage, 1983). When the source is offset from the receiver array, however, this moveout is non-linear and so it is necessary to apply filters which can selectively pass or reject arrivals with a range of apparent velocities. One such filter type is the pie-slice filter (Embree et al., 1963), which is applied to data which have undergone a two-dimensional Fourier transform into the frequency-wavenumber (*f-k*) domain.

The two-dimensional Fourier transform is implemented on digitally recorded data by means of the Fast Fourier Transform or FFT (Cooley and Tukey, 1965). This algorithm requires that the data consist of 2^n samples (n being an integer) and assumes that the data have a periodicity equal to this sample size. To carry out a two-dimensional transform on a common shot gather the algorithm may be applied first in the time direction on all traces, and then in the spatial (depth or *z*) direction at all frequencies, although the sequence of these operations is immaterial.

In dealing with digitally sampled data, there are some important factors to be considered which do not occur with analogue data. In particular, in discrete Fourier space, there may be problems due to the data being undersampled and thus not uniquely defined.

3.3.1 The Nyquist frequencies and aliasing

If the recorded data have a time sampling interval Δt and the receivers are regularly spaced at intervals of Δz, then the temporal and spatial Nyquist frequencies are respectively defined as:

$$f_{\mathrm{NYQ}} = \frac{1}{2\Delta t} \; ; \; k_{\mathrm{NYQ}} = \frac{1}{2\Delta z} \tag{3.1}$$

Only if all (f,k) components in the recorded data lie within the range governed by the positive and negative Nyquist values will the data be completely determined by the recorded samples. If (f,k) components outside the Nyquist range are present then they will be aliased when they are recorded. This means that they will wrap around in the discrete Fourier space because of the periodic nature of the transform and contaminate the unaliased (f,k) components. March and Bailey (1983) give an informative account of the *f-k* transform.

3.3.2 Two-dimensional filter application

Filter application in the *f-k* domain involves complex number multiplications of each component in *f-k* space with the corresponding component of the filter. This operation is equivalent to a convolution in the *z-t* domain of the original data with the impulse response of the filter.

One characteristic of the Fourier transform is that discontinuities or steep slopes which are present in a function in one domain lead to the Gibb's phenomenon, also known as ringing, in the transformed data. With cross-hole seismic data it is common to find that the data taper smoothly towards zero amplitude in the temporal direction but, because of the restriction imposed by the finite recording aperture of the receiver array, there are sharp discontinuities at the edges of the data in the spatial direction. Normally these would result in ringing in the wavenumber domain. It is thus necessary to apply a taper across the edge traces in the spatial direction, and a simple cosine taper over four traces is found to be adequate for this purpose.

Another problem with the discrete Fourier transform is that the data, although recorded over a finite range of times and depths, are assumed to be periodic outside the recorded ranges. Hence, a multiplication in the *f-k* domain is equivalent to a cyclic convolution, and not a transient convolution. Convolution in the time domain results in an output which has a length equal to the length of the data plus the length of the filter. When the filter is applied in the *f-k* domain, the extra output length will become wrapped around "noise" on the outer traces after the reverse transform is applied. This filter leakage can be avoided if the data are padded out with blank traces before applying the FFT. The total number of traces is made up to the next power of two, since the FFT algorithm requires that the number of samples to be processed is a power of two.

3.3.3 Filter design

In the case of pie-slice filters which are applied to common shot gathers of cross-hole seismic data, it is usually necessary to design the *f-k* filter with steep slopes in order to separate the upgoing and downgoing events, whilst rejecting as little of the appropriate P-wave reflection energy as possible. In order to accomplish this, while at the same time keeping the ringing effects induced by the steep slopes to a

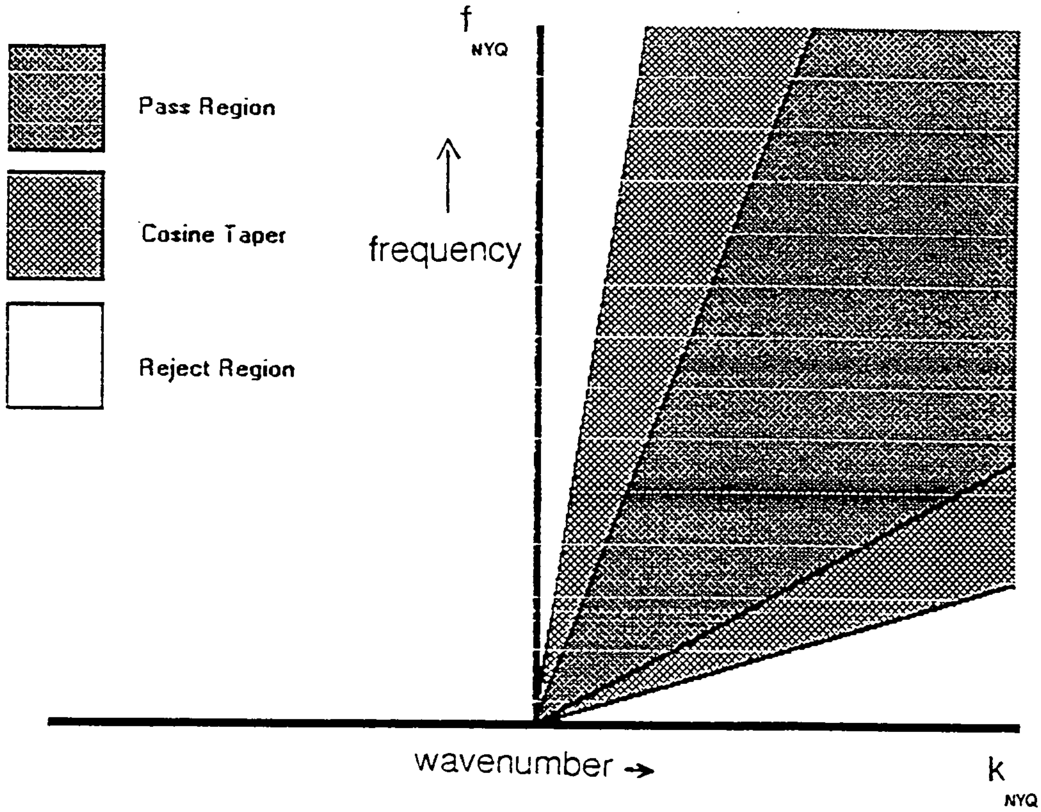


Figure 3.6 Two-dimensional f-k filter implementation

minimum, the edges of the velocity filters are selected so that they lie along low amplitude channels in the data; an approach advocated by Christie et al. (1983) and similar to the contour-slice filtering proposed by Suprajitno and Greenhalgh (1985). Filter edges are tapered by a smooth cosine taper which runs perpendicular to the bisector of two lines in *f-k* space which determine the tapering region (figure 3.6).

Other considerations of filter design include the rejection of events other than P-wave reflections. Although the hydrophone receivers used in the cross-hole surveys discussed later are pressure sensitive devices, they will also record SV energy when they are located in a borehole (Schoenberg, 1986). The apparent velocity of SV arrivals ranges from infinity (wavefronts parallel to the borehole axis) down to the SV wave velocity in the rock medium (raypaths parallel to the borehole axis). Thus direct wave SV arrivals are difficult to filter out but SV arrivals with apparent velocities less than the P-wave velocity in the rock may be readily removed. Generally, it would only be mode-converted P—>SV reflections which would arrive within the time window of interest in the surveys reported here.

3.3.4 Tube waves and spatial aliasing

Another type of coherent noise event, which is more significant in borehole seismic data, is the tube wave. The tube waves, which have been observed in the boreholes discussed in chapter V, typically have a larger amplitude and lower frequency than body waves and can be thought of as a type of surface wave (the Stoneley wave) which travels along the interface between the borehole wall and the borehole fluid with an elliptical particle motion. These waves sometimes emanate from the top (or water table) and bottom of the receiver borehole, and frequently

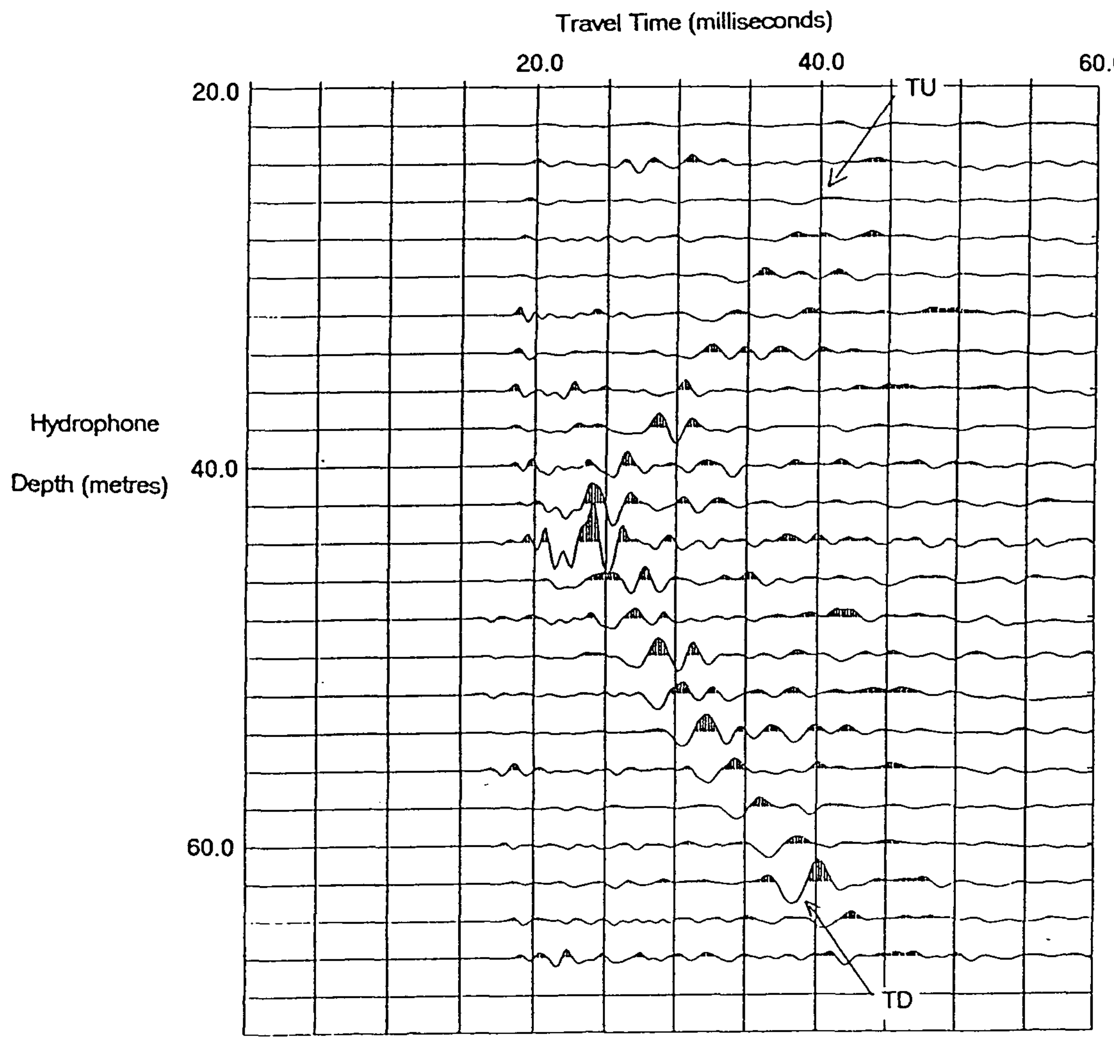


Figure 3.7 Tube waves example: upgoing and downgoing tube wave events are indicated by TU and TD respectively.

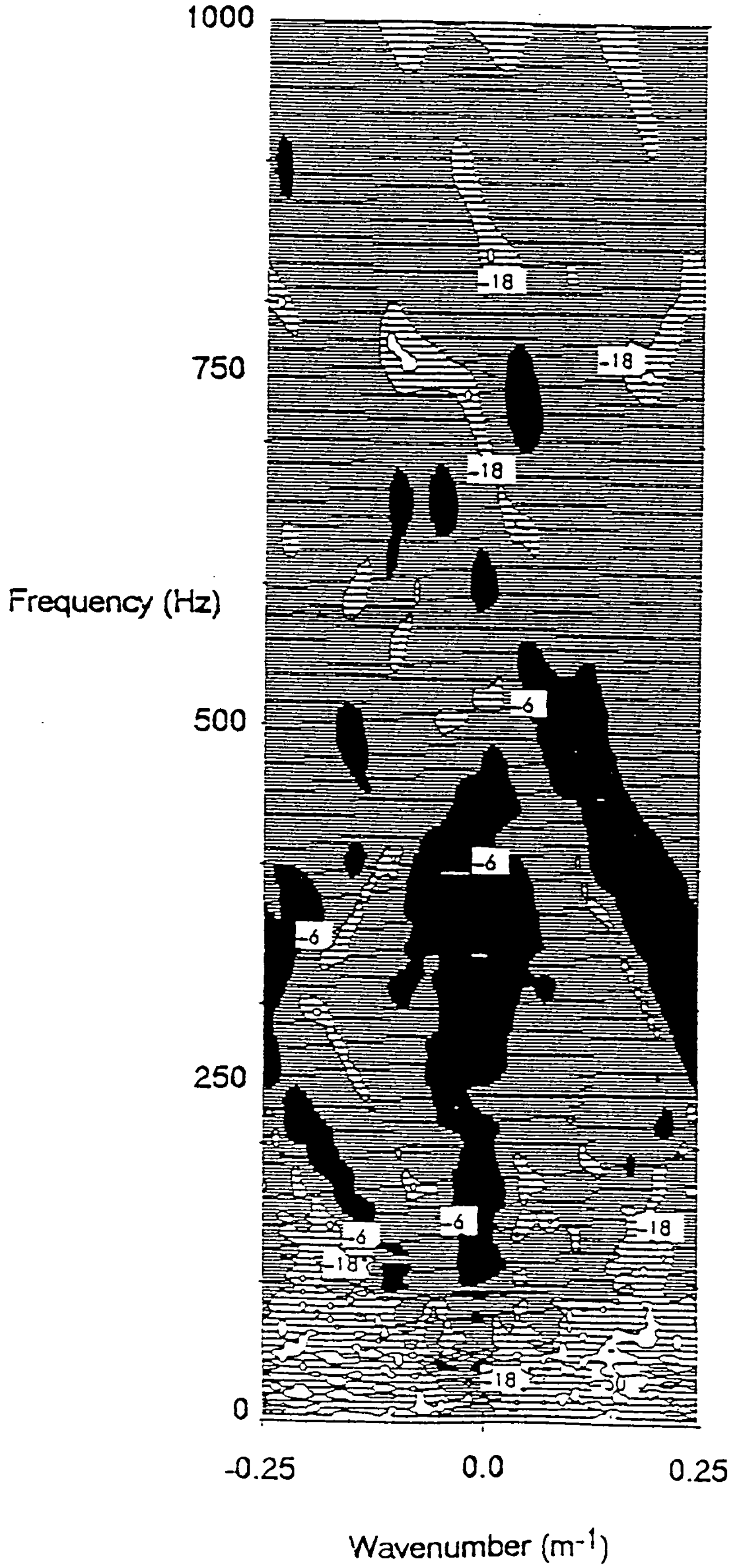


Figure 3.8 Tube wave amplitude spectrum. Contour levels are at 6, 18 and 30 dB below peak amplitude.

originate at seam level depths in shallow Coal Measures strata. One such tube wave is shown in figure 3.7 with its *f-k* spectrum in figure 3.8.

Examination of the moveout per trace of the tube wave arrival in figure 3.7 reveals that this is greater than half the dominant period of the arrival and so it is spatially aliased. An event with an apparent velocity V_{APP} will be spatially aliased for temporal frequencies greater than $f_{ALIAS} = V_{APP} / k_{NYQ}$. A spatially aliased event wraps round in the *f-k* domain (see figure 3.8) due to the periodicity of the discrete Fourier transform. Therefore, in order to remove spatially aliased noise from the data, it is necessary to apply a rejection filter which itself will wrap around in the *f-k* domain. Unfortunately, this type of filter will also remove reflected P-wave energy from the quadrant in *f-k* space into which it wraps round, thus reducing the information content of the data. In most cases where this was done it did not have a severe effect on the data.

An alternative method of removing low velocity spatially aliased noise is to apply a linear moveout to the data before applying the two dimensional FFT and thereby alter the moveouts of all events so that the spatially aliased events are no longer aliased and can be removed with ease in *f-k* space. The artificial moveout is then removed following a transformation back to the *z-t* domain. This method can lead to events, which were not previously aliased, becoming aliased, and so the method is highly data-dependent and must be applied with care. In most cross-hole surveys where tube waves occurred they were both upgoing and downgoing which meant that this method could not be applied (de-aliasing of one tube wave type would mean even more severe aliasing of the other).

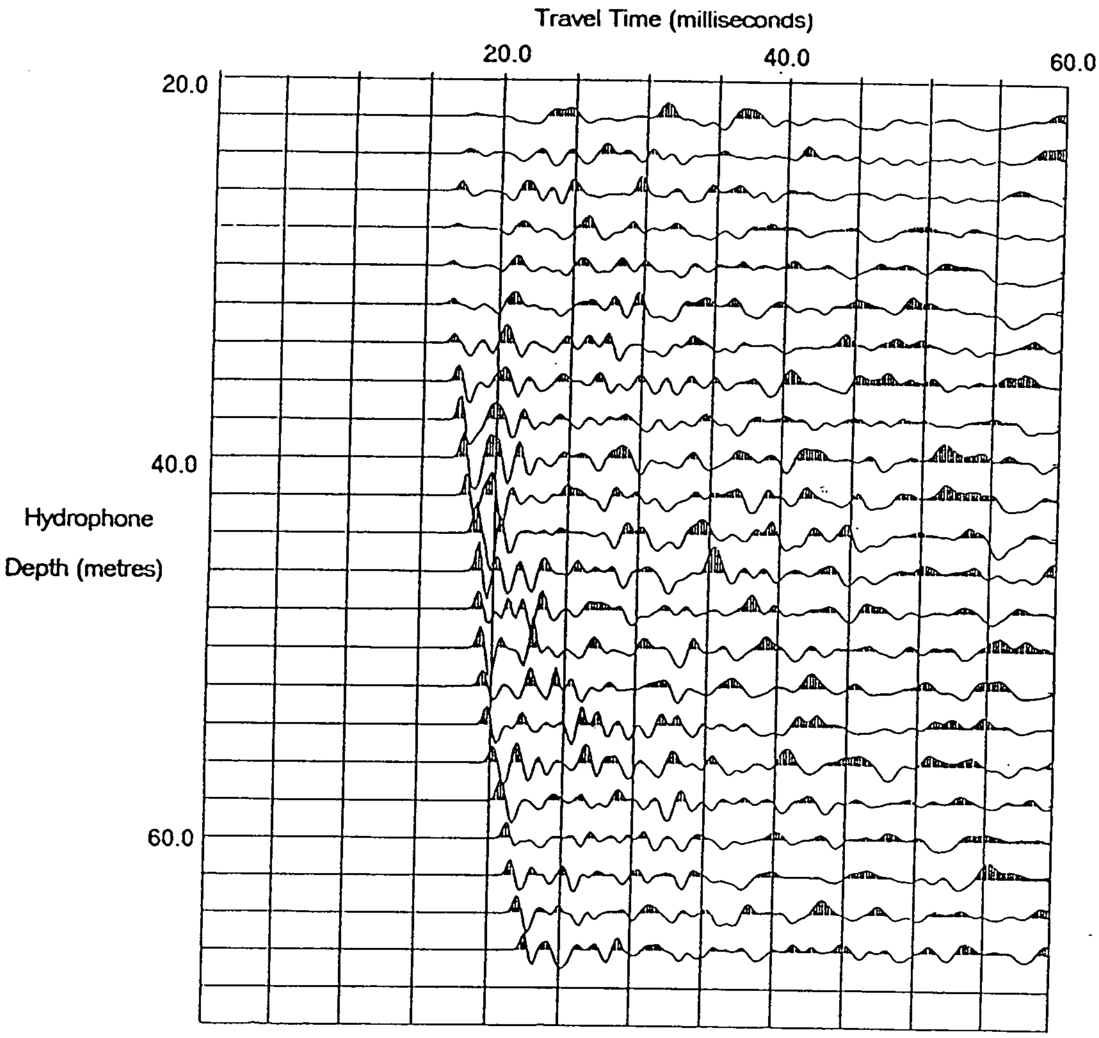


Figure3.9 A common shot gather from survey A of chapter V.

The data processing software (Appendix A.1) allows for several different filter design options, including the wrap around type of filter and trapezoidal-shaped filters as well as pie slice filters. All filters can be specified as pass or reject types.

3.3.5 Examples of wavefield separation in the f-k domain

A common shot gather from one particular survey (survey A in Chapter V) is illustrated in figure 3.9. In this case the shot was positioned at a depth of 30m and the hydrophones were positioned at 2m intervals over a depth range of 22-66m. The receiver borehole was at an offset of 56m from the source. The data consist of both upgoing and downgoing reflections with direct arrivals also being present.

The data were transformed into *f-k* space to yield the amplitude spectrum of figure 3.10. This spectrum is plotted on a dB scale with the 6dB contour representing component amplitudes which are half the maximum amplitude. The principal features of this spectrum include: large direct arrival amplitudes around the k=0 axis and to the left of it; upgoing scattered arrivals to the right of this axis; and downgoing arrivals to the left of this axis. A pie slice filter designed to pass only the upgoing energy is specified by the lines OA and OB. This filter will pass all upgoing arrivals which travel with an apparent velocity of between 2000 m/s and 8000 m/s across the receiver array. Following application of the filter, the data were transformed back into *z-t* space (figure 3.11). The filter has successfully removed downgoing energy and enhanced the appearance of the upgoing reflected energy. Some of the direct arrival energy (on the upper traces) is also upgoing and so remains after the filter has been applied, but this may be removed by the application of a mute.

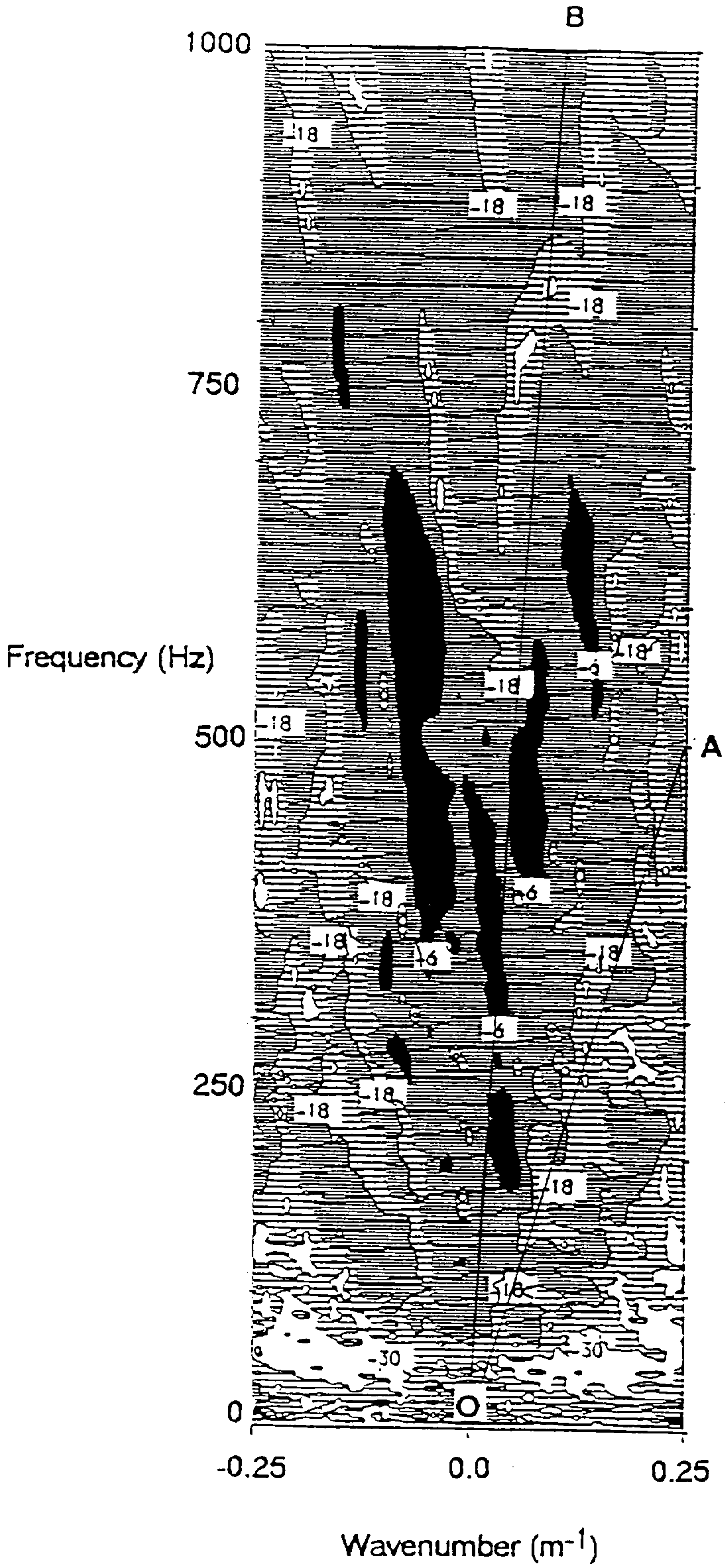


Figure 3.10 f-k amplitude spectrum of the common shot gather shown in figure 3.9. Edges of a filter to extract the upgoing wavefield are indicated by the lines OA and OB.

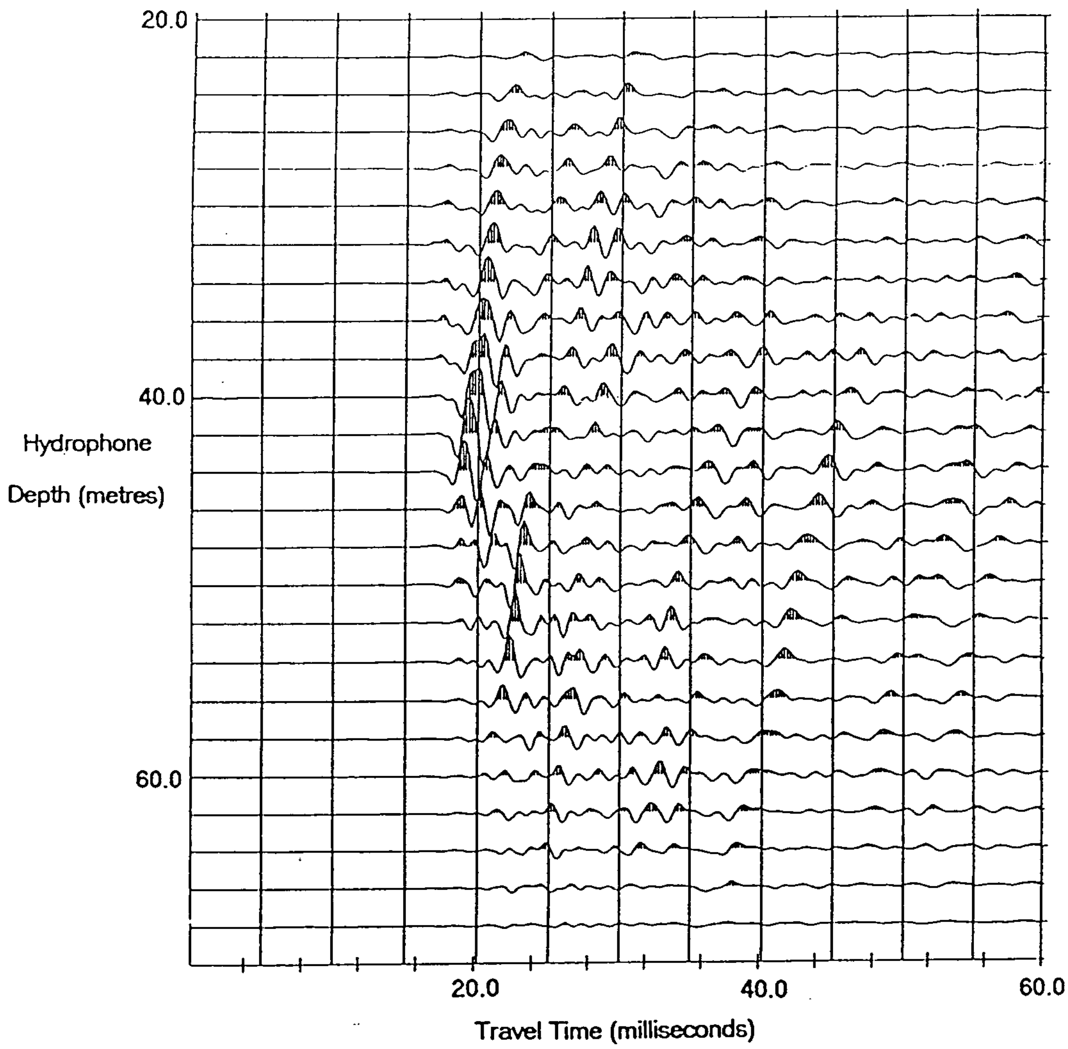


Figure 3.11 Upgoing wavefield after the application of a wavefield separation filter to the data of figure 3.9.

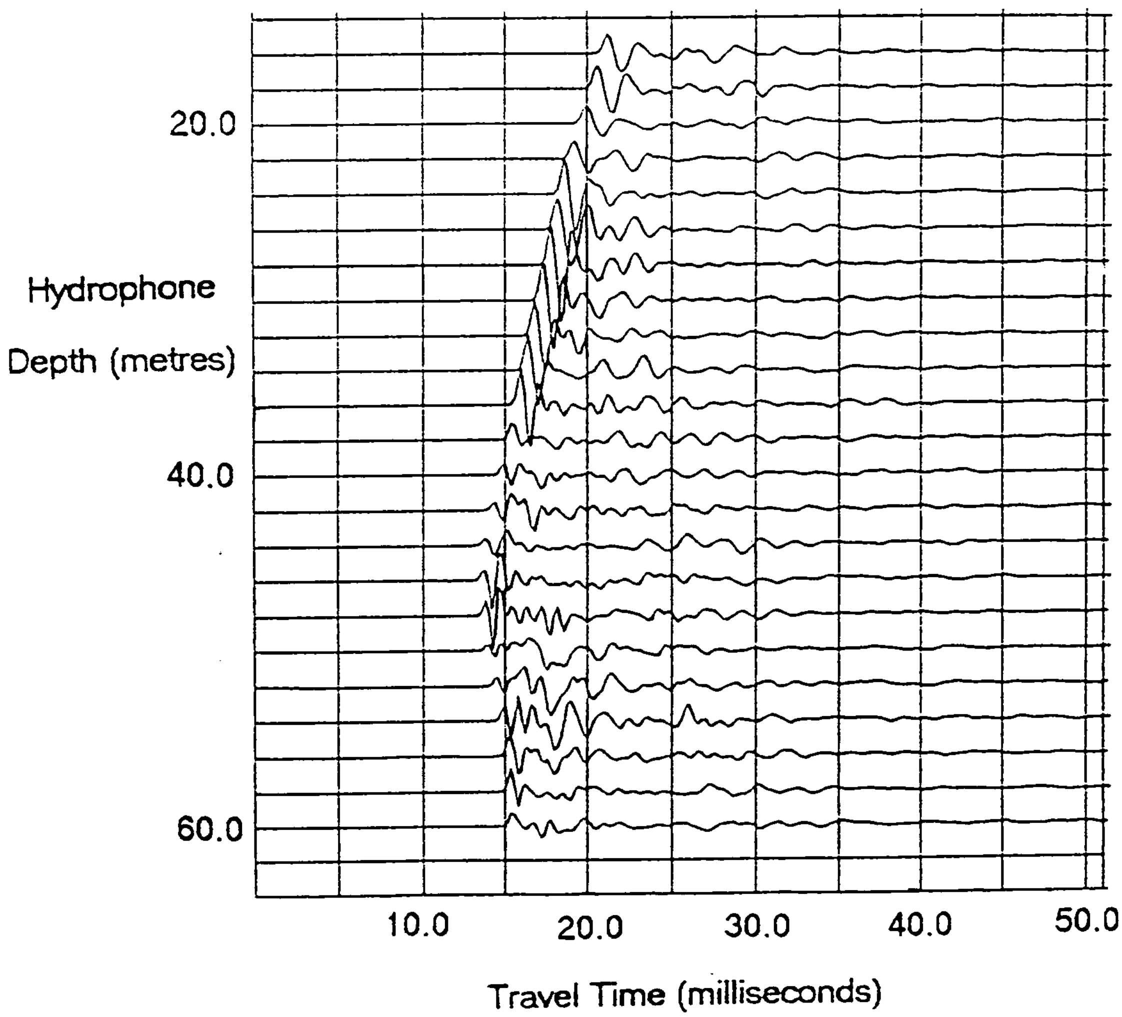


Figure 3.12 Common shot gather from survey B of chapter V.

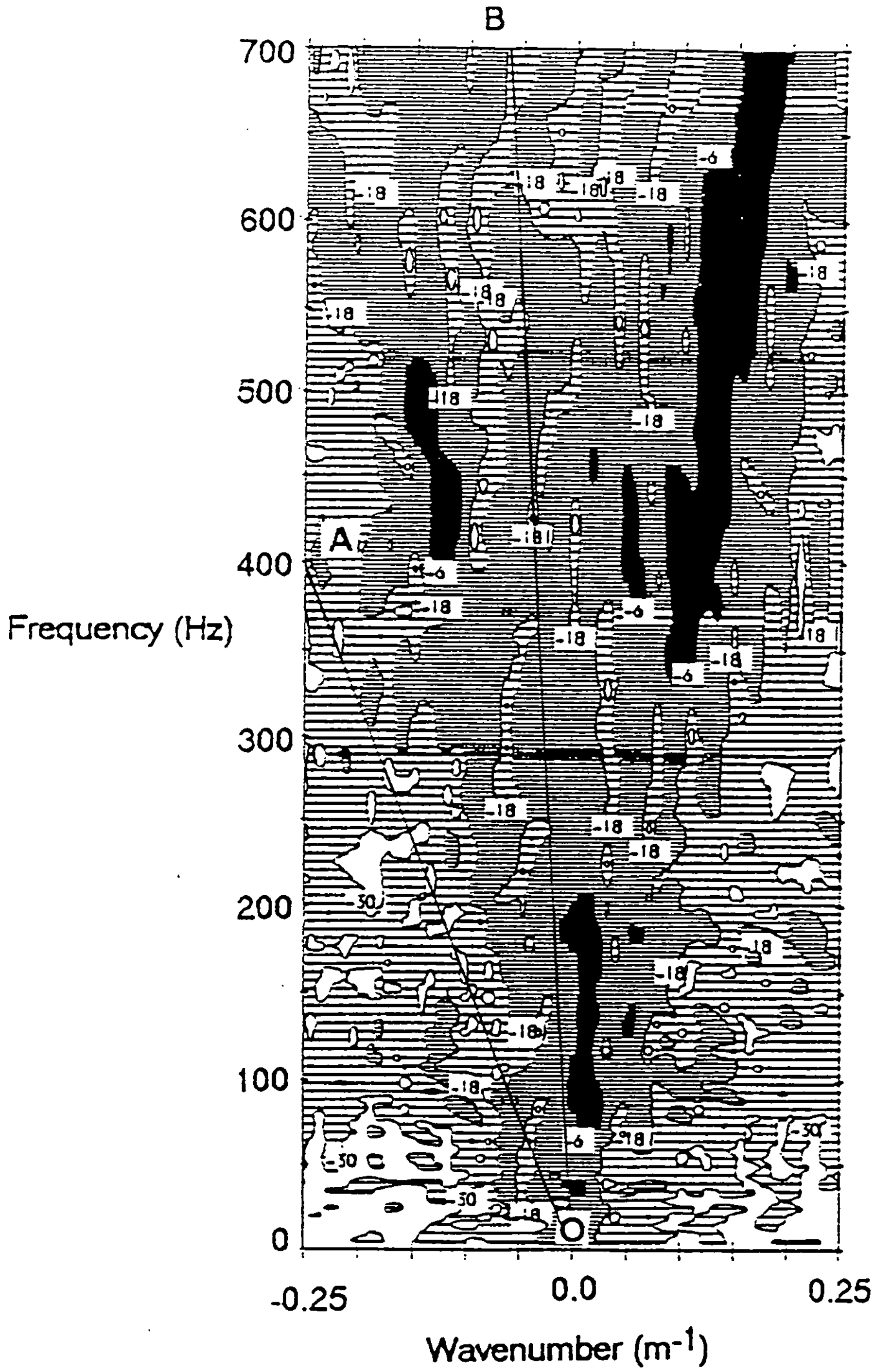


Figure 3.13 f-k amplitude spectrum of the common shot gather shown in figure 3.12. Edges of a filter to extract the downgoing wavefield are indicated by the lines OA and OB.

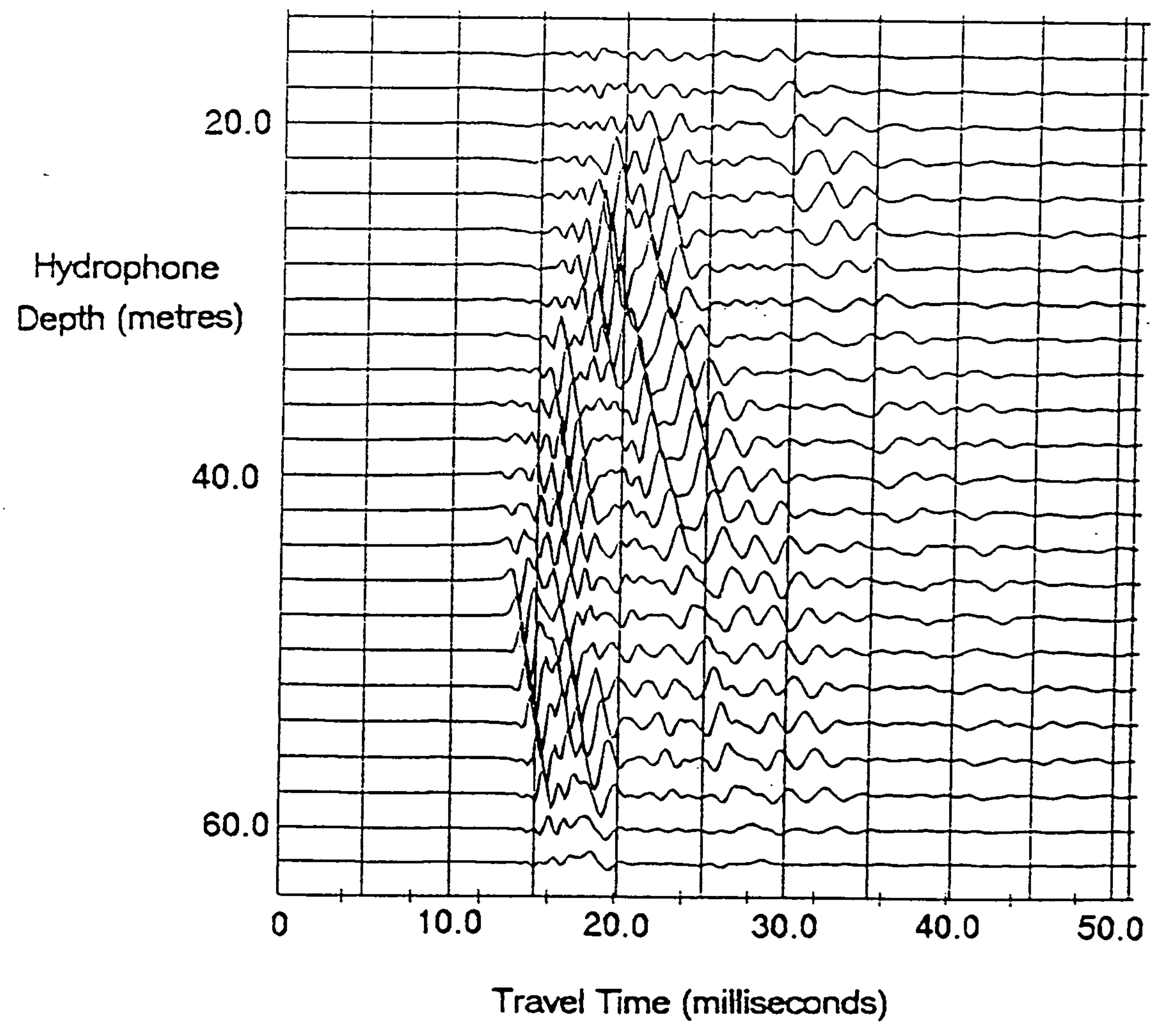


Figure 3.14 Downgoing wavefield after the application of a wavefield separation filter to the data of figure 3.12.

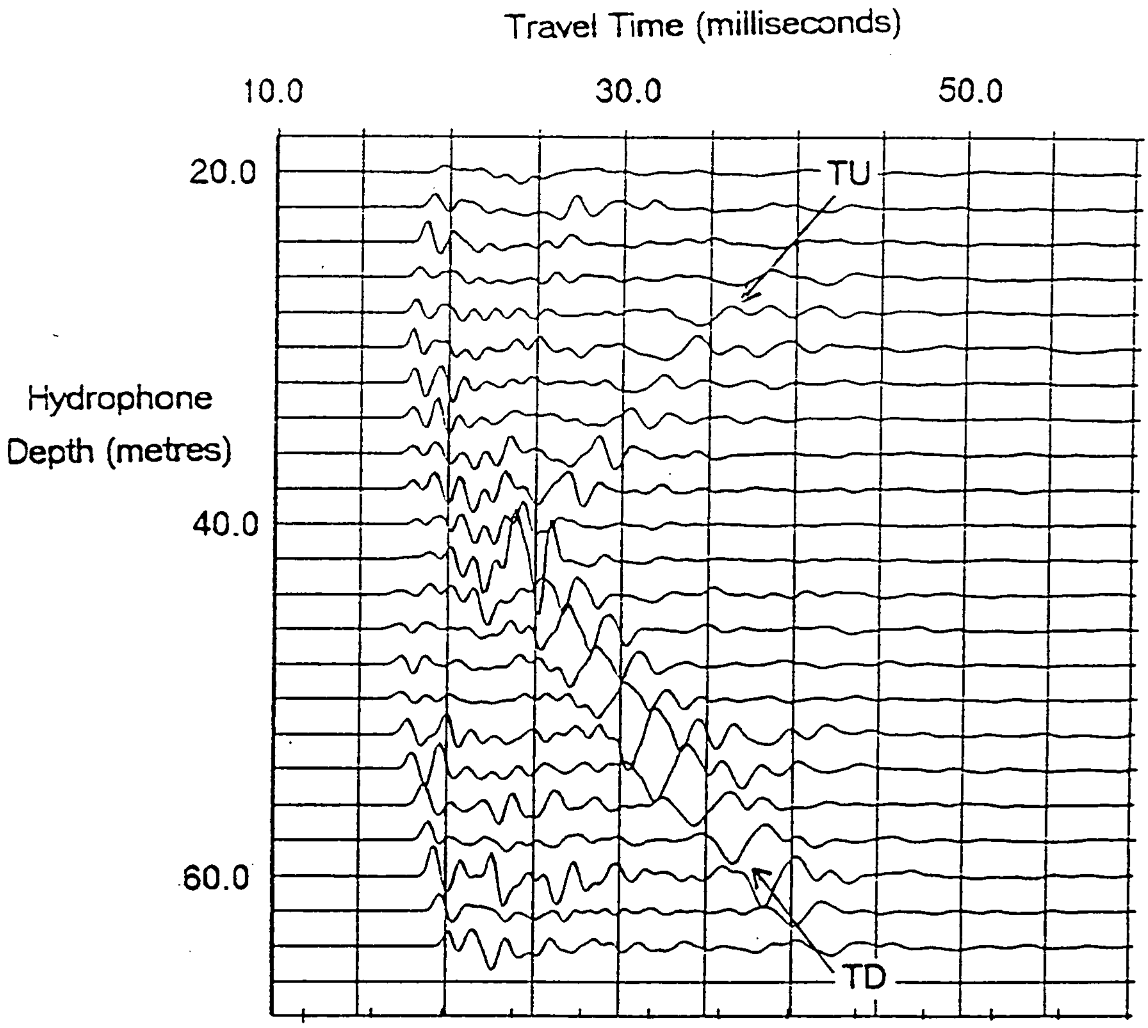


Figure 3.15 A common shot gather with tube waves indicated by TU (upgoing tube wave) and TD (downgoing tube wave).

Figure 3.12 is another common shot gather acquired on survey B of chapter V. In this case the shot depth is 48m and the receiver borehole offset is 40.9m, with 23 hydrophone positions covering a depth range of 16-60m. The two-dimensional amplitude spectrum is shown in figure 3.13. Again a filter has been defined by the lines OA and OB, in this case to pass velocities of between 1600 and 10000 m/s in the downgoing wavefield. Figure 3.14 shows the filtered common shot gather in *z-t* space. The downgoing reflected arrivals are now apparent, and the remaining direct arrival energy can again be muted out.

An example of a low-frequency high-amplitude tube wave with an apparent velocity of 1100 m/s is presented in figure 3.15. The events (both upgoing and downgoing) originate from a depth of 44m which corresponds to a coal seam in the receiver borehole. The shot was fired at the seam level depth. Presumably energy from P-wave first arrivals has been focused as "diving rays" by the low velocity of the coal relative to its surrounding bedrock. This would result in a large amplitude arrival at the receiver borehole which has in some way triggered off a tube wave, perhaps because the receiver borehole is caved at the seam level. The wave is obviously spatially aliased (i.e. undersampled by the receiver array) with the moveout per trace being greater than half the dominant period of the wave.

When the data are transformed into the *f-k* domain the amplitude spectrum (figure 3.16a) also shows the aliasing effect. The dominant downgoing tube wave wraps around in the *k*-direction from $-k_{NYQ}$ to $+k_{NYQ}$. In order to remove the tube wave noise from the data, it is necessary to apply a reject filter with parallel edges so that as much of the P-wave arrival energy is preserved as possible. The filter used is indicated by the lines AB, CD, EF and GH. On returning to *z-t* space (see figure 3.16b), we can see that the downward-travelling aliased event has been suppressed,

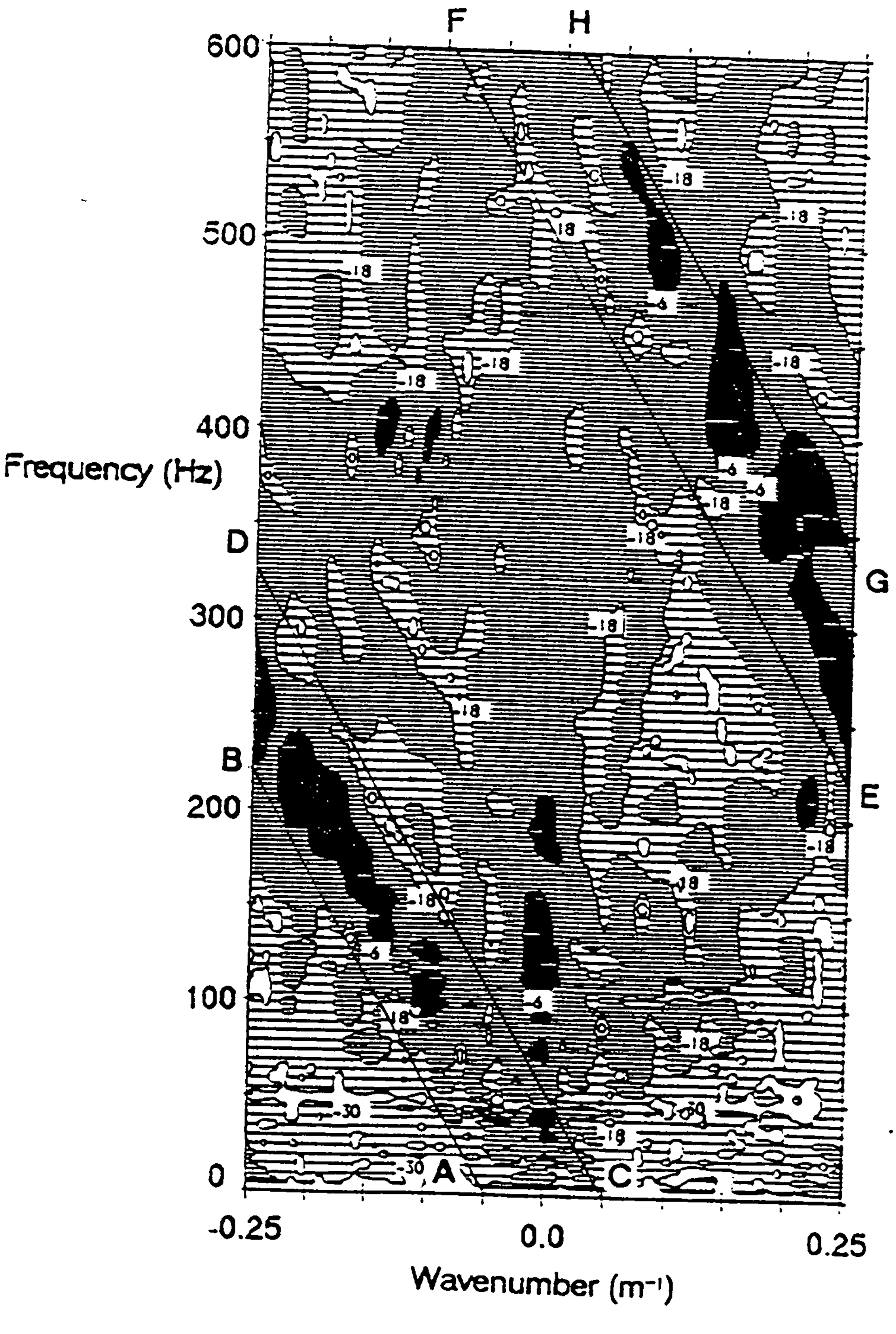


Figure 3.16a f-k amplitude spectrum of the data shown in figure 3.15. Filter edges for the removal of the downgoing tube wave are marked by AB, CD, EF, GH.

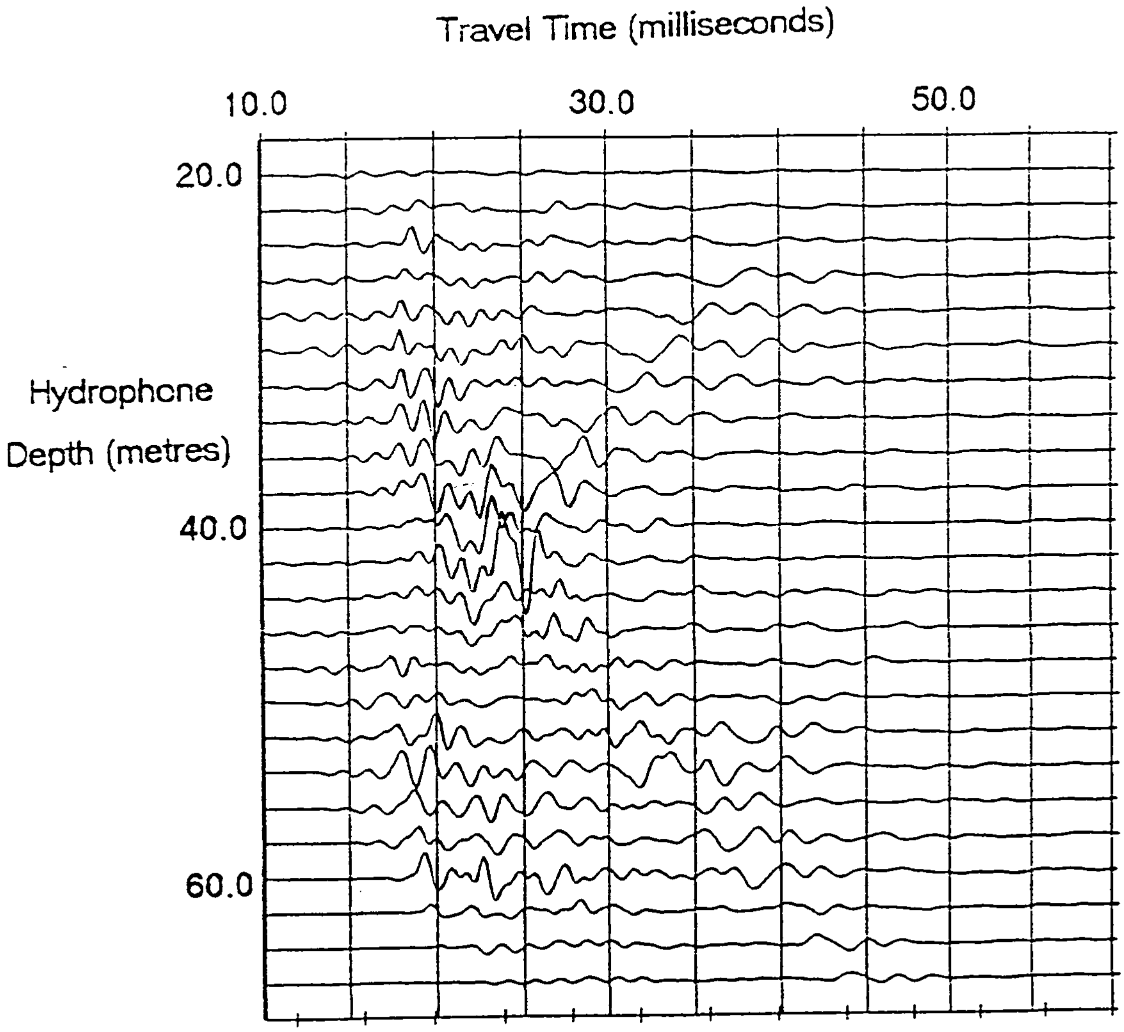


Figure 3.16b Common shot gather after the application of a reject filter to remove the downgoing tube wave.

although this has been at the expense of some of the reflected arrival information in the data. Ringing has also been introduced into the traces because of the sharp filter edges required to remove the tube wave.

3.4 Waveshaping deconvolution

In order to enhance the higher frequencies present in the data before they are imaged, a band pass filter may be applied which can suppress the low frequency (in this case below 200 Hz) components. In addition, there are advantages in changing the phase of the source wavelet in the data. The recorded seismograms may be thought of as convolutions of a real (causal) source function with the reflectivity response of the earth. As such, the onset of each arrival corresponds to the traveltime along the reflected raypath. It is preferable to produce a section in which the central peak of the arrival waveform corresponds to this traveltime. Such a waveform may be thought of as a band-limited spike with zero phase.

A least-squares energy Wiener waveshaping filter (see e.g. Robinson and Treitel, 1985) may be calculated to shape an estimate of the source wavelet into a zero-phase wavelet with a modified amplitude spectrum. This filter may then be convolved with the data to yield a zero-phase section. For the purposes of this deconvolution, the upgoing and downgoing wavefields in each common shot gather are processed separately because of possible directivity effects in the source signature. An estimate of the source waveform is obtained by assuming that the source function is a minimum phase wavelet and then applying a spectral factorisation (Claerbout, 1976) to a window of each trace in the common shot gather. The estimate of the

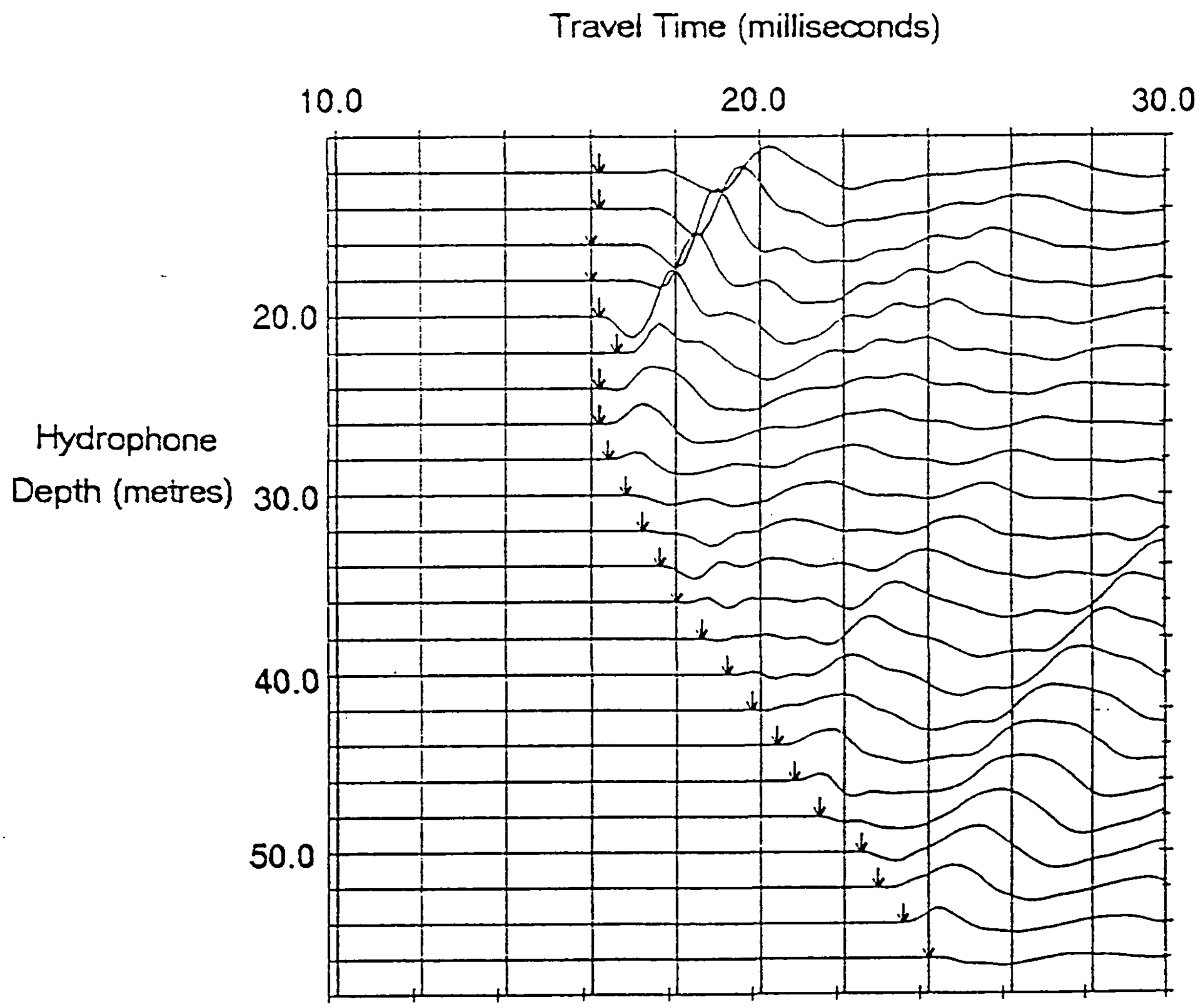


Figure 3.17 Waveshaping deconvolution: Upgoing wavefield common shot gather. Arrows indicate direct arrival picks.

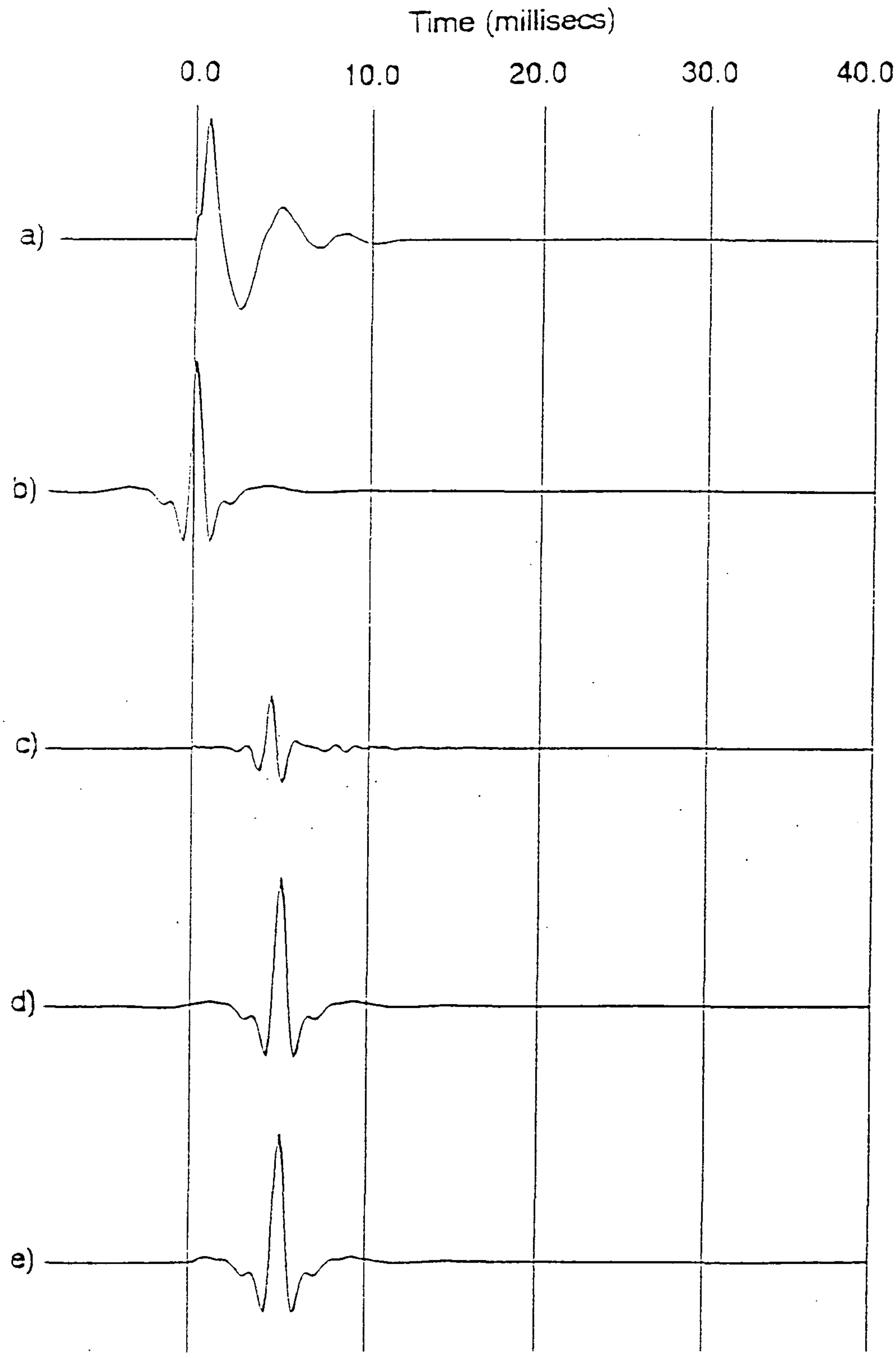


Figure 3.18a Waveshaping deconvolution: a) input wavelet, b) desired output zero-phase wavelet, c) waveshaping filter, d) lagged desired output, e) convolution of input wavelet and filter.

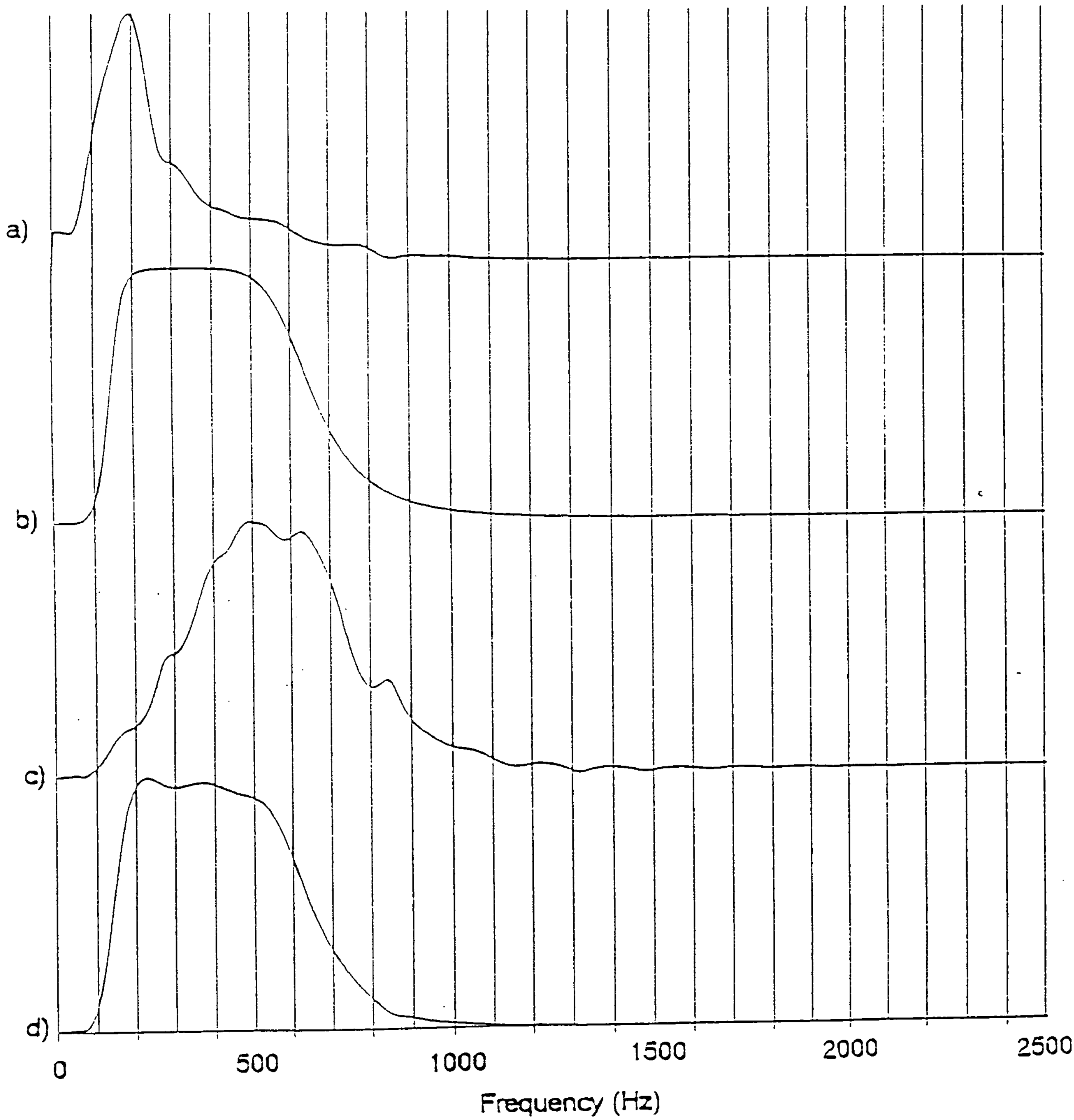


Figure 3.18b Waveshaping deconvolution amplitude spectra: a) input, b) desired output, c) filter, d) filtered input.

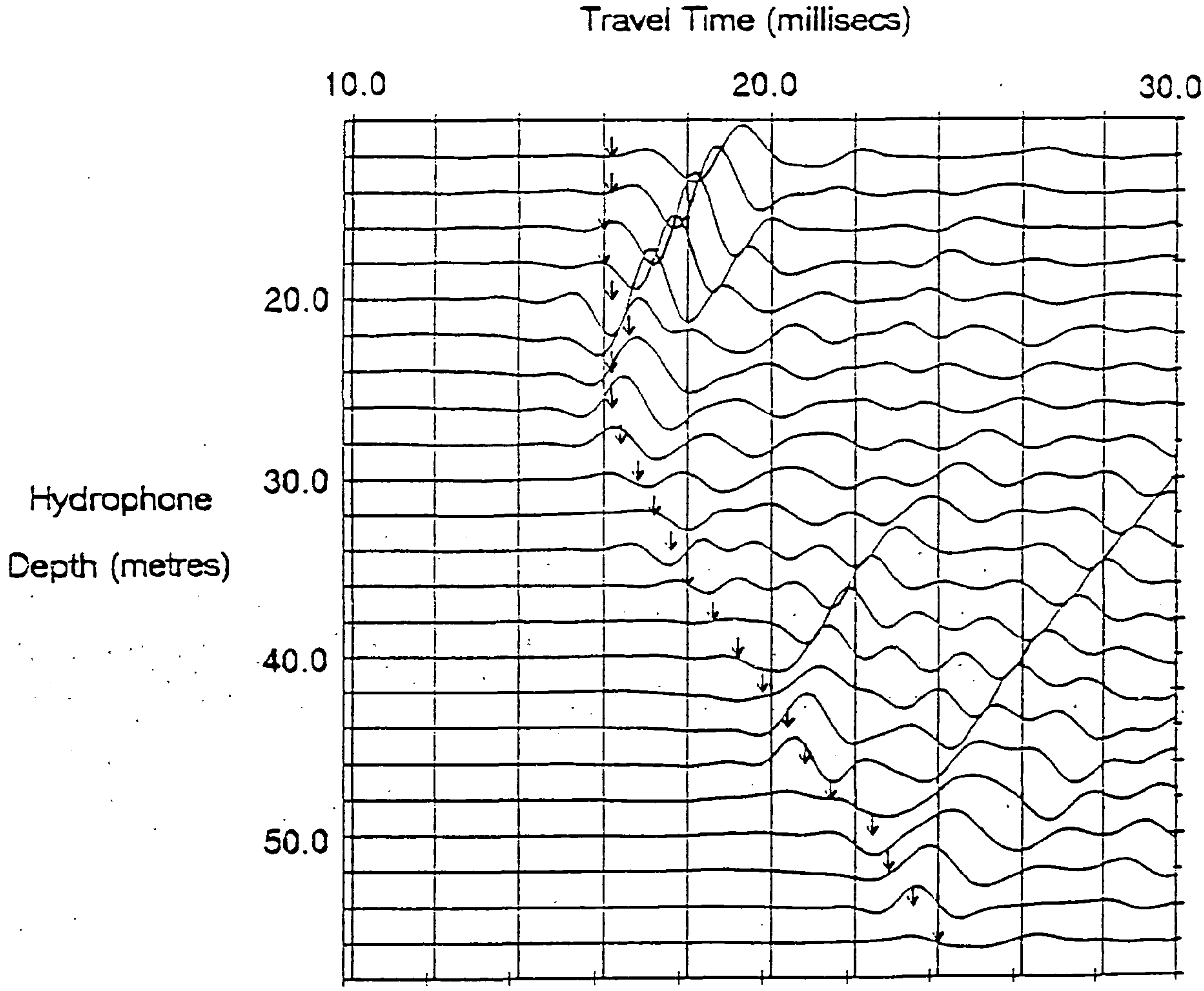


Figure 3.19 Common shot gather of figure 3.17 following waveshaping deconvolution.

waveform is then assumed to be an average of the estimates from each trace. Figures 3.17-3.19 illustrate the application of this method to the upgoing wavefield in a common shot gather.

Figure 3.17 is a plot of the upgoing wavefield after direct arrival suppression. Figure 3.18a consists of four waveforms. The first is the estimate of the source function obtained in the manner described above. The second is the desired output, a zero-phase Butterworth wavelet, and the third is the calculated filter coefficients. The bottom trace is a convolution of the filter with the input wavelet. The respective amplitude spectra of these traces are plotted in figure 3.18b. Figure 3.19 is the same common shot gather after the application of the designed waveshaping filter to all the traces. A comparison with figure 3.17 shows that the lower frequencies have been suppressed, and that zero crossings in figure 3.17 now correspond to peaks in figure 3.19.

3.5 Velocity field estimation

The direct arrival times, which are picked in the editing stage, can be used as the input to a Simultaneous Iterative Reconstruction Tomography (SIRT) velocity inversion program, written by Dyer (1988) and developed by Wye (1986), Findlay (1987) and Kragh (1990). Other P-wave velocity estimates can be obtained from uphole shots and by inspection of the near horizontal raypath traveltimes.

The results of tomographic inversion of the direct arrival times were disappointing with significant artifacts appearing in the final image at the corners. The pitfalls of using a tomographic inversion method on the cross-hole survey geometries which are available from shallow opencast exploration boreholes in the U.K. are discussed by Kragh (1990). Essentially, poor discrimination between headwave and direct arrival types and the lack of vertical raypaths provided by cross-hole surveys results in poor imaging conditions. Figure 3.20 is typical of the types of tomographic inversion obtained from cross-hole surveys in shallow Coal Measures strata. It was found to be more useful to estimate the inter-hole velocity fields by using uphole shots and by inspection of the near-horizontal raypath travel times. Velocity models were assumed to have no lateral velocity variations between the boreholes (other than some overall dip) because of the evenly bedded nature of the strata, which is typical of Coal Measures sequences, and also because no data were available to justify including lateral variations.

3.6 The reflection point mapping scheme or VSP-CDP transform

In the general case of the cross-hole survey method, sources and receivers are located at different depths. Therefore, the image points of reflected arrivals in a time section (common shot gather) do not correspond to the simple common depth point (CDP) case used in surface seismic imaging (see figure 3.21). Instead of the vertical CDP locus, the locus of possible image points follows a curved path defined by the source and receiver positions and the velocity field between the boreholes. This locus has been applied by Dillon and Thomson (1984) to offset VSP data. It has been termed the 'VSP-CDP transform' as it provides a processing route which converts the data from VSP coordinates (depth of borehole receiver, or source, and traveltime) into the familiar coordinates of surface seismic sections (lateral position and depth or

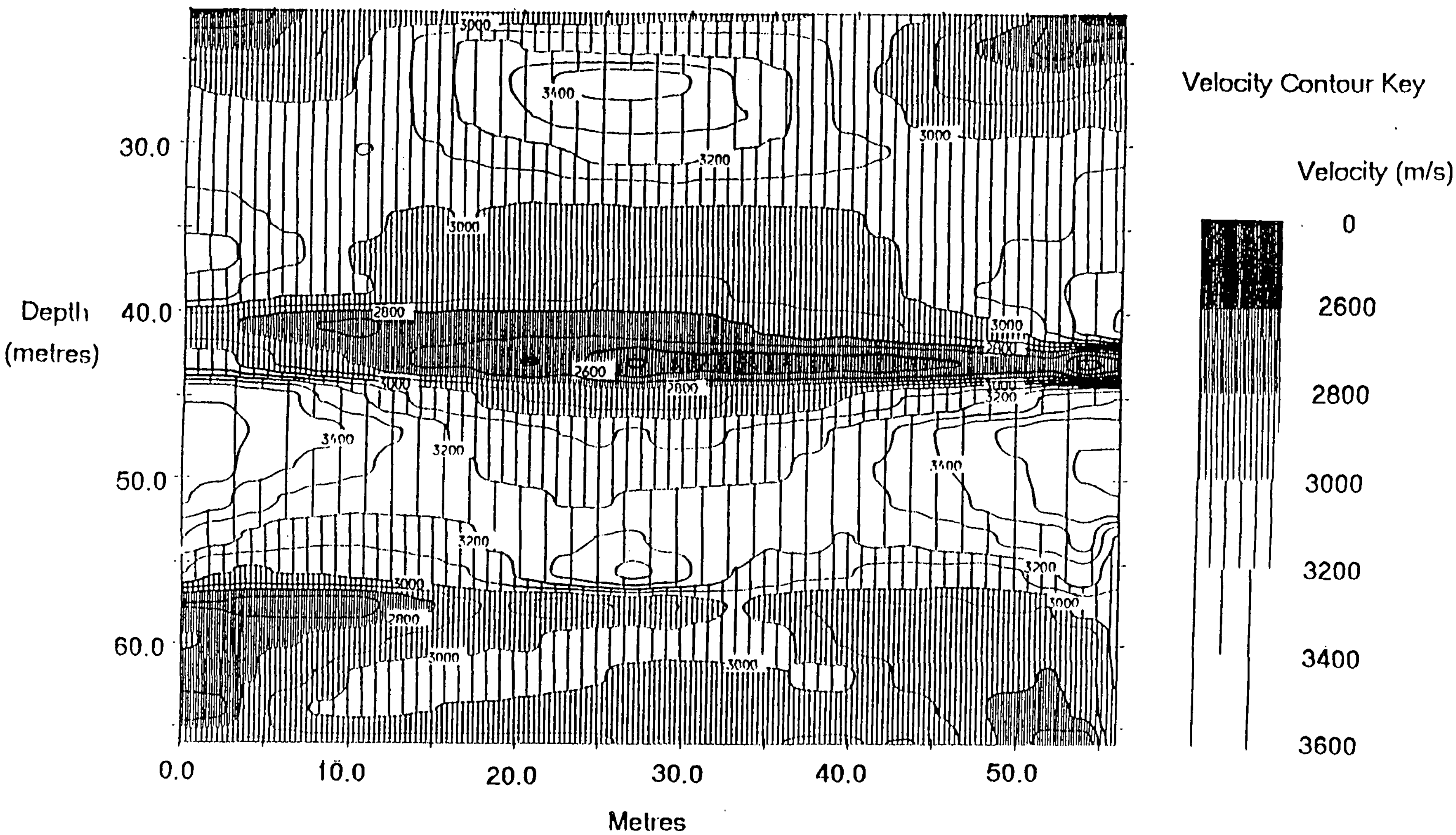


Figure 3.20 A sample tomographic velocity inversion (from Kragh, 1990).

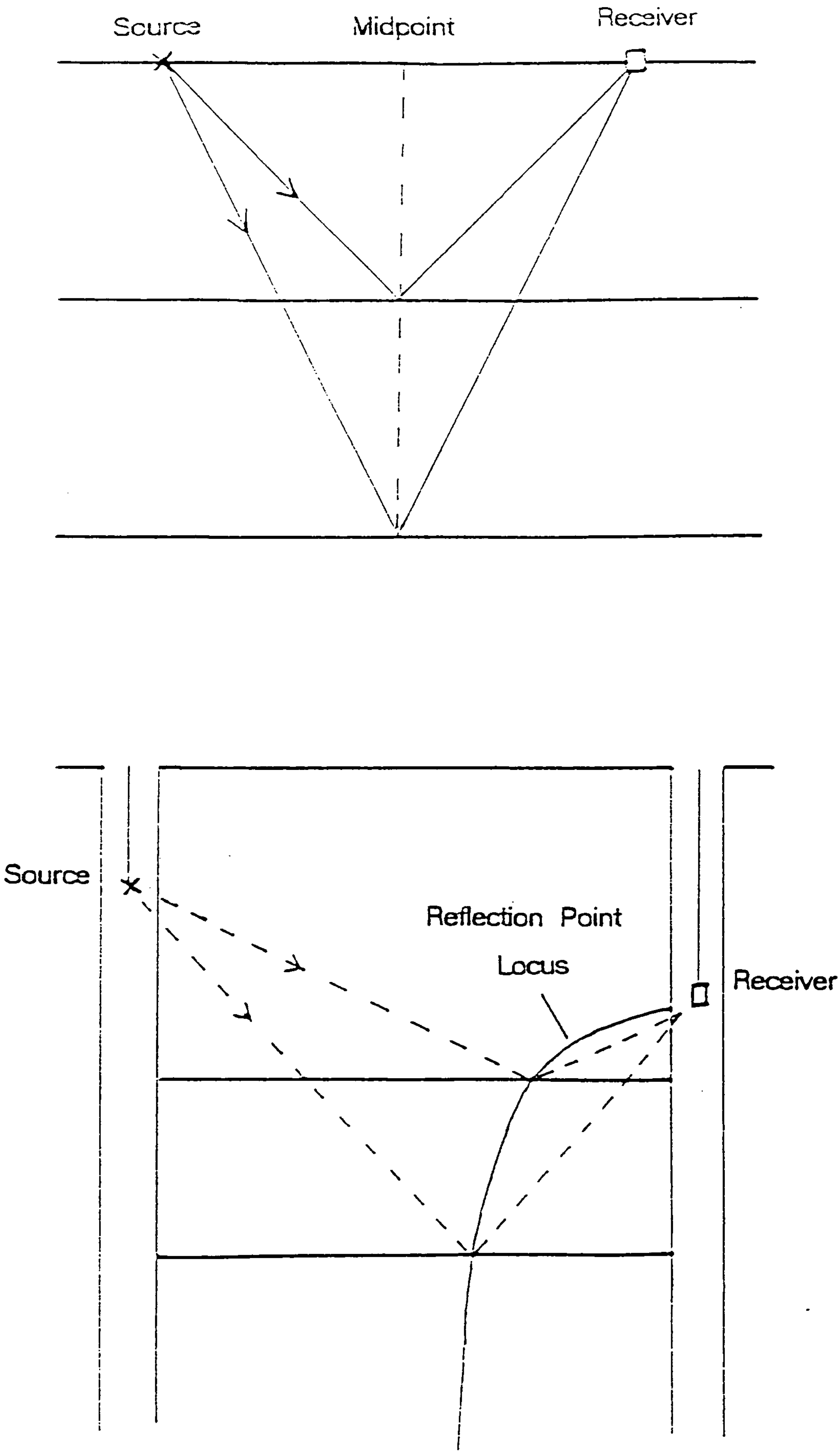


Figure 3.21 A comparison of the common midpoint of surface seismics and the reflection point locus of the cross-hole reflection method.

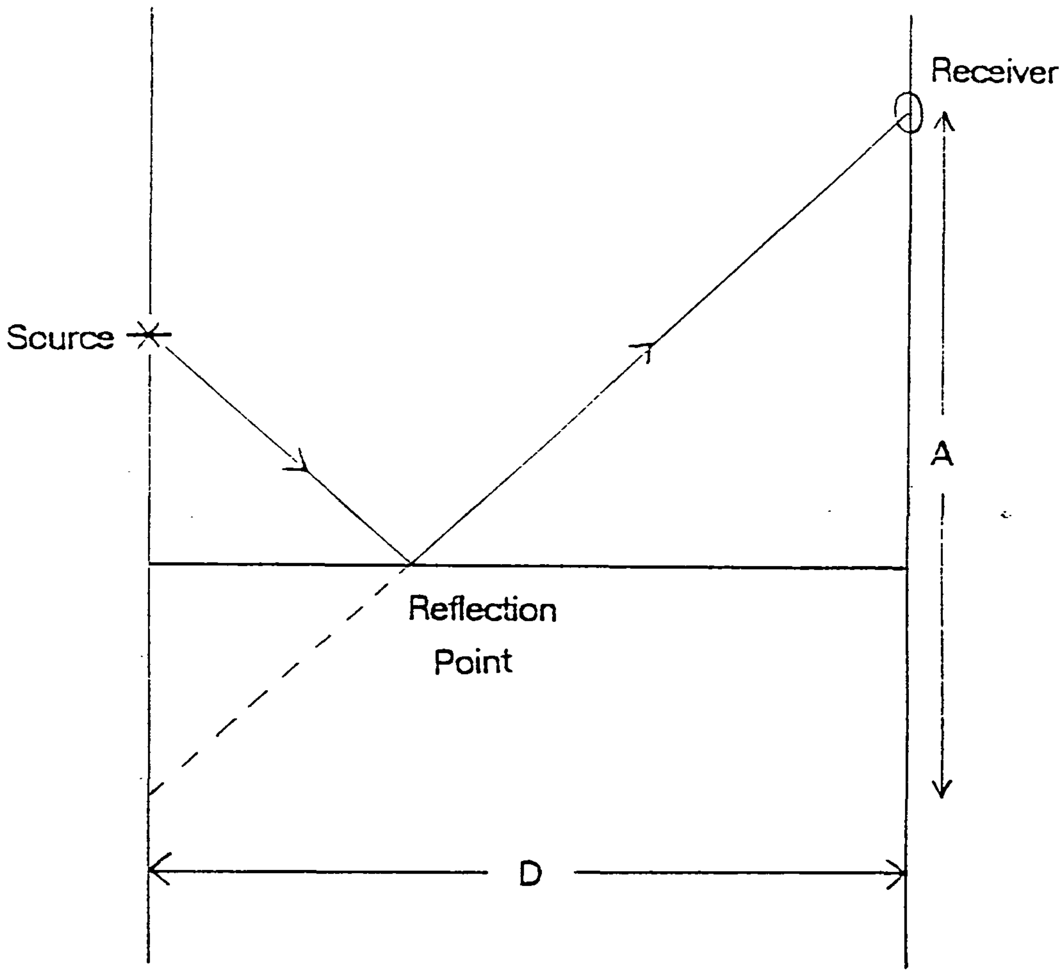


Figure 3.22 Reflection point geometry assuming a uniform velocity field.

vertical traveltime). The method involves considering each source and receiver pair independently. It is a single-channel process, not a true migration method, and therefore will not collapse Fresnel zones. The locus may be calculated by raytracing reflection raypaths between the source and the receiver over a range of take-off angles. This simultaneously provides the reflected ray traveltime, T_r for each point calculated on the locus. If a constant, isotropic velocity field and vertical boreholes are assumed (figure 3.22), then this traveltime is given by

$$VT_r = \sqrt{A^2+D^2} \qquad (3.2)$$

where V is the constant velocity,

D is the borehole separation,

and A is the total vertical distance travelled by the raypath.

The next processing stage is to distribute the appropriate trace for this source-receiver combination along the locus, by putting the signal amplitude recorded at a particular time T_{rec} at the point on the locus which has the corresponding reflection time $T_r = T_{rec}$. Interpolation is carried out to ensure that the data are not undersampled in the imaging space. The mapping can then be applied to all the traces in a common shot gather, and to all the common shot gathers in a survey.

Two programs are used to apply the VSP-CDP transform. REFLOC (Appendix A.2) calculates the reflection point loci from the given parameters of the source and receiver locations and the velocity model. The program allows velocity models which consist of plane parallel layers to be specified. It has been further modified by Kragh (1990) so that the layers may exhibit the elliptical approximation to transversely isotropic media. Raytracing is carried out by shooting a ray from the source towards the receiver borehole, and shooting a ray with the same ray parameter

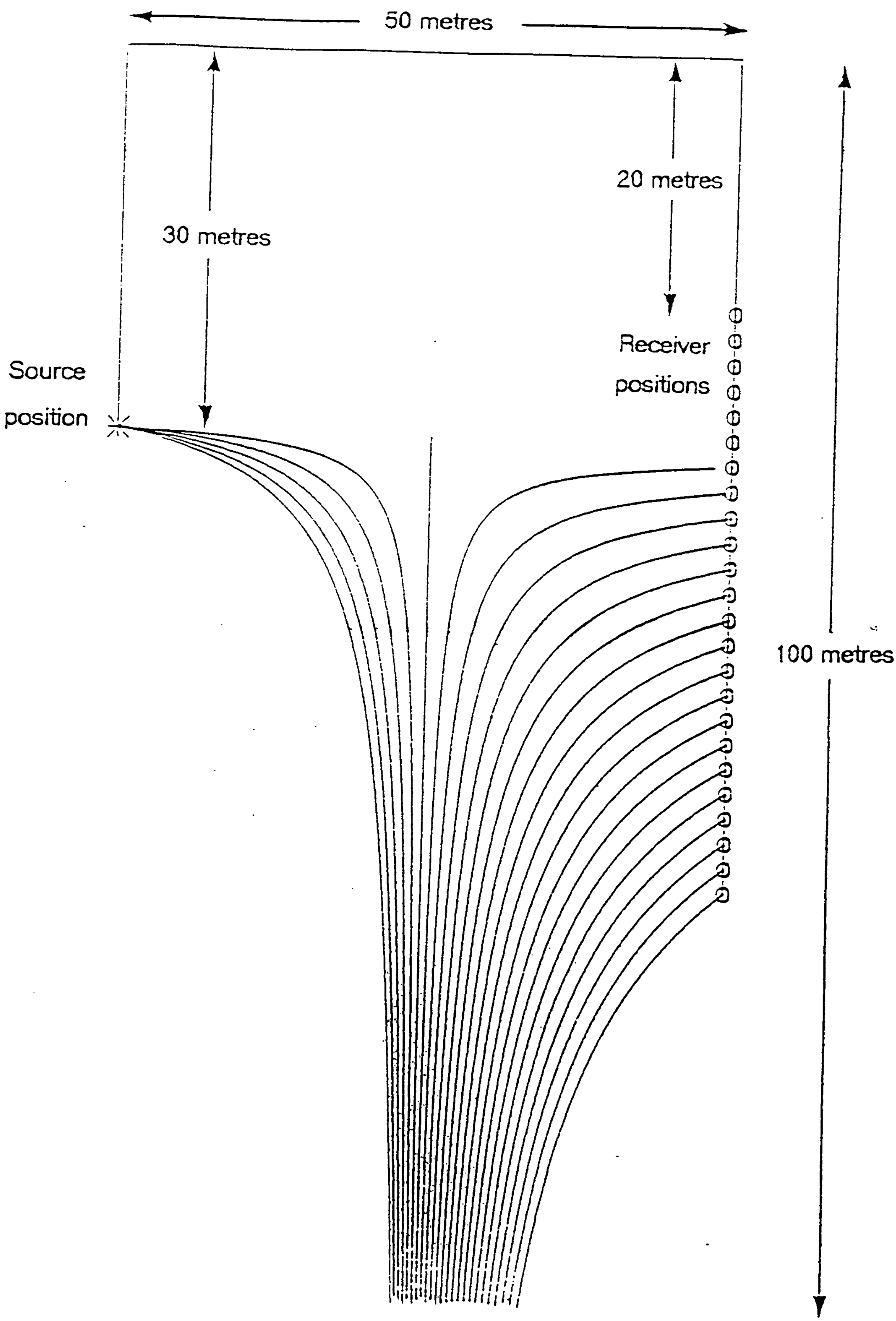


Figure 3.23 Reflection point loci for a common-shot gather assuming a uniform velocity field with recording at 24 receiver positions. The source is located in the left borehole at a depth of 30m and there are 24 receivers at 2m depth intervals ranging from 20m to 66m in the right borehole.

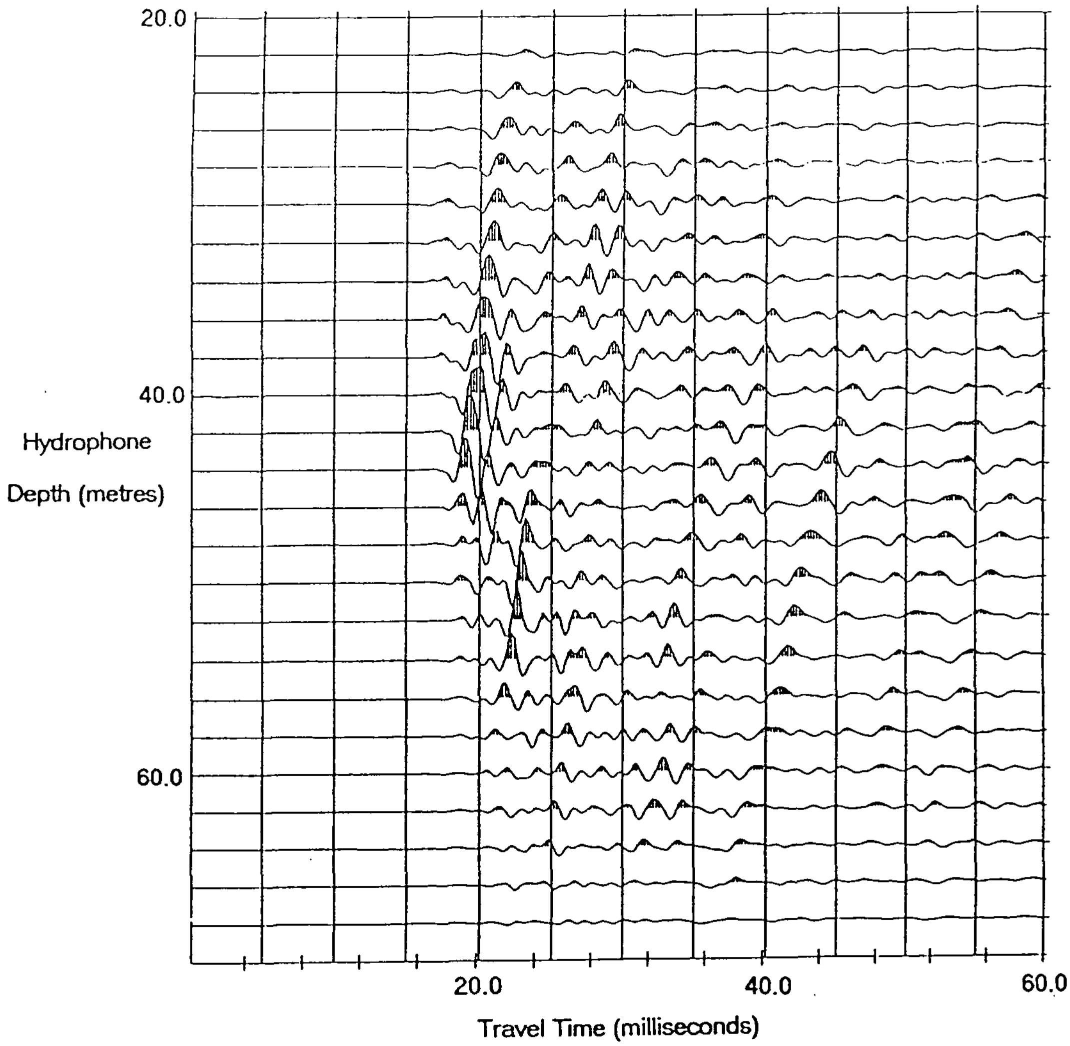


Figure 3.24 The upgoing wavefield of a common shot gather from survey A of chapter V.

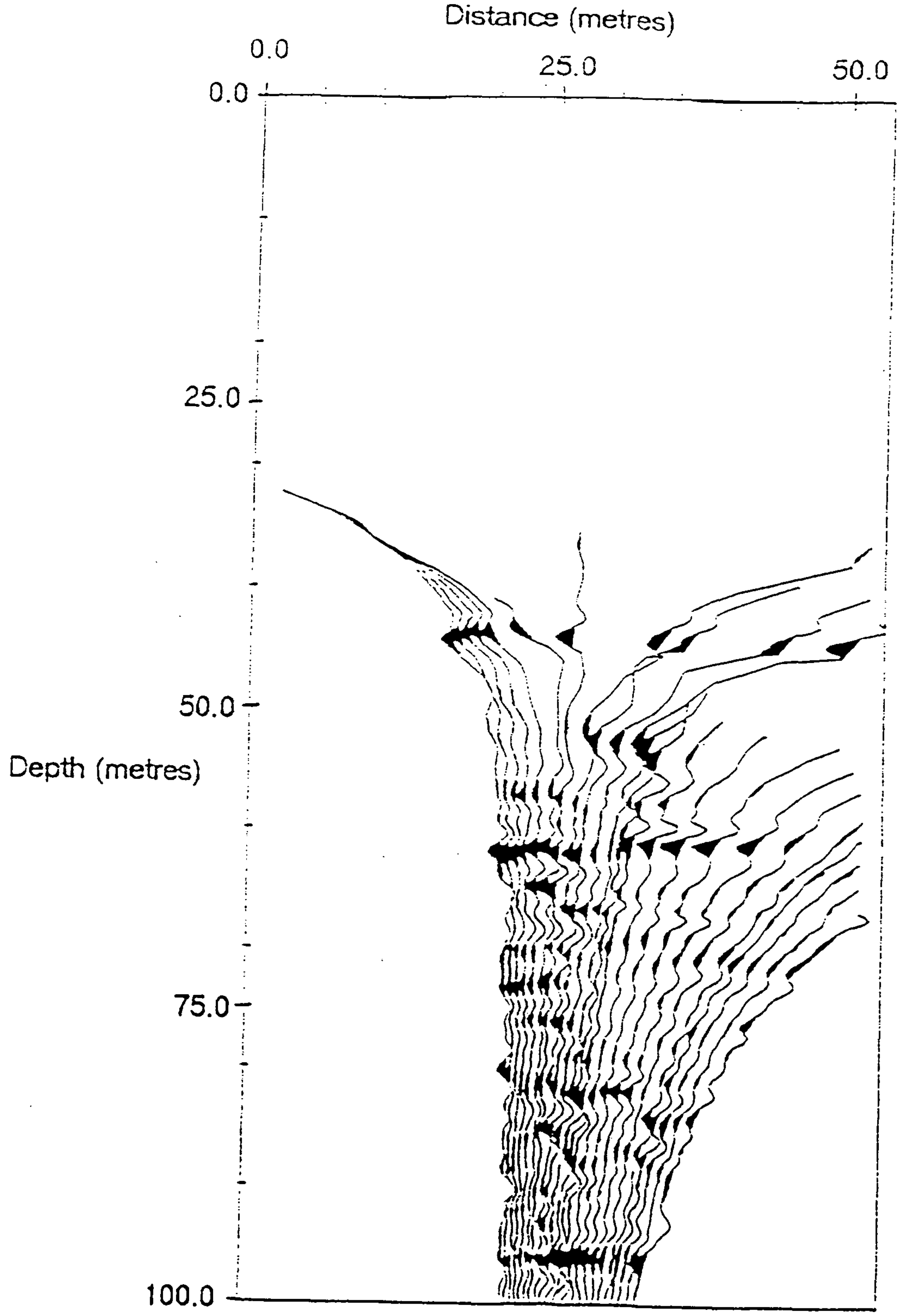


Figure 3.25 Upgoing wavefield of figure 3.24 mapped into a depth section using the VSP-CDP transformation.

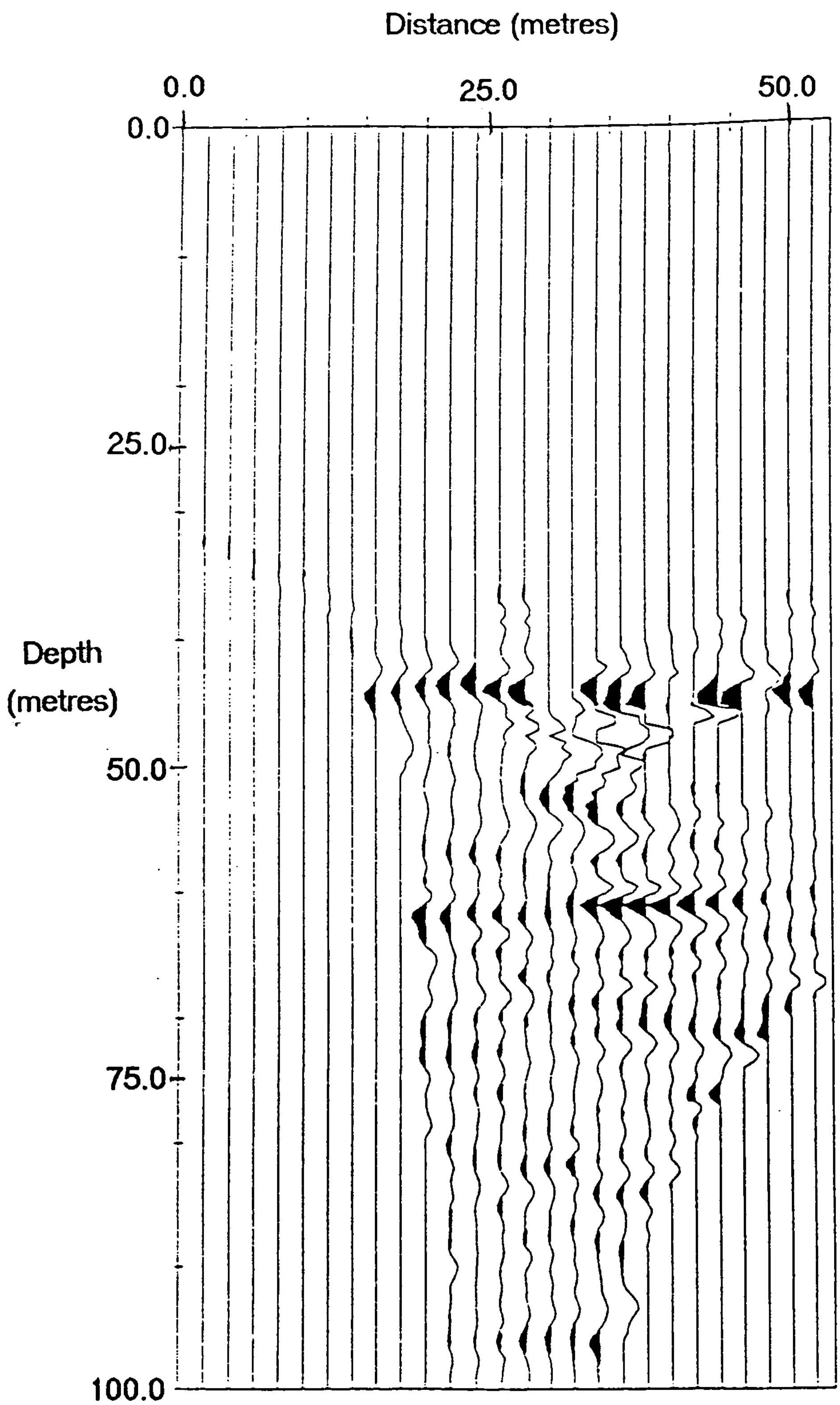


Figure 3.26 Depth section of figure 3.25 following binning on to a discrete grid.

(i.e. $\sin\theta / V$ where θ is the angle between the ray and the vertical, always taken as positive) from the receiver towards the source borehole. The point where these rays intersect will lie on the reflection point locus.

The program XHRMAP (Appendix A.3) is a menu-driven program which distributes the reflection data on to the loci and samples the mapped section on to a regular grid. The sampling is done by spreading each amplitude on each locus into its four nearest grid points with a weighting factor proportional to $(1-x_i)$ where x_i is the normalised distance of the locus point from grid point i. With the data for all the common shot gathers binned on to a regular grid, the separate sections may be stacked together, with a normalisation factor which depends on the number traces contributing at a grid point. Other program options include the ability to mute out data contributions which correspond to near-horizontal raypaths, where a relatively small error in the velocity field would lead to a significant positioning error in the locus, and the option of previewing CDP gathers (i.e. the contributions of each shot to the stack at a particular offset).

Examples of real data undergoing the VSP-CDP transform are illustrated in figures 3.23-3.26. The data form part of survey A in chapter V. Figure 3.23 illustrates the field arrangement. The source was located at a depth of 30m and 23 receivers were positioned at 2m intervals between 22m and 66m depth at an offset of 56m. The upgoing wavefield of the common shot gather is shown in figure 3.24. This has been mapped on to reflection point loci in figure 3.25 and then resampled on to a regular grid in figure 3.26.

The reflection point mapping technique also gives an indication of the type of subsurface coverage we might expect from a cross-hole reflection survey. Figure 3.27 is a plot of all the (upgoing) reflection loci for a survey in which the boreholes

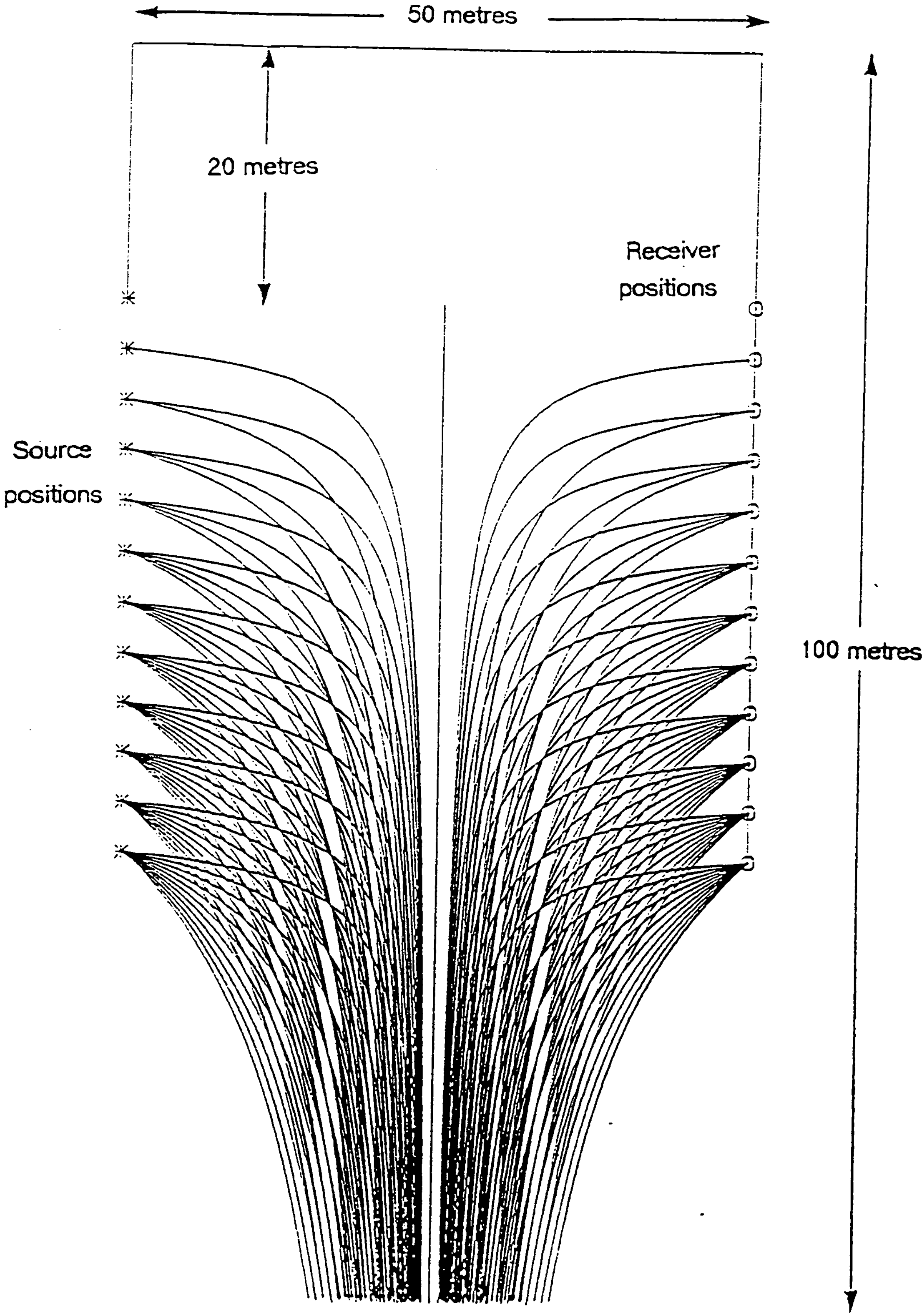


Figure 3.27 Reflection point coverage for an acquisition geometry with sources located in the left borehole and receivers in the right borehole. A uniform velocity field has been assumed. Source and receiver positions are illustrated at 4m spacings for clarity.

separation is 50m, and 13 sources and receivers are positioned at 4m intervals in the boreholes. This emphasises the funnel-shaped nature of the reflection point coverage obtained from cross-hole surveys, with no coverage at all immediately below the bottom source and the bottom receiver. The low density of reflection points near the boreholes means that the number of contributions to the stack is lower there and consequently the image quality will be poorer. Furthermore, muting direct arrivals will remove the corresponding earliest segment of each reflection point locus.

3.7 Velocity analysis using the VSP-CDP transform

Prior to stacking, the reflection point mapping technique may also be used as a velocity analysis tool by inspecting CDP gathers (i.e. stack contributions from each source position for a particular offset). It is not feasible to carry out a precise velocity analysis on real data in a single pass, due to the inability to perform a layer-stripping analysis when the source and receiver arrays are parallel to the direction of major velocity variations. Nevertheless, an estimate of velocity field corrections may be made by examining the moveout of reflections in CDP-space.

Let us assume that the velocity field V is constant between the boreholes. For any particular source and receiver combination (see figure 3.22), the reflection point travel time is given by equation (3.2)

$$\text{i.e.} \quad V^2 T_r^2 = A^2 + D^2 \qquad (3.2)$$

Let Z_S be the vertical separation of the source and the reflector,

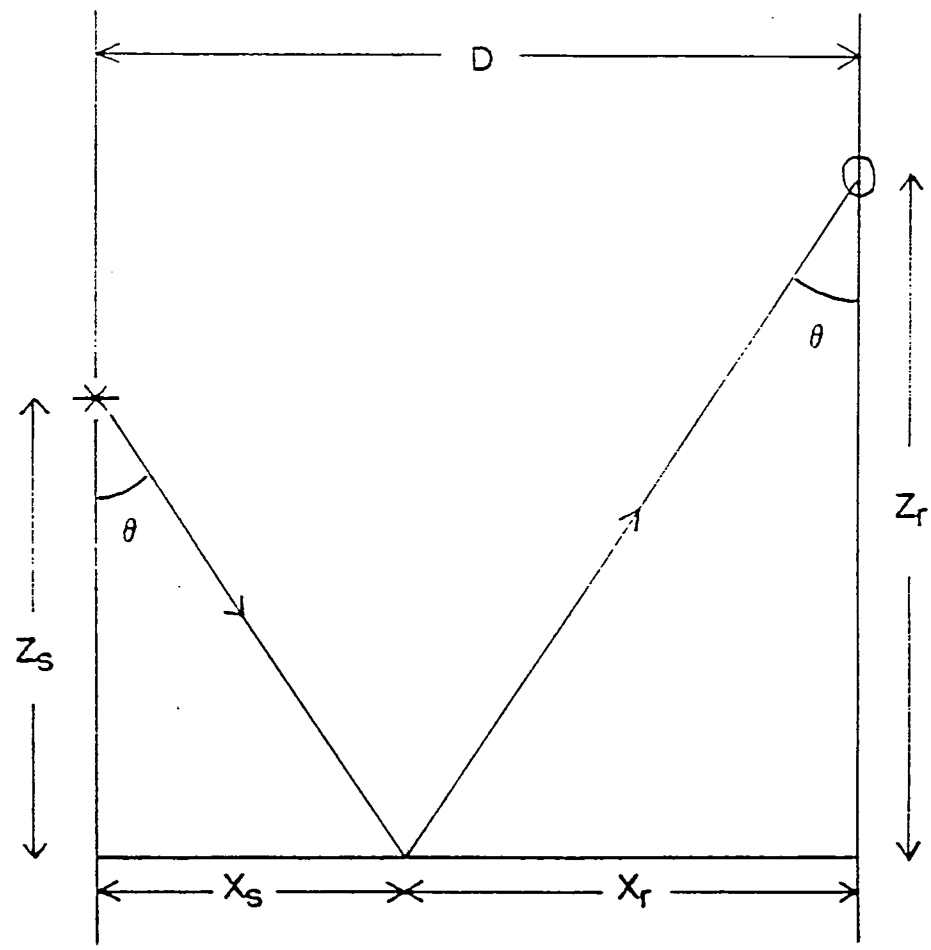


Figure 3.28 The parameters used in velocity analysis calculations.

Z_r be the vertical separation of the receiver and the reflector,

X_s be the offset of the reflection point from the source,

and θ be the angle which the raypath makes to the vertical.

Therefore,

$$\frac{X_s}{Z_s} = \frac{D}{A} = \tan\theta \qquad (3.3)$$

To estimate the vertical positioning error Δz which would be caused by an error Δv in the velocity field, equation (3.2) may be differentiated with respect to V, with T_r and D held constant.

$$VT_r^2 = A\frac{dA}{dV}$$

but from (3.2)

$$VT_r^2 = \frac{A^2+D^2}{V}$$

therefore

$$A\frac{dA}{dV} = \frac{A^2+D^2}{V} \qquad (3.4)$$

Now $\Delta A = 2\,\Delta z$, so we may rewrite the above expression as an approximation for small, but finite, Δv

$$\Delta z \cong \frac{1}{2}\,\frac{A^2+D^2}{A}\,\frac{\Delta v}{V_0} \qquad (3.5)$$

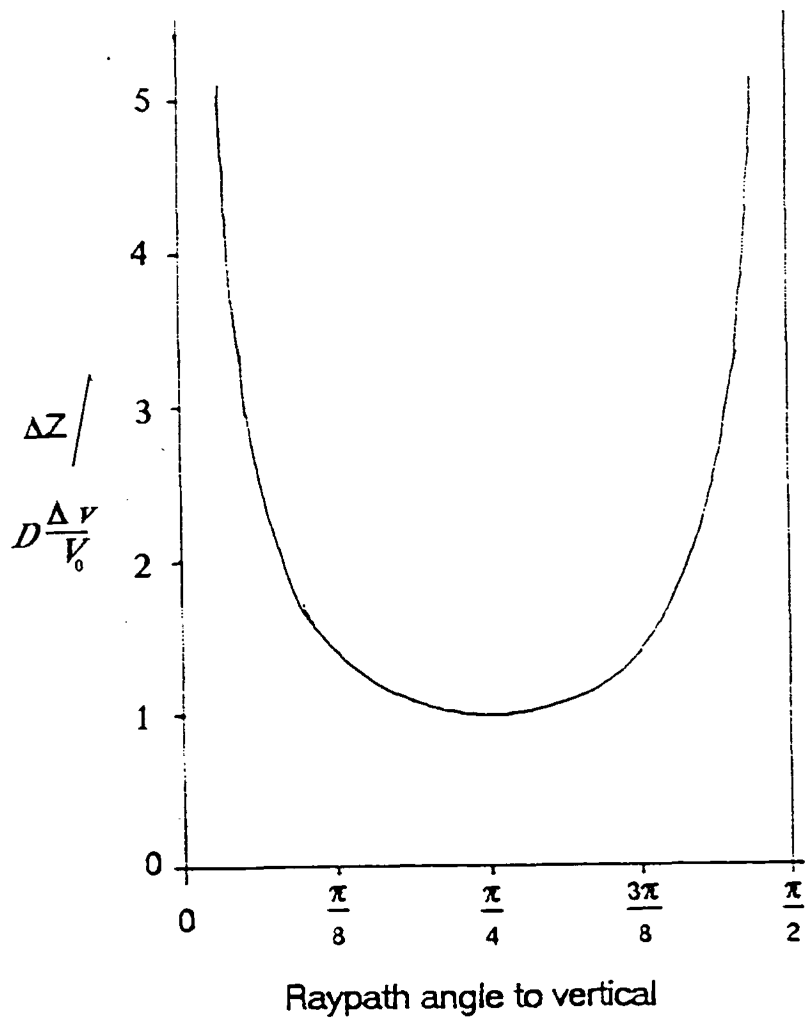


Figure 3.29 The vertical positioning error (Δz) as a function of the ray angle to the vertical.

Substituting for A from (3.3)

$$\Delta z \cong \frac{1}{2} D \,(\tan\theta + \cot\theta)\, \frac{\Delta v}{V_0} \cong \frac{D}{\sin 2\theta} \frac{\Delta v}{V_0} \qquad (3.6)$$

Thus, the vertical positioning error Δz is positive for $\Delta v > 0$ and negative for $\Delta v < 0$ and the dependence on raypath angle is shown in figure 3.29. For a given velocity error, the positioning error is a minimum when the raypath makes an angle of 45^o to the vertical and increases as this angle deviates from 45^o. If the velocity values are too large then one would expect to see the reflector depth increase as the source depth approaches that of the reflector; if the velocity values are too small the reflector depth will decrease as the source approaches the reflector depth. This therefore provides a trial-and-error method of improving the velocity field estimate by firstly applying the VSP-CDP transform, inspecting the CDP gathers, modifying the velocity field and then re-applying the VSP-CDP transform with the new velocity field.

Great care is needed in this process, because the shots and receivers are at different depths. The raypaths for contributions to the stack at a particular image point will thus be subject to different corrections when the layer velocities are modified. A change in a particular layer velocity will (in the case of upgoing reflections) affect only those CDP contributions from shots and receivers which are above or within the layer.

It is also useful to appreciate the lateral positioning error Δx which arises from a velocity field error.

From equation (3.3)

$$X_S = Z_S \tan\theta = Z_S \frac{D}{A}$$

Differentiating with respect to V,

$$\frac{dX_S}{dV} = \frac{D}{A}\frac{dZ_S}{dV} - Z_S\frac{D}{A^2}\frac{dA}{dV} \qquad (3.7)$$

Applying $\quad 2dZ_S = dA \quad$ and $\quad Z_S = \frac{AX_S}{D}$

$$\frac{dX_S}{dV} = \frac{1}{A}\left(\frac{D}{2} - X_S\right)\frac{dA}{dV}$$

$$= \left(\frac{D}{2} - X_S\right)\frac{A^2+D^2}{A^2V} \quad \text{using (3.4).}$$

For small, but finite Δv we may write this as the following approximation using (3.3).

$$\Delta x \cong \frac{D}{2}\left(1 - 2\frac{X_S}{D}\right)\frac{\Delta v}{v_0}\sec^2\theta \qquad (3.8)$$

Thus Δx is zero at $X_S = \frac{1}{2}D$ (i.e. no lateral moveout at the midpoint of the boreholes) and increases to $\frac{1}{2}\frac{D}{V}\sec^2\theta$ (see figure 3.30) at the boreholes. One would thus expect that the image quality will be much better towards the centre of a cross-

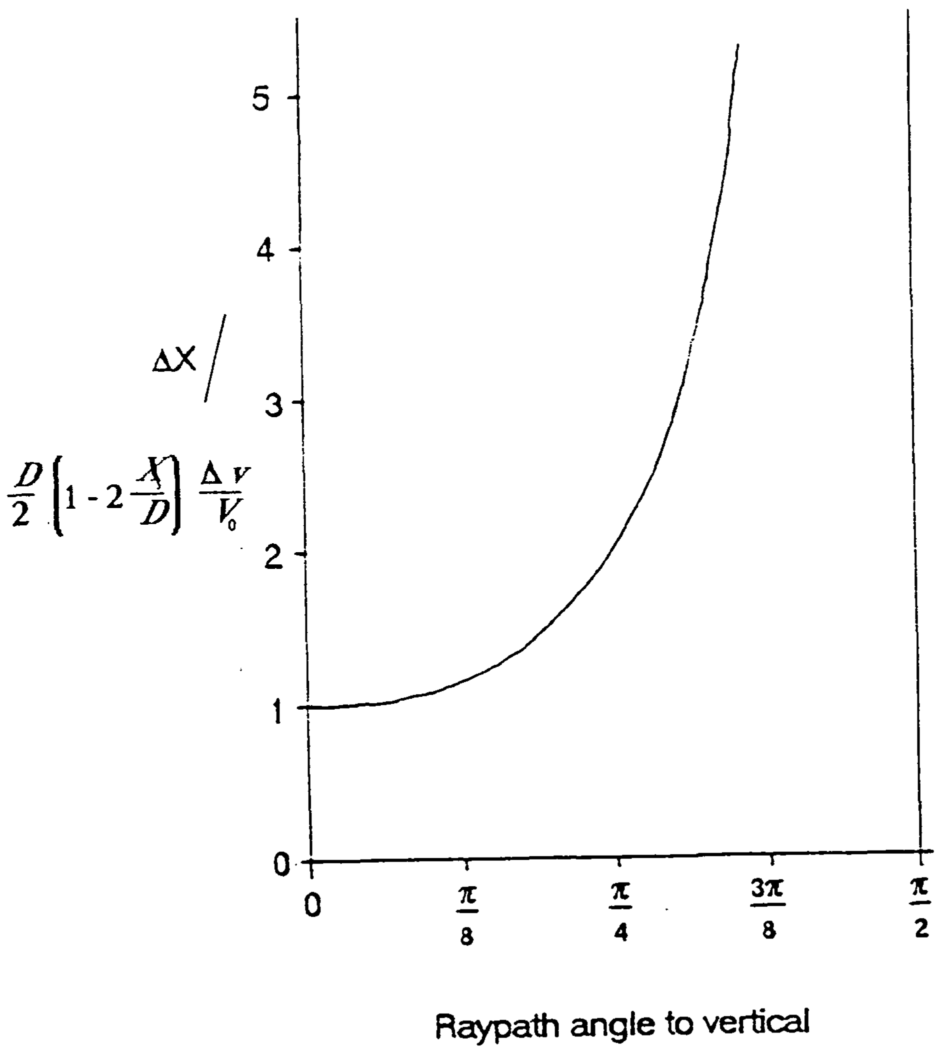


Figure 3.30 The lateral positioning error (Δx) as a function of raypath angle to the vertical.

hole reflection survey than it is nearer the boreholes, because of the increased number of stack contributions as well as the lower sensitivity of these areas to lateral positioning errors.

Once a sufficiently accurate velocity model has been obtained through the combination of experimental measurements and velocity analysis via the VSP-CDP transform, the imaging of the data can be carried out by applying migration techniques. These are discussed in chapter IV.

Chapter IV

Migration of cross-hole reflection data

4.1 Introduction

The migration of seismic data is the means whereby reflection events are relocated to their true subsurface positions and diffraction events are collapsed towards a point. Surface seismic data are generally migrated post-stack. The stacked data are assumed to be the equivalent of a zero-offset (i.e. coincident sources and receivers) section. Data will not be migrated correctly when normal moveout corrections result in a section which is not truly zero-offset, such as when conflicting reflector dips are present at the same traveltime. To get around NMO problems pre-stack migration may be used, but this is an expensive processing procedure because the data-volume is many times greater before stacking than it is after stacking. With cross-hole seismic surveys the data-volume is relatively small and so pre-stack migration methods can be more readily applied.

Two different two-dimensional migration schemes have been implemented in this work: a finite-difference method and a Kirchhoff integral method. Both algorithms were implemented specifically for cross-hole recording geometries, but with subsurface sources and receivers being the most general case, the programs will also migrate VSP and surface seismic profile data.

4.2 Finite-difference migration

A finite-difference modelling scheme for OVSP data has been developed in the (x,z,t) domain by McMechan (1985). Migration schemes based on this method have been applied to real OVSP data by Chang and McMechan (1986) and to synthetic and scale-model cross-hole data by Hu et al. (1988). In these cases the data were migrated pre-stack in common shot gathers and an acoustic migration scheme was used. Sun and McMechan (1986) have applied an elastic finite-difference algorithm to image synthetic OVSPs and Zhu and McMechan (1988) have migrated both acoustic synthetic and scale-model cross-hole data after stacking by assuming that the sources and receivers could be combined and treated as vertical planes lying perpendicular to the plane of the boreholes.

The algorithm applied here takes the upgoing or downgoing reflection energy from each common shot gather and drives a two-dimensional wavefield on a regular grid by using the traces as boundary conditions to solve the two-dimensional acoustic wave equation. By repeatedly stepping backwards in time, the wavefield $P(x,z,t)$ between the boreholes can be found for all image points at all relevant times. The relevant time at each image point is selected according to the imaging condition as defined by Claerbout (1971). Reflectors exist at points in the subsurface where the first arrival of the source-emitted wave is time-coincident with a scattered wave. Thus the time sample of interest at a particular image point (x_i,z_i) corresponds to the excitation time T_s of the point by a direct arrival wave emitted from the source position. The excitation time may be obtained by raytracing through a velocity model between the source position and the image point. When the wavefield is back-propagated in time, it is a simple matter to extract the appropriate amplitude of the wavefield $P(x_i,z_i,T_s)$ and to store it in an array which represents the imaged data.

This technique is known as reverse-time finite-difference migration with the excitation-time imaging condition.

4.3 Implementation of the finite-difference migration algorithm

The migration method involves two separate stages. Firstly rays are traced from the source to each imaging point in order to obtain the excitation time of the image points. The excitation times are then used as input parameters to the finite-difference migration program which back-propagates the recorded wavefield.

Two raytracing algorithms have been used. The first is the program TRACER (listed in Appendix A.4) which uses the ray-equation method of Lee and Stewart (1981) and which allows lateral velocity variations to be taken into account. This method was found to be too computationally expensive and so a faster two-point iterative algorithm was also developed (subroutine RAYTRA in Appendix A.5). RAYTRA ignores lateral velocity variations, but does allow transversely isotropic media to be modelled by means of an elliptical velocity approximation (Levin, 1978). The RAYTRA program was used in preference to TRACER because of its speed, particularly because lateral velocity variations between boreholes in a cross-hole survey could not be determined with sufficient confidence to justify using a laterally variant velocity structure.

The excitation time for image reconstruction is obtained by raytracing from the source location to each point in the image space. The traveltimes along the appropriate raypaths are stored in a data file for future reference by the imaging algorithm. The reverse-time wavefield extrapolation program EXTRAPREV is listed in Appendix A.6. A similar program EXTRAP is listed in Appendix A.7. EXTRAP is a forward modelling program which allows wavefields to be propagated from a source point with a given time-dependent signature and allows the wavefield at particular receiver positions to be recorded, thus generating synthetic seismograms.

The EXTRAP programs use an algorithm which carries out a second order finite-difference formulation of the acoustic wave equation. This is a two-dimensional (2-D) modelling algorithm which allows sources and receivers to be positioned at any subsurface (or surface) location in a 2-D velocity field. The finite-difference algorithm corresponds to that of McMechan (1985) which was written for offset VSPs, but with the additional provision of a variety of absorbing boundary conditions as discussed by Renaut and Petersen (1989). The programs allow the user to specify a laterally variant isotropic velocity field sampled on a rectangular grid and then the pressure response of the medium to a change in pressure with time (such as from a point source or from boundary conditions provided by a receiver array) is obtained by solving the acoustic wave equation in the time domain.

4.3.1 The finite-difference approximation

The 2-D acoustic wave equation is (Claerbout, 1976)

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial z^2} = V^{-2}(x,z)\,\frac{\partial^2 P}{\partial t^2} \qquad (4.1)$$

where P is the acoustic response and V is the velocity of acoustic waves in the medium. The solution of equation (4.1) is achieved by a second order finite-difference approximation with discretisation in time and space. A fourth order approximation (Alford et al., 1974) was tried but resulted in no noticeable improvement in imaging results. Three wavefields are involved at any particular time step t_i. These are

$P(x,z,t_i)$ the wavefield at time t_i;

$P(x,z,t_{i-1})$ the wavefield at time t_{i-1}, the previous step; and

$P(x,z,t_{i-2})$ the wavefield at time t_{i-2}.

The acoustic response at any particular grid point (x_k,z_j) may be defined as $P(x_k,z_j,t_i)$ where (x_k,z_j) is the intersection of the j^{th} horizontal grid line with the k^{th} vertical grid line.

The finite difference approximations to partial differentiations with respect to x are given by

$$\frac{\delta P}{\delta x} \cong \frac{P_{k+1} - P_k}{\Delta x} \tag{4.2}$$

$$\frac{\delta^2 P}{\delta x^2} \cong \frac{P_{k+1} - 2P_k + P_{k-1}}{\Delta x^2} \tag{4.3}$$

where Δx is the grid spacing in the x-direction. Thus equation (4.1) may be approximated by equations like (4.3) and rearranged to give a value of $P(x_k, z_j, t_i)$ which depends solely on the values of $P(x_k, z_j)$ calculated at times t_{i-1} and t_{i-2}.

$$P(x_k, z_j, t_i) = 2(1-2A^2)\, P(x_k, z_j, t_{i-1}) - P(x_k, z_j, t_{i-2}) + A^2\, [P(x_{k+1}, z_j, t_{i-1}) + P(x_{k-1}, z_j, t_{i-1}) + P(x_k, z_{j+1}, t_{i-1}) + P(x_k, z_{j-1}, t_{i-1})] \quad (4.4)$$

where $A = V(x_k, z_j)\Delta t/h$, Δt is the time step ($\Delta t = t_i - t_{i-1}$) and h is the distance between both horizontal and vertical grid lines. This algorithm has been shown to be stable (Mitchell, 1969) provided that the following condition is met.

$$\Delta t < \frac{h}{\sqrt{2}V} \quad (4.5)$$

4.3.2 Boundary conditions

A computational problem occurs at the edges of the finite-difference grid. If values of zero are used to define the acoustic response at the edges of the grid then a free surface boundary condition (zero pressure) has been created and outgoing wavefields will be reflected back into the grid. Methods of avoiding this problem include enlarging the grid size, a computationally expensive choice, or applying absorbing boundary conditions (Clayton and Engquist, 1977) at the edges of the grid. Absorbing boundary conditions are essentially a finite-difference approximation to the one-way or paraxial wave equation (Claerbout, 1976). A dispersion relation which restricts the range of propagating rays to a cone around the z-axis is (Clayton and Engquist, 1977)

$$\frac{Vk_z}{\omega} = 1 - \frac{1}{2}\left(\frac{Vk_x}{\omega}\right)^2 + O\left(\left|\frac{Vk_x}{\omega}\right|^4\right)$$

which translates to the following differential form.

$$\frac{\partial^2 P}{\partial z \partial t} + \frac{1}{V}\frac{\partial^2 P}{\partial t^2} - \frac{V}{2}\frac{\partial^2 P}{\partial x^2} = 0 \qquad (4.6)$$

The above equation is an approximation which would allow a wave to propagate in the positive z direction only. Renaut and Petersen (1989) have derived several different finite-difference approximations similar to (4.6) as follows :

$$\frac{\partial^2 P}{\partial z \partial t} + \frac{p_0}{V}\frac{\partial^2 P}{\partial t^2} + Vp_1\frac{\partial^2 P}{\partial x^2} = 0 \qquad (4.7)$$

where p_0 and p_1 are defined according to Table 4.1.

Approximation	Pade	L^2	Chebychev-Pade
p_0	1.000	$21\pi/64$	$10/3\pi$
p_1	-0.5	$-15\pi/64$	$-8/3\pi$

Table 4.1 Finite difference approximations

The program EXTRAP permits selective use of these boundary conditions and also allows the option of free-surface boundaries. The p_0 and p_1 parameters may be chosen as appropriate to the survey geometry. Generally, the L^2 approximation, which yields a least squares reflected amplitude over all incident angles, seemed to provide the best absorption for cross-hole data where waves may be striking the boundary at a wide range of incident angles.

4.3.3 Grid dispersion

One problem associated with the finite-difference approximation is that of grid dispersion (Alford et al., 1974). This manifests itself in the dispersion of the source waveform as it propagates through the discrete-model medium, with lower frequencies travelling faster than higher frequencies, the pulse becomes delayed, broadened and develops a ringing tail. The effect arises because of the discrete approximation to the differential wave equation by equation (4.4). Grid dispersion effects can be reduced by decreasing the grid spacing parameter h but, as well as increasing the data volume, this necessitates a reduction in the size of the time step Δt in order that the stability equation (4.5) remains satisfied. Reduction of the grid spacing by a factor of two thus results in a four-fold increase in the data volume and an eight-fold increase in the computational time. Alford et al. (1974) have shown that dispersive effects are not significant for wavelengths greater than about 10 times the grid spacing, and this provides a useful benchmark in determining the optimal values of Δt and h to use for a given source function.

4.3.4 Modelling seismic data with EXTRAP

Two cross-hole synthetic datasets were constructed using the EXTRAP finite-difference algorithm in order to test the Kirchhoff and reverse-time wavefield extrapolation finite-difference migration methods. These models are fully discussed in section 4.5. The required input parameters are:

Source function specification

Grid size

Temporal sampling interval

Source location

Receiver locations

Two-dimensional velocity model of medium

Program output allows the pressure response of the medium to be viewed at any given time, as well as the generation of synthetic seismograms. These implementations of the finite-difference algorithm are for the acoustic (scalar) wave equation. It is hoped that future development work may be carried out to enhance this modelling method in order to include anisotropy and elastic wave propagation.

4.3.5 Migrating seismic data with EXTRAPREV

EXTRAPREV functions in a similar manner to EXTRAP, but instead of providing a source function to the algorithm, the data recorded at the receiver positions is time-reversed and then input to the finite-difference wavefield at all receiver grid points simultaneously at the appropriate time samples. The drawback of this approach is that it is necessary to match the receiver spacing to the grid size and so a certain amount of spatial interpolation is necessary to achieve this (since a relatively small grid spacing may be necessary in order to avoid grid dispersion effects). Reduction of the grid spacing may also force an interpolation in time in order that the stability requirement (4.5) is met. This results in a substantial increase in computing time. Examples of this migration on synthetic model data are discussed in section 4.5.

4.4 Kirchhoff migration

A Kirchhoff migration technique was also developed. This is an extension of the diffraction stack migration approach which is readily understood from geometrical considerations.

4.4.1 Diffraction stack migration

The diffraction stack migration method was one of the first migration types to be applied to seismic data. It follows simple ray and wavefront theory. In the case of

Figure 4.1 Locus of possible reflector locations for an impulsive arrival at time T for a particular source and receiver combination.

zero-offset (or post-stack) surface seismic data, diffraction stack migration is implemented by summing along hyperbolic trajectories and placing the results at the apices of the hyperbolas. For cross-hole data, however, the summation operator is more complicated.

Consider a particular source-receiver combination with a single impulsive arrival recorded at time T_S and assume that the velocity of the medium is uniform and isotropic. The locus of possible reflection points for a particular traveltime must be the ellipse in image space as shown in figure 4.1 with the source and the receiver at the focal points. Migration may be accomplished by distributing the recorded amplitudes along the appropriate ellipses for each trace in a common shot gather. Constructive imaging takes place where ellipses intersect at a diffracting point.

Alternatively, each imaging point may be considered in turn. Raytracing from the source position to the point and from the receiver position to the point provides a total traveltime for scattering from the image point with the particular source-receiver combination. The amplitude corresponding to this traveltime is then summed into the imaging array together with similar contributions from other source-receiver pairings. This is the migration procedure utilised in this work.

4.4.2 The Kirchhoff operator

Kirchhoff wave equation migration is an extension of the diffraction stack imaging concept based upon Kirchhoff's integral (see French, 1975 and Schneider, 1978).

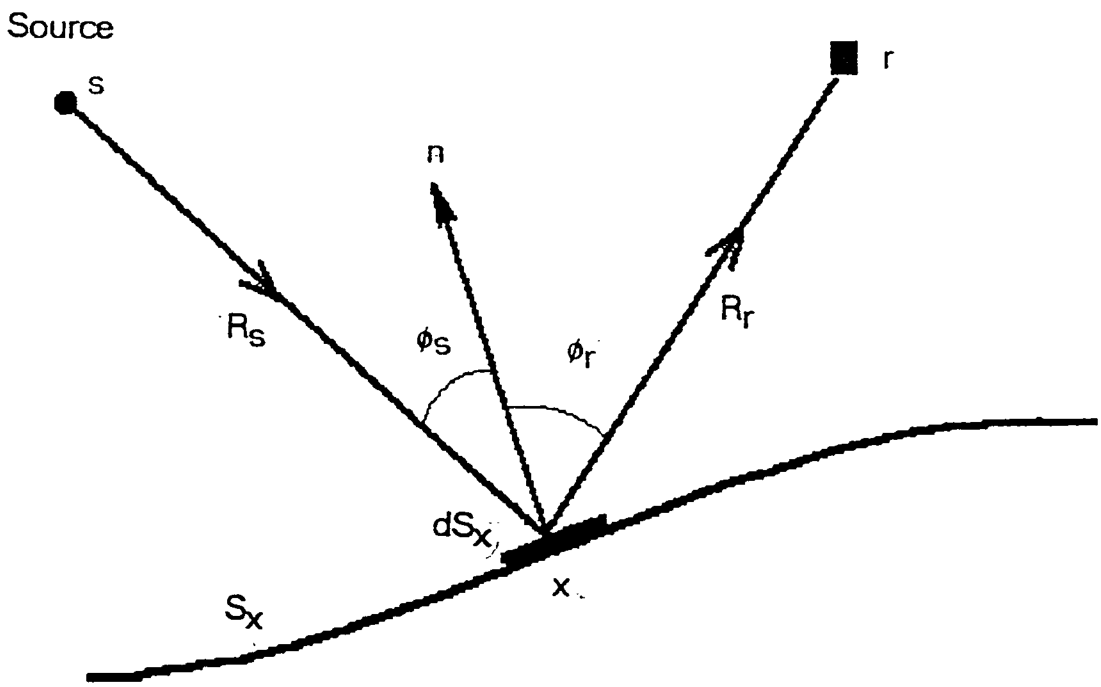


Figure 4.2 Scattering angles and raypath lengths for equation 4.8.

If we consider a wave incident on a scattering interface, then the wavefield $U(\underline{\mathbf{r}},\underline{\mathbf{s}},t)$ recorded at $\underline{\mathbf{r}}$ as a result of an impulsive source at $\underline{\mathbf{s}}$ being scattered from the interface S_x is given by (Dillon, 1990 equation (1)):

$$U(\underline{\mathbf{r}},\underline{\mathbf{s}},t) = \int_{S_x} dS_x \frac{C(\underline{\mathbf{x}},\phi_s)}{4\pi V} \frac{\cos(\phi_s) + \cos(\phi_r)}{R_s R_r} \delta'\left(t - \frac{R_s + R_r}{V}\right) \qquad (4.8)$$

The scattering angles ϕ_s and ϕ_r and raypath lengths R_s and R_r are illustrated in figure 4.2. The reflectivity $C(\underline{\mathbf{x}},\phi_s)$ is angle-dependent. Equation (4.8) is the three-dimensional response recorded at a receiver. If one assumes that the geological structure is invariant perpendicular to the plane of the survey, then by integrating along one direction, the equivalent $2\frac{1}{2}$D formula is obtained. Dillon (1990) has derived a $2\frac{1}{2}$D migration integral which yields the reflectivity $C(\underline{\mathbf{x}})$.

$$C(\underline{\mathbf{x}}) = \frac{1}{\pi} \int_{L_r} dL_r \sqrt{\frac{R_s(R_s + R_r)}{2VR_r}} \cos(\theta_r)\, M\left(\underline{\mathbf{r}}, \frac{R_s + R_r}{V}\right) \qquad (4.9)$$

where $M(\underline{\mathbf{r}},T)$ is the source wavefield $U(\underline{\mathbf{r}},T)$ following the application of a Newman half-differential filter. This filter has a spectrum with a $\frac{\pi}{4}$ phase shift and a high frequency amplitude boost of $f^{1/2}$ and is implemented in the frequency domain. Equation (4.9) may be approximated by a summation over the receiver array L_r.

$$C(\underline{x}) = \sum_{L_r} \Delta L_r \sqrt{\frac{R_s}{R_r}} \cos(\theta_r) \sqrt{R_s + R_r}\, M\left[\underline{r}, \frac{R_s + R_r}{V}\right] \tag{4.10}$$

Equation (4.10) is similar to a diffraction stack with the amplitude and phase corrections of the Newman filter and a wavefront spreading correction term being incorporated. Clearly this expression is inadequate for cross-hole geometries where we should obtain similar reflectivity responses across the survey. In equation (4.10) the reflectivity will be larger where $R_s > R_r$ (i.e. nearer the receiver borehole) and an expression which is symmetrical with respect to an exchange of source and receiver arrays would be preferable.

4.4.3 The Generalised Kirchhoff operator

Dillon (1990) derived a Generalised Kirchhoff (GK) migration integral which is reciprocal with respect to sources and receivers and which is closely related to the Generalised Radon Transform (GRT) migration integral proposed by Miller et al. (1987). The 2-D form of the GK summation operator is given by

$$C(\underline{x}) = \sum_{L_r L_s} \left[\Delta L_r \sqrt{\frac{R_s}{R_r}} \cos(\theta_r) + \Delta L_s \sqrt{\frac{R_r}{R_s}} \cos(\theta_s)\right] \times \sqrt{R_s + R_r}\, M\left[\underline{r}, \frac{R_s + R_r}{V}\right] \tag{4.11}$$

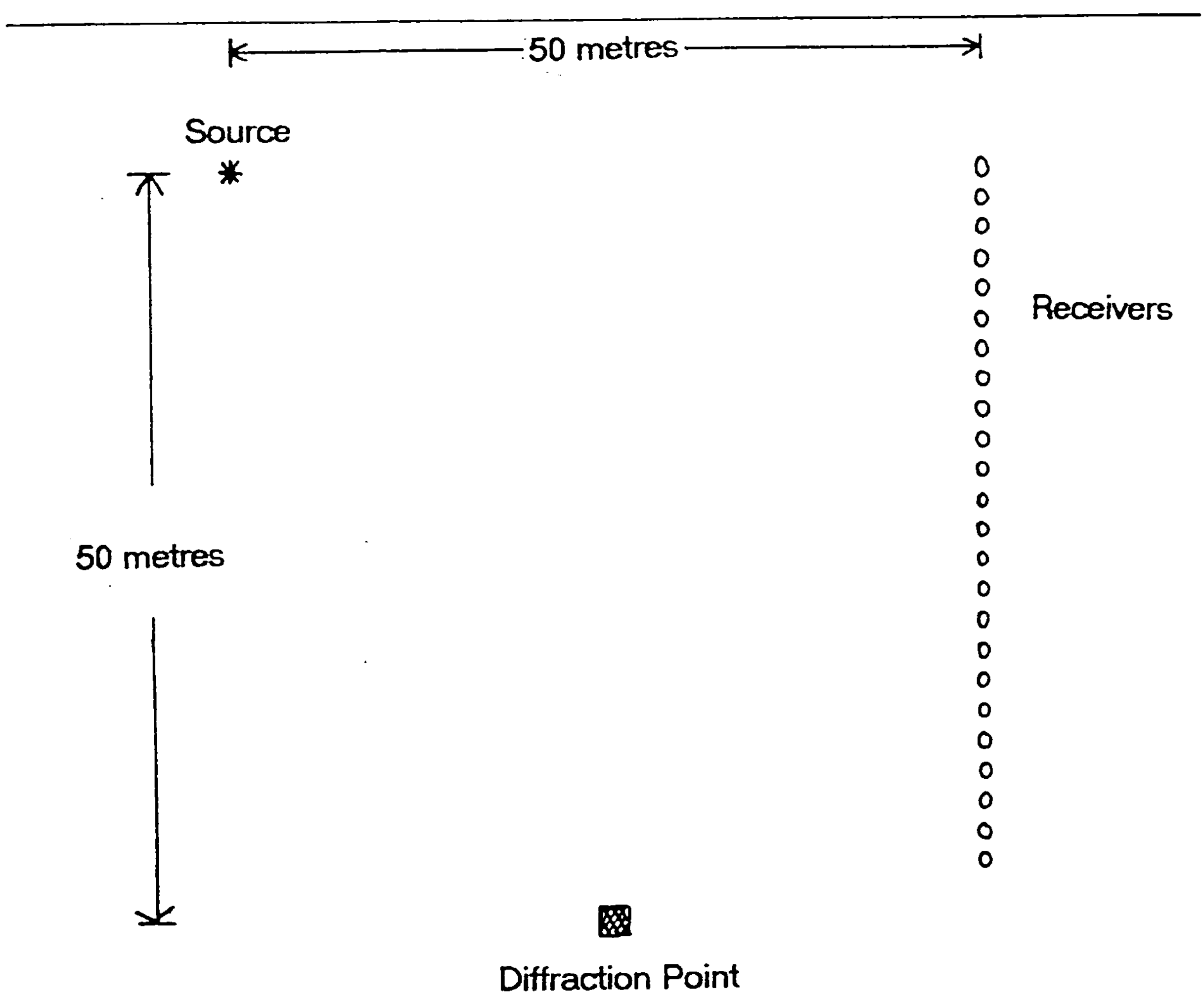


Figure 4.3 Model used to acquire synthetic dataset of point scatterer.

There is an additional small error term to the above equation which is proportional to $(\cos(\phi_s)-\cos(\phi_r))$ (Dillon, 1990), ϕ_s and ϕ_r being the scattering angles defined in figure 4.2.

The program KIRCHMIG in appendix A.8 was written to carry out diffraction stack, Kirchhoff summation and Generalised Kirchhoff summation of cross-hole data with a variety of options being variable. Amongst these is the migration aperture by which the summation locus (equivalent to a hyperbola in surface seismic migration) is spatially restricted to realistic geological dips. A very small aperture is equivalent to specular reflections and corresponds to the reflection point mapping technique (Dillon, 1988, Van der Poel and Cassell, 1989). Comparisons of the impulse responses of different migration operators are included in chapter VI.

4.5 Comparison of finite-difference and Kirchhoff migration

Synthetic datasets were created by forward modelling using the EXTRAP finite-difference method. Models of point diffractors and planar reflectors were used to study the effectiveness of the two migration techniques. In these models, no allowance for density variations was made; the only variable parameter being the structure of the velocity field.

4.5.1 Point diffractor model

The following model (see figure 4.3) was used to simulate a point diffractor. A velocity of 2500 m/s was used. The grid size h was 0.5 m, and a time step Δt of 0.1

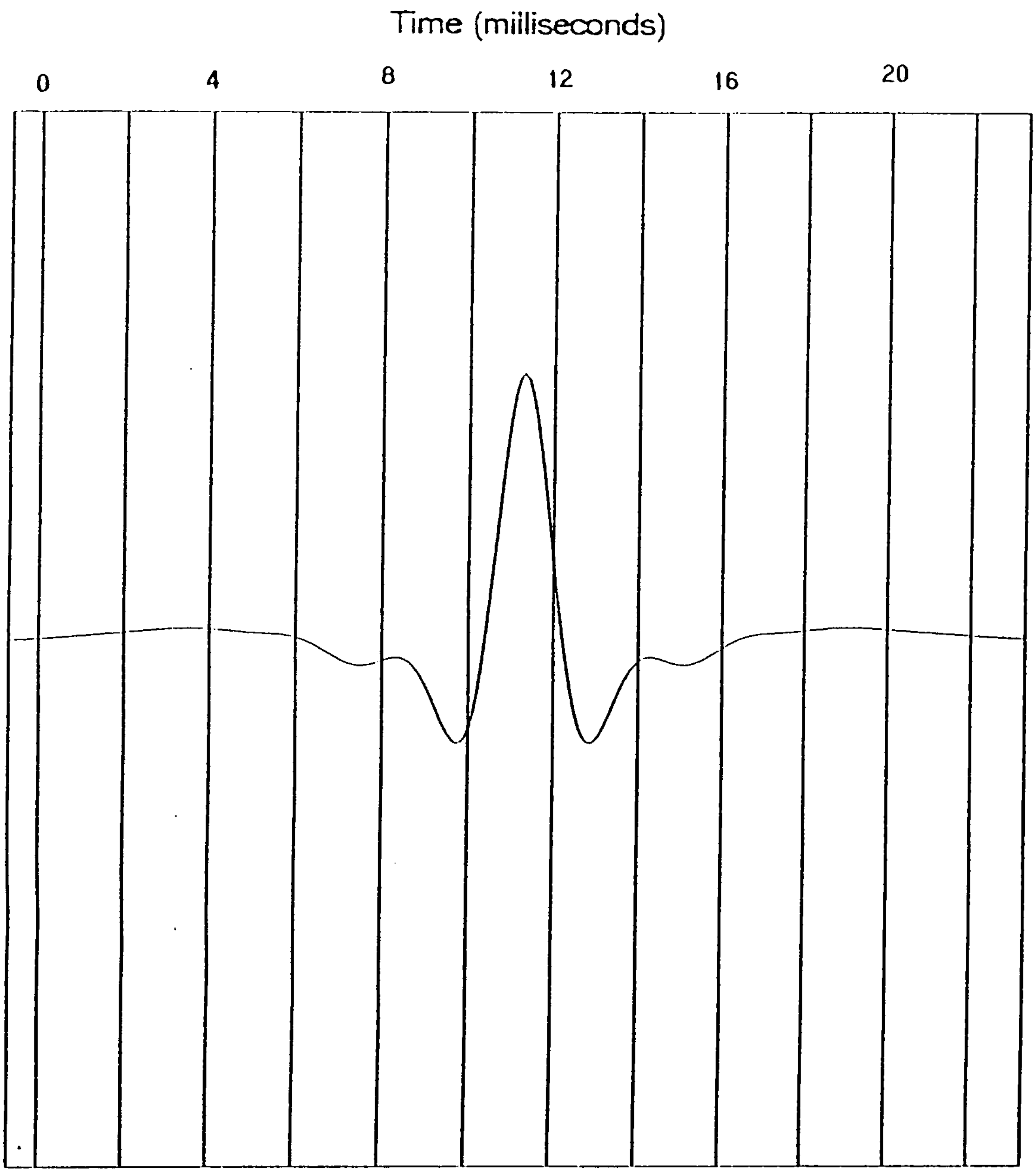


Figure 4.4 Source wavelet used in synthetic seismogram modelling.

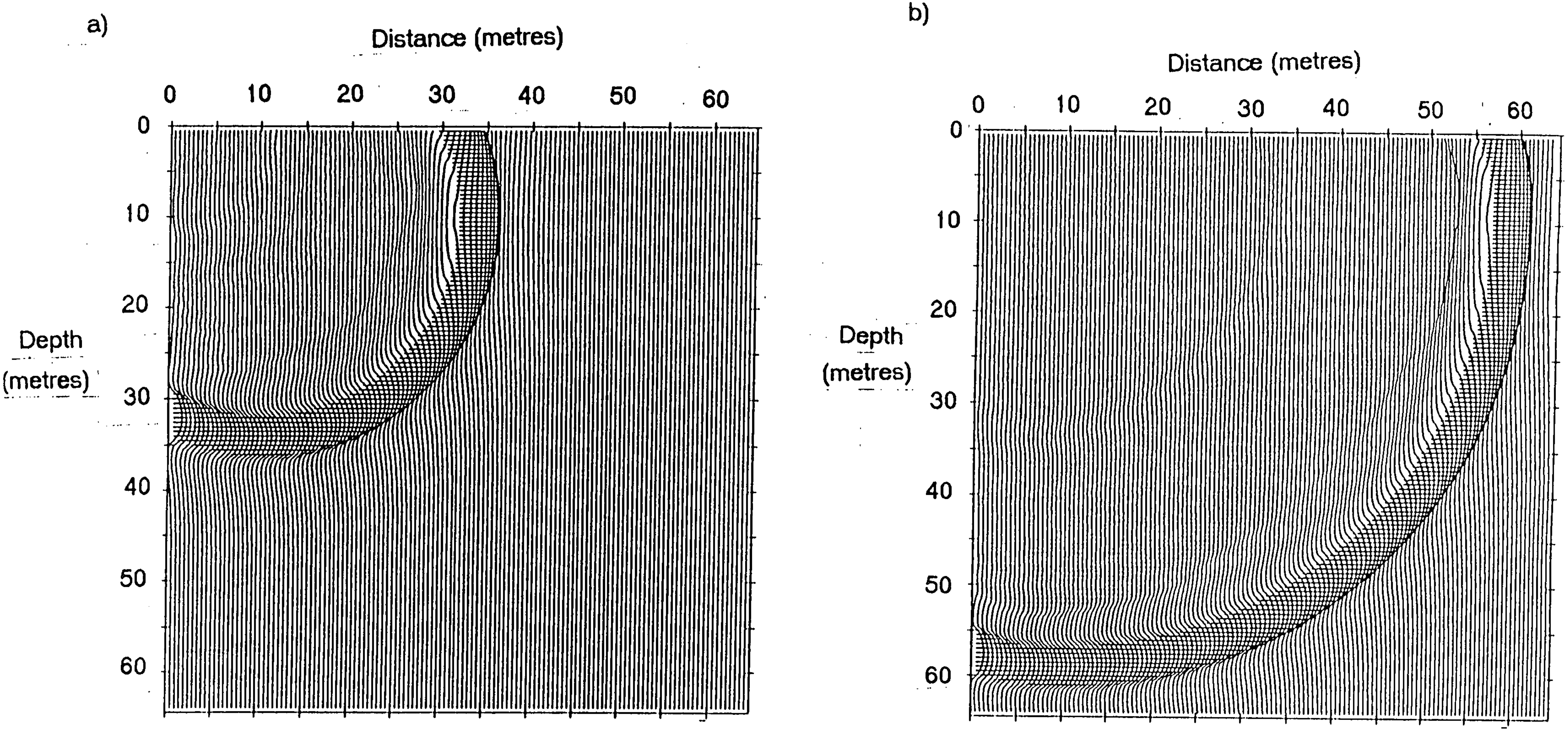
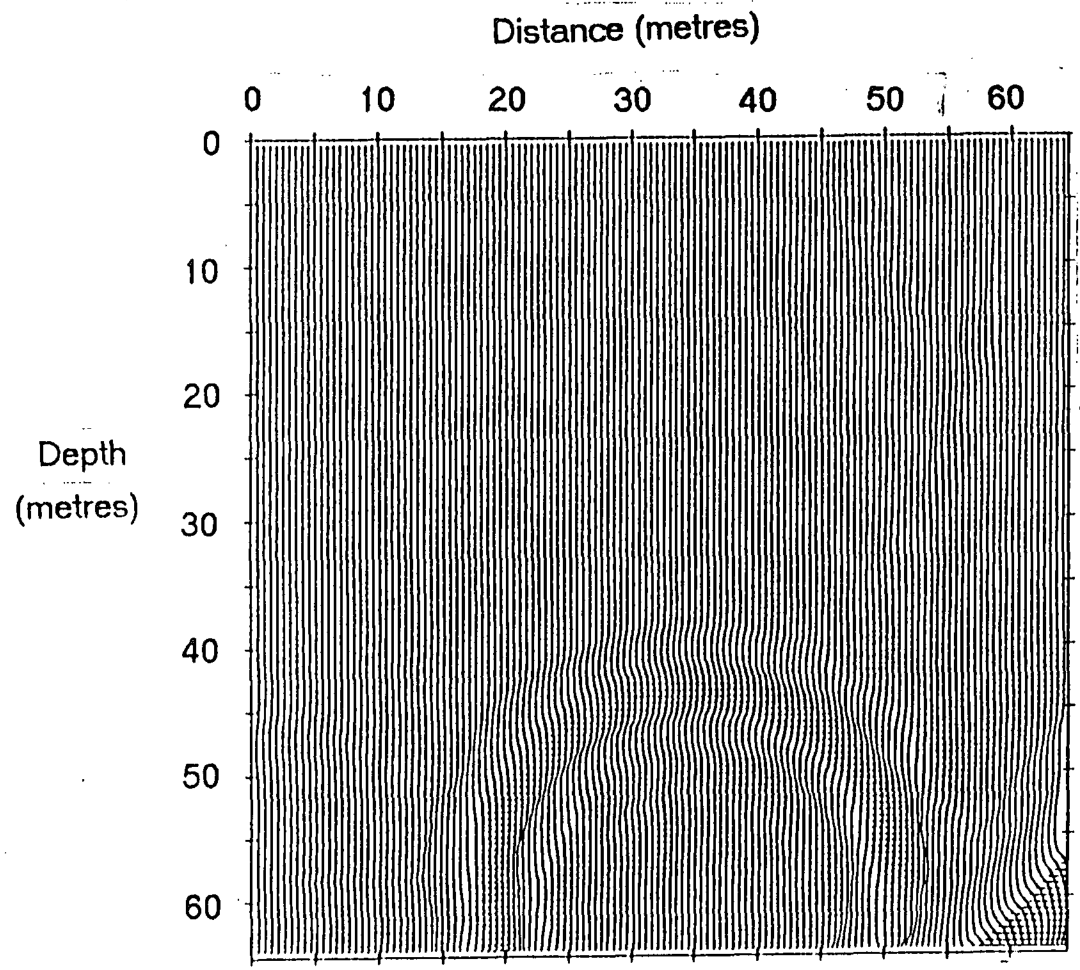
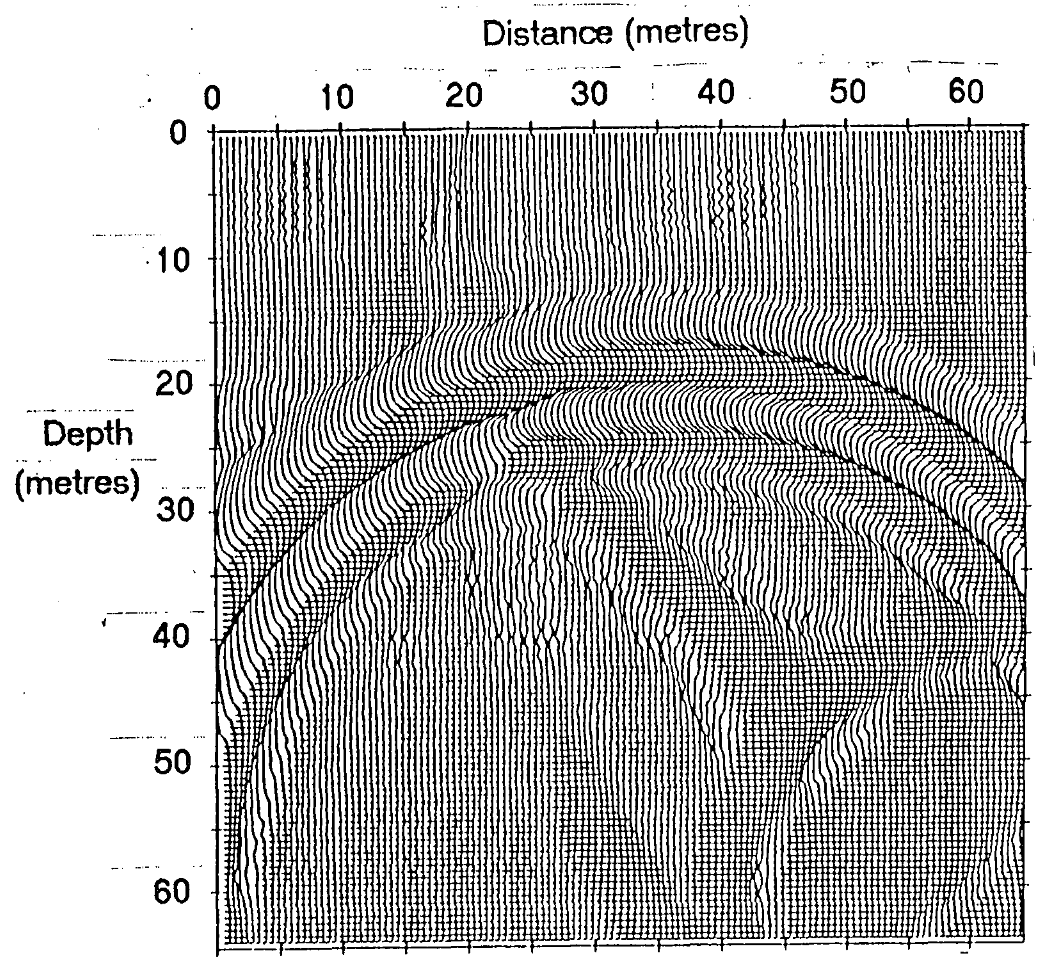


Figure 4.5 Evolution of the wavefield with time: a) 10ms, b) 20ms, c) 30ms, d) 40ms. The original source position was at (10,10).

c)


Distance (metres)
0
10
20
30
40
50
60
Depth
(metres)

d)


Distance (metres)
0
10
20
30
40
50
60
Depth
(metres)

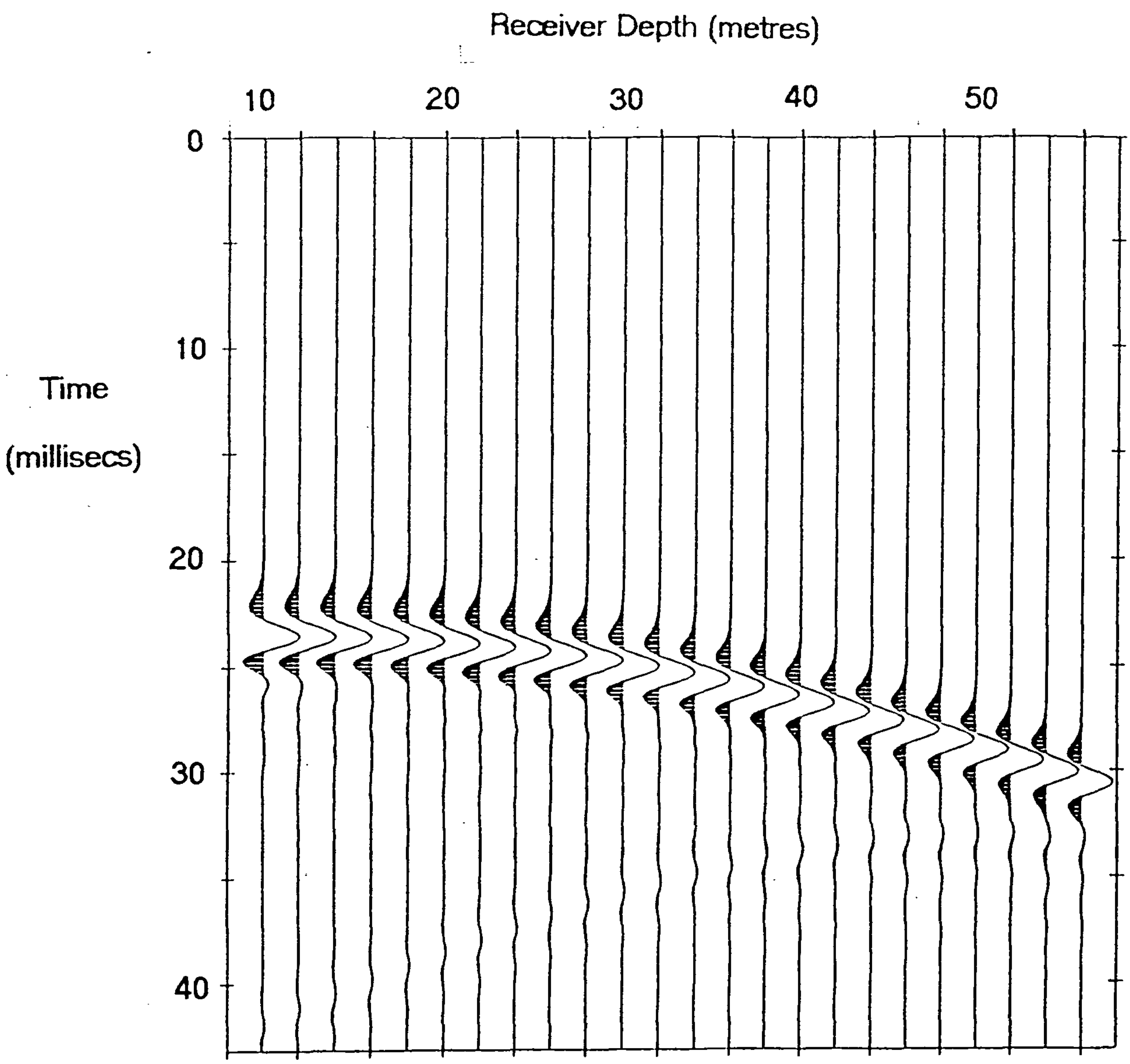


Figure 4.6 Synthetic seismogram produced for diffraction event.

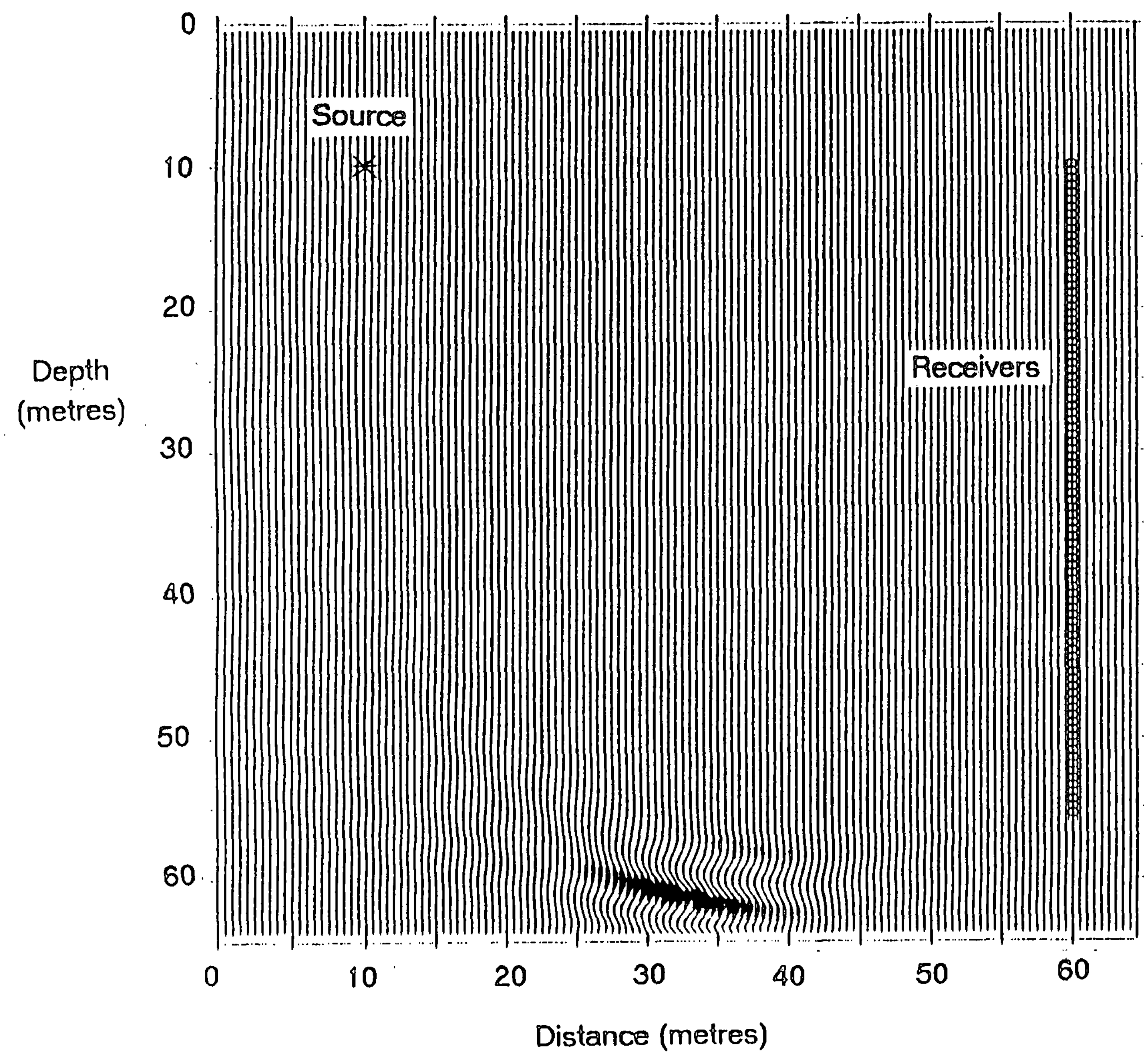


Figure 4.7 Finite-difference migrated image of the diffraction event.

ms was used. Thus the stability relation of equation (4.5) was satisfied. A Butterworth zero-phase source wavelet was used (figure 4.4) with a bandwidth of 150-500 Hz. The bandwidth was chosen to minimise the problem of grid dispersion which would occur for wavelengths greater than 10h=5m. A square diffractor of size 2m x 2m and velocity 1000m/s was positioned at the coordinates (35,60). The source was positioned at coordinates (10,10) and 24 receivers were positioned at 2m intervals, ranging in depth from 10m to 56m, at an offset of 50m from the source. The zero time of the data was set to coincide with the central peak of the source wavelet. The model was run using the L^2 absorbing boundary conditions discussed in §4.3.2. These were applied to all sides (i.e. no free surface reflections were allowed at the top of the model). Figure 4.5 illustrates the progression of the source pulse through the medium at times of 10, 20, 30 and 40 ms. Signal amplitudes have been scaled by taking the square root and retaining the polarity of the signal to enhance the diffracted energy in the diagrams. The circle of energy diffracted from the diffractor point location can be seen clearly in figures 4.5c and d. Data were calculated up to a time of 40 ms. The data "recorded" at the receiver positions are illustrated in figure 4.6. These data were then processed to remove the direct arrival. Since the data have been created by a 2-D modelling algorithm, no amplitude recovery is necessary in the preprocessing stage. The data were migrated by the finite-difference method resulting in the image of figure 4.7. This image is quite disappointing, with significant "smiles" around the diffraction point. The tilt of the migration smearing in this case is characteristic of the geometry of this survey.

Generalised Kirchhoff migration of the same data results in the image shown in figure 4.8. In this case, a full aperture (i.e. allowing all possible structural dips)

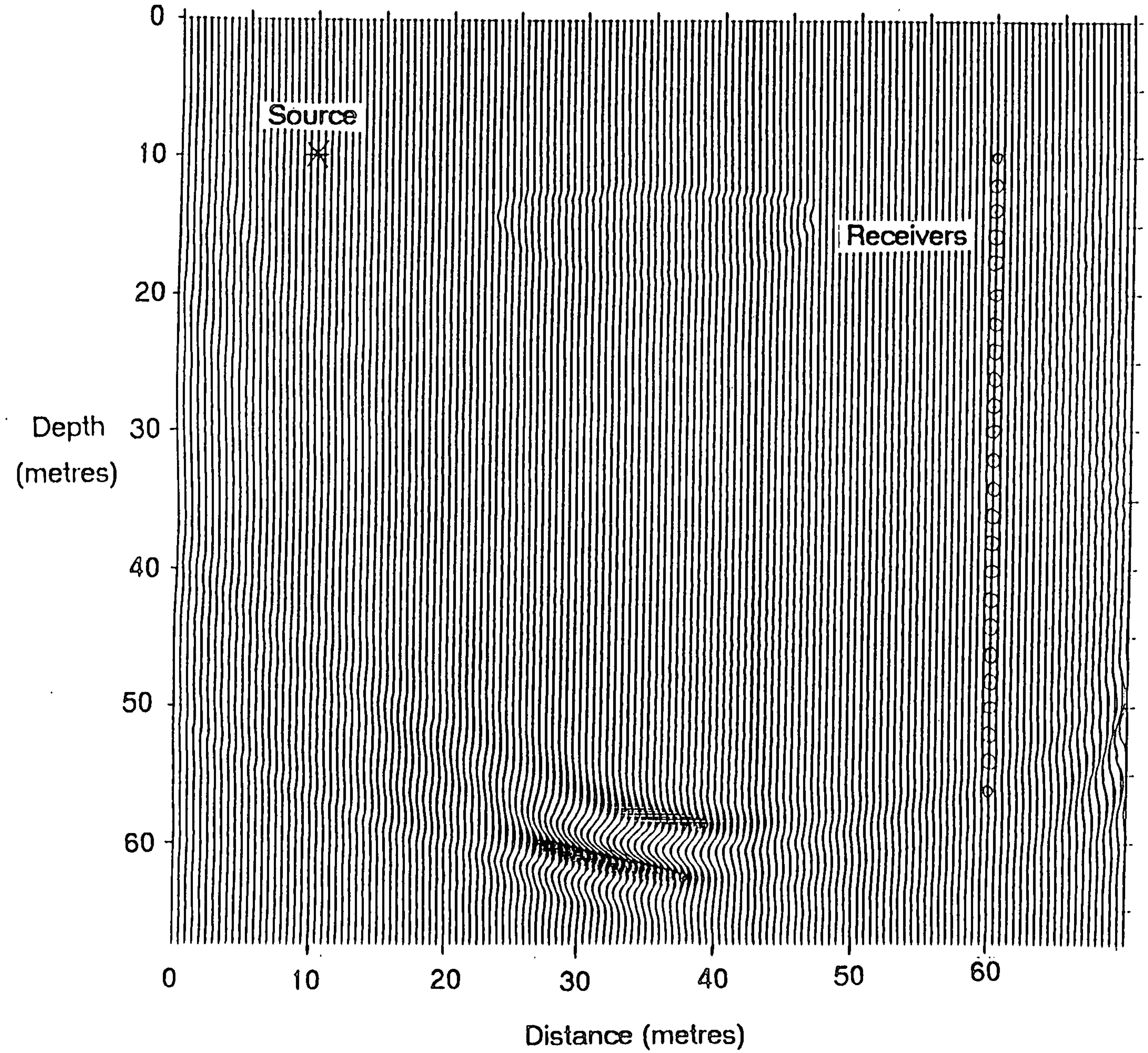


Figure 4.8 Generalised Kirchhoff migrate image of the diffraction event.

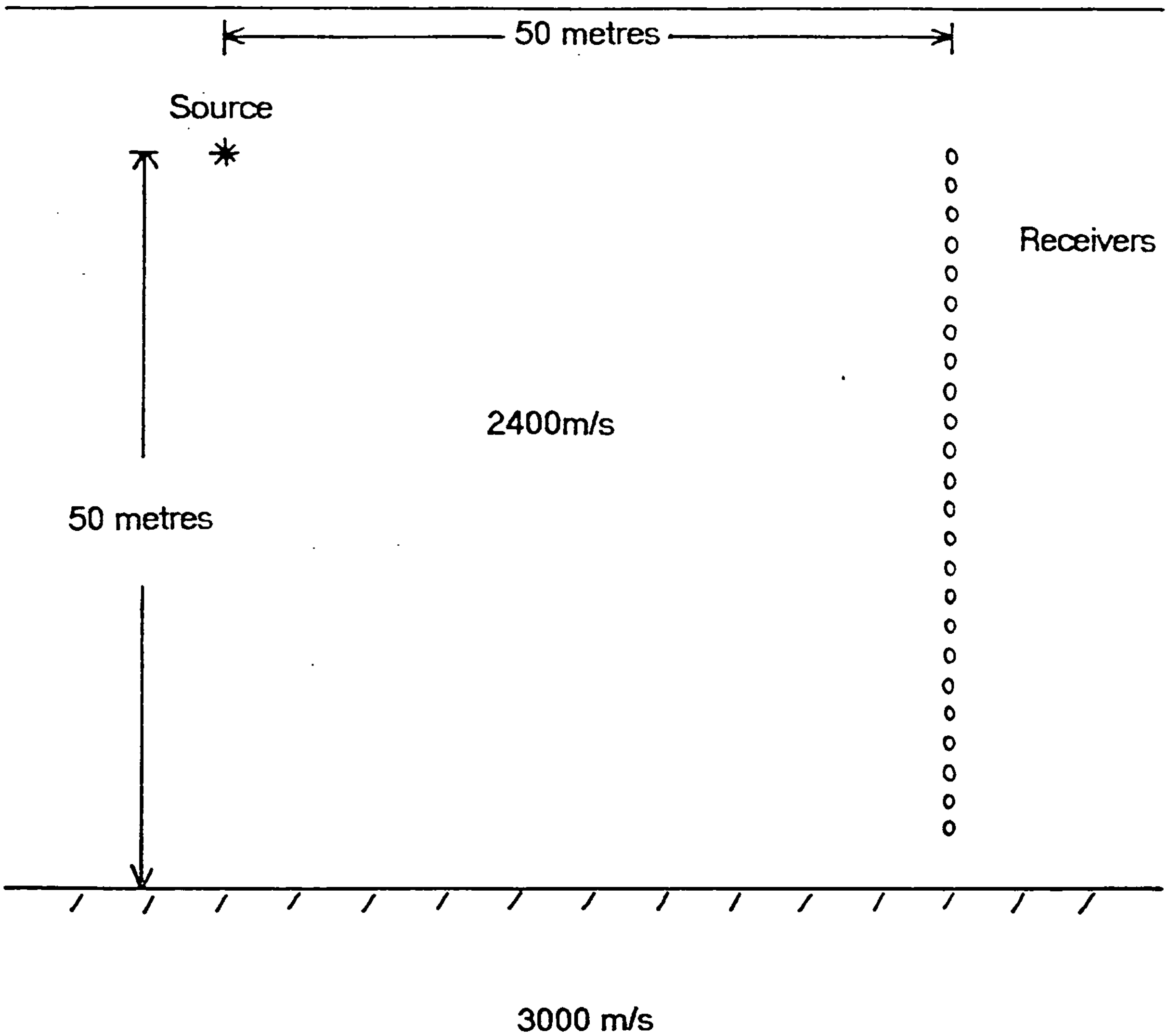
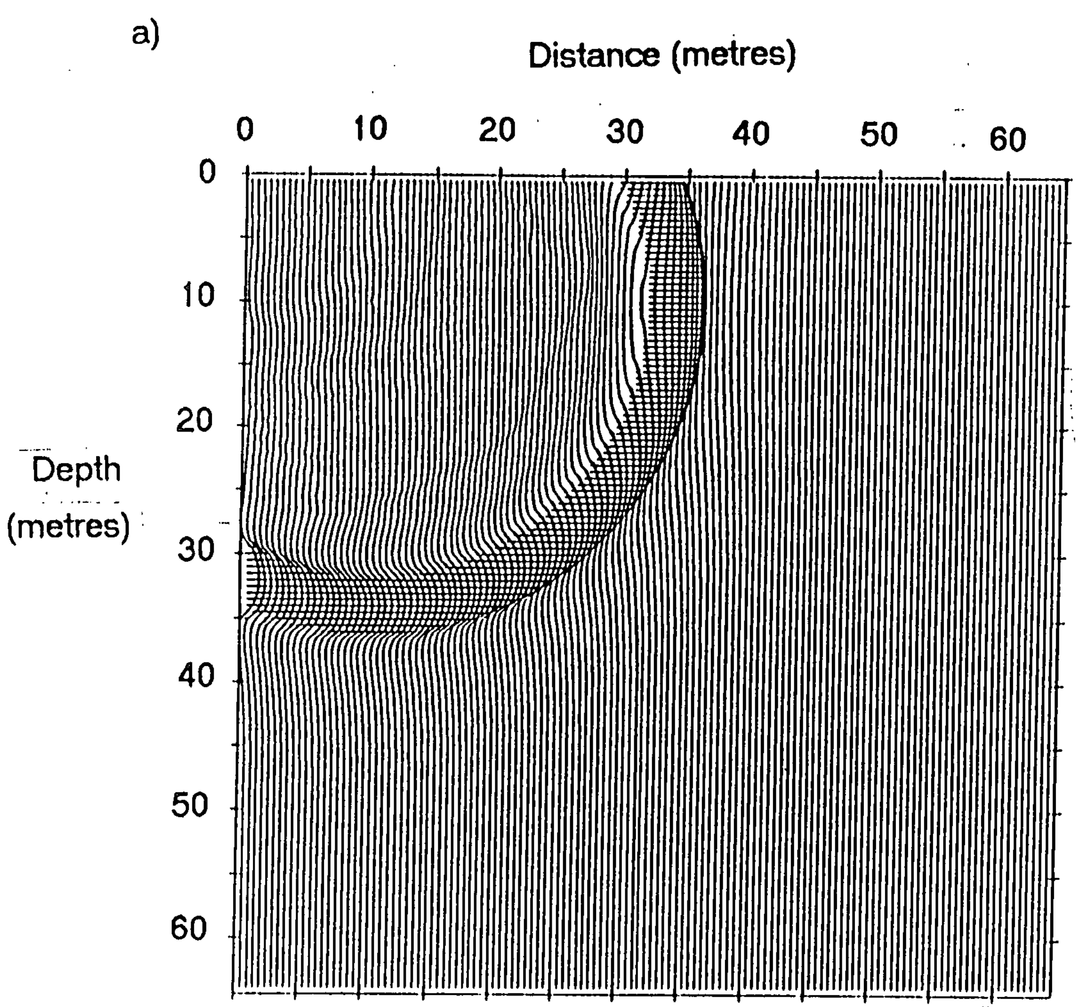


Figure 4.9 Model used to generate synthetic data for cross-hole reflectic



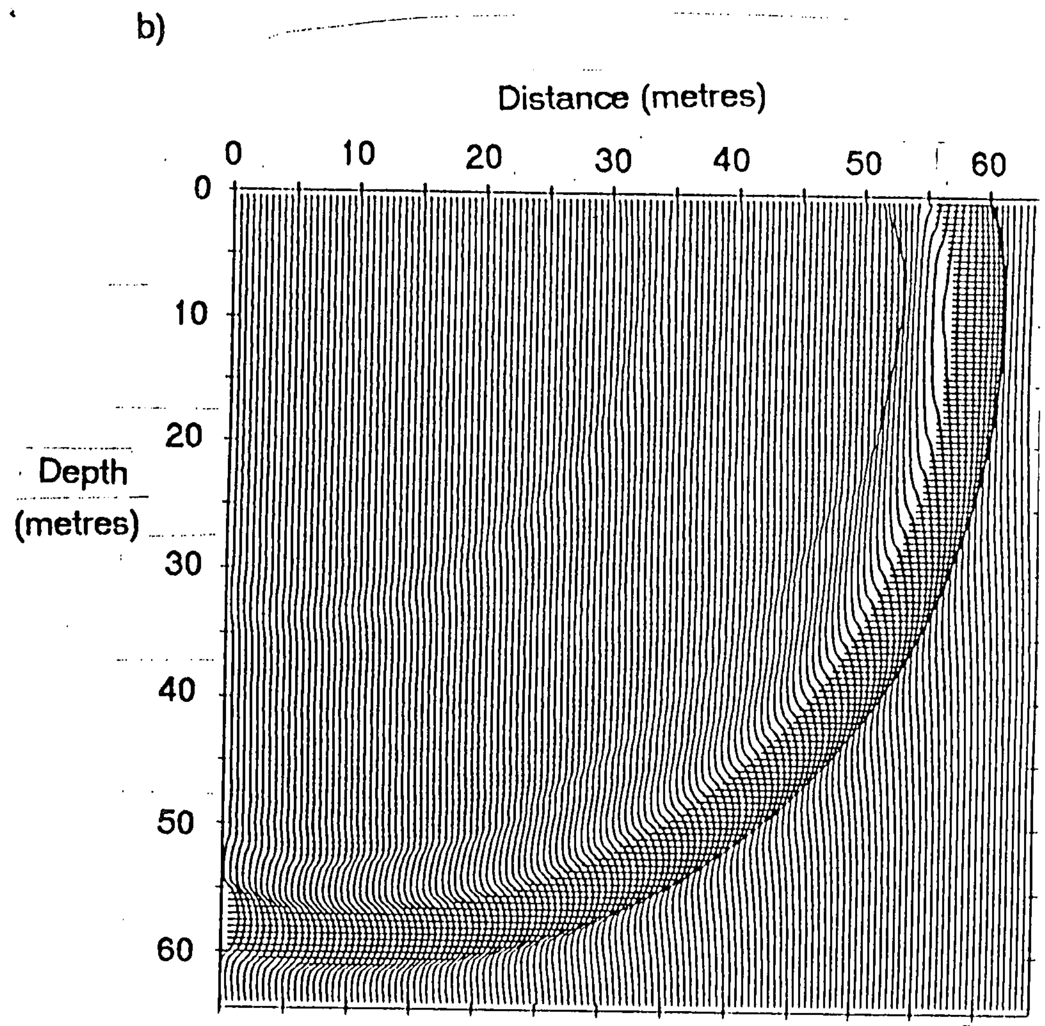
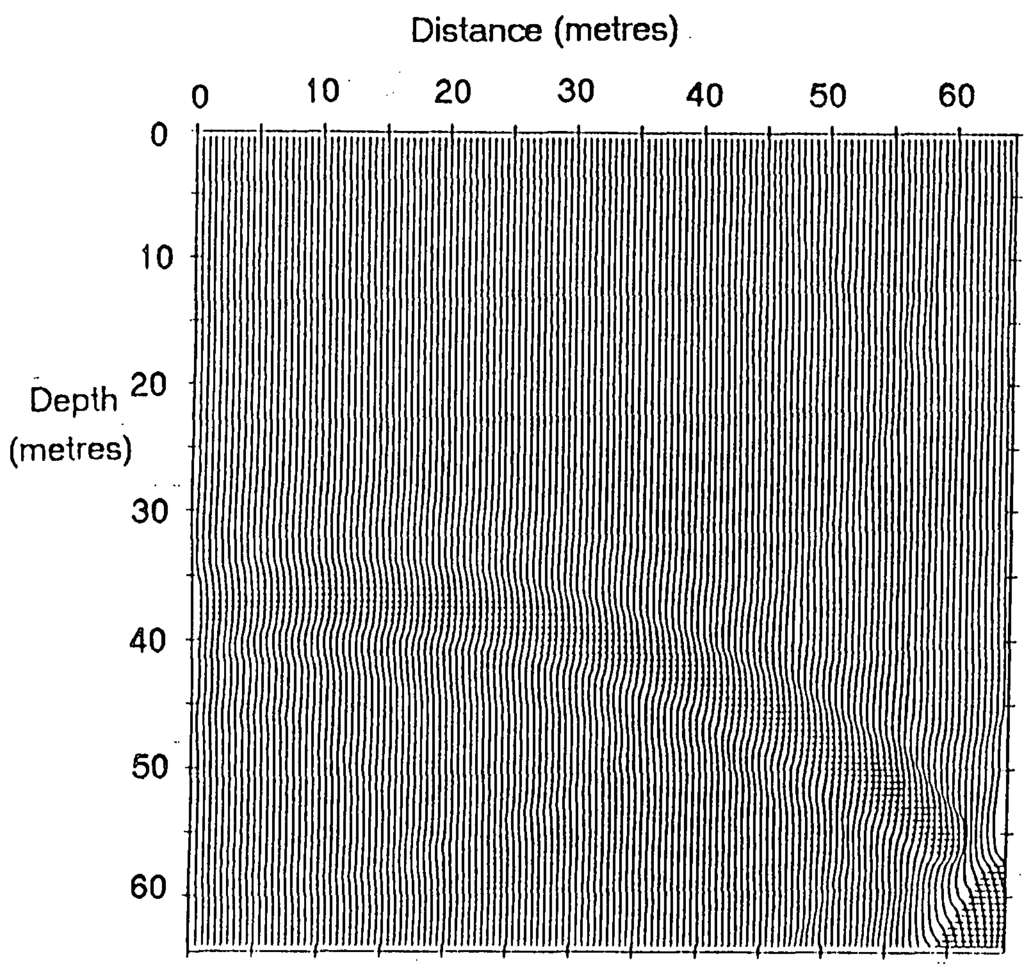
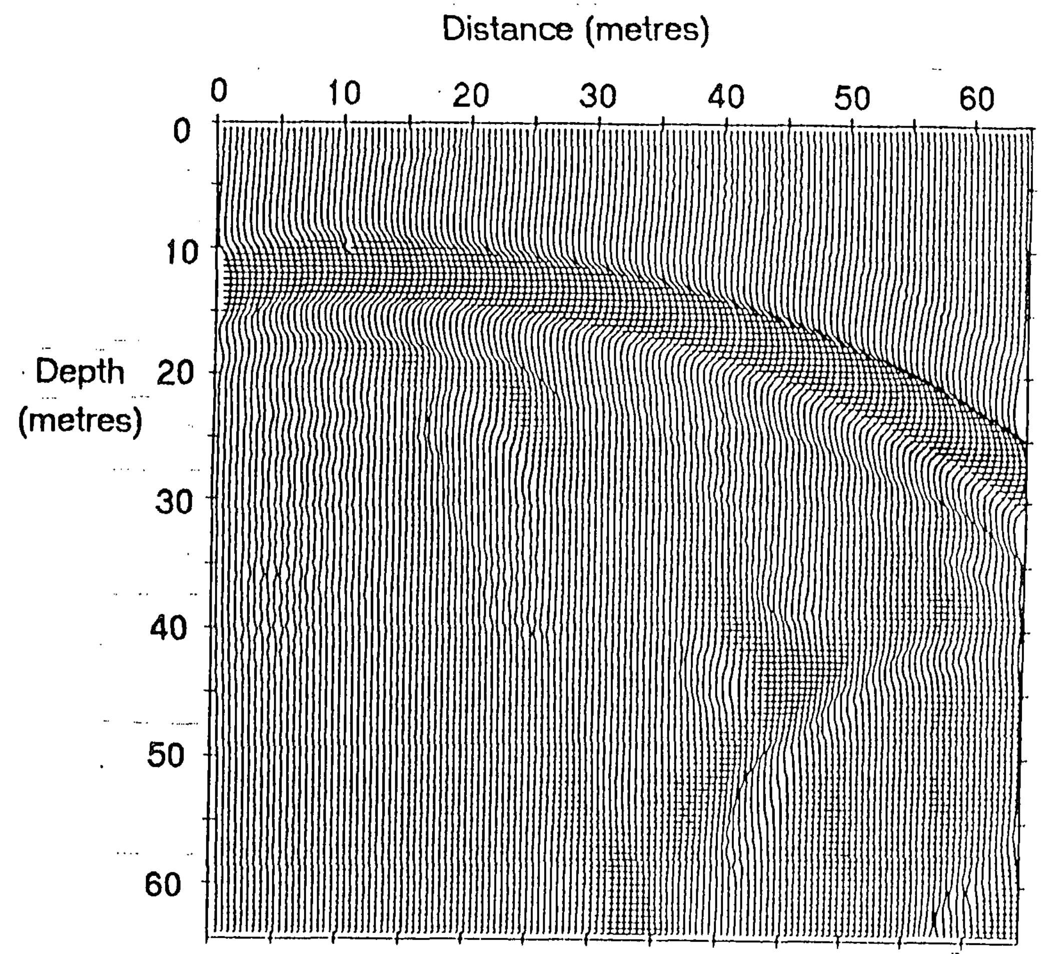


Figure 4.10 Evolution of the wavefield with time: a)10ms, b) 20ms, c) 30ms, d) 40ms. The original source position was at (10,10).

c)


Distance (metres)
0
10
20
30
40
50
60
Depth
(metres)
0
10
20
30
40
50
60

d)


Distance (metres)
0
10
20
30
40
50
60
Depth
(metres)
0
10
20
30
40
50
60

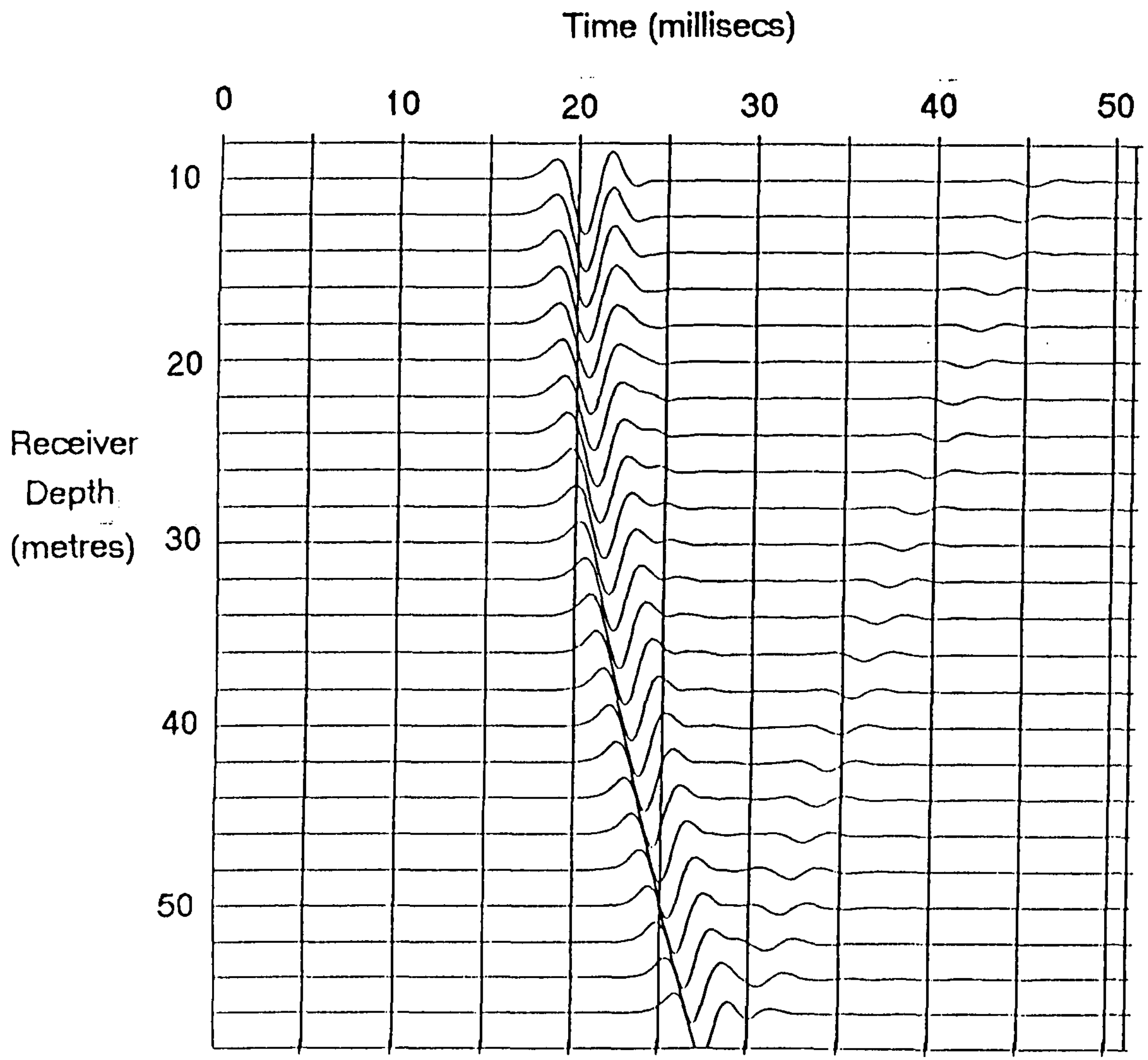


Figure 4.11 Synthetic seismogram produced for reflection event.

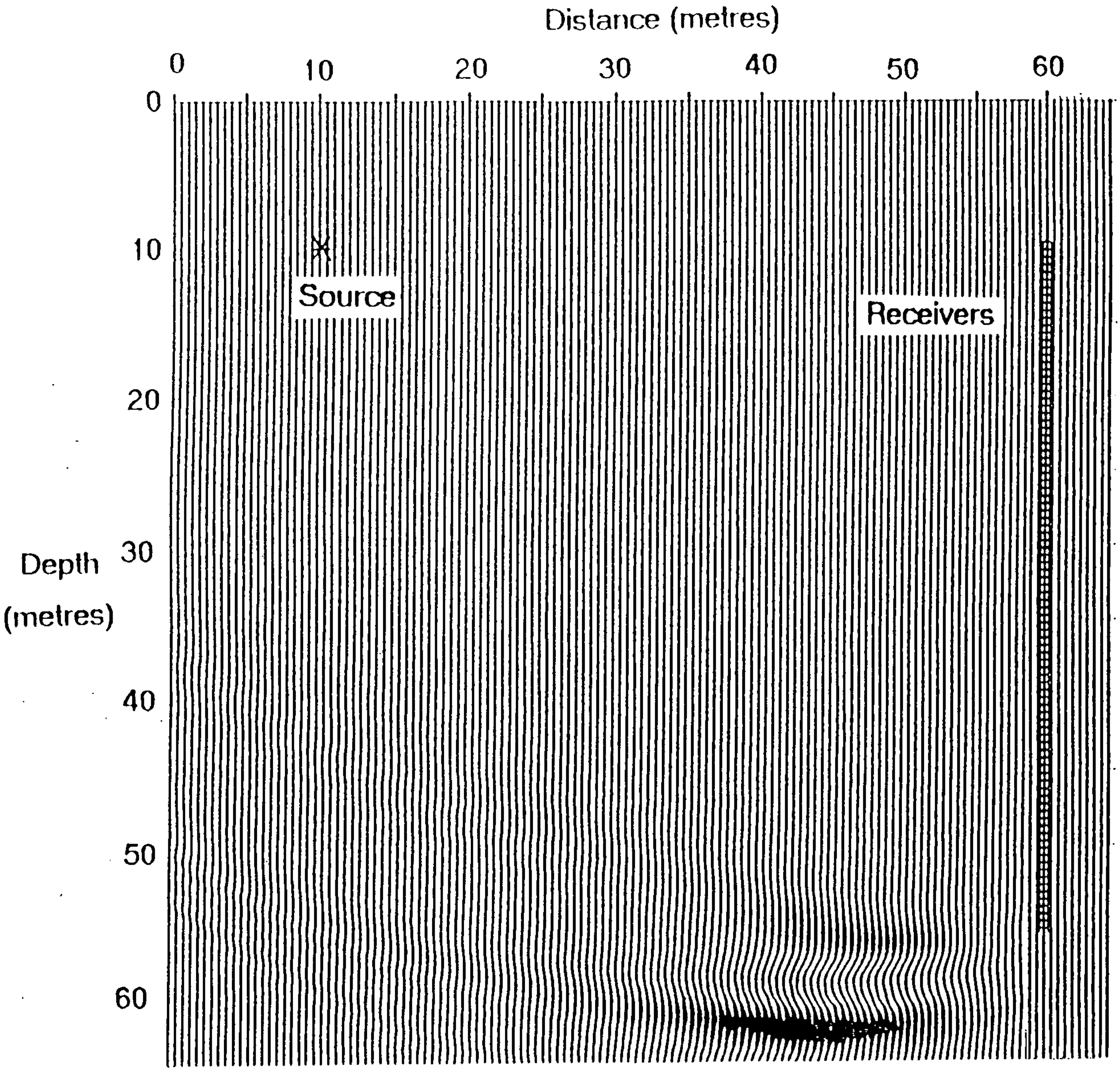


Figure 4.12 Finite-difference migrated image of the reflection event.

was used and the Newman filter was also applied. Again, smiling of the data is apparent and the image is similar to that in figure 4.7.

4.5.2 Horizontal reflecting interface model

Another synthetic dataset was modelled using the EXTRAP program. This time the reflectivity of a horizontal reflector was considered. A two-layer model was used (figure 4.9). The top layer of velocity 2400m/s was 50m thick and the bottom layer was assigned a velocity of 3000m/s. The source (again a Butterworth wavelet with a bandwidth of 150-500 Hz) was positioned at coordinates (10,20) and a vertical line of receivers were positioned at 2m intervals at depths from 10m to 56m at an offset of 50m from the source position. L^2 absorbing boundary conditions were applied on all sides of the model. The propagation of the source pulse has been plotted at times of 10, 20, 30 and 40 ms in figure 4.10, and the resultant seismogram following the application of an amplitude recovery ramp, linearly dependent on time, is shown in figure 4.11. The direct arrival and the primary reflected arrival are clearly visible.

Finite difference migration of the data following direct arrival suppression resulted in the image of figure 4.12. Substantial trailing "smiles" are apparent beyond the area of illumination of the reflecting interface. Generalised Kirchhoff migration of the same synthetic data with a full imaging aperture (i.e. allowing all possible reflector dips to be imaged) led to a very similar image (figure 4.13). Subsequently, the migration aperture was reduced to allow geological dips of less than 22.5° and the data re-migrated (figure 4.14). This image is sharper defining the zone of illumination more clearly. The Generalised Kirchhoff approach is preferable to the

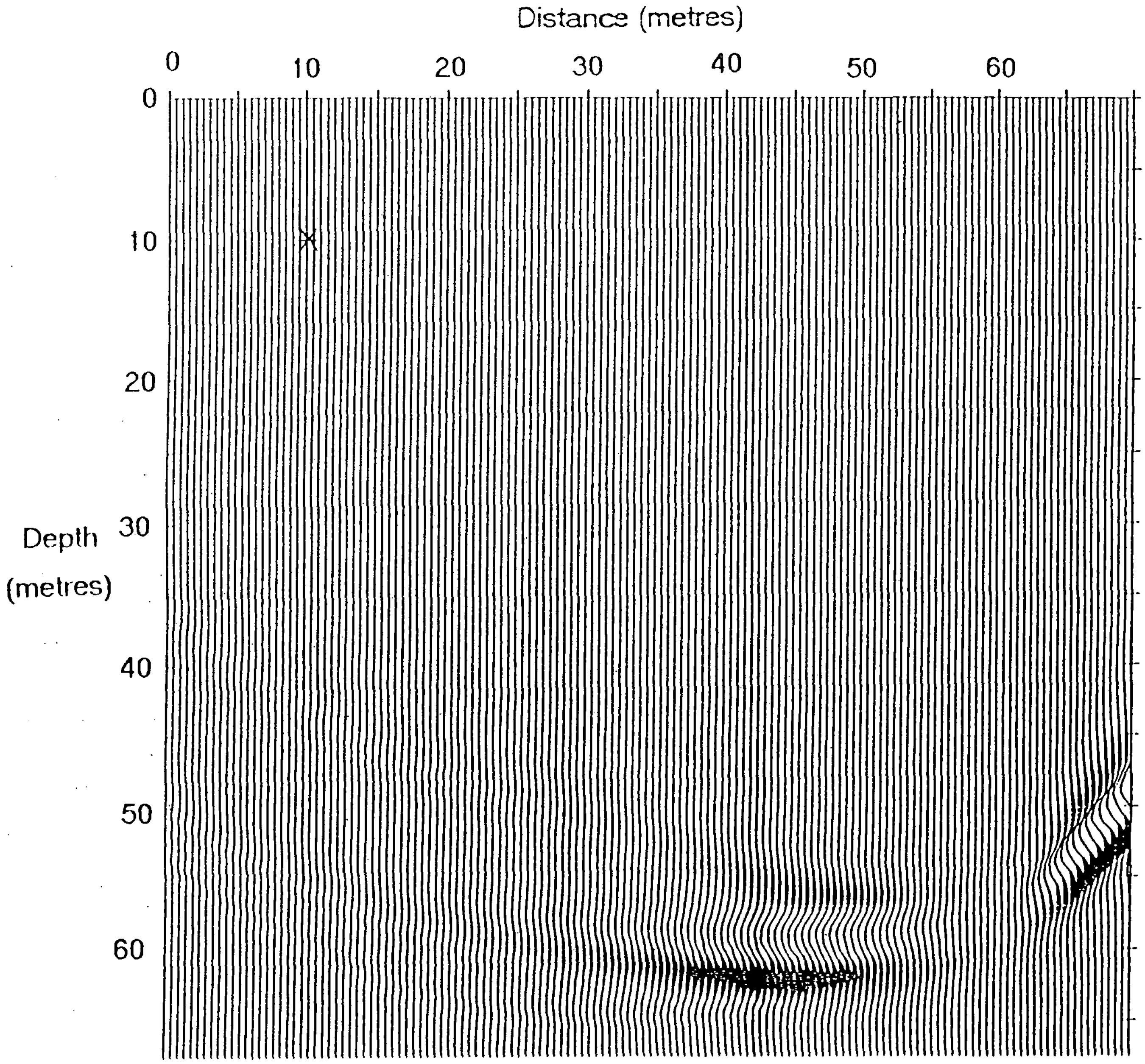


Figure 4.13 Generalised Kirchhoff (full aperture) migrated image of the reflection event.

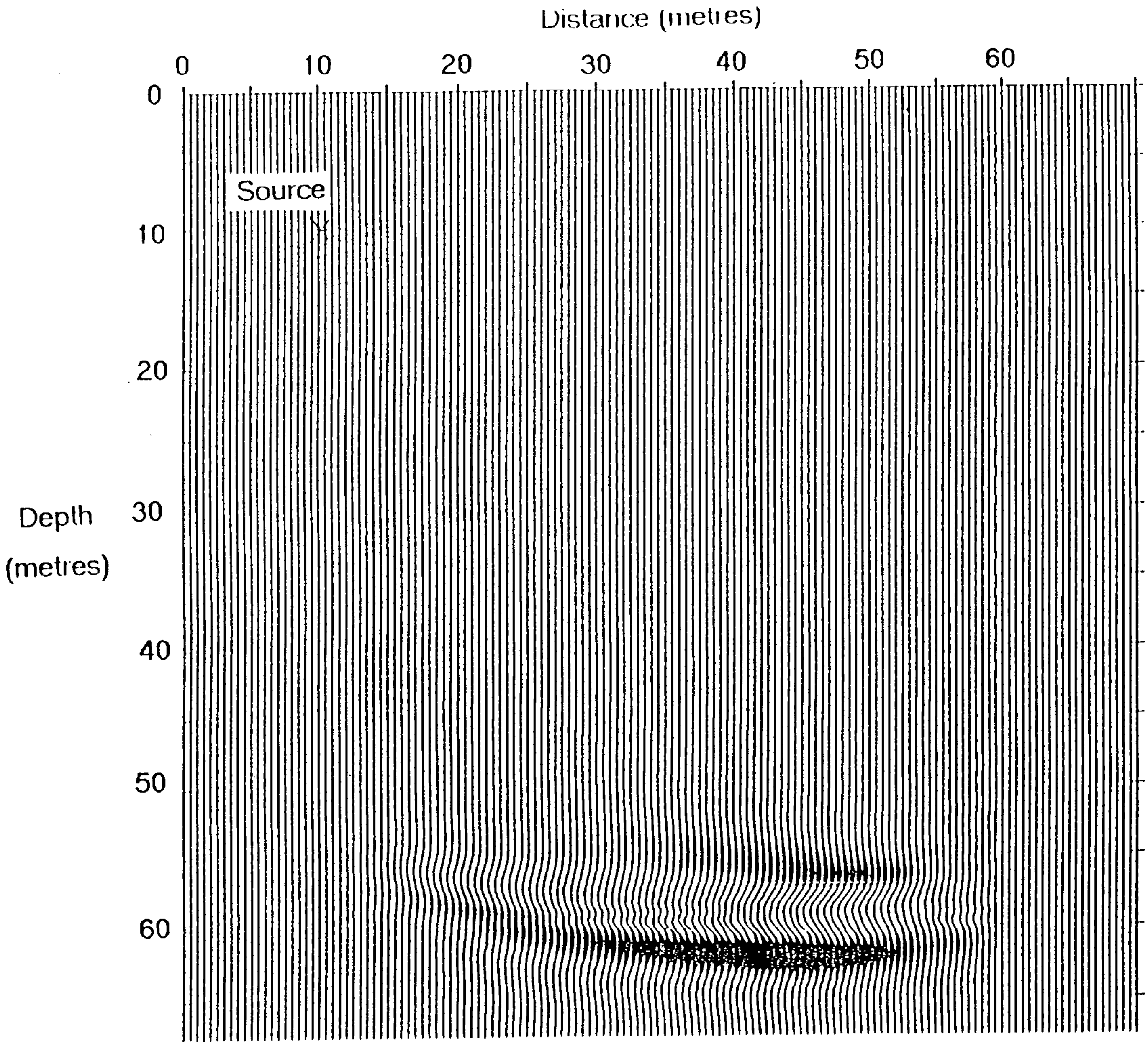


Figure 4.14 Generalised Kirchhoff (22.5° dip aperture) migrated image of the reflection event.

finite-difference approach in this case, because it is faster and also because of the extra control of image quality available during the migration process by the use of an imaging aperture.

Chapter V

Results from cross-hole surveys in Coal Measures strata

5.1 Introduction

Trial cross-hole surveys were carried out at three British Coal Opencast exploration sites in the North of England. These were Tinsley Park in South Yorkshire, Lowther South in West Yorkshire and Lostrigg in Cumbria.

5.2 Tinsley Park

Test survey A was carried out at Tinsley Park in 1988 in order to assess the feasibility of the acquisition technique. Preliminary tests had been carried out with sources and receivers positioned at depth intervals of 4m corresponding to those used in earlier cross-hole tomographic work (Findlay, 1987 and Kragh, 1990), but this resulted in spatial aliasing of the data, prohibiting the use of wavefield separation techniques. The survey presented in this section utilised 2m source and receiver intervals.

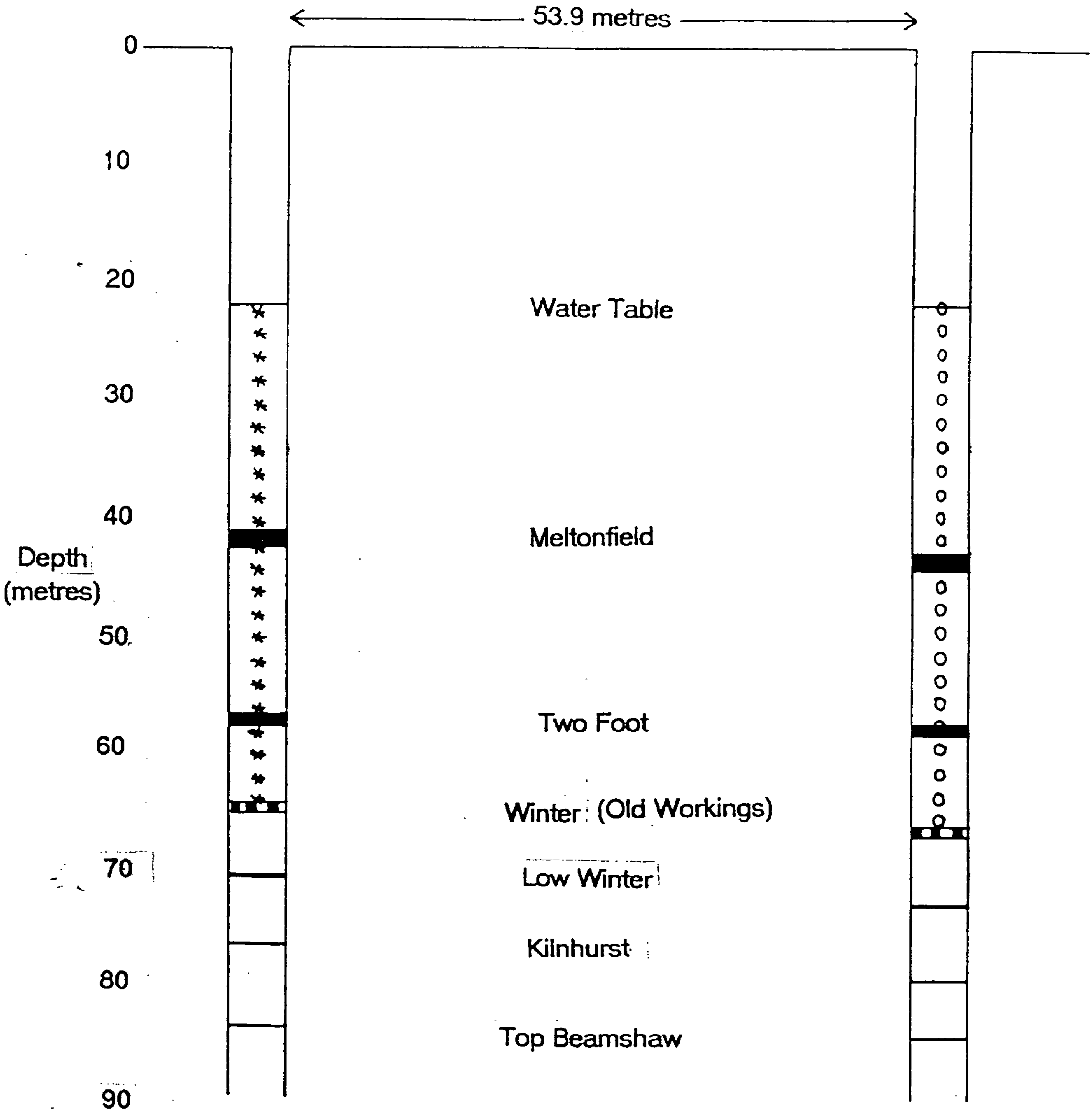


Figure 5.1 Logged coal seams and source and receiver positions for the boreholes used in survey A.

Figure 5.1 shows the interpreted stratigraphic logs and shot and receiver locations for survey A. The water table was at a depth of 22m and the boreholes were blocked at depths of 65m (source hole) and 66m (receiver hole). Repeated shots were fired at depths ranging from 22m to 64m and the hydrophone depths ranged from 22m to 66m. Seismic detonators were used as sources. The principal coal seams logged are listed in Table 5.1.

Seam	Depth to base (metres)	Thickness (metres)
Meltonfield	41.85	1.55
Two Foot	57.00	0.90
Winter	64.70	0.80
Low Winter	70.30	0.15
Kilnhurst	76.20	0.20
Top Beamshaw	83.35	0.45

Table 5.1 Principal coal seams in stratigraphic logs from survey A at Tinsley Park

Of these seams, the Winter seam is known to have been worked with virtually total extraction and the remaining seams are believed to be solid near these boreholes.

The data from this survey were processed and imaged by means of the VSP-CDP transform. A simple velocity field (see table 5.2), derived from a combination of cross-hole tomography and uphole shots, was used to map the data in to a depth section.

Depth range (metres)	**Interval Velocity (metres/sec)**
0-21	2100
21-25	2850
25-40	2950
40-43	2300
43-55	3250
55-57	2450
57-64	2800
64-66	2400
>66	3000

Table 5.2 VSP-CDP velocity field used for survey A

In the data processing stage the zero-phase waveshaping deconvolution was omitted and so reflection depths will correspond to the first break of a wavelet rather than to a peak or a trough. The depth section for the upgoing wavefield is presented in figure 5.2. An AGC of length 25m has been applied vertically down the section to compensate for variations in signal amplitude. The horizontal trace separation is 2m and the vertical sampling interval is 0.25m. Normal SEG polarity of reflection amplitudes (i.e. white amplitudes are compressive and black amplitudes are dilatational) has been used in this display and all subsequent sections. Clear reflections are observed from the two shallowest and thickest seams (the Meltonfield

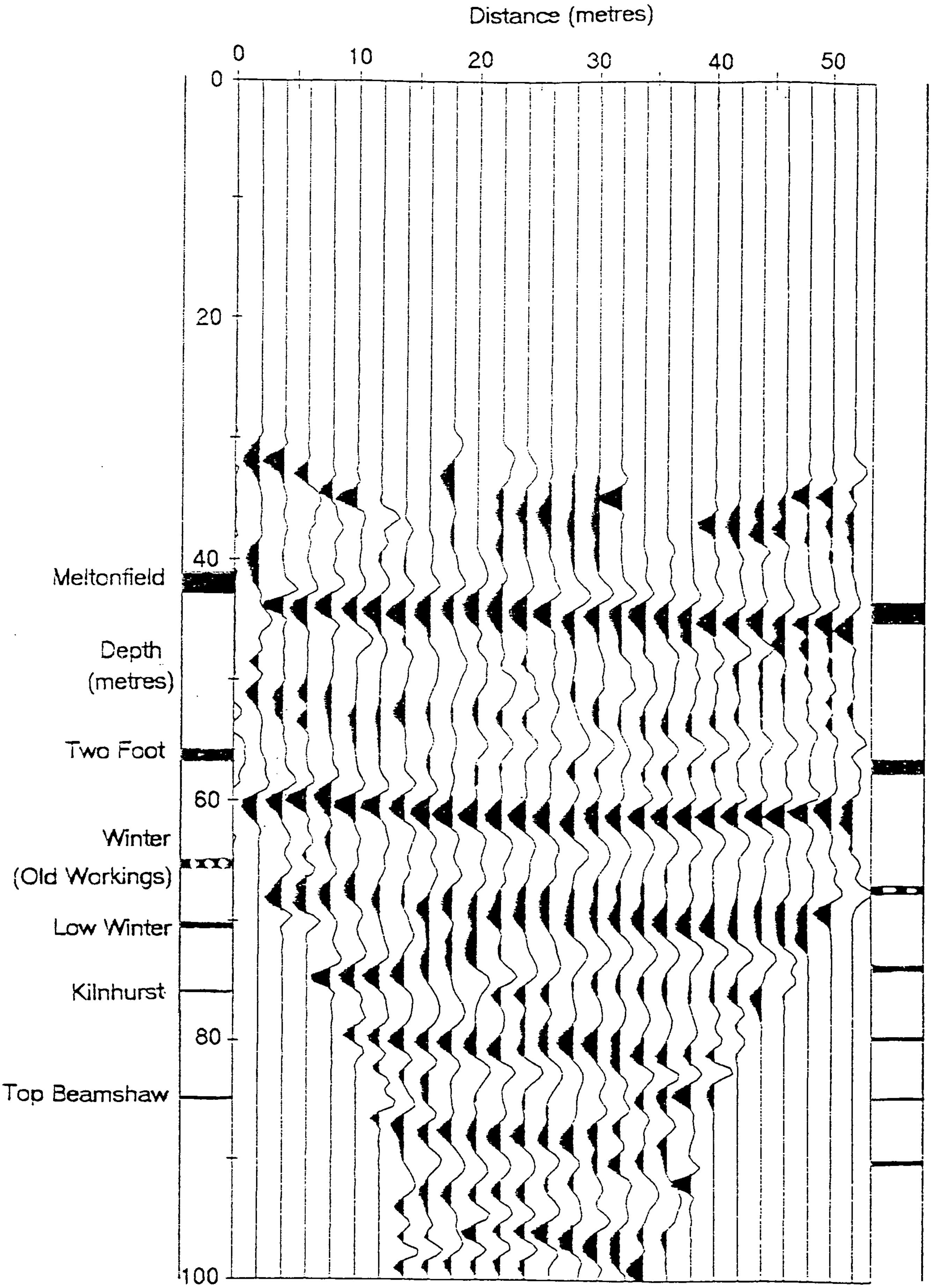


Figure 5.2 Depth section produced by VSP-CDP transform of upgoing reflections for survey A.

and the Two Foot). The reflection event seen at a depth of around 65 metres from the worked Winter seam is disrupted probably as a result of collapses in the roof of the seam and the irregular nature of the room and pillar mineworkings. Signal penetration was poor below this seam and no shots or receivers were located below the seam depth because of borehole blockages. As a result the quality of the image below the Winter seam is poor. The seams are also thinner in this area and one would expect that the reflection response from these seams would be weaker as well. The vertical resolution in the data is indicated by the wavelength of the reflections from the seams. In this case, the wavelengths are around 4m and one would therefore expect to be able to resolve reflector discontinuities caused by faulting or old mineworkings on a scale of 2m or even better. The strength of the reflections from targeted coal seams in this initial survey was very encouraging for the development of this technique.

5.3 Lowther South, West Yorkshire

Four cross-hole surveys were acquired at the Lowther South exploration site in West Yorkshire in the autumn of 1989. The first three surveys were acquired using three collinear boreholes (I, II and III) near to, but not within, a major fault zone known as the Methley-Saville fault. The line of the boreholes was selected to be perpendicular to the strike of the fault. The fourth survey was acquired between two boreholes (IV and V) located within the fault zone and lying approximately collinear

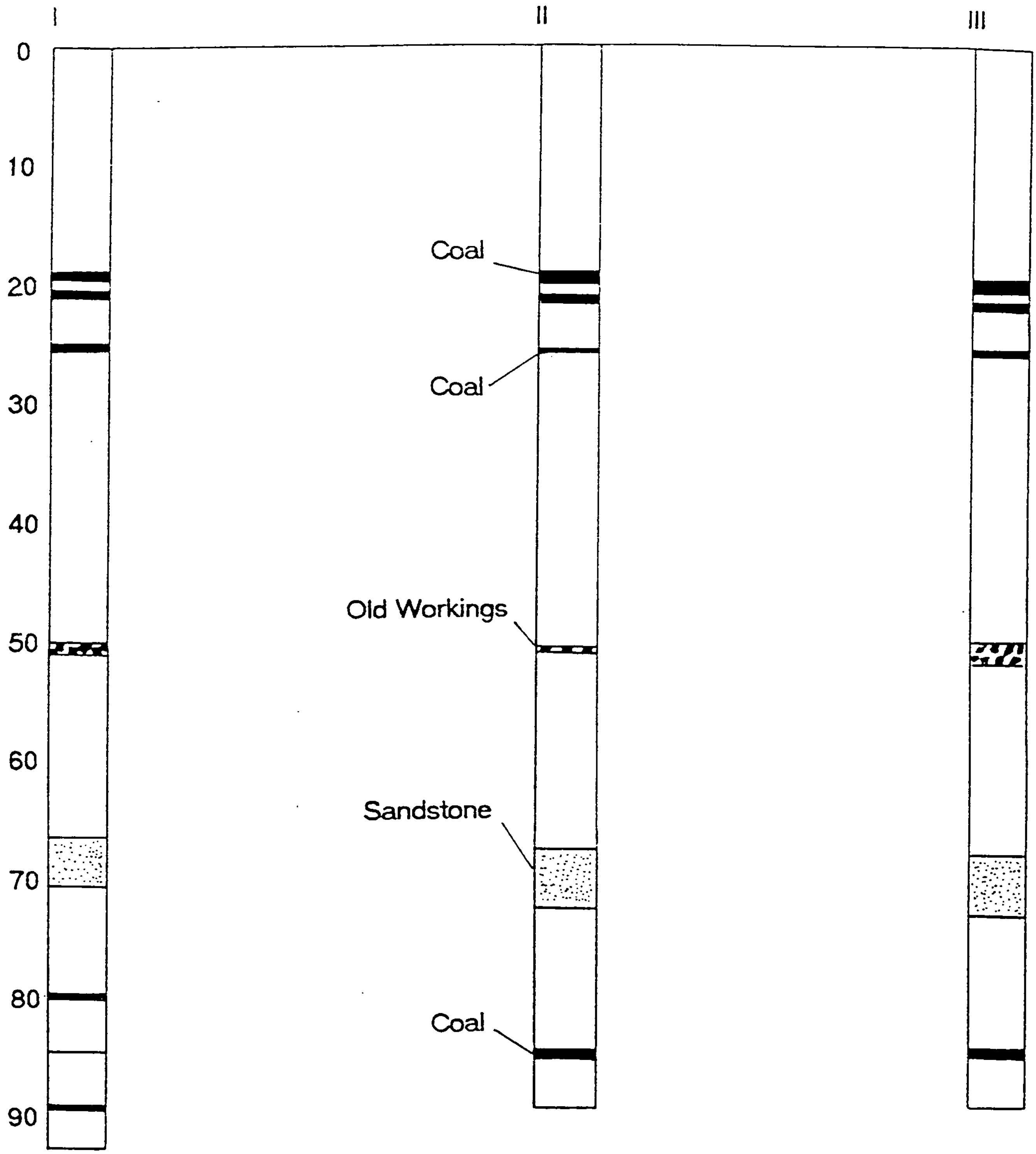


Figure 5.3 Interpreted stratigraphic log for the collinear boreholes I, II and III at Lowther South, West Yorkshire. Principal seams and their thicknesses are depicted.

to the first three boreholes. The interpreted stratigraphic logs for the three collinear boreholes are shown in figure 5.3. The principal seams are listed in Table 5.3.

Seam	Depth to base (metres)	Thickness (metres)
Kents Thick	21.4	1.3
1AY	25.5	0.2
Barnsley Top Softs	51.0	1.1
Dunsil	80.2/84.5*	0.7

*Seam is shallower in borehole I than in boreholes II and III

Table 5.3 Principal seams in boreholes I,II and III

The logs indicate that the strata lie horizontally between these boreholes with the exception of a small fault which must cut the Dunsil seam between boreholes I and II. The seams are solid apart from the Barnsley Top Softs which is known to have been extensively worked in the area. The water table intersected these boreholes at a depth of 8m and the boreholes were blocked at depths of 62m, 57m and 52m, respectively.

5.3.1 Survey B, illustrating the combination of up- and down- going sections

Shots were fired from 27 depth levels at 2m intervals ranging from 10m to 62m in borehole I and the data were recorded at 23 hydrophone depth levels at 2m intervals ranging from 16m to 60m in borehole II (see figure 5.4). The borehole

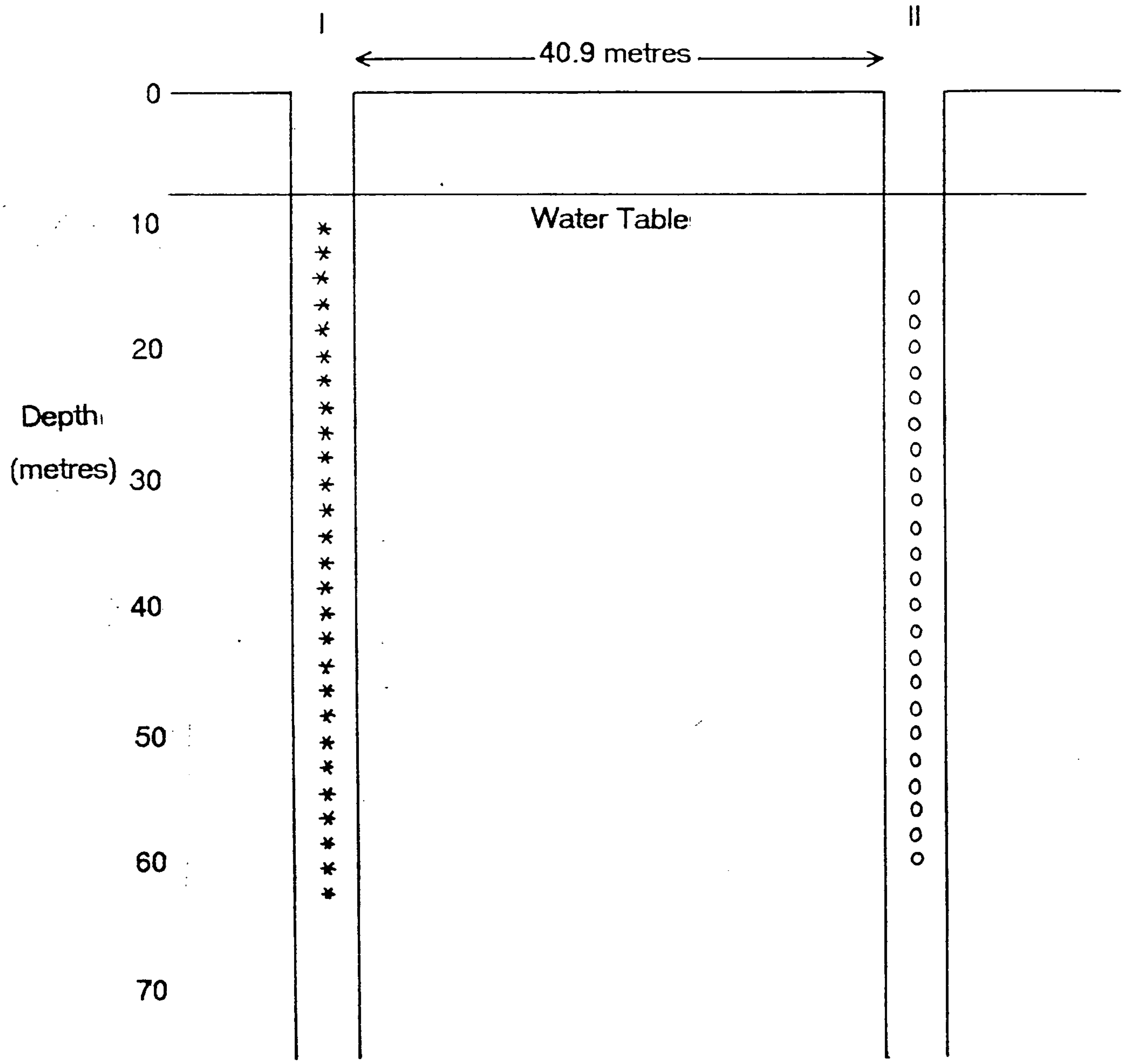


Figure 5.4 Shot and receiver positions for survey B.

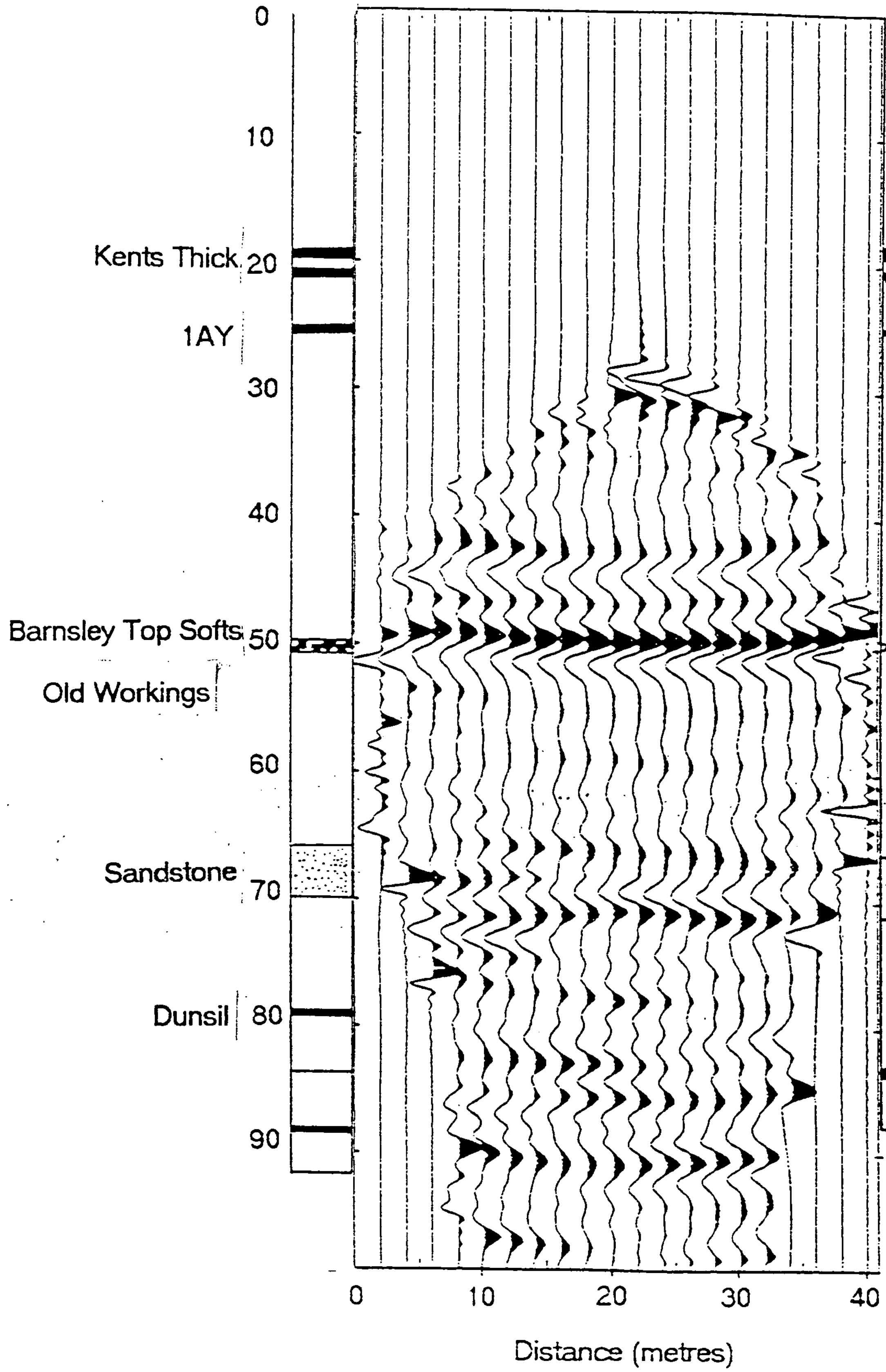


Figure 5.5a Upgoing Generalised Kirchhoff migrated section (22.5° dip aperture) for survey B.

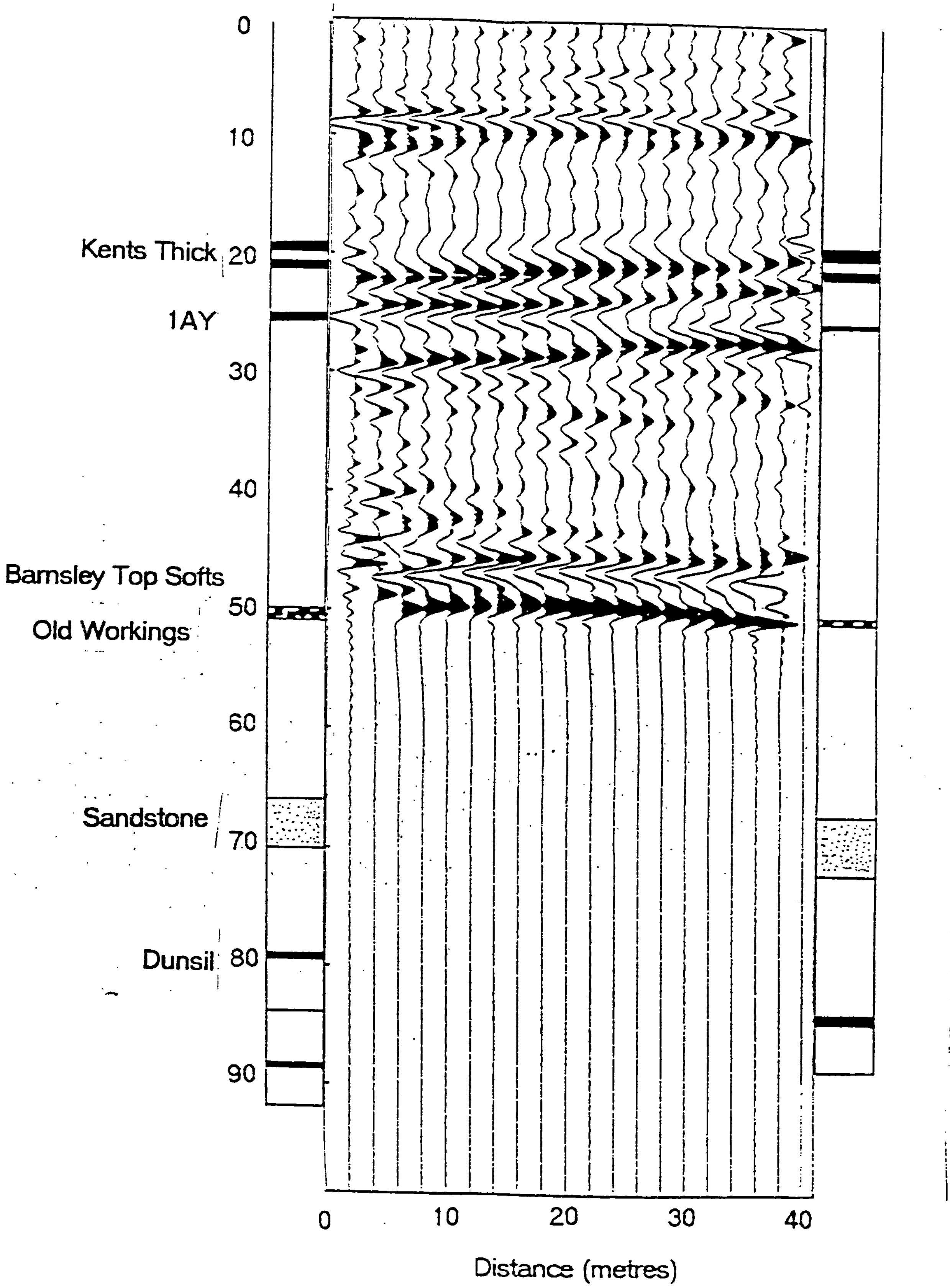


Figure 5.5b Downgoing Generalised Kirchhoff migrated section (22.5° dip aperture) for survey B.

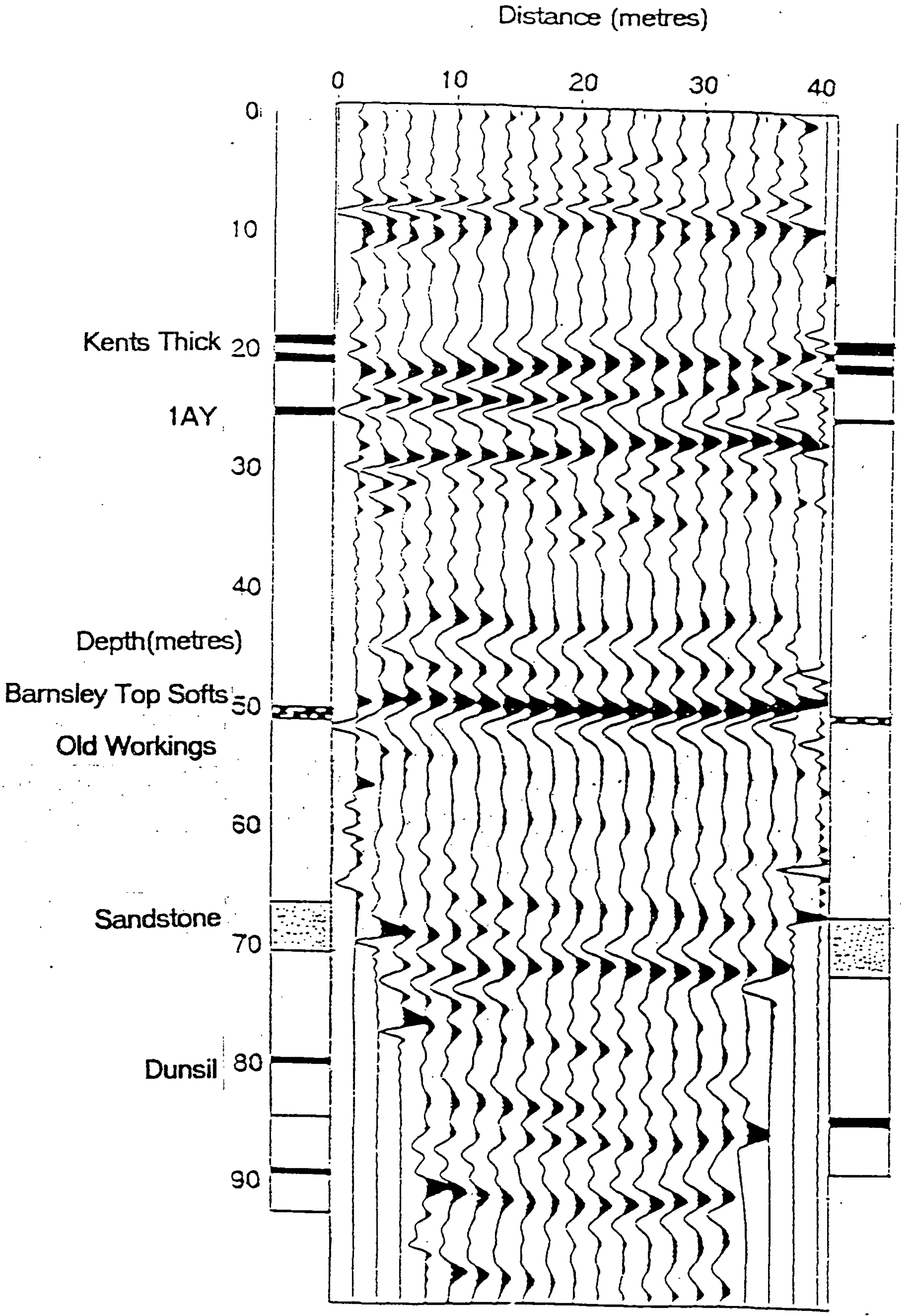


Figure 5.5c Combined upgoing and downgoing Generalised Kirchhoff migrated section for survey B. Sections are merged between 40m and 50m depth using cosine tapers.

separation was 40.9m at the surface. Both boreholes were blocked at a depth of around 62m. The data were processed as described in chapter III and imaged by means of the G-K migration algorithm. A migration dip aperture of +/- 22.5° was used. The migration velocity field is described in table 5.4.

Depth range (metres)	Migration interval velocity (metres/sec)
0-10	1200
10-22	2250
22-54	2600
54-100	2700

Table 5.4 Migration velocity field used for survey B

The depth sections are presented in figure 5.5. Figure 5.5a is the depth section imaged from the upgoing reflections and figure 5.5b is the depth section imaged from the downgoing reflections. Figure 5.5c is the depth section of the combined up- and down- going sections produced by melding the two sections together over a depth range of 40-50m. An AGC of length 25 metres has been applied vertically to balance up the amplitudes at all depths. Several clear reflectors are apparent corresponding to the coal seams at depths of 8m, 20m, 25m and 50m. The seams at 20m and 25m have a flat, continuous character as might be inferred from the stratigraphic logs. The Barnsley Top Softs seam at 50m depth has been worked right across the section, but still shows a strong, coherent reflection. The presence of a fault intersecting borehole

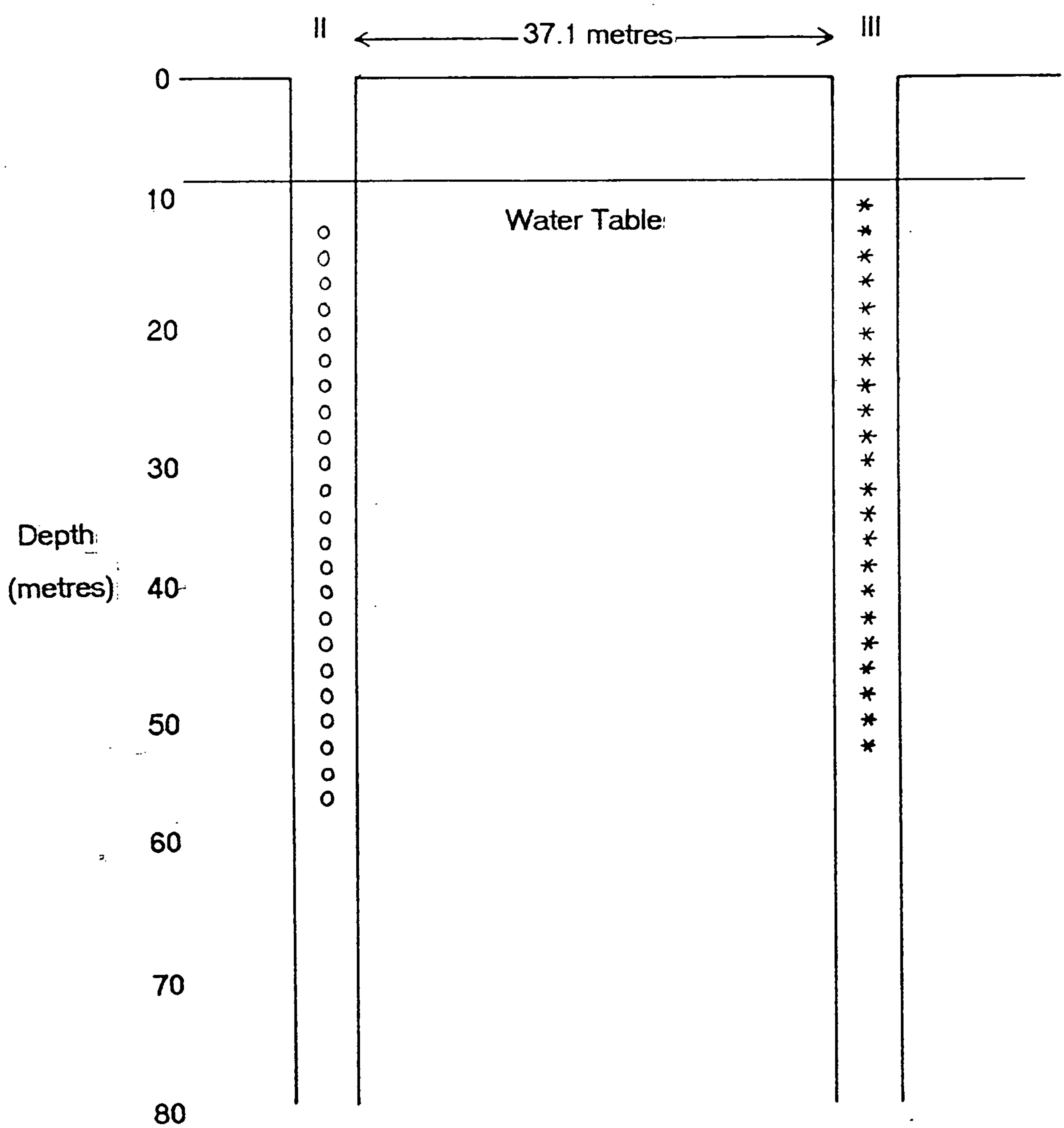


Figure 5.6 Shot and receiver locations for survey C.

B at a depth of between 50m and 80m might be expected from interpretation of the borehole logs. Unfortunately, the fault is not apparent on the cross-hole survey either because it is located too close to the borehole where reflector coverage is very poor, or else because of the lack of penetration of the signal through the old mineworkings at 50m depth. The Dunsil seam (log depth 85m) may have been imaged closer to 90m due to errors in the velocity field below the bottom source and receiver depths. Image quality is poor in those regions of the image where specular reflection raypath coverage is of a low density. These regions are in the vicinity of the boreholes and in the areas near the boreholes above the top source and receiver positions and below the bottom source and receiver positions.

5.3.2 Survey C; between boreholes II and III

In this survey a total of 22 shot positions were used in borehole III at 2m depth intervals ranging from a depth of 10m to a depth of 51.9m (see figure 5.6). Electrical detonators were used as an explosive source. Hydrophone locations were at 2m depth intervals ranging from a depth of 12m to a depth of 56m in borehole II. The borehole separation was 37.1m at the surface. The data were processed as described in chapter III and imaged by means of the G-K migration algorithm with a migration dip aperture of +/-22.5^{o} The isotropic velocity model used to migrate the data is described in table 5.5.

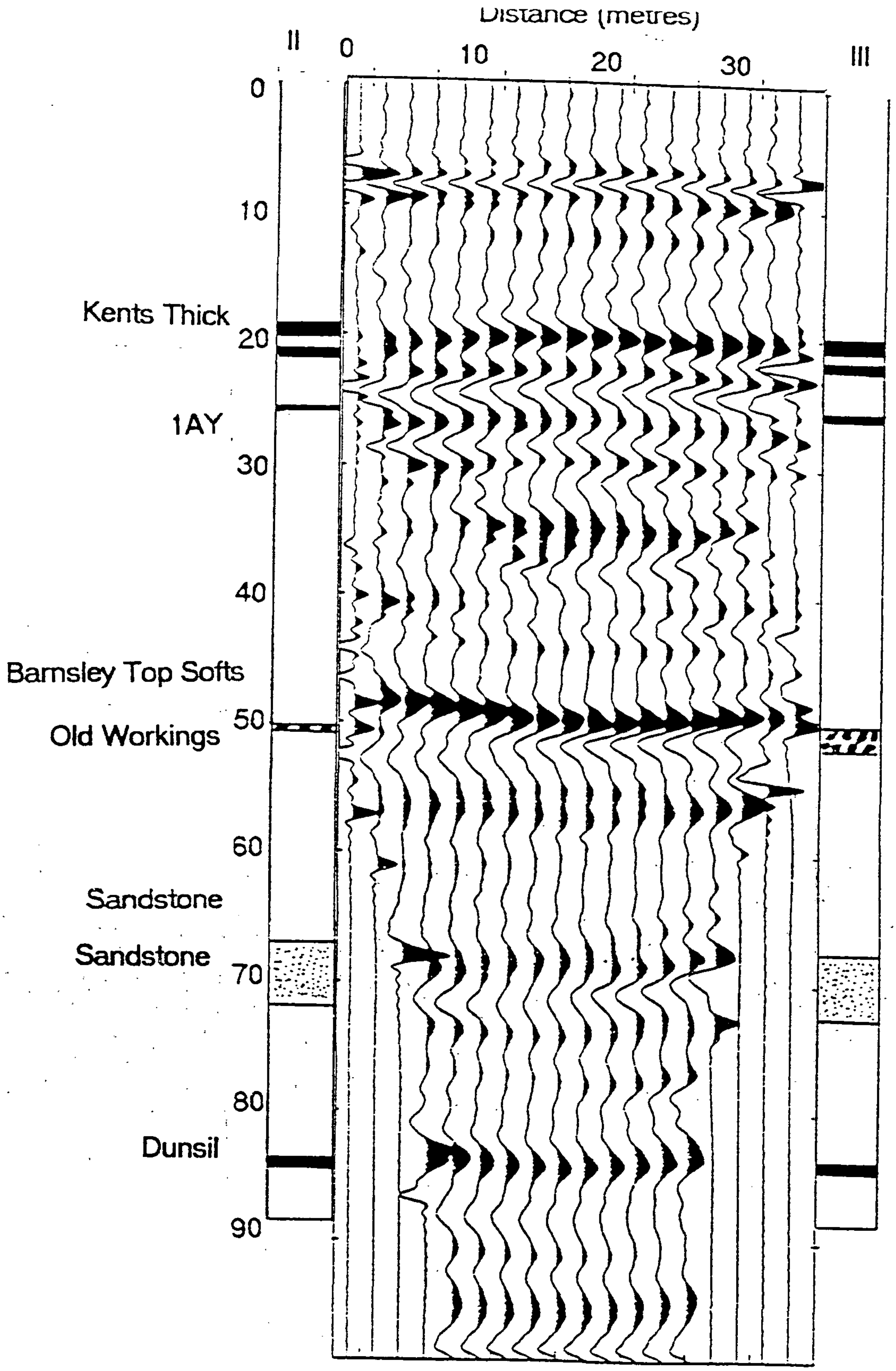


Figure 5.7 Depth section produced by combining Generalised Kirchhoff migrated sections of the upgoing and downgoing reflections for survey C.

Depth range (metres)	Migration interval velocity (metres/sec)
0-10	1200
10-22	2400
22-40	2600
40-100	2700

Table 5.5 Migration velocity field used for survey C

The depth migrated section produced by combining the sections produced from the upgoing and downgoing wavefields from this survey are shown in figure 5.7. Again an AGC of length 25 metres has been applied in the vertical direction. The section is very similar to that produced for survey B (figure 5.5c) with clear reflections from the principal coal seams. The seams appear to be of a flat and continuous nature.

5.3.3 Survey D; wider-spaced cross-hole reflection survey

A further survey was acquired between boreholes I and III (at a separation of 78.0m) for comparison purposes with surveys B and C and also in the expectation of imaging the strata near borehole II, where the image quality is very poor for surveys B and C. When the fieldwork was carried out it was found that borehole I had collapsed still further since survey B and was blocked at a depth of 52m. The borehole collapse was probably aggravated by the detonation of the source charges for survey B in this borehole. A larger charge size (25g of dynamite) was used to improve the signal-to-noise ratio because of the greater borehole spacing in this

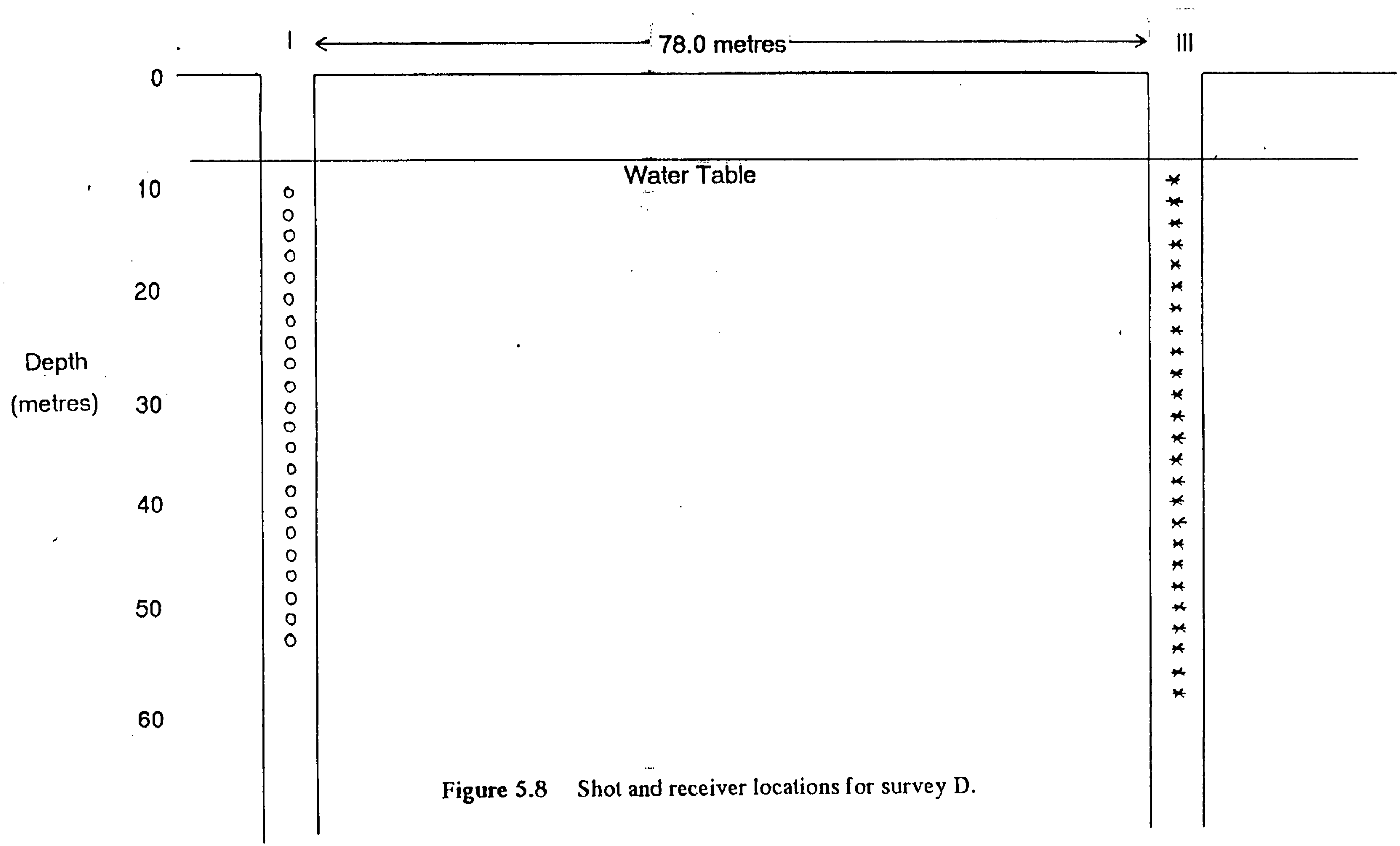


Figure 5.8 Shot and receiver locations for survey D.

survey. The data were processed as discussed in chapter III and the imaging was once more carried out by means of the Generalised Kirchhoff method with a dip aperture of +/-22.5°. The interval velocities used in the migration are listed in table 5.6.

Depth range (metres)	Migration interval velocity (metres/sec)
0-10	1200
10-22	2400
22-50	2700
50-54	2500
54-100	2800

Table 5.6 Migration velocity field used for survey D

The combined upgoing and downgoing reflection sections are presented in figure 5.9. An AGC of length 25 metres has been applied to balance out the variations in signal amplitude down the section. The section possesses some similarities to the previous two surveys. In particular, the reflection from the old mineworkings at around 50m depth has a comparable character. The reflections from the shallower seams whose true depth is around 20m have been imaged shallower, presumably because the velocity field was too large for the migration of the downgoing wavefield. The quality of this image is generally much poorer than that obtained in surveys B and C. This illustrates that there is a maximum limit to the borehole spacing which can be used successfully for a given range of depths of the source and receiver positions.

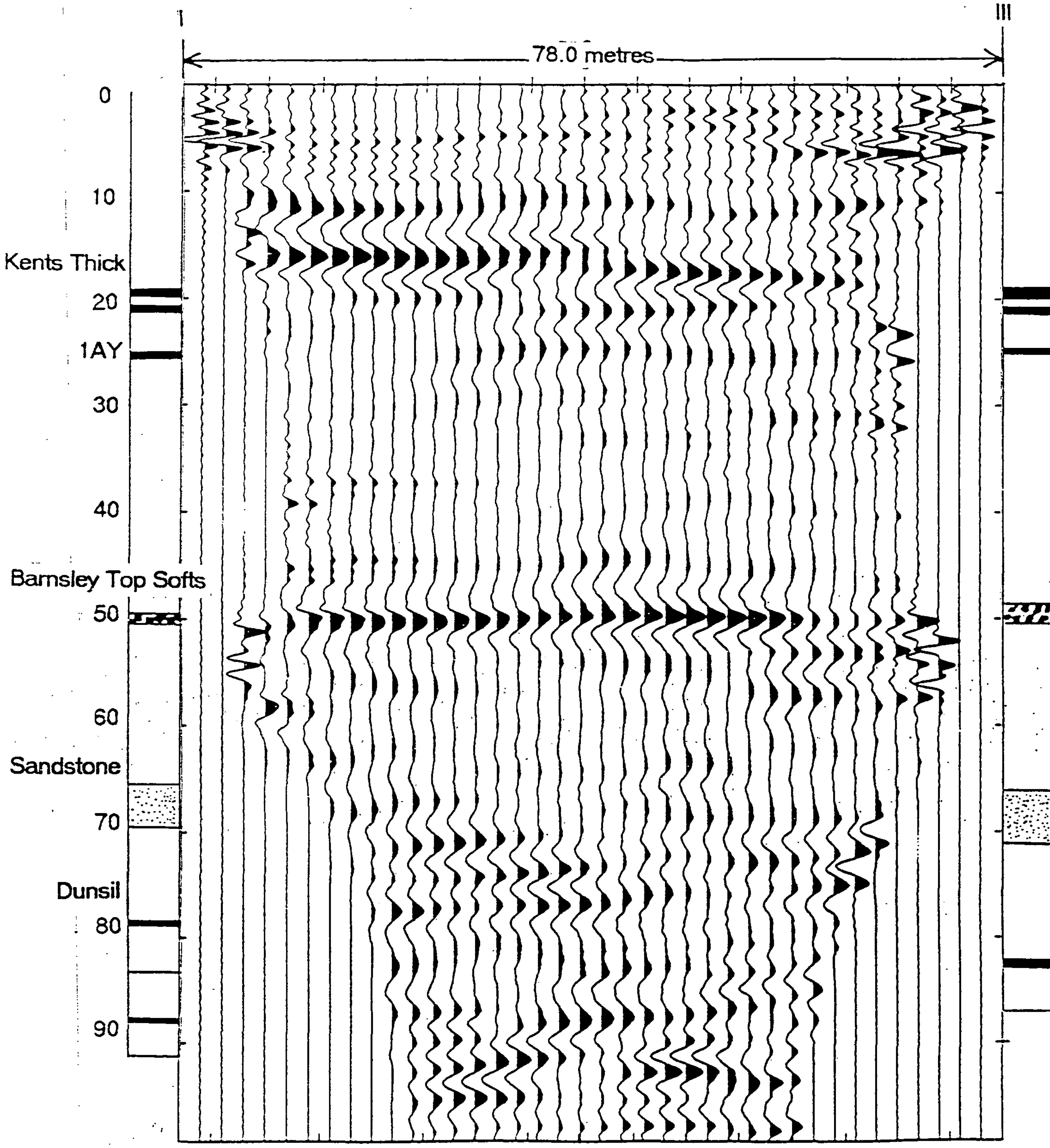


Figure 5.9 Depth section produced by combining Generalised Kirchhoff migrated sections of the upgoing and downgoing reflections for survey D.

The deterioration in the image quality is a consequence of the reflection raypaths becoming more horizontal as the borehole separation increases. This results in a problem in that a very accurate velocity model specification is needed to reduce positioning (and hence stack contribution) errors to an acceptable level (see section 3.7). The processing of shallow dipping reflections is also made more difficult because of the problems in separating the reflected energy from the direct arrivals when the travel times and moveouts are very similar.

5.3.4 Survey E; cross-hole survey through major fault zone

Another survey was carried out at the Lowther South exploration site between boreholes IV and V in a field adjacent to boreholes I, II and III. The boreholes were 32.0m apart, located in the zone of the Methley-Saville fault and the line of the boreholes was approximately perpendicular to the strike of the fault. The principal seam depths taken from the stratigraphic logs are indicated in table 5.7.

Seam	**Hole IV Depth to base (metres)**	**Hole V Depth to base (metres)**	**Thickness (metres)IV/V**
Kents Thick	13.4	22.36	1.4/2.4
1AY	ABSENT	27.84	- /0.2
Barnsley Top Softs	28.46	53.32	0.86/1.2
Dunsil	59.26	84.11	0.7/0.5

Table 5.7 Principal seams in boreholes IV and V

Shots were fired in borehole IV at 21 locations at 2m intervals in the depth range 10-50m. Electrical detonators were used as a source. 23 hydrophone positions were used in borehole V at depths between 9.79m and 53.79m. The shot and receiver locations and summary stratigraphic logs are depicted in figure 5.10.

The data were processed as described in chapter III and imaged by means of the G-K migration method with a migration dip aperture of +/-22.5°. The migration interval velocities are described in table 5.8.

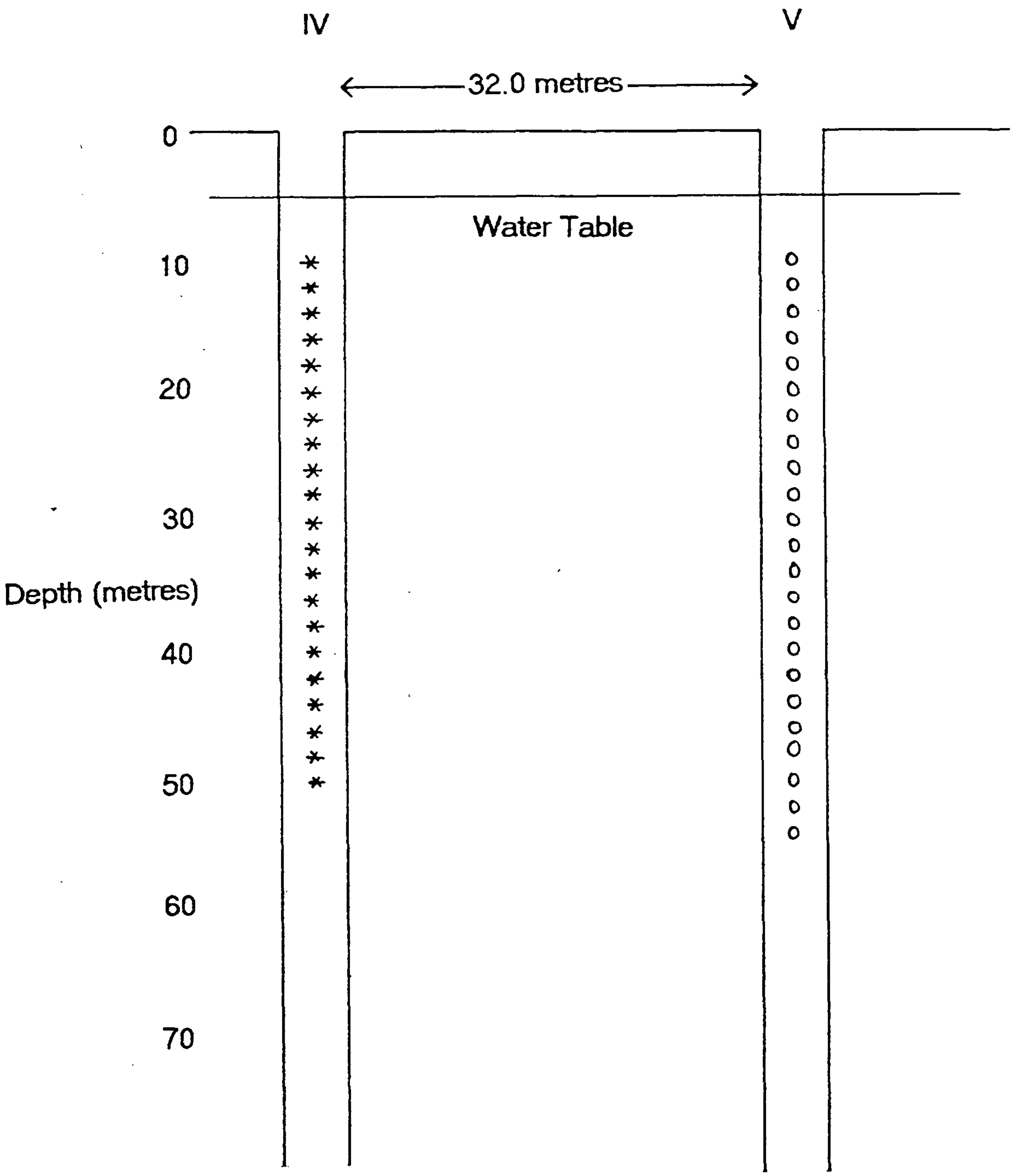


Figure 5.10 Shot and receiver locations for survey E.

Depth range (metres)	Migration interval velocity (metres/sec)
0-10	1200
10-20	2200
20-24	2250
24-40	2330
40-46	2210
46-90	2400

Table 5.8 Migration velocity field used for survey E

The combination of the migrations of the upgoing and downgoing wavefields is presented in figure 5.11. The quality of the section is good with clear reflections from the coal seams on the downthrown (right) side of the fault and from the Dunsil seam (around 60m) on the upthrown side. Errors in seam depths are a result of inaccuracies in the migration velocity model.

Interpretation of the borehole logs suggested that the fault intersects borehole IV between the Kents Thick and Barnsley Top Softs seams. It was not known whether the difference in levels of the Kents Thick seam (~7 metres) between the two boreholes was due to dipping strata or a small fault. The cross-hole seismic survey removes this ambiguity since the reflection from the Kents Thick seam is near-horizontal across the section. Therefore a small fault with a throw of 7 metres must intersect the Kents thick seam close to borehole IV where the image quality of the seismic section is poor. The location of the larger fault is clearly defined by the

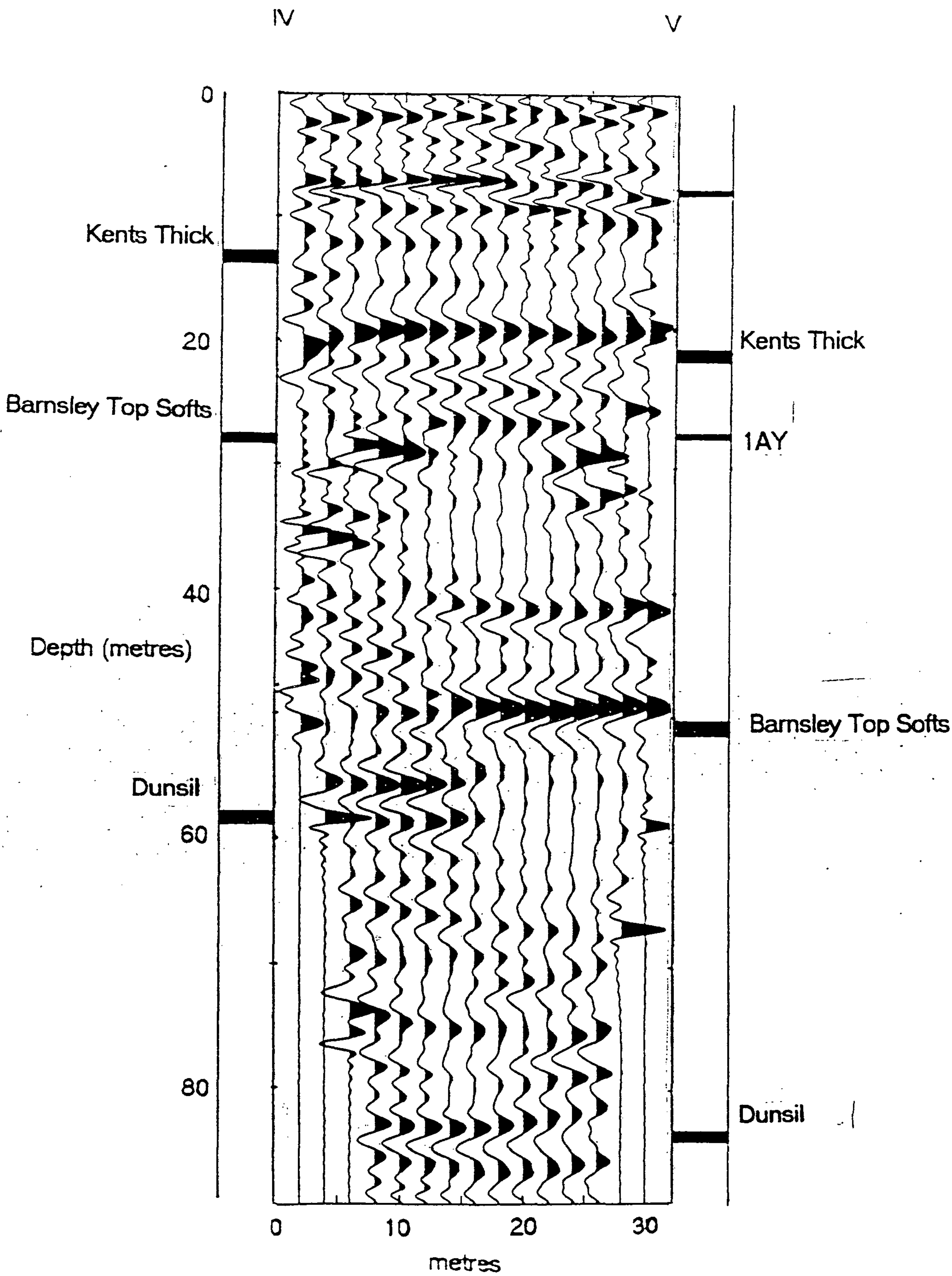


Figure 5.11 Migrated depth section with combined upgoing and downgoing reflections for survey E acquired at Lowther South.

truncations of reflections from the Barnsley Top Softs seam to the right and from the Dunsil seam to the left at the fault zone.

5.4 Lostrigg, Cumbria

The results of a further survey acquired at a British Coal opencast exploration site at Lostrigg in Cumbria are presented.

5.4.1 Survey F; old mineworkings

The target of this survey was the edge of a longwall panel in the Sixquarters seam. The boreholes (A and B) used were separated by 48.4m at the surface. The principal coal seams logged for the two boreholes are listed in table 5.9. The Sixquarters seam was worked in borehole A, but solid in borehole B. It was thought that the extent of the old mineworkings might be delimited by a small fault.

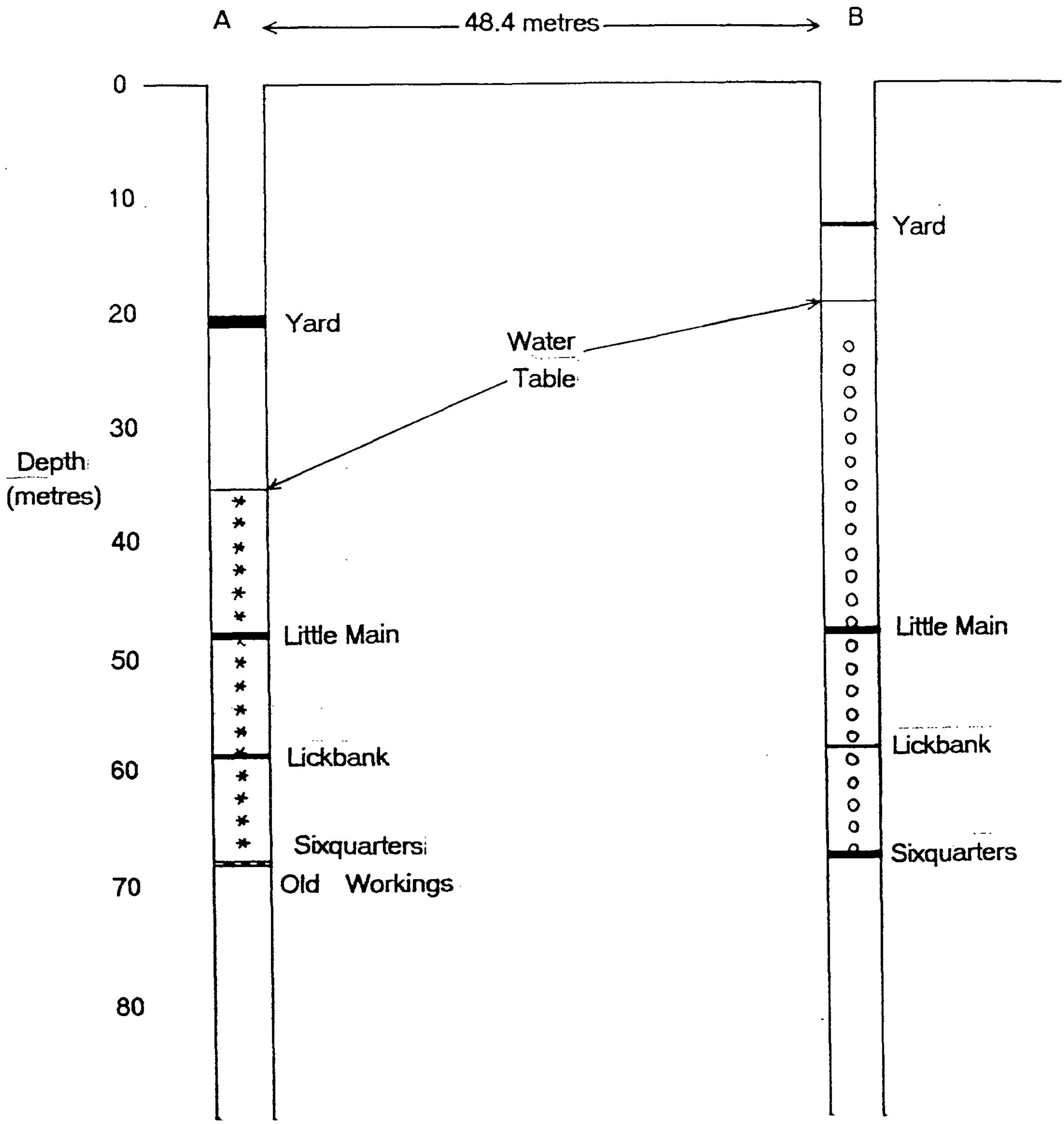


Figure 5.12 Shot and receiver locations and principal coal seams for survey F.

Seam	Hole A Depth to base (metres)	Hole B Depth to base (metres)	Thickness (metres)A/B
Yard	21.20	12.68	1.0/0.3
Lower Yard	21.42	20.87	0.1/0.2
Top Half Yard	34.41	33.40	0.2/0.2
Btm Half Yard	36.26	absent	0.2/ --
Little Main	48.21	48.06	0.6/0.6
Eighteen Inch	52.99	51.33	0.2/0.2
Lickbank	58.58	57.99	0.4/0.4
Sixquarters	68.12	67.75	0.3*/0.5

* Seam worked with some coal present

Table 5.9 Principal seams in boreholes A and B

There were several acquisition problems with this survey. Both boreholes were blocked at the level of the Sixquarters seam and the water tables were at quite different levels in the two boreholes (35m in borehole A and 19m in borehole B). There were also large amounts of tube wave noise generated on most of the shot records and this was difficult to remove successfully.

Altogether 16 shot positions were used in the survey at 2m depth intervals in borehole A ranging from 36m-66m. The hydrophones were positioned at 23 positions at 2m intervals in borehole B ranging from 22.7m-66.7m. The shot positions and principal coal seams are shown in figure 5.12. The data were imaged using the G-K

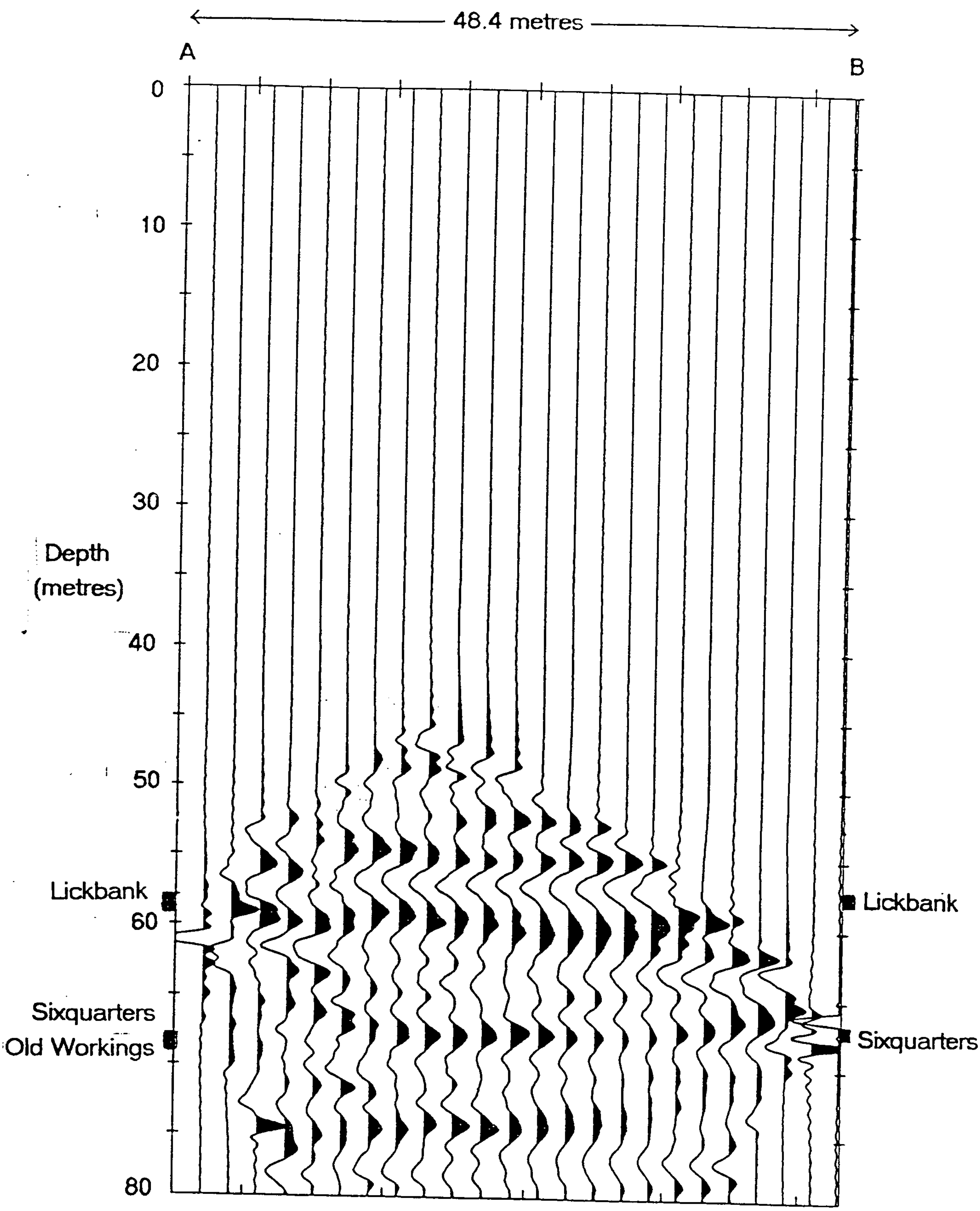


Figure 5.13 Depth section of survey F produced by Generalised Kirchhoff migration of the upgoing reflections.

migration method with a dip aperture of +/-25°. The migration velocity field is shown in table 5.10.

Depth range (metres)	Migration interval velocity (metres/sec)
0-20	1580
20-36	2470
36-80	3000

Table 5.10 Migration velocity field used for survey F

The migrated upgoing wavefield is shown in figure 5.13. The results are disappointing, but not surprising given the problems of reduced shot position coverage, probable significant lateral velocity variations produced by the variation in the water table, and the tube wave noise. A strong reflection is visible from the Lickbank seam, but the quality of the section is too poor to determine whether the old mineworkings were indeed terminated by a small fault.

Chapter VI

A comparison of different migration operators for cross-hole seismic data

6.1 Introduction

A comparison of the effectiveness of different migration techniques for cross-hole data is discussed in this chapter. The migration operators of a variety of techniques were considered: Finite difference migration in the (x,z,t) domain, diffraction stack summation, Kirchhoff migration, Generalised Kirchhoff (GK) Migration and Generalised Radon Transform (GRT) migration.

6.2 Migration operators

The migration operators for the various techniques are presented in figures 6.1-6.5. The operators were calculated assuming a single source-receiver pairing in a homogeneous, isotropic medium. The source and receiver were both located at a depth of 20 metres with an offset of 40 metres. The velocity field was assumed to be 3000m/s and a band-limited spike with a travel time of 20 ms was used as input to a single trace migration operation. In all cases a regular grid with sampling at 0.5m intervals in the x and z directions was employed and the source and receiver were assumed to be elements in vertical source and receiver arrays.

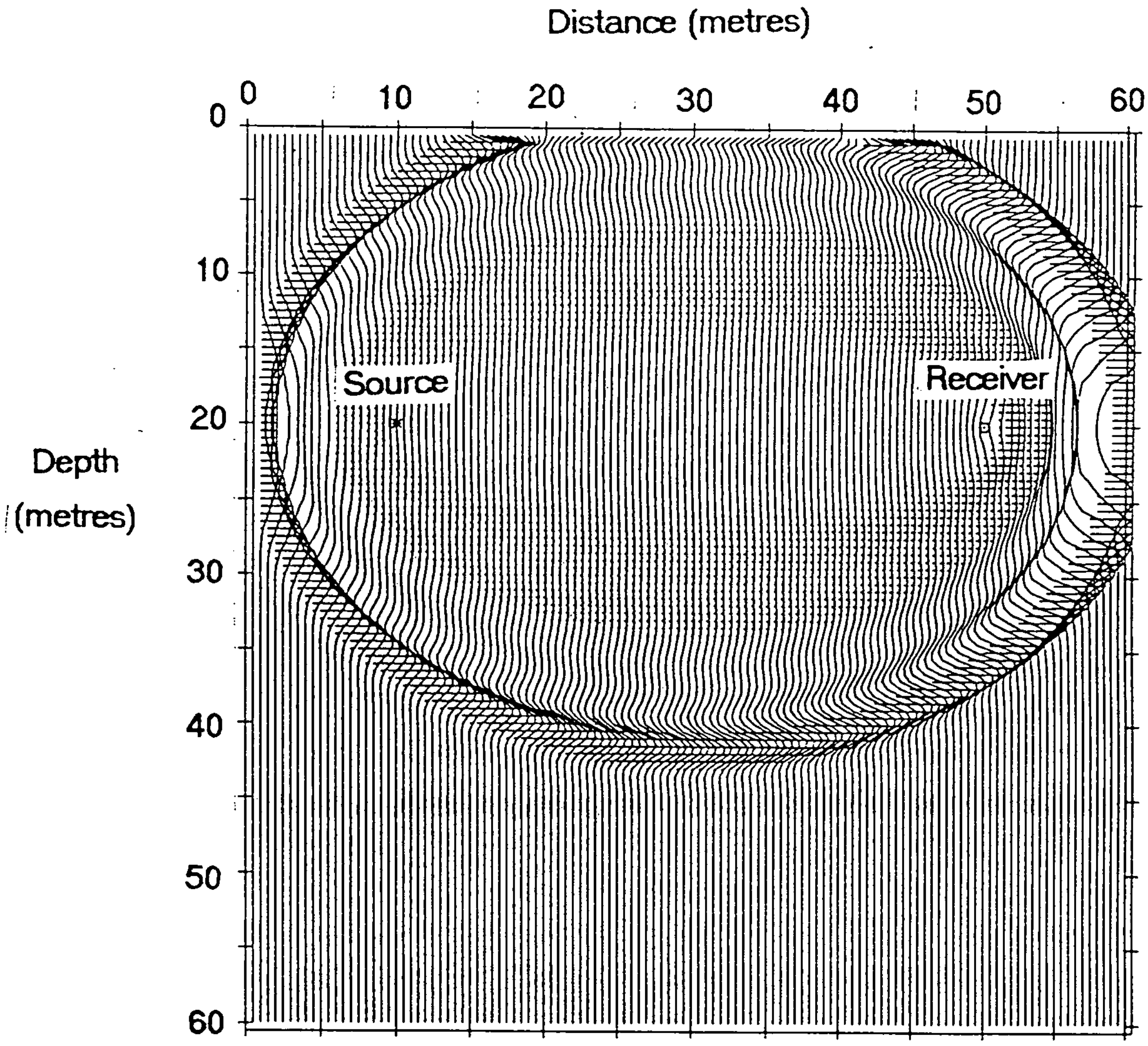


Figure 6.1 Finite-difference migration operator in a homogeneous, isotropic velocity field.

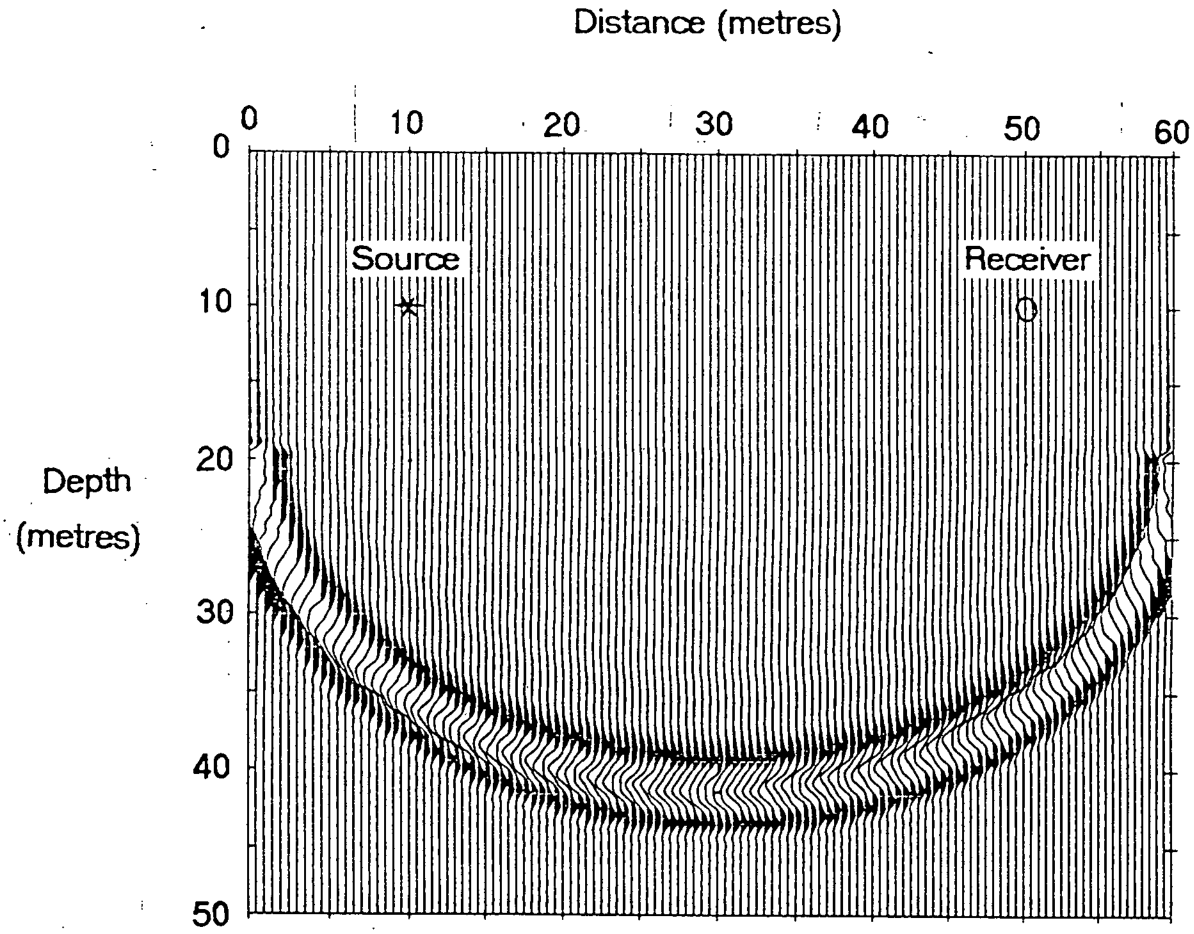


Figure 6.2 Diffraction stack migration operator in a homogeneous, isotropic velocity field.

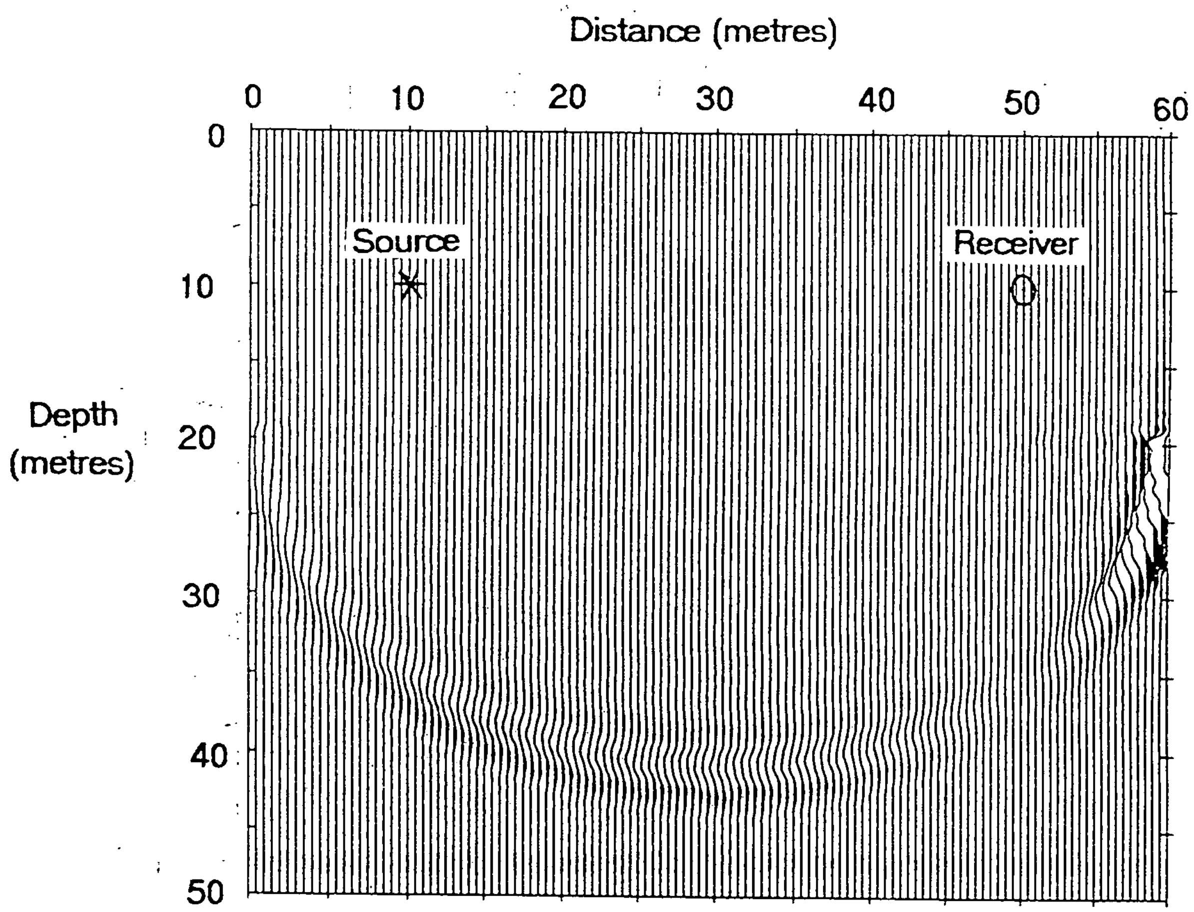


Figure 6.3 Kirchhoff migration operator in a homogeneous, isotropic velocity field.

The finite difference migration is shown in figure 6.1. Absorbing boundary conditions were used at the grid edges. The impulse response is an ellipse with the source and receiver at the focal points and is symmetrical with respect to the source and receiver. This ellipse may be thought of as the locus of possible locations for a diffracting point to produce an arrival corresponding to the input spike at 20 ms. Reverberations within the ellipse are caused by grid dispersion effects (see chapter IV). The finite difference method does not implicitly differentiate between upgoing and downgoing events and so a complete ellipse has been generated.

The result of diffraction stack migration (i.e. without an amplitude and phase correction) is shown in figure 6.2. Again, the impulse response is an ellipse (in this case a half-ellipse as only upgoing wavefields have been considered by the operator) and it is also symmetrical with respect to exchange of the source and receiver. There are fewer reverberations than were obtained by the finite-difference method, although the wavelet of the ellipse is less smooth.

The Kirchhoff migration operator is shown in figure 6.3. In this case the Newman phase and amplitude correction has been applied, but the ellipse is not symmetrical to the exchange of source and receiver positions because of a term proportional to $\sqrt{\frac{R_s}{R_r}}$ (see equation 4.10 of chapter IV) which magnifies the reflectivity near the receiver position.

The Generalised Kirchhoff migration operator is shown in figure 6.4. This operator is similar to the Kirchhoff operator but is symmetrical to the exchange of source and receiver positions because it contains the term $\sqrt{\frac{R_s}{R_r}}$ for integration over the receiver array as well as the term $\sqrt{\frac{R_r}{R_s}}$ for integration over the source array

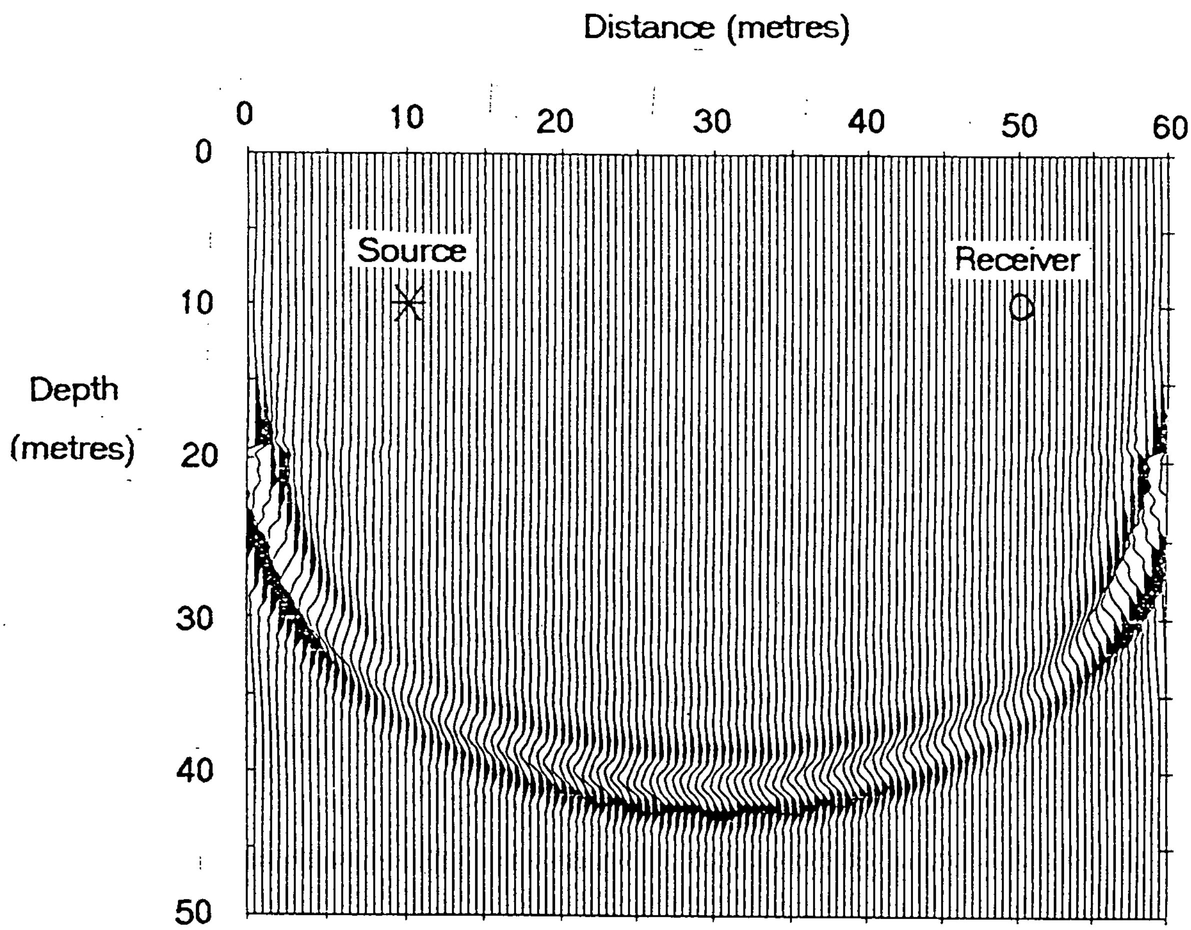


Figure 6.4 Generalised Kirchhoff migration operator in a homogeneous, isotropic velocity field.

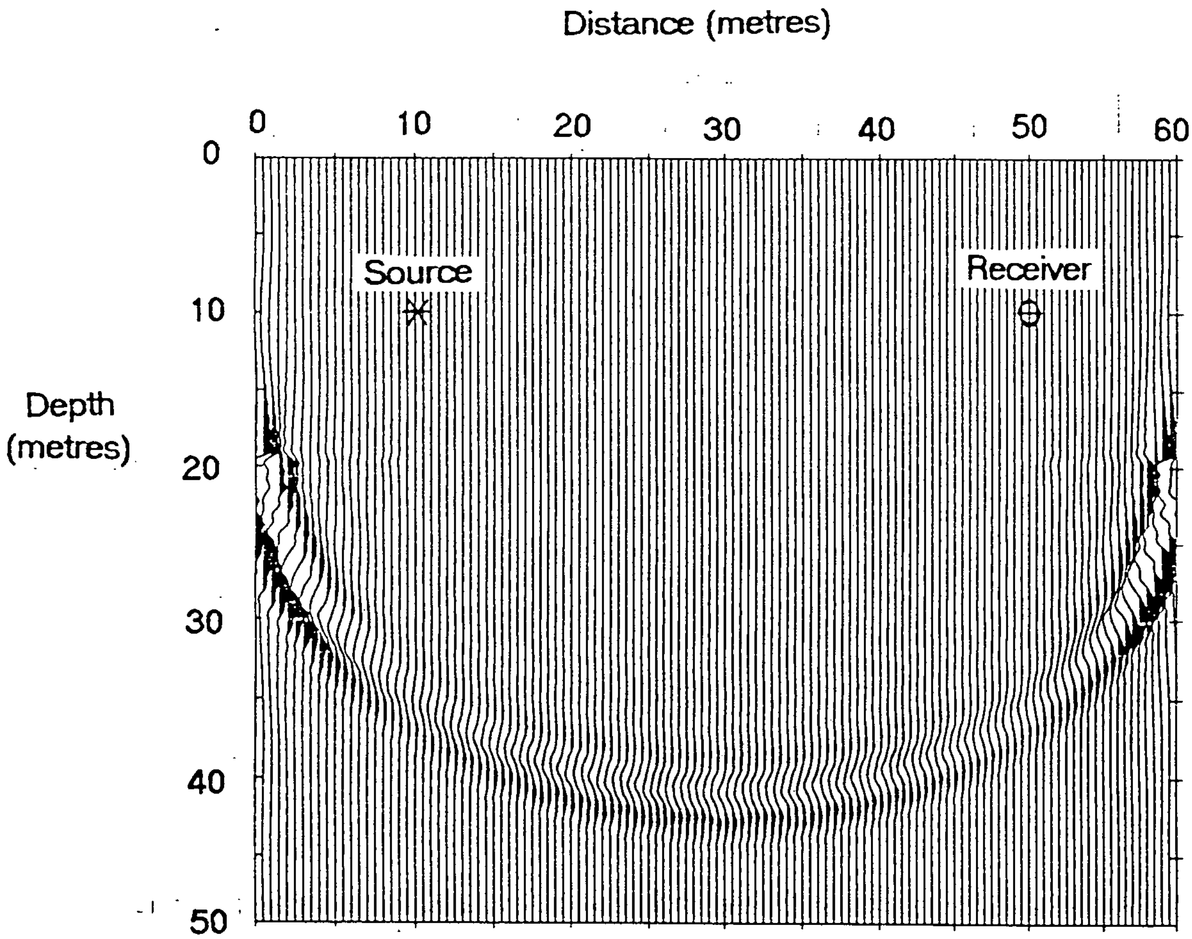


Figure 6.5 Generalised Radon Transform migration operator in a homogeneous, isotropic velocity field.

(see equation 4.11 of chapter IV). The high amplitudes to the left of the source and to the right of the receiver may be removed by a migration dip aperture taper in areas where the geology is known to be reasonably horizontal.

The Generalised Radon Transform (GRT) migration operator (Miller et al., 1987) is shown in figure 6.5. The integral is similar to that of the G-K operator but includes an additional term which depends on the scattering angle ϕ between the source and receiver raypaths at the scattering point. The term is proportional to $\cos^2 \frac{\phi}{2}$ which results in an almost constant amplitude in the part of the ellipse which lies between the source and the receiver. Again there are high reflectivities for the steeply dipping events beyond the source and receiver positions.

6.2.1 Suitability of impulse response functions for cross-hole data

Clearly the Kirchhoff migration method is unsuitable for the migration of cross-hole data due to the large variations in reflectivity produced between the source and receiver boreholes. The finite difference method is very slow and results in reverberations caused by grid dispersion effects. The diffraction stack operator does not include the theoretically correct amplitude and phase corrections provided by Kirchhoff migration. There is little to choose between the G-K and GRT migration operators. Both produce near-uniform reflectivities in the region of interest between the source and the receiver. In this work the G-K migration operator was used along with suitable controls for the dip aperture to enhance reflections from shallow-dipping strata.

Chapter VII

Conclusions and suggestions for future work

A field method for acquiring cross-hole seismic reflection data in shallow strata has been developed. The technique as it stands allows two or three cross-hole surveys to be acquired by a field crew of two or three personnel in one day. Further improvements in acquisition rates may be obtained by the use of a borehole sparker or piezoelectric source instead of a dynamite source.

Cross-hole direct arrival data may be processed using tomographic imaging software as a supplement to the cross-hole reflection method. The velocity field obtained by a tomographic survey, whilst not being successful at imaging faults or old mineworkings between boreholes (Kragh, 1990), is useful in providing a starting model for migration of the cross-hole seismic reflection data.

The cross-hole reflection method provides high-resolution seismic reflection sections of shallow Coal Measures strata. The processing of several trial surveys acquired at British Coal Opencast's exploration sites in the north of England has shown that wavelengths less than 4m are typical for these surveys with recorded reflection data frequencies lying in the bandwidth 100-500 Hz. The most pronounced reflections come from the coal seams.

It is envisaged that, for a practical exploration technique, the cross-hole reflection method should be used in conjunction with hole-to-surface surveys (Kragh, 1990). The zones of reflector coverage of the two types of survey are complementary (see figure 7.1). The cross-hole method provides better imaging in the region

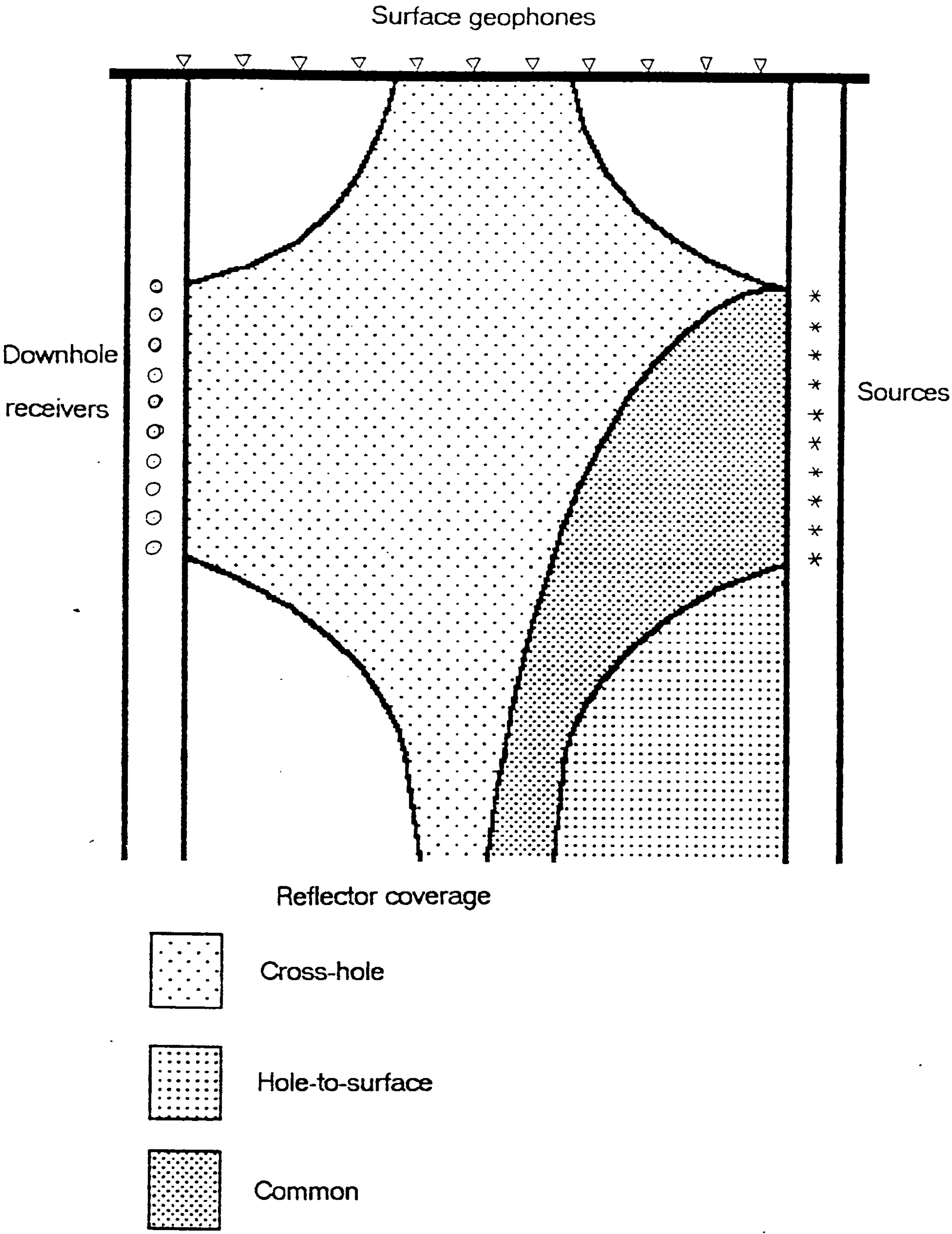


Figure 7.1 Zones of coverage of cross-hole and hole-to-surface reflection surveys with the shallowest source and down-hole receivers located near the water table.

between the boreholes, but the image quality deteriorates towards the boreholes. The hole-to-surface method provides lower resolution sections (wavelengths are around double that of the cross-hole method) but better imaging near the boreholes. The cross-hole image quality nearer the boreholes should be improved by the inclusion of a near-field correction term to the Kirchhoff integral (Dillon, 1988).

Possible uses of the cross-hole reflection method include the detailed imaging of regions of particular interest such as small-scale faulting at reservoir depths where borehole logging, conventional seismic and VSP methods cannot provide sufficient resolution. It should also be possible to acquire data from surveys beneath obstructions such as buildings, roads and water courses where surface sources and receivers cannot be used.

In addition to imaging "conventional" upgoing reflections, the cross-hole method also gives reflector coverage above the top source and receiver positions. An important characteristic of the cross-hole method is that the frequency content of the data is not effected by the depth of the region of interest as is the case with surface surveys and VSPs, but rather by the separation of the boreholes and therefore we might expect images of deeper strata to be every bit as good as those of the shallow strata included in this work. In fact the greater compaction of rocks at depth should result in better quality data.

Further important development work could include the use of elastic imaging by means of a downhole three-component geophone string. The 24-channel seismograph in use at Durham University would allow a string of eight such geophone units to be employed. This would necessitate further software development in order to implement elastic wave Generalised Kirchhoff migration. The consequential increase in computing costs would be offset by an improvement in imaging, particularly as tube wave arrivals and other noise events should be more easily suppressed. Beattie's (1990) comparative study showed that tube waves are a bigger problem for geophones than for hydrophones. However, this might be overcome by modifying the geophone design. Also, with a string of downhole geophones, the top and bottom geophones might act as baffles, thus reducing the amplitudes of tube waves on the other geophones.

Borehole blockages restrict the coverage of sources and receivers, especially in those areas of particular interest where small faults and old mineworkings exist. This problem may best be solved by the use of a plastic casing along the full length of the borehole. Plastic is most suitable for ease of use and because the casing must be expendable since there is a high probability that the casing will become stuck in the borehole. However, it is also essential that the tubing is of sufficient strength to withstand borehole collapses and explosions from small seismic sources and also flexible enough to follow the curvature of the borehole.

The restriction in source and receiver coverage imposed by the depth of the water table might be removed by the development of a borehole "packer" which could block the borehole at a shallow depth and allow water to be poured in to fill the borehole.

Finally, more test surveys will be needed to evaluate the above suggestions and, in particular to obtain images of old mineworkings and small faults.

References

Alford R.M., Kelly K.R., and Boore D.M. "Accuracy of finite-difference modeling of the acoustic wave equation." *Geophysics 39,834-842,* 1974.

Balch A.H., Lee M.W., Miller J.J. and Ryder R.T. "The use of vertical seismic profiles in seismic investigations of the earth." *Geophysics 47, 906-918,* 1982.

Balch A.H., Chang H., Hofland G. and Ranzinger K. "The use of forward and back-scattered P-, S- and converted waves in cross-borehole imaging." Presented at the 52nd Annual Meeting of the EAEG, Copenhagen, 1990.

Beattie K.E. "A comparison of receiver types in crosshole seismics." *M.Sc. thesis, University of Durham,* 1990.

Bishop I. and Styles P. "Seismic tomographic imaging of a buried concrete target." *Geophysical Prospecting 38, pp169-188,* 1990.

Brabham P.J. "The application of seismic surveys to the evaluation of shallow coal deposits." *Ph.D. Thesis, University of Durham,* 1986.

Bredewout J.W. and Goulty N.R. "Some shallow seismic reflections." *First Break 4(12) pp15-23,* 1986.

Buchanan D.J. "In-seam seismology: A method for detecting faults in coal seams." *Developments in Geophysical Exploration Methods-5 Chapter 1, Editor A.A. Fitch, Applied Science Publishers,*pp 1-34, 1983.

Chang and McMechan, "Reverse-time migration of offset vertical seismic profiling data using the excitation-time imaging condition." *Geophysics 51, pp67-84,* 1986.

Christie P.A.F., Hughes V.J. and Kennett B.L.N. "Velocity filtering of seismic reflection data." *First Break 1(3) pp9-21*, 1983.

Claerbout J.F. "Towards a unified theory of reflector mapping." *Geophysics 36 pp467-481*, 1971

Claerbout J.F. "Fundamentals of Geophysical Data Processing: with Applications to Petroleum Prospecting." *McGraw-Hill*, 1976.

Clayton R. and Engquist B. "Absorbing boundary conditions for acoustic and elastic wave equations." *Bulletin of the Seismological Society of America, 67, 1529-1540*, 1977.

Cooley J.W. and Tukey J.W. "An algorithm for the macine calculation of complex Fourier series." *Maths computations 19, pp297-301*, 1965.

Cottin J.-F., Deletie P., Jacquet-Francillon H., Lakshmanan J., Lemoine Y., Sanchez M. "Curved ray seismic tomography: application to the Grand Etang Dam (Reunion Island)." *First Break 4(7), 25-30*, 1986.

Devaney A.J. "Geophysical diffraction tomography." *IEEE Transactions on Geoscience and Remote Sensing GE-22, 3-13*, 1984.

Dillon P.B. "Vertical seismic profile migration using the Kirchhoff integral." *Geophysics 53, 786-799, 1988.*

Dillon P.B. "A comparison between Kirchhoff and GRT migration on VSP data." *Geophysical prospecting 38, 757-777*, 1990.

Dillon P.B. and Thomson R.C. "Offset source VSP surveys and their image reconstruction." *Geophysical Prospecting 32, 790-811*, 1984.

Dines K.A. and Lytle R.J. "Computerised Geophysical Tomography." *Proceedings of the IEEE 67,7*, July 1979.

Dyer B.C. "Seismic reflection and transmission tomography." *Ph.D. dissertation, University of London,* 1988

Embree P., Burg J.P. and Backus M.M. "Wide-band velocity filtering - The pie-slice process." *Geophysics 28 ,948-974*, 1963.

Findlay M.J. "A curved ray iterative technique for tomographic inversion of cross-borehole data." *M.Sc. Thesis, University of Durham*, 1987.

French W.S. "Computer migration of oblique seismic reflection profiles." *Geophysics 40, 961-980*, 1975.

Goulty N.R., Thatcher J.S., Findlay M.J., Kragh J.E. and Jackson P.D. "Experimental investigation of crosshole seismic techniques for shallow coal exploration." *Quarterly Journal of Engineering Geology 23, 217-228*, 1990.

Hardage B.A. "Vertical Seismic Profiling part A: Principles." *Geophysical Press*, 1983.

Howson M. and Sides E.J. "Borehole desurvey calculation." *Computers and Geosciences 12 ,97-104*, 1986.

Hu L.-Z., McMechan G.A. and Harris J.M. "Acoustic prestack migration of cross-hole data." *Geophysics 53, 1015-1023*, 1988.

Jackson P. "Horizontal seismic in coal seams: its use in the UK coal industry." *First Break 3(11), 15-24*, 1985.

Jackson P.J., Onions K.R. and Westerman A.J. "Use of inverted VSP to enhance the exploration value of boreholes." *First Break 7, 233-246*, 1989.

Justice J.H., Vassilou A.A., Singh S., Logel J.D., Hansen P.A., Hall B.R., Hutt P.R. and Solanki J.J. "Acoustic tomography for monitoring enhanced oil recovery." *The Leading Edge 8(2), 12-19*, 1989.

Kohler K. and Koenig M. "Reconstruction of reflecting structures from vertical seismic profiles with a moving source." *Geophysics 51, 1923-1938*, 1986.

Kragh J.E. "Borehole seismic methods for opencast coal exploration." *Ph.D. Thesis, University of Durham*, 1990.

Lee W.H.K and Stewart S.W. Principles and applications of microearthquake networks. *Pub. Academic Press Inc.*, 1981.

Levin F.K. "The reflection, refraction, and diffraction of waves in media with an elliptical velocity dependence." *Geophysics 43, 528-537*, 1978.

McMechan G.A. "Synthetic finite-offset vertical seismic profiles for laterally varying media." *Geophysics 50, 627-636*, 1985.

Macrides C.G., Kanasewich E.R. and Bharatha S. "Multiborehole seismic imaging in steam injection heavy oil recovery projects." *Geophysics 53, 65-75*, 1988.

March D.W. and Bailey A.D. "A review of the two-dimensional transform and its use in signal processing." *First Break 1(1), 9-21*, 1983.

Miller D., Oristaglio M., and Beylkin G. "A new slant on seismic imaging: migration and integral geometry." *Geophysics 52, 943-964*, 1987.

Mitchell A.R. Computational methods in partial differential equations. Pub. John Wiley and Sons, Inc., 1969.

Pratt R.G. and Goulty N.R. "Combining wave equation imaging with traveltime tomography to form high resolution images from crosshole data." *Geophysics 56, 208-224,* 1991.

Pratt R.G. and Worthington M.H. "The application of diffraction tomography to cross-hole seismic data." *Geophysics 53, 1284-1294*, 1988.

Renaut R.A. and Petersen J. "Stability of wide-angle absorbing boundary conditions for the wave equation." *Geophysics 54, 1153-1163*, 1989.

Robinson E.A.and Treitel S., Geophysical Signal Analysis, *Prentice-Hall, New Jersey*, 1985.

Schneider W.A. "Integral formulation for migration in two and three dimensions." *Geophysics 43(1), 49-76,* 1978.

Schoenberg M. "Fluid and solid motion in the neighbourhood of a fluid-filled borehole due to the passage of a low-frequency elastic plane wave." *Geophysics 51, 1191-1205*, 1986.

Stewart R.R. "VSP interval velocities from traveltime inversion." *Geophysical Prospecting 32, 608-628*, 1984.

Sun R. and McMechan G.A. "Pre-stack reverse-time migration for elastic waves with application to synthetic offset vertical seismic profiles" *Proc. IEEE, 74, 457-465*, 1986.

Suprajitno M. and Greenhalgh S.A. "Separation of upgoing and downgoing waves in vertical seismic profiling by contour slice filtering." *Geophysics 50, 950-962*, 1985.

Van der Poel N.J. and Cassell B.R. "Borehole seismic surveys for fault delineation in the Dutch North Sea." *Geophysics, 54, 1091-1100,* 1989.

Worthington M.H. "An introduction to geophysical tomography." *First Break 2(11), 20-25*, 1984.

Wye R. "An investigation into the accuracy of algebraic reconstruction techniques for tomographic inversion." *M.Sc. Thesis, University of Durham*, 1986.

Zhu X. and McMechan G.A. "Acoustic modeling and migration of stacked cross-hole data" *Geophysics 53, 492-500*, 1988.

Ziolkowski A.M. "Seismic profiling for coal on land." in Developments in Geophysical Exploration Methods edited by A.A.Fitch vol.1, *Applied Science Publishers Ltd., London,* 1979.

Ziolkowski A.M., Lerwill W.E., March D.W. and Peardon L.G. "Wavelet deconvolution using a source scaling law." *Geophysical Prospecting 28, 872-901,* 1980.

Appendix A

Computer software

A number of computer programs were written during the course of this research. These include software for data-processing, migration and plotting.

The programs are all written in IBM-Fortran77 to run on the University of Durham Amdahl 470/V8 mainframe computer. Program listings are included in the following pages of this appendix. External subroutines used include the Culham Laboratory GHOST*80 graphical subroutine library as well as a library of time series analysis subroutines (TSAR4_L in user-identifier GLK4) taken from a variety of different sources. Michigan Terminal System (MTS) routines are used for handling data stored on magnetic tape.

Appendix A.1

Data processing software

The data processing program is menu driven with a main menu providing access to a series of submenus which carry out operations such as data input/output, data plotting, Fourier transforms, filtering, 2D Fourier transforms, waveshaping deconvolution, first break picking and direct arrival muting. Data may be plotted interactively on screen or sent to plotfiles.

```
      PROGRAM XHR1
C
C  Written by M J Findlay  1987-1990
C
C. Reads seismic data from tape or disc in variety of formats
C  Dataprocessing software all Menu driven
C  Uses subroutine libraries
C          TSAR4_L (Time series analysis -- Robinson, Claerbout et al.)
C          XHR_LIB (Dataprocessing, display and file I/O -- Findlay)
C          *ghost80 (graphics library)
C          *nag (graphics and other routines)
C  Requires defaults file XHR.DFAULT to be attached to unit0 at runtime.
C
C
      PARAMETER (NSAMR=2048,NCHR=65)
      CHARACTER ANSWR*1, OPFORM*6, IPDISC*17, OPDISC*17
      CHARACTER IPSOUR*4, INPOPT*3, TITOFF*3, CHNSPL*26, POLART*7,
     1          VARARE*3
      CHARACTER*20 LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC,
     1              COMSHT
      CHARACTER*20 FILREC, A(9)
      CHARACTER*25 PROC(20)
      CHARACTER TITLE*30, XLB*30, YLB*30, FILTAP*9, BLHPAS*9
      INTEGER INPCHN, NSHOT, LEN, NFILES, NFILE(2), NRECS, NCR(2)
      INTEGER NFIRST(NCHR), IDPROC(5,NCHR), NPLFST, NPLLST, IOPT, NPROCS
      REAL SORPOS, RECDEP(NCHR), DT, R4DAT(NSAMR,NCHR), DBGAIN(NCHR)
      REAL GCMSCL(NCHR), FLOWCT, FHICUT, FLOOFF, FHIOFF, DBLOW, DBHIGH
      INTEGER LEDGE, LENFIL
      EQUIVALENCE (LOCATE,A(1)), (DATE,A(2)), (DEVICE,A(3)),
     1            (SORTYP,A(4)), (SORLOC,A(5)), (RECTYP,A(6)),
     2            (RECLOC,A(7)), (COMSHT,A(8)), (FILREC,A(9))
C
C  Set up initial default values
C       READ IN FROM FILE ATTACHED TO UNIT 0
C
      READ (0,10) LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC,
     1COMSHT, FILREC, INPOPT, IPDISC, OPDISC, OPFORM, IPSOUR
   10 FORMAT (A20, 8(/A20)/A3/A17/A17/A6/A4)
      READ (0,30) NSAM1, NCH1, NFILES, NFILE(1), NFILE(2), INPCHN,
     1NCR(1), NCR(2), SORPOS, TOPREC, RECSEP, DT, DZ, SCAL
      IF (NSAM1 .NE. NSAMR .OR. NCH1 .NE. NCHR) THEN
          WRITE (6,*)'ARRAY SIZE INCOMPATIBILITY NSAM1,NCH1 =', NSAM1,
     1        NCH1
          WRITE (6,*)'                                NSAMR,NCHR =', NSAMR,
     1        NCHR
          WRITE (6,*)'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
     1'
          WRITE (6,*)
          WRITE (6,*)'  MUST EDIT FILES XHR.1_U XHR.2_U & XHR.3_U.'
          WRITE (6,*)'  CHANGE PARAMETER STATEMENTS IN SUBROUTINES  '
          WRITE (6,*)'                XHR.1                     (XHR.1_U)
     1'
          WRITE (6,*)'          RDFILE,MENPL1,MEDFIL          (XHR.2_U)
     1'
          WRITE (6,*)'      MENUD,MENUE,MENUF,WVSHAP,GNCOMP     (XHR.3_U)
     1'
          WRITE (6,*)
          WRITE (6,*)'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
     1'
          STOP
   20 END IF
   30 FORMAT (I4/I2/I1/I3/I3/I2/I2/I2/F6.2/F6.2/F6.2/F6.2/F6.2/F6.2)
      READ (0,40) TITOFF, CHNSPL, POLART, VARARE, NPLFST, NPLLST, IOPT,
     1FLOWCT, LEDGE, LENFIL, TITLE, XLB, YLB
   40 FORMAT (A3/A26/A7/A3/I4/I4/I2/F6.2/I2/I2/A30/A30/A30)
      RECDEP(1) = TOPREC
      DO 50 I = 2, NCHR
          IF (I .EQ. NCR(2)) THEN
              RECDEP(I) = RECDEP(I - 1)
          ELSE
              RECDEP(I) = RECDEP(I - 1) + RECSEP
          END IF
   50 CONTINUE
      FHICUT = 0.5E6 / DT
      IF (NFILES .EQ. 1) NSHOT = NFILE(1)
      DO 60 I = 1, NCHR
          NPROCS = 1
          IDPROC(1,I) = 0
          NFIRST(I) = 0
          DBGAIN(I) = 0.0
          GCMSCL(I) = 1.0
   60 CONTINUE
      IDPROC(1,NPROCS) = 1
C
C  DT in microsecs, SAMFRQ in kHz
C
      WRITE (6,*)
      WRITE (6,*)'        NIMBUS TAPE DATA MANIPULATION PROGRAM'
      WRITE (6,*)'        ~~~~~~ ~~~~ ~~~~ ~~~~~~~~~~~~ ~~~~~~~'
      WRITE (6,*)
      CALL PAPER(1)
      CALL PSPACE(0.10, 0.9, 0.1, 0.75)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
      CALL J06XAF
      CALL J06XBF(0.0, 1.0, 0.0, 1.0)
      CALL J06XFF(2)
      CALL J06XGF(1.0, 2.0)
      CALL J06AHF('XHR')
      CALL J06WZF
      CALL GREND
C
C                            ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C                            ~ M J FINDLAY     1/JUNE/88 ~
C                            ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C
C  Verify that I/O parameters are OK
C
      CALL MENUIO(NSAMR, NCHR, NRECS, NSHOT, LEN, NFILES, NFILE, IPDISC,
     1     IPSOUR, INPOPT, OPDISC, OPFORM, INPCHN)
C
C  Read in data from files NFILE(1&2) to array R4DAT(1024,NCHR)
C
      CALL RDFILE(NSAMR, NCHR, NRECS, R4DAT, NFIRST, RECDEP, DBGAIN,
     1     GCMSCL, NFILES, NFILE, NCR, NSHOT, DT, LEN, SORPOS, NPROCS,
     2     IDPROC, IPDISC, IPSOUR, INPOPT, INPCHN, A, PROC)
      WRITE (6,*) NPROCS
C
C  Main menu
C
      CALL POWER2(NSAMR, NSAMP2)
```

```
70 WRITE (6,*)
   WRITE (6,*)'                  MASTER MENU       (PRESS 0 TO EXIT)'
   WRITE (6,*)'                  ~~~~~~ ~~~~                        '
   WRITE (6,*)
   WRITE (6,*)'       1   Read data from file(s)             '
   WRITE (6,*)'       2   Write contents of R4DAT to file    '
   WRITE (6,*)'       3   Plot contents of R4DAT             '
   WRITE (6,*)
   WRITE (6,*)'       4   FFT traces and plot spectra        '
   WRITE (6,*)'       5   Apply filters to traces            '
   WRITE (6,*)'       6   F-K transform traces               '
   WRITE (6,*)
   WRITE (6,*)'       7   First breaks, ramps, AGC, tapers etc '
   WRITE (6,*)'      17   Interactively interpolate saturations'
   WRITE (6,*)'       8   Apply wavelet shaping filter       '
   WRITE (6,*)
   WRITE (6,*)'       9   Adjust I/O parameters              '
   WRITE (6,*)'      10   Adjust display parameters          '
   WRITE (6,*)'      11   Adjust processing record           '
   WRITE (6,*)
   WRITE (6,*)'      12   Output first break times           '
   WRITE (6,*)
   READ (5,*) IANSWR
   IF (NPROCS .GT. 20 .OR. NPROCS .LT. 0) NPROCS = 0
   IF (IANSWR .EQ. 1) CALL RDFILE(NSAMR, NCHR, NRECS, R4DAT, NFIRST,
  1     RECDEP, DBGAIN, GCMSCL, NFILES, NFILE, NCR, NSHOT, DT, LEN,
  2     SORPOS, NPROCS, IDPROC, IPDISC, IPSOUR, INPOPT, INPCHN, A,
  3     PROC)
   WRITE (6,*) NPROCS, A

   IF (IANSWR .EQ. 2) CALL WRFILA(NSAMR, NCHR, R4DAT, NFIRST, OPFORM,
  1     OPDISC, NSHOT, LEN, LOCATE, DATE, DEVICE, SORTYP, SORLOC,
  2     RECTYP, RECLOC, COMSHT, FILREC, SORPOS, NRECS, RECDEP,
  3     DBGAIN, GCMSCL, NCR, NPROCS, IDPROC, DT, :OPCHN, PROC)
   IF (IANSWR .EQ. 3) WRITE (6,*)'NSAMR,NCHANS =', NSAMR, NRECS
   IF (IANSWR .EQ. 3) CALL MENPL2(NSAMR, NRECS, R4DAT, NFIRST,
  1     TITOFF, CHNSPL, POLART, VARARE, NPLFST, NPLLST, IOPT, SORPOS,
  2     RECDEP, NCR, DT, LOCATE, DATE, DEVICE, SORTYP, SORLOC,
  3     RECTYP, RECLOC, COMSHT, FILREC, NSHOT, NPROCS, IDPROC, TITLE,
  4     XLB, YLB, SCAL, PROC)
   IF (IANSWR .EQ. 4) CALL MENUD(NSAMR, NCHR, R4DAT, NTRACE, DT,
  1     NSHOT)
   IF (IANSWR .EQ. 5) CALL MENUE(NSAMR, NCHR, R4DAT, DT, FLOWCT,
  1     FHICUT, FLOOFF, FHIOFF, DBLOW, DBHIGH, FILTAP, BLHPAS,
  2     LENFIL, NPROCS, IDPROC)
   IF (IANSWR .EQ. 6) CALL MENUF(NSAMR, NCHR, R4DAT, DZ, DT, NCR)
   IF (IANSWR .EQ. 7) CALL GNCOMP(NSAMR, NCHR, R4DAT, NFIRST, DBGAIN,
  1     GCMSCL, RECDEP, NCR, IDPROC, NPROCS)
   IF (IANSWR .EQ. 17) CALL GRAINT(NSAMR, NRECS, NSHOT)
   IF (IANSWR .EQ. 8) CALL WVSHAP(NSAMR, NCHR, R4DAT, NFIRST, NCR,
  1     DT)
   IF (IANSWR .EQ. 9) CALL MENUIO(NSAMR, NCHR, NRECS, NSHOT, LEN,
  1     NFILES, NFILE, IPDISC, IPSOUR, INPOPT, OPDISC, OPFORM,
  2     INPCHN)
   IF (IANSWR .EQ. 10) CALL MENUDS(NCHR, SORPOS, RECDEP, NCR, DT,
  1     LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC, COMSHT,
  2     FILREC, TITLE, XLB, YLB)
   IF (IANSWR .EQ. 11) CALL PROCES(NPROCS, PROC)
   IF (IANSWR .EQ. 12) CALL OPFIRS(NCHR, NFIRST, RECDEP, LEN, IPDISC)
   IF (IANSWR .EQ. 0) CALL EXIT
```

```
      DZ = ABS(RECDEP(2) - RECDEP(1))
      IF (DZ .EQ. 0.0) DZ = 1.0
      GO TO 70
      END
C
      SUBROUTINE MENUIO(NSAMR, NCHR, NRECS, NSHOT, LEN, NFILES, NFILE,
     1           IPDISC, IPSOUR, INPOPT, OPDISC, OPFORM, INPCHN)
C
C  Menu for adjustment of I/O parameters
C
      DIMENSION NFILE(2)
      CHARACTER IPDISC*17, OPDISC*17, OPFORM*6, IPSOUR*4, INPOPT*3
   10 WRITE (6,*)
      WRITE (6,*)'              I/O Setup Menu              '
      WRITE (6,*)'              ~~~ ~~~~~ ~~~~              '
      WRITE (6,20) IPSOUR
   20 FORMAT (/'    1  Input Source (Tape/Disc)    :', A4)
      WRITE (6,30) IPDISC
   30 FORMAT (/'    2  Input Disc Name             :', A17)
      WRITE (6,40) OPDISC
   40 FORMAT (/'    3  Output Disc Name            :', A17)
      WRITE (6,50) OPFORM
   50 FORMAT (/'    4  Output Format               :', A6)
      WRITE (6,60)
   60 FORMAT (/'   14  SEG-Y output to tape         ')
      WRITE (6,70) NSAMR
   70 FORMAT (/'    5  Record Length (samples)     :', I4)
C       (4 bytes / sample)
      LEN = (NSAMR + 2) * 4
      WRITE (6,80) NCHR
   80 FORMAT (/'    6  Number of channels          :', I3)
      WRITE (6,90) NSHOT
   90 FORMAT (/'    7  Shot I.D. number            :', I3)
      WRITE (6,100) INPOPT
  100 FORMAT (/'    8  Input method                :', A3)
      IF (INPOPT .NE. 'NEW') THEN
          WRITE (6,110) (NFILE(I),I=1,NFILES)
  110     FORMAT (/'    9  I.D. nos. of files          :', 1X, I2, 1X,
     1           I2)
      END IF
      WRITE (6,120)
  120 FORMAT (/'    0  Return to MAIN MENU          ')
      READ (5,*) IANSWR
  130 FORMAT (A17)
      IF (IANSWR .EQ. 1) THEN
          IF (IPSOUR .EQ. 'DISC') THEN
              IPSOUR = 'TAPE'
              INPCHN = 1
          ELSE
              IPSOUR = 'DISC'
              INPCHN = 10
          END IF
      END IF
      IF (IANSWR .EQ. 2) THEN
          WRITE (6,*)
          WRITE (6,*)'      Input Disc name   :'
          READ (5,130) IPDISC
      END IF
      IF (IANSWR .EQ. 3) THEN
          WRITE (6,*)
```

```
            WRITE (6,*)'      Output Disc name   :'
            READ (5,130) OPDISC
         END IF
         IF (IANSWR .EQ. 4) THEN
            IF (OPFORM .EQ. 'DIRECT') THEN
               OPFORM = 'SEQUEN'
            ELSE
               OPFORM = 'DIRECT'
            END IF
         END IF
         IF (IANSWR .EQ. 14) THEN
            OPFORM = 'SEG-Y '
         END IF
         IF (IANSWR .EQ. 5) THEN
            WRITE (6,*)
            WRITE (6,*)'      Number of samples  :'
            READ (5,*) NSAMR
         END IF
         IF (IANSWR .EQ. 6) THEN
            WRITE (6,*)
            WRITE (6,*)'      Number of channels :'
            READ (5,*) NCHR
         END IF
         IF (IANSWR .EQ. 7) THEN
            WRITE (6,*)'      Shot I.D.          :'
            READ (5,*) NSHOT
         END IF
         IF (IANSWR .EQ. 8) THEN
            WRITE (6,*)' 1       DIRECT ACCESS FILE '
            WRITE (6,*)' 2       2 SEQUENTIAL SEG-D TAPE FILES'
            WRITE (6,*)' 3       1 SEQUENTIAL SEG-Y TAPE FILE'
            READ (5,*) IREPLY
            IF (IREPLY .EQ. 1) THEN
               INPOPT = 'NEW'
            ELSE IF (IREPLY .EQ. 2) THEN
               INPOPT = 'OLD'
            ELSE
               INPOPT = 'SGY'
            END IF
         END IF
         IF (IANSWR .EQ. 9 .AND. INPOPT .EQ. 'OLD') THEN
 140        WRITE (6,*)'      No. of files       :'
            READ (5,*) NFILES
            IF (NFILES .LT. 1 .OR. NFILES .GT. 2) GO TO 140
            DO 150 I = 1, NFILES
               WRITE (6,*)'I.D. File #', I, '  :'
               READ (5,*) NFILE(I)
 150        CONTINUE
         END IF
         IF (INPOPT .NE. 'OLD') NFILES = 1
         NRECS = NFILES * NCHR
         IF (IANSWR .NE. 0) GO TO 10
         RETURN
         END
C
         SUBROUTINE MENUDS(NRECS, SORDEP, RECDEP, NCR, DT, LOCATE, DATE,
        1           DEVICE, SORTYP, SORLOC, RECTYP, RECLOC, COMSHT, FILREC,
        2           TITLE, XLB, YLB)
C
C  Menu for adjustment of DISPLAY parameters
C
         CHARACTER*20 LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC,
        1             COMSHT
         CHARACTER*20 FILREC
         CHARACTER*30 TITLE, XLB, YLB
         DIMENSION RECDEP(NRECS), NCR(2)
 10      WRITE (6,*)
         WRITE (6,*)'               Display Setup Menu  (0 to EXIT) '
         WRITE (6,*)'               ~~~~~~~ ~~~~~ ~~~~              '
         WRITE (6,*)
         WRITE (6,20) LOCATE
 20      FORMAT (/'    1  Location                  : ', A20)
         WRITE (6,30) DATE
 30      FORMAT ('    2  Acquisition date          : ', A20)
         WRITE (6,40) DEVICE
 40      FORMAT ('    3  Recording instrument      : ', A20)
         WRITE (6,50) SORLOC
 50      FORMAT (/'    4  Source hole I.D.          : ', A20)
         WRITE (6,60) SORTYP
 60      FORMAT ('    5  Source type               : ', A15)
         WRITE (6,70) SORDEP
 70      FORMAT ('    6  Source depth (metres)     : ', F4.1)
         WRITE (6,80) RECLOC
 80      FORMAT (/'    7  Receiver hole I.D.        : ', A20)
         WRITE (6,90) RECTYP
 90      FORMAT ('    8  Receiver type             : ', A20)
         WRITE (6,100) RECDEP
 100     FORMAT ('    9  Receiver depths (metres)  : ', 8F5.1/37X, 8F5.1/
        1        37X, 8F5.1)
         WRITE (6,110) COMSHT
 110     FORMAT (/'   10  Common shot traces        : ', A20)
         WRITE (6,120) DT
 120     FORMAT ('   11  Sampling rate (microsecs)  : ', F5.1)
         WRITE (6,130) FILREC
 130     FORMAT ('   12  Analogue filters           : ', A20)
         IF (NCR(1) .NE. 0) WRITE (6,140) NCR(1), NCR(2)
 140     FORMAT ('   13  Common Receiver Channels   : ', I2, 1X, I2)
         WRITE (6,150) TITLE, XLB, YLB
 150     FORMAT ('   14  Plot-title and axes labels  : ', A30/38X,
        1        A30/38X, A30)
         READ (5,*) IANSWR
 160     FORMAT (A20)
 170     FORMAT (A32)
         IF (IANSWR .EQ. 1) THEN
            WRITE (6,*)
            WRITE (6,*)' Location     :'
            READ (5,160) LOCATE
         ELSE IF (IANSWR .EQ. 2) THEN
            WRITE (6,*)
            WRITE (6,*)' Date         :'
            READ (5,160) DATE
         ELSE IF (IANSWR .EQ. 3) THEN
            WRITE (6,*)
            WRITE (6,*)' Seismograph  :'
            READ (5,160) DEVICE
         ELSE IF (IANSWR .EQ. 4) THEN
            WRITE (6,*)
            WRITE (6,*)' Source hole  :'
            READ (5,160) SORLOC
         ELSE IF (IANSWR .EQ. 5) THEN
```

```
      WRITE (6,*)
      WRITE (6,*)' Source type  :'
      READ (5,160) SORTYP
    ELSE IF (IANSWR .EQ. 6) THEN
      WRITE (6,*)
      WRITE (6,*)' Source depth :'
      READ (5,*) SORDEP
    ELSE IF (IANSWR .EQ. 7) THEN
      WRITE (6,*)
      WRITE (6,*)' Receiver hole:'
      READ (5,160) RECLOC
    ELSE IF (IANSWR .EQ. 8) THEN
      WRITE (6,*)
      WRITE (6,*)' Receiver type:'
      READ (5,160) RECTYP
    ELSE IF (IANSWR .EQ. 9) THEN
      WRITE (6,*)
      WRITE (6,*)' Rec depths   :'
      READ (5,*) (RECDEP(I),I=1,NRECS)
    ELSE IF (IANSWR .EQ. 10) THEN
      WRITE (6,*)
      WRITE (6,*)' Common shot traces :'
      READ (5,160) COMSHT
    ELSE IF (IANSWR .EQ. 11) THEN
      WRITE (6,*)
      WRITE (6,*)' Sampling rate (microsecs) :'
      READ (5,*) DT
    ELSE IF (IANSWR .EQ. 12) THEN
      WRITE (6,*)
      WRITE (6,*)' Analogue filters :'
      READ (5,160) FILREC
    ELSE IF (IANSWR .EQ. 13) THEN
      WRITE (6,*)
      WRITE (6,*)' Common receiver traces :'
      READ (5,*) NCR(1), NCR(2)
    ELSE IF (IANSWR .EQ. 14) THEN
      WRITE (6,*)
      WRITE (6,*)' Enter title and axes labels : '
      READ (5,180) TITLE
      READ (5,180) XLB
      READ (5,180) YLB
180   FORMAT (A30)
    END IF
    IF (IANSWR .NE. 0) GO TO 10
    RETURN
    END

C
C  Subroutine to amend/update processing record
C  (All proceesing info is stored in data header)
C
    SUBROUTINE PROCES(NPROCS, PROCS)
    CHARACTER*25 PROCS(20)
 10 WRITE (6,*)
    WRITE (6,*)'          Process record editor'
    WRITE (6,*)'          ~~~~~~~~~~~~~~~~~~~~~'
    WRITE (6,*)
    WRITE (6,*)'   1   CLEAR all process records '
    WRITE (6,*)
    WRITE (6,*)'   2   Display all process records '
    WRITE (6,*)
    WRITE (6,*)'   3   Display particular process record '
    WRITE (6,*)
    WRITE (6,*)'   4   CHANGE particular process record '
    WRITE (6,*)
    WRITE (6,*)'   5   ADD new process record'
    WRITE (6,*)
    WRITE (6,*)'   0   EXIT                   '
    WRITE (6,*)
    READ (5,*) IANS
    IF (IANS .EQ. 1) THEN
      DO 20 II = 1, 20
        PROCS(II) = ' '
20    CONTINUE
      NPROCS = 0
    ELSE IF (IANS .EQ. 2) THEN
      DO 30 II = 1, NPROCS
        WRITE (6,40) II, PROCS(II)
30    CONTINUE
40    FORMAT (/10X, I3, 4X, A25)
    ELSE IF (IANS .EQ. 3) THEN
      WRITE (6,*)'Enter number of process record to display :'
      READ (5,*) NPR
      WRITE (6,40) NPR, PROCS(NPR)
    ELSE IF (IANS .EQ. 4) THEN
      WRITE (6,*)'Enter number of process record to ALTER :'
      READ (5,*) NPR
      WRITE (6,40) NPR, PROCS(NPR)
      WRITE (6,*)'Enter text (<25 characters) to replace above :'
      READ (5,50) PROCS(NPR)
50    FORMAT (A25)
    ELSE IF (IANS .EQ. 5) THEN
      NPROCS = NPROCS + 1
      WRITE (6,*)'Enter text (<25 characters for record ', NPROCS
      READ (5,50) PROCS(NPROCS)
    END IF
    IF (IANS .NE. 0) GO TO 10
    RETURN
    END
C
C . SUBROUTINE TO WRITE OUT FIRST BREAK PICKS
C
C
    SUBROUTINE OPFIRS(NCHR, NFIRST, RECDEP, LEN, IPDISC)
    REAL RECDEP(NCHR)
    INTEGER NCHR, NFIRST(NCHR), LEN, IDOP(60)
    CHARACTER IPDISC*17, A*180, OPNAME*17, TITLE*60, B*480
    XS = 0.0
    OPNAME = '-OUT'
 10 WRITE (6,*)
    WRITE (6,*)'              FIRST BREAK OUTPUT MENU '
    WRITE (6,*)'              ~~~~~~~~~~~~~~~~~~~~~~~ '
    WRITE (6,*)
    WRITE (6,*)'   1   OUTPUT ALL RECORDS IN FILE      '
    WRITE (6,*)
    WRITE (6,*)'   2   OUTPUT SELECTED RECORDS IN FILE '
    WRITE (6,*)
    WRITE (6,20) OPNAME
 20 FORMAT ('   3   OUTPUT FILENAME  : ', A17)
    WRITE (6,*)
```

```
      WRITE (6,*)'   0   EXIT'
      READ (5,*) IANS
      IF (IANS .EQ. 1) THEN
          WRITE (6,*)'Enter total number of records on disc :'
          READ (5,*) NOP
          DO 30 II = 1, NOP
              IDOP(II) = II
30        CONTINUE
      ELSE IF (IANS .EQ. 2) THEN
          WRITE (6,*)'Enter total no. of records to be Output :'
          READ (5,*) NOP
          DO 40 II = 1, NOP
              WRITE (6,*)'Enter i.d. of record #', II, ' :'
              READ (5,*) IDOP(II)
40        CONTINUE
      ELSE IF (IANS .EQ. 3) THEN
          WRITE (6,*)'Enter name of new output file :'
          READ (5,50) OPNAME
50        FORMAT (A17)
      END IF
      IF (IANS .EQ. 1 .OR. IANS .EQ. 2) THEN
          WRITE (6,*)'Enter title (<60 characters) :'
          READ (5,60) TITLE
          WRITE (6,*)'Enter XREC in metres :'
          READ (5,*) XR
60        FORMAT (A60)
          RNOP = REAL(NOP)
          RNCHR = REAL(NCHR)
          OPEN (10,FILE=IPDISC,STATUS='OLD',ACCESS='DIRECT',RECL=LEN)
          OPEN (18,FILE=OPNAME,STATUS='UNKNOWN',FORM='FORMATTED')
          WRITE (18,60) TITLE
          WRITE (18,*)'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
     1'
          WRITE (18,*)'No. of shots                    No. of receivers
     1'
          WRITE (18,70) RNOP, RNCHR
70        FORMAT (F5.1, 30X, F5.1)
          WRITE (18,*)'XSHOT     ZSHOT     XREC     ZREC     TTIME'
          DO 100 II = 1, NOP
              IDCODE = (IDOP(II) - 1) * (NCHR + 1) + 1
              READ (10,REC=IDCODE) A, SORPOS, NRECS, RECDEP, RECDEP,
     1             RECDEP, NFIRST, A(1:12), B, DT
              DO 80 JJ = 1, NCHR
                  TT = NFIRST(JJ) * DT / 1E6
                  WRITE (18,90) XS, SORPOS, XR, RECDEP(JJ), TT,
     1            NFIRST(JJ)
80            CONTINUE
90            FORMAT (F5.1, F9.1, F11.2, F8.1, F14.8, I12)
              WRITE (6,*)'Done for shot #', IDOP(II)
100       CONTINUE
          CLOSE (18)
          CLOSE (10)
      END IF
      IF (IANS .NE. 0) GO TO 10
      RETURN
      END
```

```
C
C  Further subroutines for XHR programs
C
C  Written by M J Findlay 1987-1989
C
      SUBROUTINE MENUD(NSAMR, NCHR, R4DAT, NTRACE, DT, NSHOT)
C
C  Subroutine to plot FFT of individual traces in current array
C
      PARAMETER (NL=2048)
      DIMENSION R4DAT(NSAMR,NCHR)
      DIMENSION P(NL), Y(NL), S(NL), G(NL)
      CHARACTER TNAME*6, TITLE*32
      CHARACTER*20 LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC,
     1             COMSHT, FILREC
      COMPLEX CSX(NL)
      CALL POWER2(NSAMR, NSAMP2)
      NTRACE = 12
   10 WRITE (6,*)
      WRITE (6,*)'             Trace Spectral Plot Menu    '
      WRITE (6,*)'             ~~~~~ ~~~~~~~~ ~~~~ ~~~~    '
      WRITE (6,*)
      WRITE (6,20) NTRACE
   20 FORMAT (/'    1  Trace number              :', I2)
      WRITE (6,30)
   30 FORMAT (/'    2  Amplitude and phase spectra ')
      WRITE (6,40)
   40 FORMAT (/'    3  Amplitude spectrum only     ')
      WRITE (6,50)
   50 FORMAT (/'    4  Power spectrum              ')
      WRITE (6,60)
   60 FORMAT (/'    5  FFT ALL traces OP to R4dat  ')
      WRITE (6,70)
   70 FORMAT (/'    6  Put Autocorrelograms of traces into R4dat')
      WRITE (6,80)
   80 FORMAT (/'    7  Cross correlate to find optimum lag ')
      WRITE (6,90)
   90 FORMAT (/'    0  Return to MAIN MENU         ')
      READ (5,*) IOPT
      IF (IOPT .EQ. 0) RETURN
      IF (IOPT .EQ. 1) THEN
        WRITE (6,*)'Enter trace number   :'
        READ (5,*) NTRACE
      END IF
      IF (NTRACE .LT. 1 .OR. NTRACE .GT. NCHR) GO TO 10
      IF (IOPT .EQ. 2 .OR. IOPT .EQ. 3) THEN
        DO 100 I = 1, NSAMR
          CSX(I) = CMPLX(R4DAT(I,NTRACE),0.0)
  100   CONTINUE
        DO 110 I = NSAMR + 1, NSAMP2
          CSX(I) = 0.0
  110   CONTINUE
        KEY = 0
        NPR = 0
        IRES1 = 0
        IRES2 = 0
        CALL TIME(KEY, NPR, IRES)
        CALL FORK(NSAMP2, CSX, -1.0)
        KEY = 15
        NPR = 0
        IRES1 = 0
        IRES2 = 0
        CALL TIME(KEY, NPR, IRES1, IRES2)
        PRINT *, 'FFT TIME IN MICROSECS =', IRES1, IRES2
        IDSH = 473
        IDRH = 475
        TNAME = 'SWT014'
        TITLE = LOCATE // DATE
        CALL SPECPL(NSAMP2, CSX, DT, TITLE, TNAME, NSHOT, NTRACE, IDSH,
     1       IDRH)
      END IF
      IF (IOPT .EQ. 4) THEN
        DO 120 I = 1, NSAMR
          G(I) = R4DAT(I,NTRACE)
  120   CONTINUE
        DO 130 I = NSAMR + 1, NSAMP2
          G(I) = 0.0
  130   CONTINUE
        CALL POWERS(G, P, NSAMP2, Y, S)
        FMIN = 0.0
        FMAX = 0.5E6 / DT
        CALL MINSN(NSAMP2/2 + 1, P, PMIN, II)
        CALL MAXSN(NSAMP2/2 + 1, P, PMAX, II)
        PRINT *, 'FMIN,FMAX,PMIN,PMAX', FMIN, FMAX, PMIN, PMAX
        CALL PAPER(1)
        CALL PSPACE(0.1, 0.9, 0.1, 0.9)
        CALL MAP(FMIN, FMAX, PMIN, PMAX)
        CALL SCALES
        CALL BORDER
        DF = 2.0 * FMAX / REAL(NSAMP2)
        DO 140 I = 1, NSAMP2
          Y(I) = REAL(I - 1) * DF
  140   CONTINUE
        CALL PTJOIN(Y, P, 1, NSAMP2/2 + 1, 1)
        CALL GREND
      END IF
      IF (IOPT .EQ. 5) THEN
        DO 180 JJ = 1, NCHR
          DO 150 II = 1, NSAMR
            CSX(II) = CMPLX(R4DAT(II,JJ),0.0)
  150     CONTINUE
          DO 160 II = NSAMR + 1, NSAMP2
            CSX(II) = 0.0
  160     CONTINUE
          CALL FORK(NSAMP2, CSX, -1.0)
          DO 170 II = 1, NSAMR
            R4DAT(II,JJ) = CABS(CSX(II))
  170     CONTINUE
  180   CONTINUE
      END IF
      IF (IOPT .EQ. 6) THEN
        WRITE (6,*)'Enter no. of lags to be calculated :'
        READ (5,*) NLAGS
        NORM = 1
        DO 200 JJ = 1, NCHR
          CALL ACF(R4DAT(1,JJ), S, NSAMR, NLAGS, NORM, I2ZC)
          CALL ZERO(NSAMR, R4DAT(1,JJ))
          DO 190 II = 1, NLAGS
            R4DAT(II,JJ) = S(II)
  190     CONTINUE
```

```
 200   CONTINUE
     END IF
     IF (IOPT .EQ. 7) THEN
       WRITE (6,*)'ENTER NO. OF LAGS TO BE CALCULATED :'
       READ (5,*) LG
       WRITE (6,*)'ENTER TRACE NUMBERS TO COMPARE :'
       READ (5,*) ID1, ID2
       CALL CROSS(NSAMR, R4DAT(1,ID1), NSAMR, R4DAT(1,ID2), LG, G)
       CALL MAXSN(LG, G, GMAX, II)
       CALL CROSS(NSAMR, R4DAT(1,ID2), NSAMR, R4DAT(1,ID1), LG, G)
       CALL MAXSN(LG, G, GMAX1, II1)
       WRITE (6,*)'OPTIMUM LAG = ', GMAX, ' AT ', II - 1
       WRITE (6,*)'OPTIMUM LEAD = ', GMAX1, ' AT ', II1 - 1
       WRITE (6,*)'LAG implies should increase time on 2nd trace.'
       WRITE (7,*)'SHOT NO. :', NSHOT
       WRITE (7,*)'OPTIMUM LAG = ', GMAX, ' AT ', II - 1
       WRITE (7,*)'OPTIMUM LEAD = ', GMAX1, ' AT ', II1 - 1
       WRITE (7,*)'LAG implies should increase time on 2nd trace.'
     END IF
     IF (IOPT .NE. 0) GO TO 10
     RETURN
     END
C
     SUBROUTINE MENUE(NSAMR, NCHR, R4DAT, DT, FLOWCT, FHICUT, FLOOFF,
    1           FHIOFF, DBLOW, DBHIGH, FILTAP, BLHPAS, LENFIL, NPROCS,
    2           IDPROC)
C
C    Subroutine to apply High pass, Low pass, and Band pass filters to
C    data
C    And Median filter
C
     PARAMETER (NL1=2048,NL2=128,N1=2048,N2=65)
     DIMENSION R4DAT(NSAMR,NCHR), IDPROC(5,NCHR)
     REAL S(NL1), Y(NL1), FL, FH, R(NL2), G(NL2), A(NL2), F(NL2),
    1     C(NL1)
     REAL DUM(NL1), DUM1(NL1)
     COMPLEX CX(NL1)
     CHARACTER FILTAP*9, BLHPAS*9, ANS*1
     CALL POWER2(NSAMR, NSAMP2)
     NRECS = NCHR
     FILTAP = 'Cosine'
     BLHPAS = 'Band pass'
     FNYQ = .5E6 / DT
     FLOOFF = 0.0
     FHIOFF = FNYQ
     DBLOW = 6.0
     DBHIGH = 6.0
  10 WRITE (6,*)
     WRITE (6,*)'              Filter Menu                '
     WRITE (6,*)'              ~~~~~~ ~~~~                '
     WRITE (6,*)
     WRITE (6,20) FLOWCT
  20 FORMAT (/'    1  Low cut frequency (Hz)      :', F6.1)
     WRITE (6,30) FHICUT
  30 FORMAT (/'    2  High cut frequency (Hz)     :', F6.1)
     WRITE (6,40) FLOOFF
  40 FORMAT (/'    3  Cosine low reject freq (Hz) :', F6.1)
     WRITE (6,50) FHIOFF
  50 FORMAT (/'    4  Cosine High reject freq (Hz):', F6.1)
     WRITE (6,60) DBLOW
  60 FORMAT (/'    5  Low dB/Octave slope         :', F6.1)
     WRITE (6,70) DBHIGH
  70 FORMAT (/'    6  High dB/Octave slope        :', F6.1)
     WRITE (6,80) FILTAP, BLHPAS
  80 FORMAT (/'    7  Filter type                 :', 1X, A9, 1X, A9)
     WRITE (6,90)
  90 FORMAT (/'    8  Apply BANDPASS filter        ')
     WRITE (6,100)
 100 FORMAT (/'    9  Apply MEDIAN filter          ')
     WRITE (6,110)
 110 FORMAT (/'   10  Apply spiking decon          ')
     WRITE (6,120)
 120 FORMAT (/'   11  APPL NEWMAN FILTER           ')
     WRITE (6,130)
 130 FORMAT (/'    0  Return to MAIN MENU          ')
     READ (5,*) IANSWR
     IF (IANSWR .EQ. 1) THEN
       WRITE (6,*)'Enter Low cutoff frequency (Hz) :'
       READ (5,*) FLOWCT
     ELSE IF (IANSWR .EQ. 2) THEN
       WRITE (6,*)'Enter High cutoff frequency (Hz) :'
       READ (5,*) FHICUT
     ELSE IF (IANSWR .EQ. 3) THEN
       WRITE (6,*)'Enter Low reject frequency (Hz) :'
       READ (5,*) FLOOFF
     ELSE IF (IANSWR .EQ. 4) THEN
       WRITE (6,*)'Enter High reject frequency (Hz) :'
       READ (5,*) FHIOFF
     ELSE IF (IANSWR .EQ. 5) THEN
       WRITE (6,*)'Enter Low cutoff slope (dB/Octave) :'
       READ (5,*) DBLOW
     ELSE IF (IANSWR .EQ. 6) THEN
       WRITE (6,*)'Enter High cutoff slope (dB/Octave) :'
       READ (5,*) DBHIGH
     ELSE IF (IANSWR .EQ. 7) THEN
       WRITE (6,*)'Select taper function (Cosine or Db/octave) :'
       READ (5,140) ANS
 140   FORMAT (A1)
       IF (ANS .EQ. 'C' .OR. ANS .EQ. 'c') THEN
         FILTAP = 'Cosine'
       ELSE
         FILTAP = 'dB/Octave'
       END IF
       WRITE (6,*)'Select pass function (Low / High / Band) :'
       READ (5,140) ANS
       IF (ANS .EQ. 'L' .OR. ANS .EQ. 'l') THEN
         FLOWCT = 0.0
         FLOOFF = 0.0
         DBLOW = 0.0
         BLHPAS = 'Low pass'
       ELSE IF (ANS .EQ. 'H' .OR. ANS .EQ. 'h') THEN
         FHICUT = FNYQ
         FHIOFF = FNYQ
         DBHIGH = 0.0
         BLHPAS = 'High pass'
       ELSE
         BLHPAS = 'Band pass'
       END IF
     ELSE IF (IANSWR .EQ. 8) THEN
       DO 180 J = 1, NCHR
```

```
      DO 150 I = 1, NSAMR
        DUM(I) = R4DAT(I,J)
150   CONTINUE
      DO 160 I = NSAMR + 1, NSAMP2
        DUM(I) = 0.0
160   CONTINUE
      WRITE (6,*)'FILTERING CHANNEL #', J
      IF (FILTAP .EQ. 'Cosine') THEN
        CALL BPSCOS(DUM, NSAMP2, CX, FLOWCT, FHICUT, FLOOFF, FHIOFF,
     1       FNYQ)
      ELSE
        CALL BPSDBS(DUM, NSAMP2, CX, FLOWCT, FHICUT, DBLOW, DBHIGH,
     1       FNYQ)
      END IF
      DO 170 I = 1, NSAMR
        R4DAT(I,J) = DUM(I)
170   CONTINUE
180 CONTINUE
    NPROCS = NPROCS + 1
    WRITE (6,*)'NPROCS = ', NPROCS
    IF (FILTAP .EQ. 'Cosine') THEN
      IDPROC(1,NPROCS) = 4
      IDPROC(2,NPROCS) = NINT(FLOOFF)
      IDPROC(3,NPROCS) = NINT(FLOWCT)
      IDPROC(4,NPROCS) = NINT(FHICUT)
      IDPROC(5,NPROCS) = NINT(FHIOFF)
    ELSE
      IDPROC(1,NPROCS) = 11
      IDPROC(2,NPROCS) = NINT(FLOWCT)
      IDPROC(3,NPROCS) = NINT(DBLOW)
      IDPROC(4,NPROCS) = NINT(FHICUT)
      IDPROC(5,NPROCS) = NINT(DBHIGH)
    END IF
  ELSE IF (IANSWR .EQ. 9) THEN
    WRITE (6,*)'Enter length of median filter (traces) :'
    READ (5,*) LENFIL
    PRINT *, NFIRST
    CALL MEDFIL(NSAMR, NCHR, R4DAT, NFIRST, LENFIL)
    NPROCS = NPROCS + 1
    IDPROC(1,NPROCS) = 8
    IDPROC(2,NPROCS) = LENFIL
    PRINT *, NFIRST
  ELSE IF (IANSWR .EQ. 10) THEN
    WRITE (6,*)'Apply triangular weighting to ACF (1=y 0=n) :'
    READ (5,*) IFJ
    WRITE (6,*)'Enter %ge white noise to add :'
    READ (5,*) RFC
    WRITE (6,*)'Enter filter length in samples :'
    READ (5,*) LF
    WRITE (6,*)'Enter prediction distance in samples :'
    READ (5,*) MM
    WRITE (6,*)'WRITE FILTER TO ARRAY R4DAT 1=Y 0=APPLY FILTER ?'
    READ (5,*) IRESP
    DO 230 JJ = 1, NCHR
      DO 190 I = 1, NSAMR
        DUM1(I) = R4DAT(I,JJ)
190   CONTINUE
      DO 200 I = NSAMR + 1, NSAMP2
        DUM1(I) = 0.0
200   CONTINUE
      IF (MM .EQ. 0) THEN
        CALL ACF(DUM1, A, NSAMR, 100, 1, I2ZC)
        M = I2ZC
      ELSE
        M = MM
      END IF
      IF (M .GT. LF) GO TO 230
      CALL PDECON(NSAMP2, DUM1, M, LF, R, G, A, F, RFC, IFJ)
      IF (IRESP .EQ. 1) THEN
        CALL ZERO(NSAMR, R4DAT(1,JJ))
        DO 210 I = 1, LF
          R4DAT(I,JJ) = F(I)
210     CONTINUE
      ELSE
        CALL ZERO(NSAMR, C)
        DO 220 I = 1, LF
          C(I) = F(I)
220     CONTINUE
        CALL FRECON(NSAMP2, DUM1, DUM, C, Y, S)
      END IF
230 CONTINUE
  END IF
  IF (IANSWR .EQ. 11) THEN
    DO 270 J = 1, NCHR
      NLC = 2 * NL1
      CALL ZERO(NLC, CX)
      DO 240 I = 1, NSAMR
        CX(I) = CMPLX(R4DAT(I,J),0.0)
240   CONTINUE
      CALL FORK(NSAMR, CX, -1.0)
      CX(1) = 0.0
      CX(NSAMR/2 + 1) = 0.0
      DO 250 I = 2, NSAMR / 2
        CX(I) = CX(I) * SQRT(REAL(I - 1))
        CX(I) = CX(I) * (1.,1.)
        CX(NSAMR + 2 - I) = CONJG(CX(I))
250   CONTINUE
      CALL FORK(NSAMR, CX, +1.0)
      DO 260 I = 1, NSAMR
        R4DAT(I,J) = REAL(CX(I))
260   CONTINUE
270 CONTINUE
  END IF
  IF (IANSWR .NE. 0) GO TO 10
  RETURN
  END
C
  SUBROUTINE MENUF(NSAM, NCHR, R4DAT, DZ, DT, NCR)
C
C Subroutine to obtain F-K spectrum of recorded data
C
  PARAMETER (N1=513,N2=64,N3=5120,N4=1024,N5=65)
  DIMENSION R4DAT(NSAM,NCHR), NCR(2)
  CHARACTER ANS*1, LOGYN*1, ANSWER*1, FNAME*10
  COMPLEX CP(N4,N2), CW(N2), CTEMP
  REAL KNYQ, FILSPC(N1,N5)
  DOUBLE PRECISION AMPSPC(N5,N1), TEMP, CHTS(8), DBCHTS(8), XM
  DOUBLE PRECISION  HF, ZBASE, ZMIN, ZMAX, RWS(N3)
  LOGICAL SOLID
  CALL POWER2(NSAM, NSAMR)
```

```
      CHTS(1) = 20.0
      CHTS(2) = 50.0
      CHTS(3) = 100.0
      CHTS(4) = 150.0
      DBCHTS(1) = 0.01
      DBCHTS(2) = 3.0
      DBCHTS(3) = 6.0
      DBCHTS(4) = 20.0
      DBCHTS(5) = 40.0
      NCHTS = 4
      NCHTDB = 5
      NF = N1
      FNYQ = .5E6 / DT
      KNYQ = .5 / DZ
      PRINT *, 'KNYQ = ', KNYQ, ' FNYQ = ', FNYQ
      ISAMP = NINT(FNYQ*2)
   10 WRITE (6,*)
      WRITE (6,*)'              F-K Spectra Menu                 '
      WRITE (6,*)'              ~~~ ~~~~~~~ ~~~~             '
      WRITE (6,*)
      WRITE (6,20)
   20 FORMAT (/'    1  Calculate 2DFFT              ')
      WRITE (6,30)
   30 FORMAT (/'    2  Output complex array to file ')
      WRITE (6,40)
   40 FORMAT (/'    3  Input complex array from file')
      WRITE (6,50)
   50 FORMAT (/'    4  Apply filters to array contents')
      WRITE (6,60)
   60 FORMAT (/'    5  Plot F-K amplitude spectrum  ')
      WRITE (6,70) (CHTS(I),I=1,NCHTS)
   70 FORMAT (/'    6  Contours for F-K spectrum : ', 8(F4.0,1X))
      WRITE (6,80)
   80 FORMAT (/'    7  dB plot of F-K amplitude spectrum  ')
      WRITE (6,90) (DBCHTS(I),I=1,NCHTDB)
   90 FORMAT (/'    8  dB contours for F-K spectrum : ', 8(F4.0,1X))
      WRITE (6,100)
  100 FORMAT (/'    9  Isometric projection plot of spectrum')
      WRITE (6,110)
  110 FORMAT (/'    0  Return to MAIN MENU          ')
      READ (5,*) IANSWR
      IF (IANSWR .EQ. 0) RETURN
      IF (IANSWR .EQ. 1) THEN
        WRITE (6,*)'To or From  F-K space     (T/F)  :'
        READ (5,120) ANS
  120   FORMAT (A1)
        NCEN = NSAMR / 2 + 1
        KCEN = N2 / 2 + 1
        IF (ANS .EQ. 'F' .OR. ANS .EQ. 'f') THEN
          SIGNA = +1.0
          SIGNB = +1.0
          DO 130 J = 1, N2
            CP(NCEN,J) = CONJG(CP(1,J))
            DO 130 I = 1, NSAMR / 2 - 1
              CP(NCEN + I,J) = CONJG(CP(NCEN - I,J))
  130     CONTINUE
C
C     SWAP AROUND TWO UPPER QUADRANTS
C
          DO 150 J = 1, N2 / 2 - 1
            DO 140 I = NCEN + 1, NSAMR
              CTEMP = CP(I,J + KCEN)
              CP(I,KCEN + J) = CP(I,KCEN - J)
              CP(I,KCEN - J) = CTEMP
  140       CONTINUE
  150     CONTINUE
        ELSE
          WRITE (6,*)'RESPONSE OF FILTER REQUIRED ?'
          READ (5,160) ANSWER
  160     FORMAT (A1)
          IF (ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') THEN
            NCP = NSAM * NCHR
            CALL ZERO(NCP, R4DAT(1,1))
            R4DAT(512,12) = 1.0
          END IF
          SIGNA = -1.0
          SIGNB = -1.0
          NZERO = N2 * N4 * 2
          CALL ZERO(NZERO, CP(1,1))
          DO 180 J = 1, NCHR
            DO 170 I = 1, NSAM
              CP(I,J) = CMPLX(R4DAT(I,J),0.0)
  170       CONTINUE
  180     CONTINUE
  190     FORMAT (4(I4,1X,F7.3,1X,F7.3))
C
C  Remove common receiver channel
C
          IF (NCR(1) .NE. 0) THEN
            PRINT *, 'Enter common receiver channel to be ignored :'
            READ (5,*) NCRIGN
            IF (NCRIGN .EQ. 0) GO TO 210
            DO 210 J = NCRIGN, NCHR
              DO 200 II = 1, NSAMR
                CP(II,J) = CP(II,J + 1)
  200         CONTINUE
  210       CONTINUE
          END IF
        END IF
        KEY = 0
        NPR = 0
        IRES1 = 0
        IRES2 = 0
        CALL TIME(KEY, NPR, IRES)
        CALL FT2D(N4, N2, CP, SIGNA, SIGNB, CW)
        KEY = 15
        NPR = 0
        IRES1 = 0
        IRES2 = 0
        CALL TIME(KEY, NPR, IRES1, IRES2)
        PRINT *, 'FFT TIME IN MICROSECS =', IRES1, IRES2
        KEY = 1
        NPR = 0
        IRES1 = 0
        CALL TIME(KEY, NPR, IRES1)
        PRINT *, 'FFT TIME IN MILLISECS =', IRES1
        IF (ANS .EQ. 'F' .OR. ANS .EQ. 'f') THEN
          PRINT *, 'WRITING CP TO R4DAT'
  220     DO 230 J = 1, NCHR
            DO 230 I = 1, NSAM
```

```
          R4DAT(I,J) = REAL(CP(I,J))
 230    CONTINUE
      END IF
    ELSE IF (IANSWR .EQ. 4) THEN
C
C  PUT filter response into array FILSPC
C
      NF = NSAMR / 2 + 1
      NK = N2 + 1
      DK = 2 * KNYQ / N2
      DF = 2 * FNYQ / NSAMR
      PRINT *, 'NF,NK,DK,DF', NF, NK, DK, DF
      WRITE (6,*)'PASS or REJECT filter (P/R)?'
      READ (5,160) ANS
      CALL PIE(NK, NF, FILSPC, DK, DF, ANS)
      IF (ANS .EQ. 'R') THEN
        DO 250 I = 1, N2
          DO 240 J = 1, NF
            FILSPC(J,I) = 1.0 - FILSPC(J,I)
 240      CONTINUE
 250    CONTINUE
      END IF
C
C APPLY FILTER FILSPC
C
      DO 270 I = 1, N2 / 2
        DO 260 J = 1, NF
          CP(J,I) = CP(J;I) * FILSPC(J,I + N2/2)
 260    CONTINUE
 270  CONTINUE
      DO 290 I = N2 / 2 + 1, N2
        DO 280 J = 1, NF
          CP(J,I) = CP(J,I) * FILSPC(J,I - N2/2)
 280    CONTINUE
 290  CONTINUE
    ELSE IF (IANSWR .EQ. 2) THEN
      DO 300 J = 1, N2
        DO 300 I = 1, NF
          AMPSPC(J,I) = DBLE(CABS(CP(I,J)))
 300  CONTINUE
C
C  rearrange array so that K=0 axis lies at sample N2/2+1
C
      DO 310 I = 1, N2 / 2
        DO 310 J = 1, NF
          TEMP = AMPSPC(I,J)
          AMPSPC(I,J) = AMPSPC(I + N2/2,J)
          AMPSPC(I + N2/2,J) = TEMP
 310  CONTINUE
      WRITE (6,*)'Enter name of file to write to :'
      READ (5,320) FNAME
 320  FORMAT (A10)
      OPEN (4,FILE=FNAME,STATUS='NEW',FORM='UNFORMATTED')
      WRITE (4) ((REAL(AMPSPC(J,I)),J=1,N2),I=1,NF)
      CLOSE (4)
    ELSE IF (IANSWR .EQ. 5 .OR. IANSWR .EQ. 7 .OR. IANSWR .EQ. 9)
   1        THEN
      PRINT *, 'SELECT MAX FREQY FOR PLOT '
      READ (5,*) FMAX
C
C   write amplitude spectrum to correctly orientated array AMPSPC
C
      DO 340 J = 1, N2
        DO 330 I = 1, NF
          AMPSPC(J,I) = DBLE(CABS(CP(I,J)))
 330    CONTINUE
 340  CONTINUE
      ISOLOG = 0
      IF (IANSWR .EQ. 9) THEN
        WRITE (6,*)'Log plot required (Y/N) ?'
        READ (5,120) ANS
        IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') ISOLOG = 1
      END IF
      IF (IANSWR .EQ. 7 .OR. ISOLOG .EQ. 1) THEN
        XM = 0.0D0
        DO 360 J = 1, NF
          DO 350 I = 1, N2
            IF (AMPSPC(I,J) .GT. XM) XM = AMPSPC(I,J)
 350      CONTINUE
 360    CONTINUE
        PRINT *, 'MAX AMPLITUDE = ', XM
        DO 380 I = 1, NF
          DO 370 J = 1, N2
            IF (AMPSPC(J,I) .LE. 1.0D-8) THEN
              AMPSPC(J,I) = 1000.0
            ELSE
              AMPSPC(J,I) = -20 * LOG10(AMPSPC(J,I)/XM)
            END IF
 370      CONTINUE
 380    CONTINUE
      END IF
C
C  Now rearrange K space so that 0.0,0.0 is in centre of K axis
C
      NF = NSAMR / 2 + 1
      NK = N2 + 1
      DO 400 I = 1, N2 / 2
        DO 390 J = 1, NF
          TEMP = AMPSPC(I,J)
          AMPSPC(I,J) = AMPSPC(I + N2/2,J)
          AMPSPC(I + N2/2,J) = TEMP
 390    CONTINUE
 400  CONTINUE
      DO 410 J = 1, NF
        AMPSPC(NK,J) = AMPSPC(1,J)
 410  CONTINUE
C
C  Now call plotting routine
C
      LOGYN = 'N'
      IF (IANSWR .EQ. 7) THEN
        LOGYN = 'Y'
        CALL FKPLOT(NK, NF, AMPSPC, DT, DZ, FMAX, NCHTDB, DBCHTS,
   1         LOGYN)
      ELSE IF (IANSWR .EQ. 5) THEN
        LOGYN = 'N'
        CALL FKPLOT(NK, NF, AMPSPC, DT, DZ, FMAX, NCHTS, CHTS, LOGYN)
      ELSE
        CALL PAPER(1)
        CALL J06WAF
```

```
      CALL J06WBF(0.0, 1.0, 0.0, 1.0, 1)
      CALL J06WCF(0.0, 1.0, 0.0, 1.0)
      CALL J06AHF('FK Amplitude Spectrum ')
      IROT = 0
      IFAIL = 0
      HF = 1.0D0
      SOLID = .TRUE.
      IBASE = +1
      ZBASE = 0.0D0
      JSECT = 0
      ZMIN = 0.0
      ZMAX = 0.0
      NFMAX = NINT(FMAX*2.0E-6*DT*NF)
      PRINT *, 'NFMAX =', NFMAX
      NRWS = 5 * NFMAX
      CALL J06HBF(AMPSPC, NK, NFMAX, NK, HF, IROT, SOLID, IBASE,
     1         ZBASE, JSECT, ZMIN, ZMAX, RWS, NRWS, IFAIL)
      CALL J06WZF
     END IF
    ELSE IF (IANSWR .EQ. 6) THEN
     PRINT *, '  No. of contours required (<=8) :'
     READ (5,*) NCHTS
     DO 420 J = 1, NCHTS
      WRITE (6,*)'  Contour level ', J, ' : '
      READ (5,*) CHTS(J)
420   CONTINUE
    ELSE IF (IANSWR .EQ. 8) THEN
     PRINT *, '  No. of contours required (<=8) :'
     READ (5,*) NCHTDB
     DO 430 J = 1, NCHTDB
      WRITE (6,*)'  Contour level ', J, ' : '
      READ (5,*) DBCHTS(J)
430   CONTINUE
    END IF
    IF (IANSWR .NE. 0) GO TO 10
    RETURN
    END
C
C
    SUBROUTINE WVSHAP(NSAMR, NCHR, R4DAT, NFIRST, NCR, DT)
C
C. Routine to apply waveshaping filters to dataset.
C  Version 1.0; Version 2.0 is MUCH better (in XHR.2_U)
C
    PARAMETER (NS1=1024,NS2=2048,NS3=512)
    DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR), NCR(2)
    REAL S1(NS1), S2(NS1), S3(NS1), A(NS1,3), B(NS1), RDAT(NS1)
    REAL C(NS2), ER(NS3), REF(NS1), XPOSNS(NS3), DSERIS(NS1)
    REAL BSERIS(NS1)
    COMPLEX CMPB(NS1)
    INTEGER NOPT(6)
    CHARACTER WEIGHT*3, ANS*1, REPLY*3
    LOGICAL FILTER
    CALL POWERS(NSAMR, NSAMP2)
C
C  DEFAULTS
C
    FILTER = .FALSE.
    NFILTS = 1
    LA = 64
    NL = 5
    LAG1 = -2
    RFC = 0.01
    WEIGHT = 'NO'
    IFJ = 0
    IDD = NCR(1)
    IDB = NCR(2)
    REPLY = 'YES'
C
 10 WRITE (6,*)
    WRITE (6,*)'             WAVESHAPING FILTER MENU     (0 to EXIT)'
    WRITE (6,*)'             ~~~~~~~~~~~ ~~~~~~ ~~~~                '
    WRITE (6,*)
    WRITE (6,20) IDD, IDB
 20 FORMAT (/' 1  Nos. of channels for shaping (REF 1st)  :', I2, 1X,
  1     I2)
    WRITE (6,30) NFILTS
 30 FORMAT (/' 2  No. of filters to be calculated (1-3)   :', I2)
    WRITE (6,40) LA
 40 FORMAT (/' 3  Length of first filter to be calculated :', I4)
    WRITE (6,50) NL
 50 FORMAT (/' 4  No. of lags to be considered            :', I3)
    WRITE (6,60) LAG1
 60 FORMAT (/' 5  First lag for shaping                   :', I3)
    WRITE (6,70) RFC
 70 FORMAT (/' 6  Amount of white noise to be added to ACF:', F8.6)
    WRITE (6,80) WEIGHT
 80 FORMAT (/' 7  Weighting for ACF ?                     :', 1X, A3)
    WRITE (6,90)
 90 FORMAT (/' 8  Calculate filter coefficients           ')
    WRITE (6,100) REPLY
100 FORMAT (/' 9  Shorten IP & REF wavelets               :', A3)
    IF (FILTER) THEN
     WRITE (6,110)
110  FORMAT (/' 10  Apply filter to alternate traces         ')
    END IF
    READ (5,*) IANS
    IF (IANS .EQ. 1) THEN
     WRITE (6,*)'Nos. of channels for shaping  (Reference first) :'
     READ (5,*) IDD, IDB
    ELSE IF (IANS .EQ. 2) THEN
     WRITE (6,*)'No. of filters to be calculated   :'
     READ (5,*) NFILTS
    ELSE IF (IANS .EQ. 3) THEN
     WRITE (6,*)'Length of first filter required   :'
     READ (5,*) LA
    ELSE IF (IANS .EQ. 4) THEN
     WRITE (6,*)'No. of lags for each filter     :'
     READ (5,*) NL
    ELSE IF (IANS .EQ. 5) THEN
     WRITE (6,*)'First lag for waveshaping   :'
     READ (5,*) LAG1
    ELSE IF (IANS .EQ. 6) THEN
     WRITE (6,*)'Fraction of white noise to add to zero lag ACF :'
     READ (5,*) RFC
    ELSE IF (IANS .EQ. 7) THEN
     IF (WEIGHT .EQ. 'YES') THEN
      WEIGHT = 'NO'
      IFJ = 0
     ELSE
```

```
          WEIGHT = 'YES'
          IFJ = 1
        END IF
      ELSE IF (IANS .EQ. 10) THEN
        WRITE (6,*)'Select required filter (1-3) :'
        READ (5,*) IDFILT
        IF (IDFILT .GT. NFILTS .OR. IDFILT .LE. 0) GO TO 10
        IODDEV = MOD(IDD,2) + 1
        DO 140 J = IODDEV, NRECS, 2
          DO 120 I = 1, NSAMR
            B(I) = A(I,IDFILT)
 120      CONTINUE
          CALL ZERO(NSAMR, S1)
          CALL ZERO(NSAMR, S2)
          CALL ZERO(NSAMR, S3)
          CALL FRECON(NSAMR, R4DAT(1,J), S1, B, S2, S3)
          LAG = NOPT(IDFILT)
          IF (LAG .GT. 0) THEN
            NXST = 1
            NYST = 1024 - LAG
            NSTEP = 1
          ELSE IF (LAG .LT. 0) THEN
            NXST = 1024 - LAG
            NYST = 1
            NSTEP = -1
          ELSE
            GO TO 140
          END IF
C
C  Shift output trace by optimum lag
C
          LAG = NOPT(IDFILT)
          DO 130 I = NXST, NYST, NSTEP
            IF (LAG .GT. 0) THEN
              R4DAT(I,J) = R4DAT(I + LAG,J)
            ELSE
              R4DAT(I + LAG,J) = R4DAT(I,J)
            END IF
 130      CONTINUE
          IF (LAG .GT. 0) CALL ZERO(LAG, R4DAT(NSAMR - LAG + 1,J))
          IF (LAG .LT. 0) CALL ZERO(LAG, R4DAT(1,J))
 140    CONTINUE
      ELSE IF (IANS .EQ. 9) THEN
        IF (REPLY .EQ. 'YES') THEN
          REPLY = 'NO'
        ELSE
          REPLY = 'YES'
        END IF
      ELSE IF (IANS .EQ. 0) THEN
        RETURN
      END IF
      IF (IANS .NE. 8) THEN
C
C  STARTS FILTER CALCULATION
C
        FILTER = .FALSE.
        GO TO 10
      END IF
C
      DO 150 I = 1, 512
        XPOSNS(I) = REAL(I)
150   CONTINUE
      CALL PAPER(1)
      LA = LA / 2
      DO 160 I = 1, NSAMR
        DSERIS(I) = R4DAT(I,IDD)
        BSERIS(I) = R4DAT(I,IDB)
160   CONTINUE
      IF (REPLY .EQ. 'YES') THEN
        IFIRST = MIN(NFIRST(IDB),NFIRST(IDD))
        PRINT *, ' INPUT LAST SAMPLE NO. FOR REFERENCE TRACE :'
        READ (5,*) NLAST1
        PRINT *, ' INPUT LAST SAMPLE NO. FOR INPUT TRACE :'
        READ (5,*) NLAST2
        PRINT *, ' TAPER OR MUTE (T/M) ?'
        READ (5,170) ANS
170     FORMAT (A1)
        DO 180 I = 1, NSAMR - IFIRST + 1
          DSERIS(I) = DSERIS(I + IFIRST - 1)
          BSERIS(I) = BSERIS(I + IFIRST - 1)
180     CONTINUE
        LASTD = NLAST1 - IFIRST + 1
        LASTB = NLAST2 - IFIRST + 1
        PRINT *, LASTD, LASTB
        IF (ANS .EQ. 'T' .OR. ANS .EQ. 't') THEN
          LEND = (LASTD) * 2
          LENB = (LASTB) * 2
          PRINT *, LEND, LENB
          CALL FEJER(DSERIS(LASTD), LEND)
          CALL FEJER(BSERIS(LASTB), LENB)
          NDZ = NSAMR - LEND
          PRINT *, NDZ
          CALL ZERO(NDZ, DSERIS(LEND + 1))
          NDZ = NSAMR - LENB
          PRINT *, NDZ
          CALL ZERO(NDZ, BSERIS(LENB + 1))
        ELSE
          NDZ = NSAMR - LASTD
          CALL ZERO(NDZ, DSERIS(LASTD + 1))
          NDZ = NSAMR - LASTB
          CALL ZERO(NDZ, BSERIS(LASTB + 1))
        END IF
      END IF
      DO 270 ICOUNT = 1, NFILTS
        LA = LA * 2
        DO 190 I = 1, NSAMR
          REF(I) = DSERIS(I)
190     CONTINUE
        DO 200 I = 1, NSAMR
          RDAT(I) = BSERIS(I)
200     CONTINUE
        LCD = NSAMR * 2 + LA - 2
        CALL ZERO(NSAMR, A(1,ICOUNT))
        LB = NSAMR
        LD = NSAMR
        LL = LD + NL / 2 + 1
        LC = LA + LB - 1
        CALL ZERO(2048, C)
        CALL ZERO(1024, S1)
        CALL ZERO(1024, S2)
```

```
      CALL ZERO(1024, S3)
      CALL ZERO(1024, A(1,ICOUNT))
      PRINT *, 'LB,LD,LA,LC,LL,NL,LAG1,RFC,IFJ', LB, LD, LA, LC, LL,
     1      NL, LAG1, RFC, IFJ
      CALL SHAPEL(LB, RDAT, LD, REF, LA, A(1,ICOUNT), LC, C, LL, NL,
     1     LAG1, IND, ER, S1, S2, S3, RFC, IFJ)
      PRINT *, 'OPTIMUM LAG :', IND
      PRINT *, 'MEAN SQUARE ENERGIES :'
      WRITE (6,*) (ER(I),I=1,NL)
      NOPT(ICOUNT) = LAG1 + IND - 1
      IF (NOPT(ICOUNT) .GT. 0) THEN
        NXST = NOPT(ICOUNT) + 1
        NYST = 1
      ELSE IF (NOPT(ICOUNT) .LT. 0) THEN
        NXST = 1
        NYST = 1 - NOPT(ICOUNT)
      ELSE
        GO TO 210
      END IF
C
C  Shift output trace by optimum lag
C
      CALL MOVE(1024, 1024, C, NXST, 1024, C, NYST)
 210  ERR = ER(IND)
C
C  Plot Reference Traces and filtered output traces together
C
      XMIN = 0.01
      XMAX = 0.48
      YMIN = 0.95 - 0.3 * ICOUNT
      YMAX = YMIN + 0.25
C
C  NORMALISE OUTPUT TRACE C(LC)
C
      FNORM = REF(1)
      DO 220 I = 2, NSAMR
        FNORM = AMAX1(REF(I),FNORM)
 220  CONTINUE
      DO 230 I = 1, NSAMR
        REF(I) = REF(I) / FNORM
        C(I) = C(I) / FNORM
        RDAT(I) = BSERIS(I) / FNORM
 230  CONTINUE
      ISIZE = MAX(LB,LD)
      IF (REPLY .EQ. 'YES') ISIZE = MAX(LASTB,LASTD)
      IF (ISIZE .GT. 512) ISIZE = 512
      SIZE = REAL(ISIZE)
      CALL PSPACE(XMIN, XMAX, YMIN, YMAX)
      CALL BORDER
      CALL MAP(1.0, SIZE, -7.0, 1.0)
      CALL PTJOIN(XPOSNS, RDAT, 1, ISIZE, 1)
      CALL MAP(1.0, SIZE, -5.0, 3.0)
      CALL PTJOIN(XPOSNS, REF, 1, ISIZE, 1)
      CALL MAP(1.0, SIZE, -3.0, 5.0)
      CALL PTJOIN(XPOSNS, C, 1, ISIZE, 1)
      ERRMAX = 0.0
      DO 240 I = 1, 512
        C(I) = REF(I) - C(I)
        ERRMAX = AMAX1(ERRMAX,ABS(C(I)))
 240  CONTINUE
      ERRMAX = ERRMAX * 100.0
      CALL NORMAN(512, C)
      CALL MAP(1., SIZE, -1.0, 7.0)
      CALL PTJOIN(XPOSNS, C, 1, ISIZE, 1)
      CALL CTRMAG(10)
      CALL PLOTCS(SIZE/2, 0.5, 'MAX ERROR (% of peak ref):')
      CALL TYPENF(ERRMAX, 2)
      Y0 = YMIN - 0.05
      CALL PSPACE(XMIN, XMAX, Y0, YMIN)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
      CALL PLOTCS(0.01, 0.5, 'LENGTH = ')
      CALL TYPENI(LA)
      CALL PLOTCS(0.26, 0.5, 'MEAN SQ. ERR = ')
      CALL TYPENE(ERR, 3)
      CALL PLOTCS(0.75, 0.5, 'OPT LAG = ')
      CALL TYPENI(NOPT(ICOUNT))
C
C  PLOT FILTER AND ITS AMPLITUDE SPECTRUM
C
      RLA = REAL(LA)
      DX = 0.23
      XMIN = 0.52
      XMAX = XMIN + DX
      YMIN = 0.95 - 0.3 * (ICOUNT)
      YMAX = YMIN + 0.25
      CALL MAXSN(LA, A(1,ICOUNT), AMAX, II)
      CALL PSPACE(XMIN, XMAX, YMIN, YMAX)
      CALL BORDER
      CALL MAP(1., RLA, -AMAX, AMAX)
      CALL XAXIS
      CALL PTJOIN(XPOSNS, A(1,ICOUNT), 1, LA, 1)
      XMIN = XMAX + 0.02
      XMAX = XMIN + DX
      DO 250 I = 1, LA
        CMPB(I) = CMPLX(A(I,ICOUNT),0.0)
 250  CONTINUE
      CALL FORK(LA, CMPB, 1.0)
      DO 260 I = 1, LA
        B(I) = CABS(CMPB(I))
 260  CONTINUE
      CALL MAXSN(LA, B, BMAX, II)
      CALL PSPACE(XMIN, XMAX, YMIN, YMAX)
      RLAL = REAL(LA/2) + 1
      LAL = LA / 2 + 1
      FNYQ = .5E3 / DT
      CALL MAP(0.0, FNYQ, 0.0, BMAX)
      CALL AXES
      CALL MAP(1., RLAL, 0.0, BMAX)
      CALL BORDER
      CALL PTJOIN(XPOSNS, B, 1, LAL, 1)
 270  CONTINUE
      CALL GREND
      FILTER = .TRUE.
      GO TO 10
      END
C. Subroutine to apply gain compensation across array of traces
C
      SUBROUTINE GNCOMP(NSAMR, NCHR, R4DAT, NFIRST, DBGAIN, GCMSCL,
     1          RECDEP, NCR, IDPROC, NPROCS)
      PARAMETER (NS1=1024,NS2=60)
```

```
      DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR), DBGAIN(NCHR),
     1          GCMSCL(NCHR)
      DIMENSION RECDEP(NCHR), IDPROC(5,NCHR), NCR(2)
      REAL TEMP(NS1)
      CHARACTER ANS*1
      INTEGER KILLID(NS2)
      WRITE (6,*)'NSAMR,NCHR = ', NSAMR, NCHR
   10 PRINT *, '                                                  '
      PRINT *, '              GAIN COMPENSATION MENU              '
      PRINT *, '              ~~~~ ~~~~~~~~~~~~ ~~~~              '
      WRITE (6,20)
   20 FORMAT (/' 1    Normalise each trace wrt rms energy      ')
      WRITE (6,30)
   30 FORMAT (/' 2    Normalise each trace wrt peak amplitude  ')
      WRITE (6,40)
   40 FORMAT (/' 3    Kill / Mute traces                       ')
      WRITE (6,50)
   50 FORMAT (/' 4    Apply AGC or T-squared ramp to traces    ')
      WRITE (6,60)
   60 FORMAT (/' 5    Apply tapers to data spatially           ')
      WRITE (6,70)
   70 FORMAT (/' 6    Remove common trace                      ')
      WRITE (6,80)
   80 FORMAT (/' 7    Remove spike / D.C. from data            ')
      WRITE (6,90)
   90 FORMAT (/' 8    Correct trace misalignment               ')
      WRITE (6,100)
  100 FORMAT (/' 9    Apply / Enter channel gains              ')
      WRITE (6,110)
  110 FORMAT (/' 10   Enter first break samples                ')
      WRITE (6,120)
  120 FORMAT (/' 11   Apply mute to channels    (Cos taper)    ')
      PRINT*
      READ (5,*) IOPT
      IF (IOPT .EQ. 1) THEN
        NPROCS = NPROCS + 1
        IDPROC(1,NPROCS) = 2
        IDPROC(2,NPROCS) = 0
        DO 130 J = 1, NCHR
          CALL RMSERR(NSAMR, R4DAT(1,J), TEMP(J))
  130   CONTINUE
        CALL MAXSN(NCHR, TEMP, RMSMAX, MAXTRC)
        DO 150 J = 1, NCHR
          IF (TEMP(J) .EQ. 0.0) GO TO 150
          SCALE = RMSMAX / TEMP(J)
          PRINT *, 'SCALE #', J, ' = ', SCALE
          GCMSCL(J) = GCMSCL(J) * SCALE
          DO 140 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J) * SCALE
  140     CONTINUE
  150   CONTINUE
        PRINT *, GCMSCL
      ELSE IF (IOPT .EQ. 2) THEN
        NPROCS = NPROCS + 1
        IDPROC(1,NPROCS) = 2
        IDPROC(2,NPROCS) = 1
        DO 160 J = 1, NCHR
          CALL MAXAMP(NSAMR, R4DAT(1,J), TEMP(J), INDAMP)
  160   CONTINUE
        CALL MAXSN(NCHR, TEMP, BIGAMP, II)
        DO 180 J = 1, NCHR
          IF (TEMP(J) .EQ. 0) GO TO 180
          SCALE = BIGAMP / TEMP(J)
          GCMSCL(J) = GCMSCL(J) * SCALE
          DO 170 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J) * SCALE
  170     CONTINUE
  180   CONTINUE
        PRINT *, GCMSCL
      ELSE IF (IOPT .EQ. 3) THEN
        PRINT *, 'Enter 1 to kill channels; 0 to TAPER ends :'
        READ (5,*) IKM
        IF (IKM .EQ. 1) THEN
          PRINT *, 'Enter No. of channels to be killed   :'
          READ (5,*) NKILLS
          DO 190 I = 1, NKILLS
            PRINT *, ' Kill #', I, ' : '
            READ (5,*) KILLID(I)
  190     CONTINUE
          DO 200 I = 1, NKILLS
            CALL ZERO(NSAMR, R4DAT(1,KILLID(I)))
  200     CONTINUE
        ELSE
          WRITE (6,*)'ENTER START AND END OF TAPER IN SAMPLES :'
          WRITE (6,*)'(TAPERS TO ZERO AT TAPER END)'
          READ (5,*) NTPST, NTPEND
          IF (NTPST .LT. NTPEND) THEN
            LENTAP = NTPEND - NTPST + 1
            WRITE (6,*)'ENTER FIRST AND LAST TRACE TO APPLY TO :'
            READ (5,*) NTR0, NTR1
            DO 230 J = NTR0, NTR1
              DO 210 I = 1, LENTAP
                FAC = REAL(LENTAP - I) / REAL(LENTAP)
                R4DAT(I + NTPST,J) = R4DAT(I + NTPST,J) * FAC
  210         CONTINUE
              DO 220 I = NTPEND + 2, NSAMR
                R4DAT(I,J) = 0.0
  220         CONTINUE
  230       CONTINUE
          ELSE
            LENTAP = NTPST - NTPEND + 1
            WRITE (6,*)'ENTER FIRST AND LAST TRACE TO APPLY TO :'
            READ (5,*) NTR0, NTR1
            DO 260 J = NTR0, NTR1
              DO 240 I = 1, LENTAP
                FAC = REAL(LENTAP - I) / REAL(LENTAP)
                R4DAT(NTPST - I,J) = R4DAT(NTPST - I,J) * FAC
  240         CONTINUE
              DO 250 I = 1, NTPEND - 1
                R4DAT(I,J) = 0.0
  250         CONTINUE
  260       CONTINUE
          END IF
        END IF

      ELSE IF (IOPT .EQ. 4) THEN
        NPROCS = NPROCS + 1
        IDPROC(1,NPROCS) = 6
        WRITE (6,*)'Ramp or AGC or reDefine data :'
        READ (5,490) ANS
```

```
      IF (ANS .EQ. 'R' .OR. ANS .EQ. 'r') THEN
        DO 280 J = 1, NCHR
          DO 270 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J) * (I - 1) ** 2 / 10000
270       CONTINUE
280     CONTINUE
        WRITE (6,*)'Taper (Y/N) '
        READ (5,490) ANS
        IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
          WRITE (6,*)'Enter length of taper in samples :'
          READ (5,*) LENTAP
          NTAP0 = NSAMR - LENTAP
          DO 300 J = 1, NCHR
            DO 290 I = NTAP0, NSAMR
              TAP = 1.0 - REAL(I - NTAP0) / REAL(LENTAP)
              IF (I .GT. NTAP0 + LENTAP) TAP = 0.0
              R4DAT(I,J) = R4DAT(I,J) * TAP
290         CONTINUE
300       CONTINUE
        END IF
      ELSE IF (ANS .EQ. 'D' .OR. ANS .EQ. 'd') THEN
        WRITE (6,*)'ENTER SPIKE (1),FLAT(2),T-RAMP(3),T1/2-RAMP(4)'
        WRITE (6,*)'T-.5 RAMP(5)'
        READ (5,*) IOP
        IF (IOP .EQ. 1) THEN
          DO 310 J = 1, NCHR
            CALL ZERO(NSAMR, R4DAT(1,J))
            R4DAT(NSAMR/2 + 1,J) = 1.0
310       CONTINUE
        ELSE IF (IOP .EQ. 2) THEN
          DO 330 J = 1, NCHR
            DO 320 I = 1, NSAMR
              R4DAT(I,J) = 1.0
320         CONTINUE
330       CONTINUE
        ELSE IF (IOP .EQ. 3) THEN
          DO 350 J = 1, NCHR
            DO 340 I = 1, NSAMR
              R4DAT(I,J) = REAL(I - 1)
340         CONTINUE
350       CONTINUE
        ELSE IF (IOP .EQ. 4) THEN
          DO 370 J = 1, NCHR
            DO 360 I = 1, NSAMR
              R4DAT(I,J) = SQRT(REAL(I - 1))
360         CONTINUE
370       CONTINUE
        ELSE IF (IOP .EQ. 5) THEN
          DO 390 J = 1, NCHR
            DO 380 I = 1, NSAMR
              R4DAT(I,J) = 1. / SQRT(REAL(I))
380         CONTINUE
390       CONTINUE
        END IF
      ELSE
        WRITE (6,*)'Enter length of AGC window in samples :'
        READ (5,*) LENAGC
        IDPROC(2,NPROCS) = LENAGC
        DO 400 J = 1, NCHR
          CALL AGC(NSAMR, 1, R4DAT(1,J), LENAGC)
400     CONTINUE
        END IF
      ELSE IF (IOPT .EQ. 5) THEN
        WRITE (6,*)'Length of taper to be applied in traces' //
     1        '(affects L-1 traces):'
        READ (5,*) LTAPER
        WRITE (6,*)'Enter first and last traces with significant data:'
        READ (5,*) NTRAC0, NTRAC1
        PI = 3.1415926535
        WRITE (6,*)'Apply / Remove  Taper (A/R):'
        READ (5,490) ANS
        DO 420 J = 1, LTAPER
          THETA = PI * REAL(J) / REAL(LTAPER)
          FAC = 0.5 * (1.0 - COS(THETA))
          IF (ANS .EQ. 'R' .OR. ANS .EQ. 'r') FAC = 1.0 / FAC
          NTR0 = NTRAC0 - 1 + J
          NTR1 = NTRAC1 + 1 - J
          IF (NTR0 .LE. 0 .OR. NTR1 .GT. NCHR) GO TO 420
          DO 410 I = 1, NSAMR
            R4DAT(I,NTR0) = R4DAT(I,NTR0) * FAC
            R4DAT(I,NTR1) = R4DAT(I,NTR1) * FAC
410       CONTINUE
420     CONTINUE
      ELSE IF (IOPT .EQ. 6) THEN
        WRITE (6,*)'Enter no. of channel to be removed :'
        READ (5,*) NCHNL0
        DO 440 J = NCHNL0, NCHR - 1
          NFIRST(J) = NFIRST(J + 1)
          RECDEP(J) = RECDEP(J + 1)
          DO 430 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J + 1)
430       CONTINUE
440     CONTINUE
        CALL ZERO(NSAMR, R4DAT(1,NCHR))
        NFIRST(NCHR) = 0
        RECDEP(NCHR) = RECDEP(2) - RECDEP(1) + RECDEP(NCHR - 1)
      ELSE IF (IOPT .EQ. 7) THEN
        WRITE (6,*)'Remove Spike or D.C.  (S/D) ?'
        READ (5,490) ANS
        IF (ANS .EQ. 'S' .OR. ANS .EQ. 's' .OR. ANS .EQ. 'M')
     1      THEN
          WRITE (6,*)'ENTER TRACE NUMBER   :'
          READ (5,*) NTRSPK
          WRITE (6,*)'ENTER SAMPLE RANGE   :'
          READ (5,*) NSMSPK, LSMSPK
          DO 450 I = NSMSPK, LSMSPK
            IF (ANS .EQ. 'M') THEN
              ALPHA = 0.0
            ELSE
              ALPHA = .5 * (R4DAT(I - 1,NTRSPK) + R4DAT(I + 1,NTRSPK))
            END IF
            R4DAT(I,NTRSPK) = ALPHA
450       CONTINUE
        ELSE
          DO 480 J = 1, NCHR
            DC = 0.0
            DO 460 I = 1, NSAMR
              DC = DC + R4DAT(I,J)
460         CONTINUE
            DC = DC / REAL(NSAMR)
```

```
          PRINT *, ' TRACE ', J, '  DC = ', DC
          DO 470 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J) - DC
470       CONTINUE
480     CONTINUE
      END IF
    ELSE IF (IOPT .EQ. 8) THEN
      WRITE (6,*)'CALCULATE COMMON TRACE MISALIGNMENT (1=Y)?'
      READ (5,*) ICORR
      IF (ICORR .EQ. 1) THEN
        WRITE (6,*)'ENTER CHANNELS #1, #2  :'
        READ (5,*) I1, I2
        WRITE (6,*)'ENTER MAX LAG :'
        READ (5,*) LG
        CALL CROSS(NSAMR, R4DAT(1,I1), NSAMR, R4DAT(1,I2), LG, TEMP)
        CALL MAXSN(LG, TEMP, GMAX, II)
        CALL CROSS(NSAMR, R4DAT(1,I2), NSAMR, R4DAT(1,I1), LG, TEMP)
        CALL MAXSN(LG, TEMP, GMAX1, III)
        WRITE (6,*) GMAX, II, GMAX1, III
        IF (GMAX1 .GT. GMAX) THEN
          WRITE (6,*)'TRACE 2 LEADS TRACE1 BY :', III - 1
        ELSE
          WRITE (6,*)'TRACE 2 LAGS TRACE1 BY:', II - 1
        END IF
        WRITE (6,*)'LAG implies INCREASE times on trace2.'
        WRITE (6,*)'ENTER 0 TO EXIT 1 TO CONTINUE:'
        READ (5,*) IGO
        IF (IGO .NE. 1) GO TO 570
      END IF
      WRITE (6,*)'Shift single or range of traces  (S/R) ?'
      READ (5,490) ANS
490   FORMAT (A1)
      IF (ANS .EQ. 'S' .OR. ANS .EQ. 's') THEN
        WRITE (6,*)'Enter no. of trace :'
        READ (5,*) NTRA
        WRITE (6,*)'POSITIVE shift reduces travel time!'
        WRITE (6,*)'Enter shift (rotational) to be applied :'
        READ (5,*) NCHANG
        WRITE (6,*)'ENTER FIRST SAMPLE TO SHIFT :'
        READ (5,*) ITOSHF
        DO 500 I = ITOSHF, NSAMR - NCHANG
          IF (I .GT. NSAMR) GO TO 500
          IF ((I + NCHANG) .LT. ITOSHF) THEN
            TEMP(I) = 0.0
            GO TO 500
          ELSE
            TEMP(I) = R4DAT(I + NCHANG,NTRA)
          END IF
500     CONTINUE
        DO 510 I = NSAMR - NCHANG + 1, NSAMR
          IF (I .GT. NSAMR) GO TO 510
          TEMP(I) = R4DAT(I - NSAMR + NCHANG,NTRA)
510     CONTINUE
        DO 520 I = 1, NSAMR
          R4DAT(I,NTRA) = TEMP(I)
520     CONTINUE
        WRITE (6,*)'Taper the trace (Y/N) ?'
        READ (5,490) ANS
        IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
          WRITE (6,*)'Enter start of taper in samples :'
          READ (5,*) NTAP0
          WRITE (6,*)'Enter length of taper in samples :'
          READ (5,*) LENTAP
          DO 530 I = NTAP0, NSAMR
            TAP = 1.0 - REAL(I - NTAP0) / REAL(LENTAP)
            IF (I .GT. NTAP0 + LENTAP) TAP = 0.0
            R4DAT(I,NTRA) = R4DAT(I,NTRA) * TAP
530       CONTINUE
        END IF
      ELSE
        WRITE (6,*)'ENTER 1ST AND LAST TRACES TO SHIFT : '
        READ (5,*) NTOGO0, NTOGO1
        WRITE (6,*)'POSITIVE shift reduces travel time of traces!'
        WRITE (6,*)'ENTER SHIFT TO APPLY IN SAMPLES :'
        READ (5,*) NSHIFT
        DO 570 J = NTOGO0, NTOGO1
          NFIRST(J) = NFIRST(J) - NSHIFT
          AVER0 = 0.0
          DO 540 I = 1, 50
            AVER0 = AVER0 + R4DAT(I,J)
540       CONTINUE
          AVER0 = AVER0 / 50.0
          AVERAG = 0.0
          DO 550 I = NSAMR / 2 + 1, NSAMR
            AVERAG = AVERAG + R4DAT(I,J)
550       CONTINUE
          AVERAG = 2.0 * AVERAG / REAL(NSAMR)
          ISHIFT = NSHIFT
          ISIG = ISIGN(1,ISHIFT)
          I0 = 1
          IL = NSAMR
          IF (ISIG .LT. 0) THEN
            I0 = NSAMR
            IL = 1
          END IF
          DO 560 I = I0, IL, ISIG
            IF (I + ISHIFT .LE. 0) THEN
              R4DAT(I,J) = AVER0
            ELSE IF (I + ISHIFT .LE. NSAMR) THEN
              R4DAT(I,J) = R4DAT(I + ISHIFT,J)
            ELSE
              R4DAT(I,J) = AVERAG
            END IF
560       CONTINUE
570     CONTINUE
      END IF
    ELSE IF (IOPT .EQ. 9) THEN
      WRITE (6,*)'Apply current gains or enter New ones (A/N)?'
      READ (5,490) ANS
      IF (ANS .EQ. 'A' .OR. ANS .EQ. 'a') THEN
        NCR(1) = 12
        NCR(2) = 14
        IF (NCR(1) .EQ. 12 .AND. NCR(2) .GE. 13) THEN
          CALL ZERO(NCHR, DBGAIN)
        END IF
        DO 590 J = 1, NCHR
          RMULT = 10 ** (-DBGAIN(J)/20.0)
          DBGAIN(J) = 0.0
          DO 580 I = 1, NSAMR
            R4DAT(I,J) = R4DAT(I,J) * RMULT
```

```
 580        CONTINUE
 590      CONTINUE
          NPROCS = NPROCS + 1
          IDPROC(1,NPROCS) = 1
          IDPROC(2,NPROCS) = 0
          WRITE (6,*)'Equate rms amps of common receiver channels ?'
          READ (5,490) ANS
          IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
            CALL RMSERR(NSAMR, R4DAT(1,NCR(1)), SCALE1, INDAMP)
            CALL RMSERR(NSAMR, R4DAT(1,NCR(2)), SCALE2, INDAMP)
            SCALE = SCALE1 / SCALE2
C  N.B. CHANGED NEXT LINE
            IF (NCR(1) .EQ. 12 .AND. NCR(2) .GE. 13) THEN
C
C  COMMON SHOT TRACES ARE TOP 12 AND BOTTOM 12 .
C
              DO 610 J = 13, 24
                DO 600 I = 1, NSAMR
                  R4DAT(I,J) = R4DAT(I,J) * SCALE
 600            CONTINUE
 610          CONTINUE
            ELSE
C
C ASSUME NCR(1) IS HIGHER COMMON TRACE
C        AND     COMMON SHOT TRACES ARE ALTERNATE
C
              IDTRAC = 2 - MOD(NCR(2),2)
              PRINT *, 'IDTRAC =', IDTRAC, ' SHOULD BE 1'
              DO 630 J = IDTRAC, NCHR, 2
                DO 620 I = 1, NSAMR
                  R4DAT(I,J) = R4DAT(I,J) * SCALE
 620            CONTINUE
 630          CONTINUE
              IDPROC(2,NPROCS) = 1
            END IF
          END IF
        ELSE
          DO 640 I = 1, NCHR
            WRITE (6,*)'Enter gain in dB for channel #', I
            READ (5,*) DBGAIN(I)
 640      CONTINUE
        END IF
      ELSE IF (IOPT .EQ. 10) THEN
        WRITE (6,*)'AUTOMATIC PICK : 1=Y 0=N ?'
        READ (5,*) IREPLY
        IF (IREPLY .EQ. 1) THEN
          WRITE (6,*)'ENTER FIRST SAMPLE TO BEGIN ESTIMATE:'
          READ (5,*) NO
          WRITE (6,*)'ENTER significant no. of S.D.s:'
          READ (5,*) SSDS
          DO 680 J = 1, NCHR
            DO 670 I = NO, NSAMR
              RMEAN = 0.0
              DO 650 III = 1, I - 1
                RMEAN = RMEAN + R4DAT(III,J)
 650          CONTINUE
              RMEAN = RMEAN / REAL(I - 1)
              RMERR = 0.0
              DO 660 III = 1, I - 1
                DIF = R4DAT(III,J) - RMEAN
                RMERR = RMERR + DIF ** 2
 660          CONTINUE
              RMERR = RMERR / REAL(I - 1)
              RMERR = SQRT(RMERR)
              DIF0 = ABS(R4DAT(I,J) - R4DAT(I - 1,J))
C
C  Criterion that 1st difference is greater than NSSDS Standard
C  Deviations from mean value to that sample.
C
              IF (DIF0 .GT. SSDS*RMERR) THEN
                NFIRST(J) = I
                GO TO 680
              END IF
 670        CONTINUE
 680      CONTINUE
        ELSE
          DO 690 I = 1, NCHR
            WRITE (6,*)'Enter 1st break SAMPLE for channel #', I
            READ (5,*) NFIRST(I)
 690      CONTINUE
        END IF
      ELSE IF (IOPT .EQ. 11) THEN
 700    WRITE (6,*) NFIRST
        WRITE (6,*)'APPLY SAME MUTE TO ALL TRACES (1=Y;0=N) :'
        READ (5,*) IOANS
        IF (IOANS .EQ. 1) THEN
          WRITE (6,*)'Enter length of cosine taper in samps :'
          READ (5,*) NTAP10
          IF (NTAP10 .EQ. 0) GO TO 730
          WRITE (6,*)'Enter start of cosine taper (0=1st break):'
          READ (5,*) NTAP00
          DO 730 J = 1, NCHR
            NTAP0 = NFIRST(J) + NTAP00
            NTAP1 = NTAP10 + NTAP0
            IF (NTAP1 - 1 .GT. NSAMR .OR. NTAP0 .LT. 1) THEN
              WRITE (6,*)'CHANNEL ', J
              WRITE (6,*)'ERROR NTAP0,NTAP1 = ', NTAP0, NTAP1
              GO TO 700
            END IF
            DO 710 I = NTAP0 + 1, NTAP1 - 1
              FAC = REAL(I - NTAP0) / REAL(NTAP1 - NTAP0)
              FAC = FAC * 3.1415926535
              FAC = 0.5 * (1.0 - COS(FAC))
              R4DAT(I,J) = R4DAT(I,J) * FAC
 710        CONTINUE
            DO 720 I = 1, NTAP0
              R4DAT(I,J) = 0.0
 720        CONTINUE
 730      CONTINUE
        ELSE
 740      WRITE (6,*)'Enter length of cosine taper (0=NO mute):'
          READ (5,*) NTAP10
          IF (NTAP1 .EQ. 0) GO TO 780
          WRITE (6,*)'Enter start of cosine taper (0=1st break):'
          READ (5,*) NTAP00
          WRITE (6,*)'ENTER FIRST AND LAST TRACES TO APPLY MUTE'
          READ (5,*) NGO0, NGO1
          DO 780 J = NGO0, NGO1
            NTAP0 = NFIRST(J) + NTAP00
            NTAP1 = NTAP10 + NTAP0
```

```
          IF (NTAP1 - 1 .GT. NSAMR .OR. NTAP0 .LT. 1) THEN
            WRITE (6,*)'ERROR NTAP0,NTAP1 = ', NTAP0, NTAP1
            GO TO 780
 750      END IF
          DO 760 I = NTAP0 + 1, NTAP1 - 1
            FAC = REAL(I - NTAP0) / REAL(NTAP1 - NTAP0)
            FAC = FAC * 3.14159265
            FAC = 0.5 * (1.0 - COS(FAC))
            R4DAT(I,J) = R4DAT(I,J) * FAC
 760      CONTINUE
          DO 770 I = 1, NTAP0
            R4DAT(I,J) = 0.0
 770      CONTINUE
 780    CONTINUE
      END IF
    ELSE IF (IOPT .EQ. 0) THEN
      RETURN
    END IF
    GO TO 10
    END
C
    SUBROUTINE RMSERR(NSAMR, X, RMS)
    REAL X(NSAMR)
    RMS = 0.0
    DO 10 I = 1, NSAMR
      RMS = RMS + X(I) ** 2
 10 CONTINUE
    RMS = RMS / NSAMR
    RMS = SQRT(RMS)
    RETURN
    END
C
    SUBROUTINE MAXAMP(NSAMR, X, AMPMAX, INDAMP)

    REAL X(NSAMR)
    AMPMAX = 0.0
    DO 10 I = 1, NSAMR
      IF (ABS(X(I)) .GT. AMPMAX) THEN
        AMPMAX = ABS(X(I))
        INDAMP = I
      END IF
 10 CONTINUE
    RETURN
    END
C
C.Subroutine to carry out simple 2D Fourier transform (Claerbout)
C
    SUBROUTINE FT2D(N1, N2, CP, SIGNA, SIGNB, CW)
    INTEGER N1, N2
    COMPLEX CP(N1,N2), CW(N2)
    REAL SIGNA, SIGNB
    DO 10 I = 1, N2
      CALL FORK(N1, CP(1,I), SIGNA)
 10 CONTINUE
    DO 40 J = 1, N1
      DO 20 K = 1, N2
        CW(K) = CP(J,K)
 20   CONTINUE
      CALL FORK(N2, CW, SIGNB)
      DO 30 L = 1, N2
        CP(J,L) = CW(L)
 30   CONTINUE
 40 CONTINUE
    RETURN
    END
C
C.    Routine to plot F-K amp. spectrum contained in the array ARR(NK,NF)
C     N.B. Sample order in K  --->  1           = -knyq
C                                   nk/2 + 1    = 0.0
C                                   nk          = +knyq
C     NF, NK    no. of frequencies ,  wavenumbers for plot
C     DT, DZ    temporal and spatial sampling intervals in microsecs and metres
C     NCHTS     no. of contour levels
C
    SUBROUTINE FKPLOT(NK, NF, ARR, DT, DZ, FMAX, NCHTS, CHTS, LOGYN)
    INTEGER NK, NF
    REAL DT, DZ, KNYQ, KMIN, KMAX, FMIN, FMAXD
    DOUBLE PRECISION ARR(NK,NF), CHTS(8)
    CHARACTER LOGYN*1
    LOGICAL UNUSED(65,1024)
    EXTERNAL J06GBY, J06GBW
    FNYQ = .5E6 / DT
    KNYQ = .5 / DZ
    FMIN = 0.0
    KMIN = -(KNYQ)
    KMAX = -KMIN
    NLF = NINT(FMAX*NF/FNYQ)
    ICH = 1
    PRINT *, 'NK, NF =', NK, NF
    PRINT *, 'KMIN,KMAX =', KMIN, KMAX
C
C  START PLOTTING ROUTINES
C
    CALL X04AAF(1, 10)
    CALL J00AAF(IFACE)
    PRINT *, IFACE
    CALL PAPER(1)
    CALL GPSTOP(30)
    CALL PSPACE(0.05, 0.75, 0.05, 0.9)
    CALL MAP(0.0, 1.0, 0.0, 1.0)
    CALL J06XAF
    CALL J06XBF(0.0, 1.0, 0.0, 1.0)
    CALL J06XFF(2)
    CALL J06XGF(1.0, 2.0)
    IF (LOGYN .EQ. 'Y') THEN
      CALL J06AHF('F-K Amplitude Spectrum (dB)')
    ELSE
      CALL J06AHF('F-K Amplitude Spectrum (linear)')
    END IF
    IFAIL = 0
    MA = 1
    NA = 1
    MB = NK
    ILAB = 2
    IHIGH = 0
    IGRID = 0
    PRINT *, 'NK,NF,NCHTS,CHTS,IFAIL,ICH', NK, NF, NCHTS, CHTS, IFAIL,
   1      ICH
    CALL PSPACE(0.05, 0.75, 0.05, 0.9)
    CALL MAP(0.0, 1.0, 0.0, 1.0)
```

```
      CALL J06XBF(0.0, 1.0, 0.0, 1.0)
      CALL J06XFF(2)
      CALL J06XGF(1.0, 2.0)
      CALL J06GBF(ARR, NK, MA, MB, NA, NLF, NCHTS, CHTS, ICH, J06GBY,
     1     ILAB, IHIGH, J06GBW, IGRID, UNUSED, IFAIL)
      PRINT *, 'IFAIL =', IFAIL
      CALL PSPACE(0.05, 0.75, 0.05, 0.9)
      PRINT *, 'KMIN,KMAX,FMIN,FMAX = ', KMIN, KMAX, FMIN, FMAX
      CALL MAP(KMIN, KMAX, FMIN, FMAX)
      CALL BORDER
      CALL AXORIG(KMIN, FMIN)
      CALL CTRMAG(15)
      CALL AXES
      PRINT *, 'IFAIL = ', IFAIL
C
C DRAW CONTOUR KEY
C
      CALL PSPACE(0.77, 0.99, 0.8, 0.9)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
      CALL BORDER
      CALL CTRMAG(20)
      CALL PCSCEN(0.5, 0.3, 'CONTOUR KEY')
      IF (LOGYN .EQ. 'Y') CALL PCSCEN(0.5, 0.8, 'dB scale')
      CALL PSPACE(0.77, 0.99, 0.5, 0.78)
      CALL BORDER
      YSIZE = REAL(NCHTS) + 0.1
      CALL MAP(0.0, 1.0, YSIZE, 0.0)
      CALL CTRMAG(12)
      DO 10 I = 1, NCHTS
        XI = REAL(I)
        HEIGHT = REAL(CHTS(I))
        CALL PLOTNI(0.1, XI, I)
        CALL PLOTNF(0.35, XI, HEIGHT, 1)
   10 CONTINUE
      CALL GREND
      RETURN
      END
C
C  Apply agc of length LEN to data in array X
      SUBROUTINE AGC(NSAMR, NCHR, X, LEN)
      REAL X(NSAMR,NCHR), XPRIME(1024)
      DO 30 J = 1, NCHR
        CALL ZERO(NSAMR, XPRIME)
        DO 10 ICEN = 1, NSAMR
          LO = LEN
          IF (ICEN .LE. LEN/2) LO = 2 * ICEN - 1
          IF (ICEN .GT. NSAMR - LEN/2) LO = (NSAMR - ICEN + 1) * 2 - 1
          CALL RMSERR(LO, X(ICEN - LO/2,J), RMS)
          IF (RMS .EQ. 0.0) GO TO 10
          XPRIME(ICEN) = X(ICEN,J) / RMS
   10   CONTINUE
        DO 20 I = 1, NSAMR
          X(I,J) = XPRIME(I)
   20   CONTINUE
   30 CONTINUE
      RETURN
      END
C
C . subroutine to calculate pie slice filter for application to FK
C spectrum
C
C  REMEMBER TO TRANSFORM TO CORRECT QUADRANTS IN MAIN ROUTINE
C   sample ordering in K space is 1 = -KNQ
C                               nk/2+1 = 0
C                               nk = +KNYQ
C  Note: must wrap around sample #1 to sample #nk before calling routine
C        must also have data arranged in appropriate sequence
C        require an odd no. of samples e.g 65,129,257
C
C
C
      SUBROUTINE PIE(NK, NF, PIEFLT, DK, DF, PORR)
      REAL PIEFLT(NF,NK), DIST, RHISLO, RHICTS, RLOSLO, RLOCTS, RM3,
     1     RM6, KKNYQ
      DOUBLE PRECISION HISLOP, HICTSL, LOSLOP, LOCTSL, M3, M6
      INTEGER KNYQ, FNYQ, K0, KL, F0, FL
      CHARACTER*1 ANS, PORR
      PI = 3.1415926535
      KNYQ = NK / 2 + 1
      KKNYQ = NK / 2 * DK
      WRITE (6,*)'ZERO QUADRANT (L/R/No) ?   -- (L = -Kspace) '
      READ (5,10) ANS
   10 FORMAT (A1)
      F0 = 1
      FL = NF
      K0 = 1
      KL = NK
      DO 20 K = 1, NK
        CALL ZERO(NF, PIEFLT(1,K))
   20 CONTINUE
      IF (ANS .EQ. 'L' .OR. ANS .EQ. 'l') THEN
        DO 30 K = 1, KNYQ - 1
          CALL ZERO(NF, PIEFLT(1,K))
   30   CONTINUE
        K0 = KNYQ
      ELSE IF (ANS .EQ. 'R' .OR. ANS .EQ. 'r') THEN
        DO 40 K = KNYQ + 1, NK
          CALL ZERO(NF, PIEFLT(1,K))
   40   CONTINUE
        KL = KNYQ
      END IF
      WRITE (6,*)'TAPER INWARDS OR OUTWARDS FROM SLOPE (I/O) ?'
      READ (5,10) ANS
      WRITE (6,*)'INPUT HIGH CUTOFF SLOPE (m/sec) (-VE for L quad) :'
      READ (5,*) HISLOP
      IF (ANS .EQ. 'O' .OR. ANS .EQ. 'o') THEN
        WRITE (6,*)'INPUT HIGH CUTOFF TAPER SLOPE  (m/sec) :'
        READ (5,*) HICTSL
        IF (HISLOP + HICTSL .EQ. 0.0) THEN
          M3 = 0.0
        ELSE
          M3 = ((HISLOP*HICTSL - 1) - SQRT(HISLOP**2 + HICTSL**2 + (
     1    HISLOP*HICTSL)**2 + 1)) / (HISLOP + HICTSL)
        END IF
        PRINT *, 'HISLOP,HICTSL,M3', HISLOP, HICTSL, M3
        MULT1 = 1
        MULT2 = 1
        IF (HICTSL .LT. 0.0) MULT1 = -1
        IF (HISLOP .LT. 0.0 .AND. HICTSL .GE. HISLOP) MULT2 = -1
      END IF
```

```
      WRITE (6,*)'INPUT LOW CUTOFF SLOPE (m/sec) (-VE for L quad) :'
      READ (5,*) LOSLOP
      IF (ANS .EQ. 'O' .OR. ANS .EQ. 'o') THEN
        WRITE (6,*)'INPUT LOW CUTOFF TAPER SLOPE (m/sec) :'
        READ (5,*) LOCTSL
        IF (LOSLOP + LOCTSL .EQ. 0.0) THEN
          M6 = 0.0
        ELSE
          M6 = ((LOSLOP*LOCTSL - 1) - SQRT(LOSLOP**2 + LOCTSL**2 + (
     1    LOSLOP*LOCTSL)**2 + 1)) / (LOSLOP + LOCTSL)
        END IF
        MULT3 = 1
        MULT4 = 1
        IF (LOCTSL .LT. 0.0) MULT3 = -1
        IF (LOSLOP .LT. 0.0 .AND. LOCTSL .LE. LOSLOP) MULT4 = -1
        PRINT *, 'LOSLOP,LOCTSL,M6', LOSLOP, LOCTSL, M6
      END IF
      WRITE (6,*)'Enter no. of wraparounds required '
      READ (5,*) NWRAPS
      IF (ANS .EQ. 'I' .OR. ANS .EQ. 'i') THEN
        WRITE (6,*)'INPUT DISTANCE IN SAMPLES FOR TAPER :'
        READ (5,*) NSAMTP
      END IF
      WRITE (6,*)'INPUT LENGTH OF TAPER FOR K-SPACE (samples) :'
      READ (5,*) LNTAPK
      WRITE (6,*)'INPUT LENGTH OF TAPER FOR F-SPACE (samples) :'
      READ (5,*) LNTAPF
      RHISLO = REAL(HISLOP)
      RHICTS = REAL(HICTSL)
      RLOSLO = REAL(LOSLOP)
      RLOCTS = REAL(LOCTSL)
      RM3 = REAL(M3)
      RM6 = REAL(M6)
      IF (ANS .EQ. 'O' .OR. ANS .EQ. 'o') THEN
        WRITE (6,*)'Enter frequency axis intercepts Hicut, Hizero, ' //
     1        'Locut, Lozero :'
        READ (5,*) RHSLIN, RHCTIN, RLSLIN, RLCTIN
        WRITE (6,*)'RHICTS,RHCTIN,MULT1 ', RHICTS, RHCTIN, MULT1
        WRITE (6,*)'RHISLO,RHSLIN,MULT2 ', RHISLO, RHSLIN, MULT2
 50     DO 70 J = K0, KL
          JIND = 0
          IF (NWRAPS .EQ. 0 .AND. J .EQ. 33) JIND = 1
          PRINT *, 'J = ', J
          X = DK * (J - KNYQ)
          DO 60 I = 1, NF
            Y = DF * (I - 1)
            IF (DIST(X,Y,RHICTS,RHCTIN,MULT1) .GT. 0.0) THEN
              RESP = 0.0
            ELSE IF (DIST(X,Y,RHISLO,RHSLIN,MULT2) .GT. 0.0)
     1            THEN
              D1 = (Y - HISLOP*X - RHSLIN) / (HISLOP - M3)
              D2 = (Y - HICTSL*X - RHCTIN) / (HICTSL - M3)
              D1 = ABS(D1)
              D2 = ABS(D2)
C
C  NOTE : COSM3 TERM CANCELS OUT
C
              THETA = PI * D2 / (D1 + D2)
              RESP = 0.5 * (1 - COS(THETA))
            ELSE IF (DIST(X,Y,RLOSLO,RLSLIN,MULT3) .GT. 0.0)
     1            THEN
              RESP = 1.0
            ELSE IF (DIST(X,Y,RLOCTS,RLCTIN,MULT4) .GT. 0.0)
     1            THEN
              D1 = (Y - LOSLOP*X - RLSLIN) / (LOSLOP - M6)
              D2 = (Y - LOCTSL*X - RLCTIN) / (LOCTSL - M6)
              D1 = ABS(D1)
              D2 = ABS(D2)
              THETA = PI * D2 / (D1 + D2)
              RESP = 0.5 * (1 - COS(THETA))
            ELSE
              RESP = 0.0
            END IF
            IF (RESP .EQ. 0.0) GO TO 60
            IF (PIEFLT(I,J) .GT. 0.0) THEN
              PIEFLT(I,J) = PIEFLT(I,J) * RESP
            ELSE
              PIEFLT(I,J) = RESP
            END IF
 60       CONTINUE
 70     CONTINUE
        IF (NWRAPS .NE. 0) THEN
          NWRAPS = NWRAPS - 1
          RHCTIN = 2.0 * ABS(RHICTS) * KKNYQ + RHCTIN
          RHSLIN = 2.0 * ABS(RHISLO) * KKNYQ + RHSLIN
          RLSLIN = 2.0 * ABS(RLOSLO) * KKNYQ + RLSLIN
          RLCTIN = 2.0 * ABS(RLOCTS) * KKNYQ + RLCTIN
          PRINT *, 'INTERCEPTS :', RHCTIN, RHSLIN, RLSLIN, RLCTIN
          GO TO 50
        END IF
      ELSE
        HISLOP = HISLOP / (DF/DK)
        LOSLOP = LOSLOP / (DF/DK)
        MULT = 1
        IF (HISLOP .LT. 0.0 .AND. LOSLOP .GT. 0.0) MULT = -1
        D0 = -REAL(NSAMTP)
        D1 = -D0
        PRINT *, 'HISLOP,LOSLOP,D0,D1', HISLOP, LOSLOP, D0, D1
        DO 90 J = K0, KL
          X = REAL(J - KNYQ)
          DO 80 I = 1, NF
            Y = REAL(I - 1)
            IF (DIST(X,Y,RHISLO,RHSLIN,MULT) .GT. 0.0) THEN
              RESP = 0.0
            ELSE IF (DIST(X,Y,RHISLO,RHSLIN,MULT) .GT. D0 .AND. DIST(X,
     1            Y,RLOSLO,RLSLIN,1) .GT. 0.0) THEN
              THETA = DIST(X,Y,RHISLO,RHSLIN,MULT) * PI / D0
              RESP = 0.5 * (1 - COS(THETA))
              IF (DIST(X,Y,RLOSLO,RLSLIN,1) .LE. D1) THEN
                THETA = DIST(X,Y,RLOSLO,RLSLIN,1) * PI / D1
                RESP = RESP * 0.5 * (1 - COS(THETA))
              END IF
            ELSE IF (DIST(X,Y,RLOSLO,RLSLIN,1) .GT. D1) THEN
              RESP = 1.0
            ELSE IF (DIST(X,Y,RLOSLO,RLSLIN,1) .GT. 0.0) THEN
              THETA = DIST(X,Y,RLOSLO,RLSLIN,1) * PI / D1
              RESP = 0.5 * (1 - COS(THETA))
            ELSE
              RESP = 0.0
            END IF
```

```
          IF (PIEFLT(I,J) .GT. 0.0) THEN
            PIEFLT(I,J) = PIEFLT(I,J) * RESP
          ELSE
            PIEFLT(I,J) = RESP
          END IF
   80     CONTINUE
   90   CONTINUE
      END IF
      IF (LNTAPK .GT. 0) THEN
        DO 110 J = KL - LNTAPK, KL
          THETA = REAL(J - (KL - LNTAPK)) / LNTAPK * PI
          THETA = PI - THETA
          LOWLT = KL - J + K0
          FAC = 0.5 * (1.0 - COS(THETA))
          DO 100 I = 1, NF
            PIEFLT(I,J) = PIEFLT(I,J) * (FAC)
            PIEFLT(I,LOWLT) = PIEFLT(I,LOWLT) * (FAC)
  100     CONTINUE
  110   CONTINUE
      END IF
      IF (LNTAPF .GT. 0) THEN
        DO 130 J = 1, NK
          DO 120 I = 1, LNTAPF
            THETA = REAL(I - 1) / LNTAPF * PI
            FAC = 0.5 * (1.0 - COS(THETA))
            PIEFLT(I,J) = PIEFLT(I,J) * FAC
  120     CONTINUE
  130   CONTINUE
      END IF
C
C  NOW SET LOW NYQUIST (-KNYQ) TO HIGH NYQUIST (+KNYQ)
C
      DO 140 I = 1, NF
        PIEFLT(I,1) = PIEFLT(I,NK)
  140 CONTINUE
      RETURN
      END
C
      FUNCTION DIST(X, Y, M, INTERC, MULT)
      REAL DIST, M, INTERC
      DIST = ((Y - M*X - INTERC)/SQRT(1 + M**2)) * MULT
      END
C
C. Subroutine to bandpass filter data using linear dB/Octave taper
C
      SUBROUTINE BPSDBS(X, NSAMR, CX, FLOWCT, FHICUT, DBLOW, DBHIGH,
     1            FNYQ)
      REAL X(NSAMR)
      REAL ALPHA, DDBLOW, DDBHIG, F, F0LOW, F0HIGH
      COMPLEX CX(NSAMR)
      DDBLOW = (ABS(DBLOW))
      DDBHIG = (ABS(DBHIGH))
      F0LOW = 0.0D0
      IF (DDBLOW .GT. 1E-3) F0LOW = FLOWCT * 2.0E0 ** (3.0E0/DDBLOW)
      F0HIGH = FNYQ
      IF (DBHIGH .GT. 1E-3) F0HIGH = FHICUT * 2.0E0 ** (-3.0E0/DDBHIG)
      DO 10 I = 1, NSAMR
        CX(I) = CMPLX(X(I),0.0)
   10 CONTINUE
      CALL FORK(NSAMR, CX, -1.0)
      LL = NSAMR / 2 + 1
      DF = 2.0 * FNYQ / NSAMR
      DO 20 I = 1, LL
        F = ((I - 1)*DF)
        IF (F .LT. 1E-2) THEN
          ALPHA = 0.0
        ELSE IF (F .LT. F0LOW) THEN
          ALPHA = DDBLOW / 20.0E0 * (LOG10(F/F0LOW)) / (LOG10(2.0E0))
          ALPHA = 10.0E0 ** ALPHA
        ELSE IF (F .LT. F0HIGH) THEN
          ALPHA = 1.0E0
        ELSE
          ALPHA = DDBHIG / 20.0E0 * (LOG10(F0HIGH/F)) / (LOG10(2.0E0))
          ALPHA = 10.0D0 ** ALPHA
        END IF
        CX(I) = CX(I) * REAL(ALPHA)
   20 CONTINUE
      DO 30 I = LL + 1, NSAMR
        CX(I) = CONJG(CX(NSAMR - I + 2))
   30 CONTINUE
      CALL FORK(NSAMR, CX, +1.0)
      DO 40 I = 1, NSAMR
        X(I) = REAL(CX(I))
   40 CONTINUE
      RETURN
      END
C
C. SUBROUTINE TO BANDPASS FILTER DATA USING COSINE TAPER
C
      SUBROUTINE BPSCOS(X, NSAMR, CX, FLOWCT, FHICUT, FLOOFF, FHIOFF,
     1           FNYQ)
      REAL X(NSAMR)
      COMPLEX CX(NSAMR)
      PI = 3.1415926535
      SAMHZ = 0.5 * NSAMR / FNYQ
      LOCUT = INT(FLOWCT*SAMHZ) + 1
      LOOFF = INT(FLOOFF*SAMHZ) + 1
      IHICUT = INT(FHICUT*SAMHZ) + 1
      IHIOFF = INT(FHIOFF*SAMHZ) + 1
      DO 10 I = 1, NSAMR
        CX(I) = CMPLX(X(I),0.0)
   10 CONTINUE
      CALL FORK(NSAMR, CX, -1.0)
      LL = NSAMR / 2 + 1
      DO 20 I = 1, LL
        IF (I .LE. LOOFF) THEN
          CX(I) = 0.0
        ELSE IF (I .LE. LOCUT) THEN
          CX(I) = CX(I) * 0.5 * (1.0 + COS((LOCUT - I)*PI/(LOCUT -
     1    LOOFF)))
        ELSE IF (I .LE. IHICUT) THEN
          CX(I) = CX(I)
        ELSE IF (I .LE. IHIOFF) THEN
          CX(I) = CX(I) * 0.5 * (1.0 + COS((I - IHICUT)*PI/(IHIOFF -
     1    IHICUT)))
        ELSE
          CX(I) = 0.0
        END IF
   20 CONTINUE
      DO 30 I = LL + 1, NSAMR
```

```
      CX(I) = CONJG(CX(NSAMR - I + 2))
   30 CONTINUE
      CALL FORK(NSAMR, CX, +1.0)
      DO 40 I = 1, NSAMR
        X(I) = REAL(CX(I))
   40 CONTINUE
      RETURN
      END
```

```
C
C.  Additional subroutines for use with XHR programs
C   Written by M J Findlay 1987-1989
C
      SUBROUTINE RDFILE(NSAMR, NCHR, NRECS, R4DAT, NFIRST, RECDEP,
     1           DBGAIN, GCMSCL, NFILES, NFILE, NCR, NSHOT, DT, LEN,
     2           SORPOS, NPROCS, IDPROC, IPDISC, IPSOUR, INPOPT, INPCHN,
     3           A, PROC)
C
C   requires  SUBROUTINE  RDNIM1 in NIMRWSUB for TAPES :  reads in arrays to
C   R4DAT
C
      PARAMETER (NS1=1024,NS2=12)
      DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR), RECDEP(NCHR),
     1          DBGAIN(NCHR)
      DIMENSION GCMSCL(NCHR), NFILE(2), NCR(2), IDPROC(5,NCHR),
     1          TEMP(NS1)
      CHARACTER IPDISC*17, IPSOUR*4, A*180, INPOPT*3, B(9)*20
      CHARACTER*25 PROC(20)
      INTEGER*2 I2DAT(NS1,NS2)
      CHARACTER ANS*1
      IF (INPOPT .EQ. 'NEW') GO TO 70
      IF (INPOPT .EQ. 'SGY') GO TO 160
C
C  Open disc file if needed
C
      IF (IPSOUR .EQ. 'DISC') THEN
          ILEN = 25000
          OPEN (10,FILE=IPDISC,STATUS='OLD',ACCESS='DIRECT',RECL=ILEN)
      END IF
      K24 = 1024 * NCHR
      CALL ZERO(K24, R4DAT(1,1))
      IF (NFILES .EQ. 1) THEN
          PRINT *, NCHR, NSAMR, NFILE(1), INPCHN
          CALL RDNIM1(I2DAT, NCHR, NSAMR, NFILE(1), INPCHN)
          DO 20 J = 1, NCHR
              DO 10 I = 1, NSAMR
                  IVAL = I2DAT(I,J)
                  R4DAT(I,J) = REAL(IVAL)
   10         CONTINUE
   20     CONTINUE
      ELSE
          CALL RDNIM1(I2DAT, NCHR, NSAMR, NFILE(1), INPCHN)
          DO 40 J = 1, NCHR
              K = 2 * J - 1
              DO 30 I = 1, NSAMR
                  IVAL = I2DAT(I,J)
                  R4DAT(I,K) = REAL(IVAL)
   30         CONTINUE
   40     CONTINUE
          CALL REWIND(INPCHN)
          CALL RDNIM1(I2DAT, NCHR, NSAMR, NFILE(2), INPCHN)
          DO 60 J = 1, NCHR
              K = 2 * J
              DO 50 I = 1, NSAMR
                  IVAL = I2DAT(I,J)
                  R4DAT(I,K) = REAL(IVAL)
   50         CONTINUE
   60     CONTINUE
      END IF
      IF (INPCHN .EQ. 1) CALL REWIND(INPCHN)
      IF (INPCHN .EQ. 10) CLOSE (INPCHN)
      RETURN
C
   70 CONTINUE
C
C  Open disc file if needed
C
C NSHOT = NO. OF SHOT (i.d.)
C
      PRINT *, LEN
      IDCODE = (NSHOT - 1) * (NCHR + 1) + 1
      PRINT *, IDCODE, NSHOT
      WRITE (6,*)'Stack or New (1 or 0  -1 == REVERSE POLARITY ) :'
      READ (5,*) ISTACK
      IF (IPSOUR .EQ. 'DISC') THEN
          OPEN (10,FILE=IPDISC,STATUS='OLD',ACCESS='DIRECT',RECL=LEN)
      END IF
      K24 = 1024 * NCHR
C      CALL ZERO(K24,R4DAT(1,1))
      IF (ISTACK .EQ. 0) CALL ZERO(K24, R4DAT(1,1))
C
C  READ IN HEADER PARAMETERS
C
      DO 90 J = 1, NCHR
          DO 80 I = 1, 4
              IDPROC(I,J) = 0
   80     CONTINUE
   90 CONTINUE
      NPROCS = 0
      PRINT *, 'READING HEADERS ......'
      READ (10,REC=IDCODE) A, SORPOS, NRECS, RECDEP, DBGAIN, GCMSCL,
     1     NFIRST, NCR, NPROCS, IDPROC, DT, PROC
C
C  READ IN SEISMOGRAM RECORDS
C
      ISTACK = 0
      IF (GCMSCL(1) .EQ. 0.0) GCMSCL(1) = 1.0
      DO 110 J = 1, NCHR
          NREC = IDCODE + J
          READ (10,REC=NREC) (TEMP(I),I=1,NSAMR)
          DO 100 I = 1, NSAMR
              IF (ISTACK .GE. 0) THEN
                  R4DAT(I,J) = R4DAT(I,J) + TEMP(I)
              ELSE
                  R4DAT(I,J) = R4DAT(I,J) - TEMP(I)
              END IF
  100     CONTINUE
          CALL MAXSN(NSAMR, R4DAT(1,J), XMAX, IMAX)
          CALL MINSN(NSAMR, R4DAT(1,J), XMIN, IMIN)
          IF (ABS(XMIN) .GT. XMAX) THEN
              XMAX = -XMIN
              IMAX = IMIN
          END IF
  110 CONTINUE
      IF (INPCHN .EQ. 1) CALL REWIND(INPCHN)
      IF (INPCHN .EQ. 10) CLOSE (INPCHN)
      PRINT *, 'Reset parameters to defaults (Y/N)?'
      READ (5,120) ANS
  120 FORMAT (A1)
```

```
      IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
          REWIND (0)
          READ (0,130) B, INPOPT, IPDISC, OPDISC, OPFORM, IPSOUR
 130      FORMAT (A20, 8(/A20)/A3/A16/A16/A6/A4)
          A = B(1) // B(2) // B(3) // B(4) // B(5) // B(6) // B(7) // B(
     1    8) // B(9)
          WRITE (6,*) B
          WRITE (6,*) A
          NRECS = NCHR
          READ (0,140) NA, NA, NA, NA, NA, NA, NCR(1), NCR(2), SA,
     1    TOPREC, RECSEP, SA
 140      FORMAT (I4/I2/I1/I3/I3/I2/I2/I2/F6.2/F6.2/F6.2/F6.2)
          RECDEP(1) = TOPREC
          DO 150 I = 2, NRECS
              IF (I .EQ. NCR(2)) THEN
                  RECDEP(I) = RECDEP(I - 1)
              ELSE
                  RECDEP(I) = RECDEP(I - 1) + RECSEP
              END IF
 150      CONTINUE
      END IF
C
C  Check for saturation -- code removed
C
      GO TO 170
C
C  READ IN SEGY TAPE
C
 160  CONTINUE
      INPCHN = 1
      CALL SEGYRD(R4DAT, NRECS, NSAMR, NSHOT, INPCHN)
 170  RETURN
      END
C
C  Subroutine to write out data to disc file
C
      SUBROUTINE WRFILA(NSAMR, NCHR, R4DAT, NFIRST, OPFORM, OPDISC,
     1           NSHOT, LEN, A1, A2, A3, A4, A5, A6, A7, A8, A9, SORPOS,
     2           NRECS, RECDEP, DBGAIN, GCMSCL, NCR, NPROCS, IDPROC, DT,
     3           IOPCHN, PROC)
      DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR), RECDEP(NCHR), A(9)
      DIMENSION DBGAIN(NCHR), GCMSCL(NCHR), NCR(2), IDPROC(5,NCHR)
      CHARACTER OPDISC*17, OPFORM*6, A*20
      CHARACTER*20 A1, A2, A3, A4, A5, A6, A7, A8, A9
      CHARACTER*25 PROC(20)
      A(1) = A1
      A(2) = A2
      A(3) = A3
      A(4) = A4
      A(5) = A5
      A(6) = A6
      A(7) = A7
      A(8) = A8
      A(9) = A9
      NRECS = NCHR
      IF (OPFORM .EQ. 'SEQUEN') THEN
          PRINT *, 'OPTION NOT AVAILABLE YET'
      ELSE IF (OPFORM .EQ. 'DIRECT') THEN
          IDCODE = (NSHOT - 1) * (NRECS + 1) + 1
          OPEN (2,FILE=OPDISC,STATUS='UNKNOWN',FORM='UNFORMATTED',
     1          ACCESS='DIRECT',RECL=LEN)
C
C  OUTPUT PROCESSING AND DISPLAY PARAMETERS
C
          WRITE (2,REC=IDCODE) A, SORPOS, NRECS, RECDEP, DBGAIN, GCMSCL,
     1          NFIRST, NCR, NPROCS, IDPROC, DT, PROC
C
C  WRITE SEISMOGRAM RECORDS
C
          DO 10 J = 1, NRECS
              NREC = IDCODE + J
              WRITE (2,REC=NREC) (R4DAT(I,J),I=1,NSAMR)
 10       CONTINUE
      ELSE
          WRITE (6,*)'SEG-Y OUTPUT TO TAPE ATTACHED TO UNIT 19 :'
          IOPCHN = 19
          CALL SEGYWR(R4DAT, NRECS, NSAMR, NSHOT, IOPCHN)
      END IF
      CLOSE (2)
      RETURN
      END
C
C  ARRAY Plotting subroutine for seismic data
C  Plenty of interactive options included to obtain required scaled data.
C  Can apply AGC etc to plot without affecting original data
C  Allows manual (interactive) first break picking/confirmation.
C
      SUBROUTINE MENPL1(NSAMR, NCHANS, R4DAT, NFIRST, TITOFF, CHNSPL,
     1           POLART, VARARE, NPLFST, NPLLST, IOPT, SORPOS, RECDEP,
     2           NCR, DT, LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP,
     3           RECLOC, COMSHT, FILREC, NSHOT, NPROCS, IDPROC)
C
C  Subroutine for graphics output of array R4DAT
C
      PARAMETER (NS1=2048,NS2=60)
      CHARACTER*20 LOCATE, DATE, DEVICE, SORTYP, SORLOC, RECTYP, RECLOC,
     1           COMSHT
      CHARACTER*20 FILREC
      CHARACTER TITLE*20, STR1*3, FLAGBR*3, COMENT*40, ANS*1
      CHARACTER*4 RES(5)
      CHARACTER VARARE*3, TITOFF*3, CHNSPL*26, POLART*7, NONE*4, STRING*
     1           10
      REAL RECDEP(NCHANS)
      REAL A(NS1), B(NS1), RDAT(NS1,NS2), R4DAT(NSAMR,NCHANS)
      INTEGER NFIRST(NCHANS), NCR(2), IDPROC(5,NCHANS)
      CALL TIME(6, 0, RES)
      TITLE = 'X-hole Reflection'
      FLAGBR = 'OFF'
      COMENT = ' '
C
C  SET UP DUMMY PLOT ARRAY RDAT(NSAMR,NCHANS)
C
 10   DO 20 J = 1, NCHANS
          DO 20 I = 1, NSAMR
              RDAT(I,J) = R4DAT(I,J)
 20   CONTINUE
C
C  MENU FOR PLOT OPTIONS
C
 30   WRITE (6,*)
```

```
      WRITE (6,*)'               Plot Options Menu              '
      WRITE (6,*)'               ~~~~ ~~~~~~~ ~~~~            '
      WRITE (6,*)
      WRITE (6,40) TITOFF
   40 FORMAT (/'    1  Titles off or on            :', A3)
      WRITE (6,50) NPLFST, NPLLST
   50 FORMAT (/'    2  First and last samples      :', I3, 1X, I4)
      WRITE (6,60) CHNSPL
   60 FORMAT (/'    3  Channels to be plotted      :', A26)
      WRITE (6,70) POLART
   70 FORMAT (/'    4  Normal/Reverse Polarity     :', A7)
      WRITE (6,80) VARARE
   80 FORMAT (/'    5  Variable Area               :', A3)
      WRITE (6,90)
   90 FORMAT (/'    6  Plot Seismograms             ')
      WRITE (6,100) FLAGBR
  100 FORMAT (/'    7  First break flags           :', A3)
      WRITE (6,110)
  110 FORMAT (/'    8  Include comment              ')
      WRITE (6,120)
  120 FORMAT (/'    9  PRINT out window of trace    ')
      WRITE (6,130)
  130 FORMAT (/'   10  Apply AGC / Time ramp        ')
      WRITE (6,140)
  140 FORMAT (/'    0  Return to MAIN MENU')
      READ (5,*) IANSWR
      IF (IANSWR .EQ. 1) THEN
          IF (TITOFF .EQ. 'OFF') THEN
              TITOFF = 'ON'
          ELSE
              TITOFF = 'OFF'
          END IF
      END IF
      IF (IANSWR .EQ. 2) THEN
          WRITE (6,*)'1st and last samples to be plotted  :'
          READ (5,*) NPLFST, NPLLST
      END IF
      IF (IANSWR .EQ. 3) THEN
          WRITE (6,*)'              SELECT OPTION              '
          WRITE (6,*)'  1    All channels                      '
          WRITE (6,*)'  2    Odd channels                      '
          WRITE (6,*)'  3    Even channels                     '
          WRITE (6,*)'  4    All omitting top common channel'
          READ (5,*) IOPT
          IF (IOPT .EQ. 1) CHNSPL = 'ALL'
          IF (IOPT .EQ. 2) CHNSPL = 'ODD'
          IF (IOPT .EQ. 3) CHNSPL = 'EVEN'
          IF (IOPT .EQ. 4) CHNSPL = 'ALL W/O TOP COMMON CHANNEL'
      END IF
      IF (IANSWR .EQ. 4) THEN
          IF (POLART .EQ. 'REVERSE') THEN
              POLART = 'NORMAL'
          ELSE
              POLART = 'REVERSE'
          END IF
      END IF
      IF (IANSWR .EQ. 5) THEN
          IF (VARARE .EQ. 'OFF') THEN
              VARARE = 'ON'
          ELSE
              VARARE = 'OFF'
          END IF
      END IF
      IF (IANSWR .EQ. 6) THEN
C
C LX=NSAMR,LY=NCHR2,X=R4DAT,NFILE=NFILE(1),NFILE2=NFILE(2),NSH=IDSH,NR
C IDRH,
C   NCR1,NCR2=NCR(1),NCR(2),A & B ARE ARRAYS OF LEN 1024 TIMES IS ARRA
C OF 5
C NONE IS A4 STRING
C  units : DT in microsecs                             50
        NCHR2 = NCHANS
        NONE = 'None'
        TMIN = (NPLFST - 1) * DT * 1E-3
        TMAX = (NPLLST - 1) * DT * 1E-3
        THYD = TOPREC
        DZ = RECSEP
        SAMF = REAL(NPLFST)
        SAML = REAL(NPLLST)
        RNCHR = REAL(NCHR2) + 1.0
C
C  Initialise the plotting format
C
        CALL PAPER(1)
        CALL PSPACE(0.0, 1.0, 0.0, 1.0)
        CALL MAP(0.0, 1.0, 0.0, 1.0)
        CALL J06XAF
        CALL J06XBF(0.0, 1.0, 0.0, 1.0)
        CALL J06XFF(2)
        CALL J06XGF(1.0, 2.0)
        IF (TITOFF .EQ. 'OFF') GO TO 160
        CALL CTRMAG(20)
        CALL PCSCEN(0.875, 0.78, TITLE)
        CALL PSPACE(0.73, 0.99, 0.49, 0.77)
        CALL BORDER
        CALL CSPACE(0.73, 1.00, 0.49, 0.77)
        CALL CTRMAG(14)
        CALL PLACE(1, 1)
        CALL HLINFD(1)
        CALL TYPECS('Site              :')
        CALL TYPECS(LOCATE)
        CALL CRLNFD
        CALL TYPECS('Date recorded     :')
        CALL TYPECS(DATE)
        CALL CRLNFD
        CALL TYPECS('Seismograph type  :')
        CALL TYPECS(DEVICE)
        CALL CRLNFD
        CALL TYPECS('Source location   :')
        CALL TYPECS(SORLOC)
        CALL CRLNFD
        CALL TYPECS('Source type       :')
        CALL TYPECS(SORTYP)
        CALL CRLNFD
        CALL TYPECS('Source depth      :')
        CALL TYPENF(SORPOS, 1)
        CALL TYPECS(' metres')
        CALL CRLNFD
        CALL TYPECS('Receiver location :')
        CALL TYPECS(RECLOC)
```

```
      CALL CRLNFD
      CALL TYPECS('Receiver type     :')
      CALL TYPECS(RECTYP)
      CALL CRLNFD
      CALL TYPECS('Common shot setup :')
      CALL TYPECS(COMSHT)
      CALL CRLNFD
      CALL TYPECS('Common receivers  :')
      IF (NCR(1) .NE. 0) THEN
          CALL TYPENI(NCR(1))
          CALL TYPENC(44)
C  COMMA
          CALL TYPENI(NCR(2))
      ELSE
          CALL TYPECS(NONE)
      END IF
      CALL CRLNFD
      CALL TYPECS('Sample rate       :')
      CALL TYPENF(DT, 1)
      CALL CTRFNT(2)
      CALL TYPENC(109)
C  Greek Mu
      CALL CTRFNT(1)
      CALL TYPECS('secs')
      CALL CRLNFD
      CALL TYPECS('Analogue filters  :')
      CALL TYPECS(FILREC)
      CALL CRLNFD
      CALL PSPACE(0.73, 0.99, 0.17, 0.47)
      CALL CSPACE(0.73, 0.99, 0.17, 0.47)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
      CALL BORDER
      CALL PLACE(5, 1)
      CALL TYPECS('PROCESSING SEQUENCE')
      CALL CRLNFD
      CALL HLINFD(1)
      DO 150 KK = 1, NPROCS
          IF (IDPROC(1,KK) .EQ. 1) THEN
              CALL TYPECS('Gain recovered ')
              IF (IDPROC(2,KK) .EQ. 1) THEN
                  CALL TYPECS(' Shot sizes equated')
              END IF
          ELSE IF (IDPROC(1,KK) .EQ. 2) THEN
              CALL TYPECS('Gain comp : ')
              STRING = 'Norm RMS'
              IF (IDPROC(2,KK) .EQ. 1) STRING = 'Norm Peak'
              CALL TYPECS(STRING)
          ELSE IF (IDPROC(1,KK) .EQ. 3) THEN
              CALL TYPECS('Tapering :')
              STRING = ' '
              IF (IDPROC(2,KK) .EQ. 0) STR1 = ' Z '
              IF (IDPROC(2,KK) .EQ. 1) STR1 = ' T '
              CALL TYPECS(STR1)
              CALL TYPENI(IDPROC(3,KK))
              IF (IDPROC(2,KK) .EQ. 0) STRING = ' Traces'
              IF (IDPROC(2,KK) .EQ. 1) STRING = ' Samples'
              CALL TYPECS(STRING)
          ELSE IF (IDPROC(1,KK) .EQ. 4) THEN
              CALL TYPECS('Bandpass : ')
              CALL TYPENI(IDPROC(2,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(3,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(4,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(5,KK))
          ELSE IF (IDPROC(1,KK) .EQ. 5) THEN
              CALL TYPECS('Waveshaping :')
              CALL TYPENI(IDPROC(2,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(3,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(4,KK))
          ELSE IF (IDPROC(1,KK) .EQ. 6) THEN
              IF (IDPROC(2,KK) .EQ. 0) THEN
                  CALL TYPECS('T-squared ramp')
              ELSE
                  CALL TYPECS('AGC : Window size = ')
                  CALL TYPENI(IDPROC(2,NPROCS))
              END IF
          ELSE IF (IDPROC(1,KK) .EQ. 7) THEN
              CALL TYPECS('FK Pie slice filter : ')
              CALL TYPENI(IDPROC(2,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(3,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(4,KK))
              CALL TYPECS('/')
              CALL TYPENI(IDPROC(5,KK))
          ELSE IF (IDPROC(1,KK) .EQ. 8) THEN
              CALL TYPECS('Median Filter  length:')
              CALL TYPENI(IDPROC(2,KK))
          ELSE IF (IDPROC(1,KK) .EQ. 9) THEN
              CALL TYPECS('D.C. Removed ')
          ELSE IF (IDPROC(1,KK) .EQ. 10) THEN
              CALL TYPECS('True amplitude recovered ')
          END IF
          CALL CRLNFD
          CALL HLINFD(1)
150   CONTINUE
      CALL PSPACE(0.73, 0.99, 0.09, 0.16)
      CALL CSPACE(0.73, 0.99, 0.09, 0.16)
      CALL BORDER
      CALL PLACE(1, 1)
      CALL TYPECS(COMENT)
      CALL PSPACE(0.73, 0.99, 0.04, 0.08)
      CALL CSPACE(0.73, 0.99, 0.04, 0.08)
      CALL BORDER
      CALL PLACE(3, 7)
      CALL TYPECS(RES(1))
      CALL TYPECS(RES(2))
      CALL SPACE(2)
      CALL TYPECS(RES(3))
      CALL TYPECS(RES(4))
      CALL TYPECS(RES(5))
160   CONTINUE
      CALL CTRMAG(10)
      CALL PSPACE(0.0, 1.0, 0.0, 1.0)
      CALL CSPACE(0.0, 1.0, 0.0, 1.0)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
```

```
      CALL PCSCEN(0.4, 0.790, 'Travel Time (milliseconds)')
      CALL PCSCEN(0.4, 0.025, 'Sample Number')
      CALL CTRORI(90.0)
      CALL PCSCEN(0.028, 0.4, 'Receiver Depth (metres)')
      CALL CTRORI(0.0)
      CALL PSPACE(0.0, 1.0, 0.07, 0.75)
      CALL MAP(0.0, 1.0, RNCHR, 0.0)
      RI = 0.035
      DO 170 J = 1, NCHR2
          RJ = REAL(J)
          CALL POSITN(RI, RJ)
          CALL TYPENF(RECDEP(J), 1)
170   CONTINUE
      CALL PSPACE(0.07, 0.70, 0.07, 0.75)
      CALL BORDER
      CALL MAP(TMIN, TMAX, RNCHR, 0.0)
      CALL AXORIG(TMAX, 0.0)
      CALL ANNOTP(1, 1)
      CALL XAXIS
      CALL YAXISI(1.0)
      CALL XGRAT
      CALL MAP(SAMF, SAML, RNCHR, 0.0)
      CALL AXORIG(SAMF, RNCHR)
      CALL ANNOTP(0, 0)
      CALL XAXIS
      XDIV = (SAML - SAMF) / 10
      CALL SAMNOR(NSAMR, NCHR2, RDAT, NPLFST, NPLLST)
      IF (IOPT .EQ. 1) THEN
          N1 = 1
          N2 = NCHR2
          NSTEP = 1
      ELSE IF (IOPT .EQ. 2) THEN
          N1 = 1
          N2 = NCHR2 - 1
          NSTEP = 2
      ELSE IF (IOPT .EQ. 3) THEN
          N1 = 2
          N2 = NCHR2
          NSTEP = 2
      ELSE IF (IOPT .EQ. 4) THEN
          N1 = 1
          N2 = NCHR2 - 1
          NSTEP = 1
      END IF
      DO 210 J = N1, N2, NSTEP
          DEP = REAL(J)
          IF (IOPT .EQ. 4 .AND. J .GT. NCR(1)) THEN
              DEP = DEP - 1.0
          END IF
          IF (IOPT .EQ. 4 .AND. J .EQ. NCR(1)) GO TO 210
          DO 180 I = 1, NSAMR
              A(I) = FLOAT(I)
              IF (POLART .EQ. 'REVERSE') THEN
                  B(I) = DEP - RDAT(I,J)
                  ISIGN = -1
              ELSE
                  B(I) = RDAT(I,J) + DEP
                  ISIGN = +1
              END IF
180       CONTINUE
          CALL PTJOIN(A, B, NPLFST, NPLLST, 1)
          IF (FLAGBR .EQ. 'OFF') GO TO 190
          CALL CTRMAG(20)
          ARROWD = DEP - 0.3
          DO 190 I = NPLFST, NPLLST
              IF (I .EQ. NFIRST(J)) CALL PLOTNC(A(I), ARROWD, 187)
190       CONTINUE
          IF (VARARE .EQ. 'OFF') GO TO 200
          DO 200 I = NPLFST, NPLLST
              IF (RDAT(I,J)*ISIGN .GT. - 0.01) GO TO 200
              CALL POSITN(A(I), DEP)
              CALL JOIN(A(I), B(I))
200       CONTINUE
210   CONTINUE
      CALL CTRMAG(10)
      CALL GREND
      GO TO 10
  END IF
  IF (IANSWR .EQ. 7) THEN
      IF (FLAGBR .EQ. 'OFF') THEN
          FLAGBR = 'ON'
      ELSE
          FLAGBR = 'OFF'
      END IF
  ELSE IF (IANSWR .EQ. 8) THEN
      PRINT *, 'COMMENT :'
      READ (5,220) COMENT
220   FORMAT (A40)
  END IF
  IF (IANSWR .EQ. 9) THEN
      WRITE (6,*)' No. of channel to be printed :'
      READ (5,*) IDCHAN
      WRITE (6,*)'Range of samples to be printed :'
      READ (5,*) NSAM0, NSAM1
      WRITE (6,230) ((I,R4DAT(I,IDCHAN)),I=NSAM0,NSAM1)
230   FORMAT (4(I4,1X,F12.1,2X))
      WRITE (6,*)'Select first break sample no. :'
      READ (5,*) NFIRST(IDCHAN)
  END IF
240 FORMAT (A1)
  IF (IANSWR .EQ. 10) THEN
      WRITE (6,*)'Ramp or AGC      :'
      READ (5,240) ANS
      IF (ANS .EQ. 'R' .OR. ANS .EQ. 'r') THEN
          WRITE (6,*)'T-Squared or Exponential (S or E) ?'
          READ (5,240) ANS
          IF (ANS .EQ. 'S' .OR. ANS .EQ. 's') THEN
              DO 260 J = 1, NCHANS
                  DO 250 I = 1, NSAMR
                      RDAT(I,J) = RDAT(I,J) * (I - 1) ** 2
250               CONTINUE
260           CONTINUE
          ELSE
              WRITE (6,*)'Enter Alpha (Exponential constant) :'
              READ (5,*) ALPHA
              DO 280 J = 1, NCHANS
                  DO 270 I = 1, NSAMR
                      TI = REAL(I - 1)
                      T1 = EXP(ALPHA*TI)
                      RDAT(I,J) = RDAT(I,J) * TI * T1
```

```
270               CONTINUE
280           CONTINUE
          END IF
      ELSE
          WRITE (6,*)'Length of AGC to be applied :'
          READ (5,*) LENAGC
          CALL AGC(NSAMR, NCHANS, RDAT, LENAGC)
      END IF
  END IF
  IF (IANSWR .NE. 0) GO TO 30
  RETURN
  END
C
C  Subroutine to median filter seismic data
C  Really only useful for zero-offset VSP
C
  SUBROUTINE MEDFIL(NSAMR, NCHR, R4DAT, NFIRST, LENFIL)
  PARAMETER (NS1=60,NS2=1024,NS3=60)
  DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR)
  REAL X(NS1), Y(NS1), DGDAT(NS2,NS3), UGDAT(NS2,NS3)
  CHARACTER*1 ANS
  NRECS = NCHR

C
C  Shift the traces :   FIRST BREAKS AT NALIGN SAMPLES
C
10 FORMAT (A1)
  LENDU = NS2 * NS3
  CALL ZERO(LENDU, UGDAT(1,1))
  PRINT *, 'REMOVE COMMON TRACE (Y/N) ?'
  READ (5,10) ANS
  IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
      WRITE (6,*)'Enter no. of trace to be removed :'
      READ (5,*) NDEAD
      DO 30 J = NDEAD, NRECS - 1
          NFIRST(J) = NFIRST(J + 1)
          DO 20 I = 1, NSAMR
              R4DAT(I,J) = R4DAT(I,J + 1)
20        CONTINUE
30    CONTINUE
      CALL ZERO(NSAMR, R4DAT(1,NRECS))
      NFIRST(NRECS) = 100
  END IF
  DO 50 J = 1, NRECS
      DO 40 I = 1, NSAMR
          DGDAT(I,J) = R4DAT(I,J)
40    CONTINUE
50 CONTINUE
  IF (NFIRST(1) .EQ. 0) THEN
      PRINT *, 'INPUT FIRST BREAK SAMPLES :'
      READ (5,*) NFIRST
  END IF
  PRINT *, 'ALIGNING TRACES...'
  NALIGN = 50
  DO 80 J = 1, NRECS
      NDT = NFIRST(J) - NALIGN
      DO 60 I = 1, NSAMR - NDT
          DGDAT(I,J) = DGDAT(I + NDT,J)
60    CONTINUE
      DO 70 I = NSAMR - NDT + 1, NSAMR
          DGDAT(I,J) = 0.0
70    CONTINUE
80 CONTINUE
C
  LN = NALIGN - 5
C
C  MUTE  before first arrivals
C
  DO 90 J = 1, NRECS
      CALL ZERO(LN, DGDAT(1,J))
90 CONTINUE
  PRINT *, 'TRACES ALIGNED ...  PLOT (Y/N)? '
  READ (5,10) ANS
  IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
      CALL MENPL1(NSAMR, NRECS, DGDAT, NFIRST)
  END IF
C
C  Apply median filter across traces
C
100 PRINT *, 'APPLYING MEDIAN FILTER ....'
  DO 140 I = LN + 1, NSAMR
      DO 110 J = 1 - LENFIL / 2, NRECS + LENFIL / 2
C  Pad with zeros
          IF (J .LT. 1 .OR. J .GT. NRECS) THEN
              X(J + LENFIL/2) = 0.0
          ELSE
              X(J + LENFIL/2) = DGDAT(I,J)
          END IF
110   CONTINUE
      DO 130 J = 1, NRECS
          DO 120 LL = 1, 48
              Y(LL) = X(LL)
120       CONTINUE
          CALL MDIAN1(Y(J), LENFIL, DGDAT(I,J))
130   CONTINUE
140 CONTINUE
C
C  DISPLAY
C
  PRINT *, 'TRACES STILL ALIGNED ...  PLOT (Y/N)? '
  READ (5,10) ANS
  IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
      CALL MENPL1(NSAMR, NRECS, DGDAT, NFIRST)
  END IF
  PRINT *, 'RE-APPLY MEDIAN FILTER (Y/N)?'
  READ (5,10) ANS
  IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') GO TO 100
C  WRITE(7,129)((I,DGDAT(I,J),I=1,NSAMR),J=1,NRECS)
C 129 FORMAT(5(I4,1X,F5.2,2X))
C
C  Shift back the traces
C
  PRINT *, 'SHIFTING BACK TRACES ...'
  DO 170 J = 1, NRECS
C     WRITE(7,*)NFIRST
      NDT = NFIRST(J) - NALIGN
C     WRITE(7,*)NDT
      DO 150 I = NSAMR, NALIGN, -1
          DGDAT(I,J) = DGDAT(I - NDT,J)
150   CONTINUE
```

```
      DO 160 I = 1, NALIGN - 1
          DGDAT(I,J) = 0.0
160   CONTINUE
170 CONTINUE
C
    PRINT *, 'TRACES SHIFTED BACK ... PLOT (Y/N)?'
    READ (5,10) ANS
    IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
        CALL MENPL1(NSAMR, NRECS, DGDAT, NFIRST)
    END IF
    PRINT *, 'DISPLAY UPGOING WAVEFIELD (Y/N)?'
    READ (5,10) ANS
    IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
        DO 190 J = 1, NRECS
            DO 180 I = 1, NSAMR
                UGDAT(I,J) = R4DAT(I,J) - DGDAT(I,J)
180         CONTINUE
190     CONTINUE
        CALL MENPL1(NSAMR, NRECS, UGDAT, NFIRST)
    END IF
    PRINT *, 'COPY WAVEFIELD TO R4DAT (Up/Down/No) ?'
    READ (5,10) ANS
    IF (ANS .EQ. 'U' .OR. ANS .EQ. 'u') THEN
        DO 210 J = 1, NRECS
            DO 200 I = 1, NSAMR
                R4DAT(I,J) = UGDAT(I,J)
200         CONTINUE
210     CONTINUE
    ELSE IF (ANS .EQ. 'D' .OR. ANS .EQ. 'd') THEN
        DO 230 J = 1, NRECS
            DO 220 I = 1, NSAMR
                R4DAT(I,J) = DGDAT(I,J)
220         CONTINUE
230     CONTINUE
    END IF
    RETURN
    END
C
C.  Subroutine to obtain median value of array X(N)  (XMED)
C   The array X is left sorted on exiting
C   SOURCE :  Numerical recipes
C
    SUBROUTINE MDIAN1(X, N, XMED)
    DIMENSION X(N)
    CALL PIKSRT(N, X)
    N2 = N / 2
    IF (2*N2 .EQ. N) THEN
        XMED = 0.5 * (X(N2) + X(N2 + 1))
    ELSE
        XMED = X(N2 + 1)
    END IF
    RETURN
    END
C
    SUBROUTINE PIKSRT(N, ARR)
C
C SOURCE :  Numerical recipes
C
    DIMENSION ARR(N)
    DO 30 J = 2, N
        A = ARR(J)
        DO 10 I = J - 1, 1, -1
            IF (ARR(I) .LE. A) GO TO 20
            ARR(I + 1) = ARR(I)
10      CONTINUE
        I = 0
20      ARR(I + 1) = A
30  CONTINUE
    RETURN
    END
C
C
    SUBROUTINE WVSHAP(NSAMR, NCHR, R4DAT, NFIRST, NCR, DT)
C
C  Version 2.0 -- Menu-driven waveshaping code
C. Routine to apply waveshaping filters to dataset.
C  Displays input,desired output, filter and filter output as time seies
C  and as amplitude spectra.
C
    PARAMETER (NS1=1024,NS2=2048,NS3=513)
    DIMENSION R4DAT(NSAMR,NCHR), NFIRST(NCHR), NCR(2)
    REAL S1(NS1), S2(NS1), S3(NS1), A(NS1), B(NS1), RDAT(NS1)
    REAL C(NS2), ER(NS3), REF(NS1), XPOSNS(NS1), DSERIS(NS1)
    REAL BSERIS(NS1), S4(NS1)
    REAL TEMP(NS1), X(NS1), ACF(NS1), TEMP2(NS1), BUTT(NS1),
   1     BUTT2(NS1)
    REAL D(NS1), P1(NS3), P2(NS3), P3(NS3), P4(NS3)
    COMPLEX CMPB(NS1), CBUTT(NS1), C1(NS1), C2(NS1), C3(NS1), C4(NS1)
    COMPLEX CXA(NS1), CXB(NS1), CXC(NS1), CXD(NS1), CTEMP(NS1)
    INTEGER NOPT(6), NDO(64)
    CHARACTER WEIGHT*3, ANS*1, REPLY*3
    LOGICAL FILTER
    CALL POWER2(NSAMR, NSAMP2)
C
    NSAMS = NSAMP2
    FNYQ = .5E6 / DT
    DF = FNYQ / REAL(NSAMS/2)
    DO 10 I = 1, NSAMS
        XPOSNS(I) = REAL(I)
10  CONTINUE
C
C  DEFAULTS
C .
    FILTER = .FALSE.
    NFILTS = 1
    LA = 64
    NL = 5
    LAG1 = -2
    RFC = 0.01
    WEIGHT = 'NO'
    IFJ = 0
    IDD = NCR(1)
    IDB = NCR(2)
    REPLY = 'YES'
C
20  WRITE (6,*)
    WRITE (6,*)'            WAVESHAPING FILTER MENU     (0 to EXIT)'
    WRITE (6,*)'            ~~~~~~~~~~~ ~~~~~~ ~~~~                '
    WRITE (6,*)
    WRITE (6,30)
```

```
 30 FORMAT (/' 1   Select "input" wavelet')
    WRITE (6,40)
 40 FORMAT (/' 2   Select "desired output" wavelet')
    WRITE (6,50)
 50 FORMAT (/' 3   Calculate filter ')
    WRITE (6,60)
 60 FORMAT (/' 4   Apply filter')
    WRITE (6,70)
 70 FORMAT (/' 0   Exit ')
    READ (5,*) IANS
    IF (IANS .EQ. 1) THEN
 80     WRITE (6,*)
        WRITE (6,*)'                "Input" wavelet selection '
        WRITE (6,*)'                ~~~~~~~~~~~~~~~~~~~~~~~~~ '
        WRITE (6,90)
 90     FORMAT (/' 1     Window of single trace ')
        WRITE (6,100)
100     FORMAT (/' 2     Extract Minimum phase wavelet ')
        WRITE (6,110)
110     FORMAT (/' 3     Plot input wavelet ')
        WRITE (6,120)
120     FORMAT (/' 0     Exit ')
        READ (5,*) IOPT
        IF (IOPT .EQ. 1) THEN
            WRITE (6,*)' Enter trace number :'
            READ (5,*) NTRACE
            WRITE (6,*)' ENTER window on trace in samples :'
            READ (5,*) NWT1, NWT2
            NWTDIF = NWT2 - NWT1 + 1
            CALL ZERO(NSAMS, ACF)
            DO 130 I = 1, NWTDIF
                ACF(I + NSAMS/2) = R4DAT(I + NWT1 - 1,NTRACE)
130         CONTINUE
            CALL NORMAN(NSAMS, ACF)
            LB = NSAMS / 2 + NWTDIF
        ELSE IF (IOPT .EQ. 2) THEN
            WRITE (6,*)'Enter 1=same window 0=selection for channels :
  1'
            READ (5,*) IREP
            IF (IREP .EQ. 1) THEN
                WRITE (6,*)'ENTER  window on traces :'
                READ (5,*) IW1, IW2
                WRITE (6,*)'ENTER NUMBER OF CHANNELS :'
                READ (5,*) NAV
                WRITE (6,*)'ENTER FIRST CHANNEL :'
                READ (5,*) NCHANN
            END IF
            CALL ZERO(NSAMS, TEMP2)
            IF (IREP .NE. 1) THEN
                WRITE (6,*)' Average over N traces ENTER N :'
                READ (5,*) NAV
            END IF
            DO 160 J = 1, NAV
                CALL ZERO(NSAMS, TEMP)
                IF (IREP .NE. 1) THEN
                    WRITE (6,*)'Enter channel number (', J, ') :'
                    READ (5,*) NCHANN
                    WRITE (6,*)'Enter window on trace :'
                    READ (5,*) IW1, IW2
                END IF
                DO 140 I = IW1, IW2
                    TEMP(I) = R4DAT(I,NCHANN)
140             CONTINUE
                CALL CROSS(NSAMS, TEMP, NSAMS, TEMP, NSAMS, ACF)
                IF (ACF(1) .NE. 0.0) THEN
                    DO 150 I = 1, NSAMS
                        TEMP2(I) = TEMP2(I) + (ACF(I)/ACF(1))
150                 CONTINUE
                END IF
                IF (IREP .EQ. 1) NCHANN = NCHANN + 1
160         CONTINUE
C
C  Do minimum phase conversion.
C
            CALL MINPH(TEMP2, NSAMS)
            WRITE (6,*)'Enter taper start and end for wavelet :'
            READ (5,*) NWT1, NWT2
            LB = NWT2
            CALL LINTAP(NSAMS, TEMP2, 0, 0, NWT1, NWT2)
C  Shift so origin is at sample NSAMS/2
            DO 170 I = 1, NSAMS / 2
                ACF(I + NSAMS/2) = TEMP2(I)
                ACF(I) = TEMP2(NSAMS/2 + I)
170         CONTINUE
C  NORMALISE INPUT WAVELET
            CALL NORMAN(NSAMS, ACF)
            LB = LB + NSAMS / 2
        ELSE IF (IOPT .EQ. 3) THEN
            CALL MAXSN(NSAMS, ACF, ACFMAX, II)
            CALL MINSN(NSAMS, ACF, ACFMIN, II)
            SCALE = ACFMAX
            IF (ABS(ACFMIN) .GT. ACFMAX) SCALE = ABS(ACFMIN)
            SCALE = SCALE * 2
            CALL PSPACE(0.05, 0.95, 0.05, 0.95)
            RX = REAL(NSAMS)
            RX0 = RX / 2 - 2.0 * REAL(NWT2) + 1
            RX1 = RX0 + 4.0 * REAL(NWT2)
            CALL MAP(RX0, RX1, -SCALE, SCALE)
            CALL BORDER
            CALL AXORIG(513.0, -2.0)
            CALL XGRATI(20.0)
            CALL CTRMAG(20)
            CALL XAXISI(20.0)
            CALL YAXISI(1.0)
            CALL CTRMAG(10)
            CALL PTJOIN(XPOSNS, ACF, 1, NSAMS, 1)
            CALL FRAME
        END IF
        IF (IOPT .NE. 0) THEN
            GO TO 80
        END IF
    ELSE IF (IANS .EQ. 2) THEN
180     WRITE (6,*)'               Desired output wavelet '
        WRITE (6,*)'               ~~~~~~~~~~~~~~~~~~~~~~ '
        WRITE (6,190)
190     FORMAT (/, '  1     Butterworth wavelet ')
        WRITE (6,200)
200     FORMAT (/, '  2     Trace in record   ')
        WRITE (6,210)
210     FORMAT (/, '  3     Plot output wavelet ')
```

```
      WRITE (6,220)
 220  FORMAT (/, '  4      MINIMUM PHASE extracted wavelet ')
      WRITE (6,230)
 230  FORMAT (/, '  0      EXIT')
      READ (5,*) IOPT
      IF (IOPT .EQ. 1) THEN
          WRITE (6,*)'Enter low-cut, slope, high-cut, slope '
          READ (5,*) BUT1, BUT2, BUT3, BUT4
C  HIGH CUT
          RNL = ALOG10((2.*(10.**(BUT4/10.))) - 1.0)
          WRITE (6,*)'RNL = ', RNL
          RNL = RNL / (2.*ALOG10(2.))
          WRITE (6,*)'RNL = ', RNL
          DO 240 J = 1, NSAMS / 2 + 1
              RFR = DF * REAL(J - 1)
              TEM = 1. / (1. + ((RFR/BUT3)**(2.*RNL)))
              BUTT(J) = SQRT(TEM)
 240      CONTINUE
C  LOW CUT
          WRITE (6,*)'NOW LOW CUT.. '
          RNL = ALOG10((2.*(10.**(BUT2/10.))) - 1.0)
          WRITE (6,*)'RNL = ', RNL
          RNL = RNL / (2.*ALOG10(2.))
          WRITE (6,*)'RNL = ', RNL
          BUTT2(1) = 0.0
          DO 250 J = 2, NSAMS / 2 + 1
              RFR = DF * REAL(J - 1)
              TEM = 1. / (1. + ((BUT1/RFR)**(2.*RNL)))
              BUTT2(J) = SQRT(TEM)
 250      CONTINUE
          DO 260 J = 1, NSAMS / 2 + 1
              BUTT(J) = BUTT(J) * BUTT2(J)
 260      CONTINUE
C  TRANSFORM TO TIME DOMAIN
          ISAM = 2
          DO 270 I = NSAMS, NSAMS / 2 + 2, -1
              BUTT(I) = BUTT(ISAM)
              ISAM = ISAM + 1
 270      CONTINUE
          DO 280 I = 1, NSAMS
              CBUTT(I) = CMPLX(BUTT(I),0.0)
 280      CONTINUE
          CALL FORK(NSAMS, CBUTT, 1.)
C  Shift origin to NSAMS/2
          DO 290 I = 1, NSAMS / 2
              BUTT2(I + NSAMS/2) = REAL(CBUTT(I))
              BUTT2(I) = REAL(CBUTT(I + NSAMS/2))
 290      CONTINUE
C  Normalise output wavelet
          CALL NORMAN(NSAMS, BUTT2)
          LD = NSAMS
      ELSE IF (IOPT .EQ. 2) THEN
          WRITE (6,*)'Enter trace i.d. number :'
          READ (5,*) NTRACE
          WRITE (6,*)'Enter taper points (4) :'
          READ (5,*) NTAP0, NTAP1, NTAP2, NTAP3
          DO 300 I = 1, NSAMS
              BUTT2(I) = R4DAT(I,NTRACE)
 300      CONTINUE
          CALL LINTAP(NSAMS, BUTT2, NTAP0, NTAP1, NTAP2, NTAP3)
          DO 310 I = NTAP0, NTAP3
              BUTT2(I - NTAP0 + NSAMS/2 + 1) = BUTT2(I)
 310      CONTINUE
          DO 320 I = 1, NSAMS / 2
              BUTT2(I) = 0.0
 320      CONTINUE
          DO 330 I = NTAP3 + 1 + NSAMS / 2, NSAMS
              BUTT2(I) = 0.0
 330      CONTINUE
          CALL NORMAN(NSAMS, BUTT2)
          WRITE (6,*)'NORMALISED OK'
          LD = NSAMS
      ELSE IF (IOPT .EQ. 3) THEN
          CALL MAXSN(NSAMS, BUTT2, BMAX, II)
          CALL MINSN(NSAMS, BUTT2, BMIN, II)
          SCALE = BMAX
          IF (ABS(BMIN) .GT. BMAX) SCALE = ABS(BMIN)
          SCALE = SCALE * 2
          CALL PSPACE(0.05, 0.95, 0.05, 0.95)
          RX = REAL(NSAMS)
          CALL MAP(RX0, RX1, -SCALE, SCALE)
          CALL BORDER
          CALL AXORIG(513.0, 0.0)
          CALL XGRATI(20.0)
          CALL PTJOIN(XPOSNS, BUTT2, 1, NSAMS, 1)
          CALL FRAME
      ELSE IF (IOPT .EQ. 4) THEN
          WRITE (6,*)'Enter 1=same window 0=selection for channels :
     1'
          READ (5,*) IREP
          IF (IREP .EQ. 1) THEN
              WRITE (6,*)'ENTER  window on traces :'
              READ (5,*) IW1, IW2
              WRITE (6,*)'ENTER NUMBER OF CHANNELS :'
              READ (5,*) NAV
              WRITE (6,*)'ENTER FIRST CHANNEL :'
              READ (5,*) NCHANN
          END IF
          CALL ZERO(NSAMS, TEMP2)
          IF (IREP .NE. 1) THEN
              WRITE (6,*)' Average over N traces ENTER N :'
              READ (5,*) NAV
          END IF
          DO 360 J = 1, NAV
              CALL ZERO(NSAMS, TEMP)
              IF (IREP .NE. 1) THEN
                  WRITE (6,*)'Enter channel number (', J, ') :'
                  READ (5,*) NCHANN
                  WRITE (6,*)'Enter window on trace :'
                  READ (5,*) IW1, IW2
              END IF
              DO 340 I = IW1, IW2
                  TEMP(I) = R4DAT(I,NCHANN)
 340          CONTINUE
              CALL CROSS(NSAMS, TEMP, NSAMS, TEMP, NSAMS, BUTT2)
              IF (BUTT2(1) .NE. 0.0) THEN
                  DO 350 I = 1, NSAMS
                      TEMP2(I) = TEMP2(I) + (BUTT2(I)/BUTT2(1))
 350              CONTINUE
              END IF
```

```
              IF (IREP .EQ. 1) NCHANN = NCHANN + 1
 360          CONTINUE
C
C  Do minimum phase conversion.
C
              CALL MINPH(TEMP2, NSAMS)
              WRITE (6,*)'Enter taper start and end for wavelet :'
              READ (5,*) NWT1, NWT2
              LD = NWT2
              CALL LINTAP(NSAMS, TEMP2, 0, 0, NWT1, NWT2)
C  Shift so origin is at sample NSAMS/2
              DO 370 I = 1, NSAMS / 2
                  BUTT2(I + NSAMS/2) = TEMP2(I)
                  BUTT2(I) = TEMP2(NSAMS/2 + I)
 370          CONTINUE
C  NORMALISE INPUT WAVELET
              CALL NORMAN(NSAMS, BUTT2)
              LD = LD + NSAMS / 2
          END IF
          IF (IOPT .NE. 0) GO TO 180
      ELSE IF (IANS .EQ. 3) THEN
          WRITE (6,*)
          WRITE (6,*)'           Calculating filter '
          WRITE (6,*)'           ~~~~~~~~~~~~~~~~~~ '
C
C  Calculating the filter coefficients
C
          WRITE (6,*)'LD =' ', LD
          WRITE (6,*)'LB = ', LB
          LB = 1024
          LD = 1024
          WRITE (6,*)'   Enter filter length in samples :'
          READ (5,*) LA
          WRITE (6,*)'   Enter no. of lags to try :'
          READ (5,*) NL
          LL = LD + NL / 2 + 1
          LL = 2048
          WRITE (6,*)'   Enter 1st lag to try (-ve == OP leads IP) :'
          READ (5,*) LAG1
          RFC = 0.02
          IFJ = 0
          CALL ZERO(NS2, C)
          CALL ZERO(NSAMS, S1)
          CALL ZERO(NSAMS, S2)
          CALL ZERO(NSAMS, S3)
          CALL ZERO(NSAMS, A)
          DO 380 I = 1, NSAMS
              B(I) = ACF(I)
C  INPUT
              D(I) = BUTT2(I)
C  OUTPUT
 380      CONTINUE
C
C  Get ACF of input trace ---> S1
          CALL CROSS(LB, B, LB, B, LA, S1)
          S1(1) = S1(1) * (1. + RFC)
C
C  Loop over specified range of lags
C
          DO 480 L = 1, NL
              LAG = LAG1 + (L - 1)
              WRITE (6,*)'LAG NO. :', LAG
C
C  Move shifted desired output to C
              CALL ZERO(2048, C)
              DO 390 J = 1, LAG
                  C(J) = D(LD - LAG + J)
 390          CONTINUE
              DO 400 J = LAG + 1, LD
                  C(J) = D(J - LAG)
 400          CONTINUE
C
C  GET XCF OF  B & Desired OP
              CALL ZERO(NS1, S2)
              CALL CROSS(LL, C, LB, B, LA, S2)
C  Solve Normal equations
              CALL EUREKA(LA, S1, S2, A, S3)
C
C  TRANSFORM FILTER AND INPUT
              WRITE (6,*)'LA = ', LA
              DO 410 I = LA + 1, NS1
                  A(I) = 0.0
 410          CONTINUE
              LA1 = LA * 7 / 8
              LA2 = LA / 8
              DO 420 I = 1, LA2
                  A(NS1 - I + 1) = A(LA - I + 1)
                  A(LA - I + 1) = 0.0
 420          CONTINUE
C
C  TAPER FILTER
              DO 430 I = 1, NS1
                  CXA(I) = CMPLX(A(I),0.0)
                  CXB(I) = CMPLX(B(I),0.0)
                  CXD(I) = CMPLX(D(I),0.0)
                  CXC(I) = CMPLX(C(I),0.0)
 430          CONTINUE
              CALL FORK(NS1, CXA, -1.0)
              CALL FORK(NS1, CXB, -1.0)
              CALL FORK(NS1, CXC, -1.0)
              CALL FORK(NS1, CXD, -1.0)
              DO 440 I = 1, NS1 / 2 + 1
                  S4(I) = CABS(CXA(I))
                  S2(I) = CABS(CXB(I))
 440          CONTINUE
C
C  Test filter
              DO 450 I = 1, NS1
                  CTEMP(I) = CXA(I) * CXB(I)
                  S4(I) = CABS(CTEMP(I))
 450          CONTINUE
              CALL FORK(NS1, CTEMP, +1.0)
              DO 460 I = 1, NS1
                  TEMP(I) = REAL(CTEMP(I))
 460          CONTINUE
C
C  Calculate ERROR
              ER(I) = 0.0
              CALL NORMAN(NS1, C)
              CALL NORMAN(NS1, TEMP)
```

```
          DO 470 I = 1, NS1
             ER(I) = ER(I) + ((C(I) - TEMP(I))**2)
 470      CONTINUE
          ER(I) = SQRT(ER(I)/REAL(NS1))
 480   CONTINUE
       WRITE (6,*)'MEAN SQUARE ENERGIES :', (ER(I),I=1,NL)
C
C  Find optimum lag
       ERMIN = 1.E10
       DO 490 I = 1, NL
          IF (ER(I) .LE. ERMIN) THEN
             ERMIN = ER(I)
             IND = I
          END IF
 490   CONTINUE
       NLAGOP = IND + LAG1 - 1
       WRITE (6,*)'OPTIMUM LAG :', NLAGOP, '(', IND, ')'
       WRITE (6,*)'Minimum energy : ', ERMIN
C
C  Now repeat filter calculation for a length of 1024 with optimum lag
C
C  Move shifted desired output to C
       LA = 1024
       LL = 2048
       CALL ZERO(2048, C)
       DO 500 J = 1, NLAGOP
          C(J) = D(LD - NLAGOP + J)
 500   CONTINUE
       DO 510 J = NLAGOP + 1, LD
          C(J) = D(J - NLAGOP)
 510   CONTINUE
C
C  Get ACF of B
       CALL ZERO(NS1, S1)
       CALL CROSS(LB, B, LB, B, LA, S1)
       S1(1) = S1(1) * (1. + RFC)
C
C  GET XCF OF  B & Desired OP
       CALL ZERO(NS1, S2)
       CALL CROSS(LL, C, LB, B, LA, S2)
C  Solve Normal equations
       CALL EUREKA(LA, S1, S2, A, S3)
C
C  TRANSFORM FILTER AND INPUT
C
C  TAPER FILTER
       L1 = NS1 / 4
       L2 = 3 * NS1 / 4
       R1 = REAL(L1)
       R2 = REAL(L2)
       DO 520 I = 1, NS1
          CXA(I) = CMPLX(A(I),0.0)
          CXB(I) = CMPLX(B(I),0.0)
          CXD(I) = CMPLX(D(I),0.0)
          CXC(I) = CMPLX(C(I),0.0)
 520   CONTINUE
       CALL FORK(NS1, CXA, -1.0)
       CALL FORK(NS1, CXB, -1.0)
       CALL FORK(NS1, CXC, -1.0)
       CALL FORK(NS1, CXD, -1.0)
C
C  Test filter
       DO 530 I = 1, NS1
          CTEMP(I) = CXA(I) * CXB(I)
 530   CONTINUE
       CALL FORK(NS1, CTEMP, +1.0)
       DO 540 I = 1, NS1
          TEMP(I) = REAL(CTEMP(I))
 540   CONTINUE
C
C  Calculate ERROR
       ERMIN = 0.0
       CALL NORMAN(NS1, C)
       CALL NORMAN(NS1, TEMP)
       DO 550 I = 1, NS1
          ERMIN = ERMIN + ((C(I) - TEMP(I))**2)
 550   CONTINUE
       ERMIN = SQRT(ERMIN/REAL(NS1))
 560   CONTINUE
       WRITE (6,*)'MEAN SQUARE ENERGY:', ERMIN

       RX = REAL(NSAMS)
       LA1 = LA * 7 / 8
       LA2 = LA / 8
C
C  Shift filter so that t=0 is at sample 513
       DO 570 I = 1, NS1
          XPOSNS(I) = REAL(I)
 570   CONTINUE
C  Rotate filter trace A
       CALL ZERO(NS1, S4)
       DO 580 I = 1, NS1 / 2
          S4(I + NS1/2) = A(I)
          S4(I) = A(I + NS1/2)
 580   CONTINUE
       WRITE (6,*)'NSAMS = ', NSAMS
       L1 = NS1 / 3
       L2 = 3 * NS1 / 4
       R1 = REAL(L1)
       R2 = REAL(L2)
       CALL PSPACE(0.05, 0.95, 0.0, 1.0)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL AXORIG(513.0, 0.0)
       CALL XGRATI(64.0)
       CALL PSPACE(0.05, 0.95, 0.8, 0.99)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL PTJOIN(XPOSNS, B, L1, L2, 1)
       CALL PSPACE(0.05, 0.95, 0.60, 0.8)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL PTJOIN(XPOSNS, D, L1, L2, 1)
       CALL PSPACE(0.05, 0.95, 0.4, .60)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL PTJOIN(XPOSNS, S4, L1, L2, 1)
       CALL PSPACE(0.05, 0.95, 0.2, 0.4)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL PTJOIN(XPOSNS, C, L1, L2, 1)
       CALL PSPACE(0.05, 0.95, 0.0, 0.2)
       CALL MAP(R1, R2, -1.0, 1.0)
       CALL PTJOIN(XPOSNS, TEMP, L1, L2, 1)
       CALL FRAME
```

```
C Now plot transforms
        DO 590 I = 1, NSAMS
            C1(I) = CMPLX(B(I),0.0)
            C2(I) = CMPLX(D(I),0.0)
            C3(I) = CMPLX(A(I),0.0)
            C4(I) = CMPLX(CTEMP(I))
 590    CONTINUE
        CALL FORK(NSAMS, C1, -1.0)
        CALL FORK(NSAMS, C2, -1.0)
        CALL FORK(NSAMS, C3, -1.0)
        CALL FORK(NSAMS, C4, -1.0)
        NSFT = NSAMS / 2 + 1
        DO 600 I = 1, NSFT
            P1(I) = CABS(C1(I))
            P2(I) = CABS(C2(I))
            P3(I) = CABS(C3(I))
            P4(I) = CABS(C4(I))
 600    CONTINUE
        CALL NORMAN(NSFT, P1)
        CALL NORMAN(NSFT, P2)
        CALL NORMAN(NSFT, P3)
        CALL NORMAN(NSFT, P4)
        R1 = 0.0
        R2 = REAL(NSFT) * DF
        L1 = 1
        L2 = NSFT
        CALL PSPACE(0.05, 0.95, 0.09, 0.99)
        CALL MAP(R1, R2,'0.0, 1.0)
        CALL AXORIG(0.0, 0.0)
        CALL XGRATI(100.0)
        CALL CTRMAG(20)
        CALL XAXISI(200.0)
        CALL CTRMAG(10)
        R1 = 0.0
        R2 = REAL(NSFT)
        L1 = REAL(R1)
        L2 = REAL(L2)
        CALL PSPACE(0.05, 0.95, 0.765, 0.99)
        CALL MAP(R1, R2, 0.0, 1.0)
        CALL PTJOIN(XPOSNS, P1, L1, L2, 1)
        CALL PSPACE(0.05, 0.95, 0.54, 0.765)
        CALL MAP(R1, R2, 0.0, 1.0)
        CALL PTJOIN(XPOSNS, P2, L1, L2, 1)
        CALL PSPACE(0.05, 0.95, 0.315, .54)
        CALL MAP(R1, R2, 0.0, 1.0)
        CALL PTJOIN(XPOSNS, P3, L1, L2, 1)
        CALL PSPACE(0.05, 0.95, 0.09, 0.315)
        CALL MAP(R1, R2, 0.0, 1.0)
        CALL PTJOIN(XPOSNS, P4, L1, L2, 1)
        CALL FRAME
    ELSE IF (IANS .EQ. 4) THEN
 610    WRITE (6,*)
        WRITE (6,*)'          FILTER APPLICATION'
        WRITE (6,*)'          ~~~~~~~~~~~~~~~~~~'
        WRITE (6,*)
        WRITE (6,*)' 1  Select channels to apply filter  '
        WRITE (6,*)
        WRITE (6,*)' 2  Apply filter to channels '
        WRITE (6,*)
        WRITE (6,*)' 0  EXIT '
        READ (5,*) IOPT
        IF (IOPT .EQ. 1) THEN
            WRITE (6,*)'Enter "1" if you want to apply to all :'
            READ (5,*) IREPL
            IF (IREPL .EQ. 1) THEN
                NAPPLY = NCHR
                DO 620 I = 1, NAPPLY
                    NDO(I) = I
 620            CONTINUE
            ELSE
                WRITE (6,*)' Enter number of channels to apply filter
     1:'
                READ (5,*) NAPPLY
                DO 630 I = 1, NAPPLY
                    WRITE (6,*)'Enter channel #', I
                    READ (5,*) NDO(I)
 630            CONTINUE
            END IF
        ELSE IF (IOPT .EQ. 2) THEN
            DO 700 I = 1, NAPPLY
                II = NDO(I)
                CALL RMSERR(NSAMR, R4DAT(1,II), RMS0)
                DO 640 J = 1, NSAMR
                    CXB(J) = CMPLX(R4DAT(J,II))
 640            CONTINUE
                DO 650 J = NSAMR + 1, NSAMS
                    CXB(J) = 0.0
 650            CONTINUE
                CALL FORK(NSAMS, CXB, -1.0)
                DO 660 J = 1, NSAMS
                    CXB(J) = CXB(J) * C3(J)
 660            CONTINUE
                CALL FORK(NSAMS, CXB, +1.0)
                DO 670 J = 1, NLAGOP
                    IF (NSAMS - NLAGOP + J .GT. NSAMR) GO TO 670
                    R4DAT(NSAMS - NLAGOP + J,II) = REAL(CXB(J))
 670            CONTINUE
                DO 680 J = NLAGOP + 1, NSAMS
                    IF (J - NLAGOP .GT. NSAMR) GO TO 680
                    R4DAT(J - NLAGOP,II) = REAL(CXB(J))
 680            CONTINUE
                CALL RMSERR(NSAMR, R4DAT(1,II), RMS1)
                SCALE = RMS0 / RMS1
                DO 690 J = 1, NSAMR
                    R4DAT(J,II) = R4DAT(J,II) * SCALE
 690            CONTINUE
 700        CONTINUE
        END IF
        IF (IOPT .NE. 0) GO TO 610
    END IF
    IF (IANS .NE. 0) THEN
        GO TO 20
    END IF
    RETURN
    END


C
    SUBROUTINE LINTAP(NX, X, N1, N2, N3, N4)
C
```

```
C  Applies linear taper to both sides of time series
C
      DIMENSION X(NX)
      DO 10 I = 1, N1
          X(I) = 0.0
   10 CONTINUE
      DO 20 I = N1 + 1, N2 - 1
          X(I) = REAL(I - N1) * X(I) / REAL(N2 - N1)
   20 CONTINUE
      DO 30 I = N3 + 1, N4 - 1
          X(I) = REAL(N4 - I) * X(I) / REAL(N4 - N3)
   30 CONTINUE
      DO 40 I = N4, NX
          X(I) = 0.0
   40 CONTINUE
      RETURN
      END
```

Appendix A.2

The reflection point loci program

REFLOC

The program REFLOC takes a given model with layer velocities and source and receiver coordinates and calculates the locus of reflection points for each source and receiver pairing. The loci are output to a file which is attached as unit 7 at run-time and these loci are then used by the VSP-CDP mapping program XHRMAP in Appendix A.3.

```
C
C. Program to find loci of reflection points for a plane parallel
C  homogeneous layered model with source at position XS,ZS ; receiver
C  at XR(i),ZR(i) ;   Locus for each source/receiver pair will be
C  contained in the arrays X(i), Z(i) : output to disc for later
C  interpolation.
C       The method involves raytracing by iterating over different
C  initial ray parameters from the source and repeating with the same
C  ray parameter from the receiver.  The intersection of the 2 raypaths
C  yields the reflector locus.
C
C  Subroutines called :  MAXSN,MINSN,ZERO from REAL*4 TSAR4_1 Lib
C                        Routines from *ghost80
C
C  Program output used by XHRMAP program
C  N.B.  May be necessary to play around with DTHETA (step angle)
C
C  Written by M J Findlay 1988
C  Modified to include anisotropy in raytracing by Ed Kragh 1989
C~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C  Modified to handle Hole-to-surface geometry as well as crosshole
C  The following convention should be used: The borehole is at x=0.
C  Space to the right is -ve x and space to the right is +ve x. If a
C  single sided survey is being processed then -ve x must be used. If a
C  two sided survey is being processed then -ve x comes first.
C~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      PROGRAM REFLOC
      REAL XS, ZS, XR(24), ZR(24), X(52000), Z(52000), T(52000),
     1     DIST(31)
      REAL XINTR(31), XINTS(31), THICK(30), VV(30), VH(30), THET(31)
      REAL DEPTH(31), TIME(31)
      LOGICAL RECLAY
      CHARACTER MODE*1, HSTYPE*1, WAVFLD*1, GATHER*1

      PI = ACOS(-1.)
      PI2 = PI / 2.0
      KOUNT = 1


C      parameterise the velocity structure  layer i ; thickness THICK(i),
C                                                   ; velocity  V(i)
C      attached to unit 1  Output goes to unit 7
C      read in the survey type.... F=full two sided ..... else single
C      sided
C
      PRINT *, 'Enter F for full two sided survey   else single sided'
      READ (1,10) HSTYPE
   10 FORMAT (A1)

      PRINT *, 'Enter R for common receiver gathers or S for common shot
     1s'
      READ (1,10) GATHER

      PRINT *, 'Enter TOTAL no of loci to be calulated '
      READ (1,*) NLOCI

      READ (1,*) NLAMAX
      IF (NLAMAX .GT. 30) THEN
        WRITE (6,*)' MAXIMUM NO. OF LAYERS = 30  : PLEASE MODIFY UNIT 1'
        STOP
      END IF

      DEPTH(1) = 0.0
      DO 20 I = 1, NLAMAX
        READ (1,*) THICK(I), VV(I)
        DEPTH(I + 1) = DEPTH(I) + THICK(I)
   20 CONTINUE
      DEPMAX = DEPTH(NLAMAX + 1)

      READ (1,*) ANISO
      DO 30 I = 1, NLAMAX
        VH(I) = VV(I) + VV(I) * ANISO
   30 CONTINUE

      READ (1,*) PHI1
C      PHI  = angle of dip      +ve for dip UP from borehole to RIGHT
      IF (GATHER .EQ. 'S' .OR. GATHER .EQ. 's') PHI1 = -PHI1
      PHI = PHI1

      READ (1,10) WAVFLD

C      wavfld is not used in this version of refloci
C      Read in display mode (Full scale/ Optimal fill)
      READ (1,10) MODE

C      Read in stepping angle for raysearch
      READ (1,*) DTHETA

C       Read in max number of takeoff angle spreads & NUMBERS FOR
C       INCREASE IN DTHETA
C
      READ (1,*) MAXLOP, NLP10, NLP100

   40 CONTINUE


C      Read in source and receiver positions
C      The borehole is at x=0 and -ve values are to the left.
C      If a full survey is being processed do the -ve half first.
      IF (GATHER .EQ. 'R' .OR. GATHER .EQ. 'r') THEN
        PRINT *, 'Borehole is at x=0    -ve is to the right'
        PRINT *, 'If processing a full survey do the -ve half first'
        PRINT *, 'Enter XREC ZREC'
        READ (1,*) XS, ZS
        IF (KOUNT .EQ. 2) XS = -XS
        XSPLOT = XS
        PRINT *, 'Enter the no of downhole shots'
        READ (1,*) NRECS
        PRINT *, 'Enter XSHOT ZSHOT for every shot'
        DO 50 I = 1, NRECS
          READ (1,*) XR(I), ZR(I)
   50   CONTINUE
      END IF


      IF (GATHER .EQ. 'S' .OR. GATHER .EQ. 's') THEN
        PRINT *, 'Borehole is at x=0    -ve is to the right'
        PRINT *, 'If processing a full survey do the -ve half first'
        PRINT *, 'Enter XSHOT ZSHOT'
        READ (1,*) XS, ZS
```

```
      PRINT *, 'Enter the no of surface receivers'
      READ (1,*) NRECS
      PRINT *, 'Enter XREC ZREC for every receiver'
      DO 60 I = 1, NRECS
        READ (1,*) XR(I), ZR(I)
 60   CONTINUE
      DO 70 I = 1, NRECS
        IF (KOUNT .EQ. 1) XR(I) = -XR(I)
 70   CONTINUE
      DO 80 I = 1, NRECS
        PRINT *, '  XR(I) =', XR(I)
 80   CONTINUE
      CALL MAXSN(NRECS, XR, XXXX, II)
      XSPLOT = -XXXX
    END IF

C     Pick out maximum and minimum values of X & Z
    CALL MAXSN(NRECS, XR, XMAX, II)
    XMAX = AMAX1(XMAX,XS)
    CALL MINSN(NRECS, XR, XMIN, II)
    XMIN = AMIN1(XMIN,XS)
    CALL MAXSN(NRECS, ZR, ZMAX, II)
    ZMAX = AMAX1(ZMAX,ZS)
    CALL MINSN(NRECS, ZR, ZMIN, II)
    ZMIN = AMIN1(ZMIN,ZS)
    XMINP = XMIN
    XMAXP = XMAX

C     Shift axes so that all Xs and Zs are >0
    XSHIFT = 0.0
    ZSHIFT = 0.0
 90 IF (XMIN .LT. 0.0) THEN
      XS = XS - XMIN
      DO 100 J = 1, NRECS
        XR(J) = XR(J) - XMIN
 100  CONTINUE
      XSHIFT = XMIN
      XMIN = 0.0
    END IF
    IF (ZMIN .LT. 0.0) THEN
      ZS = ZS - ZMIN
      DO 110 J = 1, NRECS
        ZR(J) = ZR(J) - ZMIN
 110  CONTINUE
      ZSHIFT = ZMIN
      ZMIN = 0.0
    END IF

C     Now apply rotational transformation of PHI to source&receiver
C posns
 120 DISTS = SQRT(XS**2 + ZS**2)
    IF (XS .EQ. 0.0) THEN
      ALPHA = PI2
    ELSE
      ALPHA = ZS / XS
      ALPHA = ATAN(ALPHA)
    END IF
    DZS = DISTS * (SIN(ALPHA) - SIN(ALPHA - PHI))
    DXS = DISTS * (COS(ALPHA - PHI) - COS(ALPHA))
    XS = XS + DXS
    ZS = ZS - DZS
    PRINT *, 'NEW SOURCE POSN = ', XS, ZS
    DO 130 J = 1, NRECS
      DISTR = SQRT(XR(J)**2 + ZR(J)**2)
      IF (XR(J) .EQ. 0.0) THEN
        ALPHA = PI2
      ELSE
        ALPHA = ZR(J) / XR(J)
        ALPHA = ATAN(ALPHA)
      END IF
      DZR = DISTR * (SIN(ALPHA) - SIN(ALPHA - PHI))
      DXR = DISTR * (COS(ALPHA - PHI) - COS(ALPHA))
      XR(J) = XR(J) + DXR
      ZR(J) = ZR(J) - DZR
      PRINT *, 'NEW RECEIVER POSN ', J, ' = ', XR(J), ZR(J)
 130 CONTINUE

C     If new source position is lt zero then shift source + all recs
    RESET = 0.0
    IF (XS .LT. 0.0) THEN
      RESET = XS
      XS = 0.0
      DO 140 J = 1, NRECS
        XR(J) = XR(J) - RESET
 140  CONTINUE
    END IF
    PRINT *, ' Reset = ', RESET

C      Pick out maximum and minimum values of X & Z IN SHIFTED
C COORDINATES
    CALL MAXSN(NRECS, XR, X0, II)
    XMAX = AMAX1(XMAX,X0)
    CALL MINSN(NRECS, XR, X1, II)
    XMIN = AMIN1(XMIN,X1)
    CALL MAXSN(NRECS, ZR, Z0, II)
    ZMAX = AMAX1(ZMAX,Z0)
    CALL MINSN(NRECS, ZR, Z1, II)
    ZMIN = AMIN1(ZMIN,Z1)

C  Find source layer number
    DO 150 I = 1, NLAMAX
      IF (DEPTH(I + 1) .GE. ZS) THEN
        LAYSOR = I
        GO TO 160
      END IF
 150 CONTINUE
 160 CONTINUE
    PRINT *, 'SOURCE LAYER = ', LAYSOR


    IF (KOUNT .EQ. 1) THEN
      CALL PAPER(1)
 170  CALL PSPACE(0.1, 0.9, 0.1, 0.9)
      IF (HSTYPE .EQ. 'F' .OR. HSTYPE .EQ. 'f') THEN
        CALL MAP(-XSPLOT, XSPLOT, DEPMAX, 0.0)
      ELSE
        CALL MAP(0.0, XSPLOT, DEPMAX, 0.0)
      END IF
```

```
         CALL SCALES
       END IF
       PRINT *, ' XMAXP = ', XMAXP


C***********************************************************************
C   Loop over each receiver  ; THETA0 is initial takeoff angle to
C horizontal
C                            ;    -ve ==> upwards
       IF (KOUNT .EQ. 1) WRITE (7,*) NLOCI
       DO 370 J = 1, NRECS
         PRINT *, 'RECEIVER no.: ', J, ' At depth  ', ZR(J)

C  Find receiver layer
         DO 180 NL = 1, NLAMAX
           IF (DEPTH(NL + 1) .GE. ZR(J)) THEN
             LAYREC = NL
             GO TO 190
           END IF
 180     CONTINUE
 190     CONTINUE

         IF (LAYREC .EQ. LAYSOR .OR. LAYREC .EQ. 1) THEN
           THETA0 = 0.0
           GO TO 200
         END IF
         IF (VH(LAYREC) .LE. VH(LAYREC - 1)) THEN
           THETA0 = 0.0
         ELSE
           TEM1 = VH(LAYREC) ** 2 - VH(LAYREC - 1) ** 2
           TEM2 = TEM1 * VV(LAYREC - 1) ** 2
           TEM3 = VH(LAYREC - 1) ** 4
           THETA0 = ATAN(SQRT(TEM3/TEM2))
           THETA0 = PI2 - THETA0
         END IF
 200     DTHETA = ABS(DTHETA)
         DTHET0 = DTHETA
         THETA0 = THETA0 - DTHETA + DTHETA / 100.

C  Loop over takeoff angles (Lay parameters)
         LOOP = 1
 210     DO 320 I = 1, MAXLOP
           IF (I .GT. NLP10) DTHETA = 10. * DTHET0
           IF (I .GT. NLP100) DTHETA = 100. * DTHET0
           RECLAY = .FALSE.
           CALL ZERO(31, DIST)
           CALL ZERO(31, XINTR)
           DO 220 JJ = 1, 31
             XINTS(JJ) = -1000
 220       CONTINUE
           THETA0 = THETA0 + DTHETA
           IF (THETA0 .EQ. 0.0) THETA0 = THETA0 + DTHETA
           IF (ABS(THETA0) .GE. PI2) GO TO 320
           THETA = THETA0
           NLAYER = LAYSOR
           XPO = XS
           ZPO = ZS

 C     Now start raytracing loop

 230       CONTINUE

C      Ensure ray goes deeper than rec (FOR THETA>0 :: SHALLOWER FOR
C      THETA<0)
             FAC = (ZR(J) - ZPO)
             IF (NLAYER .EQ. LAYREC) THEN
               RECLAY = .TRUE.
               IF (ABS(TAN(THETA)) .LT. ABS(FAC/(XR(J) - XPO)))
     1            GO TO 320
             END IF

             IF (THETA .LT. 0) THEN
               DZ = DEPTH(NLAYER) - ZPO
               ZPO = DEPTH(NLAYER)
             ELSE
               DZ = DEPTH(NLAYER + 1) - ZPO
               ZPO = DEPTH(NLAYER + 1)
             END IF
             IF (ABS(THETA) .EQ. PI2) THEN
               DX = 0.0
             ELSE
               DX = DZ / TAN(THETA)
             END IF
             DIST(NLAYER) = DIST(NLAYER) + SQRT(DX**2 + DZ**2)
             THET(NLAYER) = THETA
             TEMP1 = VV(NLAYER) ** 2
             TEMP2 = VH(NLAYER) ** 2
             TEMP3 = TEMP1 * COS(THETA) ** 2
             TEMP4 = TEMP2 * SIN(THETA) ** 2
             VTHETA = SQRT(TEMP1*TEMP2/(TEMP3 + TEMP4))
             TIME(NLAYER) = DIST(NLAYER) / VTHETA
             XPO = XPO + DX
             IF (THETA .LT. 0.0) THEN
               XINTS(NLAYER) = XPO
             ELSE
               XINTS(NLAYER + 1) = XPO
             END IF

C     Check for ray passing beyond receiver or out top
C
             IF (XPO .GT. XR(J)) THEN
               IF ( .NOT. RECLAY) THEN
                 IF ((THETA .LT. 0.0 .AND. FAC .LT. 0.0) .OR. (THETA .GT.
     1              0.0 .AND. FAC .GT. 0.0)) GO TO 320
               END IF
               GO TO 250
C ************* RAY BEYOND RECEIVER ===> STOP THIS RAY & START FROM
C RECEIVER
             ELSE IF (THETA .LT. 0.0 .AND. NLAYER .EQ. 1) THEN
               GO TO 250
C************* RAY OUT TOP =====> STOP THIS RAY AND START FROM RECEIVER
             ELSE IF (THETA .GE. 0.0 .AND. NLAYER .EQ. NLAMAX)
     1          THEN
               GO TO 250
C ************* RAY OUT BOTTOM ======> STOP THIS RAY AND START RAY FRO
C RECEIVER
             END IF
C
C  Check for critical reflection
C
```

```
      V0 = VH(NLAYER)
      V00 = VV(NLAYER)
      IF (THETA .LT. 0.0) THEN
        V1 = VH(NLAYER - 1)
      ELSE
        V1 = VH(NLAYER + 1)
      END IF
      IF (V0 .GE. V1) GO TO 240
C                 No crit rays
      TEM = V00 ** 2 * (V1**2 - V0**2) / V0 ** 4
      CRIT = ATAN(SQRT(1./TEM))
      CRIT = PI2 - CRIT
      IF (ABS(THETA) .LT. CRIT) THEN
C                    PRINT*,'SUPERCRITICAL AT LAYER ',NLAYER
        IF ((ZPO - ZR(J))*SIGN(1.0,THETA) .GT. 0.0) THEN
          GO TO 250
        ELSE
          GO TO 320
        END IF
C***********  SUPERCRITICAL ===> STOP THIS RAY & START FROM RECEIVER
C************* APPLY SNELL'S LAW, UPDATE LAYER NO. & RESTART RAYTRACE
      ELSE
 240    NLAYER = NLAYER + NINT(SIGN(1.0,THETA))
        TEMA = VH(NLAYER) ** 4 * VV(NLAYER - 1) ** 2
        TEMB = VV(NLAYER) ** 2
        TEMC = VH(NLAYER - 1) ** 4 / (TAN(PI2 - ABS(THETA))**2)
        TEMD = VH(NLAYER - 1) ** 2 - VH(NLAYER) ** 2
        TEMDD = VV(NLAYER - 1) ** 2
        TEME = TEMB * (TEMC + TEMDD*TEMD)
        THETA2 = ATAN(SQRT(TEMA/TEME))
        THETA2 = (PI2 - ABS(THETA2)) * SIGN(1.0,THETA)
        THETA = THETA2
        GO TO 230
      END IF
C
C  Code for tracing from receiver
C
 250  IF (LAYREC .GE. LAYSOR) THETA = THET(LAYREC)
      IF (LAYREC .LT. LAYSOR) THEN
        V0 = VH(LAYREC)
        V00 = VV(LAYREC)
        V1 = VH(LAYSOR)
        IF (V0 .GE. V1) GO TO 260
C                        No ray will reach sor layer
        TEM = V00 ** 2 * (V1**2 - V0**2) / V0 ** 4
        CRIT = ATAN(SQRT(1./TEM))
        CRIT = PI2 - CRIT
C **********  SUPERCRITICAL ===> STOP THIS RAY & TRY NEXT ONE
 260    CONTINUE
        TEMA = VH(LAYSOR) ** 4 * VV(LAYREC) ** 2
        TEMB = VV(LAYSOR) ** 2
        TEMC = (TAN(PI2 - ABS(THET(LAYSOR)))**2)
        TEMC = (1.0/TEMC) * TEMA / TEMB
        TEMD = VH(LAYREC) ** 2 - VH(LAYSOR) ** 2
        TEMDD = VV(LAYREC) ** 2
        TEME = TEMC - TEMDD * TEMD
        TEME = TEME / (VH(LAYREC)**4)
        IF (TEME .LT. 0.0) GO TO 320
        THETA = ATAN(SQRT(1.0/TEME))
        THETA = (PI2 - ABS(THETA))
          IF (ABS(THETA) .LT. CRIT) THEN
            PRINT *, ' CRIT RAY ... FOR REC CODE'
            GO TO 320
C **********  SUPERCRITICAL ===> STOP THIS RAY & TRY NEXT ONE
          END IF
        END IF
        RECLAY = .FALSE.
        IF (LAYREC .EQ. LAYSOR) THETA = THETA0
        XPO = XR(J)
        ZPO = ZR(J)
        NLAYER = LAYREC
C
C  Now start raytracing code for receiver
C
 270    CONTINUE
        FAC = (ZS - ZPO)
        IF (NLAYER .EQ. LAYSOR) THEN
          IF (ABS(TAN(THETA)) .LT. ABS(FAC/(XS - XPO))) THEN
            GO TO 320
          END IF
        END IF
        IF (THETA .LT. 0.0) THEN
          DZ = DEPTH(NLAYER) - ZPO
          ZPO = DEPTH(NLAYER)
        ELSE
          DZ = DEPTH(NLAYER + 1) - ZPO
          ZPO = DEPTH(NLAYER + 1)
        END IF
        IF (ABS(THETA) .EQ. PI2) THEN
          DX = 0.0
        ELSE
          DX = DZ / TAN(THETA)
        END IF
        DIST(NLAYER) = DIST(NLAYER) + SQRT(DX**2 + DZ**2)
        TEMP1 = VV(NLAYER) ** 2
        TEMP2 = VH(NLAYER) ** 2
        TEMP3 = TEMP1 * COS(THETA) ** 2
        TEMP4 = TEMP2 * SIN(THETA) ** 2
        VTHETA = SQRT(TEMP1*TEMP2/(TEMP3 + TEMP4))
        TIME(NLAYER) = DIST(NLAYER) / VTHETA
        XPO = XPO - DX
        IF (THETA .LT. 0.0) THEN
          XINTR(NLAYER) = XPO
        ELSE
          XINTR(NLAYER + 1) = XPO
        END IF
C
C  Check for raypath intersection
C
        IF (THETA .LT. 0.0) THEN
          IF (XINTR(NLAYER) .LE. XINTS(NLAYER)) GO TO 290
        ELSE
          IF (XINTR(NLAYER + 1) .LE. XINTS(NLAYER + 1)) GO TO 290
        END IF
C
C  Check for ray passing beyond SOURCE or out top
C
        IF (XPO .LT. XMIN) THEN
          GO TO 320
C************* RAY BEYOND RECEIVER ===> STOP THIS RAY & TRY NEXT ONE
```

```
        ELSE IF (THETA .LT. 0.0 .AND. NLAYER .EQ. 1) THEN
          GO TO 320
C************* RAY OUT TOP =====> STOP THIS RAY AND TRY NEXT ONE
        ELSE IF (THETA .GE. 0.0 .AND. NLAYER .EQ. NLAMAX)
     1        THEN
          GO TO 320
C************* RAY OUT BOTTOM ======> STOP THIS RAY AND TRY NEXT ONE
        END IF
C************* APPLY SNELL'S LAW, UPDATE LAYER NO. & RESTART RAYTRACE
        V0 = VH(NLAYER)
        V00 = VV(NLAYER)
        IF (THETA .LT. 0.0) THEN
          V1 = VH(NLAYER - 1)
        ELSE
          V1 = VH(NLAYER + 1)
        END IF
        IF (V0 .GE. V1) GO TO 280
C                 No crit rays
        TEM = V00 ** 2 * (V1**2 - V0**2) / V0 ** 4
        CRIT = ATAN(SQRT(1./TEM))
        CRIT = PI2 - CRIT
        IF (ABS(THETA) .LT. CRIT) THEN
          GO TO 320
C **********  SUPERCRITICAL ===> STOP THIS RAY & TRY NEXT ONE
        ELSE
 280      NLAYER = NLAYER + NINT(SIGN(1.0,THETA))
          TEMA = VH(NLAYER) ** 4 * VV(NLAYER - 1) ** 2
          TEMB = VV(NLAYER) ** 2
          TEMC = VH(NLAYER - 1) ** 4 / (TAN(PI2 - ABS(THETA))**2)
          TEMD = VH(NLAYER - 1) ** 2 - VH(NLAYER) ** 2
          TEMDD = VV(NLAYER - 1) ** 2
          TEME = TEMB * (TEMC + TEMDD*TEMD)
          THETA2 = ATAN(SQRT(TEMA/TEME))
          THETA2 = (PI2 - ABS(THETA2)) * SIGN(1.0,THETA)
          THETA = THETA2
          GO TO 270
        END IF
C
C  Now establish point of intersection of the rays
C
 290    IF (THETA .LT. 0.0) THEN
          X(LOOP) = 0.5 * (XINTS(NLAYER) + XINTR(NLAYER))
          IF (X(LOOP) .LT. 0.0) WRITE (6,*)'XINTS(NL),XINTR(NL) = ',
     1          XINTS(NLAYER), XINTR(NLAYER)
          DZ = (X(LOOP) - XINTS(NLAYER)) * TAN(THETA)
          Z(LOOP) = DEPTH(NLAYER) + DZ
          IF (NLAYER .EQ. LAYSOR) THEN
            X1DASH = XS
            Z1DASH = ZS
          ELSE
            X1DASH = XINTS(NLAYER + 1)
            Z1DASH = DEPTH(NLAYER + 1)
          END IF
          IF (NLAYER .EQ. LAYREC) THEN
            X2DASH = XR(J)
            Z2DASH = ZR(J)
          ELSE
            X2DASH = XINTR(NLAYER + 1)
            Z2DASH = DEPTH(NLAYER + 1)
          END IF
          TEMP1 = VV(NLAYER) ** 2
          TEMP2 = VH(NLAYER) ** 2
          TEMP3 = TEMP1 * COS(THETA) ** 2
          TEMP4 = TEMP2 * SIN(THETA) ** 2
          VTHETA = SQRT(TEMP1*TEMP2/(TEMP3 + TEMP4))
          T(LOOP) = SQRT((X2DASH - X1DASH)**2 + (2*Z(LOOP) - Z1DASH -
     1    Z2DASH)**2) / VTHETA
          DO 300 M = NLAYER + 1, NLAMAX, 1
            T(LOOP) = T(LOOP) + TIME(M)
 300      CONTINUE
        ELSE
          X(LOOP) = 0.5 * (XINTS(NLAYER + 1) + XINTR(NLAYER + 1))
          IF (X(LOOP) .LT. 0.0) THEN
            WRITE (6,*)'XINTS(NL+1),XINTR(NL+1)=', XINTS(NLAYER + 1),
     1          XINTR(NLAYER + 1)
            WRITE (6,*)'XINTS = ', XINTS
            WRITE (6,*)'NLAYER = ', NLAYER
            WRITE (6,*)'THETA=', THETA
            WRITE (6,*)'RECEIVER=', J
            WRITE (6,*)'LAYREC=', LAYREC
          END IF
          DZ = (X(LOOP) - XINTS(NLAYER + 1)) * TAN(THETA)
          Z(LOOP) = DEPTH(NLAYER + 1) + DZ
          IF (NLAYER .EQ. LAYSOR) THEN
            X1DASH = XS
            Z1DASH = ZS
          ELSE
            X1DASH = XINTS(NLAYER)
            Z1DASH = DEPTH(NLAYER)
          END IF
          IF (NLAYER .EQ. LAYREC) THEN
            X2DASH = XR(J)
            Z2DASH = ZR(J)
          ELSE
            X2DASH = XINTR(NLAYER)
            Z2DASH = DEPTH(NLAYER)
          END IF
          TEMP1 = VV(NLAYER) ** 2
          TEMP2 = VH(NLAYER) ** 2
          TEMP3 = TEMP1 * COS(THETA) ** 2
          TEMP4 = TEMP2 * SIN(THETA) ** 2
          VTHETA = SQRT(TEMP1*TEMP2/(TEMP3 + TEMP4))
          T(LOOP) = SQRT((X2DASH - X1DASH)**2 + (2*Z(LOOP) - Z1DASH -
     1    Z2DASH)**2) / VTHETA
          DO 310 M = NLAYER - 1, 1, -1
            T(LOOP) = T(LOOP) + TIME(M)
 310      CONTINUE
        END IF
        LOOP = LOOP + 1
C
C Next ray
C
 320  CONTINUE
      DTHETA = DTHET0
      IF (LOOP .LE. 1) GO TO 370
C
C Now map X,Z coordinates back to dipping space
C apply rotational transformation of minus PHI to source&receiver posns
C
 330  PHI = -PHI
```

```fortran
      DO 340 K = 1, LOOP - 1
        DISTP = SQRT(X(K)**2 + Z(K)**2)
        IF (X(K) .EQ. 0.0) THEN
          ALPHA = PI2
        ELSE
          ALPHA = Z(K) / X(K)
          ALPHA = ATAN(ALPHA)
        END IF
C           First reset the x position before the rotation
C           The x position was shifted if after the rotation the
C           source had -ve x value
        IF (RESET .LT. 0.0) THEN
          X(K) = X(K) + RESET
        END IF
        DZP = DISTP * (SIN(ALPHA) - SIN(ALPHA - PHI))
        DXP = DISTP * (COS(ALPHA - PHI) - COS(ALPHA))
        X(K) = X(K) + DXP + XSHIFT
        Z(K) = Z(K) - DZP + ZSHIFT

        IF (GATHER .EQ. 'S' .OR. GATHER .EQ. 's') X(K) = -X(K)
        IF (KOUNT .EQ. 2) X(K) = -X(K)
 340  CONTINUE
      PHI = -PHI
      CALL PTJOIN(X, Z, 1, LOOP - 1, 1)
      WRITE (7,*) (LOOP - 1)
      DO 350 M = 1, LOOP - 1
        WRITE (7,*) T(M), -X(M), Z(M)
 350  CONTINUE
 360  CONTINUE
 370 CONTINUE
     IF (KOUNT .EQ. 1) THEN
       IF (HSTYPE .EQ. 'F' .OR. HSTYPE .EQ. 'f') THEN
         KOUNT = 2
         PHI = -PHI1
         GO TO 40
       END IF
     END IF
     CALL GREND
     END
```

Appendix A.3

The VSP-CDP transform program

XHRMAP

The program XHRMAP takes upgoing or downgoing reflection data and transforms it on to reflection point loci calculated by the program REFLOC. Mapped data are subsequently binned on to a rectangular grid and then plotted.

```
      PROGRAM XHRMAP
C
C.  Program to map XHR reflection data to correct CDP position
C         Initially for upgoing wavefield only
C    MUST  first run REFLOCI -to calculate reflection locus for
C source/receiver
C    Option allows user to stack individual CDP sections in unformatte
C file
C
C  Subroutines required:   *ghost80 and TimeSeriesAnalysis(REAL*4) libs
C                          SAMNOR  (included in this file)
C
C  WRITTEN BY M J FINDLAY 1988
C
      CHARACTER FNAME*16, A1*20, ANS*1, INSTAK*16, ANSWR*1
      DIMENSION A1(9)
      REAL R4DAT(1024,40), RECDEP(24), DBGAIN(24), GCMSCL(24),
     1     REFL(300,40)
      REAL X(1024), Z(1024), X0(1024), WT(300,40), REF0(300,40)
      REAL NSTACK(300,40)
      REAL TT(1500,24), XX(1500,24), ZZ(1500,24), NPOINT(24),
     1     WT0(300,40)
      REAL CSGS(300,40,24), CDP(300,24), SECTN(300,40), RNORM(24)
      INTEGER NFIRST(24), IDPROC(4,24), NCR(2)
      N1 = 300
      N2 = 40
      N3 = 24
      XOFF = 0.0
      CALL PAPER(2)
   10 WRITE (6,*)
      WRITE (6,*)'                         XHRMAP  MENU'
      WRITE (6,*)'                         ~~~~~~  ~~~~'
      WRITE (6,*)
      WRITE (6,*)'    1     Put reflectors on loci, plot and bin '
      WRITE (6,*)
      WRITE (6,*)'    2     Plot binned traces                   '
      WRITE (6,*)
      WRITE (6,*)'    3     Stack binned traces                  '
      WRITE (6,*)
      WRITE (6,*)'    4     Output binned traces                 '
      WRITE (6,*)
      WRITE (6,*)'    5     AS OPTION 1 but for headerless files '
      WRITE (6,*)
      WRITE (6,*)'    6     Selective CDP stacking               '
      WRITE (6,*)
      WRITE (6,*)'    7     Bandpass filter binned data          '
      WRITE (6,*)
      WRITE (6,*)'    8     Apply AGC to binned record           '
      WRITE (6,*)
      WRITE (6,*)'    0     STOP                                 '
      WRITE (6,*)
      READ (5,*) IANS
      IF (IANS .EQ. 1 .OR. IANS .EQ. 5) THEN
          WRITE (6,*)'True scale plot (Y/N)?'
          READ (5,100) ANSWR
          WRITE (6,*)'Enter data file name :'
          READ (5,20) FNAME
   20     FORMAT (A16)
          WRITE (6,*)'Enter shot ID number :'
          READ (5,*) NSHOT
          WRITE (6,*)'Enter source offset :'
          READ (5,*) XOFF
          WRITE (6,*)'Enter Maximum depth to be plotted :'
          READ (5,*) DMAX
          WRITE (6,*)'ENTER  amplitude scaling factor:'
          READ (5,*) AMPSCL
   30     WRITE (6,*)'Enter polarity (-1=SEG-normal +1=SEG-reverse):'
          READ (5,*) IPOLAR
          IF (ABS(IPOLAR) .NE. 1) GO TO 30
          WRITE (6,*)'Enter vertical sampling in metres :'
          READ (5,*) DELTAZ
          WRITE (6,*)'Enter vertical trace spacing in metres :'
          READ (5,*) DELTAD
          NTRCEX = INT(XOFF/DELTAD) + 1
          NDIMZ = INT(DMAX/DELTAZ) + 1
          WRITE (6,*)'NTRCEX,NDIMZ = ', NTRCEX, NDIMZ
          NN = 300 * 40
          CALL ZERO(NN, REF0(1,1))
          CALL ZERO(NN, REFL(1,1))
          CALL ZERO(NN, WT(1,1))
          LEN = 4104
          NSAMR = 1024
          NRECS = 24
          IDCODE = (NSHOT - 1) * 25 + 1
          IF (IANS .EQ. 1) THEN
              OPEN (10,FILE=FNAME,STATUS='OLD',ACCESS='DIRECT',RECL=LEN)
              READ (10,REC=IDCODE) A1, SORPOS, NRECS, RECDEP, DBGAIN,
     1             GCMSCL, NFIRST, NCR, NPROCS, IDPROC, DT
              IF (DT .EQ. 0.0) PRINT *, 'DT = 0'
              DT = 200.0 * 1E-6
              DO 40 J = 1, NRECS
                  NREC = IDCODE + J
                  READ (10,REC=NREC) (R4DAT(I,J),I=1,NSAMR)
   40         CONTINUE
              CLOSE (10)
          ELSE
              WRITE (6,*)'Enter (uniform) velocity field in metres/sec:'
              READ (5,*) VFLAT
              WRITE (6,*)'ENTER source depth (metres):'
              READ (5,*) SORDEP
              WRITE (6,*)'Enter shallowest receiver & receiver sepn:'
              READ (5,*) ZMINR, DZR
              ZRECS = ZMINR
              DT = 200E-6
   50         FORMAT (8F10.4)
              OPEN (11,FILE=FNAME,STATUS='OLD',FORM='FORMATTED')
              DO 60 J = 1, NRECS
                  READ (11,*) JDUM
                  READ (11,50) (R4DAT(I,J),I=1,NSAMR)
                  TD = SQRT(XOFF**2 + (SORDEP - ZRECS)**2) / VFLAT
                  NFIRST(J) = 1
                  ZRECS = ZRECS + DZR
   60         CONTINUE
              CLOSE (11)
          END IF
C
C  Normalise so that Peak RMS amplitude over all traces is 1.0
C
          RMSMAX = 0.0
          DO 80 J = 1, NRECS
```

```
          RMS = 0.0
          DO 70 I = 1, NSAMR
              RMS = RMS + R4DAT(I,J) * R4DAT(I,J)
 70       CONTINUE
          RMS = SQRT(RMS/NSAMR)
          IF (RMS .GT. RMSMAX) RMSMAX = RMS
 80   CONTINUE
      DO 90 J = 1, NRECS
          DO 90 I = 1, NSAMR
              R4DAT(I,J) = R4DAT(I,J) / RMSMAX
 90   CONTINUE
      WRITE (6,*)'Apply T-squared ramp (Y/N) ?'
      READ (5,100) ANS
100   FORMAT (A1)
      IF (ANS .EQ. 'y' .OR. ANS .EQ. 'Y') THEN
          DO 120 J = 1, NRECS
              DO 110 I = 1, NSAMR
                  R4DAT(I,J) = R4DAT(I,J) * (I - 1) ** 2 / 10000
110           CONTINUE
120       CONTINUE
      END IF
      WRITE (6,*)'Enter name of file of reflection loci :'
      READ (5,20) FNAME
      OPEN (1,FILE=FNAME,STATUS='OLD')
      READ (1,*) NRECS
      DO 140 JJ = 1, NRECS
          READ (1,*) NPOINT(JJ)
          DO 130 II = 1, NPOINT(JJ)
              READ (1,*) TT(II,JJ), XX(II,JJ), ZZ(II,JJ)
130       CONTINUE
140   CONTINUE
      CLOSE (1)
C
C  PLOT REFLECTORS ON LOCI
C
      P0X = 0.1
      P1X = 0.9
      IF (ANSWR .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
          DPX = XOFF / DMAX
          P1X = P0X + 0.8 * DPX
      END IF
      CALL PSPACE(P0X, P1X, 0.1, 0.9)
      CALL MAP(0.0, XOFF, DMAX, 0.0)
      CALL AXES
      CALL BORDER
      TTRMS = 0.0
      DO 200 J = 1, NRECS
          PRINT *, 'CHANNEL = ', J
          WRITE (4,*)'RECEIVER #', J
          TG = (NFIRST(J) - 1) * DT
          WRITE (4,*)'First break time = ', TG
          INDT = 2
          N0 = 0
          TTERR = TG - TT(1,J)
          TTRMS = TTRMS + TTERR ** 2
          WRITE (4,*)'RECEIVER ', J, ' TTERR = ', TTERR
          IF (ABS(TTERR) .GT. 0.001) WRITE (6,*) J, ' TTERR = ',
     1          TTERR
          WRITE (6,*) NFIRST(J), NSAMR
          DO 160 I = NFIRST(J), NSAMR
              INDI = I
              TSAMP = (I - 1) * DT
150           IF (INDT .GT. NPOINT(J)) GO TO 170
              IF (TSAMP .LT. TT(1,J)) THEN
                  N0 = N0 + 1
                  GO TO 160
              END IF
              NPJ = NPOINT(J)
              IF (TSAMP .GT. TT(NPJ,J)) GO TO 170
              IF (TSAMP .GT. TT(INDT,J)) THEN
                  INDT = INDT + 1
                  GO TO 150
              END IF
              DELTAT = TT(INDT,J) - TT(INDT - 1,J)
              FAC = (TSAMP - TT(INDT - 1,J)) / DELTAT
              X0(I) = XX(INDT - 1,J) + FAC * (XX(INDT,J) - XX(INDT -
     1         1,J))
              Z(I) = ZZ(INDT - 1,J) + FAC * (ZZ(INDT,J) - ZZ(INDT -
     1        1,J))
              X(I) = X0(I) + AMPSCL * R4DAT(I,J)
160       CONTINUE
C
C  Simple plot of repositioned traces
C
170       LEN = INDI - 1
          CALL PTJOIN(X, Z, NFIRST(J) + N0, LEN, 1)
          DO 180 I = NFIRST(J) + N0, LEN
              IF (R4DAT(I,J)*IPOLAR .LT. - 0.01) THEN
                  CALL POSITN(X0(I), Z(I))
                  CALL JOIN(X(I), Z(I))
              END IF
180       CONTINUE
C
C Now calculate array REFL(300,40) of binned traces for surface reflctn
C
          DO 190 I = NFIRST(J), NSAMR
              NHORI = INT(X0(I)/DELTAD) + 1
              NVERT = INT(Z(I)/DELTAZ) + 1
              IF (NHORI .GT. NTRCEX .OR. NVERT .GT. NDIMZ)
     1           GO TO 190
              IF (NHORI .LE. 0 .OR. NVERT .LE. 0) GO TO 190
              G2 = (X0(I) - (NHORI - 1)*DELTAD) / DELTAD
              G1 = 1.0 - G2
              F2 = (Z(I) - (NVERT - 1)*DELTAZ) / DELTAZ
              F1 = 1.0 - F2
              REFL(NVERT,NHORI) = R4DAT(I,J) * F1 * G1 + REFL(NVERT,
     1        NHORI)
              REFL(NVERT,NHORI + 1) = R4DAT(I,J) * F1 * G2 + REFL(
     1        NVERT,NHORI + 1)
              REFL(NVERT + 1,NHORI) = R4DAT(I,J) * F2 * G1 + REFL(
     1        NVERT + 1,NHORI)
              REFL(NVERT + 1,NHORI + 1) = R4DAT(I,J) * F2 * G2 +
     1        REFL(NVERT + 1,NHORI + 1)
              WT(NVERT,NHORI) = F1 * G1 + WT(NVERT,NHORI)
              WT(NVERT,NHORI + 1) = F1 * G2 + WT(NVERT,NHORI + 1)
              WT(NVERT + 1,NHORI) = F2 * G1 + WT(NVERT + 1,NHORI)
              WT(NVERT + 1,NHORI + 1) = F2 * G2 + WT(NVERT + 1,
     1        NHORI + 1)
190       CONTINUE
200   CONTINUE
```

```
C
C  No longer need record of weighting
C
         REFMAX = 0.0
         WRITE (6,*)'NTRCEX, NDIMZ ', NTRCEX, NDIMZ
         DO 220 JJ = 1, NTRCEX
            DO 210 II = 1, NDIMZ
               IF (WT(II,JJ) .EQ. 0.0) WT(II,JJ) = 1.0
               REFL(II,JJ) = REFL(II,JJ) / WT(II,JJ)
               REFMAX = AMAX1(REFMAX,ABS(REFL(II,JJ)))
 210        CONTINUE
 220     CONTINUE
         TTRMS = SQRT(TTRMS/NRECS)
         WRITE (4,*)'RMS TTERROR = ', TTRMS
         CALL FRAME
C
C    End of option 1
C
      ELSE IF (IANS .EQ. 2) THEN
C
C    Plot binned traces
C
         IF (XOFF .EQ. 0.0) THEN
            WRITE (6,*)'True scale plot (Y/N) ?'
            READ (5,100) ANSWR
            WRITE (6,*)'Enter source offset :'
            READ (5,*) XOFF
            WRITE (6,*)'Enter Maximum depth to be plotted :'
            READ (5,*) DMAX
            WRITE (6,*)'ENTER  amplitude scaling factor:'
            READ (5,*) AMPSCL
            WRITE (6,*)'Enter vertical sampling in metres :'
            READ (5,*) DELTAZ
            WRITE (6,*)'Enter vertical trace spacing in metres :'
            READ (5,*) DELTAD
            NTRCEX = INT(XOFF/DELTAD) + 1
            WRITE (6,*) NTRCEX
         END IF
 230     WRITE (6,*)'Enter polarity (-1=SEG-normal +1=SEG-reverse):'
         READ (5,*) IPOLAR
         IF (ABS(IPOLAR) .NE. 1) GO TO 230
         WRITE (6,*)'Normalise traces by RMS(1), PEAK(2), None(0):'
         READ (5,*) IVAL
         PEAKMX = 1.0
         IF (IVAL .EQ. 1) THEN
            WRITE (6,*)'Enter depth range for RMS calculation :'
            READ (5,*) Z0, Z1
            NZ0 = INT(Z0/DELTAZ) + 1
            NZ1 = INT(Z1/DELTAZ) + 1
            PEAKMX = 0.0
            DO 250 I = 1, N2
               RMS = 0.0
               PEAK = 0.0
               DO 240 J = NZ0, NZ1
                  RMS = RMS + REFL(J,I) ** 2
                  IF (ABS(REFL(J,I)) .GT. PEAK) PEAK = ABS(REFL(J,I)
   1              )
 240           CONTINUE
               RMS = RMS / REAL(N1)
               RMS = SQRT(RMS)
               IF (RMS .GT. 0.0) PEAK = PEAK / RMS
               IF (PEAK .GT. PEAKMX) PEAKMX = PEAK
               IF (RMS .GT. 0.0) THEN
                  RNORM(I) = RMS
               ELSE
                  RNORM(I) = 1.0
               END IF
 250        CONTINUE
            PEAKMX = PEAKMX / 1.4
         ELSE IF (IVAL .EQ. 2) THEN
            DO 260 I = 1, N2
               CALL MAXSN(N1, REFL(1,I), PEAK, IND)
               CALL MINSN(N1, REFL(1,I), PEAK0, IND)
               IF (ABS(PEAK0) .GT. PEAK) PEAK = ABS(PEAK0)
               RNORM(I) = PEAK
 260        CONTINUE
         ELSE
            N12 = N1 * N2
            CALL MAXSN(N12, REFL(1,1), PEAK, IND)
            CALL MINSN(N12, REFL(1,1), PEAK0, IND)
            IF (ABS(PEAK0) .GT. PEAK) PEAK = ABS(PEAK0)
            DO 270 I = 1, N2
               RNORM(I) = PEAK
 270        CONTINUE
         END IF
         NREFL = N1 * N2
         CALL MAXSN(NREFL, REFL(1,1), REFMAX, IND)
         CALL MINSN(NREFL, REFL(1,1), REFMIN, IND)
         IF (ABS(REFMIN) .GT. REFMAX) REFMAX = ABS(REFMIN)
         IF (AMPSCL .EQ. 0.0) AMPSCL = DELTAD / REFMAX
         P0X = 0.1
         P1X = 0.9
         IF (ANSWR .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
            DPX = XOFF / DMAX
            P1X = P0X + 0.8 * DPX
         END IF
         CALL PSPACE(P0X, P1X, 0.1, 0.9)
         CALL MAP(0.0, XOFF, DMAX, 0.0)
         CALL BORDER
         CALL AXES
         NDIMZ = INT(DMAX/DELTAZ) + 1
         WRITE (6,*)'NDIMZ = ', NDIMZ
         DO 280 J = 1, NDIMZ
            Z(J) = (J - 1) * DELTAZ
 280     CONTINUE
         DO 310 I = 1, NTRCEX
            X1 = (I - 1) * DELTAD
            IF (RNORM(I) .EQ. 0.0) RNORM(I) = 1.0
            IF (RNORM(I) .NE. 1.0) AMPSCL = DELTAD / (RNORM(I)*PEAKMX)
            DO 290 J = 1, NDIMZ
               X(J) = X1 + REFL(J,I) * AMPSCL
 290        CONTINUE
            CALL PTJOIN(X, Z, 1, NDIMZ, 0)
            DO 300 J = 1, NDIMZ
               IF (REFL(J,I)*IPOLAR .LT. - 0.01) THEN
                  CALL POSITN(X1, Z(J))
                  CALL JOIN(X(J), Z(J))
               END IF
 300        CONTINUE
 310     CONTINUE
```

```
      CALL FRAME
C
C  End of option 2
C
    ELSE IF (IANS .EQ. 3) THEN
C
C  Stack binned traces
C
        NN = 300 * 40
        CALL ZERO(NN, REF0)
        CALL ZERO(NN, REFL)
        CALL ZERO(NN, WT)
        WRITE (6,*)'Enter dimensions of section (NX,NZ) :'
        READ (5,*) NTRCEX, NDIMZ
        WRITE (6,*)'Enter no. of common shot records to be stacked'
        READ (5,*) NSTAK
        DO 320 J = 1, NTRCEX
            DO 320 I = 1, NDIMZ
                NSTACK(I,J) = NSTAK
 320    CONTINUE
        DO 360 II = 1, NSTAK
            WRITE (6,*)'Enter input filename for stack :'
            READ (5,20) INSTAK
            WRITE (6,*)'NTRCEX  , NDIMZ =', NTRCEX, NDIMZ
            OPEN (8,FILE=INSTAK,STATUS='OLD')
            READ (8,340) (((REF0(I,J)),I=1,NDIMZ),J=1,NTRCEX)
 330        CONTINUE
            CLOSE (8)
 340        FORMAT (16F10.6)
            DO 350 J = 1, NTRCEX
                DO 350 I = 1, NDIMZ
                    REFL(I,J) = REFL(I,J) + REF0(I,J)
                    IF (ABS(REF0(I,J)) .LT. 1E-3) NSTACK(I,J) =
   1                NSTACK(I,J) - 1
 350        CONTINUE
 360    CONTINUE
        DO 370 J = 1, NTRCEX
            DO 370 I = 1, NDIMZ
                IF (NSTACK(I,J) .EQ. 0.0) NSTACK(I,J) = 1.0
                REFL(I,J) = REFL(I,J) / NSTACK(I,J)
 370    CONTINUE
C
C   End of option 3
C
    ELSE IF (IANS .EQ. 4) THEN
C
C  output binned traces
C
        WRITE (6,*)'Output the section (1=Y   0=Output bin):'
        READ (5,*) NANS
        WRITE (6,*)'Enter OUTPUT filename :'
        READ (5,20) INSTAK
        NLEN = NDIMZ * NTRCEX
        OPEN (8,FILE=INSTAK,STATUS='UNKNOWN')
        WRITE (6,*)'NTRCEX , NDIMZ = ', NTRCEX, NDIMZ
        IF (NANS .EQ. 0) THEN
            WRITE (8,340) ((REFL(I,J),I=1,NDIMZ),J=1,NTRCEX)
        ELSE
            WRITE (8,340) ((SECTN(I,J),I=1,NDIMZ),J=1,NTRCEX)
        END IF
        CLOSE (8)
C
C  End option 4
C
    ELSE IF (IANS .EQ. 6) THEN
C
C  OPTION TO USE CDP SELECTIVE STACKING
C
        WRITE (6,*)'Enter dimensions of binned arrays : NX,NZ '
        READ (5,*) NTRCEX, NDIMZ
        WRITE (6,*)'Enter no. of common shot gathers : NY '
        READ (5,*) NGATH
 380    FORMAT (A10)
        DO 390 KK = 1, NGATH
            WRITE (6,*)'Enter name of file containing binned gather #'
   1             , KK
            READ (5,380) FNAME
            OPEN (12,FILE=FNAME,STATUS='OLD')
            READ (12,340) ((CSGS(I,J,KK),I=1,NDIMZ),J=1,NTRCEX)
            CLOSE (12)
 390    CONTINUE
        WRITE (6,*)'Enter horizontal trace separation in metres : DX:'
        READ (5,*) DELTAD
        WRITE (6,*)'Enter vertical sampling interval in metres : DZ '
        READ (5,*) DELTAZ
        CALL CDPSTK(N1, N2, NGATH, NDIMZ, NTRCEX, DELTAD, DELTAZ,
   1         NGATH, CSGS, CDP, SECTN)
C
C  END OF OPTION 6
C
    ELSE IF (IANS .EQ. 7) THEN
        WRITE (6,*)'Enter sample interval in metres :'
        READ (5,*) DELTAZ
        NSC = 1024 * 40
        CALL ZERO(NSC, R4DAT)
        DO 410 J = 1, NTRCEX
            DO 400 I = 1, NDIMZ
                R4DAT(I,J) = REFL(I,J)
 400        CONTINUE
 410    CONTINUE
        WRITE (6,*)'Plot spectra 1=Y 0=N?'
        READ (5,*) NPLOT
        IF (NPLOT .EQ. 1) THEN
            CALL FOURPL(1024, 40, R4DAT, DELTAZ)
        END IF
        WRITE (6,*)'Filter traces 1=Y 0=N?'
        READ (5,*) NFILT
        IF (NFILT .EQ. 1) THEN
            CALL FILTER(1024, 40, R4DAT, DELTAZ)
        END IF
        DO 420 J = 1, NTRCEX
            DO 420 I = 1, NDIMZ
                REFL(I,J) = R4DAT(I,J)
 420    CONTINUE
    ELSE IF (IANS .EQ. 8) THEN
        WRITE (6,*)'Enter sample interval in metres :'
        READ (5,*) DELTAZ
        WRITE (6,*)'Do you want to apply muting prior to AGC (1=Y 0=N)
   1?'
        READ (5,*) MUTAGC
```

```
      IF (MUTAGC .EQ. 1) THEN
 430      WRITE (6,*)'Enter trace no., start depth, end depth:'
          READ (5,*) NTRMUT, ZMUTO, ZMUT1
          IF (NTRMUT .EQ. 0) GO TO 450
          NMUTO = NINT(ZMUTO/DELTAZ) + 1
          NMUT1 = NINT(ZMUT1/DELTAZ) + 1
          DO 440 IMUT = NMUTO, NMUT1
              REFL(IMUT,NTRMUT) = 0.0
 440      CONTINUE
          GO TO 430
      END IF
 450  WRITE (6,*)'Enter length of AGC to be applied in metres :'
      READ (5,*) RLEN
      WRITE (6,*)'Enter low amplitude cutoff mute :'
      READ (5,*) OFF
      DO 460 JMUT = 1, NTRCEX
          DO 460 IMUT = 1, NDIMZ
              IF (ABS(REFL(IMUT,JMUT)) .LT. OFF) THEN
                  REFL(IMUT,JMUT) = 0.0
              END IF
 460  CONTINUE
      LENAGC = NINT(RLEN/DELTAZ)
      WRITE (6,*)'NDIMZ,NTRCEX = ', NDIMZ, NTRCEX
      CALL AGC(N1, N2, REFL, LENAGC)
  ELSE IF (IANS .EQ. 0) THEN
      STOP
 470 END IF
 480 GO TO 10
     END
C
     SUBROUTINE SAMNOR(LX, LY, X, NSAMF, NSAML)
C
C  NORMALIZES 2D ARRAY TO PEAK WITHIN REQUIRED RANGE (NORMALISES ENTIR
C ARRAY)
C
     DIMENSION X(LX,LY)
     RMAX = 0.0
     DO 20 J = 1, LY
         DO 10 I = NSAMF, NSAML
             IF (I .EQ. 7) GO TO 10
             IF (ABS(X(I,J)) .GE. RMAX) RMAX = ABS(X(I,J))
  10     CONTINUE
  20 CONTINUE
     IF (RMAX .EQ. 0.0) GO TO 50
     DO 40 J = 1, LY
         DO 30 I = 1, LX
             IF (I .EQ. 7) X(I,J) = X(I - 1,J) + X(I + 1,J)
             X(I,J) = X(I,J) / RMAX
  30     CONTINUE
  40 CONTINUE
  50 RETURN
     END
```

Appendix A.4

The raytracing program

TRACER

The program TRACER carries out two-point raytracing within a velocity model defined at points on a rectangular grid. The algorithm presented by Chang and McMechan (1986) is used. The program traces rays from each source point to each each grid point and then from each receiver point to each grid point, thus providing an image time for all the grid points for each combination of source and receiver positions. The image times can then be used by the reverse-time finite difference migration program.

```
C
C.  program to raytrace through 2-d velocity model to obtain image times
C   for reverse time migration.
C
      PROGRAM TRACE1
C
C  Algorithm from Chang & McMechan  (source Lee & Stewart)
C
C     At any point along ray there exist 4 quantities :
C         x ,   dx/ds  ,  z  ,  dz/ds
C     x & z are spatial coordinates  ds is along ray.
C     These 4 quantities are the initial conditions required to extend
C     the ray by one additional step.
C     Let U = 1/V  be the slowness; velocity=V(x,z)
C     Define Ux = dU/dx   Uz = dU/dz
C     Rewrite ray equation as:  dW1/ds = W2
C                               dW2/ds = V * (Ux - G*W2)
C                               dW3/ds = W4
C                               dW4/ds = V * (Uz - G*W4)
C
C   W1 = x ,  W2 = dx/ds , W3 = z , W4 = dz/ds , G = Ux*W2 + Uz*W4
C
C    Solve for W1,W2,W3,W4 by 4th order Runge-Kutta algorithm
C    Travel time for a ray is calculated by
C
C           SIGMA  (  ds  )
C             i    ( ---- )      where Vi is the average velocity on the ith
C                  (  Vi  )                          segment
C
C
      PARAMETER (N1=64,N2=90,N3=128,N4=180,NVAR=4,PI=3.1415926535)
      DOUBLE PRECISION T, Y(4), X, H, W(4,7), X0, Z0, X0MIN, X0MAX
      DOUBLE PRECISION Z0MIN, Z0MAX, V(N1,N2), V0, UX0, UZ0
      DOUBLE PRECISION H0, XS(24), ZS(24), SMOTH1, SMOTH2
      DOUBLE PRECISION XVAL(50000), ZVAL(50000), TVAL(50000)
      DOUBLE PRECISION LAMBDA(104), MU(104), FF(N3*N4), W1(50000)
      DOUBLE PRECISION SIGMA, C0(5000), CT(5000), FVAL(50000)
      DOUBLE PRECISION XVAL0(N3*N4), ZVAL0(N3*N4)
      DOUBLE PRECISION XPT(1), ZPT(1), VAL(1)
      DOUBLE PRECISION XAXIS(N3), ZAXIS(N4), WRK(250000), SMOOTH
      REAL XCOORD(10000), ZCOORD(10000), FF1(N3,N4), CLEVL(15)
      INTEGER IW2, ADRES(N3*N4), PX, PZ
      INTEGER VPOINT(51000), IWRK(50000)
      CHARACTER*1 START
      EXTERNAL FCN
      COMMON /DATA/ V0, UX0, UZ0
      IW2 = 6
      WRITE (6,*)'NUMBER OF SOURCES :'
      READ (5,*) NSOURC
      DO 10 NS = 1, NSOURC
        WRITE (6,*)'ENTER SOURCE POSITION (X,Z) in metres :'
        READ (5,*) XS(NS), ZS(NS)
   10 CONTINUE
      WRITE (6,*)'******* SOURCE  :', XS(1), ZS(1), ' *****'
      WRITE (6,*)'ENTER XMIN,XMAX   ,   ZMIN,ZMAX :'
      READ (5,*) XMIN, XMAX, ZMIN, ZMAX
      WRITE (6,*)'Enter velocity grid spacing in metres:'
      READ (5,*) H0
      WRITE (6,*)'ENTER image time grid spacing in metres:'
      READ (5,*) H0IM
      WRITE (6,*)'Enter DT in millisecs for SMOOTH estimation :'
      READ (5,*) DT
      DT = DT * 1.E-3
      WRITE (6,*)'Enter values of SMOOTH for velocity and time grids:'
      READ (5,*) SMOTH1, SMOTH2
      NX = INT((XMAX - XMIN)/H0)
      NXIM = INT((XMAX - XMIN)/H0IM)
      NZ = INT((ZMAX - ZMIN)/H0)
      NZIM = INT((ZMAX - ZMIN)/H0IM)
      IF (NX .GT. N1 .OR. NZ .GT. N2) THEN
        WRITE (6,*)'  *** WARNING --- ARRAYS TOO SMALL *** '
        STOP
      END IF
      WRITE (6,*)'ENTER RAY STEP LENGTH IN METRES :'
      READ (5,*) H
      WRITE (6,*)'ENTER NUMBER OF RAYS TO BE TRACED :'
      READ (5,*) NANG
      DANG = PI / REAL(NANG)
      WRITE (6,*)'Enter fine stepping angle (radians) :'
      READ (5,*) FINANG
      IF (ABS(FINANG) .LT. PI/2.) THEN
        WRITE (6,*)'Enter stepping interval increase (times) :'
        READ (5,*) ANGFAC
        WRITE (6,*)'Enter number of rays for fine stepping :'
        READ (5,*) NRAYFN
        NANG = NANG + NRAYFN
      END IF
      WRITE (6,*)'Enter NUMBER of layers :'
      READ (5,*) NLAYER
      IDEPTH = 0
      VMAX = 0.0
      CDEP = 0.0
      CALL ZERO(80, MU)
      CALL ZERO(40, LAMBDA)
      DO 30 NL = 1, NLAYER
        WRITE (6,*)'ENTER VELOCITY OF MEDIUM ', NL, ' (metres / sec)'
        READ (5,*) VL
        IF (VL .GT. VMAX) VMAX = VL
        WRITE (6,*)'VL = ', VL
        WRITE (6,*)'ENTER THICKNESS OF LAYER ', NL, ' (metres)'
        READ (5,*) THICK
        WRITE (6,*)'THICK = ', THICK
        CDEP = CDEP + THICK
        NTHICK = NINT(THICK/H0)
        WRITE (6,*)'NTHICK = ', NTHICK
        WRITE (6,*)'IDEPTH = ', IDEPTH
        DO 20 IZ = 1, NTHICK
          WRITE (6,*)'IZ = ', IZ
          DO 20 IX = 1, NX
            V(IX,IZ + IDEPTH) = VL
   20   CONTINUE
        IDEPTH = IDEPTH + NTHICK
   30 CONTINUE
      WRITE (6,*)'READ VELOCITIES OK'
      IFAIL = 0
      WRITE (6,*)'IFAIL = ', IFAIL
C
C  E02DCF-NAG  GIVES LEAST SQUARE BICUBIC SPLINE FIT TO SURFACE
C
C  ICONT0,PX,PZ,XVAL0,ZVAL0,LAMBDA,MU,VPOINT,NPOINT  AS E02ZAF ABOVE
```

```
C
C  FVAL(ICONTO)  IS GRID POINT VALUE
C  CO(NC)  COEFFICIENTS OF FIT  CO((PY-4) * (I-1) + J) IS C(I,J)
C  SMOOTH  Smoothing factor for spline accuracy
C
      SMOOTH = SMOTH1
      NXEST = 50
      NZEST = NZ
      LWRK = 4 * (NX + NZ) + 11 * (NXEST + NZEST) + NXEST * NZ + NZ + 54
      LWRK = LWRK * 2
      LIWRK = 3 + NX + NZ + NXEST + NZEST
      LIWRK = LIWRK * 2
      IFAIL = 0
      START = 'C'
      NKNOTX = 8
      NKNOTZ = 8
C
C   ARRAY FVAL SHOULD CONTAIN VALUES S.T. F(NZ*(Q-1)+R)
C   contains          grid point (X(Q),Z(R))
C
      ICOUNT = 0
      DO 40 IX = 1, NX
        DO 40 IZ = 1, NZ
          ICOUNT = ICOUNT + 1
          FVAL(ICOUNT) = V(IX,IZ)
   40 CONTINUE
      DO 50 IZ = 1, NZ
        ZAXIS(IZ) = REAL(IZ) * H0
   50 CONTINUE
      DO 60 IX = 1, NX
        XAXIS(IX) = REAL(IX) * H0
   60 CONTINUE
      WRITE (6,*)'NX,NZ,NXEST,NZEST,LWRK,LIWRK', NX, NZ, NXEST, NZEST,
     1      LWRK, LIWRK
      CALL E02DCF(START, NX, XAXIS, NZ, ZAXIS, FVAL, SMOOTH, NXEST,
     1     NZEST, NKNOTX, LAMBDA, NKNOTZ, MU, CO, SIGMA, WRK, LWRK,
     2     IWRK, LIWRK, IFAIL)
      WRITE (6,*)'IFAIL = ', IFAIL
      WRITE (6,*)'SIGMA = ', SIGMA
      DO 70 I = 1, 104
        WRITE (12,*) I, LAMBDA(I), MU(I)
   70 CONTINUE
      IFAIL = 0
      WRITE (6,*)'IFAIL = ', IFAIL
C
C  NOW BEGIN RAYTRACING FROM SOURCE
C
      SCA = (ZMAX - ZMIN) / (XMAX - XMIN)
      IF (SCA .LT. 1.0) THEN
        PX0 = 0.1
        PX1 = 0.9
        PZL = 0.8 * SCA
        PZ0 = 0.1
        PZ1 = PZ0 + PZL
      ELSE
        PZ0 = 0.1
        PZ1 = 0.9
        PXL = 0.8 / SCA
        PX0 = 0.1
        PX1 = PX0 + PXL
      END IF
      DO 200 NS = 1, NSOURC
        X0 = XS(NS)
        Z0 = ZS(NS)
        WRITE (7,*)'SOURCE NUMBER :', NS
        CALL PAPER(1)
        CALL PSPACE(PX0, PX1, PZ0, PZ1)
        CALL MAP(XMIN, XMAX, ZMAX, ZMIN)
        CALL SCALES
C
C  LOOP OVER TAKEOFF ANGLES MEASURED FROM HORIZONTAL (DOWN=+VE)
C
        ANG = -PI / 2.
        ICOUNT = 0
        WRITE (6,*)'RAY-TRACING FOR SOURCE #', NS
        IFIN = 0
        DO 100 I = 1, NANG
          WRITE (7,*)'RAY NUMBER ', I
          IF (ANG .GT. FINANG .AND. IFIN .LT. NRAYFN) THEN
            ANG = ANG + DANG / ANGFAC
            IFIN = IFIN + 1
          ELSE
            ANG = ANG + DANG
          END IF
C
C  SET UP INITIAL RAY CONDITIONS
C
          X = -H
          T = -H
          Y(1) = X0
          Y(2) = COS(ANG)
          Y(3) = Z0
          Y(4) = SIN(ANG)
C
C  STEP ALONG RAY
C
          DO 80 IRAY = 1, 2000
            ICOUNT = ICOUNT + 1
            IF (ICOUNT .GT. 50000) THEN
              WRITE (6,*)'STOPPED ... ARRAY TVAL TOO SMALL'
              STOP
            END IF
            T = T + H
            X = X + H
            XCOORD(IRAY) = REAL(Y(1))
            ZCOORD(IRAY) = REAL(Y(3))
            XVAL(ICOUNT) = XCOORD(IRAY)
            ZVAL(ICOUNT) = ZCOORD(IRAY)
            XPT(1) = Y(1)
            ZPT(1) = Y(3)
            NEARX = NINT(XPT(1)/H0)
            NEARZ = NINT(ZPT(1)/H0)
            IFAIL = 0
            NC = (NKNOTX - 4) * (NKNOTZ - 4)
            NADRES = (NKNOTX - 7) * (NKNOTZ - 7)
            N = 1
            NPOINT = N + NADRES
            IF (XPT(1) .LT. LAMBDA(4)) XPT(1) = LAMBDA(4)
            IF (XPT(1) .GT. LAMBDA(NKNOTX - 3)) XPT(1) = LAMBDA(NKNOTX -
     1       3)
```

```
      IF (ZPT(1) .LT. MU(4)) ZPT(1) = MU(4)
      IF (ZPT(1) .GT. MU(NKNOTZ - 3)) ZPT(1) = MU(NKNOTZ - 3)
      CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XPT, ZPT, VPOINT,
     1     NPOINT, ADRES, NADRES, IFAIL)
      IFAIL = 0
      N = 1
      CALL E02DBF(N, NKNOTX, NKNOTZ, XPT, ZPT, VAL, LAMBDA, MU,
     1     VPOINT, NPOINT, C0, NC, IFAIL)
      V0 = VAL(1)
      IF (V0 .LT. 1.0) THEN
        WRITE (6,*)'V0 = ', V0
        WRITE (6,*)'XPT,ZPT = ', XPT, ZPT
      END IF
      IFAIL = 0
      XPT(1) = XPT(1) - H0 / 5.
      DELTAX = H0 * .4
      IF (XPT(1) .LT. LAMBDA(4)) THEN
        XPT(1) = LAMBDA(4)
        DELTAX = H0 / 5.
      END IF
      N = 1
      CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XPT, ZPT, VPOINT,
     1     NPOINT, ADRES, NADRES, IFAIL)
      IFAIL = 0
      N = 1
      CALL E02DBF(N, NKNOTX, NKNOTZ, XPT, ZPT, VAL, LAMBDA, MU,
     1     VPOINT, NPOINT, C0, NC, IFAIL)
      UX0 = VAL(1)
      IFAIL = 0
      XPT(1) = XPT(1) + DELTAX
      IF (XPT(1) .GT. LAMBDA(NKNOTX - 3)) THEN
        XPT(1) = LAMBDA(NKNOTX - 3)
        DELTAX = H0 / 5.
      END IF
      N = 1
      CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XPT, ZPT, VPOINT,
     1     NPOINT, ADRES, NADRES, IFAIL)
      IFAIL = 0
      N = 1
      CALL E02DBF(N, NKNOTX, NKNOTZ, XPT, ZPT, VAL, LAMBDA, MU,
     1     VPOINT, NPOINT, C0, NC, IFAIL)
      VX0 = (VAL(1) - UX0) / (DELTAX)
      UX0 = -VX0 / V0 ** 2
      IFAIL = 0
      XPT(1) = Y(1)
      ZPT(1) = Y(3) - H0 / 5.
      DELTAZ = H0 * 2. / 5.
      IF (ZPT(1) .LT. MU(4)) THEN
        ZPT(1) = MU(4)
        DELTAZ = H0 / 5.
      END IF
      N = 1
      CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XPT, ZPT, VPOINT,
     1     NPOINT, ADRES, NADRES, IFAIL)
      IFAIL = 0
      N = 1
      CALL E02DBF(N, NKNOTX, NKNOTZ, XPT, ZPT, VAL, LAMBDA, MU,
     1     VPOINT, NPOINT, C0, NC, IFAIL)
      UZ0 = VAL(1)
      IFAIL = 0
          ZPT(1) = ZPT(1) + DELTAZ
          IF (ZPT(1) .GT. MU(NKNOTZ - 3)) THEN
            ZPT(1) = MU(NKNOTX - 3)
            DELTAZ = H0 / 5.
          END IF
          N = 1
          CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XPT, ZPT, VPOINT,
     1         NPOINT, ADRES, NADRES, IFAIL)
          IFAIL = 0
          CALL E02DBF(N, NKNOTX, NKNOTZ, XPT, ZPT, VAL, LAMBDA, MU,
     1         VPOINT, NPOINT, C0, NC, IFAIL)
          VZ0 = (VAL(1) - UZ0) / (DELTAZ)
          UZ0 = -VZ0 / V0 ** 2
          ZPT(1) = Y(3)
          IF (IRAY .EQ. 1) THEN
            TVALP = 0
          ELSE
            TVALP = TVAL(ICOUNT - 1)
          END IF
          TVAL(ICOUNT) = H / V0 + TVALP
C
C  CALCULATED INTERPOLATED VELOCITY FIELD AND GRADIENTS NOW FIND
C  DERIVATIVES OF FCNS AND APPLY R-K STEP
C
          CALL FCN(T, Y, W(1,1))
          CALL D02YAF(X, H, NVAR, Y, FCN, W, NVAR, IW2)
          IF (Y(1) .GT. XMAX .OR. Y(3) .GT. ZMAX .OR. Y(1) .LT. XMIN +
     1            H0 .OR. Y(3) .LT. ZMIN + H0 .OR. (ANG .LT. 0.0 .AND.
     2           Y(3) .GT. ZVAL(ICOUNT)) .OR. (ANG .GT. 0.0 .AND. Y(3)
     3            .LT. ZVAL(ICOUNT))) THEN
C   RAY TERMINATED !
            LENRAY = IRAY
            GO TO 90
          END IF
 80     CONTINUE
 90     CALL PTJOIN(XCOORD, ZCOORD, 2, LENRAY, 1)
100   CONTINUE
      CALL FRAME
      WRITE (7,*) ICOUNT
      PX = 8
      PZ = 7 + NLAYER * 4
      CALL ZERO(40, LAMBDA)
      NADRES = (PX - 7) * (PZ - 7)
      NPOINT = ICOUNT + NADRES
      IFAIL = 0
C
C  ROUTINE FOR BICUBIC SPLINE CALCULATION
C
      DO 110 III = 1, ICOUNT
        W1(III) = 1.0
110   CONTINUE
      ICOUNT = ICOUNT + 1
      W1(ICOUNT) = 100.
      XVAL(ICOUNT) = X0
      ZVAL(ICOUNT) = Z0
      TVAL(ICOUNT) = 0.0D0
      WRITE (6,*)'ICOUNT = ', ICOUNT
      NXEST = 20
      NZEST = 40
      WRITE (6,*)'NXEST , NZEST =', NXEST, NZEST
```

```
      IU = NXEST - 4
      IV = NZEST - 4
      IW = IV
      IF (IU .GT. IV) IW = IU
      LWRK = (7*IU*IV + 25*IW) * (IW + 1) + 2 * (IU + IV + 4*ICOUNT) +
     1  23 * IW + 56
      WRITE (6,*)'LWRK = ', LWRK
      LIWRK = ICOUNT + 2 * (NXEST - 7) * (NZEST - 7)
      WRITE (6,*)'LIWRK = ', LIWRK
      IF (SMOTH2 .LT. 1E-10) THEN
        SMOOTH = DBLE(DT**2*(REAL(ICOUNT) - SQRT(REAL(ICOUNT*2))))
      ELSE
        SMOOTH = SMOTH2
      END IF
      WRITE (6,*)'SMOOTH = ', SMOOTH
      IFAIL = 0
      WRITE (6,*)'CALCULATING BICUBIC SPLINE FIT TO TRAVELTIMES '
      CALL E02DDF(START, ICOUNT, XVAL, ZVAL, TVAL, W1, SMOOTH, NXEST,
     1     NZEST, NKNOTX, LAMBDA, NKNOTZ, MU, CT, SIGMA, IRANK, WRK,
     2     LWRK, IWRK, LIWRK, IFAIL)
      WRITE (6,*)'IFAIL1 = ', IFAIL
C
C  BICUBIC SPLINE CALCULATION
C
      WRITE (6,*)' SIGMA , RANK          = ', SIGMA, IRANK
      WRITE (6,*)'NKNOTX,NKNOTZ', NKNOTX, NKNOTZ
      NC = (NKNOTX - 4) * (NKNOTZ - 4)
      NADRES = (NKNOTX - 7) * (NKNOTZ - 7)
      N = NZIM * NXIM
      INUM = 0
      DO 120 III = 1, NKNOTX
        WRITE (6,*) LAMBDA(III), MU(III)
 120  CONTINUE
      X0MIN = LAMBDA(4)
      X0MAX = LAMBDA(NKNOTX - 3)
      Z0MIN = MU(4)
      Z0MAX = MU(NKNOTZ - 3)
      WRITE (6,*) X0MIN, X0MAX, Z0MIN, Z0MAX
C
C  SETUP  GRID POINT ARRAYS
C
      DO 130 IZ = 1, NZIM
        ZAXIS(IZ) = REAL(IZ) * HOIM
 130  CONTINUE
      DO 140 IX = 1, NXIM
        XAXIS(IX) = REAL(IX) * HOIM
 140  CONTINUE
      DO 150 JJJ = 1, NZIM
        DO 150 III = 1, NXIM
          INUM = INUM + 1
          XVAL0(INUM) = XAXIS(III)
          ZVAL0(INUM) = ZAXIS(JJJ)
          IF (XVAL0(INUM) .LT. X0MIN) XVAL0(INUM) = X0MIN
          IF (XVAL0(INUM) .GT. X0MAX) XVAL0(INUM) = X0MAX
          IF (ZVAL0(INUM) .LT. Z0MIN) ZVAL0(INUM) = Z0MIN
          IF (ZVAL0(INUM) .GT. Z0MAX) ZVAL0(INUM) = Z0MAX
 150  CONTINUE
      NPOINT = N + NADRES
      IFAIL = 0
      CALL E02ZAF(NKNOTX, NKNOTZ, LAMBDA, MU, N, XVAL0, ZVAL0, VPOINT,
     1     NPOINT, ADRES, NADRES, IFAIL)
      IFAIL = 0
      WRITE (6,*)'INTERPOLATING TRAVEL TIMES '
      CALL E02DBF(N, NKNOTX, NKNOTZ, XVAL0, ZVAL0, FF, LAMBDA, MU,
     1     VPOINT, NPOINT, CT, NC, IFAIL)
      WRITE (6,*)'IFAIL3 = ', IFAIL
      WRITE (6,*)'OK1'
      DO 160 JJJ = 1, NZIM
        I0 = (JJJ - 1) * NXIM
        WRITE (8,190) (FF(IIII + I0),IIII=1,NXIM)
 160  CONTINUE
      XM0 = HOIM
      XM1 = NXIM * HOIM
      ZM0 = HOIM
      ZM1 = NZIM * HOIM
      ZMW = ZM1 - ZM0
      XMW = XM1 - XM0
      IF (XMW .GT. ZMW) THEN
        XP0 = .05
        XP1 = .95
        ZWID = .9 * ZMW / XMW
        ZP0 = .5 * (1. - ZWID)
        ZP1 = .5 * (1. + ZWID)
      ELSE
        ZP0 = .05
        ZP1 = .95
        XWID = .9 * XMW / ZMW
        XP0 = .5 * (1. - XWID)
        XP1 = .5 * (1. + XWID)
      END IF
      CALL PSPACE(XP0, XP1, ZP0, ZP1)
      CALL MAP(XM0, XM1, ZM1, ZM0)
      CALL BORDER
      CALL SCALES
      LEV0 = 1
      LEV1 = 15
      DO 170 NLEVL = LEV0, LEV1
        CLEVL(NLEVL) = 2.5E-3 * REAL(NLEVL)
 170  CONTINUE
      NXP = NX - 1
      NZP = NZ - 1
      CALL ZERO(10000, FF1)
      DO 180 IZ = 1, NZIM
        DO 180 IX = 1, NXIM
          FF1(IX,NZIM - IZ + 1) = REAL(FF(IX + (IZ - 1)*NXIM))
 180  CONTINUE
      CALL CONTRA(FF1, 1, NXIM, N3, 1, NZIM, N4, CLEVL, LEV0, LEV1)
 190  FORMAT (8F10.6)
      CALL FRAME
 200  CONTINUE
      CALL GREND
      END
C
C
      SUBROUTINE FCN(T, Y, F)
C
C    Routine required to calculate the derivatives F(n) of the variable Y(n)
C    for RK extrapolation using the above equations.
C
      DOUBLE PRECISION Y(4), T, F(4)
```

```
DOUBLE PRECISION V0, UX0, UZ0
COMMON /DATA/ V0, UX0, UZ0
G = UX0 * Y(2) + UZ0 * Y(4)
F(1) = Y(2)
F(2) = V0 * (UX0 - G*Y(2))
F(3) = Y(4)
F(4) = V0 * (UZ0 - G*Y(4))
RETURN
END
```

Appendix A.5

The raytracing subroutine

RAYTRA

The subroutine RAYTRA is another two-point raytracing program. It uses a simple, laterally invariant velocity model, resulting in very fast raytracing. The subroutine is called from the Kirchhoff migration program in appendix A.8 and returns the travel time between any two points in the velocity model.

```
C
C. SUBROUTINE TO RAYTRACE FROM POINT (XSTART,ZSTART) TO (XEND,ZEND)
C  IN 2-DIMENSIONAL VELOCITY FIELD DEFINED BY :
C        DEPTH(layer top), VV(layer), VH (layer)
C  Variables:  ACC defines raytracing accuracy in metres
C              LAYIMG = layer of starting point
C              THETA0 = takeoff angle (-pi/2 --> 3pi/2) 0.0=horizontal to right
C              THETAL = Raypath angle at (XEND,ZEND)
C              TAU0 = travel time
C              NLAMAX = total no. of layers there are (NLAMAX+1) depths
C              DZGRID = Vertical grid size used by migration algorithm
C              MAXLOP = Maximum no. of searches for raypath
C              VH,VV specify horizontal and vertical velocity components in
C                     each layer (elliptical approxn to transverse isotropy)
C  No lateral velocity variations
C
C  Written by M J Findlay 1990
C
      SUBROUTINE RAYTRA(NLAMAX, NDEPTH, DEPTH, VH, VV, XSTART, ZSTART,
     1             XEND, ZEND, DZGRID, ACC, MAXLOP, THETAP, THETA0, TAU0,
     2             THETAL, NRAY)
      REAL DEPTH(NDEPTH), VH(NLAMAX), VV(NLAMAX), XINTS(31), DIST(31)
      REAL TIME(31), THET(31)
      DOUBLE PRECISION TEMA, TEMB, TEMC, TEMCC, TEMD, TEME, TEMDD
      LOGICAL RECLAY
      PI = 3.1415926535
      PI2 = PI / 2.
      NRAY = 1
C
C  CHECK FOR ZERO - LENGTH RAYPATH
C
      IF (XSTART .EQ. XEND .AND. ZSTART .EQ. ZEND) THEN
          TAU0 = 0.0
          GO TO 150
      END IF
C
C  DETERMINE IMAGE POINT LAYER
C
      DO 10 NL = 1, NLAMAX
          IF (DEPTH(NL + 1) .GT. ZSTART - DZGRID/100.) THEN
              LAYIMG = NL
              GO TO 20
          END IF
   10 CONTINUE
   20 CONTINUE
C
C  DETERMINE END POINT LAYER
C
      DO 30 NL = 1, NLAMAX
          IF (DEPTH(NL + 1) .GT. ZEND - DZGRID/100.) THEN
              LAYSOR = NL
              GO TO 40
          END IF
   30 CONTINUE
   40 CONTINUE

C
C  RAYTRACE FROM IMAGEPOINT TO SOURCE / RECEIVER
C
      IF (ABS(DEPTH(LAYIMG + 1) - ZSTART) .LT. DZGRID/100.)
     1         THEN
          IF (ZEND .LT. ZSTART) THEN
              ZSTART = ZSTART - DZGRID / 100.
          ELSE
              ZSTART = ZSTART + DZGRID / 100.
              LAYIMG = LAYIMG + 1
          END IF
      END IF
      IF (ABS(DEPTH(LAYSOR + 1) - ZEND) .LT. DZGRID/100.) THEN
          IF (ZEND .LT. ZSTART) THEN
              ZEND = ZEND + DZGRID / 100.
          ELSE
              ZEND = ZEND + DZGRID / 100.
              LAYSOR = LAYSOR + 1
          END IF
      END IF

   50 CONTINUE

C
C   TRACING FROM (XSTART,ZSTART) in layer LAYIMG  TO (XEND,ZEND) in
C LAYSOR(isor)
C
      IF (THETAP .LT. 2.*PI) THEN
          THETA0 = THETAP
      ELSE IF (XEND .EQ. XSTART) THEN
          THETA0 = PI2
          IF (ZEND .LT. ZSTART) THETA0 = PI + PI2
      ELSE
          THETA0 = (ZEND - ZSTART) / (XEND - XSTART)
          THETA0 = ATAN(THETA0)
          IF (XEND .LT. XSTART) THETA0 = THETA0 + PI
      END IF
      IF (XEND - XSTART .LT. - DZGRID/100.) THEN
          THETAB = PI2 - .01
          THETAT = PI + PI2 + .01
      ELSE IF (XEND - XSTART .GT. DZGRID/100.) THEN
          THETAB = PI2 + .01
          THETAT = -PI2 - .01
      ELSE
C
C  SPECIAL CASE FOR VERTICAL RAYPATHS
C
          IF (LAYSOR .EQ. LAYIMG) THEN
              D0 = ABS(ZEND - ZSTART)
              TAU0 = D0 / VV(LAYSOR)
          ELSE IF (THETA0 .EQ. PI2) THEN
C  DOWN
              D0 = DEPTH(LAYIMG + 1) - ZSTART
              TAU0 = D0 / VV(LAYIMG)
              DO 60 NL = LAYIMG + 1, LAYSOR - 1
                  D0 = DEPTH(NL + 1) - DEPTH(NL)
                  T0 = D0 / VV(NL)
                  TAU0 = TAU0 + T0
   60         CONTINUE
              D0 = ZEND - DEPTH(LAYSOR)
              TAU0 = TAU0 + D0 / VV(LAYSOR)
          ELSE
C  UP
              D0 = ZSTART - DEPTH(LAYIMG)
```

```
              TAU0 = D0 / VV(LAYIMG)
              DO 70 NL = LAYIMG - 1, LAYSOR + 1, -1
                  D0 = DEPTH(NL + 1) - DEPTH(NL)
                  T0 = D0 / VV(NL)
                  TAU0 = TAU0 + T0
   70         CONTINUE
              D0 = DEPTH(LAYSOR + 1) - ZEND
              TAU0 = TAU0 + D0 / VV(LAYSOR)
          END IF
          THETA = THETA0
          GO TO 150
      END IF
      ZINTB = 1E9
      ZINTT = -1E9
      DTHETA = 0.05
      TAU0 = 0.0
C
C  NOW START RAYTRACING
C
      DO 140 I = 1, MAXLOP
          NRAY = I
          CALL ZERO(31, TIME)
          RECLAY = .FALSE.
          CALL ZERO(31, DIST)
          DO 80 JJJ = 1, 31
              XINTS(JJJ) = -1000.
   80     CONTINUE
          IF (THETA0 .GT. 3.*PI2 .OR. THETA0 .LT. - PI2) THEN
              IF (THETA0 .GT. 3.*PI2) THETA0 = THETA0 - DTHETA
              IF (THETA0 .LT. - PI2) THETA0 = THETA0 + DTHETA
              GO TO 140
          END IF
          XPO = XSTART
          ZPO = ZSTART
          THETA = THETA0
          NLAY = LAYIMG
   90     CONTINUE
          IF (ABS(THETA) .LT. 1.E-3 .OR. ABS(THETA - PI) .LT. 1.E-3)
     1             THEN
              THETA = THETA + 2.E-3
          END IF
          IF (NLAY .EQ. LAYSOR) RECLAY = .TRUE.
          IF (THETA .LT. 0.0 .OR. THETA .GT. PI) THEN
              DZ = DEPTH(NLAY) - ZPO
              ZPO = DEPTH(NLAY)
          ELSE
              DZ = DEPTH(NLAY + 1) - ZPO
              ZPO = DEPTH(NLAY + 1)
          END IF
          IF (ABS(THETA) .EQ. PI2 .OR. THETA .EQ. 3*PI2) THEN
              DX = 0.0
          ELSE
              DX = DZ / TAN(THETA)
          END IF
          DIST(NLAY) = SQRT(DX**2 + DZ**2)
          THET(NLAY) = THETA
          TEMP1 = VV(NLAY) ** 2
          TEMP2 = VH(NLAY) ** 2
          TEMP3 = TEMP1 * COS(THETA) ** 2
          TEMP4 = TEMP2 * SIN(THETA) ** 2
          VTHETA = (TEMP1*TEMP2/(TEMP3 + TEMP4))
          IF (VTHETA .LT. 0.0) WRITE (6,*)'108', TEMP1, TEMP2, TEMP3,
     1         TEMP4
          VTHETA = SQRT(VTHETA)
          TIME(NLAY) = DIST(NLAY) / VTHETA
          XPO = XPO + DX
          IF (THETA .LT. 0.0 .OR. THETA .GT. PI) THEN
              XINTS(NLAY) = XPO
          ELSE
              XINTS(NLAY + 1) = XPO
          END IF
C
C  FIRST CHECK FOR RAY WITHIN CAPTURE RADIUS
C
          ERR = SQRT((XPO - XEND)**2 + (ZPO - ZEND)**2)
          IF (ERR .LE. ACC) THEN
C   RAY FOUND
              TAU0 = 0.0
              DO 100 NL = 1, NLAMAX
                  TAU0 = TAU0 + TIME(NL)
  100         CONTINUE
              GO TO 150
          END IF
C
C  CHECK FOR RAY PASSING BEYOND ENDPOINT
C
          IF ((THETA .GT. PI2 .AND. XPO .LT. XEND) .OR. (THETA .LE.
     1             PI2 .AND. XPO .GT. XEND)) THEN
              IF (THETA .GT. PI2) THEN
C                           WRITE (6,*)'RAY OUT L.H. SIDE '
              ELSE
C                           WRITE(6,*)'RAY OUT R.H. SIDE '
              END IF

C
C  FIND INTERSECTION POINT
C
              IF (DX .EQ. 0.0) THEN
                  ZINT = ZPO
                  DXDASH = 0.0
                  DZDASH = ZEND - (ZPO - DZ)
              ELSE
                  XOLD = XPO - DX
                  ZOLD = ZPO - DZ
                  DXDASH = XEND - XOLD
                  DZDASH = DZ * DXDASH / DX
                  ZINT = ZOLD + DZDASH
              END IF
C
C  CHECK TO SEE IF CLOSE TO SOURCE POSITION
C
              IF (ABS(ZINT - ZEND) .LT. ACC) THEN
C
C  RAY FOUND
                  DIST(NLAY) = SQRT(DXDASH**2 + DZDASH**2)
                  THET(NLAY) = THETA
                  TEMP1 = VV(NLAY) ** 2
                  TEMP2 = VH(NLAY) ** 2
                  TEMP3 = TEMP1 * COS(THETA) ** 2
                  TEMP4 = TEMP2 * SIN(THETA) ** 2
```

```
                VTHETA = (TEMP1*TEMP2/(TEMP3 + TEMP4))
                IF (VTHETA .LT. 0.0) WRITE (6,*)'152', TEMP1, TEMP2,
     1                TEMP3, TEMP4
                VTHETA = SQRT(VTHETA)
                TIME(NLAY) = DIST(NLAY) / VTHETA
                TAU0 = 0
                DO 110 NL = 1, NLAMAX
                    TAU0 = TAU0 + TIME(NL)
 110            CONTINUE
C
C  RAY FOUND SO RETURN TO MAIN PROGRAM
C
                GO TO 150
C
C  NEED TO STORE THETA0 FOR INTEGRAL KERNEL
C
            ELSE
C
C  NEXT RAY (RAY NOT FOUND)
                IF (ZINT .GT. ZINTT .AND. ZINT .LT. ZEND)
     1                   THEN
                    THETAT = THETA0
                    ZINTT = ZINT
                ELSE IF (ZINT .LT. ZINTB .AND. ZINT .GT. ZEND)
     1                   THEN
                    THETAB = THETA0
                    ZINTB = ZINT
                END IF
                THETA0 = .5 * (THETAT + THETAB)
                GO TO 140
            END IF
C
C  CHECK FOR RAY OUT TOP OR BOTTOM & CALCULATE NEW INTERCEPTION POINTS
C
        ELSE IF (NLAY .EQ. 1 .AND. (THETA .LT. 0.0 .OR. THETA .GT. PI)
     1        ) THEN
C  RAY OUT TOP
            DXNEW = XEND - XPO
            IF (ABS(THETA) .EQ. PI2) THEN
                ZINT = -1.E9
            ELSE
                ZINT = ZPO - ABS(DXNEW*TAN(THETA))
            END IF
            IF (ZINT .GT. ZINTT .AND. ZINT .LT. ZEND) THEN
                THETAT = THETA0
                ZINTT = ZINT
            ELSE IF (ZINT .LT. ZINTB .AND. ZINT .GT. ZEND)
     1               THEN
                THETAB = THETA0
                ZINTB = ZINT
            END IF
            THETA0 = .5 * (THETAT + THETAB)
            GO TO 140
        ELSE IF (NLAY .EQ. NLAMAX .AND. (THETA .GT. 0.0 .AND. THETA .
     1        LT. PI)) THEN
C
C  RAY OUT BOTTOM
            DXNEW = XEND - XPO
            IF (ABS(THETA) .EQ. PI2) THEN
                ZINT = 1.E9
            ELSE
                ZINT = ZPO + ABS(DXNEW*TAN(THETA))
            END IF
            IF (ZINT .GT. ZINTT .AND. ZINT .LT. ZEND) THEN
                THETAT = THETA0
                ZINTT = ZINT
            ELSE IF (ZINT .LT. ZINTB .AND. ZINT .GT. ZEND)
     1               THEN
                THETAB = THETA0
                ZINTB = ZINT
            END IF
            THETA0 = .5 * (THETAT + THETAB)
            GO TO 140
        END IF
C
C  RAY NOT FOUND AND STILL IN GRID SO APPLY SNELL'S LAW AND CHECK FOR
C  SUPERCRITICAL RAYS
C
        V0 = VH(NLAY)
        V00 = VV(NLAY)
        IF (ABS(THETA) .EQ. PI2 .OR. THETA .EQ. 3*PI2) THEN
            NLAY = NLAY + 1
            IF (THETA .LT. 0.0 .OR. THETA .GT. PI) NLAY = NLAY - 2
            GO TO 130
        END IF
        IF (THETA .LT. 0.0 .OR. THETA .GT. PI) THEN
            V1 = VH(NLAY - 1)
        ELSE
            V1 = VH(NLAY + 1)
        END IF
        IF (V0 .GE. V1) GO TO 120
C  RAY NOT CRITICAL SO JUMP OUT
        TEM = V00 ** 2 * (V1**2 - V0**2) / V0 ** 4
        IF (TEM .LT. 0.0) WRITE (6,*)'235', V00, V1, V0
        CRIT = ATAN(SQRT(1./TEM))
        CRIT = PI2 - CRIT
        IF (ABS(THETA) .LT. CRIT .OR. ABS(THETA - PI) .LT. CRIT)
     1         THEN
            IF (THETA .GT. PI) THEN
                IF (ZPO .LT. ZEND) THEN
                    THETAT = THETA0
                    ZINTT = ZPO
                ELSE
                    THETAB = THETA0
                    ZINTB = ZPO
                END IF
                THETA0 = .5 * (THETAT + THETAB)
            ELSE IF (THETA .GT. PI2) THEN
                IF (ZPO .LT. ZEND) THEN
                    THETAT = THETA0
                    ZINTT = ZPO
                END IF
                IF (ZPO .GT. ZEND) THEN
                    THETAB = THETA0
                    ZINTB = ZPO
                END IF
                THETA0 = .5 * (THETAB + THETAT)
            ELSE IF (THETA .GT. 0.0) THEN
                THETA0 = THETA0 + DTHETA
            ELSE IF (THETA .GT. - PI2) THEN
```

```
                THETA0 = THETA0 - DTHETA
             END IF
             GO TO 140
C  RAY IS SUPERCRITICAL SO JUMP OUT AND TRY NEXT RAY
C
          ELSE
C
C APPLY SNELL'S LAW
 120         NLAY0 = NLAY
             NLAY = NLAY + 1
             IF (THETA .LT. 0.0 .OR. THETA .GT. PI) NLAY = NLAY - 2
             TEMA = VH(NLAY) ** 4 * VV(NLAY0) ** 2
             TEMB = VV(NLAY) * VH(NLAY0)
             TEMCC = DBLE(PI2 - THETA)
             TEMCC = TAN(TEMCC)
             TEMC = DBLE(VH(NLAY0)) / TEMCC
             TEMC = TEMC ** 2
             TEMD = VH(NLAY0) ** 2 - VH(NLAY) ** 2
             TEMDD = VV(NLAY0) / VH(NLAY0)
             TEMDD = TEMDD ** 2
             ALFAC = TEMC + TEMDD * TEMD
             IF (ALFAC .LT. 0.0) WRITE (6,*)'281', VH(NLAY0), VH(NLAY),
    1              VV(NLAY0), VV(NLAY), THETA, TEMA, TEMB, TEMC, TEMCC,
    2              TEMD, TEMDD, TEME
             TEME = TEMB * SQRT(TEMC + TEMDD*TEMD)
             THETA2 = ATAN(SQRT(TEMA)/TEME)
C THETA2 IS NOW ANGLE TO VERTICAL
             IF (THETA .GT. PI) THEN
                 THETA2 = 3 * PI2 - THETA2
             ELSE IF (THETA .GT. PI/2) THEN
                 THETA2 = PI2 + THETA2
             ELSE IF (THETA .GT. 0.0) THEN
                 THETA2 = PI2 - THETA2
             ELSE
                 THETA2 = THETA2 - PI2
             END IF
             THETA = THETA2
 130         CONTINUE
             GO TO 90
          END IF
C NEXT RAY TO THIS SOURCE
 140 CONTINUE
C START RAYTRACING TO RECEIVERS
 150 CONTINUE
     THETAL = THETA
C set thetal to final ray angle at XEND,ZEND
C GO BACK TO MAIN PROG
     RETURN
     END
```

Appendix A.6

The finite-difference migration program

EXTRAPREV

The program EXTRAPREV carries out finite-difference migration in the (x,z,t) domain. A file of imaging times generated for each grid point by raytracing is attached to unit 11 at run time. The wavefield may be plotted at particular time steps as it regresses from the receivers, and the final migrated section is plotted.

```
C
C. PROGRAM TO CARRY OUT ACOUSTIC REVERSE TIME EXCITATION IMAGING
C  CONDITION FINITE DIFFERENCE MIGRATION.
C  ALGORITHM PROVIDED BY MCMECHAN  (GEOPHYSICS V50 P627-636)
C
C  (ABSORBING BOUNDARY CONDITIONS FROM RENAUT&PETERSEN GEOPHYSICS 1989)
C  CAN HANDLE LATERAL VELOCITY VARIATIONS
C
C  REQUIRES USE OF SUBROUTINE LIBRARY TSAR4_L,*GHOST80
C  AND PRIOR DETERMINATION OF EXCITATION TIMES BY RAYTRACING PROG.
C  (TRAVEL TIMES ATTACHED TO UNIIT 11 AT RUN TIME)
C
C  WRITTEN BY M J FINDLAY 1989
C
      PROGRAM EXTRAP
      PARAMETER (NHOR=140,NVER=140,NTIM=3,NSAM=1024,NCHN=95)
      PARAMETER (PI=3.1415926535898,POL0=21.*PI/64.,POL2=-15.*PI/64.)
C
C POL0, POL2 DEFINE POLYNOMIAL COEFFICIENTS FOR ABSORBING BOUNDARIES
C SEE RENAUT&PETERSEN, GEOPHYSICS 1989
C
      IMPLICIT REAL(A - H,O - Z)
      REAL U(NHOR,NVER,NTIM), TERM1, TERM2, TERM3, A
      REAL V(NHOR,NVER), TRACES(NSAM,NCHN)
      REAL TT(NSAM), AMPMAX, XMAX, ZMAX, AMPSCL, RREC, TMAX
      REAL UR4(NVER,NHOR), RPLOT(NSAM), Z(NVER), XCORS(NCHN),
     1     ZCORS(NCHN)
      REAL REFRES(NVER,NHOR), IMT(NHOR,NVER), ARR(128), RMT(NHOR)
      DOUBLE PRECISION X(256), X1(256), Z1(256), C(256), XEVAL,
     1       XPRIME(256)
      DOUBLE PRECISION ZPRIME(256)
      CHARACTER*1 ALPDUM(NVER*4)
      COMPLEX CX(2048), CX1(256)
      INTEGER NMOV(20), IXS(NCHN), IZS(NCHN), NCOL(9)
      CHARACTER*17 OPFILE, IPFILE, IFNAM1, IFNAM2, IFNAM3
      DATA NCOL /1, 7, 4, 6, 5, 3, 8, 2, 1/
      WRITE (6,*) PI
      ITO = 3
      NSAMSP = NHOR * NVER
      CALL ZERO(NSAMSP, REFRES(1,1))
      NSAMT = NHOR * NVER * NTIM
      CALL ZERO(NSAMT, U(1,1,1))
      DO 10 I = 1, NVER * 4
          ALPDUM(I) = '@'
   10 CONTINUE
C
C THIS ZEROS ARRAY U(X,Z,T=0,1,2)
C
      WRITE (6,*)'ENTER GRID POINT SPACING (METRES):'
      READ (5,*) H
      WRITE (6,*)'ENTER MAXIMUM GRID VALUES IN X & Z (<128) :'
      READ (5,*) IXMAX, IZMAX
      WRITE (6,*)'ENTER TIME SAMPLE INTERVAL (millisecs):'
      READ (5,*) DT
      DT = DT * 1.E-3
      WRITE (6,*)'LOCATION OF REAL SOURCE :'
      READ (5,*) IX0, IZ0
      WRITE (6,*)'ENTER DELAY TIME OF SOURCE IN MILLISECS :'
      READ (5,*) DELAYT
      DELAYT = DELAYT * 1.E-3
      WRITE (6,*)'Enter number of "source" positions :'
      READ (5,*) NSOR
      DO 20 II = 1, NSOR
          WRITE (6,*)'Enter coords (X,Z) of "source" #', II, ' : '
          READ (5,*) XCORS(II), ZCORS(II)
   20 CONTINUE
      WRITE (6,*)'ENTER NAME OF FILE CONTAINING SEISMOGRAMS '
      READ (5,190) IFNAM2
      LEN = 4104
      WRITE (6,*)'Enter shot number to be restored in file:'
      READ (5,*) NSHOT
      IDSHOT = (NSHOT - 1) * (NSOR + 1) + 1
      OPEN (12,FILE=IFNAM2,STATUS='UNKNOWN',FORM='UNFORMATTED',ACCESS=
     1     'DIRECT',RECL=LEN)
      DO 30 J = 1, NSOR
          NIDC = IDSHOT + J
          READ (12,REC=NIDC) (TRACES(I,J),I=1,NSAM)
   30 CONTINUE
      CLOSE (12)
      LENTAP = NINT(REAL(NSOR)/5.0) * 2
      DO 50 J = 1, LENTAP / 2
          FACTOR = .5 - COS(2.*PI*REAL(J)/REAL(LENTAP)) / 2.
          DO 40 I = 1, NSAM
              TRACES(I,J) = TRACES(I,J) * FACTOR
              TRACES(I,NSOR - J + 1) = TRACES(I,NSOR - J + 1) * FACTOR
   40     CONTINUE
   50 CONTINUE
      WRITE (6,*)'REMOVE T**2 RAMP 0=NO 1=YES(AND APPLY T**.5) :'
      READ (5,*) NOYST2
      IF (NOYST2 .EQ. 1) THEN
          DO 70 I = 1, NSAM
              FACTOR = 1. / (REAL(I)) ** 1.5
              DO 60 J = 1, NSOR
                  TRACES(I,J) = TRACES(I,J) * FACTOR
   60         CONTINUE
   70     CONTINUE
      END IF
      WRITE (6,*)'INTERPOLATE SPATIALLY BY POWER OF 2 (ENTER POWER) :'
      READ (5,*) NPOWER
      RNP = REAL(2**NPOWER)
      IF (NPOWER .EQ. 0) GO TO 180
      NSAMFT = NSOR
      CALL POWER2(NSAMFT, LX0)
      NSAMIT = NSAMFT * 2.0 ** NPOWER
      CALL POWER2(NSAMIT, LX1)
      LRAMP = LX0 - NSAMFT
      DO 130 JJ = 1, NSAM
          CALL ZERO(512, CX)
          RAMP0 = TRACES(JJ,NSAMFT)
          DO 80 II = 1, NSAMFT
              CX(II) = CMPLX(TRACES(JJ,II),0.0)
   80     CONTINUE
          DO 90 II = NSAMFT + 1, LX0
              FAC = REAL(LX0 - II) / REAL(LRAMP)
              CX(II) = CMPLX(RAMP0*FAC)
   90     CONTINUE
          CALL FORK(LX0, CX, -1.0)
          DO 100 II = LX0 / 2 + 2, LX1
              CX(II) = 0.0
  100     CONTINUE
```

```
          DO 110 II = LX1, LX1 / 2 + 2, -1
              CX(II) = CONJG(CX(LX1 + 2 - II))
 110      CONTINUE
          CALL FORK(LX1, CX, 1.0)
          DO 120 II = 1, NSAMIT - 1
              TRACES(JJ,II) = REAL(CX(II)) * SQRT(RNP)
 120      CONTINUE
 130  CONTINUE
C
C   NOW DO INTERPOLATION OF COORDINATE VALUES
C
      DXINTF = 1.0
      DXINTL = DXINTF / (RNP)
      NFINAL = NSOR * 2 ** NPOWER - (2*NPOWER - 1)
      N1 = NSOR
      N2 = (N1 - 1) * N1 / 2
      N0 = N1 - 1
      WRITE (6,*)'DXINTL = ', DXINTL
      WRITE (6,*)'NFINAL = ', NFINAL
      DO 160 II = 1, NFINAL
          DO 140 III = 1, NSOR
              X(III) = DBLE(III)
              X1(III) = XCORS(III)
              Z1(III) = ZCORS(III)
 140      CONTINUE
          XEVAL = X(1) + DBLE(DXINTL*(II - 1))
          CALL E01AAF(X, X1, C, N1, N2, N0, XEVAL)
          XPRIME(II) = C(N2)
          DO 150 III = 1, NSOR
              X(III) = DBLE(III)
 150      CONTINUE
          CALL E01AAF(X, Z1, C, N1, N2, N0, XEVAL)
          ZPRIME(II) = C(N2)
 160  CONTINUE
      DO 170 II = 1, NFINAL
          XCORS(II) = XPRIME(II)
          ZCORS(II) = ZPRIME(II)
 170  CONTINUE
      NSOR = 2 ** NPOWER * NSOR - (2*NPOWER - 1)
 180  CONTINUE
 190  FORMAT (A17)
      WRITE (6,*)'NSOR = ', NSOR
      IXSMAX = 0
      DO 200 II = 1, NSOR
          IXS(II) = NINT(XCORS(II)/H)
          IZS(II) = NINT(ZCORS(II)/H)
          IF (IXS(II) .GT. IXSMAX) IXSMAX = IXS(II)
 200  CONTINUE
      WRITE (6,210) (II,IXS(II),IZS(II),II=1,NSOR)
 210  FORMAT (5(I3,2X,I3,1X,I3,4X))
      WRITE (6,*)'Enter first time sample to start from :'
      READ (5,*) NSTART
      WRITE (6,*)'INTERPOLATE TEMPORALLY (ENTER POWER OF 2):'
      READ (5,*) NPOWER
      RNP = REAL(2**NPOWER)
      IF (NPOWER .EQ. 0) GO TO 280
      NSAMFT = NSTART
      CALL POWER2(NSAMFT, LX0)
      NSAMIT = NSAMFT * 2.0 ** NPOWER
      CALL POWER2(NSAMIT, LX1)
      LRAMP = LX0 - NSAMFT
      DO 270 JJ = 1, NSOR
          CALL ZERO(2048, CX)
          RAMP0 = TRACES(NSAMFT,JJ)
          DO 220 II = 1, NSAMFT
              CX(II) = CMPLX(TRACES(II,JJ),0.0)
 220      CONTINUE
          DO 230 II = NSAMFT + 1, LX0
              FAC = REAL(LX0 - II) / REAL(LRAMP)
              CX(II) = CMPLX(RAMP0*FAC)
 230      CONTINUE
          CALL FORK(LX0, CX, -1.0)
          DO 240 II = LX0 / 2 + 2, LX1
              CX(II) = 0.0
 240      CONTINUE
          DO 250 II = LX1, LX1 / 2 + 2, -1
              CX(II) = CONJG(CX(LX1 + 2 - II))
 250      CONTINUE
          CALL FORK(LX1, CX, 1.0)
          DO 260 II = 1, NSAMIT - 1
              TRACES(II,JJ) = REAL(CX(II)) * SQRT(RNP)
 260      CONTINUE
 270  CONTINUE
      DT = DT / RNP
      NSAM0 = NSAM * 2 ** NPOWER
      NSTART = NSTART * 2 ** NPOWER
 280  CONTINUE
      NSAMP0 = 2
      LENTIM = NINT(REAL(NSTART)/10.0) * 2
 290  FORMAT (8(F10.4))
      DO 310 J = 1, NSOR
          DO 300 I = 1, LENTIM / 2
              FAC = .5 - COS(2.*PI*REAL(I)/REAL(LENTIM)) / 2.
              TRACES(NSTART - I + 1,J) = TRACES(NSTART - I + 1,J) * FAC
 300      CONTINUE
 310  CONTINUE
      WRITE (6,*)'ENTER NO. OF LAYERS :'
      READ (5,*) NLAYER
      IDEPTH = 0
      VMAX = 0.0
      DO 330 NL = 1, NLAYER
          WRITE (6,*)'ENTER VELOCITY OF MEDIUM ', NL, ' (metres / sec)'
          READ (5,*) VL
          IF (VL .GT. VMAX) VMAX = VL
          WRITE (6,*)'ENTER THICKNESS OF LAYER ', NL, ' (metres)'
          READ (5,*) THICK
          NTHICK = NINT(THICK/H)
          DO 320 IZ = 1, NTHICK
              DO 320 IX = 1, IXMAX
                  V(IX,IZ + IDEPTH) = VL
 320      CONTINUE
          IDEPTH = IDEPTH + NTHICK
 330  CONTINUE
      IXP = IX0
      IZP = IZ0
      WRITE (6,*)'INCLUDE POINT DIFFRACTOR 1=Y 0=N:'
      READ (5,*) IYNANS
      IF (IYNANS .EQ. 1) THEN
          WRITE (6,*)'ENTER IX,IZ,VEL(IX,IZ)'
          READ (5,*) IXP, IZP, VPOINT
```

```
           V(IXP,IZP) = VPOINT
        END IF
        WRITE (6,*)'ENTER NUMBER OF DIFFERENT MOVIE FRAMES REQUIRED'
        READ (5,*) NMOVIE
        DO 340 NM = 1, NMOVIE
           WRITE (6,*)'ENTER SAMPLE TIME #', NM
           READ (5,*) NMOV(NM)
 340    CONTINUE
        WRITE (6,*)'ENTER CUTOFF RATIO FOR S/N :'
        READ (5,*) CUT0
        WRITE (6,*)'2nd or 4th Order finite difference approximation :'
        READ (5,*) NORD
 350    FORMAT (A10)
        WRITE (6,*)'ENTER WAVEFIELD PLOT TYPE (1=WIGGLE 2=PIXEL(COLOUR)) :
       1'
        READ (5,*) IPTYPE
        WRITE (6,*)'ENTER OUTPUT FILE NAME :'
        READ (5,190) IFNAM3
C
C  DEFINE COLOURS FOR GHOST80 OUTPUT
C
        CALL PAPER(1)
C
C  H=GRID POINT SPACING
C
C NOW DEFINE INITIAL WAVEFIELD INCLUDING SOURCE TERM
C
 360    IT = NSTART
        DO 370 II = 1, NSOR
           U(IXS(II),IZS(II),ITO - 1) = TRACES(NSTART,II)
C
C START OF SOURCE AT T = 0
C
           A = (V(IXS(II),IZS(II))*DT/H)
           IF (DT .GE. H/(SQRT(2.)*V(IXS(II),IZS(II)))) THEN
              WRITE (6,*)'ALGORITHM UNSTABLE '
              WRITE (6,*)'DT,H,V =', DT, H, V(IXS(II),IZS(II))
              STOP
           END IF
 370    CONTINUE
C
C  SET UP IMAGE TIME CONDITION
C
        DO 390 JJ = 1, NVER
           READ (11,400) (RMT(II),II=1,NHOR)
           DO 380 II = 1, NHOR
              IMT(II,JJ) = NINT(RMT(II)/DT)
              IMT(II,JJ) = IMT(II,JJ) + NINT(DELAYT/DT) + 1
 380       CONTINUE
 390    CONTINUE
 400    FORMAT (8F10.6)
C
C  SETUP PLOTTING ARRAY Z(NZ)
C
        DO 410 II = 1, IZMAX
           Z(II) = REAL(II) * H
 410    CONTINUE
C
C  START LOOP OVER ALL TIME SAMPLES
C
 420    NPLOT = 1
        DO 560 IT = NSTART - 1, NMOV(NMOVIE), -1
           WRITE (6,*)'TIME SAMPLE : ', IT
           TIMEIT = (IT - 1) * DT
           DO 430 IZ = 2, IZMAX - 1
C
C  INCLUDE FREE SURFACE BY MAKING U(IX,Z=0) = 0.0 ????
C
              DO 430 IX = 2, IXMAX - 1
                 A = (V(IX,IZ)*DT/H)
                 IF (NORD .EQ. 2 .OR. IX .EQ. 2 .OR. IZ .LE. 1 .OR.
     1                  IX .EQ. IXMAX - 1 .OR. IZ .EQ. IZMAX - 1)
     2                  THEN
                    TERM1 = 2 * (1 - 2*A**2) * U(IX,IZ,ITO - 1)
                    TERM2 = U(IX,IZ,ITO - 2)
                    TERM3 = U(IX + 1,IZ,ITO - 1) + U(IX - 1,IZ,ITO -
     1              1) + U(IX,IZ + 1,ITO - 1)
                    IF (IZ .GT. 1) TERM3 = TERM3 + U(IX,IZ - 1,ITO -
     1              1)
                    TERM3 = TERM3 * A ** 2
                    U(IX,IZ,ITO) = TERM1 - TERM2 + TERM3
                 ELSE
                    TERM1 = (2. - 5.*A**2) * U(IX,IZ,ITO - 1)
C                          TERM1 = (2. -10. * A**2 / 3.) *U(IX,IZ,ITO-1)
                    TERM2 = U(IX + 1,IZ,ITO - 1) + U(IX,IZ + 1,ITO -
     1              1) + U(IX - 1,IZ,ITO - 1)
                    IF (IZ .GT. 1) TERM2 = TERM2 + U(IX,IZ - 1,ITO -
     1              1)
                    TERM3 = U(IX + 2,IZ,ITO - 1) + U(IX,IZ + 2,ITO -
     1              1) + U(IX - 2,IZ,ITO - 1)
                    IF (IZ .GT. 2) THEN
                       TERM3 = TERM3 + U(IX,IZ - 2,ITO - 1)
                    END IF
                    ALPHA = TERM1 + A ** 2 * (16*TERM2 - TERM3) / 12.
                    U(IX,IZ,ITO) = ALPHA - U(IX,IZ,ITO - 2)
                 END IF
                 IF (IT .EQ. IMT(IX,IZ)) THEN
                    WRITE (8,*) IX, IZ, IMT(IX,IZ)
                    REFRES(IZ,IX) = U(IX,IZ,ITO)
                 END IF
 430       CONTINUE
C
C  NOW APPLY ABSORBING BOUNDARY CONDITIONS
C
C  OPTION TO MAKE SURFACE BOUNDARY ABSORBING
           DO 440 IX = 3, IXMAX - 2
              IZ = 1
              A = V(IX,IZ) * DT / H
              TERM1 = U(IX,IZ,ITO - 1) + U(IX,IZ + 1,ITO - 1)
              TERM1 = TERM1 * 2.0 * POL0
              TERM2 = U(IX,IZ + 1,ITO) + U(IX,IZ,ITO - 2)
              TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
              TERM3 = U(IX + 1,IZ + 1,ITO) + U(IX - 1,IZ + 1,ITO) + U(
     1        IX + 1,IZ,ITO - 2) + U(IX - 1,IZ,ITO - 2)
              TERM3 = -TERM3 * A ** 2 * POL2
              UINIT = (TERM1 + TERM2 + TERM3) / (A + POL0)
              U(IX,IZ,ITO) = UINIT - U(IX,IZ + 1,ITO - 2)
 440       CONTINUE
C
C     LHS FIRST
```

```
C
      DO 450 IZ = 3, IZMAX - 2
         IX = 1
         A = V(IX,IZ) * DT / H
         TERM1 = U(IX,IZ,IT0 - 1) + U(IX + 1,IZ,IT0 - 1)
         TERM1 = TERM1 * 2.0 * POL0
         TERM2 = U(IX + 1,IZ,IT0) + U(IX,IZ,IT0 - 2)
         TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
         TERM3 = U(IX,IZ + 1,IT0 - 2) + U(IX,IZ - 1,IT0 - 2) + U(
     1   IX + 1,IZ + 1,IT0) + U(IX + 1,IZ - 1,IT0)
         TERM3 = -TERM3 * A ** 2 * POL2
         UINIT = (TERM1 + TERM2 + TERM3) / (POL0 + A)
         U(IX,IZ,IT0) = UINIT - U(IX + 1,IZ,IT0 - 2)
 450  CONTINUE
C
C    NOW BOTTOM
C
      DO 460 IX = 3, IXMAX - 2
         IZ = IZMAX
         A = V(IX,IZ) * DT / H
         TERM1 = U(IX,IZ,IT0 - 1) + U(IX,IZ - 1,IT0 - 1)
         TERM1 = TERM1 * 2.0 * POL0
         TERM2 = U(IX,IZ - 1,IT0) + U(IX,IZ,IT0 - 2)
         TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
         TERM3 = U(IX + 1,IZ - 1,IT0) + U(IX - 1,IZ - 1,IT0) + U(
     1   IX + 1,IZ,IT0 - 2) + U(IX - 1,IZ,IT0 - 2)
         TERM3 = -TERM3 * A ** 2 * POL2
         UINIT = (TERM1 + TERM2 + TERM3) / (A + POL0)
         U(IX,IZ,IT0) = UINIT - U(IX,IZ - 1,IT0 - 2)
 460  CONTINUE
C
C  NOW RHS
C
      DO 470 IZ = 3, IZMAX - 2
         IX = IXMAX
         A = V(IX,IZ) * DT / H
         TERM1 = U(IX,IZ,IT0 - 1) + U(IX - 1,IZ,IT0 - 1)
         TERM1 = TERM1 * 2.0 * POL0
         TERM2 = U(IX - 1,IZ,IT0) + U(IX,IZ,IT0 - 2)
         TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
         TERM3 = U(IX,IZ + 1,IT0 - 2) + U(IX,IZ - 1,IT0 - 2) + U(
     1   IX - 1,IZ + 1,IT0) + U(IX - 1,IZ - 1,IT0)
         TERM3 = -TERM3 * A ** 2 * POL2
         UINIT = (TERM1 + TERM2 + TERM3) / (POL0 + A)
         U(IX,IZ,IT0) = UINIT - U(IX - 1,IZ,IT0 - 2)
C                    IF(ABS(U(IX,IZ,IT0))*TIMEIT .LT.A0*TREF/CUT0)
C     1                 U(IX,IZ,IT0) = 0.0
 470  CONTINUE
C
C  NOW MAKE BOTTOM CORNERS ABSORBING TOO
C
C     LOWER RIGHT HAND CORNER
C
      IX = IXMAX - 1
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = IZMAX - 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C  UPPER RIGHT HAND CORNER
C
      IX = IXMAX - 1
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
      U(IX,IZ,IT0) = 0.0
C
      IX = IXMAX
      IZ = 2
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C     LOWER LEFT HAND CORNER
C
      IX = 1
      IZ = IZMAX - 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = 2
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = 1
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
```

```
C
C  UPPER LEFT CORNER
C
          IX = 1
          IZ = 2
          VDASH = V(IX,IZ)
          TERM1 = (U(IX,IZ + 1,ITO) + U(IX + 1,IZ,ITO)) / H
          TERM2 = (U(IX,IZ,ITO - 1)) * SQRT(2.) / (VDASH*DT)
          U(IX,IZ,ITO) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
          IX = 2
          IZ = 1
          VDASH = V(IX,IZ)
          TERM1 = (U(IX,IZ + 1,ITO) + U(IX + 1,IZ,ITO)) / H
          TERM2 = (U(IX,IZ,ITO - 1)) * SQRT(2.) / (VDASH*DT)
          U(IX,IZ,ITO) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
          U(IX,IZ,ITO) = 0.0
C
          IX = 1
          IZ = 1
          VDASH = V(IX,IZ)
          TERM1 = (U(IX,IZ + 1,ITO) + U(IX + 1,IZ,ITO)) / H
          TERM2 = (U(IX,IZ,ITO - 1)) * SQRT(2.) / (VDASH*DT)
          U(IX,IZ,ITO) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C  MAKE THIS LINE THE LAST STEP
C
          DO 480 II = 1, NSOR
              IF (IZS(II) .EQ. IZMAX) GO TO 480
              U(IXS(II),IZS(II),ITO) = TRACES(IT,II)
 480      CONTINUE
          WRITE (19,*) IXP, IZP, IT, U(IXP,IZP,ITO)
          DO 490 J = 1, NVER
              DO 490 I = 1, NHOR
                  U(I,J,ITO - 2) = U(I,J,ITO - 1)
                  U(I,J,ITO - 1) = U(I,J,ITO)
 490      CONTINUE
          IF (IT .LT. NMOV(NMOVIE) + 1) THEN
C
C  WRITE  OUT U(IX,IZ,ITEND) TO FILE ATTACHED TO UNIT 13
C
              DO 500 J = 1, NVER
                  WRITE (13,290) (U(I,J,ITO - 1),I=1,NHOR)
 500          CONTINUE
          END IF
          IF (IT .EQ. NMOV(NPLOT)) THEN
C     GO TO 500
C  INCLUDE ABOVE COMMENTED STATEMENT TO SUPPRESS PLOT OUTPUT
 510          CONTINUE
C
C DATA OUT TO UNIT 14
C
              DO 520 J = 1, NVER
                  WRITE (14,290) (U(I,J,ITO - 1),I=1,NHOR)
 520          CONTINUE
C
C  NOW GET GRAPHICAL OUTPUT OF U(IX,IZ,ITEND)
C
              AMPMAX = 0.0
              DO 530 I = 1, IXMAX
                  DO 530 J = 1, IZMAX
                      UR4(J,I) = REAL(U(I,J,ITO - 1))
                      IF (ABS(UR4(J,I)) .GT. AMPMAX) AMPMAX = ABS(UR4(J,
     1                I))
 530          CONTINUE
              IF (AMPMAX .EQ. 0.0) AMPMAX = 1.0
              CALL DEFPEN
              CALL PSPACE(0.91, 0.99, 0.65, 0.90)
              CALL MAP(0.0, 1.0, 0.0, 1.0)
              CALL BORDER
              CALL CTRMAG(15)
              CALL PCSCEN(0.5, 0.8, 'Time')
              CALL PCSCEN(0.5, 0.7, 'Index')
              CALL PLOTNI(0.7, 0.6, IT)
              CALL PCSCEN(0.5, 0.4, 'SCALE')
              NSCALE = NINT(2000/AMPMAX)
              CALL PLOTNI(0.7, 0.3, NSCALE)
              XMAX = (REAL(IXMAX) + 1.) * H
              ZMAX = (REAL(IZMAX) + 1.) * H
              RATIO = XMAX / ZMAX
              IF (RATIO .LT. 1) THEN
                  P0 = RATIO * .85
                  PX1 = 0.475 - P0 / 2.
                  PX2 = PX1 + P0
                  PZ1 = 0.05
                  PZ2 = 0.90
                  NCHARS = ZMAX / .85
              ELSE
                  P0 = .85 / RATIO
                  PZ1 = 0.475 - P0 / 2.
                  PZ2 = PZ1 + P0
                  PX1 = 0.05
                  PX2 = 0.90
                  NCHARS = XMAX / .85
              END IF
              CALL PSPACE(PX1, PX2, PZ1, PZ2)
              CALL MAP(0.0, XMAX, ZMAX, 0.0)
              CALL BORDER
              CALL SCALES
              WRITE (6,*)'IPTYPE = ', IPTYPE
              AMPMAX = SQRT(AMPMAX)
              DO 550 IX = 1, IXMAX
                  DO 540 IZ = 1, IZMAX
                      IF (UR4(IZ,IX) .LT. 0.0) THEN
                          TERMSQ = -SQRT(-1.*UR4(IZ,IX))
                      ELSE
                          TERMSQ = SQRT(UR4(IZ,IX))
                      END IF
                      RPLOT(IZ) = REAL(IX) + TERMSQ * 2. / AMPMAX
 540              CONTINUE
                  CALL PTJOIN(RPLOT, Z, 1, IZMAX, 1)
 550          CONTINUE
              CALL FRAME
              NPLOT = NPLOT + 1
          END IF
 560  CONTINUE
      AMPMAX = 0.0
      DO 580 IX = 1, IXMAX
          DO 570 IZ = 1, IZMAX
              IF (ABS(REFRES(IZ,IX)) .GT. AMPMAX) THEN
```

```
               AMPMAX = ABS(REFRES(IZ,IX))
            END IF
 570    CONTINUE
 580 CONTINUE
     LEN = (IZMAX + 2) * 4
     OPEN (10,FILE=IFNAM3,STATUS='UNKNOWN',FORM='UNFORMATTED',ACCESS=
    1     'DIRECT',RECL=LEN)
     NXOUT = IXMAX
     IDSHOT = (NSHOT - 1) * (NXOUT + 1) + 1
     NIDC = IDSHOT
     WRITE (10,REC=NIDC) (ALPDUM(I),I=1,LEN)
     DO 590 J = 1, IXMAX
         NIDC = IDSHOT + J - IX0 + 1
         WRITE (10,REC=NIDC) (REFRES(I,J),I=1,IZMAX)
 590 CONTINUE
     CLOSE (10)
C     X0PL = REAL(IX0) * H
C     X1PL = REAL(IXSMAX) * H
C     XSIZ = X1PL-X0PL
C     ZMAX = REAL(IZMAX) * H  + 1.
     XMAX = (REAL(IXMAX) + 1.) * H
     ZMAX = (REAL(IZMAX) + 1.) * H
     RATIO = XMAX / ZMAX
     X0PL = 0.0
     X1PL = XMAX
     XSIZ = XMAX
     IF (RATIO .LT. 1) THEN
         P0 = RATIO * .85
         PX1 = 0.475 - P0 / 2.
         PX2 = PX1 + P0
         PZ1 = 0.05
         PZ2 = 0.90
         NCHARS = ZMAX / .85
     ELSE
         P0 = .85 / RATIO
         PZ1 = 0.475 - P0 / 2.
         PZ2 = PZ1 + P0
         PX1 = 0.05
         PX2 = 0.90
         NCHARS = XSIZ / .85
     END IF
     CALL PSPACE(PX1, PX2, PZ1, PZ2)
C     CALL MAP(X0PL,X1PL,ZMAX,0.0)
     CALL MAP(0.0, XMAX, ZMAX, 0.0)
     CALL BORDER
     CALL SCALES
     DO 620 IX = 1, IXMAX
         DO 600 IZ = 1, IZMAX
C                    IF(IX .LT. IX0 .OR. IX .GT. IXSMAX) THEN
C                             GO TO 1800
C                    ELSE
             RPLOT(IZ) = REAL(IX) * H + REFRES(IZ,IX) * 3. / AMPMAX
C                    ENDIF
 600     CONTINUE
         CALL PTJOIN(RPLOT, Z, 1, IZMAX, 1)
         DO 610 IZ = 1, IZMAX
             IF (RPLOT(IZ) .GT. (REAL(IX)*H + 1.E-2)) THEN
                 CALL POSITN(REAL(IX)*H, Z(IZ))
                 CALL JOIN(RPLOT(IZ), Z(IZ))
             END IF
 610     CONTINUE
 620 CONTINUE
     RX0 = REAL(IX0) * H
     RZ0 = REAL(IZ0) * H
     CALL PLOTNC(RX0, RZ0, 250)
     DO 630 JJJ = 1, NSOR
         RXI = REAL(IXS(JJJ)) * H
         RXZ = REAL(IZS(JJJ)) * H
         CALL PLOTNC(RXI, RXZ, 245)
 630 CONTINUE
     PZ3 = PZ2 * 1.1
     CALL PSPACE(PX1, PX2, PZ2, PZ3)
     CALL MAP(0.0, 1.0, 0.0, 1.0)
     CALL PLOTCS(0.05, 0.5, 'DELAY TIME (millisecs) :')
     DEL = DELAYT * 1.E3
     CALL PLOTNF(0.8, 0.5, DEL, 3)
     CALL GREND
     GO TO 710
C JUMP TO AVOID FILTERING STAGE
 640 CONTINUE
C
C Now filter in vertical direction to remove artifacts
C
     N1 = 128
     N2 = 128
     FNYQ = .5 / H
     FHICUT = FNYQ
     FHIOFF = FNYQ
     FLOWCT = .125
     FLOOFF = 0.05
     DO 670 JJ = 1, IXMAX
         CALL ZERO(N1, ARR)
         DO 650 II = 1, IZMAX
             ARR(II) = REFRES(II,JJ)
 650     CONTINUE
         CALL BPSCOS(ARR, N1, CX, FLOWCT, FHICUT, FLOOFF, FHIOFF, FNYQ)
         DO 660 II = 1, IZMAX
             REFRES(II,JJ) = ARR(II)
 660     CONTINUE
 670 CONTINUE
     CALL PSPACE(PX1, PX2, PZ1, PZ2)
     CALL MAP(0.0, XMAX, ZMAX, 0.0)
     CALL BORDER
     CALL SCALES
     DO 700 IX = 1, IXMAX
         DO 680 IZ = 1, IZMAX
             RPLOT(IZ) = REAL(IX) + REFRES(IZ,IX) * 2. / AMPMAX
 680     CONTINUE
         CALL PTJOIN(RPLOT, Z, 1, IZMAX, 1)
         DO 690 IZ = 1, IZMAX
             IF (RPLOT(IZ) .GT. (REAL(IX) + 1.E-2)) THEN
                 CALL POSITN(REAL(IX), Z(IZ))
                 CALL JOIN(RPLOT(IZ), Z(IZ))
             END IF
 690     CONTINUE
 700 CONTINUE
     CALL PLOTNC(RX0, RZ0, 250)
     DO 710 JJJ = 1, NSOR
         RXI = REAL(IXS(JJJ))
         RXZ = REAL(IZS(JJJ))
```

```
      CALL PLOTNC(RXI, RXZ, 245)
710 CONTINUE
    END
```

Appendix A.7

The forward modelling program

EXTRAP

The program EXTRAP is a forward modelling finite-difference program which generates synthetic seismograms for a given velocity model and source and receiver geometry. A tapered zero-phase wavelet is used as the source function and the wavefield may be plotted as it expands in time. The final seismograms recorded at the receiver positions are also plotted.

```
C
C. PROGRAM TO CARRY OUT WAVEFIELD EXTRAPOLATION BY FINITE DIFFERENCE APPROXN
C  TO ACOUSTIC WAVE EQUATION
C  SYNTHETIC SEISMOGRAM GENERATION SUPPORTED
C  ALGORITHM TAKEN FROM MCMECHAN  (GEOPHYSICS V50 P627-636)
C
C  WRITTEN BY M.J. FINDLAY 1989
C
      PROGRAM EXTRAP
      IMPLICIT DOUBLE PRECISION (A - H,O - Z)
      PARAMETER (PI=3.14159265358,POL0=1.0,POL2=-.5)
C
C  ABSORBING BOUNDARY CONDITIONS
C  VALUES OF P0 & P2 (RENAUT&PETERSEN GEOPHYSICS 1989)
C (1,-.5)                       PADE
C (3G-2G**3,-2G) G=SIN(PI/8)    CHEBYCHEV
C (21PI/64,-15PI/64)            L2
C (10/3PI,-8/3PI)               CHEBYCHEV-PADE
C
C  SOURCE FUNCTION IS ZERO-PHASE BUTTERWORTH WAVELET
C
C
      DOUBLE PRECISION U(128,128,3), TERM1, TERM2, TERM3, A,
     1       SORSIG(1024), V(128,128)
      REAL SEIS(1024,40), TT(1024), AMPMAX, XMAX, ZMAX, AMPSCL, RREC
      REAL UR4(128,128), RPLOT(1024), Z(128), BUTT(1024), BUTT2(1024),
     1     RNL, TMAX
      REAL BUT1, BUT2, BUT3, BUT4, VINL(5), WIDTH(5)
      COMPLEX CBUTT(1024)
      INTEGER NMOV(20), IXR(40), IZR(40)
      CHARACTER*10 OPFILE, IPFILE, IFNAM1, IFNAM2
      IT0 = 3
      NSAMS = 128 * 128
      NSAMT = NSAMS * 6
      CALL ZERO(NSAMT, U(1,1,1))
C
C THIS ZEROS ARRAY U(X,Z,T=0,1,2)
C
      WRITE (6,*)'ENTER GRID POINT SPACING (METRES):'
      READ (5,*) H
      WRITE (6,*)'ENTER MAXIMUM GRID VALUES IN X & Z (<128) :'
      READ (5,*) IXMAX, IZMAX
      WRITE (6,*)'ENTER TIME SAMPLE INTERVAL (millisecs):'
      READ (5,*) DT
      DT = DT * 1.E-3
      FNYQ = .5 / DT
      NT = 1024
      NF = NT / 2
      DF = FNYQ / NF
      WRITE (6,*)'ENTER SOURCE POSN (X,Z) GRIDPOINT NUMBERS'
      READ (5,*) IX0, IZ0
      WRITE (6,*)'SOURCE IS ZERO PHASE BUTTERWORTH  FNCTN '
      WRITE (6,*)'Enter low-cut, slope, high-cut, slope '
      READ (5,*) BUT1, BUT2, BUT3, BUT4
C  HIGH CUT
      RNL = ALOG10((2.*(10.**(BUT4/10.))) - 1.0)
      WRITE (6,*)'RNL = ', RNL
      RNL = RNL / (2.*ALOG10(2.))
      WRITE (6,*)'RNL = ', RNL
      DO 10 J = 1, NT / 2 + 1
          RFR = DF * REAL(J - 1)
          TEM = 1. / (1. + ((RFR/BUT3)**(2.*RNL)))
          BUTT(J) = SQRT(TEM)
 10   CONTINUE
C  LOW CUT
      WRITE (6,*)'NOW LOW CUT.. '
      RNL = ALOG10((2.*(10.**(BUT2/10.))) - 1.0)
      WRITE (6,*)'RNL = ', RNL
      RNL = RNL / (2.*ALOG10(2.))
      WRITE (6,*)'RNL = ', RNL
      BUTT2(1) = 0.0
      DO 20 J = 2, NT / 2 + 1
          RFR = DF * REAL(J - 1)
          TEM = 1. / (1. + ((BUT1/RFR)**(2.*RNL)))
          BUTT2(J) = SQRT(TEM)
 20   CONTINUE
      DO 30 J = 1, NT / 2 + 1
          BUTT(J) = BUTT(J) * BUTT2(J)
 30   CONTINUE
C  TRANSFORM TO TIME DOMAIN
      ISAM = 2
      DO 40 I = NT, NT / 2 + 2, -1
          BUTT(I) = BUTT(ISAM)
          ISAM = ISAM + 1
 40   CONTINUE
      DO 50 I = 1, NT
          CBUTT(I) = CMPLX(BUTT(I),0.0)
 50   CONTINUE
      CALL FORK(NT, CBUTT, 1.)
C
C  APPLY TAPER
C
      NTAP0 = NINT(1.E0/(BUT3*DT)) * 1.5
      NTAP1 = NINT(1.E0/(BUT3*DT)) * 0.75
      LTAP = NTAP0 - NTAP1
      WRITE (6,*)'NTAP1,NTAP0,LTAP', NTAP1, NTAP0, LTAP
      DO 60 I = NTAP1, NTAP0
          FACTOR = REAL(NTAP0 - I) / REAL(LTAP)
          CBUTT(I + 1) = CBUTT(I + 1) * FACTOR
          CBUTT(NT - I) = CBUTT(NT - I) * FACTOR
 60   CONTINUE
      DO 70 I = NTAP0 + 2, NT - NTAP0 - 1
          CBUTT(I) = 0.0
 70   CONTINUE
C  Shift origin to NTAP0+1
      CALL ZERO(NT, BUTT2)
      DO 80 I = 1, NTAP0 + 1
          BUTT2(I + NTAP0 + 1) = REAL(CBUTT(I))
          BUTT2(I) = REAL(CBUTT(I + NT - NTAP0 - 1))
 80   CONTINUE
C  Normalise output wavelet
      CALL NORMAN(NT, BUTT2)
      BMAX = 0.0
      DO 90 I = 1, NT
          IF (ABS(BUTT2(I)) .GT. BMAX) THEN
              BMAX = ABS(BUTT2(I))
              INDSHF = I
          END IF
          SORSIG(I) = DBLE(BUTT2(I))
 90   CONTINUE
```

```
      WRITE (6,*)'INPUT SOURCE WAVEFIELD FROM FILES 1=Y 0=N'
      READ (5,*) IPSORY
  100 FORMAT (A10)
      NSAMP0 = 2
      IF (IPSORY .EQ. 1) THEN
          WRITE (6,*)'ENTER NAME OF FILE 1:'
          READ (5,100) IFNAM1
          WRITE (6,*)'ENTER TIME SAMPLE NUMBER FOR FIRST FILE'
          READ (5,*) NSAMP0
          WRITE (6,*)'ENTER NAME OF FILE 2:'
          READ (5,100) IFNAM2
          WRITE (6,*)'ENTER SHIFT IN DEPTH TO APPLY +VE ==> UP '
          READ (5,*) IZSHFT
          OPEN (UNIT=11,FILE=IFNAM1,FORM='FORMATTED',STATUS='OLD')
          DO 110 JJ = 1, 128
              READ (11,120) (U(II,JJ,1),II=1,128)
  110     CONTINUE
  120     FORMAT (8(D10.4))
          CLOSE (11)
          OPEN (UNIT=12,FILE=IFNAM2,FORM='FORMATTED',STATUS='OLD')
          DO 130 JJ = 1, 128
              READ (12,120) (U(II,JJ,2),II=1,128)
  130     CONTINUE
          CLOSE (12)
          DO 140 JJ = 1, 128 - IZSHFT
              DO 140 II = 1, 128
                  U(II,JJ,1) = U(II,JJ + IZSHFT,1)
                  U(II,JJ,2) = U(II,JJ + IZSHFT,2)
  140     CONTINUE
          DO 150 JJ = 128 - IZSHFT, 128
              DO 150 II = 1, 128
                  U(II,JJ,1) = 0.0
                  U(II,JJ,2) = 0.0
  150     CONTINUE
          WRITE (6,*)'APPLY COSINE WEIGHTING TO SOURCE WAVEFIELD 1=Y:'
          READ (5,*) ICSANS
          IF (ICSANS .EQ. 1) THEN
              DO 160 JJ = 1, 128
                  DO 160 II = 1, 128
                      RLEN = SQRT(REAL((II - IX0)**2 + (JJ - IZ0)**2))
                      IF (RLEN .EQ. 0.0) RLEN = 1.0
                      FAC = ABS(REAL(JJ - IZ0)) / RLEN
                      U(II,JJ,1) = U(II,JJ,1) * FAC
                      U(II,JJ,2) = U(II,JJ,2) * FAC
  160         CONTINUE
          END IF
      END IF
      WRITE (6,*)'ENTER NO. OF LAYERS :'
      READ (5,*) NLAYER
      IDEPTH = 0
      VMAX = 0.0
      DO 190 NL = 1, NLAYER
          WRITE (6,*)'ENTER NO. OF variations in layer :'
          READ (5,*) NVARIA
          WRITE (6,*)'ENTER VELOCITY(S) OF MEDIUM ', NL, ' (m / sec)'
          READ (5,*) (VINL(I),I=1,NVARIA)
          WRITE (6,*)'ENTER WIDTHS OF FIELD(S) IN METRES :'
          READ (5,*) (WIDTH(I),I=1,NVARIA)
          WRITE (6,*)'ENTER THICKNESS OF LAYER ', NL, ' (metres)'
          READ (5,*) THICK
          NTHICK = NINT(THICK/H)
          IXF = 1
          DO 180 I = 1, NVARIA
              VL = VINL(I)
              IF (VL .GT. VMAX) VMAX = VL
              IXL = WIDTH(I) / H + IXF
              DO 170 IZ = 1, NTHICK
                  DO 170 IX = IXF, IXL
                      V(IX,IZ + IDEPTH) = VL
  170         CONTINUE
              IXF = IXL
  180     CONTINUE
          IDEPTH = IDEPTH + NTHICK
  190 CONTINUE
      WRITE (6,*)'INCLUDE POINT DIFFRACTOR 1=Y 0=N:'
      READ (5,*) IYNANS
      IF (IYNANS .EQ. 1) THEN
          WRITE (6,*)'ENTER IX,IZ,VEL(IX,IZ)'
          READ (5,*) IX, IZ, VPOINT
          V(IX,IZ) = VPOINT
      END IF
      WRITE (6,*)'ENTER NUMBER OF DIFFERENT MOVIE FRAMES REQUIRED'
      READ (5,*) NMOVIE
      DO 200 NM = 1, NMOVIE
          WRITE (6,*)'ENTER SAMPLE TIME #', NM
          READ (5,*) NMOV(NM)
          NMOV(NM) = NMOV(NM) + NTAP0 + 1
  200 CONTINUE
      WRITE (6,*)'ENTER CUTOFF RATIO FOR S/N :'
      READ (5,*) CUTO
      WRITE (6,*)'ENTER NUMBER OF RECEIVERS TO BE SEISMOGRAMMED :'
      READ (5,*) NREC
      DO 210 NR = 1, NREC
          WRITE (6,*)'ENTER GRID LOCATION (IX,IZ) OF RECEIVER #', NR
          READ (5,*) IXR(NR), IZR(NR)
  210 CONTINUE
      WRITE (6,*)'2nd or 4th Order finite difference approximation :'
      READ (5,*) NORD
      WRITE (6,*)'APPLY T-RAMP 1=Y 0=N:'
      READ (5,*) IRAMP
      WRITE (6,*)'Enter name of file for seismogram output :'
      READ (5,220) OPFILE
  220 FORMAT (A10)
C
C UNIFORM VELOCITY TO START WITH
C
C
C  H=GRID POINT SPACING
C
      KB40 = 1024 * 40
      CALL ZERO(KB40, SEIS(1,1))
      IF (IPSORY .EQ. 1) GO TO 250
C
C NOW DEFINE INITIAL WAVEFIELD INCLUDING SOURCE TERM
C
  230 IT = 1
      WRITE (7,*) IT, SORSIG(IT)
      U(IX0,IZ0,IT0 - 1) = (SORSIG(1))
C
C START OF SOURCE AT T = 0
```

```
C
      A = (V(IX0,IZ0)*DT/H)
      IF (DT .GE. H/(SQRT(2.)*V(IX0,IZ0))) THEN
          WRITE (6,*)'ALGORITHM UNSTABLE '
          WRITE (6,*)'DT,H,V =', DT, H, V(IX0,IZ0)
          STOP
 240  END IF
C
C  START LOOP OVER ALL TIME SAMPLES
C
 250  NPLOT = 1
      DO 410 IT = NSAMP0, NMOV(NMOVIE)
          WRITE (6,*)'TIME SAMPLE : ', IT
          TIMEIT = (IT - 1) * DT
          DO 270 IZ = 2, IZMAX - 1
C
C  INCLUDE FREE SURFACE BY MAKING U(IX,Z=0) = 0.0 ????
C
              DO 270 IX = 2, IXMAX - 1
                  A = (V(IX,IZ)*DT/H)
                  IF (NORD .EQ. 2 .OR. IX .EQ. 2 .OR. IZ .LE. 1 .OR.
     1                    IX .EQ. IXMAX - 1 .OR. IZ .EQ. IZMAX - 1)
     2                    THEN
                      TERM1 = 2 * (1 - 2*A**2) * U(IX,IZ,IT0 - 1)
                      TERM2 = U(IX,IZ,IT0 - 2)
                      TERM3 = U(IX + 1,IZ,IT0 - 1) + U(IX - 1,IZ,IT0 -
     1                1) + U(IX,IZ + 1,IT0 - 1)
                      IF (IZ .GT. 1) TERM3 = TERM3 + U(IX,IZ - 1,IT0 -
     1                1)
                      TERM3 = TERM3 * A ** 2
                      U(IX,IZ,IT0) = TERM1 - TERM2 + TERM3
                  ELSE
                      TERM1 = (2. - 5.*A**2) * U(IX,IZ,IT0 - 1)
                      TERM2 = U(IX + 1,IZ,IT0 - 1) + U(IX,IZ + 1,IT0 -
     1                1) + U(IX - 1,IZ,IT0 - 1)
                      IF (IZ .GT. 1) TERM2 = TERM2 + U(IX,IZ - 1,IT0 -
     1                1)
                      TERM3 = U(IX + 2,IZ,IT0 - 1) + U(IX,IZ + 2,IT0 -
     1                1) + U(IX - 2,IZ,IT0 - 1)
                      IF (IZ .GT. 2) THEN
                          TERM3 = TERM3 + U(IX,IZ - 2,IT0 - 1)
                      END IF
                      ALPHA = TERM1 + A ** 2 * (16*TERM2 - TERM3) / 12.
C
C                         ALPHA = TERM1 + A**2 * (4.*TERM2 + TERM3) /6.
                      U(IX,IZ,IT0) = ALPHA - U(IX,IZ,IT0 - 2)
                  END IF
                  IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0)
     1            U(IX,IZ,IT0) = 0.0
                  DO 260 NR = 1, NREC
                      IF (IX .EQ. IXR(NR) .AND. IZ .EQ. IZR(NR))
     1                    THEN
                          IF (IT .GT. (NTAP0 + 1)) SEIS(IT - NTAP0 - 1,
     1                    NR) = REAL(U(IX,IZ,IT0))
                      END IF
                      IF (IX .EQ. IX0 .AND. IZ .EQ. IZ0 .AND. IT .LT. 2*
     1                    NTAP0 + 3) THEN
                          U(IX,IZ,IT0) = SORSIG(IT)
                          SEIS(IT,1) = REAL(SORSIG(IT))
                      END IF
 260                  CONTINUE
 270          CONTINUE
C         GO TO 399
C    ABOVE LINE INSERTED TO REMOVE ABSORBING BOUNDARY CONDITIONS
C
C   NOW APPLY ABSORBING BOUNDARY CONDITIONS
C   OPTION TO MAKE SURFACE ABSORBING
C
C
C   TOP FIRST
C
              DO 280 IX = 3, IXMAX - 2
                  IZ = 1
                  A = V(IX,IZ) * DT / H
                  TERM1 = U(IX,IZ,IT0 - 1) + U(IX,IZ + 1,IT0 - 1)
                  TERM1 = TERM1 * 2.0 * POL0
                  TERM2 = U(IX,IZ + 1,IT0) + U(IX,IZ,IT0 - 2)
                  TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
                  TERM3 = U(IX + 1,IZ,IT0 - 2) + U(IX - 1,IZ,IT0 - 2) + U(
     1            IX + 1,IZ + 1,IT0) + U(IX - 1,IZ + 1,IT0)
                  TERM3 = -TERM3 * A ** 2 * POL2
                  UINIT = (TERM1 + TERM2 + TERM3) / (POL0 + A)
                  U(IX,IZ,IT0) = UINIT - U(IX,IZ + 1,IT0 - 2)
                  IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0)
     1            U(IX,IZ,IT0) = 0.0
 280          CONTINUE
C
C      LHS FIRST
C
 290          DO 300 IZ = 3, IZMAX - 2
                  IX = 1
                  A = V(IX,IZ) * DT / H
                  TERM1 = U(IX,IZ,IT0 - 1) + U(IX + 1,IZ,IT0 - 1)
                  TERM1 = TERM1 * 2.0 * POL0
                  TERM2 = U(IX + 1,IZ,IT0) + U(IX,IZ,IT0 - 2)
                  TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
                  TERM3 = U(IX,IZ + 1,IT0 - 2) + U(IX,IZ - 1,IT0 - 2) + U(
     1            IX + 1,IZ + 1,IT0) + U(IX + 1,IZ - 1,IT0)
                  TERM3 = -TERM3 * A ** 2 * POL2
                  UINIT = (TERM1 + TERM2 + TERM3) / (POL0 + A)
                  U(IX,IZ,IT0) = UINIT - U(IX + 1,IZ,IT0 - 2)
                  IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0)
     1            U(IX,IZ,IT0) = 0.0
 300          CONTINUE
C
C      NOW BOTTOM
C
              DO 310 IX = 3, IXMAX - 2
                  IZ = IZMAX
                  A = V(IX,IZ) * DT / H
                  TERM1 = U(IX,IZ,IT0 - 1) + U(IX,IZ - 1,IT0 - 1)
                  TERM1 = TERM1 * 2.0 * POL0
                  TERM2 = U(IX,IZ - 1,IT0) + U(IX,IZ,IT0 - 2)
                  TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
                  TERM3 = U(IX + 1,IZ - 1,IT0) + U(IX - 1,IZ - 1,IT0) + U(
     1            IX + 1,IZ,IT0 - 2) + U(IX - 1,IZ,IT0 - 2)
                  TERM3 = -TERM3 * A ** 2 * POL2
                  UINIT = (TERM1 + TERM2 + TERM3) / (A + POL0)
                  U(IX,IZ,IT0) = UINIT - U(IX,IZ - 1,IT0 - 2)
 310          CONTINUE
```

```
C
C   NOW RHS
C
      DO 320 IZ = 3, IZMAX - 2
          IX = IXMAX
          A = V(IX,IZ) * DT / H
          TERM1 = U(IX,IZ,IT0 - 1) + U(IX - 1,IZ,IT0 - 1)
          TERM1 = TERM1 * 2.0 * POL0
          TERM2 = U(IX - 1,IZ,IT0) + U(IX,IZ,IT0 - 2)
          TERM2 = TERM2 * (A - POL0 + 2.*POL2*A**2)
          TERM3 = U(IX,IZ + 1,IT0 - 2) + U(IX,IZ - 1,IT0 - 2) + U(
    1     IX - 1,IZ + 1,IT0) + U(IX - 1,IZ - 1,IT0)
          TERM3 = -TERM3 * A ** 2 * POL2
          UINIT = (TERM1 + TERM2 + TERM3) / (POL0 + A)
          U(IX,IZ,IT0) = UINIT - U(IX - 1,IZ,IT0 - 2)
          IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0)
    1     U(IX,IZ,IT0) = 0.0
 320  CONTINUE
C
C   NOW MAKE BOTTOM CORNERS ABSORBING TOO
C
C      LOWER RIGHT HAND CORNER
C
      IX = IXMAX - 1
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = IZMAX - 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C   UPPER RIGHT HAND CORNER
C
      IX = IXMAX - 1
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = IXMAX
      IZ = 2
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
      IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0) U(IX,IZ,IT0) =
    1  0.0
C
      IX = IXMAX
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX - 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
      IF (ABS(U(IX,IZ,IT0))*TIMEIT .LT. A0*TREF/CUT0) U(IX,IZ,IT0) =
    1  0.0
C
C     LOWER LEFT HAND CORNER
C
      IX = 1
      IZ = IZMAX - 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = 2
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
      IX = 1
      IZ = IZMAX
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ - 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C   UPPER LEFT CORNER
C
      IX = 1
      IZ = 2
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
      IX = 2
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
      IX = 1
      IZ = 1
      VDASH = V(IX,IZ)
      TERM1 = (U(IX,IZ + 1,IT0) + U(IX + 1,IZ,IT0)) / H
      TERM2 = (U(IX,IZ,IT0 - 1)) * SQRT(2.) / (VDASH*DT)
      U(IX,IZ,IT0) = (TERM1 + TERM2) / (2./H + SQRT(2.)/(VDASH*DT))
C
C   MAKE THIS LINE THE LAST STEP
C
 330  WRITE (7,*) IT, SORSIG(IT)
      DO 340 J = 1, 128
          DO 340 I = 1, 128
```

```
              U(I,J,ITO - 2) = U(I,J,ITO - 1)
              U(I,J,ITO - 1) = U(I,J,ITO)
 340      CONTINUE
          IF (IT .GE. NMOV(NMOVIE) - 1) THEN
C
C   WRITE  OUT U(IX,IZ,ITEND-1) & U(IX,IZ,ITEND) TO FILE ATTACHED TO
C UNIT 13
C
            DO 350 J = 1, 128
              WRITE (13,120) (U(I,J,ITO - 1),I=1,128)
 350        CONTINUE
          END IF
          IF (IT .EQ. NMOV(NPLOT)) THEN
C
C  NOW GET GRAPHICAL OUTPUT OF U(IX,IZ,ITEND)
C
            AMPMAX = 0.0
            DO 360 I = 1, IXMAX
              DO 360 J = 1, IZMAX
                UR4(J,I) = REAL(U(I,J,ITO - 1))
                IF (ABS(UR4(J,I)) .GT. AMPMAX) AMPMAX = ABS(UR4(J,
     1          I))
 360        CONTINUE
            IF (AMPMAX .EQ. 0.0) AMPMAX = 1.0
            CALL PAPER(1)
            CALL PSPACE(0.91, 0.99, 0.65, 0.90)
            CALL MAP(0.0, 1.0, 0.0, 1.0)
            CALL BORDER
            CALL CTRMAG(15)
            CALL PCSCEN(0.5, 0.8, 'Time')
            CALL PCSCEN(0.5, 0.7, 'Index')
            INDEX = IT - NTAPO
            CALL PLOTNI(0.7, 0.6, INDEX)
            CALL PCSCEN(0.5, 0.4, 'SCALE')
            RSCALE = (1.0/AMPMAX)
            CALL PLOTNE(0.7, 0.3, RSCALE, 2)
            CALL PSPACE(0.05, 0.90, 0.05, 0.90)
            XMAX = REAL(IXMAX) + 1.
            ZMAX = REAL(IZMAX) + 1.
            CALL MAP(0.0, XMAX, ZMAX, 0.0)
            CALL BORDER
            CALL SCALES
            DO 370 II = 1, IZMAX
              Z(II) = REAL(II)
 370        CONTINUE
            DO 400 IX = 1, IXMAX
              DO 380 IZ = 1, IZMAX
                IF (UR4(IZ,IX) .LT. 0.0) THEN
                  AMPPL = -1.0 * SQRT(-UR4(IZ,IX))
                ELSE
                  AMPPL = SQRT(UR4(IZ,IX))
                END IF
                RPLOT(IZ) = REAL(IX) + AMPPL * 2. / SQRT(AMPMAX)
 380          CONTINUE
              CALL PTJOIN(RPLOT, Z, 1, IZMAX, 1)
              DO 390 IZ = 1, IZMAX
                IF (RPLOT(IZ) .GT. (REAL(IX) + 1.E-2))
     1                   THEN
                  CALL POSITN(REAL(IX), Z(IZ))
                  CALL JOIN(RPLOT(IZ), Z(IZ))
                  END IF
 390            CONTINUE
 400          CONTINUE
              CALL FRAME
              NPLOT = NPLOT + 1
            END IF
 410  CONTINUE
C
C  WRITE OUT SEIS(1024,40) TO FILE OPFILE
C
      LEN = 4104
      WRITE (6,*)'Enter shot number to be saved in file:'
      READ (5,*) NSHOT
      IDSHOT = (NSHOT - 1) * (NREC + 1) + 1
      OPEN (2,FILE=OPFILE,STATUS='UNKNOWN',FORM='UNFORMATTED',ACCESS=
     1     'DIRECT',RECL=LEN)
      WRITE (2,REC=IDSHOT) (SEIS(I,1),I=1,1024)
      DO 420 J = 1, NREC
          NIDC = IDSHOT + J
          WRITE (2,REC=NIDC) (SEIS(I,J),I=1,1024)
 420  CONTINUE
      CLOSE (2)
C
C  NOW PLOT OUT SEISMOGRAMS IN SEIS(1024,40)
C
      CALL PSPACE(0.1, 0.9, 0.1, 0.9)
      RREC = REAL(NREC) + 1.
      TMAX = REAL(IT)
      CALL MAP(0, RREC, TMAX, 0)
      CALL BORDER
      CALL SCALES
      DO 430 II = 1, IT
          TT(II) = REAL(II)
 430  CONTINUE
      DO 450 NR = 1, NREC
          DO 440 NT = 1, IT
              IF (IRAMP .EQ. 1) SEIS(NT,NR) = SEIS(NT,NR) * TT(NT)
              IF (ABS(SEIS(NT,NR)) .GT. AMPSCL) AMPSCL = ABS(SEIS(NT,NR)
     1        )
 440      CONTINUE
 450  CONTINUE
      AMPSCL = AMPSCL * 1.
      IF (AMPSCL .EQ. 0.0) AMPSCL = 1.0
      DO 480 NR = 1, NREC
          DO 460 NT = 1, IT
              RPLOT(NT) = REAL(NR) + SEIS(NT,NR) / AMPSCL
 460      CONTINUE
          CALL PTJOIN(RPLOT, TT, 1, IT, 1)
          DO 470 NT = 1, IT
              IF (RPLOT(NT) .LT. (REAL(NR) - 1.E-2)) THEN
                  CALL POSITN(REAL(NR), TT(NT))
                  CALL JOIN(RPLOT(NT), TT(NT))
              END IF
 470      CONTINUE
 480  CONTINUE
      CALL GREND
      END
```

Appendix A.8

The migration program

KIRCHMIG

The program KIRCHMIG carries out Kirchhoff-type migrations by raytracing from each image point to each source and receiver using the subroutine RAYTRA (appendix A.5). The image time calculated for each source receiver pairing is then used to extract the contribution to the image from the appropriate sample in the seismic data. The migrated image is then output to a file for later viewing. The program include several processing options such as the choice of migration operator and the range of reflector dips allowed.

```
C
C .  Program to do Kirchhoff migration using RAYTRA anisotropic
C raytracing algorithm
C  Allows general source&receiver positions
C  Options of different diffraction stacks: Diffraction stack,
C                                           Kirchhoff,
C                                           GRT
C   Selective raypath muting for shallow-dipping rays, and geological
C dip range
C
C  Needs subroutine RAYTRA for raytracing
C        subroutine library TSAR4_L  (Time series analysis -- Robinson,
C                                                     Claerbout et al.)
C
C

      PROGRAM KIRCH
C
C  DEPTH(ilay) = depth to top of layer ilay
C  VH(ilay) = horizontal velocity in layer ilay
C  VV(ilay) = vertical velocity in layer ilay
C  (XSOR(isor),ZSOR(isor)) = coordinates of source isor
C  (XREC(irec),ZREC(irec)) = coordinates of receiver irec
C  CSG(itime,irec,isor) = recorded data
C  IMAGE(idepth,ioffset) = IMAGED reflectivity at (idepth,ioffset)
C
C
C  VERSION 4.0 WITH FASTER RAYTRACING CODE
C
      PARAMETER (NSM=512,NSOR1=27,NREC1=24,NIMAGZ=200,NIMAGX=128)
      REAL DEPTH(31), VH(31), VV(31), XSOR(100), ZSOR(100)
      REAL XREC(NREC1), ZREC(NREC1), CSG(NSM,NREC1,NSOR1)
      REAL IMAGE(NIMAGZ,NIMAGX)
      REAL TAUS(NSOR1), TAUR(NREC1), ANGS(NSOR1), ANGG(NREC1),
     1     ANG0(NSOR1)
      REAL ANG1(NREC1)
      COMPLEX CX(NSM), C0, C1
      CHARACTER*17 FNAME
      CHARACTER*1 A(256)
      PI = 3.1415926535
      PI2 = PI / 2.
      DO 10 I = 1, 256
          A(I) = '@'
   10 CONTINUE
      NIMAGE = NIMAGZ * NIMAGX
      CALL ZERO(NIMAGE, IMAGE)
C
C  SET UP VELOCITY MODEL
C
      WRITE (6,*)'ENTER NO. OF LAYERS :'
      READ (5,*) NLAMAX
      NDEPTH = NLAMAX + 1
      DEPTH(1) = 0.0
      DO 20 J = 1, NLAMAX
          WRITE (6,*)'Enter VH,VV,Thickness(S.I.) for layer ', J
          READ (5,*) VH(J), VV(J), THICK
          DEPTH(J + 1) = THICK + DEPTH(J)
   20 CONTINUE
C
C  SET UP RAYTRACING PARAMETERS
C
      WRITE (6,*)'ENTER RAYTRACING ACCURACY IN METRES :'
      READ (5,*) ACC
      WRITE (6,*)'Enter no. of angles to try for each raypath :'
      READ (5,*) MAXLOP
      WRITE (6,*)'ENTER GRID POINT SPACINGS (DX,DZ) :'
      READ (5,*) DXGRID, DZGRID
      WRITE (6,*)'ENTER MINIMUM AND MAXIMUM X-VALUES :'
      READ (5,*) XMIN, XMAX
      WRITE (6,*)'Enter Imaging grid area (X0,X1,Z0,Z1) :'
      READ (5,*) XIM0, XIM1, ZIM0, ZIM1
      NX = INT((XMAX - XMIN)/DXGRID) + 1
      NZ = INT(DEPTH(NDEPTH)/DZGRID) - 1
C
C  SET UP SOURCE AND RECEIVER COORDINATES
C
      WRITE (6,*)'Enter no. of source positions :'
      READ (5,*) NSOR
      DO 30 J = 1, NSOR
          WRITE (6,*)'ENTER COORDINATES OF SOURCE ', J, ' :'
          READ (5,*) XSOR(J), ZSOR(J)
   30 CONTINUE
      WRITE (6,*)'Enter no. of receiver positions :'
      READ (5,*) NREC
      DO 40 J = 1, NREC
          WRITE (6,*)'ENTER COORDINATES OF RECEIVER ', J, ' :'
          READ (5,*) XREC(J), ZREC(J)
   40 CONTINUE
      DSG = SQRT((ZREC(2) - ZREC(1))**2 + (XREC(2) - XREC(1))**2)
      IF (NREC .EQ. 1) DSG = 1.0
      DSS = SQRT((ZSOR(2) - ZSOR(1))**2 + (XREC(2) - XREC(1))**2)
      IF (NSOR .EQ. 1) DSS = 1.0
      WRITE (6,*)'Apply Newman amplitude-phase correction (1=Y) ?'
      READ (5,*) NEWMAN
      WRITE (6,*)'Enter aperture,taper,raymute,apemute in degrees :'
      READ (5,*) APRANG, APRTAP, THETMU, APRMUT
C  APRMUT is also used as stacking angle cut-off
      APRANG = .5 * APRANG * PI / 180.
      APRTAP = APRTAP * PI / 180.
      THETMU = THETMU * PI / 180.
      APRMUT = .5 * APRMUT * PI / 180.
      WRITE (6,*)'ENTER Migration type 1=Kir stack,2=Kir int,3=GK,4=GRT,
     15=CDP gath'
      READ (5,*) IMIGTY
      IF (IMIGTY .EQ. 5) NX = 1
      WRITE (6,*)'ENTER stacking cutoff :'
      READ (5,*) STKOFF
      WRITE (6,*)'ENTER DIPS OF SOURCE AND RECEIVER ARRAYS IN DEGREES :'
      READ (5,*) DIPS, DIPR
      DIPS = DIPS * PI / 180.
      DIPR = DIPR * PI / 180.
C
C  READ IN DATA FILE
C
      WRITE (6,*)'Enter name of datafile to migrate : '
      READ (5,50) FNAME
   50 FORMAT (A17)
      WRITE (6,*)'UP (1) or DOWN (0) -going wavefield :'
      READ (5,*) IUP
      IF (FNAME .EQ. 'DUMMY') THEN
C
```

```
C  INVERSE IMPULSE RESPONSE
C
         WRITE (6,*)'Enter coordinates of diffracting point :'
         READ (5,*) XDIF, ZDIF
         DO 70 K = 1, NSOR
             D0 = SQRT((XSOR(K) - XDIF)**2 + (ZSOR(K) - ZDIF)**2)
             T0 = D0 / VV(1)
             NSAMR = 256
             DT = .5E-3
             K24 = NSM * NREC
             CALL ZERO(K24, CSG(1,1,K))
             DO 60 J = 1, NREC
                 D1 = SQRT((XREC(J) - XDIF)**2 + (ZREC(J) - ZDIF)**2)
                 T1 = D1 / VV(1)
                 TIMAG = T0 + T1
                 AMP = 1.0 / SQRT(TIMAG)
                 NIMAG = INT(TIMAG/DT) + 1
                 CSG(NIMAG,J,K) = AMP
 60          CONTINUE
 70      CONTINUE
      ELSE
         WRITE (6,*)'Enter no. of samples per trace & NO. NEEDED  :'
         READ (5,*) NSAMR, NSAM0
         WRITE (6,*)'Enter sampling interval in millisecs :'
         READ (5,*) DT
         DT = DT * 1.E-3
         LEN = 4 * (NSAMR + 2)
         WRITE (6,*)'Enter I.D. of first common shot gather to migrate
     1:'
         READ (5,*) IDSHOT
         WRITE (6,*)'Enter spreading correction (power of T) to apply:'
         READ (5,*) TPOWER
         OPEN (10,FILE=FNAME,STATUS='OLD',ACCESS='DIRECT',FORM=
     1        'UNFORMATTED',RECL=LEN)
         DO 160 J = 1, NSOR
             WRITE (6,*)'READING SHOT ... ', J
             JREC = (NREC + 1) * (J - 2 + IDSHOT) + 1
             RMS = 0.0
             DO 90 K = 1, NREC
                 KREC = JREC + K
                 READ (10,REC=KREC) (CSG(I,K,J),I=1,NSAM0)
C
C  CORRECT DATA FROM 3-D TO 2D
C
                 DO 80 I = 1, NSAM0
                     CSG(I,K,J) = CSG(I,K,J) * (REAL(I)) ** TPOWER
                     RMS = RMS + CSG(I,K,J) ** 2
 80              CONTINUE
 90          CONTINUE
             RMS = SQRT(RMS/REAL(NSAM0*NREC))
CC
C  NOW EQUATE RMS ENERGIES OF CSG
CC
             DO 110 K = 1, NREC
                 DO 100 I = 1, NSAM0
                     CSG(I,K,J) = CSG(I,K,J) / RMS
100              CONTINUE
110          CONTINUE
C
C  NOW APPLY 1/2-DIFFERENTIAL OPERATOR IF NEEDED
C
             IF (NEWMAN .EQ. 1) THEN
                 FNYQ = .5 / DT
                 DF = FNYQ / REAL(NSAM0/2)
                 DO 150 K = 1, NREC
                     DO 120 I = 1, NSAM0
                         CX(I) = CSG(I,K,J)
120                  CONTINUE
                     CALL FORK(NSAM0, CX, -1.0)
C
C FORWARD FFT
C
                     CX(1) = 0.0
                     C0 = SQRT(REAL(NSAM0/2)) * (1.,-1.)
                     C0 = 0.0
                     CX(NSAM0/2 + 1) = CX(NSAM0/2 + 1) * C0
C
C  Subtract PI/4 from PHASE AND MULTIPLY CX BY OMEGA**.5 RAMP
C
                     DO 130 I = 2, NSAM0 / 2
                         FI = DF * (I - 1)
                         C1 = SQRT(REAL(I - 1)) * (1.,-1.)
                         IF (FI .GT. 3*FNYQ/4.) THEN
                             C1 = SQRT(REAL(NSAM0)*3./8.) * (1.,-1.)
                             C1 = C1 * 4. * (FNYQ - FI) / FNYQ
                         END IF
                         CX(I) = CX(I) * C1
                         CX(NSAM0 + 2 - I) = CONJG(CX(I))
130                  CONTINUE
C
C  INVERSE FFT
C
                     CALL FORK(NSAM0, CX, +1.0)
                     DO 140 I = 1, NSAM0
                         CSG(I,K,J) = CX(I)
140                  CONTINUE
150              CONTINUE
             END IF
160      CONTINUE
         CLOSE (10)
     END IF
C
C  DATA NOW IN ARRAY CSG(time,receiver,source)
C
     NTRIES = MAXLOP
     NTOT = NX * NZ
     LRATOT = 0
     LOST = 0
     IFOUND = 0
C
C  LOOP OVER EACH IMAGE POINT DEPTH
C
     DO 220 JJ = 1, NZ
         ZSTART = JJ * DZGRID
         IF (ZSTART .LT. ZIM0 .OR. ZSTART .GT. ZIM1) GO TO 220
         WRITE (6,*)'Migrating depth ', ZSTART, '....'
C
C  LOOP OVER EACH IMAGE POINT HORIZONTALLY
C
         DO 210 II = 1, NX
```

```
            XSTART = (II - 1) * DXGRID + XMIN
            NMUTE = 0
            IF (IMAGTY .EQ. 5) XSTART = XIM0
C
C  COMMON DEPTH POINT GATHER
C
            IF (XSTART .LT. XIM0 .OR. XSTART .GT. XIM1) GO TO 210
            STACK = 0.0
C
C  LOOP OVER EACH SOURCE POINT
C
C  PUT TIMES INTO ARRAY TAUS(nsor), ANGLES into ANG0,ANGS
C
            CALL ZERO(NSOR, TAUS)
            CALL ZERO(NSOR, ANG0)
            CALL ZERO(NSOR, ANGS)
            DO 170 KK = 1, NSOR
                XEND = XSOR(KK)
                ZEND = ZSOR(KK)
                IF (IUP .EQ. 1) THEN
                    IF (ZSTART - 0.0 .LT. ZEND) GO TO 170
C  CHECK FOR UPGOING WAVEFIELD
                ELSE
                    IF (ZSTART + 0.0 .GT. ZEND) GO TO 170
C  CHECK FOR DOWNGOING WAVEFIELD
                END IF
C
C  NOW RAY TRACE TO SOURCÉ FROM IMAGE POINT
C
                THETAP = 9.9
                TAU0 = 0.0
                CALL RAYTRA(NLAMAX, NDEPTH, DEPTH, VH, VV, XSTART,
     1               ZSTART, XEND, ZEND, DZGRID, ACC, NTRIES, THETAP,
     2               THETA0, TAU0, THETAS, NRAY)
                IF (NRAY .EQ. NTRIES) THEN
C  RAY NOT FOUND
C             WRITE (7,*)'Source position not found '
                    WRITE (7,*)'XSTART,ZSTART = ', XSTART, ZSTART
                    WRITE (7,*)'XEND,ZEND = ', XEND, ZEND
                    LOST = LOST + NREC
                    GO TO 170
                END IF
                TAUS(KK) = TAU0
                ANG0(KK) = THETA0
                ANGS(KK) = THETAS
                IFOUND = IFOUND + 1
 170        CONTINUE
C
C  NOW RAY trace to receivers
C
            THETAP = 9.9
            CALL ZERO(NREC, TAUR)
            CALL ZERO(NREC, ANG1)
            CALL ZERO(NREC, ANGG)
            DO 180 LL = 1, NREC
                XEND = XREC(LL)
                ZEND = ZREC(LL)
                IF (IUP .EQ. 1) THEN
                    IF (ZSTART - 0.0 .LT. ZEND) GO TO 180
C  CHECK FOR UPGOING WAVEFIELD
                ELSE
                    IF (ZSTART + 0.0 .GT. ZEND) GO TO 180
C  CHECK FOR DOWNGOING WAVEFIELD
                END IF
                CALL RAYTRA(NLAMAX, NDEPTH, DEPTH, VH, VV, XSTART,
     1               ZSTART, XEND, ZEND, DZGRID, ACC, NTRIES, THETAP,
     2               THETA1, TAU1, THETAG, NRAY)
                IF (NRAY .EQ. NTRIES) THEN
C  RAY NOT FOUND
C             WRITE (6,*)'Receiver position not found '
                    WRITE (7,*)'XSTART,ZSTART = ', XSTART, ZSTART
                    WRITE (7,*)'XEND,ZEND = ', XEND, ZEND
                    LOST = LOST + 1
                    GO TO 180
                END IF
                TAUR(LL) = TAU1
                ANG1(LL) = THETA1
                ANGG(LL) = THETAG
                IFOUND = IFOUND + 1
 180        CONTINUE
C
C  LOOP FOR EACH SOURCE
C
            DO 200 KK = 1, NSOR
                TAU0 = TAUS(KK)
                THETA0 = ANG0(KK)
                THETAS = ANGS(KK)
                IF (TAU0 .EQ. 0.0) GO TO 200
                IF (THETA0 .GT. PI) THEN
                    IF (3.*PI2 - THETA0 .GT. THETMU) GO TO 200
                ELSE IF (THETA0 .GT. PI2) THEN
                    IF (THETA0 - PI2 .GT. THETMU) GO TO 200
                ELSE IF (THETA0 .GT. 0.0) THEN
                    IF (PI2 - THETA0 .GT. THETMU) GO TO 200
                ELSE
                    IF (PI2 + THETA0 .GT. THETMU) GO TO 200
                END IF
                XEND = XSOR(KK)
                ZEND = ZSOR(KK)
                IF (IUP .EQ. 1) THEN
                    IF (ZSTART .LT. ZEND) GO TO 200
C  CHECK FOR UPGOING WAVEFIELD
                ELSE
                    IF (ZSTART .GT. ZEND) GO TO 200
C  CHECK FOR DOWNGOING WAVEFIELD
                END IF
C
C  LOOP FOR EACH RECEIVER
C
                DO 190 LL = 1, NREC
                    TAU1 = TAUR(LL)
                    THETA1 = ANG1(LL)
                    THETAG = ANGG(LL)
                    THETAL = THETAG
                    IF (THETA1 .GT. PI) THEN
                        IF (3.*PI2 - THETA1 .GT. THETMU)
     1                      GO TO 190
                    ELSE IF (THETA1 .GT. PI2) THEN
                        IF (THETA1 - PI2 .GT. THETMU) GO TO 190
                    ELSE IF (THETA1 .GT. 0.0) THEN
```

```
                    IF (PI2 - THETA1 .GT. THETMU) GO TO 190
                ELSE
                    IF (PI2 + THETA1 .GT. THETMU) GO TO 190
                END IF
                IF (TAU1 .EQ. 0.0) GO TO 190
                XEND = XREC(LL)
                ZEND = ZREC(LL)
                IF (IUP .EQ. 1) THEN
                    IF (ZSTART .LT. ZEND) GO TO 190
C  CHECK FOR UPGOING WAVEFIELD
                ELSE
                    IF (ZSTART .GT. ZEND) GO TO 190
C  CHECK FOR DOWNGOING WAVEFIELD
                END IF
C
C  Check to see if ray within imaging aperture
C
                XIANG = (THETA0 + THETA1) / 2.
                IF (XIANG .GT. PI) THEN
                    IF (ABS(XIANG - 3.*PI2) .GT. APRANG)
     1                       THEN
C                       WRITE(6,*) 'XIANG OUT OF RANGE'
                        GO TO 190
                    ELSE
                        IF (ABS(XIANG - 3.*PI2) .LT. APRMUT)
     1                  NMUTE = NMUTE + 1
                    END IF
                    XIANG = ABS(XIANG - 3.*PI2)
                ELSE IF (XIANG .GT. 0.0) THEN
                    IF (ABS(XIANG - PI2) .GT. APRANG)
     1                       THEN
C                       WRITE(6,*) 'XIANG OUT OF RANGE'
                        GO TO 190
                    ELSE
                        IF (ABS(XIANG - PI2) .LT. APRMUT)
     1                  NMUTE = NMUTE + 1
                    END IF
                    XIANG = ABS(XIANG - PI2)
                ELSE
                    IF (ABS(XIANG + PI2) .GT. APRANG)
     1                       THEN
C                       WRITE(6,*) 'XIANG OUT OF RANGE'
                        GO TO 190
                    ELSE
                        IF (ABS(XIANG + PI2) .LT. APRMUT)
     1                  NMUTE = NMUTE + 1
                    END IF
                    XIANG = ABS(XIANG + PI2)
                END IF
C
C  Source and receiver found so image appropriate travel time
C
                TTOT = TAU0 + TAU1
                NT = INT(TTOT/DT) + 1
                IF (IMIGTY .EQ. 1) THEN
C  KIRCHHOFF DIFFRACTION STACK
                    FAC = 1.0
                ELSE IF (IMIGTY .EQ. 2 .OR. IMIGTY .EQ. 6)
     1                     THEN
C
```

```
C  KIRCHHOFF INTEGRAL - THETAL IS FINAL (RECEIVER) RAY ANGLE
C
                    IF (TAU1 .EQ. 0.0) GO TO 190
                    THETAG = THETAG - DIPR - PI / 2.
                    FAC = SQRT(TAU0/TAU1) * ABS(COS(THETAG))
                ELSE IF (IMIGTY .EQ. 3 .OR. IMIGTY .EQ. 4)
     1                  THEN
C
C  GK Integral or GRT Integral
C
                    IF (TAU1 .EQ. 0.0 .OR. TAU0 .EQ. 0.0)
     1                 GO TO 190
                    THETAS = THETAS - DIPS - PI / 2.
                    THETAG = THETAG - DIPR - PI / 2.
                    IF (IMIGTY .EQ. 5) THEN
                        THETAS = 0.0
                        THETAG = 0.0
                    END IF
                    FAC = (DSS*ABS(COS(THETAS))*SQRT(TAU1/TAU0) +
     1              DSG*ABS(COS(THETAG))*SQRT(TAU0/TAU1))
                    IF (IMIGTY .EQ. 4) THEN
                        SCAT = THETA0 - THETA1
                        CSCAT2 = COS(SCAT/2.0)
                        FAC = FAC * CSCAT2 ** 2
                    END IF
                END IF
                STACK = STACK + 1.0
                IF (ABS(XIANG) .LT. (APRANG - APRTAP))
     1                  THEN
                    RAMP = 1.0
                ELSE
                    RAMP = 1.0 - (ABS(XIANG) - (APRANG - APRTAP))
     1              / (APRTAP)
                END IF
C
C  TAPER KIRCHHOFF OPERATOR
C
                DELTAP = CSG(NT,LL,KK) * FAC * RAMP
                IMAGE(JJ,II) = IMAGE(JJ,II) + DELTAP * REAL(IUP*2
     1          - 1)
C  REVERSES SIGN OF CONTRIBUTION FROM DGW
C
C  NEXT RECEIVER TRACE
C
 190            CONTINUE
C
C  NEXT SOURCE POSITION
C
 200        CONTINUE
C
C  NEXT GRID POSITION
C
            STACK = REAL(NMUTE)
            IF (STACK .GT. STKOFF) THEN
                IMAGE(JJ,II) = IMAGE(JJ,II) / STACK
            ELSE
                IMAGE(JJ,II) = 0.0
            END IF
            IF (NMUTE .EQ. 0) IMAGE(JJ,II) = 0
C
```

```
C  MUTES point if NO. contributions from narrow aperture
C
 210     CONTINUE
C
C  NEXT GRID DEPTH
C
 220 CONTINUE
     WRITE (6,*)'Enter name of output file for image :'
     READ (5,50) FNAME
     LEN = (NZ + 2) * 4
     WRITE (6,*)'Enter I.D. of image to save :'
     READ (5,*) ISHOT
     IDCODE = (ISHOT - 1) * (NX + 1) + 1
     OPEN (11,FILE=FNAME,STATUS='UNKNOWN',ACCESS='DIRECT',FORM=
    1     'UNFORMATTED',RECL=LEN)
     WRITE (6,*)'WRITING HEADER TO RECORD ..', IDCODE
     WRITE (11,REC=IDCODE) (A(I),I=1,NZ)
     DO 230 K = 1, NX
         XIM = K * DXGRID + XMIN
         KREC = IDCODE + K
         WRITE (11,REC=KREC) (IMAGE(I,K),I=1,NZ)
 230 CONTINUE
     WRITE (6,*)'LEN, NX, NZ = ', LEN, NX, NZ
     WRITE (6,*)'LOST RAYS < ', LOST
     WRITE (6,*)'FOUND RAYS = ', IFOUND
     PERCL = 100. * REAL(LOST) / REAL(LOST + IFOUND)
     WRITE (6,*)'PERCENT LOST < ', PERCL
     CLOSE (11)
     END
```