



UNIVERSITY
of
GLASGOW

**TODD CAMPUS WEST 3-D SEISMIC
REFLECTION SURVEY**



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DEPARTMENT OF GEOLOGY & APPLIED GEOLOGY
GLASGOW G12 8QQ

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WITH CONTRIBUTIONS BY
Z Z T HARITH

September 1997

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SUMMARY

There is a need for novel methods of geotechnical site surveying to be developed, which can accurately image the shallow geological structure and underground workings, down to 30-40 m depth. The report describes the results of a 3-D seismic reflection experiment carried out during summer 1996. It is believed to be the first 3-D vibroseis seismic survey undertaken in the UK at the engineering or site-survey scale.

Geophones were planted on a 2 m grid. The swath of 144 geophones always had a geometry of 8 rows by 18 columns, or 18 columns by 8 rows. The primary seismic source was the OYO minivibrator. Preliminary tests were also carried out with sledgehammer and weight drop impulsive sources as well. The source was moved along columns or rows of the survey grid. Most of the survey was done with a 4 m source spacing. The source was not placed on a regular grid but at a pseudo-random location, to smear out the subsurface reflection mid-points.

The uncorrelated data length was 4 s (3850 ms of sweep and 150 ms listening time); the correlated data and impulsive source data were of 150 ms length. After the first swath the acquisition of weight drop data was discontinued to save time. Part of the area was shot with a 2 m source spacing, giving an extra-dense coverage. A single 2-D line was shot using a fixed receiver geometry with shots moving through it. The line was shot successively with vibroseis, hammer and weight drop.

All the data were processed with *ProMAX/3D*. Final stack and migrated data volumes were transferred to a 486 PC running *GMAplus 3D*, a computer package for viewing, manipulating, and interpreting 3-D datasets.

Field correlation used a convolution filtering process in place of conventional correlation. The raw uncorrelated data as well as the field 'correlated' data were both

recorded. In the lab, the raw data were correlated using first a 100-700 Hz synthetic sweep; this lab-correlated dataset is the primary dataset for processing. However, a secondary dataset was constructed by correlating the raw data again, using a sweep from 200-700 Hz only.

The 140,000 CMPs were binned into a grid of 2 m square bins. Most of the area has at least 20-fold coverage, and exceptionally high values of up to 570-fold were achieved where the 2 m source spacing was used in place of the general 4 m spacing. The total number of bins is $53 \times 33 = 1749$, giving a mean 80-fold CMP coverage.

Using the combination of *ProMAX* and *GMPlus*, the processing was much more iterative and interpretive than is normally the case with 3-D seismic processing. Some 24 different complete output datasets were created, then viewed and interpreted with *GMPlus*. The data of interest are all within the first 50 ms, and there is no suggestion at present of any useful data at depths greater than 30-40 m.

Two major contrasting processing strategies were evolved. Strategy A was an attempt to yield the highest resolution at the smallest possible zero-offset reflection times. It had limited success in imaging the solid geology, although the 200-700 Hz lab-correlated dataset yielded a reasonable high-resolution image of the base of the boulder clay at 3-5 m depth. Strategy B, proposed by Professor Ewald Brückl, included use of the 100-700 Hz lab-correlated dataset for broadest bandwidth, spectral shaping to whiten the spectrum, use of the data at long offsets rather than short offsets, and low stacking velocities.

With strategy B considerable reflection detail has been revealed between 5 ms and 30 ms TWT (approximately 2 m to 20 m depth), together with hints of deeper reflectors. A preliminary interpretation of two horizons has been carried out. A horizon has been picked as the shallowest identifiable consistent event, and may represent the base of the boulder clay. A strong deeper picked horizon is reversed in polarity. This is what

would be expected of a reflector from the upper surface of an air- or water-filled void such as an old mineworking. This is the strongest indication to date of the imaging of such mineworkings. The overall structure shows a general deepening to the top right-hand corner of the 3-D area, cut across by possible fault zones. The two mapped horizons should not be regarded as definitive.

Quality of the 2-D field data is poor to moderate. First break refraction analysis yields a good shallow velocity-depth model. The results from the three different sources are comparable.

It is concluded that the minivibrator is best source out of the three tested, since it yields far higher reflection frequencies than either of the two impulsive sources. Furthermore, it does not take any longer to deploy and record. The 2 m bin interval is more than adequate for horizontal resolution, but the randomised source positioning leaves the option open of rebinning the data on any other grid interval and at any orientation desired. Once a robust processing method has been developed it should be possible to process future surveys within weeks, not months. Offset binning successfully reduced the size of the dataset, and suggests that the fold of coverage has been higher than necessary in the present survey.

The experiment has shown that the 3-D seismic reflection method using a minivibrator source has considerable potential as a tool for imaging underground cavities in the 5-50 m depth range. However, the data obtained so far are too complex to understand yet. Further R&D work is required before the 3-D surface seismic reflection method can be put to work as a useful tool for routinely imaging underground cavities.

1 INTRODUCTION

1.1 Scope of this report

This factual report describes the results of the fieldwork carried out during summer 1996 under a small University of Glasgow research contract with the Glasgow Development Agency. The report includes a description of the background to the problem and the approach taken; the fieldwork itself at the Todd Campus West site, and the subsequent processing and interpretation of the data.

Being factual in nature, the report describes the geophysical survey work and its execution in detail. Although 3-D seismic reflection surveying is a standard exploration industry technique, the project is novel because it is believed to be the first 3-D vibroseis seismic survey undertaken in the UK at the engineering or site-survey scale, which is around ten times smaller than the oil industry scale. This unusual aspect justifies the detail of description given herein of the non-standard or novel methods employed.

1.2 Aims and objectives of the survey

1.2.1 The problem

Many potential development sites in the Glasgow area and elsewhere need to be decontaminated and stabilised. In particular, old mineworkings have left a legacy of shallow underground voids which may have collapsed or are at risk of collapse, or have perhaps been infilled with waste. There is a need for novel methods of geotechnical site surveying to be developed which can accurately image the shallow geological structure and the underground workings down to 30-40 m. The ideal method should be non-invasive, non-destructive, and accurate enough to provide three-dimensional (3-D) images at a resolution fine enough (perhaps 1-2 m) for both

engineering consolidation works to be planned and carried out, and for input to detailed 3-D groundwater modelling studies to predict the flow of pollutants.

1.2.2 *Suggested solution*

The 3-D seismic reflection method has been used routinely by the oil industry since about 1990 to characterise the structure and fluid content of oil reservoirs to a precision of better than 10 m, within volumes of rock 2000-3000 m deep. The field survey equipment and the computing and software facilities for this task are highly advanced. The two-dimensional (2-D) seismic method is often used in geotechnical surveys, primarily in the refraction mode, where, for example, it can successfully define the depth of overburden overlying bedrock. The 2-D reflection method, using essentially the same equipment, provides more resolution than refraction, but is more labour- and computer-intensive.

To date, the problem of identifying mineworkings using highly detailed 2-D profiles has been partially solved. By taking the step in going from 2-D to 3-D there is an inherent leap in interpretability of the data. The oil industry experience suggests that, using comparable acquisition and processing methods, the interpretability of 3-D data is about five times better - i.e. finer resolution - than the equivalent 2-D profiles. The main delay in progressing to 3-D at the site engineering scale has probably been the fact that the processing software and costs are still beyond the capabilities of geotechnical survey companies.

In addition to detailed structural images formed by reflections from the subsurface, 3-D seismic reflection also supplies detailed velocity information which may go some way towards characterising the rock volume, such as how badly fractured it might be, and in what direction. This information can be input to a realistic 3-D groundwater flow model.

2. PLANNING

2.1 Outline programme of research

The aim was to carry out a trial 3-D acquisition survey covering up to 1 ha of the Todd Campus West site in the West of Scotland Science Park, with access to the site provided by GDA. The costings were designed to allow:

- About 1 week of advance on-site topographic survey (levelling and setting out), followed (after a gap if need be) by,
- 1-2 days of experimental acquisition methods,
- 4-6 days of intensive 'production mode' data acquisition, and
- Hire of state-of-the-art high-resolution recording equipment.

The fieldwork was scheduled to take place during July 1996. It was hoped that time would permit a comparison of seismic sources such as the new portable vibratory source and the more usual hammer/weight drop impulsive sources. Alternative seismic sources to these, of which there is a great variety, were not considered, as they are expensive and/or slow to use, and are therefore unlikely to show promise as a cost-effective 3-D tool.

Acquisition parameters were to be chosen so that the data would be acquired in the densest and broadest-band mode possible, even though this may imply that some part of the dataset was subsequently found to be surplus or unnecessary. It was expected that between half a million and one million seismic traces (channels of information) would be recorded; for comparison, a typical site investigation refraction survey might record a couple of hundred traces on each 2-D profile. Some acquisition parameters would prove to have been too widely drawn, but we could not know which ones until we had completed the study. This was the philosophy behind the 3-D trial survey

successfully undertaken for UK Nirex Ltd by us in summer 1994 at the potential nuclear waste repository at Sellafield, Cumbria (Smythe *et al.* 1995).

Data were to be fully processed in the Department of Geology & Applied Geology using the industry-standard *ProMAX/3D* software by Mr Zuhar Tuan Harith, a research student under the supervision of Professor David Smythe. Calibration of the results was to be made possible using geotechnical drilling data to be supplied by GDA. In the original work programme, results of the trial survey were to be supplied to GDA in the form of a report by the end of December 1996, but this timescale proved not to be possible due to the difficulties in interpreting the data.

The present report should be regarded as a final report as far as the GDA contract is concerned, but is only an interim report as far as the scientific research is concerned. If and when improved results are obtained after further processing, they will be communicated to GDA in the first instance. It is also hoped that the work will be published as a case history, whether it turns out to be successful or otherwise.

2.2 Survey location

The site was a green field at the time of the initial survey work. The field lies north of the junction of Acre Road and Maryhill Road, Glasgow. Part of the area occupied by the 3-D survey was stripped of its topsoil during the course of the survey, and all the topsoil has subsequently been removed.

At the time of the geophysical surveys two old pits - Acre No. 7 and Acre no. 8 - dating from the Victorian era Acre Colliery had been re-excavated and were in the course of being stabilised. The operations and temporary enclosed yards around these pits restricted the location of the geophysical surveys to the central and northern part of the field. Some additional trial pits and boreholes were sunk during the 3-D survey by site subcontractors.

2.3 Base maps

Paper copies of the site maps were generated for GU by Peter Fraenkel & Partners using their *Autocad* system. Scales varied from 1:500 to 1:200. Peter Fraenkel also supplied relevant *Autocad* map and position data as DXF (Digital Exchange Format) ASCII files on floppy disk. Although The Department of Geology & Applied Geology has a licence for *Autocad* (an older version than that used by Peter Fraenkel), it was decided to make all maps and diagrams using the public domain *GMT (Generic Mapping Tools)* software. This uses the UNIX operating system, producing *Postscript* output.

The *Autocad* DXF files were converted to forms useful for input to *GMT* by a specially-written Fortran program *acad2gmt*. The mapping coordinate system is National Grid. The files were then edited down to leave only relevant line boundaries, elevation contours and point data, such as the boreholes and trial pits. Additional files for labelling the points were generated. Figure 2.1 shows the resulting map, with topographic contour data omitted.

2.4 Initial geophysical surveys

During June 1996 some preliminary surveys were carried out at the site by third-year Geology undergraduates of Glasgow University for training purposes, under the direction of Professor Smythe and Drs Watts and Doody. These surveys comprised several 24-channel refraction lines of 50-60 m in length, using the Department's OYO McSeis 12-bit seismic recording system, with a sledgehammer as the source. Several 1-D Wenner method resistivity lines with offsets of up to 64 m were also observed.

A summary of the students' results has been made by Mr Harith (Fig. 2.1). In general their geophysical results tie in well to the borehole data (to which the students did not have access), and confirm that about 3-4 m of clay (P-wave velocity c. 600 m/s)

overlie solid rock varying in P-wave velocity from 1500-2800 m/s. This general geological structure is very similar to that at the 2-D coalmine working survey carried out in India by colleagues of the Technical University of Vienna (Brückl *et al.* 1997).

2.5 Generation of position data

A 3-D survey requires an accurate square survey grid to be pegged out on the ground, and tied into the National Grid. After investigation of various possible survey marker points (mainly small drain covers in Acre Road and Maryhill Road), the survey baseline was selected to run between the centres of the two manhole covers over the main sewer running through the site parallel to the Maryhill Road. These points are denoted NMH (Northern Manhole Cover) and CMH (Central Manhole Cover), respectively, in Figure 2.1. The line of the sewer at 16-20 m below the surface is also shown on the GU basemaps, since it might be a feature identifiable on the seismic data.

A 2 m grid was designed to run parallel to the sewer, and with its origin near the southern corner of the field. Figure 2.2 shows this grid, with 141 rows running SW-NE and 35 columns running SE-NW. The origin of the Cartesian grid is taken as the southern (lower left) corner. The bottom row and the westernmost column are numbered 0. The grid was generated from the false origin, viz. easting 55602.77, northing 70281.16, azimuth of columns $-29^{\circ}.177$ ($\equiv 330^{\circ}.823$), and from this was produced a listing of $141 \times 35 = 4935$ positions, given in column order, to be defined in the field by numbered wooden pegs. The lowermost row is 000 and most westerly column is 00, thus the highest row is numbered 140 and the highest column numbered 34. Pegs are given a 5-digit number. The first three digits refer to the row number and the last two to the column number. Thus the top right-hand corner of the grid has a peg numbered 14034 (Fig. 2.2). Data are held in an ASCII file *grid.lst*. All geophysical source and receiver positions are referenced to this grid.

3. TOPOGRAPHIC SURVEY

3.1 Introduction and objectives

The primary purpose of the topographic survey was to set out pegs in a prearranged layout (Figure 2.2) to enable the geophones and seismic sources to be positioned. The locations of the grid points (defined by a five-digit integer - the peg number) were firstly converted to National Grid coordinates quoted to two decimal places, i.e. a precision of 1 cm. These grid points were then defined additionally in terms of the range (in metres) and bearing (azimuth in degrees) from the known positions NMH and CMH (northern and central manhole covers).

Subsidiary purposes of topographic surveying were (a) to check by surveying in the actual randomised source positions and (b) to obtain the elevation of each peg.

3.2 Methods of measurement

3.2.1 Control

The survey control points were the centres of the central and northern manhole covers (CMH and NMH, respectively in Table 1). The baseline was the line joining these two points.

Table 1. Survey control points.

Station	Easting (m)	Northing (m)	Relative height (m above OD)
CMH	55568.08	70421.31	37.80
NMH	55505.12	70534.07	35.51

3.3.2. *Setting out*

The pegs were constructed of softwood, 250 mm x 35 mm x 10 mm in size, each numbered uniquely on a white background. Each peg is numbered with five numbers, the first three representing the row and the last two the column. Therefore the southern corner of the grid was represented by peg number 0000, the western by 14000, the northern by 14034 and the eastern corner by peg number 00034.

The pegs were set out at 4 m intervals, i.e. every second row and column, from row 052 to row 140. This covered the central and northern parts of the field

The bearing and back-bearing between the two control stations permitted orientation of the horizontal circle of the theodolite, which was set up at one or other of them. Setting out tables were produced for each station, listing the range and whole circle bearing to pegs within a specified range (500 m) of the each station.

A Wild (Leica) TC-500 semi-total station was employed for the survey. The pegs were set out from the semi-total station by setting the whole circle bearing on the instrument to the appropriate value of a chosen peg, and then moving the prism until both (1) coincidence with the cross hairs was found, and (2) the range to the prism also matched. At the same time the semi-total station also computes the difference in height between the instrument and the prism. This allows the reduced level of the peg to be recorded at the same time as its installation.

3.3.3 *Precision, error and accuracy in positioning of grid pegs*

Eastings and northings are calculated to a precision of 0.01 m. Conversion to range and bearing using double precision arithmetic ensures that the range and bearing of the prism are also given to the same precision. The trial and error method of walking the prism to the correct range and bearing, following instructions from the surveyor at

the theodolite, resulted in field accuracies of better than 0.1 m. This is within the precision required of the high-resolution seismic reflection method, in which errors of the order of 0.1 m in horizontal and vertical coordinate are acceptable.

An independent check on accuracy of the peg positioning was afforded by the visual line-up of pegs along rows, columns and diagonals. Pegs set out from different control points still lined up well, and a last check is that pegs are placed correctly in relation to cultural features. Field Photograph 3 (below) illustrates the grid of pegs.

Errors in vertical measurement (the reduced levels) were checked at the processing stage by:

- (1) Re-gridding and contouring the data, to see whether anomalous peg positions stand out, and
- (2) Comparing the heights with the gridded topographic elevations supplied by Peter Fraenkel.

3.4 Problems

Set-out pegs sometimes disappeared. This was due to:

- (1) Removal of pegs in the course of topsoil stripping of part of the area,
- (2) Covering over by new earthworks, e.g. from topsoil stripping or the digging of new trial pits,
- (3) Damage or loss due to vehicles running them over.

Missing pegs were normally reinstated by using a tape measure and visual line-up along the rows and columns of existing pegs. This sometimes had to be carried out in between the drilling rigs, but was only done after the drilling work had ceased for the day and the equipment was stationary and inactive.

4 SEISMIC RECORDING

4.1 Personnel

Glasgow University provided a total of 8 staff, comprising 3 academic staff, 1 research student and 4 student labourers. Not all these staff were present all the time; on average there were about 5 staff present at any one time during the seismic survey period.

4.2 Recording parameters

Most of the recording parameters are either constrained by the equipment, or had been decided during the planning phase. These are tabulated in Table 2 and marked by a star. The primary seismic source was the OYO minivibrator; however, preliminary tests and the 2-D line (Chapter 6) were also carried out with sledgehammer and weight drop impulsive sources as well.

4.2.1 Vibroseis sweep type

The recording parameters that remained to be determined at the start of the survey were those pertaining to the sweep type and duration (Table 2, parameters not marked by a star).

The 3850 ms, 10-700 Hz linear sweep was chosen because it would permit the acquisition of high frequencies, if the target zone did not attenuate them too much, but on the other hand there is adequate energy in the lower band (100-200 Hz) for orthodox processing and interpretation, should the attempt to record high frequencies prove to be unsuccessful. A non-linear sweep, with more time spent at the upper end of the band (at the expense of time at the lower end) might have been too risky if the

high frequencies did prove to be elusive, unless the total duration of the sweep were also lengthened to maintain sufficient time at the lower frequencies.

Table 2. Recording parameters (3-D).

Station interval	2 m	*
Geometry	8 rows x 18 columns (or 18 columns x 8 rows)	*
No. of stations	144	*
Source array	None	*
Source type	OYO minivibrator (+ hammer, weight drop)	*
Source interval	4 m normally (2 m for part of survey)	*
Sweeps per VP/SP	4 (uncorrelated vib), 8 (hammer, weight drop)	*
Moveup	None	*
Nominal fold of coverage	75 (in 2 m square bins)	*
Maximum offset	55 m	*
Sweep length	3850 ms	
Sweep	100-700 Hz	
Sweep type	Linear	
Start and end tapers	50 ms, cosine	
Field correlation taper	50 ms, cosine	
Recording instrument	OYO-DAS-1	*
Recording format	SEG-2 32-bit	*
Sample interval	0.5 ms	*
Record length	4 s (vibrator), 150 ms (hammer, weight drop)	*
Low cut filter	3 Hz, 6 dB/Oct	*
High cut filter	Out	*
Early gain	48 dB	*
Notch	Out	*
Geophone type	Sensor SM4 30 Hz	*
Geophone array	None - single elements	*

The figure of 3850 ms for the sweep duration is derived from the OYO set-up parameters of 4000 ms total recording time, of which 150 ms would be the listening time (i.e. after the sweep had finished). After correlation the record length is thus 150 ms. This gives a potential penetration into the ground of the order of 150-200 m.

The DAS-1 was set up to sum four uncorrelated sweeps at each VP, and write the summed uncorrelated data to a disk file. A field correlated file was also written to disk. With the weight drop phase of the 3-D survey 8 drops were summed at each SP. The record length was 150 ms.

4.2.2 Geophone and receiver swath geometry

Geophones were offset by 0.1 m in each of the row and column directions from the peg location, in the direction of increasing row and column number. This was simply to avoid having to remove the peg, where present. Geophones were planted at a 2 m interval, but since the pegs were only planted every 4 m, a 2 m long surveyor's ranging rod was used to interpolate the positions where there was no peg.

The *swath* is defined here as the layout of 144 geophones connected up by analogue cabling to the DAS-1, and remaining in a fixed configuration for a number of shots. The swath always had a geometry of 8 rows by 18 columns, or 18 columns by 8 rows. This fixed rectangular layout, together with the accompanying source positions, is termed the *pattern*.

The geophones were connected to the recording instrument by three separate sets of cabling, termed here the *spreads*. Each spread consisted of 48 geophone stations connected to one cable. Figure 3.1 shows by way of example the geometry of three spreads C, D and E, making up one swath CDE.

In orthodox seismic reflection the pattern usually comprises a rectangular array of receivers similar to that shown in Figure 3.1, together with a long line of sources crossing through the centre of the rectangle from top to bottom. The pattern is then 'rolled' (moved by one or two grid units to the left, right, up or down). This arrangement is only feasible when the pattern area is a small percentage (1-2%) of the overall survey area, and when the receiver equipment is of the telemetry type, to enable efficient switching of channels. It also requires a lot of extra ground equipment to be available to be switched in remotely from the recording truck.

With the present site survey the swath area itself is a large percentage (5-10%) of the total area to be surveyed, and the edge effects of the shot-receiver configuration are dominant. In addition, the work in moving one or more spreads is large in comparison

to the work in shooting, so a different strategy is required. The strategy employed here to maximise acquisition efficiency was to shoot many shots into a fixed swath, then to move only one or two of the three spreads, when feasible, and shoot again.

Table 3 lists the spreads, which were labelled alphabetically, which made up each swath, and the number of shots fired into each. Figure 4.1 shows the layout of the 24 spreads. These were arranged in adjacent trios to make up 9 swaths in total. Figures 4.2-4.5 show each pattern (swath plus shots) diagrammatically. A planned rectangular swath VWX lying in rows below swath STU was not observed, but was replaced by the irregular swath V'W'Y (Fig. 4.2), because most of spread V would have lain across the topsoil-stripped area where the grouting rigs were actively working. Field Photograph 4 below illustrates the problem of conducting seismic surveys beside drilling rigs.

Table 3. 3-D vibrator receiver patterns.
 FFID = Field File Identification Number

Pattern no.	Swath	No. of stations	No. of pairs of files	FFIDs	Comments
1	CDE	70	70	101-240	Also shot with weight drop
2	FGH	66	68	241-376	
3	HIJ	60	64	377-504	
4	JKL	197	197	505-898	Mostly 2 m shot spacing
5	MNO	194	194	899-1286	Mostly 2 m shot spacing
6	PQR	130	139	1287-1564	
7	STU	84	90	1565-1744	
8	V'W'Y	84	98	1745-1940	
9	YZA	70	70	1941-2080	

Figure 4.6 shows all the patterns on a common basemap. Although there is no duplication (overlap) of receiver spreads, many shot positions were observed several times, shooting into different swaths on each occasion. This is a more efficient method than a geometry in which each shot position is observed only once, but in which many more movements of the receiver spreads would then have to be made.

4.2.3 *Description and deployment of the vibrator source*

The OYO minivibrator source is a compact portable device weighing about 75 kg, with dimensions similar to that of an aluminium beer cask (see Field Photograph 1). Two side handles permit it to be lifted by two people. It is connected to the recording truck by a 100-m long armoured umbilical cable. There is an acoustic housing which is placed over the unit once it has been set in position. This was found to reduce the amplitude of the air blast to a useful degree, but is not essential. A team of three persons is ideal (two to lift and place, one to carry the acoustic hood, the check sheet, and radio); however progress is still adequate with only two persons.

It was found that much better results were obtained at the site when the vibrator was placed directly on the topsoil, with the overlying turf cut away. Almost all of the source points were therefore observed with turf removed.

4.2.4 *Description and deployment of the impulsive sources*

Both the hammer and weight strike a steel plate 40 cm in diameter, 2.5 cm thick, weighing about 20 kg. The plate has a tangentially drilled cylindrical hole into which is put the trigger. The plate is placed in the ground in the same hole as used for the vibrator. The weight drop is a shot putt weighing 16 lb (7.26 kg), and was dropped from a height of 2 m. The design of the plate was supplied to GU by OYO, and the triggers (including spares) were designed and supplied by OYO.

There is no easy way to prevent a double bounce of the weight on the plate. In contrast, the 7 kg sledgehammer can be wielded in such a way as to give an initial impulse of the same order of energy as the weight drop, but without a later bounce. The only advantage of the weight drop is that it is more reproducible than hammer blows, which tend to vary in amplitude from one to the next, and also with different operators.

The baseplate-mounted trigger proved to be very reliable, in contrast to previous experience with triggers mounted on the hammer shaft. In the latter case triggers frequently get damaged by misdirected hits, or the impact fails to send a sufficiently large signal through the trigger to initiate the recording cycle.

4.2.5 *Source stations*

The source was moved along columns or rows of the survey grid. Table 3 shows the number of vibrator source stations for each swath and the number of pairs of field files recorded. There are two files for each recording - the first is the uncorrelated (raw) data, and the second is the field correlated data. The number of pairs of files is sometimes larger than the number of stations, because duplicate shots or tests were occasionally recorded. Most of the survey employed a 4 m source spacing, but patterns 4 and 5 were shot mostly with a 2 m source interval. Pattern 1 was observed also with the weight drop source.

4.2.6 *Randomised source positioning*

The source was not placed on a regular grid - say next to the marker peg, or at a fixed distance ('offset') from it - but at a pseudo-random location within the 1.8 m square area up and to the right of the marker peg. This is illustrated in Figure 4.7. The physical peg locations are shown by the bold crosses every 4 m, and notional peg positions are indicated by the small crosses. All the crosses together make up the 2 m survey grid of rows and columns. Circles denote geophone positions, which are all offset both to the right and upwards by 0.1 m. The shaded area indicates one example of the randomised source area within which the source is placed, relative to its fiducial peg P.

A random number generator was used to generate a table of offsets in the row and column direction for every possible shot position, in increments of 0.2 m. The aim of

this was to smear out the surface source locations, and hence also the subsurface reflection mid-point positions, so that binning of the resulting dataset could be carried out at the processing stage in any desired fashion. Such a randomising of sources and/or receivers is a recognised practice in 3-D oil exploration seismic surveys. If the sources lay on a regular grid like the receivers, then binning of common mid-points (CMPs) would be restricted to integral multiples of the basic survey grid, and would also have to be aligned with that grid.

With 10 permissible offsets in each coordinate (0.0 to 1.8 m in 0.2 m increments) there is a total of 100 possible positions within the randomised source area shown in Figure 4.7.

In advance of each shot, a field assistant consulted the table and measured the offsets required in the row and column direction using a graduated survey ranging rod. The position was then marked by the digging of a shallow hole if turf had to be removed. At those shot stations where the topsoil had already been stripped, the randomised position was marked instead by an un-numbered peg, coloured yellow to minimise confusion with the numbered white pegs (see Field Photographs 1 and 3).

Four successive sweeps were recorded at each location, without a move-up. For swath CDE, where the weight drop source was also deployed, the weight was dropped 8 times at each shot-point.

4.2.7 Seismic data recording and transfer

Recording took place inside the mobile laboratory of the 4WD International geophysical recording truck (Field Photograph 2). This is equipped with three independent 12 VDC power supplies running off its own generator. The laboratory has dual air-conditioning. An additional external generator was used to run the

vibrator power supply. Communication with the outside field personnel was either verbally, in view of the short ranges involved, or by UHF radio.

Summing of the data (the four sweeps of the vibrator source, or the eight shots of the weight drop) was done automatically by the DAS-1 recording instrument in the recording truck. The summed raw data were written to an external SCSI hard disk. Correlation of each summed sweep was carried out in real time and also written to a disk file. Therefore there are two files for each vibrator point (VP). The uncorrelated data length was 4 s (3850 ms of sweep and 150 ms listening time); the correlated data and impulsive source data were of 150 ms length.

Observer's logsheets for each day were passed to the Party Chief at the end of the day, and taken back to the Department along with the SCSI hard disk. The disk was connected to a networked office PC, and SEG-2 format field files were downloaded to the processing workstation *via* the PC. Visual and numerical checks of the data were made the same evening before the data on the hard disk were erased in preparation for the next day's surveying.

4.3 2-D reflection line field procedure

On completion of the last 3-D pattern a single 2-D line was shot along row 072. To minimize time, a fixed receiver geometry, with shots moving through it, was chosen. The length of the 2-D line was 70.5 m. Receiver spacing was 0.5 m. Channel 1 was on column 00 and channel 140 on column 34. Channels 141-144 were not connected due to lack of room on the NE side of the survey area (see Figure 2.2).

The line was observed three times in total, once each with vibroseis, hammer and weight drop as the source. The first source was placed at column 1 (at receiver channel 5) which was 2 m from the Channel 1, and then moved on every 2 m (i.e. every column). The source was not placed directly on the line, but was offset by 0.5 m

towards the higher row number. Each source was placed in a 0.5 m wide, 10 cm deep pre-prepared hole in order to provide good source-ground coupling. A total of 34 VPs (4896 traces) and 31 shots (4464 traces) each with hammer and weight drop, respectively, were recorded. At each SP the stack of 4 shots was recorded. All the field data were written to an external SCSI hard disk in SEG-2 format, as with the 3-D data.

Table 4 summarises the changed recording parameters for the 2-D line, as compared to the original parameters given in Table 2.

Table 4. Recording parameters modified for 2-D line.

Station interval	0.5 m
Geometry	Fixed linear spread with shots moving through
No. of receiver stations	140
Source offset	0.5 m towards higher row number
Source type	OYO minivibrator (+ hammer, weight drop)
Source interval	2 m
Sweeps per VP/SP	4 (uncorrelated vib), 4 (hammer, weight drop)

4.4 Summary of progress

4.4.1 Daily production

Table 5 summarises the daily production of seismic data. The day number starts with day 1 on Monday 15 July 1996, ending on day 12 on Friday 26 August.

4.4.2 Rate of progress

Mr Roger Caldwell of OYO UK Ltd arrived at 0900 on Day 1 with the recording equipment and minivibrator. He donated a morning of his time to instruction in the use of the equipment. The rest of Day 1 and most of Day 2 were devoted to laying out

the first swath CDE, and to field tests. Production of data started with both vibrator and weight drop acquisition on this swath.

Table 5. Summary of daily production of seismic data.

Vib - vibrator; WD - weight drop

Date (July 96)	Day no.	Work	Swaths	Shots	Weather	Comments
Mon 15	1	Field testing	CDE	0	Very good	First swath laid; test shots
Tue 16	2	Testing, production	CDE	42	Very good	Vib only
Wed 17	3	Production	CDE	73	Very good	Vib and WD
Thu 18	4	Production	CDE	31	Very good	WD; spreads moved
Fri 19	5	Production	FGH, HIJ	132	Very good	Vib only; WD discontinued
Sat 20	6	Production	JKL	197	Very good	Second hard disk added
Sun 21	7	Production	MNO	194	Hot, cloudy	Spread and pegs removed from topsoil-stripped area afterwards
Mon 22	8	Production	PQR	0	OK am then heavy rain	Work ceased early pm No recording.
Tue 23	9	Production	PQR, STU	154	Good	Drilling noise
Wed 24	10	Production	STU, V'W'Y	173	Good	Drilling noise
Thu 25	11	Production	YZA	104	Good	End of 3-D; 2-D line shot
Fri 26	12	Clear-up	-	0	Good	All spreads and pegs removed

After the first swath CDE had been completed at the end of Day 4 it was decided to drop the acquisition of weight drop data entirely, and concentrate solely on the vibroseis data. Had this decision not been taken the area of useful subsurface data collected using each method would probably have been too small to be of use.

A considerable effort was made to obtain as much data as possible over the topsoil-stripped area at the southern end of the survey over the weekend of 21-22 July, when the drilling engineers were not working. This meant that there was no drilling noise, as well as enabling full access to the grouting area. Most of swaths MNO and PQR were shot with a 2 m source spacing, so that part of the survey area has an extra-dense coverage. Field Photograph 1 illustrates a moment during this phase of the survey.

Starting on Monday 22 July (Day 8), seismic recording had to continue in the presence of the five active rigs drilling grouting holes (see Field Photograph 4). This noise source has undoubtedly reduced the quality of the data somewhat. However, the correlation process in vibroseis data acquisition is good at removing such impulsive noise sources, whereas the impulsive seismic source of either hammer or weight drop would have been swamped by the drilling noise.

In general the rate of progress when on-line was about 1 VP per minute, with the time taken in sweeping and moving the vibrator about the same as the time required for recording, correlation and writing to disk. The weight drop source, in contrast, took 2-3 minutes per shot-point, with 8 drops at each point. During the 2-D line survey carried out at the end of the fieldwork on Day 11 (discussed in the following Section) each of the alternating weight drop and hammer source impacts (4 of each type summed) only took about 30 s.

Moving a whole swath (3 spreads) took around two hours. The geophones were left connected to the cable, and each spread, comprising eight cable sections (48 channels in total; see Fig. 3.1) was loaded hand-over-hand into the Landrover without breaking the spread into its component 6-channel sections. This method of speeding up survey progress also had the additional advantage that the two or three bad channels (or suspected reversed-polarity channels) remained at the same relative place within the swath. This made equipment checking easier at the start of recording of each new swath.

4.4.3 Review of data quality during survey

Very little use of the hard-copy camera facility of the DAS-1 was made during the survey, as this would have wasted valuable survey time. It was sufficient simply to view the data on the PC screen before it was written to hard disk. However, when the data were downloaded to the Sun workstation in the Department each evening, they

could be viewed with *ProMAX/3D*. Noise problems were apparent due to the grouting in progress on days 9 and 10, but there was little or nothing that could be done about this noise source.

The source of error with a few of the bad channels could not be found, despite repeated replacing of both suspect cable sections and geophones by new ones. The efficient solution adopted was to accept that recording would continue with up to 3 of the 144 channels of suspect quality. Reversed polarity can be easily corrected at the processing stage. An electrically noisy channel can be improved after filtering, so it is not necessarily completely useless.

4.4.4 *Night security*

A lot of time - perhaps ten to twelve man-hours a day - was saved because the spreads could be left on the ground overnight. The risk was considered to be slight because the site is fenced off and there was a contractor's security guard on overnight duty in the yard at the south end of the field. The recording truck was locked up with the vibrator and its umbilical cable inside the laboratory, and the mobile generator was left outside the security guard's hut.

4.4.5 *Down time*

Down time is defined as time lost to production recording because of unforeseen events, breakdowns, etc. It excludes the necessary daily travel time and equipment checking. Over the 12 survey days the amount of down time was approximately as follows:

(1) Spread faults	5 h
(2) Recording truck problems (flat batteries)	4 h
(3) DAS-1 problems (setting up configuration files)	1 h

(4) Severe rain (Day 8)	3 h
<i>Total</i>	<i>13 h</i>

The working day averaged about 10 hours, so there was a loss of about 1 hour per day. Additional to this time was the period spent each evening by Professor Smythe downloading the data from the hard disk, which took another 2-3 hours.

4.4.6 *Clear-up*

After the last day of production (Day 11) the morning of the last field day (Day 12) was spent in removing all ground equipment and the remaining pegs. Mr Roger Caldwell of OYO arrived to take away the hired OYO recording equipment.

5 3-D SEISMIC PROCESSING

5.1 Preprocessing

5.1.1 *Software, hardware and data organisation*

All the data, including the 2-D data discussed in Chapter 6 below, were processed with *ProMAX/3D*, industry-standard software installed on a Sun SPARCstation 20 with 132 Mb RAM and 27 Gb hard disk storage. Final stack and migrated data volumes were transferred to a 486 PC running *GMPlus 3D*, a computer package for viewing, manipulating, and interpreting 3-D datasets. Interpreted horizons were transferred from *GMPlus* back to the Sun workstation for gridding and contouring using the public-domain *GMT* mapping package.

Within *ProMAX/3D* the Area is defined as *todd campus*, containing the following Lines:

- *3d vib* - all the 3-D vibrator data
- *3d weight* - the weight drop 3-D data (swath CDE only)
- *2d hammer* - 2-D line, hammer source
- *2d weight* - 2-D line, weight drop source
- *2d all with geometry* - 2-D line, vibrator, hammer and weight drop sources with geometry information added.

The principal dataset is *3d vib*. The combined source *2d all with geometry* has been processed separately by Mr Z Z T Harith, and is discussed in Chapter 6 below. The partial dataset comprising 3-D coverage of swath CDE with the weight drop source has not yet been studied.

5.1.2 *Editing and geometry*

The uncorrelated and field-correlated shot files were stored in compressed format within *ProMAX*. The correct FFID (field file identification number) was added to each file. This relates the file uniquely to the Observer's logsheets. Noise tests and other non-production mode files were edited out. After visual inspection of the files on screen, noisy traces were identified and zeroed, and reversed traces corrected. The channel numbers requiring such corrections were consistently the same throughout any one swath.

Shot locations were checked and corrected by making detailed *GMT* maps of surveyed shot positions. The randomised-offset surveyed position was cross-checked against the position expected from the randomising table. Discrepancies were found to be due to surveyor's mis-reading the theodolite, or manual recording of incorrect values. Normally the errors affected an entire group of readings in a systematic way, and a simple solution could be found, for example, by altering the recorded azimuth by an integral number of degrees. An independent check on shot location in the few remaining suspect cases was also afforded by examining the air-blast travel times (and hence shot-receiver distance at the constant velocity of 330 m/s, the speed of sound in air) on the correlated data.

Figure 5.1 shows one detailed example map from the many used to edit and correct the geometry. It compares the randomised offset locations as specified by the table used in the field (vectors with black arrowheads) with the actual locations surveyed in afterwards (vectors with white arrowheads). The vectors point from the peg position on the regular grid to the randomised or actual source positions, respectively. The unit grid of the rows and columns is 2 m. In most cases the discrepancies between proposed (randomised) position and actual (surveyed) position are very small - just a few centimetres - but larger discrepancies such as the VPs in column 12 of Figure 5.1 have been checked and accounted for. The map includes part of the area within which a 2 m source spacing was used. The randomising table was only generated for even-

numbered rows and columns, so there are no randomised vectors for the odd-numbered rows and columns in the lower part of Figure 5.1. In these cases the source position was simply selected by the crew operating the vibrator as it proceeded, and marked afterwards with a peg for later survey (see Field Photograph 1). Figure 5.2 is a map of all the final surveyed offset vectors, after checking and corrections.

Surveyed peg heights and VP heights were cross-checked by looking for large discrepancies between the surveyed peg height and the height of the corresponding VP. Differences of greater than 10 cm were examined. They could normally be accounted for by a deeper than average hole dug for the source. A further check was made by gridding and contouring the data. Figure 5.3 shows the elevation contour map for the receiver positions, i.e. the peg locations, contoured at a 10 cm interval. Contour values are in metres above sea level. Any large errors would show up on such a map as a spike in the contouring. From this map 37.0 m was adopted as a convenient mean value of the elevation, to be used in later static corrections. The dashed line on the figure shows the area where topsoil had been stripped ready for the grouting exercise.

After the survey information had all been corrected, this geometry information was loaded from the ASCII survey files into the *ProMAX* database and thence applied to the seismic data. From this stage onwards every seismic trace carries the geometry information in its trace header.

5.1.3 *Field correlation*

Correlation of vibroseis data is usually the earliest process applied to the data; indeed, it is still routine practice within the oil exploration industry for correlation to be computed in real time by a purpose-built ‘correlator/stacker’, and for only the correlated data to be preserved. The much more voluminous uncorrelated data are simply never recorded onto disk or tape.

With the OYO DAS-1 and minivibrator system the baseplate and reaction mass accelerations are measured and recorded on two auxiliary traces. The weighted sum of the two accelerations is used in a convolution filtering process, which replaces conventional correlation. This is done presumably on grounds of computational efficiency. In the present survey it was decided to preserve the raw uncorrelated data as well as the ‘correlated’ data output from the OYO convolution. The latter data are referred to as the field correlated data. However, it was suspected that the field correlated data, although useful for QC, were not yielding the maximum possible signal from the raw data.

5.1.4 *Lab correlation*

A synthetic pilot sweep was generated using *ProMAX*, based on the field sweep parameters, and covering the full frequency range (100-700 Hz) of the field sweep. All the uncorrelated data were correlated in the laboratory using this pilot signal, since tests showed that this produced much better data than the field correlated shots. It is suspected that the OYO field ‘correlation’ method, involving a convolutional filter rather than a correlation with a pilot signal, is in some way unstable or unreliable.

The 100-700 Hz sweep lab-correlated dataset is the primary dataset for processing. However, a secondary dataset was constructed by correlating the raw data again, using a sweep from 200-700 Hz only. This is a method for filtering out the 100-200 Hz low frequency end of the spectrum. The reasons for doing this are discussed below. The synthetic sweep used for this correlation was the original 100-700 Hz sweep, but with the early portion containing the 100-200 Hz frequencies muted out.

5.1.5 Common mid-point binning

Common mid-points (CMPs) are simply the point on the surface midway between a source and a receiver. In 3-D shooting the CMPs cover an area, rather than lying along a line as with 2-D surveys. Figure 5.4 shows all the 140,000 CMPs, defined within *ProMAX* geometry. The set of all CMPs is also referred to as the subsurface coverage, because with flat reflectors the CMP marks the surface location of the subsurface reflection point. CMP is sometimes still referred to as CDP (common depth point), but the two terms are only identical if reflectors are flat.

The solid appearance of the diagram is due to the density of CMPs at this small scale; however the outlines of the survey area can be discerned, and also the row-column geometry around the edges of the survey. There is a oblong gap in subsurface coverage about 2 m wide and 6 m long, due to the shift of spread V to V' (Section 4.2.2 above).

The CMPs in 3-D seismic surveying are grouped together into small unit cells called bins, for subsequent processing together in CMP gathers. Using the interactive *ProMAX geometry* processor, a grid of square bins with a 2 m side was defined and fitted to the dataset (Fig. 5.5). The azimuth was defined as the same as the surface geometry azimuth, although in principle, the grid could be aligned in any direction. Figure 5.6 shows a detail of the binned CMPs at the southern corner of the survey. The bin at the bin grid origin (row 1 and column 1) is marked by a cross. Note that it contains only one CMP; however bins a few rows and columns higher have about 100 CMPs. The number of CMPs per bin is referred to as the *fold of coverage*. Figure 5.7 shows a detail from the centre of the survey, where the fold of coverage is very high, and Figure 5.8 shows the northern corner of the survey, where the topmost bin (column 33, row 53) has only 1-fold coverage (i.e. only one seismic trace falls within this bin).

5.1.6 *Fold of coverage*

Figure 5.9 summarises the fold of coverage in colour, with the key to the colours given in Figure 5.10. The colour key spectrum has been rotated to make the darkest reds showing a fold of less than 20. This figure might be considered as a threshold value for good coverage. Twenty-fold or higher (the blues), as in the centre of the area, is considered to be good coverage. Exceptionally high values of up to 570-fold are achieved at two peaks in the lower left corner, where the 2 m source spacing was used in place of the general 4 m spacing. In orthodox hydrocarbon exploration 3-D seismic acquisition, 10 to 30-fold would be considered good.

Note that the gap in subsurface coverage does not result in any empty bins in the middle of the area (Fig. 5.5), due to the binning geometry used. However, there are seven bins in this locality with a CMP fold of less than 20 (Fig. 5.9).

The total number of bins is $53 \times 33 = 1749$. Therefore the mean fold of coverage, with 140 000 traces recorded, is 80-fold. If we consider the edited dataset of 138 500 traces and only the 1482 'live' bins - i.e. excluding the empty bins around the edge of the survey (Fig. 5.5) - then the mean fold is 93. This very high figure compared to orthodox surveys gives a lot of scope for processing with subsets of the data, while still retaining a high fold (say 20 or more).

5.1.7 *Comparison of surface and subsurface geometry*

After *ProMAX* geometry has been applied to the data, each seismic trace falls into one of the CMP bins. These are numbered consecutively 1-1749, from the southern corner to the northern corner, respectively. However, this is not a very convenient sorting parameter. Instead, a row of subsurface bins is defined arbitrarily to be the Inline direction, and columns constitute the Xline (cross-line) direction. The geometry of Inlines 1-33 and Xlines 1-53 corresponds to the surface rows 61-113 and columns 0-

32 respectively, as shown in Figure 5.11. The centre of each subsurface bin lies within a few centimetres of the surface peg position. Figure 5.11 also shows the 2-D line location along Inline 12, and the line of the sewer (Fig. 2.2), which lies along Xline 20.

The two sets of processed seismic sections - the Inlines and the Xlines - are vertical sections or slices through the data volume. They contain exactly the same data from the 33×53 bins; the only difference is in the order of sorting. At the intersection of an Inline with an Xline the trace will be identical. The crucial additional feature of 3-D, in contrast to 2-D seismic data, is that we can also sort and look at the same data volume sorted by time; a panel in plan view of all the 1749 bins at a particular time is called a time-slice. So a third way in which the data can be presented is as the set of time-slices from 0 ms to the deepest time recorded (150 ms) at 0.5 ms intervals.

5.1.8 *Comments on preprocessing*

Three datasets resulted from preprocessing:

- Field correlated
- Lab correlated (100-700 Hz)
- Lab correlated (200-700 Hz)

The field correlated dataset was determined to be of no further use. The two lab-correlated datasets are used as alternatives in the later processing, as described below. Elevations statics are optionally applied to the data before these later steps. A mean elevation of 37.0 m was chosen (Fig. 5.3), and a velocity of 600 m/s was used initially to correct sources and receivers to this datum. The correction is of the order of ±3 ms or less. Spherical divergence correction, applied routinely at this stage with deep seismic reflection data, was not applied since the data of interest are so close in time

behind the first breaks. Instead, simple automatic gain control (AGC) was applied where appropriate to balance trace amplitudes laterally and vertically.

5.2 Processing

5.2.1 Methodology

ProMAX contains facilities neither for interpretation nor for viewing of time slices. Tests of complete processing flows - i.e. from preprocessed data through to final stacked or migrated sections - was achieved by writing the data to a SEG-Y diskfile, which was then read into *GMaPlus 3D*. This is a PC-based interpretation package for 3-D datasets. The Sun SPARCstation 20 (hosting *ProMAX*) and the 486 PC (hosting *GMaPlus*) sit on the same desk and share common file storage, so immediate transfer and viewing is very practicable. In effect, the processing can become much more iterative and interpretive than is normally the case with 3-D seismic processing.

With large-scale 3-D surveys only a small fraction of the data can be test-processed. The parameters decided upon as a result of this testing are then applied to the entire dataset. However, the present dataset is so small in comparison that it can all be tested. A stacked or migrated dataset to 50 ms two-way time (TWT) occupies under 4 Mb of *ProMAX* storage. After conversion to the format for *GMaPlus* the trace data and the timeslices take up less than 2 Mb. In large-scale surveys the final results will be saved as one or perhaps two alternative datasets; however in the present case some 24 different complete output datasets have been created, viewed and interpreted with *GMaPlus*. Within each of these datasets some of the individual processing techniques will have been tested several times before the sequence leading to the *GMaPlus* dataset is decided upon.

The data of interest are all within the first 50 ms, so processing to the full 150 ms time was not necessary. These TWTs correspond, very approximately, to about 50 m and

150 m depth, respectively. There has been no suggestion of any useful data at depths greater than 30-40 m.

From the extensive trials carried out, two major contrasting processing strategies were evolved. These are referred to as A and B. These are discussed below after a discussion of the reasons for re-correlating the data in the lab (Sections 5.1.3 and 5.1.4 above).

5.2.2 Comparison of correlation methods

The data were correlated three times - first in the field, and then twice in the lab using different sweeps each time. Parameters used for generating a synthetic pilot sweep for the lab correlation are shown in Table 6.

Table 6. Synthetic sweep parameters for lab correlation.

Sweep bandwidth (Hz)	100-700	200-700
Delay (ms)	0	642
Start time (ms)	0	642
End time (ms)	3850	3850
End tapers (ms)	100	100

The 200-700 Hz sweep was designed to eliminate the low-frequency end of the spectrum (100-200 Hz) at the correlation stage, rather than by later filtering. The pilot sweep used was simply the 100-700 Hz sweep, but with a front-end mute to zero the first portion of the sweep containing the 100-200 Hz components. The phase characteristics of the rest of the sweep are then identical to those of the 100-700 Hz sweep. A 100 ms taper length was used, rather than the field 50 ms length, to minimise any phase alteration.

Three figures are presented to illustrate the differences in the three correlation methods. In Figure 5.12 channels 1-48 are shown in raw shot gathers. The left-hand panel is the field-correlated data, the central one is the 100-700 Hz lab correlated data,

and the right-hand panel is the 200-700 Hz lab-correlated data, all from the same shot. The field-correlated data have been reversed in polarity to match the polarity of the other two datasets. The chevron pattern of arrivals is due to the shot-receiver offsets varying up and down the six columns of the spread (Fig. 3.1). The field correlated data are very ‘ringy’, and of low frequency, in comparison to the 100-700 Hz lab-correlated data. The air blast between 80 and 120 ms is not well correlated at all by the field method. However the first arrivals are completely missing using the 200-700 Hz pilot sweep (Fig. 5.12, right-hand panel). The 48 channels shown from this shot are all at large offsets (>25 m) from the source.

Figure 5.13 shows panels of 48 channels from another shot at intermediate offset ranges (15-30 m). Again, the 100-700 Hz correlation (central panel) is sharper than the field-correlated panel. The high-frequency air blast is correlated best by the 200-700 Hz sweep, but the first arrivals are still rather poor. Figure 5.14 shows 48 channels from another shot at small offsets (2-15 m). Here the field-correlated data still have the problems of the previous examples, but the first arrivals are sharpest on the 200-700 Hz data (right-hand panel). These results suggested that for near-offset processing the highest resolution might be obtained by using the 200-700 Hz correlated dataset.

5.2.3 *Strategy A*

This processing strategy was evolved first, but had limited success in imaging the solid geology. In summary, the main processing steps were various combinations of the following:

- Use mainly of the 200-700 Hz dataset as input
- Severe front-end trace muting to eliminate refracted first arrivals
- No deconvolution before (or after) stack
- Only near offsets (<20 m) used
- Elevation statics (datum 37.0 m, velocity 600 m/s)

- Offset binning of the CMPs into 1 m bins
- Constant velocity or simple 1-D velocity models for NMO
- More trace muting (e.g. inner mute)
- Stack, pad stack volume to 3-D cube
- Trace mixing to smooth data
- Simple Kirchhoff time migration using same velocities as for NMO

The strategy was an attempt to yield the highest resolution at the smallest possible reflection times (10-20 ms), (a) without the risk of spoiling the source wavelet (e.g. by deconvolution), and (b) avoiding any possibility of stacking in refracted arrivals (hence the use of muting and only short offsets).

5.2.4 Strategy A results and comments

The 200-700 Hz dataset yielded a reasonable high-resolution image of the base of the boulder clay at 3-5 m depth. Table 7 shows the processing flow used to produce this result.

Table 7. Processing flow for base boulder clay in Strategy A.

Input dataset	200-700 Hz correlated, 0- 50 ms, offsets < 5m only
Elevation statics	Datum 37.0 m, velocity 350 m/s
Spectral shaping	200-500 Hz
AGC	20 ms centred window
NMO/stack	Constant velocity 350 m/s
AGC	10 ms centred window
Pad stack volume	Producing 52 inlines and 33 crosslines
Bandpass filter	Ormsby zero phase 100-400 Hz
SEG-Y output	Imported into <i>GMAPlus</i> as file <i>gdav9.sgy</i>

The constant velocity of 350 m/s was taken from the 2-D line refraction interpretation. Note that this velocity, typical of dry clays above the water table, is only just higher than the speed of sound in air, 330 m/s. The spectral shaping is a way of whitening the zero-phase vibroseis wavelet.

A pair of typical sections - inline I33 and crossline X16 from the data volume - is shown in Figure 5.15. A positive impedance contrast is represented by a black peak on these displays. Figure 5.16 shows the same examples with the filled red circles marking the interpreted Base Clay horizon. The picks are very 'jittery', indicating a low signal to noise ratio, and it can be seen that the whole wavelet is made up of: peak - trough - central peak (picked) - trough - peak, spanning 10 ms. Thus the dominant frequency is about 200 Hz. Some traces are empty since certain bins would have had no traces with offsets of less than 5 m.

The contour map of the Base Clay horizon is shown in Figure 5.17, which is in units of vertical unmigrated two-way time. The values range from 6 ms (dark blues) to about 18 ms (dark orange), and a division by 3 gives an approximate depth in metres below the datum of 37.0 m. Thus the depths vary from about 2 m to about 6 m below datum. Note that the colour pattern and contours follow very closely the topography (Fig. 5.3). This indicates that the Base Clay horizon is at a roughly constant depth of 3-4 m below the ground surface.

This exercise in identifying and mapping the base of the boulder clay has pushed the seismic reflection method to its limits of resolution. Strategy A also yielded limited signs of horizons within the Carboniferous bedrock, dipping ENE, but since much better results for solid rock reflectors were obtained using strategy B, described below, the Strategy A results for the bedrock are not presented here.

One useful result from Strategy A was in offset binning of CMP gathers. For any CMP gather there is a variety of offsets at irregular spacings. Figure 5.18 shows an example in which the trace spacing is proportional to the offset, which in this case varies from 1.5-19.5 m. Examination of such gathers shows that traces with similar offsets fortunately are very similar, even though the source-receiver azimuths of the traces being compared may be very different. This fact made it feasible to bin the traces into

1 m offset bins. The results of doing so with the gather of Figure 5.18 are shown in Figure 5.19. Here the trace with offset bin no. (OFB_NO) 2 is the sum of traces with offsets between 1-2 m, and has a nominal offset of 1.5 m. Other traces are similarly binned, so that the resulting gather has an even spacing of offsets at 1 m intervals. This procedure has two benefits; (a) in reducing the size of the total dataset by a factor of about four, and (b) helping to reduce the amplitude of the air blast, which tends to be summed destructively by the binning, due to a combination of its high frequency content and low velocity.

5.2.5 Strategy B

Strategy B was proposed by Professor Ewald Brückl of Vienna Technical University, who visited Glasgow on a short sabbatical in July 1997. In summary, his proposals contrasting with Strategy A included:

- Use of the 100-700 Hz dataset for broadest bandwidth
- Spectral shaping to whiten the spectrum (i.e. increase the high-frequency content)
- Use data at long offsets, not short offsets
- Low stacking velocities ensure that refracted events are not stacked
- Ignore (by muting) data later than the air blast.

The preliminary migrated data volume produced from this strategy is illustrated by way of four lines shown in the key map of Figure 5.20; inlines I17, I29 and crosslines X6 and X20. The processing flow is summarised in Table 8.

Table 8. Processing flow for Strategy B.

Input dataset	100-700 Hz correlated, 1 m offset bins, 0-150 ms
Elevation statics	Datum 37.0 m, velocity 600 m/s
Spectral shaping	100-400 Hz
AGC	30 ms centred window
Trace muting	Air blast and all later data

NMO/stack	1-D velocity function; 60% NMO stretch mute
AGC	40 ms centred window
Pad stack volume	Producing 52 inlines and 33 crosslines
Migration	Kirchhoff post-stack time, 0-50 ms only, 0-500 Hz
Reverse polarity	White (trough) represents +ve impedance contrast
Spectral shaping	100-400 Hz
SEG-Y output	Imported into <i>GMAplus</i> as file <i>gdav8mss1.sgy</i>

The 1-D velocity function of time-velocity pairs was: 0-600, 10-800, 20-1200, 50-1500; units in ms and m/s respectively. The offset binning strategy developed in Strategy A was retained, but the main difference is in the broad-band approach - using the whole useful bandwidth from 100 Hz upwards, and sharpening up the data by spectral shaping. This process retains the zero phase character of the vibroseis data, and scales up all frequency components within the desired window to the same amplitude.

Migration used the same velocities as for NMO. Post-migration bandpass filtering and AGC were found to be unnecessary. Note that with the output dataset the polarity has been reversed to make it conform to the SEG standard for display of seismic data.

5.2.6 Strategy B results and comments

The example vertical sections in Figure 5.21 show that considerable reflection detail has been revealed between 5 ms and 30 ms TWT (approximately 2 m to 20 m depth), together with hints of deeper reflectors. A preliminary interpretation of two horizons has been carried out, and is shown by the red and yellow picks on the example sections shown in Figure 5.22. Colour spectrum and line contour maps of the red and yellow horizons are shown in Figures 5.23 and 5.24, respectively.

The red horizon is a trough (white), and therefore represents a horizon across which the acoustic impedance increases in the downward direction. It has been picked as the shallowest identifiable consistent event, although locally there are even shallower reflectors. It may represent the base of the boulder clay, as the general structure (Fig. 5.23) is similar to the interpretation presented above from Strategy A data (Fig. 5.17). Note that the Strategy A data were not phase-reversed for display; thus the picked peak events (red picks on Figure 5.16) corresponds to the same polarity as the red trough event picked in the Strategy B dataset (Fig. 5.22). The overall vertical resolution of the red event on the two datasets is similar, but the interpretation in Strategy B implies some faulting or very steep scarp-like features (e.g. at I10 on X6 of Figure 5.22).

The yellow horizon is an attempt at picking the strongest feature (i.e. a consistent, high amplitude feature) beneath the red horizon. It is significant that this event is reversed in polarity, corresponding to a *decrease* in acoustic impedance in the downward direction. This is what would be expected of a reflector from the upper surface of an air- or water-filled void such as an old mineworking. This is the strongest indication to date of the imaging of such mineworkings. The overall structure of the mapped yellow horizon (Fig. 5.24) shows a general deepening to the top right-hand corner of the 3-D area, cut across by possible fault zones (or trough-like features) trending WNW-ESE, which is the strike direction of the Carboniferous rocks

below the boulder clay. The yellow event reaches a maximum reflection time of 25 ms at the top right-hand corner of the area (Fig. 5.24); this corresponds to about 16-17 m depth.

The two mapped horizons have been presented merely to give an indication of what the data may produce after further processing and research. They should not be regarded as in any way final or definitive.

6 2-D DATA PROCESSING

6.1 Preprocessing

All the 2-D data were processed as described in Section 5.1 above, but using *ProMAX/2D*, which is a subset of *ProMAX/3D*.

Figure 6.1 shows shot gathers (after the vertical stacking) for the three methods at the same location in the middle of the line. The quality of the field data is poor to moderate. Most of the shot records were dominated by direct wave, ground roll and air blast. Far offset traces were badly contaminated by the noise (Figure 6.2) and to make the processing even more difficult, there was no clear indication of any reflectors on the shot records.

The amplitude spectrum of the vibroseis data is confined essentially to the correlation range of 100-700 Hz (Fig. 6.3). The peak frequencies are at the low end of this band - about 150 Hz. In contrast the impulsive source records have an amplitude spectrum peaking at frequencies of 30-80 Hz. Figures 6.4 and 6.5 show a shot gather and the corresponding amplitude spectrum of a hammer and a weight drop record, respectively. They are evidently very similar to each other. Although these records had a very poor signal to noise ratio, they are useful for refraction interpretation since the first arrivals are very strong.

Since there was no clear indication of the reflectors in the shot gathers, and the far offsets were badly contaminated with noise, all the data were sorted into common mid-point (CMP) gathers prior to any processing. This sorting resulted in 276 CMPs for the vibroseis and 263 CMPs for each of the hammer and weight drop, with a maximum fold of coverage of 34 and 31, respectively. The spacing between each CMP was very small; 0.25 m. However, since the source interval was 2 m, the traces within these CMPs also had a 2 m spacing (Figure 6.6). The data are severely aliased

spatially. The density of the CMPs was improved by summing 4 CMPs together. By doing so, the CMP spacing was increased to 1 m, but the spacing of the traces within the gathers was reduced to 0.25 m. Figure 6.7 shows the improvement compared with Figure 6.6, with both figures displayed at the same scale.

6.2 Processing

To obtain the near surface velocity structure, first break times were picked on the hammer data for refraction analysis. Refraction analysis of the picks was carried out by Prof. Brückl at the Technical University of Vienna. The results show that the average velocity of the first layer is about 350 m/s (Figure 6.8). This value has been used in the elevation and static corrections applied to the 3-D data, discussed in Chapter 5.

Extra care was taken in muting the first arrivals. The mute was only applied when we really confident that it was a refracted arrival. All the signal below the air blast was also muted out. Only a bandpass filter was applied to all data. An F-K filter was not applied because the signal to noise ratio was poor.

To improve the quality of the data, a minimum phase predictive deconvolution with a very small (1 ms) prediction distance was applied for the hammer and weight drop data. Because the deconvolution would only be successful if the input signal is of minimum phase, such deconvolution was not applied to the vibroseis data. The stacking velocity was derived from velocity analysis of the 3-D data.

Table 9 summarises the processing flows for the vibroseis data and impulsive source data.

Table 9. Processing flow for vibroseis and impulsive data on 2-D line.

Input data	Vibroseis: lab-correlated data 100-700 Hz; impulsive sources: field data
Geometry	2D land geometry (min/max offsets 0/70 m, bin increment 0.25 m)
Editing	Kill: channels 44,66,74,75, 141-144
Elevation statics	Datum 37.0 m, velocity 600 m/s
Spectral shaping (vibroseis only)	100 - 400 Hz
Predictive decon.	(Impulsive only): 40 ms operator length, 1ms predictive distance.
AGC	30 ms centered (vibroseis); 15 ms centered (impulsive)
Bandpass filter	Ormsby frequency bandpass filter (100-400 Hz)
Trace muting	Air blast and all later data
NMO/stack	1-D velocity function; 60% NMO stretch mute
Output	Hardcopy for this report
Migration	Kirchhoff post-stack time (not presented herein)

6.3 Results

The resulting brute stacks of the 2-D line, with vibroseis, hammer and weight drop are shown in Figures 6.9, 6.10 and 6.11, respectively. The results from the three different sources are comparable. The strong continuous reflector at 10-20 ms is probably the base of the boulder clay.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Field acquisition

The logistics of a 3-D survey are simple in principle. It is simply a matter of having good organisation. In future, short cables should be used, rather than the 20 m interval take-out cables used in 1996. Analogue ground equipment is sufficient, and telemetry systems, as now used universally at the oil industry exploration scale, are not needed. Single 30 Hz geophones appear to be adequate, although if the receiver spacing were to be increased greatly from the present 2 m, strings of geophones might be cost-effective.

The minivibrator proved to be the best source out of the three tested, as it yields far higher reflection frequencies than either of the two impulsive sources. Furthermore, it does not take any longer to deploy and record than the latter. The problem limiting the interpretability of the dataset has not been one of horizontal (trace-to-trace) resolution, but of vertical (time) resolution. To solve this problem the highest possible bandwidth is required. In addition, the correlation process inherent in the vibroseis method removes broad-band and 'spiky' noise sources, so it is deployable in a noisy industrial or urban environment where the impulsive source method might fail.

The 2 m bin interval used in the present processing is more than adequate for horizontal resolution, but the randomised source positioning that was used, resulting in a very even spatial density of CMP coverage, leaves the option open of rebinning the data on any other grid interval and at any orientation desired.

The 144 channels used is the minimum acceptable. Time would have been saved if this number were doubled. However, without roll-along capability there is probably not much to be gained by increasing the number of live channels much beyond the

250-300 level. It would simply mean that many of them would have offsets so large in relation to the target depth that they would be omitted from the processing.

The EDM theodolite needs to be available throughout the survey, to record any late alterations and/or add in new points. A total station (with digital recording of the survey parameters) would have avoided the manual logging errors that crept in by the use of a semi-total station (which is otherwise identical to the whole system or 'total station', but lacking only the digital logging facility).

7.2 Data processing

There has been a very slow turnaround in the data to date, which is clearly unsatisfactory if the method is to develop into a routine survey tool. However, the delays have been due to the unknown factors involved in research. Once a robust method has been developed out of the current research, it will be possible to process under routine conditions a survey as large as the one described here within a matter of weeks, not months.

The concept of offset binning has been demonstrated to be good at reducing the size of the dataset. This suggests, in turn, that the fold of coverage has been far too high. A much lower fold of coverage, while retaining the long offsets, may be sufficient. Careful refraction inversion and analysis, using these long offsets, is needed. On-site pre-processing, and even full processing, would be advantageous at sites further away from the processing department than the 3 km or so that Maryhill is from Glasgow University. The field recording truck illustrated in Field Photograph 2 could accommodate the processing computers as well as the recording equipment in such a future survey.

8.3 Recommendations

8.3.1 *Completion of present study*

To date the experiment has shown that the 3-D seismic reflection method using a minivibrator source has considerable potential as a tool for imaging underground cavities in the 5-50 m depth range. However, the data obtained so far are too complex to understand yet, so the method must be regarded as still in the early R&D phase.

Additional work which will be carried out within GU over the next year will probably include:

- Re-binning the data using 1 m width bins.
- Applying the new filtering methods being developed by the Geophysical Research Group's Wavelet Transform Consortium.
- Careful refraction interpretation in collaboration with Vienna Technical University.
- Detailed velocity analysis.
- Winnowing of the dataset to see how low a fold of coverage can yield useful data.

Any of these methods, aside from the last, may yield a greatly improved dataset for interpretation. The aim of reducing the dataset progressively (the last test above) would be to learn what density of survey would be required in future surveys; clearly the less that has to be done, the faster and cheaper will be the field acquisition progress.

8.3.2 *Comparisons with other methods*

Two-dimensional methods, yielding discrete vertical slice profiles, can never achieve the detailed imaging of the 3-D method in which an underground *volume* is surveyed. This is as true of other geophysical methods as it is with seismic reflection, for example resistivity or ground-penetrating radar (GPR). Resistivity imaging is a tomographic method; to survey in 3-D would be as complex and expensive as with seismic, but without the same resolution as the latter. In the UK the obvious disadvantage of GPR is the lack of penetration in wet and/or clay environments, where, in general, useful GPR is limited to the uppermost metre or so.

Potential field methods, such as gravity and electromagnetic tools (apart from GPR) are not imaging methods. The best they can do is permit non-unique models to be developed with which the data can be compared. They are best suited to finding point-source or edge-effect anomalies in the underground, such as vertical shafts.

8.3.3 *Conclusions*

The experiment has been a qualified success. The results show promise, but considerable further R&D work is required before the 3-D surface seismic reflection method can be put to work as a useful tool for routinely imaging underground cavities.

At the Todd Campus West Site there were presumed to be very shallow-depth small-scale, probably collapsed stoop and room structures at several horizons within moderately steeply-dipping coal-bearing sediments. With hindsight, this constitutes probably a rather ambitious target for preliminary 3-D experiments. Simpler targets would include larger excavations within flat-lying sediments, such as the coalmine workings in India surveyed in 2-D by Brückl *et al.* (1997). Larger and simpler targets would also include old limestone workings (for example, in the Bath region) or old evaporite mines (Kourfakas and Goult 1996).

In view of the costs of grouting suspected or known mineworkings, and the fact that the 3-D seismic method might become useful as a pre- and post-grouting imaging tool, it is the most promising geophysical survey method available to date. It is therefore worthy of further study.

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GLOSSARY

The context within a word or phrase is used herein is shown, where necessary, in square brackets thus []. Cross-referenced terms are shown in *italics*.

3-D [seismic survey] Three-dimensional configuration in which there are two horizontal spatial directions parallel to the earth's surface and one vertical time or depth dimension.

Aperture [seismic survey] The surface area (3-D) or line (2-D) over which sources or receivers are laid out in order to image a *target*.

Array [seismic survey] Set of *source* or *receiver elements* summed into a pattern.

Barycentre [seismic survey] The geometrically weighted centre [of an *array*].

Bin [seismic survey] One of a set of small square areas into which 3-D seismic data are sorted; the exact position within the bin is by definition unimportant.

Channel [seismic survey] Logical path for transfer of seismic data from the ground into the recording instrument.

Common mid-point [seismic survey] The geometric half-way point between the *source* and *receiver* positions. In reflection processing, the subsurface location of reflections on a seismic trace is initially assumed to be at this point (often abbreviated CMP).

Continuity [seismic survey] Correct electrical connection of the *ground equipment*. [seismic processing] A measure of the quality of reflectors as judged by phase correlation from trace to trace.

Control point [topographic survey] Known position in a *control traverse*.

Control traverse [topographic survey] Set of connected, calibrated known positions, usually forming a closed polygon in plan view, used as the framework from which survey points can be *set out*.

Correlation [seismic survey] The digital process of comparing the recorded seismic data with the *sweep* to convert the long-duration signals into short pulses; usually carried out in real time by a dedicated computer in the *recording truck*.

Coupling [seismic survey] In the context of *static corrections*, the interdependence of two sets of simultaneous equations, one for the *source* and one for the *receiver*. In the context of acquisition, the connection of *sources* or *geophones* to the ground.

Coverage [seismic survey] Abbreviation of *fold of coverage*.

Element [seismic survey] Unit of the *source* or *receiver*, made up into *arrays*.

Early gain [seismic survey] The fixed amplification factor in a *telemetry* box.

Fold of cover(age) [seismic survey] The multiplicity in which unit segments (line or area) of the earth are observed by repeated observations.

Geophone [seismic survey] Sensor connected to the ground to measure the ground motion (usually the vertical component of ground velocity, converted to a low-impedance electrical analogue signal).

Geophone string [seismic survey] Set of *geophones* connected together in series.

Ground equipment [seismic survey] The set of cables, *telemetry* boxes and *geophone strings* comprising the *receiver arrays*.

Leakage [seismic survey] Undesirable electrical connection from the *ground equipment* to earth, usually caused by water.

Line [seismic survey] In 3-D work, a row of receiver *ground equipment*.

Linear pattern [seismic survey] Set of *elements* of a *source* or *receiver* with an equal spacing, and electrically or mechanically summed together.

Move-up [seismic survey] The distance by which the *source array* is advanced during *shooting* between successive sweeps at the same VP.

Linear sweep [seismic survey] *Sweep* in which the rate of increase or decrease of instantaneous frequency is constant.

Multiple [seismic survey] Secondary, undesired reflection data coming in later than the desired primary data.

Notch [seismic survey] Filter centered upon a specific frequency, usually designed to reject 50 Hz electrical pickup.

Offset [seismic survey] The distance from *source* to *receiver*.

Pattern [seismic survey] The fixed geometry of receiver *swath* plus *sources* shot into that swath.

Pre-processing [seismic survey] Preliminary, routine sorting out of digital seismic data, not requiring knowledge of the geology or physical characteristics of the *prospect*, undertaken before processing can be done.

Prism [topographic survey] Corner-cube reflector sighted upon by a *theodolite*.

Processing centre [seismic survey] Offsite, remote location at which bulk, intensive processing of seismic data is conducted.

Production (mode) [seismic survey] The routine collection of the survey data with fixed *recording parameters* determined during a preliminary *wave test*.

Prospect [seismic survey] The locality or *target zone* of the survey.

Receiver [seismic survey] The instrument (usually a *geophone string*) which picks up the reflected waves from the subsurface.

Recording advisory sheet [seismic survey] The tabulated outcome of *permitting* and access investigations, to tell the survey crew where to go and what to do.

Recording parameters The set of instrument settings and survey geometry decided upon as being the most appropriate; not normally altered in the course of the survey.

Recording truck [seismic survey] Field vehicle containing the seismic recording, control and test equipment.

Sample interval [seismic survey] The time between successive instants at which an analogue signal is converted to a digital number.

Set out [topographic survey] The process of marking pre-determined survey coordinates on the earth.

Shooting [seismic survey] The process of setting off the *source* in a seismic survey; although referring originally to dynamite shots, it is also used in *vibroseis*.

Shot-point [seismic survey] The place at which a seismic shot (pulse source) is to be fired; used also loosely for *vibroseis* work.

Side-lobe [seismic survey] Unwanted concentration of energy before or after the (central) peak of a *correlated* seismic signal.

Source [seismic survey] The origin of the signal used to generate seismic reflections from the subsurface. In the present survey there are two types of source - the long-duration *vibroseis* and the impulsive impact of hammer or weight drop

Spread [seismic survey] Analogue seismic cable with its *geophones*. In the present survey there are three spreads of 48 *channels* each.

Spectral analysis Method of transforming time-series signals to view the frequency content.

Static corrections Fixed, location-dependent corrections to seismic data to correct for relative delays in the upward or downward passage of seismic reflections due to the low-velocity, unconsolidated material at the earth's surface.

Steep structure [seismic survey] Geological structures amenable to the seismic reflection method, but which dip at greater than about 45°.

Swath [seismic survey] Parallel set of *lines* of *sources* or *receivers*, forming a rectangular area. In the present survey this is defined as the layout of 144 receiver *channels* made up of three separate *spreads*.

Sweep [seismic survey] The long-duration signal, sinusoidal in character, but with the frequency increasing or decreasing with time, generated by a *vibrator*.

Target [topographic survey] The prism observed by the *theodolite*.

[seismic survey] The zone of the subsurface in which the survey is to concentrate.

Telemetry [seismic survey] Conversion of data received at a *receiver* for transmission digitally by wire or radio to the recording instrument on demand.

Total station [topographic survey] The set of instruments required to set out survey control and then survey or set out points. A semi-total station does not include the digital logging of the data.

Trace header [seismic processing] A fixed part of each data file preceding the seismic trace data, and containing useful information about the trace.

Theodolite [topographic survey] Precision topographic surveying instrument.

Vibrator [seismic survey] Servo-hydraulic device to generate sweeps transmitted into the earth.

Vibroseis [seismic survey] The technique of using a quasi-sinusoidal low-power but long-duration burst of energy into the earth using a *vibrator*.

Wave test [seismic survey] The preliminary process to the *production mode* of a seismic field survey, of observing the potentially interfering waves and other unwanted signals and

noise, with the aim of minimising their effect by setting the most appropriate *recording parameters*.

ABBREVIATIONS

ASCII	American Standard Computer Information Interchange [format for computer data]
CDP	Common depth-point
CMP	Common mid-point
EDM	Electronic distance measuring
GMT	Generic Mapping Tools [public-domain software map-making package]
GU	Glasgow University
Nirex	United Kingdom Nirex Limited
QC	Quality control
R&D	Research and development`
SEG	Society of Exploration Geophysicists
SEG-2	SEG standard data format for seismic field data in PCs
SEG-Y	SEG standard data format for exchange of and storage of seismic data
SP	Shot-point (synonymous with VP, but including sources other than vibrators)
TTL	Through the lens
VP	Vibration point

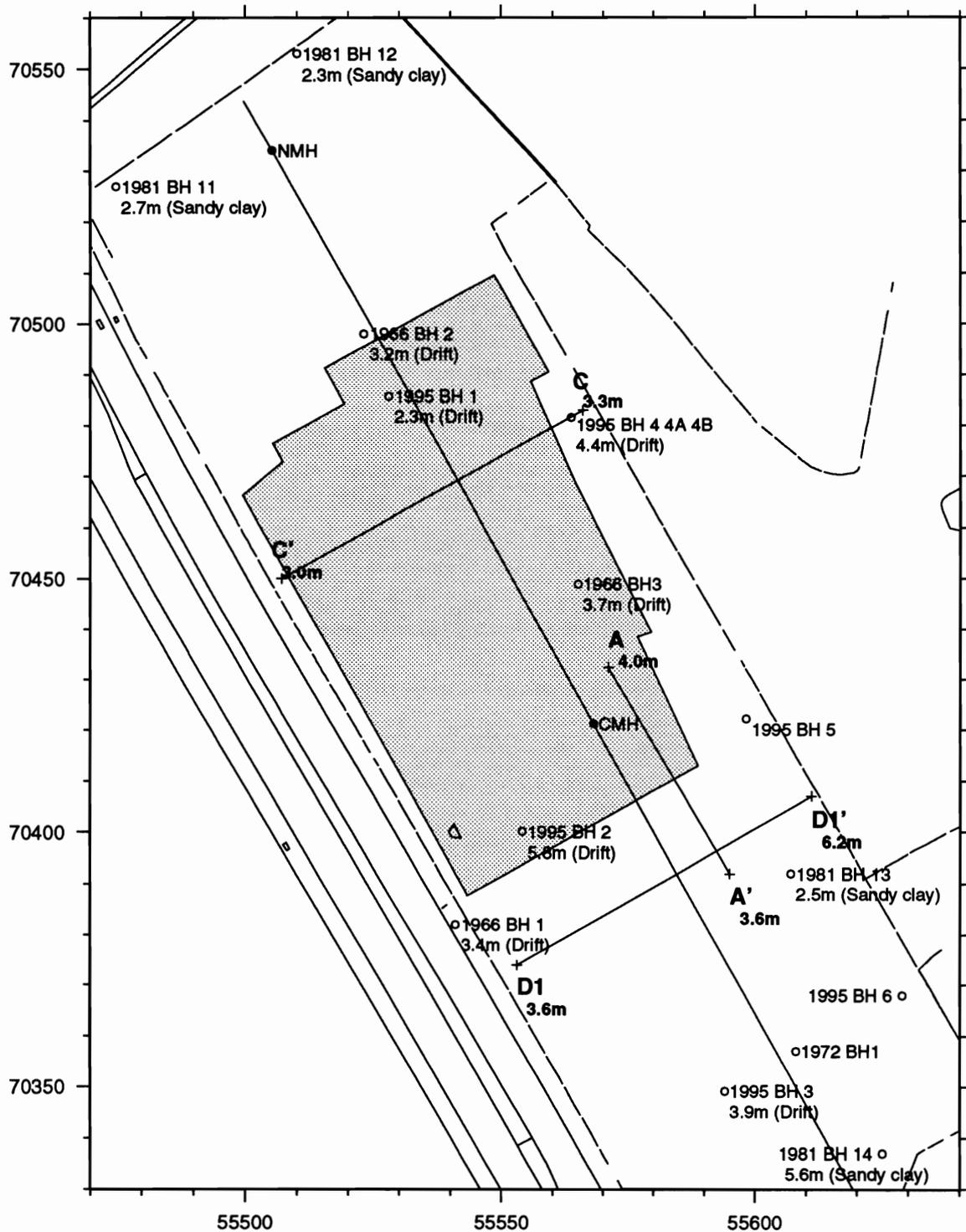


Figure 2.1 Depth to bedrock from boreholes and seismic refraction data

Refraction lines have crosses at each end, and are annotated with a letter and depth to bedrock.

Open circles are boreholes. Shaded area is 3-D subsurface seismic coverage (Fig. 5.5). Line through NMH (northern manhole) and CMH (central manhole) is line of sewer.

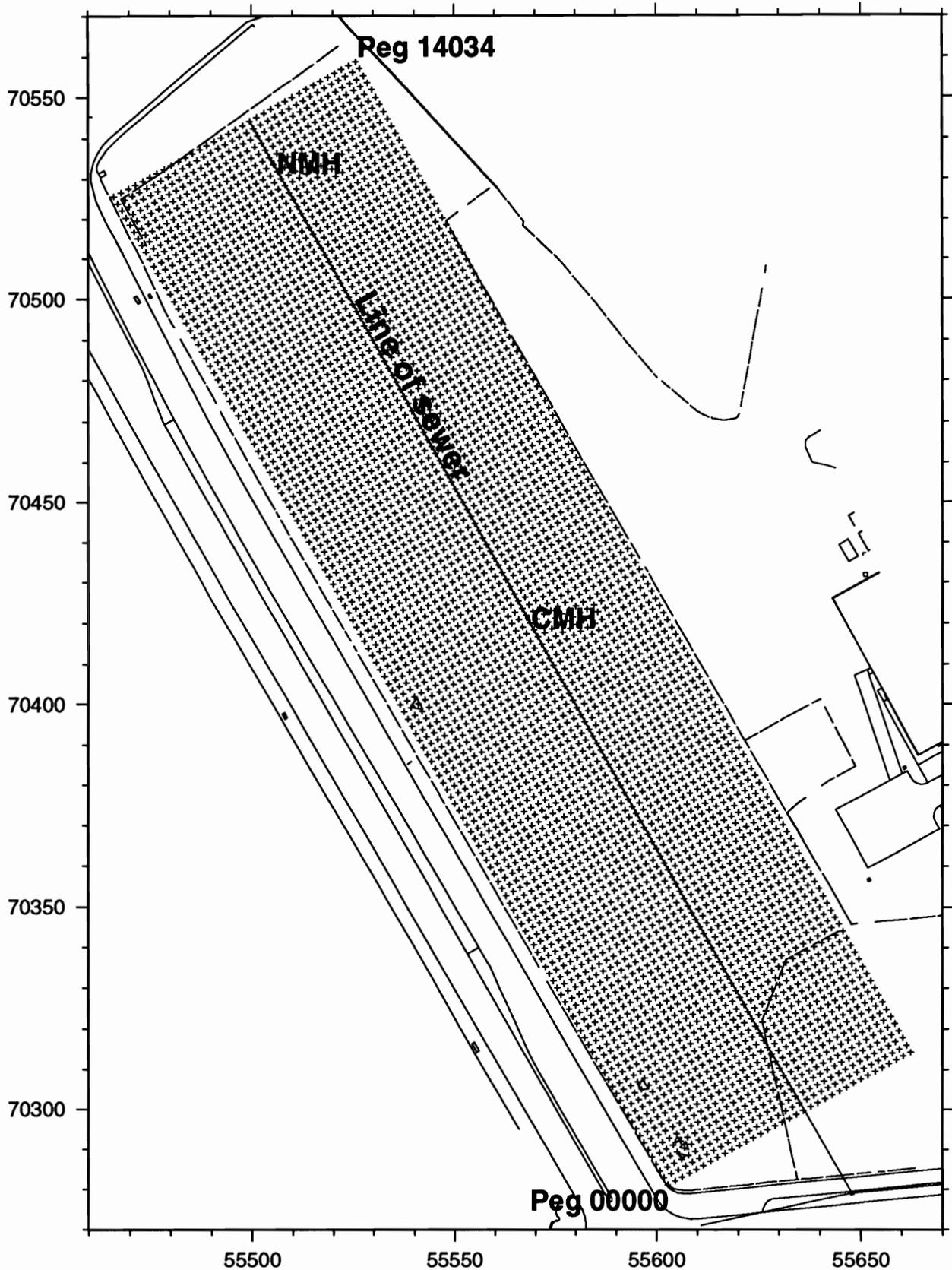


Figure 2.2 Grid of survey pegs at 2 m spacing

There are 140 rows and 34 columns. The pegs at the bottom and top corners are annotated with the 5-digit numbering system.

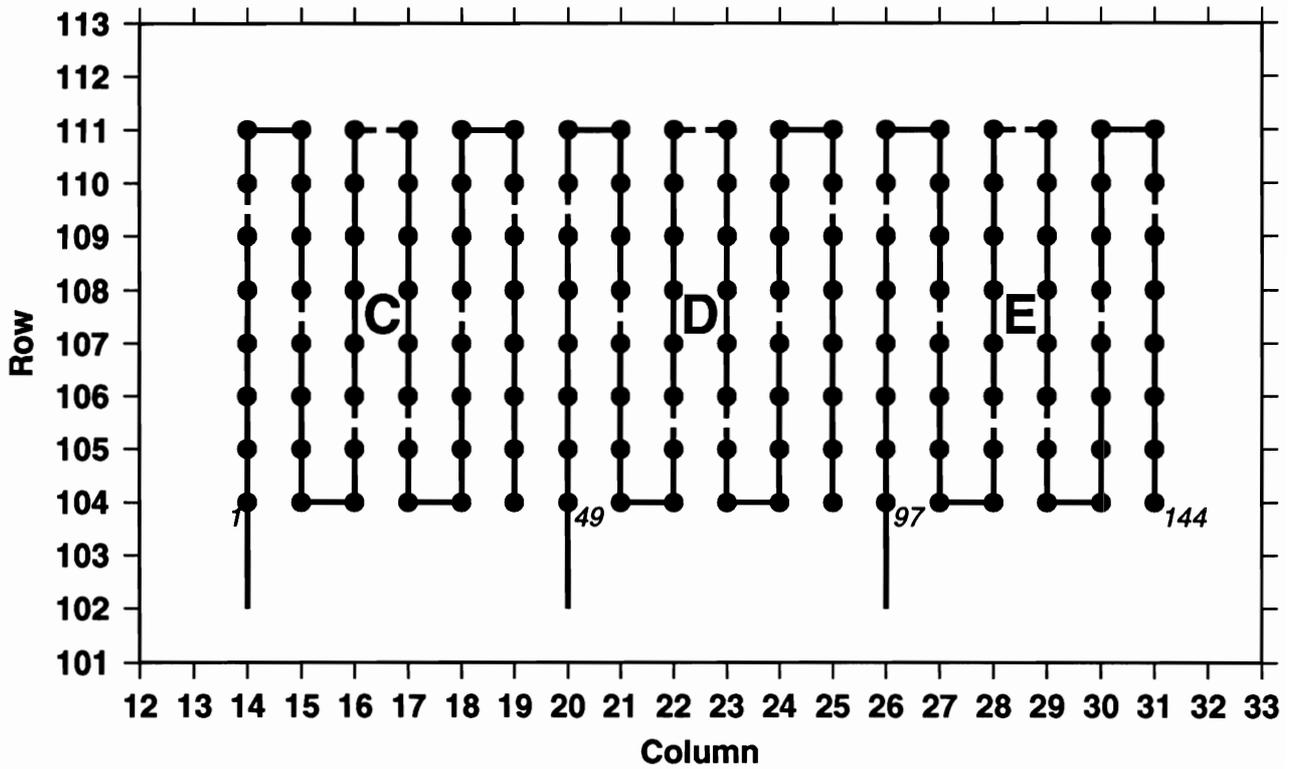


Figure 3.1 Cable and geophone swath geometry - swath CDE

Each spread comprises 48 channels labelled with a letter. The three cables are connected at channels 1, 49 and 97. The rectangular layout of 3 such spreads is the swath of 144 channels.

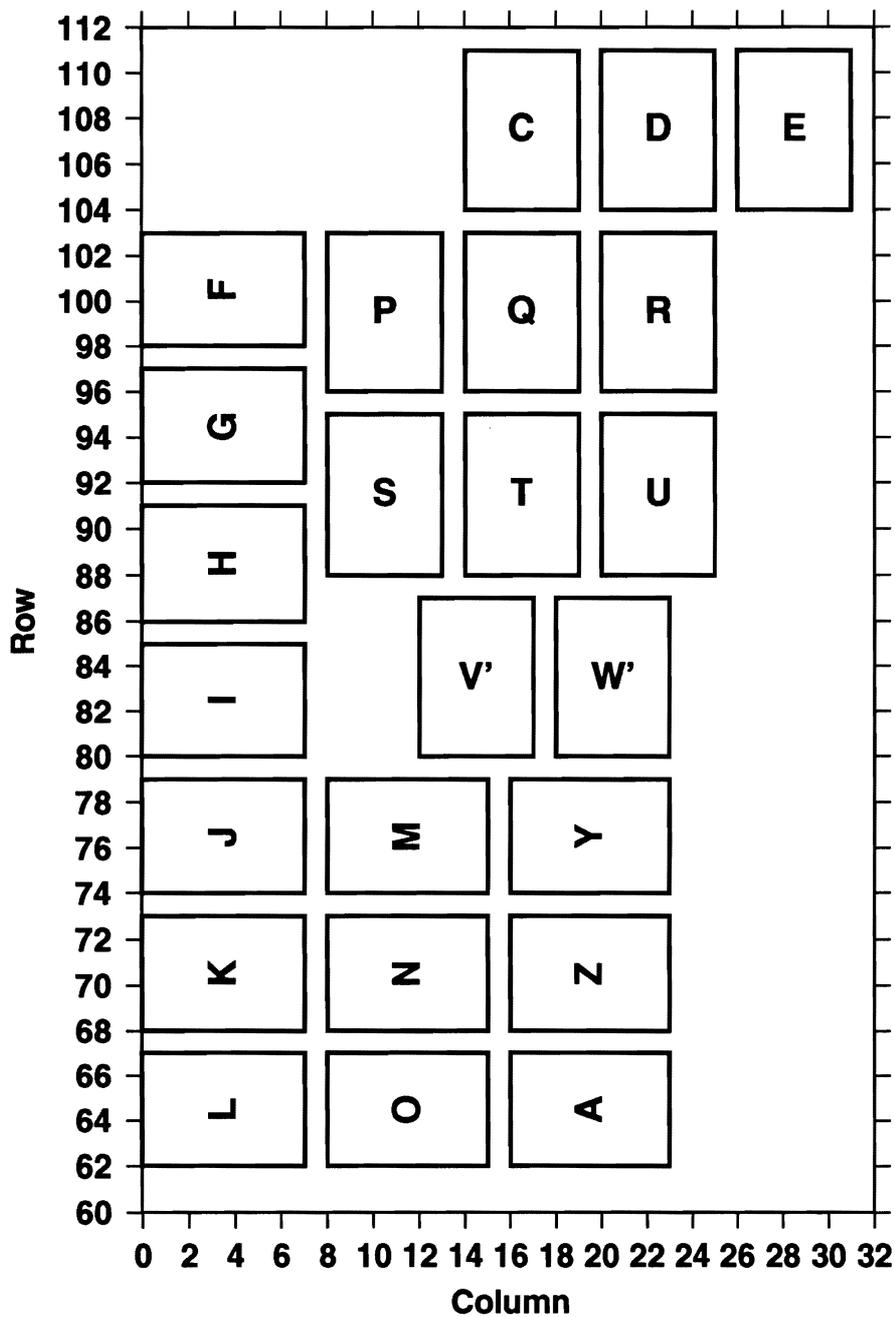


Figure 4.1 Layout of all spreads

Spreads of 48 channels are labelled A, C-W, Y, Z. Spreads V and W were moved right from their original positions to V' and W', respectively.

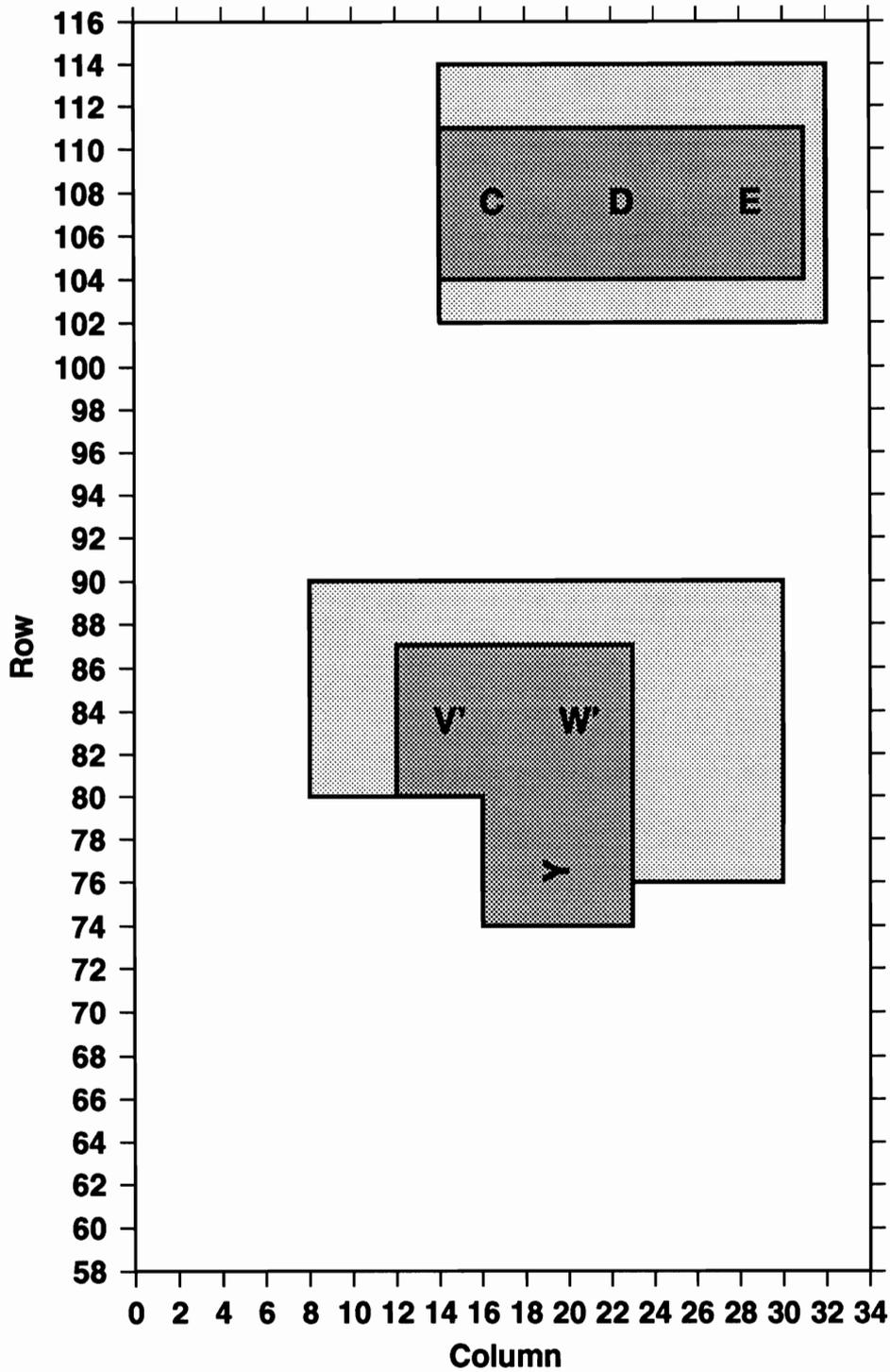


Figure 4.2 Layout of patterns CDE and V'W'Y

Dark shading indicates swath receiver area, lighter shading indicates area of the shots into the swath.

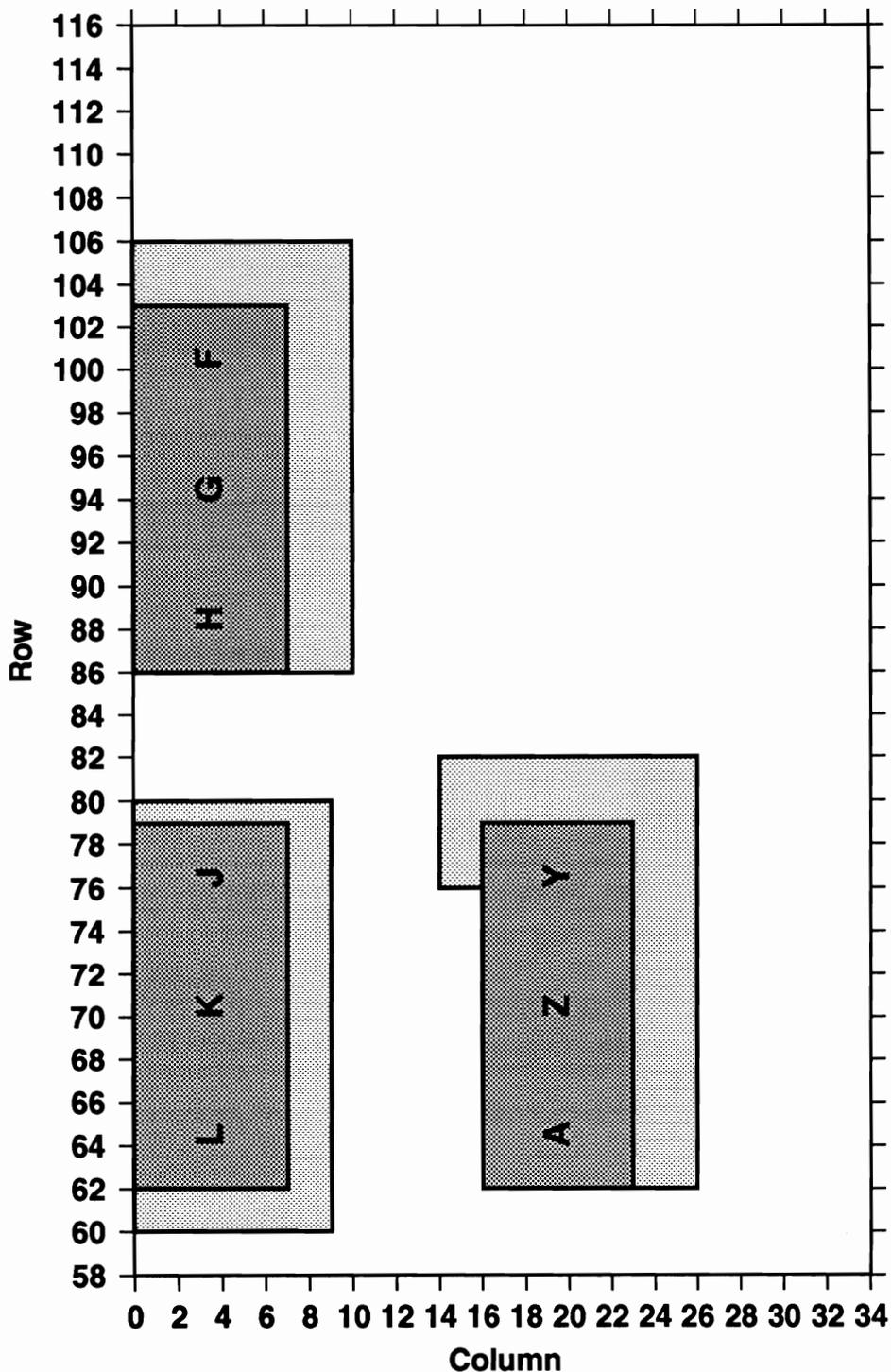


Figure 4.3 Layout of patterns FG, JKL and YZA

Dark shading indicates swath receiver area, lighter shading indicates area of the shots into the swath.

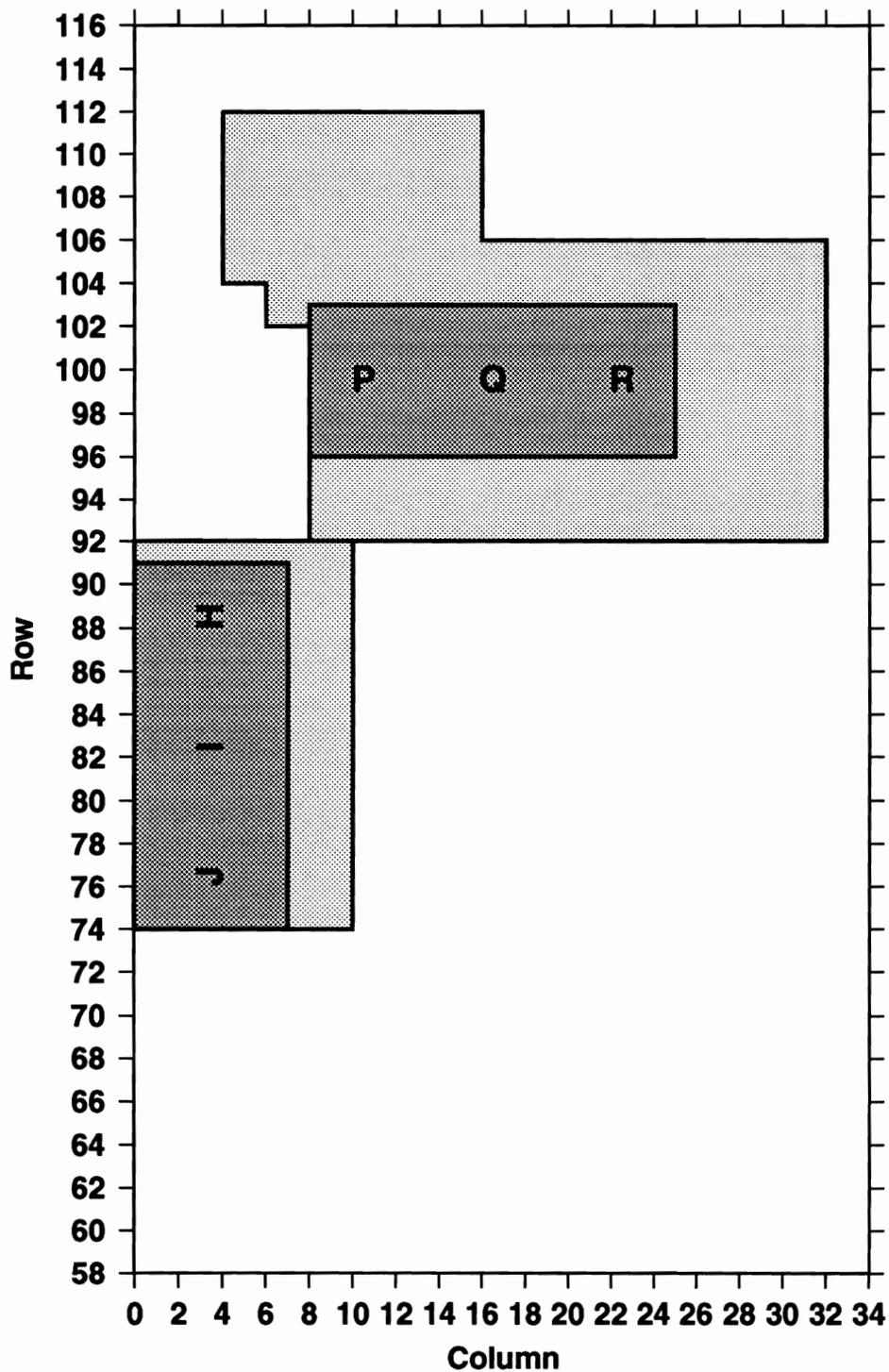


Figure 4.4 Layout of patterns PQR and HIJ

Dark shading indicates swath receiver area, lighter shading indicates area of the shots into the swath.

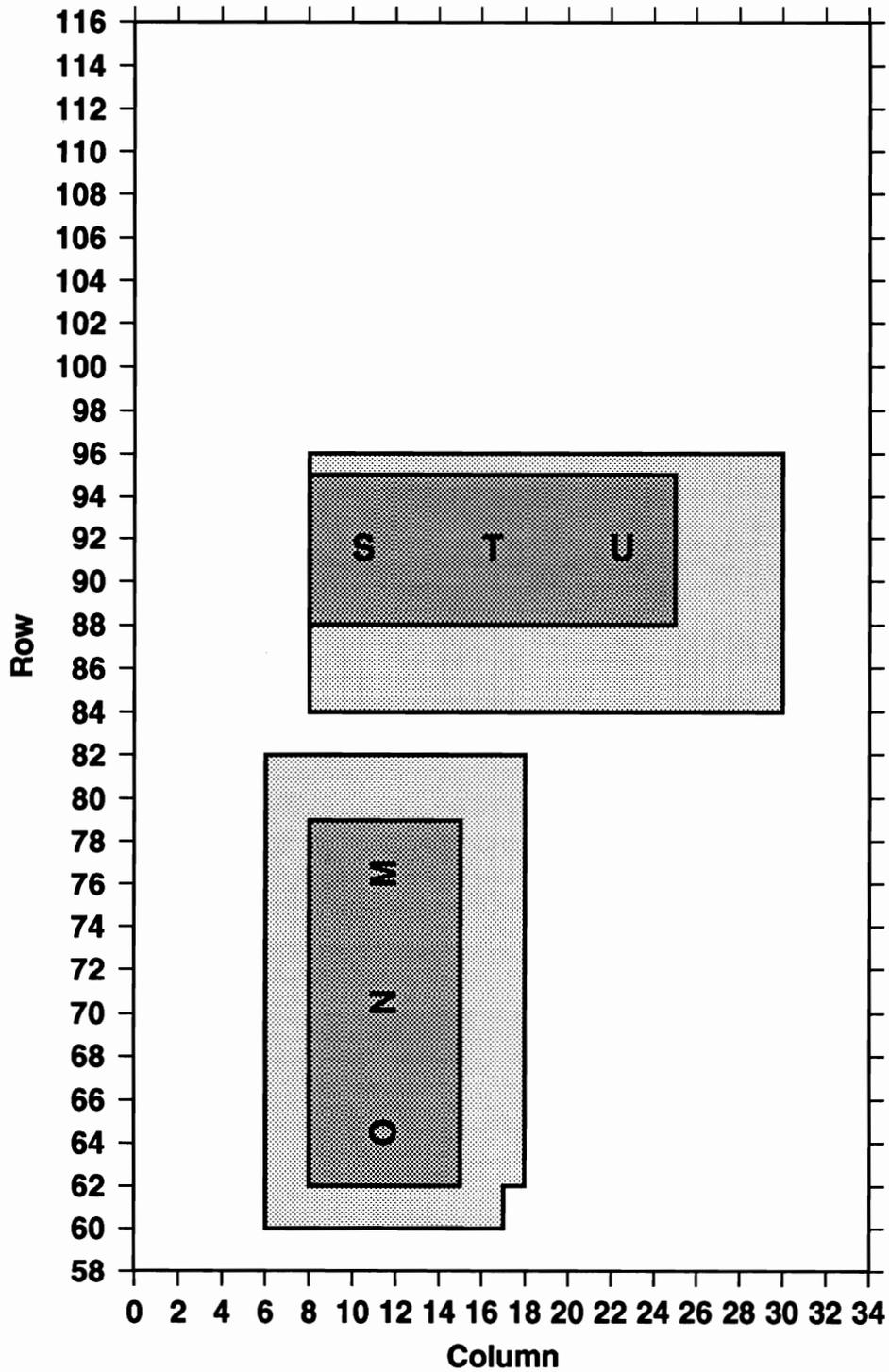


Figure 4.5 Layout of patterns STU and MNO

Dark shading indicates swath receiver area, lighter shading indicates area of the shots into the swath.

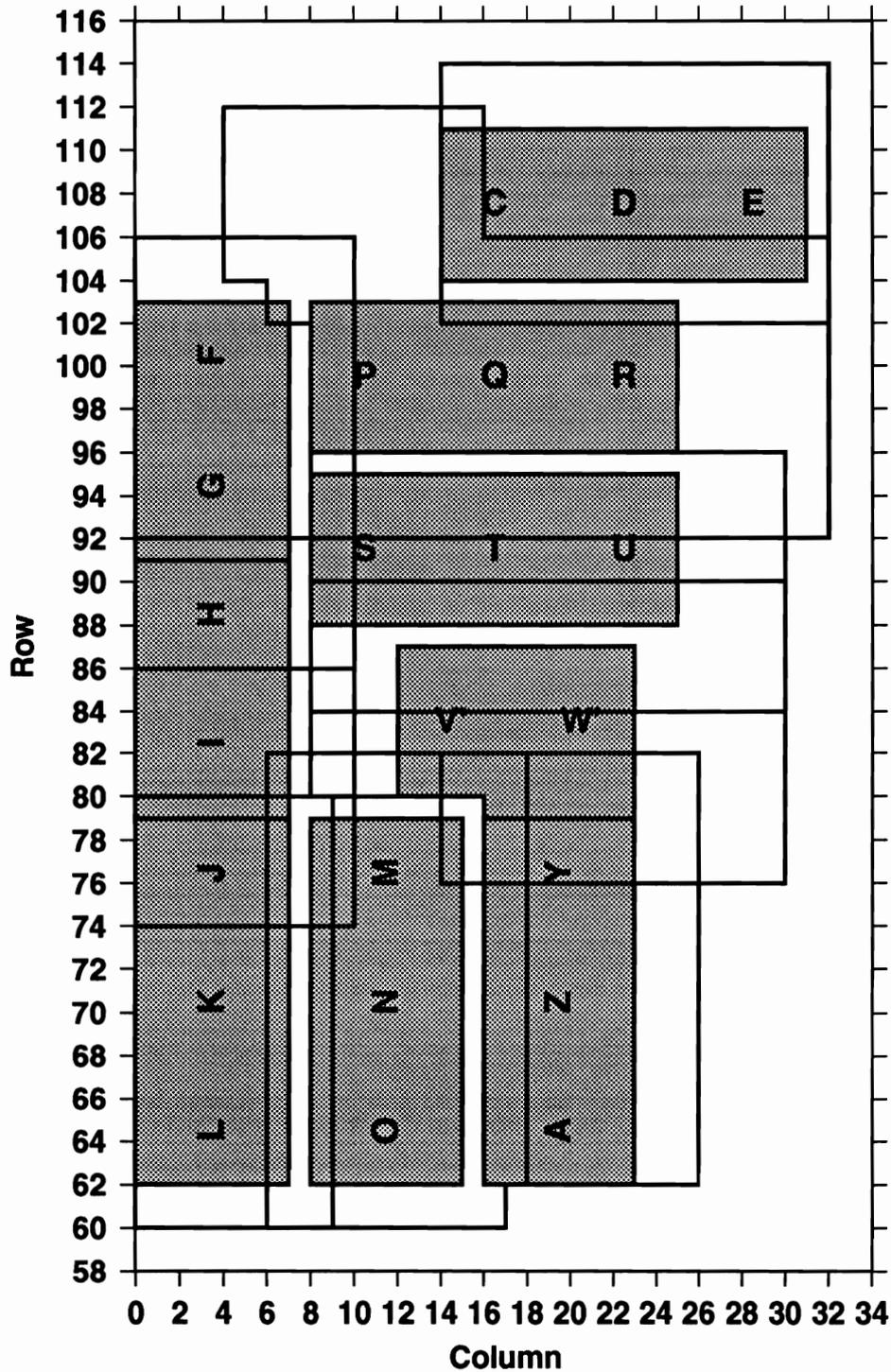


Figure 4.6 Layout of all patterns

Shading indicates swath receiver areas, outlines indicate areas of the shots into the swaths.

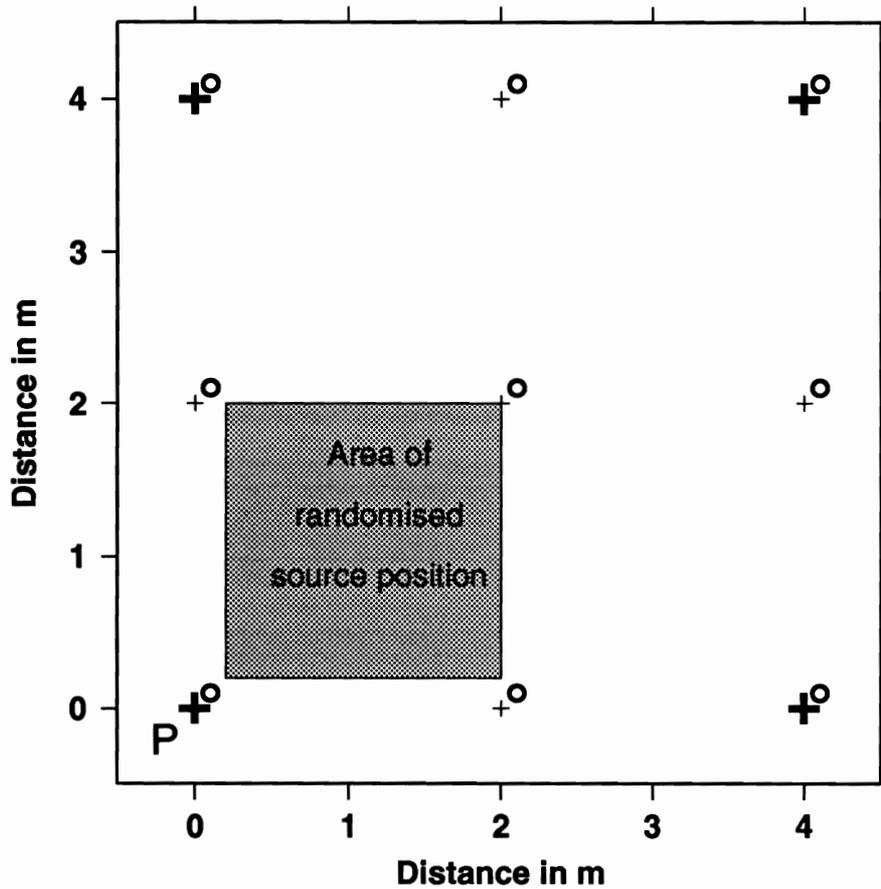


Figure 4.7 Randomised source positioning

Bold crosses are pegs physically marking every second row and column; light crosses mark the intervening rows and columns. Geophones (circles) are planted every 2 m. The shot for peg location P is placed anywhere inside the shaded square, following x,y offsets supplied by a pseudo-random table.

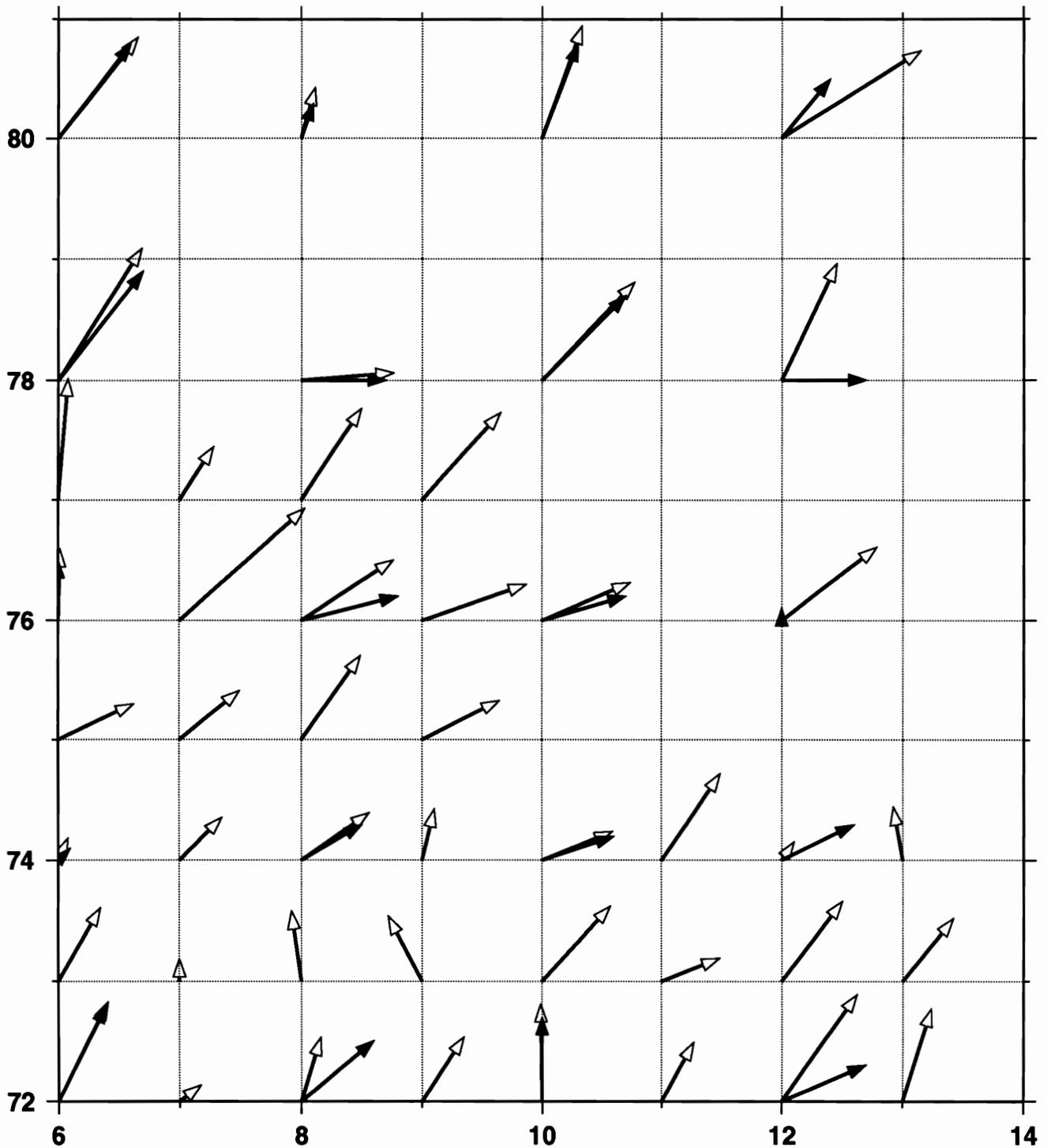


Figure 5.1 Detail of offset vectors

Row and column numbers are shown at the left-hand and lower sides, respectively. The source offsets from the pegs are shown by a pair of vectors. The black-headed vectors are the randomised positions from the table, the white-headed vectors are the actual source positions as surveyed after the shot. The area shown lies partially within the bottom left-hand corner of the survey area, where a 2 m source spacing was used.

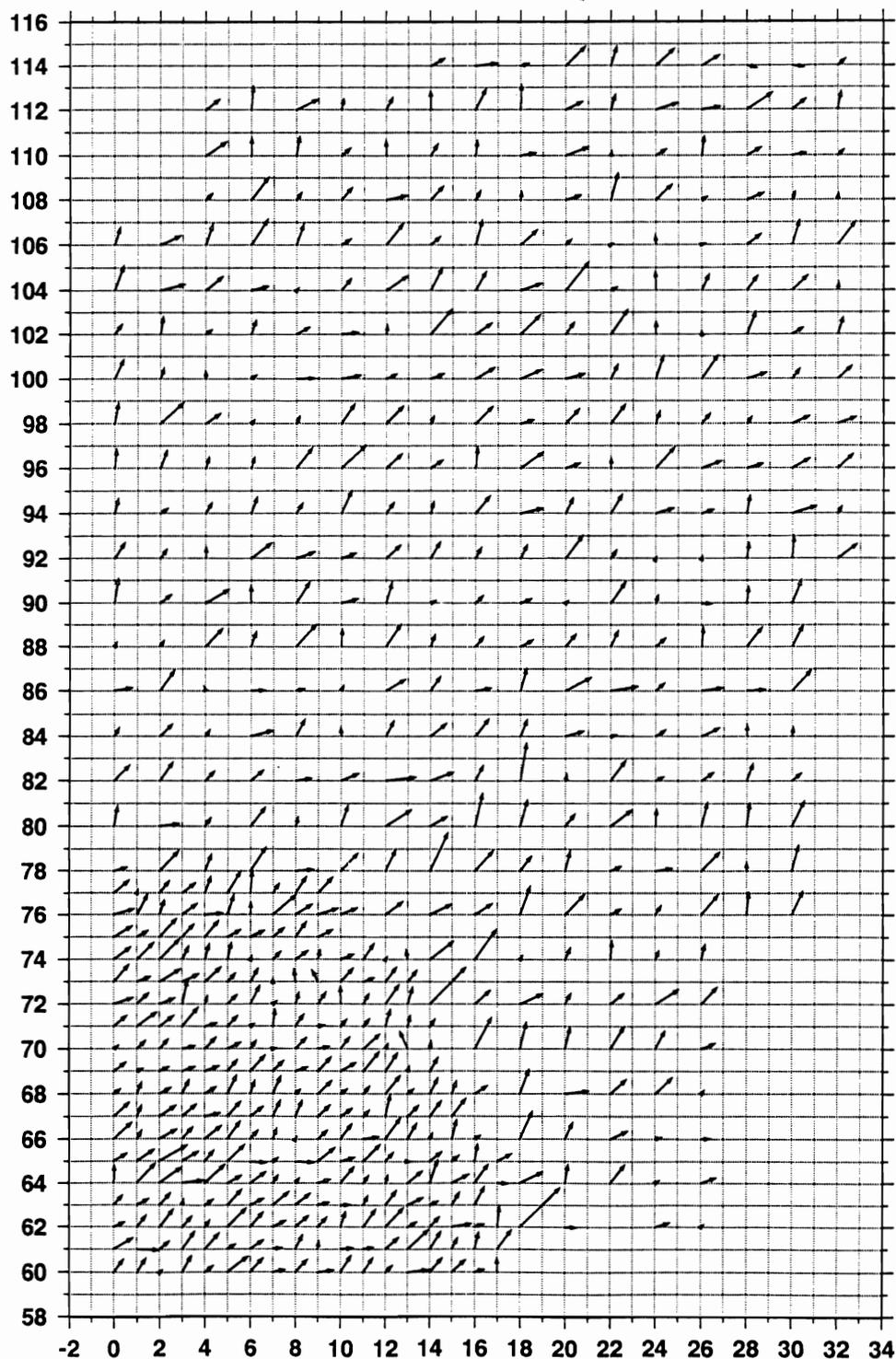


Figure 5.2 All corrected surveyed offset vectors

Row and column numbers are annotated at the edges. Source positions are offset to the position of the arrow head from the tail, where the grid peg lies.

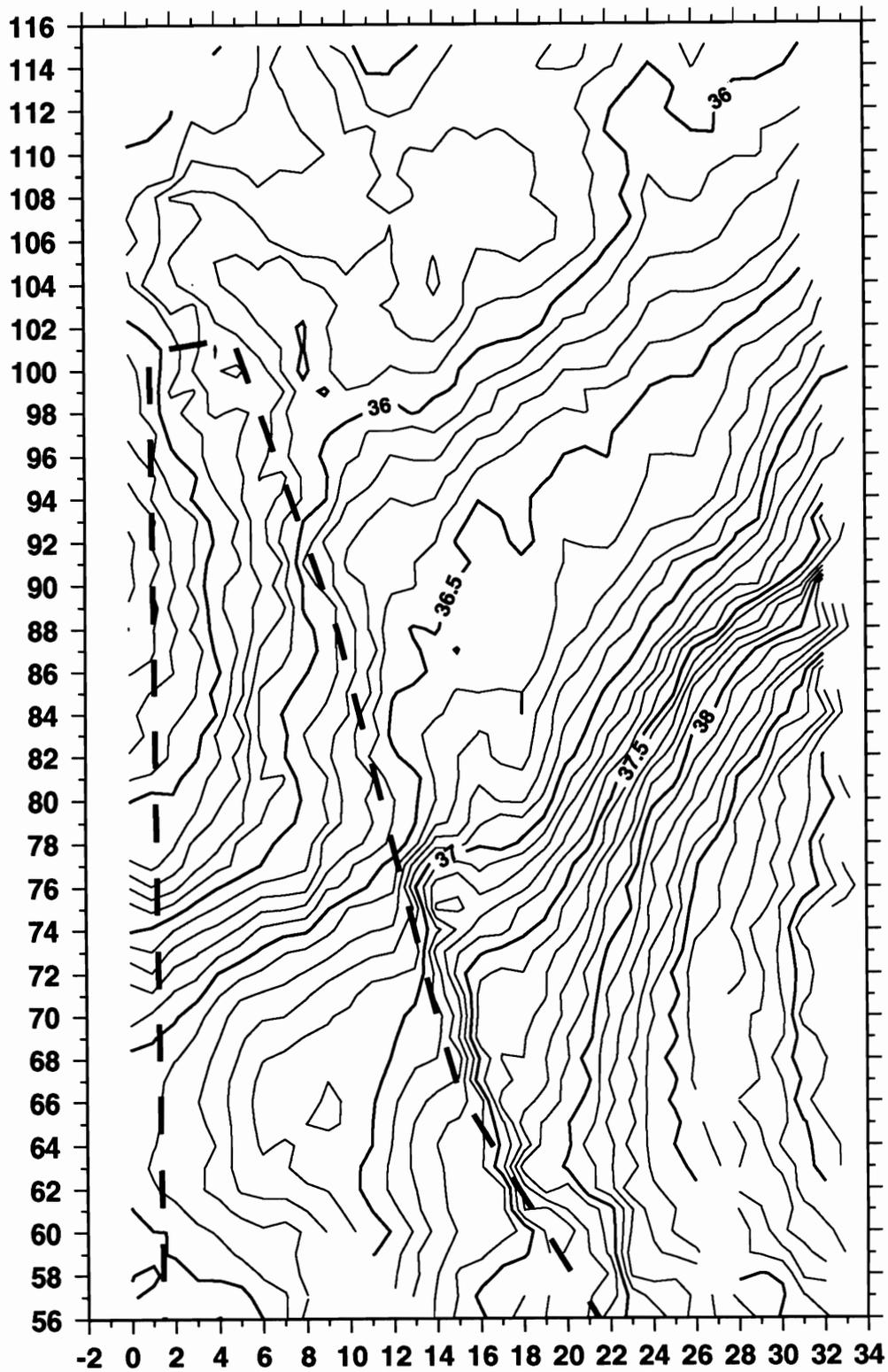


Figure 5.3 Elevation contours of receiver positions

Height in metres from OD; contour interval 0.1 m. Dashed line encloses area from which topsoil was stripped.

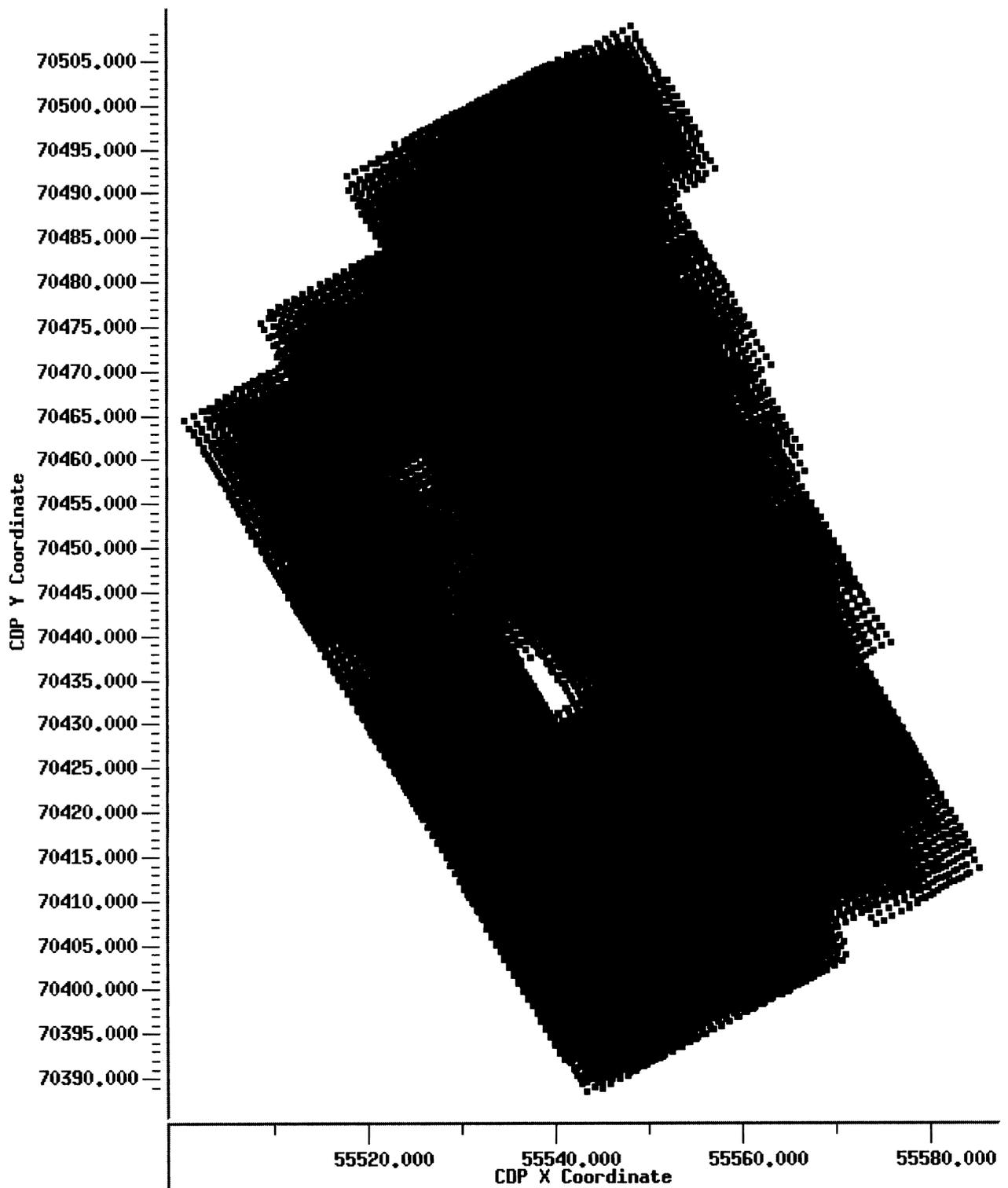


Figure 5.4 CMP coverage

National Grid coordinates. Detailed views of parts of this map are shown in Figures 5.6-5.8.

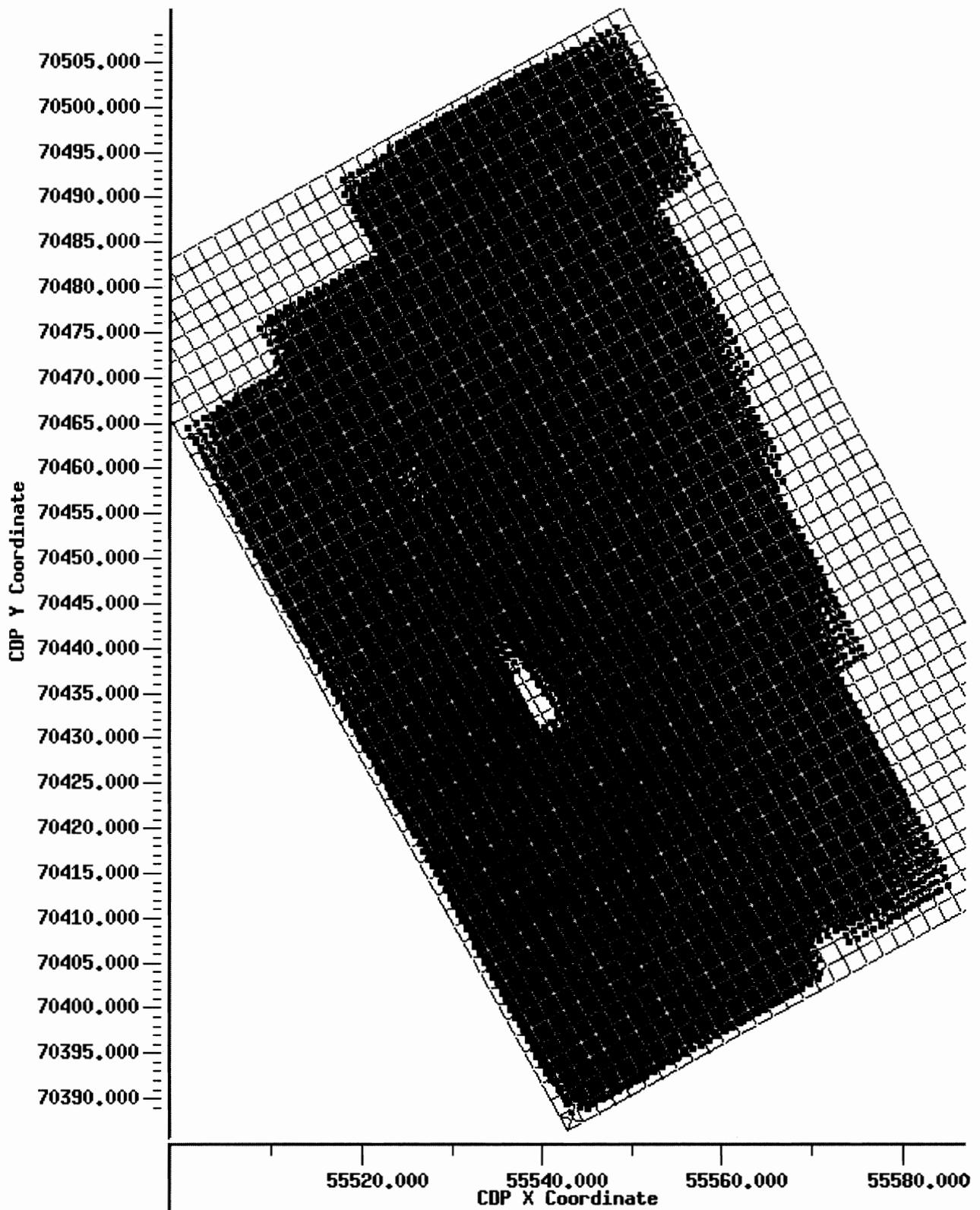


Figure 5.5 CMPs with 2 m binning grid overlain

National Grid coordinates. Detailed views of parts of this map are shown in Figures 5.6-5.8.

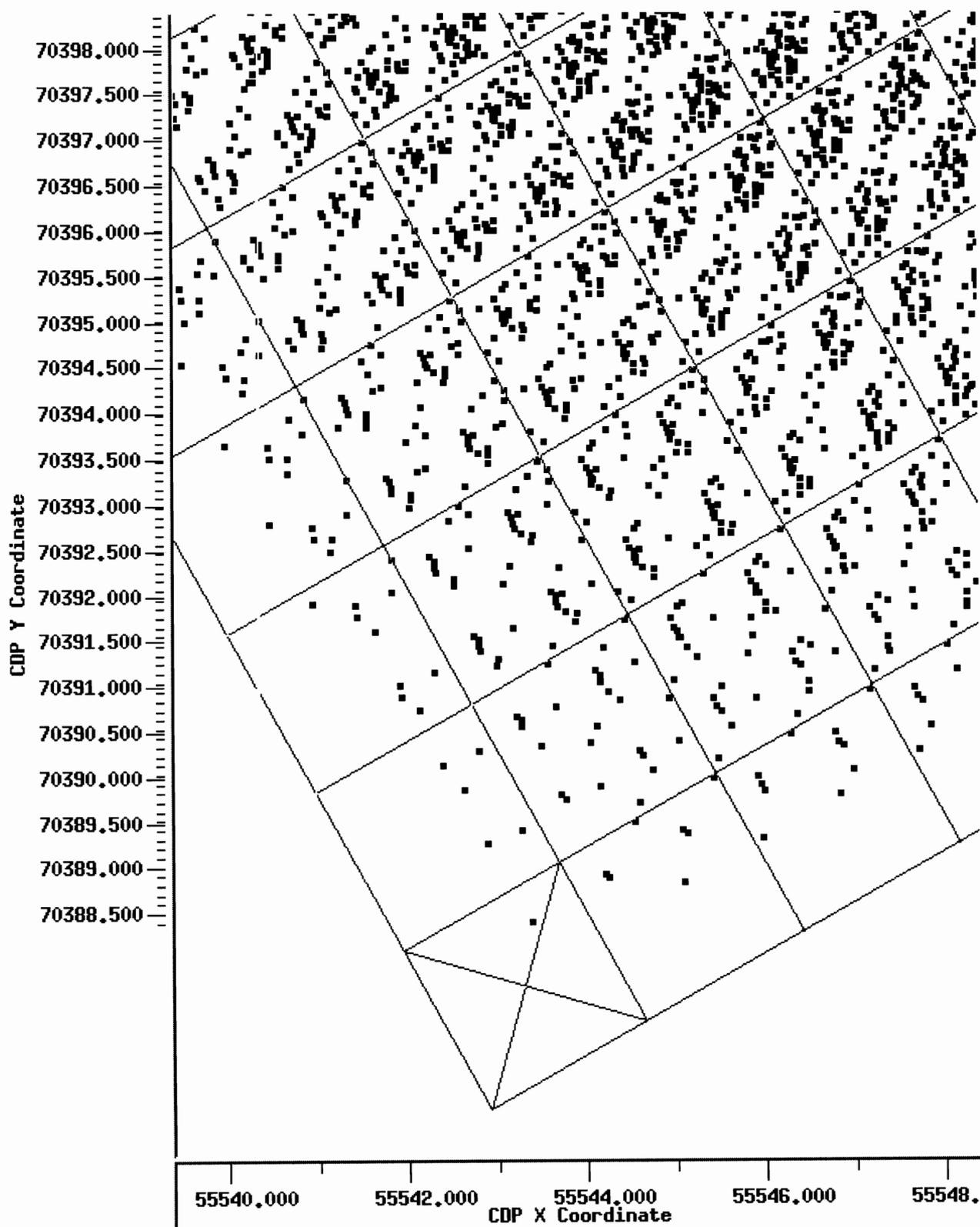


Figure 5.6 Detail of binned CMPs at southern edge of survey

Each small black square corresponds to the CMP of one seismic trace. Row 1, column 1 is marked by the large cross within the bin.

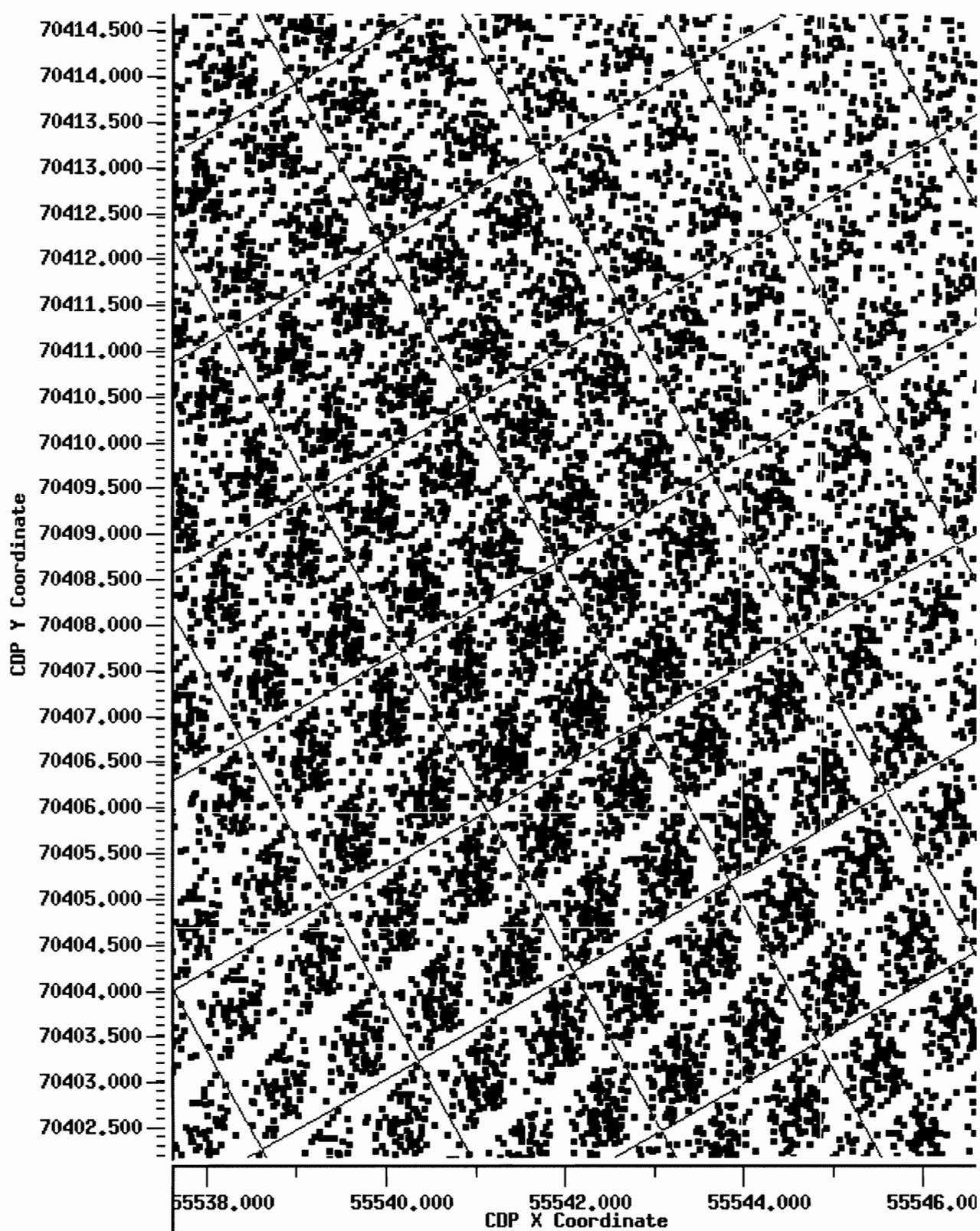


Figure 5.7 Detail of binned CMPs from centre of survey

Here there are several hundred CMPs within each bin. The density of coverage is very even, but with a slight 1 m periodicity superimposed.

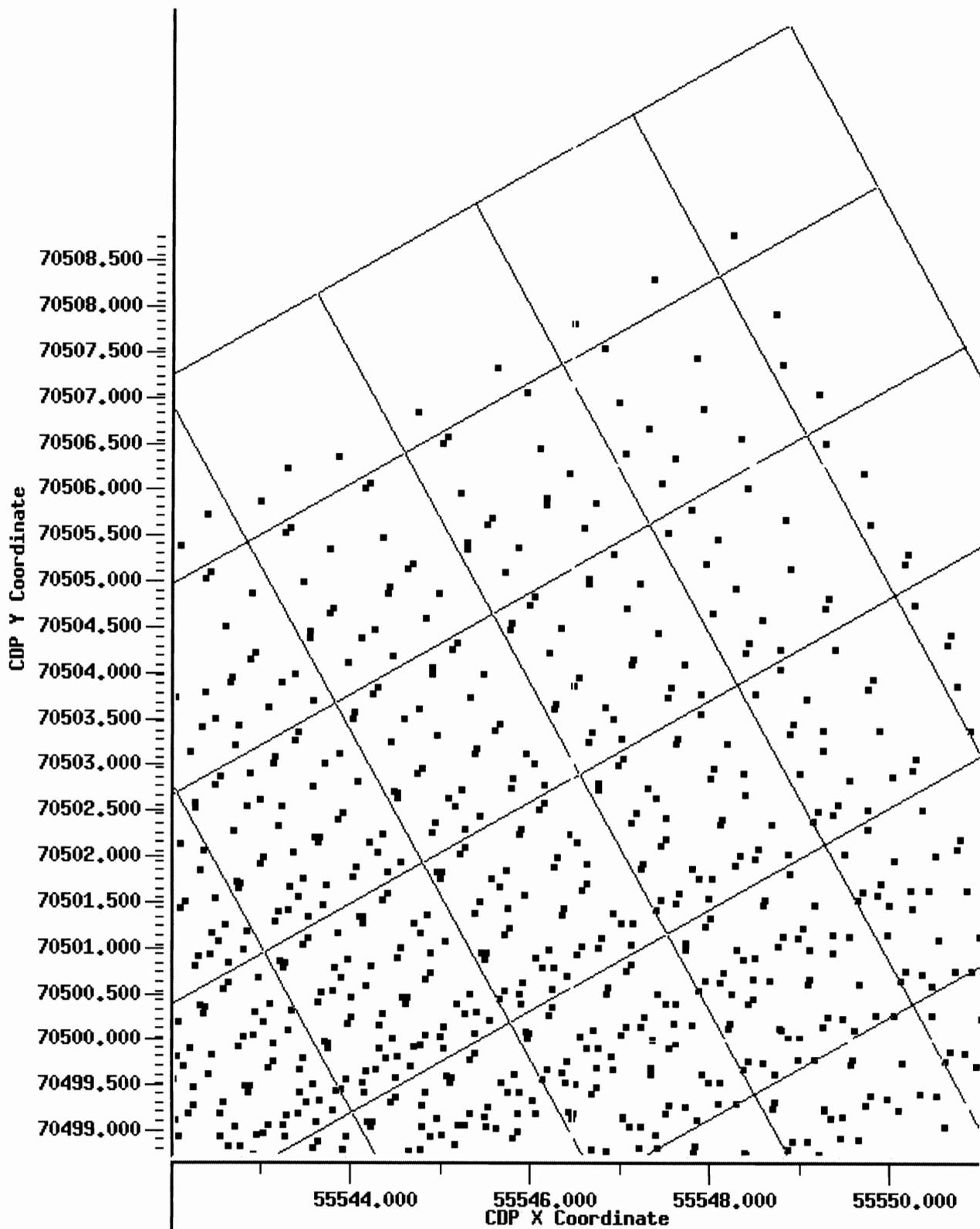


Figure 5.8 Detail of binned CMPs at northern corner of survey

The density of coverage at the topmost bin, row 53 column 33, is reduced to only one trace (i.e. 1-fold coverage).

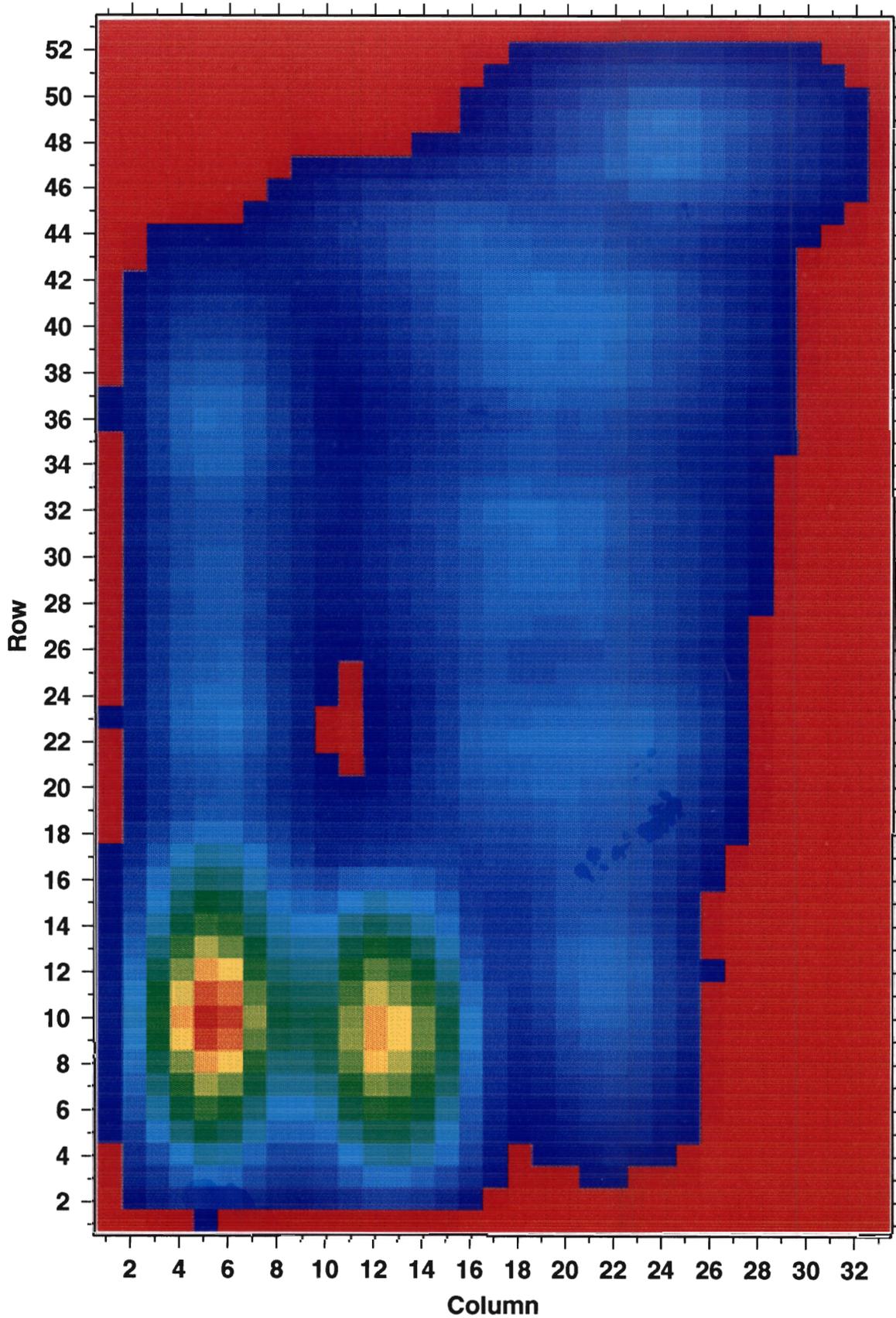


Figure 5.9 Fold of coverage
Key to colours is given in Figure 5.10.

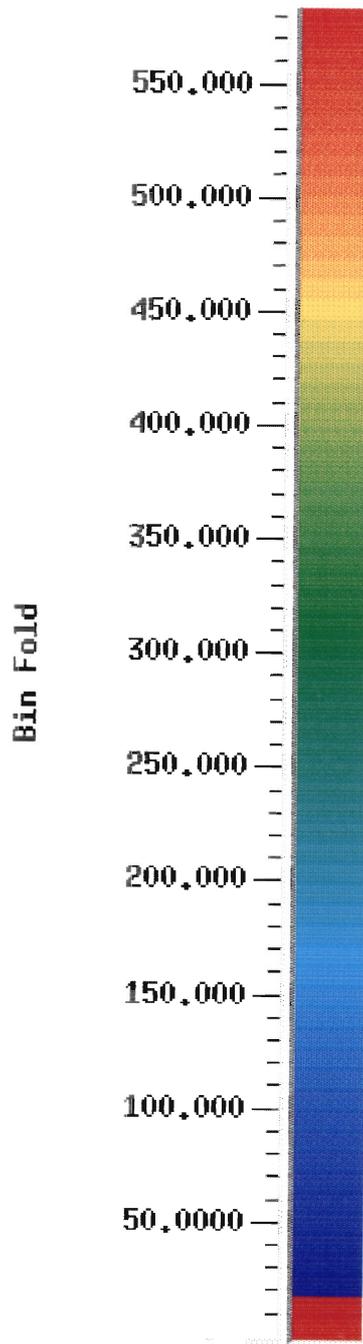


Figure 5.10 Colour key spectrum for Figure 5.9

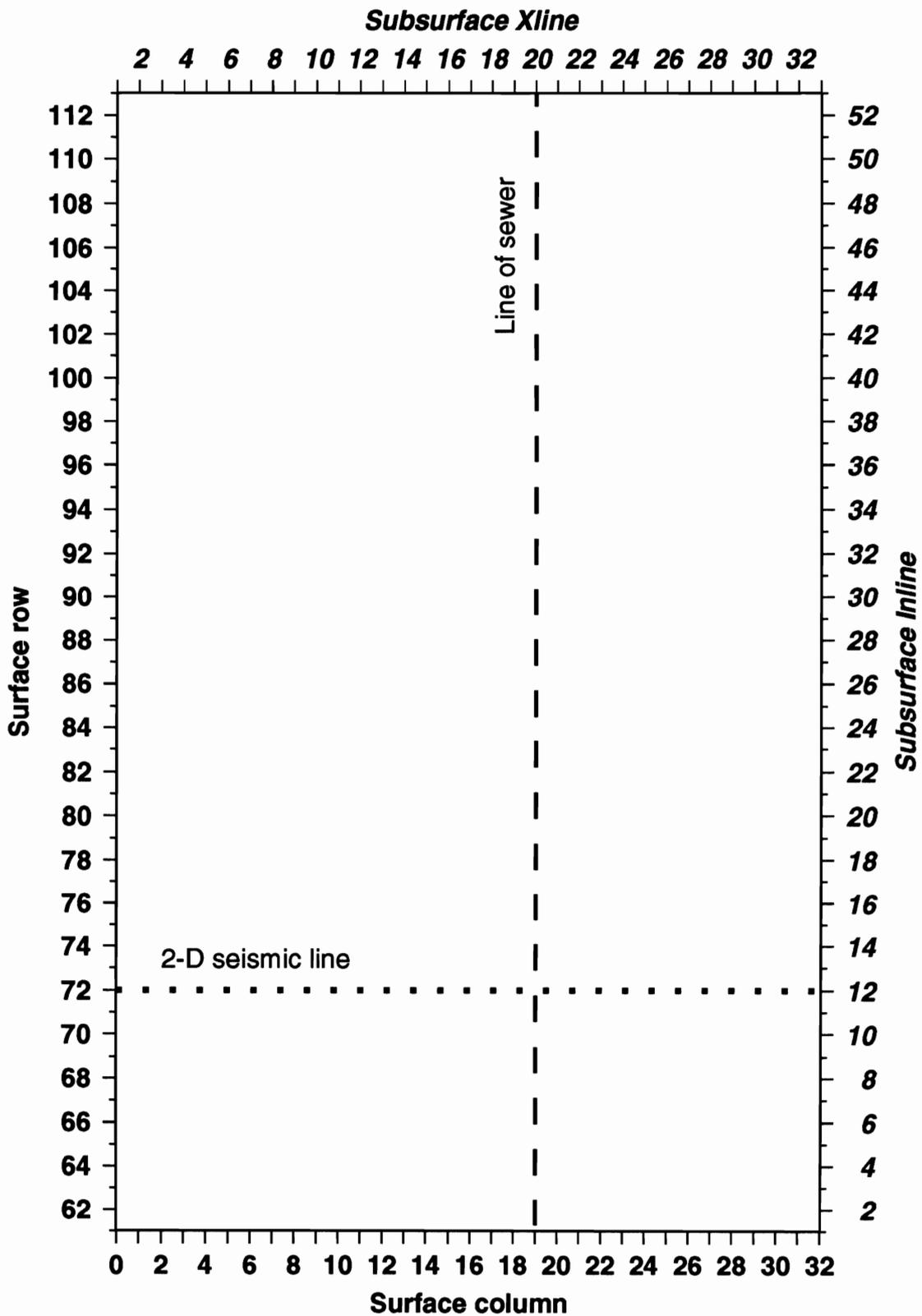


Figure 5.11 Surface and subsurface coordinate systems

Surface numbers are in upright font, subsurface numbers in italic. The 2-D seismic line along row 072 (Chapter 6) corresponds to Inline 12 of the 3-D coverage.

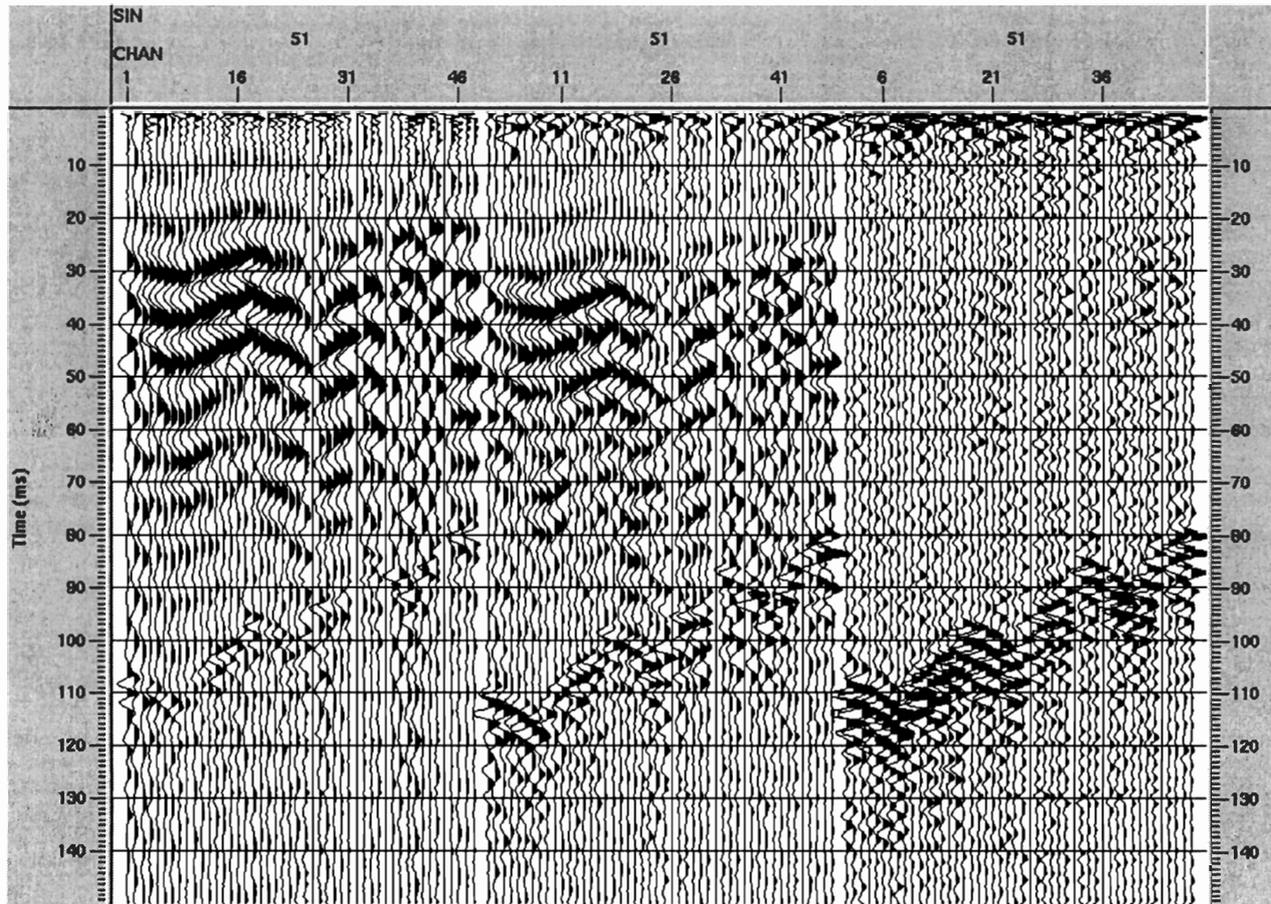


Figure 5.12 Raw shot gather correlated in three different ways

Only the first 48 channels of a shot are shown, repeated in three panels. From left to right, the panels have been correlated with (1) a field deconvolution, (2) a synthetic sweep 100-700 Hz, and (3) a synthetic sweep 200-700 Hz.

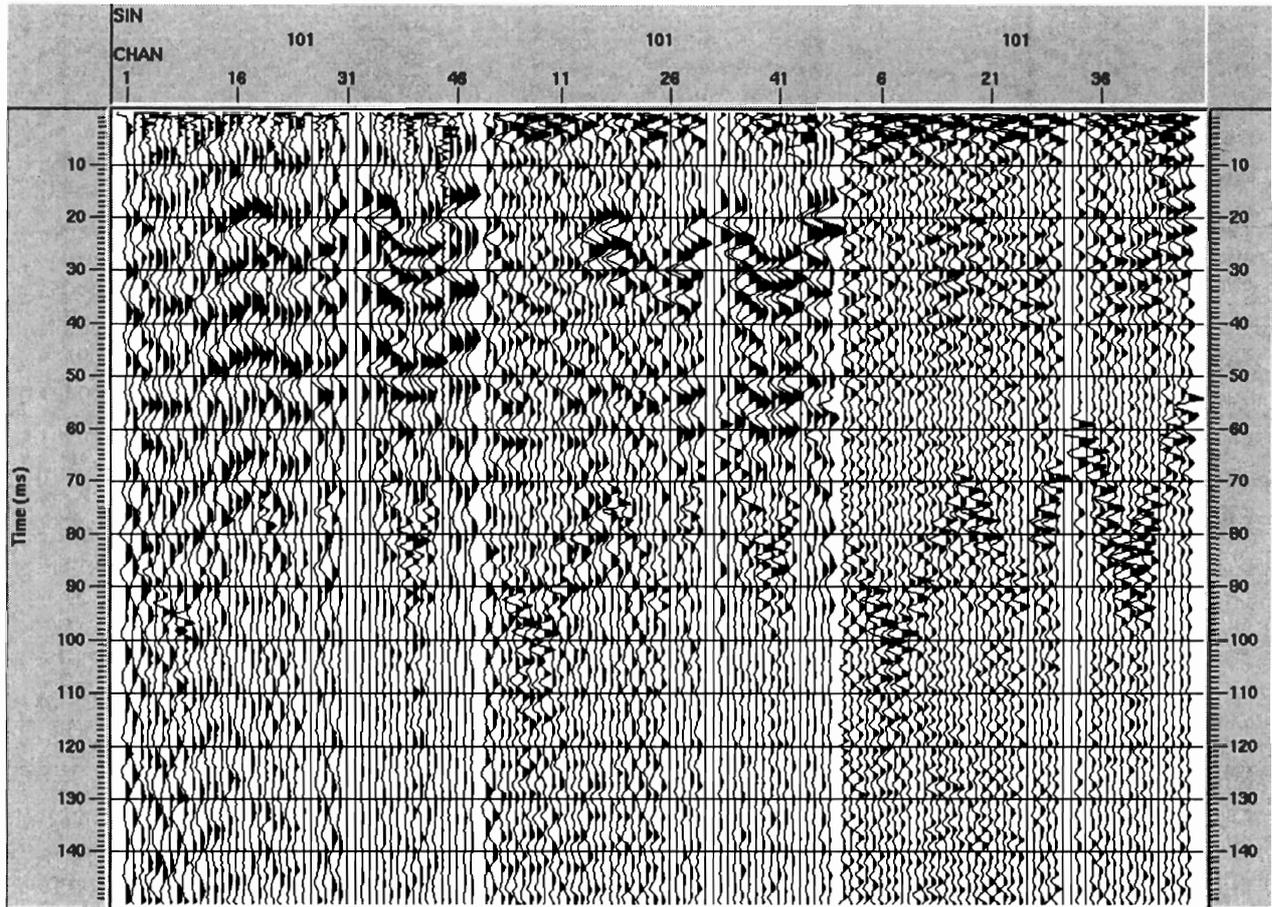


Figure 5.13 Raw shot gather at intermediate offsets

Details as in Figure 5.12.

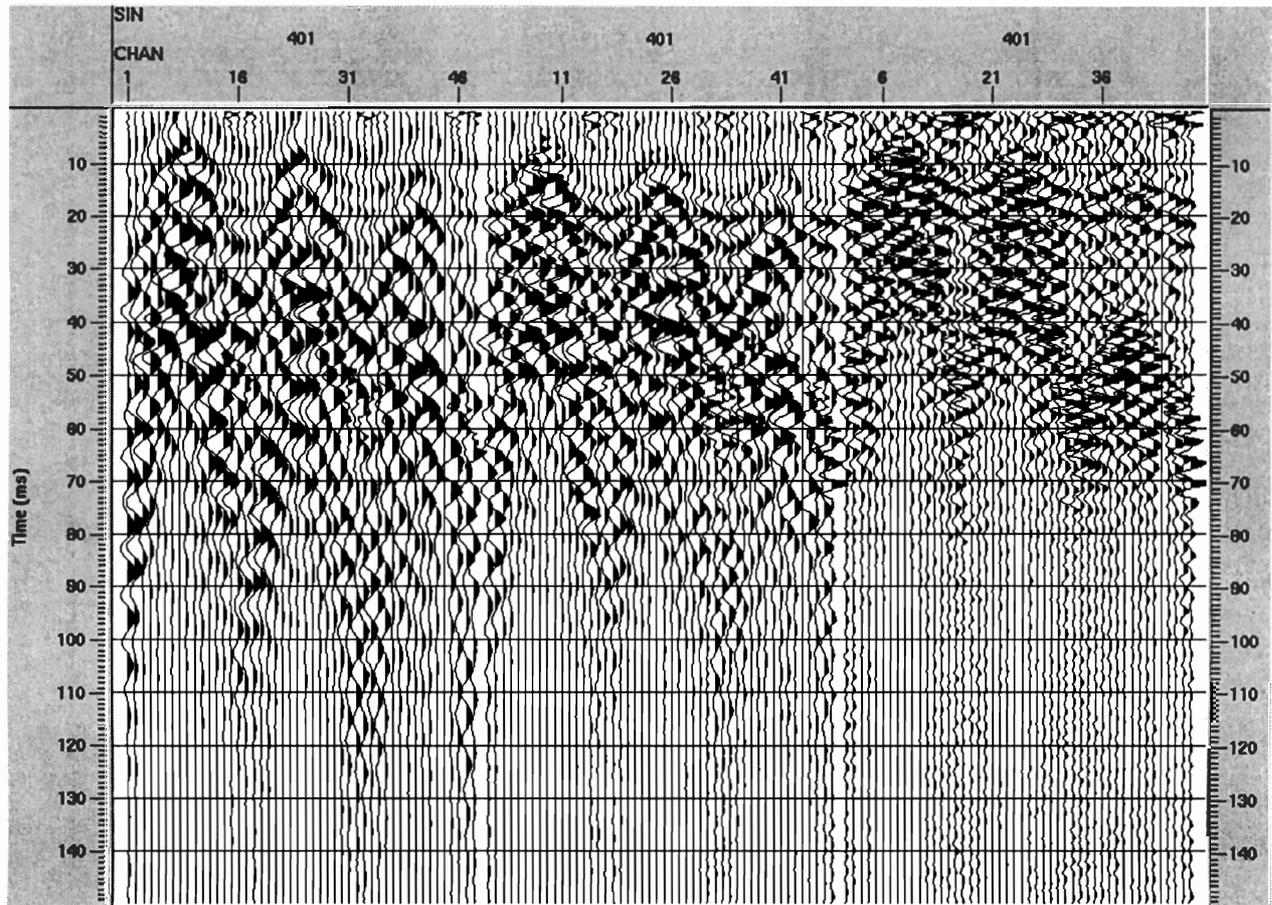


Figure 5.14 Raw shot gather at small offsets

Details as in Figure 5.12.

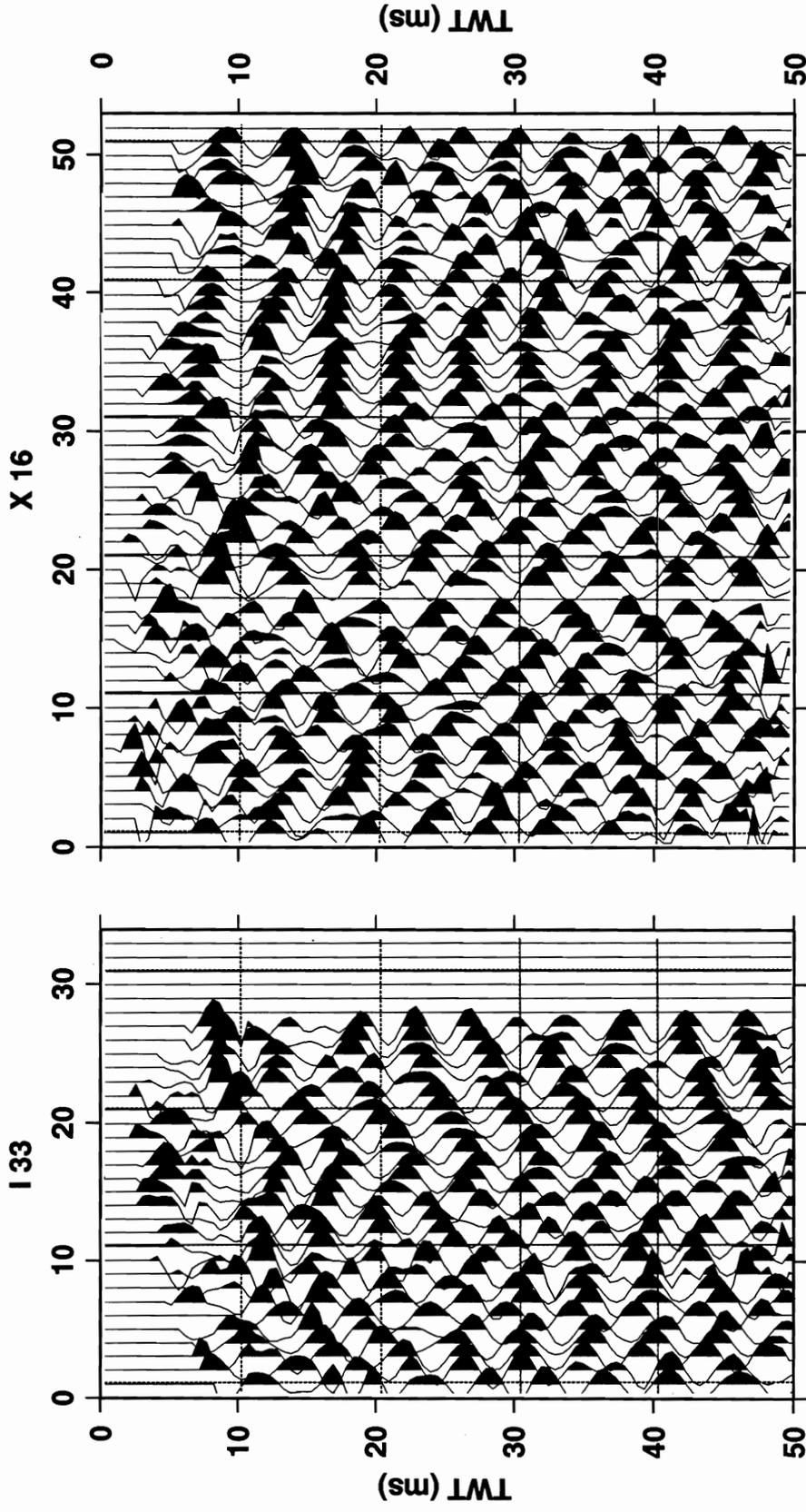


Figure 5.15 Sample inline and crossline sections - strategy A

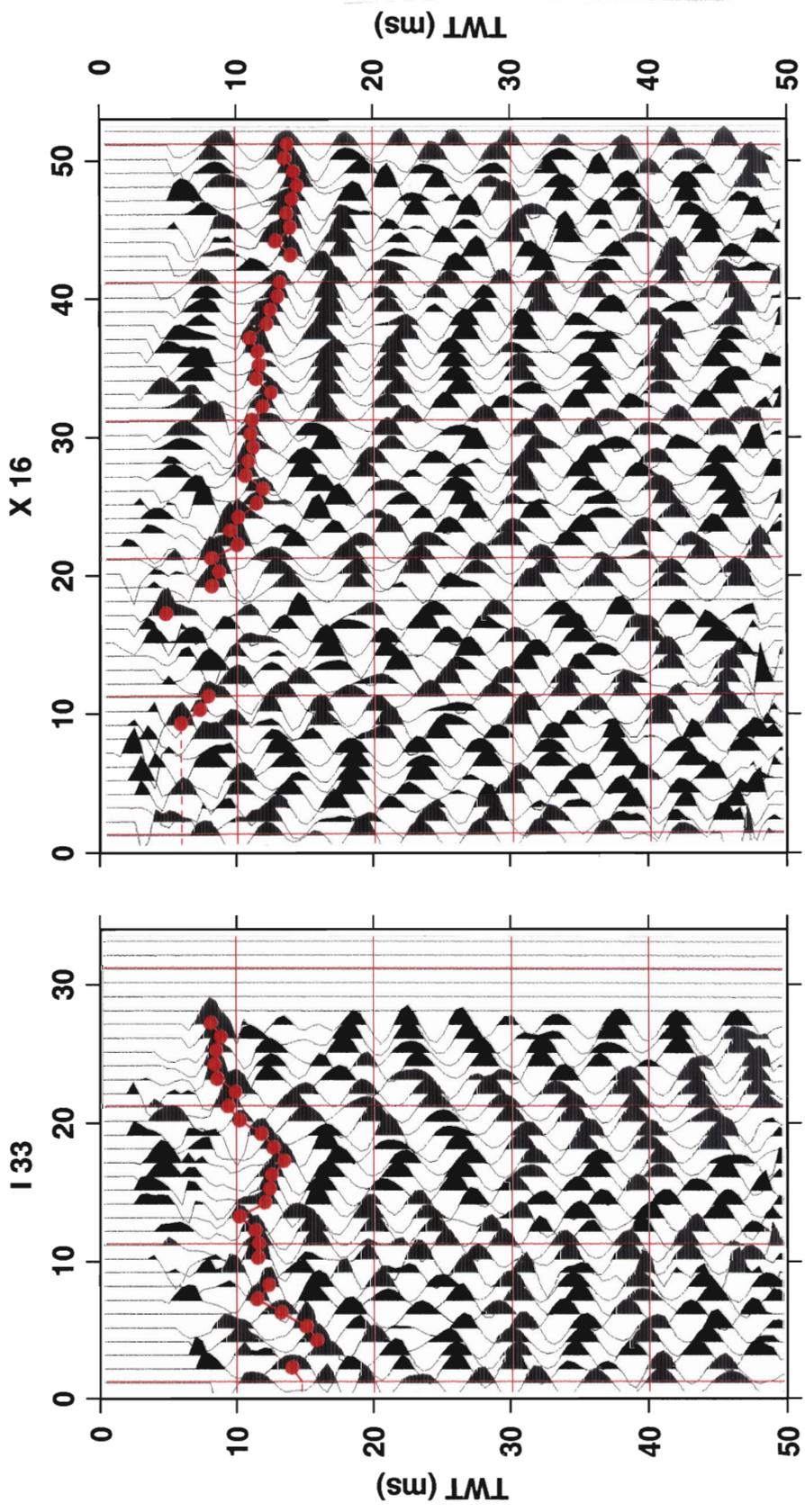


Figure 5.16 Sample inline and crossline sections - strategy A, interpreted

Red dots mark the interpreted base of the Boulder Clay. Display polarity is reversed relative to the SEG convention.

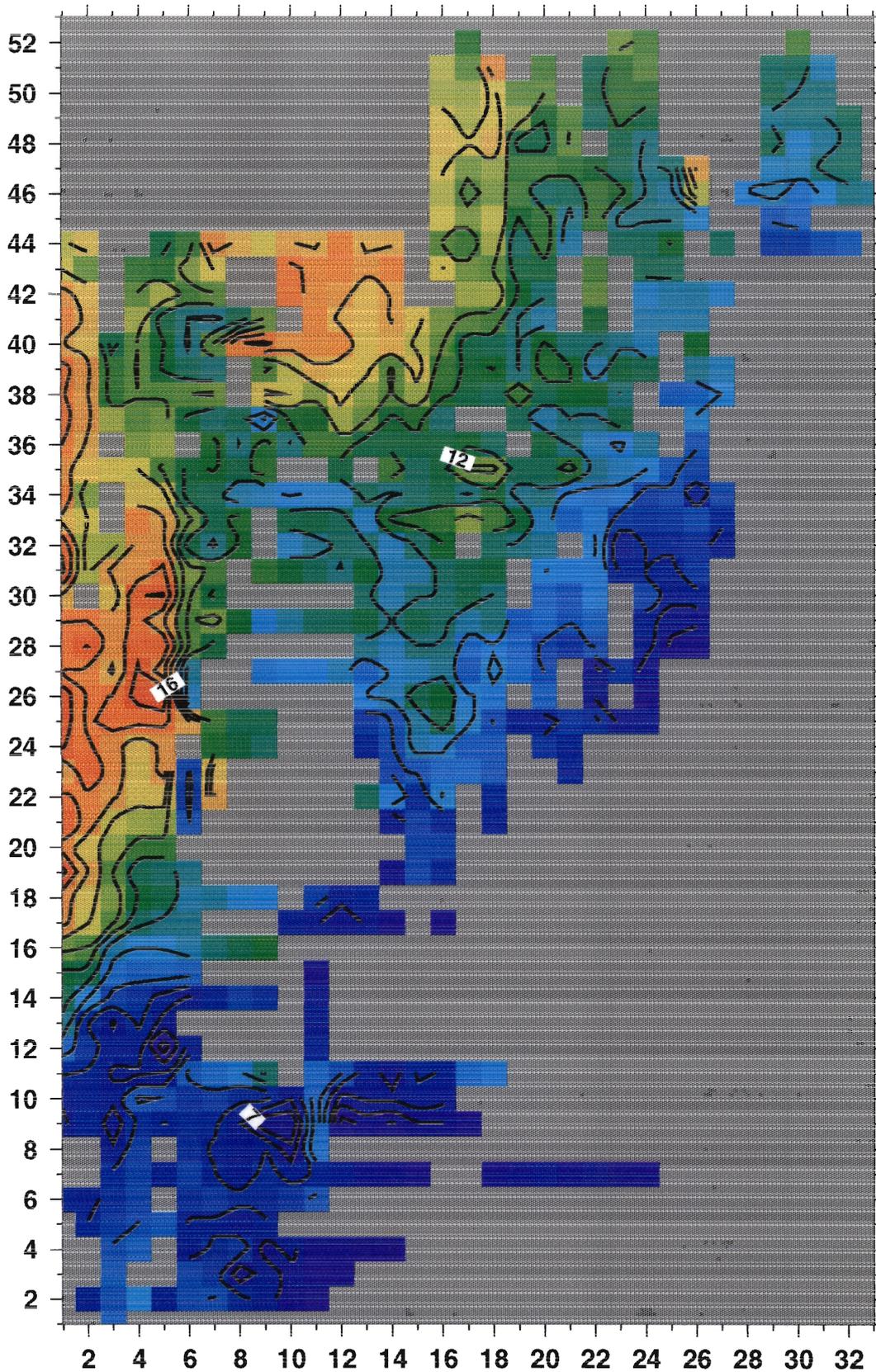


Figure 5.17 Contour map of Base Clay horizon, strategy A

Contour interval 1 ms TWT. Dark blue hue - 6 ms; dark orange - 18 ms; grey - no picks.

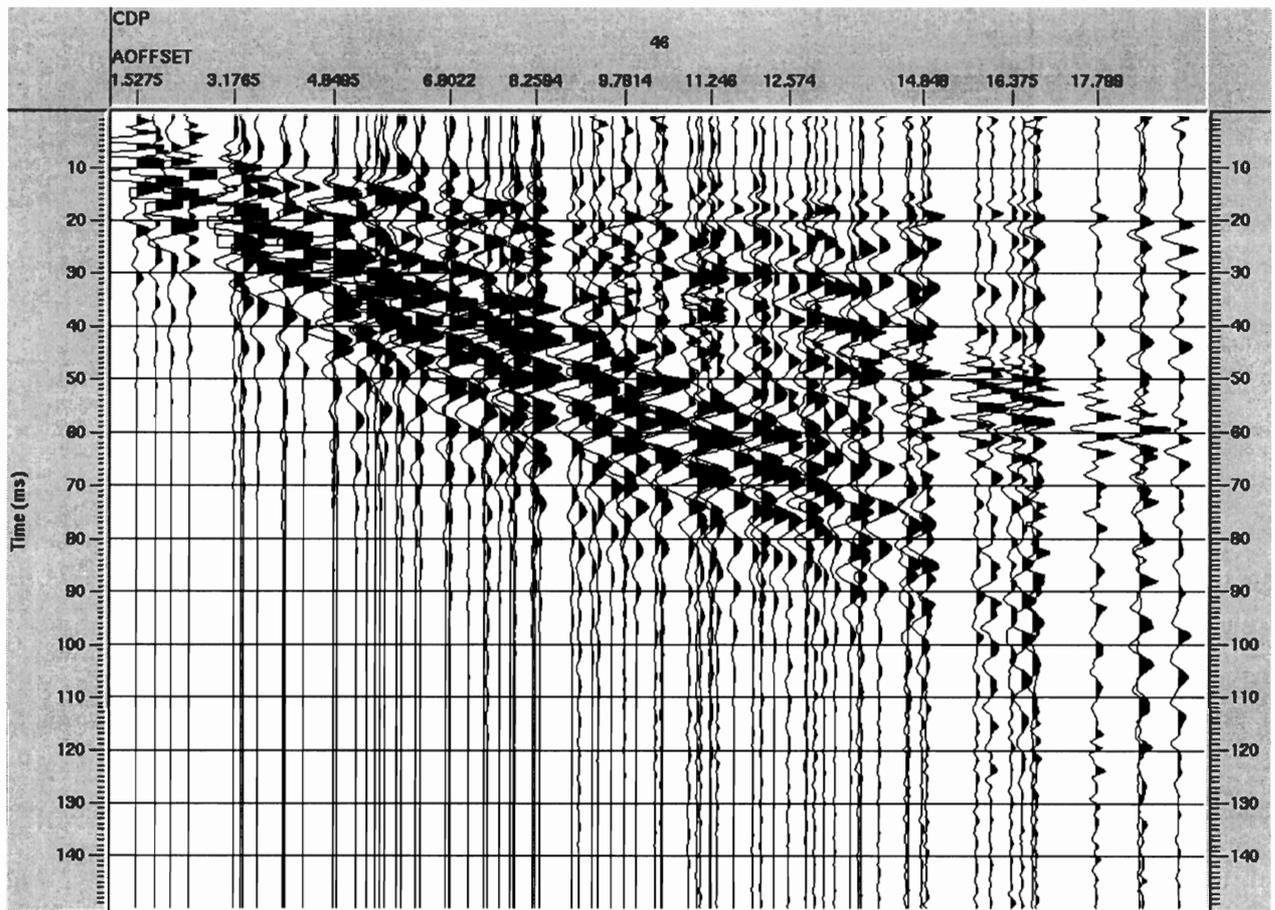


Figure 5.18 CMP gather with trace spacing proportional to offset

Offsets range from 1.5 m to 19.5 m.

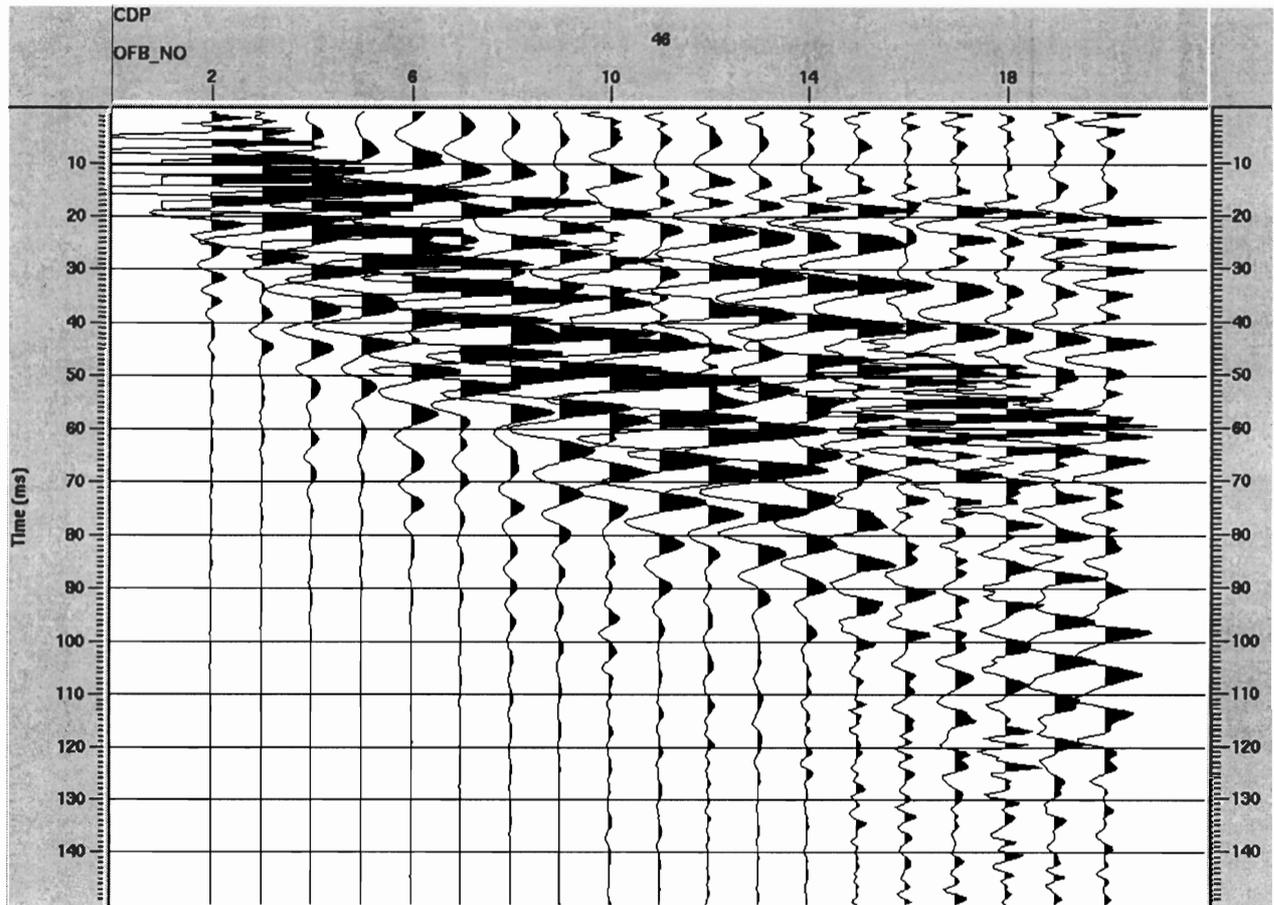


Figure 5.19 CMP gather of Figure 5.18 after 1 m offset binning/summing

Trace at offset bin no. (OFB_NO) 2 is the sum of all traces with offsets between 1.0 and 2.0 m. The mean value is 1.5 m. The offsets increase at a 1 m increment up to 19.5 m (offset bin no. 20) at the right-hand side.

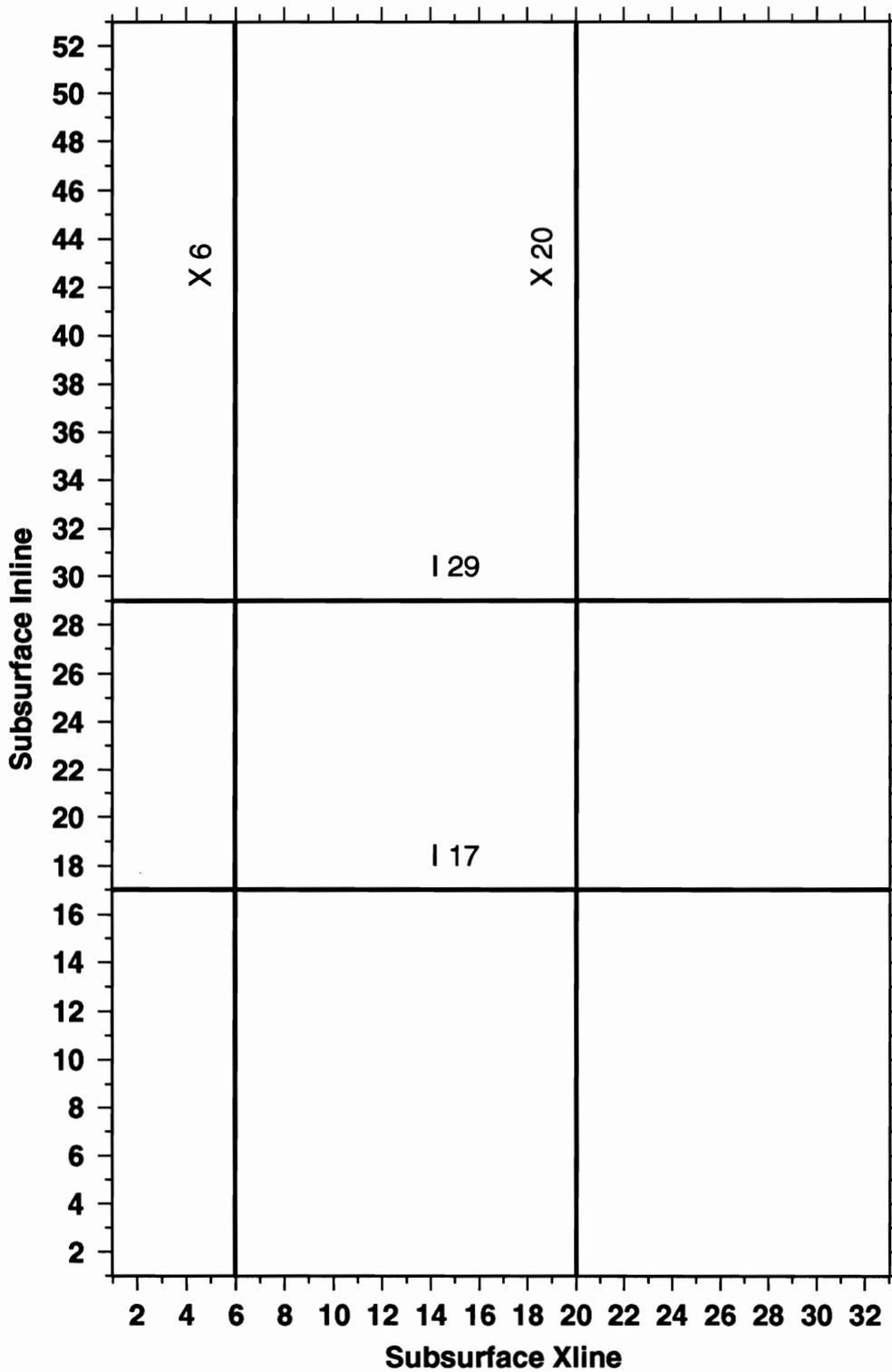


Figure 5.20 Key map for sections shown in Figures 5.21 and 5.22

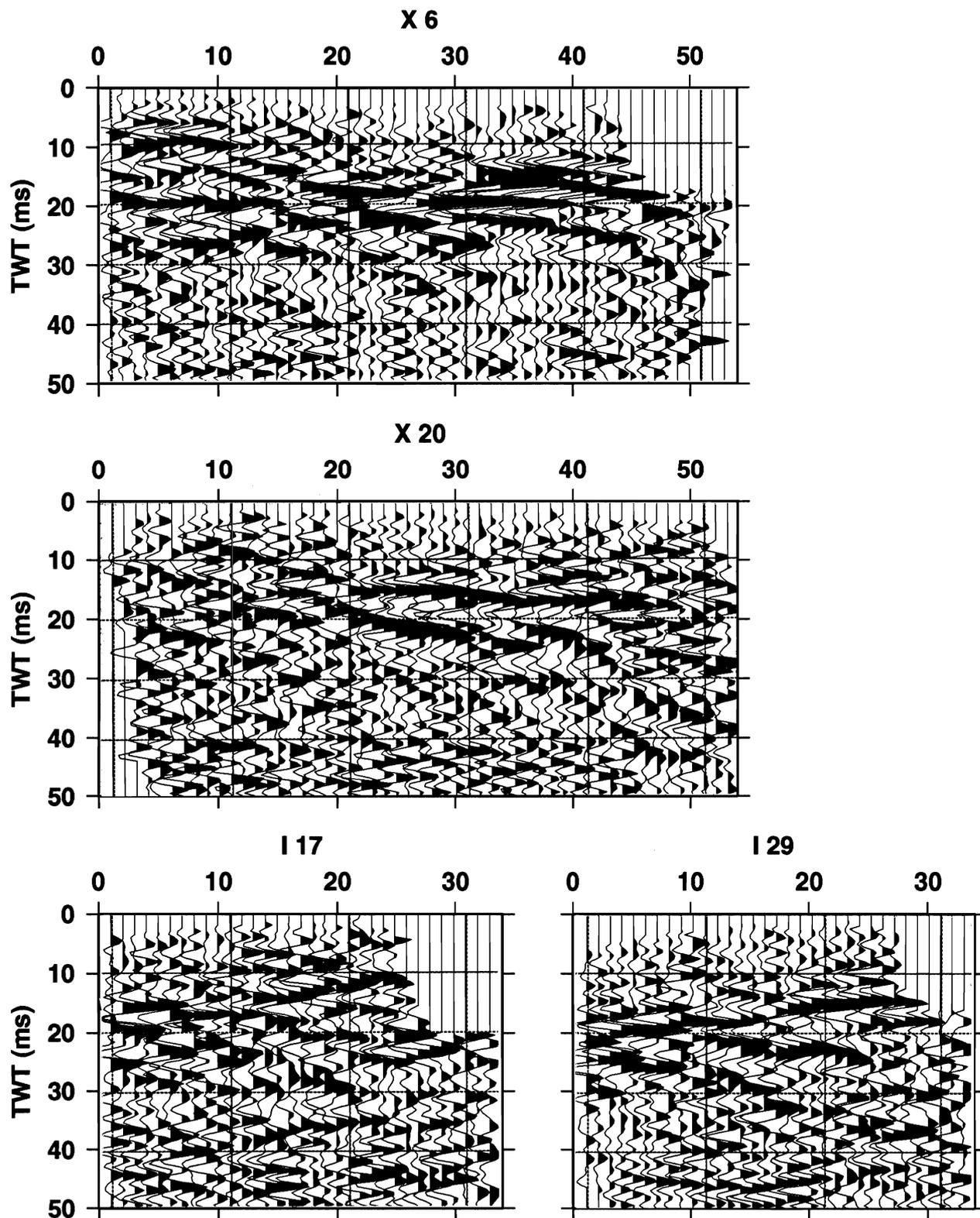


Figure 5.21 Four sections - strategy B

X6 and X20 are crosslines, I17 and I29 are inlines. Time-migrated data.

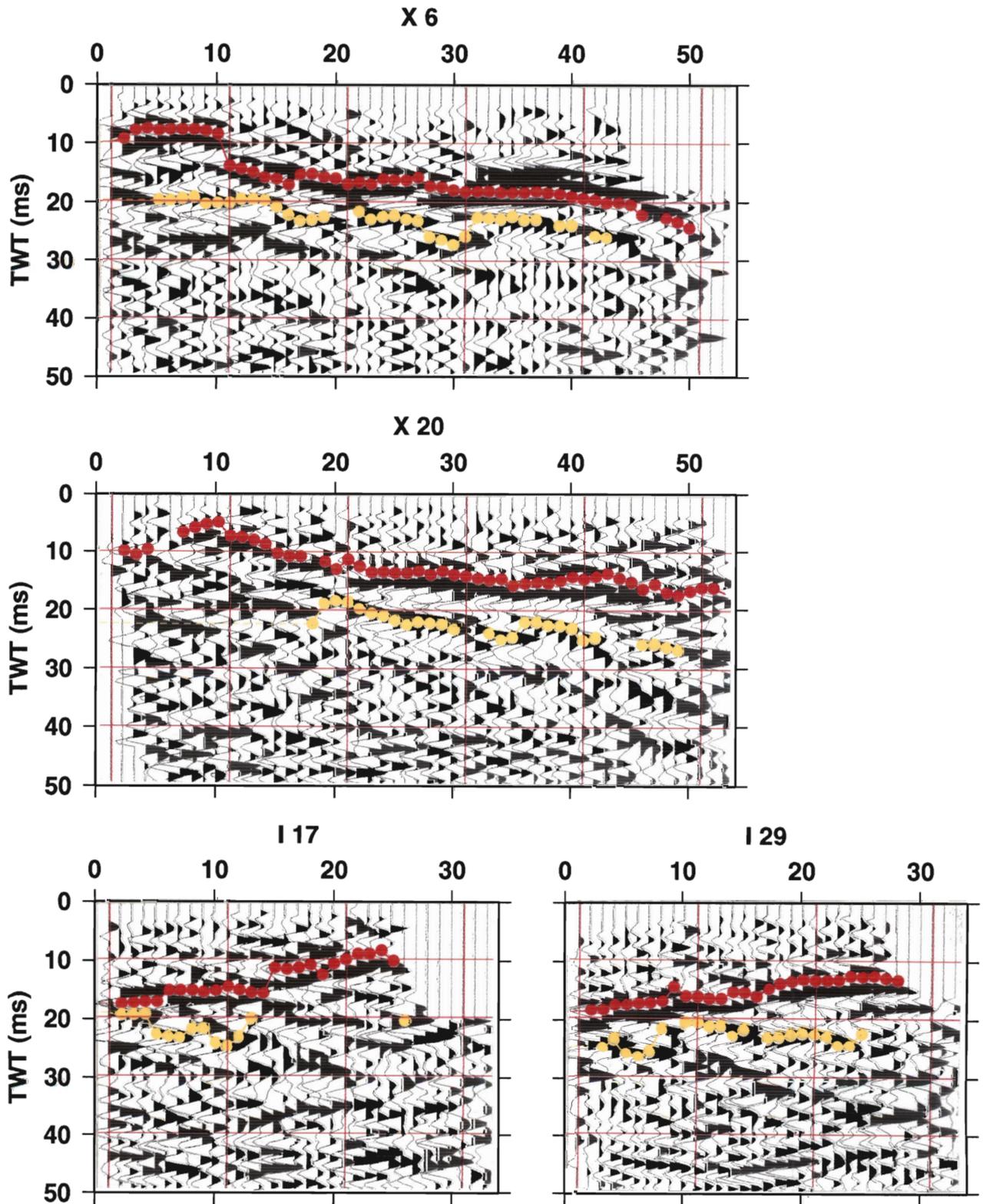


Figure 5.22 Four sections - strategy B, with interpretation
Sections as in Figure 5.21, with interpreted red and yellow horizons.

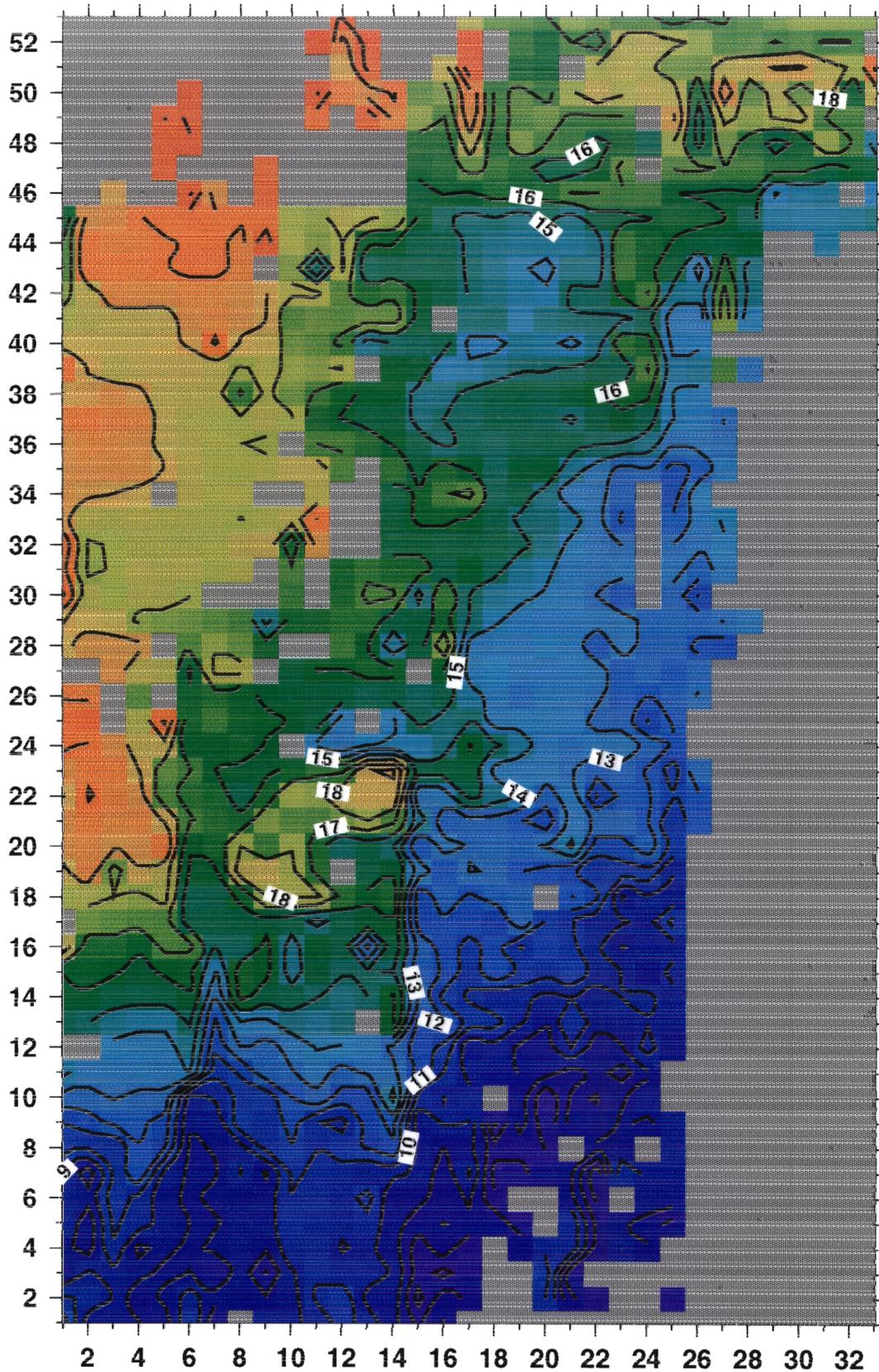


Figure 5.23 Contour map of red horizon, strategy B

Contour interval 1 ms TWT. Dark blue hue - 8 ms; dark orange - 20 ms; grey - no picks.

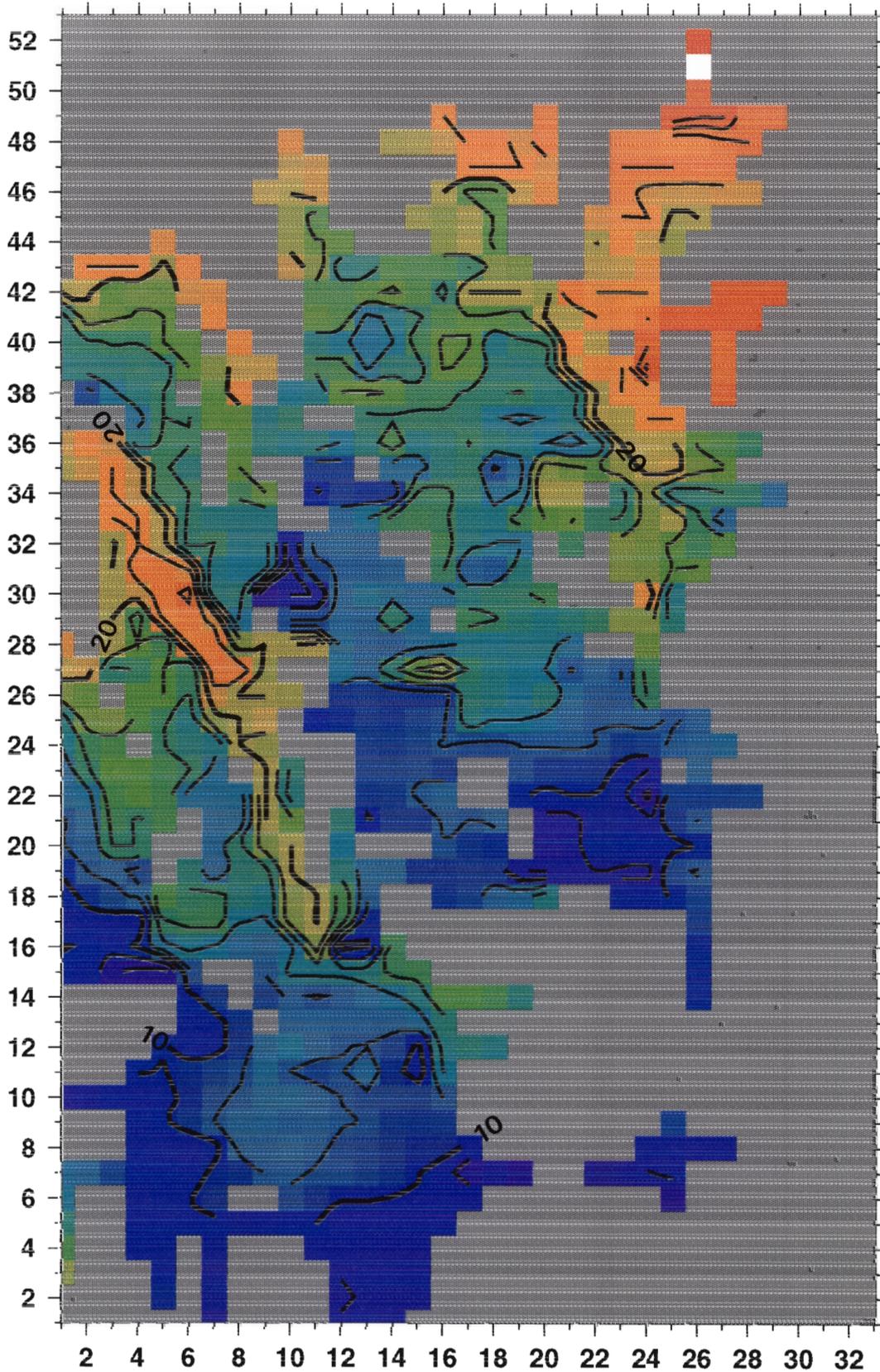


Figure 5.24 Contour map of yellow horizon, strategy B

Contour interval 1 ms TWT. Dark blue hue - 9 ms; dark orange - 22 ms; grey - no picks.

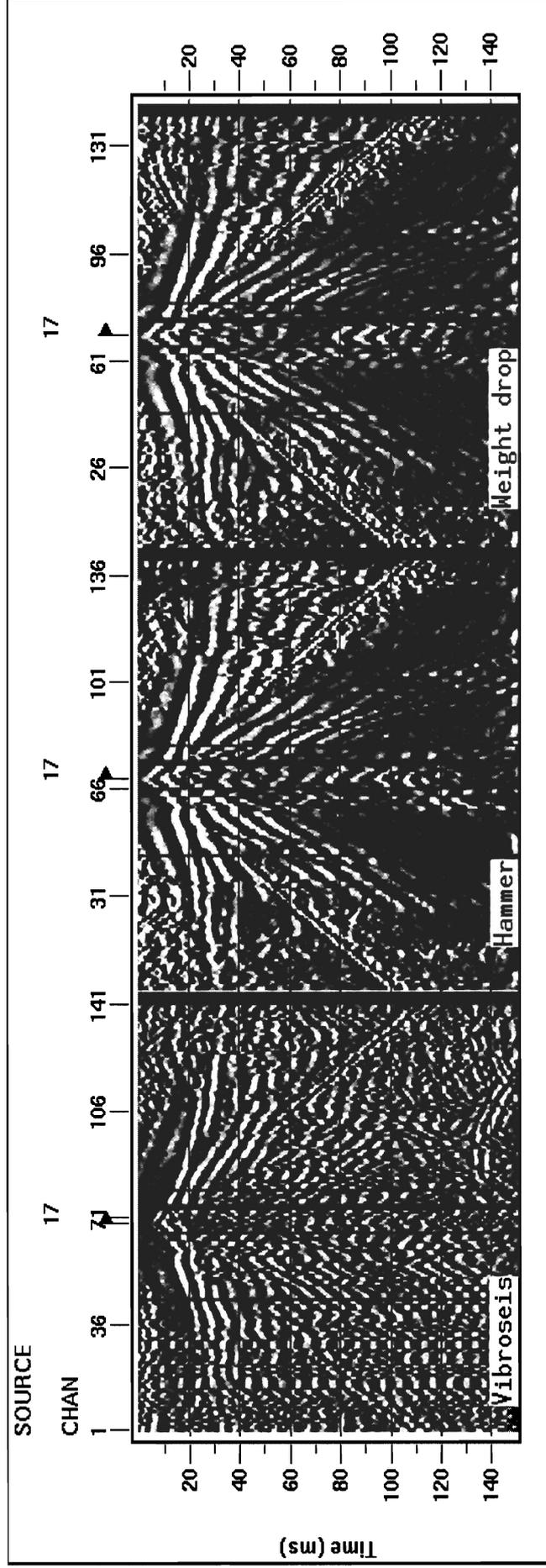


Figure 6.1 Shot gather comparison using three different sources

Note the higher frequency content of the vibroseis data compared to the two impulsive sources.

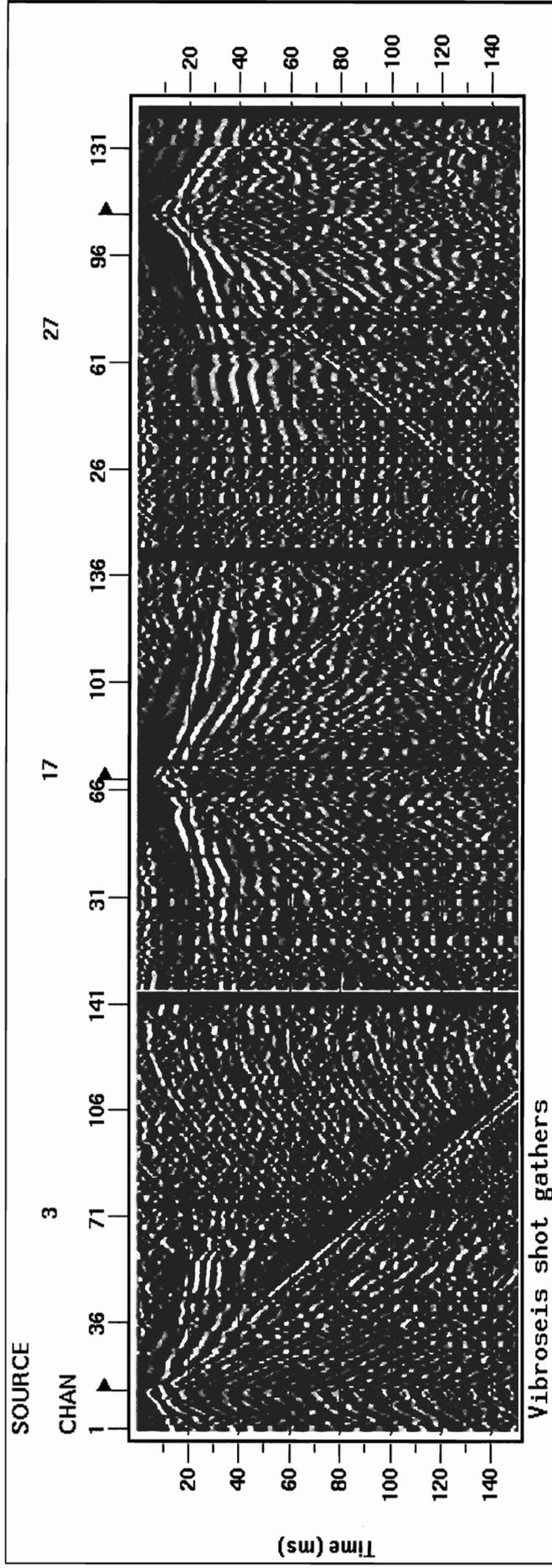


Figure 6.2 Vibroseis shot gathers showing noise contamination

The first breaks are only visible to about 20 m from the source. There are no discernible reflections from the subsurface.

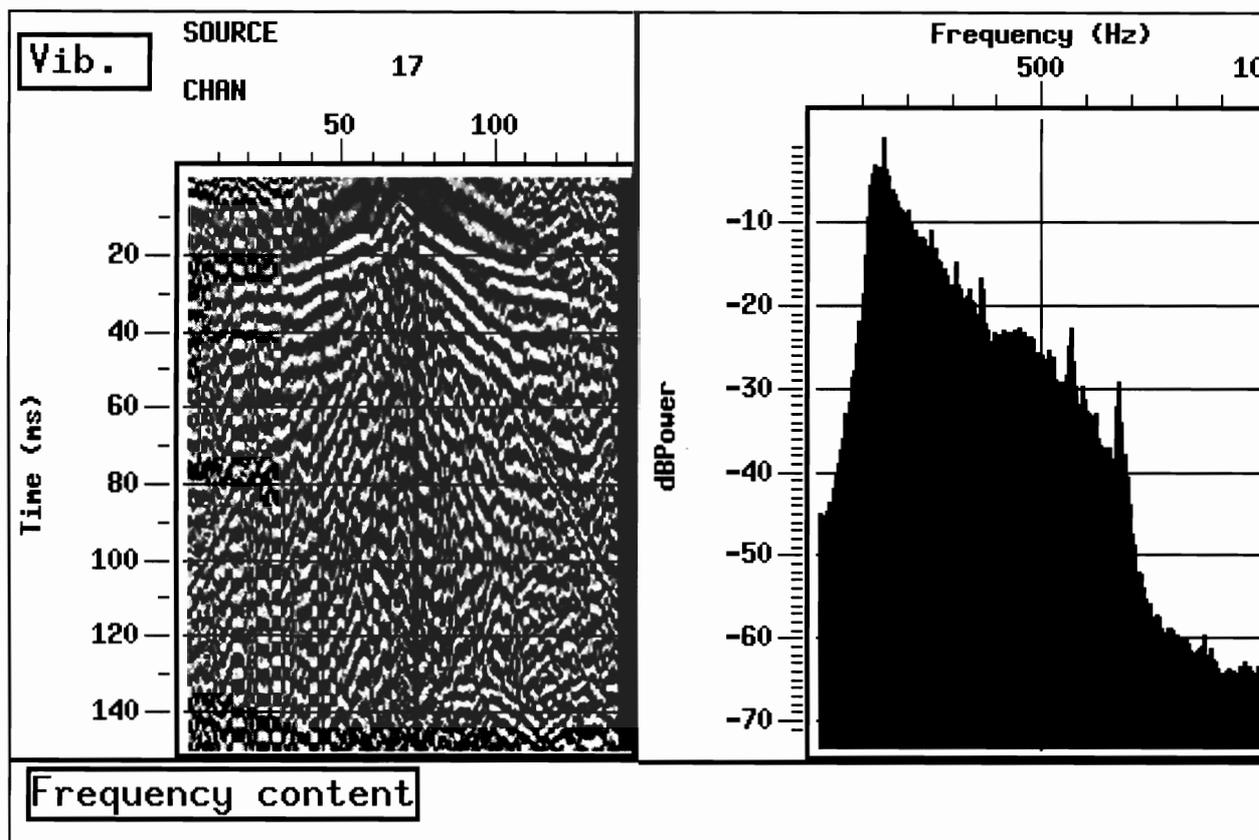


Figure 6.3 Shot gather and frequency amplitude spectrum - vibroseis

The frequency spectrum is band-limited to the 100-700 Hz range of the correlation.

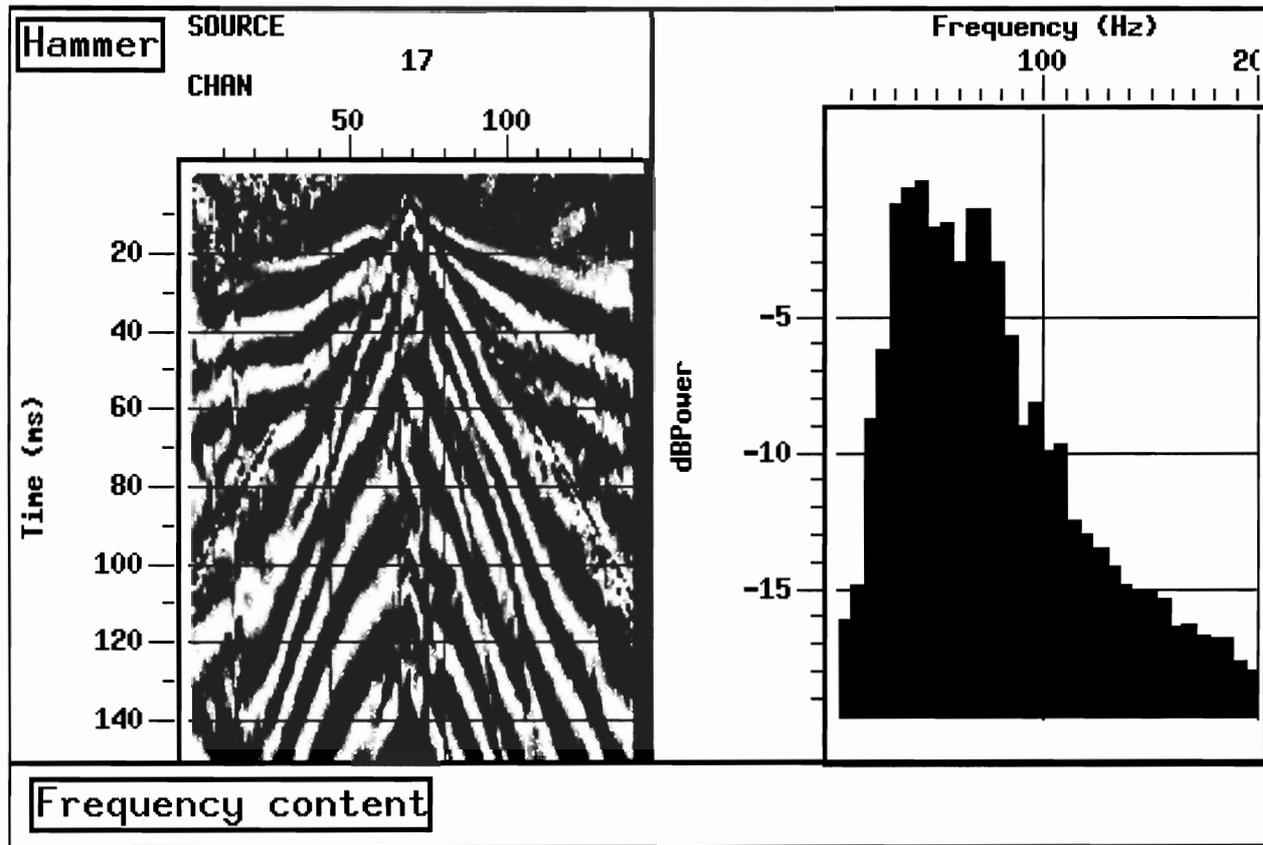


Figure 6.4 Shot gather and frequency amplitude spectrum - hammer

Dominant frequencies are in the range 30-80 Hz.

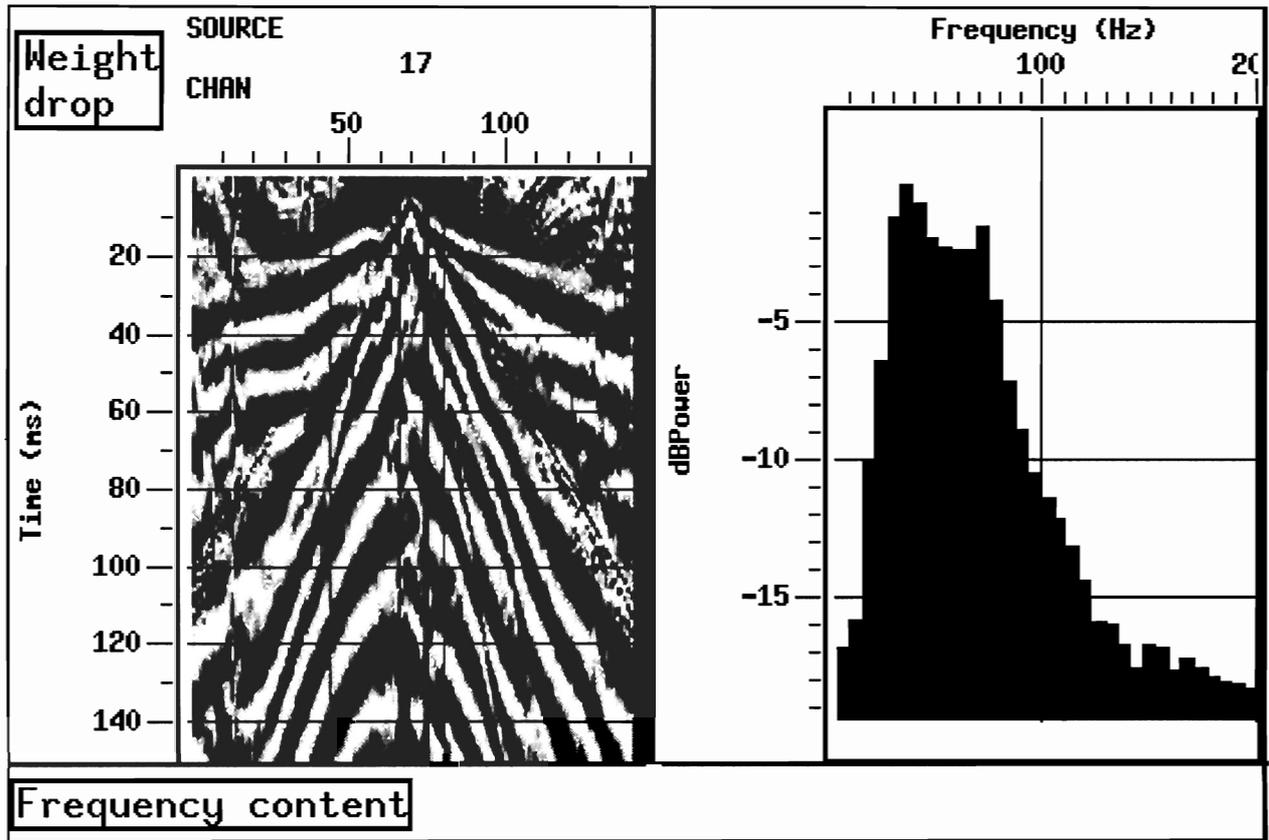


Figure 6.5 Shot gather and frequency amplitude spectrum - weight drop

The spectrum is very similar to the hammer source shown in Figure 6.4.

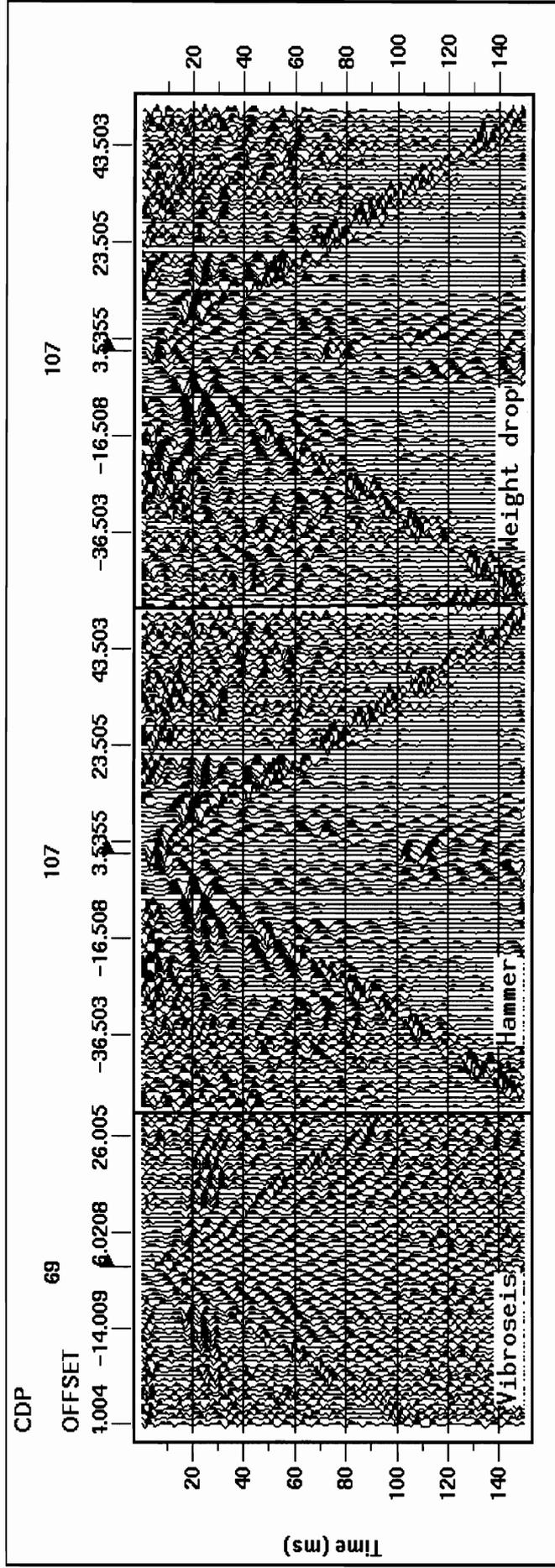


Figure 6.7 CMP gathers after summation of 4 adjacent CMPs
The spatial aliasing problem shown in Figure 6.6 has been cured.

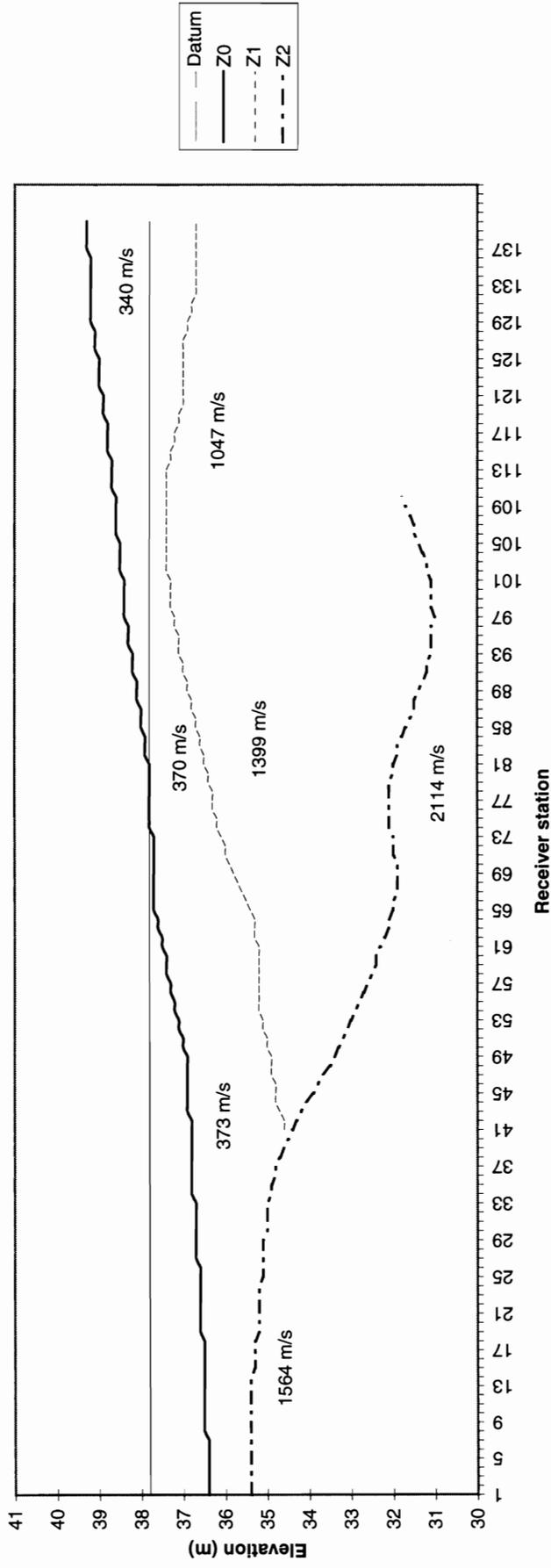


Figure 6.8 2-D refraction model from Vienna Technical University

The ground surface is the Z0 direct wave (heavy solid line). Datum is 37.8 m above OD. Representative velocities from the laterally varying velocity field are shown.

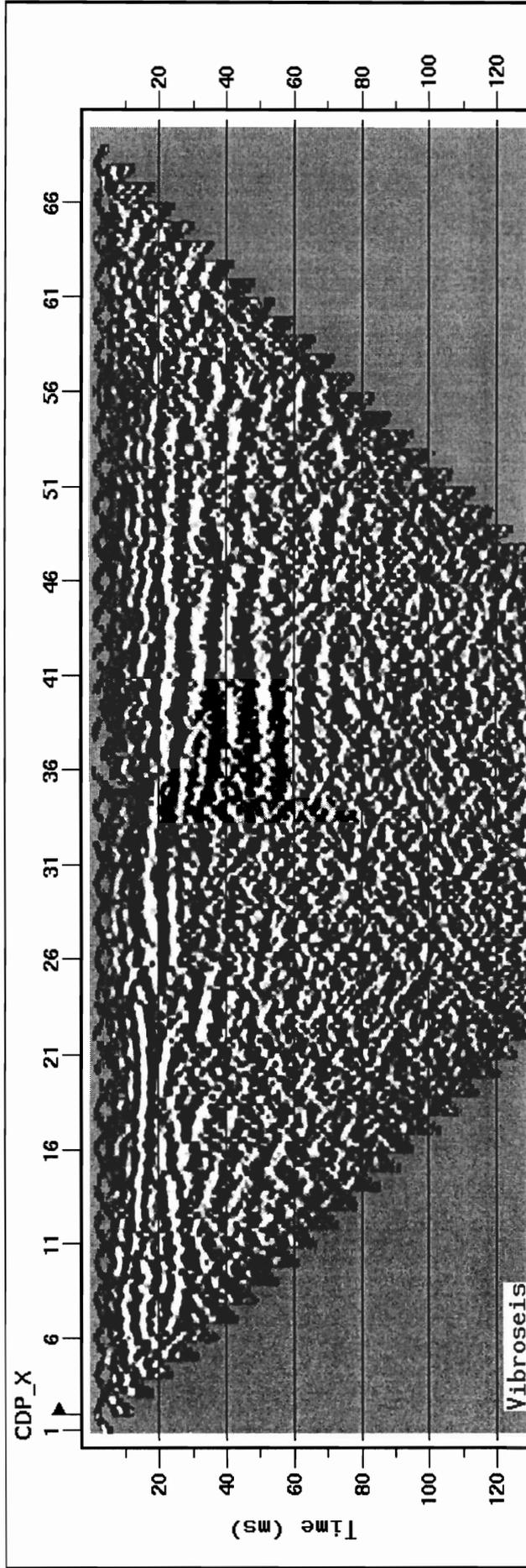


Figure 6.9 2-D line brute stack - vibroseis

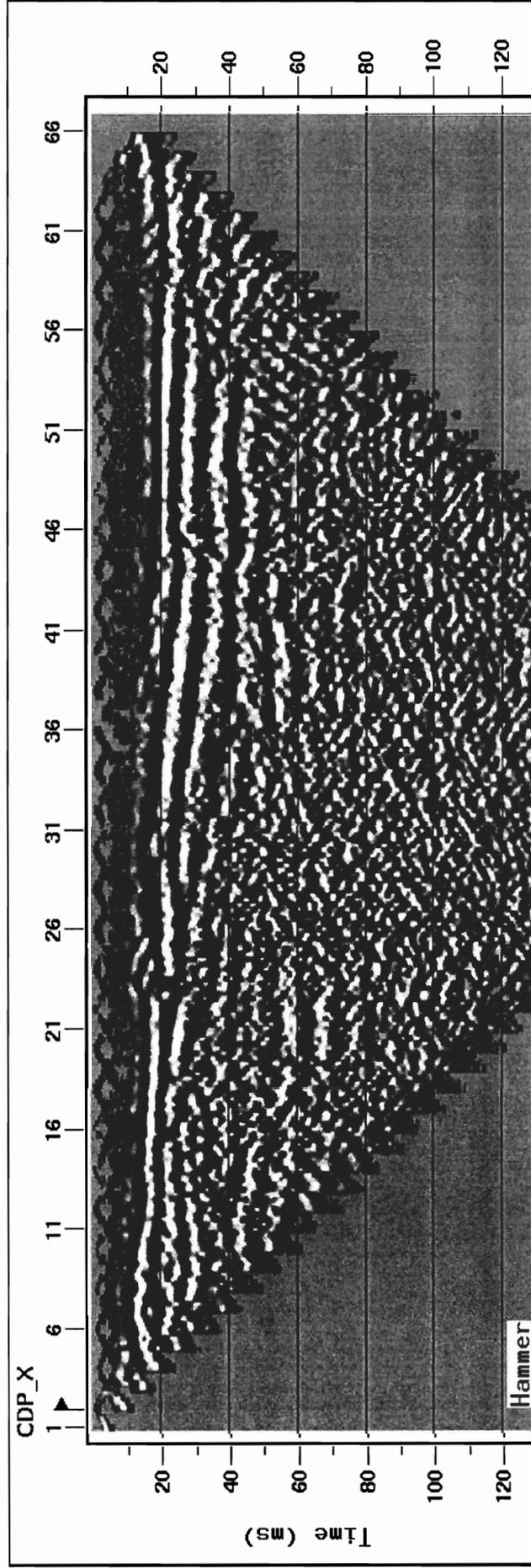


Figure 6.10 2-D line brute stack - hammer

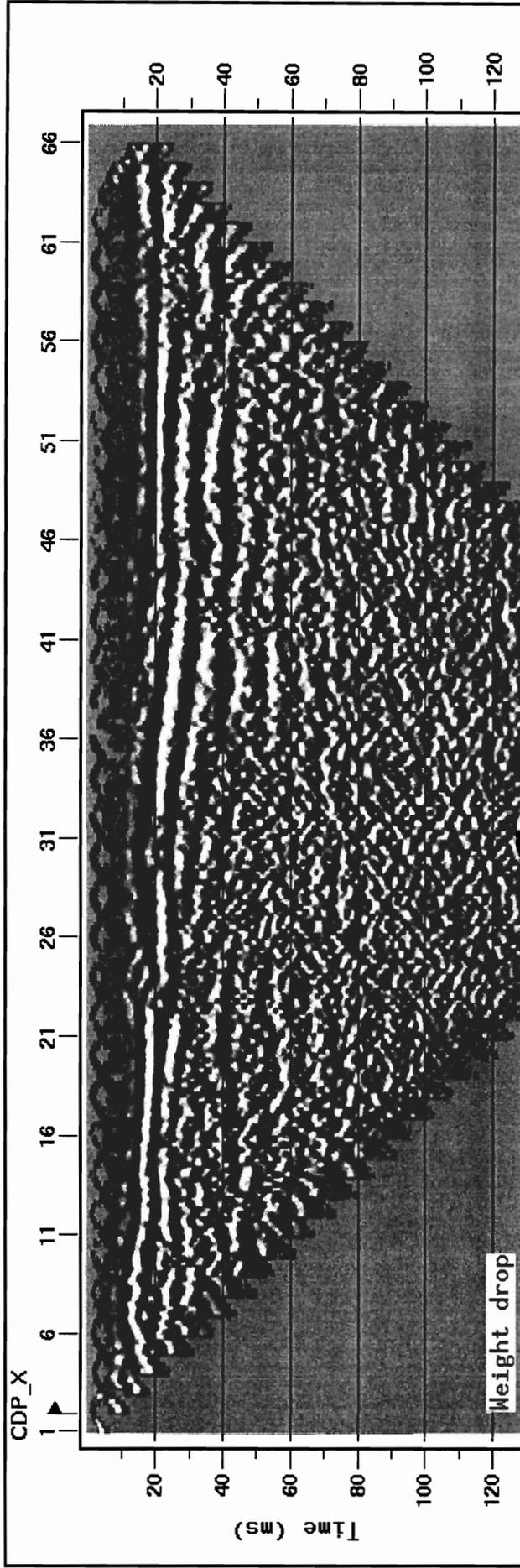


Figure 6.11 2-D line brute stack - weight drop



Photo 1 Deployment of minivibrator

Looking east; Maryhill Road behind. Two people lift the minivibrator, weighing 75 kg, while the person on the right holds the acoustic hood which covers it when it is in position. The person on the left is about to hammer in a yellow peg to record the exact position of the vibrator point just finished with, for later surveying in. Cables in the foreground are part of the receiver spread. The area has been stripped of topsoil.



Photo 2 Field recording truck

This 4WD vehicle has an air-conditioned laboratory and a built-in 4 KVA generator supplying 12 VDC and 240 VAC for the recording equipment. A separate portable generator, lying some distance away to minimise noise, is required for the minivibrator power supply. The minivibrator acoustic hood and coils of receiver spread cables lie in the foreground.



Photo 3 View of swath

Looking NW, Maryhill Road at left-hand side. A swath of 18 rows by 8 columns is ready for shooting on the topsoil-stripped area. There are many coils of receiver cable, which is built for 20 m geophone interval rather than the 2 m interval used here. White survey pegs mark even-numbered rows and columns, making up a 4 m grid of pegs. The yellow pegs mark the randomised shot locations.



Photo 4 Grouting in progress next to swath

Looking WNW, Maryhill Road in background. From Monday 22 July 1996 the seismic survey had to be completed alongside the drilling operations (see Table 4). Swath V'W'Y in the foreground has an irregular geometry (see Fig. 4.2) because it had to be shifted out of the path of the grouting rigs, one of which is seen at work. The tops of the black plastic casing of holes for drilled ready for grouting (on a 3 m grid) can be seen protruding from the boulder clay. White and yellow pegs are seismic survey markers. The step between the grassy field on the right and the topsoil-stripped area on the left shows up clearly on the topographic elevation contour map (Fig. 5.3).