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SELLAFIELD GEOLOGICAL INVESTIGATIONS FOR DEEP RADIOACTIVE WASTE REPOSITORY

NIREX REPORT NO. 760

3-D SEISMIC REFLECTION TRIAL SURVEY OF THE POTENTIAL REPOSITORY ZONE, SELLAFIELD, WEST CUMBRIA

VOL 1 OF 2: TEXT AND FIGURES

VIA VERITAS VITA

UNIVERSITY *of* GLASGOW

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SELLAFIELD GEOLOGICAL INVESTIGATIONS FOR

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FACTUAL REPORTING

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3-D SEISMIC REFLECTION TRIAL SURVEY OF THE POTENTIAL REPOSITORY ZONE, SELLAFIELD, WEST CUMBRIA

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VOLUME 2 OF 2: ENCLOSURES

1 INTRODUCTION

1.1 Scope of this report

This final report describes the results of the field experiment carried out during summer 1994 under a University of Glasgow research contract with UK Nirex Ltd (Contract no. SCRS/1231). It should be read in conjunction with the factual account of the fieldwork (*3-D seismic reflection trial: data acquisition report.* Nirex Report No. 622), which includes a description of the planning and actions taken until the finish of the fieldwork in September 1994.

The project is novel in several ways:

(1) It is the first 3-D vibroseis seismic survey undertaken in the UK,

(2) It is the first 3-D seismic survey of a potential radioactive waste repository, and

(3) It is one of the most intensive 3-D test data sets ever observed.

The report presents the 3-D seismic reflection data and highlights particular aspects of them so that some specific recommendations for a future survey can be made.

1.2 Aims and objectives of the survey

The aim of the survey was to determine whether a full 3-D seismic survey of the Potential Repository Zone (PRZ) using a vibroseis energy source is technically and logistically feasible, and could provide useful additional information.

The objectives of this trial stated in the contract agreement can be summarised as follows:

(1) To determine whether useful high resolution reflection energy up to 100 Hz or greater can be obtained using vibroseis.

(2) To find suitable field acquisition parameters for a full-scale 3-D survey.

(3) To find the optimum use of the 4-vibrator source array, taking into account parameters such as energy efficiency, logistics of use and operational timescale.

1.3 Summary recommendations

A full-scale 3-D vibroseis survey has been proven to be feasible and is recommended as a useful and cost-effective means of exploring the PRZ. The source need only be one large vibrator or two medium-sized units (as used in 1994). A cost-effective means of estimating the source signature should be employed. The sweep bandwidth should be 20-100 Hz. The density of subsurface coverage need only be about 2 traces per square metre, half that acquired in 1994. The acquisition geometry and recording should be designed to allow various methods of binning the data after the survey, rather than by fixing the CMP bin design beforehand. Three-component recording is not considered to be cost-effective.

2. SEISMIC DATA PROCESSING

2.1 Topographic survey data

2.1.1 Elevation

The primary purpose of the topographic survey was to set out 3055 pegs in a grid pattern of 65 columns and 47 rows to mark the surface stations. Columns were numbered from 0 to 64 and rows from 0 to 46. The pegs were set out at 25 m intervals, with a horizontal field accuracy of better than 0.1 m. Some pegs were offset due to the proximity of hedge centrelines, walls, buildings, culverts, pipelines, cables etc. Omissions were also necessary in areas that were densely wooded, had restricted access or were unsuitable for vibroseis. In total 2262 pegs were set out with their height surveyed.

Errors in vertical measurement (the reduced levels) have been checked by re-gridding and contouring the data using the GMT system. The 2262 (x,y,z) triplets at quasi-random positions (actually approximating to a regular 25 m grid) were re-gridded at a 25 m interval, and the resulting file fed to a contouring program. The output from this program with a 2 m contour interval is shown in Figure 1. It shows that there are no major errors (anomalous or inconsistent heights), although a few points might benefit from re-examination of the survey data. Comparing the heights with those on the OS and RCF maps shows that the 3-D survey heights are generally consistent.

2.1.2 Receiver group locations

The receiver group, comprising the geophone string, was generally laid out along a row, starting from a reference peg and ending at the next peg along the row belonging to the column one number higher than the reference. The barycentre, or weighted centre of the array would therefore normally be 12.5 m in the positive inline direction from the reference peg. In addition, some receiver groups were bunched or offset from peg positions, which themselves may have been offset from the initial ideal grid. The barycentre of every geophone string was calculated in the field and expressed as a position inline (I) and cross-line (C) in metres relative to the actual position of the reference peg. These data are in the Supporting Records Package. Note that these *surface* coordinates are not to be confused with the completely separate *subsurface* coordinate line numbering system used for the CMP locations. A positive I is in the direction of higher column numbers, and a positive C is in the direction of higher row numbers. The angle between the rows of the survey and National Grid eastings is 48º.75. The National Grid easting and northing of the string barycentre is calculated as:

$$E_s = E_p + I.\cos 48.75 + C.\sin 48.75$$
$$= E_p + 0.659\,I + 0.752\,C$$

$$N_s = N_p - I.\sin 48.75 + C.\cos 48.75$$
$$= N_p - 0.752\,I + 0.659\,C$$

where the suffix s refers to the string barycentre, and the suffix p refers to the peg position. The resulting data file containing the (E_s, N_s) coordinates for the receiver group barycentres is required in the seismic data processing.

Surface stations that were omitted from the topographic survey included 36 stations that were required for positioning geophones, but the relevant pegs had never been set out due to obstructions. The barycentres of the surveyed receiver surface stations are shown by the circles in Figure 2, and the 36 unsurveyed stations are shown by the black square symbol in the same figure. Twenty-two of these are within the area of BH5 pad. However, receiver spread cables had been run through these stations, and in some cases geophone strings had been planted as well, so survey data for these points were required for processing. The data were obtained by (a) estimating the horizontal location (easting and northing) of the barycentre of the geophone string from information supplied by the field crew, and (b) estimating the height either by reading off contours from the detailed RCF maps or by interpolating the height from surrounding surveyed pegs. The resulting data are shown in Table 1 below.

Table 1. Interpolated peg heights.

Peg	Col	Row	Easting	Northing	Height	Comments
2115	21	15	305068.1	503852.6	75.0	Contours
2116	21	16	305086.9	503869.1	80.0	BH5: near control point GU4
2117	21	17	305105.7	503885.5	80.0	BH5 pad
2118	21	18	305124.5	503902.0	80.0	BH5 pad
2119	21	19	305143.3	503918.5	81.5	Edge of BH5 pad
2216	22	16	305103.4	503850.3	80.0	BH5 pad
2217	22	17	305122.2	503866.7	80.0	BH5 pad
2218	22	18	305141.0	503883.2	80.0	BH5 pad
2219	22	19	305159.8	503899.7	81.5	Edge of BH5 pad
2316	23	16	305119.9	503831.5	80.0	BH5 pad
2317	23	17	305138.7	503847.9	80.0	BH5 pad
2318	23	18	305157.5	503864.4	80.0	BH5 pad
2319	23	19	305176.3	503880.9	81.7	Edge of BH5 pad
2416	24	16	305136.3	503812.7	80.0	BH5 pad
2417	24	17	305155.2	503829.1	80.0	BH5 pad
2418	24	18	305173.9	503845.6	80.0	BH5 pad
2419	24	19	305192.8	503862.1	81.9	Edge of BH5 pad
2516	25	16	305152.8	503793.9	80.0	BH5 pad
2517	25	17	305171.7	503810.3	80.0	BH5 pad
2518	25	18	305190.4	503826.8	80.0	BH5 pad
2519	25	19	305209.3	503843.3	82.0	Edge of BH5 pad
2520	25	20	305228.0	503859.8	83.6	Contours
4923	49	23	305680.0	503458.2	68.0	From neighbours
4932	49	32	305849.2	503606.5	79.0	From neighbours
3829	38	29	305611.5	503763.8	81.4	
3830	38	30	305630.3	503780.3	81.6	
3038	30	38	305648.8	504062.5	94.1	Interpolation
3132	31	32	305552.5	503944.8	93.5	RCF3 pad
3232	32	32	305568.9	503926.1	93.5	RCF3 pad
3332	33	32	305585.4	503907.3	93.5	RCF3 pad
3432	34	32	305601.9	503888.5	94.0	Edge of RCF3 pad
3930	39	30	305646.8	503761.5	81.2	In wood
4030	40	30	305663.3	503742.7	81.0	In wood
4130	41	30	305679.8	503723.9	81.4	In wood
3135	31	35	305608.9	503994.3	93.0	
5232	52	32	305898.6	503550.2	75.5	From neighbours

2.1.3 Source group locations

The source group locations required for the seismic data processing comprise the actual peg locations. Although the source array is normally offset from a peg in an analogous manner to the receiver groups, the inline and crossline offsets can be entered independently into a database within the processing package, in contrast to the offsets of the receiver groups. However, instead of entering peg locations into the database, then applying the offsets, the offset source location itself has been put into the database. A single uniform (default) offset of 12.5 m in the direction of increasing column number has been used, calculated by the same formulae as shown in section 2.1.2 above. This direction is shown in Figure 4. In practice this gives the actual location of the centre of the source array in more than 95% of the source positions used. These live source locations are shown in Figure 3 by crosses. The rectangle bounding the outer perimeter of pegs is also shown in this figure, in which it can be seen that the columns of crosses are displaced to the south-east by 12.5 m.

The non-default offsets of source array positions, which affect less than 5% of the live shots, have not been entered into the database. These locations deviate by less than 10 m from the assumed positions shown in Figure 3, so that the resulting mis-location of the common mid-points (CMPs) will be 5 m or less. This small error will not affect the binning of the CMPs into 12.5 m square bins described below.

2.2 Pre-processing

2.2.1 Post-plot positioning data

The position data discussed in section 2.1 above were converted to (UKOOA) SEG-P1/90 format. The main problem encountered was that the field pegs, denoted by their row and column number, can be common to either a receiver group or a source, whereas the SEG-P1/90 format requires explicit line names for shots and for receivers. The format comprises three separate types of ASCII file, discussed in turn below. The header record common to all the files is shown in Table 2.

Table 2. Header record for the SEG-P1/90 data files.

H0100	SURVEY AREA	LONGLANDS DRILL SITE, WEST CUMBRIA, UK
H0200	SURVEY DATE	AUG-SEP 1994
H0201	TAPE DATE (D.M.Y)	10 NOV 1994
H0202	TAPE VERSION	UKOOA SEG P1/90; TAPE VERSION 1
H0300	CLIENT	UK NIREX LTD
H0400	GEOPHYSICAL CONTRACTOR	IMCL
H0500	POSITIONING CONTRACTOR	UNIVERSITY OF GLASGOW
H0600	POSITIONING PROCESSING	UNIVERSITY OF GLASGOW
H0700	POSITIONING SYSTEM	TRAVERSE FROM BNFL CONTROL
H0800	SHOTPOINT POSITION	SHOTPOINT
H1100	RECEIVER GROUPS PER SHOT	240
H1400	GEODETIC DATUM AS SURVEYED	
H1500	GEODETIC DATUM AS PLOTTED	ORDNANCE SURVEY
H1600	DATUM SHIFTS	NOT APPLICABLE
H1700	VERTICAL DATUM	O.D.
H1800	PROJECTION	UK NATIONAL GRID
H1900	ZONE	NOT APPLICABLE
H2000	GRID UNITS	1 INTERNATIONAL METRES
H2001	HEIGHT UNITS	2 HUNDREDTHS OF METRES 100.0
H2002	ANGULAR UNITS	
H2301	PROJECTION ORIGIN	
H2302	GRID COORDINATES AT ORIGIN	
H2401	SCALE FACTOR AT ORIGIN	
H2500		
H2600		

The first file required by the standard comprises data records with the positions of receiver groups. Each receiver swath A, B and C is subdivided into three live sub-swaths 1, 2 and 3, respectively. These are denoted, A1, A2, A3, ... C2 and C3. There are nine in total. The extent of each sub-swath in terms of the row and column numbers is shown in Table 3. Two of these swaths, A1 and B2, are shown in outline form in Figure 4, whereas swath C3 is depicted in more detail.

The receiver group line names are defined to be the row number, from rows 9 to 38 inclusive. The individual receiver group position within each line is given by the column number, varying from 20 to 52 inclusive. Figure 4 shows an example line, where receiver line 12 within swath C3 is denoted by the 24 circles corresponding to each group. In this example the column numbers run from 20 to 43. The other 9 receiver lines within swath C3 are shown by continuous parallel lines in Figure 4.

Table 3. Receiver group sub-swaths.

Sub-swath name	Top row	Bottom row	Left col	Right col
A1	38	29	29	52
A2	38	29	24	47
A3	38	29	20	43
B1	28	19	29	52
B2	28	19	24	47
B3	28	19	20	43
C1	18	09	29	52
C2	18	09	24	47
C3	18	09	20	43

A Fortran-77 program seggrp.f converted the receiver group survey data into the correct format. It incorporates the BGS Fortran-77 subroutine NGCV, which converts National Grid coordinates to the geographical system.

The second file required by the standard comprises data records with the positions of shots. The shot records have to associate the live spread with the shots into that spread. This necessitated defining each live spread, or sub-swath, as the shot line. Each of the swaths A, B and C were split into the three component sub-swaths 1, 2 and 3. The nine sub-swaths were each denoted by line names 94-3D-A1, -A2. . . . -C3. It should be noted that the shot ‘line’ in each of these cases comprises a set of shots within a finite area, rather than along a line *sensu stricto*. Table 4 summarises the shot positions for each of these ‘lines’ in terms of the row and column numbers. A Fortran-77 program segsht.f, similar in form and function to seggrp.f, converted the shot position survey data into the correct format.

Figure 5 illustrates the relationship between the shots into swath C3. All the shots within the stippled area (defined by the bottom row in Table 4) comprise the shot line 94-3D-C3. There are 9 such overlapping areas in total.

The third file required comprises relation records specifying for each shot the relation between recording channel numbers and receiver groups. For each sub-swath (i.e. shot line) there is a record for each receiver line (i.e. row). Since there are ten receiver rows live for each shot, every shot-point is represented by ten records. For example, shot 1008, denoted by the star within the stippled area of Figure 5, requires a record for receiver line 12 (the row of receivers in the figure depicted by the 24 small circles). Table 5 illustrates the ten records for swath C3, shot-point 1008, with the record for receiver line 12 highlighted. Note that each record in this file accounts for 24 receiver channels.

Table 4. Shot 'lines'.

Line name	Top row	Bottom row	Left col	Right col
94-3D-A1	46	21	38	64
94-3D-A2	46	21	34	37
94-3D-A3	46	21	08	33
94-3D-B1	36	11	38	64
94-3D-B2	36	11	34	37
94-3D-B3	36	11	08	33
94-3D-C1	26	00	38	64
94-3D-C2	26	00	34	37
94-3D-C3	26	00	08	33

A Fortran-77 program segrel.f wrote the appropriate set of records from input data in the form of Table 5. The layout shown in Table 5 unambiguously relates shots and receivers to recording channels, which increase in number from bottom left to top right along rows. For example, the highlighted receiver line 12 specifies that these receivers were recorded on channels 73 to 96. The code X specifies that these are relations records.

Table 5. Relations records for shot-point (VP) 1008, swath C3.

Record code	Shot line name	Shot-point	From channel	To channel	Receiver line name	From column	To column
X	94-3D-C3	1008	1	24	09	20	43
X	94-3D-C3	1008	25	48	10	20	43
X	94-3D-C3	1008	49	72	11	20	43
X	94-3D-C3	1008	73	96	12	20	43
X	94-3D-C3	1008	97	120	13	20	43
X	94-3D-C3	1008	121	144	14	20	43
X	94-3D-C3	1008	145	168	15	20	43
X	94-3D-C3	1008	169	192	16	20	43
X	94-3D-C3	1008	193	216	17	20	43
X	94-3D-C3	1008	217	240	18	20	43

'Shot-point' in Table 5 is synonymous with vibration point, or VP. There were normally five sweeps at each VP, therefore each of these sweeps will have a relations record in common. Shot-points in the location database which had never been observed were deleted, to leave only the live shot-points shown in Figure 3.

2.2.2 Demultiplexing

The nine-track SEG-B tapes were demultiplexed by IMCL, using the *Sercel-348* option within the *SEG-B Input* processor of ProMAX V.5.0. The internal disk storage format was the ProMAX compressed format, comprising 16-bit integers with a gain sample every 100 data samples. This saves about 50% of storage space as compared to the standard 32-bit floating point format and with apparently no loss of dynamic range.

IFP and Pre-amp gain were applied in this process. However, IMCL has discovered since completion of the processing that there is a bug in this processor. Subsequent study by GU of the problem suggests that there is a constant gain applied to groups of five consecutive data channels, that may be many orders of magnitude - 10^9 to 10^{13} -

greater than the correct value. The processor may have been wrongly applying a gain which was appropriate to the five auxiliary channels. However, the gain disparity is not restricted to this group of five traces. A varying proportion (2-10%) of the traces within each shot file seem to have a larger gain than expected, although not as extreme as the group of five.

This gain problem was not noticed during the processing because the various trace display methods routinely scale the entire trace to an amplitude useful for viewing. ProMAX's proprietors, Landmark Graphics Corporation, state that the way to bypass this bug is to demultiplex the data with the *IFP only* option, thereby ignoring the fixed pre-amp gain which was in fact used on recording.

Examination of the demultiplexing gain problem suggests that after demultiplexing to SEG-Y format, the groups of five traces with abnormally large gain occur at regular intervals of 245 traces within a demultiplexed tape reel. Thus the abnormal traces are conscutively numbered 1-5, 246-250, 491-495 and so on, within each reel. Summation of five sweeps at a single VP is therefore likely to result in 25 traces out of 240 within the summed shot gather having abnormally large gain. This would feed through to the trace binning stage such that about 10% of the traces in any one bin would have the very large gain, and would therefore completely dominate the stack. In effect, the stack would comprise only 10% of the number of traces nominally within the ensemble, and the resulting deleterious effect would be very obvious. However, this effect has not occurred because trace equalisation was carried out before stack (section 2.5.7 below).

It is concluded, therefore, that the faulty demultiplexing gain problem described above may have degraded the dataset somewhat, but not in a significant way.

2.2.3 Shot record editing, sorting and summing

Field quality control checks on the data have been described in the factual account of the fieldwork (*3-D seismic reflection trial: data acquisition report.* Nirex Report No. 622), section 5.4.6. Before the discovery of the faulty correlation problem, which affected one record in every 50 or 100, there may have been some records in which this problem may have occurred and which were not deleted and re-shot. No attempt has been made to identify any such faulty shot files in the processing stage. The problem might affect up to about a dozen shot files recorded within the first few days of the survey. However, the apparent first break multiple produced by this intermittent problem only affects the raw data below 1.2 s, and there is no evidence that it has affected the final stacked data.

Field file numbers in the Sercel SN348 recording system are restricted to three decimal digits. There can therefore be 1000 unique numbers (000-999). In practice, production field files are numbered to start at 101, with the smaller numbers usually reserved for test and calibration files. Field file numbers therefore have to be renumbered in the processing centre to avoid duplication within the dataset. This was done by adding multiples of 900 to each successive set.

The sorting and editing process inserted the correct VP into each file. A unique record number for each ensemble of sweeps at a single VP was used as a key to sum the sweeps. Summing was carried out with the *Ensemble Stack/Combine* processor, which divides the sum of the traces by the number in the ensemble. It therefore calculates a mean trace.

The summed shot files are not always the sum of the five sweeps envisaged in the design of the survey. In practice the number of sweeps contributing to the sum was usually less than or equal to five. Obstructions frequently prevented the proper move-up of the source array. If the unsummed shot files for a common VP spanned a tape change the summation was carried out within separate processing jobs, to create two separate summed files for the same VP. However, in a few instances the summed shot file is the sum of more than five records. This was because most of the duplicate files recorded on tape, marked as “ignore” in the field log by the field observer, were found by inspection to comprise valid data, and were therefore included in the summation.

Erroneous VP numbers in the file headers were corrected at this stage. The identity of the sub-swath was checked for accuracy. The output of this stage of processing was a set of SEG-Y summed shot files with a unique field file number, taken as the first such number occurring within each ensemble of unsummed files.

There are 2188 shot files in the dataset prepared by IMCL for the processing described below. Subsequent re-examination and re-summing of the unsummed data by GU (not presented herein) shows that there should only be 2138 such files. The excess of 50 files is accounted for by the duplicates occurring at a tape change noted above, and by a very few files having a wrongly numbered VP. At the end of acquisition there were 2148 VPs recorded. This figure includes 10 VPs which were re-shot for one reason or another - for example, if it was suspected that a shot had been omitted it would shot again. In summary, the number of shots is as follows:

2138	Correct number of VPs to be observed.
10	Re-shot VPs.
40	Extra files due to recording across tape change or mis-numbering.
2188	Total number of summed shot files used in present processing.

After this phase of pre-processing had been completed the unsummed, demultiplexed files were archived, then deleted from the IMCL on-line computer storage. As a result it has not been possible directly to compare the results of processing with a single sweep at each VP as compared to the summed sweep dataset.

2.3 Near-surface (static) corrections

2.3.1 Velocity database

A report by J Arthur & Associates to Nirex, entitled '*Sellafield velocity database procedural report'* had been supplied to the University in early 1994, together with a floppy disk containing digital files of the tabulated data quoted in the report.

A 1:5000 scale map of average velocity (ref. JAA/167/001#1) showing the locations of the velocity data has also been supplied. Further study of these shallow velocities has been carried out by GU since the completion of the 3-D trial fieldwork. This additional study concentrated on the LVL surveys, since only these (in the form of the data available) can supply extra information on the shallow layer (above OD) velocity structure. The uphole data (JAA velocity database, table 3) only provide an average velocity between OD and the surface for each of 15 boreholes.

2.3.2 Low velocity layer (LVL) surveys

The LVL surveys were carried out as part of the 1992 dynamite 2-D reflection survey. The LVL spreads are of the order of 200 m in length, some reversed, some not. The shot-point map of Enclosure 1 shows the locations of both the 1992 dynamite survey and the LVL surveys.

Table 6 shows the mean LVL data derived from the JAA velocity database report, table 4. The columns in Table 6 have the same meaning as in the JAA report, in which V is velocity in km/s or m/ms, T is one-way travel time in ms, and the subscripts refer to layers, with 0 being the surface layer. The columns Z_i give the thickness of the i'th layer (m), and Elev is elevation above OD in m. The table rows are ordered in general from north to south. LVL12 has been omitted, as it is far to the SW of the 3-D trial area. Anomalous values are highlighted.

Table 6. Mean LVL data.

	V_0	T_1	V_1	T_2	V_2	T_3	V_3	Z_0	Z'_0	Z_1	Z_2	Elev
	m/ms	ms	m/ms	ms	m/ms	ms	m/ms	m	m	m	m	m
LVL6	0.31	10	0.91	20	1.94	27	2.74	1.5	1.6	6.6	12.1	97
LVL7	0.13	13	0.81	20	2.06	32	2.83	0.9	2.1	4.4	17.7	96
LVL5	0.35	7	0.66	16	2.15	33	2.93	1.5	1.2	3.8	23.4	102
LVL10	0.22	13	**1.70**	17	2.19	24	2.91	1.5	2.0	6.1	13.8	91
LVL2	0.47	4	1.00	13	2.36	24	3.07	0.9	0.6	6.2	21.5	95
LVL1	0.35	6	1.09	18	2.31	32	3.11	1.1	0.9	7.1	25.6	101
LVL15	0.40	9	1.07	17	2.26	25	2.90	2.1	1.4	6.0	12.8	97
LVL14	0.28	10	0.85	20	**2.61**	39	**3.77**	1.4	1.6	5.6	33.7	80
LVL8	0.26	12	0.81	22	1.43	45	2.48	1.6	1.9	5.8	20.6	77
LVL9	0.17	17	0.95	29	1.61	49	2.28	1.4	2.7	7.2	24.8	84
LVL3	0.40	6	0.59	19	1.67	37	2.39	1.5	1.0	5.3	19.1	74
LVL4	0.30	8	0.88	18	1.66	27	2.48	1.2	1.3	6.3	11.5	69
LVL13	0.30	8	0.50	17	1.09	35	2.22	1.5	1.5	3.5	10.8	38

The surface layer below each spread is only 1-3 m thick, but the very wide range of estimated velocities (varying by a factor of nearly four) suggests that it cannot be considered as representing a single homogeneous layer underlying the whole area. In addition, some of the velocity values suggest that what may have been observed on the T-X graphs at short ranges is a coupled surface wave being excited by the air blast (V = 0.33 m/ms), and not a direct or refracted P-wave. Figure 6 shows the strong negative correlation between the values of V_0 and the intercept time T_1 for the refractor at the base of layer 0. This graph implies that the thicker the layer, the lower is the velocity, again suggesting that the data do not represent a single simple layer. The values in column Z'_0 are the thickness of the surface (zero'th) layer, assuming a velocity of V_0 for the surface layer of a constant 0.3 km/s, rather than the values shown in the second column. However, the resulting difference in thickness is negligible. For the purpose of static corrections to reflection surveys it can be concluded that there is an uppermost layer or layers comprising topsoil and probably dry clay, of the order of 1-3 m in thickness, and with a mean velocity of around 0.3 km/s.

Three velocities are highlighted in Table 6. The value of V_1 = 1.7 km/s in LVL10 is much higher than the other values for V_1, which are generally around 1.0 km/s or less.

LVL10 is an unreversed profile. LVL14 is anomalous in that both the velocities of V_2 and V_3 are high. The value for V_2 = 2.6 km/s would be more appropriate for solid rather than weathered bedrock (viz. layer 3), and the value V_3 = 3.8 km/s presumably originates in a faster layer within solid bedrock.

In general, the LVL surveys show the following very approximate structure:

Layer No.	*Possible lithology*	*V (m/s)*	*Z (m)*
0	Clay	300	1-3
1	Boulder clay	700-1100	4-7
2	Weathered bedrock	1500-2400	11-25
3	Solid bedrock	2500-3100	

However, it has not been possible to construct a realistic 3-dimensional near-surface geological model from these data, as neither the velocities nor the thicknesses of any of the layers shown above vary in a systematic way.

2.3.3 Static corrections from LVL results

Since it has not been possible to construct a model of each layer separately from the LVL data (section 2.3.2), the only recourse is to use averaged results. Table 7 shows the static corrections S_i for each layer i, with the results using the anomalous velocities in Table 6 also highlighted. S'_0 is the static correction assuming a constant V_0 = 0.3 km/s rather than the variable values calculated. In practice this makes little or no difference to the static correction, since there is 1 ms or less variation between S_0 and S'_0. The average velocity V(a) is the total static correction ($S'_0 + S_1 + S_2 + S_3$) divided into the elevation above OD. This assumes that the velocities computed for the top of layer 3 (bedrock; column V_3 in Table 6) are appropriate for the interval from the elevation of the bedrock refractor down to OD.

Table 7. Static corrections from LVL survey data.

	Elev OD	Bedrock elev	S_0	S'_0	S_1	S_2	S_3	Static	V(a)	Comments
	m	m	ms	ms	ms	ms	ms	ms	km/s	
LVL6	97	77	5	5	6	3	31	45	2.18	
LVL7	96	72	7	7	4	6	28	45	2.13	Unreversed
LVL5	102	74	4	4	4	9	27	44	2.33	
LVL10	91	69	7	**7**	3	3	27	40	2.31	Unreversed
LVL2	95	67	2	2	5	6	24	37	2.51	
LVL1	101	67	3	3	6	8	24	41	2.41	
LVL15	97	77	5	5	4	3	29	41	2.36	
LVL14	80	39	5	5	5	**11**	**12**	33	2.42	
LVL8	77	49	6	6	5	10	23	44	1.68	
LVL9	84	49	8	9	6	11	26	52	1.60	
LVL3	74	49	4	3	6	8	23	40	1.78	
LVL4	69	50	4	4	6	3	23	36	1.90	Unreversed
LVL13	38	22	5	5	4	7	12	28	1.36	100 m SW of area

An attempt has been made to compute shot and receiver static corrections from the LVL data. Firstly, a hand-drawn contour map was made from the 13 average velocity data points in Table 7. This contour map was then represented by 82 spot values which were then fed to the gridding, contouring and plotting routines within the GMT system. This results in the map shown in Figure 7. Secondly, the elevations of the same 82 spot values within the survey area, which had been selected to represent the topography of the area to better than 5 m, were also fed to the GMT gridding and contouring programs, to yield the elevation contour map shown in Figure 8, which can be overlain on the 1:10,000 OS map for comparison. The purpose of these two steps was to supply a gridded set of average velocities accompanied by elevations. The grid used was the surface stations at the 25 m interval, as shown in Figures 7 and 8.

A static correction map (= elevation/V(a)) can then be derived (Fig. 9). This map could have been interpolated at all the shot and receiver positions to supply elevation statics for the processing. However, the map suffers from the limitation discussed above of assuming weathered bedrock down to datum. The same result would be achievable by interpolating the LVL average velocity map (Fig. 7) and defining the data as elevation static velocities in the ProMAX database, which already contains the elevations.

Comparison of the LVL average velocity map (Fig. 7) with the uphole data shows that the LVL velocity contours are generally within 100-200 m/s of the point values of the uphole data. The exception is the uphole value for a location about 100 m south-east of Borehole 2. The uphole velocity here is about 1570 m/s, which is about 440 m/s lower than the LVL velocity of 2010 m/s predicted from Figure 7. However, this uphole value is also much lower than the borehole velocities from nearby Boreholes 2 and 4, which average about 1850 m/s.

The LVL-derived statics were not used because it was thought that accurate results could be obtained from a simple elevation static correction followed by residuals statics.

2.3.4 Elevation static correction

A realistic shallow-layer velocity-depth model cannot be constructed from the LVL data available (for the reasons discussed in section 2.3.2), and there are some discrepancies (albeit not severe) between the LVL-based average velocity above OD, as compared to the average velocities obtained from uphole and borehole measurements. The simplest approach is therefore to assume a constant elevation velocity for an elevation static correction, and to allow residual statics computations to refine and improve the statics model.

The static correction applied in the first pass of processing (discussed in section 2.5 below) assumed simply a constant velocity of 2000 m/s to datum. This is the contour value running through the centre of Figure 7. The shot and receiver elevations are already in the database. This initial estimate of a complete static correction is therefore simply identical to the elevations as shown in Figure 8, for example, but with the numerical values half of those annotated - e.g. 100 m ≡ 50 ms.

The likely error involved in assuming a constant velocity rather than a laterally varying elevation static velocity can be estimated by comparing Figures 8 and 9. At any point the error (in ms) is:

elevation from Fig 8 (m) /2 - LVL static correction from Figure 9.

Visual comparison of the two maps shows that this error is at most about 6 ms. It would still be the same order of magnitude if another average velocity map, such as one based on uphole data, were to be used instead. This small error will be corrected for in the application of residual statics.

The datum for the elevation statics is OD. Normally a floating datum would be used first in processing, followed by a later correction to a horizontal datum. The floating datum is usually a smoothed surface following the topography, but averaged over the order of the receiver spread dimension. The entire dimensions of the present survey occupy no more than two spread lengths (each of about 600 m) in the NE-SW direction and three spread lengths in the NW-SE direction, therefore an appropriate floating datum would have been a near-planar surface. This surface would dip SW from about 100 m above OD in the NE (along row 46; see Figure 8) to about 50 m above OD in the SW (row 0).

If such a floating datum were to be used, then the correction to datum would require an estimate of travel time over vertical distances of no more than about 10 m. However, a knowledge of the velocity over this interval is required, and it is this near-surface velocity-depth structure that the LVL study (section 2.3.2) has shown to be rather variable. However, the likely overall static correction to OD was estimated from the LVL average velocities to vary by only about 20 ms over the whole survey area (Figure 9). It was therefore considered reasonable to apply statics by going directly to OD as the initial and final datum, rather than by following the intermediate path of a floating datum.

2.4 Common mid-point sorting

2.4.1 Source and receiver group barycentres

Figure 10 illustrates the ideal geometry when there are no offsets. In this Figure the square surface grid of rows and columns is marked by pegs (large white squares) at a 25 m interval. The row of 12 ‘x’s represents the 12 elements of a geophone group laid to the right of a peg. The ‘B’ marks the geophone group barycentre, which therefore lies on a row and halfway between a pair of columns.

The source array moves parallel to columns but midway between a pair of columns. Normally there are 5 sweeps at a 5 m move-up over the 25 m between VPs. The positions of 5 sweeps for one such VP are marked by the ‘v’s in Figure 10, with the larger central V denoting the barycentre of the summed sweeps. The Vs are coincident with the Bs, so that the barycentres of both sources and receivers lie on the common grid marked by the circles. Part of the design strategy was to have coincident sources and receivers so that the system of simultaneous equations for residual static calculations would be tightly coupled, leading to a more accurate solution than if the sources and receivers were at different places.

2.4.2 Common mid-point (CMP) binning

Within ProMAX, the receiver group barycentres are located at the circles shown in Figure 10, because the geophone string barycentres were directly entered into the database (section 2.1.2). In contrast, the source barycentres such as V are initially located at the reference peg 12.5 m to the left of V, because the actual peg location is used as the source location (section 2.1.3). The result is that the source - receiver common mid-points (CMPs) are nominally located at the black squares shown in Figure 10. These CMPs are at the centre of the 12.5 m square grid shown in Figure 10.

This difference in locating sources and receivers within ProMAX might appear to lead to inaccurate positioning and binning. However, remember that the offset of the source array from the location peg is entered into the database separately, so that the true position (V in the example shown in Figure 10) is correctly recorded. This addition of the source offset to the geometry database corrects the initial mismatch of the source and receiver positions, and moves the sources back to their true coincidence with the receiver barycentres.

A by-product of the ProMAX position recording method described above results in an apparent peculiarity in the numbering system of the default CMP bins, represented by the 12.5 m square grid shown in Figure 10. In the case of rows, the bin mid-points will lie at multiples of half the row number - 0.5, 1.0, 1.5, etc. However the column mid-points, although having the same increment of 0.5, lie on units of 0.25 higher or lower than a column number - e.g. 0.75, 1.25, 1.75, etc.

Traces were sorted into common mid-point (CMP) bins using the default 12.5 m square grid defined automatically by ProMAX from the surface coordinates. In the surface row/column coordinate system the bins range from rows 4.5 to 42.5 (77 rows of bins) and from columns 13.75 to 58.25 (90 columns of bins).

Once the decision to use 12.5 m bins had been made, as defined in the contract work programme, there was no need to employ any particular strategy for binning. After the binning grid has been defined, but before the sorting of traces into bins is carried out, there is the option within ProMAX to adjust the position of the binning grid, by rotation, by translation, or both. At this stage a very small adjustment to the bin grid (of a few metres) was made to maximise the concentration of CMPs at the centre of each bin.

Figure 11 illustrates a portion of the binned CMPs, together with the bin grid, near the NE border of the survey area. There is a concentration of CMPs towards the centre of each bin, as can be judged by viewing the diagram obliquely along either rows or columns. It can be seen that here is little room for manoeuvre to adjust the binning grid any further, to try to improve the distribution within bins, for example, of azimuths or offset ranges.

2.4.3 CMP coordinate system

The numbering system for the bins is shown in Figure 12. Bin columns are numbered from 1 to 90, and bin rows from 1 to 77. Columns of CMP bins are defined to be the inline direction and rows are defined as crosslines (Fig. 12). Vertical sections made up from rows or columns are denoted by the prefix I or X, respectively. Note that the origin of this right-handed Cartesian coordinate system is at the top right, rather than at the bottom left as with the surface (peg) coordinate system. This was an unavoidable limitation of ProMAX/3D V. 5.0, which has apparently been cured in Version 6.0. It would have been preferable to have had the CMP origin at the bottom left of Figure 12, as is the case with the surface coverage coordinate system.

Figure 12 confirms what would be expected from an ideal planar flat-layered earth model, that the subsurface (CMP) coverage extends halfway between the area of theoretical full-fold coverage (the dashed outline in Figure 12) and the surface coverage area. ‘Full-fold’ in this 3-D context is understood to mean the maximum possible fold of coverage obtainable from the idealised acquisition geometry with the source grid spacing the same as the receiver grid spacing.

Figure 13 depicts the bins as a grid of squares, with the density of infill of each bin corresponding to the fold of cover. Inline I90 is completely empty, so that all plotted crossline seismic sections run from columns 1 to 89 only. The creation of this empty row of bins by the default binning algorithm within ProMAX may have been another by-product of the unusual relationship between surface and subsurface geometry described in section 2.4.2 above and illustrated in Figure 10. It does not arise within Version 6.0.

2.4.4 Fold of CMP coverage

What fold of cover was theoretically obtainable? The basic swath pattern used, or ‘template’, comprises 26 shots at the surface unit interval of 25 m. These are shot into 240 channels at the same spacing. This yields 6240 traces. For every unit shot and receiver area (25 m squared) there are 4 bins. Therefore every time we move the template by one surface unit we observe one quarter of the subsurface coverage, because we have jumped 4 subsurface bins *for both source and receiver*. If the template is moved around over an infinite area, with no edge effects, the CMP fold obtained by this pattern is therefore 26 x 240 / 16 = 390. This is the theoretical full-fold cover for this swath template. The full-fold area of coverage shown in Figure 12 and elsewhere is defined here as the area within which there are no survey edge effects to reduce either the multiplicity of coverage or the range of offsets. It is simply the area occupied by the receiver groups (Fig. 2).

However, edge effects dominate the survey design so we cannot ignore them, and, furthermore, the template was not rolled with every shot. The actual survey has a very large surface area of about twice the area of full-fold coverage (Fig. 12) and a 3-swath layout. If every VP on every swath had been shot, there would have been a total of 4503 VPs. The fold of coverage, taking an average over the CMP bin area (Fig. 12) would have been 154. A more realistic estimate of what would have been obtained if every VP had been shot would be to assume that all the CMPs lie in bins within the full-fold area of the swaths. In this case the fold would have been 273. However, this is a slight over-estimate of the coverage within the swath area, as some of the CMPs lie outside it.

A total of 2138 VPs were actually shot (excluding duplicates; see section 2.2.3 above), or 47% of the theoretically achievable number. Figure 14 shows the fold of cover within the CMP bin area. The fold varies from 0 to 255, averaging about 130. Fold of coverage is adequate (≥30) or better within the theoretical full-fold area shown by the red rectangle, except at the bottom left-hand and right-hand corners (as viewed with in-lines vertical and cross-lines horizontal).

Zero fold of coverage is not discriminated from one-fold or greater in the colour-coded presentation of Figure 14. Figure 13 shows an alternative fold of coverage map with the density of infill corresponding to the fold. This demonstrates that towards the ends of crosslines and in-lines near the edge of the binned area, the fold is zero. Displays of these lines will therefore be shorter than the full length of 77 traces (inline) or 89 traces (crossline). The empty inline I90 at the left-hand side of the figure has been created as a by-product of the ProMAX default binning system, but obviously does not exist. Figure 13 confirms that there are no internal 'holes', or gaps in coverage, within the binned area.

To summarise the discussion above, the CMP fold of coverage figures for the full-fold subsurface area defined above are as follows:

- If template used were rolled over an infinite surface 390
- Actual surface survey area; if all VPs had been shot ~270
- Actual surface survey area; VPs actually shot ~130

2.4.5 Distribution of CMPs within bins

There are two end-member strategies for designing 3-D subsurface coverage, each of them useful in different ways. One end-member strategy is to aim for a quasi-random

CMP distribution, whereas the other end-member is a tight concentration of CMPs in the centre of each predetermined bin. The survey design in the present case was to aim for the latter strategy.

Figure 11 shows a detail of the CMP bin map, with inlines I32 to I40 running from the top-right-hand corner to the bottom left corner of the diagram (north is up). Crossline X1 has one-fold coverage. The figure shows that even where the fold of coverage becomes very high, in the centre, there is still a pronounced concentration of the mid-points towards the centre of each bin.

2.4.6 Shot-point map

The set of CMP bin centres has been drafted onto a shot-point map at 1:2,500 scale (Enclosure 1), which also includes some well locations and existing 2-D line locations. The central area of this map, where the 3-D subsurface coverage exists, is reproduced at a small scale as Figure 15.

2.4.7 Offset and azimuth distribution

There is no direct method of examining the offset distribution of the 550,000 traces in the dataset in a spatially varying mode. The only graphical display that can be made from the database is the global offset frequency distribution. This is shown in Figure 16a as the number of traces per offset bin. The offset bins are at 25 m intervals. Figure 16b shows the same data presented as a cumulative frequency distribution of offsets, normalised to 100% of the total number of traces. The figure shows that 90% of the traces have offsets of under 600 m, and that the distribution of offsets is reasonably uniform over this range. The most frequent offsets are around 300 m.

There is no method within the standard ProMAX database of examining the azimuthal distribution of shot-receiver offsets. However, the design of the swath template and the three-swath surface layout was examined quantitatively in March 1994 by IMCL for GU using the MESA survey design analysis package. The study was based on the survey pattern subsequently adopted. Figure 17a shows the grid of source points over an area of 1550 m by 1400 m, with the receiver columns occupying the darker rectangular central area. Red squares indicate shot points occupied once and lilac squares those occupied more than once. This model grid and the 3-swath manner in which it is built up is similar to what was actually observed in summer 1994, except that a 200 m width of source and receiver columns at the left-hand side of Figure 17a was not surveyed.

The MESA bin analysis assumed that all 6804 possible VPs were observed. The predicted azimuthal distribution is shown in Figure 17b. There is an extremely good azimuthal distribution over all angles between 0° and 360° (the upward direction in the plan of Figure 17a corresponds to 0° in Figure 17b). In fact 2138 VPs were observed over a more equilateral area than shown in Figure 17a, due to the reduction in the size of the survey area. Bearing in mind these two difference between the MESA model and the survey actually conducted, it can be seen that there is a slight excess of traces in the horizontal direction (90° and 270°) due to the rectangular shape of the survey. The spikes in the distribution at 45°, 135°, 225° and 315° are due to the diagonals in the square grid with its coincident sources and receivers.

The model shown in Figure 17 assumes about 1.6 million traces, about three times as many as were actually recorded. The difference between the two figures is due to the reduction in the survey area mentioned above, and the fact that only 47% of the possible VPs were shot. The missing VPs are fairly evenly distributed over the north-eastern half of the survey area, and more are missing in the south-west (those not shot into swath C), as can be seen from Figure 3. We therefore conclude that the azimuthal distribution of offsets in the actual survey will be very even, following the general pattern shown in Figure 17b.

2.5 Processing sequence

2.5.1 Processing flow

Some of the processing steps have already been mentioned above in the context of pre-processing. These steps form part of a standard processing flow summarised as follows:

1. Pre-processing
   - Demultiplex SEG-B to SEG-Y
   - Elevation static definition
   - 3-D geometry (bin definition, binning)
2. System response filter
3. Low cut filter
4. First break mute
5. Spherical divergence correction

6 True amplitude recovery

7. Decon before stack
8. Trace equalisation
9. Elevation statics

Iterative loop:

10. Interactive velocity analysis
11. NMO correction
12. Surface consistent residual statics

[repeat of steps 10-12:]

13. Mute, scaling and stack: output raw stack file ‘Res2’

[Alternative post-stack processes]

14. Bandpass filter
15. Display

These steps are discussed in turn below. Alternative processes inserted into the flow immediately after step 13 above are discussed separately. Note that no separate step for sorting from shot gathers to CDP gathers (or any other ensemble type) is required within ProMAX. Once the geometry has been defined and applied (step 1 above), the traces, which may be stored in shot ordered files, are sorted on input into the ensemble type (e.g. CDP) required.

2.5.2 System response filter

This was designed from a system instrument response recorded on 16 August 1994, stored on SEG-B field tape 1051, file number 8. The topmost 100 ms of 157 channels numbered 84-240 were stacked together. The resulting trace was used in the ProMAX V. 4.0 processor *Derive Match Filter* to produce a 51-sample match filter. 0.1% additive noise was added in the convolution. This filter was then specified in the V. 4.0 processor *Filter Application*, where it was convolved with the CDP data gathers.

2.5.3 Low cut filter

This was applied using the Ormsby frequency domain single filter option within *Bandpass Filter*. The 100% and 0% low-cut ramp points were 6 Hz and 8 Hz respectively, whereas the high-cut end of the filter was effectively not applied, having 260 and 280 Hz 0% and 100% points respectively.

2.5.4 First break mute

This was applied using the *Trace Muting* processor with the top of the trace option, and with a 5 ms ramp on the amplitudes at the start of the mute. Sample picks were made as shown in Figure 18. These picks were then automatically interpolated in time and space over the complete dataset.

2.5.5 Spherical divergence correction

This was applied to the shot data in time and space varying mode using the *True Amplitude Recovery* processor in spherical divergence correction, 1/distance mode without anelastic attenuation correction. Velocities for converting distance to time were taken from the database. The first pass of the data through the processing flow used brute velocities.

2.5.6 Deconvolution before stack

A minimum phase (Wiener-Levinson) spiking, 40 ms operator with 0.1% added white noise was applied using the *Spiking/Predictive Decon* processor. The picked gate varied from 350 - 1200 ms at zero offset, interpolated through 500 - 1700 ms at 600 m offset. The trace mute was re-applied afterwards.

2.5.7 Trace equalisation

This was achieved with the *Time-Offset Variant Gain* processor in the ‘generate and apply’ iterative mode. The amplitude decay characteristics of the data are first analysed, inverse tables are generated, then all the input data are passed with the appropriate compensating gain applied. The amplitude decay analysis was based on two CDP locations with 10 CDP gathers each. Trace sample magnitudes were smoothed over a 10 ms gate. Traces were assigned to 50 m wide offsets bins up to a maximum offset of 600 m. Below 1000 ms a constant gain was applied.

This process results in a trace to trace balance, in which the faulty demultiplexing gain problem discussed in section 2.2.2 above would have been corrected. However, any true amplitude *versus* offset information will have been removed by this process.

2.5.8 Elevation statics

The *Apply Elevation Statics* processor used a smoothed mean of source and receiver statics (smoothed over 51 traces), using a replacement velocity of 2000 m/s to final datum. The reasons for using neither an intermediate (floating, NMO) datum nor a more sophisticated velocity function have been explained in section 2.3.3 above.

2.5.9 Velocity analysis and NMO correction

The two passes of *Interactive Velocity Analysis* (IVA; a Version 5 processor) were performed at 28 locations, as part of an iterative process; steps 10-12 were repeated once. The IVA locations, shown by the black dots in Figure 19, were concentrated somewhat towards the centre of the CDP area - between inlines I20-I75 and crosslines X10-X70, where the CMP fold is above about 50.

An example working display is shown in Figure 20. Note that in this figure the origin of the inline and crossline axes is at the bottom left of the location plan, with north indicated by the arrow. One position is highlighted on the location plan. The rms and interval velocity picks for this location are shown on the right. The horizontal bar at 320 ms on this T-V graph is the time for the colour-coded rms velocity interpolated over the whole survey from this and the other 27 locations.

Figure 21 illustrates a sample CMP gather, at X20, I25, after NMO correction, stretch mute and first break mute. The central upper panel is a stack of the trace and 5 other traces on either side in the inline direction, viz. 11 traces of I25, from X15 to X25. The semblance plot appears at the top right. The bottom colour panels are a plan view of the survey area on the left (cf. Fig. 20) and a colour contoured rms velocity map for the whole of I25, interpolated from the 5 velocity analysis points on that line (see Fig. 20).

Forward NMO correction was applied with a stretch mute of 30%.

2.5.10 Surface consistent residual statics

Applying residual statics is an iterative process; steps 10-12 were repeated, so that the stack after two applications of residual statics, with improved velocity analysis in between, showed a great improvement over the original.

The residual statics calculation was made each time on NMO corrected gathers. The mode used was *External Model Autostatics: Cross-correlation Sum*, a stand-alone processor. The pilot trace was smoothed over 5 traces. An 800 ms flat gate was used, and the maximum source or receiver static allowable was 10 ms.

After the first round of calculation and pre NMO application the velocities were re-picked, and a new NMO correction was made using these velocities. The second pass of residual statics was then computed, and applied to pre-NMO CDP gathers. These gathers are denoted 'Res2' below.

A by-product of the residual static correction is a statics map. Two of these have been produced. Enclosure E2 is the shot static map and E3 is the receiver group static map. Both are at 1:2500 scale, and result from contouring the final static corrections after the second pass. These maps are discussed in the following chapter.

2.5.11 Stack

After the second pass of residual statics and NMO had been applied the following processes were applied to the Res2 gathers:

Trace Muting - front end, using a post NMO picked database
Time-Variant Scaling - RMS scaling in 4 overlapping gates over 0-250 ms
Stack - mean of traces, square root power stack normalisation

2.5.12 Post-stack bandpass filter

A *Bandpass Filter* - an Ormsby zero-phase filter was tested in the following ways:

- A 10 Hz narrow pass (between 100% points) with 5 Hz ramps (100-0%) over the range 10 to 80 Hz.
- A 20 Hz narrow pass (between 100% points) with 5 Hz ramps (100-0%) over the range 80 to 180 Hz.
- A selection of broader pass bands of an octave or more in width.

The following filter was chosen, based on these tests:
30-80 Hz from 0-500 ms (5 Hz ramps) and
20-70 Hz for data deeper than 500 ms (also 5 Hz ramps).

Displays were produced after this step.

2.5.13 Post-stack processes

From the raw stack (‘Res2’) made from the second pass of residual statics, two other post-stack processes were tested separately and together, to see whether they could improve the data. Process *F-XY Decon* ('FXY') is a 3-D version of the frequency *versus* offset filter FX used in 2-D processing, and *F-K Filter* ('FK') is a 3-D version of frequency-wavenumber processing. Two post-stack migration methods have also been tried. The full test flow paths are shown in Figure 22.

Test panel displays were produced after four of the seven possible stages by adding the steps *Bandpass Filter* and *Screen Display*. Figures 23-25 show the test panels for inlines I25, I41 and I71 respectively, and Figures 26-28 show the same set of panels for crosslines X12, X30 and X51 respectively. The 4 panels on each figure have the following sequence (see also Figure 22):

1.				Filter	Display
2.	FXY			Filter	Display
3.	FXY	FK		Filter	Display
4.	FXY	FK	Mig	Filter	Display

The *F-K Filter* was of the arbitrary polygon type, with a separate reject polygon for each of the positive and negative wavenumber quadrants. Its effectiveness is illustrated in Figure 29, in which the upper F-K domain display panel is without the filter and the lower is with the filter applied. The test trace is I60, X1 from the stacked dataset with FXY already applied. The two reject polygons have been added to the lower display and are shown by the black outlines. The colour-coded amplitude scale is in decibels below the maximum, shown in the key column. The colours indicate the following approximate amplitudes:

White	0	dB
Yellow	-5	
Lilac	-10	
Pink	-14	

Light blue	-18	
Light green	-23	
Royal blue	-27	
Grey	-30	dB

with a range of more subdued colours for the lower amplitudes. The frequency content of the data is discussed in the next chapter.

The *F-XY Decon* process was run with a 500 ms operator time window with tapers of 100 ms length within this window (i.e. 0-100 and 400-500 ms). It is intended to remove random noise. It operates in the complex frequency domain on individual discrete frequency slices, using a prediction operator to enhance signal and reject random noise.

The migration method in these panels is the phase-shift method, with 90% stacking velocities. Figures 23-28 demonstrate that FXY considerably improves the data, whereas if FK is applied after FXY there is only a marginal extra benefit, mainly for the deeper reflections (e.g. around 800 ms on line I71; Figure 25).

The *Stolt 3D Migration* method was tested separately, firstly with the second pass of stacking (RMS) velocities and then with constant factors of 90% and 70% of these velocities in addition. Maximum frequency was 120 Hz.

The *Phase-Shift 3D Migration* processor was tested with a time - interval velocity function derived directly from the stacking velocities and then with constant factors of 90%, 80% and 70% of these velocities. From the seven separate migration tests (three Stolt and four phase-shift) it was concluded that the best results were obtained using the *phase-shift method with 90% velocities*. All the test displays and enclosures reproduced in this report which have post-stack migration applied use this migration method.

Filtered stacked or migrated tapes have been written after each of the seven stages depicted in Figure 22. The definitive dataset is considered to be the phase-shift migrated stack after FXY and FK (panel 4 in Figures 23-28, respectively).

3. RESULTS

3.1 Data

3.1.1 SEG-Y post-stack files

The following nine output files, on exabyte cartridges in SEG-Y format, are supplied along with this report. Each trace is duplicated by being represented once on a file of inline sections and again on a file of crossline sections:

Res2
Res2 + FXY
Res2 + FXY + FK

Res2 + 3-D phase shift migration
Res1 + FXY + FK + 3-D phase shift migration
* Res2 + FXY + FK + 3-D phase shift migration

Res2 + 3-D Stolt migration
Res1 + FXY + FK + 3-D Stolt migration
Res2 + FXY + FK + 3-D Stolt migration

* The definitive dataset

The nine pairs of output files shown above are grouped into stacks, phase-shift migrations and Stolt migrations. Alternatively they can be grouped into:

- The seven files based on the ‘Res2’ raw stack dataset; see section 2.5.10 above and Figure 22) and

- Two versions of migration which were performed after one pass of residual statics (‘Res1’ in the list above).

The two migrated datasets based on one pass of residual statics are only of interest to see the improvement resulting from doing residual statics twice. The definitive dataset in the above list of nine pairs is flagged with a star. The migrated and stacked seismic sections presented in sections 3.1.2 and 3.1.3 below are based on this dataset and its unmigrated equivalent (Res2 + FXY + FK).

3.1.2 Colour amplitude displays

Colour-coding instantaneous trace amplitude, rather than plotting the amplitude as a wiggle, is a useful way of displaying seismic data, especially at a small scale. The colour code scheme used here is as follows:

Colour	**Numbers**	**Ground motion**	**Wiggle trace**
Red	↑ Increasing negative	Upward	Trough - white
Light blue			
Yellow			
White	Zero amplitude	None	Zero crossing
Green			
Purple			
Dark blue	↓ Increasing positive	Downward	Peak - black

This sign convention is the SEG normal polarity convention.

Three inline vertical stacked sections (I25, I47 and I65) and two crosslines (X12 and X30) are shown in this mode (Figures 30 and 31 respectively). The same two crosslines are shown in migrated form in Figure 32 and a side-by-side comparison of crossline X47 in stacked and migrated form is shown in Figure 33.

Colour time slices are shown in Figures 34 through 50. Each Figure shows a stacked and a migrated pair. Figures 34-41 progress downwards in 10 ms steps from 150 ms to

220 ms, whereas the remaining Figures 42-50 are separated by a 20 ms step, finishing at 400 ms. This deepest time slice corresponds to about 1000 m depth. Note that the crossline direction scale is stretched by nearly 50% relative to the inline direction, although the two scales should be the same. This is due to ProMAX *Screendump* Version 5.0 plot limitations.

3.1.3 Vertical sections

A set of representative vertical sections at full scale in conventional monochrome wiggle & variable area display is enclosed. Horizontal scale is 1:10,000, vertical scale is 20 cm/s and the sections extend to 1900 ms. Figure 51 is a key map showing which lines have been selected. The selection of about one line in every five has been made in the following way:

- There is an inline and crossline through each of the principal boreholes.
- The lines are evenly spaced.
- There is a sample group of consecutive lines in each direction through the area of maximum fold of coverage (Figure 14), so that line-to-line continuity may be examined.

The Enclosures of the vertical sections are as follows:

E4	Stack	Inline	5, 11, 16, 21, 25, 30, 36, 41, 47, 53
E5	Stack	Inline	60-71, 76, 84
E6	Stack	Crossline	5, 9, 12, 22, 25-33
E7	Stack	Crossline	38, 43, 47, 51, 56, 61, 67
E8	Migration	Inline	5, 11, 16, 21, 25, 30, 36, 41, 47, 53
E9	Migration	Inline	60-71, 76, 84
E10	Migration	Crossline	5, 9, 12, 22, 25-33

E11	Migration	Crossline	38, 43, 47, 51, 56, 61, 67

3.2 Effect of reduced fold of coverage

3.2.1 Actual fold of cover

Subsurface fold of cover in the 12.5 m bins averages 130, but what is perhaps more significant than a high average fold is that more than 90% of the area of full-fold cover (Figures 12 and 14) has a coverage of 50-fold or better. The effect of the reduced fold of cover - say where coverage is less than 60 - is examined with the six lines shown in Figures 52 through 57. These comprise four inlines I13, I32, I50 and I75 (Figs. 52-55) and crosslines X23 and X49 (Figs. 56-57).

3.2.2. Restricted range and fold

Going from the edge of the full-fold area outwards to the edge of the subsurface coverage (see Figure 12) results in a progressive loss of fold as the short-offset traces are lost from the CMP gathers. The very outermost CMP bins will only contain one trace (e.g. those very close to the top right-hand corner of Figure 11) with a very large offset of about 650 m. With the dataset currently processed to date, this reduction in fold of coverage around the edge of the CMP area is coupled to a restriction in range of azimuths.

The progressive loss of the short-offset traces, as the edge of the CMP area is approached, results in the muting of the stacked seismic data at the shallowest depths. Figures 52-57 illustrate that the very edge of the CMP area contains no information above about 200 ms. This follows from the fact that the outermost stacked traces are stacked from one trace (or a few) with offsets of the order of 500 m or more. Figure 18 shows that these have already been muted in the shot gather domain above about 200 ms, to remove first breaks. The muting above 100 ms of the entire inline I5 (enclosures E4 and E8) is simply due to the fact that it is stacked with traces all having offsets of more than about 200 m.

However, there are areas where the fold of cover is low, but include short ranges. This is especially true of the southern corner of the CMP area (Fig. 12). Inline I13 (Fig. 52) crosses this area. In this line the fold to the south-west (left) of trace 45 is only 20 or less, as compared to the right-hand part of the same line. A deterioration in quality of the left part of the section is evident, compared to the right part. The same effect can be seen on X49 (Fig. 57) where there is a progressive loss of fold to the south-east (right), accompanied by a progressive loss of data quality.

3.3 Source energy

3.3.1 Array length considerations

Source arrays can be used physically in the field (e.g. the four vibrators in-line, as used at the start of the survey), or can be synthesised afterwards in processing. Long arrays may be desirable to help reduce horizontally travelling waves such as ground roll and to help smooth out local unmeasurable irregularities in the near surface. However, there is no good *theoretical* reason to form the array in the field rather than later by synthesis.

There may be logistical reasons for using a long physical field array. Obviously an array with many vibrators will put more energy per unit length of survey line into the ground than a similar array with fewer vibrators. The minimum distances between array elements will be constrained by the dimensions of vibroseis vehicles. Most of the 3-D trial (81% of the sweeps recorded; 71% of the field recording time) was conducted with the 2-vibrator array. In the present project the normal number of 5 sweeps per VP were summed in the processing centre before any further work was done. The array lengths of the 2- and 4-vibrator array, before and after this sweep summing are summarised below:

Array	Physical length (m)	Source length (m) (1 sweep)	Source length (m) (5 sweeps)
2 vibrators	23	12.5	32.5
4 vibrators	47	37.5	57.5

However, since the individual sweeps were recorded, the option of processing the dataset with the short (12.5 m) source arrays is available.

3.3.2 Vibrator power

The four vibrator array used initially at a nominal 30% drive level (about 13,000 lbs) implies a total force of 52,000 lbs, assuming that the vibrators are all perfectly in phase and that there are no non-linear interactions between them. The reduced 2-vibrator array, with each vehicle operating at a nominal 50% drive level (about 80% of the peak force of 27,000 lbs) implies a total force of 43,000 lbs.

The restriction of the drive level to 80% (or less) of the achievable peak force of the vibrator is aimed at ensuring that the source operates in the linear way in which it is intended. In practice, however, the interaction of the vehicle with the near field (the subsurface within a wavelength or so of the base plate) plays an important role, but the study of the source signature of the vibrators as used in this trial survey is beyond the scope of this project. The effects of the source - its power, frequency distribution and directivity - may, however, be *estimated* from the dataset recorded in the trial survey.

3.3.3 Useful energy content of summed sweeps *vs.* single sweeps

Due to the summing of the sweeps before further processing, a direct comparison of single sweeps *versus* summed sweeps and the resulting effect on stacked data could only be made if the single central sweep from each VP is extracted from the field data and the whole processing sequence applied. This comparison would be somewhat artificial, because if we started the processing from scratch with a single sweep per VP, then many of the parameters would probably have been chosen differently from those selected with the five-sweep summed dataset. A reasonable comparison would only be achievable by processing the single sweep field dataset from scratch without reference to the summed data results. This is beyond the scope of the present study.

However, useful and instructive comparisons can be made using demultiplexed shot gathers before and after summing of the five sweeps. The demultiplexing gain problem discussed in section 2.2.2 above has been circumvented in the following examples by applying a trace amplitude balancing process based on the mean amplitudes of the bottom 200 ms of the traces, i.e. from 1800 to 2000 ms. Assuming that the mean amplitude within that window on every trace should be the same, a scalar is calculated to do that and is then applied to the whole trace.

Figure 58 shows the 240 traces from a single sweep on Swath B. The source was a single vibrator at VP 3635 on the RCF3 drill pad, operating at 50% drive level. The first breaks and air blast show the receiver array pattern of 10 lines. Figure 59 shows amplitude power spectra for this shot. The upper display shows the average spectrum for the whole 0-2000 ms, 240 channels. The Hanning window applied to each trace is shown between the data display box on the left and the spectrum on the right. The 12-120 Hz bandwidth of the sweep source clearly stands out. The lower panels show a window of the data where there may be reflections. The same characteristic spectrum is evident.

Interpolating between the two segments of the spectrum outside the sweep bandwidth (i.e. from 0-12 Hz and 120-250 Hz) suggests that the vibrator has raised the spectrum by 25-40 dB above background noise levels. However, this is an oversimplification. The correlation process introduces correlation noise into the sweep spectrum, so that we cannot conclude that the signal to noise ratio within the sweep bandwidth is as high as might be expected from the lifting of the spectrum within the 12-120 Hz bandwidth. This problem is illustrated by Figure 60, in which one sweep at VP 3635 has been subtracted from another sweep at exactly the same location. There was no move-up of the vibrator at this VP due to obstructions. The subtraction data panel should therefore contain no signal. AGC was applied to the two shots before the subtraction, but there has been no gain adjustment afterwards. The plot confirms that this method removes signal. The strips of 25 Hz sinusoidal noise remain.

Three portions of the subtraction data panel are shown in Figure 61 together with their power spectra. The uppermost comprises about 155 traces from 1760-1980 ms (at a depth where little signal would be expected); the middle panels show a small segment selected to avoid the 25 Hz sinusoidal machinery noise on some groups of traces, and the bottom set of panels shows a narrow time zone before the first breaks. Obviously there should be no signal at all within this area. However, it is evident that all three panels retain a frequency spectrum corresponding to the sweep. This is due to correlation noise. It is band-limited, but incoherent. Noise outside the sweep bandwidth is suppressed by correlation, and may be neglected since any remaining such noise can be bandpass-filtered to remove it.

Given that correlation noise is introduced as an unavoidable consequence of the vibroseis technique, we can increase the signal to noise ratio by summing correlated sweeps. Note, however, that this is identical in effect to the stacking of binned traces. A discussion of its usefulness or otherwise is postponed to Chapter 4, in which it is discussed within the wider context of acquisition geometry and binning.

One VP is used here as an example to investigate whether sweep summing has an advantageous effect on signal, particularly at the higher frequencies of interest. Figure 62 shows four receiver lines (channels 1-96) from one sweep at VP 5426 into swath B. The source was the 2-vibrator array. An Ormsby bandpass filter has been applied in a high-pass mode, with frequency points 0-100-100-0% at 40-50-220-250 Hz. Potentially useful signal is thus in the 50-120 Hz band. A 200 ms centred AGC filter has been applied. The corresponding 5-sweep sum is shown in Figure 63. The two records look extremely similar, as is confirmed by the subtraction of one from the other shown in Figure 64. This shows some difference in the first breaks due to the 5 m move-up of the summed version. However, elsewhere the display shows that the chief difference is merely in random correlated noise. The low-amplitude reflection energy seen below the first breaks in Figures 62 and 63 is not perceptibly improved by the summing.

The spectra of the two sweeps shown in Figures 62 and 63 are shown in Figure 65 (top and bottom panels, respectively). These have been made without the 50 Hz high-pass filter applied to the displayed data panels. The spectra are identical except that the summed sweep spectrum is about 5 dB higher than the single-sweep spectrum, as measured relative to the spectrum above about 150 Hz. This corresponds to the increase in signal to noise ratio of 2.2 expected from summing 5 sweeps.

In conclusion, there is no inherent benefit in the increased source array dimension as a result of summing 5 sweeps. The only benefit is the improvement in signal to noise ratio due to stacking.

3.4 Source resolution

3.4.1 Bandwidth

One of the main aims of the study was to determine whether the vibroseis source applied to this area could deliver enough high frequency energy. Peak frequency is not crucial *per se*, since penetration is not a problem with a shallow target; similar vibroseis sources to those used in the 3-D trial have been proven in many areas to return reflections from the base of the crust, 30-40 km deep. Rather, it is the bandwidth that gives reflectors their character and interpretability. Naturally it is the high-frequency end of the reflected spectrum that permits high resolution - *if* all the practical problems of phase can be resolved. In other words, the lower frequencies are more robust to seismic processing.

3.4.2 Frequency content

Amplitude and phase spectra derived from suitable windows of the seismic traces tell us about the relative frequency content, but the high frequencies may be of no use if the phase correlation from trace to trace is lost due to vibrator source problems or statics. Figure 66 shows a raw stack of crossline X30. The FXY and FK processes have been applied, but no bandpass filter. Note that in this panel north-west is on the right. This line runs through the two highest-fold peaks (Fig. 14).

Figure 67 shows two frequency power spectra based on subsets of X30. The upper panels show the spectrum where there are some good reflections, whereas the lower panels show an area of noise near the bottom of the section. The lower panels confirm that the effective frequency content is in the band 12-120 Hz, i.e. the sweep bandwidth. The upper panels show that the reflection energy peaks in the 20-60 Hz band, but with a suggestion of useful energy at higher frequencies. A similar inference may be drawn from the F-K plot of Figure 29. The suggestion is examined next using narrow bandpass filters.

Narrow bandpass filters applied to stacked sections give a good indication of the usable frequency content of the data. Eight test panels for X30 are displayed in Figures 68-71. The 0-100-100-0% points for the Ormsby zero phase bandpass filter applied to each of these panels is as follows:

- Control (recording instrument bandpass 8-125 Hz)
- 10 20 50 60
- 20 30 70 80
- 30 40 90 100
- 40 50 110 120
- 50 60 120 130
- 60 70 200 250
- 70 80 200 250

These value have been selected to yield at least an octave within the band passed, except at the higher values where the upper frequencies are limited by the recording instrument and the sweep. The last two panels are ‘ringy’ due to the narrow band effectively available (70-120 and 80-120 Hz, respectively).

The filter test shows that there is usable energy higher than 80 Hz, perhaps up to about 100 Hz. In the present survey this can only be used to add character to a broad-band source wavelet, where the main energy is in the 20-60 Hz band. The 30-80/20-70 Hz bandpass for the final plots (section 2.5.12) is a compromise between maximising the energy and retaining useful high frequencies.

3.5 Residual statics

3.5.1 Residual static correction maps

The two passes of residual statics which were applied are clearly a crucial factor in improving the data from the raw shot records (e.g. Figs. 58, 62 and 63) and the early stacked sections (e.g. panel 1 in Figures 23-28). The validity of the statics can be checked by the separation into surface-consistent statics. The single static correction for a trace is split into its components for the source and receiver respectively. Well-computed statics for the sources and receivers over the same area should then match - i.e. be consistent with a physical near-surface model. The layout of the geophone arrays and the summed vibrator sweeps for each VP was designed to make the source and receiver barycentres coincident. This maximises the correlation between source and receiver statics when a residual method is used.

The separate source and receiver statics are very similar in the overlap zone where the receivers were located (Enclosures E2 and E3). The contoured values differ by only a few milliseconds. The match is improved if the shot static map is shifted to the SE by 12.5 m. The contouring of the source static correction appears to have been referred to the VP peg and not to the offset source.

There are a few isolated extrema on both maps. These correlate with local highs or lows on the topographic grid (Fig. 1), which, as discussed above, may be artefacts of isolated survey errors. In general, the residual statics maps correlate closely with the topography and in fact the numerical values are similar, implying a static correction averaging 1 ms/m of elevation above O.D.

3.5.2 Comparison of residual statics with the LVL static model.

The static correction model derived from the LVL surveys but not used (section 2.3.3 above) suggested much lower values than those computed from the residual method actually used. The reason for this is not understood. Comparison of the 3-D data with the existing 2-D lines underlines the mismatch as discussed below, and suggests that the residual statics applied to the 3-D dataset are of the order of 30 ms larger than they should be.

3.6 2-D dynamite vs. 3-D vibroseis reflection results

3.6.1 Coincident data

Six 2-D lines from the UKN92-2D survey cross the 3-D survey area (Enclosure 1 and Figure 15). Four of these run approximately parallel to the inline direction (the dip direction for the sedimentary cover sequence of the solid geology) and two lines run very closely parallel to 3-D crosslines. Stacked versions of the relevant 3-D inlines and crosslines have been displayed at the same horizontal and vertical scales as the 2-D data to enable comparison. The six pairs of lines are shown in Figures 72-77 and are as follows:

3-D line	2-D line	CDPs (2-D)	Figure no.
I13	92-2D-05	415-532	72
I32	92-2D-04	390-508	73
I50	92-2D-03	408-526	74
I75	92-2D-02	479-597	75
X23	92-2D-14	337-447	76
X49	92-2D-15	341-451	77

3.6.2 Comparisons

First, the 2-D data have to be raised by about 30 ms relative to the 3-D lines to achieve a visual match. Alternatively, this implies that 30 ms too much in static correction have been taken off the 3-D dataset. The source of this static mismatch is not understood at present. When that is done the stacked data in each pair look broadly comparable.

The horizontal resolution of the 2-D data is better than that of the 3-D data, but that is because the CMP (trace) spacings are 8 m and 12.5 m respectively. Even though the final bandpass filter on the dynamite 2-D data is 30-130 Hz, in contrast to 30-80 Hz for the 3-D data above 500 ms, the vertical resolution of the dynamite data is not significantly better.

The dynamite sections suffer from a blank zone above 200 ms, in contrast to the vibroseis data. This is presumably a consequence of the much more severe ground roll induced by dynamite; after removal of ground roll there is simply no dynamic range left in the recording system to reveal reflectors.

Penetration (coherent energy from depth) is clearly better on the vibroseis data, especially on Figures 75 and 76.

3.7 Continuity

Line to line continuity on the vertical sections is good at the minimum 12.5 m spacing. Enclosures E5 and E6 include a subset of adjacent stacked inlines and crosslines, respectively (see also the key map of Figure 51). However, some features within the BVG die out over the order of five or so lines, of the order of 40-100 m horizontally. This suggests complex structure. The stacked time slices within the BVG (Figs. 43-50; 260-400 ms) show many features which are coherent over the order of 100 m or so, as well as some bigger events. Again, these features suggest complex, small scale structure; they are not simply due to random noise. The time slices shallower than about 100 ms show no coherent energy and all the data above OD have been discarded. Processing with improved statics may help fill this apparent data gap.

3.8 Migration

3.8.1 Vertical sections

The vertical sections of the post-stack 3-D time-migrated data (Enclosures E8-E11) tend to be rather characterless below the Permian (roughly 0-250 ms). There are certainly strong coherent events on the stacked data, but they do not appear to be enhanced by migration. There is no edge effect apparent from the reduced fold at the edge of the survey area.

3.8.2 Time slices

The strong SW-dipping reflectors on the very shallow data appear to have increased horizontal resolution after migration; however, this is mainly the result of steeper dip after migration. Within the BVG the display interval of 20 ms is too great to correlate some of the data reliably from level to level, i.e. the data may be temporally aliased at this display sample interval.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Planning 3-D seismic acquisition

4.1.1 Introduction

The acquisition phase of the trial provided valuable information about the feasibility of carrying out a 3-D survey of the PRZ. The following recommendations are based on the experience gained during summer 1994 and on the assumption that a similar type of 3-D survey, but on a bigger scale, might be carried out in future.

4.1.2 Maps

There are no publicly available OS maps other than the 1:10,000 scale sheets. It is crucial that digitally produced, up-to-date large-scale maps (say 1:2,500 scale) are provided at the earliest possible planning stage. Digital versions of the OS maps are commercially available. These maps will form the database and must be subject to continued updating.

4.1.3 Access and permitting

All the relevant fields and other areas such as roads should be given identification numbers which form the primary means of locating areas.

In 1994 initial contact with local farmers was made by Nirex's land agents Dixon Webb. A specialist permit man, familiar with the problems of a seismic survey, was then appointed as Liaison Officer. This dual arrangement worked very well, but in contrast, neither party acting alone could have done the required job. Therefore a similar arrangement is recommended for future work.

Information on crop coverage, ownership, access, obstructions, sensitive structures etc. must be added to the map database as early as possible and preferably under the direct control of the planning crew. An in-house, on-site GIS package is necessary. The remote production of maps for the 1994 trial survey, involving steps from:

subcontractor - contractor - client (Nirex) - BNFL - map subcontractor

proved to be too cumbersome and slow.

In the 1994 survey all the land was owned by BNFL and tenanted by only five farmers. The permitting logistics were therefore much simpler than will be the case for a full survey.

4.1.4 Visual recording

As in 1994, photography before survey of any structure which might be subject to damage (or a claim for damage) and video recording of activities should be carried out.

4.1.5 Safety distances

Safe distances to various structures during operation of the vibrator arrays were predicted by Spectrum Acoustic Consultants. They appear to be sound and conservative; observed levels were always well under the prescribed limits. However, the definition of certain features such as ‘retaining wall’ needs to be clarified well in advance. If every dry stone dyke is so classified, for example, the movements of the source array are going to be severely curtailed.

4.2 Recording parameters

4.2.1 Introduction

It is not possible to define exactly what should (or could) be done in any future survey, without a prior knowledge of the timescale, location, budget and targets. However, some general lessons have been learned from the 1994 3-D trial which should be applicable to any future work.

4.2.2 Three-component acquisition?

The applicability of three-component surface seismic reflection recording to a complex, shallow target, although excellent in principle, is very limited with present technology and understanding. The aim of such recording is to record the full wave-field so that S-waves can be recognised. However, the shear-wave window severely limits the offsets possible within which undistorted shear wave information is recordable, even in principle. For a target at 500 m the maximum offset (i.e. the diameter of the window) may be as little as 50-100 m.

Extracting useful extra information from three-component data is extremely difficult in practice due to the near surface. Near-surface effects create enough problems for vertical component data, but are far worse for shear waves. Although such acquisition has been occasionally tried by the oil industry, there are no published case histories of any three-component, 3-D seismic surveys of a complex target. This suggests that the oil industry, the leading force behind the development of new seismic exploration techniques, has yet to see the benefit of such three-component surveys.

Lastly, the cost and logistic difficulties introduced by using three-component geophone arrays would degrade the survey in all other respects. Therefore, a three-component acquisition geometry is *not* recommended for a full-scale 3-D survey.

4.2.3 Source

The vibroseis source has clearly been successful in the trial survey, and is recommended as the sole or main source for any new work. It is concluded that the vibrator source can deliver enough high frequency energy, approaching that of the alternative source, dynamite in deep shot holes.

The shallow target of the PRZ has been successfully imaged with a vibroseis source comprising only two vibrators for 81% of the VPs shot. There is therefore no need to use a full array of the type used by the oil industry, which aims at targets five times deeper. The array need only be two units. One unit operating at about 40,000 lb will provide as much energy as the 1994 2-vibrator source (section 3.3.2 above). Source arrays can be synthesised if necessary in processing. As in 1994, the extra vehicles can be on hand to reduce down time caused by detours from one field to another.

Putting enough energy into the ground is not a problem and generating sufficient energy at over 80 Hz is not a problem either. The problem lies in recording accurately and analysing the *phase* of any such high frequency energy. If the trace to trace phase on gathers, after static and dynamic corrections, does not match to better than 40-50° (1-2 ms) then stacking will degrade the data. A source of the problem is the non-linearity of the vibroseis source. The phase of the energy going into the earth can turn out to be significantly different from the ‘recorded’ sweep. A simple and affordable solution would be to record various parameters of the vibrator behaviour, so that the phase of the energy going into the ground can be measured. All that is required is a commercially available ‘add-on’ pressure sensing plate bolted underneath the vibrator baseplate. This is recommended as part of the specification for a future survey.

Although there is usable energy at the very low end of the 12-120 Hz sweep employed in 1994, it is of relatively little use if there is more energy over a broad bandwidth at higher frequencies. A sufficiently broad bandwidth would be attained by sweeping from 20 Hz upwards to perhaps 100 Hz only. This would also save field acquisition time.

4.2.4 Fold of coverage, binning strategy and offset range

The 130 average fold of coverage obtained in 1994 is clearly far higher than actually needed to achieve good structural information. This extra coverage could be used to analyse azimuthal variations, and to extract as much information as possible from the RCF (see section 4.4.2 below). In a future 3-D survey a 60-fold cover is recommended, with the fold being allowed to drop to as low as 30 in difficult areas. In effect, this would mean shooting a survey like that in 1994, but with half the number of columns being surveyed by the source as were observed in 1994. The rate of progress could then be double that of the rate towards the end of last year's work, in other words about 240 VPs per day.

Hidden within the figure of 130 as the average fold of cover is the fact that each binned trace is the sum of five sweeps. This post-correlation stacking process has increased the signal to noise ratio but appears not to have provided any significant benefit from the longer array thus synthesised (section 3.3.3 above). An alternative philosophy to consider when planning a future survey would be to shoot just one sweep at any one VP. For the same total sweep injection time about five times as many VPs could then be acquired. This leads naturally to the consideration of a quasi-random pattern of sources and receivers, the advantage of which is to allow considerable freedom as to how the data acquired may subsequently be binned. The recommendation that a 60-fold cover will suffice for a future survey may be reformulated as a statement that 300 individual (unsummed) traces per 12.5 m square CMP bin are required, or of the order of 2 traces per square metre. It is further recommended that this trace density be acquired in a quasi-random mode with one sweep per VP.

It is recommended that the offset range employed in a future survey should be of the same order as the present survey, with 90% of the traces in the range 0-600 m (Fig. 16b). This conforms to the rule of thumb that the largest offsets should be of the same order as the depth to the target. However, consideration of alternative acquisition templates to the simple swath pattern used in this trial survey may yield a more even distribution of offsets than the present rather peaked offset distribution (Fig. 16a), in which 50% of the traces are in the 200-400 m offset range.

4.2.5 Recording

A further doubling of rate of progress can be obtained if the receiver spread is specified to be at least 480 channels, i.e. double the number used in 1994. This is not an unrealistic aim and will not reduce the number of industry contractors likely to tender.

In addition to preserving individual sweeps unsummed, the recording instrument should record uncorrelated traces as the archive dataset. This will permit new methods of processing to be applied (some in conjunction with the source signature recording specified above) with the aim of increasing the resolution. The extra cost of recording in this mode is minimal.

4.2.6 Minimising spatial aliasing

The linear arrays of geophones along rows, as used in 1994, are designed to prevent spatial aliasing in the row direction. Synthesis of source arrays along columns helps to give the same effect, so that the two arrays combine to prevent spatial aliasing at any source-receiver azimuth. A future survey design geometry should try to minimise spatial aliasing. A further consideration for the field geometry, whatever type of 3-D template is used, is to couple the source and receiver positions to aid residual statics computations.

Obstructions sometimes forced the geophone pattern to be altered. It was sometimes offset laterally, i.e. fractionally towards a higher or lower row, but still parallel to the rows. If the surface over which the array was to be planted varied by more than 2 m over the 25 m distance, then the geophones were bunched up so that the relative heights of individual elements did not vary by more than 2 m. Enforced gaps, such as roadway crossings, meant that elements had to be bunched on either side. In all cases the aim was nevertheless to obtain the barycentre of the string to be as close as possible to the desired mid-point position.

4.2.7 Migration aperture

Definition of the migration aperture using modern criteria will save field effort. In summary, the aperture need not be as wide as was previously believed to be required, but data will not be compromised by the new method of calculating the aperture. It should be noted that the migration aperture in the 1994 trial survey is not sufficiently large to image steep dips within the BVG.

4.3 Recording logistics

4.3.1 Vandalism prevention

An expensive lesson learned in 1994 was that Nirex is the target of objectors who are prepared to disrupt any scientific work in furtherance of their beliefs. An important part of the specification for a future survey will be ways of minimising vandalism. A continuous watch may have to be kept; this is one argument against the case for speeding up progress by having many more live recording channels, since the effort required in guarding the ground gear would cancel out the potential savings in survey effort.

4.3.2 On-site computing resources

The MESA 3-D survey planning software package, supplied by IMCL during the 1994 survey, proved to be useful in checking for flaws and unforeseen gaps in the coverage being obtained. This type of effort will be needed even more for a large-scale survey, but the field geometry data will have to be entered in advance and then updated. Links between this kind of software package and the general-purpose GIS recommended above should be made well in advance of the survey taking place.

As in modern marine 3-D surveys, much of the processing of a land survey can be done during the course of acquisition. This is most effective if it is done on-site rather than remotely, as was the case in 1994.

4.4 Recommendations for further work on the existing data

4.4.1 Criteria for future surveys

The existing dataset should be reprocessed at a couple of uniform folds of stack, for example 30-fold and 60-fold. This may help to determine whether there is a migration aperture edge effect and, if so, how much it increases with depth.

The central single sweep and the three central sweeps of each VP can be extracted from the field data and used as the basis for reprocessing. This will test how much energy is required and whether the longer array produced by the present 5-sweep sum is degrading steeply dipping data.

4.4.2 Obtaining attributes for the RCF

The 1994 3-D seismic reflection trial dataset over the RCF is probably the most dense coverage of a volume of subsurface ever acquired in 3-D. It offers the opportunity for a variety of further laboratory experiments by processing the dataset in ways designed to extract some of the physical properties of the BVG. Useful by-products of reprocessing will also include a better structural image of the volume and definition of the most efficient way to process any future 3-D data (section 4.4.1 above).

There is a major discrepancy between the LVL statics and those derived by surface consistent residual methods. Application of refraction field statics to the first breaks on the existing dataset may provide a third and better way to solve the statics problem than either of the two methods discussed above.

CMP gathers should be sorted azimuthally so that azimuth-dependent stacking velocities can be estimated. These can then be used in pre-stack migrations to give a 3-D structural depth image at the current limits of seismic exploration technology. The azimuthally and depth-varying velocity field can then be analysed using 3-D interpretation workstation display techniques. Such information will be used as a constraint in the stochastic estimation of the micro-fracture orientation in the BVG and possible three-dimensional variation in poroperm within each formation.

GLOSSARY

The context within a word or phrase as 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*].

Base plate [seismic survey] The rectangular pad underneath a *vibrator*, through which the energy is transmitted to the ground.

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.

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.

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

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

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

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.*

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*.

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.

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

Permitting [seismic survey] The process of arranging the preliminary planning of an onshore seismic survey involving landowners, tenants, the public and relevant authorities, to help to decide where it is possible, practicable and cost-effective to site the survey.

Potential Repository Zone Region in which it is considered that a deep radioactive waste repository might be located.

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.

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 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.

Rock Characterisation Facility The proposed test site at which subsurface investigations of the Potential Repository Zone are proposed to be carried out.

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 for *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.

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.

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

Target [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.

Vibrator [seismic survey] Servo-hydraulic device mounted on a truck or *buggy* 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

AGC	Automatic gain control
ASCII	American Standard Computer Information Interchange [format for computer data]
BNFL	British Nuclear Fuels [plc]
BVG	Borrowdale Volcanic Group
CDP	Common depth-point
CMP	Common mid-point
GIS	Graphical information system
GMT	Generic Mapping Tools (software for the UNIX operating system)
GU	Glasgow University
IMCL	International Mining Consultants Ltd
Nirex	United Kingdom Nirex Limited
PRZ	Potential Repository Zone
RCF	Rock Characterisation Facility
SEG	Society of Exploration Geophysicists
SEG-P1/90	SEG/UKOOA standard for exchange of position data (1990 version)
SEG-Y	SEG standard for seismic exchange data tapes
UKOOA	United Kingdom Offshore Operators' Association
VP	Vibration point