

REMARKS ON 3D SURVEY DESIGN AS APPLIED TO NGAIRE (PML 38141), ONSHORE TARANAKI

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Abstract

All seismic surveys are a compromise between cost and quality. 3D surveys are designed to solve a variety of problems, but most importantly the designs are related to the geology of the prospect.

There are two fundamentals to be addressed.

The first is quite easy — the design criteria. Fundamental rules and 2D experience coupled with dip, depth and azimuth of the target horizon provide the survey dimensions.

The second task is the most difficult and the most important. In order to maximise quality the field approach has to be well planned. This can only be achieved by an experienced team, with a dedication to make things happen efficiently and effectively.

Introduction

This paper describes and explains the process followed in designing the Ngaere 3D survey (PML 38141), which was shot in 1992. 3D surveys are designed to solve a variety of problems, but most importantly they are designed to image the geology of subsurface prospects.

Where the structural aspects of the geology are targeted the surveys are designed to account for structural dip, azimuth of the structural features, stacking velocities, signal-to-noise, subsurface spatial sampling, fold, fringe zones, and interpolation options. When analysing prospects driven by stratigraphy, surveys are designed to account for the required vertical and horizontal resolution, azimuth of the stratigraphic feature, velocities, signal-to-noise, fold, diffraction effects and interpolation options.

Survey design can be optimised by using FD* software on a personal computer. This programme was in continuous use during the design and during the surveying and shothole positioning phases of the Ngaere 3D project. Deviations from desired shothole locations were checked to ensure that fold coverage, offset and azimuth distribution were adequately maintained.

Structural Style

Discussion

It is necessary to check the structural shape and trend of the prospect to be imaged by 3D. The dominant structural strike and dip directions determine the azimuth of acquisition such that rapid acquisition will not jeopardise the desired technical result. In addition, on land, the most efficient use of the 3D

system is to lay out enough lines for at least one day's shooting and recording.

Ngaere Survey Objectives

The Ngaere prospect presented two geological aspects that required simultaneous solution; a deep, steeply dipping structure and shallow, relatively flat stratigraphic traps, both coupled with faulting.

The primary objective of the survey was to image the thrust-folded Tikorangi Limestone, the producing formation in the Waihapa oilfield immediately to the south, and the underlying, structurally conformable Kapuni interval. The secondary objective was the shallower Moki and Mount Messenger sands, which are faulted and gently dipping.

Azimuth of Acquisition

Receiver and shot lines are oriented to optimise technical quality and rapid acquisition. It is very simple to gather steep-dipping, closely spaced data by laying the geophones along the in-line dip direction.

The cross-line orientation is more complex — it is dependent upon the geophone line spacing, the shot point spacing and is very much cost influenced. The cross-line direction should be parallel to the structural axis, which can tolerate a coarser sampling interval. Structural symmetry and/or stratigraphic complexities may require the crossline subsurface sampling interval to be the same as the in-line interval.

Figure 1 generalises the configuration of the Tarata Thrust in the Ngaere area. Because it was the primary objective and

* Proprietary name for a 3D field design programme developed by Seismic Imaging Software Ltd

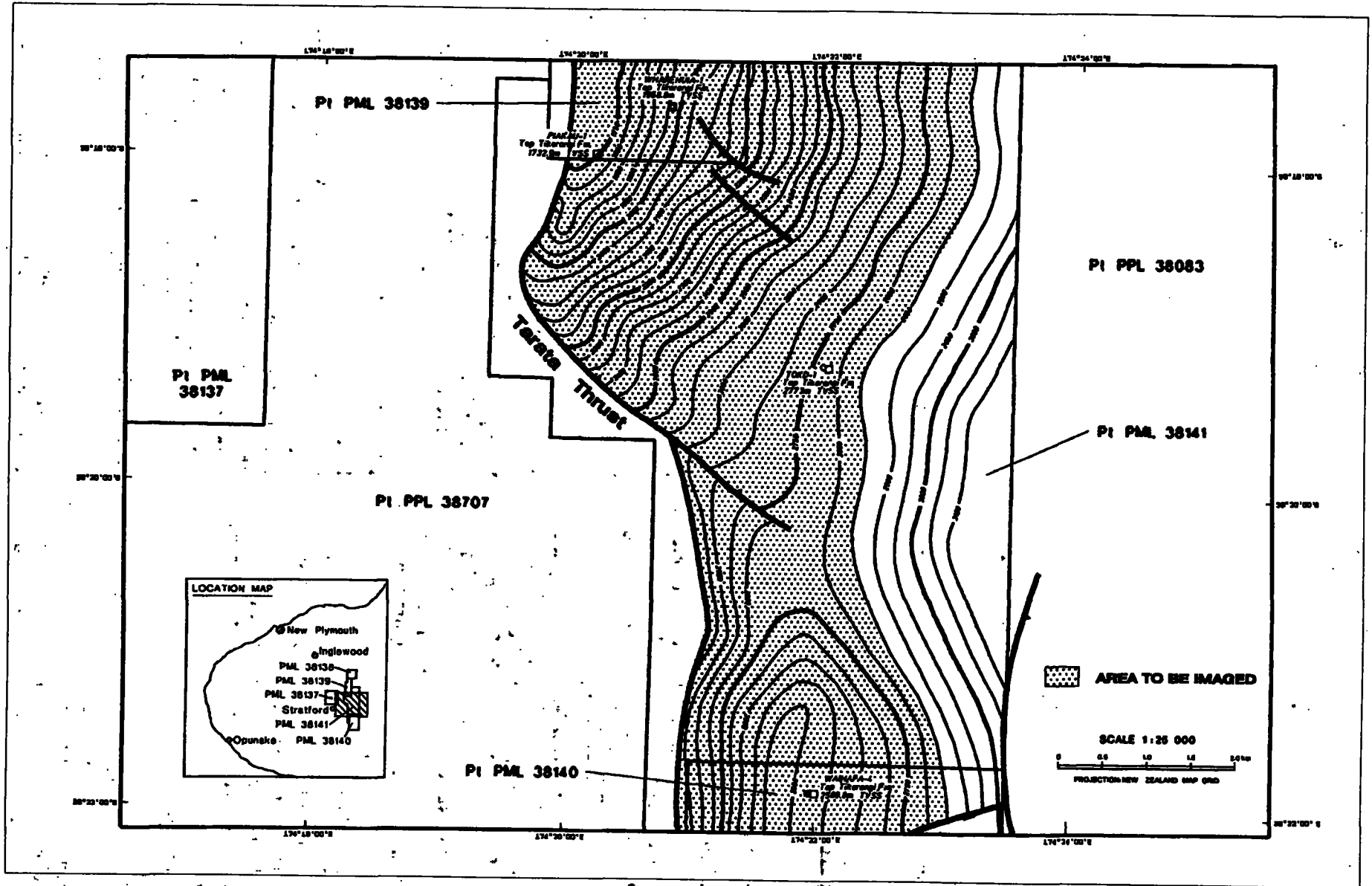


Fig. 1. Depth contours on Top Tikorangi Formation. This is the economic level which drove the 3D design. It also shows the area to be imaged and the structural style for the main level of interest.

more structurally complex than the secondary objective, the shot and receiver line azimuths were dictated by its shape and dimension. The dip component is strongly east-west, so the receiver lines were oriented in that direction, with the shotlines oriented north-south.

Area to be Imaged

The area to be imaged is the area in which a fully 3D migrated dataset is required of the features of principal interest.

At Ngaere the area to be imaged was determined solely by the limits of the Tarata Thrust at Tikorangi level. The area to be imaged occupies 22 km² (figures 1 and 2). To the west the area is bounded by the Tarata Thrust, 2300-3300 m subsurface, and to the east by the predicted oil-water contact at 3100 m subsurface. The structure dips 30° to the east. The dips and forecast dip diffractions from the Tarata

thrust front together dictated that the acquisition area must be significantly larger than the area to be imaged, to allow for migration distance (aperture).

Migration Distance (Aperture)

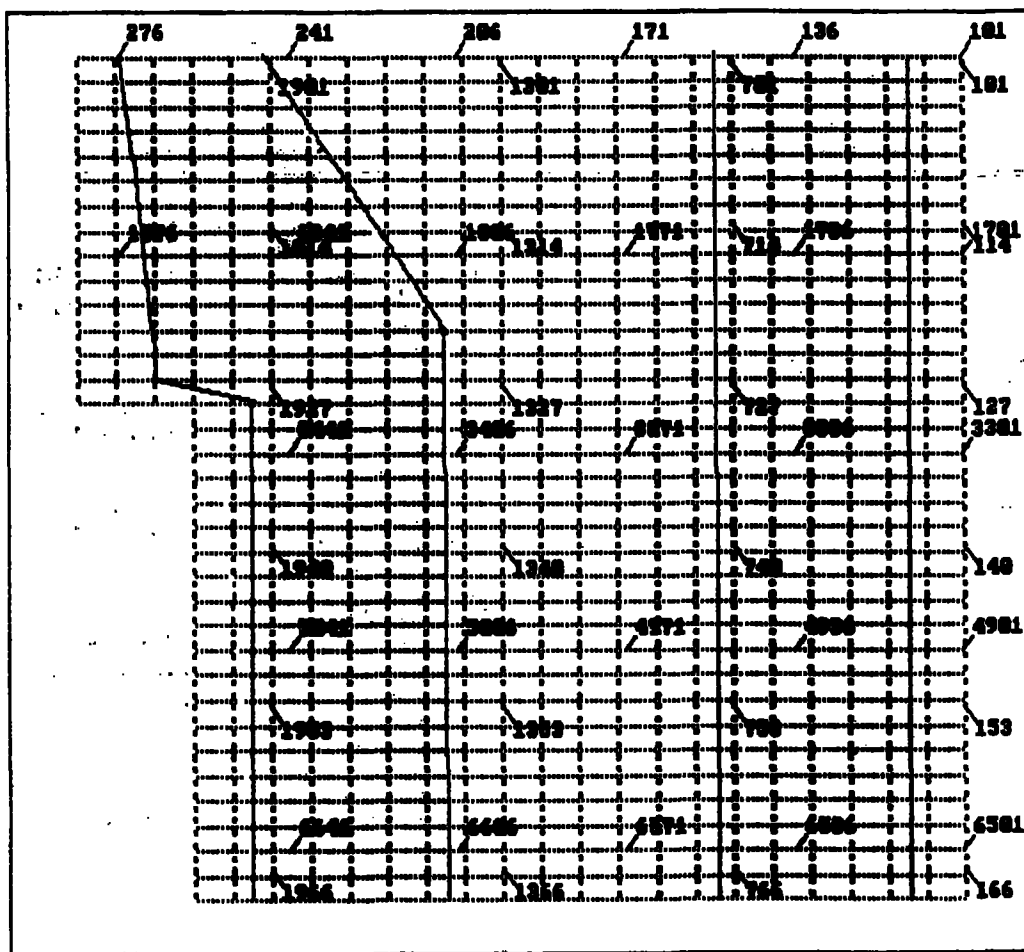
Migration distance is the maximum distance an event will move during migration. It is a function of target depth and maximum target angle. Two factors must be taken into account :

- The distance applies from the extremity of the area to be imaged
- Deeper events with less dip may enlarge the survey area by a greater amount. This is because the greater depth may be of more significance than the magnitude of dip.

Migration distance is provided by :

$$XMig = 2 \times \text{TAN } \phi$$

Where XMig = migration distance



- Target dimension
- Migration distance dimension
- Fringe zone dimension

Fig. 2. The areal extent of the survey expands to accommodate dip, fresnel zone, and edge effects.

X = depth to target
 ϕ = maximum dip at target

The migration distance is important as this is the amount by which the area to be imaged must be expanded. It has a tremendous influence on the cost of a survey.

Diffraction patterns have to be analysed in determining the migration distance; they can be treated as dipping events. An examination of unmigrated 2D data provides information as to the migration distance required to adequately capture them. A simplistic approach is to compute the diffraction dip at the point where the rate of change of slope appears to be at a maximum. It is rarely necessary to capture the maximum dip value as the diffraction velocity increasingly differs from the associated migration velocity towards the diffraction tail.

The migration distance chart, indicated that at 3100 m subsurface the receiver lines had to be extended 1800 m, both east and west, in order to capture 30° dips (figure 3). A check on an unmigrated 2D line across the prospect (figure 4) confirmed that this dimension was adequate to capture both structure and diffractions for restoration and collapse after migration.

At Ngaere an additional 27 km² of acquisition area was required (figure 2). The survey was expanded to provide a fringe zone.

Fringe Zone

The survey area was also extended to the fringe zone. This extension is measured by calculating the radius of the Fresnel Zone for the target of interest.

$$\text{Fresnel Zone Radius} = \frac{V \times T}{2 \times S_F}$$

Where T = Seismic travel time in seconds
V = Seismic RMS velocity
F = Frequency in hertz

By adding the fringe zones, undesirable edge effects are moved outward from the edge of the 3D dataset. On land some savings can be gained by shooting through the spread to build-up fold in the fringe zone.

To accommodate the fringe zone at Ngaere an extra 600 m was added at the eastern and western ends of each line and 400 m at the northern and southern ends. For Ngaere the survey area grew to 58 km² (figure 2), some 2.64 times the size of the area to be imaged. This necessary expansion of the survey area continually directs focus on the need to compromise between the cost and the quality of 3D surveys.

Sub-Surface Sample Spacing

Sub-surface sample spacing is a critical factor in the design of 3D surveys. The steeper the dip, the closer the sub-surface spacing. The cost of acquisition and processing must be weighed against the need to provide a sample density that will adequately describe the sub-surface features and prevent migration aliasing. Consequently, most 3D surveys are a compromise between cost, resolution and sample aliasing problems. To achieve the correct balance is difficult.

Very often it is sufficient to work with the horizon of steepest dip because the shallower horizons exhibit significantly less dip. When this is not the case then shallower dips become critical and must be analysed.

There are two ways to calculate the sub-surface spacing. The first is to use the RMS velocity, the maximum frequency at the target level and the dip at the target level.

$$\text{Sub-surface spacing} = \frac{V_{\text{RMS}}}{4 \times F_{\text{MAX}} \times \sin \phi}$$

Where V_{RMS} = RMS velocity to target level
F_{MAX} = Maximum frequency in hertz at target level
 ϕ = Maximum dip angle at target level

The second way to calculate the sub-surface spacing is to use the target zone frequency content to calculate the time difference between traces. This value when coupled with dip determines the sub-surface spacing.

$$\text{Time difference } (\Delta T) = \frac{1000}{2 \times F_{\text{MAX}}}$$

Where F_{MAX} = Maximum frequency in hertz at target level

To find the sampling interval, select the appropriate frequency, read off the ΔT and apply the following formula

$$\Delta T = \frac{2 \times \text{Sample Interval} \times \sin \phi}{V_{\text{RMS}}}$$

Where ΔT = Time in milliseconds between adjacent traces

ϕ = Dip angle at target level
V_{RMS} = RMS velocity

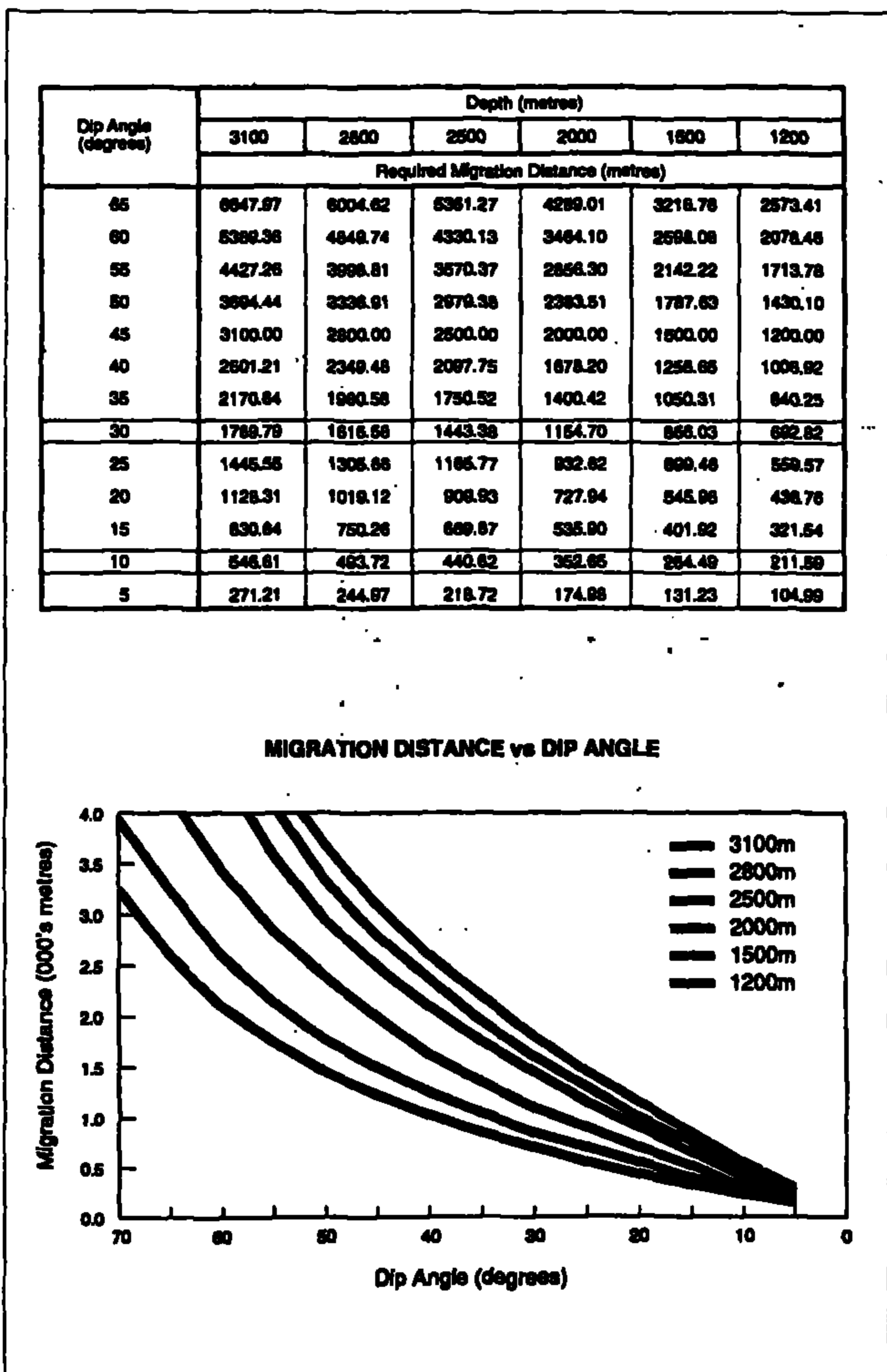


Fig. 3. Example of chart and graph to ready reference survey expansion to accommodate anticipated reflection dip angle.

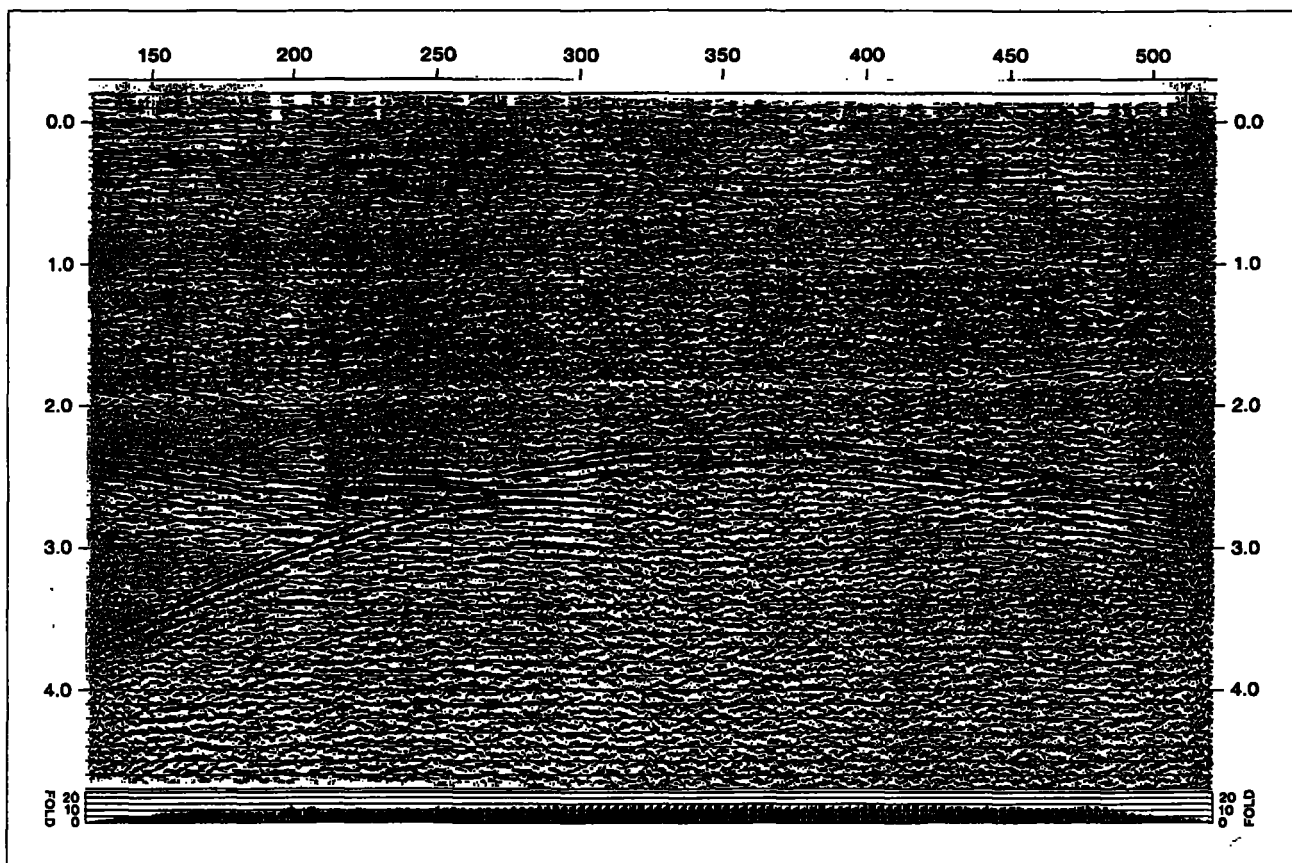


Fig. 4. Example from within the survey area of an unmigrated seismic line to check whether the survey area is wide enough to support calculations from figure 3.

Rearranging :

$$\text{Sample interval} = \frac{\Delta T \times V_{\text{RMS}}}{2 \times \sin \phi}$$

At Ngaere, the geophone group intervals required to capture 30° dips at the Tikorangi level were calculated assuming,

$$\begin{aligned} \text{Velocity} &= 3400 \text{ m/sec} \\ \text{Frequency} &= 45 \text{ HZ} \\ \text{Dip} &= 30 \text{ degrees} \end{aligned}$$

Figure 5 computes a sample interval not greater than 37.78 m. The geophone group interval is calculated as twice the subsurface sample interval. In reality a geophone spacing of 50 m was preferred. This could capture up to 50° dips, assuming signal content of 45 hertz.

At Ngaere, structural mapping indicated that along-strike dips greater than 10° would be rare, but cross-faulting could be common. Shot spacing was set at 100 m, representing a sample interval of 50 m. Figure 6 demonstrates how a change in velocity-down-to can change the sample interval.

Bin Dimension

Bins (boxes) are the 3D building blocks that determine the number and spacing of subsurface sample points. For the ideal survey they must be acquired symmetrically. Once again, the designer must address cost versus quality and imaging decisions. After acquisition the bin dimensions can be changed to expand or contract the size of the bins into which the traces are gathered. The designer has the choice to fractally bin or to superbin. Reduction in bin size will reduce fold. Either way may be of assistance in the processing and interpretation.

Alternatively, subsurface density may be increased after acquisition by trace interpolation. This process builds an in-between trace by using the signal content of adjacent traces. At Ngaere the acquisition bin dimensions were set at :

$$\begin{aligned} \text{East-west} &= 25 \text{ metres} \\ \text{North-south} &= 50 \text{ metres} \end{aligned}$$

Line Spacing

Line spacing influences fold and the coarseness of the acquired data, particularly for shallow horizons. Use of the FD tools programme allows the survey designer to simulate the options and cost the result. Experience from the 1990 Waihapa survey dictated a reduction in line-spacing by a factor of two. Thus at Ngaere shot lines were spaced 400 m apart north-south, and receiver lines 200 m apart east-west.

Fold

One effective way to reduce the cost of a 3D survey is to reduce the amount of fold. This is a difficult step to take as it means escaping from the comfort of previous 2D experience. The goal is to ensure that reduced fold does not result in an inferior product. Fortunately, today, we have many processing facilities that favourably compensate for reduced acquired fold. The following are to be taken as general guidelines that alert the thinking process when considering fold.

- a) When deciding on the fold level the paramount reason for designing the survey must be kept in mind. If the shallow events are not the economic driver then it is a waste of money and effort to enhance fold at that level.

Dip Angle	Frequency							
	80	70	60	50	45	40	35	30
5	121.90	139.30	162.60	195.10	216.80	243.90	278.70	325.10
10	61.20	69.94	81.60	97.92	108.80	122.40	139.90	163.20
15	41.06	46.93	54.75	65.70	72.99	82.12	93.85	109.50
20	31.07	35.51	41.43	49.71	55.24	62.14	71.02	82.86
25	25.15	28.74	33.53	40.23	44.70	50.29	57.48	67.05
30	21.25	24.29	28.34	34.01	37.78	42.51	48.58	56.68
35	18.53	21.17	24.70	29.64	32.94	37.05	42.35	49.41
40	16.53	18.89	22.04	26.45	29.39	33.06	37.79	44.09
45	15.03	17.18	20.04	24.05	26.72	30.06	34.35	40.08
50	13.87	15.85	18.50	22.19	24.66	27.74	31.71	36.99
55	12.97	14.83	17.30	20.76	23.06	25.94	29.65	34.59
60	12.27	14.02	16.36	19.63	21.81	24.54	28.05	32.72
65	11.72	13.40	5.63	18.76	20.84	23.45	26.80	31.27
70	11.31	12.92	15.08	18.09	20.10	22.62	25.85	30.15

Fig. 5. Spatial sampling requirements Vmax 3400 m/s.

Dip Angle	Frequency							
	80	70	60	50	45	40	35	30
5	86.07	98.36	114.80	137.70	153.00	172.10	196.70	229.50
10	43.20	49.37	57.60	69.12	76.80	86.40	98.74	115.20
15	28.98	33.12	38.64	46.37	51.53	57.97	66.25	77.29
20	21.93	25.07	29.24	35.09	38.99	43.87	50.13	58.49
25	17.75	20.29	23.67	28.40	31.55	35.50	40.57	47.33
30	15.00	17.15	20.00	24.00	26.67	30.01	34.29	40.01
35	13.08	14.95	17.44	20.92	23.25	26.16	29.89	34.87
40	11.67	13.34	15.56	18.67	20.75	23.34	26.67	31.12
45	10.61	12.12	14.14	16.97	18.86	21.22	24.25	28.29
50	9.792	11.19	13.06	15.67	17.41	19.58	22.38	26.11
55	9.157	10.47	12.21	14.65	16.28	18.31	20.93	24.42
60	8.661	9.899	11.55	13.86	15.40	17.32	19.80	23.10
65	8.276	9.458	11.03	13.24	14.71	16.55	18.92	22.07
70	7.982	9.122	10.64	12.77	14.19	15.96	18.24	21.29

Fig. 6. Spatial sampling requirements Vmax 2400 m/s.

- b) Examine previous surveys. If not available, test reprocess 2D data. Reduce the fold by throwing out every other trace; compare the results.
- c) Remember signal-to-noise ratio. Simplistically this means energy and noise levels on a given trace. The aim of 3D is to produce a dataset in which the interpreter is sufficiently confident to produce a good geologic solution. If the confidence factor is high then the dataset is perceived to have a good signal-to-noise ratio irrespective of what the individual traces tell us.
- d) A reduction of fold to one half of that used for 2D acquisition is generally safe.
- e) Reduced fold at shallow levels tends to produce a coarseness in the stacked data. Stacking assumes that the same signal is on every trace and that noise is random. This is not always so. Therefore low fold areas of low dip may produce seismic artefacts that may confuse subtle stratigraphy.
- f) With more complex geology more fold is required to adequately determine static and velocity solutions. A similar weight of in-line and cross-line fold is best for residual statics. This is because a wide range of shot-to-receiver azimuths can be collected. However, in areas of steep dip a good velocity solution may be compromised, thereby incurring unnecessary increased processing costs.
- g) Shot and receiver line spacing governs the fundamental fold, operational efficiency, technical merit and cost.
- h) The dimension of the shot patch has an impact on fold. It also impacts on the static solution and the velocity solution because of the cross-line shot-to-receiver azimuths.
- i) In order to cancel source generated noise and multiples, cross-line fold may require the staggering of cross-line shots. This will increase acquisition costs.
- k) Check the stacking mute before settling on fold. There is no point shooting into traces that will not be live at the target level.
- m) Bear in mind the use of fractal binning. For velocity and statics analysis the fold power can be increased by enlarging the in-line bin dimensions. This will increase the cost of processing but will tend to give a more satisfactory solution. Remember to preserve spatial sampling by fractally binning down to desired bin dimensions.

Fold at Ngaere

Since 1971 several surveys have been shot in the Ngaere area. Figure 7 was shot 6-fold in 1973, using pattern holes with a dynamite source. The energy level is good, and in spite of low fold, shallow events are identifiable. Figure 8 was shot 20-fold using 2 kg charges with grouped phones. The energy level is good, and shallow events are identifiable. Continuity is not good, probably indicating static and velocity problems. Figure 9 is a 15-fold line shot in 1984 using single

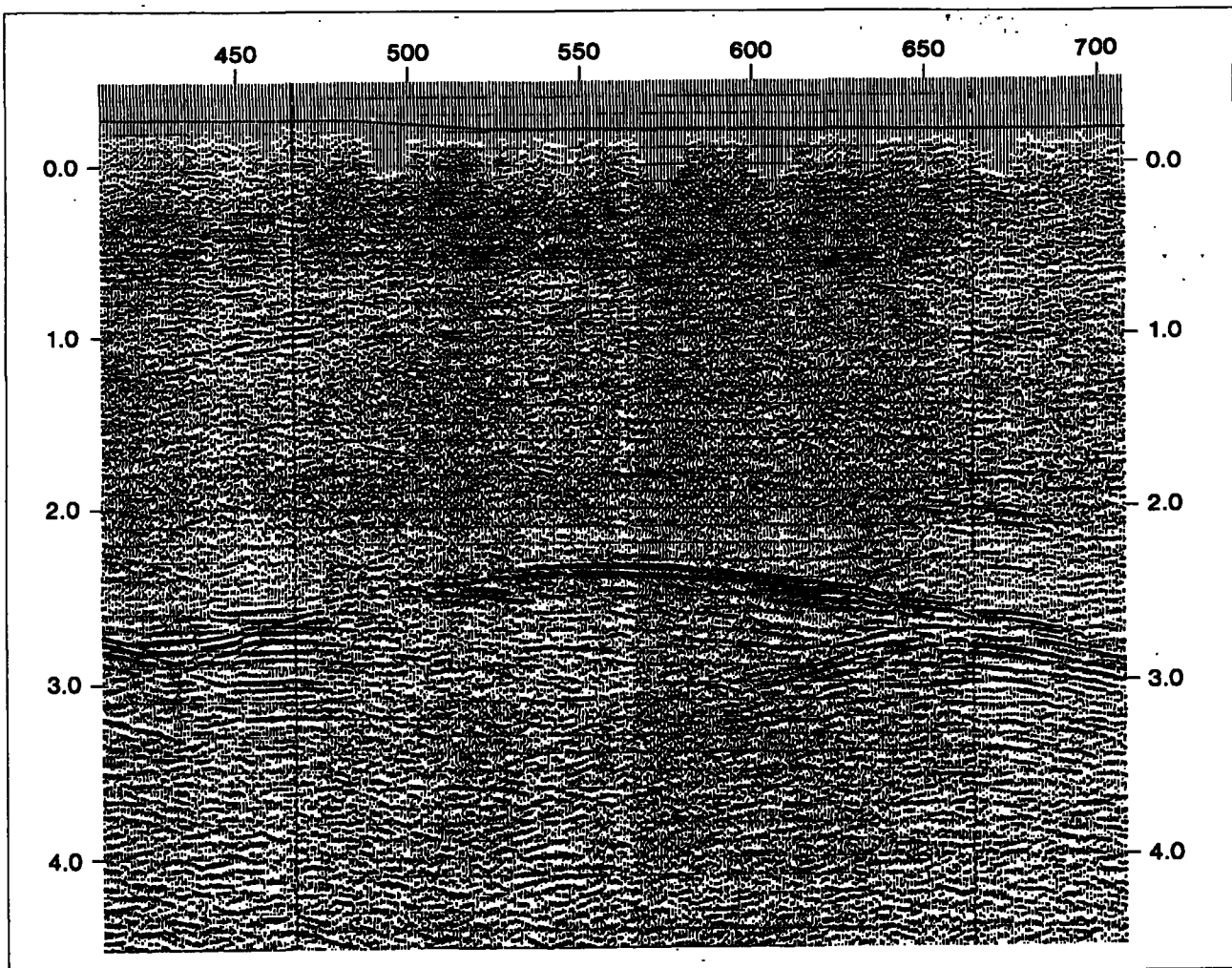


Fig. 7. A check on previously acquired seismic will provide a base level from which to build 3D fold. This is 6-fold 2D data. Energy level is reasonable and shallow reflectors are apparent.

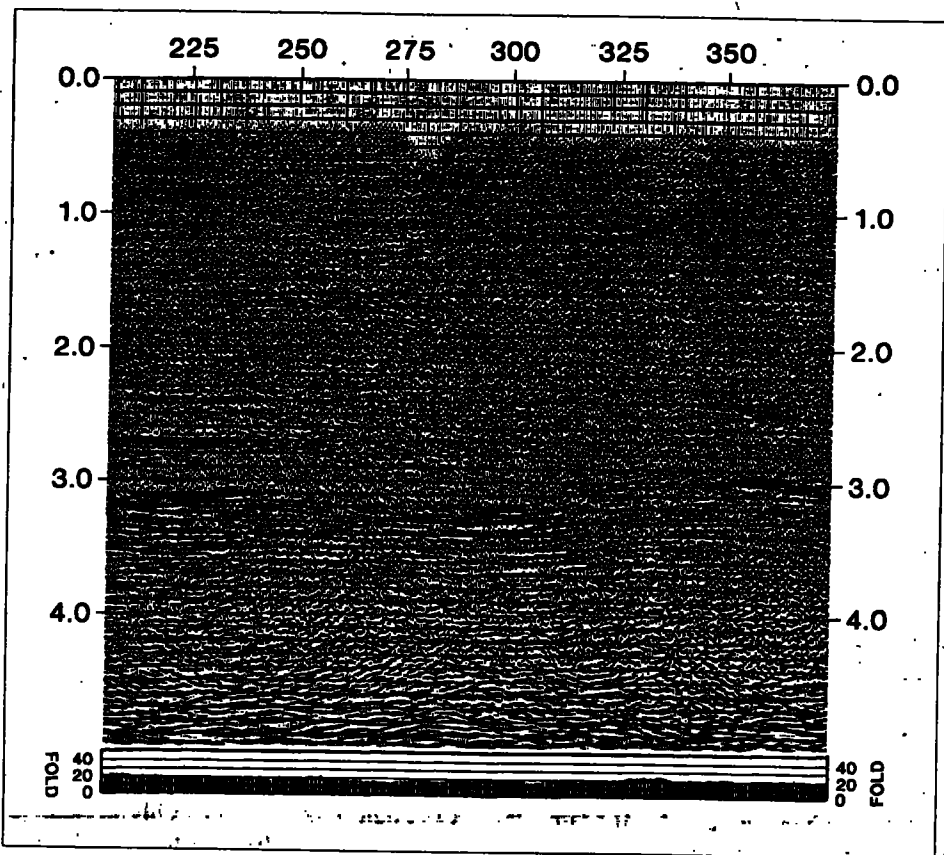


Fig. 8. A 20-fold 2D line shot with 2 kg charge. Energy level is reasonable. Reflectors are apparent but they suffer from inadequate static and velocity control.

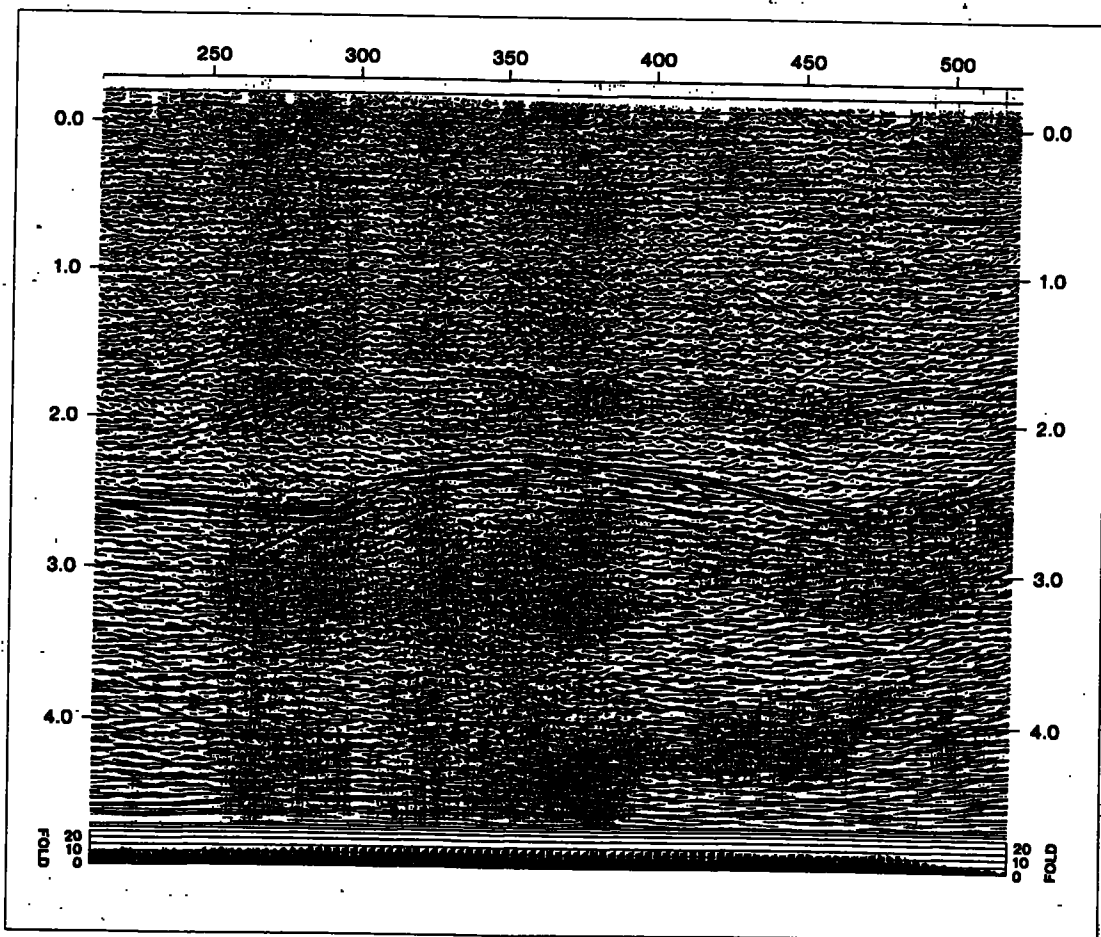


Fig. 9. A 15-fold 2D line with good energy level and identifiable shallow reflectors. There are also apparent problems with statics and velocities.

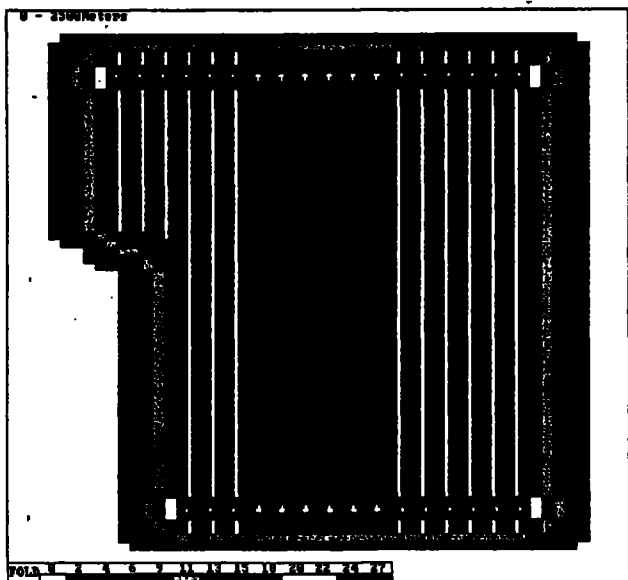


Fig. 10 At any nominated offset the fold level can be checked. The fold level is at 2500 m (top Tikorangi level) using a recording patch consisting of 6 lines each having 96 geophone groups.

holes with a 10 kg charge. Energy level is good and shallow events are identifiable.

From the above it was concluded that 15-fold 2D data provided a base from which to design a 3D dataset to image the steeply dipping Tikorangi limestone.

Each trial was plotted to examine the fold at different levels; examples of which are given by figures 10 and 11. The areal distribution and distances between the subsurface sample points is given by an example of the mid-point distribution plot (figure 12). To check the orientation of shot receiver pairs that make up each bin star-plot azimuths are displayed (figure 13). Figure 14 is an example of the offsets of shot

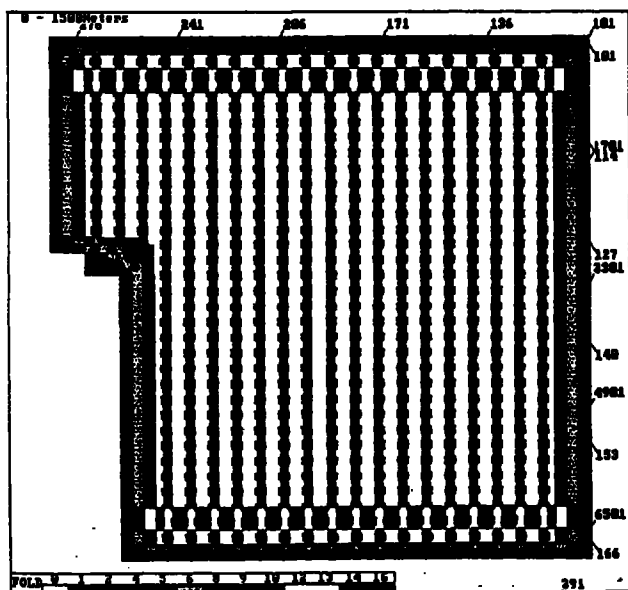


Fig. 11. The fold level at 1500 m having the same patch configuration as for figure 10.

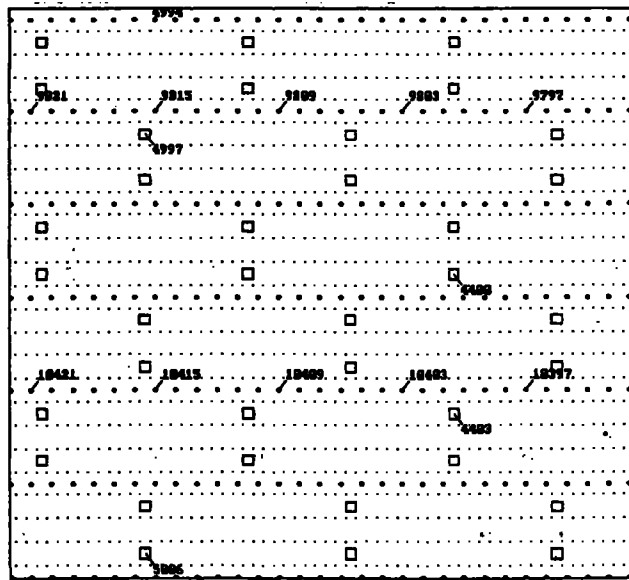


Fig. 12. An example from within the survey of the distribution of the mid points of the 25 m by 50 m bins. Each midpoint is the summation of traces falling within the respective bin. A lack of symmetry for bin spacing may require an infill for extra shots.

receiver pairs; i.e. the range of distances between shots and receivers that make up each bin. Figures 15 and 16 are examples of the layout of field geophone patches into which selected shots are fired.

Processing of successive generations of Ngaere area data has been plagued by static and velocity problems. Therefore, to maintain cross-line fold balance the swath was moved one line at a time. At Ngaere the FD programme enabled different combinations of numbers of lines and numbers of geophones per shot to be tested. In determining the shot and receiver combinations the logistics of moving the appropriate volume of field equipment was borne in mind, as was the ability of the field crews to move rapidly across the ground.

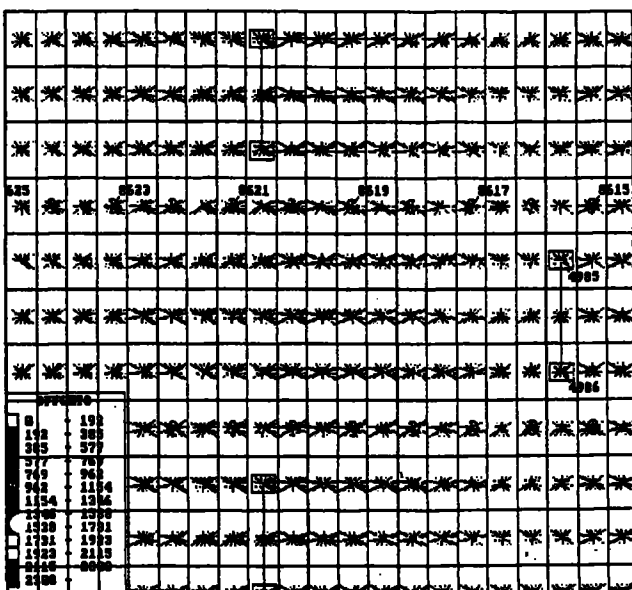


Fig. 13. A plot of the azimuths within selected bins. It shows the points around the compass from where different shot and receiver pairs come from to make up a midpoint bin summation.

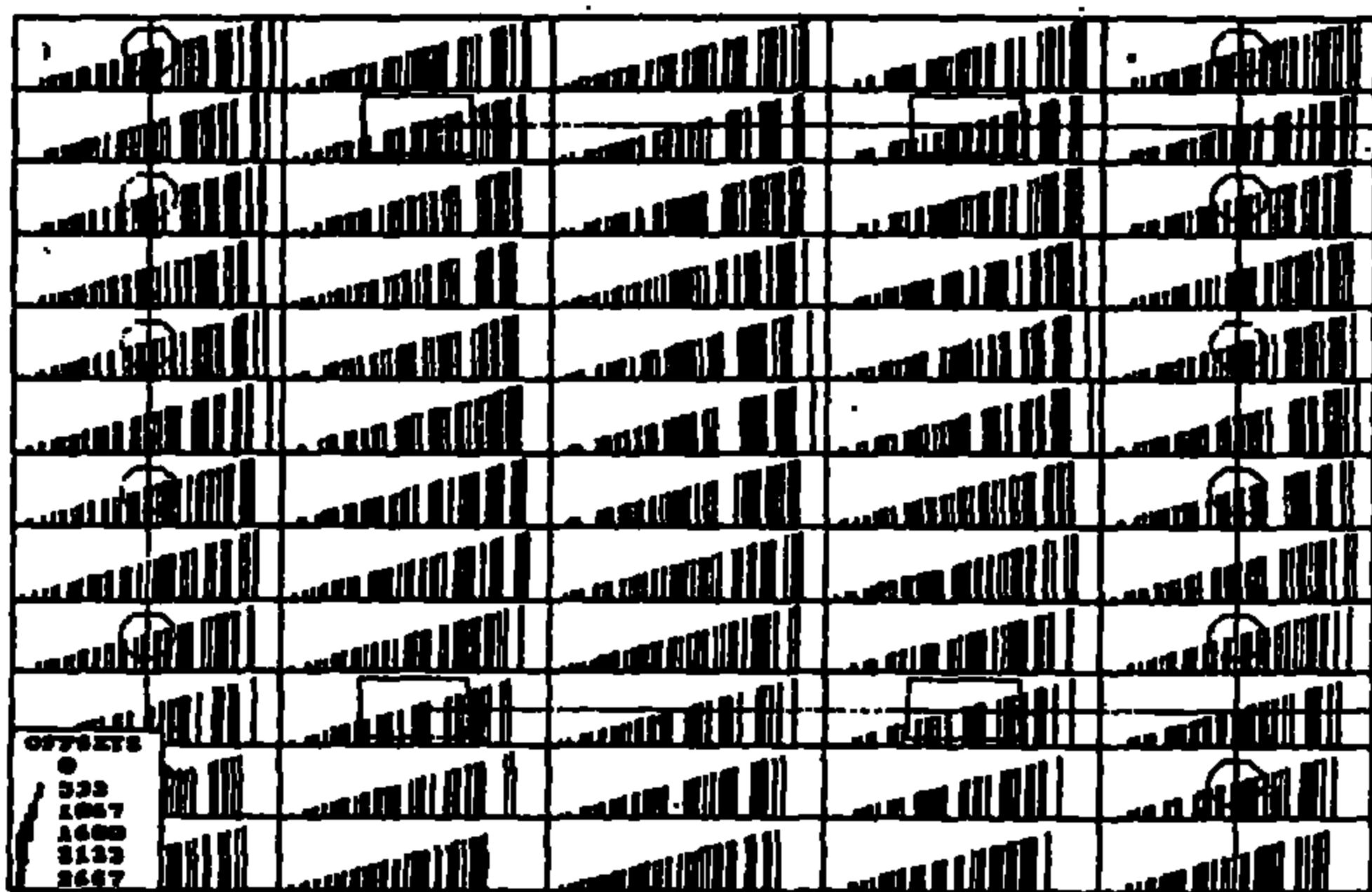


Fig. 14. The offset distribution is a display of the distances between shot and geophone pairs making up a bin summation. The aim is for an even distribution of offsets.

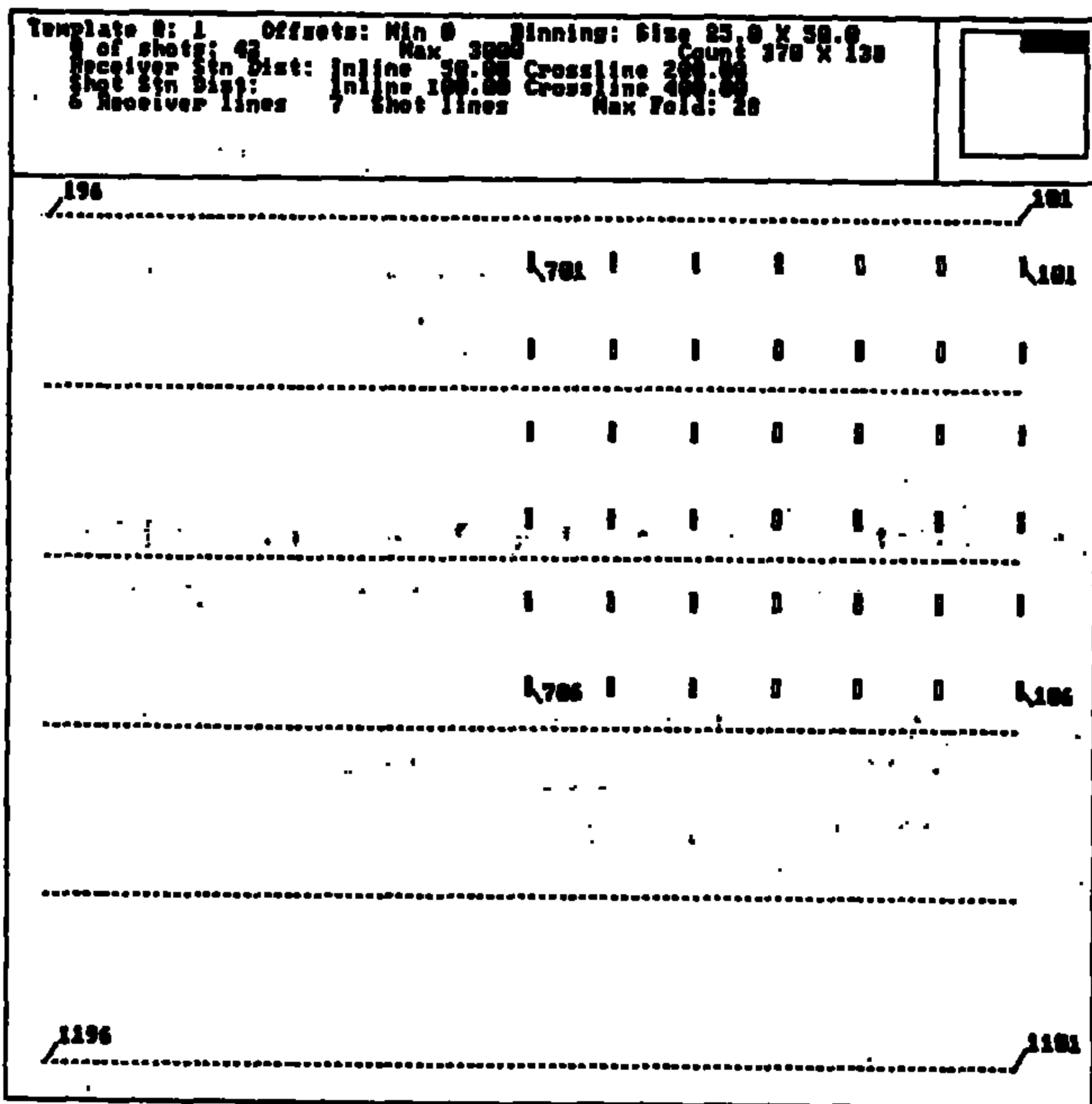


Fig. 15. Individual template showing selected shot receiver combination. Once the shooting procedure has been decided a template can be produced for each shot and receiver patch. The template shows number receiver lines, shot lines and fold level.

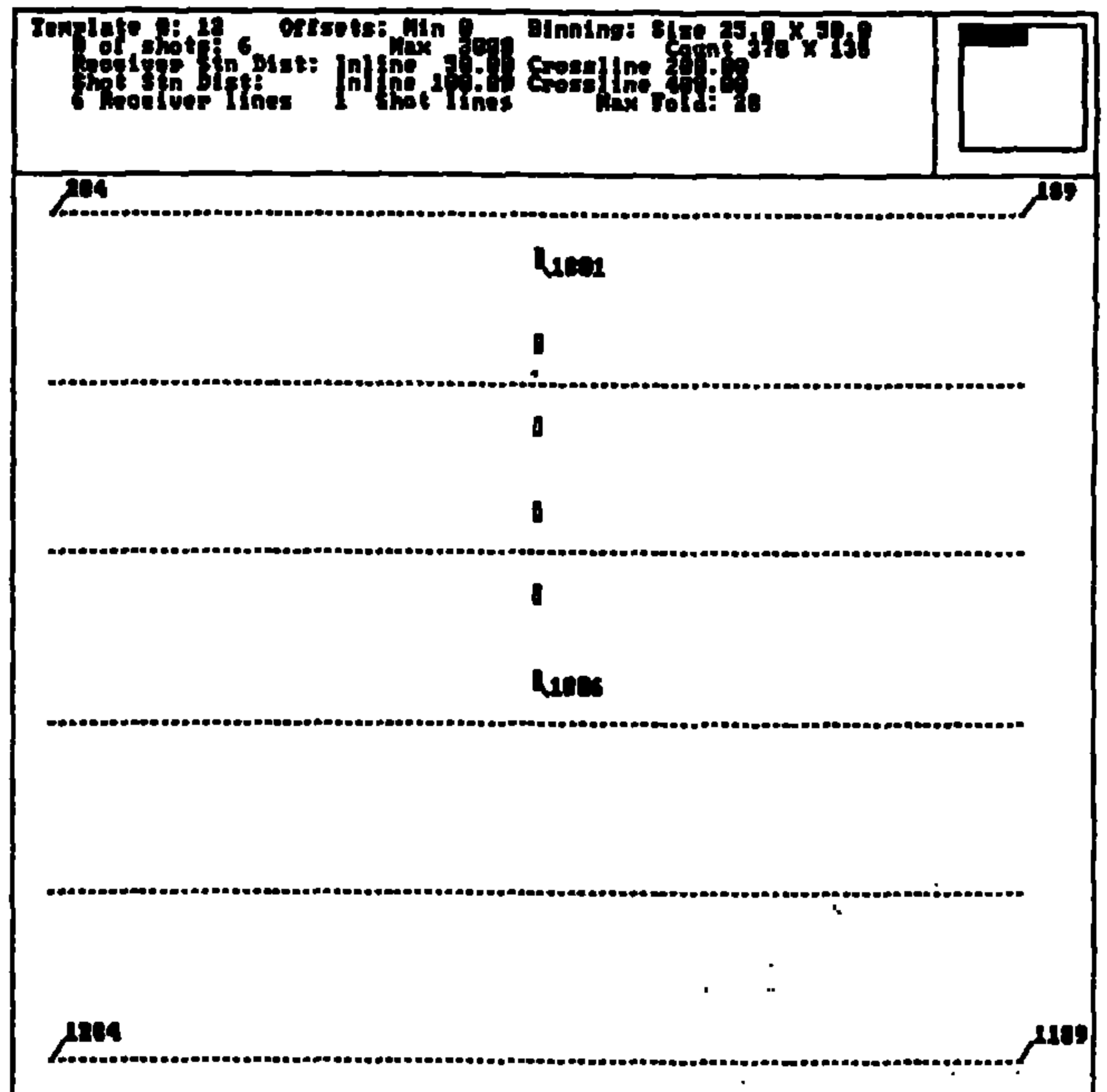


Fig. 16. Selected template progressing through the 3D survey the number of shots into each patch will change.

Other Factors

Dynamite charge size was set at 4 kg, loaded into 20 m deep holes. A containing tamp of pea gravel was used.

The spectral shaping filter of the Input/Output System One recording system was selected, to enhance high frequencies.

Conclusions

The use of FD software very efficiently enabled numerous alternative survey designs to be simulated and evaluated for effectiveness and cost.

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Ian has resided in Australia, U.S.A., Holland, England, Singapore, Indonesia and Tunisia. His previous employers were Tenneco Oil and Union Oil of California.