HOW TO OPTIMIZE 3-D SEISMIC LAND SURVEYS – SOME RULES FOR AREAL DATA GATHERING

by

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1. INTRODUCTION

Relevant publications on 3-D data collection have been scarce from the beginning as compared to the spectacular literature and almost hectic activity in the field of 3-D processing.

Areal data collection problems have hardly entered the consciousness of a broad geophysical public. Time seemed to be ripe to the author, therefore, to compile a kind of compendium of the specific rules for areal data gathering needed to optimize the data and procedures of 3-D land seismic surveys which have been developed by us during the last five years.

2. AREAL TECHNIQUES OF DATA GATHERING

Basically there are only two different methods for 3-D data gathering: the parallel-profiling (PP-)method and the cross-array (XA-)method.

2.1. PARALLEL-PROFILING METHOD

A large number of parallel lines successively surveyed in the conventional manner – if possible at intervals equalling the line station interval – would finally yield the surveyed area. Such a technique would be very uneconomical for land surveys. It is a standard, however, in marine surveys, in particular in the variation of the so-called Swath-Method if use can be made of the streamer feathering produced from tidal or general cross currents. In this case a strip (or a swath) of more or less constant width is unilaterally recorded. As offshore 3-D surveys are not the topic here, we can immediately pass over to the discussion of the other basic method, which represents the fundamental form of nearly all our areal land seismic surveys.

2.2. CROSS-ARRAY (XA-)METHOD

The many variants of the cross-array method are all reducible to the crosswise configuration of a receiver line and shotpoint line. The well known diagram in fig. 1 shows equally spaced geophone stations which respond to 24 shotpoints arrayed along the midpoint perpendicular. The corresponding data point area is a square. The data points are the midpoints of $24 \times 24 = 576$ emitter-receiver configurations and are organized in 24 24-trace seismograms parallel to the geophone line. In the upper time range the amount of information from the outer data points is markedly reduced as compared to the inner ones. This is the consequence of the large lateral offsets between the receiver line and the outer shots.

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When the shot traverse is shifted sidewards over 12 geophone stations and the geophone line correspondingly moved forward, an areal "continuous profiling" is achieved analogous to the line survey procedure. When these steps are reduced to one station interval, the areal equivalent of 12-fold linear coverage is achieved in the geophone line direction x. In contrast, only a single coverage in y (parallel to the shot traverses) is achieved.

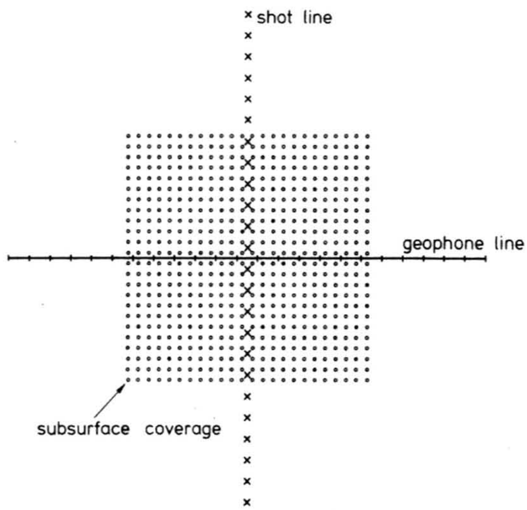


Fig. 1 Crossed (or X-) Array

If the geophone line were deployed 12 times successively in parallel, at a spacing equal to the station and shotpoint intervals and recorded from repeatedly used shotpoint positions, a 12-fold roll-along in y would result. The combination of both, i.e. the total coverage, would be 144. Of course, nobody would apply such an excessive coverage, but the principle which we employ in our areal surveys thus is shown up; e.g. 3-fold in x times 3-fold in y, producing a total 9-fold. As the number of seismic channels used nowadays in areal surveying has increased to 120, 240, 360 and even to 480, the two-directional roll-along system is entirely feasible, even from the economical point of view.

3. GUIDE FOR AREAL DATA GATHERING

From experience and the search for better solutions to the problems arising with a new method, a guide has been compiled which may serve as a standard for checking the suitability of new designs and field parameters. This guide comprises six main points to be observed. The first four points are relevant when drafting a specific and individual design. Points 5 and 6 are generally to be observed in areal surveys. The points are:

1. Adequacy of temporal and spatial sampling.
2. Shaping and dimensioning the field layout.
3. Orientation of the field layout.

4. Areal roll-along in x- and y-directions.
5. Accuracy requirements in station positioning.
6. Areal receiver patterns for omnidirectional effectiveness.

At the beginning of an areal survey the degree of resolution has to be defined which is required for the proper solution of the respective problem; that means: a decision has to be made as to the choice of the temporal and spatial sampling rates. The proper use of the sampling rates may be crucial for the final costs of an areal survey. A decision to employ 2 ms for a deep target where 4 ms would be adequate may double the costs when otherwise the number of channels available could have been doubled. Even more cost-effective ist the choice of an unnecessarily small spatial sampling rate. A data grid scaling of 20 m, where 40 m would do, would quadruple the costs. On the other hand an improper resolution caused by too large a temporal or spatial sampling rate may even mean wasted money when the problems remains unsolved due to oversized sampling rates.

The number of recording channels available immediately influences costs and design for an areal survey. For a given stack multiplicity the numerical product of the number of receiver groups times the number of shots to be recorded is a constant. 240-channel recording saves half the shotpoints and thus reduces the fieldwork time by half as compared to 120-channel recording. 480-channel recording seems to be an optimum: it can still be handled in the field and may pay off when the duplication of the stack multiplicity, e.g. 12-fold instead of 6-fold, would remarkably increase the stack quality. The design of an areal survey, i.e. the shaping and dimensioning of the field layout, may widely depend on the terrain encountered, but it certainly also depends on other points of view to be discussed in detail.

The orientation of the field layout must be seen in close relation to the geological strike direction: the geophone field extension in dip direction may be decisive to avoid difficulties in later data processing.

Roll-along field procedures in two directions, i.e. in x-direction parallel to the receiver line layout, as well as in y-direction parallel to the shotline layout, is considered to be of extreme importance and is treated therefore in great detail.

3.1. TEMPORAL AND SPATIAL SAMPLING

Time sampling rates of 1, 2, or 4 ms are familiar from line seismics. They are related to distinct high-cut frequencies of 250, 125, and 62.5 Hz, respectively. This filter setting is made in order to cut off frequencies beyond the relevant Nyquist frequencies of 500, 250, and 125 Hz, which otherwise might produce aliasing noise within the required frequency range of the signals.

The size of spatial sampling is defined by the intervals between receiver stations (Δx) and shot positions (Δy), or, more generally, by the scaling of the subsurface data grid. The problem of the adequacy of spatial sampling is seldom realized when fixing the respective parameters of a 2-D line survey, simply because the station intervals normally chosen in line seismics are considerably smaller as compared to areal seismics. This means that the aliasing problem which may arise when 2-D migration is applied to conventional stacked sections is seldom encountered. In principle, however, the effect of too large a spatial sampling rate would be the same in 2-D as in 3-D migration. Migration involves a re-sampling from a stacked trace to another one; the larger the dip of the horizons to be migrated, the more sensitive are the data against spatial aliasing. It is the migration process which discloses whether or not a small enough spatial sampling had been employed. If not, aliasing appears in the migrated sections: the resolving power still present in the stacks is considerably reduced, resulting in a mix of low-frequency signals and low-frequency alias noise. This means that the spatial Nyquist frequency (or wave number) is exceeded when less than two samples have been used to pick up the minimum apparent wavelength of the seismic spectrum present.

The relationship to be strictly observed between

- ○ maximum spatial sampling rate a_{max} (in m) of the data grid,
- ○ stacking velocity v_{st} (in m/s),
- ○ highest serviceable frequency f_{max} in the seismic signal expected which is immediately indicative of the temporal sampling rate to be applied, and the
- ○ maximum admissible dip α of the signals

is given by the equation

$$a_{max} = \frac{v_{st}}{4 \cdot f_{max} \cdot \sin \alpha_{max}} \qquad (1)$$

In case the maximum signal frequency recorded exceeds the value determined by a_{max}, v_{st} and $\sin \alpha_{max}$, the respective high-cut frequency filter must be applied to the stacked data before migration in order to avoid the detrimental aliasing effect.

3.2. SHAPING AND DIMENSIONING THE FIELD LAYOUT

A 3-D survey concept begins with outlining the area under discussion. This area is then subdivided into strips to be successively surveyed. Each strip is built up by a number of blocks, a block being the system unit. Shape and dimensions of a block depend on the depth of interest to be explored and on the resolution required. Shallow targets normally require high resolution, and, in general, the respective blocks are rather small and of square shape. Targets at depths of 2000 m to 3000 m and more require larger dimensions and rectangular block shaping, because greater depths require increased efforts in the suppression of multiple reflections.

In conventional 2-D multiple coverage surveys shot-receiver distances comparable in size to the depths of interest have been the standard answer to this problem. The number of *different* shot-receiver distances involved equals the number of receiver stations used, in the case when unilateral recording is applied. Linear increments in the shot-receiver distances cause squared increments in the respective NMO-values. Consequently the amplitudes of the multiples can only be insufficiently attenuated by destructive interference.

In an areal survey the number of different shot-receiver distances equals the product of the number of different shot-receiver distances in x-direction times the number of different shot-receiver distances in y-direction minus a number of multiply occurring distances (being in the order of 10 to 20%). The greatly increased number of different pairs of shot-receiver configurations becomes very effective in the suppression of multiples after application of a 3-D migration process, however. This is in consequence of the fact that in areal surveying – in contrast to the situation in linear surveys mentioned – the phase differences increase nearly linearly when progressing from small to larger shot-receiver distances (see references [2], [3], and [5]).

In areal surveying the extension of the longer side (x-direction) of the rectangle built up by the geophone field layout is generally chosen to be only two thirds of the depth of interest. This rule of thumb should be checked, however, in each individual case: the longest shot-receiver distance required for proper multiple suppression is indicated by the longest period τ_{max} of a multiple reflection to be attenuated at a distinct time t_0.

The well known equation for dynamic (or NMO-)corrections

$$\Delta t = \frac{s^2}{2t_0 \cdot \tilde{v}^2} \tag{2}$$

may be used to define the distance s_{max} at which the difference $\Delta\Delta t$ between the NMO's of a primary and a multiple reflection at a distinct time t_0 equals the longest period τ_{max} of the respective multiple.

$$\Delta\Delta t = \tau_{max} = \frac{s_{max}^2}{2t_0 v_m^2} - \frac{s_{max}^2}{2t_0 \tilde{v}^2} \tag{3a}$$

(where $\tilde{v}$ is the RMS-velocity for the primary reflection, and v_m the velocity for the multiple at time t_0.)

Solving for s_{max} we find

$$s_{max} = \sqrt{\tau_{max} \cdot 2t_0 \cdot \tilde{v}^2 \cdot v_m^2 (\tilde{v}^2 - v^2)^{-1}} \tag{3b}$$

Example: $\tau_{max} = 50$ ms (of a 20 Hz multiple)

$t_0 = 2.0$ s; $\tilde{v} = 3.0$ km/s; $v_m = 2.5$ km/s

$s_{max} = \sqrt{0.2 \cdot 9 \cdot 6.25 \cdot (9 - 6.25)^{-1}} = 2.02$ km

This confirms the rule of thumb mentioned above and is a range of extension one can easily handle in practice.

3.3. ORIENTATION OF THE FIELD LAYOUT

In contrast to the common practice in 2-D line seismics of aligning the line direction *parallel to the general dip* direction, in 3-D areal surveying the larger shot-geophone distances, and thus the larger side of the rectangular block, should be orientated *parallel to the general strike* direction. The reason for such a measure is dictated by practical considerations, namely to avoid shortcomings in data processing, which will be explained here in some detail [1].

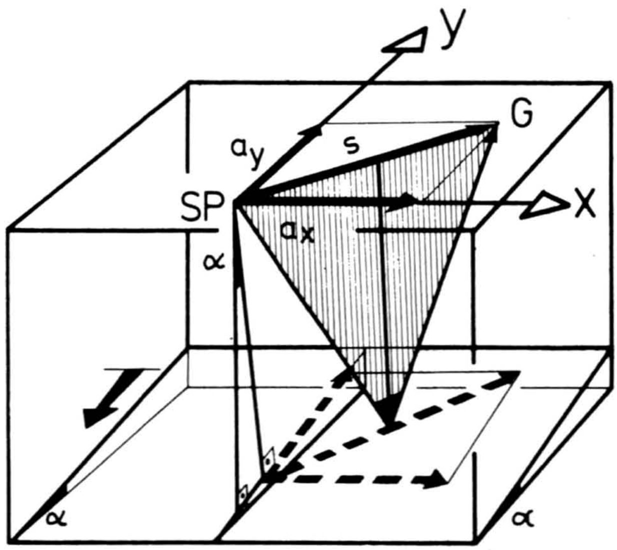


Fig. 2 Components of a Seismic Vector

The magnitude of the dynamic correction (NMO) depends not only on the amount of the areal vector between emitter and receiver, but also on its spatial orientation, we say: on its azimuth. One of the most important factors which determine the magnitude of the dynamic corrections is the dip of the reflecting horizon. When the local coordinate system is orientated in such a way that the x-direction points parallel to the strike direction, then the y-direction points to the direction of the true dip. When the components of the shot-geophone vector s are designated by a_x and a_y (see fig. 2), and when v_{st} is the stacking velocity, the well known equation

$$\Delta t = \frac{s^2}{2 t_0 \cdot \tilde{v}^2} \qquad (2)$$

may be written as

$$\Delta t = \frac{1}{2 t_0 \cdot v_{st}^2} (a_x^2 + a_y^2 \cos^2 \alpha). \qquad (4)$$

As it would be very inconvenient in data processing to consider the α-values encountered each time, the a_y-values must be kept small enough so that $\cos\alpha$ can be made equal to 1.

When postulating that signals of frequency f_{max} and of all lower frequencies should not be impaired in their amplitudes by more than 3 dB as a consequence of the intended neglection of the dip influence, one must postulate

$$d\,\Delta t = \frac{a^2_{y\,max}}{2\,t_0 \cdot v^2_{st}}\,(1-\cos^2\alpha_{max}) \leqq \frac{1}{2\,f_{max}} \tag{5}$$

From this follows

$$a^2_{y\,max} \leqq \frac{1}{\sin^2\alpha_{max}} \cdot \frac{t_0 \cdot v^2_{st}}{f_{max}} \tag{6}$$

As can be shown, $a_{y\,max}$ should be reduced to 70% only of this value when the strike direction is afflicted with an uncertainty of $\pm 20°$.

3.4. ROLL-ALONG TECHNIQUES IN X- AND Y-DIRECTIONS

This point was already mentioned in the general discussion on the cross-array, and also the way we apply the cross-array in general was discussed. Little information on how others apply this method is to be found in the literature, except in Gardner's contribution for the course of the SEG-School in September 1979: "Introduction: 3-D Seismic Techniques". In the section on "Overlapping Cross-Arrays" we find: "The basic idea is to overlap the midpoint coverage for adjacent crossed arrays so as to obtain data with a range of offset distances at every grid-point (or a range of azimuths if the offset direction is significant)". The "range of offset distances" is the basis for velocity determinations from areal data. (Our own restrictions as to the emitter-receiver distances in the anticipated dip-direction were already noted in section 3.3.) The next sentence in Gardner's paper reads: "In obtaining overlapping coverage it is *useful for static measurements to record several parallel lines for the same range of shots* and *to record several parallel lines of shots by the same range of receivers*". The latter is in essence what we do in our two-component roll-along procedures; the first part of this quotation means: *roll-along in y-*, the second part means: *roll-along in x-direction.*

Gardner's argument that overlapping crossed arrays were useful for static measurements proved true to us only in early 1979 when we succeeded in our first applications of 3-D residual statics (see example in section 4.2).

Our initial motivation for an additional roll-along in y had been to reduce excessive lateral offsets and thus reduce loss of information in the upper range. Additional roll-along in y-direction is apt to reduce the lateral offsets in y to the magnitude of the y-spacing applied between shotpoints or geophone lines (which ever is the larger).

Coming back to the residual statics: when adjoining lines (or swaths) are independently recorded, the later static residual processes must also be independently performed in 2-D residual processes in adjoining lines or strips. When, after these processes, the traces are organized in the direction perpendicular to the original direction, the unavoidable consequence is jittering in adjoining traces. When static corrections and, in particular, long-term static anomalies are of minor importance, as is commonly the fact in marine surveys, one may accept 2-D static residual processes in 3-D surveys. When planning areal *land* surveys, however, one must insist upon close connections between shots and receivers in the adjoining strips n and (n + 1) to be surveyed, otherwise proper static residual processes would become impossible. Either the shotpoint positions of strip n are partly reused when recording the geophones in strip (n + 1), or the same geophone stations or part of them, are reoccupied in strip n when shooting shots in strip (n + 1) without repeating shot positions. The latter solution is the ideal one because it actually establishes the genuine two-component roll-along procedure (see fig. 14 and 15).

Repeated use of shot positions may seem necessary when the number of seismic channels available is limited. Shot positions used twice or even more often, however, may lead to ambiguities in the determination of the proper shot static correction for the multiply used shot position. (This does not come true, of course, when surface sources, as e.g. VIBROSEIS, are utilized.) The later 3-D static residual process requires an unequivocal (preliminary) shot static value. It is advisible, therefore, to design the areal survey system in such a way that repeated use of shot positions becomes obsolete.

In 1962 Harry Mayne in his basic paper "Common Reflection Point Horizontal Data Stacking Techniques" (Geophysics, Vol. XXVII, Dec. 1962) had given a general expression for the multiplicity in the coverage of line surveys:

$$M = \frac{N \cdot S}{2 \cdot n},$$

where (quotation)

"M = path multiplicity ($= M_x$ = multiplicity in x-direction)
N = number of detector stations in the spread
n = number of stations by which the spread is advanced
S = number of shot positions for each spread."

In an effort to find an equivalent general expression for the multiplicity M_y in y-direction perpendicular to the geophone line direction, the author arrived at the following expression

$$M_y = \frac{1}{2} \cdot \frac{L \cdot S}{n \cdot m} \tag{7}$$

where

L = number of receiver lines simultaneously recorded
S = number of shot positions for recording a single block
n = number of shot positions between adjacent receiver lines
m = number of receiver lines to be advanced for the adjacent strip

Equation (7) seems to be a reasonable auxiliary means for drafting areal designs. For a desired multiplicity M_y the factors L, S, n and m can be always modified in such a way that the equation is satisfied. It has to be observed, however, that other important restrictions – e.g. the condition of the maximum y-component (y_{max}) – are maintained. A graphical control is recommended, in particular to check that no shot repetitions will occur when surveying the subsequent strip.

In case the receiver line distance A is smaller than the shotpoint interval in y (as in our example Prosper Haniel 1975, fig. 4), equation (7) is still valid, the meaning of n, however, turns to: "number of receiver line intervals between shotpoint intervals in y", and the meaning of m becomes: "number of shotpoint intervals to be advanced, where m may be an integer or a fraction". The case $A < \Delta y$ is, however, not recommendable, as the respective shotpoints would have to be reused.

3.5. ACCURACY IN STATION POSITIONING

In conventional line seismics it is common practice to allow moderate lateral offsets of shotpoints when the regular in-line positions cannot be realized as a result of the terrain. Even when the respective dynamic corrections are properly determined, the respective cross dip influence is necessarily neglected in the stacking process.

In areal surveying, deviations from the regular surface positions are even more influential because the offsets are not merely lateral now, but multidirectional. Even when proper dynamics are applied, an improper data grid would result which would possibly be detrimental to the stacks. Replacement shots have to be applied when the actual deviations from the presumed positions exceed a distinct tolerance value.

In the following it will be shown how to determine the acceptable tolerance value [4]. The relationship between seismic resolution and positioning accuracy of emitter and receiver stations is found in equation (2) for the determination of dynamic corrections, when assuming zero or small dips only of the reflections,

$$\Delta t = \frac{s^2}{2 t_0 \cdot \tilde{v}^2} \tag{2}$$

This equation, after partial differentiation with respect to the distance s and solved for ∂s, gives

$$\partial s = \frac{t_0 \cdot \tilde{v}^2}{s} \, \partial \Delta t \tag{8}$$

When the sampling rate (SR) is considered to be the maximum admissible error, which should not be exceeded by an error ∂s in the distance s, then the respective RMS errors are defined as one third of a sampling rate $= \frac{(SR)}{3} = \frac{1}{3} \partial \Delta t$.

The maximum distance s_{max} between emitter and receiver is often directly correlated with the maximum depth of interest z_{max}. If we replace s by z in equation (8), regarding that $z = \frac{t_0 \cdot \tilde{v}}{2}$, one finds

$$\frac{t_0 \cdot \tilde{v}^2}{2} = 2\tilde{v} \tag{9}$$

and (8) becomes

$$\partial s = \tilde{v} \, \frac{2}{3} \, (SR) \tag{10}$$

The corresponding accuracy of the limiting points of distance s, namely of the positions of shot and receiver stations, can then be defined by the tolerance radius ∂r around these positions

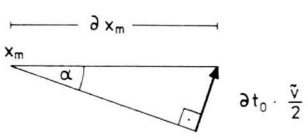
$$\partial r = \frac{\partial s}{\sqrt{2}}$$

or, using (10)

$$\partial r \approx \frac{(SR)}{2} \cdot \tilde{v} \tag{11}$$

This simple relationship between sampling rate, RMS-velocity $\tilde{v}$ down to the horizon of interest, and the tolerance radius is compiled in Table I and is valid for dips $\alpha \leqq 10°$.

When larger dips are expected the influence of these dips on the zero-time determination at the midpoint between shot and receiver depends on the positioning error of the midpoint x_m.



$$\partial t_0 = \frac{2 \sin \alpha}{\tilde{v}} \, \partial x_m \tag{12}$$

A lengthy calculation, which is not given here, results in the generally valid equation

$$\partial r = \frac{(SR)}{2} \cdot \tilde{v} \cdot \frac{1}{2 - \cos^2 \alpha} \tag{13}$$

Admissible tolerance radius for station positioning

SR \ $\tilde{v}$	2,0	2,5	3,0	3,5	4,0	4,5
1 ms	1 m	1,25	1,5	1,75	2,0	2,25
2 ms	2 m	2,50	3,0	3,50	4,0	4,5
4 ms	4 m	5,00	6,0	7,00	8,0	9,0

TABLE I

Admissible elevation error

SR \ v_1	1,6	2,0	2,5	3,0	3,5	4,0	4,5
1 ms	±0,5 m	±0,6	±0,75	±0,9	±1,05	±1,2	±1,35
2 ms	±1,0 m	±1,2	±1,5	±1,8	±2,1	±2,4	±2,7
4 ms	±2,0 m	±2,4	±3,0	±3,6	±4,2	±4,8	±5,4

$m_h = 0{,}3\ SR \cdot v_1$

TABLE II

For values of $\alpha = 0°$, 45° and 90° the additional factor $\frac{1}{2 - \cos^2 \alpha}$ becomes 1; 0.66; and 0.5 respectively; the figures for the no-dip case have to be reduced correspondingly.

To complete the catalogue, the requirements of the elevation accuracy are given. Elevation errors produce static correction errors if certain limits are exceeded. Again let the mean error in time measurement equal one third of the sampling rate $\left(\partial t_0 = \pm \frac{(SR)}{3}\right)$, then the respective RMS elevation error (in m) equals the product of correction velocity v_{sw} and $\frac{(SR)}{3}$ (in m/ms and ms, respectively) (see Table II)

$$m_e = \pm \frac{(SR) \cdot v_{sw}}{3} \tag{14}$$

3.6. OMNIDIRECTIONAL RECEIVER PATTERNS

Source-generated noise enters the receiver patterns from all directions during the course of an areal survey. A geophone pattern having an omnidirectional response may have a 3-arm windmill design, presented in fig. 3. The 12 to 14 dB overall attenuation in the noise reject range from 5 m to 40 m is considered to be a good compromise. The 60°-symmetry makes sure that never more than 3 to 4 of the 18 receivers are in phase.

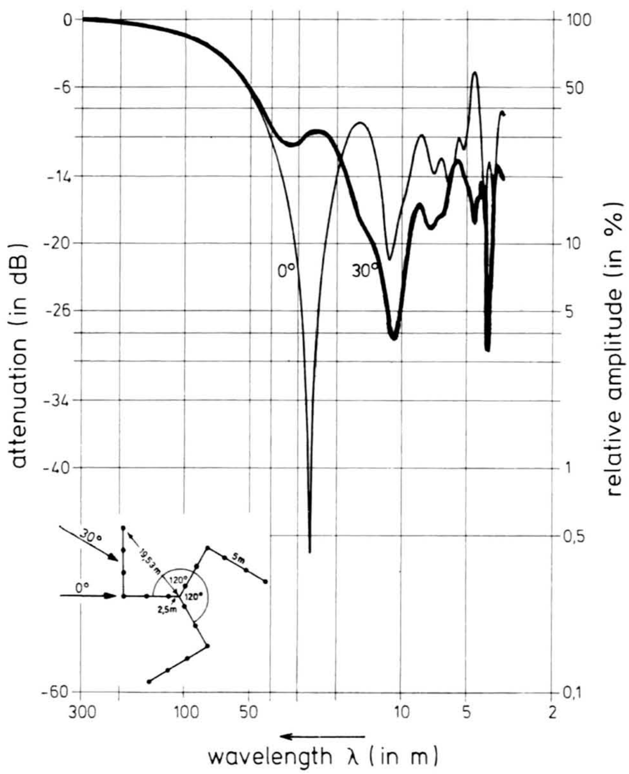


Fig. 3 Omnidirectional Pattern Response of the "3-Arm Windmill"

4. SOME EXAMPLES OF AREAL SEISMIC SURVEYS

The areas surveyed up to now have been rectangles of 3.5 km² to 41 km², typically about 16 km². The majority of our 3-D surveys (more than 75%) have been carried out for the German Ruhrkohle in the northern forefield of the Ruhr district. The very first survey in 1975 confirmed the presumed expectations. Since then, 3-D surveys have become standard practice for surface coal-mining surveys. This can be understood when one realizes that seismics does not actually discover the coal layers, but, instead, helps plan the coal mining by outlining the economically exploitable areas through detailed surveys. And that is the typical task of 3-D surveys!

Further detailing with 3-D seismics has been done in inaccessible alpine areas (with VIBROSEIS), in river surveys using airguns, for geothermal water exploration, shallow non-coal mining, and in producing oil- and gasfields. In the following, besides diagrams of the survey geometry designs, some results will be shown. In each case the respective clients have given their permission for us to show the presented information.

4.1. PROSPER HANIEL (1975)

This was our very first regular areal survey for coal mining [5], [6]. It covered an area of 16 km^2. The survey geometry in fig. 4 shows a variation of the x-array system: two 48-channel DFS IV instruments simultaneously record a strip of 8 parallel geophone lines with 12 receiver groups each, which are shot from 4 shot positions of a central shot traverse (5 in the marginal strip only). The roll-along in x is done in steps of two station intervals, giving a 3-fold coverage in x.

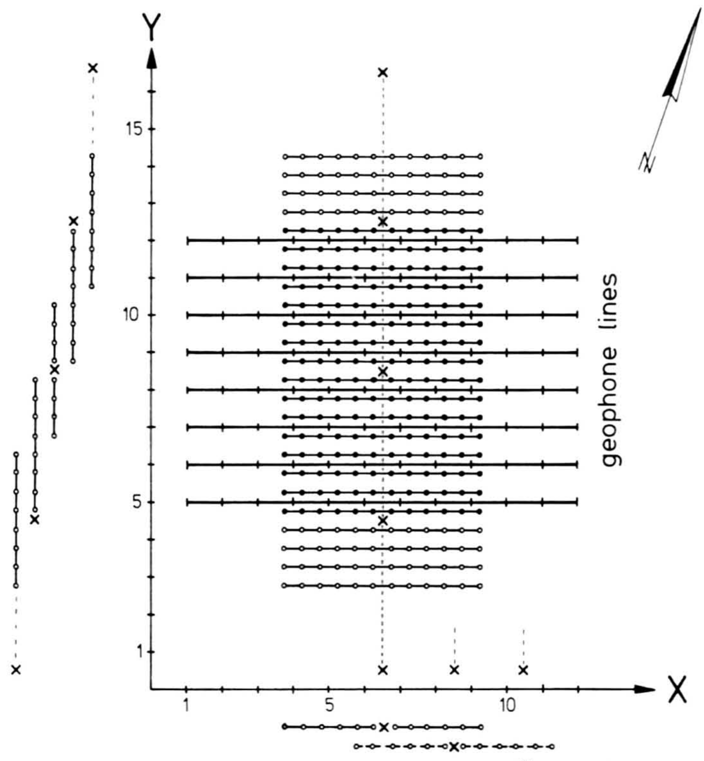


Fig. 4 Layout Prosper Haniel (1975)

The roll-along in y is attained by repeating 2 shotpoints of strip n for recording strip (n + 1), resulting in a 2-fold coverage in y. Using equation (7) and the parameters L = 8, S = 4, n = 4, m = 2
(where n = number of receiver lines between adjacent shotpoints (in y) and m = number of shotpoints advanced for the next strip),
one obtains

$$M_y = \frac{1}{2} \frac{8 \cdot 4}{4 \cdot 2} = 2\text{-fold in y.}$$

The total coverage is therefore 6-fold. Fig. 5 shows the shot-receiver configurations of two arbitrarily picked CDP's. This system comprises a total of 48 different

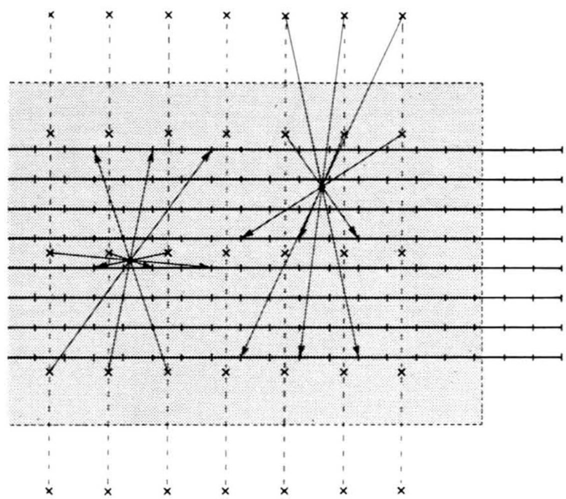


Fig. 5 Shot-Receiver Configuration, Prosper Haniel (1975)

shot-receiver distances distributed in 16 kinds of differently composed CDP-families, two alternating ones in each profile. In periods of 8 successive profiles 16 different kinds of multiple reflection remainders are found. This fact is clearly seen in fig. 6. This figure shows a sequence of 10 adjoining 6-fold stacked sections in the x-direction at 50 m spacings. From this picture it is understandable why mining surveyors were so enthusiastic about this by-product of areal surveying. These sections are displayed with the time range from 0.3 to 0.8 s and show a nearly unfaulted Mesozoic overburden (Cretaceous and Buntsandstein) overlying a complicated Carboniferous horst and graben system. The multiple remainders inside the Carboniferous layers vary in phase and amplitude on the adjoning profile sections: a consequence of the differently composed CDP-families.

Fig. 7 shows in the upper part a stacked section now organized in the y-direction. Little faulting only is recognized because the section parallels the general fault trend. Recognizable are the base Cretaceous, top Carboniferous and, weakly indicated by high-frequency signals, some intra-carboniferous coal seam indications.

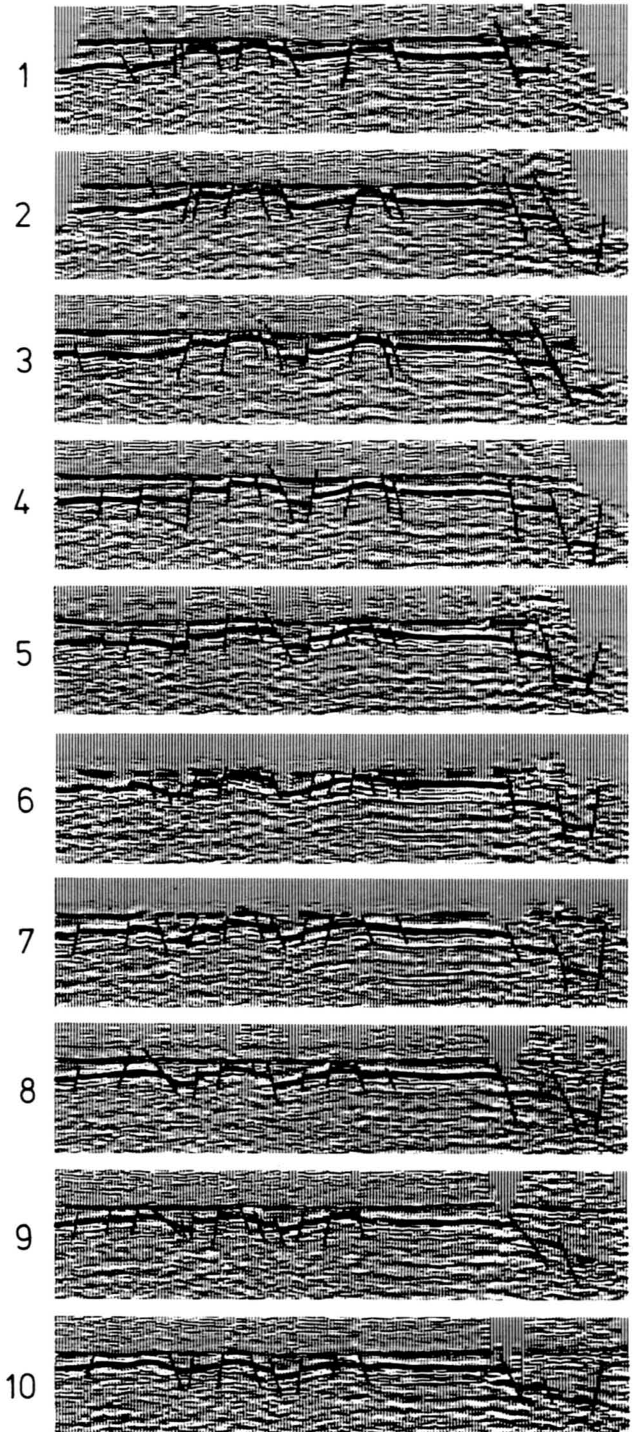


Fig. 6 Echelon Profiles at 50 m Intervals, Prosper Haniel (1975)

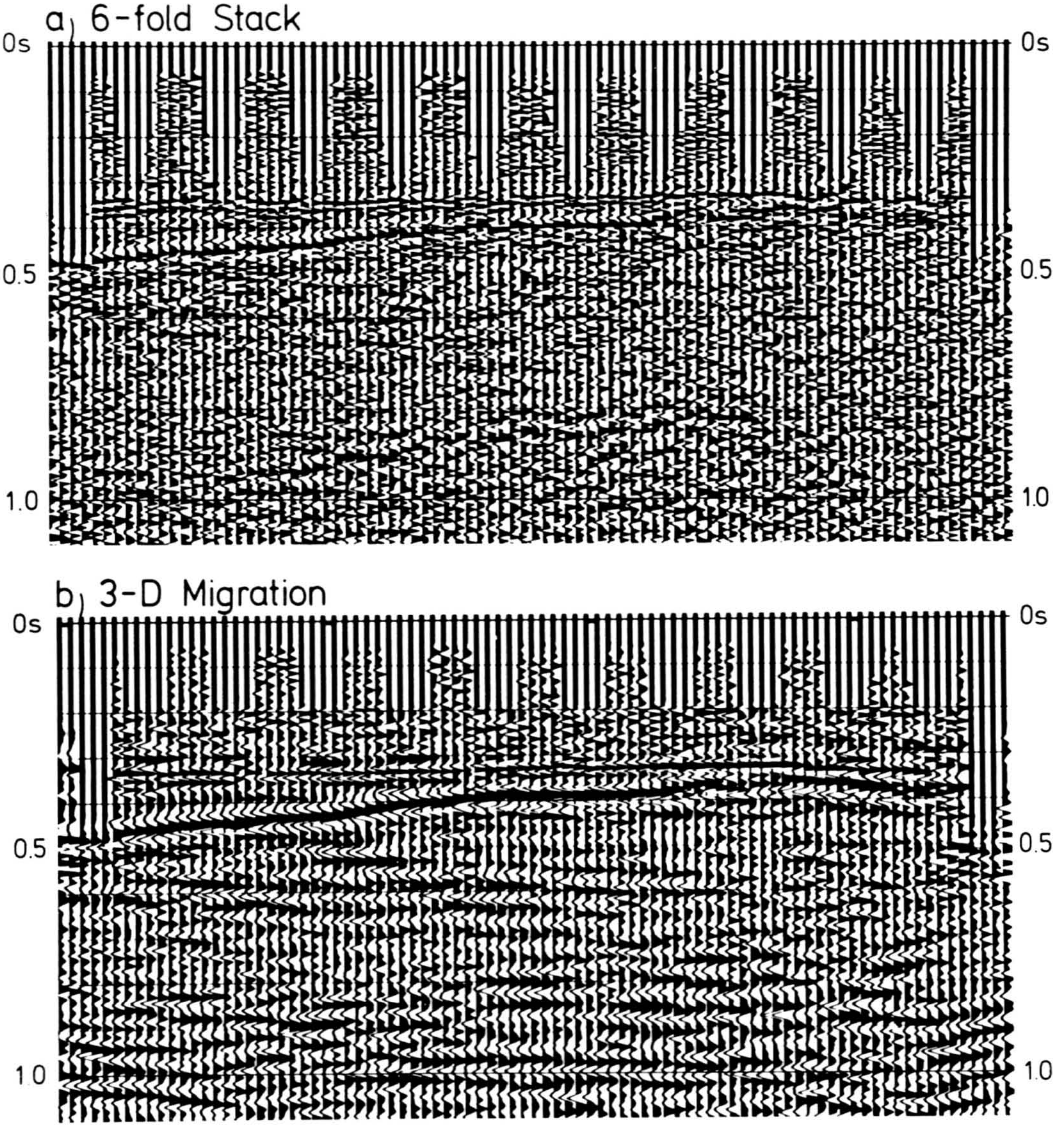


Fig. 7 3-D Migration on 6-fold Stack, Prosper Haniel (1975)

In spite of phase differences the surface multiple of the top Carboniferous reflection is clearly shown by energy accumulations. The result of our very first 3-D Kirchhoff migration, made at the same position, is seen in the lower section: a clearly improved S/N ratio was obtained in the upper part; inside the Carboniferous, however, an undifferentiated picture of low frequency signals is seen, which has the same tendency as indicated in the stack. The latter is evidently the result of the excessive spatial sampling rate of 100 m on the surface. This is because in the survey planning it had not been realized that the Nyquist frequency f_{max} of the reflections is only 30 Hz when spatial sampling is done in the subsurface with 50 m spacing over an anticipated dip of $\geqq 30°$. Equation (1) yields

$$f_{max} = \frac{\tilde{v}}{4 \cdot \frac{\Delta x}{2} \cdot \sin 30^{\circ}} = \frac{3000}{4 \cdot 50 \cdot 0.5} = 30 \text{ Hz}.$$

This means, that frequencies higher than 30 Hz could not have been expected after a migration process for dips exceeding 30°. On the other hand, the elimination of the strong multiples still visible in the stacked section is a success which is due to the high multiplicity of different shot-receiver distances present in the first Fresnel zone, which is the constructive migration zone, or: the width over which the wavefront is curved less than 1/2 period of the peak frequency. The radius r_{fr} of the first Fresnel zone is given by

$$r_{fr} = \sqrt{\frac{t_0 \cdot \tau}{4}} \cdot \tilde{v} \tag{15}$$

For comparison with fig. 7 we show in fig. 8 the result of another survey in which an extremely dense spatial sampling rate has been applied [3]. The data grid produced had spacings as small as 12.5 m (compared to 50 m in the first example) in order not to disturb the intracarboniferous high-frequency signal. The coverage was two-fold only. Fig. 9 may be compared with the lower section of fig. 7. It shows a Kirchhoff 3-D summation migration on top of the two-fold stack in fig. 8. The migration produced an extremely good vertical section containing high-frequency signals around 80 Hz from a stack with a rather poor S/N ratio.

To conclude the coal-mining demonstration, one of today's routine survey schemes is introduced in fig. 10. It is designed for 120 receiver groups in 10 lines at 12 stations each. The spacing between lines and stations is reduced to 40 m (instead of 100 m in the first areal survey), and the subsurface grid width is 20 m. Instead, the coverage multiplicity was raised from two-fold to six-fold, with

$$M_x = \frac{N \cdot S}{2 \cdot n} = \frac{12 \cdot 2}{2 \cdot 4} = 3\text{-fold in x}$$

$$M_y = \frac{1}{2} \frac{L \cdot S}{n \cdot m} = \frac{1}{2} \frac{10 \cdot 4}{5 \cdot 2} = 2\text{-fold in y}$$

The multiplicity was again increased because primarily a better S/N ratio is required when a finite-difference migration is to be applied instead of a Kirchhoff 3-D migration. (The finite-difference 3-D migration is indispensable for today's en-bloc migration of the entire area surveyed.) Two examples of our non-coal mining 3-D surveys will be demonstrated in the following.

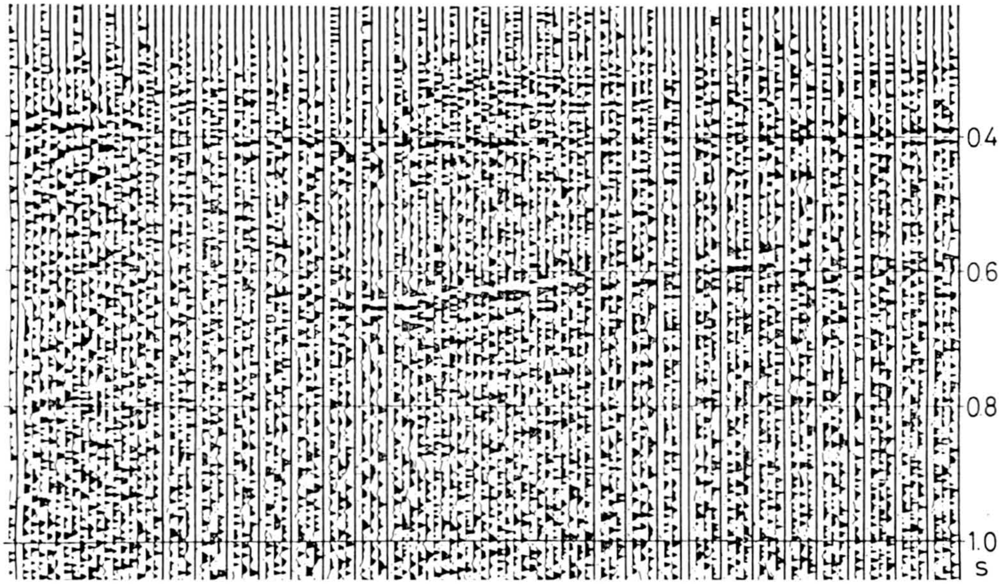


Fig. 8 2-fold Stack; Data Grid Spacing 12.5 m

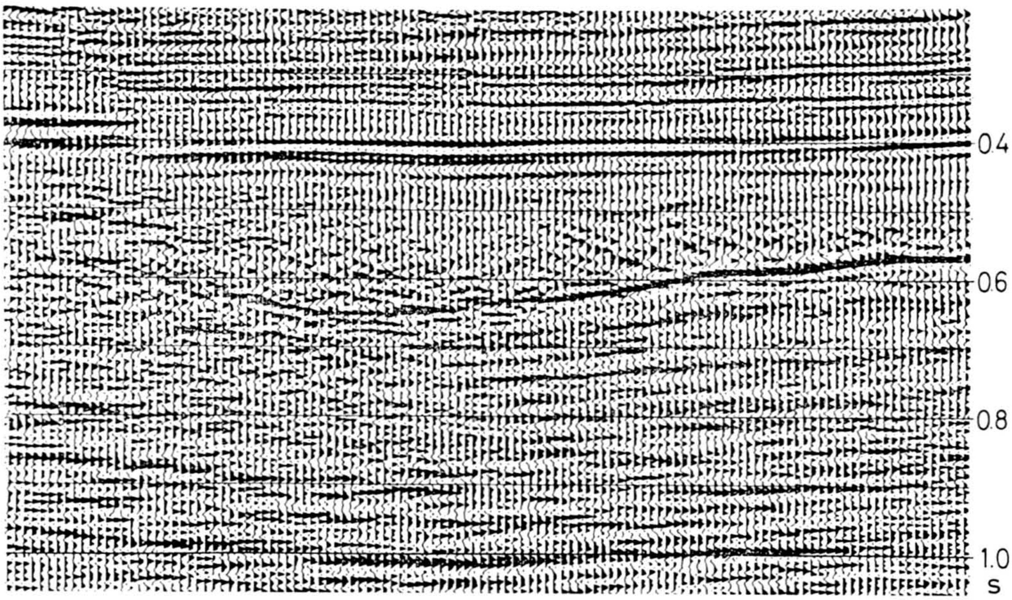


Fig. 9 3-D Kirchhoff Migration on 2-fold Stack in Fig. 8

4.2. 3-D HIGH-RESOLUTION SURVEY (1978)

The survey covered a $1.2\ \text{km} \times 3.0\ \text{km} = 3.6\ \text{km}^2$ area and was carried out to provide support for the planning of a mine at 200 to 300 m depth. It had to be confirmed that no tectonic disturbances would be encountered by future mining at the respective depth [7].

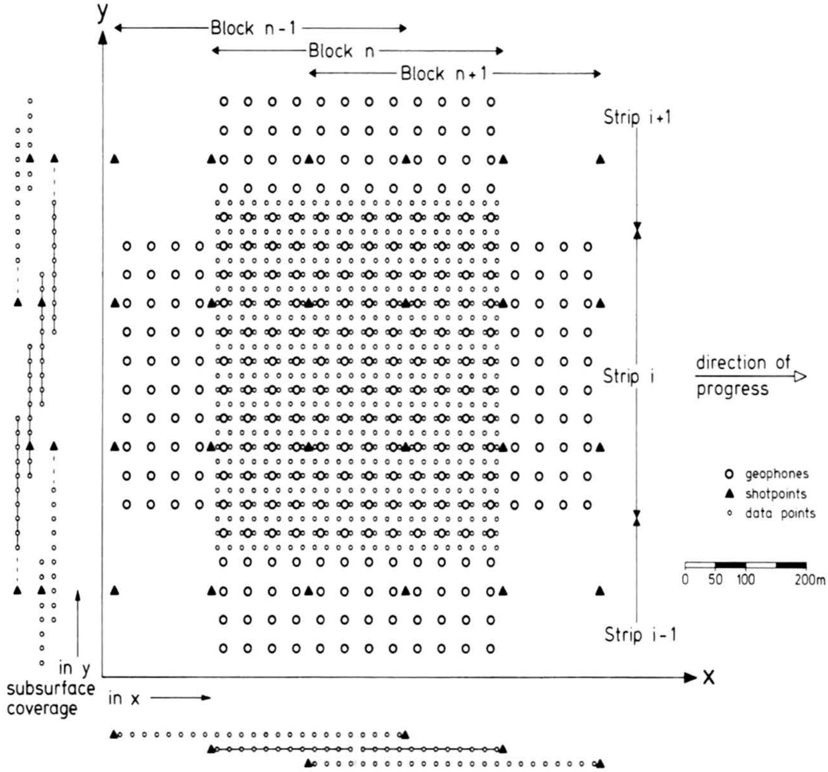
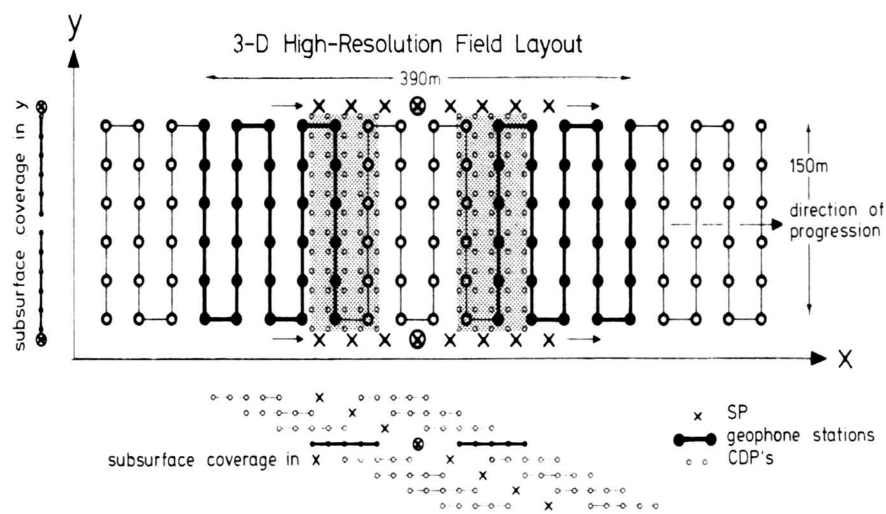


Fig. 10 Modern Survey Scheme for 120-channel Recording



Meandering geophone layout (150 × 390m) 2 times 5 rows each arranged perpendicularly to direction of progression. Roll-along shotpoint pairs on lines paralleling the strip produce 5-fold CDP-coverage

Surface gridding: 30m SP-spacing in x: 30m
CDP gridding: 15m SP-spacing in y: 180m
Shot-receiver distances: s_{max} = 255m; s_{min} = 75m

Fig. 11 Layout of a High-Resolution Survey

This survey is one of the few exceptions in which we abandoned the x-array system because of the terrain conditions in favour of a variant of the parallel-profiling system. The survey geometry in fig. 11 shows a single block within a strip. The important survey data are:

- 6 parallel geophone lines bordered by two paralleling shot lines,
- 30 m-spacings of receivers and shotpoints,
- $x_{max} = 195$ m, $y_{max} = 165$ m,
- Sercel telemetry instrument for 60-channel recording,
- 1 ms sampling, 20 Hz bunched geophones,

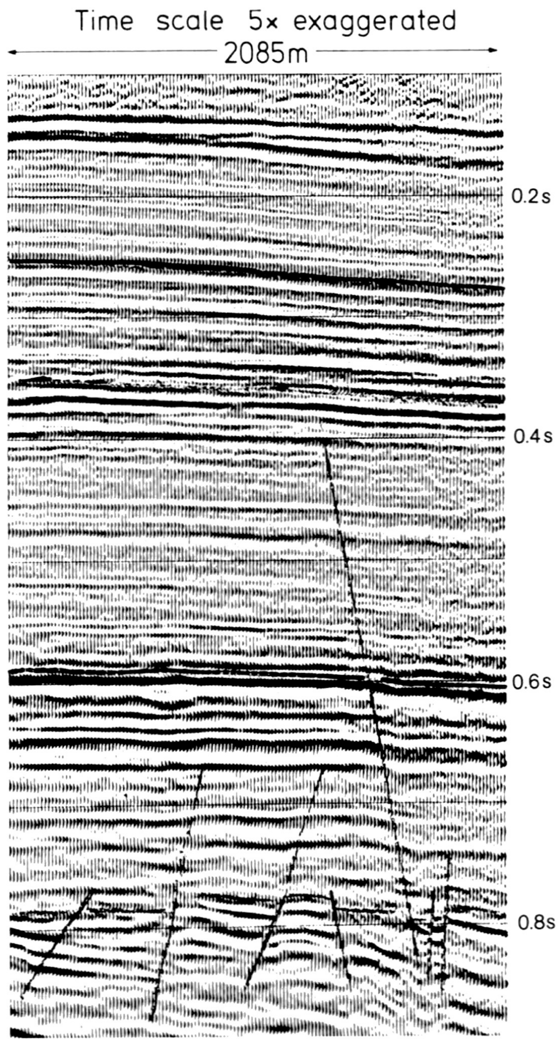


Fig. 12 3-D Migration Section of a High-Resolution Survey (3-D residual statics having been applied)

- 5-fold coverage in x, singlefold in y,
- shotpoints between adjoining strips used twice,
- single-hole shots charged with 100 g dynamite at 2 m depth.

Two figures illustrate the quality attained and how certain processing steps can provide interpretational aid.

Fig. 12 shows a 2085 m long section after 3-D migration. The time scale is 5 times exaggerated. A horst and graben fault system is disclosed in the Carboniferous part. Some faults were still active in Cretaceous time; one flexure can still be followed into the Tertiary section up to 0.4 s. The true dip of this afterworking fault is about 45°.

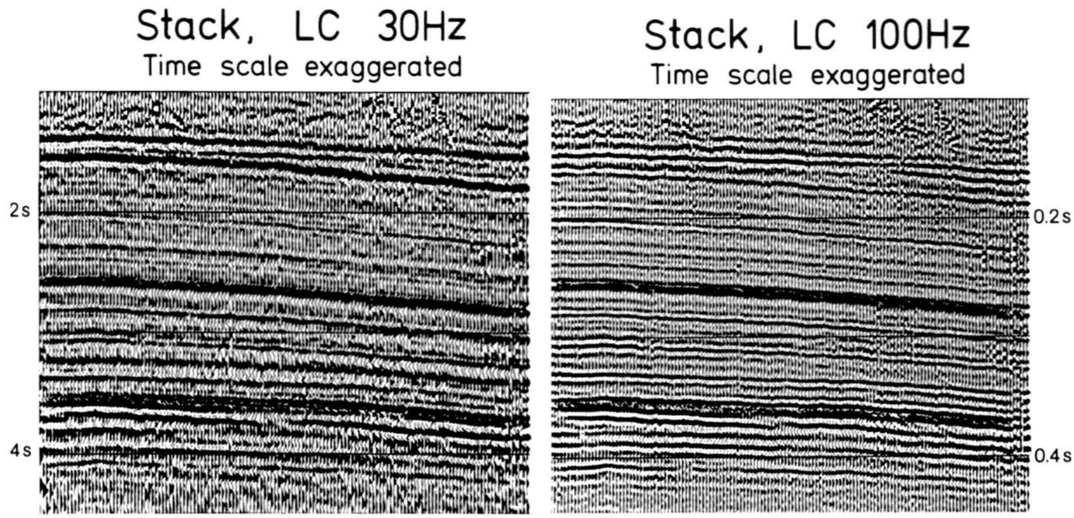


Fig. 13 Portion of Fig. 12 without Migration

Fig. 13: Same section as in fig. 12 but without migration. The critical upper time range does not reveal any faulting, even after a 100 Hz low-cut filter. (Signal frequencies in the 200 to 400 ms portion are nearly as high as 200 Hz.)

4.3. 3-D SURVEY SCHOLEN (1979)

This last example deals with greater prospective depths. The survey was conducted in November/December 1979 and shows the last stage in the development of our own data acquisition techniques. It comprised an area of 8.5×4.8 km $= 40.8$ km^2 and is the largest single areal land survey we had carried out up to then. It covered the area of two producing gasfields lying at about 3000 m depth and an oilfield lying at 1500 m depth. The client's intention was to gain more reliable information for the future development of these fields.

Two 120-channel DFS V instruments were used for simultaneous 240-trace recording. The survey geometry of a block is indicated in fig. 14: 240 receiver groups are

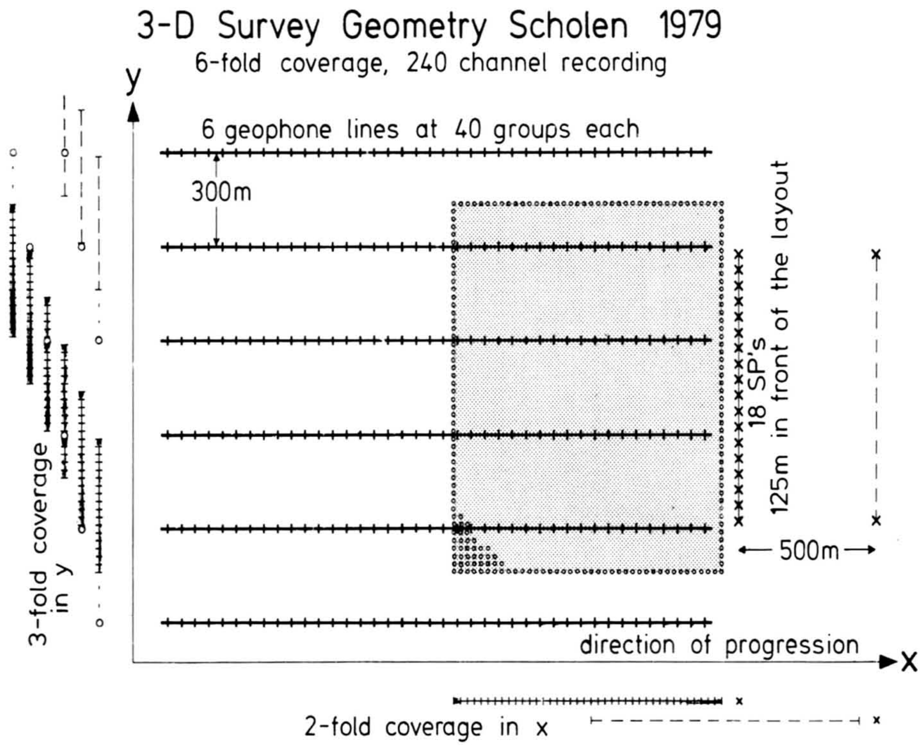


Fig. 14 Layout of 3-D Survey Scholen (1979)

distributed over 6 parallel geophone lines, 40 stations at 50 m spacings on each line. Distances between adjacent lines amount to 300 m. A shot traverse with 18 SPs at 50 m spacings is arranged perpendicular to the direction of the geophone lines so that it lies symmetrical in front of the smaller side of the rectangular geophone field. The offset between the geophone field and the shotline was 125 m. The subsurface diagram indicates a 3-fold coverage in y-direction. Subsequent shot traverses are at intervals of 500 m, i.e. 10 stations, which provide a 2-fold coverage in x, the total coverage, thus, being 6-fold.

A strip is made up of 16 blocks. Each subsequent strip overlays the preceding one on the surface with 3 geophone lines, which is 50%. This means that the respective geophone stations are used twice, the second time for recording the 18 shots of the strip (n + 1). A genuine roll-along is thus attained in the y-direction without reusing any shotpoint position.

Some *statistical data* show that the efforts made for data acquisition are economically acceptable when a high multiplicity of recording channels is applied:

Subsurface covered:	40.8 km^2
Shots recorded:	1420
Number of profiles in x:	192
Number of profiles in y:	340

Total length of x-profiles produced:	1632 km
Field survey time:	230 hrs
Shots recorded per 10 hrs:	62
Profile-km per 10 hrs:	71
Total number of 6-fold data points produced:	65 280

5. APPLICATION OF THE GUIDE AS A CHECKLIST

To practically demonstrate the applicability of the "guide for areal data gathering" commented in detail in this paper, this guide may serve as a checklist for the parameters chosen for the last presented Scholen 3-D survey:

5.1. TEMPORAL AND SPATIAL SAMPLING RATES

For the main traveltime range of 2.0 s a time sampling rate of 4 ms might have been adequate in view of the signal frequency content (= 60 Hz) to be expected. With respect to the shallower oilfield information to be implicated, however, the 2 ms rate was preferred, in particular as a 4 ms rate would not have opened the facility to

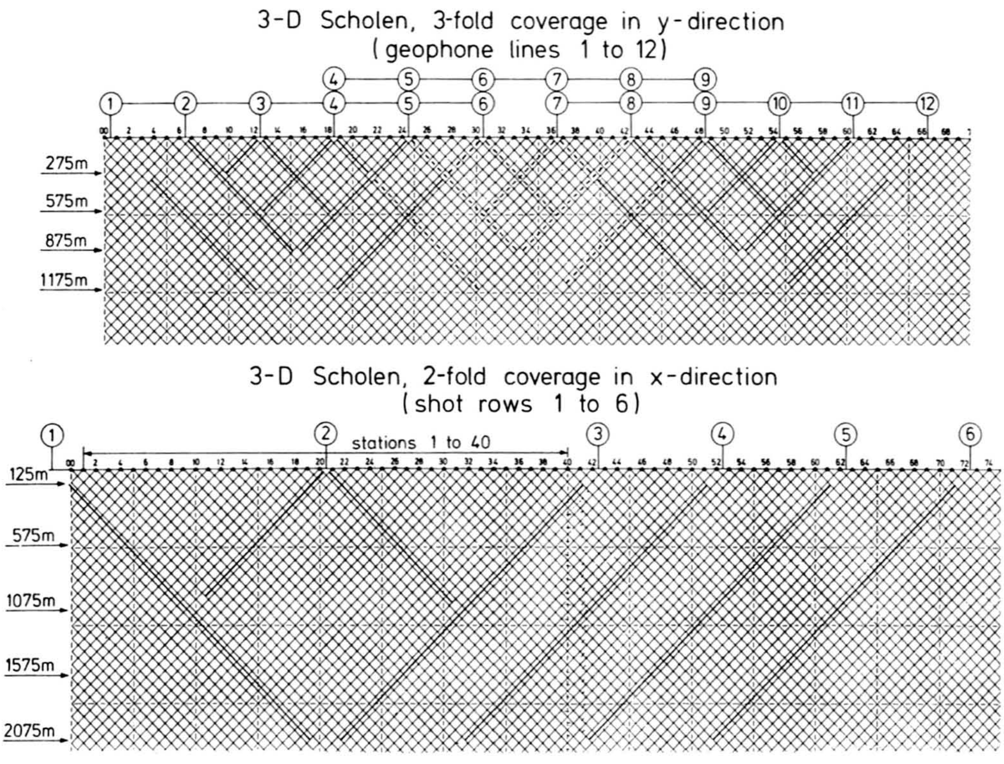


Fig. 15 45°-Subsurface Coverage Diagram Revealing the Different Shot-Geophone Distances in x and y

employ 480 instead of the actually used 240-channel recording with this type of instrument (TI, DFS V) in default of further analogue modules.
The check concerning the spatial sampling rate a_{max} to be chosen can be done by inserting the actual values in equation (1) in section 3.1.

$$a_{max} = \frac{v_{st}}{4 f_{max} \cdot \sin\alpha_{max}} \tag{1}$$

$$= \frac{3000 \text{ m/s}}{4 \cdot 60 \text{ Hz} \cdot \sin 30°} = \underline{\underline{25 \text{ m}}}$$

This figure exactly fits the data grid spacing used.

5.2. SHAPING AND DIMENSIONING THE FIELD LAYOUT

The main target was at a depth of approx. 3000 m. According to a rule of thumb the longer extension of the rectnagled geophone field should be two thirds of the maximum depth of interest, i.e. 2000 m. The recommendation for a closer check was already anticipated in the example in section 3.2; the data on: traveltime t_0, primary and multiple reflection velocity at that time, and the supposed multiple signal frequency, all refer to the Scholen survey area. The required amount $s_{max} = 2023$ m for the smallest maximum shot-receiver distances needed for a thorough multiple suppression is already covered by the x-component $x_{max} = 2075$ m (from 1950 m plus 125 m offset between shot traverse and the first geophone groups, see fig. 14).

5.3. ORIENTATION OF THE FIELD LAYOUT

The x-direction of the area surveyed corresponds to the general geological strike. From equation (6) for the maximum extension y_{max} allowed in the direction perpendicular to the strike and from the 70% restriction because of the 20° uncertainty in strike direction results

$$a_{y_{max}} \leqq \left(\frac{t_0 \cdot v_{st}^2}{f_{max} \cdot \sin^2 \alpha} \right)^{\frac{1}{2}} \cdot 70\,\%$$

Introducing again: $t_0 = 2.0$ s; $v_{st} = 3.0$ km/s; $f_{max} = 60$ Hz, and the maximum expected dip $\alpha = 20°$,

$$a_{y_{max}} \leqq \left(\frac{2.0 \cdot 9.0}{60 \cdot 0.12} \right)^{\frac{1}{2}} \cdot 0.7$$

$$\underline{\underline{a_{y_{max}} \leqq 1106 \text{ m},}}$$

which is fairly close to the actual values 1175 m for cables 1 and 6, and 875 m for cables 2 to 5 (fig. 14).

5.4. ROLL-ALONG IN X- AND Y-DIRECTIONS

Referring to the layout for the Scholen survey (fig. 14) and the 45°-diagram (fig. 15) one finds that a perfect roll-along in x- and y-directions is attained by the Scholen design for 240-channel recording. Six geophone lines (1 to 6) are recorded from 18 SPs on a shot traverse perpendicular to the geophone lines. After termination of a roll-along in x in strip n, three geophone lines advance in y-direction and three remain at their former positions to establisch strip (n + 1). No shotpoint repetitions and consequently no uncertainty as to the true shot static value can occur. Again applying the equation (7) to check the multiplicity in y:

$$M_y = \frac{1}{2}\,\frac{L \cdot S}{n \cdot m} = \frac{1}{2}\,\frac{6 \cdot 18}{6 \cdot 3} = 3\text{-fold}.$$

A previous draft for a 120-channel survey, providing three instead of six geophone lines of the same extension, and 36 instead of 18 shots per block would have meant twice the amount of shotpoint. Moreover, 50% of the shotpoints would have been reused in each subsequent survey strip, possibly causing static correction ambiguities as mentioned earlier. For this variant we have

$$M_y = \frac{1}{2}\,\frac{3 \cdot 36}{6 \cdot 3} = 3\text{-fold}.$$

A 480-channel recording in Scholen area would have rendered a 12-fold instead of a 6-fold coverage. The number of shots would have been the same as for the actually used 240-channel recording. The only variation in the field layout needed for a 480-channel survey would be the application of the areal equivalent of a splitspread line recording, namely 240 geophone groups behind as well as in front of the respective shot traverses, thus doubling the multiplicity in x from 2-fold to 4-fold.

5.5. ACCURACY REQUIREMENTS FOR THE TOPOGRAPHICAL SURVEY

The ample treatment in section 3.5 on the accuracy requirements in an areal survey arrived at an admissible tolerance radius of 3 m around the proper geophone and shot positions. The strict adherence to the tolerance limits defined for the intended station positions grants that the seismic resolution is not endangered by mistakes in the engineering survey. The adherence of the *receiver* stations to the tolerance radii is seldom a problem. Already in the planning stage the situation of the line positions can usually be adapted to the terrain by slightly shifting and/or turning the whole line-work, because, in general, the 300 m line intervals provide sufficient play. Where the shot positions cannot be strictly adhered to within the 3 m radius postulated (because of buildings, safety distances to pipelines, or other obstacles) replacement shotpoints can be found in unit distances (of 50 m in our case) up to ±450 m in x-direction. If necessary, displacements can even be made in y-direction, undershooting locations with those obstacles which otherwise cannot be overcome. This is – by the way – a further advantage of the two-component system recommended.

The inner accuracy inside the local coordinate system can be checked by ties to trigonometric points of the national geodetic survey. In doing so, the RMS-error of an individual receiver or emitter station was found to be ± 0.7 m compared to the admissible tolerance of ± 3 m (for $v_{st} = 3.0$ km/s and a sampling rate SR of 2 ms) found in Table I.

5.6. AREAL RECEIVER PATTERN FOR OMNIDIRECTIONAL EFFECTIVENESS

The areal receiver pattern of the 3-arm windmill with 18 geophones and a diameter of about 40 m has been one of our standards for a long time. Its omnidirectional attenuation power of 12 to 14 dB in the noise-reject range from 5 m to 40 m is fairly acceptable. The layout of the 3-arm pattern proves less critical than may be expected from the 120°-angle design. Some irregularities in the actual layout are not dangerous as long as the gravity center remains within the limits just mentioned under point 5. (Some people even say: the more random, the better.)

6. FINAL REMARK

From the reference list of published and internal papers the author's cooperation with Professor Th. Krey may be seen as well as the latter's personal engagement in the development of 3-D seismic data collection techniques, which he spent in spite of the fact that the advent of this new era in seismic activities almost coincided with his retirement from professional activity with PRAKLA-SEISMOS in 1975.

The catalogue of discussions on the optimization of areal data gathering methods is, therefore, also a documentation of the author's internal discussions with Professor Th. Krey, to whom he would like to dedicate this paper.

REFERENCES

[1] Krey: 3D-Seismik mit Neigung (3-D seismic in the presence of dip), internal note, June 16, 1978

[2] Bading/Krey: Optimum attenuation of multiples by appropriate CDP-field techniques and migration. Paper presented 1976 at the SEG-Meeting in Houston/Texas

[3] Krey: Reconciling the demands of 3-D seismics with those of improved resolution. Paper presented 1978 at the SEG-Meeting in Tulsa-Oklahoma

[4] Bading: Zur Genauigkeit von Lage- und Höheneinmessung für reflexionsseismische Messungen, Truppleitertagung 1980

[5] Bading/Krey: Flächenhafte reflexionsseismische Feldaufnahmen als Voraussetzung für 3-dimensionale Datenverarbeitung, Vortrag gehalten auf der DGG-Tagung 1976 in Bochum

[6] Bading: Applying areal seismics to coal-mining problems in the Ruhr area. Paper presented 1976 at the Coal Seam Discontinuity Symposium (d'Appolonia Consulting Engineers Inc.) in Pittsburgh/Pennsylvania

[7] Bading/Edelmann: The potential of multi-channel recording; paper presented 1979 at the SEG-Meeting in Hamburg