

Aspects to the resolving power of 3D Seismic Surveys

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Abstract: Hydrocarbon exploration using 3-Dimensional seismic techniques can look back onto a series of experienced enterprises of encouraging work. Successful results of 3D surveys offshore and onshore have proved to be based on careful interactions of data acquisition, data processing as well as data interpretation already during the planning stage.

Sophisticated techniques in each of these domains have been developed in the past few years for enhancing the resolution of the resulting data volumes to enable higher reliability in interpretation work. Important aspects such as spatial sampling, careful positioning, effective binning and powerful imaging are discussed with respect to practical applications.

INTRODUCTION

Experience in the past has proved that the three-dimensional seismic technique can be considered a valuable tool in developing fields which have already been thoroughly explored by conventional methods. In some cases it will be the only tool for enhancing the reliability of the interpretational work.

The subsurface layering is of three dimensional extension thus ray paths of seismic energy can only be traced reasonably by means of three dimensional methods.

Successful results of 3D surveys offshore and onshore have always to be based on careful interactions of data acquisition and data processing already during the planning stage. Sophisticated techniques in each of these domains have been developed in the past few years for improving the resolution of the resulting data volumes.

Before pointing out some important aspects to be considered for conducting a 3D survey the state-of-the-art of 3D field techniques currently in use will be roughly illustrated.

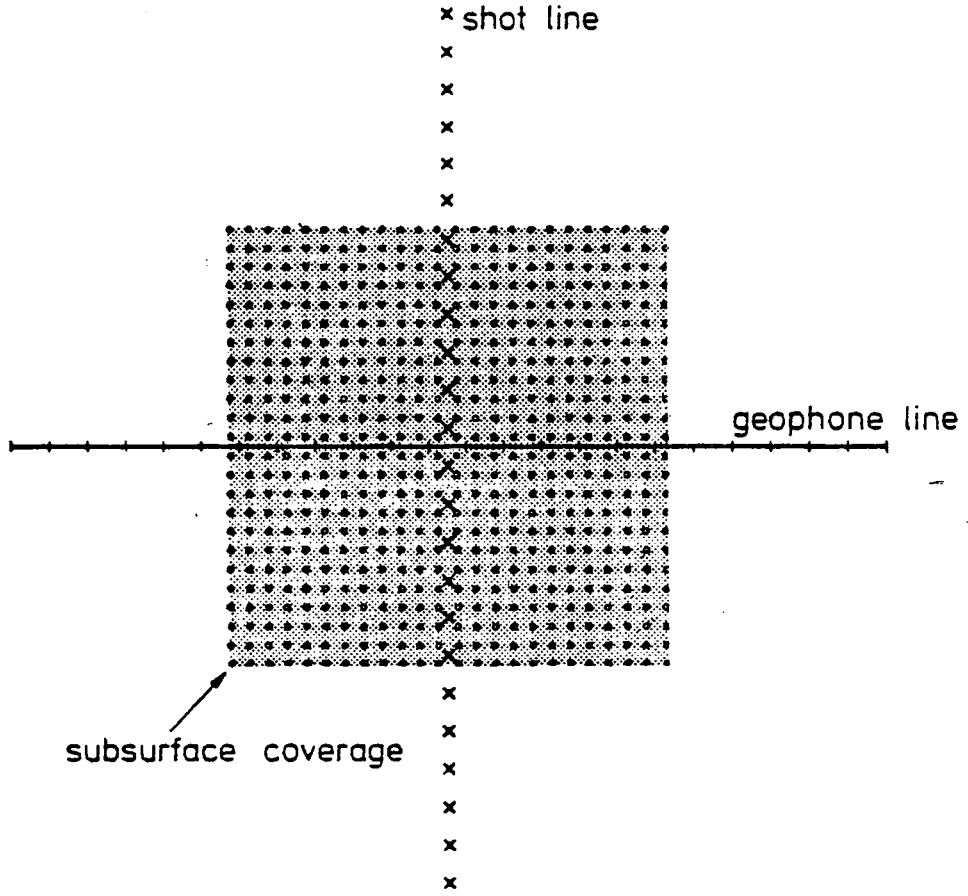
ACQUISITION

Field-techniques

Generally there is a need to distinguish between 3D marine and 3D land acquisition systems.

The crossed-array method as outlined in Fig. 1 is the basic type of areal data collection applied for land surveys. The principle is shown by the configuration of a straight geophone line and a symmetrical shotpoint arrangement on a straight line perpendicular to the geophone line. The area in the subsurface is evenly but only single fold covered by all the midpoints between the respective geophone and shot positions. When the shot traverse is shifted, and the geophone line is moved forward

Crossed Array



Basic System for 3-D Land Seismics

Fig. 1. Crossed Array

correspondingly, an areal "continuous profiling" is achieved in analogy to the conventional straight line survey. Then a multiple coverage is produced in the geophone line direction. By shifting the geophone line in shot traverse direction a multiple coverage is produced in this direction, too. The aim should be to achieve a coverage as uniform as possible. This is necessary also for a sufficient multiple suppression.

A lot of different field systems of this type have been developed in the past, modified and adapted to the local geological problems.

Land 3D-surveys are receiver intensive: quite a large number of geophone stations (e.g. 500 or more) are used simultaneously. In Fig. 2 the surface layout of an actual survey system is presented. Eight geophone lines with 60 geophone groups each form a block for the recording of 16 shots per traverse. The shaded areas indicate the extent and degree of subsurface coverage produced within the single block. The 4-5 fold coverage in x-direction and the 4fold coverage in y-direction results in a total coverage of about 17fold. The maximum offset is about 1.300 m. By shifting this block system in x and y the complete data set for the whole survey area is generated.

The advantage of such regular shooting schemes is its uniformity of coverage. The common mid-points are located on a regular grid, the multiplicity and the range of offsets is also nearly uniform. Whenever possible, the field layouts should enable nearly constant azimuth angles between sources and receivers for the longer offsets. This simplifies the complex task of velocity estimation, which will be discussed later in more detail.

If regular field layouts are impossible because of access problems, irregular source-receiver configurations must be handled. The irregular surface layout necessarily leads to irregular subsurface gridding. Therefore, an appropriate set of so-called bins is defined for regridding the data, and all traces that are spatially located in one of these bins are processed as representing the same subsurface point. It is clear that source- and receiver positions have to be determined very carefully for this procedure.

Binning of data is also generally necessary in 3D marine surveys. In comparison to the areal field systems used in 3D land work in the common 3D marine acquisition technique is still based on the continuous profiling method. Thereby the single boat method is mostly employed. Fig. 3 shows a typical 3D marine seismic survey arrangement, where the boat scans the field blockwise utilizing the continuously updated knowledge of currents and their variations for improved performance. By arranging many parallel closely spaced survey lines a good uniformity of areal subsurface coverage can be achieved. The number of receiver groups is comparable with those of 2D marine surveys.

These acquisition techniques for 3D land- and 3D marine surveys have not changed in principle since the beginning of 3D seismics. However, much effort has been spent on refinements and the solution of single problems in order to obtain higher

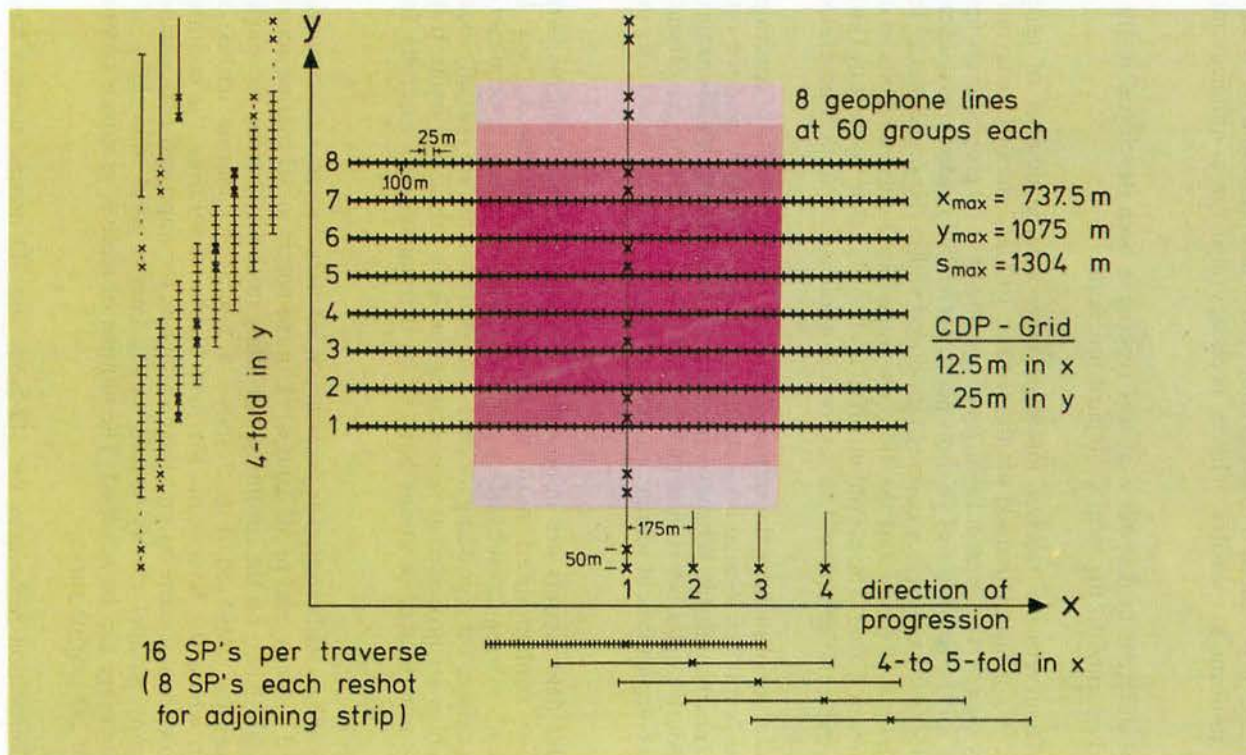


Fig. 2. 3D Survey System (land)

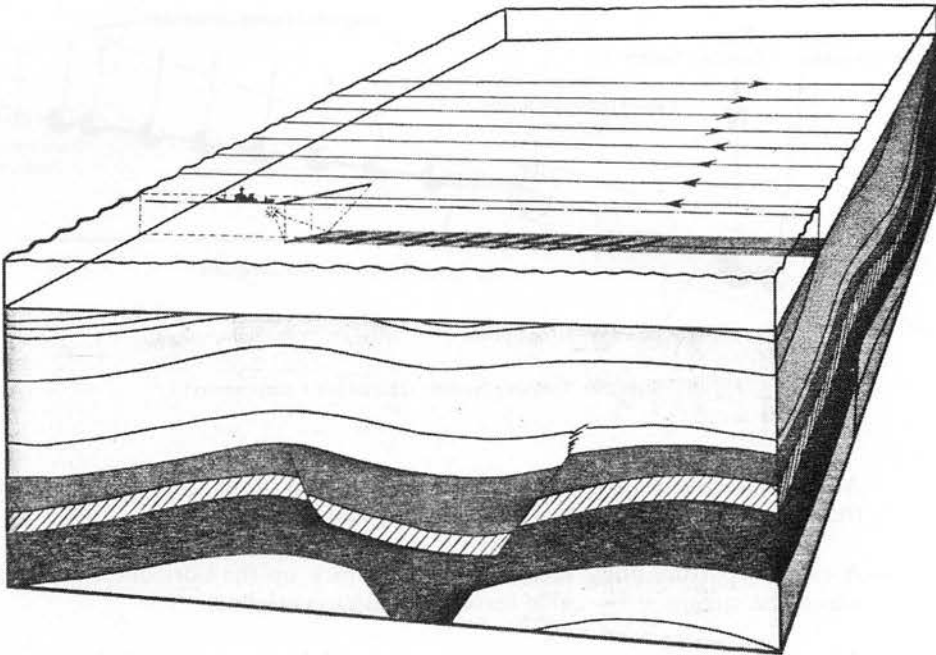


Fig. 3. 3D Survey System (marine)

resolution. Some aspects concerning these improvements shall be discussed in the following.

Positioning

Generally the number of traces has been drastically increased in consequence to the development of powerful recording systems both for land and marine work. About 480 traces might become standard in the near future though there are instruments already on the market which claim to record a lot more traces than that. Also the density of data concerning the CDP spacings have reached the upper limits of cost and feasibility. Spacings of 6.25 m and below are often required in land as well as in marine surveys.

The determination of source- and receiver coordinates therefore is of great significance for processing the data. Advanced 3D marine surveys nowadays require a much higher degree of accuracy in streamer positioning than was accepted some years ago. The accuracy should enable determination of the position of each CDP to within ± 10 m absolutely. Therefore, besides the ship's conventional navigation system additional hardware and software components are necessary as shown in Fig. 4 and outlined below:

- A set of magnetic heading sensors, regularly spaced along the streamer.

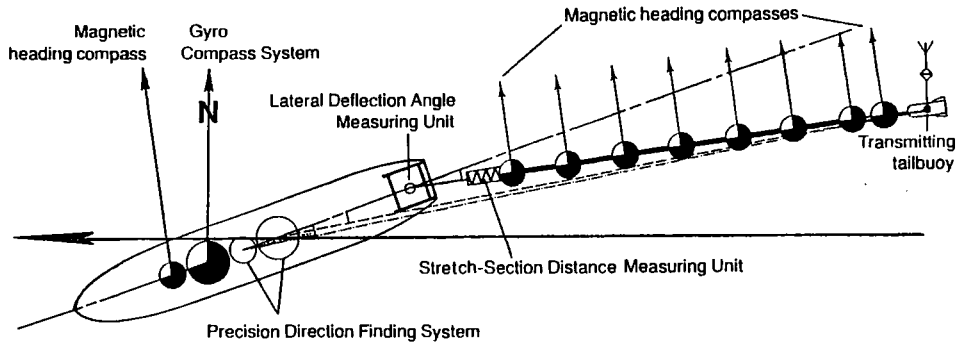


Fig. 4. Streamer Tracking System (Hardware Components)

Additional sensors are mounted at the extreme ends of the streamer to indicate the direction to the tow point or tail-buoy respectively.

- A cable departure angle measuring unit to pick up the horizontal angle, at which the streamer tow cable leaves the ship's centerline.
- An acoustic distance measuring system to record the elongation of the streamer stretch sections in the towing cable. A similar system controls the position of the airgun arrays.
- A multiple gyrocompass system.
- A precise direction finding system for azimuthal tracking of the streamer tailbuoy.
- A realtime processing and quality control computer system.

Streamer tracking data are controlled and processed in realtime to attain optimized and reliable coverage. Fig. 5 shows as an example of onboard control devices, the bin coverage display. It reports the coverage separately for three selected streamer sections, usually the near, central and far offset ranges. Full nominal coverage is achieved if the bins are coloured completely, as indicated for the near section in this example. This system enables the crew to react immediately by adjusting the ship's course or by shooting infill-lines if needed.

In order to reduce the field effort and thus saving time and money during the acquisition stage, and also to reduce the cross line spacing a special source array configuration has been introduced for routine work. The source systems on both sides of the boat are spread by a special device and fired alternately. This procedure delivers two subsurface lines at the same time during one ship's course. The principle view is presented in Fig. 6 where the source arrays are spread by 50 m. With the ship's track spacing of 50 m and an inline group spacing of 50 m the bin size will be 25 × 25 m.

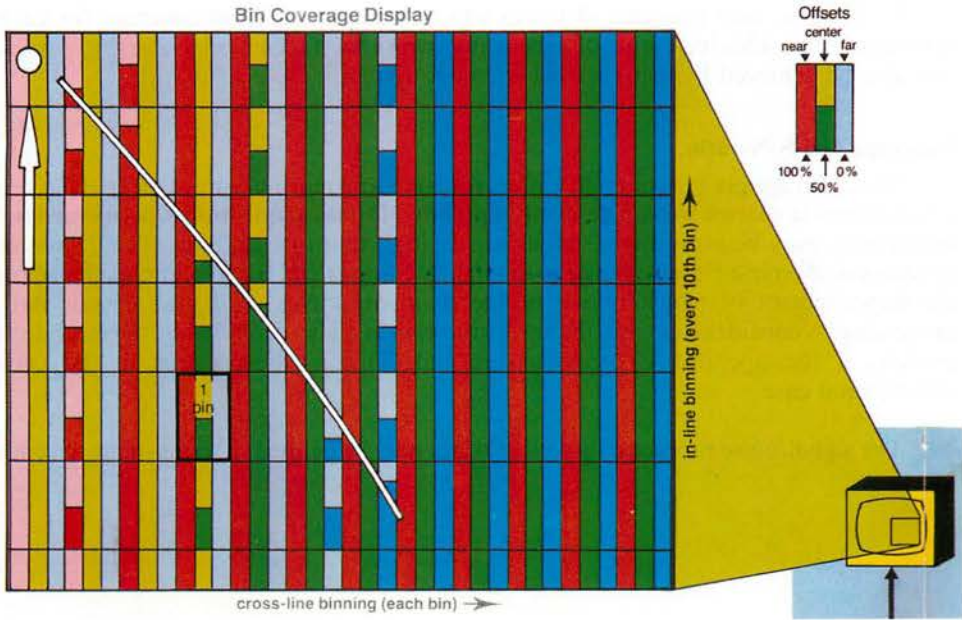


Fig. 5. Bin Coverage Display

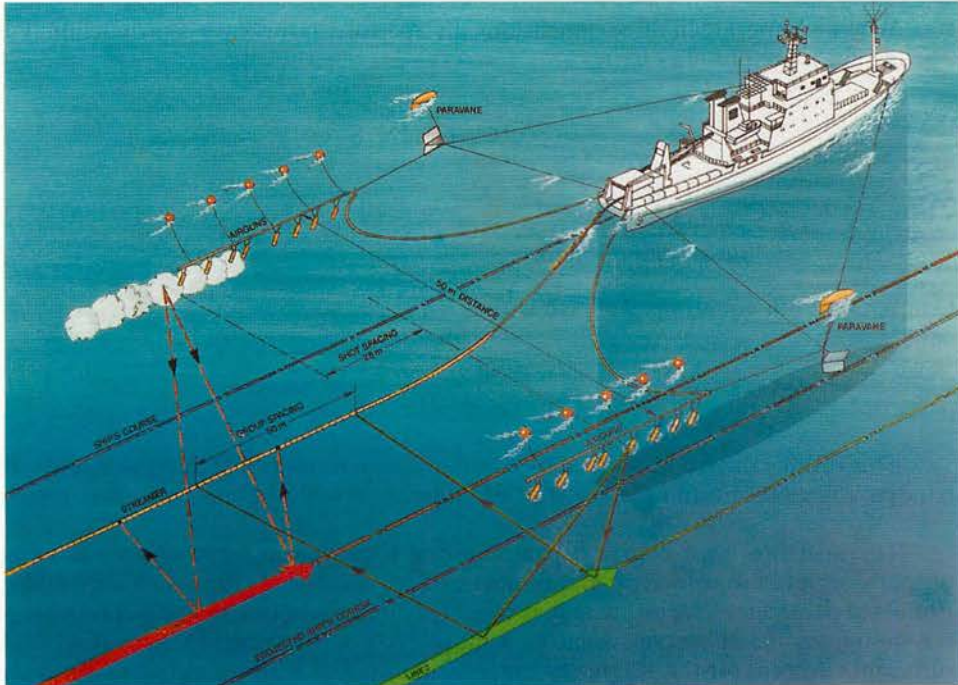


Fig. 6. Wide Array

A 2400 m cable then provides 48 traces which results in a 24fold coverage for each subsurface line. This technique of generating two subsurface lines by one ship's track can also be achieved by using a dual streamer system.

Coverage and S/N-ratio

The coverage per bin generally differs for land- and marine work. Due to the given environment in marine work where only a pseudo 3D data acquisition is performed the multiplicity may be more than 3 times higher than that of land data. The degree of coverage is of course closely related to the signal to noise (S/N) ratio of the stacked data the improvement of which is one of the main objectives of digital seismic data processing. A considerable contribution to these aims is also provided by the migration process, if the operator is properly designed. This is already true in the two-dimensional case.

The signal/noise ratio of migrated 2D data may be defined in terms of amplitudes as:

$$\frac{S}{N_{(2D)}} \sim \sqrt{C_x \cdot N}$$

where C_x = coverage in inline direction

N = aperture of migration operator (i.e. number of traces)

When we migrate in three dimensions the aperture in this case is proportional to $2N$ and we therefore may write

$$\frac{S}{N_{3D}} \sim \sqrt{C_x \cdot C_y \cdot 2N \cdot S}$$

where $C_x \cdot C_y = C_{3D}$ and

S = "out of plane"-factor

Combining both equations we have with $S = 1$:

$$\frac{C_{3D}}{C_{2D}} \sim \frac{1}{2}$$

This result can also be verified by comparing the result of 2D migration with the bandpass filter result and the result of 3D migration with the matched filter result.

The aperture N of course depends on the CDP-spacing Δx which has to be properly adapted to velocity v and frequency f_{MAX} and the maximum structural dip. For usual parameters, we estimate that roughly half of the corresponding 2D coverage is required for the 3D survey when we want to achieve the same S/N as in the 2D. A sufficient coverage for the 3D survey has to be maintained with respect to an optimum velocity field determination for stacking *and* migration.

Spatial aliasing and migration aperture

The reliability of imaging the prospect in question depends basically on a proper sampling of reflection data in spatial and temporal directions. These parameters are of course governed by the depth and the maximum dip of the objective horizons as well as the desired bandpass to meet the geological objectives. Considering the actual dip we have to distinguish between structural dip and diffractive dip. In terms of 3D migration the structural dip strongly influences the correct lateral position after 3D migration, while the diffractive dip influences the resulting resolution after 3D migration.

Therefore, the maximum dip per trace for the area has to be evaluated and the inline- and crossline spacing has to be selected accordingly. In addition, the maximum structural dip defines the migration distance which has to be taken into account when the extension of the survey area is designed, i.e. a certain run-in and run-out coverage has to be considered for allowing a proper migration of the data volume.

The rate of spatial sampling with respect to maximum resolution being obtained is closely related to the size of the so-called first Fresnel-zone:

$$R_{\alpha} = \sqrt{\lambda \cdot Z/2}$$

where R_{α} = radius of FRESNEL-ZONE for plane wave
 Z = depth of target
 λ = wave length = v/f

The radius of the Fresnel zone depends on the wavelength of sampled data and the depth of the target. Thus as an example a diffracting point at depth 4000 m and transmitting a signal of 20 Hz requires a minimum radius of 592 m of information to be gathered for reconstruction of the image. As has been shown in a series of papers the size of the first Fresnel zone decides on the strength of the signal after the migration process and the size of the migration aperture decides on the power of lateral resolution.

By proper sampling the effect of grid-dispersion may be greatly reduced. Fig. 7 shows an example for grid dispersion on synthetic and actual data. Of course the actual grid-dispersion depends on the wavelength and the wavelength in turn depends on the actual velocities.

DATA PROCESSING

The data processing stream may be divided into three parts:

Pre-stack processing, including data organization, parameter estimation procedures as well as a proper derivation of the 3D velocity model and 3D residual statics, to be applied in land seismics,

Pre-migration processing, including final 3D stacking, derivation of migration velocities, and if required, trace interpolation procedures, and

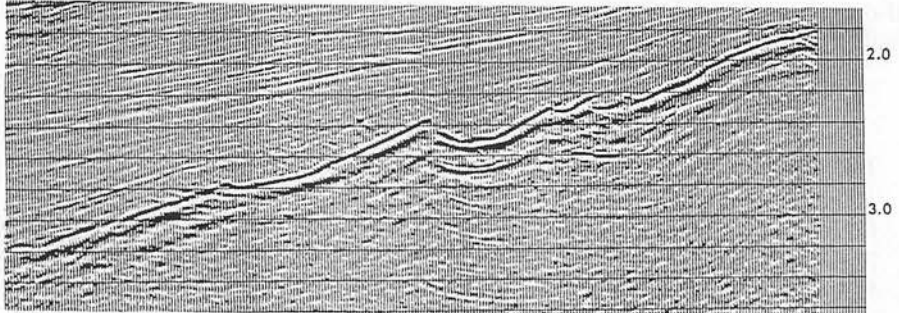
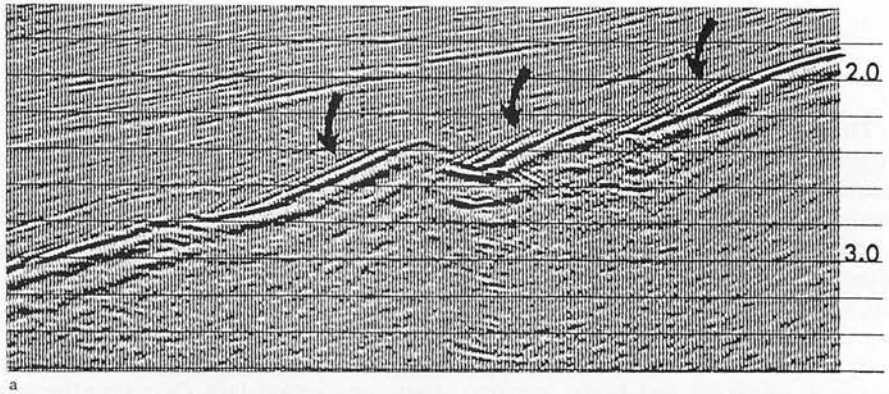
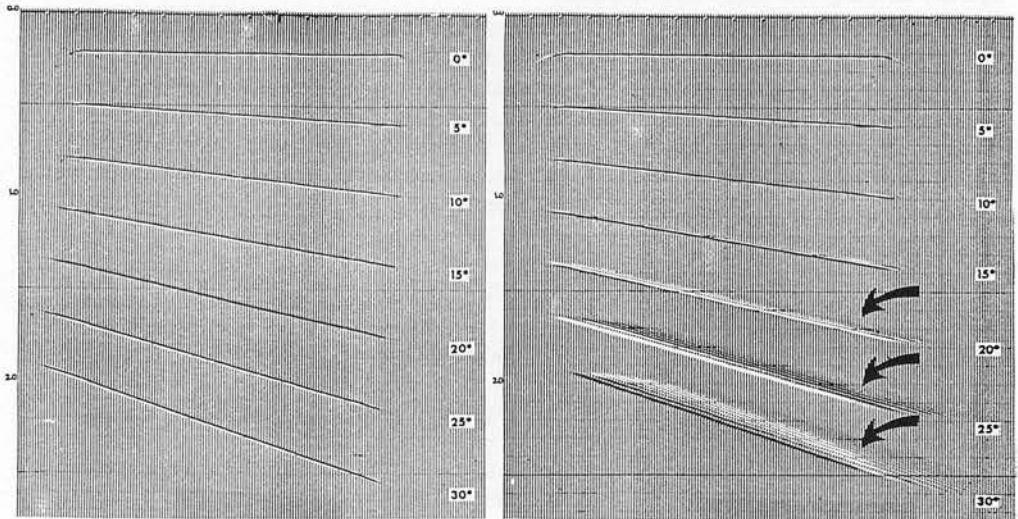


Fig. 7. Grid Dispersion

3D Migration, including, if requested, depth conversion and display of true vertical and horizontal sections.

The 3D processing starts with colour coded CDP coverage maps which are derived from careful positioning calculations providing each seismic trace with x- and y-coordinates. Different colours represent different degrees of coverage. When we realize a higher coverage than normally expected, as may happen sometimes with marine data, then several traces of the same offset have been collected into the same bin. Standard equalization procedures before migration could be a simple, but not sufficient solution. As mentioned before, the offset ranges should be as uniform as possible. So, only that trace which is nearest to the bin centre should be maintained by 100%. The other traces of same offset can be weighted according to their distance to the bin centre. Bins with insufficient coverage have to be filled up with missing offsets. This is performed by a special process, which searches for appropriate traces in the neighbouring bins and shifts them to the reference bin taking into account the actual dip. That procedure of coverage adjustment in marine data processing can also be achieved by dynamically changing the bin location according to the degree of cable feathering along the ship's track. This is to collect only traces of the same shot.

The 3D stacking procedure is significantly different for land data in comparison to marine data, since marine 3D data acquisition in principle is two-dimensional.

Therefore with land data we need to treat two additional problems:

- a. azimuth-dependent stacking velocities
- b. three-dimensional residual statics.

Since the shotpoint- and the geophone-coordinates are documented in the trace-header, the application of azimuth-dependent dynamic corrections is not a real problem.

Azimuthal velocity analysis

The problem simply is reduced to finding for preselected key-horizons the two axes of the corresponding velocity-ellipses, a_i and b_i , which are related to the maximum and minimum velocity values at that location (Fig. 8).

$$\begin{aligned} a_i &= V_{RMS_i} = V_{MIN} \\ b_i &= V_{RMS_i} / \cos \theta'_i = V_{MAX} \quad i = 1, 2, \dots, N \end{aligned}$$

Due to overburden effects, usually neither of the axes coincide with the corresponding dip and strike direction of the horizons under consideration nor does θ'_i represent the true dip angle θ_i . However, starting the iteration of the true dip direction and the true dip value serve very well as initial values for each selected horizon.

The procedure of velocity derivation is of central importance to the success of 3D

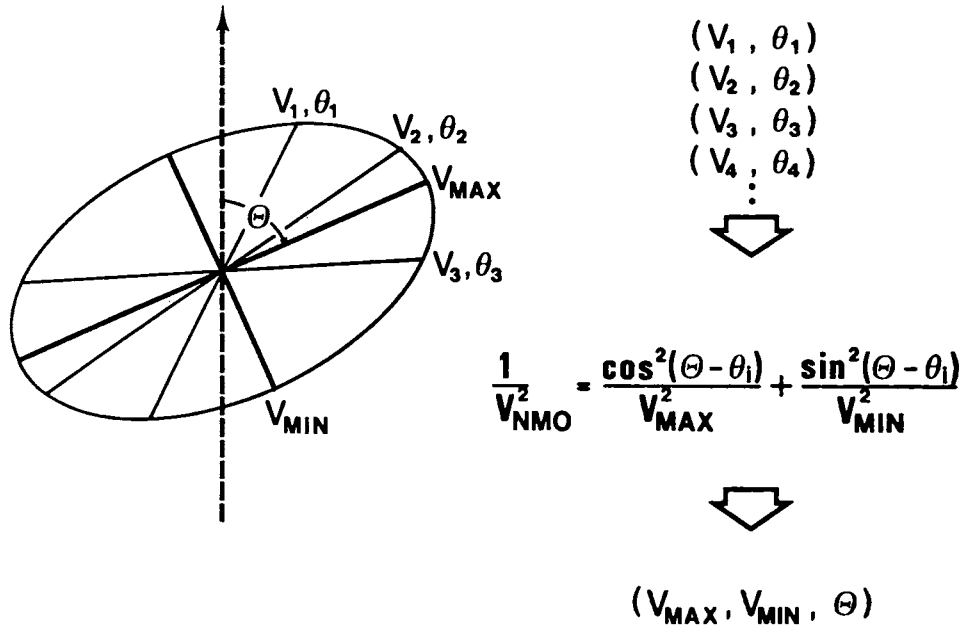


Fig. 8. Estimation of the Velocity Ellipse

stack and 3D migration. Conventional 2D analyses can be applied if all or at least the long source-receiver vectors have nearly the same direction. This can be achieved by an appropriate selection of the field layout on land or by using lines with nearly no feathering in marine work. In this case the azimuth dependency of the velocity is negligible. There is only *one* velocity function per CDP to be used for stacking. However, if the shot-receiver vectors show a random distribution an azimuthal velocity estimation is necessary.

The sector-analysis is an approximate but efficient and economic way for its determination. The data will be grouped and analysed within certain azimuth sectors. Fig. 9 illustrates the principle of sector analysis. A typical variation of shot-geophones vectors contributing to a CDP of high coverage is considered.

By selecting data from individually specified sectors of the spider figure, which will cover a certain range of shot-receiver directions, for instance 20, 30 or 45 degrees, some pseudo 2D profiles are created. That means, all traces within such a sector are used for standard velocity analysis, independent of the individual source-receiver directions; they are assumed to be arranged along a straight line.

Traces of the near offset range (as in this example those within the inner green area) are used as common traces for all sectors, since they are not affected by azimuthal velocity variation.

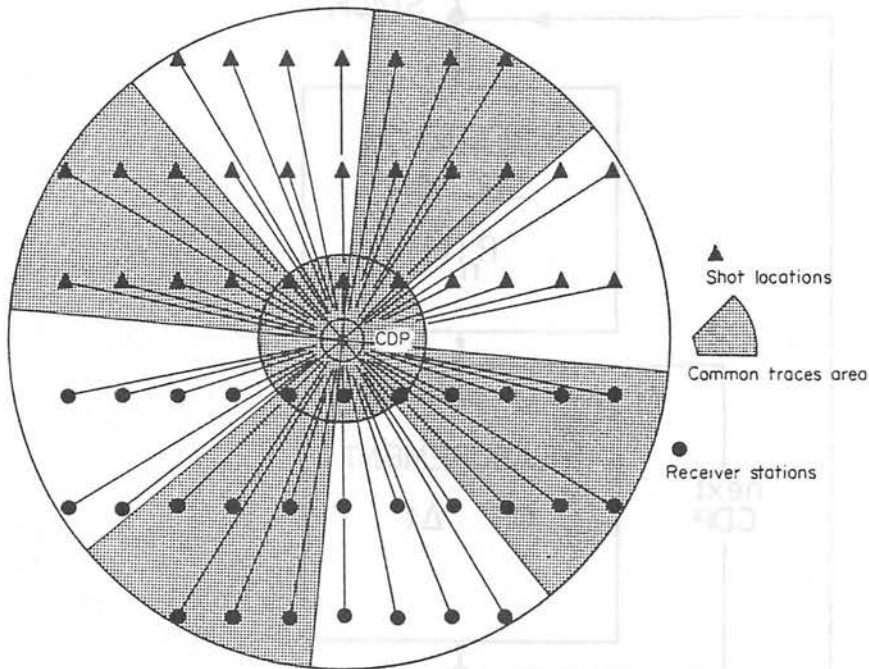


Fig. 9. Trace Selection in Sectors

The velocity estimates obtained by conventional 2D analyses of the sector traces then are valid for the mean sector azimuths, which are computed by a weighting procedure from shot-receiver offsets and directions.

These velocity/azimuth pairs (Fig. 8), are input data for an ellipse inversion program which computes the maximum and minimum stacking velocity and the orientation of the main axis. If more than 3 directions can be supplied, a least-squares fit improves the results.

There are several other procedures on the market for deriving adjusted velocities, but attention has always to be paid on a good ratio of cost and effectivity.

Residual statics

The solution of the 3D residual statics problem in 3D land work also needs some constraints: e.g. that one geophone position shows one and only one static correction value. This implies rotational symmetry for the statics around each geophone position. This is not necessarily true. But also here it is very easy to introduce azimuth-dependent statics, since the shot-receiver vector is known for each recorded trace.

In general the statics computation is performed by an iterative procedure. First a reference section is established (Fig. 10) which in 3D data processing actually is a

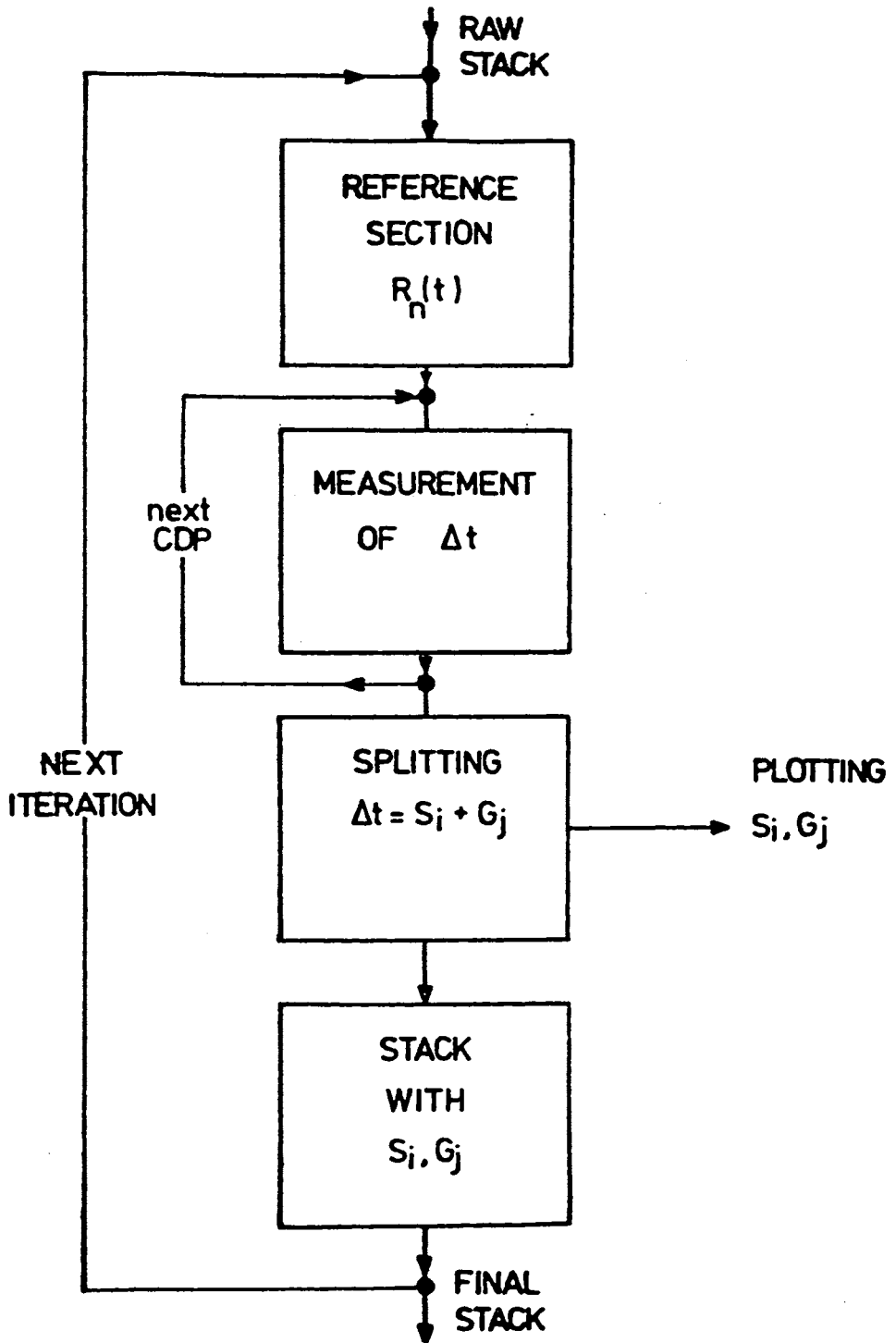


Fig. 10. Residual Statics

reference plane with respect to which the residuals are computed. After application of these residual statics the reference data are updated and the residuals are computed again in a loop until an optimum stack is obtained.

This iterative procedure is surface consistent and delivers equalized statics in both inline- and crossline direction, which can be provided by looking at horizontal sections before and after the process (Fig. 11).

3D migration

After 3D stack, the data have been properly prepared for the 3D migration process. 3D migration is the central procedure in any 3D data processing sequence. It corrects for events reflected from outside the plane of stacked data and thus provides true geological sections for interpretation work.

The basic mathematical tool is the acoustic wave equation which enables us to derive the wave field at any depth from reflected energy recorded at the surface of the earth. The procedure, which is called "downward continuation" of a wave field, requires the solution of a system of partial differential equations which is of course of higher order in the three-dimensional case than in the two-dimensional case.

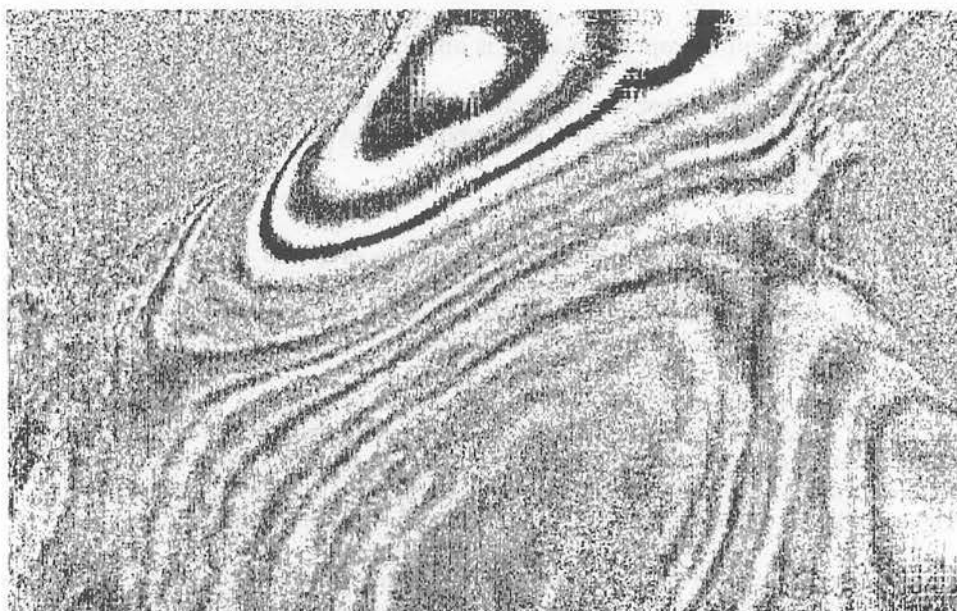
To overcome these mathematical difficulties and to provide economic procedures two distinct 3D migration approaches have been developed in the past, which are based on the same idea namely the separation of the three-dimensional migration operator by two two-dimensional operators, but which are different from each other in their implementation:

- 3D migration as splitting approach, using finite difference techniques,
- 3D migration as two-step approach, using any type of conventional procedures.

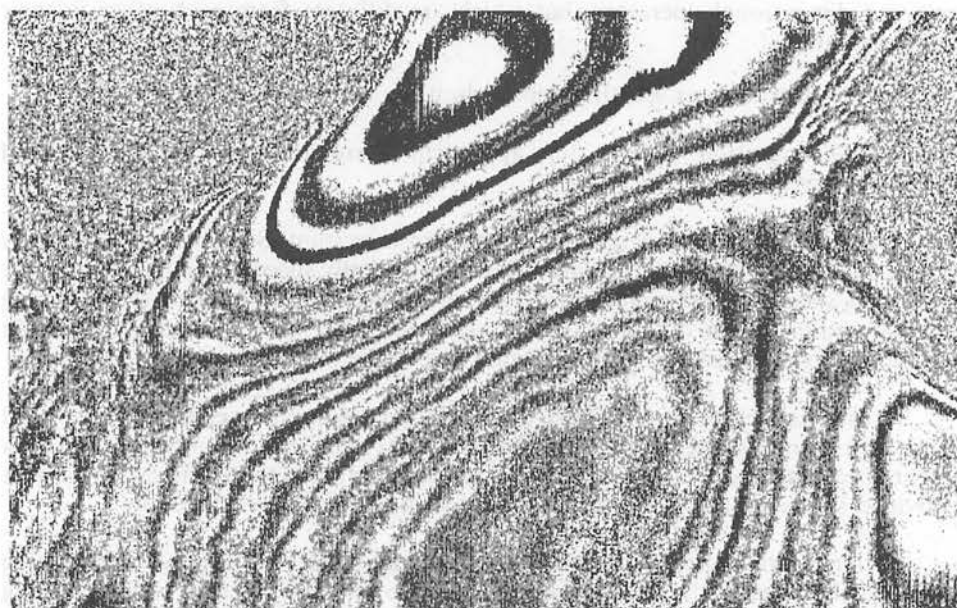
Fig. 12 shows the principle of 3D splitting migration. Starting from vertically organized stacked sections, the data will be horizontally sliced and migrated slice by slice with specified step increments. They are generally multiples of the sampling interval and may even vary with depth to save computer time. The migrated output data are of course sampled with the same rate as the input data.

In the two-step method the two 2D operators are applied separately in vertical sections, as demonstrated in Fig. 13. The first step is the migration of the stacked data in one specified direction. The second step is the migration of the 2D migrated data set provided by the first step, however, reordered in perpendicular direction.

Both migration approaches are equivalent in the single-velocity case. 3D splitting migration however, is the more accurate procedure from the aspect of better handling of lateral velocity variations. The velocities derived in the prestack phase are generally used for both stacking and migration. However, for a successful migration so-called RMS-velocities are necessary, which sometimes can deviate considerably from stacking velocities.



Horizontal Section of Brute Stack Data



Horizontal Section of Final Stack Data

Fig. 11. Brute Stack—Final Stack, Horizontal Section

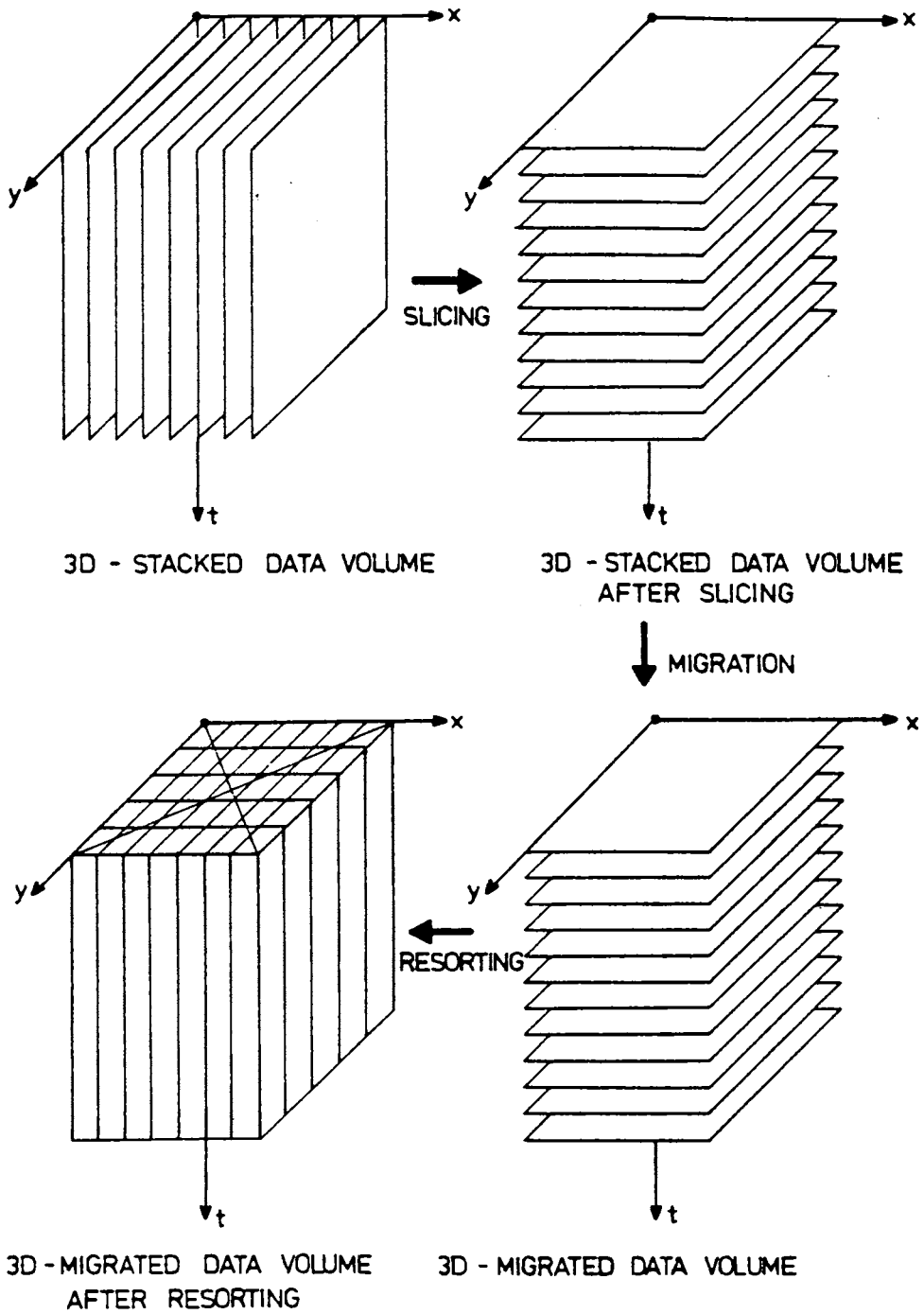


Fig. 12. 3D Splitting Migration

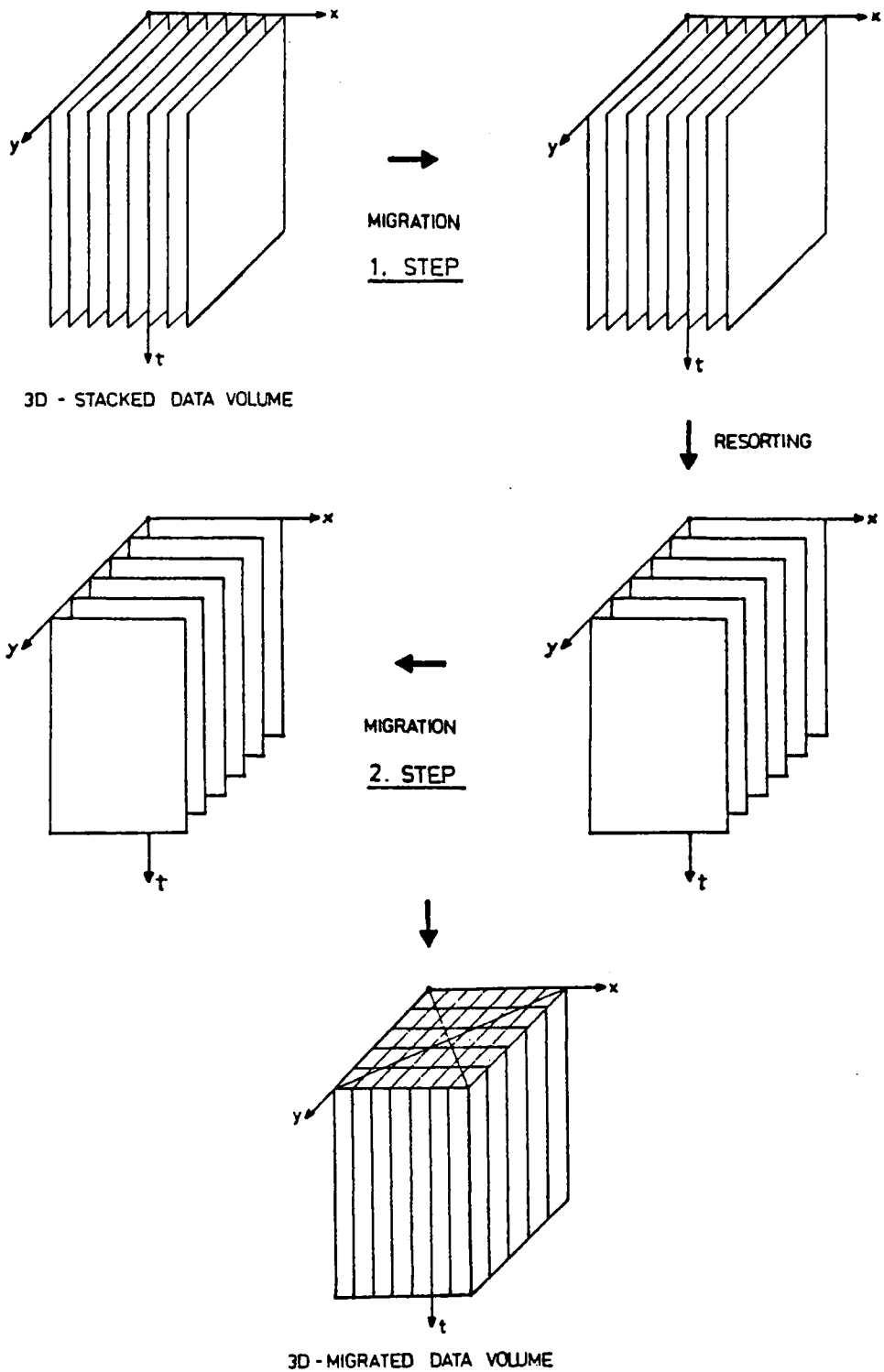


Fig. 13. Two-Step Migration

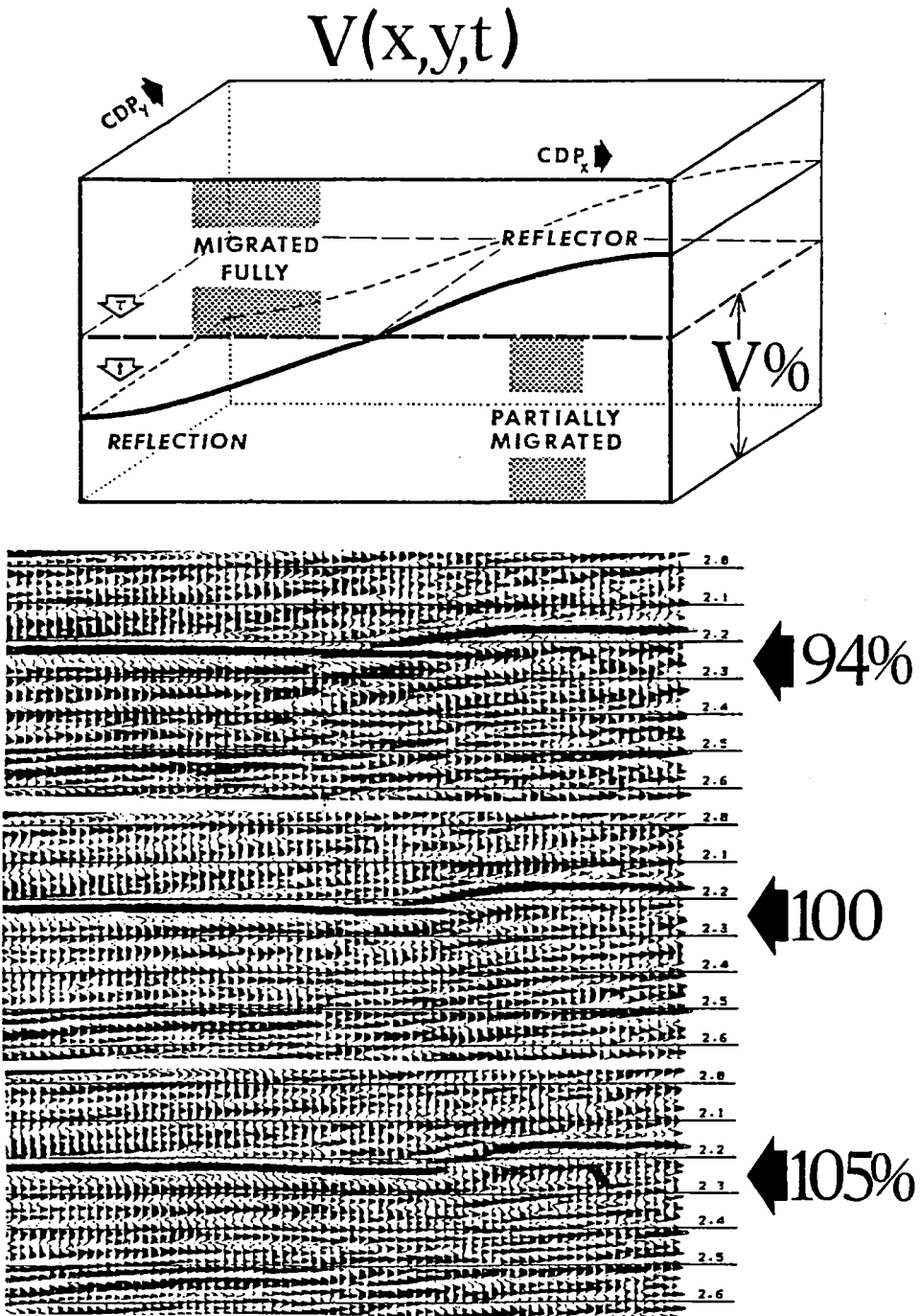


Fig. 14. Migration Velocity Check

A further advantage of the 3D splitting migration is the possibility of testing the migration during the migration process itself (Fig. 14). The process is interrupted at a certain level. For the full migration of the lower part now different velocities may be applied. With the two step migration algorithm this relative cheap check of migration velocities is basically not feasible.

Interpolation

To enhance the resolving power of the subsequent 3D migration process very often interpolation methods are applied to the stacked data. This is to reduce the basic bin size, e.g. from 25×50 m to 25×25 m. The finite difference migration operators are very sensitive to the spatial sampling parameters, introducing some kind of coherent noise such as grid dispersion and aliasing frequencies. Thus, when a proper sampling of data, which must be tailored to the actual geologic problem, is not feasible in the field, trace generation by interpolation is a powerful tool to improve the data set.

Two procedures are generally at our disposal:

- a. interpolation in constant time-planes, involving sine-functions,
- b. interpolation along seismic events, involving pattern recognition techniques.

The interpolation operator must have the allpass-character, at least within the signal frequency band. Recursive filter techniques are involved to great advantage for an economic application of the interpolation operator.

When acting in constant time planes dipping events have to be carefully considered before applying the interpolation process. As the 3D data volume will be drastically increased after interpolation, it is recommended for saving computer time to apply the two-step method of 3D migration, since the interpolation can be applied after the first step on 2D migrated data. In contrast to this, when using the splitting method, the interpolation has to be applied to the 3D stacked data prior to the 3D migration.

The 3D technique delivers a properly migrated data volume, from which sections in any orientation can be displayed. Not only vertical but also horizontal sections provide a spatially continuous perspective of the hydrocarbon prospect under evaluation. Figs. 15 and 16 show a comparison of 2D and 3D migrated sections. The differences are obvious. Fig. 17 shows an example of horizontal sections. For horizontal sections it is particularly interesting to use in addition to the conventional display of amplitudes also a colour display of the instantaneous phase (Fig. 18). From these displays quick information can be gained about the amount of up and down dipping events all over the area.

INTERPRETATION

The tremendous amount of data accumulated during 3D surveys cannot be interpreted within a reasonable period of time using conventional paper sections. Consequently, a new approach was chosen to handle the interpretation of 3D surveys

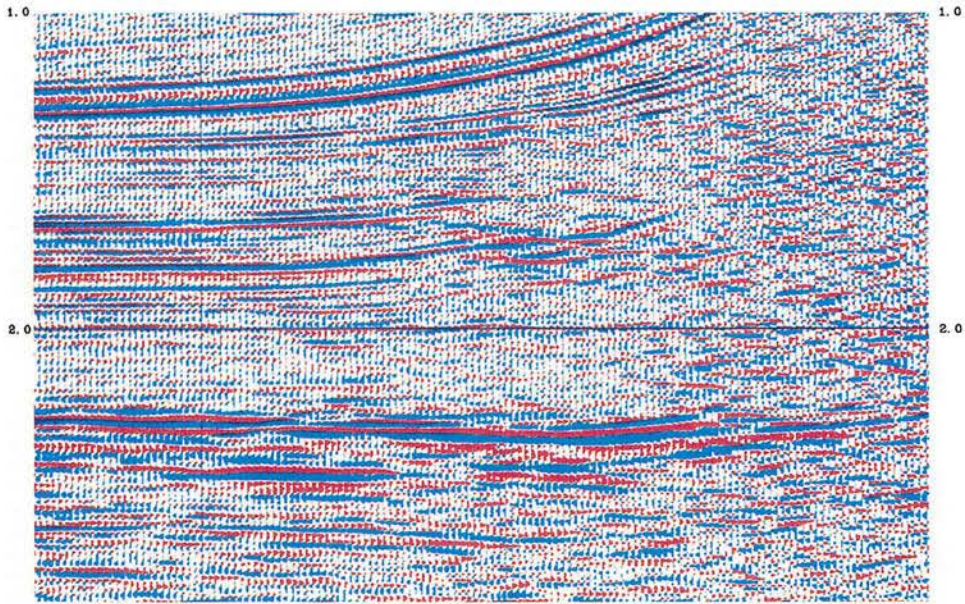


Fig. 15. 2D FD-Migration

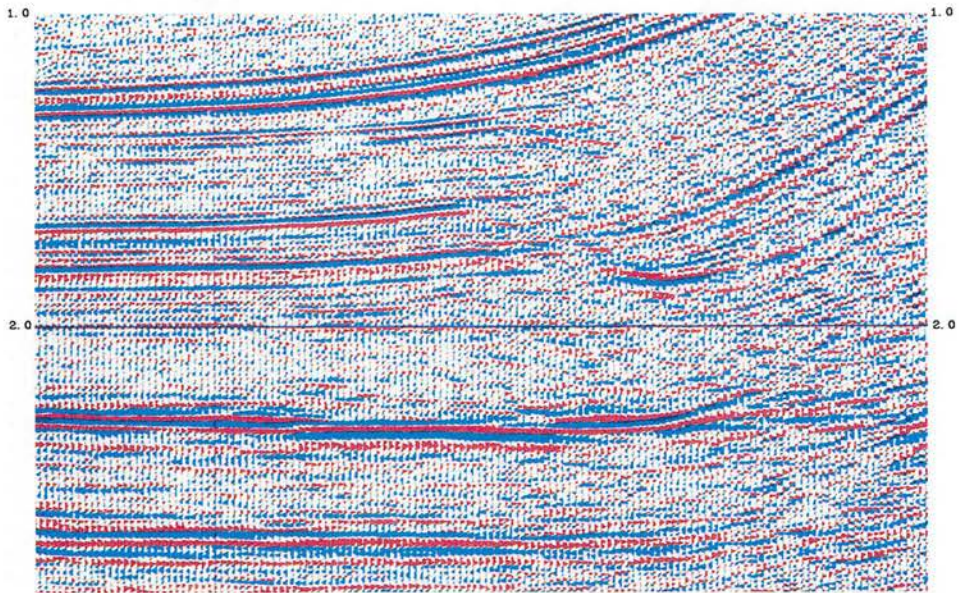


Fig. 16. 3D FD-Migration

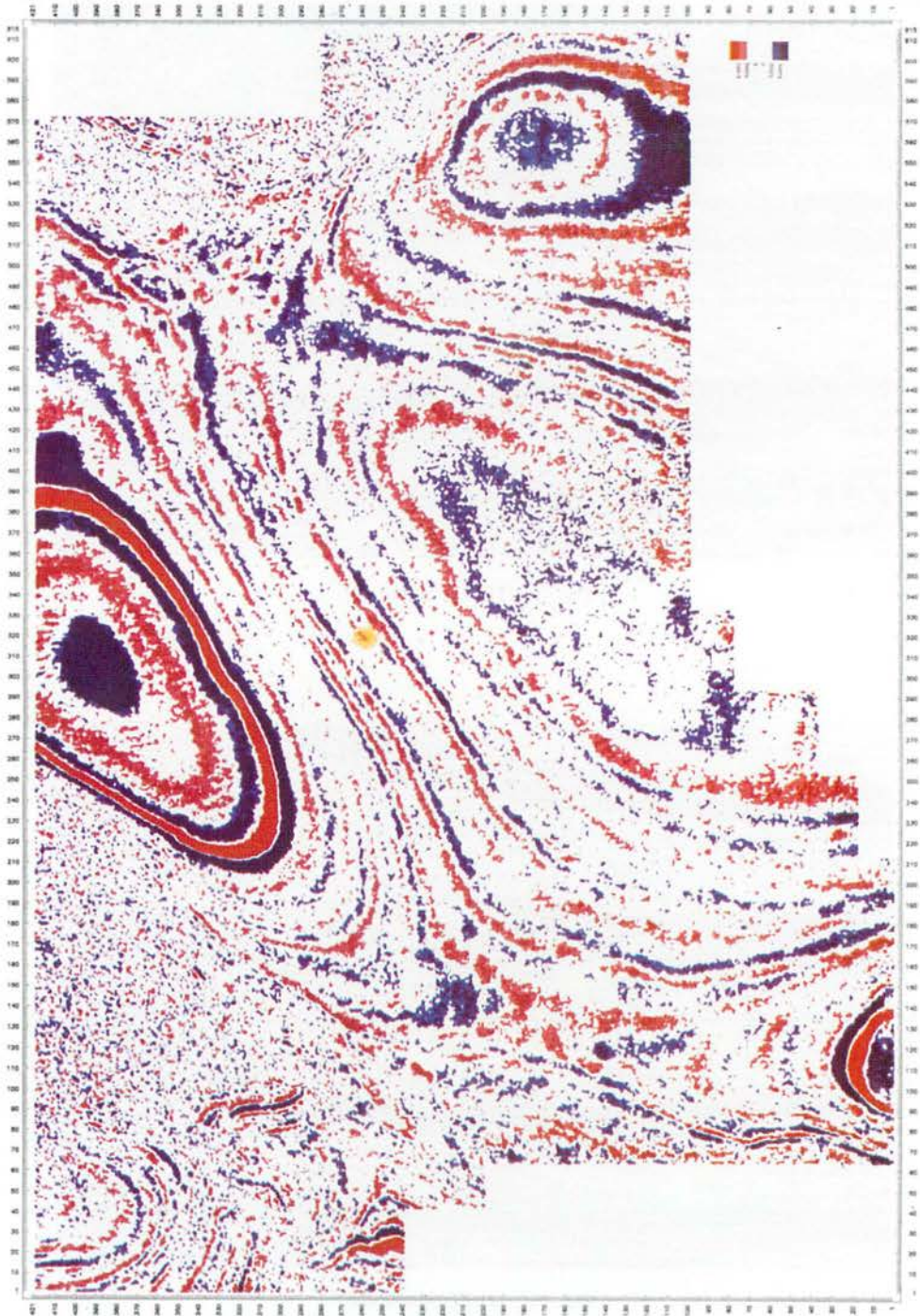


Fig. 17. Horizontal Section (Amplitudes)

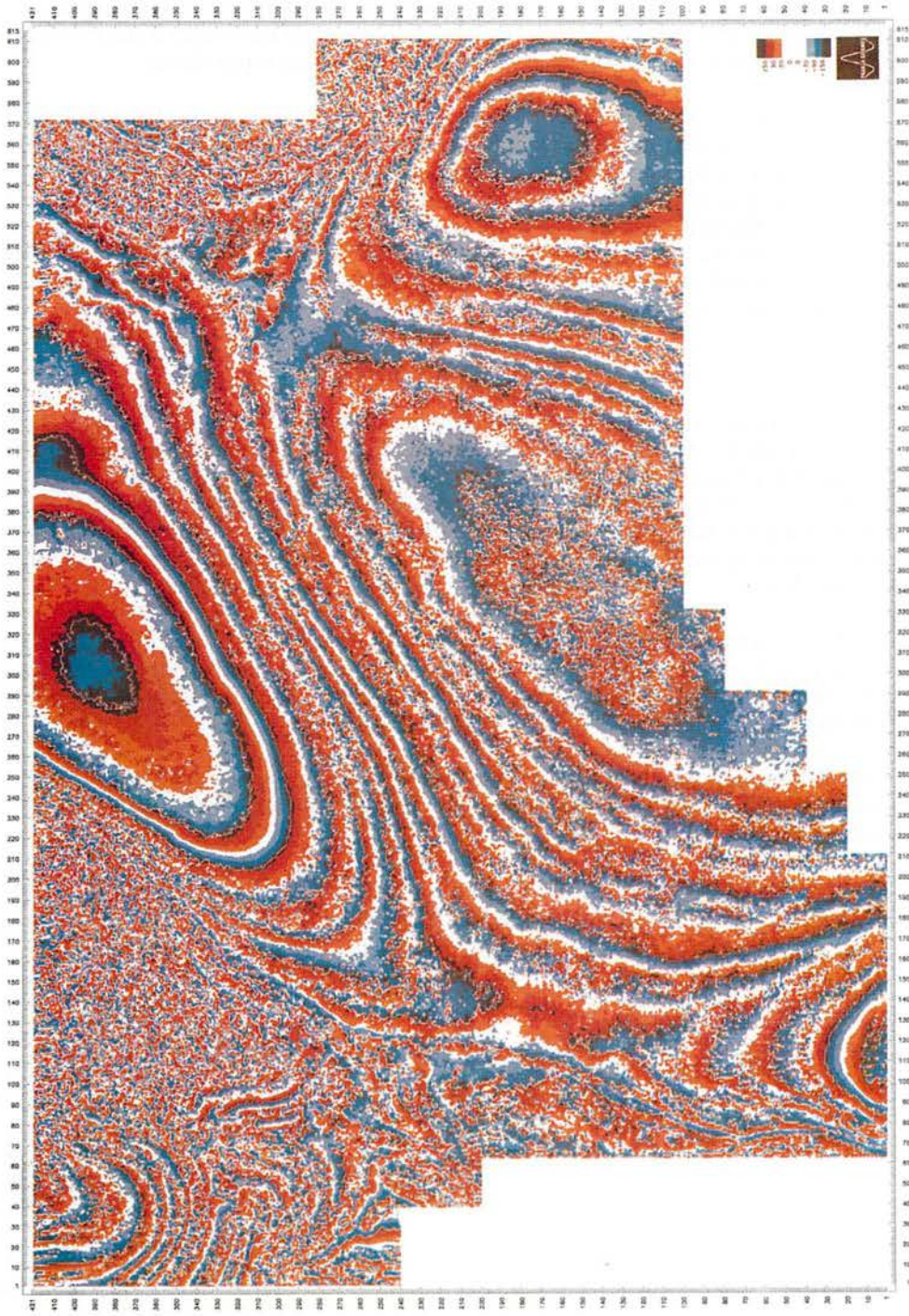


Fig. 18. Horizontal Section (Instantaneous Phase)

using a micro-computer supplemented by a number of peripheral devices, such as digitizer, plotter, and a graphic display processor. The core of the system is the graphic work station, which serves as a display device as well as an input device.

The interactive program supports the interpreter in various ways. The migrated seismic data are stored on disc, from which they can be displayed as vertical or horizontal sections. Selection of certain windows allows the contents of the window to be zoomed without losing any resolution. Horizons and faults can be picked on the screen or, if reflection quality is good, a semi-automatic picking procedure can be utilized. Ties with the intersecting lines are displayed automatically. Furthermore, well data can be tied with the seismic section. Appropriate software provides the necessary tool for interactive interpretation of high reliability.

CONCLUSION

Some aspects in 3D seismic data processing have been discussed. Leaving the conventional path of exploration by acting in three spatial directions additional problems in both acquisition and processing are to be solved. The solutions are based on many years of experience all over the world. The procedures derived are adapted to the state of the art technologies and thus are subject to further development. From the economic point of view they always will have to consider an optimum ratio between cost and efficiency.

3D surveys naturally generate a tremendous amount of data to be processed. The new generation of supercomputers allows for an enormous increase in processing speed compared with the fastest conventional computers. This in turn, enables seismic processing of much larger 3D surveys than some years ago.

With increasing number of traces and more powerful computer programs further improvements in the 3D seismic technique are expected for the near future to keep on the way of higher resolution.