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High-resolution 3D reflection seismics on a tidal flat: acquisition, processing and interpretation

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The academic teacher of exploration geophysics is faced with the quandary of how to provide hands-on experience of reflection seismic acquisition, by far the most important exploration method of our time. Gravity, magnetics and geoelectrics are well within the reach of even a small university department, and refraction seismics is probably done more often for research than for commercial purposes. Reflection seismics, however, requires expensive equipment and large crews. Even where reflection surveys are carried out in an academic context, the acquisition—and often the processing—is done by professionals; the consequences of even innocent mistakes are too dire to let the student learn by trial and error. This is true for any reflection seismic project, but *a fortiori* for three-dimensional (3D) surveys.

As far as two-dimensional (2D) seismics is concerned, the didactical problem was solved at Utrecht University by working on tidal flats (Doornenbal & Helbig 1983). The ease with which high frequencies can be generated allows the survey parameters to be scaled down by at least a factor of 10. The resolution of the data thus acquired is nearly unparalleled on land and the small scale reduces the logistic parameters (sizes, weights, distances and cost) and the difficulties of supervision to a magnitude that can be handled easily. For nearly a decade all students of geophysics have acquired, processed and interpreted a meaningful amount of reflection seismic data. Fortuitously the results of this exercise provide significant data for a continuing sedimentology research project.

In recent years the importance of 3D seismics has steadily increased, so that the question arose as to how the specific features of the technique could best be introduced to the students. Moreover, the correct interpretation of the small-scale sedimentary features observed in 2D surveys on tidal flats often requires intersecting lines. The same flooding of the flats that helps us generate and transmit high frequencies makes the maintenance of positional markers difficult. Particularly after a storm it is almost impossible to relocate a line to an accuracy of 1 m. Therefore, data referring to one structure have to be acquired in a single field period.

The survey described here was designed to test the possibility of expanding the mandatory field work to cover 3D seismics. It provided a starting point for the development of the necessary software and display technology. J. Corsmit and W.H. Versteeg (then students at Utrecht) were asked to develop the field technique, acquire a data set for test purposes, write the necessary expansions to the existing 2D processing package (Doornenbal & Helbig 1983) and carry out the preliminary interpretation. J. Brouwer and K. Helbig were involved in planning and supervision and are responsible for some of the display technology.

The acquisition phase lasted two weeks. Three people were continuously involved, but a routine survey of this magnitude could, in principle, be carried out by two people (a total of about 120 man-hours). The data were originally processed on an HP-1000 minicomputer. Processing was time consuming since it was combined with programme development. To reprocess the data on our current Gould PN 6000 super-minicomputer takes about 8 h connect time (with known parameters). Interactive processing of a comparable new data set would require about 32 h. Several of the illustrations were prepared on the Gould PN 6000.

Location and target

The survey was carried out on the Plaat van Oude Tonge (Fig. 1), an intertidal shoal in the Eastern Scheldt inlet, where 2D surveys have been carried out since 1981 by students of the University of Utrecht as part of their field work (see Doornenbal & Helbig 1983). While most of the shallow features in the early lines are subhorizontal, lines 8102 and 8103 show an interesting dune-like structure at traveltimes between 15 and 40 ms (Fig. 2). This structure was the target of our survey. Since the two lines recorded in 1981 did not intersect—accessibility is

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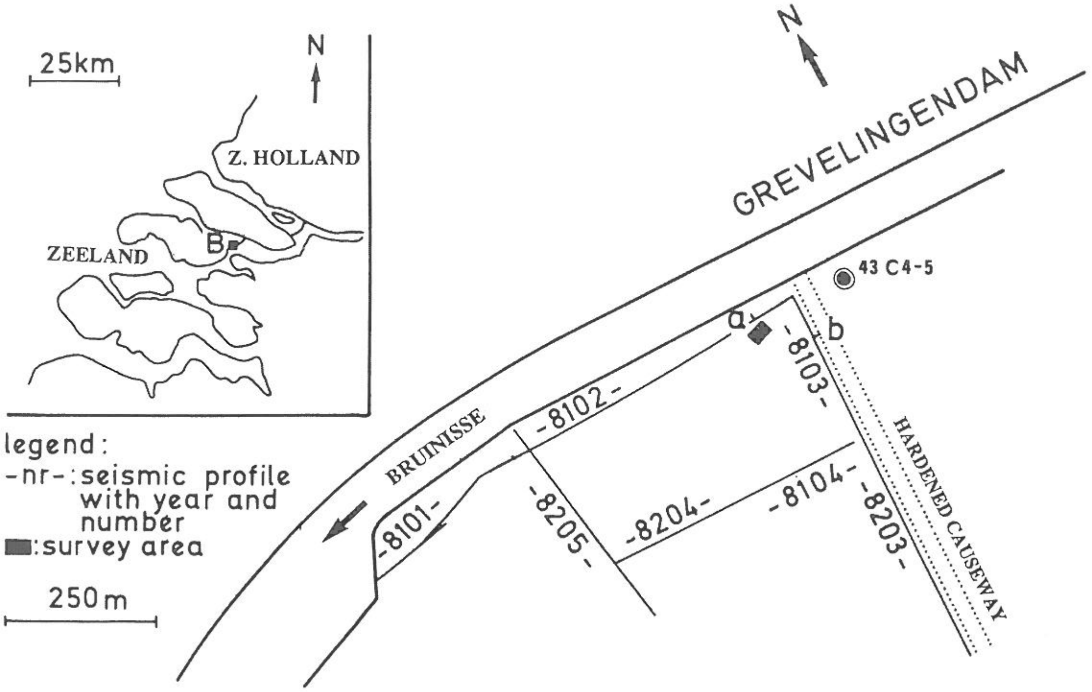


Fig. 1. Locations of some 2D lines shot in recent years on the Plaat van Oude Tonge and borehole location 43 C4-5. The markers a and b, indicated on line 8102 and 8103, correspond to the markers on the profiles in Fig. 2. Inset: topographical map showing the location of the survey area in the south-western part of The Netherlands. The letter B indicates the village of Bruinisse.

restricted by the Grevelingen dam and a hardened causeway on the shoal itself—the detailed geometry of the structure and consequently its classification and probable origin were still uncertain. In particular, it was not clear whether the two antiforms represented a single dune-like structure striking NW–SE or two separate features striking NE–SW. The latter strike appears to be more common in the area for the aeolian deposits of the Twente Formation (van Staalduinen *et al.* 1979).

Equipment

The equipment used in this survey was described by Doornenbal & Helbig (1983). The source was a 30 kg steel ball, dropped from a height of 3 m on to a steel plate of about 30 kg mass. Under the survey conditions the signal observed during the first 50 ms after the impact has a peak frequency of about 250 Hz. Twenty-four 100 Hz electrodynamic geophones (GS 100/QSC 27) were laid out simultaneously. A simple roll-along switch allowed the selection of 12 consecutive channels. The recording unit was a 12-channel enhancement seismograph (Nimbus ES 1200) with 1024 words of 10 bits each per channel, a cathode ray tube display, analogue output for hard copy, and data storage on magnetic cartridge tapes. The storage unit did not have read-after-write or field-playback facilities, so that data quality and the field performance had to be judged on the CRT or paper display. The recording unit was triggered by a pulse from a piezoelectric switch built into the impact plate of the source.

Field layout

General considerations

The ideal 3D survey should be designed so that:

- the data points (i.e. the 'normal' reflection points in a vertically inhomogeneous medium) of different source–receiver pairs exactly coincide so that binning is unnecessary:
- the common data points (CDPs) lie on a regular—preferably square—grid;
- each CDP gather has the same number of traces;
- each CDP gather has a range of source–geophone distances that are distributed fairly regularly in the x^2–t^2 domain to allow reliable determination of the stacking velocity by least-squares regression;
- the source–geophone azimuths are evenly distributed to allow the determination of azimuth-corrected stacking velocities;
- any chosen field technique can easily be adapted to different targets.

Considerations for 3D surveys on intertidal shoals

On intertidal shoals the low-water period lasts about 6 h. Therefore

- the survey grid must be relocatable after high-water;
- no equipment can be left in the survey area during high-water;
- since it takes 1 to 2 h to move a complete 24-channel layout with two persons, moving the geophone spread within a low-water period is inefficient and should be avoided.

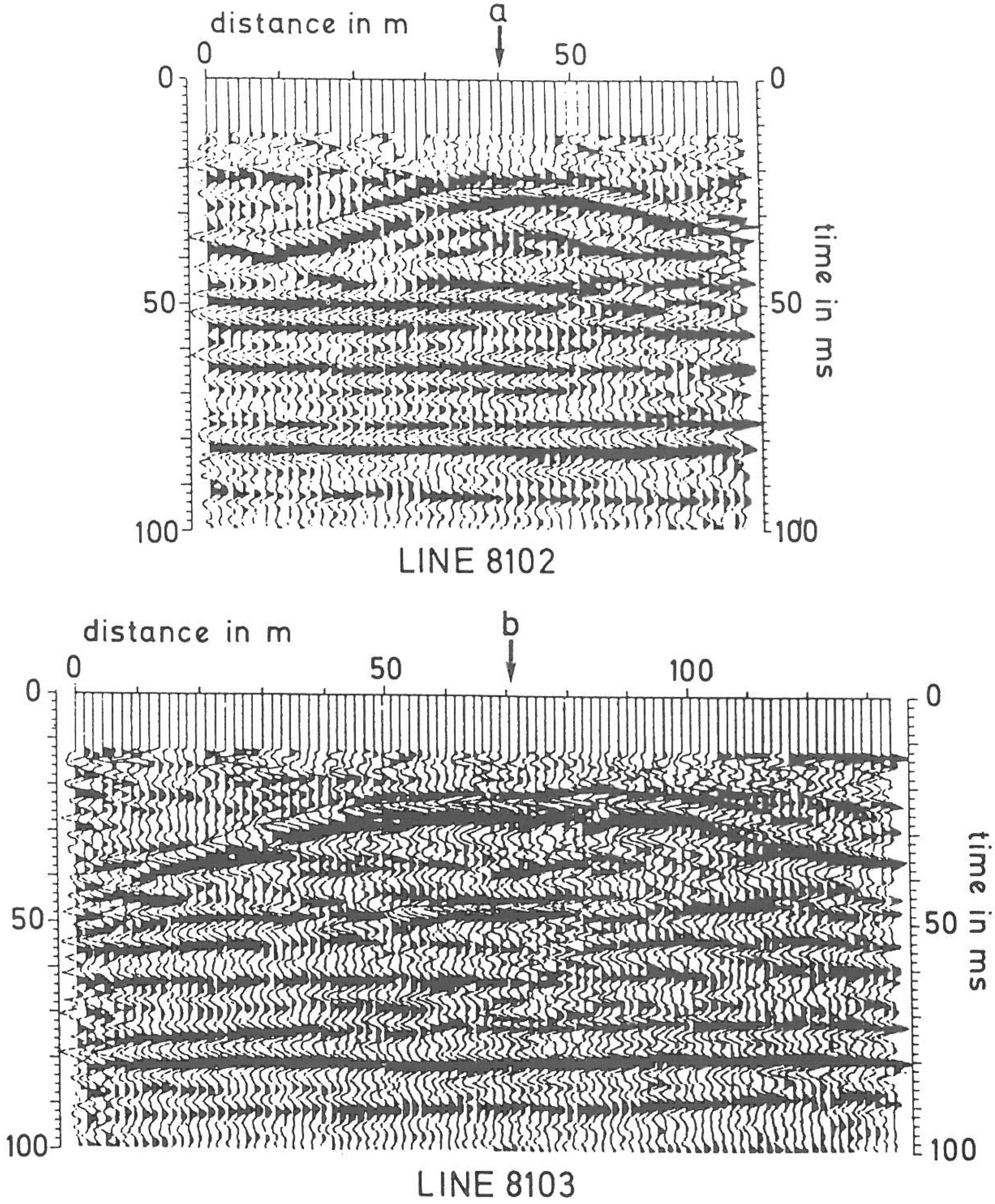


Fig. 2. High-resolution stacked time section, shot in 1981. Survey parameters for these sections were: recording time 200 ms, sampling rate 0.2 ms, 12 recording channels, off-end spread, geophone spacing 3 m, one geophone per station, near-trace offset 15 m, six-fold CDP coverage. The location of markers a and b is given in Fig. 1.

Implementation

A square grid of data points was generated from building blocks based on a regularly spaced strip, 12 geophones long and two geophones wide (Fig. 3). The geophone spacing is used as the unit of distance in the following discussion. The spacing of data points is, of course, half a distance unit.

Twenty-four source locations with an interval spacing of two distance units were combined with these 24 geophone positions. The resulting 576 source–receiver points are located in two strips of 13×3 distance units. Forty-eight data points at the narrow ends of the strips are singly covered; the 264 points in the central parts of the strips have two-fold coverage. Each source location was used twice with each geophone spread, once with geophones 1 to 12 and once with geophones 13 to 24. With a 24-channel acquisition unit these observations could have been obtained as a single record (Fig. 4).

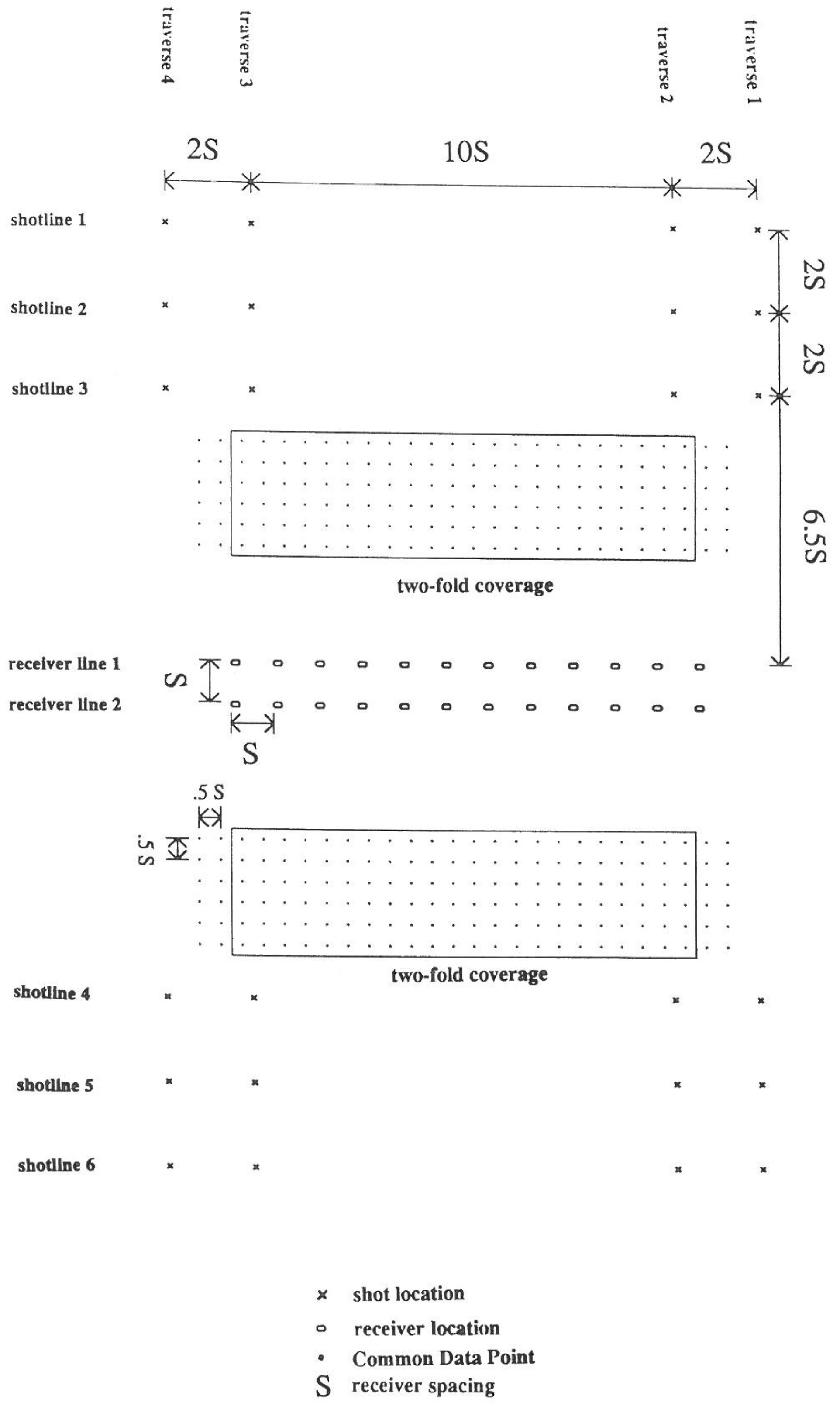


Fig. 3. Basic field geometry. The geophone stations are located on two parallel lines (the receiver lines). The shot locations are placed on four traverses perpendicular to the receiver lines. Each shot location is used twice, once for each geophone spread.

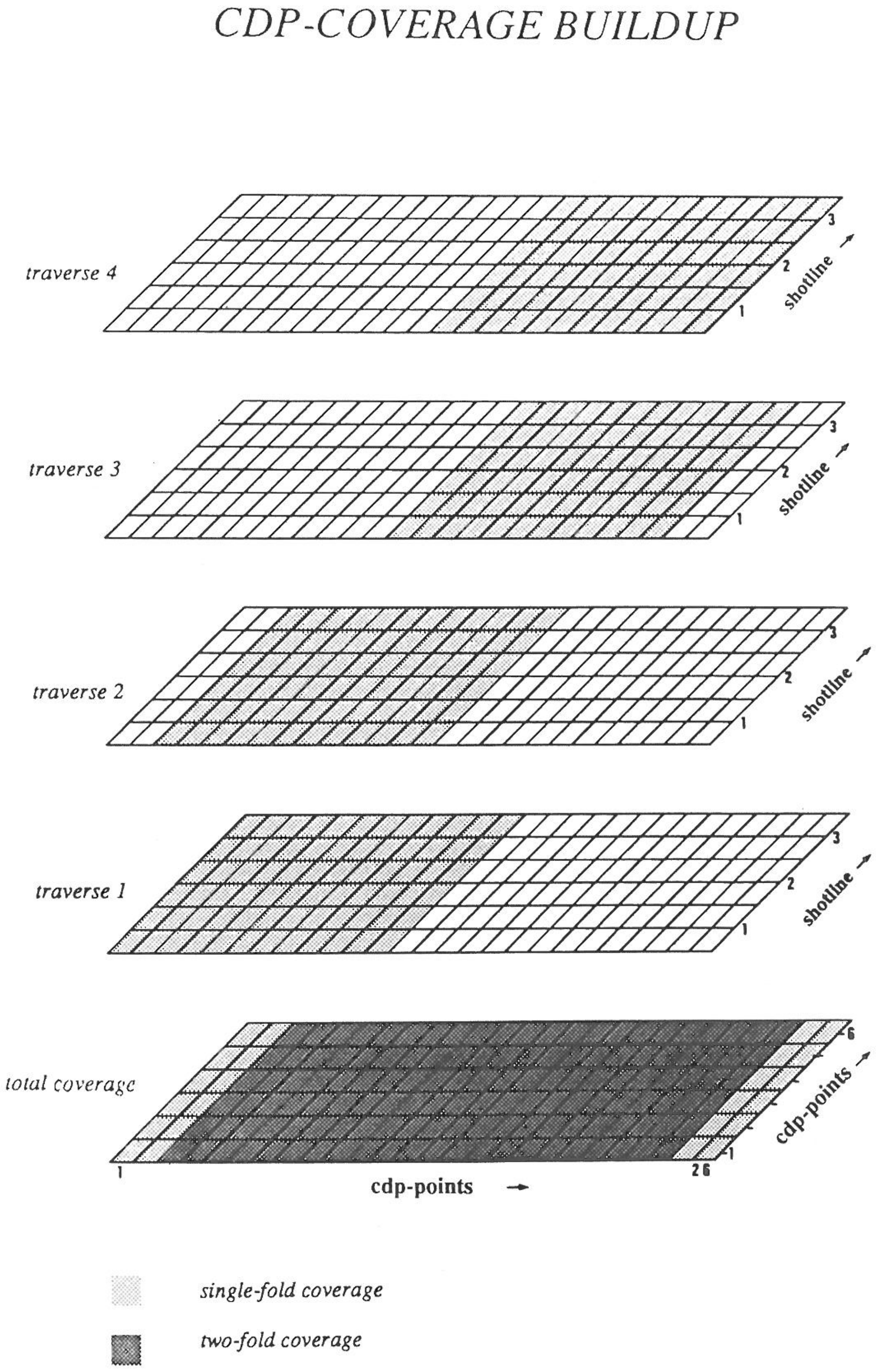


Fig. 4. The source–receiver configuration generates two areas of 26×6 grid points. In each area we find a square grid of 22×6 two-fold covered CDPs. The grid points at the boundaries of each area have single-fold coverage.

Once the 576 traces were recorded, the entire layout was shifted by 3 distance units in the direction at right angles to the orientation of the geophone spreads to expand the area covered by the square grid of data points. After the recording of three layouts, a contiguous doubly-covered area measures 22 data points in the direction of the geophone spread and 36 data points in the direction of the shot traverse, and is lined on either side by two lines of 36 singly-covered data points.

A further shift of the entire layout in the shot traverse direction results in a central four-fold grid. This four-fold grid consists of unit areas of 22×6 data points. The corresponding unit data volumes are the basic units for data processing. The azimuths within the four-fold area are reasonably distributed.

The grid of data points belonging to one strip consists at both ends of three unit areas of double coverage. If full coverage of the entire grid is wanted, the survey should start and end with shooting the first and last three geophone spreads from one side.

Shifts in the geophone spread direction by 12 distance units results in an homogeneous four-fold coverage since the two-fold lines at both sides of the strip overlap precisely.

Field parameters and data acquisition

In the summer of 1983 a unit data volume was acquired for test purposes. This preliminary survey set out to test field performance and timing, to establish standard parameters (vertical stack, sampling rate and recording time, and amplification factor), to verify that for the chosen distance unit the reflections from the target depth occurred in the 'window' between first arrivals and the surface waves, and to obtain test data for the software that had been developed.

The following parameters were chosen: distance unit 2 m (i.e. geophone spacing 2 m, data point spacing 1 m, source point spacing 4 m, offsets between 13 and 34 m), three-fold vertical stack, sampling rate 0.2 ms, recording time 204.8 ms, a fixed amplifier gain setting of 40 dB (factor 100) throughout. No acquisition filter (other than that provided by the 100 Hz geophones) was used.

The survey took place in the late autumn of 1983 during nine low-tide periods spread over two weeks. With a total of 288 source points, 792 traces were recorded corresponding to 22×36 uniformly four-fold data points, arranged in a strip oriented at right angles to the supposed strike of the target structure. Positioning accuracy was maintained by using a theodolite and a measuring chain, and the field operations were documented carefully.

Processing

The processing sequence consisted of

- reading field cartridges into a database on standard tape;

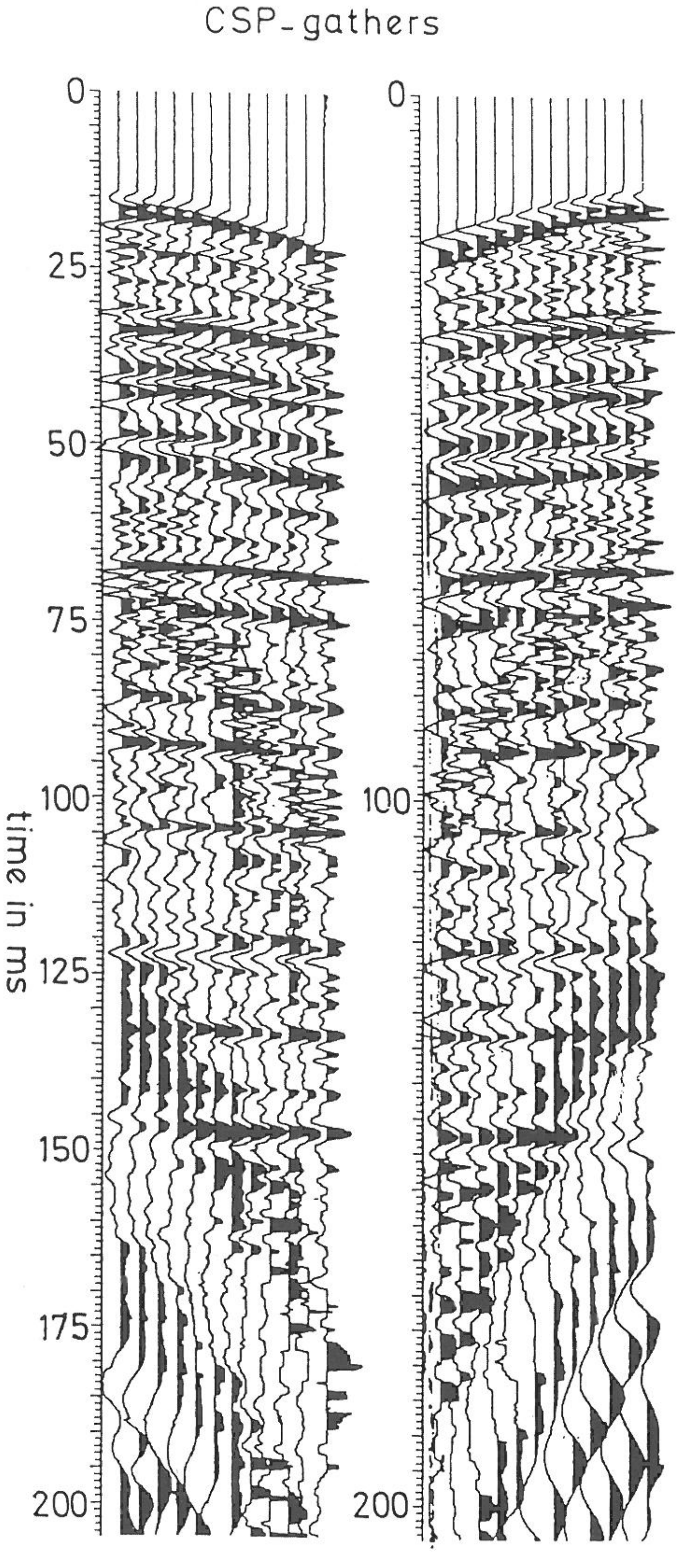


Fig. 5. A Common Shotpoint Gather for both 12-channel geophone spreads in the same strip. The trace sequence versus distance is opposite in the two spreads. Between 65 and 105 ms a relatively slow event of high frequency can be distinguished. This is the sound wave through the air. The low-frequency noise is the groundroll.

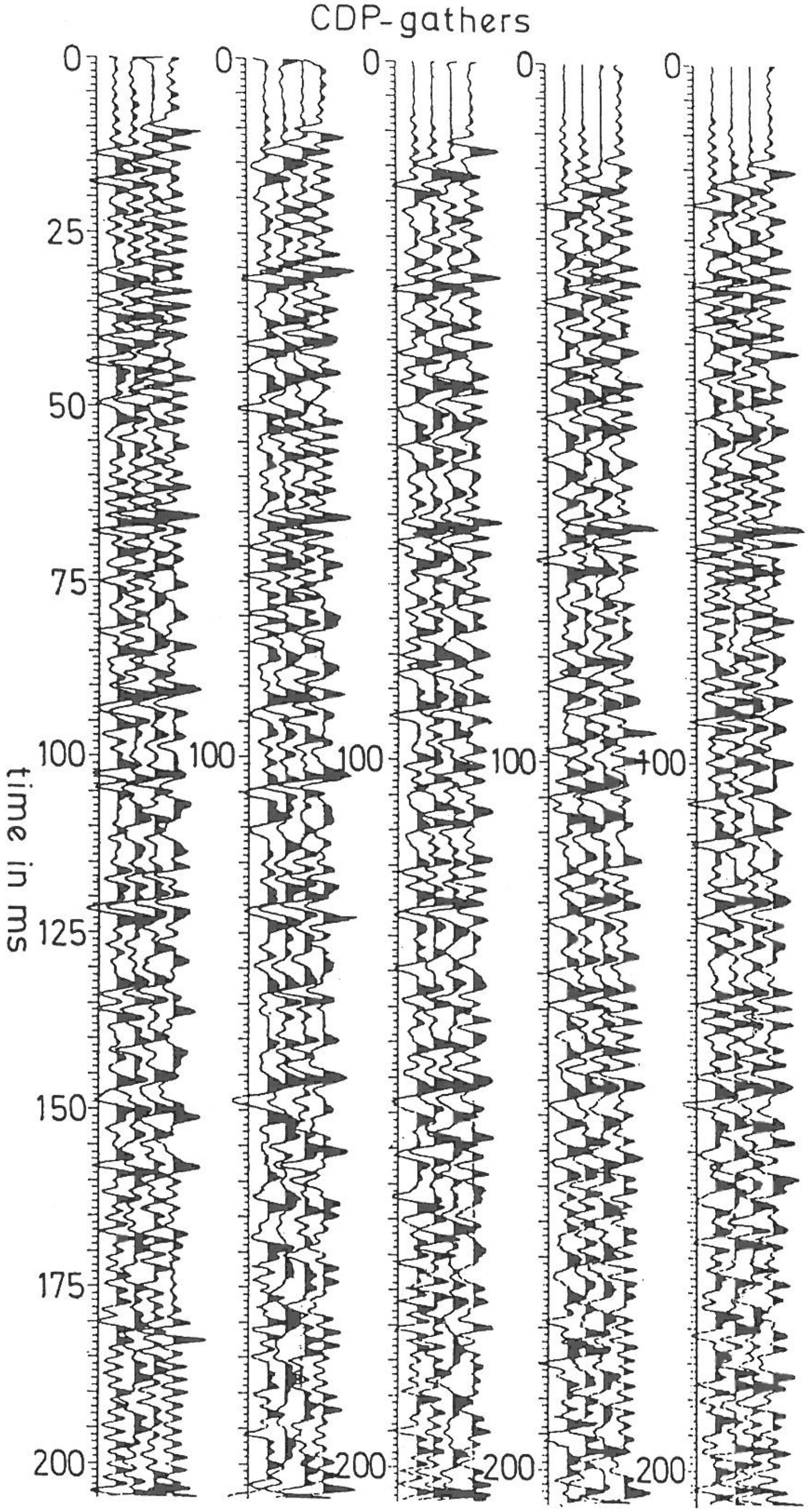


Fig. 6. A few CDP gathers after muting, bandpass filtering (120–550 Hz) and deconvolution (spiking).

- sorting into common shotpoint (CSP) gathers (Fig. 5) and generating headers containing information on field parameters and geometry;
- muting and trace editing;
- suppression of surface waves and high-frequency noise by frequency filtering;
- deconvolution;
- construction of CDP gathers (Fig. 6);
- determination of the stacking velocity function by optimization of 'constant velocity stacks'. Early in the processing the dependence of the stacking velocity on the apparent dip (i.e. on azimuth) was investigated by using 'common azimuth gathers' (Fig. 7). No significant azimuth effect was detected, most likely because the accuracy of velocity determination at four-fold coverage was only 10%. Therefore the azimuth dependence was not taken further into account.

Display

3D surveys are a particular challenge to the display technology: the interpreter has to see the data from different aspects to understand the geometrical relations between different events. The original software package contained three plotting modes for the display of the *x*, *y*, *t*-data volume:

- vertical time sections through the data volume with arbitrary location and azimuth (Fig. 8);
- horizontal sections through the data volume at arbitrary times (time slices) are contours of equal amplitude (Fig. 9);
- time maps of arbitrary reflection events as iso-time contours ('horizon slices') based on automatic picking routines (see Fig. 10).

After the completion of the investigation, an additional set of 3D display utilities was written for use on a colour terminal. These utilities permitted a fast and flexible interpretation of the dataset as described above. The following display modes became available:

- The stereometric combination of two arbitrary perpendicular vertical time sections and a time slice of horizon slice (Figs 11 and 12). In these figures amplitudes are colour coded according to the displayed colour wedge.
- The stereometric combination of the four limiting time sections and arbitrary time slices or 'horizon slices' (Figs 13 and 14).
- The stereometric display of a stack of time slices or a stack of 'horizon slices' (Figs 15 and 16).

There are many display methods. The strength of 3D seismic display methods is not found in any single method but in the possibility of looking at the dataset in a number of ways.

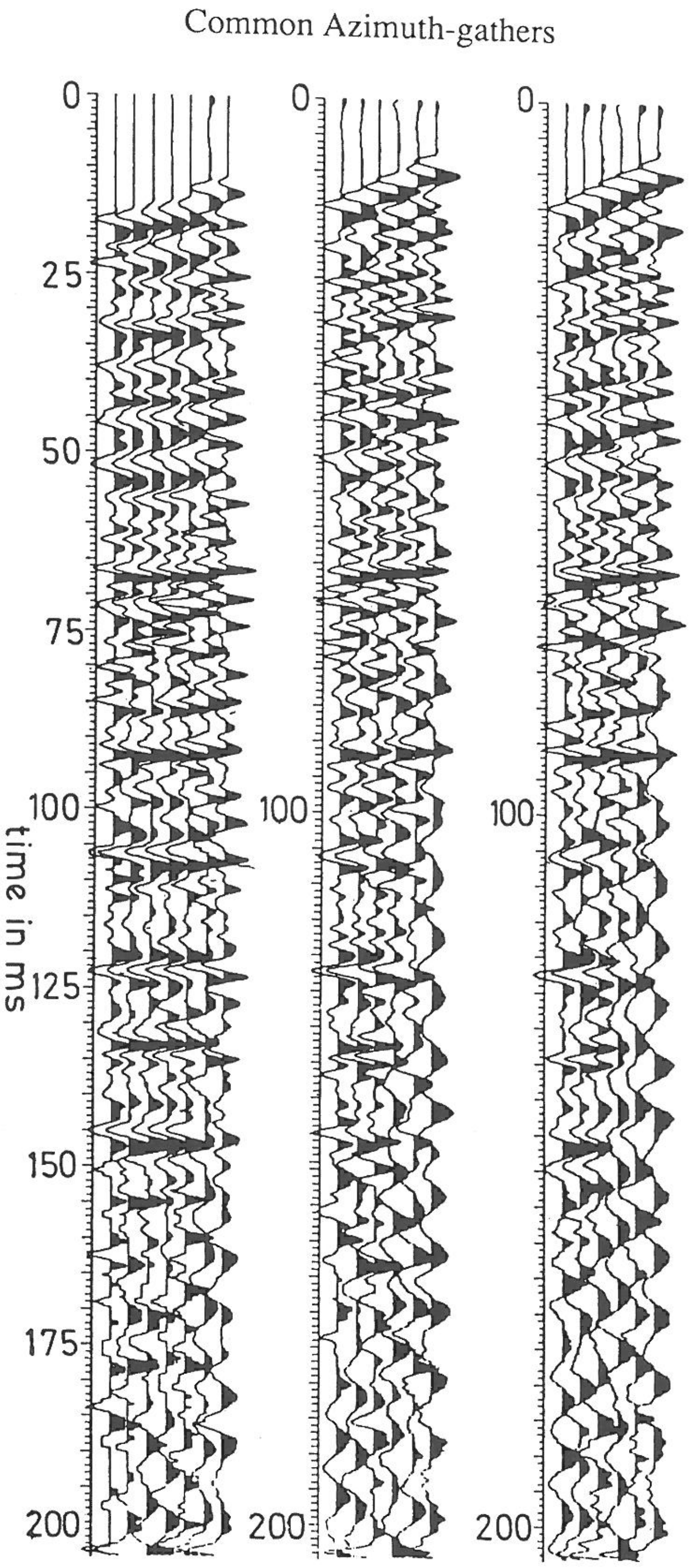


Fig. 7. Set of common azimuth gathers. Design criteria within such gathers are: preferably a regularly spaced and large range of offsets, variation in azimuth less than 5° and the selected traces as close to the central CDP as possible.

Each displayed gather in this figure has the same central CDP. The azimuths of the displayed gathers vary over nearly 40°.

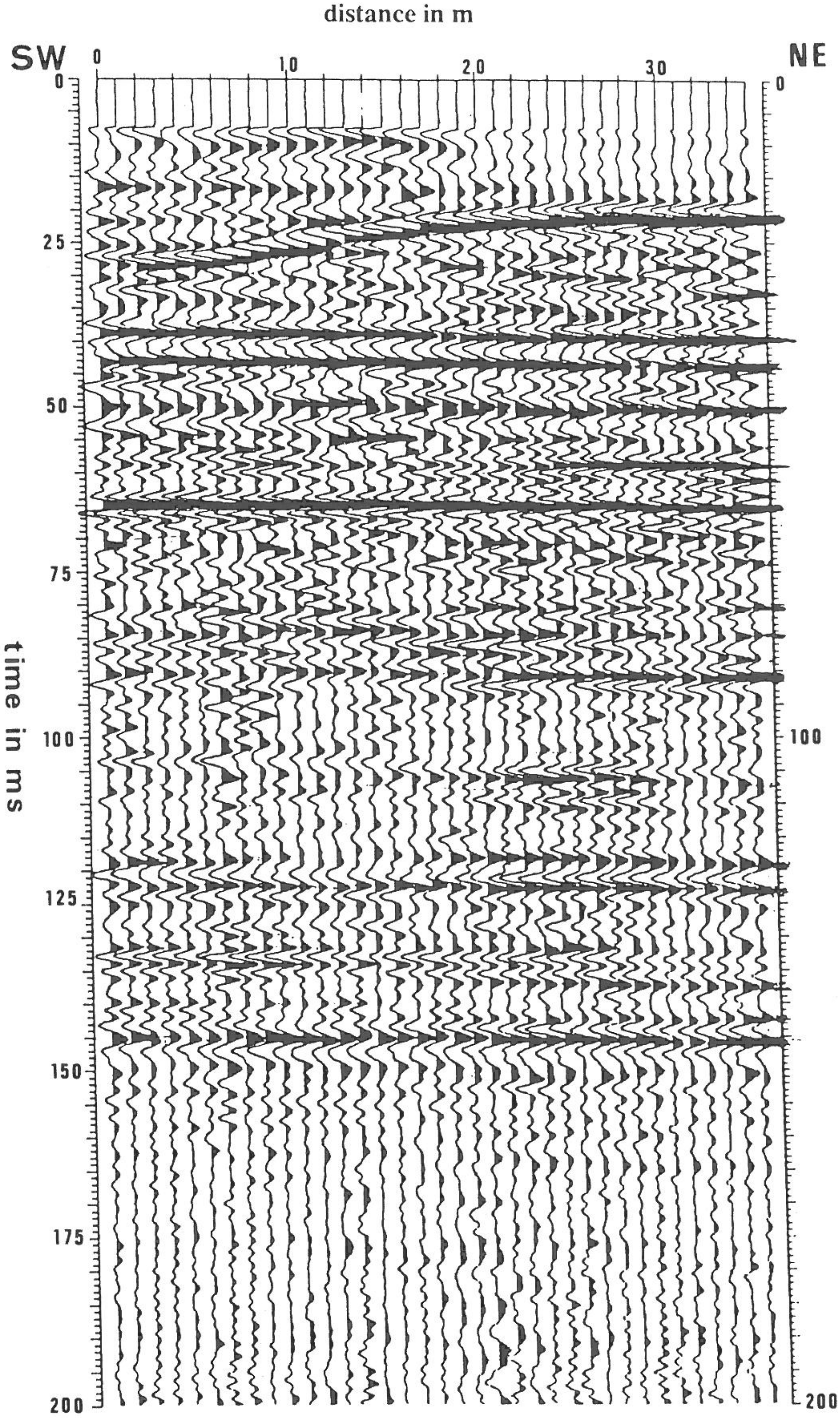


Fig. 8. A vertical time section through the data volume, perpendicular to the expected strike of the dune.

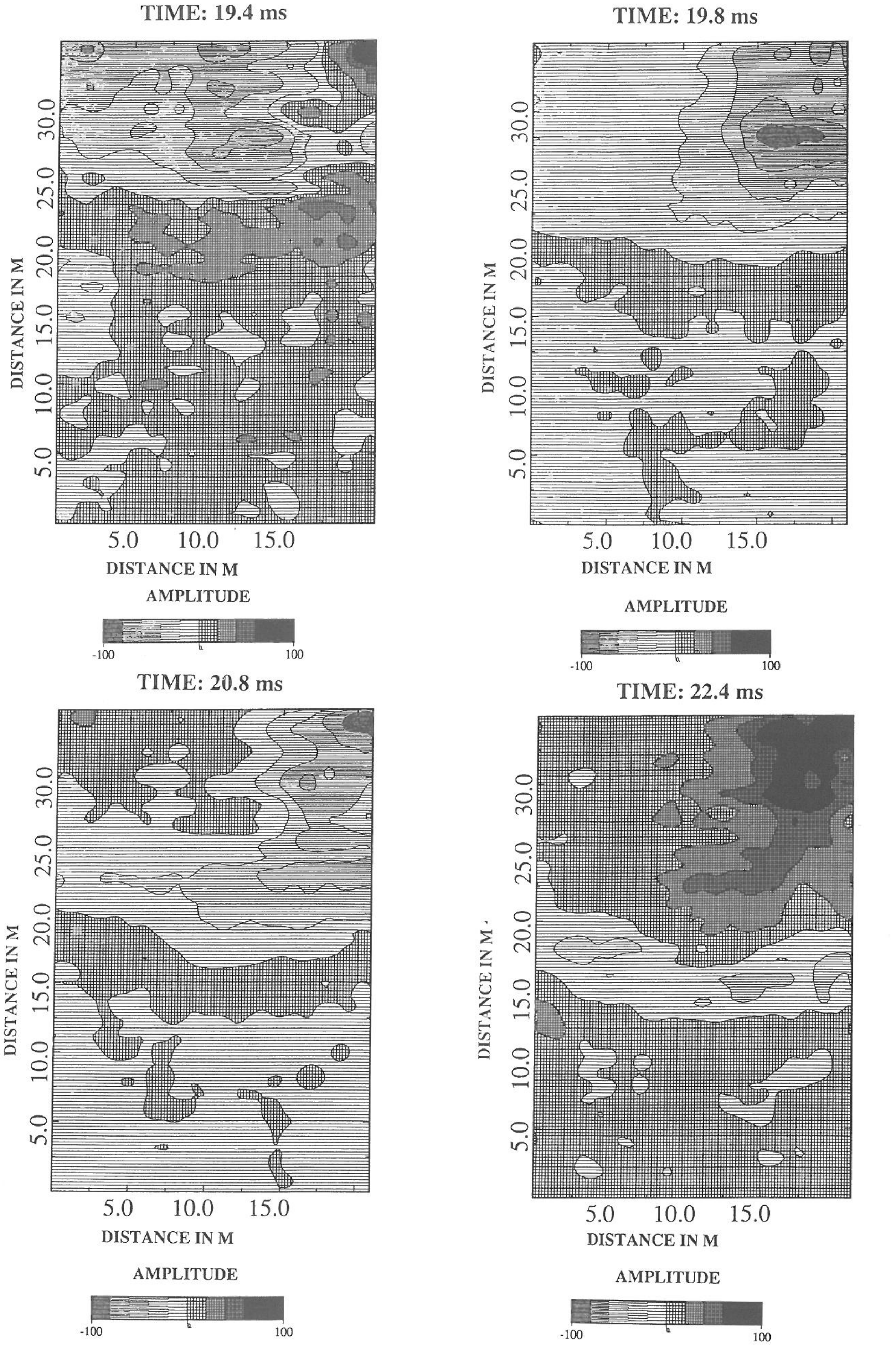


Fig. 9. Time slices ('horizontal' cuts through the 3D data volume). For each slice the amplitudes are scaled between −100 and 100. The following relative amplitudes are plotted according to the shading on the linear scale bar.

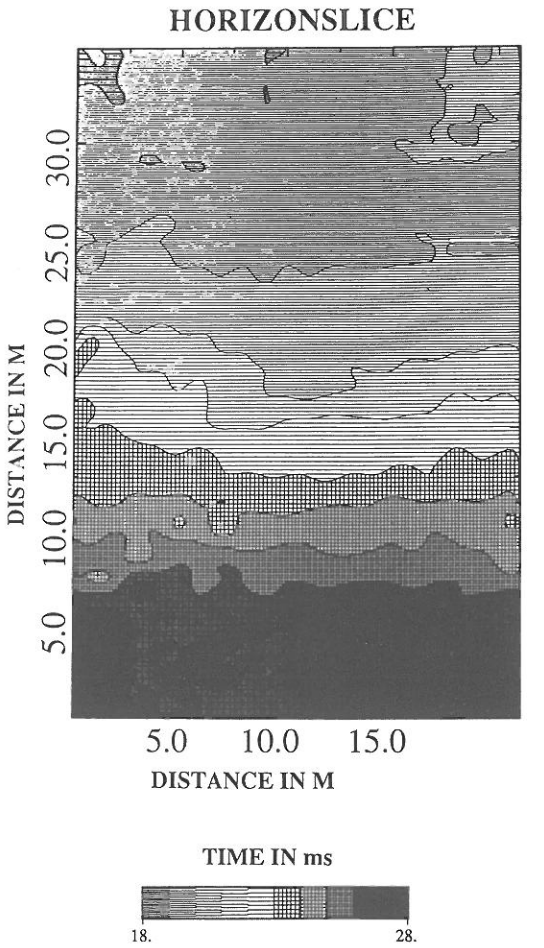


Fig. 10. A time map of the dune. In this figure the time of the negative reflector is plotted in milliseconds from 18–20 ms according to the shading on the linear scale bar.

Results

In Fig. 8 the top of the dune is represented as a strong reflector with negative reflection amplitude. This apparent negative amplitude is caused by the negative polarity of the source wavelet. Fig. 14 shows the shape of the dune in 3D. A shift in arrival time is introduced by picking the negative peaks as representing the top of the dune instead of the onset of the reflected wavelet.

It can also be seen that the amplitude decreases at the flanks of the dune. This is illustrated by the change in colour along the flanks of the dune (Fig. 14). The change in amplitude is partly caused by geometrical spreading and a change in dip. Nevertheless, the remaining amplitude decrease must be due to changes in the contrast in seismic impedance, probably caused by changes in grain size, sorting and degree of water saturation.

The time slices in Fig. 9 clearly show the orientation of the dune. Its main axis strikes N35°W. This is perpendicular to the strip direction of the acquisition geometry.

Geological interpretation

Geological information about the survey area came from a schematic stratigraphic column that was compiled during an extensive study of the regional geology of the Province of Zeeland (van Staalduinen *et al.* 1979). Detailed information was obtained from a shallow borehole near seismic line 8103 (for location, see Fig. 1). The geological formations that can be expected in the seismic data are described in Fig. 17).

The time section of Fig. 8 served to fit the seismic data to the geology. Clear events can be recognized in the first 150 ms. At 65 ms an abrupt change in reflection strength and reflector configuration can be seen. Just before 65 ms we see parallel, discontinuous reflections with moderate amplitudes. In addition, some bifurcating and undulating reflections are found. After 65 ms the reflections become weaker. The 65 ms boundary can be interpreted as the top of the Maassluis Formation. The strength of the reflection can be explained by a depositional hiatus after the deposition of the Maassluis Formation.

Between 38 and 65 ms many parallel reflections of variable continuity and amplitude are found. These reflections have been identified with the Tegelen and Eem Formations (Fig. 17). A distinction between these two Formations was not possible from the seismic record.

The base of the Twente Formation is found at 38 ms. The top of this Formation is a buried-dome unconformity capped by the Westland Formation. We interpret this unconformity as representing the top of a dune. The reflections in the Twente Formation are curved and of high amplitude, while those of the Westland Formation are mainly horizontal and weak. The deepest reflectors of the Westland Formation show clear onlap features.

Conclusions

These acquisition and processing techniques resulted in data that allowed detailed interpretation. The high resolution reveals some internal structures in the dune. The 3D figures show some relief in the flanks of the dune. These structures may have been caused by erosion from surface water run-off.

The flank of the dune strikes N35°W. This is in contradiction with the general NE–SW trend of the ridges of the Westland Formation. Subsequent surveys have shown that the N35°W trend of the dune is consistent over a larger area and is not due to the small scale of this survey.

Though the dataset is small by any standard, the project has demonstrated that 3D acquisition and processing lies within the reach of a department with limited resources. However, even at this small scale the acquisition is too time consuming to make it part of the curriculum, since mandatory assignments must correspond to a reasonably steep part of the 'learning curve'. On the

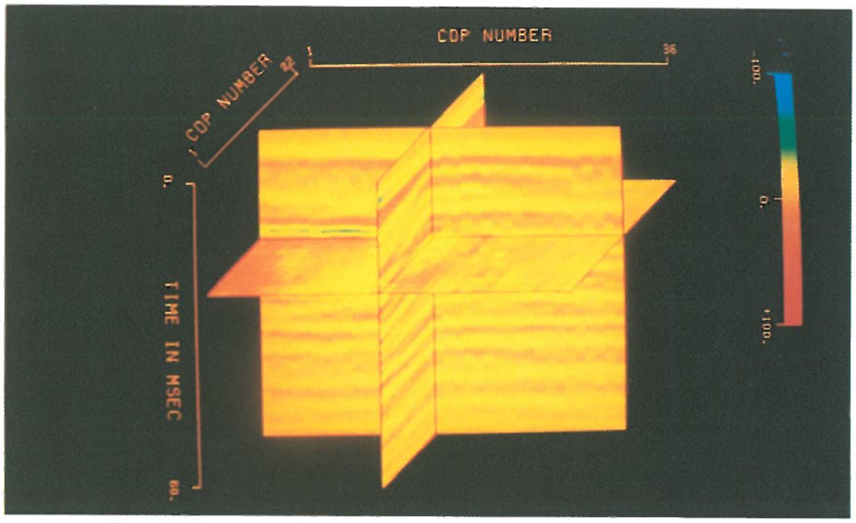


Fig. 11. Stereometric combination of two arbitrary perpendicular vertical time sections and a time slice. Amplitudes are scaled between −100 and 100. In these figures amplitudes are colour coded according to the displayed colour wedge.

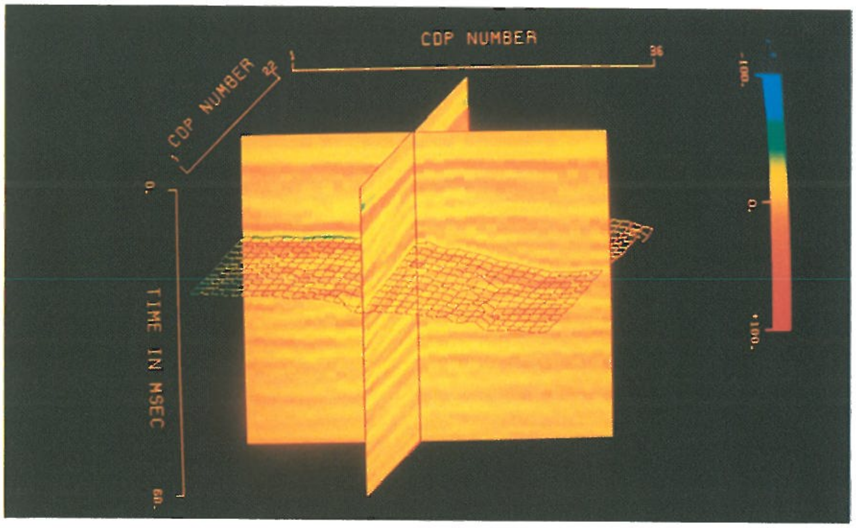


Fig. 12. Stereometric combination of two arbitrary perpendicular vertical time sections and a 'horizon slice'.

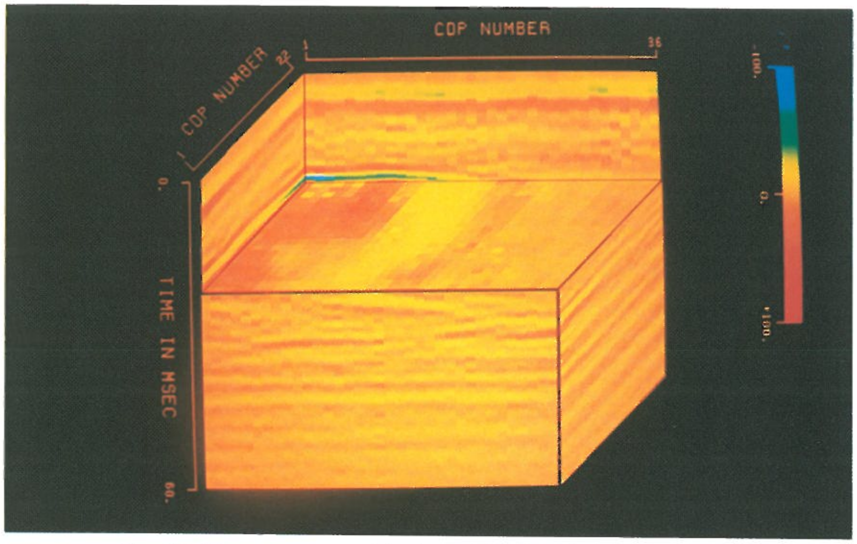


Fig. 13. Stereometric combination of the four limiting time sections and arbitrary time slice.

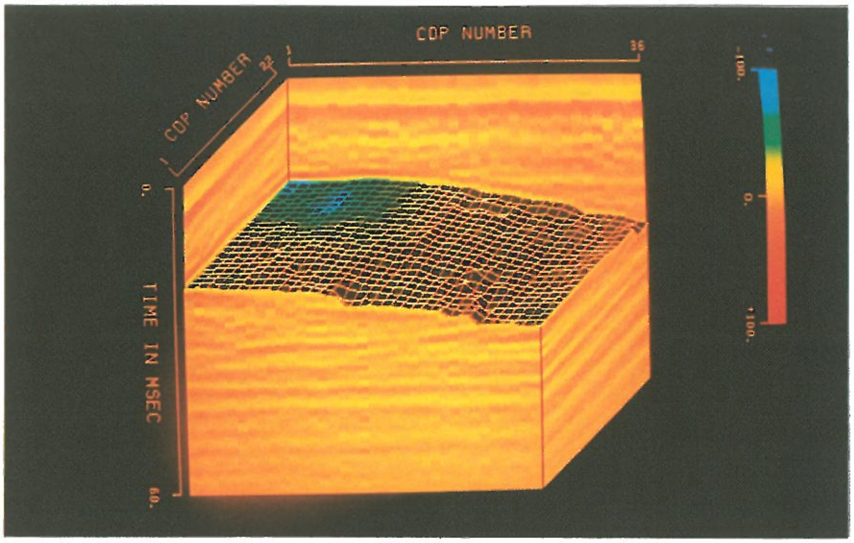


Fig. 14. Stereometric combination of the four limiting time sections and arbitrary 'horizon slice'. Amplitudes are scaled between −100 and 100. In these figures amplitudes are colour coded according to the displayed colour wedge.

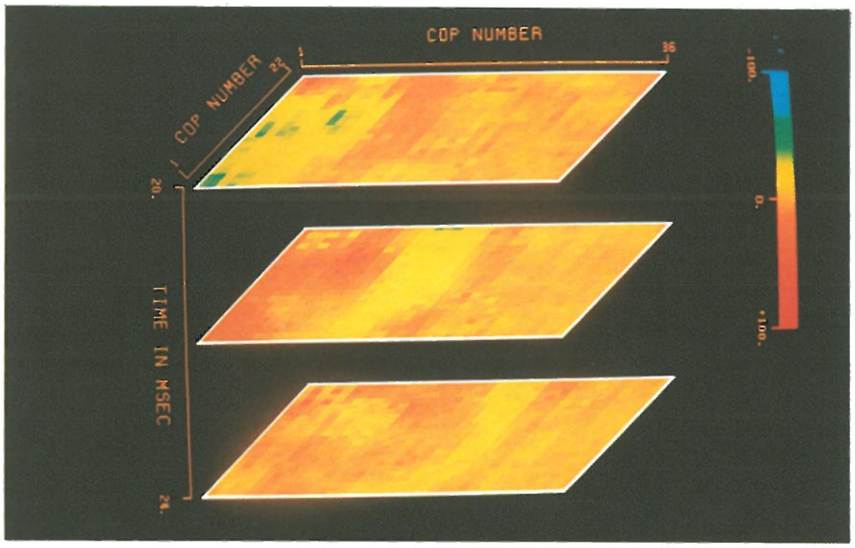


Fig. 15. Stereometric display of a stack of time slices.

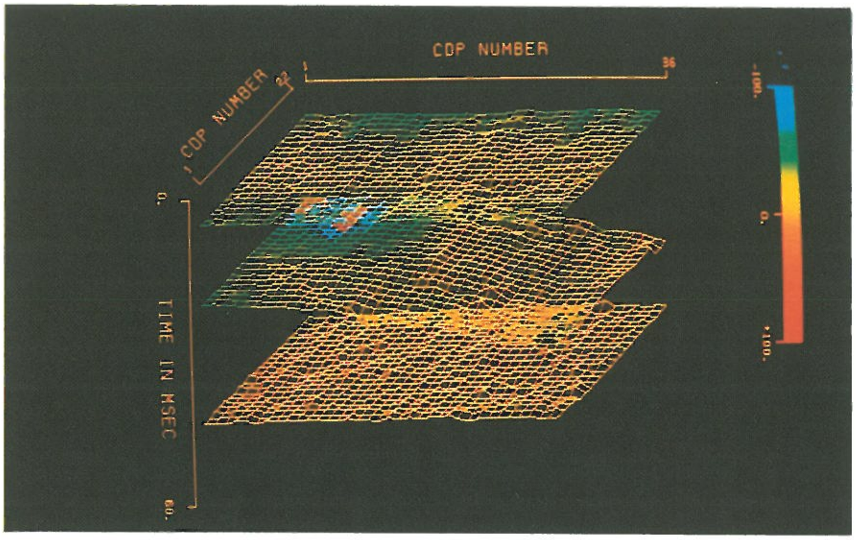
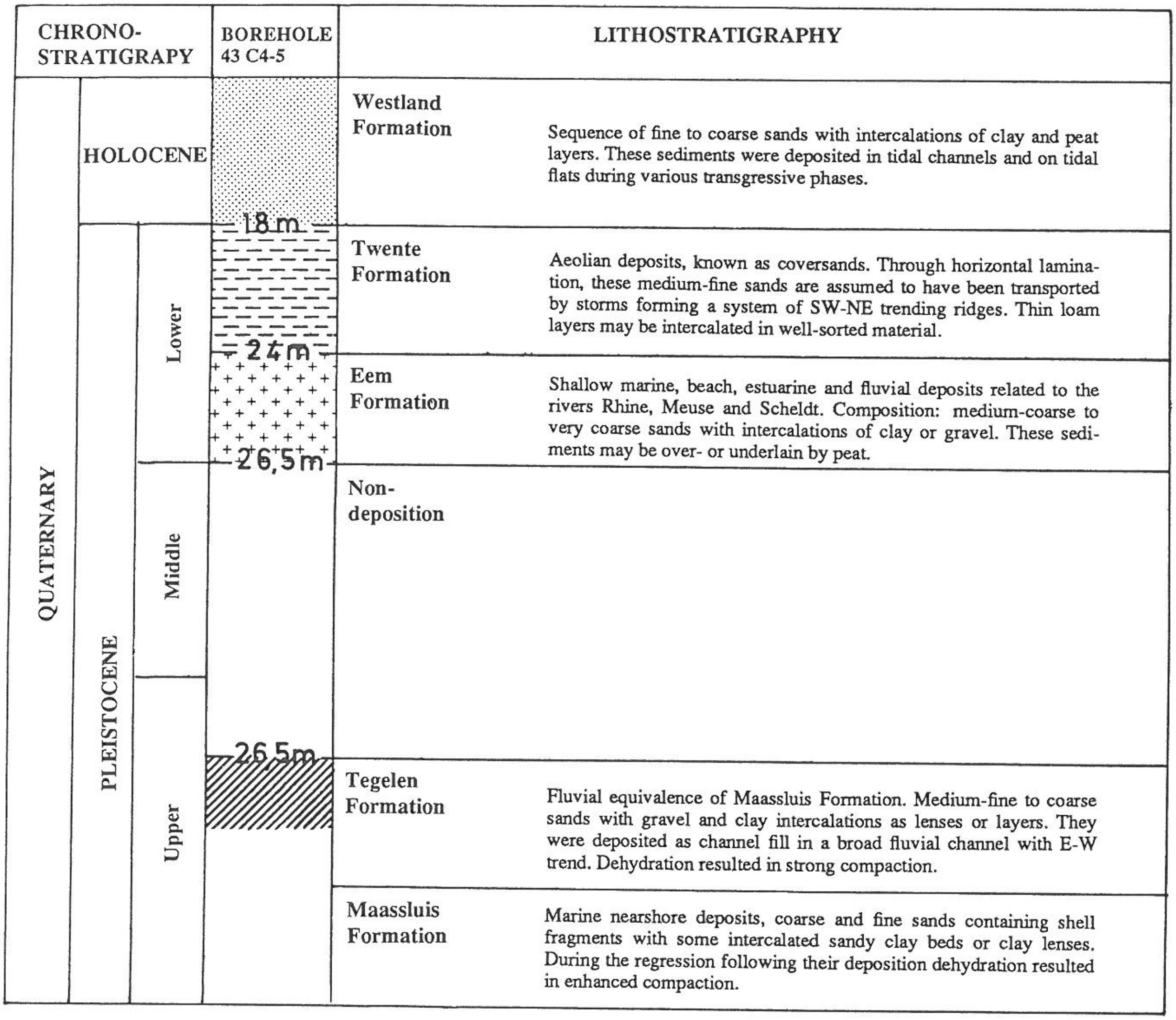


Fig. 16. Stereometric display of a stack of 'horizon slices'.



Westland Formation: Sequence of fine to coarse sands with intercalations of clay and peat layers. These sediments were deposited in tidal channels and on tidal flats during various transgressive phases.

Twente Formation: Aeolian deposits, known as coversands. Through horizontal lamination, these medium-fine sands are assumed to have been transported by storms forming a system of SW-NE trending ridges. Thin loam layers may be intercalated in well-sorted material.

Eem Formation: Shallow marine, beach, estuarine and fluvial deposits related to the rivers Rhine, Meuse and Scheldt. Composition: medium-coarse to very coarse sands with intercalations of clay or gravel. These sediments may be over- or underlain by peat.

Tegelen Formation: Fluvial equivalence of Maassluis Formation. Medium-fine to coarse sands with gravel and clay intercalations as lenses or layers. They were deposited as channel fill in a broad fluvial channel with E-W trend. Dehydration resulted in strong compaction.

Maassluis Formation: Marine nearshore deposits, coarse and fine sands containing shell fragments with some intercalated sandy clay beds or clay lenses. During the regression following their deposition dehydration resulted in enhanced compaction.

Fig. 17. Stratigraphic column of Quaternary formations and facies, including information from borehole 43 C4-5 (van Staalduinen *et al.* 1979).

other hand, the tedium of the full week of routine data acquisition is likely to be accepted by students who have a stake in the results. Without a breakthrough in automation the acquisition of 3D data will remain a thesis assignment.

Even then the question remains whether other university departments could follow our lead. The paramount requirement is a suitable survey area comparable to the tidal flats. There should be no weathered layer, the ground should provide sufficient resistance to surface impacts or small explosions so that high-frequency signals can be generated by simple means, and the area should be easily accessible in the technical and the legal sense. Under favourable conditions of sedimentation beaches (below the high-water line) should have such properties. However, the area should also be interesting scientifically so that the seismic survey does not degenerate into a laboratory experiment that, by accident, is carried out in the field.

If a suitable survey area exists, only minor difficulties remain. Any enhancement seismograph with at least 12 channels and permanent digital storage will do. Together with cables, geophones, a self-built source and some means of transportation the equipment currently comes to not more than US$60000. The software we have used has evolved slowly, so that the effort is not easily estimated. If it had to be done again we would budget 18 man-months, 12 for the basic (2D) package two to three months for the 3D extensions, and a similar time to develop the display package. Most of our programs are written in FORTRAN (a few exceptions are subroutines written in C) and the whole package runs under UNIX® on a 34-bit computer. Graphical output is possible on a large Versatec plotter, a pen plotter, a laser printer, and for interactive work on colour terminals or on the semi-graphical Qume QVT–211GX.

Acknowledgments
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