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Seismic stratigraphy of shallow water Quaternary sediments around the UK

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SEISMIC STRATIGRAPHY OF SHALLOW WATER QUATERNARY SEDIMENTS AROUND THE UK.

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ABSTRACT

This research represents an investigation into the application of seismic stratigraphy to studies of Quaternary sediments in some shallow water environments around the UK. The shallow water environment (and predominantly the intertidal zone) has some unique problems associated with it regarding geophysical data acquisition and as a result has been a previously difficult environment to work in; this has often resulted in a "knowledge gap", particularly in the intertidal zone. Sequence analysis, although applied to Quaternary sediments, has rarely been applied to the complex sediments found around the UK coastline, and facies analysis has been shown to have problems associated with it in circumstances where there is insufficient groundtruthing.

The research was performed by investigating a series of case study sites, through which a recommended methodology has been developed using an often integrated approach incorporating high resolution analogue and digital seismic marine and land surveying with control provided by borehole and CPT sampling.

In order to satisfy the aims of this research, four coastal sites (the Tees and Humber estuaries, the Menai Strait and Liverpool Bay) around the UK were investigated, providing, on the whole, data of excellent quality. Using these data seismic sequence analysis has been conducted on Quaternary sediments with some success. Seismic facies analysis has been performed and has been enhanced by digital data acquisition and subsequent display of instantaneous attributes.

This research has shown that: a) analogue and digital boomer data can be routinely acquired in the intertidal zone, b) single channel high resolution digital seismic data has great potential for mapping sediment physical and geotechnical properties, c) the theory of seismic stratigraphy is applicable to Quaternary sediment investigations in that some of the principles can be applied to Quaternary deposits, d) an investigation of Quaternary sediments has limited ability to predict major sea level change, e) integration of digital seismic and CPT data has the potential to provide a powerful method for rapid mapping of geotechnical properties of sediments.

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LIST OF ABBREVIATIONS

A(t) = accommodation function
Ag = area of groove at base of (CPT) cone
BP = before present (years)
CD = chart Datum
D_r = relative density
E = Young's modulus
E_u = undrained Young's modulus
E_{25} = drained secant modulus at 25% of failure stress
E_{50} = drained secant modulus at 50% of failure stress
K = elastic constants
K_o = horizontal stress ratio (coefficient of earth pressure at rest)
M = constrained modulus
N_c = bearing capacity factor
N_k = cone factor
N_k^* = corrected cone factor (Bjerrum correction)
OD = ordnance Datum
R = reflection coefficient
SSSI = site of special scientific interest
V = velocity (m/s)
Z = acoustic impedance

c_u = undrained shear strength
f = frequency
f_s = sleeve friction
h_c = height of (CPT) cone
k = constant
k = coefficient of permeability
m_v = (vertical) coefficient of volume change
n = exponent of frequency
q_c = cone resistance
r = radius
s_u = vane shear strength

$\dot{A}(t)$ = accommodation function (time derivative)
α = attenuation
α_m = constrained modulus coefficient
Δ_u = change in pore pressure
κ = bulk modulus
μ = dynamic rigidity
σ'_{ho} = horizontal effective stress
σ'_{vo} = vertical effective stress (effective overburden pressure)
ø = phi (grain size)
ϕ' = effective angle of shearing resistance
ρ = density

CHAPTER 1
Introduction

1.1 Background

Seismic stratigraphy is defined by Mitchum (1977) as "the study of stratigraphy and depositional facies as interpreted from seismic data". Since the publication of the series of papers in "Seismic Stratigraphy - Applications to Hydrocarbon Exploration" (Payton, 1977) the field of seismic stratigraphic application and research has attracted much attention.

Seismic reflections, according to Vail and Mitchum (1977), follow time lines. It is therefore possible not only to identify postdepositional deformation but to make the following stratigraphic interpretations from the geometry of seismic reflection patterns: (1) geologic time correlations, (2) definition of genetic depositional units, (3) thickness and depositional environment of genetic units, (4) palaeobathymetry, (5) burial history, (6) relief and topography on unconformities, and (7) paleogeography and geologic history. These interpretations can be achieved through a three-step interpretational procedure: (1) seismic sequence analysis, (2) seismic facies analysis, and (3) analysis of relative changes of sea level (Vail and Mitchum, 1977).

The seismic stratigraphic technique incorporates the method of seismic data analysis known as seismic sequence stratigraphy. Sequence stratigraphy is defined by Van Wagoner *et al.* (1988) as "the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities". It is a procedure that allows the subdivision and correlation of seismic sections into depositional intervals called sequences. The fundamental control of depositional sequences is, according to Vail (1987), short term eustatic changes of sea level superimposed on longer term tectonic change. Once identified, these sequences may be associated with different depositional processes and hence can be associated with certain depositional environments and lithofacies (Vail, 1987).

Seismic facies analysis usually follows from sequence analysis and is defined by Mitchum (1977) as "the description and geologic interpretation of seismic reflection parameters, including configurations, continuity, amplitude, frequency, and interval velocity". It becomes of particular relevance if performed on specific sequences as it may be more accurate due to the association of particular sequences with particular depositional processes (Vail, 1987). The purpose of seismic facies analysis is to determine variations within seismic sequences in order to determine environmental setting and estimates of lithology (Mitchum *et al*, 1977). The principal seismic parameters used for this determination are geometry (e.g. mounds and banks) of reflectors, amplitude, frequency, continuity of events and interval velocity.

The *routine* use of seismic stratigraphy was only achieved in the late 1970s (Payton, 1977) and came about primarily through advancements of data quality brought about by developments of electronic technology. Since this time, the use of sequence stratigraphic concepts to enhance understanding of geologic relationships within a time-statigraphic framework has achieved widespread acceptance (Posamentier and James, 1993). Not only have technological advances allowed improvement in data quality that can assist at the interpretation stage, but also the seismic stratigraphic principles themselves have been able to be developed since their inception (Vail, 1987; Van Wagoner *et al.*, 1988; Posamentier and Vail, 1988; Posamentier *et al.*, 1988) and reviewed (Thorne, 1992).

The concepts of seismic stratigraphy were originally applied to "deep exploration" seismics (seismic penetration of 100s of metres, low frequency source, low resolution), i.e. in petroleum exploration of mature depositional basins. The theory should however be independent in space and time as there are no such constraints in its definition and it should therefore be applicable to any seismic data set. The theory has in fact been successfully tested and applied practically to "shallower" Quaternary seismic data sets (higher frequency source, high resolution) that range from sequences which are typically tens of metres thick (Chiocci, 1994; Chiocci *et al.*, 1991; Hernàndez-Molina *et al.*, 1994), to direct observation of sequences that are of only a few decimetres thick e.g. occurring in natural fan deltas (Posamentier *et al.*, 1992) and being developed in laboratory flume experiments (Wood *et al.*, 1993).

Although the development of depositional sequences appears to have no temporal limits, some researchers (e.g. Boyd *et al.*, 1989) are sceptical regarding the application of sequence analysis, without modification, in the study of sediments deposited during high frequency eustatic cycles such as occur in the Quaternary. Clearly, the application of seismic stratigraphic theory to high resolution data is not without problems. Stoker *et al.* (1992) identify a number of problems that arise from too much reliance on the interpretation of high-resolution seismic profiles without adequate groundtruth data during facies analysis of Quaternary seismic sequences. They provide examples of inconsistencies between acoustic signature and expected lithology and geotechnical properties namely: (1) that vertical and lateral changes in acoustic signature do not necessarily correspond to changes in lithology or geotechnical character, (2) acoustically unstratified seismic units are often associated with diamicton lithologies, but this does not necessarily imply a subglacial origin, (3) an acoustically layered seismic reflection configuration does not necessarily represent a real lithological layering. They suggest that calibration of seismic data with control data is essential in seismic facies analysis of Quaternary sediments.

Seismic stratigraphic analysis may be significant geotechnically since it provides a means by which the physical properties of sediments can be estimated. This can be accomplished through the recognition of depositional environments associated within sequences and by seismic facies analysis, in that the influence that the depositional environment has on the physical properties of a sediment is well documented, as is that of the influence of physical properties on the acoustic signal. A large number of empirical relations exist between the acoustic impedance, velocity and attenuation of acoustic waves and the geotechnical properties of a sediment (e.g. Buchan *et al.*, 1972; Hamilton, 1979; Hamilton, 1980; Haynes *et al.*, 1993b). This effectively provides a basis for obtaining geotechnical information from the seismic waveform.

It has long been the goal of geophysicists to remotely assess the physical properties of sediments. Recent developments in the acquisition of seismic data have led to methodologies which can be applied to the direct extraction of geotechnical information from acoustic data (Haynes *et al.*, 1993b; Panda *et al.*, 1994), coming about mainly through technological improvements leading to the more widespread availability of relatively inexpensive powerful computers. One of the major technical improvements that has affected the field of high resolution seismic surveying is widespread digital acquisition. The facility to record digital data and the computer software and hardware to process these data are now more commonly available. Digital data provide a means to perform post survey signal enhancement (e.g. through the application of filter and gain settings). The use of instantaneous attributes and previously mentioned empirical relationships can ultimately assist with seismic facies determination with a minimum of groundtruth information.

The aim of the study reported in this thesis is to test the application of seismic stratigraphy in the analysis of Quaternary sediments around the UK coast. This will be achieved applying primarily marine surveying methods in the shallow coastal environment and the often "difficult to investigate" intertidal zone. The intertidal zone represents an area of considerable importance for engineering projects such as pipeline installation, cable laying and dredging.

The work will primarily concentrate on the role and feasibility of seismic stratigraphy as applied to complex Quaternary sequences. It will also address the problems that need to be overcome and the factors that need to be considered in the acquisition and interpretation of data in very shallow water. The interpretation will also be extended regarding the use of digitally recorded data which, in this case, will be used to generate instantaneous attribute information and can potentially be used to provide geotechnical information.

En route to accomplishing these aims seismic data sets will be subjected to seismic sequence and facies analysis. Seismic facies analysis will be carried out by examination of stratal geometry and by examination of specific seismic parameters either semi-quantitatively (based on analysis of analogue data), or quantitatively where digital data permits. The accuracy of the interpretation will be constantly reviewed by calling upon groundtruth information wherever available (and appropriate). The interpretation will also attempt to answer questions relating to the physical and geotechnical characteristics of the seismic sequences.

1.2 Thesis layout

The thesis will initially describe some of the basics of geophysical theory and seismic stratigraphy (chapters 2 and 3). It will also describe the cone penetration test (CPT) as, in a latter part of the thesis, the results of CPTs will be presented and discussed in the context of seismic stratigraphic interpretations. The aims of this study will be tested on four case studies (chapters 5, 6, 7, and 8). These case studies are presented in the order that they were collected and illustrate a progression in the methodology. The conclusions gained from the four investigations will be discussed in chapters 9 and 10.

CHAPTER 2

Introduction to geophysical theory

Seismic surveying primarily relies on measuring travel time and amplitude characteristics of seismic energy waves that have been propagated from a seismic source through the earth and refracted or reflected back to the surface by subsurface acoustic boundaries. The resultant data are used to infer the subsurface geological structure of the survey area. It is obvious therefore that a knowledge of how the physical properties of the media under study affect the seismic energy in terms of amplitude, frequency and velocity of propagation is essential to the understanding and interpretation of seismic data. This chapter aims to address these topics through a discussion of what seismic waves are, how they propagate, what determines the speed of propagation, and of what factors contribute to the attenuation of seismic energy.

The affect that the physical properties have on the media through which the seismic energy travels is well documented and has been extensively modelled in the laboratory. Further, a large number of empirical relationships between seismo-acoustic and physical properties exist in the literature (e.g. Buchan *et al.*, 1972; Hamilton, 1979; Hamilton, 1980; Hamilton and Bachman, 1982; Haynes *et al.*, 1993a&b) as will be shown later.

2.1 Seismic Waves

Seismic waves are parcels of elastic strain energy that propagate from a seismic source. The latter may take the form of natural tectonic movement providing the propagating energy, or it may be energy specifically generated for survey purposes. Sources suitable for seismic surveying generate short-lived wave trains known as pulses. The strains associated with the passage of a seismic pulse are assumed, quite reasonably, to be elastic and hence the propagation velocities may be determined from the solutions to the general wave equation (2.1) which are based on the elastic moduli and densities through which they pass.

The wave equation for compressional waves (Telford *et al.*, 1976) describes the propagation velocity as:

$$V = \sqrt{\frac{\kappa + {}^{4}/_{3}\mu}{\rho}} \qquad (2.1)$$

Where: κ = bulk modulus

μ = dynamic rigidity

ρ = density

The wave equation (correctly) predicts that seismic waves exist either as body waves which propagate through the body of an elastic solid, or surface waves which are confined to the ground surface. Body waves propagate either by compressional and dilatational uniaxial strains in the direction of wave travel (as uniaxial compressional (primary) or 'P'-waves), or by shear strain in a direction perpendicular to the direction of wave travel (as (secondary) shear or 'S'-waves).

2.1.1 Ray paths in layered media

Since most of the seismic data used in this project will be reflection, it is now appropriate to consider how seismic energy is partitioned at an acoustic boundary.

2.1.1.1 Normal incidence reflection/transmission

When a compressional ray of amplitude A_0 is propagated at normal incidence to an interface between two media of differing velocity and density, a transmitted ray of amplitude A_2 travels through the interface in the same direction as the incident ray, and a reflected ray of amplitude A_1 travels back along the original path of the incident ray (Figure 2.1).

The transmitted and reflected rays will have, in a uniform lossless material, the same energy as the incident ray, and their relative energy proportions will be determined by the contrast in acoustic impedance (Z) across the interface. The acoustic impedance is the product of a material's density and seismic wave velocity ($Z=\rho V$). The smaller the contrast in acoustic impedance, the greater is the proportion of energy transmitted through the interface.

Figure 2.1 An example of normal incidence effects (after Kearey and Brooks, 1991).

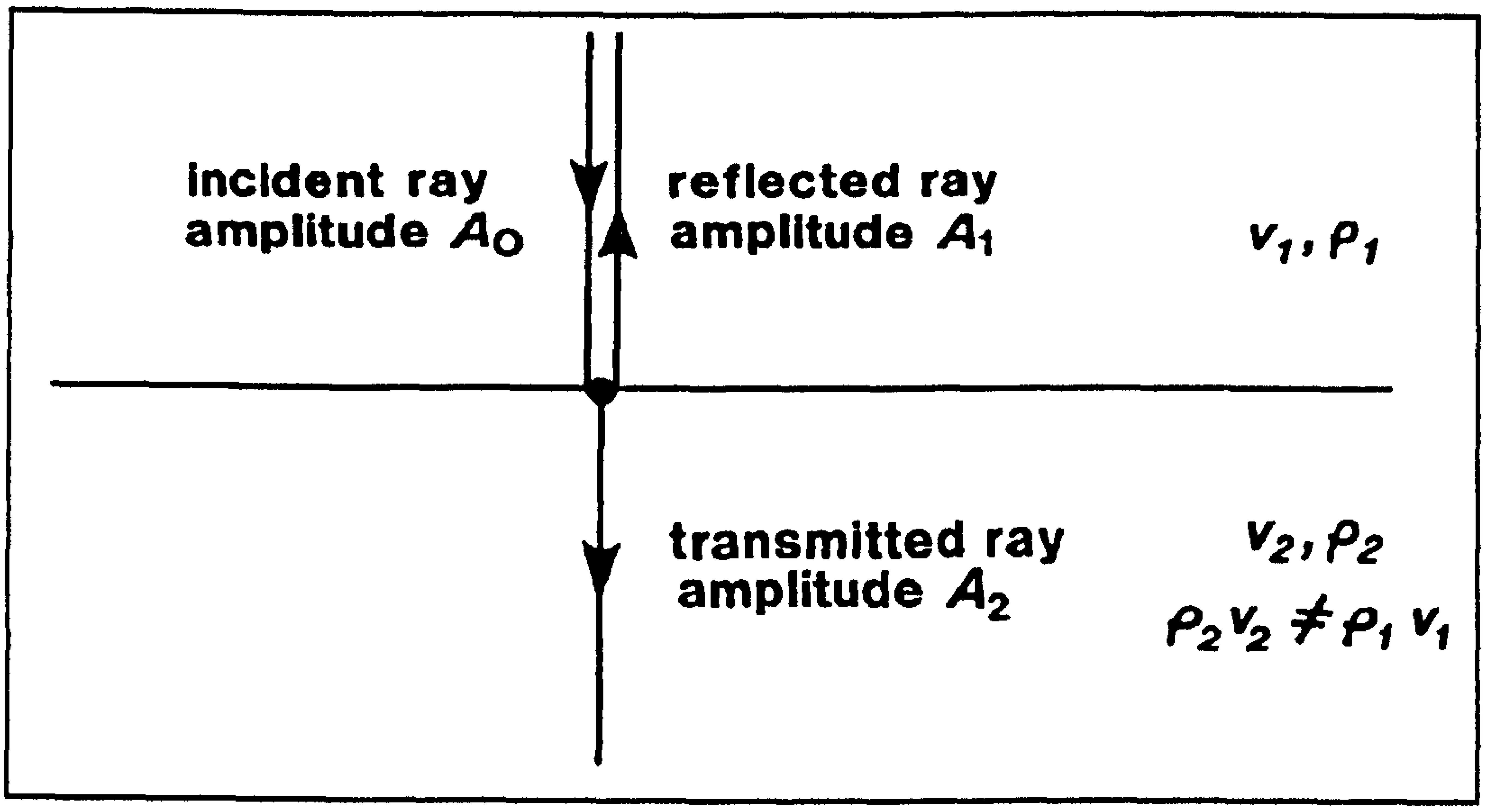
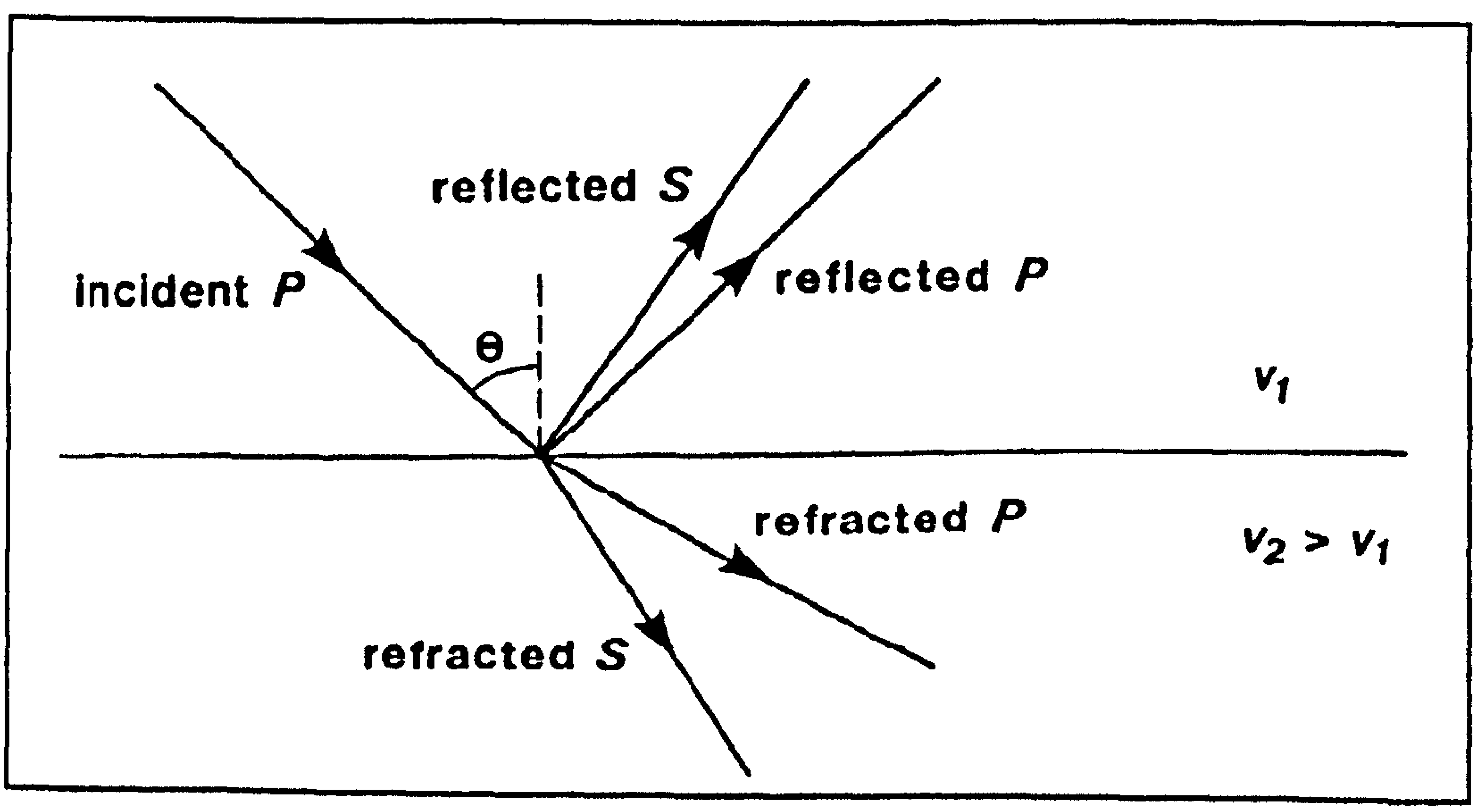


Figure 2.2 Reflected and transmitted (refracted) P- and S- waves.



The reflection coefficient (R) is the ratio of the amplitude A_1 of the reflected ray to the amplitude of the incident ray A_0. If the reflection is at the surface of a medium of lower acoustic impedance the reflection coefficient is negative, resulting in a reversal of phase of the reflected pulse.

Numerically, R may be given by:

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \qquad (2.2)$$

For the case where R = 0 (i.e. no reflector), then all the incident energy is transmitted; if R = 1, then all the incident energy is reflected (this situation is approximated at the interface between air and a smooth water surface interface). Practically, R values of around 0.2 would be regarded as large for interfaces between most sediment types. Values larger than this are observed but are unusual. Values of ± 0.1 are reported by O'Doherty and Anstey (1971) to occur in "abundance" and lower values in "profusion". Sheriff (1975) considers a number of variations of velocity contrasts and density contrasts to show how they affect the reflection coefficient (Table 2.1). It would appear therefore that, normally, the bulk of seismic energy incident on a sediment to sediment interface is transmitted and only a small proportion is reflected.

Table 2.1 Examples of the interaction of velocity and density contrasts on the reflection coefficient (Sheriff, 1975).

	Velocity contrast (values in m/s)	Density contrast	Reflection coefficient
Very strong reflector	2000 / 3000	none	0.2
Fair reflector	2800 / 3000	none	0.04
Weak reflector	2000 / 2050	none	0.012
Soft ocean bottom	none	1.0 / 2.0	0.33
Hard ocean bottom	1600 / 3200	1.0 / 2.5	0.67
Base of weathering	500 / 2000	1.5 / 2.0	0.69
Gas sand at 1500m, 30% porosity, normal pressure	2000 / 3000	1.85 / 2.35	0.29

In unconsolidated sediments the reflection coefficient is considered by Theilen *et al.* (1992) to be mainly dependent on changes in wet bulk density and less on seismic velocity contrasts. Comparisons of density-depth curves and seismic sections indicate that transparent zones correlate with nearly constant layer densities. Areas characterised by a gradual increase in density are associated with areas which show a high diffusive reflectivity.

2.1.1.2. Reflection and refraction of obliquely incident waves

When a P-wave is obliquely incident on an interface of acoustic impedance contrast, as well as reflected and transmitted P-waves being generated, some of the incident energy is converted into reflected and transmitted S-waves (Figure 2.2). This effect has to be taken into account when analysing reflection signatures.

2.2 Factors controlling seismic velocity

From the equations of velocity mentioned thus far, the dependence of velocity upon the elastic constants (K) and density appears straightforward. The situation is however complicated because K and ρ are interrelated, both depending to a greater or lesser degree upon a number of factors, summarised by Sheriff and Geldart (1995) as porosity, lithology, interstitial fluid pressure, depth and degree of cementation. It is the relationship of these factors that make it difficult to relate velocity to any one geological property, the so called 'master variable' of Anstey (1991). It is however a widespread view that porosity is the most important factor in determining the velocity of a sedimentary rock (Sheriff and Geldart, 1995) as it affects both the elasticity and density.

Velocity gradients are usually positive and may be linear in a thick sediment layer as a function of overburden, but more often are parabolic and decrease with depth in the sediments (Hamilton, 1979). Velocity gradients can be used to compute layer thicknesses (with a knowledge of travel times) and to aid in the correlation of sediment and rock layers.

For a saturated sediment, wave velocities can be considered by the elastic properties of the two-phase medium (sea water in pores and the mineral structure)

(Hamilton and Bachman, 1982). The properties of an unconsolidated sediment such as porosity, grain size, cementation, depth, age, pressure regime and interstitial fluids are known to affect sound velocity through their influence on the elasticity of the sediment, and hence some of these factors will be considered here.

2.2.1 Porosity

As previously stated, porosity is considered the most important factor in determining a sediment's velocity. In natural, unconsolidated, marine sediments porosity usually varies between about 35% - 90% (Hamilton and Bachman, 1982). Sand sized minerals, upon settling to the sea floor, assume positions relative to each other under the influence of gravity and water motions. Porosity will depend on packing. When finer-sized sand, silt and clay particles are present in a sand the finer particles may fill the voids with a tendency to reduce porosity, although depending on the shape of this finer material, an increase of porosity may be experienced.

Fine silts and clays form high porosity structures which are distinctly different from single and mixed grain structures. These fine particles have adsorbed water layers on their surfaces and form structures controlled by interparticle forces (Hamilton and Bachman, 1982).

In general, porosity increases with a decrease in grain size, but there is, according to Hamilton and Bachman (1982), much scatter for the relationship between mean grain size and porosity. This is due to a number of interrelated factors including grain size, sorting, grain shape, packing and mineralogy.

Sediment porosity can be reduced by increasing effective pressures; this leads to an increase in the bulk modulus (Hamilton, 1979). Also, as porosity decreases, rigidity is affected in many ways: 1) mineral grains become more densely packed causing more interparticle contacts and increased interlocking of grains (larger particles), and possibly an increase of cohesive forces (smaller particles); 2) increasing number of contacts increases sliding and rolling friction; 3) increasing intergranular pressure aids cementation (lithification). The net effect of these changes is an increase in dynamic rigidity with decreasing porosity and increasing pressure.

In summary, the pressure effects discussed above reduce porosity and increase density, (effecting a decrease in velocity), but increase the sediment system bulk modulus, κ, and the system rigidity, μ, (effecting increases in velocity). With reference to equation 2.1, the net effect is an increase in sound velocity.

2.2.2 Grain size

The mean grain size for all marine sediment environments, and percent clay size material in deep-sea environments, were determined by Hamilton (1970) to be important indices to sound velocity. Hamilton and Bachman (1982) subsequently confirmed Hamilton's earlier findings that sound velocity increases with increasing mean grain size and decreasing amount of clay-size material.

2.2.3 Other factors influencing seismic velocity

Of the complex interrelated factors which determine velocity, only porosity has been considered here in detail. The major factors that determine velocity and velocity gradients (up to depths of 500m) are considered by Hamilton (1979) to be pressure induced porosity reductions and its affect on the sediment mineral frame (66% of the gradient), temperature increase due to heat flow (17%), pore-water pressure increases (2%), and increase in rigidity caused by lithification (15%). These aportioned percentages change with sediment depth.

2.3 Factors influencing reflection amplitude.

Seismic waves, as discussed, will experience redistribution of energy at reflection interfaces. Seismic amplitudes propagating through a medium will be further affected by the phenomena of spherical divergence and attenuation.

2.3.1 Spherical divergence

In a uniform, homogenous medium, the original energy generated by a seismic event is distributed over a spherical shell of expanding radius 'r'. The energy contained in a ray path falls off as r^{-2} due to the geometrical spreading of the energy. Wave amplitude, which is proportional to the square of the wave energy, falls off as r^{-1}.

This simple case is however complicated in nature by the general presence of an increase in seismic velocity with depth (O'Doherty and Anstey, 1971). Therefore amplitude decay is subject to an additional effect associated with refraction of the propagating wave front (Figure 2.3).

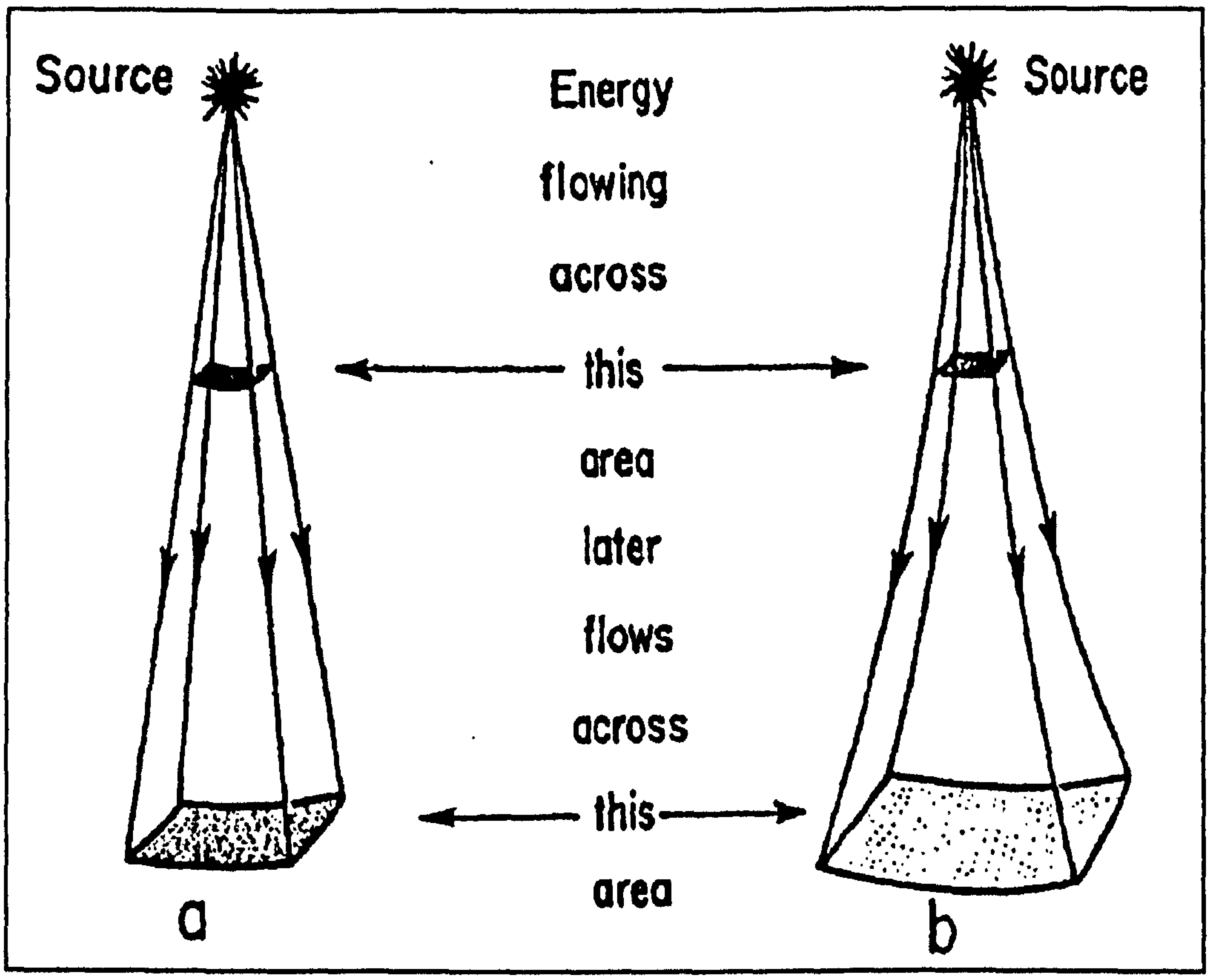
2.3.2 Attenuation

Elastic energy associated with the wave motion is also absorbed into the medium itself. Two mechanisms of attenuation have been identified (Hamilton, 1972 and Sheriff, 1975): 1) visoelastic, in which pore water moves relative to mineral grains, and in which pore water viscosity and media permeability are dominant factors in viscous sound absorption, and 2) frictional, in which attenuation is due to internal friction of intergrain movements.

2.3.2.1 Visoelastic attenuation

All rocks and sediments in the upper crust are partially or completely saturated with some fluid (Johnston *et al.*, 1979). In highly porous and permeable rocks and sediments, relative motion may take place between the mineral frame and the saturating fluid as the seismic waves propagates. Biot (1956a,b and 1962) derived a theory for acoustical wave propagation in an isotropic solid with interacting pores. He and others (Stoll, 1980) showed that attenuation is due to fluid motion that results from variations in the average pressure and inertial forces that have the same wavelength as the dilational or shear wave that is propagating through the medium. Other potential sources of viscous loss include the localised movement of fluid in and out of a crack as it opens and closes in a variable stress field (Biot, 1962), and attenuation due to flow induced between two adjacent cracks due to the relative volume change caused by the stress wave, the commonly called "squirting mechanism".

Figure 2.3 Amplitude decay associated with geometrical divergence in (a) uniform material (b) material with a velocity increase with depth. (O'Doherty and Anstey, 1971).



2.3.2.2 Solid frictional attenuation

Attenuation of seismic waves in a rock matrix can, according to Johnston *et al.* (1979), be attributed to two factors: (1) intrinsic inelasticity of matrix minerals, and (2) frictional dissipation due to relative motions at the grain boundaries and across crack surfaces. The exact mechanism of grain boundary and crack dissipation is not known, but frictional dissipation due to relative motions of the two sides of a crack surface may be the major factor (Walsh, 1966). Losses are characterised by a linear variation of attenuation coefficient with frequency and a small velocity dispersion over a frequency range from 1 to 10^8 Hz (Attewell and Ramana, 1966). Attenuation should depend very strongly on the surface conditions that affect friction between grains (Johnston *et al.*, 1979). Among these are whether rocks and sediments are saturated or dry, the properties of saturating fluids and the amount of clay or other soft components in the matrix.

2.3.2.3 Frequency dependent attenuation

Hamilton (1972) compiled data from numerous sources of laboratory and *in-situ* measurements of attenuation in a discussion of compressional wave attenuation in marine sediments. An example of *in-situ* attenuation data obtained at various frequencies is presented in table 2.2.

Hamilton (1972) discribes the dependence of attenuation on frequency using:

$$\propto = kf^n \qquad (2.3)$$

Where '$\propto$' is attenuation (dB/m), 'k' is a constant, 'f' is frequency (kHz) and 'n' is the exponent of frequency.

Hamilton demonstrated that attenuation in dB/unit length is approximately dependent on the first power of the frequency therefore 'n' can be assumed to be one.

The absorption coefficient ($\propto$) expresses the proportion of the energy lost during transmission through a distance equivalent to a complete wavelength (λ). Values of $\propto$ for common earth materials range from 0.2 to 0.75 dBλ^{-1}. For example, consider an absorption coefficient of $0.2dB\lambda^{-1}$, a velocity of 1800 m/s and a path length of 20m. At a frequency of 5kHz this path length represents 55 wavelengths (1800/20) * 5000)). Each of the 55 compressions will be 0.2 dB less in amplitude than the one before; thus the amplitude of the second is about 98% of that of the first, the third 98% of the second etc. The loss therefore over 20m will be 11dB at 5kHz.

Within the range of frequencies used in seismic surveying (i.e. 10s - 100,000sHz), the absorbtion coefficient is assumed to be independent of frequency. If the amount of absorption per frequency wavelength is constant, it follows that higher frequency waves attenuate more rapidly than lower frequency waves as a function of time or distance. The shape of a seismic pulse with a broad frequency content therefore changes continuously during propagation due to the preferential loss of the higher frequencies, the Earth essentially acting as a low pass filter, and the peak amplitude decaying as the pulse length is lengthened by dispersion.

Losses by spreading are more important than losses by absorption for low frequencies and short distances. As the frequency and the distance increase, the relative losses by absorption increase and eventually become dominant.

Table 2.2 *In-situ* attenuation, velocity and other physical properties of sediments (Hamilton, 1972).

Sediment type	Water depth (m)	Mean grain diameter (mm)	Density (gm/cm^3)	Porosity (%)	Velocity (m/sec)	Attenuation (dB/m) at f (kHz)			k (unitless)	n (unitless)
						3.5	7.0	14.0		
Coarse sand	32	0.5704	2.060	38.0	1817	—	3.4	6.6	0.53 —	0.96 —
Medium sand	20	0.4931	2.008	39.2	1798	1.5	3.8	6.8	0.41±0.12	1.09±0.14
Fine sand	8	0.1708	1.967	45.6	1686	1.7	3.2	7.2	0.45±0.07	1.04±0.07
Very fine sand	13	0.1015	1.933	47.0	1708	1.5	3.5	7.0	0.38±0.05	1.11±0.06
Clayey silt	1087	0.0058	1.374	77.8	1459	—	1.2	2.3	0.19 —	0.94 —

2.3.2.4 Attenuation and grain size

When wavelengths approach grain size, Rayleigh scattering takes place, and attenuation is proportional to the fourth power of frequency (Knopoff and Porter, 1963). As stated earlier, attenuation is related to the first power of frequency making the only variable the constant 'k' in equation 2.3. Empirically, it has been observed that this constant varies with sediment type and is related to mean grain diameter (Figure 2.4).

Figure 2.4 illustrates the variability between mean grain size and the constant 'k' (or attenuation). In sands (0-4ø) 'k' increases gradually with ø (or decreasing grain size) from coarse into fine sands (to about 2.6ø) and then increases rapidly into the finer sands. The maximum values of 'k' are in very fine sand and mixtures of sand, coarse silt and clay in the grain size range 3.5 to 4.5ø. Attenuation decreases with decreasing grain size (increasing ø) from about 4.5ø to 6ø and then gradually declines with decreasing grain size into fine silts and clays (Hamilton, 1972).

2.3.2.5 Attenuation and porosity

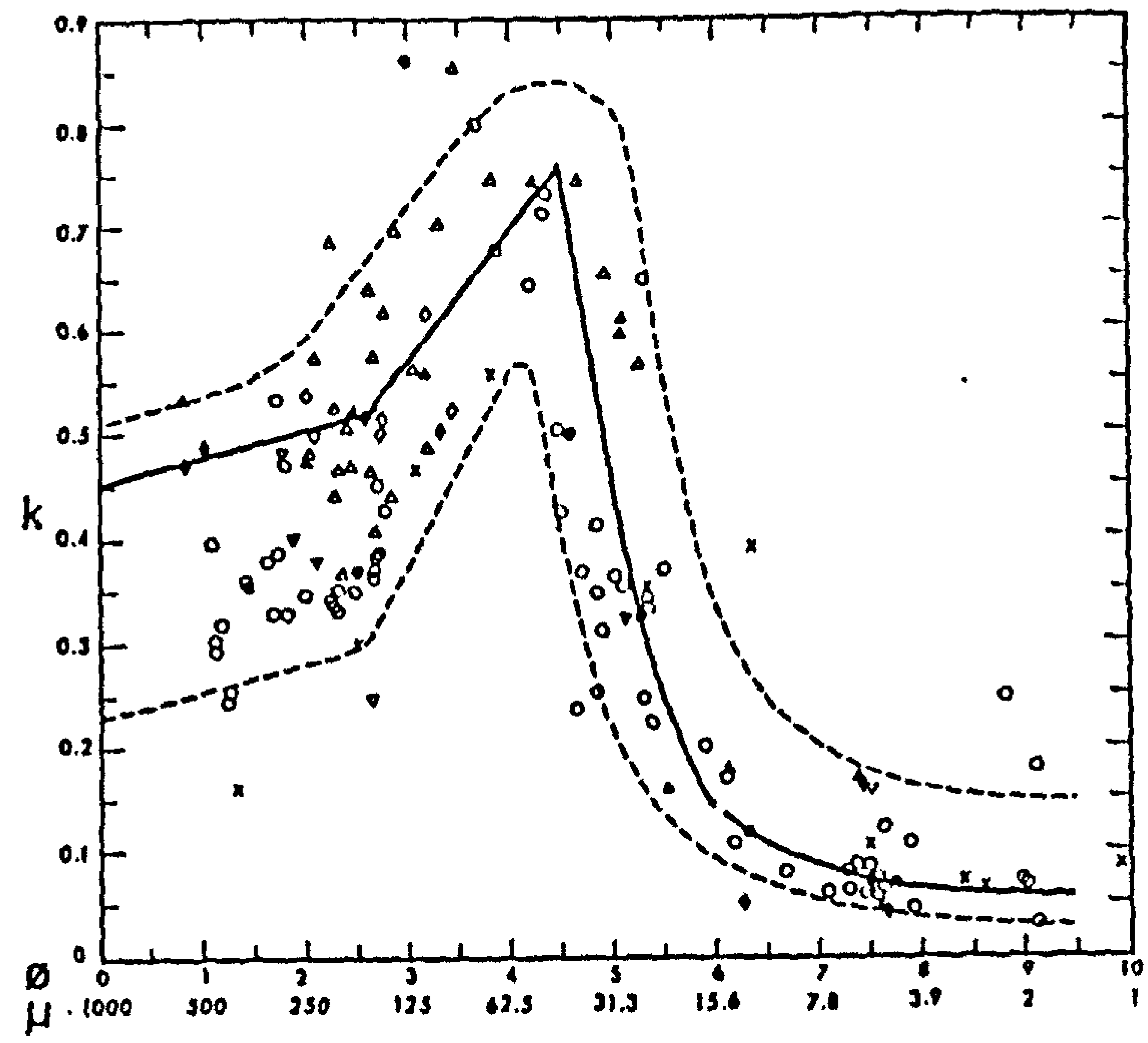
Porosity varies with 'k' in the same way as mean grain size. Equivalent values of 'k' are found in the coarser sizes of sand and in higher-porosity silts and sandy silts. The highest values of 'k' are in very fine sands, silty sands and sandy silts in the range of 50-45%. In silt-clays 'k' decreases with increasing porosity (Hamilton, 1972).

2.3.2.6 Attenuation and fluid saturation

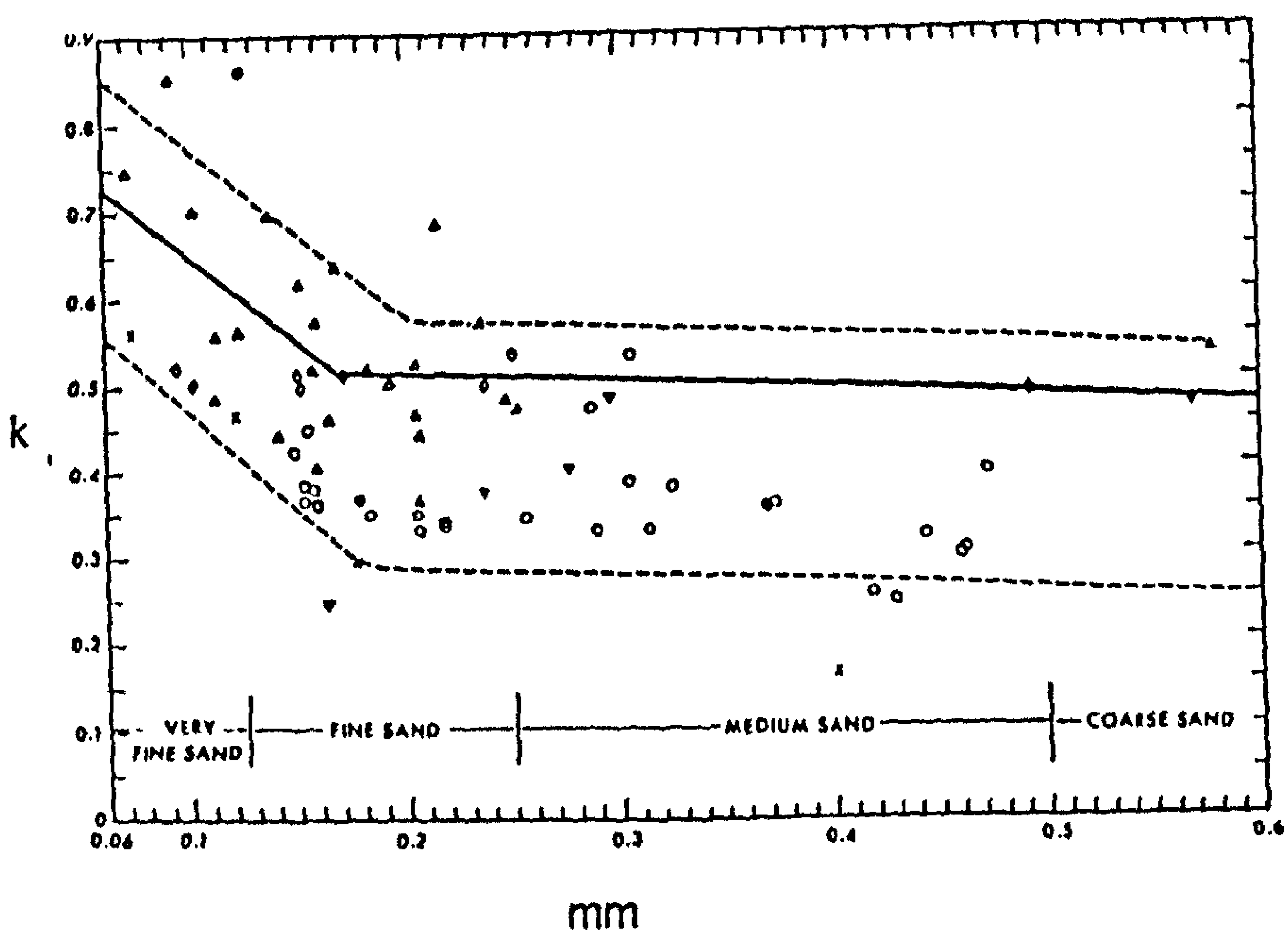
Attenuation in brine- and water-saturated rocks and sediments is greater than in dry or methane saturated rocks. Attenuation in frozen consolidated rocks is very much lower than in saturated consolidated rocks (Toksöz *et al.*, 1979).

Figure 2.4 Empirical relationship between constant k and mean grain diameter (Hamilton, 1972).

Mean grain size M_z in ø units and microns μ verse k in natural saturated sediments



Mean grain size (mm) versus k emphasising the relationship in sands



2.3.2.7 Attenuation and pressure and stress dependence

Attenuation decreases with increasing confining pressure (e.g. overburden pressure) for both P- and S-waves in all cases of saturation. The rate of increase is high at low pressures and levels off at higher pressures (Toksöz *et al.*, 1979). The effect is summarised by Hamilton (1972); as previously stated, an increase of effective pressure increases rigidity, and shear- and compressional-wave velocity in rocks and sand (the only materials discussed by Hamilton, 1972), however, attenuation and log decrement decrease. These effects are apparently due to pressure effects on grain elastic moduli and grains in harder contact offering greater resistance to shear stress, but allowing less intergrain movement which reduces energy loss through intergrain friction. Johnston *et al.* (1979) considers the effect to be due to the closing of cracks in the matrix of the medium.

2.3.3 Diffraction

It is not always the case that interfaces will be continuous and more or less horizontal. At abrupt discontinuities in interfaces or structures whose radius of curvature is comparable to, or shorter than, the wavelength of the incident waves, there will be radial scattering of incident seismic energy known as diffraction. Diffraction tends to distribute any sharp amplitude changes over a larger region as wavefronts travel away from a diffracting point (Sheriff, 1975). Sources of diffraction include the edges of faulted layers and isolated boulders.

2.3.4 Multiples

Multiples are seismic events that have undergone more than one reflection. The energy of a multiple is the product of the energy reflection coefficients 'R' for each of the reflectors involved and, since R is very small for most interfaces, only the strongest impedance contrasts will generate multiples strong enough to be recognised as seismic events.

Multiples can be grouped into two categories, long and short path. A long path multiple is one whose travel path is long compared with the primary reflection and hence will appear as a separate event on the seismic record.

A short path multiple is one that occurs so soon after the associated primary reflection from the same interface that it extends the overall length of the recorded pulse. Primary paths are systematically reinforced by short-delay two bounce multiple reflections whose amplitude is the product of the upper and lower reflection coefficients and the sign of the multiple reflection is always the same as that of the direct signal (O'Doherty and Anstey, 1971). Examples of short and long multiples are presented in Figure 2.5.

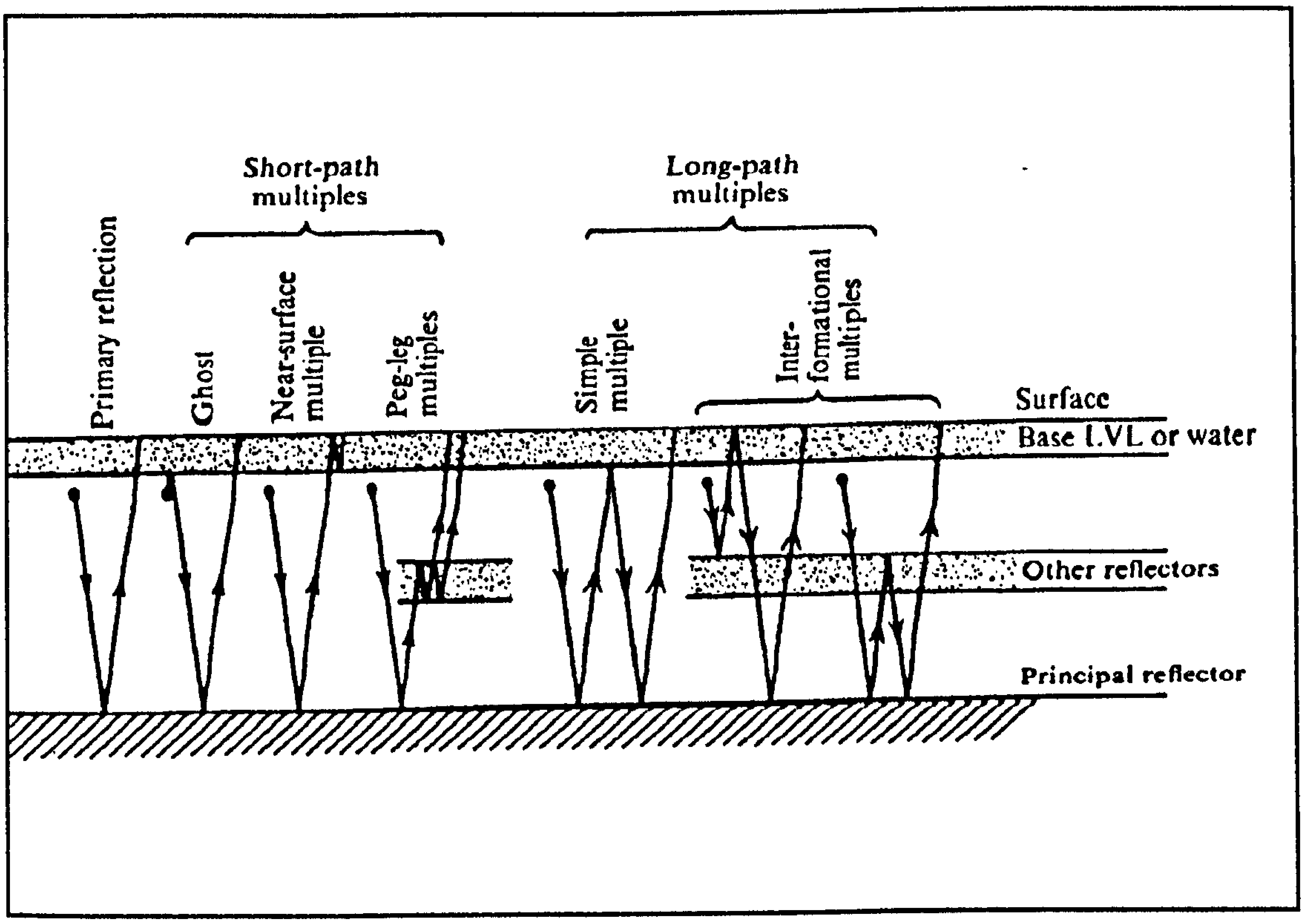
2.4 Vertical and horizontal resolution

Vertical resolution is the ability to recognise individual reflectors in a vertical plane. For a reflected pulse represented by a simple wavelet, the maximum resolution possible is between one quarter and one eighth of the dominant wavelength of the pulse. Widess (1957) defines a bed as being "thin" when its thickness is less than about $\lambda_b/8$ where λ_b is the (predominant) wavelength computed using the velocity of the bed. A bed that is thin for one frequency is, of course, not necessarily thin for a higher frequency. When bed thickness is large enough so that the individual reflected wavelets from each of the two interfaces are completely separated in time, the trace on the record yields maximum information. As bed thickness diminishes more and more energy becomes a composite of the two reflections (Widess, 1957).

Knapp (1993) concludes, through an argument of energy distribution in wavelets, that the class of wavelets that includes the zero phase wavelet has maximum instantaneous total energy, and those wavelets share maximum resolving power. However, the zero-phase wavelet still has the maximum possible amplitude. It, therefore, will perform best in the presence of noise and on a standard amplitude section will have the greatest detectability.

Horizontal resolution is determined by the spacing of the individual depth estimates from which reflector geometry is reconstructed. For a reflection survey on a horizontal reflector, resolution can be no more than half the detector spacing.

Figure 2.5 Examples of short and long path multiples (after Telford *et al.*, 1984).



A further factor to limit the achievable horizontal resolution is the Fresnel zone, the portion of the reflecting surface from which energy returns to a geophone within a half cycle after the reflection onset (Figure 2.6). Energy reflected from this zone interferes constructively and builds up the reflection.

The effect of this can be illustrated in Figure 2.7 which shows the reflection from reflectors of different lengths. When the reflector is larger than one Fresnel zone, the reflection shows the shape of the reflector, whereas for small reflectors, the arrival time patterns are almost identical.

Figure 2.6 Fresnel zone. a) the area of the reflector from which energy can reach the geophone within the next half-cycle is limited by the circle that the wavefront a 1/4 wavelength later makes with the reflector. b) Fresnel zone is larger for low frequency components (after Sheriff, 1980).

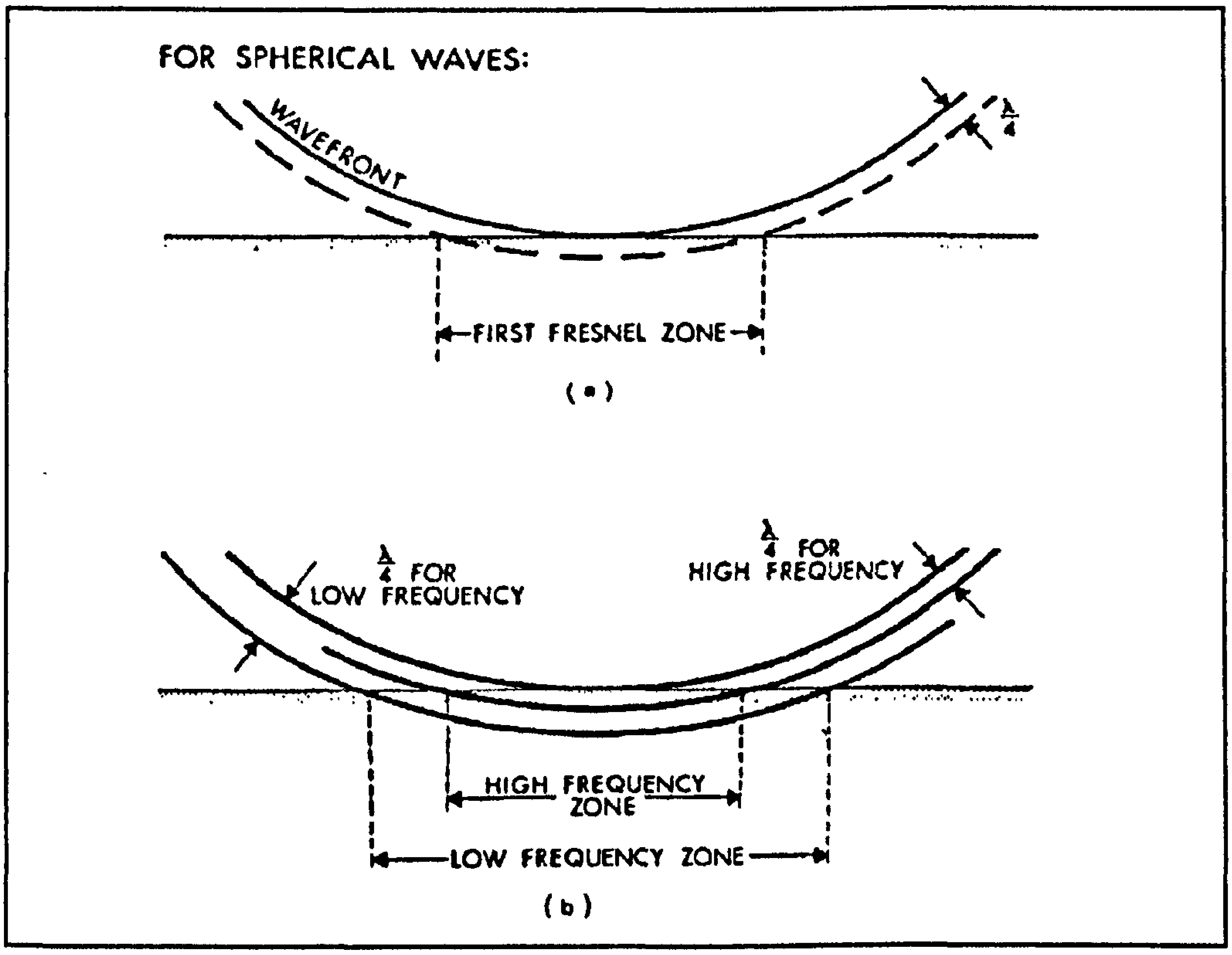
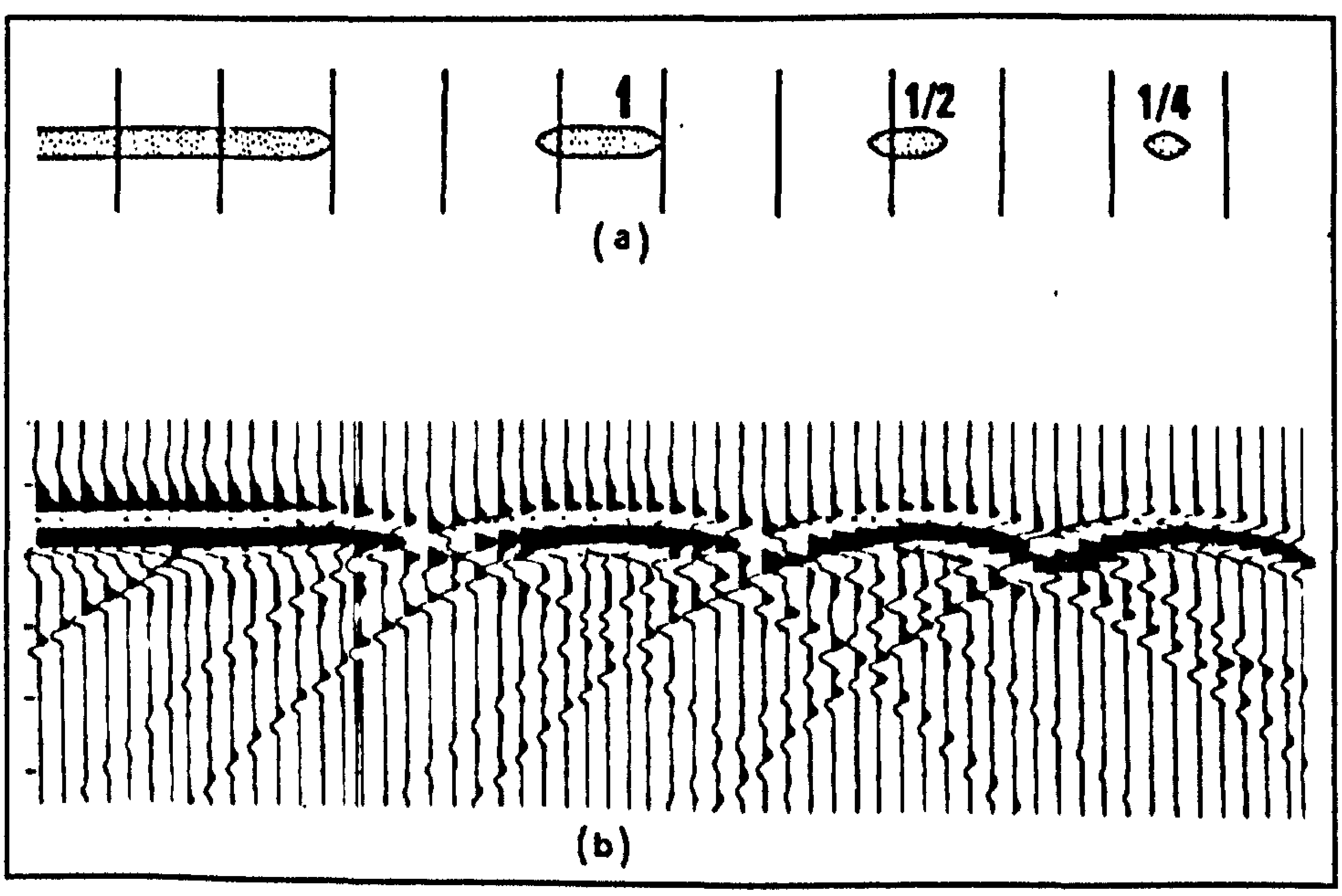


Figure 2.7 Reflections from reflectors of limited dimensions. a) Cross section of model with vertical lines showing Fresnel zone size. b) Seismic section resulting from profile over model (as model size decreases peak amplitude decreases) (after Sheriff, 1980).



CHAPTER 3
Seismic stratigraphy

3.1 Introduction

The theory of seismic stratigraphy as a method of seismic data interpretation is considered to owe its wider acceptance to the publication of the "classical" text by the American Association of Petroleum Geologists, Memoir 26 *Seismic Stratigraphy - Applications to Hydrocarbon Exploration* (Payton, 1977). In hydrocarbon exploration the historical use of seismic data has been in the mapping of geologic structures. The distinction of seismic stratigraphy is that it goes beyond merely mapping structure and searches for more direct seismic evidence as to the nature of the rocks and the fluid contained within the pore spaces.

The development of seismic stratigraphy since the 1970s and the advances made in the methodology offer a new and more dynamic view of stratigraphy in which linkage can be made between variations in sea level and sedimentation (Hemàndez-Molina *et al.*, 1994).

Stratigraphy is defined by Sheriff (1980) as "the branch of geology that deals with the definition and description of major and minor natural divisions of rock and with the interpretation of their significance in geologic history specifically the geologic study of the form, arrangement, geographic distribution, chronologic succession, classification and especially correlation and mutual relationships of rock strata in terms of their origin, occurrence, environment, thickness, lithology, composition, fossil content, age, history, palaeogeographic condition, relation to organic evolution and relation to other geologic concepts".

Seismic stratigraphy is defined by Mitchum (1977) as "the study of stratigraphy and depositional facies as interpreted from seismic data". The most fundamental assumption and underlying basis of the seismic stratigraphic method is that a seismic reflection, in most cases and for all practical purposes, is a *time line* (Bally, 1987).

There are considered to be four major variables that control variations in stratal patterns and lithofacies distribution between sedimentary rocks:

1) Subsidence of the crust because of tectonic and/or isostatic reasons; this creates the space or accommodation available to receive sediments.

2) Eustatic changes of sea level. This is believed to be the major control on the stratal patterns and the distribution of lithofacies. Eustatic changes are generally rapid and compared to subsidence they predominate in determining the position of sediment deposition.

3) Sediment inflow, which provides the sediments for infilling the accommodation.

4) Climate, which mainly determines the type of sediment being deposited.

The early version of making seismic stratigraphic studies using seismic data is, according to Mitchum and Vail (1977):

1) Seismic sequence analysis-
   subdividing the seismic section into sequences which are the seismic expression of depositional sequences.

2) Seismic facies analysis-
   analysing the configuration of reflections interpreted as strata within depositional sequences to determine environmental setting and estimate lithology.

3) Sea level analysis-
   analysis of regional relative changes of sea level for comparison with global data. This is designed to date a set of sequences and aid prediction of depositional facies.

With refining of the technique, Vail (1987) suggests a more detailed seismic stratigraphic interpretation procedure consisting of the following seven steps:-

1) Seismic sequence analysis-

    definition of reflection packages referred to as seismic sequences and subordinately to seismic systems tracts by identifying discontinuities on the basis of reflection termination patterns.

2) Well-log sequence analysis-

    the making of preliminary estimates of sequences and systems tracts by interpreting the depositional lithofacies on wireline logs using cores and cuttings to calibrate the log independently of seismic sequence analysis.

3) Synthetic, well-to-seismic ties-

    the tying-in of information from well logs to the seismic section.

4) Seismic facies analysis-

    to determine all variations of seismic parameters within individual seismic sequences and systems tracts in order to determine lateral lithofacies and fluid type changes.

5) Interpretation of depositional environment and lithofacies-

    achieved using the objectively determined seismic facies parameters and maximum knowledge of regional geology.

6) Forward seismic modelling-

    wave form analysis to interpret stratigraphy, seismic simulation of a geologic cross section to help understand the seismic response and simulation of the reflection patterns seen on seismic sections by calculating stratal patterns from rates of subsidence, eustasy, and sediment supply.

7) Final interpretation-

    integrated final interpretation based on interpretation objectives and data available.

Within this project, the interpretation will be limited to using steps 1 and 2 as proposed by Mitchum and Vail (1977) and steps 5 and 7 of the Vail (1987) procedure. These steps, and the relationship of reflections as time lines, will be discussed in more detail in this chapter.

3.2 Seismic reflections and geological time lines

A depositional sequence is chronostratigraphically significant because it was deposited during a given interval of geological time. According to Vail (1987) there are three types of relations between seismic reflections and geologic time lines identifiable on seismic sections. They are: (1) seismic discontinuities such as unconformities and downlap surfaces that follow geologic time boundaries; (2) seismic reflections that follow synchronous geologic time lines; (3) rare seismic reflections caused by fluid interfaces and certain diagenetic changes that follow surfaces that are diachronous to geologic time lines.

Stratal surfaces represent ancient surfaces of deposition and therefore are essentially time synchronous. Discontinuities themselves are geologic time boundaries because they separate rocks of different ages and do not cross other chronostratigraphic surfaces. Time lines may merge along a discontinuity but will not cross it.

Working on the assumption that reflections follow time lines it therefore follows that reflections will cross lithofacies boundaries. The seismic reflections will follow former depositional surfaces which are true physical surfaces and are not time-transgressive lithofacies boundaries. Lithofacies boundaries may be observed as, possibly subtle, acoustic impedance contrasts varying along the time lines.

3.3 Seismic sequence analysis

Seismic sequence analysis is defined by Mitchum (1977) as "the seismic identification and interpretation of depositional sequences by subdividing the seismic section into packages of concordant reflections separated by surfaces of discontinuity, and interpreting them as depositional sequences". This definition is modified by Vail (1987) to include the identification of both depositional sequences and systems tracts by identifying discontinuities on the basis of reflection terminations. Reflection terminations can be recognised wherever reflections converge, examples of which are illustrated in Figure 3.1.

Seismic sequence stratigraphic concepts were first introduced by the series of papers in Payton (1977). Through a discussion of seismic stratigraphy, the application of seismic stratigraphic interpretation techniques to sedimentary basin analysis has, according to Vail (1987), resulted in a new way to subdivide, correlate, and map sedimentary rocks. This technique is termed "sequence stratigraphy". The application of this procedure to a grid of seismic data groups seismic reflections into packages that correspond to chronostratigraphically constrained genetic depositional intervals termed depositional sequences and systems tracts. They have predictable stratal patterns and lithofacies. Thus, they provide a new way to establish a chronostratigraphic correlation framework based on physical criteria.

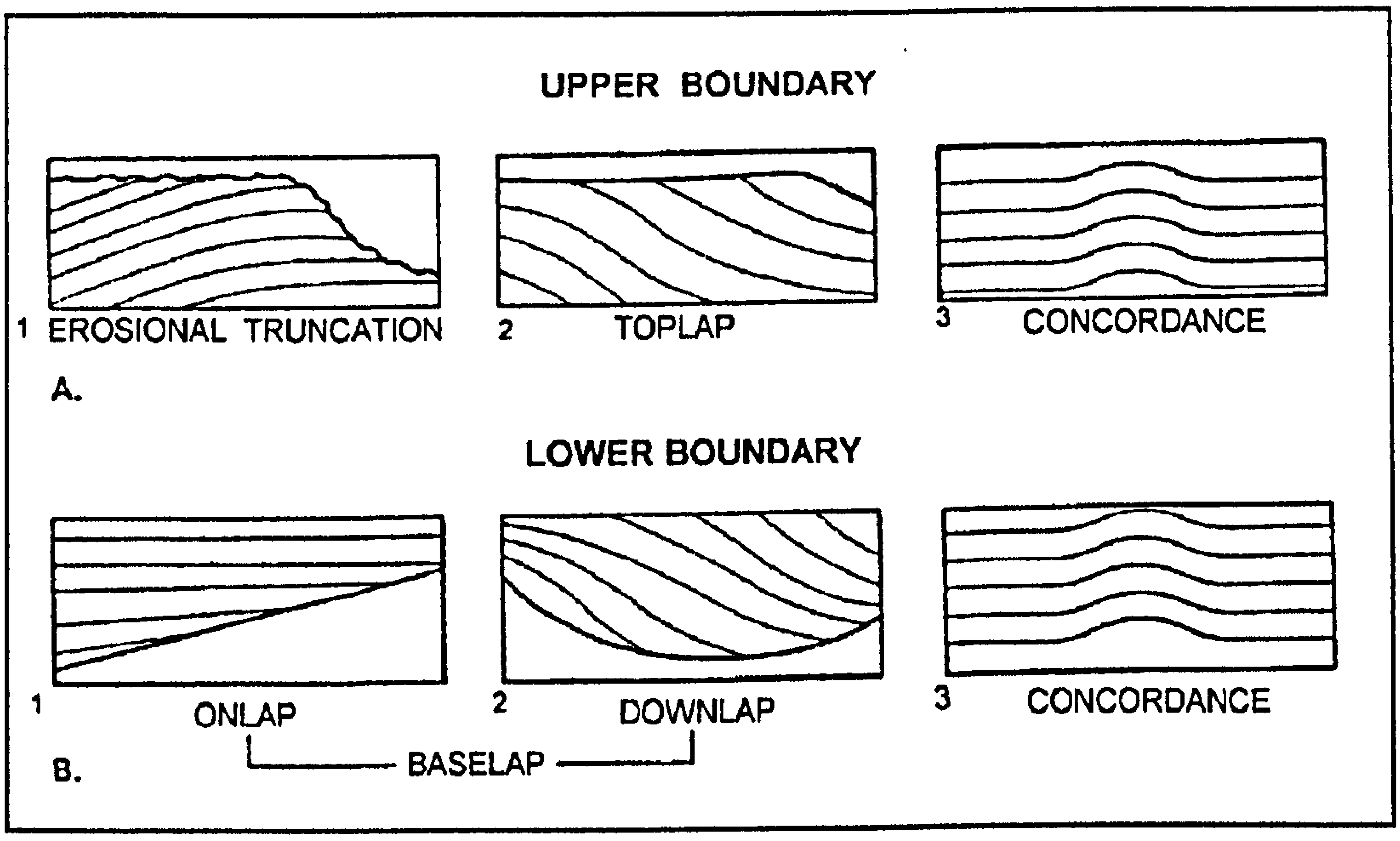
The fundamental principle behind seismic sequence stratigraphy is that sequences and their stratal components are interpreted to form in response to the interaction between rates of eustasy, subsidence and sediment supply (Van Wagoner *et al.*, 1988 & Posamentier *et al.*, 1988). Sequence stratigraphic concepts can be summarised as dealing with the stratigraphic response to the interaction between sediment flux and the space that is made available (accommodation) on the shelf for those sediments to fill, the main control being, according to Vail (1987), short term eustatic change superimposed on longer term tectonic change.

The principle unit of sequence stratigraphy is the sequence (Van Wagoner *et al.*, 1988). The "sequence" was defined by Mitchum (1977) as "a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or correlative conformities". This definition was refined by Posamentier *et al.* (1988) to include the concept that it is "composed of a succession of systems tracts and is interpreted to be deposited between fall inflection points" on the eustatic sea level cycle.

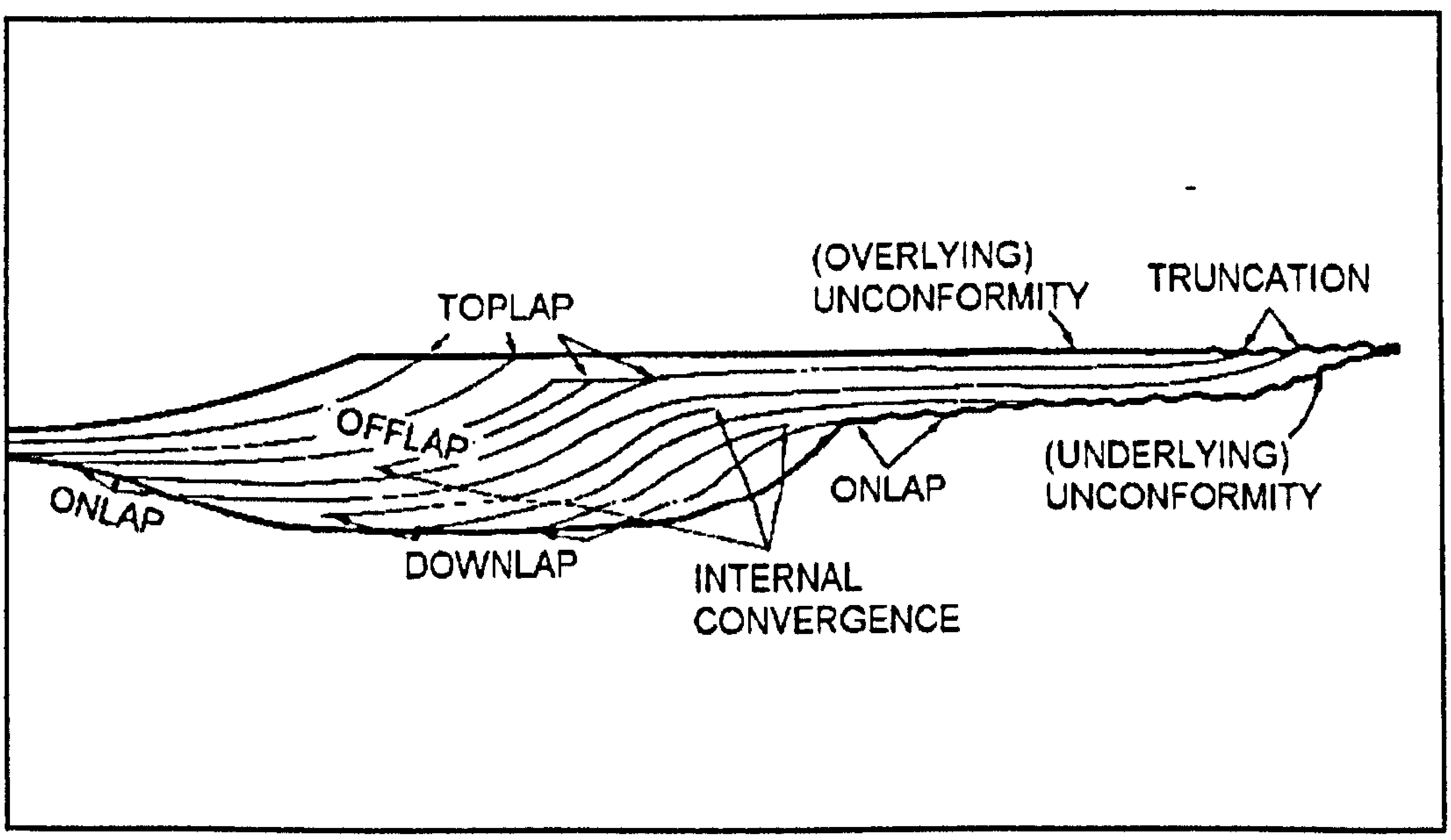
Sequences then, can be subdivided into a succession of systems tracts, which are defined by their position within the sequence and by the stacking patterns of parasequence sets and parasequences bounded by marine flooded surfaces. The relationship between sequences, systems tracts and parasequences is illustrated

Figure 3.1 A) Seismic reflection terminations. B) Schematic showing occurrence of termination patterns in a sequence. (Mitchum *et al.*, 1977).

A



B



in Figure 3.2. Further, Table 3.1 has been formulated in order to clarify their inter-relationships and to assist in understanding the concepts and terminology associated with seismic sequence stratigraphy in general.

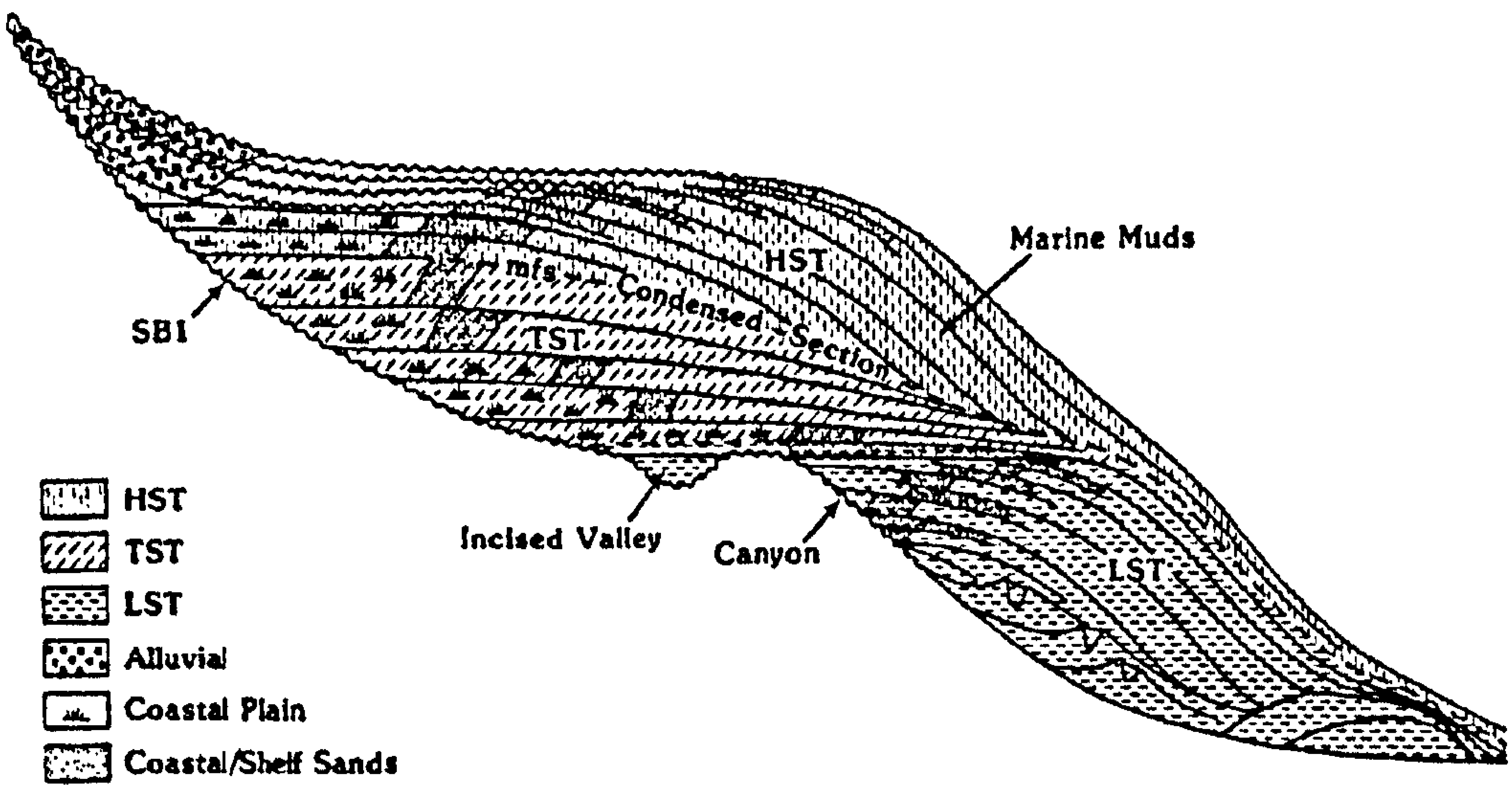
Boundaries of sequences, parasequence sets and parasequences provide a chronostratigraphic framework for correlating and mapping sedimentary rocks (Van Wagoner *et al.,* 1988). Sequences, parasequence sets and parasequences are defined and identified by the physical relationships of strata, including the lateral continuity and geometry of the surfaces bounding the units, vertical and lateral stacking patterns, and the lateral geometry of the strata within these units (Van Wagoner *et al.,* 1988).

Parasequence sets and parasequences constitute a description of a succession that is devoid of inferences regarding sea level change, stratal geometries or other interpretive aspects. In contrast, systems tracts explicitly involve interpretations regarding sea level change and temporal and spatial relationships between facies tracts and the nature and significance of bounding surfaces (Posamentier and James, 1993).

Particular sets of depositional processes and thus certain depositional environments and lithofacies are associated with particular systems tracts. Therefore the identification of a systems tract on a seismic record provides a framework for more accurate prediction of depositional environment and lithofacies. The seismic expression of sequences and systems tracts therefore provides information to assist in the prediction of stratigraphy (Vail, 1987). A depositional sequence may have more significance in geologic history than a unit bounded only by synchronous surfaces that are chosen arbitrarily. A sequence represents a genetic unit that was deposited during a single episodic event.

According to Posamentier and James (1993) sequence-stratigraphic concepts may be applied in two fundamentally different ways: (1) the construction of age models for given stratigraphic successions based on the correlation of local stratigraphy with the global cycle chart published by Haq *et al.* (1987); (2) lithology prediction based on the interpretation of the cyclicity in the rock records (i.e. Figures 1-6 in Posamentier *et al.*, 1988).

Figure 3.2 Major features of sequence and associated systems tracts for a shelf/basin setting. (Boyd *et al.*, 1989).



LST = lowstand systems tract; TST = transgressive systems tract; HST = high stand systems tract; SB1 = Type 1 sequence boundary; mfs = maximum flooding surface. Boundaries within sequences define parasequences.

Table 3.1 Relationship between sequences, parasequences and systems tracts.

SEQUENCE -
A RELATIVELY CONFORMABLE SUCCESSION OF GENETICALLY RELATED STRATA BOUNDED BY UNCONFORMITIES AND THEIR CORRELATIVE CONFORMITIES (Mitchum, 1977).

SYSTEMS TRACT -
A linkage of contemporaneous depositional systems (Brown and Fisher, 1977). Systems tracts are defined on the basis of types of bounding surfaces, position within a sequence and parasequence and parasequence set stacking patterns Systems tracts are also characterised by geometry and facies associations. The term systems tract is used to designate three subdivisions within each sequence.

Type 1 sequence- Lowstand, Transgressive, Highstand.

Type 2 sequence- Shelf margin, Transgressive, Highstand.

The terms lowstand and highstand are not meant to imply a unique period of time or position on a cycle of eustatic or relative change of sea level. The actual time of initiation of a systems tract is interpreted to be a function of the interaction between eustasy, sediment supply and tectonics.

PARASEQUENCE SETS -
A succession of genetically related parasequences which form a distinctive stacking pattern bounded in many cases by marine-flooding surfaces and their correlative surfaces (Van Wagoner, 1985). Parasequence set boundaries: (1) separate distinctive parasequence stacking patterns, (2) may be coincident with sequence boundaries, and (3) may be downlap surfaces and boundaries of systems tracts.

PARASEQUENCE -
Relatively conformable succession of genetically beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces (Van Wagoner, 1985).
Parasequences may, depending on the ratio of depositional to accommodational rates, be:-

PROGRADATIONAL

RETROGRADATIONAL

AGGRADATIONAL

LOWERMOST SYSTEMS TRACT -
The lowermost systems tract is defined as a lowstand systems tract or shelf margin systems tract dependent on it lying on either a Type 1 or Type 2 sequence boundary respectively

LOWSTAND SYSTEMS TRACT -

If deposited in a basin with a shelf break it can be divided into three separate units

LOWSTAND WEDGE - Characterised on the shelf by incised valley fill which commonly onlaps onto the sequence boundary, and on the slope by progradational fill with wedge geometry overlying and commonly downlapping onto the basin floor fan or the slope fan. Lowstand wedge deposition is not coeval with basin floor deposition. Lowstand wedges are composed of progradational to aggradational parasequence sets The top of the lowstand wedge, coincident with the top of the lowstand systems tract is a marine flooding surface called the transgressive surface.
Occurs during the late eustatic fall or early rise.

SLOPE FAN - Characterised by turbidite and debris flow deposition on the middle or base of the slope. Slope fan deposition can be coeval with the basin floor fan or with the early portion of the lowstand wedge. The top of the slope fan is a downlap surface for the middle and upper portions of lowstand wedge.
Occurs during the late eustatic fall or early eustatic rise.

BASIN FLOOR FAN - Characterised by deposition of submarine fans on the lower slope or basin floor. Fan formation is associated with the erosion of canyons into the slope and the incision of fluvial valleys into the shelf. Siliclastic sediment bypasses the shelf and slope though the valleys and canyons to feed the basin floor fan.
Occurs during a time of rapid eustatic fall.

If deposited in a basin with a ramp margin consists of a

THIN LOWSTAND WEDGE - May contain two parts.
The first part is characterised by stream incision and sediment bypass of the coastal plain interpreted to occur during a relative fall in sea level during which the shoreline steps rapidly basinward until the relative fall stabilises. The second part of the wedge is characterised by a slow relative rise in sea level, the infilling of incised valleys, and continued shoreline progradation, resulting in a lowstand wedge composed of incised valley fill deposits updip and one or more progradational parasequence sets downdip. The top of the lowstand wedge is the transgressive surface; the base of the lowstand wedge is the lower sequence boundary.

SHELF MARGIN SYSTEMS TRACT -
Characterised by one or more weakly progradational to aggradational parasequence sets; the sets onlap onto the sequence boundary in a landward direction and downlap onto the sequence boundary onto a basinward direction. The top of the shelf margin systems tract is the transgressive surface, which also forms the base of the transgressive systems tract. The base of the shelf margin systems tract is a Type 2 sequence boundary.

TRANSGRESSIVE SYSTEMS TRACT -
Middle systems tract of both Type 1 & 2 sequences. Characterised by one or more retrogradational parasequence sets. The base of the transgressive systems tract is the transgressive surface at the top of the lowstand or shelf margin systems tract. Parasequences within the transgressive systems tract onlap onto the sequence boundary in a landward direction and downlap onto the transgressive surface in a basinward direction. The top of the transgressive systems tract is the downlap surface.
Occurs during a rapid eustatic rise.

HIGHSTAND SYSTEMS TRACTS -
Upper systems tract of either Type 1 or 2 sequences. This systems tract is commonly widespread on the shelf, and may be characterised by one or more aggradational parasequence sets that are succeeded by one or more progradational parasequence sets with prograding clinoform geometries. Parasequences within the highstand systems tract onlap onto the sequence boundary in a landward direction and downlap onto the top of the transgressive or lowstand systems tracts in a basinward direction. The highstand systems tract is bounded at the top by a type 1 or 2 sequence boundary and at the bottom by the downlap surface.
Occurs during the late part of eustatic rise, a eustatic stillstand, and the early part of eustatic fall.

TYPE 1 SEQUENCE -
A sequence bounded below by a Type 1 sequence boundary and above by a Type 1 or a Type 2 sequence boundary.

TYPE 2 SEQUENCE -
A sequence bounded below by a Type 2 sequence boundary and above by a Type 1 or a Type 2 sequence boundary.

TYPE 1 SEQUENCE BOUNDARY - Characterised by subaerial exposure and concurrent subaerial erosion associated with stream rejuvenation, a basinward shift of facies, a downward shift in coastal onlap, and onlap of overlying strata. A Type 1 sequence boundary is interpreted to form when the rate of eustatic fall exceeds the rate of basin subsidence at the depositional shoreline break, producing a relative fall in sea level at that position.

TYPE 2 SEQUENCE BOUNDARY - Marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional shoreline break; however, it lacks both subaerial erosion associated with stream rejuvenation and a basinward shift in facies. Onlap of overlying strata landward of the depositional shoreline break also marks a Type 2 sequence boundary. A Type 2 sequence boundary is interpreted to form when the rate of eustatic fall is less than the rate of basin subsidence at the depositional shoreline break, so that no relative fall in sea level occurs at this shoreline position.

UNCONFORMITY - A surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated. This definition with its restriction to subaerial erosion has been modified from Mitchum (1977) to allow differentiation between sequence and parasequence boundaries.
CONFORMITY - A surface separating younger from older strata along which there is no evidence of erosion (subaerial or marine), or non-deposition, and along which no significant Hiatus is indicated
MARINE FLOODING SURFACE - A surface that separates younger from older strata across which there is evidence of an abrupt increase in water depth. Deepening is commonly accompanied by minor submarine erosion (but no erosion or basinward shift in facies) and non deposition, and a minor hiatus may be indicated. Onlap of overlying strata onto a marine flooding surface does not occur unless the surface is coincident with sequence boundary.
DEPOSITIONAL SHORE LINE BREAK - Position on the shelf, landward of which the depositional surface is at or near base level (sea-level) Posamentier *et al.* (1988), and seaward of which the depositional surface is below base level.
DEPOSITIONAL SYSTEM - A three dimensional assemblage of lithofacies (Fisher and McGowan, 1967).
TRANSGRESSIVE SURFACE - The first significant marine-flooding surface across the shelf within the sequence.
DOWNLAP SURFACE - A marine flooding surface onto which the toes of prograding clinoforms in the overlying highstand systems tract downlap. This surface marks the change from a retrogradational to an aggradational parasequence set and is the surface of maximum flooding.

The use of sequence-statigraphic principles in construction of age models is based on the assumption that stratigraphic successions preserved in a basin are a function primarily of eustatic rather than local tectonic fluctuations. In order for this assumption to be valid, eustatic change must vary with a higher frequency and amplitude than tectonics and consequently be the dominant signal to which the sediments respond (Posamentier and James, 1993).

The recognition of a predictable lithological succession occurring in response to variations of relative sea level (a function of both eustasy and tectonics) as well as sediment flux and physiography does not depend on whether eustatic change or tectonics is the dominant process or what is (are) the cause(s) of sea level. The principle consideration is that relative sea level changes operating in concert with sediment flux and physiography are the primary control on stratigraphic succession (Posamentier and James, 1993).

3.4 Seismic facies analysis

Mitchum (1977) defines seismic facies analysis as "the description and geologic interpretation of seismic reflection parameters, including configurations, continuity, amplitude, frequency and interval velocity", and a seismic facies unit as "a mappable three-dimensional seismic unit composed of groups of reflections whose parameters differ from those of adjacent facies units". Once the interval reflection parameters, the external form, and the three-dimensional associations of the seismic facies units are delineated, the unit can then be interpreted in terms of environmental setting, depositional processes, and estimates of lithology. This interpretation is carried out using previously identified depositional sequences.

As a tool for predicting lithofacies, seismic facies analysis of sequences is more accurate because of the association of particular systems tracts with particular depositional processes (Vail, 1987). The purpose of seismic facies analysis is to determine, as objectively as possible, all variations of seismic parameters within individual seismic sequences and systems tracts in order to determine lateral lithofacies and fluid type changes. Well processed instantaneous attribute sections are ideal for the description and mapping of the parameters identified by Mitchum (1977) and for assisting with seismic facies analysis.

Seismic sequence and systems tracts boundaries interpreted on the basic seismic profiles can be used to identify physical discontinuities. The abrupt changes across these discontinuities should be separated from more gradual lithofacies changes within the genetic sequences and systems tracts.

The overall geometry of a seismic facies unit consists of the external form and the internal reflection configuration of the unit (Table 3.2, columns 2 and 3 and Figures 3.3 and 3.4). Both must be described in order to understand the geometric interrelation and depositional setting of the facies unit. However, analysis always starts in the two-dimensional mode of single seismic sections and these apparent configurations are later corroborated in a three-dimensional grid of seismic sections. An understanding of three dimensional forms and areal associations of seismic facies units is important in their analysis.

Reflection configuration reveals gross stratification patterns from which depositional processes, erosion, and palaeotopography can be interpreted. Seismic reflection configuration is the most obvious and directly analysed seismic parameter. Stratal configuration is interpreted from seismic reflection configuration, and refers to the geometric patterns and relations of strata within a stratigraphic unit. Mitchum *et al.* (1977) and Bally (1987) provide an excellent description and interpretation of reflection configuration and their work will be discussed here. Analysis and mapping of stratal configuration from seismic reflection configuration is the first step in a complete seismic facies analysis.

3.4.1 Types of internal reflection configuration patterns

Some significant reflection configuration patterns are listed on Table 3.2, and are diagrammatically illustrated in Figures 3.3 - 3.6. Description and interpretation of reflection configurations begins with recognition of simple patterns and continues to an identification of the more complex patterns. Variations within configurations can commonly be described with modifying terms such as those shown on Table 3.2 and Figure 3.6.

REFLECTION TERMINATIONS (AT SEQUENCE BOUNDARIES)	REFLECTION CONFIGURATIONS (WITHIN SEQUENCES)	EXTERNAL FORMS (OF SEQUENCES AND SEISMIC FACIES UNITS)
LAPOUT	PRINCIPAL STRATAL CONFIGURATION	SHEET
BASELAP	PARALLEL	SHEET DRAPE
ONLAP	SUBPARALLEL	WEDGE
DOWNLAP	DIVERGENT	BANK
TOPLAP	PROGRADING CLINOFORMS	LENS
TRUNCATION	SIGMOID	MOUND
EROSIONAL	OBLIQUE	FILL
STRUCTURAL	COMPLEX SIGMOID-OBLIQUE	
CONCORDANCE	SHINGLED	
(NO TERMINATION)	HUMMOCKY CLINOFORM	
	CHAOTIC	
	REFLECTION FREE	
	MODIFYING TERMS	
	EVEN HUMMOCKY	
	WAVY LENTICULAR	
	REGULAR DISRUPTED	
	IRREGULAR CONTORTED	
	UNIFORM	
	VARIABLE	

Table 3.2 Geologic interpretation of seismic facies parameters (after Mitchum *et al.*, 1977).

Figure 3.3 Seismic reflection configurations within sequences (after Mitchum *et al.*, 1977).

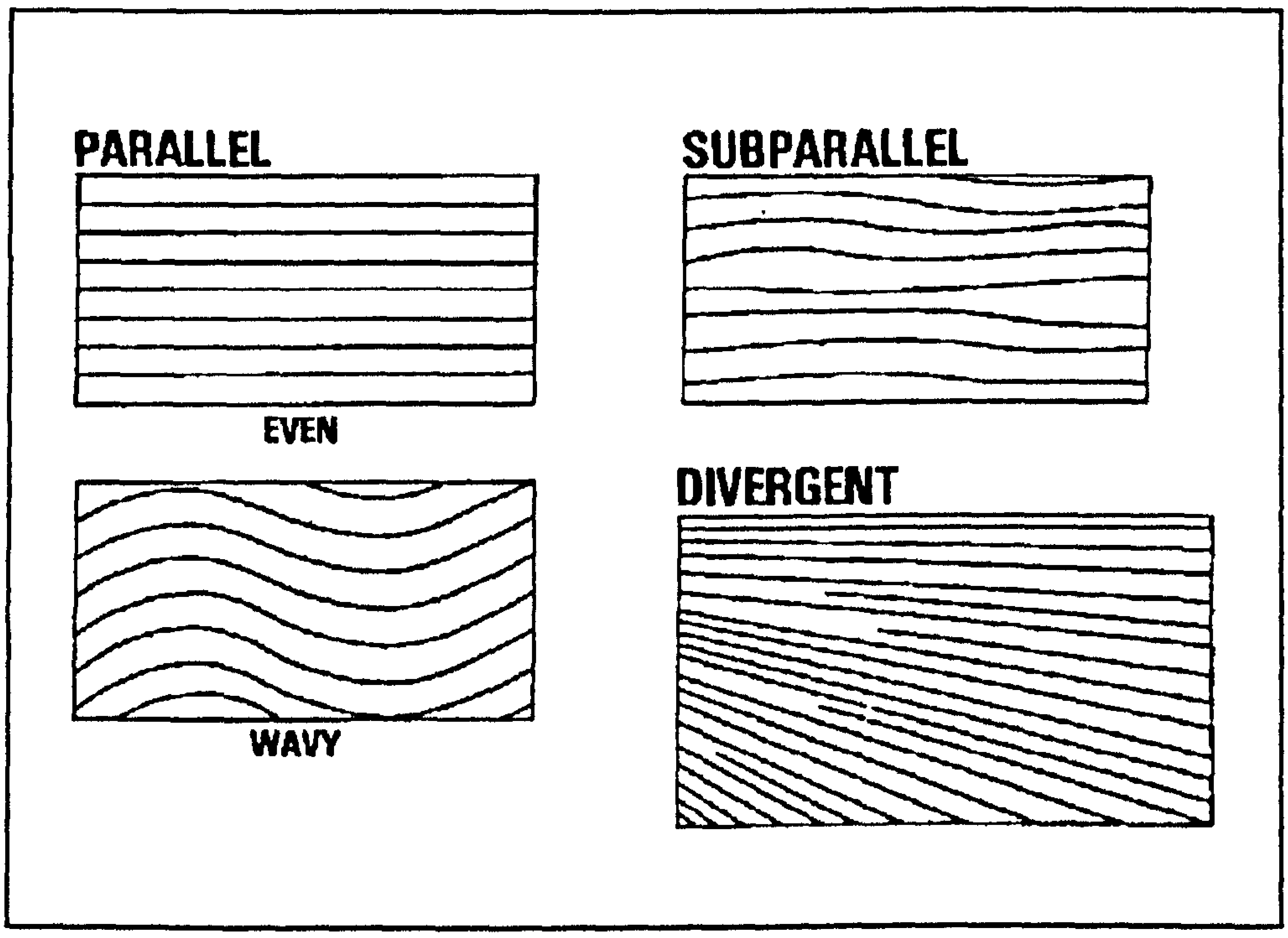


Figure 3.4 Seismic reflection patterns interpreted as prograding clinoforms (after Mitchum *et al.*, 1977).

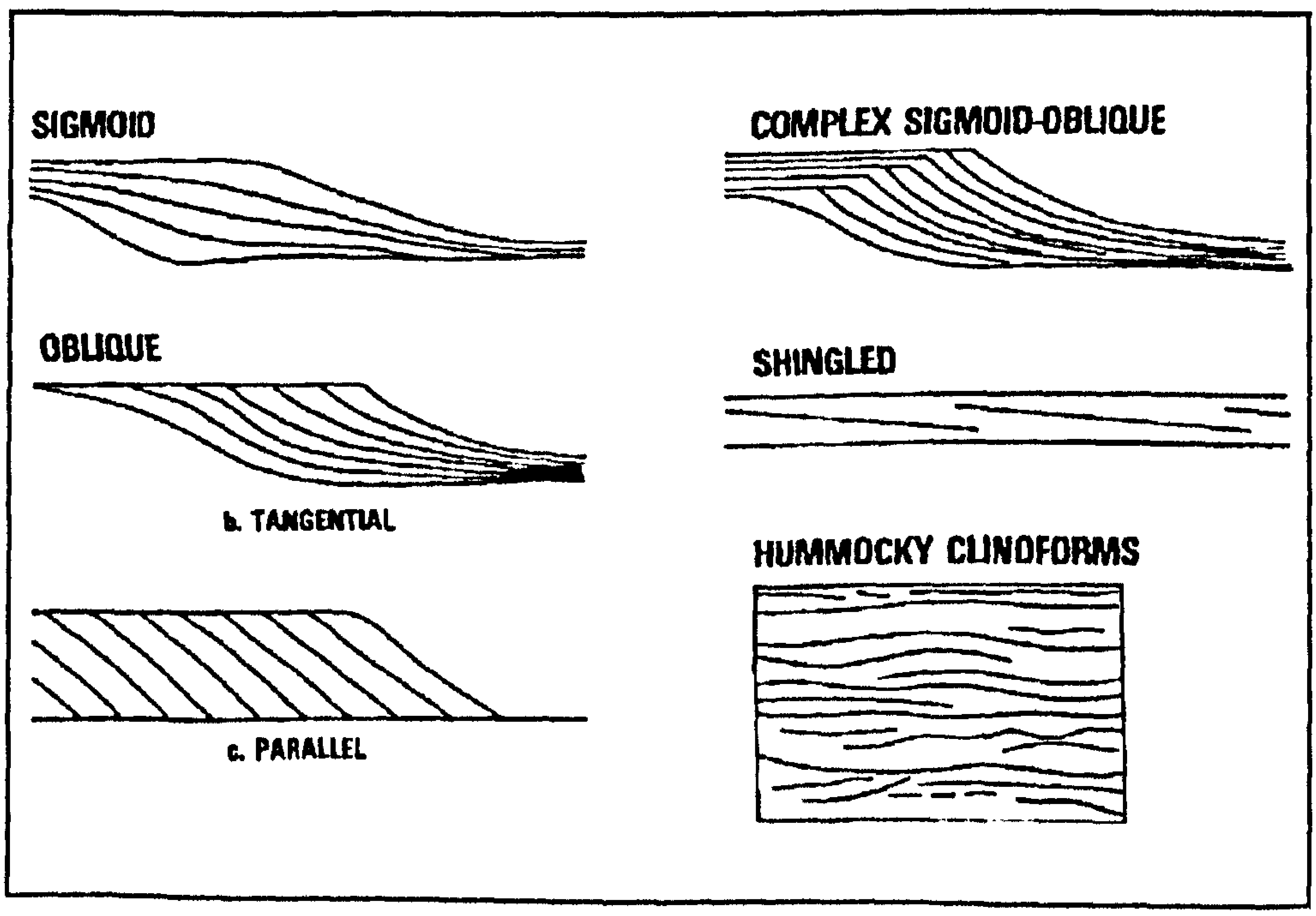


Figure 3.5 Chaotic and reflection-free seismic reflection patterns. The left hand chaotic pattern may be interpreted as original stratal features still recognisable after pencontemporaneous deformation; in the right hand example reflections are not recognisable as stratal patterns. (after Mitchum *et al.*, 1977).

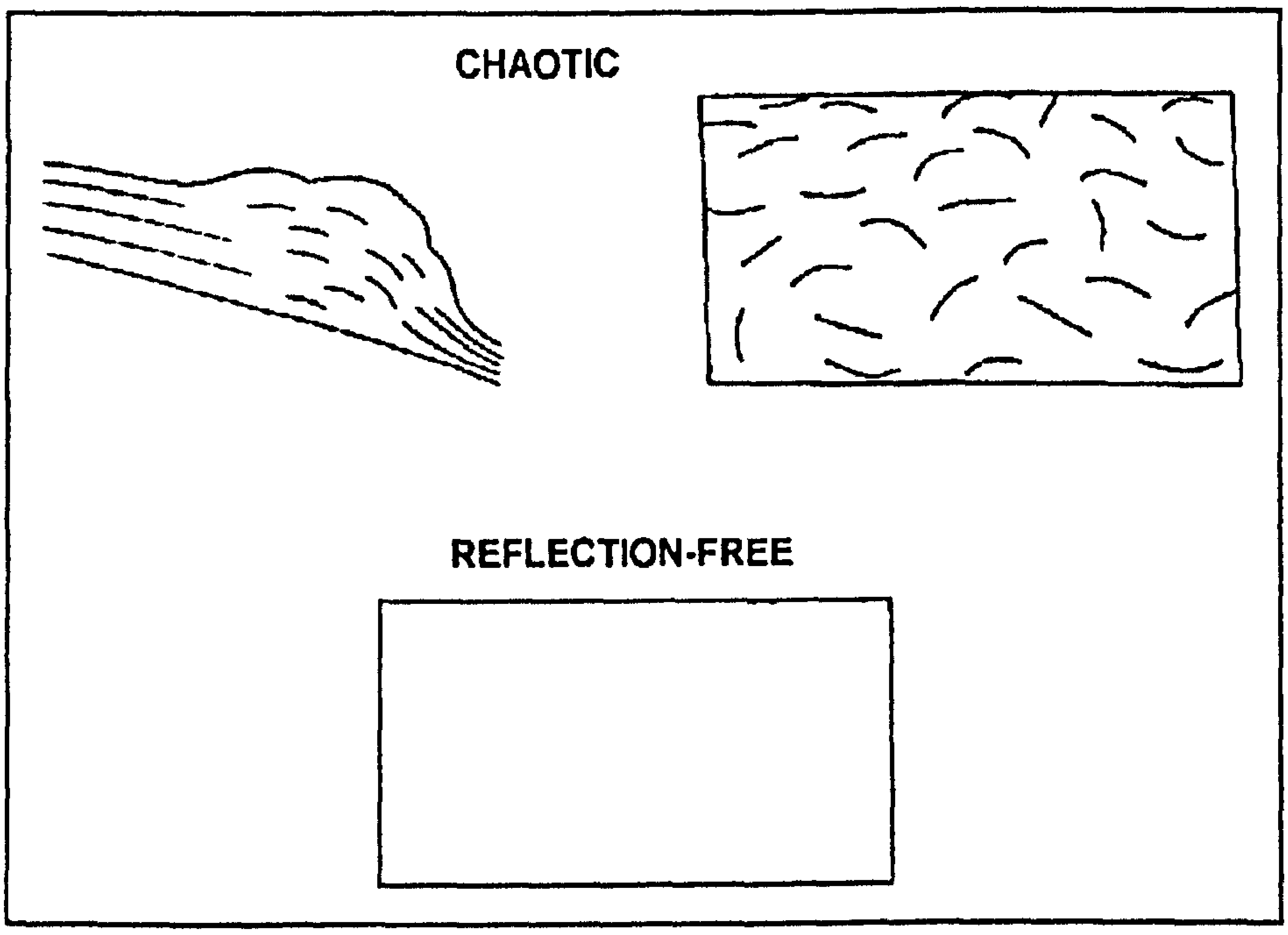
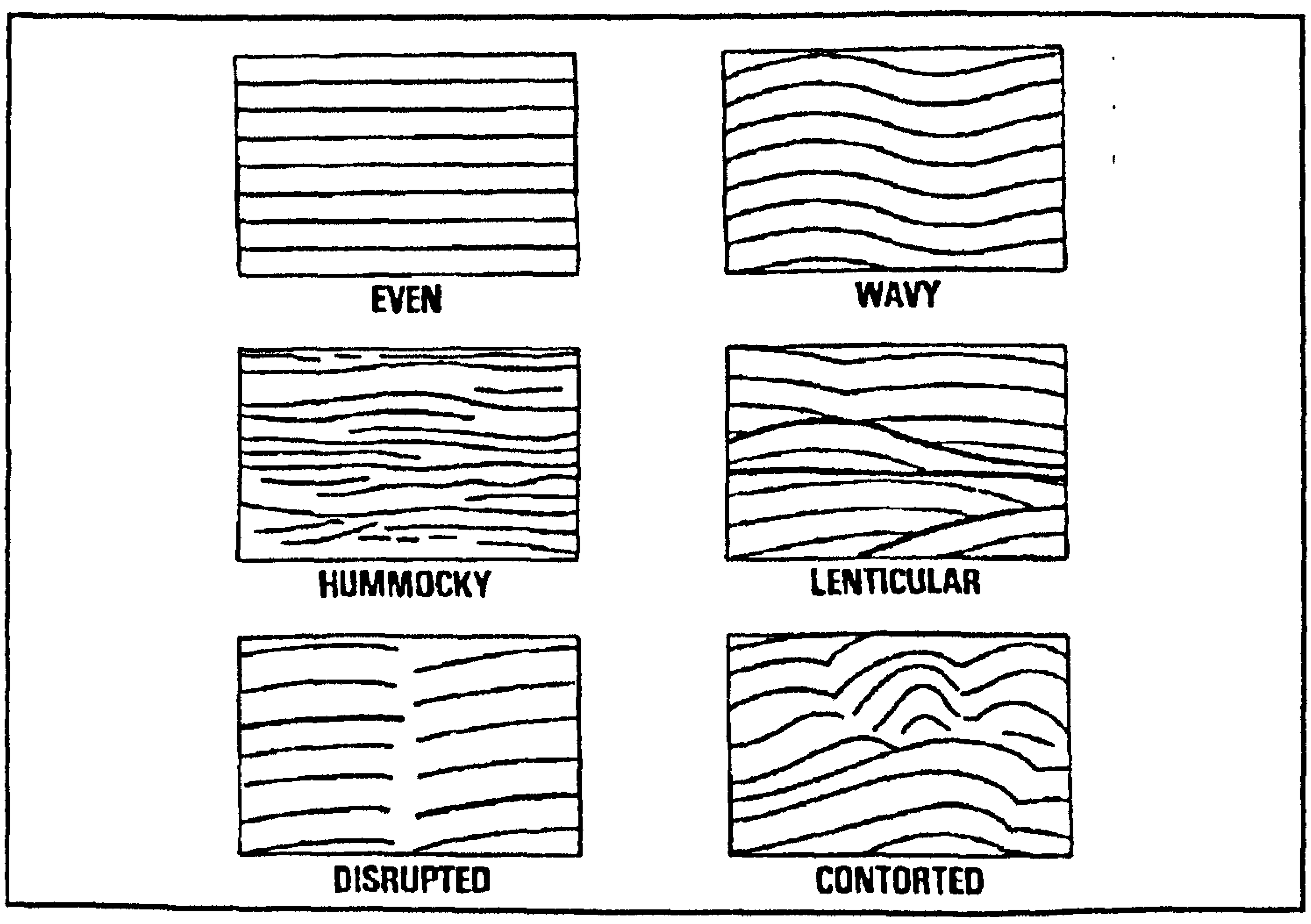


Figure 3.6 Some modifying seismic reflection configurations. (after Mitchum *et al.*, 1977).



Experience with oil exploration data has led researchers to make the following interpretation from the internal configuration patterns shown in Figures 3.3 - 3.6

Parallel and Subparrallel - This pattern (Figure 3.3) suggests uniform rates of deposition on a uniformly subsiding shelf or stable basin plane setting.

Divergent - Divergent configurations (Figure 3.3) suggest lateral variations in the rate of deposition, or progressive tilting of the depositional surface.

Prograding Reflection Configurations - Several complex reflection configurations occur (Figure 3.4), interpreted as strata in which significant deposition is due to lateral outbuilding or prograding. The progradational patterns illustrated form through progressive lateral development of gently sloping depositional surfaces called clinoforms (one of the most common depositional features). Differences in prograding clinoform patterns result in large part from variations in rate of deposition and water depth.

Sigmoid progradational configurations imply relatively low sediment supply, relatively rapid basin subsidence, and/or rapid rise in sea level to allow deposition and preservation of the topset units. A relatively low-energy sediment regime is interpreted.

Oblique progradational reflection configuration implies depositional conditions with some combination of relatively high sediment supply, slow to no basin subsidence, and a stillstand of sea level to allow rapid basin infill and sedimentary bypass or erosion of the upper depositional surface. A relatively high energy sedimentary regime is indicated.

Complex sigmoid-oblique implies strata with a history of alternating upbuilding and depositional bypass in the topset segment within a high energy depositional regime.

Shingled seismic configuration is most common in seismic facies units interpreted as depositional units prograding into shallow water.

Hummocky clinoform is interpreted as strata forming small, interfingering clinoform lobes building into shallow water in a prodelta or inter-deltaic position.

Chaotic Reflection Configuration - Chaotic patterns (Figure 3.5) are discontinuous reflections suggesting a disordered arrangement of reflection surfaces. They are interpreted either as strata deposited in a variable, relatively high-energy setting, or as initially continuous strata which have been deformed.

Reflection -Free Areas - Homogenous, nonstratified, highly contorted or steeply dipping geologic units may be expressed as essentially reflection free areas on seismic data (Figure 3.5).

Modifying Terms - Minor variations in basic patterns of reflection configurations may be described by common modifying terms (Figure 3.6).

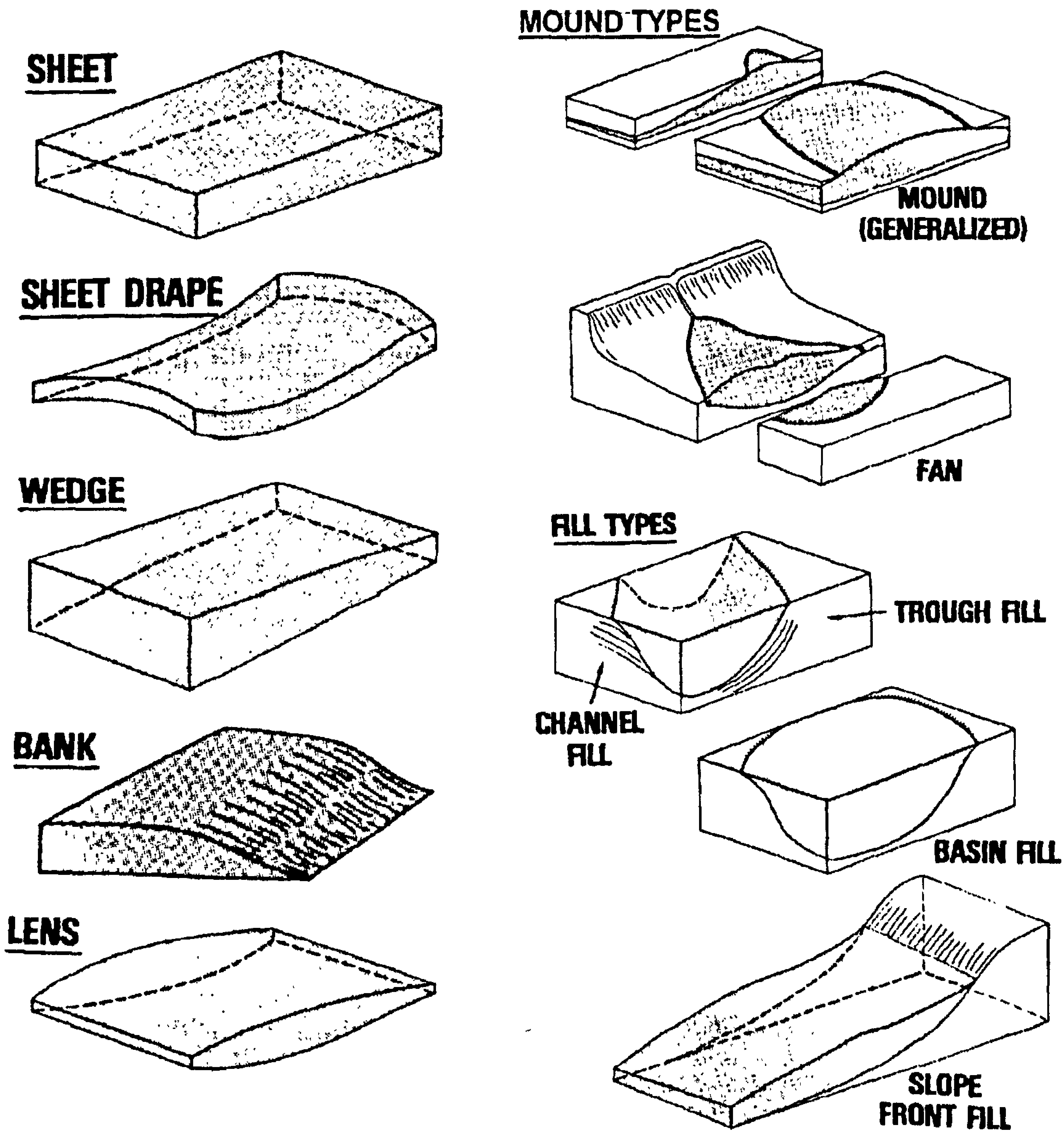
3.4.2 Types of external forms of seismic facies units

An understanding of three-dimensional external forms and areal associations of seismic facies units is important in their understanding. Table 3.2 and Figure 3.7 illustrate some important external forms.

The interpretation of the external form is based on geological knowledge and common sense. The most common shelf seismic facies units are sheets, banks and wedges which may be large. A variety of parallel, divergent and prograding patterns may make up the internal reflection configuration within these units. Sheet drapes commonly consist of parallel reflections interpreted as strata draped over underlying topography in a pattern suggesting uniform, low energy, deep-marine deposition independent of bottom relief.

Mounds and fills are groups of seismic forms derived from strata with diverse origins, forming prominences or filling depressions on depositional surfaces. Mounds are reflection configurations interpreted as strata-forming elevations or prominences, rising above the general level of the surrounding strata.

Figure 3.7 External form of some seismic facies units (after Mitchum *et al.*, 1977).



Fill reflection patterns are interpreted as strata filling negative relief features in the underlying strata. Underlying reflections may show either erosional truncation or concordance along the basal surface of the fill unit. Fill units may be classified by external form (channel fill, trough fill, basin fill, or slope front fill (Figure 3.7). They also show a variety of internal reflection configurations, some of which are illustrated in Figure 3.8.

3.4.3 Use of instantaneous seismic attributes

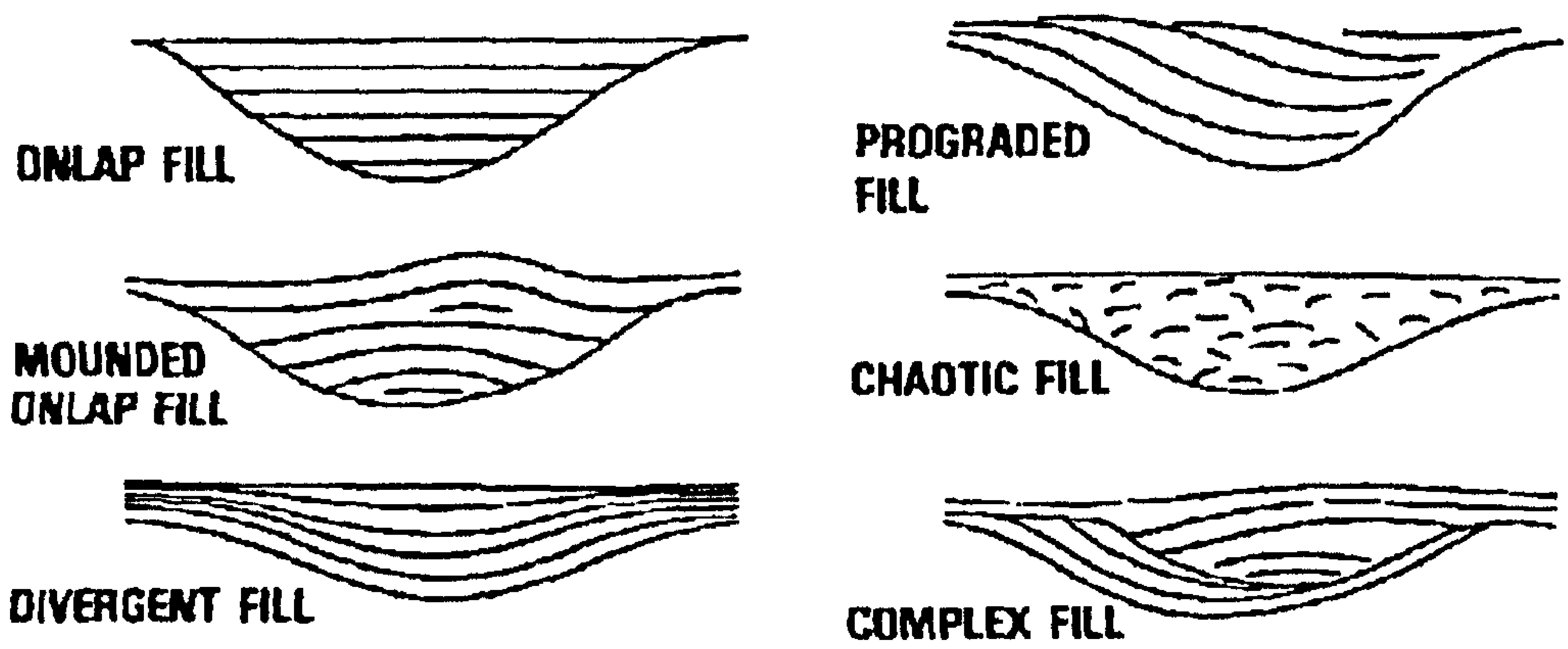
The remaining seismic reflection parameters of amplitude, phase (continuity) and frequency have become known as "instantaneous attributes". Seismic waves can be thought of as an analytical signal with both real and imaginary parts, of which only the real part is detected and displayed (Taner and Sheriff, 1977). Since a seismic trace is a causal time series, the imaginary part of the complex function can be computed directly from itself using a Hilbert transform. The real and imaginary (also called quadrature) parts are then the inputs which can be used to determine specific properties of the complex function such as instantaneous attributes of amplitude, phase and frequency (Robertson and Nogami, 1984). Lithological variation along bedding is, according Taner *et al.* (1979), the principal interest in attribute interpretation and evidence of its application will be presented here. Seismic attributes have been used as hydrocarbon indicators for some time (Taner and Sheriff, 1977 and Sheriff, 1980).

The successful use of instantaneous attributes requires minimum processing and good quality data. One of the problems in shallow water and intertidal surveying is the frequent need to adjust gain settings to produce good quality analogue data. Changes in gain settings and filters during acquisition must be restricted to the analogue output only. Digitally recorded data must retain its integrity at the acquisition stage and be subjected to minimum processing.

3.4.3.1 Instantaneous amplitude

Instantaneous amplitude (amplitude envelope or reflecting strength) is equivalent to the envelope function of the seismic trace and is a robust, smoothed, polarity independent measure of the energy in a trace at a given time. Where the data consist of separate primary reflectors, instantaneous amplitude provides an

Figure 3.8 Some fill seismic facies units (after Mitchum *et al.*, 1977).



indication of the magnitude of the change in acoustic impedance (velocity and density, and following on from them the physical and geotechnical properties) at the reflecting interface (Sheriff, 1980). High reflection strength is often associated with major lithological changes between adjacent rock layers, such as across unconformities and boundaries associated with sharp changes in sea level or depositional environment (Taner *et al.*, 1979).

Reflection strength may have its maximum at phase points other than peaks or troughs especially where the reflection is the interference composite of several sub-reflections. Colour-coded reflection strength display provides a measure of reflection character. It can be used, for example, in distinguishing reflections from massive reflectors (an individual thick unit) and those which are interference composites of a number of thinner beds. Reflections from massive interfaces tend to remain constant over a large region. Reflections which result from the interference of several separate reflections tend to vary along a seismic line as the thickness or contrast of the individual component reflector changes (Taner and Sheriff, 1977).

3.4.3.2 Instantaneous phase

Instantaneous phase displays emphasise the continuity of events and can be used to help identify certain physical properties of sediments and the presence of gas (by identifying phase reversal). Instantaneous phase is the angle between the trace and its Hilbert transform at a given point in time and is an amplitude-independent estimate of the character of the trace (Robertson and Nogami, 1984). As phase is independent of amplitude (reflection strength) both weak and strong coherent reflections show up equally. Phase displays are effective in showing pinchouts, angularities and the interference of events with different dip attitudes (Taner and Sheriff, 1977). Prograding sedimentary layer patterns and regions of on-lap and off-lap layering often show more clearly so that phase displays are helpful in picking seismic sequence boundaries (Taner *et al.*, 1979).

3.4.3.3 Instantaneous frequency

Instantaneous frequency is a sample-by-sample measure of the frequency in the trace and is equivalent to the time derivative of instantaneous phase (Robertson and Nogami, 1984).

Most reflection events are the composite of individual reflections from a number of closely spaced reflections which remain nearly constant in acoustic impedance contrast and separation (Taner *et al.*, 1979). The superposition of individual reflections may produce a frequency pattern which characterises the composite reflection. Frequency character often produces a useful correlation tool.

Variation along bedding is of principal interest in attribute interpretation. Lateral variation in pattern suggests stratigraphic or other changes. Sometimes the meaning of a variation is clear only when control data (e.g. borehole) are correlated with seismic data (Taner *et al.*, 1979).

Instantaneous frequency is sensitive to the interference pattern between closely spaced reflections, and consequently instantaneous frequency often characterises a particular sequence of reflectors. It is sensitive to changes in bedding sequence and is useful in identifying where stratigraphic changes occur (Sheriff, 1980).

Robertson and Nogami (1984) demonstrate the use of complex trace attributes in the definition of thin beds in seismic sections when definition of the beds is not obvious on conventional seismic sections. "Thin beds" are so identified following the description by Widess (1957) as a bed whose thickness is substantially less than the dominant wavelength of the seismic pulse propagating through the bed.

If the wavelet in a section is zero phase, low impedance strata whose thicknesses are of the order of half the peak to peak period of the dominant seismic energy show up as anomalously high-amplitude zones on instantaneous amplitude sections. These anomalies result from the well known amplitude tuning effect which occurs when reflection coefficients of opposite polarity a half period apart are convolved with a seismic wavelet.

As the layer thins to a quarter period of the dominant seismic energy, thinning is revealed by an anomalous increase in instantaneous frequency. This behaviour results from the less well known but equally important phenomenon of frequency tuning by beds which thin laterally. Instantaneous frequency reaches an anomalously high value when bed thickness is about one quarter of a period and remains high as the bed continues to thin.

3.4.3.4 Lithological Changes

Breitzke and Spieß (1992) conducted a narrow-beam, normal incidence echosounding survey of a unconsolidated sediment core using frequencies in the "lower kilohertz-range". They found that grain size variations with depth correlate with changes in instantaneous phase and frequency.

It was found that sections of undisturbed clayey silt were marked by a vertical continuity of the waveforms and instantaneous phases and by high instantaneous frequencies (350-400 kHz). Transitions to sandy silt or sand layers correlated with changes in the waveform character and instantaneous seismic attributes. Sandy silt sequences were found to show smooth variations in the waveform and instantaneous phase at the layer top and bottom, and average to high, smeared instantaneous frequencies. In contrast, sand sequences which were identified as turbidite layers, clearly revealed abrupt changes in the waveform and instantaneous phase and displayed only very low instantaneous frequencies (50-100 kHz).

Turbidite layer graduation was recognised by slowly prograding waveforms and phases versus depth, which sharply jump at the turbidite layer base. Thus, since lithological variations from sand to sandy and clayey silt simultaneously imply variations in the sediment grain size, mapping of the normalised transmission seismograms and their instantaneous seismic attributes is a sensitive tool for imaging the grain size as an additional physical parameter.

3.5 Sea level analysis

The fundamental control of depositional sequences is considered to be short term eustatic sea level changes superimposed on longer term tectonic changes. The combination of eustacy and tectonic subsidence produces relative changes of sea level. The key to understanding stratigraphy is an understanding of the relative changes of sea level (Vail, 1987).

Relative changes in sea level provide accommodation, or available space for sediment. The depositional stratal patterns and distribution of lithofacies are controlled by relative sea level changes. If a sufficient supply of sediment is available, one or more depositional sequences are deposited during one cycle of relative rise and fall of sea level.

A relative change of sea level is defined by Vail *et al.* (1977a), as "an apparent rise or fall of sea level with respect to the land surface. Either sea level itself, or the land surface, or both in combination may rise or fall during a relative change".

According to Vail *et al.* (1977a) relative changes of sea level can be determined from the onlap of coastal deposits in maritime sequences. Analysis of relative changes of sea level consists of constructing chronostratigraphic correlation charts and charts of cycles of relative changes of sea level on a regional basis and comparing them with global data. Similarities of the regional cycles to the global cycles are significant in seismic stratigraphic analysis because they introduce a dimension of predictability into stratigraphy, allowing more accurate prediction of age, time of unconformities, palaeoenvironments, and lithologies (Vail and Mitchum, 1977) in areas with no control data.

Seismic sections provide the best means of determining the onlap and toplap patterns within the depositional sequences, and well control can provide the determinations of coastal and marine facies. Each cycle is plotted on a chart in chronologic order, dating and measuring the relative rise by increments of coastal aggradation, dating any relative stillstands by the duration of coastal toplap, and dating and measuring the relative fall by the downward shift of coastal onlap.

3.5.1 *Indicators of relative sea level change*

The most reliable stratigraphic indicators of relative changes of sea level are the depositional limits of onlap. By identifying these termination patterns during seismic sequence analysis relative sea level changes may be inferred. The next sections discuss some basic concepts dealing with the stratigraphic indicators used to determine relative changes of sea level in maritime sequences as proposed by Vail *et al.* (1977a).

3.5.1.1 Relative rise in sea level

A relative rise in sea level is an apparent sea level rise with respect to the underlying initial depositional surface and is indicated by coastal onlap. It may result from: (1) sea level rising while the underlying initial surface of deposition subsides, remains stationary, or rises at a slower rate; (2) sea level remaining stationary while the initial surface of deposition subsides; or (3) sea level falling while the initial surface of deposition subsides at a faster rate. During a relative rise of sea level, where the sedimentary supply is sufficient, coastal deposits progressively onlap the underlying initial surface of deposition. The process is unable to build much above sea level, which approximates effective depositional base level. Without the rise of effective base level, the depositional site would be unable to accommodate the sediment, and each increment of coastal deposition would be terminated laterally before it could onlap the depositional surface.

A relative rise in sea level can be measured where littoral deposits onlap the underlying depositional surface; either the vertical or horizontal components of coastal onlap can be used, and are termed coastal aggradation and coastal encroachment, respectively (Figure 3.9).

During a relative rise of sea level, a transgression or regression of the shoreline, and vertical repositioning (altitude) of the sea bottom may take place and will be determined by the rate of terrigenous influx (Figure 3.9). A transgression of the shoreline is indicated by a landward migration of the littoral facies in a given stratigraphic unit, and a regression is indicated by a seaward migration of the littoral facies. A balanced terrigenous influx to relative rise will result in a stationary shoreline.

Although either a transgression or deepening of the sea bottom may indicate at least a part of a relative rise of sea level, neither can be assumed to indicate the entire rise. A transgression may be terminated by an increase in terrigenous

Figure 3.9 Transgression, regression and coastal onlap during relative rise of sea level. Rate of terrigenous input determines behaviour of shoreline during a relative rise of sea level (Vail *et al.*, 1977a).

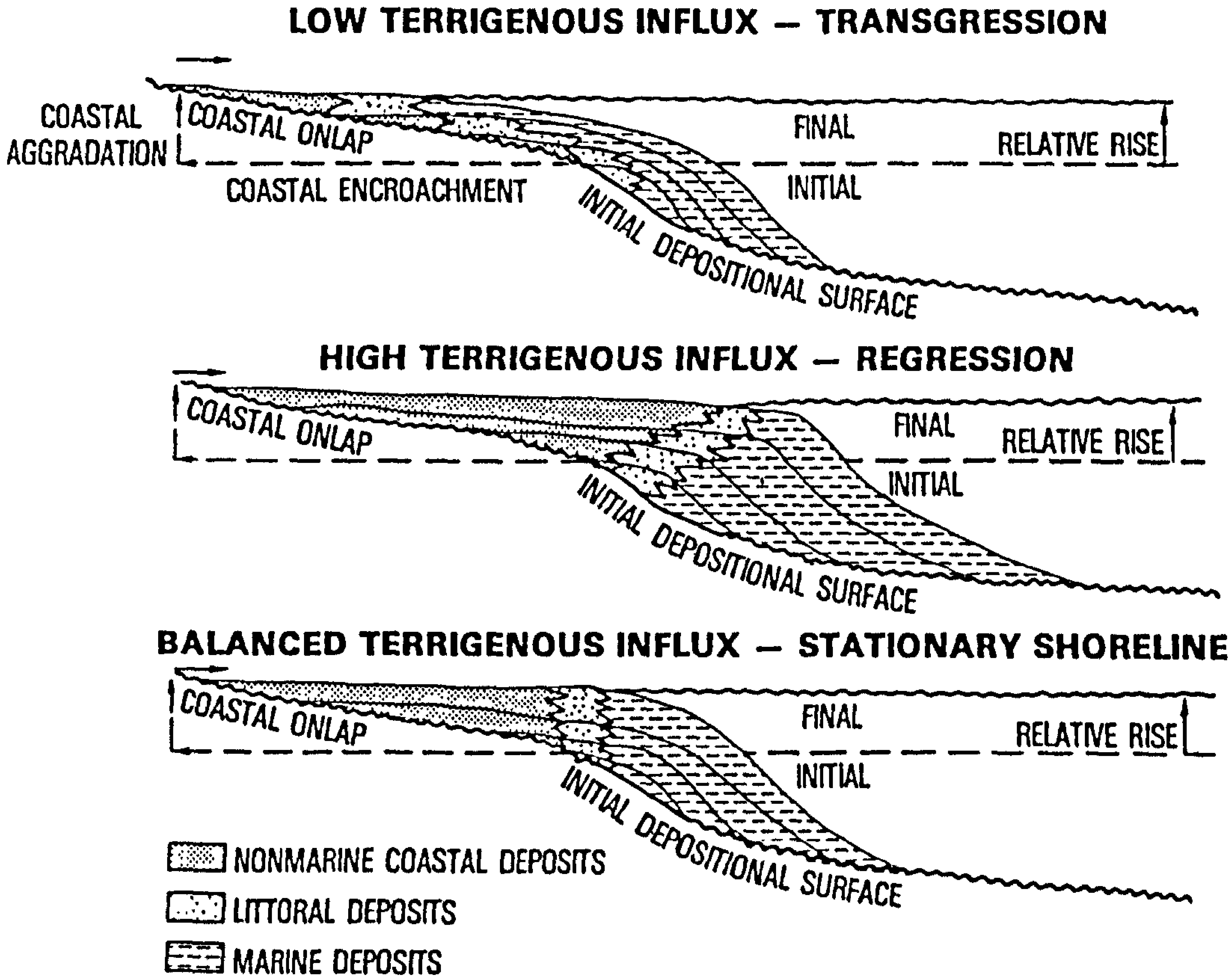
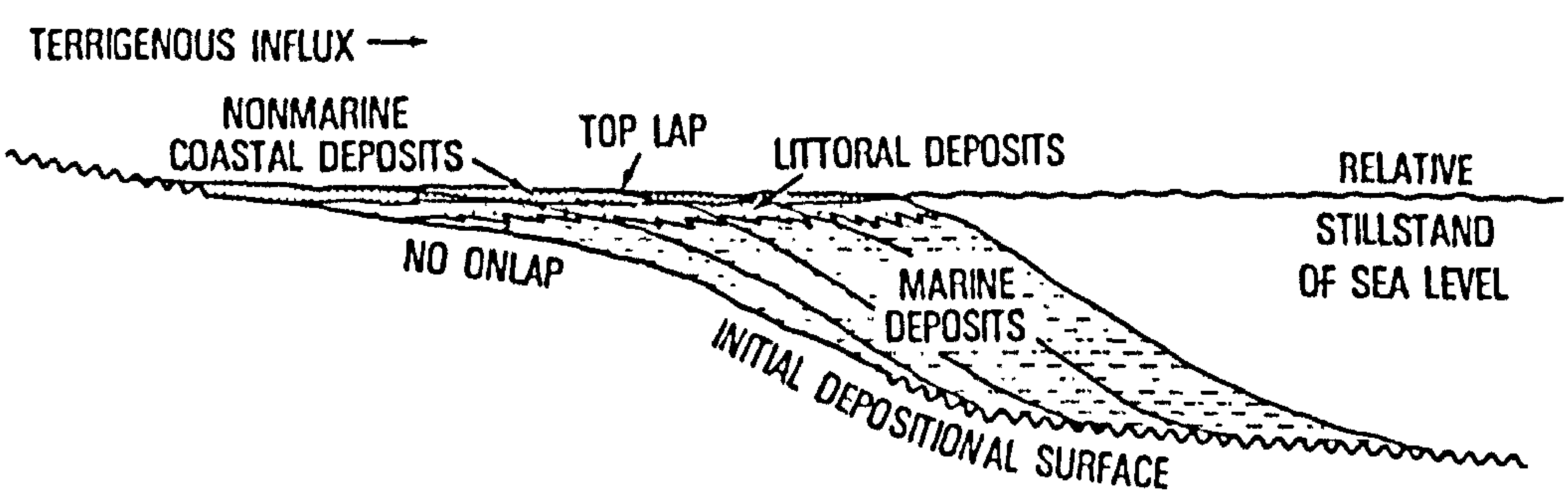


Figure 3.10 Coastal toplap indicates relative stillstand of sea level. With no relative rise of base level, non marine coastal and/or littoral deposits cannot aggrade, by-passing produces toplap (Vail *et al.*, 1977a).



clastic supply to produce a stationary shoreline or a regression while the relative rise of sea level continues.

On a seismic section through the coastal facies of a maritime sequence, a relative rise of sea level can be recognised by onlapping reflections. Transgressions and regressions of the shoreline are recognised with more difficulty by lateral changes in reflection characteristics.

3.5.1.2 Relative stillstand of sea level

A relative stillstand of sea level is an apparently constant position of sea level with respect to the underlying initial surface of deposition. It may result if both sea level and the underlying initial surface of deposition actually remain stationary, or if both rise or fall at the same rate.

During a relative stillstand of sea level, where the sedimentary supply is sufficient, deposition in the coastal environment is hindered in any attempt to build above the effective base level, and the strata are prevented from onlapping the initial depositional surface (Figure 3.10). The result is coastal toplap.

A cumulative relative rise of sea level that occurs over several million years commonly is characterised by shorter pulses of sea level rise alternating with intervals of stillstand. The cyclic pulses consisting of alternations of rapid rises and stillstands are called paracycles. They are recognised as smaller scale depositional sequences on detailed well-log or outcrop sections but commonly are too small to be recognised on "deep" exploration seismic sections.

3.5.1.3 Relative fall of sea level

A relative fall of sea level is an apparent fall of sea level with respect to the underlying initial surface of deposition, indicated by a downward shift of coastal onlap. It may result if: (1) sea level actually falls while the initial surface of deposition rises, remains stationary, or subsides at a slower rate; (2) sea level remains stationary while the surface is rising; or (3) if sea level rises while the surface is rising at a faster rate.

A downward shift of coastal onlap is a shift downslope and seaward from the highest position of coastal onlap in a given marine sequence to the lowest position of coastal onlap in the overlying sequence. In Figure 3.11a, the downward shift occurs between the highest coastal onlap of unit 5 in sequence A and the lowest coastal marine onlap of unit 6 in sequence B. The patterns of onlap indicate a relative rise of sea level during deposition of sequence A, then an abrupt relative fall to the position of unit 6 in sequence B, followed by another rise during deposition of sequence B. The above example illustrates an abrupt lowering of sea level.

A gradual fall in sea level shown on Figure 3.11b shows a series of units prograding at successively lower levels during a gradual fall of sea level.

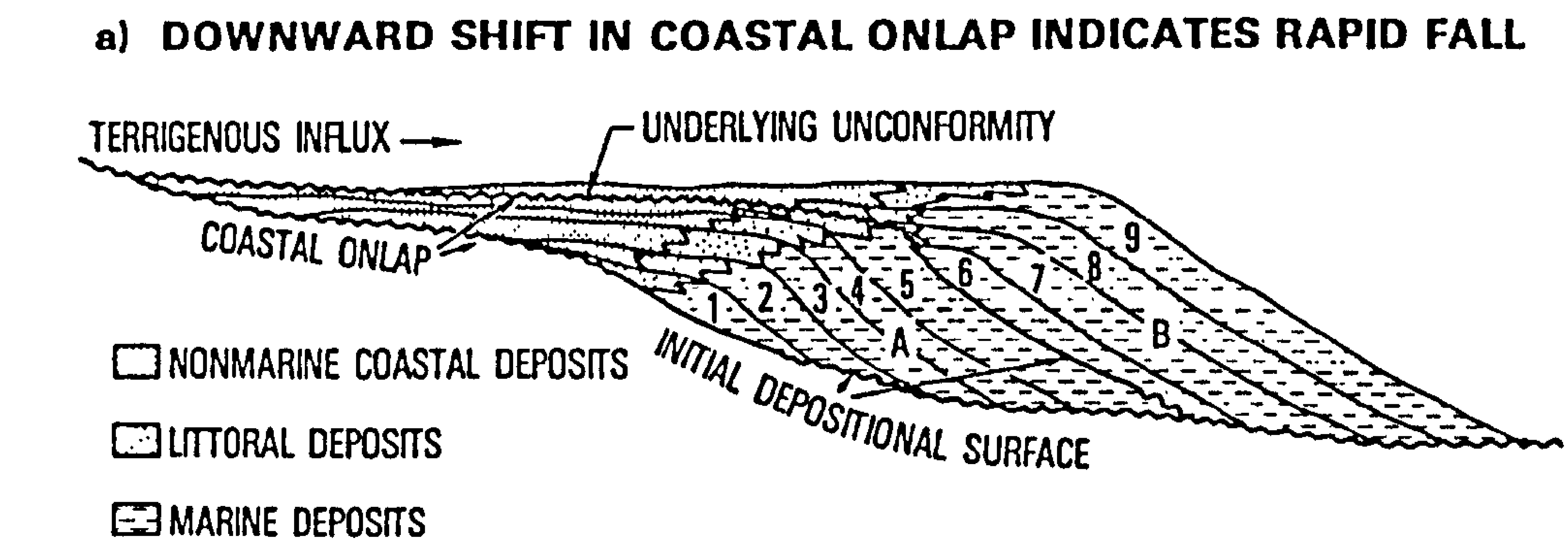
After a major relative fall of sea level, the shelf tends to be bypassed, and the area of coastal onlap may be restricted to the apex of a fan at the basin margin.

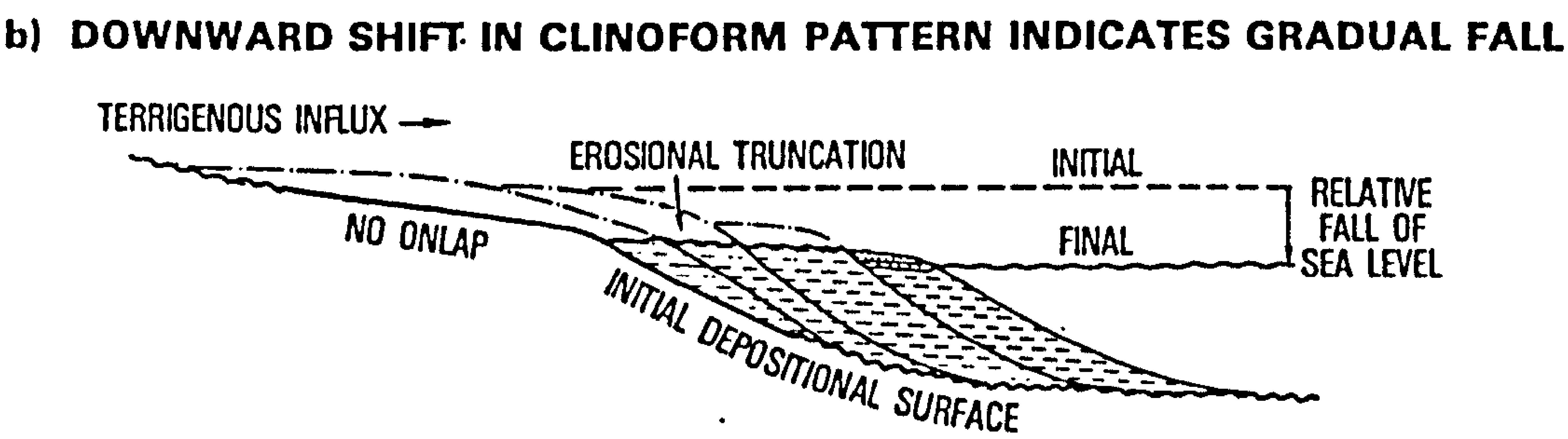
3.5.2 Modelling sea level changes

A number of workers in the field of seismic stratigraphy disagree with some of the assumptions that exist in the present theory. Modelling provides a means to investigate the controlling variables through inverting the forward model.

Kendall and Lerche (1988) developed a model to determine the sizes of the different variables needed to produce the sedimentary geometries observed within given basins. They developed a model that generated two-dimensional representations of the sediment geometry observed on dip-trending seismic lines that cross buried shelf margins. The simulation varied sedimentation, subsidence and positions of eustatic change in sea level and plotted the resulting geometries. A good match between the simulation and real data allowed some interpretation about rates of sediment accumulation and subsidence and sea level. The model produced interesting observations regarding sea level curves. The sea level curve produced by the model took into account sediment compaction and subsidence and produced a sea level excursion half that as would be interpreted using the measurement of onlap method described previously in the Vail *et al.* (1977b) models.

Figure 3.11 Downward shift of coastal onlap indicates relative fall of sea level. With relative fall of base level, erosion is likely: deposition is resumed with coastal onlap during subsequent rise. a) Downward shift in coastal onlap indicates rapid fall. b) Downward shift in clinoform pattern indicates gradual fall (Vail *et al.*, 1977a).





Steckler *et al.* (1993) modelled stratigraphic sequences to assist in the understanding of the sedimentary response to sea level change. As implied in the Vail *et al.* (1977b) model, they found sequence geometry to be most sensitive to sea level, but they also found other factors such as subsidence rates and sediment supply capable of producing similar changes and concluded that further work was needed to understand quantitatively the role of sea level and the tectonic and sedimentary processes controlling sequence formation and influencing sequence architecture.

Wood *et al.* (1993) modelled the effects of a base (sea) level change in a flume. They found that the rate of base level change influences the number of incised (developed by fluvial erosion) valleys that develop on the shelf and slope, the thickness, character and geometry of the valley fill and delta deposits, and the preservation potential of fluvial deltaic and slope deposits.

3.6 Problems associated with the use of seismic stratigraphy

The application of seismic stratigraphic methods should be independent of space and time (Posamentier *et al.*, 1992) as there are no such constraints in its definition. The theory of sequence stratigraphy has, according to a number of authors, been successfully tested and applied to "shallower" Quaternary seismic data (high frequency source, high resolution) that ranges from sequences that are typically tens of metres thick (Chiocci, 1994; Chiocci *et al.,* 1991; Hernàndez-Molina *et al.*, 1994), to direct observation of sequences that are a few decimeters thick occurring in natural fan deltas (Posamentier *et al.*, 1992) and created in flume experiments (Wood *et al.*, 1993). Sequence stratigraphic theory has also been theoretically modelled (Nummedal *et al.*, 1993).

These tests of seismic stratigraphy have concentrated on the identification of sequences and systems tracts and their use in sea level analysis and to a much lesser degree, if at all, on seismic facies analysis. The locations selected as test sites are predominantly on sloping continental margins in the Mediterranean Sea in deep water (typically in water depths of 30m, occasionally in water depths around 100m) or these tests have been undertaken in 'unnatural' environments.

Although sequence stratigraphic concepts have achieved widespread acceptance (Posamentier and James, 1993), a number of authors suggest caution when applying the theory in certain circumstances and question some of the assumptions of the fundamental theory. Along with its acceptance has come misunderstanding regarding its application. The most important misunderstanding according to Posamentier and James (1993) is its erroneous use as a rigid template instead of tool or approach. The key to proper application of these concepts is to understand the concepts, the first principles involved, and then tailor the sequence model to account for local factors such as tectonics, sediment flux and physiography.

3.6.1 Sequence stratigraphy

Thorne (1992) conducts an in-depth analysis of the interpretive nature and implied assumptions (some 24) of seismic sequence stratigraphy using, what is considered as the most recent authority, the Vail (1987) model. The observations of Thorne (1992) are summarised in his work by the production of a "data check list" which, by comparison with a seismic data set, helps to provide a qualitive assessment of the level of confidence in the interpretation. The interpretive nature and assumptions in the use of the Vail (1987) model identified and discussed by Thorne (1992) will be briefly summarised here.

3.6.1.1 The interpretive nature of seismic sequence stratigraphy

Vail (1987) identifies seven steps for seismic stratigraphy.

Step 1 - The identification of onlap, downlap, toplap and truncation "signals" in the seismic data. This is considered as a subjective step as the "signal" is that part of the recorded signature that is considered by the interpreter to be data and not noise.

Step 2 - Delineation of surfaces of chronostratigraphic significance on which onlap, downlap, toplap and truncation can be "consistently" correlated through the seismic grid. This step is also considered to be interpretive as it relies on what the interpreter judges to be "consistent". Consistency relates to the identified surface tieing throughout a seismic grid and/or the arrangement of signals (onlap etc.) along this surface having a degree of consistency.

Steps 3 and 4 - The break out of a relative time history of deposition and inference of a sea level history of deposition respectively. Once steps 1 and 2 are completed steps 3 and 4 can be determined uniquely. However, gaps in the first two steps will prevent a unique third and fourth level interpretation. It has been demonstrated that a successful interpretation is often best achieved by a reverse order interpretation i.e. the recognition of a third or fourth level pattern and checking that the supporting lower level features are consistent with this pattern.

Steps 5 and 6 - The integration with other studies such as seismic facies or velocity analysis and well-log calibration and inference of the likely distribution of source, seal and reservoir facies, these are not considered by Thorne (1992).

3.6.1.2 Implicit assumptions of seismic stratal geometry identification

Thorne (1992) identifies four assumptions (A1-A4) implicit in the identification of seismic stratal geometry.

A1: "Problems with seismic imaging do not seriously lower the stratal geometry signal to noise ratio."

As data quality reduces, stratal geometries may be picked by visual averaging of packages of poorly resolved reflectors.

A2: "Visual extrapolation of reflection trend surfaces provides an accurate and precise estimate of reflection termination locations."

The limits of seismic resolution often require a certain amount of visual extrapolation to approximate the position of reflection terminations. This will also be complicated by elongated pulses as discussed by Tucker and Yorston (1982). Misinterpreted termination locations can lead to an inaccurate overall interpretation.

A3: "The classification of any reflection termination into the four primary types can be done, with few exceptions, unambiguously."

Problems sometimes exist as to the correct identification of termination patterns. Vail (1987) recognises that truncation may also be described as apparent truncation. This occurs where the identification of what is a true erosive unconformity is confused with what seismically appears to be one due to thinning. Vail (1987) also uses the term baselap where the reflection pattern cannot be classified as downlap or onlap due to depositional tilting.

A4: "The use of higher levels of interpretation to help identify a consistent stratal geometry signal allows a "best guess" interpretation to be made."

As previously mentioned the identification of primary stratal geometry signals often makes use of reverse interpretation using higher levels of interpretation to validate the lower levels of interpretation. This procedure involves a certain amount of circular reasoning; the assumption is made that this methodology allows a best educated guess interpretation.

3.6.1.3 Sequence stratigraphy: the forward and inverse models

Sequence stratigraphic analysis is an "inverse model" of seismic data. It is a model because it results in a geological model of the geologic history of sedimentation, subsidence and sea level. It is an inverse model because this time history is inferred, or inverted from the seismic data. An inverse model is based on a corresponding forward model. Vail (1987) outlines a forward model for sequence stratigraphy describing stratigraphic processes of stratal geometry generation.

The implicit assumptions of the forward model describing patterns of infilling sediment are referred to as B1-B10. The assumptions of the inverse model that allow an interpreter to work backwards from the seismic data to an inferred depositional history are referred to as C1-C7, and the assumptions of the global correlation model for use of sequence analysis as a chronostratigraphic tool are referred to as D1-D3.

B1: "The arrangement of sediment source terrains, drainage and subsidence depocenters creates a well-defined directionality to basin infill."

Sequence stratigraphic interpretation depends on the identification of seismic geometries as characteristically strike versus dip features. It is assumed that basin infill can be described in terms of well-defined directions of net sediment transport. However, an ideal arrangement of source terrains and subsidence depocenters is not always present in nature. The trend of subsidence may not be parallel to the trend of source terrains, or multiple sediment sources may exist in different directions.

B2: "The topographic equilibrium surface controlling accommodation is approximately at sea level."

This assumption makes the fundamental control of accommodation sea level variations. However, as discussed by Thorne (1992), sediment accommodation is complicated by a number of other factors. Also, as far as sequence analysis is concerned, patterns of sediment infill are assumed to be independent of differences in the rate of sediment input or the climatic, oceanic or earthquake climate from area to area or from one sequence to the next.

B3: "Stratal geometries are controlled by the rate of change of accommodation."

Stratal geometries are assumed to reflect, primarily, the rate of change of accommodation, not simply accommodation. The emphasis on the rate of change has a pragmatic basis: that is, uniform deposition rates that characterise sedimentation under time invariant accommodation do not create interpretable seismic geometric features.

B4: "The position of the fall line is approximately given by the location where the rate of tectonic subsidence equals the rate of eustatic sea level change (the equilibrium point of Posamentier *et al.*, 1988)."

Much of seismic sequence stratigraphy is based on analysis of patterns of coastal onlap that record the successive positions of the fall line (the sourceward terminus of net deposition). Assumption B4 describes a sedimentological system that is always in equilibrium. This assumption implies that sedimentation responds immediately to the instantaneous rate of change of accommodation at basin positions near the fall line. The assumption is also made that the fall line is always located approximately at the equilibrium position.

The assumption that the fall line is approximately at the equilibrium position allows the Vail (1987) model to infer time correlations between sedimentary response and accommodation. For example, the assumed immediate response of the fall line implies that coastal onlap responds to accommodation change ($\dot{A}(t)$) with little or no time distortion. This assumption also allows Vail *et al.* (1977b) to distinguish type 1 or type 2 unconformities on the basis of the relative rates of subsidence and eustatic sea level fall at the depositional shelf edge. If the rate of eustatic sea-level fall is greater than the rate of subsidence at the shelf edge, then the shelf edge lies in the zone of falling relative sea level sourceward of the equilibrium position. Hence, from assumption B4 the fall line lies basinward, sediments onlap the slope and a type 1 unconformity must extend out to the depositional shelf edge.

The question of immediate response has no simple answer. An answer for one temporal and spatial scale may not be appropriate for another.

B5: "No deposition can occur until all accommodation to the sourceward direction has been filled."

Accommodation defines the limits of potential sedimentation. The simple assumption stated by B5 would result in an unrealistic infill pattern of vertical beds. This can be corrected by restating the principle of accommodation as: accommodation is infilled by progradation (except in deep-marine sedimentation). Assumption B5 is important in the Vail *et al.* (1977b) placement of most slope and basin deposits in the lowstand system tract. Slope or basin deposits, it is argued, cannot occur if there is available accommodation on the shelf or landward generally available during high stand time.

B6: "Bypass of foreset beds implies drainage incision of topset beds and *vice versa.*"

An idealised type 1 sequence boundary is defined by: (1) incision into topset beds, (2) onlap of overlying strata out into the basin and (3) downlap or bidirectional downlap by base of slope or basin deposits. The latter two of these features imply that, during sequence boundary formation, the slope or incised slope acts as a zone of sediment bypass.

Assumption B6 provides a genetic relationship between these three defining elements by making a necessary condition for slope (foreset) bypass drainage incision of the topset beds. The use of assumption B6 makes the three defining features independently diagnostic of a type 1 sequence boundary.

B7: "Clastic deep-water sediments are primarily point sourced by submarine canyons."

The Vail (1987) model describes the lowstand system tract primarily as a canyon fan system. However, other erosive shelf and slope features can also be important sources for deep water sediments.

B8: "Submarine canyons originate when accommodation reaches its maximum rate of fall."

Vail (1987) hypothesises that the origin of submarine canyons can be genetically linked to subareal exposure caused by relative sea level fall. However other causes of canyons may exist.

B9: "Variations in the volume of sediment density flows respond to changes in accommodation to produce three stages of basin fill."

The genetic elements of the lowstand system tract model of Vail (1987) are derived from Mutti (1985). In this work, a conceptual model is introduced suggesting that variations in the volume of sediment density flows respond to variations in accommodation in such a way as to produce three stages of basin fill: (1) a channel-detached sand lobe formed by large volume turbidity currents, (2) a channel attached sand lobe formed by medium-volume turbidity currents, and (3) a channel levee complex formed by small volume turbidity currents. Vail (1987) assumes that these stages of the Mutti (1985) model correspond to: (1) a basin floor fan, (2) a slope fan, and (3) a prograding complex.

B10: "Variations in sediment supply do not in themselves cause significant changes in accommodation rates."

It has long been recognised that sedimentary loads are isostatically compensated by flexural bending of the lithosphere which will produce more accommodation. It is unclear under what conditions this feedback between sedimentation and accommodation can cause fundamentally different sequence geometries than predicted by the Vail (1987) model. During relatively constant sedimentation, flexural and tectonic subsidence sum to produce net subsidence. Relative sea level is then a combination of net subsidence and eustasy

C1: "A seismic reflection, for all practical purposes, is a time line."

This is considered to be the most widely recognised assumption of seismic stratigraphic interpretation. It allows: (1) the geometry of depositional stratal surfaces to be inferred from corresponding reflection patterns, and (2) provides a chronostratigraphic tool for correlation. Although assumption C1 is widely accepted it has been shown by Thorne (1992) to be erroneous in some cases.

C2: "Sequence stratigraphic analysis is independent of spatial scale."

Thorne (1992) cites that there is confusion in the application of the seismic stratigraphic technique. This is attributed to the fact that the analysis of patterns does not depend on spatial scale. Although these purely geometric aspects are independent of spatial scale, it is not clear if inferences of physical processes require that the scale of the problem be defined. The use of assumption C2 implies that scale considerations will not invalidate resultant seismic stratigraphic interpretations.

C3: "Sequence stratigraphic analysis is independent of temporal scale."

The seismic expression of relative sea level cycles from 100,000 years to 10 Ma have been interpreted with the same methodology.

C4: "Sedimentation geometries can be mapped onto a grid without prior knowledge of palaeogeographic dip and strike directions."

One of the assumptions of seismic stratigraphic interpretation is that direction can be determined by mapping sedimentation geometries on a seismic grid. It is assumed that in this process depositional dip lines will not be misinterpreted as showing characteristic strike orientated features.

C5: "Sedimentation geometries can be interpreted as a response to a single harmonic sine curve function for rate of accommodation change Å(t)."

Vail *et al.* (1977b) recognise that sea level (accommodation) changes form a hierarchy of cycles, in that upon one long term rise and fall of sea level are imposed other, higher frequency events of sea rise and fall. This multiharmonic nature of the accommodation function A(t) and its time derivative Å(t) are not explicitly dealt with by the Vail *et al.* (1977b) method.

C6: "Sedimentation can be put into a chronostratigraphic framework by assuming only one depocentre occurs at a time."

A unique interpretation can only be achieved if this assumption is assumed to be satisfied. The problems generated by multiple centres of deposition on a seismic section would render the Vail (1987) interpretation ineffective.

C7: "Sediment accumulation is characterised by large changes in accumulation rate over relatively short lateral distances."

The Vail (1987) model relies on delineating downlap and onlap surfaces rather than intervals and assumes therefore, that sediment accumulation is characterised by large changes in accumulation rate over short lateral distances.

3.6.1.4 Implicit assumptions of the global correlation model

The Exxon sea level cycle chart (version 3.1B, Bally, 1987) is constructed using three assumptions D1-D3.

D1: "The magnitude and timing of the accommodation function Å(t) can be accurately estimated by sequence analysis of observed stratigraphy."

D2: "The accommodation function Å(t) determined by such analysis is synchronous on a global basis."

D3: "Globally synchronous variations of accommodation Å(t) are controlled by the rate of change of sea level."

There are four measures of accommodation on the Exxon cycle chart: (1) the global onlap chart which plots relative landward to basinward positions of the fall line, which by assumption B4 is directly related to accommodation; (2) sequence boundaries are identified as type 1 or type 2 unconformities, a type 1 sequence boundary implying a greater rate of accommodation decrease than a type 2; (3) the timing of condensed horizons within each sequence is indicated.

The final measure of accommodation (4), the eustatic sea level curve, is largely derived from the first three measures; this however assumes that the changes in accommodation documented by these three measures, after correcting for the effects of local subsidence, represent the effects of eustasy.

An assessment of the reliability of the Exxon cycle chart is, according to Thorne (1992), difficult to make due to many complicating factors, the most critical problems being that local tectonic subsidence can never be independently measured allowing only the timing of sea level changes to be made not measures of absolute magnitude of change. Other problems involve problems of seismic resolution in determining the timing of sequence stratigraphic cycles.

The accommodation function should vary within basin and from basin to basin because of local variations in tectonic subsidence. The Exxon global chart should, therefore, be constructed from a global average in which variations due to subsidence have been accounted for by tectonic subsidence analysis.

In any area, using any particular set of seismic data, some of the 24 assumptions discussed above may be valid and others questionable. Thorne (1992) created an "assumption checklist" (Table 3.3) to provide a qualitive assessment of the level of confidence in the seismic interpretation. If the answer is no to all questions then the interpretation has a high level of confidence. An answer of yes or maybe to any of the questions lowers the confidence of the interpretation based on the Vail (1987) model.

3.6.2 Seismic facies

Stoker *et al.* (1992) examine problems associated with seismic facies analysis of Quaternary sediment using a number of examples from the North Sea. The widely held expectation that laterally persistent, acoustically homogeneous seismic units are associated with consistent lithologies and geotechnical properties (a view fundamental to seismic facies analysis) is examined by comparisons being made between acoustically unstratified and acoustically layered deposits together with groundtruth data. The belief that lateral or vertical changes in seismic texture necessarily indicate a change of sediment type or character is also examined. Stoker *et al.* (1992) proved that these relationships are not infallible and their data suggests a variable relationship between acoustic texture and lithology exists in places. They conclude that successful seismic facies analysis of Quaternary sediments is dependent on the integration of seismic with other subsurface information.

3.6.3 Considerations of sea level

As previously mentioned, seismic sequence stratigraphic concepts may be applied in two different ways. Firstly they can be used in the construction of age models of given stratigraphic successions which can be correlated with the global cycle chart published most recently by Haq *et al.* (1987). The other application involves lithology prediction based on the interpretation of cyclicity of the rock record.

Table 3.3 "Assumption Checklist" for the Vail (1987) seismic sequence stratigraphic stratal geometry identification, forward, inverse and global correlation models (Thorne, 1992).

A: Example assumption checklist for seismic stratal geometry identification

1) Is the stratal geometry "signal-to-noise" ratio too low to allow interpretation?

2) Are the locations of reflection termination poorly resolvable given the quality of the seismic data?

3) Has post depositional tilting or structure made the distinction between downlap and onlap meaningless? Has an inconsistent distinction between toplap and truncation been made? Does an interpreted truncation surface show little signs of relief created by erosion?

4) Is there an overreliance on higher levels of interpretation based on conceptual and numerical models of sequence geometries in the delineation of stratal geometry signals? Is there a danger that interpretations are "model driven"?

B: Example assumption checklist for use of the Vail (1987) forward model

1) Is the arrangement of sediment source terrains and subsidence depocenters complicated? For example, the trend of subsidence may not be parallel to the trend of source terrains, multiple sediment sources terrains may exit in different directions, or the source and sinks of sedimentation may be too close to each other to define a sourceward and basinward direction.

2) Are shallow water conditions unlikely to extend out to the topset/foreset rollover? Are significant changes in sedimentation rate, sediment type, wave climate, etc. likely to produce changes in accommodation that affect sequence geometry?

3) Are basin subsidence rates very low so that the magnitude of accommodation becomes more important then the rate of change of accommodation? Are basin subsidence rates very high so that the rate of change of sediment supply becomes more important then the rate of change of accommodation.

4) Are accommodation cycles too fast to allow the fall line to move to the location where the rate of tectonic subsidence equals the rate of eustatic sea level change?

5) Is a significant amount of sedimentation due to *in-situ* production? Are conditions inappropriate to create a topset, foreset or bottomset morphology at the appropriate scale of study?

6) Are other processes controlling slope bypass other than drainage incision? Are the three defining elements of a sequence boundary (incision into topset beds, onlap of overlying strata and downlap or bidirectional downlap by base-of-slope or basin deposits) difficult to correlate on the seismic data?

7) Do other erosive features exist besides canyons? Do geologic conditions in the study area suggest that the area may not be canyon prone?

8) Are other geologic scenarios for canyon formation (e.g. transgressive reworking of a lowstand shelf edge delta or catastrophic failure of the slope due to mass failure) particularly appropriate for the study area?

9) Do observed geometries of deep-basin fill poorly fit the idealised Vail-Mutti model?

10) Have variations in sediment supply caused significant changes in accommodation rate due to flexural subsidence? Is there any indication of a flexural bulge? Has sediment loading triggered salt or growth fault movement?

C: Example assumption checklist for use of the Vail (1987) inverse model

1) Are seismic reflectors locally parallel to bedding but regionally not correlatable in time?

2) Is the predicted facies distribution based on the sequence geometry inappropriate for the spatial scale of the studied deposits? Have misleading analogies been drawn between characteristic deposits at differing spatial scales?

3) Is the predicted facies distribution based on the sequence geometry inappropriate for the temporal scale of the studied deposits? Have misleading analogies been drawn between characteristic deposits at differing temporal scales?

4) Are paleogeographic dip and strike directions difficult to determine by characteristic sequence geometries? Do these directions vary locally within the grid?

5) Have characteristically different sequence geometries been created by a sawtooth or multiharmonic sea level curve? Can tectonically created megasequence boundaries be separated from the cyclicly created sequence boundaries?

6) Are reinterpretations of depositional history possible if it is assumed that more than one depocenter can occur at one time? Are sedimentation processes likely in the particular study area that may cause multiple depocenters (e.g. multiple sediment supply sources, local subsidence depocenters)?

7) Is sediment accumulation characterised by relatively small changes in accumulation rate over large lateral distances causing poor delineation of downlap and onlap surfaces?

The construction of age models assumes that eustatic change varies with a higher frequency and amplitude than tectonics. However Cloetingh (1988) reports that local tectonic change can, locally, vary at frequencies equivalent to sea level change. This would restrict the world wide application of the Haq *et al.* (1987) model to the Atlantic-margin stratigraphy upon which it is based. Steckler *et al.* (1993) also suggests caution when estimating sea level variations from sequence stratigraphic data without a better understanding of all the processes that take place on the continental shelves.

Thorne (1992) states that the Exxon global sea level chart should be constructed from a global average in which variations due to subsidence have been accounted for by global tectonic subsidence analysis. Practical considerations however make this impractical. However, if uncorrected onlap curves from around the world generally show a particular event synchronous within biostratigraphic resolution, then the occurrence of a synchronous eustatic event is noted on the global cycle chart. Subsequent analysis may however reveal corrections need to be applied to any part of the cycle and hence it should be considered as ongoing work.

3.7 Discussion and conclusions

Following the previous description of seismic stratigraphy and discussion of the application and reliability of the seismic sequence and facies analysis of Quaternary sediments it should be noted that there are a number of differences in the seismic stratigraphy methodologies adopted in this project and the methodologies cited in the literature examples. Some of the major differences are identified below.

1) In all analyses of sequence or facies analysis discussed in the literature the water depths at the study sites typically exceeded 30m.

2) The examples from the Mediterranean (Chiocci, 1994; Chiocci *et al.*, 1991; Hernàndez-Molina *et al.*, 1994), although limited to the Quaternary cover, surveyed sedimentary units of thickness typically greater than 40m, units of great lateral extent, and units forming in depositional environments of apparently low energy. The sediments studied and reported in the literature had typically low acoustic attenuation allowing good seismic penetration.

3) Facies analysis discussed for the Mediterranean examples underwent only limited physical testing, facies determination being mainly limited to inferences on environmental information from systems tracts. Facies, where "proven" with reference to ground truth data, were limited by relatively shallow surficial sampling techniques.

4) In all descriptions in the literature of high resolution facies analysis of Quaternary sediments reference appeared only to have been made to analogue data i.e. interpretation presumably based on analysis of analogue data.

In contrast, the work presented in this project aims to test seismic stratigraphic concepts for very shallow (including intertidal) waters. The discussion will be based on both analogue and digital data interpretation, with digital data used to provide displays of instantaneous attributes that can be used to assist in seismic facies analysis and can potentially be used to extract quantitative geotechnical information. In this way it is to be hoped that the analysis may lead to a more confident stratigraphic interpretation of the seismic data.

CHAPTER 4
The Cone Penetration Test (CPT)

4.1 Introduction

The case studies that follow this chapter include, in places, discussion of geotechnical data and the potential for using seismic data to infer physical characteristics of sediments. Chapter 7, a case study from Liverpool Bay, will illustrate examples of and allow a discussion of potential uses of CPT data in calibrating seismic data. The method of data collection and the interpretation of a CPT is not always self-evident and this chapter has therefore been included as a reference to the use and potential of the CPT and potential seismo-acoustic property interrelations.

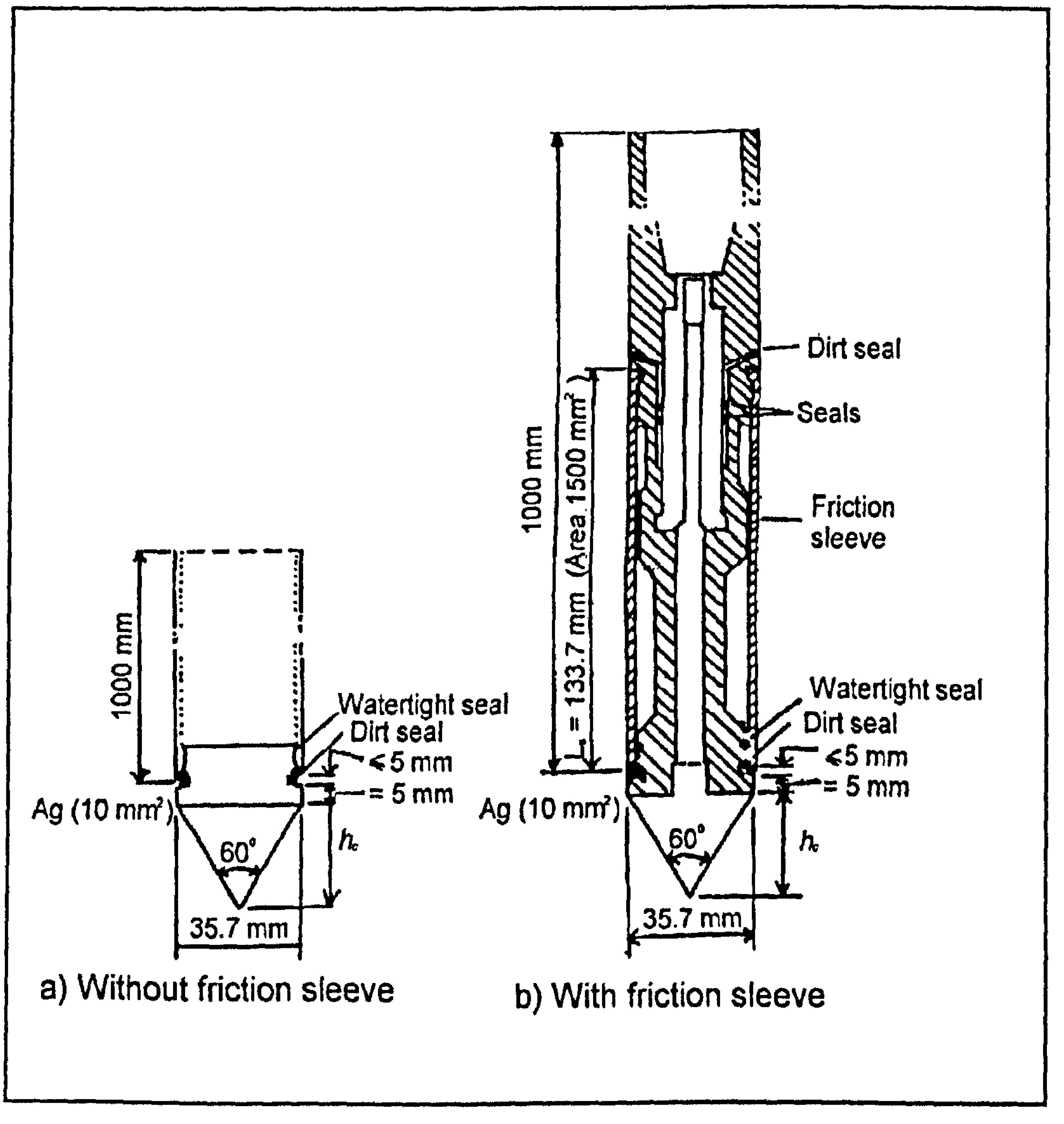
The cone penetration (or Dutch Cone) test is a popular *in-situ* site investigation and geotechnical design technique (Robertson & Campanella, 1983). As a geotechnical logging tool the technique is unequalled with respect to the delineation of stratigraphy (hence its link to seismic data) and continuous rapid measurement of parameters like bearing capacity and friction.

In the cone penetration test, a cone (Figure 4.1) on the end of a series of rods is pushed into the ground at a constant rate, and continuous or intermittent measurements are made of resistance to penetration of the cone q_c. If required, measurements can also be made of resistance of a surface sleeve (sleeve friction f_s) (Meigh, 1987). With the additional incorporation of pore pressure measurement, the CPT (piezocone) becomes an even more powerful tool for soil analysis.

The role of the CPT has, according to Meigh (1987) and Schmertmann (1978), a number of applications which include:

1 - Evaluation of site or route stratigraphy: the types, layering, uniformity, continuity, permeability and strength of the various soils encountered.
2 - Interpolation of ground conditions between control boreholes.
3 - Evaluation of engineering parameters of the soils and assessment of bearing capacity and settlement.

Figure 4.1 An electric penetrometer tip conforming to reference test requirements (after Meigh, 1987). Ag = area of groove at base of cone (mm^2). h_c = height of cone (>31.0mm <31.3mm).



4 - Control of the removal of 'poor' soil materials, and the proper placement and compaction of stabilised soils.

5 - Design of slopes and fill.

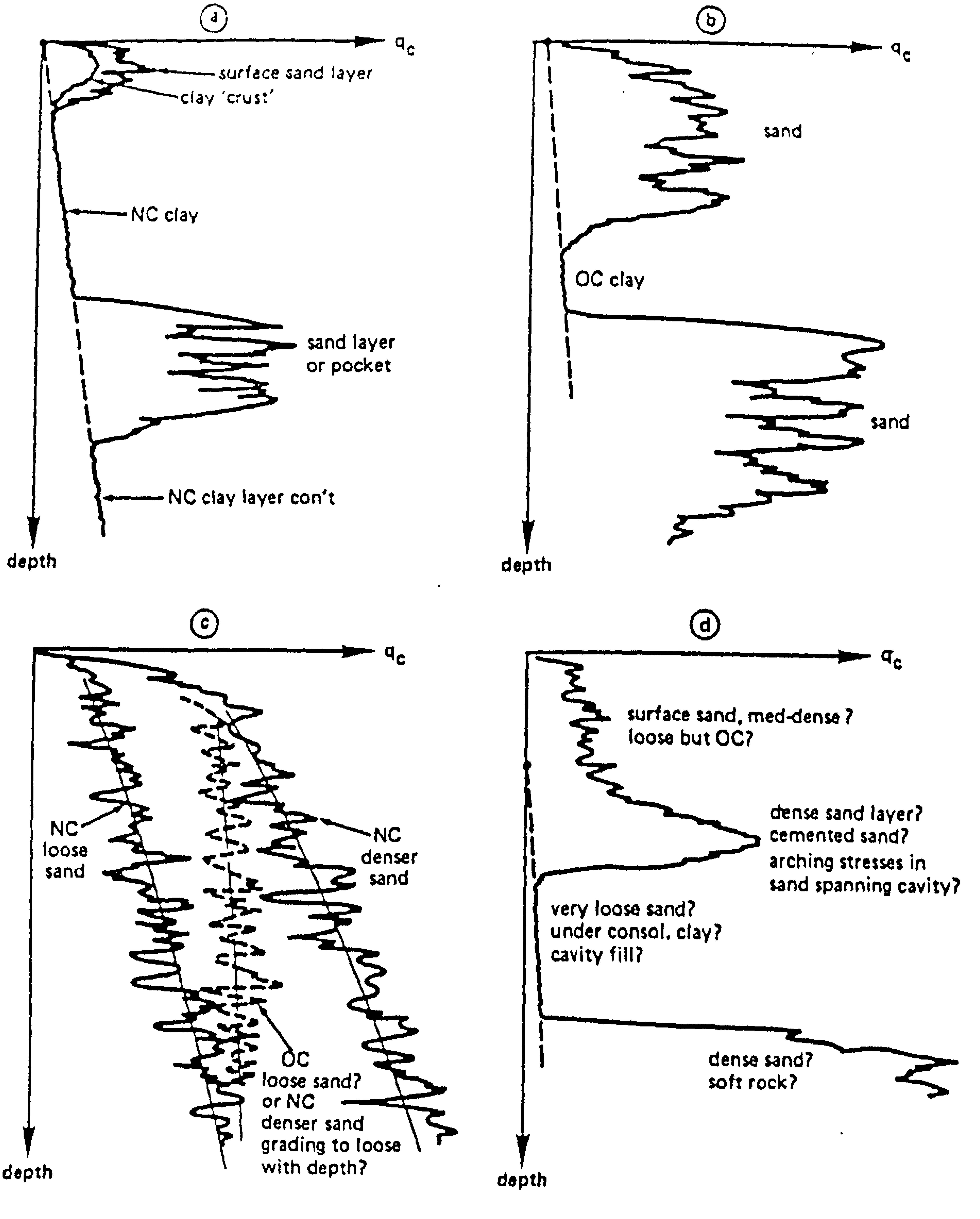
The identification and assessment of engineering parameters and soils is achieved by means of empirical correlations between soil types and the ratio of local side friction to cone resistance (skin friction ratio) considered in relation to the cone resistance. The additional measurement of pore pressure with the piezocone also assists in identifying soil type and properties.

4.2 Use of CPT results

During a cone penetration test complex changes in stresses, strains and pore pressure occur around the cone tip. The interpretation of these changes allows empirical correlations to be made to obtain required geotechnical parameters. One of the important uses of the CPT is to delineate the soil profile, i.e how the geotechnical and lithological parameters change with depth. Cone penetration tip resistance is influenced by the soil properties ahead and behind the tip. Chamber studies by Schmertmann (1978) showed that the tip senses an interface between 5 and 10 cone diameters ahead and behind. The distance over which the cone tip senses an interface increases with increasing soil stiffness. Since stiffness increases with increasing overburden pressure, the distance over which the cone tip senses an interface tends to increase with depth. For interbedded relatively shallow deposits, the thinnest stiff layer for which the measured cone bearing represents a full response (i.e. q_c to reach full value characteristics for the soil within the layer) is about 10-20 cone diameters. This leads to some imprecision in locating soil interfaces, and it has some effect on the evaluation of engineering parameters. For example, cone resistance may not reach its full value in a sand layer bounded by soft clay layers if the sand layer is less than about 0.7m thick.

Figure 4.2 illustrates a simplified form of different q_c profiles and suggests possible interpretations. As illustrated by parts (a) and (b) clays have, in general, considerably lower q_c than sands due to a lower effective angle of shearing resistance (ϕ') and pore pressure effects. Part (c) illustrates that a normally consolidated sand (i.e. sand which, at no time in its history, has been subjected to pressure greater than its existing overburden pressure) would increase in q_c with

Figure 4.2 Simplified examples of q_c log profiles showing likely and possible interpretations for soil types and conditions (Schmertmann, 1978).



depth while an overconsolidated sand (i.e. sand which, during its history, has been subjected to pressure greater than its existing overburden pressure) varies little. Causes of overconsolidation include the erosion of material that once existed above the sand or the removal of ice) might have an approximately constant q_c with depth from additional q_c due to additional lateral stress from the overconsolidation. The overconsolidated state might be confused with a normal state for the case when density increases with depth. This illustrates a fundamental uncertainty when interpreting q_c profiles: increased stress and increased density produce similar q_c effects. Part (d) suggests different possible interpretations for, amongst other things, an unusually high q_c layer over a much weaker layer (Schmertmann, 1978).

As further illustrated in parts (a) and (b), the passage of the penetrometer tip probably does not produce a smooth, continuous failure phenomena. More likely, penetration produces a succession of failures which involves a slip, a recovery of cone bearing strength and/or pushrod friction with simultaneous pushrod advance followed by another slip etc.

In clays this succession may occur so rapidly that the q_c profile appears relatively smooth. However, in sands, and particularly dense sands, a pattern may also result from layering and variations in sand densities and perhaps lateral stresses inherent in the variable, intermittent deposition of sand deposits (Schmertmann, 1978).

A broad identification of soils can be obtained from the magnitude of the cone resistance, and more specifically from their friction ratios (i.e. the ratio of local side friction to cone resistance) at the same level, considered in relation to the cone resistance.

The continuous monitoring of pore pressures during cone penetration can significantly improve the identification of the soil profile. Particularly relevant is that pore pressure responds to the soil type in the immediate area of the cone tip.

The permeability, compressibility, saturation and dilatency behaviour of the soil penetrated, the method of penetration and the shape of the penetrometer tip control the excess hydrostatic pore pressures developed in the immediate vicinity of the penetrometer tip during its advance. Water pressures govern effective stresses and, therefore have an important influence on the measured q_c and f_s.

Soils with positive dilatency (expanding structure) will decrease water pressure when subjected to shear strain. In the same way soils with negative dilatency (contracting structure) will increase water pressure with the application of shear strain. Positive dilatency is usually associated with dense or strong soils and negative dilatency with loose and weak soils (Schmertmann, 1978). Thus, soil dilatency and the consequent water pressure effects make weak soils appear weaker and strong soils appear stronger in the CPT than their strengths fully drained.

However, with higher confining pressure the tendency for positive dilatency decreases in all particulate materials. At very high confining pressures laboratory triaxial tests show only negative dilatency.

Present data indicate negative changes in excess hydrostatic pore water pressure effects may be very important in dense soils with a coefficient of permeability $(k) < 10^{-4}$ cm/s, and that the effect might be important under high hydrostatic water pressures (as in the offshore environment) because greater negative changes in excess hydrostatic water pressure can develop before cavitation occurs (Schmertmann, 1978).

At present little is known about pore pressure effects on q_c and f_s in the field. The greater dependence of q_c on radial effective stress suggests pore pressure effects may be very significant.

A scheme for the identification of soils when using a cone conforming to reference tip geometry (Figure 4.1) by Douglas and Olsen (1981) is presented in Figure 4.3(a) and a simplified working version by Robertson and Campanella (1983) is presented in Figure 4.3(b). Because of some of the problems with using CPTs to identify soil, Meigh (1987) recommends that checks of CPT data be made against one or more reference boreholes, preferably with continuous sampling and every opportunity be taken to derive correlations based on local conditions.

Figure 4.3a Soil classification chart for standard electric friction cone (after Douglas and Olsen, 1981); 1 bar = 100kPa.

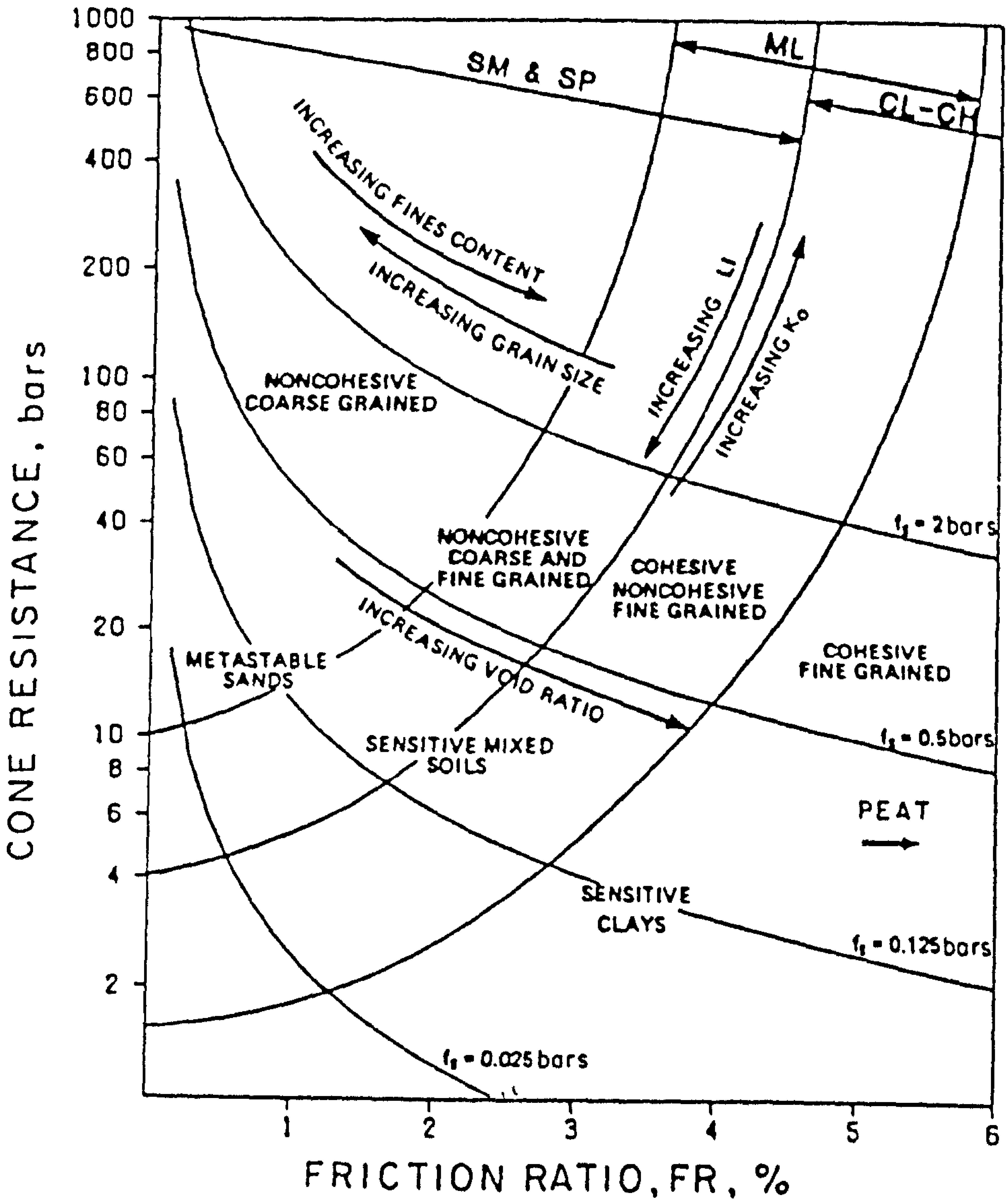
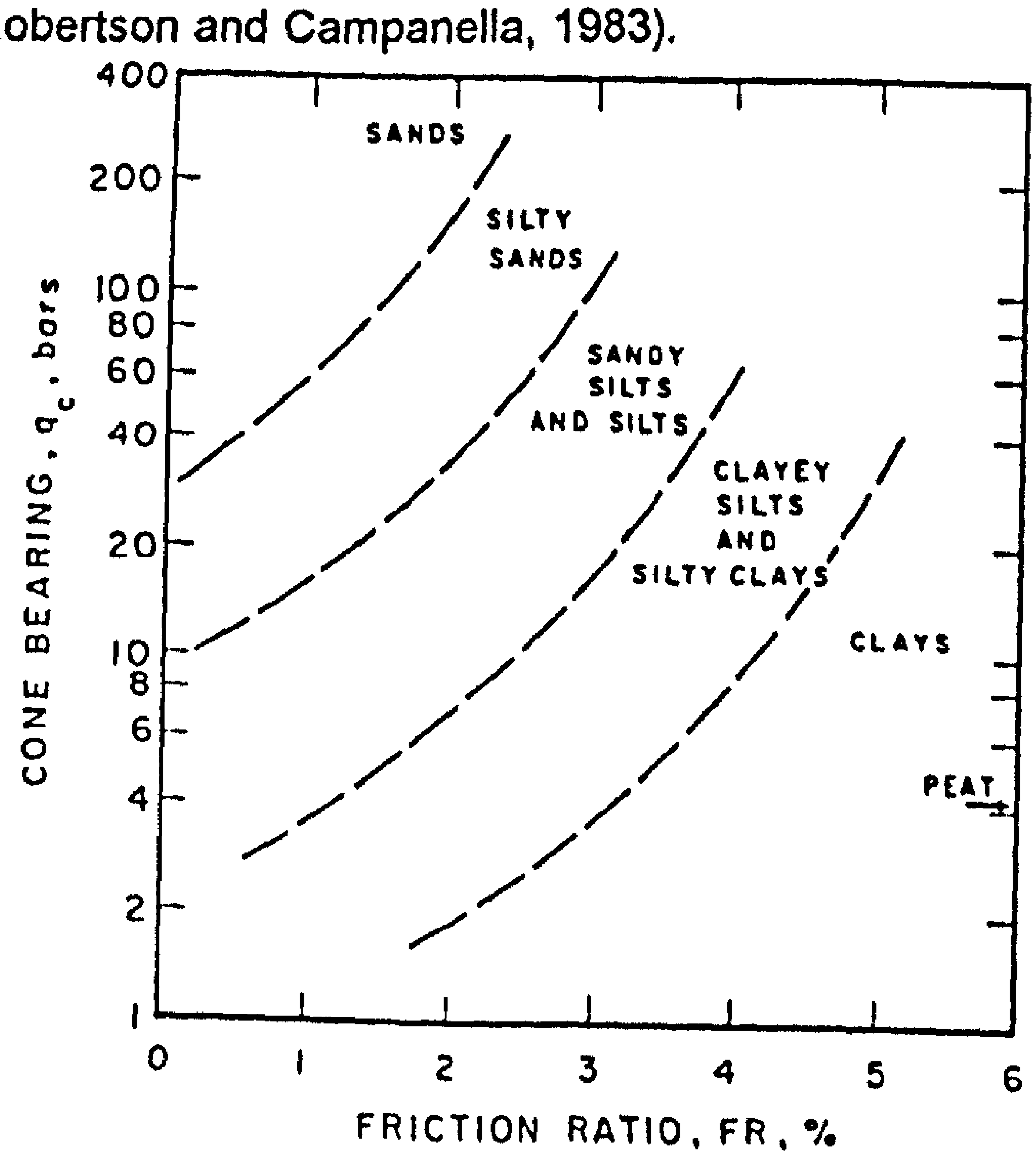


Figure 4.3b Simplified soil classification chart for standard electric friction cone (Robertson and Campanella, 1983).



4.3 Parameters in cohesionless soils

The CPT has an important role in the exploration of cohesionless soils because there is a lack of satisfactory alternative methods. Laboratory testing is generally not feasible because of the difficulty in obtaining undisturbed samples (Meigh, 1987). Direct derivations from cone resistance of relative density, angle of shearing resistance and modulus values do however depend on empirical correlations

4.3.1 Relative density

For cohesionless soils the density, or more commonly the relative density, is often used as an intermediate soil parameter. There are many problems associated with determining maximum, minimum and *in-situ* densities as well as problems correlating relative densities with measured soil properties (Robertson and Campanella, 1983). Most knowledge of the relationship between relative density, D_r, and cone resistance, q_c, come from calibration chamber tests, which usually require correction for the effects of chamber size. However relative density is still used by engineers as a guide in design.

In normally consolidated sands there is no unique relationship between q_c, *in-situ* effective stress, and relative density (D_r) since other factors such as soil compressibility also influence cone resistance. For a given value of relative density and effective overburden pressure (σ'_{vo}) a sand of high compressibility has a lower q_c than a sand of low compressibility.

Figure 4.4 shows that sands of moderate compressibility follow the regression line. Highly compressible sands tend towards the upper line, and low compressible sands tend towards the lower line. These data apply to relatively uniform, uncemented, clean normally consolidated predominantly quartz sands where the *in-situ* horizontal stress ratio K_o is about 0.45. In using Figure 4.4 the probable compressibility of the sand should be taken into account, bearing in mind that compressibility is greater where the sand is uniform in grading, where the sand grains are angular, and where there is an appreciable mica content. In a thin sand layer, an underestimate of D_r may be obtained because the full cone resistance may not have developed (Meigh, 1987).

Figure 4.4 Relationship between relative density and cone resistance of uncemented, normally consolidated quartz sand. (Meigh, 1987).

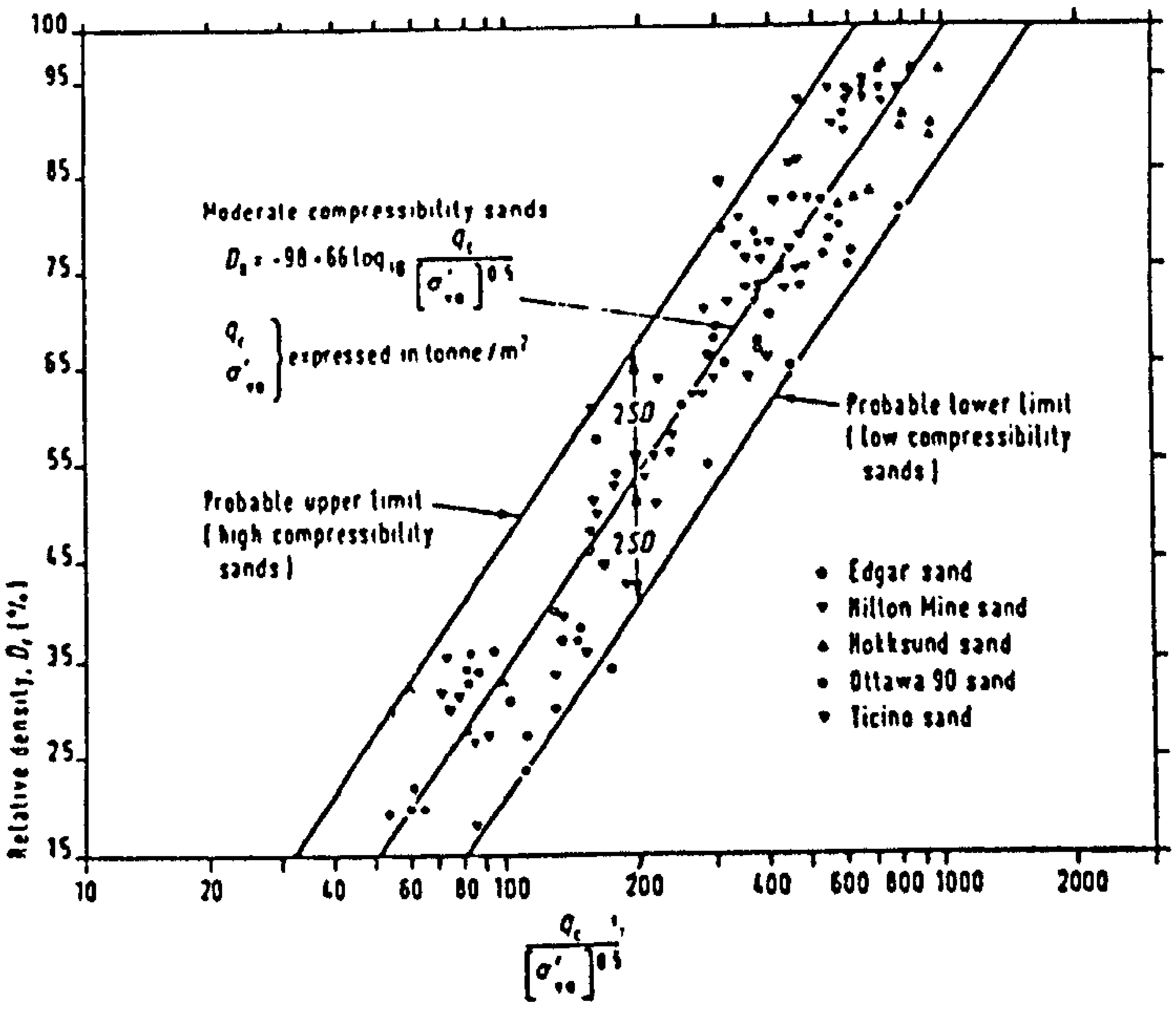


Figure 4.5a
Relationship between peak angle of shearing resistance and relative density of quartz sands (after Schmertmann, 1978).

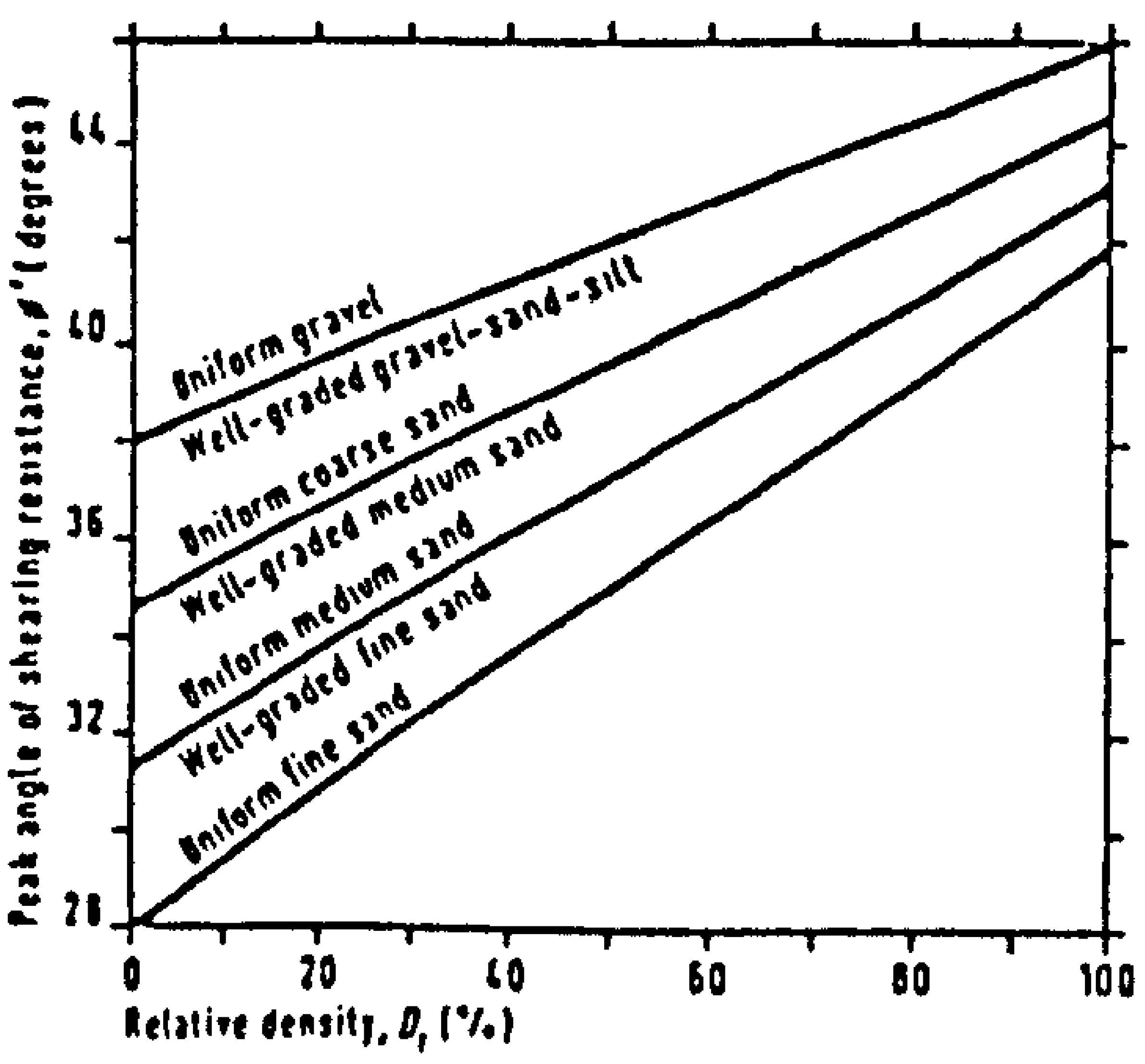
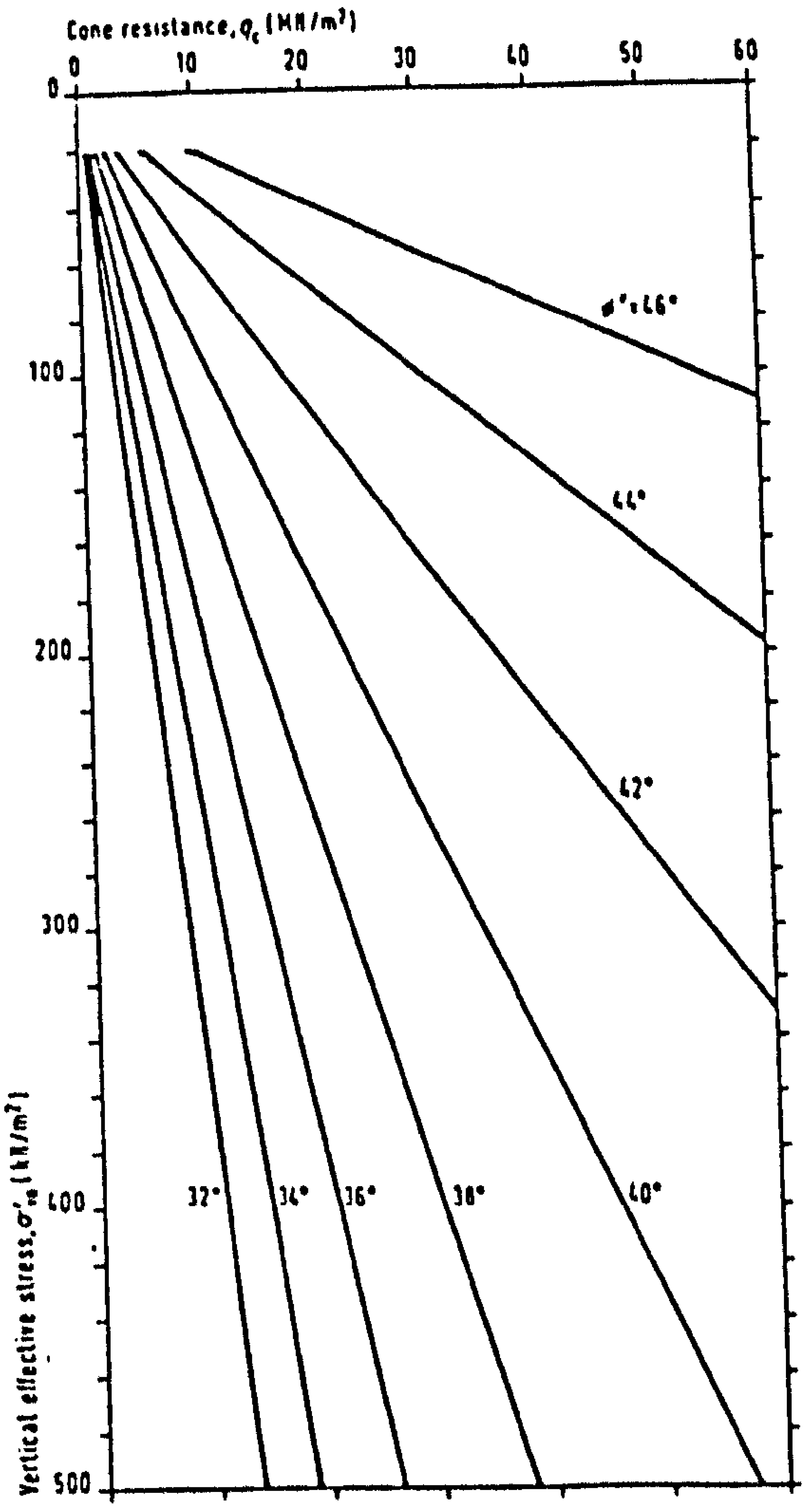


Figure 4.5b
Relationship between angle of shearing resistance and cone resistance for an uncemented normally-consolidated quartz sand (after Durgunoglu and Mitchell, 1975).



In overconsolidated sands chamber tests show that for a given sand, D_r is better correlated with initial horizontal effective stress σ'_{ho} than with initial vertical effective stress, σ'_{vo}. Figure 4.4 can therefore be used with overconsolidated sands if the *in-situ* effective horizontal stress is known or can be estimated by substitution of σ'_{ho} for σ'_{vo}. This should be regarded as only an approximation, with a possible error in D_r of ± 20%. As with normally consolidated sands a correction for chamber size is required.

4.3.2 Strength

It is possible to estimate the peak effective angle of shearing resistance, ϕ', of free draining sands using relative density as an intermediate parameter, taking values from Figure 4.4 and the relationships between ϕ' and D_r given by Schmertmann (1978) as shown in Figure 4.5a.

A direct correlation between q_c and ϕ' is shown in Figure 4.5b. It is derived from a bearing capacity theory developed by Durgunoglu and Mitchell (1975) using a soil-to-cone friction angle equal to $0.5\phi'$ and a lateral earth pressure coefficient $K_o = 1-\sin\phi'$. The theory ignores the effects of compressibility. The use of Figure 4.5b for overconsolidated sands overestimates the secant angle, ϕ', by 1 or 2°

4.3.3 Constrained modulus

As the cone penetration resistance in sand is a complex function of both strength and deformation properties, there is no generally applicable analytical solution for cone resistance as a function of deformation modulus. However, correlations between constrained drained modulus (M) and cone resistance (q_c) are commonly expressed in the form (Robertson and Campanella, 1983):

$$M = \alpha_m \cdot q_c \qquad (4.1)$$

where α_m, the constrained modulus coefficient, is often stated to be between 1.5 to 4.

Vesic (1970) proposes α_m where D_r= relative density

$$\alpha_m = 2\left(1+\left(\frac{D_r}{100}\right)^2\right) \qquad (4.2)$$

which gives α_m values in the range of about 2.25 to 4. However, Lunne and Kleven (1981) suggest that for normally consolidated sands α_m lies in the range 3 to 11 with higher values for overconsolidated sands.

4.3.4 Youngs modulus

For cases other than one dimensional, Youngs modulus, *E*, is more appropriate than the constrained modulus, *M*. As with *M*, *E* is dependent on stress level, and for normally consolidated sands, Figure 4.6 gives values of drained secant modulus at 25% (E_{25}) and 50% failure stress (E_{50}), and cone resistance q_c for different levels of vertical effective stress based on chamber test results. The use of Figure 4.6 may underestimate the *in-situ* Young's modulus because it is based on laboratory measured moduli using reconstituted samples. Many *in-situ* sand deposits have had some past stress history that can cause a significant increase in soil stiffness (Robertson and Campanella, 1983).

For overconsolidated sands, E_{50} , varies between $6q_c$ and $11q_c$ (Baldi *et al.*, 1982). E_{25} is some 50% higher for overconsolidation ratios up to about 3 but approximately equal to E_{50} for overconsolidation ratios greater than 4. However, as a result of the limited data available for overconsolidated sands, it is considered prudent by Meigh (1987) to adopt *E* values not more than twice those given in Figure 4.6 for normally consolidated sands.

4.3.5 Dynamic shear modulus

Figure 4.7 shows the correlations obtained by Robertson and Campanella (1983) between dynamic shear modulus, cone resistance and vertical effective stress. It is based on laboratory correlations between dynamic shear modulus at small strains (less than 10^{-3}% dynamic strain amplitude), relative density and the relationship (developed by Baldi *et al.*, 1981) between D_r and q_c .

Figure 4.6 Relationship between cone bearing and drained Youngs modulus for normally-consolidated uncemented, quartz sand (Robertson and Campanella, 1983).

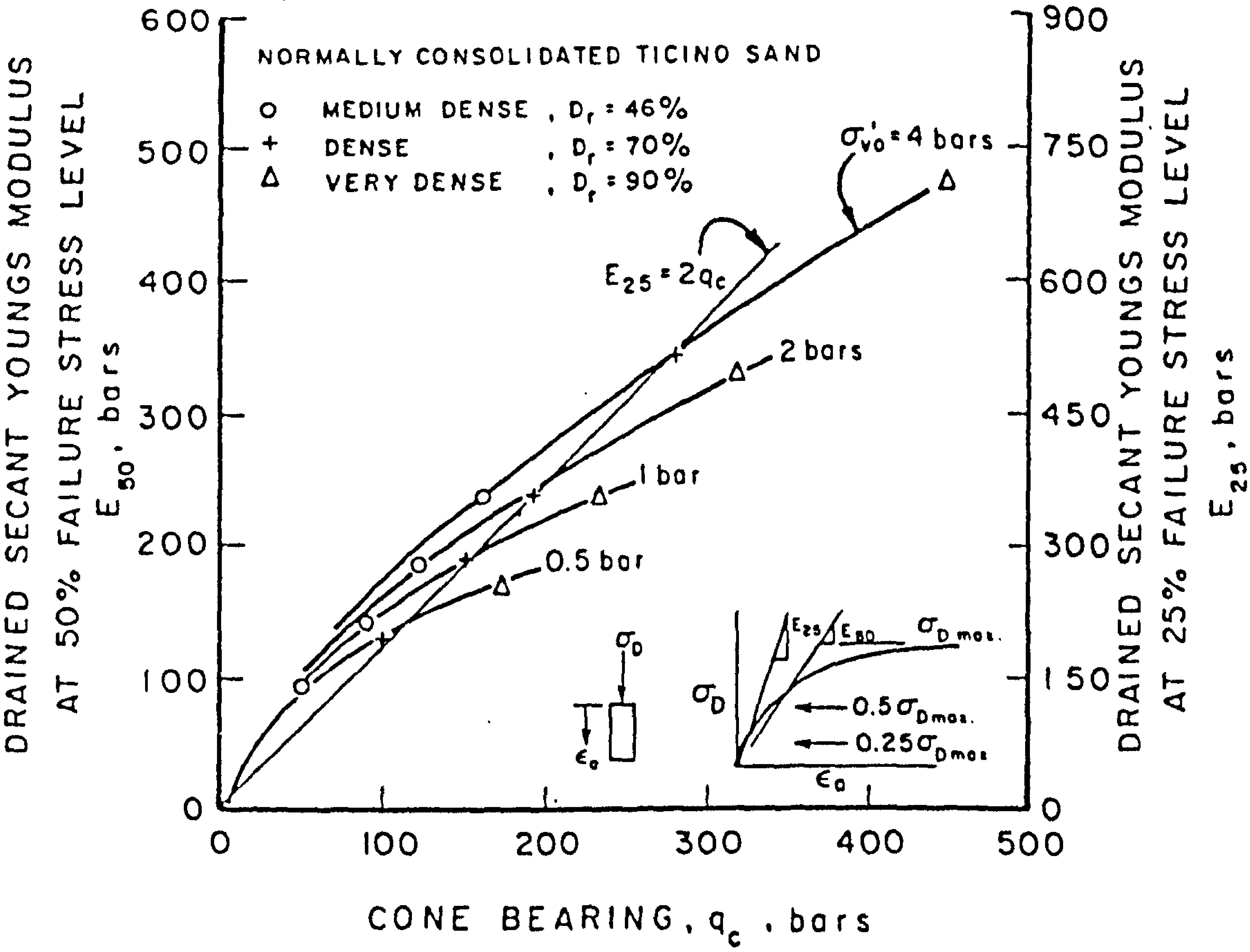
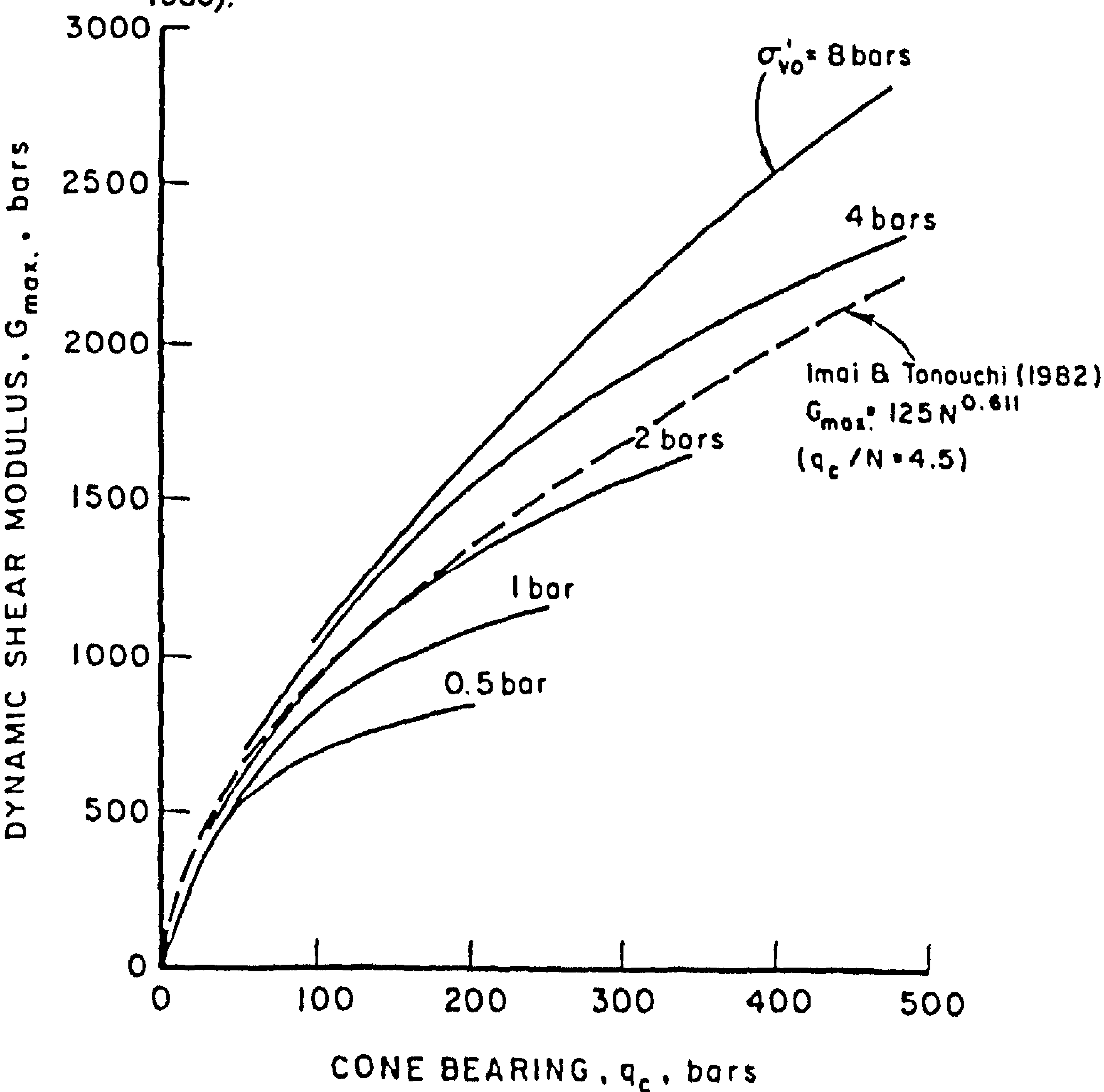


Figure 4.7 Relationship between cone bearing and dynamic shear modulus for normally consolidated uncemented sand (Robertson and Campanella, 1983).



4.4 Parameters in cohesive soils

Historically cohesive soils have formed a less important field of use for the CPT compared to cohesionless soils because established alternative methods are available. However, in the offshore environment, CPTs appear to becoming more routinely used where the CPT has the advantage of rapid coverage and good identification of variations in stratification.

4.4.1 Strength

In overconsolidated clays, particularly stiff, fissured clays vane tests are unsuitable, and laboratory tests for strength and elastic modulus suffer from the effects of sample disturbance. Unfortunately, the macrofabric of such clays also makes for difficulty in the interpretation of CPT results and for determination of constrained modulus, laboratory tests are preferable.

The cone resistance in clays varies with the rate of penetration. The available data in Figure 4.8 show that the variation corresponding to the specified tolerance of ±5mm/s on the standard 20mm/s is acceptable.

The relationship between cone resistance and undrained shear strength of a cohesive soil can be expressed as:

$$q_c = N_k \, .c_u \, .\sigma_{vo} \qquad (4.3)$$

Where σ_{vo} = total vertical stress

N_k = the 'cone factor', is analogous to the bearing capacity factor, N_c

However, N_k is not a constant; it is affected by the method, and reliability of measurement of c_u, by the shape of the penetrometer tip, by the rate of penetration, by strength anisotropy, and by the macrofabric of the clay and its stiffness ratio (the ratio of shear modulus to undrained shear strength).

In normally consolidated clays q_c is usually correlated with vane shear strength, s_u, either as measured (N_k) or as corrected using Bjerrum's (1972) correction (N_k^*). Considerable caution is needed in using the CPT to determine undrained shear strength. For normally consolidated clays of low or moderate sensitivity, the

Figure 4.8 The effect of rate of penetration in clays (Meigh, 1987).

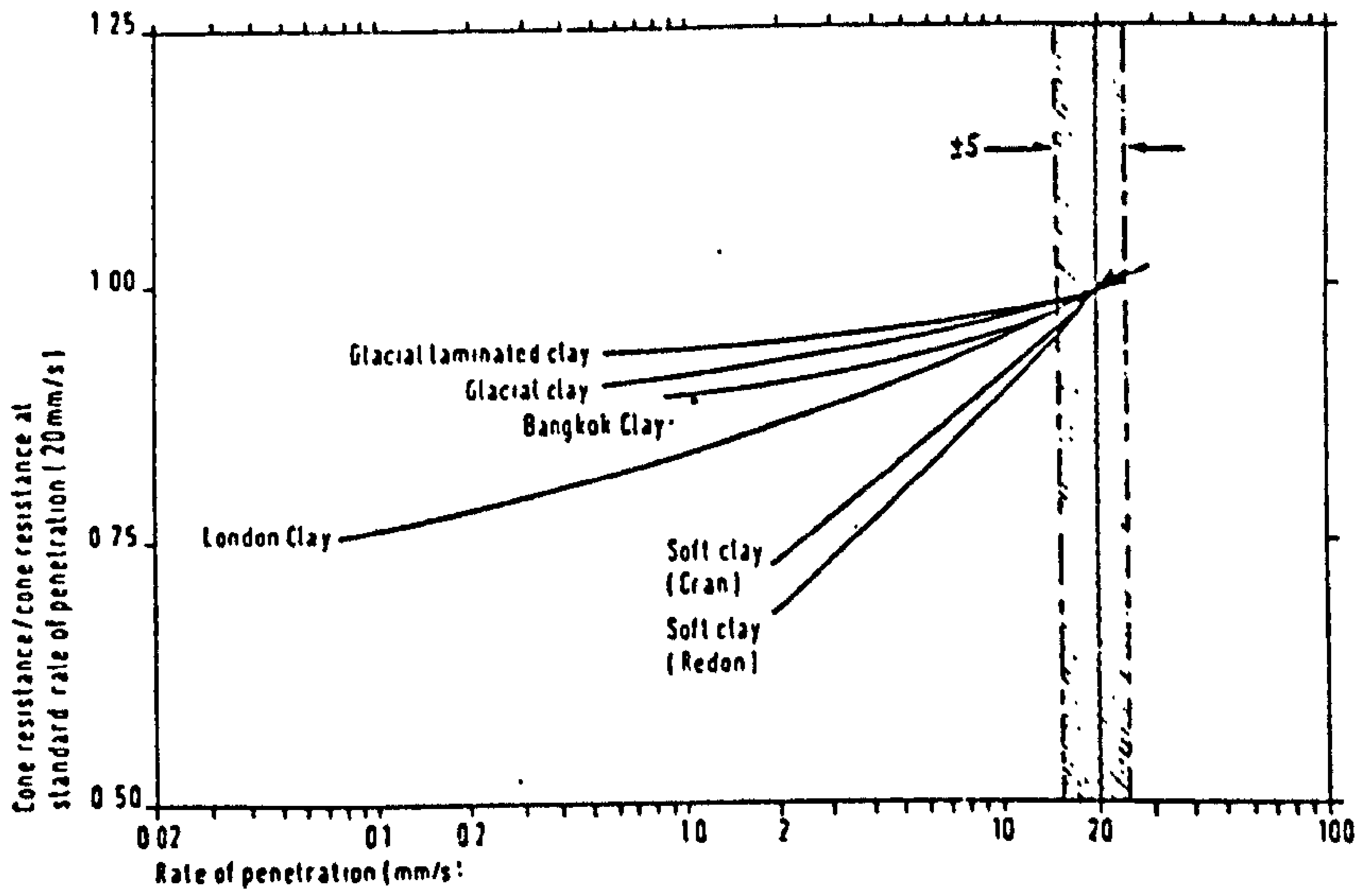
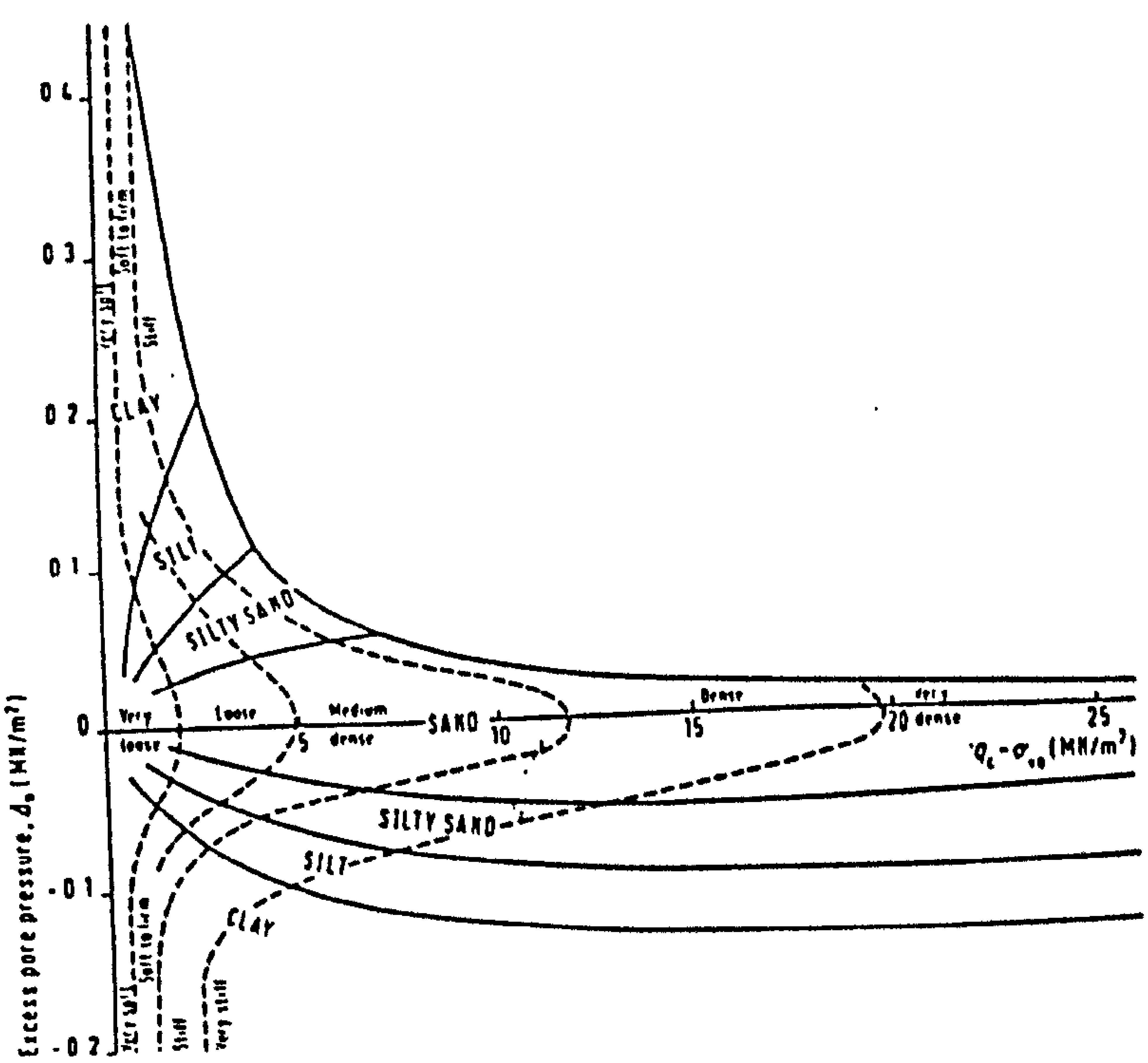


Figure 4.9 Tentative soil type identification by piezocone (porous element placed on shoulder immediately above base of cone) (Meigh, 1987).



choice of value for the corrected cone factor as discussed by Meigh (1987) will depend (in an engineering context) on the particular application and factor of safety to be adopted.

In overconsolidated clays, the macrofabric has a marked effect on cone factor, making interpretation in terms of shear strength more difficult and uncertain than with normally consolidated clays. The effect of macrofabric varies with the spacing and other discontinuities. The greater the spacing of fissures, the more accurately the intact strength of the clay is measured.

For determination of cone factor values (N_k), authors have correlated cone resistance of overconsolidated clays with field vane shear strength, strength from laboratory compression tests and strength back analysed from plate-loading tests. Vane strength is unsuitable because the vane overestimates the shear strength in overconsolidated clays. Whether laboratory tests are suitable depends on the specimen size in relation to fissure spacing and on the degree of disturbance during sampling and specimen preparation. With wide fissure spacing and low sample disturbance, laboratory test strengths are close to the intact strength of the deposit. With significant sample disturbance, strengths may well fall below the 'mass' strength.

Plate-loading tests give a better basis for comparison provided that the tests are of a sufficient size to take into full account the effect of the fissures (Meigh, 1987).

4.4.2 Constrained modulus

Constrained modulus, *M*, for clays can be expressed in terms of a coefficient α_m, and cone resistance:

$$M = \frac{1}{m_v} = \alpha_m \cdot q_c \qquad (4.4)$$

For normally consolidated and lightly overconsolidated clays and silts up to firm in consistency (q_c less than about 1.2MN/m^2) a first approximation can be obtained by using published values for α_m (Meigh, 1987). Values of α_m (=M/q_c) range from between 2.5 and 7.5 for highly plastic clays and silts to 0.5 to 1.25 for peats and organic clays. These are applicable for a small stress increment (up to about 100 kN/m^2) above *in-situ* vertical effective stress.

For a given q_c there is a wide range of α_m values. For a better estimate of constrained modulus, it is preferable to use index properties and oedometer test data, but local correlations between q_c and M can be very useful particularly in assessing variation in compressibility (Meigh, 1987).

4.4.3 Undrained Young's modulus

There is even greater difficulty in assessing a value of undrained Young's modulus, E_u, from q_c values. There are, according to Meigh (1987), insufficient data available to make a direct correlation, and it is recommended that c_u (undrained shear strength) should first be derived using corrections. E_u can then be estimated from, as a rough order of value, one of the available correlations between E_u and c_u. E_u decreases with increasing shear stress levels.

4.5 Role of the Piezocone

According to Meigh (1987) the role of the piezocone falls into two groups: soil profile determination and assessment of engineering parameters. The additional measurement of pore pressure with the piezocone assists identifying soil type. Variations in pore pressure reflect changes in stratification that cannot always be determined by cone resistance q_c or sleeve friction f_s alone. For instance, changes in pore pressure response in clay layers may indicate thin permeable seams or lenses that can greatly influence the drainage characteristics of the deposit.

Applications in assessment of engineering parameters include:

1) Assistance in the interpretation of cone resistance and skin friction in terms of shear strength and deformation characteristics.
2) Assessment of *in-situ* permeability and consolidation characteristics.
3) Assistance in the assessment of stress history and overconsolidation ratio of cohesive soils.
4) Measurement of static porewater pressure.

Application 4 is straightforward, however 1-3 are in the early stages of development without a supporting body of experience. With future development however, they are likely to offer potential advantages.

Piezocone data are particularly useful in mixed deposits where it is often difficult with the CPT to know whether the data refer to drained or undrained conditions.

4.5.1 Profiling and identification with the piezocone

The pore pressure response of the piezocone is such that thin layers can be identified. Where there is a good contrast in permeability of adjacent layers, the thinnest identifiable layer is 30 to 50mm thick.

It is however not yet possible to produce a positive correlation between pore pressure measurements during a CPT and soil type (Meigh, 1987). A tentative correlation based on changes in pore pressure, Δ_u, and the net cone resistance, $(q_c-\sigma_{vo})$ is presented by Jones and Rust (1982) for use with a penetrometer tip with the filter placed immediately above the base of the cone (Figure 4.9).

The use of the piezocone for the assessment of engineering parameters is in an early stage of development. Correction of cone resistance and skin friction to pore pressure effects is still under development (Meigh, 1987).

4.6 Discussion

The use of the CPT with the piezocone is becoming more widespread in the offshore industry. The integration of CPT and seismic data to provide a more comprehensive interpretation regarding lithology and geotechnical characteristics is becoming more widely accepted. The CPT is widely used by the oil and gas industry during foundation installation and anchor design. In pipeline and cable laying, especially were burial is required, CPT data help, within the overall seismic survey, in the selection of the type of plough required and the depth of burial that can be achieved.

The integration of CPT data with seismic data can usually be accomplished with confidence as many of the properties that the CPT measures also determine the seismo-acoustic properties of the sediment. This makes it an ideal method to calibrate seismic data at control points, then allowing the seismic data to be used for the larger scale geotechnical interpretation.

CHAPTER 5
Tees Estuary Case Study

5.1 Introduction

The Tees estuary, the first site investigated, was selected as a suitable location to be investigated within this project for a number of reasons. The geology of the area, discussed in the following sections, is of Triassic mudstones and sandstones covered by a thick succession of Quaternary deposits. These deposits, as proved by boreholes around the survey area, are shown to be complex, the geology being variable both laterally and horizontally, thus providing a challenge to the application of seismic stratigraphic principles.

Logistically the physical conditions at Seal Sands make it possible to safely operate a small boat laden with survey equipment: the area is well protected from sea swell and has a relatively small connection to the open sea. The use of a small boat in turn allows optimum shallow water intertidal coverage. The protection from the open sea allows the collection of high quality data with expected wave noise likely to be kept to a minimum. The potential for the collection of a land data set overlapping the marine survey site allows an investigation of any benefits of integrating land and marine survey data and provides a means for extending the marine and intertidal surveys landward. Land acquisition can also more readily provide a multichannel digital data set with the associated potential to derive quantitative information on the subsurface geology.

Such conditions were expected to provide an excellent opportunity to test the application of the seismic stratigraphic method, and its usefulness as a tool to provide information on facies and physical characteristics in what is a potentially geologically complicated area.

5.1.1 Setting/general area

As part of the NERC LOIS programme (Land Ocean Interaction Study) the University of Wales Bangor (UWB) performed a high resolution digital and analogue, marine and terrestrial seismic reflection survey in the Tees estuary. The aim of data acquisition was to provide a potential case study for this project and to provide data for NERC to help locate suitable positions for future investigative geological boreholes.

The Tees estuary is situated on the NE coast of England (Figure 5.1). The target area of study was Seal Sands situated inside the mouth of the estuary. Seal Sands is a small intertidal land locked embayment with a maximum width of about 2km. It has a relatively small connection to the sea in the NE corner, and Greatham Creek enters in the SW corner. Over the past 65 years the surrounding area has been extensively reclaimed for port or industrial developments (Figure 5.2); as a result only a relatively small intertidal zone (approximately $2km^2$) now remains.

5.1.2 Solid geology of Teeside

The underlying solid geology within the survey area comprises of Mercia mudstones (=Keuper marl) and Sherwood (formerly Bunter) sandstone deposited during the major arid episode of the Triassic (Kent, 1980). Local boreholes reveal a typical bedrock depth of around -25m Ordnance Datum (OD).

5.1.3 Drift geology of Teeside (after Catt, 1991 a & b)

Local boreholes show that the bedrock in the area is covered by glacial and post glacial deposits, which is typical for this part of the east coast of England and the adjoining offshore area. Tills, glacio-fluvial and glacio-lacustrine deposits result from the major glaciation that occurred during the late Devensian time, defined by Rose (1985) as the Dimlington Stadial (26,000 to 13,000 years BP).

During the later Loch Lomond Stadial (11,000 to 10,000 years BP), although glaciers reformed in parts of Scotland, they never reached eastern England. As there is no evidence for an early Devensian glaciation in the sediments of eastern Britain or within the North Sea succession (Stoker *et al.*, 1985) it must be assumed that there was only one (Dimlington Stadial) glacial advance over eastern England during the Devensian.

Figure 5.1 The Tees Estuary.

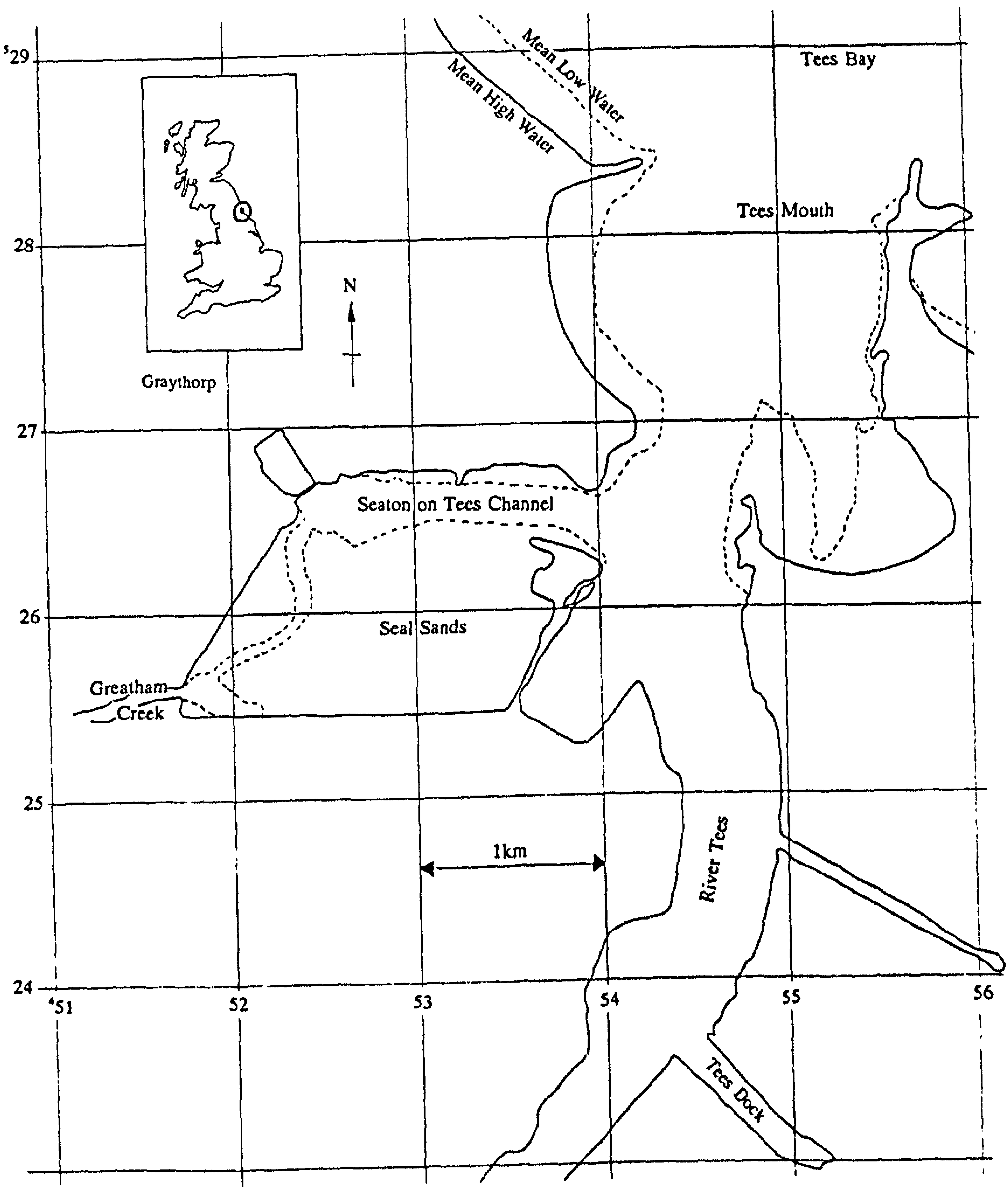


Figure 5.2 Land reclamation since 1930 (Carter, 1988).

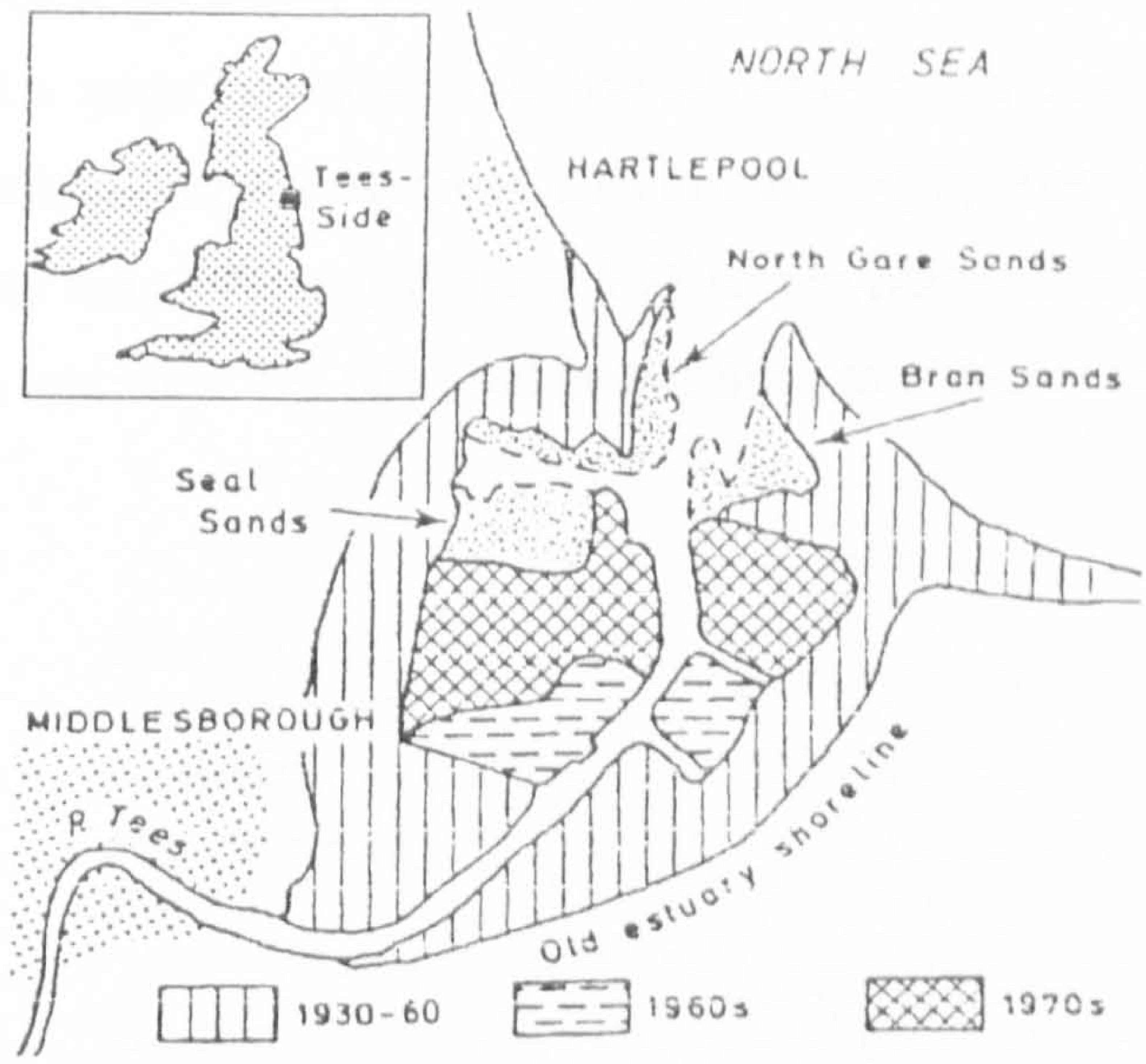
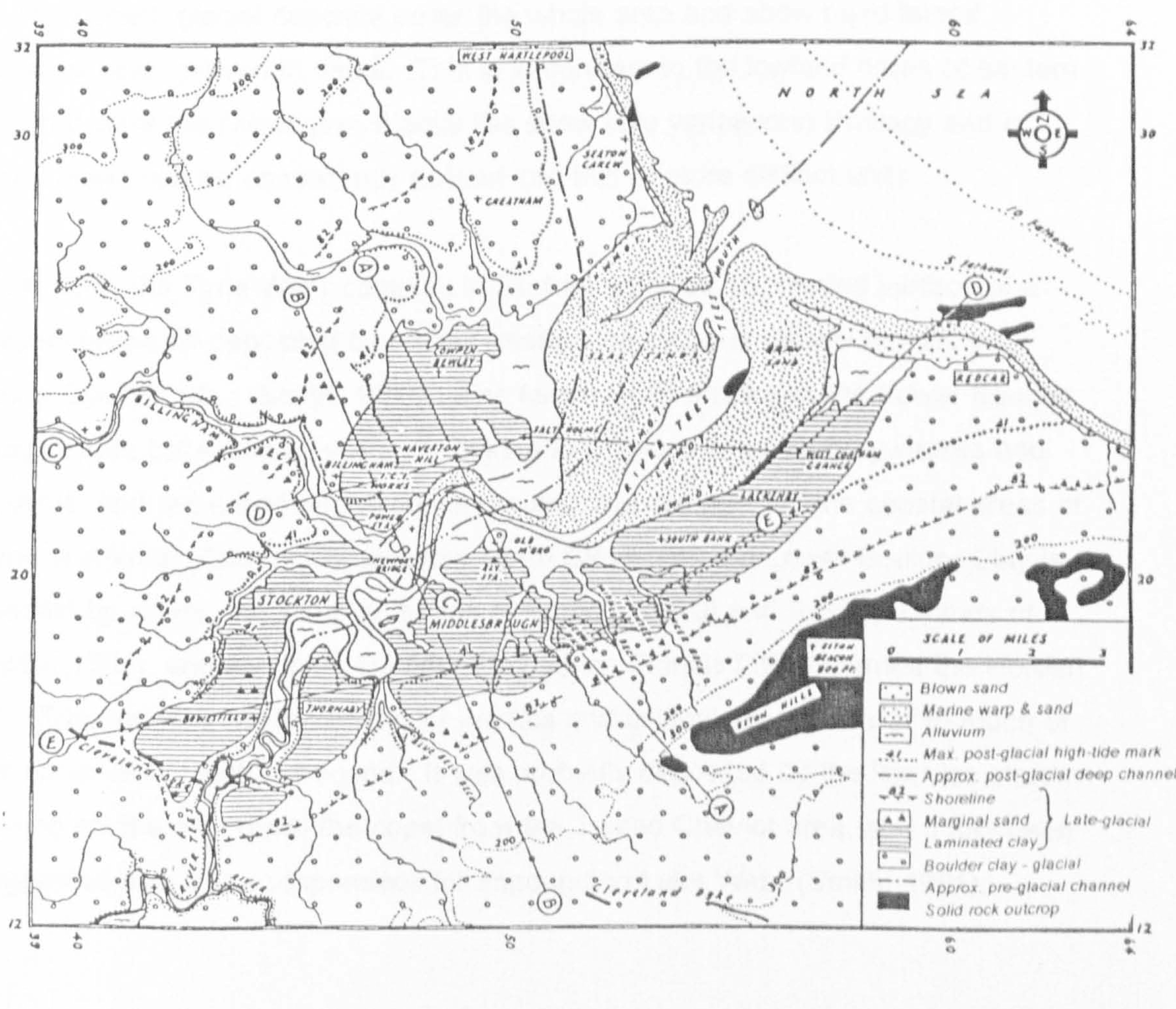


Figure 5.3 Seal Sands and the Tees Estuary - sediment distribution and physical features (Agar, 1954).



The Tees estuary appears, surprisingly, to have received little specific geological attention. The reason for this is unclear but may be due in the past to the inaccessibility of the large intertidal area and at present to industrialisation. However, one notable study of the area was conducted by Agar (1954). Agar (1954) attempted to map the area (Figure 5.3) and hypothesised a glacial and post glacial history and ascribed the deposits in the area to either recent, late-glacial or glacial:

Recent	Blown sand Marine warp Alluvium Marine sand Peat
Late-glacial	*erosion* Marginal sand Laminated clay
Glacial	Boulder clay Sand Gravel

As mentioned, glacial deposits cover the whole area and show rapid lateral variation when proved in detail. This is in contrast to the lowland areas of eastern England were the Dimlington Stadial tills show little variation in lithology and in many areas can be consistently divided into two or more distinct units.

Elsewhere, the Tyne-Wear complex in Durham overlies the eroded surface of a greyish-brown till deposited by earlier western ice. This is usually termed the Lower Boulder Clay (Smith, 1981). The far travelled erratics in the Lower Boulder Clay include Lake District volcanic rocks and granites, Scottish greywackes and granites, and red sandstone of Devonian and Triassic age. In the coastal areas of Tyne and Wear, County Durham and North Cleveland, the Lower Boulder Clay is overlain by sands, the Peterlee sands of Francis (1970) and Rhyhope sands of Smith (1981), and an Upper Boulder Clay which Francis (1970) named the Horden Till. The upper till contains Cheviot erratics and is lithologically similar to much of the upper till in Northumberland. It was probably deposited by the later ice stream flowing southwards down the coast from the Tweed Cheviot area, and it has been suggested that it was responsible for impounding Lake Wear (Smith, 1981).

It is likely that the Upper Boulder Clay or Horden Till was deposited by a southward ice advance reaching only the Northern side of the lower Tees Valley and extending inland as far as a moraine between Easington and Elwick. This occurred at a somewhat later stage in the Dimlington Stadial than the main invasion of eastern England.

The Dimlington stadial type site deposits are found in the cliff section at Dimlington Farm, SE Holderness, where the Pre-Devensian Basement Till is overlain by two distinct tills, notably the Skipsea and Withernsea tills of Madgett and Catt (1978). The lower (Skipsea) till is locally separated from the Basement Till by silts containing arctic moss remains which have been radiocarbon dated to 18,500 (± 400) years BP and 18,240 (± 280) years BP (Penny *et al.*, 1969).

Madgett and Catt (1978) suggested that the Withernsea till came from a Tees valley (Stainmore) ice stream which overrode the coastal (Skipsea Till) ice near the mouth of the Tees causing a surge which then carried it southwards on its back into eastern Yorkshire.

The glacial deposits in the Tees will have been eroded to an as yet unknown extent by marine and river action and subsequently covered by water deposited clays, silts, sands and gravel. Boreholes in the area prove such deposits to have great lateral variation.

Catt (1991a) proposes that, due to marine erosion during the early Flandrian eustatic sea level, deposits left by the Dimlington Stadial ice sheet in the area offshore from the Tees estuary and North Yorkshire coast will have been almost entirely removed.

Agar (1954) proposed a late glacial lake in the lower Tees estuary in which laminated clay was deposited. Clay layers were interpreted as indicating quiet periods of deposition, possibly under ice and sand being deposited in flood conditions. Peripheral to the laminated clay were irregular patches and strips of sand. These were interpreted as being a marginal or shore deposit of the body of water in which the laminated clay was laid down.

When the body of water that allowed the accumulation of the laminated clay to accumulate drained, the main river would have cut into the soft laminated clay and tougher glacial deposits as the river drained to the then much lower sea level.

Subsequent sea level rise along the east coast (i.e. Figure 5.3a) would start the change from fluvial conditions to estuarine conditions in the area with the associated deposition of alluvium (Agar, 1954).

This project will hopefully go some way to help in determining something of the hypothesised geological history of the lower Tees estuary. Continuous seismic profiles should provide a better understanding of the subsurface geology which appears, on the strength of borehole data, to be laterally variable. It is hoped that where variations of sediment type exist they may be indicated on the seismic data and that, at least, qualitative comments may be able to be made on the lithological and geotechnical properties of this sediment through a study of the seismic character.

5.1.4 Borehole data

Logs of several boreholes in the Seal Sands area were provided by Tees and Hartlepool Port Authority and others obtained from records help at Durham University. The area has good spatial coverage of boreholes due to the large amount of construction work carried out in the area. These boreholes reveal that the area has considerable lithological variability. Selected boreholes, of relevance to the marine survey, are illustrated in Figure 5.4 (their relative positions are shown in Figure 5.10).

5.2 Seismic investigation

Part of this project is concerned not only with the testing of seismic stratigraphic methods in Quaternary sediments but also with the development of the methodology of collecting analogue and digital seismic data in shallow water and the intertidal zone. This case study is fairly unique in that it hopes to integrate a shallow marine survey with an intertidal terrestrial survey. Inshore seismic surveying, especially in the intertidal zone in a relatively environmentally sensitive area can often require more coordination and present more difficulties than a true

Figure 5.3a Sea level curves for selected sites in England, Wales and Scotland (Lambeck, 1995).

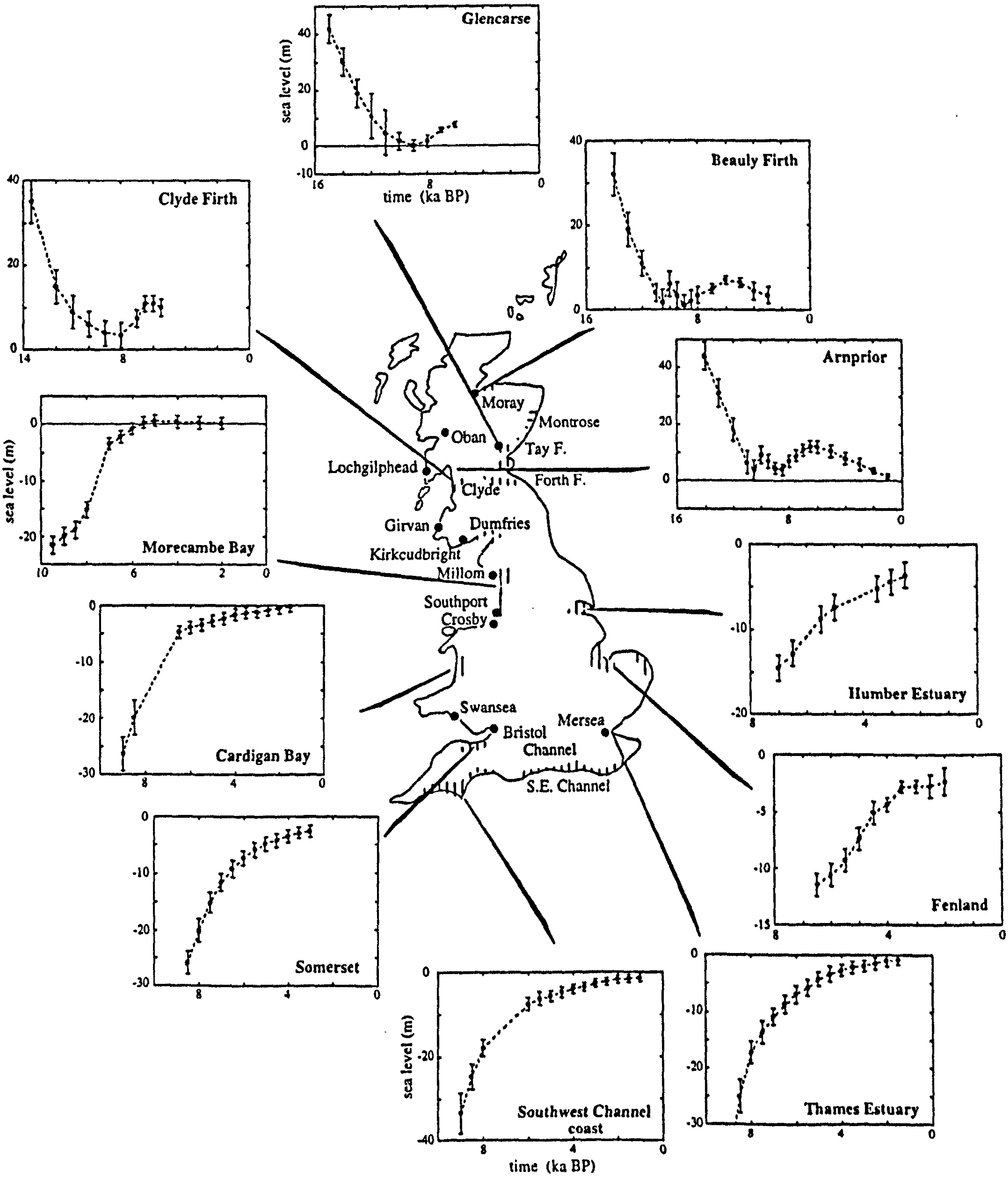
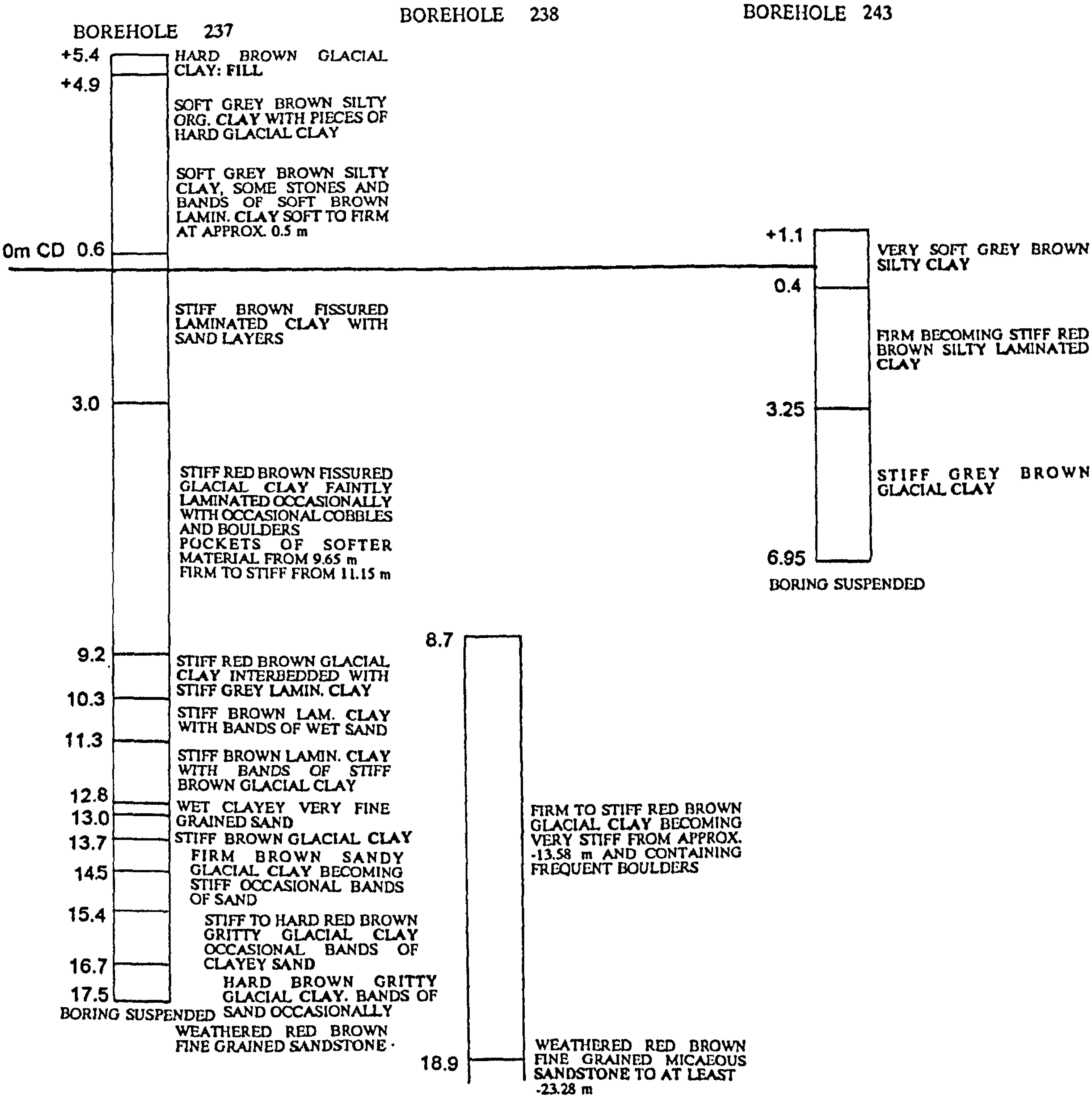


Figure 5.4 Borehole data, Seal Sands.



offshore survey. As such, some of the factors of equipment and logistics will be discussed here.

5.2.1 Survey details

Seal Sands is a designated SSSI (Site of Special Scientific Interest) with important bird and seal colonies, consequently permission to conduct survey work in this area was obtained by liaising with the Nature Conservancy Council for England (English Nature). Permission was granted on the prerequisite that there would be a daily liaison with the site warden who would provide advice regarding day to day work restrictions caused by the bird or seal populations. A number of restrictions were also necessary to avoid disturbance to known 'haul out' points frequented daily by seals. Durham University Biological Science department have several long term bird monitoring projects operating in the area, so every effort was also taken to avoid disturbing this work. Permission was also obtained from Tees and Hartlepool Port Authority, who granted an access permit to the land surrounding Seal Sands.

Because of the intertidal nature of Seal Sands the area could only be surveyed using marine techniques during high tide (preferably a spring tide), and from a safety point of view in daylight hours.

The location of the land-based survey was dictated by a number of factors. The location finally selected was chosen because the ground proved suitable (sand instead of very soft mud), because it was within the area of marine coverage, and also because it would not interfere with biological survey work.

Taking into account the factors discussed above, the survey programme was as shown on Figure 5.5. The marine data were acquired during one high tide and the land data were collected over five days at periods of low water.

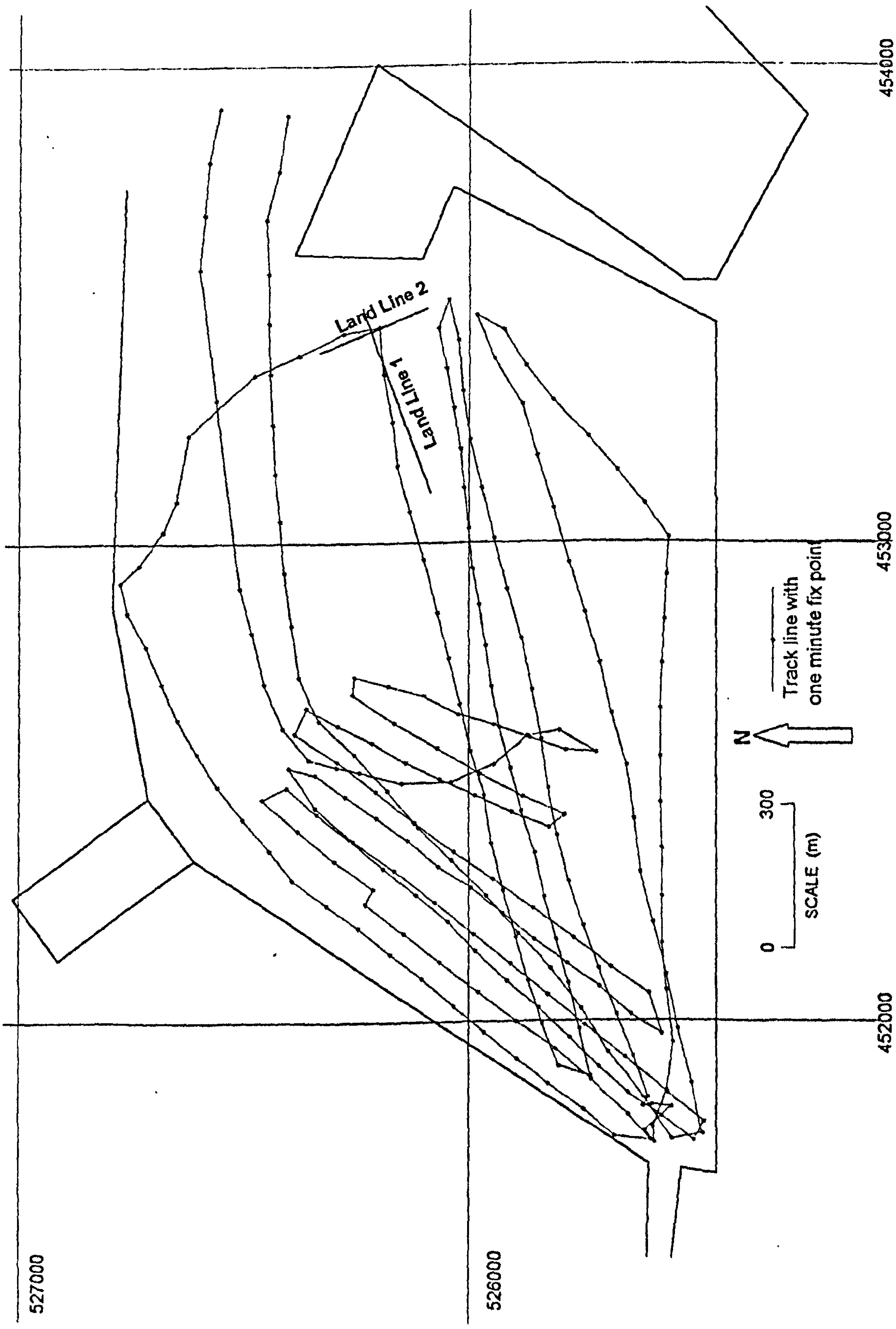


Figure 5.5 Marine and land based survey programme.

5.2.2 Marine sub-bottom profiling

5.2.2.1 Equipment and vessel

All marine survey work was carried out from the UWB vessel 'Sandpebbler', a Chub 21 with a draft of 18", working out of Cleveland Wharf, Middlesbrough. Throughout the survey the IKB Seistec was used as both source and receiver.

The Seistec was selected as the preferred survey tool for this specific study and throughout the entire project for a number of reasons. One of the aims of this project was the collection of marine digital data in the intertidal zone. The use of digital data in the context of this project was expected to be two fold: (a) it would allow the generation and display of instantaneous attributes of the seismic data which, as discussed in chapter 3, would be an important part of seismic facies analysis, and (b) as identified by Haynes *et al.* (1993b) digital processing of high resolution digital data would provide acoustic parameters which could potentially be utilised *via* acoustical-geotechnical inter-relationships to predict engineering properties of the marine sediments.

There are traditionally however problems associated with the acquisition of shallow water data which are discussed by Haynes *et al.* (1993b) and Simpkin (1993) and include (amongst others) interference through multiples, interference between source and receiver, changes in source receiver separation and environmental noise.

The generation of a water surface/seabed multiple which can mask shallow reflectors is a major problem encountered when carrying out high-resolution surveys in shallow water. This is due to the short time lag between multiple and primary reflections. The advantage that the Seistec has is that the system has a source receiver configuration whereby the receiver hydrophones are shielded within a cone. This leads to focusing of the return signal and elimination of energy returned 'off-angle' from the sea surface. This, as discussed in chapter 2.1, can act as a near perfect reflector of seismic energy, so helping to cut down the potential energy of multiples (although not eliminating them entirely) (Simpkin and Davis, 1993).

The Seistec is designed around a boomer seismic source which has been recognised by McGee *et al.* (1992) as having the widest bandwidth of commercially available sources that are able to achieve the depth of penetration required of this project. This leads to higher resolution and corresponding discrimination of "thin" layers.

The Seistec source and line-in-cone hydrophones are both mounted on the same catamaran. This configuration also acts as an aid to interpretation because the source receiver spacing is fixed and known. The boomer is powered by a Geopulse unit which acts to discharge 4000 volts instantaneously through the boomer coil.

Marine analogue data were output to a thermal printer. Digital marine data were recorded but unfortunately lost by a third party before they could be processed. Consequently they will not be discussed further in this chapter.

The following equipment was mobilised to site and used during the marine survey of Seal Sands:

University of Utrect digital acquisition system (MDAS)
Elics Delph 1 Digital Acquisition System
IKB Seistec seismic source and receiver
Geopulse power supply (model 5420A)
Differential GPS and logging computer
GPS (Raytheon Raystar 920)
Two generators
Dowty (Waverly) thermal printer (model 3700)
Calibrated (single) Hydrophone

5.2.2.2 Operating parameters

The Seistec (boomer) was towed behind the vessel with a layback between GPS antenna and Seistec of 9m. The operating parameters of the boomer system were as follows:

Source power:	175 Joules
Firing interval:	4 Sec^{-1}
Low cut filter:	1 kHz
High cut filter:	6 kHz

Dowty thermal printer set-up:

Record length:	30/50 milliseconds
Record delay:	0 milliseconds
Sensitivity:	1.0 volts
White level:	5
Black level:	63
Paper speed:	50 mm/min

5.2.2.3 Position fixing

Underway position fixing was originally intended to be achieved directly *via* differential GPS. However, due to various logging problems, the non-differential set was used and a correction from the differential set (logged by the MDAS system) applied later. Positions were automatically logged by computer every four seconds. An accuracy of ± 15m can be expected from such an arrangement.

5.2.2.4 Navigation

Because of the relatively small size of the survey area, the short amount of time on a survey line and the relatively short amount of time (due to tide limitations) to conduct the whole survey, the line plan was decided 'on line' as dictated by the prevailing water depths, with the primary aim of gaining maximum coverage.

Navigation was achieved using line of sight (aided by the many obvious surrounding industrial features), compass bearings, and through experience of water depths obtained in the previous days tests.

5.2.3 Land Seismics

During the land seismic survey two lines where shot (the positions of which are shown on Figure 5.5). Line 1 was 420m long and ran roughly N - S across Seal Sands, line 2 was 420m long and ran across and perpendicular to line 1. The purpose of collecting land data was to provide a multichannel data set that would overlap the marine survey and be continued landward. Such a data set would provide a means to tie landward geology with marine geology and provide an extension of the marine data set. Land seismic records also provide data in a suitable format for digital processing. These data can be used for facies determination based on the instantaneous seismic attributes discussed in chapter 3.4.3, and can potentially be used to provide geotechnical information.

5.2.3.1 Equipment

The following equipment was used in the land survey of Seal Sands:

ABEM Terraloc Mk3
Two 12 channel geophone cables
24 geophones
Trigger cable and geophone
Sledge hammer and metal plate
GPS

5.2.3.2 Position fixing

As mentioned above, two survey lines were run: line 1 was run from a known position, established using a time averaged GPS position, to a prominent feature along a compass bearing. Line 2 was run perpendicular to line 1 along a second compass bearing at a known distance along line one.

5.2.3.3 Operating parameters

Twenty-four geophones were deployed throughout the survey, however only 12 of these were live at any one time. The data were collected using the common-midpoint method in that after a shot was taken (using a sledgehammer impact on a metal plate) the source would be advanced down line and the next 12 channels would be 'rolled along' and made live. The geophone spacing was 4m which gives a theoretical horizontal resolution of 2m. The offset of the source from the first geophone was 8m and was advanced down line 4m before subsequent shots. This arrangement provides 6 fold or 600% coverage of subsurface sample points.

The field layout and spacing used was decided upon for a number of reasons. The collection of multifold data would, although being slower to acquire than single fold data, improve the signal to noise ratio at the processing stage and hopefully improve data quality. The source offset was determined by a 'walk away' noise test to determine ideal shot to first receiver distance. The recording length was set at 100ms as this was within the recording length of the marine survey (50ms) but would also facilitate recording of any seismic reflections deeper than those observed on the marine data. This was deemed useful as penetration with this lower frequency source was expected to be significantly greater. The vertical resolution as commented on previously (section 2.4) is determined by the source frequency. The hammer source is expected to have a frequency of tens to hundreds of Hz giving a resolution of approximately 2m (dependent in part on media velocity).

During collection of the land data a low cut filter of 50Hz was applied. This filter was used to remove low frequency ground roll so allowing a higher gain to be applied at the acquisition stage without saturation of the signal. In this way compressional wave energy can be recorded over greater distances.

5.2.4 Interpretation procedure

The land data and examples of the marine data set are presented in the following sections for discussion. To assist in the interpretation, and provide a 3D visualisation, contour maps have been constructed using data from the entire marine survey. These plots illustrate bathymetry and subbottom reflectors. The data examples and contour plots are presented (in chapter 5.3) and have been constructed using the parameters discussed below.

5.2.4.1 Marine data

5.2.4.1.1 Boomer interpretation

The interpretation of data collected in the Tees estuary using the Seistec and in subsequent case studies has assumed that the signals were collected using a source-receiver configuration with "zero separation", hence assuming normal incidence reflection.

In the interpretation of the boomer data an assumed seismic velocity of 1500m/s was used for water in all depth determinations. This velocity is a widely used assumed value for sea water. In this case however it is recognised that Seal Sands is located quite some way inland and that the estuarine conditions will make the water less saline and therefore of potentially lower velocity. However as distilled water at standard atmospheric pressure and temperature has a velocity of 1482m/s, the errors that will arise for depth determination in brackish waters in the mostly shallow waters (2m) of the survey area would at most be approximately 0.05m and therefore negligible. An assumed seismic velocity of 1650m/s was used for sediment. This "average" sediment velocity was obtained from analysis of the land data and is discussed in the following sections.

5.2.4.1.2 Tidal correction

Tide levels were not monitored during the survey. In order to correct for the variation in water depth with time a tidal curve was generated from a simplified harmonic tidal prediction computer programme (NP159a) using admiralty harmonic constants for the standard port of Teeside. Although this does not take into account the meteorological conditions at the time of the survey, the fact that the weather was fairly stable throughout the survey period means that such a correction can be considered sufficiently accurate for the purpose of this study.

5.2.4.1.3 Charting

Contour maps, where presented, have been corrected to Chart Datum (CD) by subtracting the tidal elevation, as predicted from the computer programme, from the tidally elevated water depth as measured from the boomer record. A correction factor of 0.46m (the average depth of the boomer/hydrophone below the sea surface on the Seistec) is also added to derive a seabed elevation relative to Chart Datum (CD). In this area, CD is 2.85m below OD Newlyn (Admiralty Chart 2566). This method was also used in the calculation of vertical scales for interpreted seismic sections. The speed of the survey vessel was almost constant throughout the survey, allowing a horizontal average scale to be calculated and presented on the seismic sections.

5.2.4.2 Land data

5.2.4.2.1 Data processing.

Data processing was achieved using the Sierra Seis computer package as it was the most powerful software available allowing the use of a number of different processing options and display types. The processing sequence was divided into two routines, namely: pre-processing and stacking (Figure 5.6). These routines manipulate the multichannel data into a format that is easy to interpret visually and allows examination of the previously mentioned instantaneous attributes. The Pre-processing and stacking routines are discussed below:

Graph name - GEdit Pre_proc

Pool/Processor	Function
Line_1_In	Pool containing all files is ISX format as read from tape.
Edit	Processor can be used to zero or reverse the polarity of traces. In this case it was used to reverse the polarity of 427 traces.
Mute	Sets ends of traces to zero. Mutes only need to be established for discrete traces and will be linearly interpolated between shots. In this case a front and tail mute were applied.

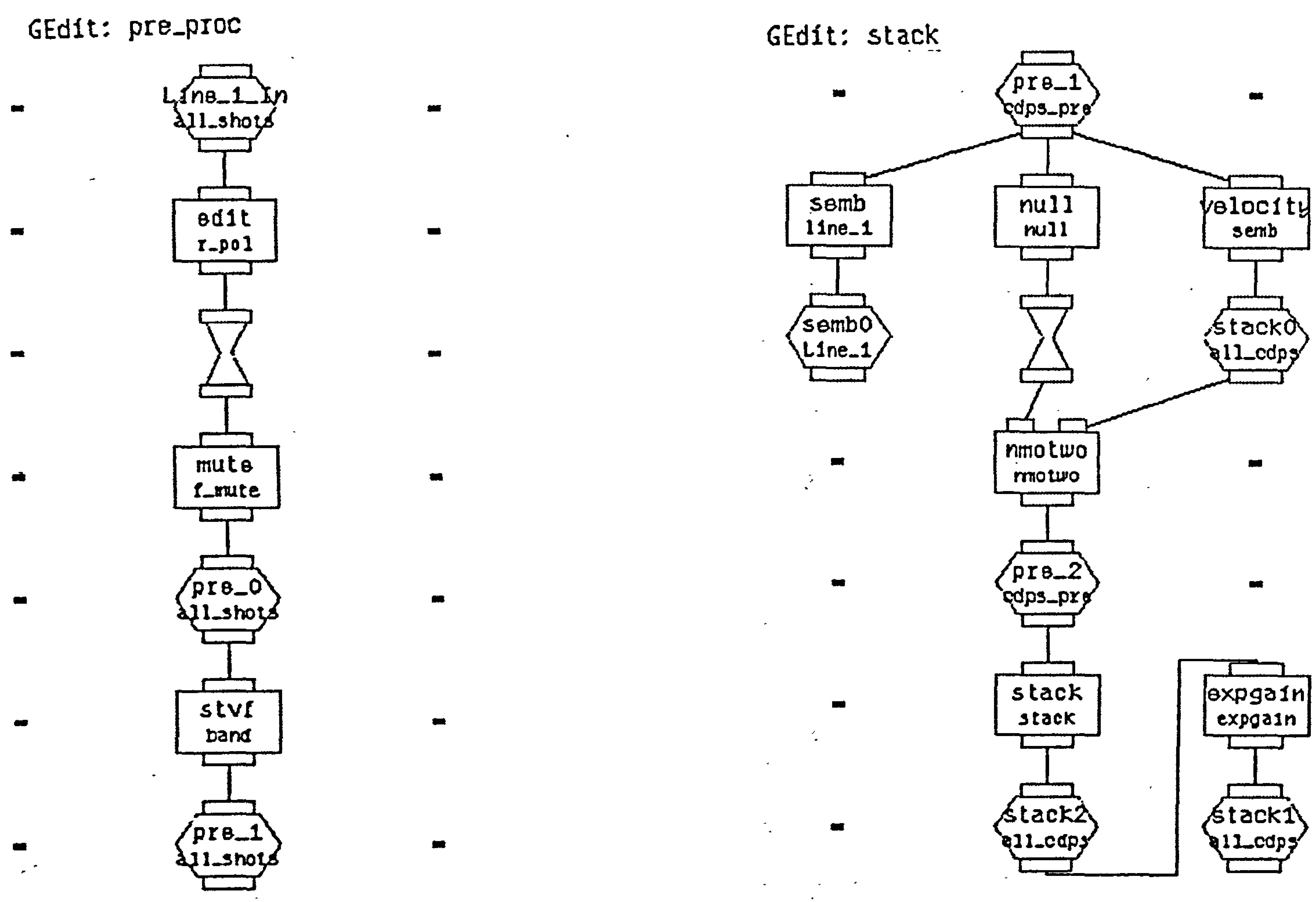


Figure 5.6 Digital data processing sequences to preprocess and stack data.

STVF — Computes and applies space and time varying filter. One bandpass filter was designed:

Low cut frequency	150 Hz
Low cut slope	50 dB/oct
High cut frequency	600 Hz
High cut slope	120 dB/oct

Type of window to apply filter = Hanning window.

The effects of these various processes on the data can be observed in Figure 5.7.

Polarity editing was important as some geophones used through the survey recorded data inversely to others. It is important that the data have the same polarity to ensure useful information is not lost in the stacking process (discussed in the latter section). Muting removes unwanted areas of signal by effectively blanking them out. The front mute was used to exclude first-breaks and the refraction wave train that follows. This was necessary as they are strong signals that degrade the quality of shallow reflections of interest. The tail mute applied set the tails of short-offset traces to zero removing unwanted signal generated as air waves or ground roll strike the geophones (Sheriff and Geldart, 1995).

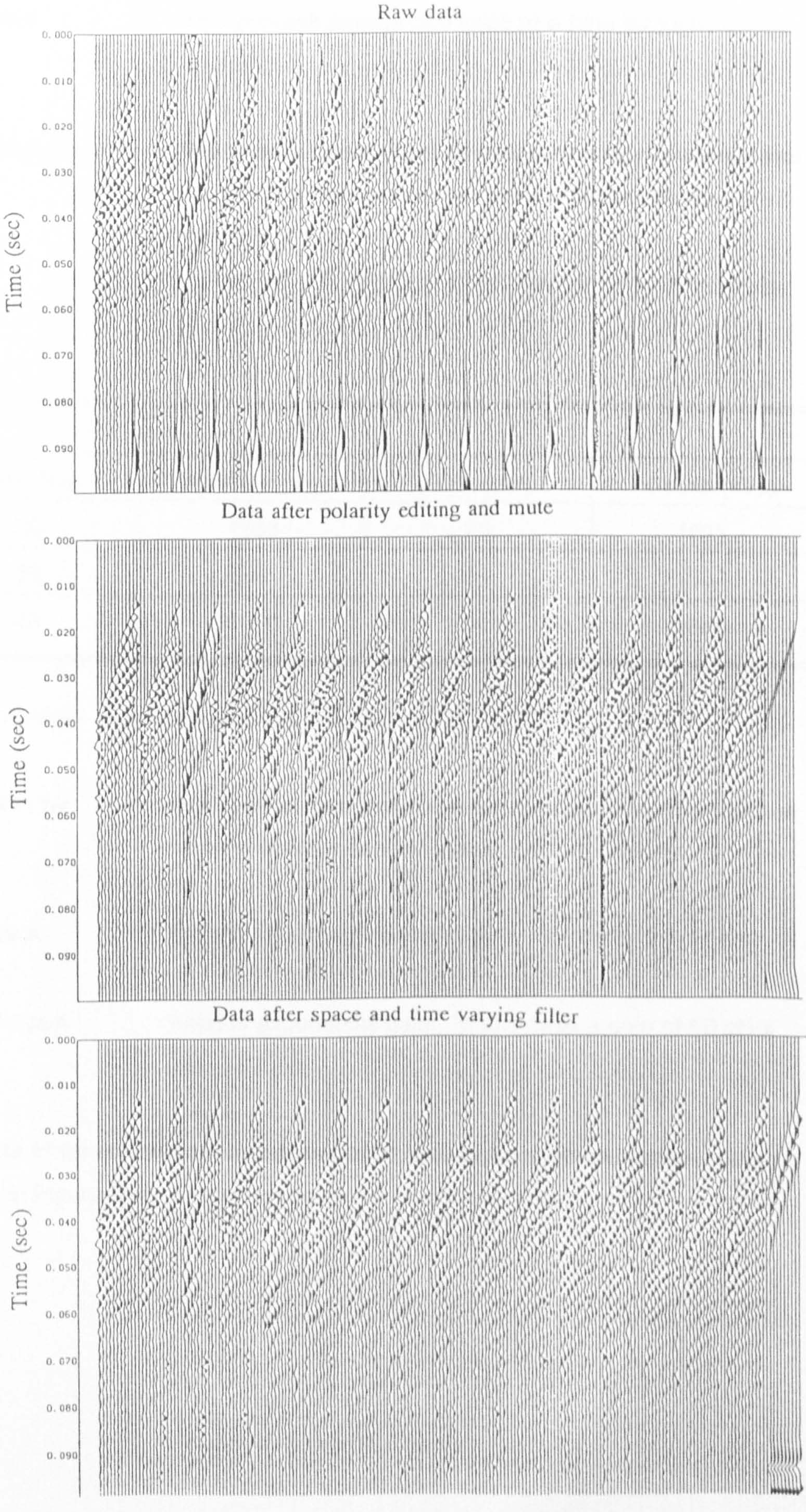
The space and time varying filter was used to further remove unwanted noise by removing spurious high and low frequencies across the whole data window. The improvement in data quality as observed in Figure 5.7 has resulted in a data set that will hopefully portray the actual geological conditions more accurately. This is essentially through the removal of unwanted noise and unwanted refraction information.

The stacking routine used is as shown in Figure 5.6; it has the following components:

Graph name - GEdit stack

Pool/Processor	Function
pre_1	This pool contains the data traces as processed by the pre-processing routine described above.

Figure 5.7 Example of raw (unprocessed data) and data quality after subsequent processing steps.



semb — Computes semblance for velocity analysis. Applies Hilbert transform to input data. The velocity limits used for semblance were 1400 m/s to 2500 m/s (Figure 5.8).

null — This process passes one trace at a time through unchanged.

Velocity — Generates gridded RMS or internal velocity function. The velocity function is determined by picking from the semblance plot.
An example of velocities determined by picking from the semblance plot is :

CMP 10		CMP50	
Time (ms)	Velocity (m/s)	Time (ms)	Velocity (m/s)
26	1663	26	1621
36	1681	36	1663
48	1850	44	1668

Velocity analysis was performed at CMP gathers 10,15,20-60.

nmo two — Performs normal moveout correction on input trace at port 1 using velocity trace at port 2.

stack — Stacks, sums and scales data.

expgain — Applies exponential gain. In this case a gain of 60 dB/s over 100 ms.

The effects of these various processes on the data at the various stages can be observed in Figure 5.9.

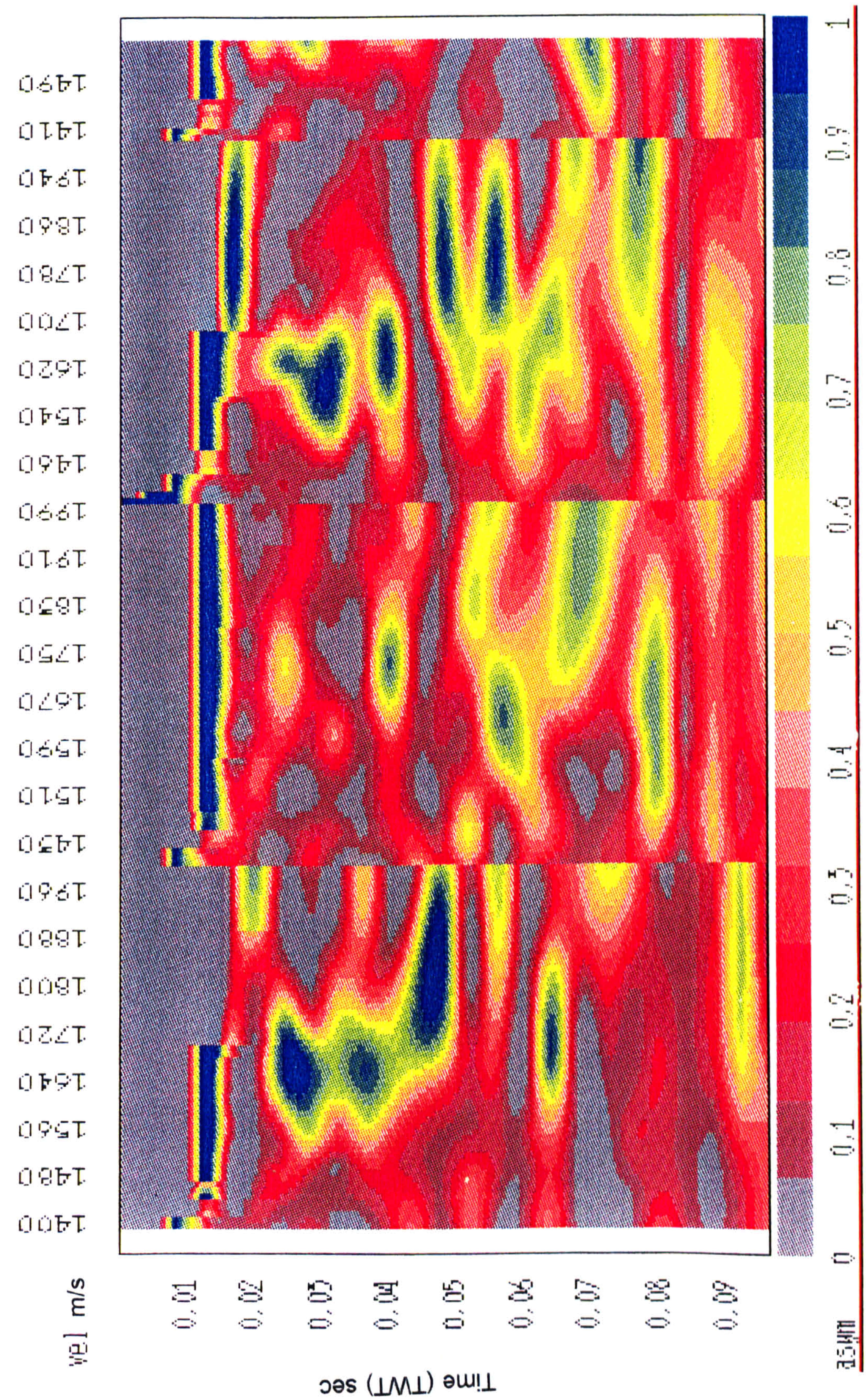


Figure 5.8 Example of semblance plot for CDP's 10, 15 and 20.

Figure 5.9 The results of the final data processing sequence at the various processing steps. In this case 'Raw' data refers to data from the previous processing sequence.

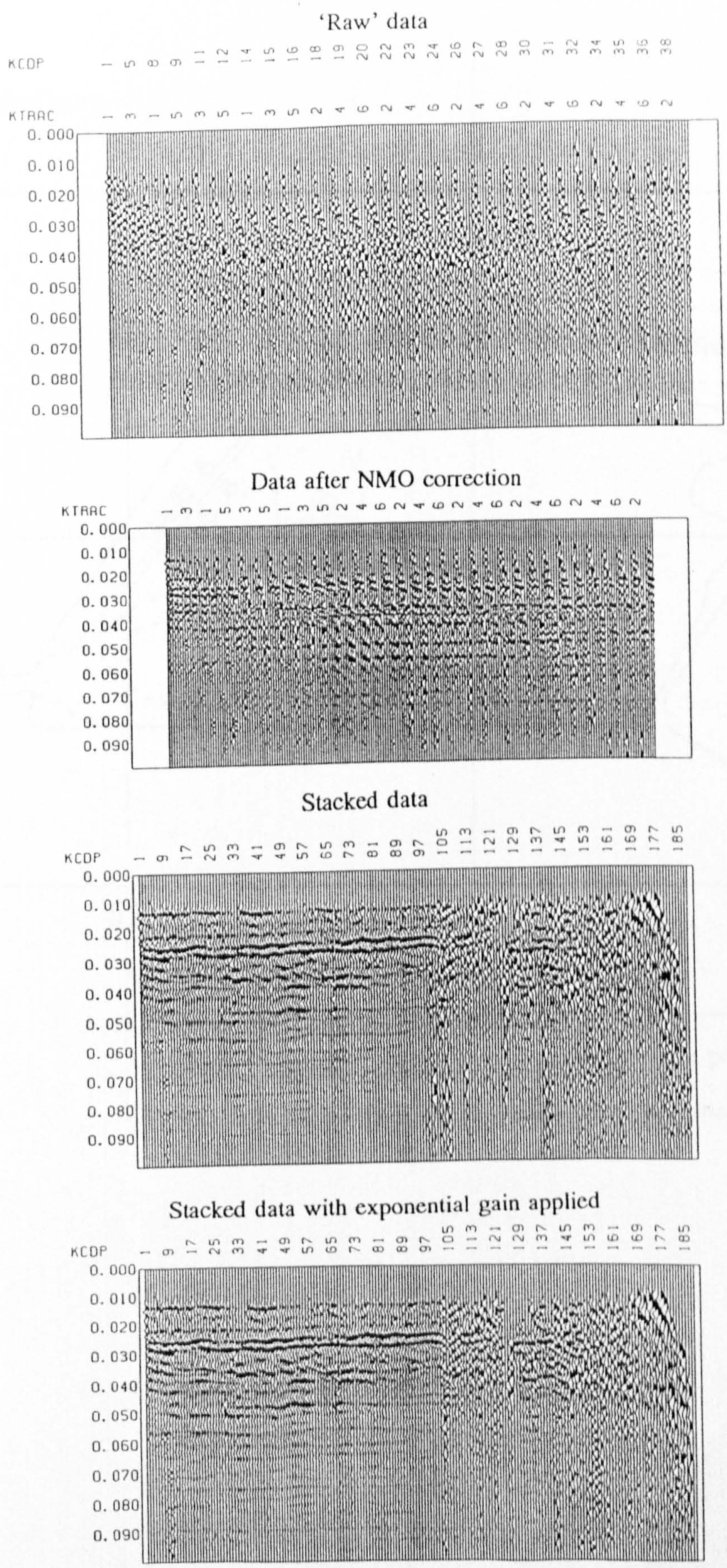
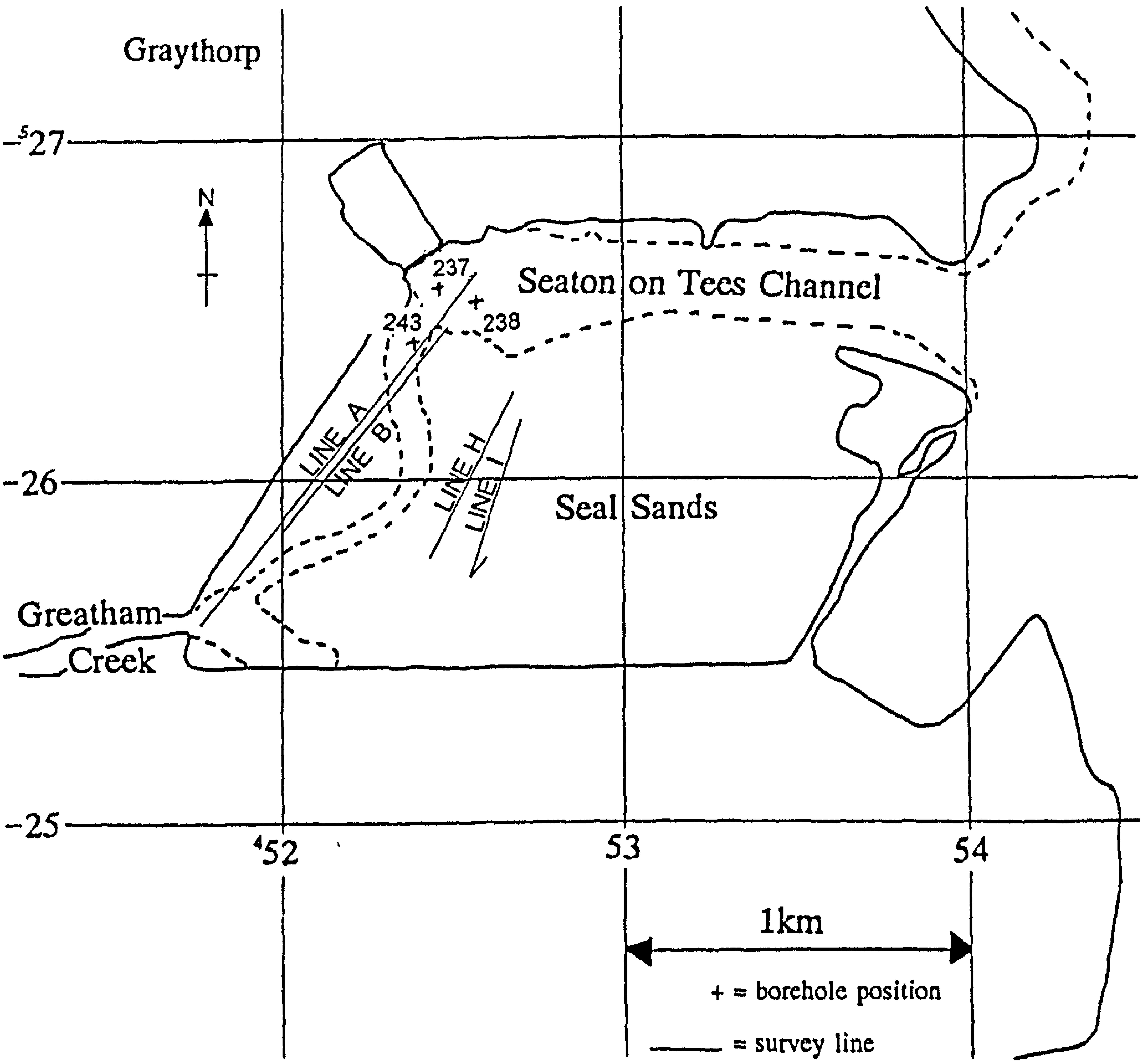


Figure 5.10 Location of boreholes and marine seismic lines presented as data examples.



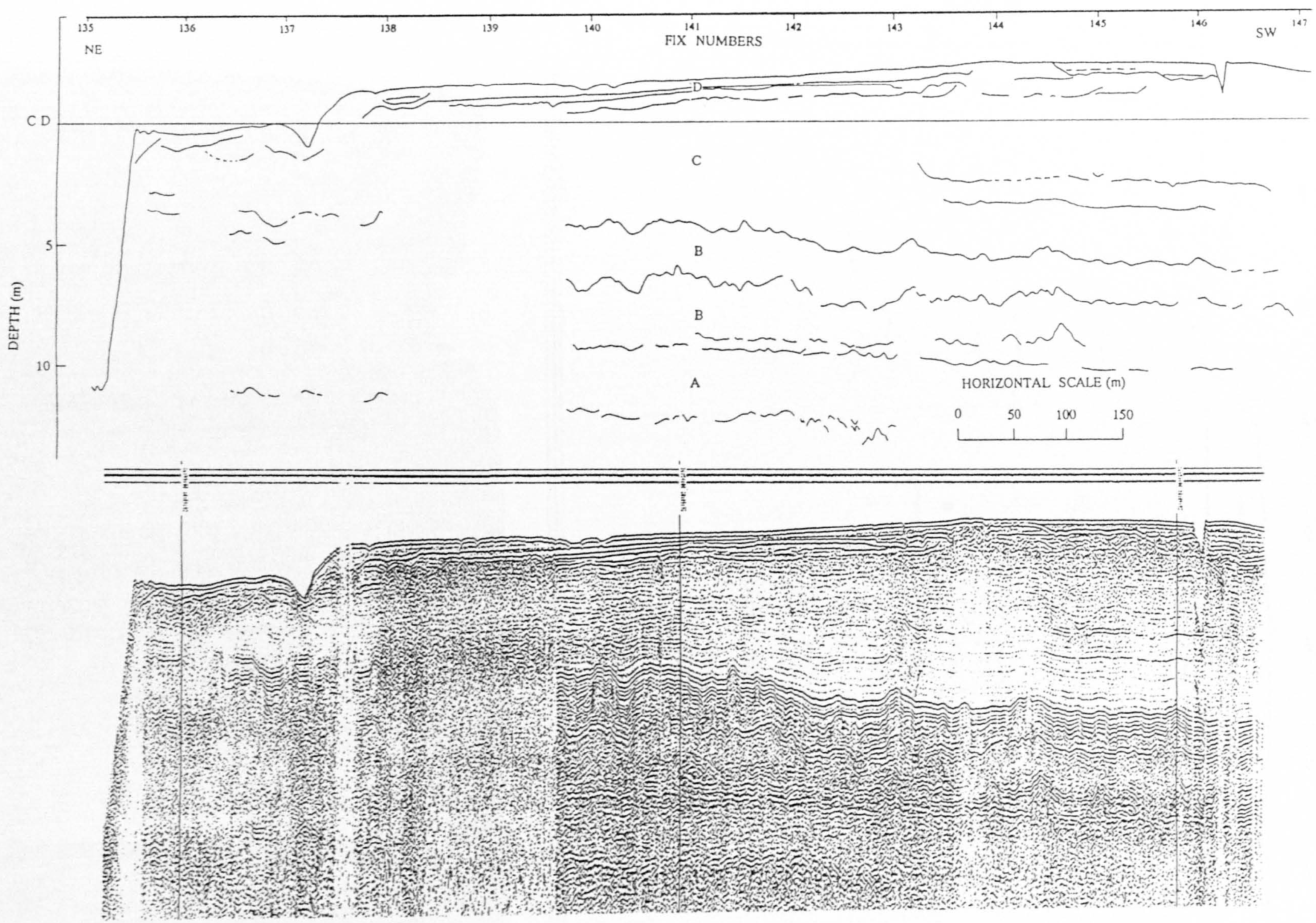


Figure 5.11 Analogue marine data (line A) with interpretation showing significant reflectors.

Figure 5.12 Analogue marine data (line B) with interpretation showing significant reflectors.

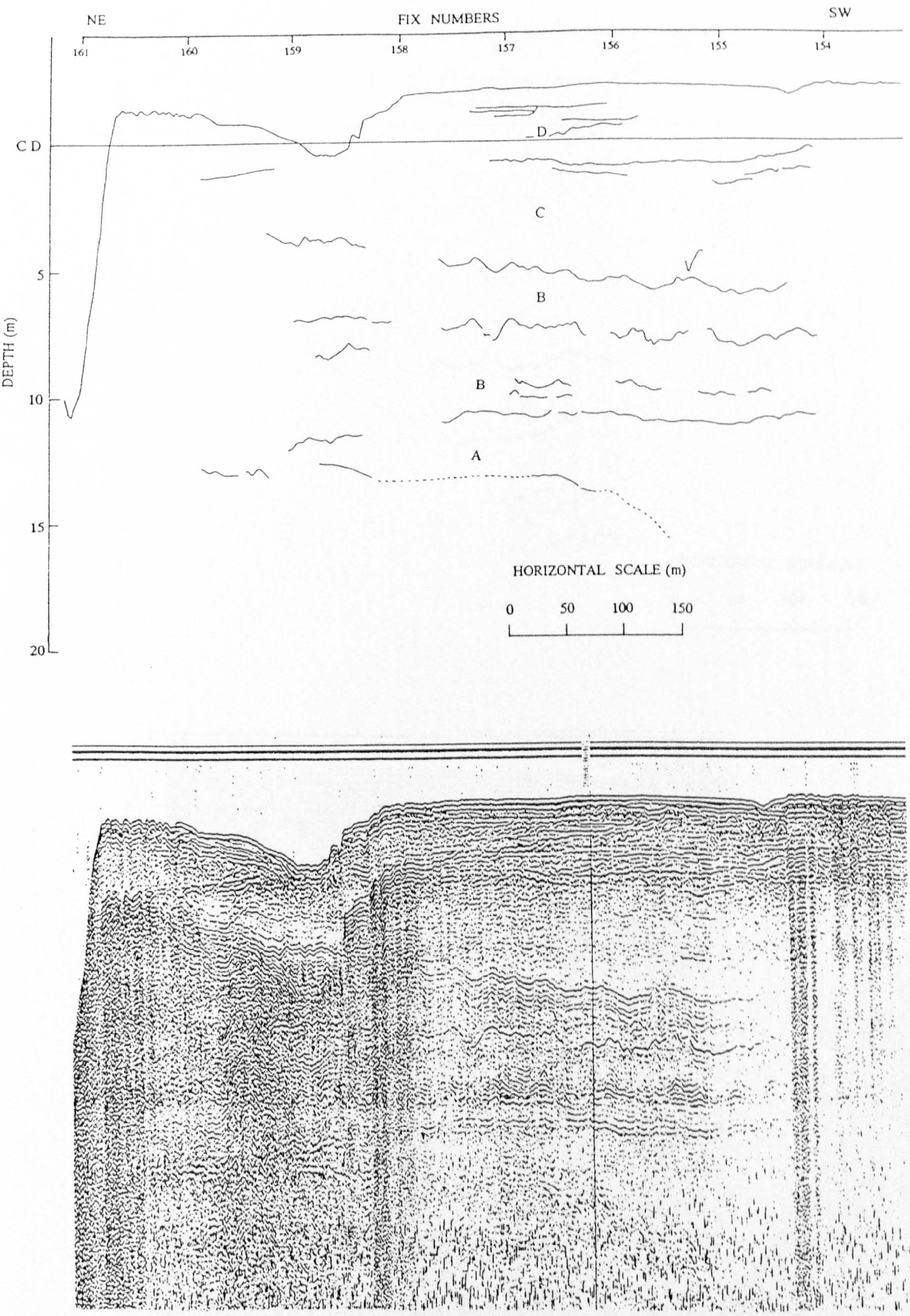
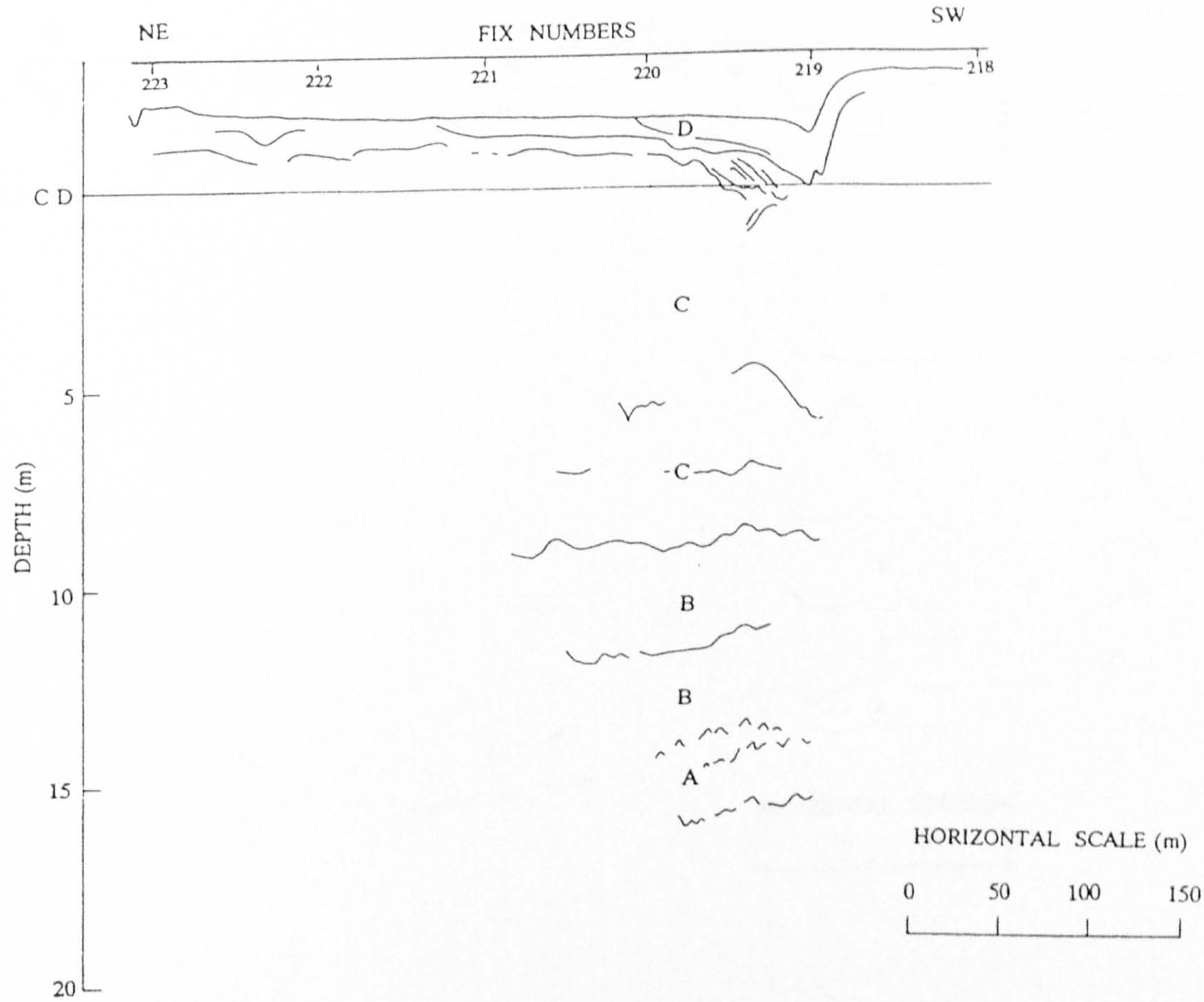


Figure 5.13 Analogue marine data (line H) with interpretation showing significant reflectors.



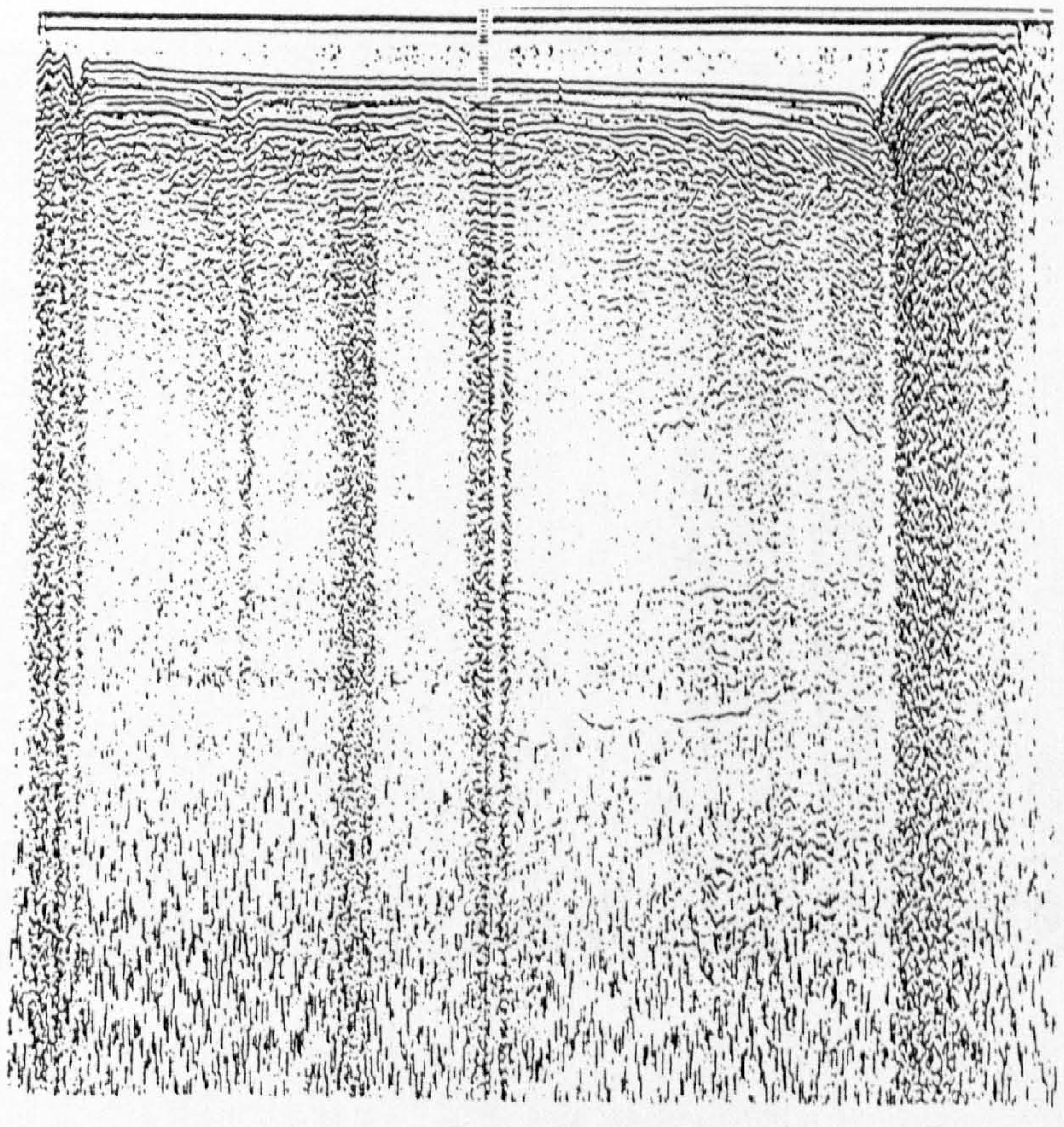
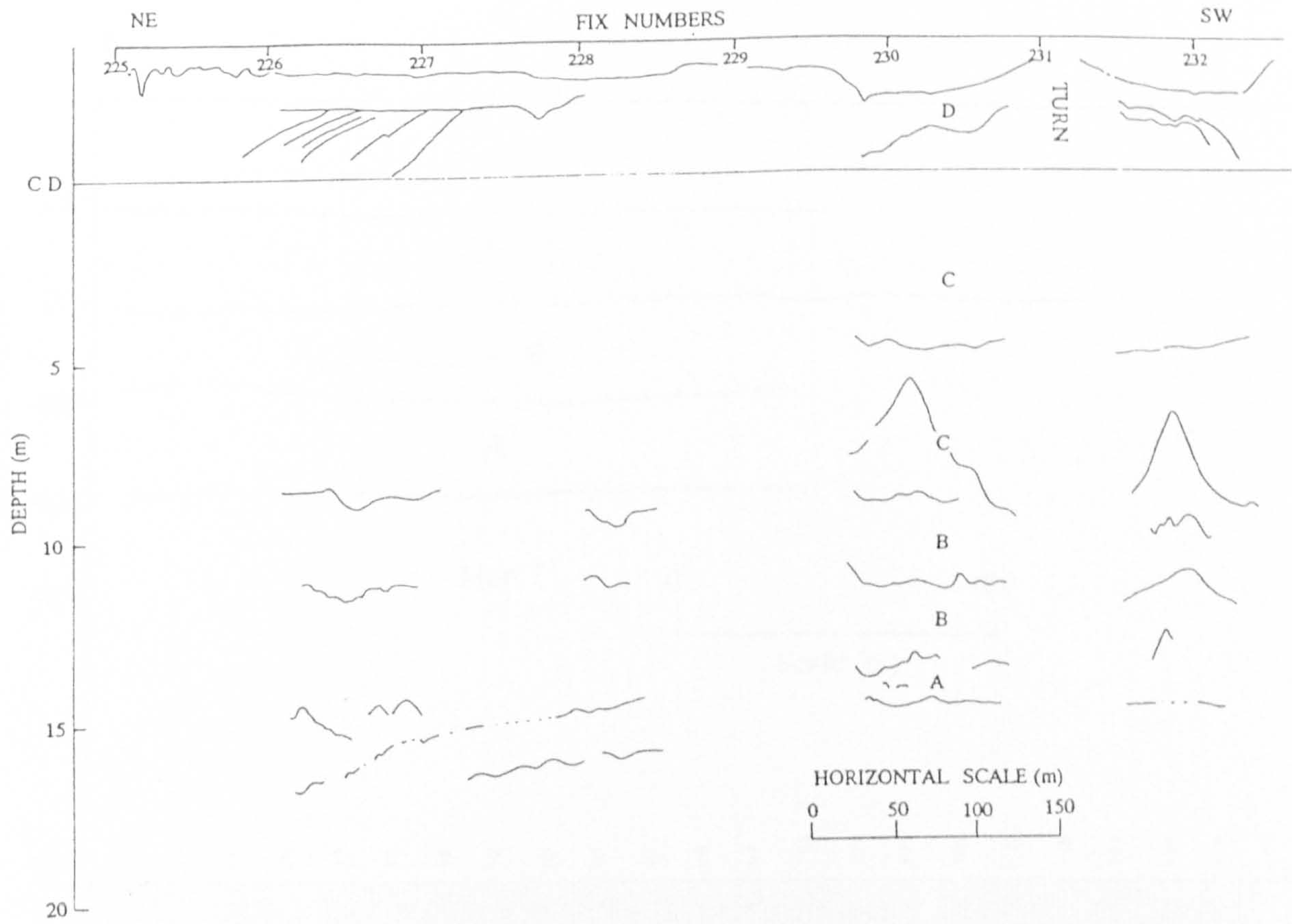


Figure 5.14 Analogue marine data (line I) with interpretation showing significant reflectors.



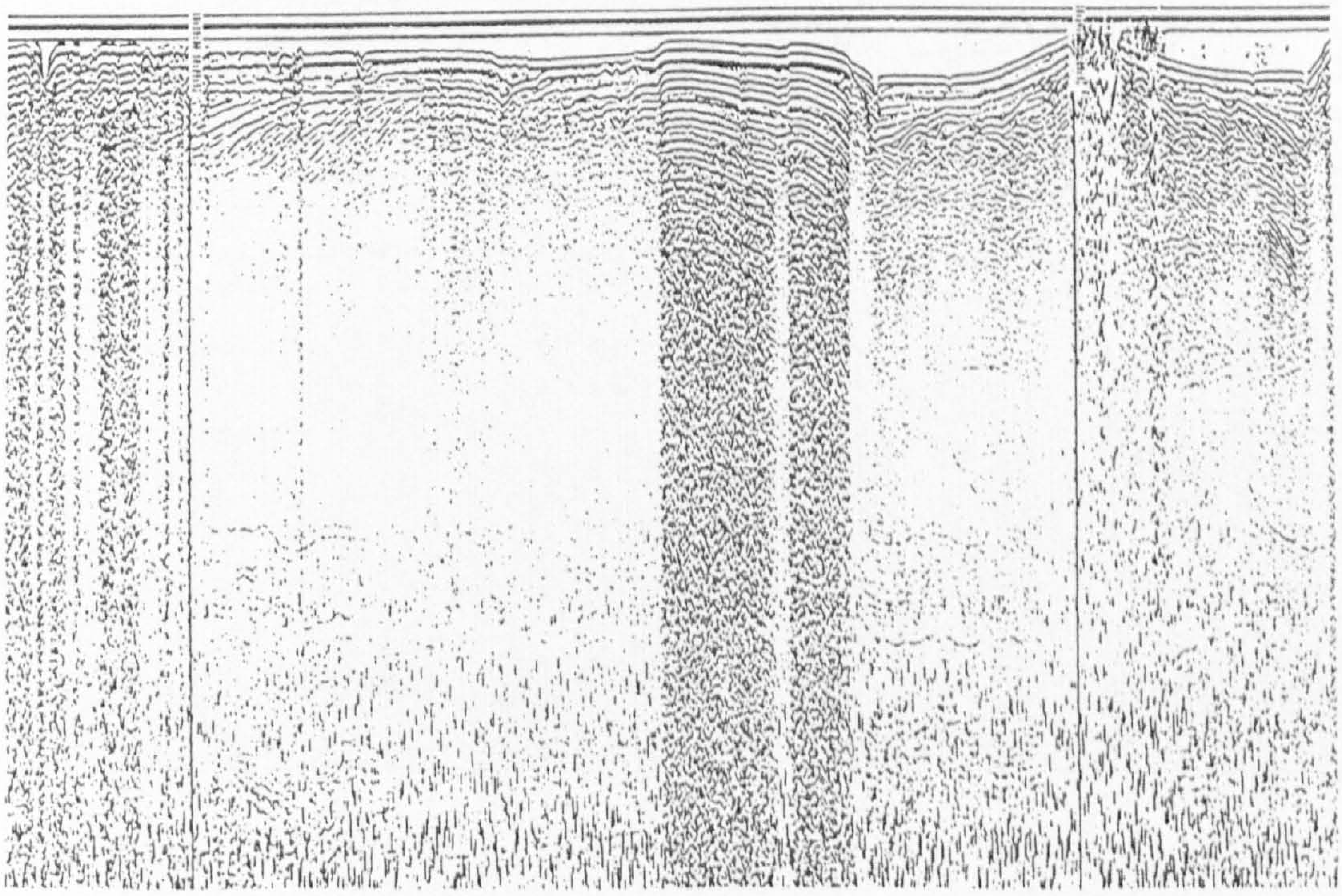


Figure 5.15 Processed land data (line 1) with interpretation showing significant reflectors.

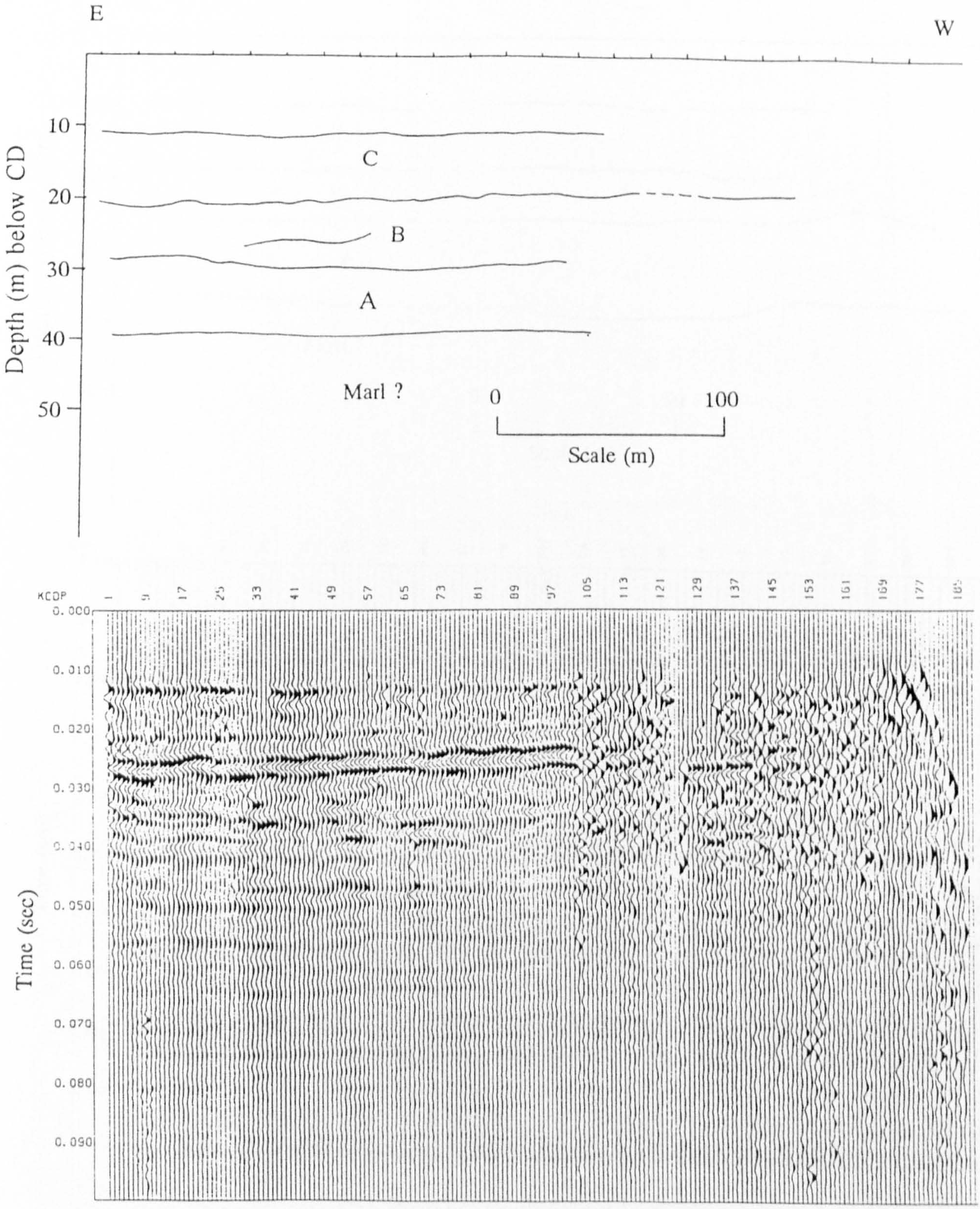
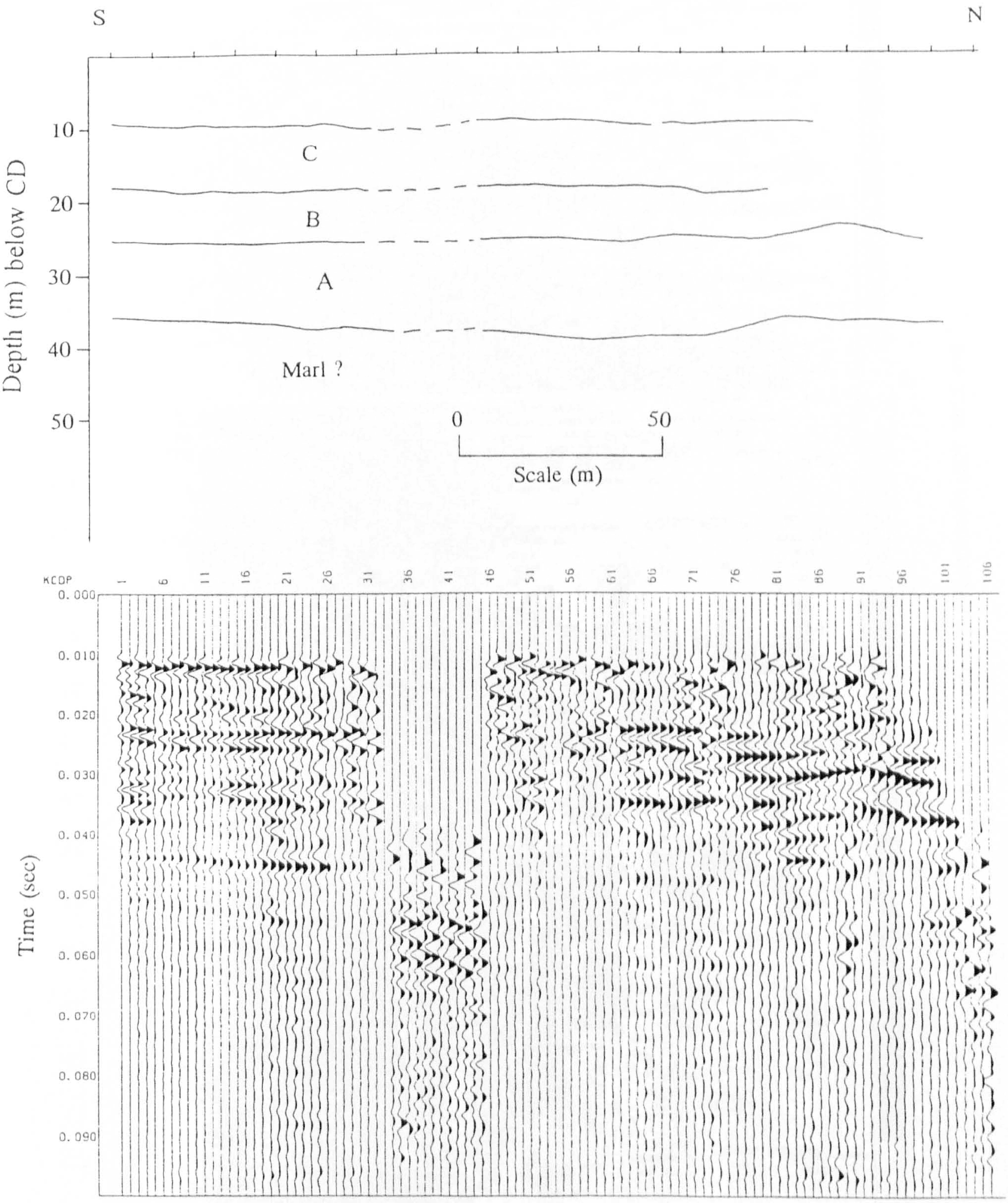


Figure 5.16 Processed land data (line 2) with interpretation showing significant reflectors.



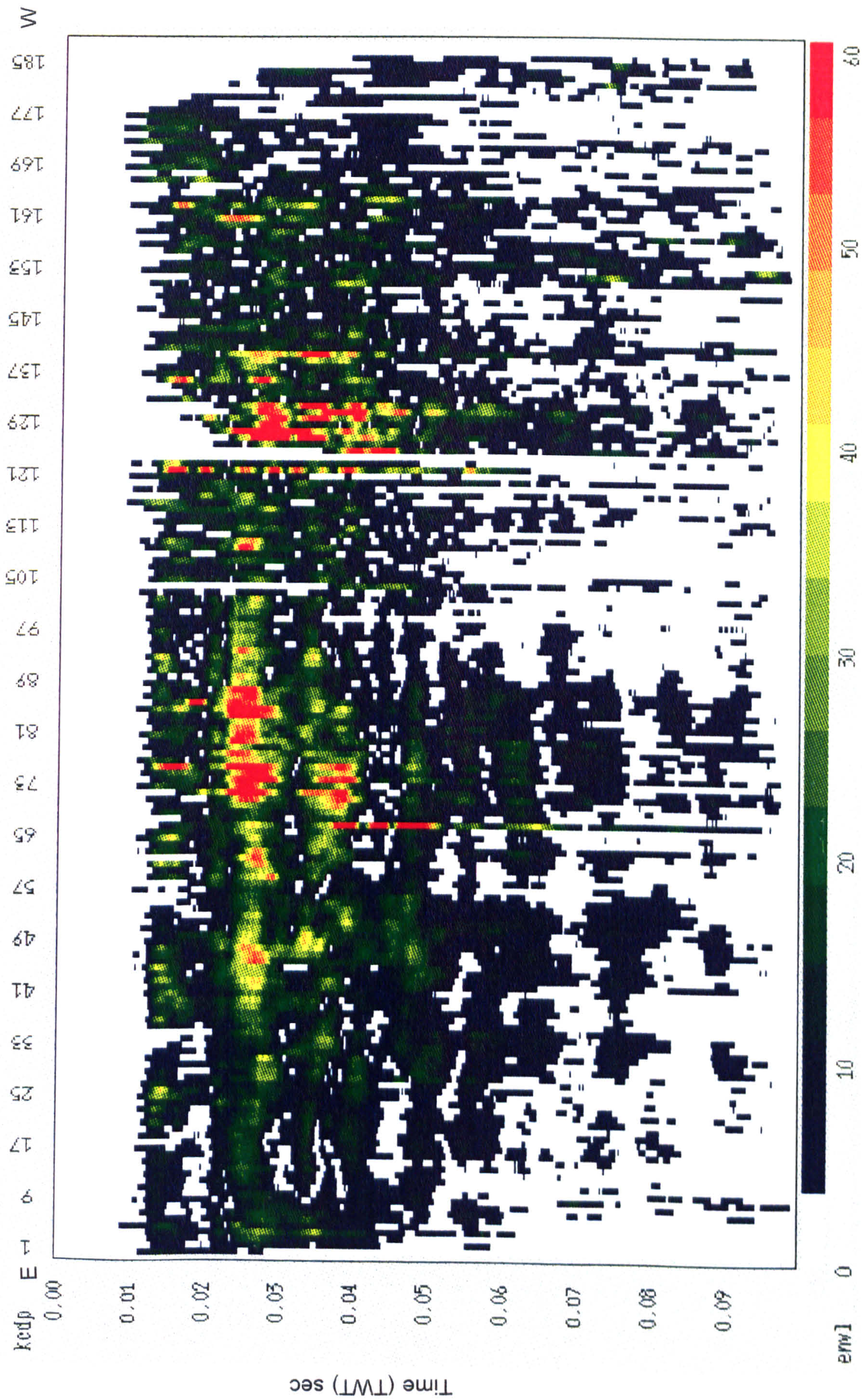


Figure 5.17 Instantaneous amplitude plot, land line 1.

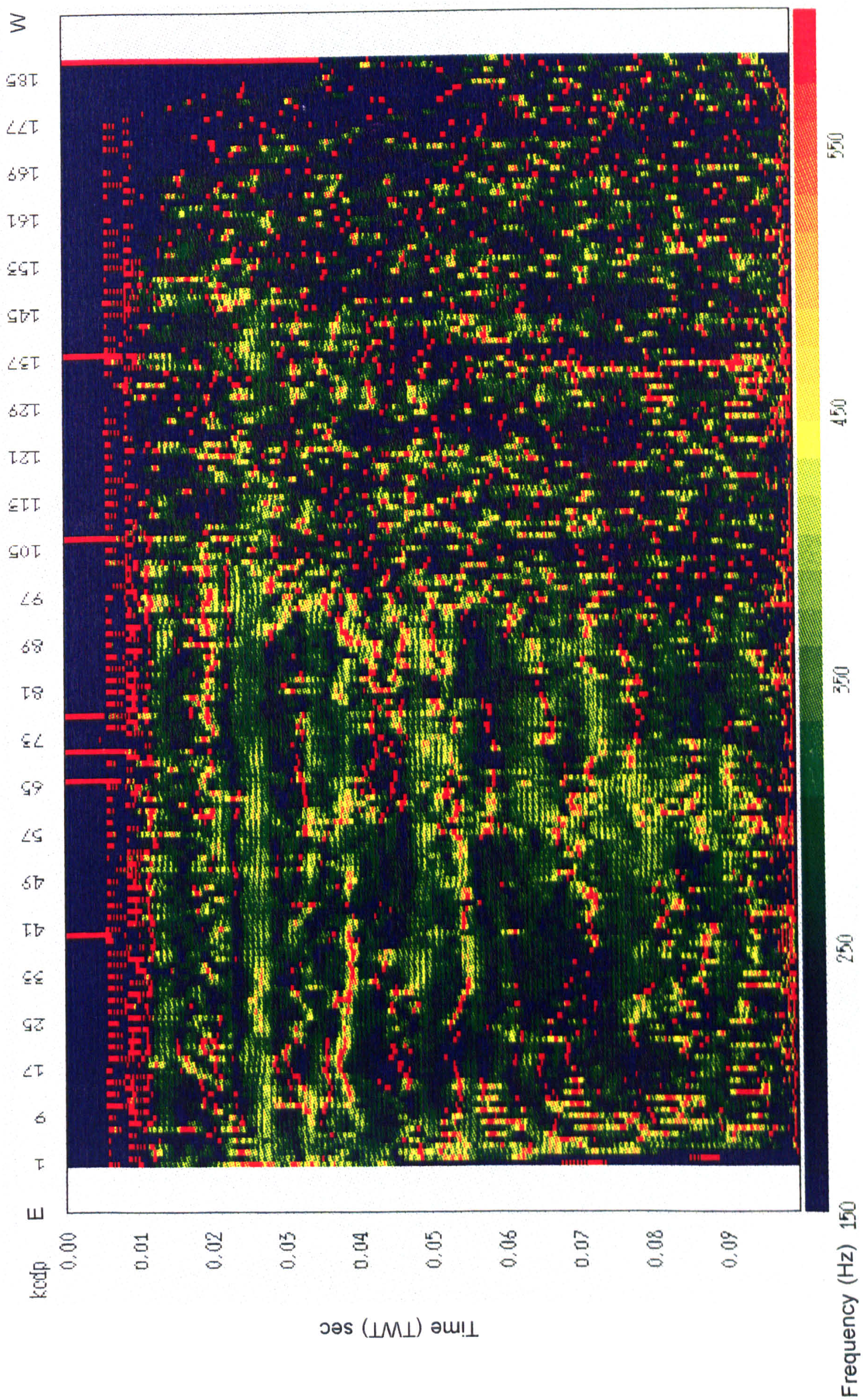


Figure 5.18 Instantaneous frequency plot, land line 1.

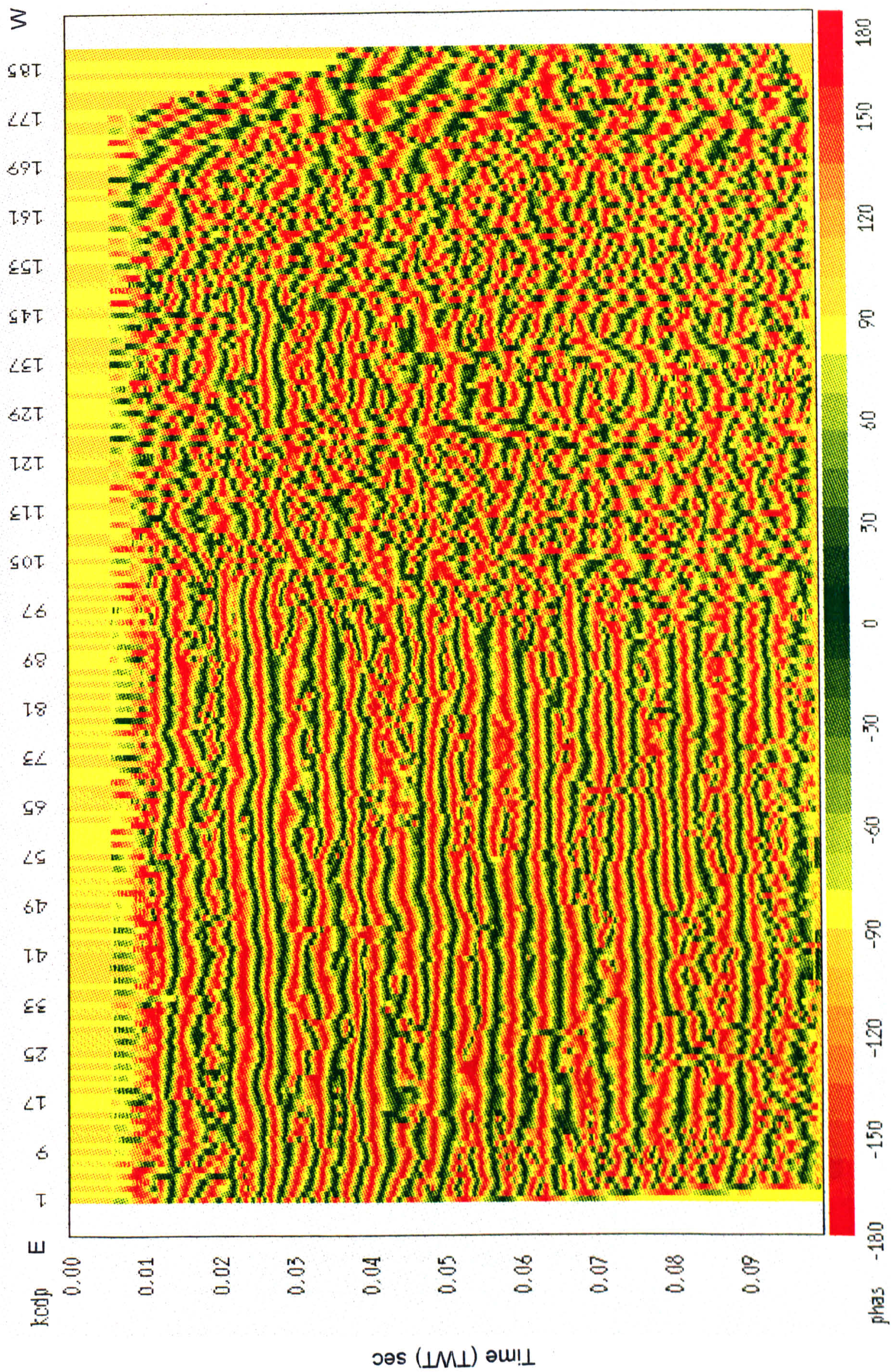


Figure 5.19 Instantaneous phase plot, land line 1.

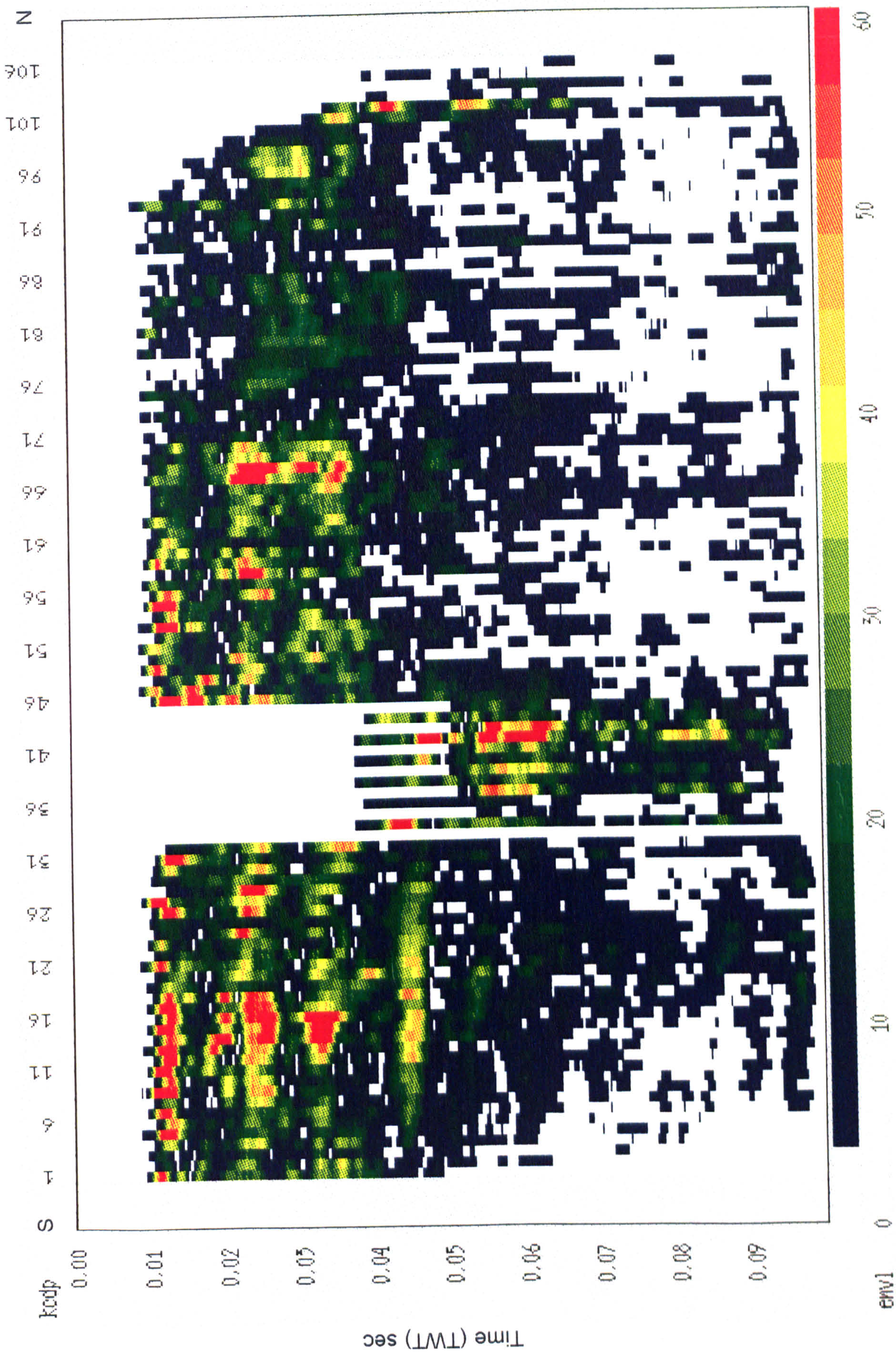


Figure 5.20 Instantaneous amplitude plot, land line 2.

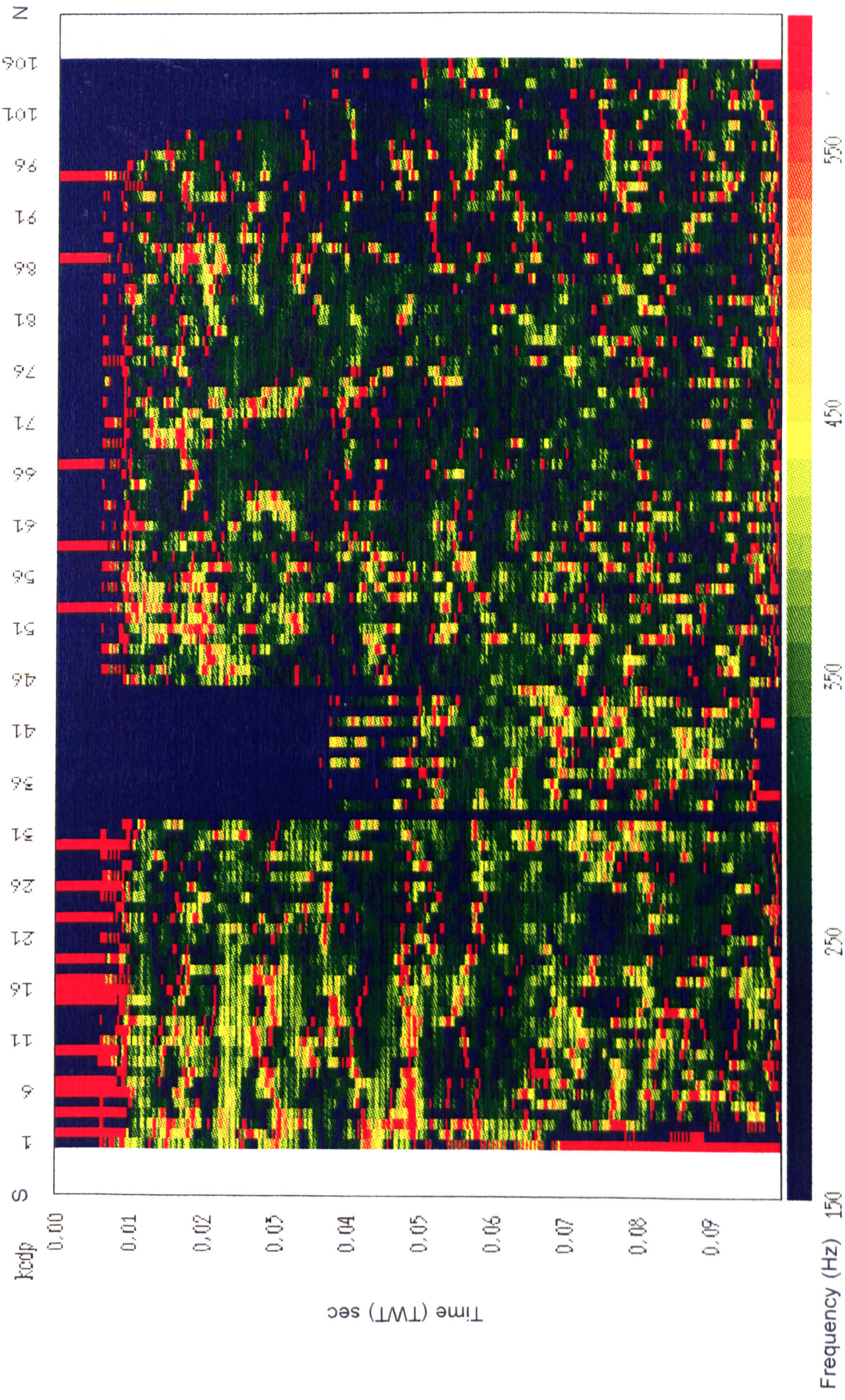


Figure 5.21 Instantaneous frequency plot, land line 2.

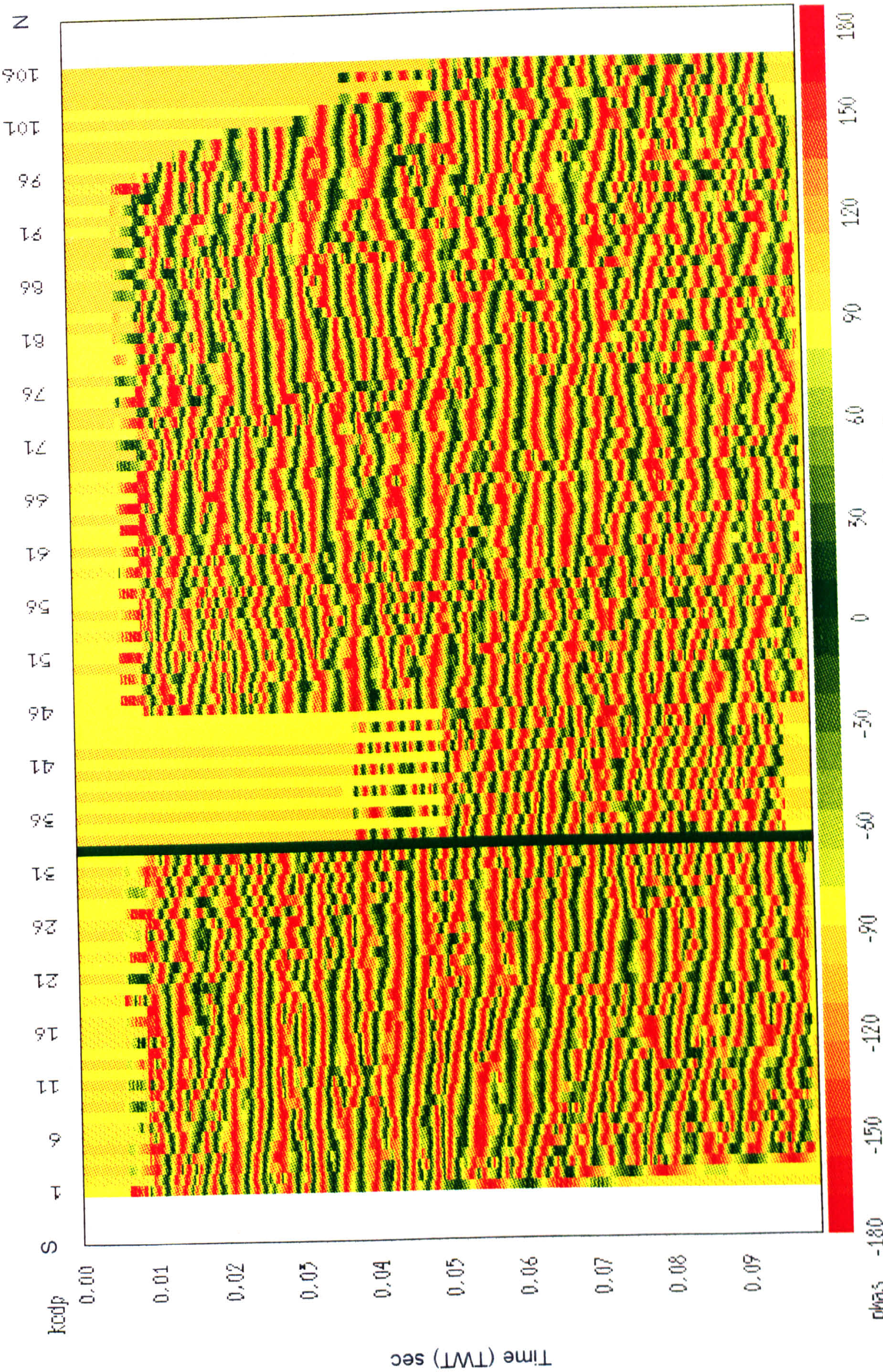


Figure 5.22 Instantaneous phase plot, land line 2.

Figure 5.23 Contour plot of top of unit A (m CD).

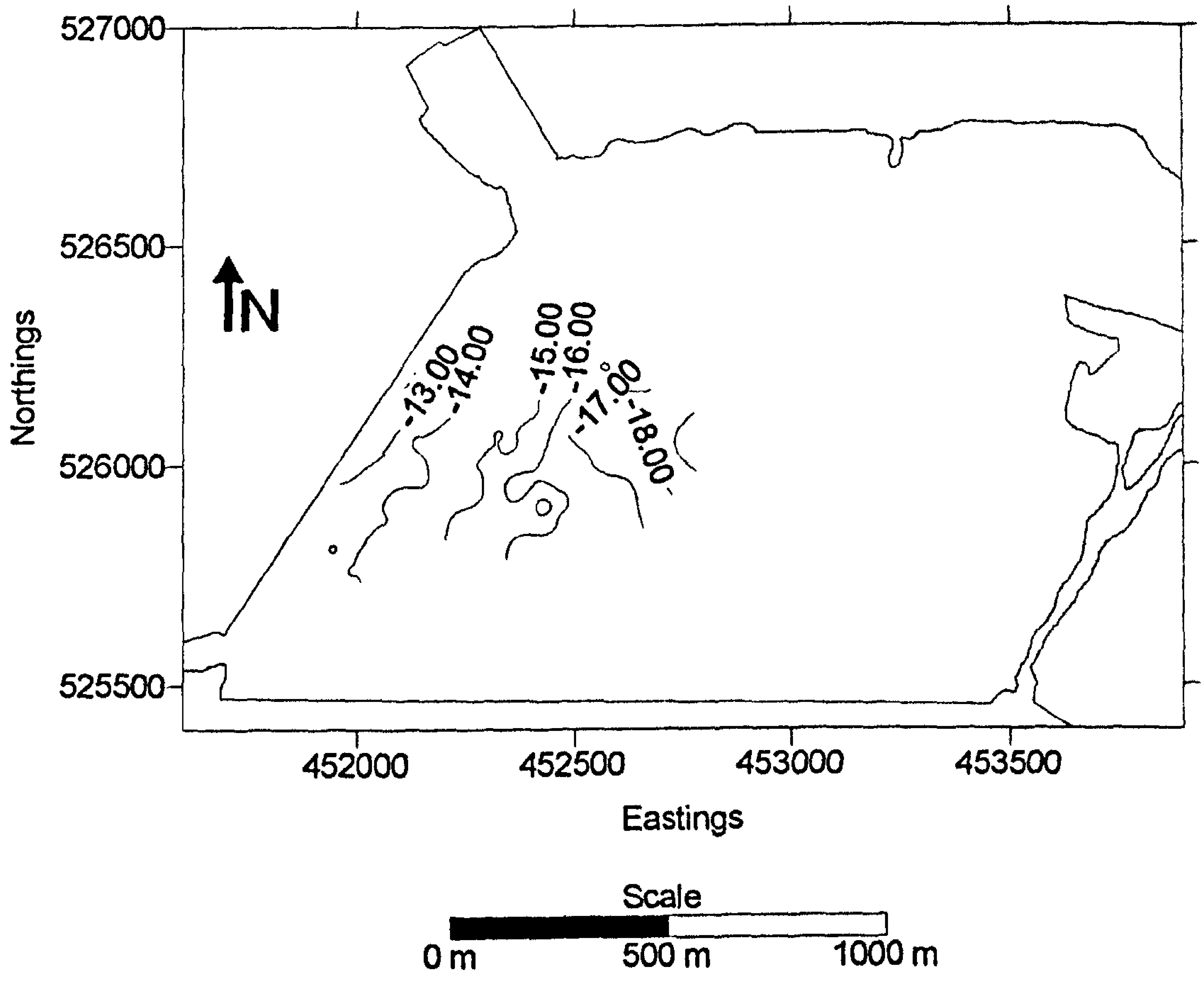
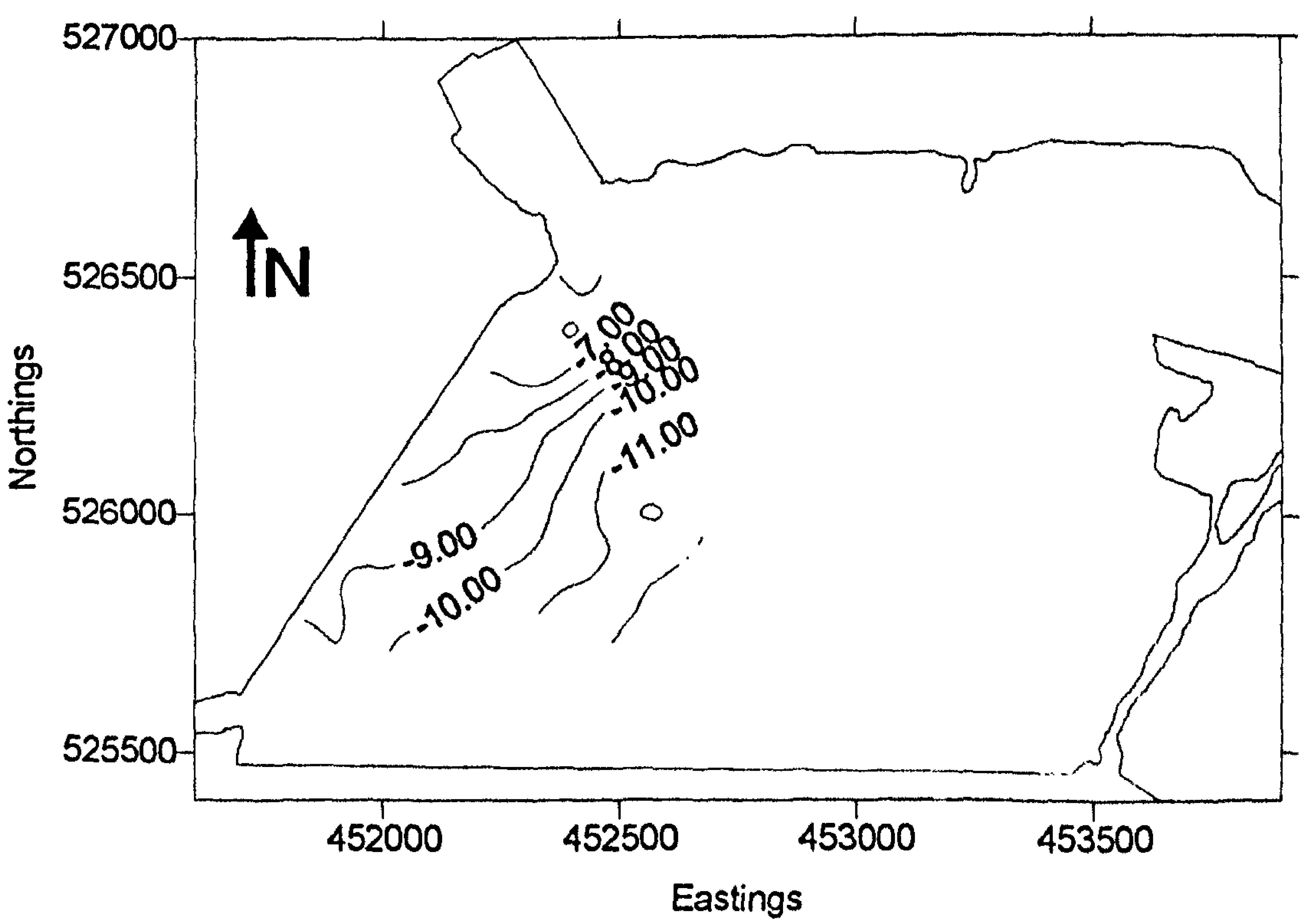


Figure 5.24 Contour plot of top of unit B (m CD)



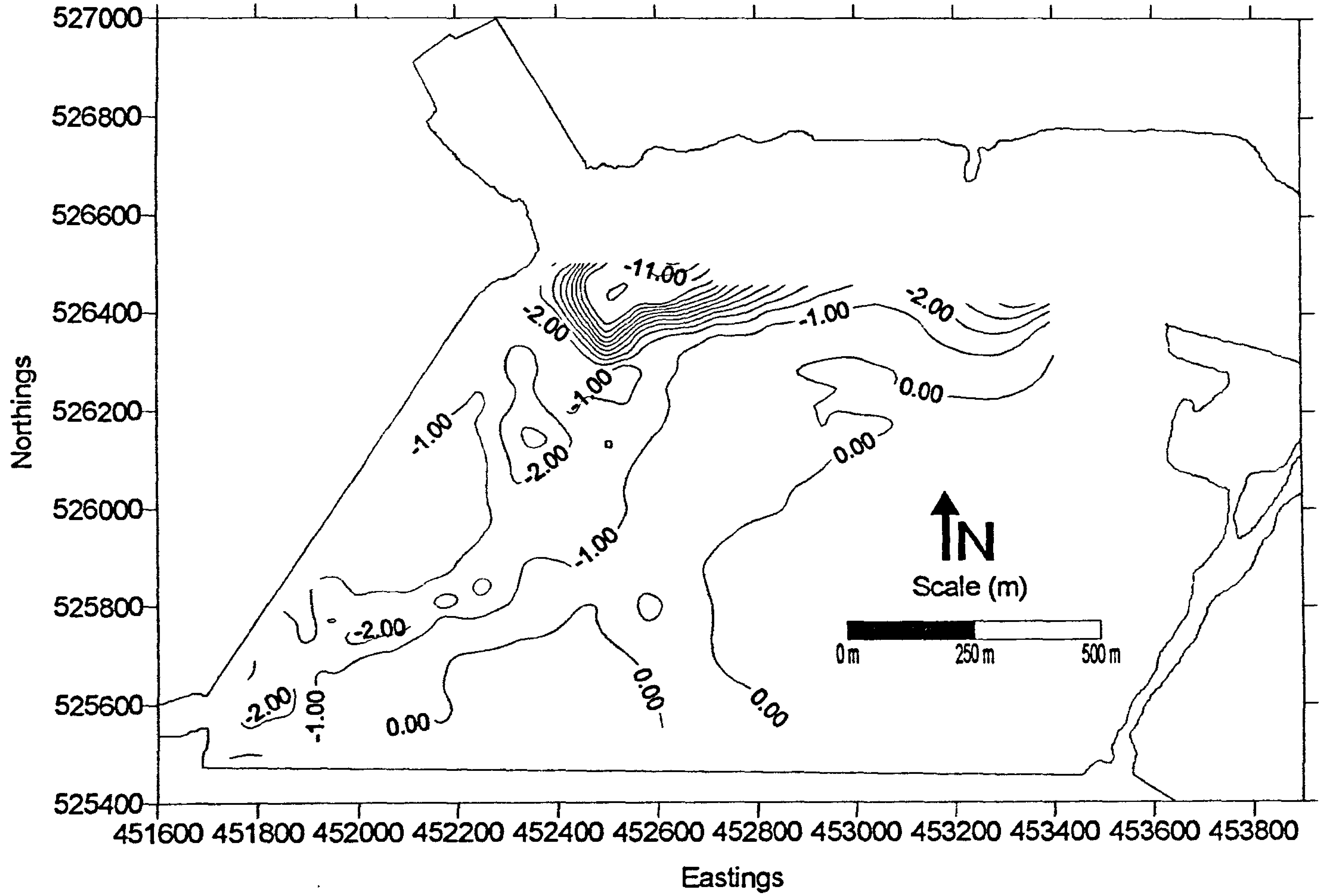


Figure 5.25 Bathymetry of Seal Sands as determined by marine survey (m CD).

5.3 Seismic stratigraphic interpretation

To assist in the interpretation a number of representative data examples (the positions of which are shown on Figure 5.10) and contour plots have been selected for discussion. These include examples of analogue marine data with a corresponding interpretation (Figures 5.11 - 5.14), processed and interpreted land data (Figure 5.15 - 5.16), and displays of instantaneous attribute plots of the land data (Figure 5.17 - 5.22). Contour plots of various units of interest (Figure 5.23 - 5.24) have also been presented.

Although no common point exists where land and marine data demonstrate sufficient quality to allow a tie by overlaying the two data sets, it is possible to attempt a correlation. The marine and land data have been tied together by extrapolating unit B from the marine set (using its observed dip 0.2°) to where it intercepts a significant (high amplitude) reflector in the land data. Using this method the marine data successfully intercepted the land data at a predicted depth of approximately -18m CD. The land data can be related to CD using the bathymetry of the area as determined by the marine survey (Figure 5.25).

As previously discussed, the vertical resolution achievable by the two survey methods differs considerably. The land survey data has a resolution of approximately 2m and the marine survey of approximately 0.25m, this difference being a function of the frequencies of the seismic source characteristics.

The availability of an integrated data set that combines both survey methods does however have some advantages. The penetration achievable with the land survey seismic source (a sledgehammer and metal plate) is significantly greater than that achieved with a boomer due to the frequency dependent nature of attenuation as discussed in chapter 2.3. However, what the boomer lacks in penetration it compensates for in resolution.

Even with the low resolution of the land data it is clearly useful for the overall interpretation as it will identify the major geological boundaries and will tend to ignore thin beds within an overall similar lithological unit (because thin beds will be below resolution). The collection and processing of the land data also provides a true velocity that can be used to determine depths for both the land and marine data. In these respects an integrated marine and land survey is a useful combination.

5.3.1 Seismic sequence analysis

An examination of the survey data reveals what appears to be a fairly simple geological history as far as sequence analysis is concerned.

The units identified as A and B (Figures 5.11-5.16, 5.23 and 5.24) appear laterally continuous and roughly horizontal. Internal bedding within these units appears conformable, the only evidence of reflection terminations being at the northern end of the survey lines where reflections are truncated by the dredged Seaton-on-Tees channel.

Unit C appears to rest conformably upon unit B, and has in places low amplitude internal parallel reflections that show evidence of channelling.

The topmost unit, unit D, appears to rest conformably upon unit C. Unit D is nowhere thicker than 3m and shows complex internal bedding that is probably the result of channel migration and sediment reworking.

In summary, the deposits observed in the survey area appear, at least from stratal geometry, as a conformable succession with no apparent hiatus indicated. The subdivisions (i.e A - D) identified within the seismic sections are therefore based mainly on seismic facies appearance and are discussed below.

5.3.2 Seismic facies analysis

The land data in combination with borehole data have identified what is thought to be the Keuper marl (identified in the area by Kent, 1980). The surface of the marl is between 43 - 47msec (TWT) (a depth of -35 to -39m CD). The land data (Figures 5.15 and 5.16) show beneath unit A a number of low amplitude reflections that are laterally continuous. These events are more obvious on the phase plots (Figures 5.19 and 5.22) which are non-amplitude dependant displays. Although it is not possible (at this level of interpretation) to say if these events are real or artifacts, it should be noted that they do appear to have some unique internal structuring suggesting they may be real. The interface between the marl and unit A is marked by a high instantaneous amplitude. The amplitude varies locally along the interface, suggesting variations in the physical properties, and reaches a maximum at the southern end of line 2 (Figure 5.17).

Unit A is observed over most of the survey area (Figure 5.23). It dips to the ENE and is observed to vary from -13m CD to -19m CD with an external structure that can be described as sheet drape. There is a significant reflector, marking a possible base to unit A, observable on the marine survey lines (Figures 5.11 - 5.14). It is not clear, due to the limits of boomer penetration, whether this is the base of unit A or whether it extends to the top of the proposed marl.

The internal bedding of unit A is mainly chaotic but occasionally faintly subparallel. On the land data unit A is displayed simply as a massive deposit that is fairly horizontal. The instantaneous amplitude displays (Figures 5.18 and 5.21) show, as mentioned above, the base of the unit to have a laterally variable amplitude. At the top of the unit there is a similar situation in that amplitudes are also variable but with, on the whole, more frequent occurrences of higher amplitudes. Instantaneous phase displays (Figures 5.19 and 5.22) as mentioned above are, in this case, better suited to identifying reflectors and reveal a number of mostly horizontal beds not observed on the variable area displays (Figures 5.15 and 5.16).

The instantaneous frequency displays (Figure 5.18 and 5.21) do not appear to show much lateral coherency or display much variation throughout the seismic section as a whole. There is however a trend for the significant reflectors identified to have higher frequencies than existing within the units themselves. At the boundaries of unit A the instantaneous frequency is typically 330 - 420Hz.

Unit B was found to be laterally extensive (Figure 5.24). It dips to the SE from -6m CD to -12m CD and appears as a wedge shape deposit the thickest part being where it is shallowest. The unit is dominated by slightly incoherent subparrallel beds becoming, at the top of the unit, strongly coherent parallel beds that are highly reflective. There is also within the overall unit a notable internal and significant reflector.

The top of unit B is marked by a high acoustic impedance contrast resulting in a high instantaneous amplitude. The amplitude although strong in places is variable which indicates a possible variable lithology across this interface.

The instantaneous frequency displays are, as mentioned previously, variable but are predominantly between 370 - 460Hz along the top of unit B.

Unit C was found throughout the survey area. It has an internal parallel bedding that is on the whole noticeably less coherent and of lower amplitude than unit B. Within unit C there is evidence of channel erosion with a divergent fill pattern.

The instantaneous amplitude displays show that the top of the upper boundary of unit C is marked as a high amplitude event. This amplitude is however lower than that at the base of the unit. The instantaneous frequency display shows the upper boundary of unit C has an instantaneous frequency of approximately 370Hz.

Unit D is of variable thickness across the survey area but is nowhere thicker than 3m. The unit consists of complex prograding and parallel high amplitude reflectors. There appears, in places, to be gas trapped at the base of unit D, the evidence for this gas being acoustic blanking of the units beneath unit D. An example of this can be seen in Figure 5.11 between fixes 138 and 139. The presence of gas below a water saturated medium could be proven by digital data as gas bearing sediments manifest themselves as a high amplitude reflector (at the surface) with high instantaneous frequency and reversed phase.

5.3.3 Geological interpretation and discussion

The integration of the marine and land survey data has provided some points of interest, specifically it has given a further insight into the geological and geotechnical conditions at Seal Sands.

From an analysis of the analogue seismic data the area does not appear to have been subjected to a particularly complex depositional history. The majority of the units i.e. B - D appear to be conformably deposited indicating an uninterrupted succession of sedimentation. The geology of the units at Seal Sands and their relative relationships will be discussed here.

Unit A, as discussed, is a chaotic deposit. A chaotic reflection configuration, as discussed in chapter 3, suggests a disordered arrangement of reflection surfaces. It can be interpreted as either strata deposited in variable, relatively high energy settings or as initially continuous strata which have been deformed. These interpretations could both be accurate as borehole logs, which correlate well with the interfaces identified from the seismic data, ascribes this unit to being a stiff glacial clay interbedded with stiff laminated clay (Figure 5.4, borehole 237, at a depth of -9.15m CD). According to Stoker *et al.* (1992), the formation of a significant acoustic reflecting or scattering surface, by overconsolidation or iceberg ploughing, may result in no internal acoustic stratification even if the unit is lithologically stratified.

Unit B appears to rest conformably on unit A and has at its base bedding which is, relative to unit A, less chaotic becoming hummocky which in turn becomes at its top parallel bedding. The transition to parallel bedding suggests more uniform rates of deposition in perhaps an environment of lower energy. The parallel bedding within this unit and less so in the units above appear to be distorted. This distortion becomes less accentuated in the overlying units. The cause of the distortion is unknown but could be due to deformation by glacial processes or post depositional disruption caused by mobile fluids as, for instance, the sediment de-waters.

Unit B is most probably the deposit described as a stiff glacial clay with faint laminations and occasional cobbles and boulders in borehole 237 at a depth between -3.05m and -9.15m CD and, in borehole 243, between a depth of -3.25m and at least -6.95m CD (Figure 5.4).

The lateral variability of instantaneous amplitude that exists at the top of unit B indicates variability of density and/or velocity.

Unit C is dominated by low reflectivity and parallel bedding indicating a fairly homogenous unit deposited in a possibly low energy environment. The sediments of unit C appear to drape the disrupted unit beneath and these draped sediments become more horizontal as sediment thickness increases. The evidence of channelling with subsequent infilling with acoustically similar material indicates deposition in a marine/fluvial environment. This unit is interpreted (from borehole data) as being stiff laminated clay/silty clay with sand layers and is identified in borehole 237 at a depth between -0.55m and -3.05m CD and in borehole 243 at a depth of between -0.35m and -3.25m CD (Figure 5.4).

Unit C, as identified from the borehole data, is not ascribed in the soil description as having a glacial origin. These clays and the clays beneath (unit B) are however both described as stiff. It is not clear from the borehole descriptions what criteria were used in the differentiation between a glacial and non-glacial clay. However, it is possible that the differentiation may have been attributed to a visual inspection. There is an obvious difference between these two clay types on the seismic data (best illustrated on Figure 5.11), the contrast in reflector strength being quite striking. It is possible that this variation in facies could be attributed to the fact that the lower unit (B) is overconsolidated (and therefore denser) and that the overlying unit (C) is normally consolidated. The stiffness of the lower unit could be attributed to it having a subglacial origin. The stiffness of the upper unit could potentially come about due to its deposition in, for instance, an intertidal environment (as at present) where layers were repeatedly deposited and desiccated in the intertidal zone.

Unit D probably consists of the soft silty sands and clays observed at the surface today, the complicated internal structuring being the result of the intertidal drainage that prevails at the present time. The higher reflection strength within the unit (than that of the unit beneath) could indicate the presence of possibly more sandy deposits that could potentially have come about due to the changed hydraulic regime caused by land reclamation in the area.

5.3.4 Environmental reconstruction

Using the seismic, borehole and published geological work it is possible to hypothesise a fairly simple history of the area:

Deposition of glacial units A and B
Deposition of estuarine/lacustrine unit C
Deposition of estuarine unit D

Glacial till is extensive over the survey and surrounding area. Agar (1954) reported these deposits to be thickest in the north and west thinning to the east and south. This description of thinning beds appears to be confirmed by the wedge shape of unit B which dips to the SE. The glacial units observed probably relate to the Skipsea and Withernsea tills of Madgett and Catt (1978).

Agar (1954) described a laminated clay of lacustrine origin in the area around Seal Sands (Figure 5.3). This could possibly relate to unit C interpreted as a laminated clay/silty clay with sand layers. Such a lacustrine origin could account for the drapped appearance of the unit. Alternatively this unit could represent a combination of terrestrial and estuarine deposits. Whatever the depositional process it appears that the unit was deposited in the post glacial conditions either before sea level rose (a lacustrine origin) or as sea level rose (an estuarine origin) or a combination of both. It is possible to determine that the area was subjected to erosion by water towards the top of the unit due to the observed channelling.

The soft silty sands and clays of unit D with their associated complicated bedding patterns could be associated with sea level reaching its present maximum, the reworking of this unit being caused by repeated erosion and infill of gulleys caused by tidal waters repeatedly flooding and draining the area.

5.4 Discussion and conclusions

The survey methods used in the intertidal zone were successful, in particular the Seistec providing excellent data quality where conditions permitted.

The seismic stratigraphic interpretation method has been demonstrated to be of some use in this case study. Much of the information that can be gathered about the geological history of an area can be gained from stratal architecture. However for this to be most effective it requires reflectors to terminate so that units can be placed within the context of an overall depositional environment. Such termination patterns were, however, not apparent in the area surveyed.

Seismic facies analysis has been proven in this case study to be a particularly useful tool. It has provided strong evidence, mostly through an examination of reflector strengths, to help identify and delineate the various lithological units and has allowed comment on their composition and variability as well as helping identify possible geotechnical boundaries relating to consolidation state. The geological boundaries interpreted from the seismic data have been correlated to borehole logs and proven to be lithologically significant.

The use of land methods to provide multichannel seismic data allowed the calculation of velocity information, and provided data in a suitable format to display instantaneous attributes with the potential to provide quantitative information suitable for the calculation of geotechnical parameters.

The land seismic method did however prove to be a slow method of data collection. In 20 minutes of marine profiling more area was surveyed than in 5 days of land surveying.

CHAPTER 6
Humber Estuary Case Study

6.1 Introduction

The Humber estuary was selected as a suitable location to be included in this project for a number of reasons. The estuary and more specifically Spurn Bight has an extensive intertidal area (virtually all of Spurn Bight is intertidal) that is protected from the open sea by the natural barrier of Spurn Head. This barrier helps to provide suitably sheltered conditions that allows small boat work. This in turn allows shallower water depths to be surveyed maximising inshore coverage. The very size and shallow water nature of the area has restricted previous surveys to the main channel of the estuary (i.e. McQuillin *et al.*, 1969) and this has resulted in a gap in the regional Quaternary knowledge of the area (i.e. Berridge and Pattison, 1994). Although little is known of the Quaternary deposits and geological history of Spurn Bight itself the surrounding area is well documented and, as such, could provide information to compare against any interpretation. This combination of factors made the site suitable to test the method of data acquisition (i.e. shallow water analogue and digital data acquisition) and to test the application of seismic stratigraphic interpretation to Quaternary deposits over a large area. This increase in the survey area may allow the identification and mapping of reflection terminations that were not observed in the Tees estuary case study. It would also hopefully provide some of the missing geological information in an otherwise already well documented area.

This chapter will initially describe some of the physical aspects of the estuary, the solid and drift geology and discuss how the Humber estuary itself has evolved throughout the Quaternary. The survey procedures will then be described and the interpreted data discussed in the context of the project aims.

6.1.1 Setting/general area

The Humber estuary has since 1992 been under study as part of the NERC LOIS programme. As a part of this study the University of Wales Bangor (UWB) performed a high resolution, digital and analogue, sub-bottom seismic reflection survey in November 1992.

The Humber estuary is situated on the east coast of England (Figure 6.1). The specific target area within the estuary was the north side of the estuary mouth in the Spurn Bight area around Trinity sands. Spurn Bight has a unique character and shape. It is a large intertidal area of some 40 square kilometres, resembling a bay that is separated from the North Sea on the east by the narrow shingle bank joining Spurn Head to the mainland, and on the west by the reclaimed land of Sunk Island (Figure 6.2).

The Humber is one of the largest estuaries in the United Kingdom, draining approximately one fifth of the area of England. Pethick (1990) describes the Humber as the type example of a macrotidal estuary, with a maximum tidal range of 7.2m and a marked tidal asymmetry. It has a maximum width of 14km at its mouth, and its tidal length is around 130km. Channel depth at high water exceeds 18m in the outer estuary.

While the tidal curve at Spurn is almost sinusoidal, with both flood and ebb times of 6.25 hours, this distorts upstream to give a 4.5 hour flood and an 8 hour ebb at Brough (Pethick, 1990). This results in higher flood than ebb velocities and a net input of sediments from the North Sea into the Humber. This accounts for the high suspended sediment concentrations in the estuary and the rapid accretion rates experienced in many of the intertidal areas.

Suspended sediment concentrations of 2000ppm are common in the estuary during the winter. This net input of sediment means that the physical size of the Humber estuary is effectively decreasing gradually in volume (Pethick, 1990). The turbidity maximum, and therefore maximum sediment concentration and deposition rates, occur in the vicinity of the Humber Bridge.

6.1.2 Solid geology (after Catt, 1990, 1991a, 1991b)

The solid geology of the area is of dipping Chalk which outcrops in the west to form the Yorkshire and Lincolnshire Wolds. Eastward the Chalk dips beneath an increasing thickness of Quaternary glacial deposits in Holderness and in the Lincolnshire Marsh (Figure 6.3). On the eastern side of the Vale of York there are narrow N - S outcrops of Jurassic rocks (mudstone, limestones and sandstones) and of Cretaceous deposits older than the Chalk.

Figure 6.1 The Humber region (after Ellis and Crowther, 1990).

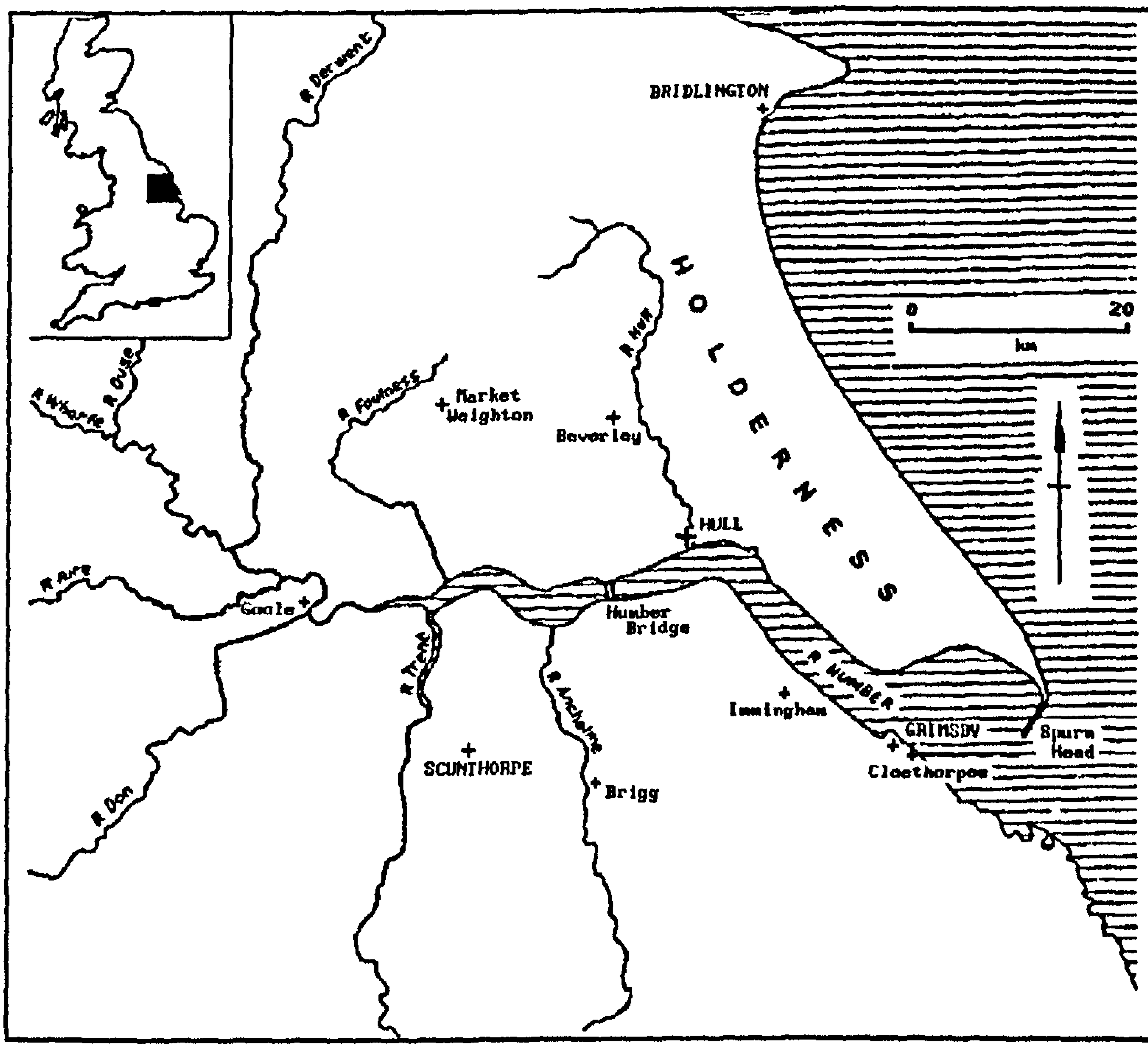


Figure 6.2 The Humber Estuary (after Pethick, 1990).

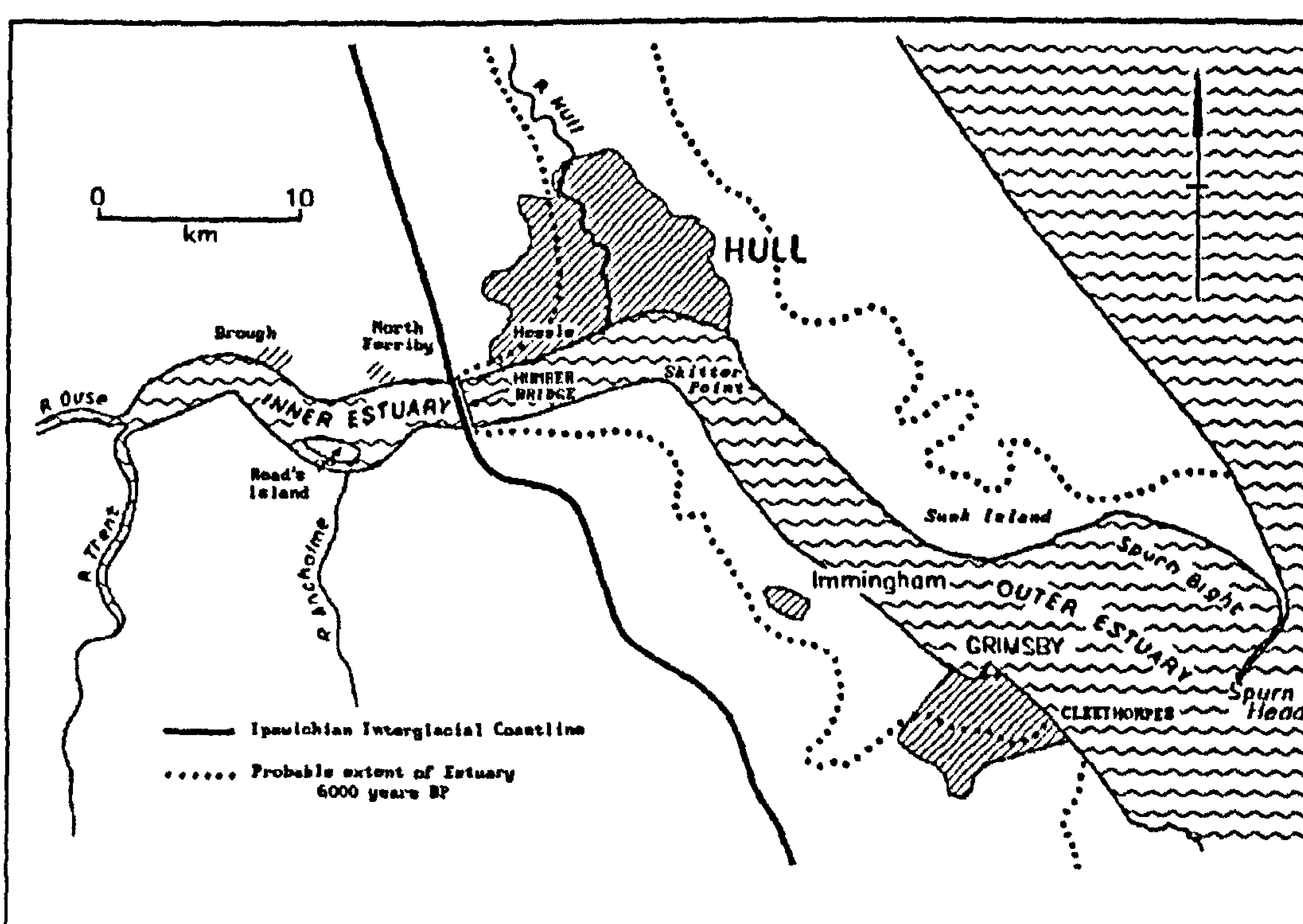
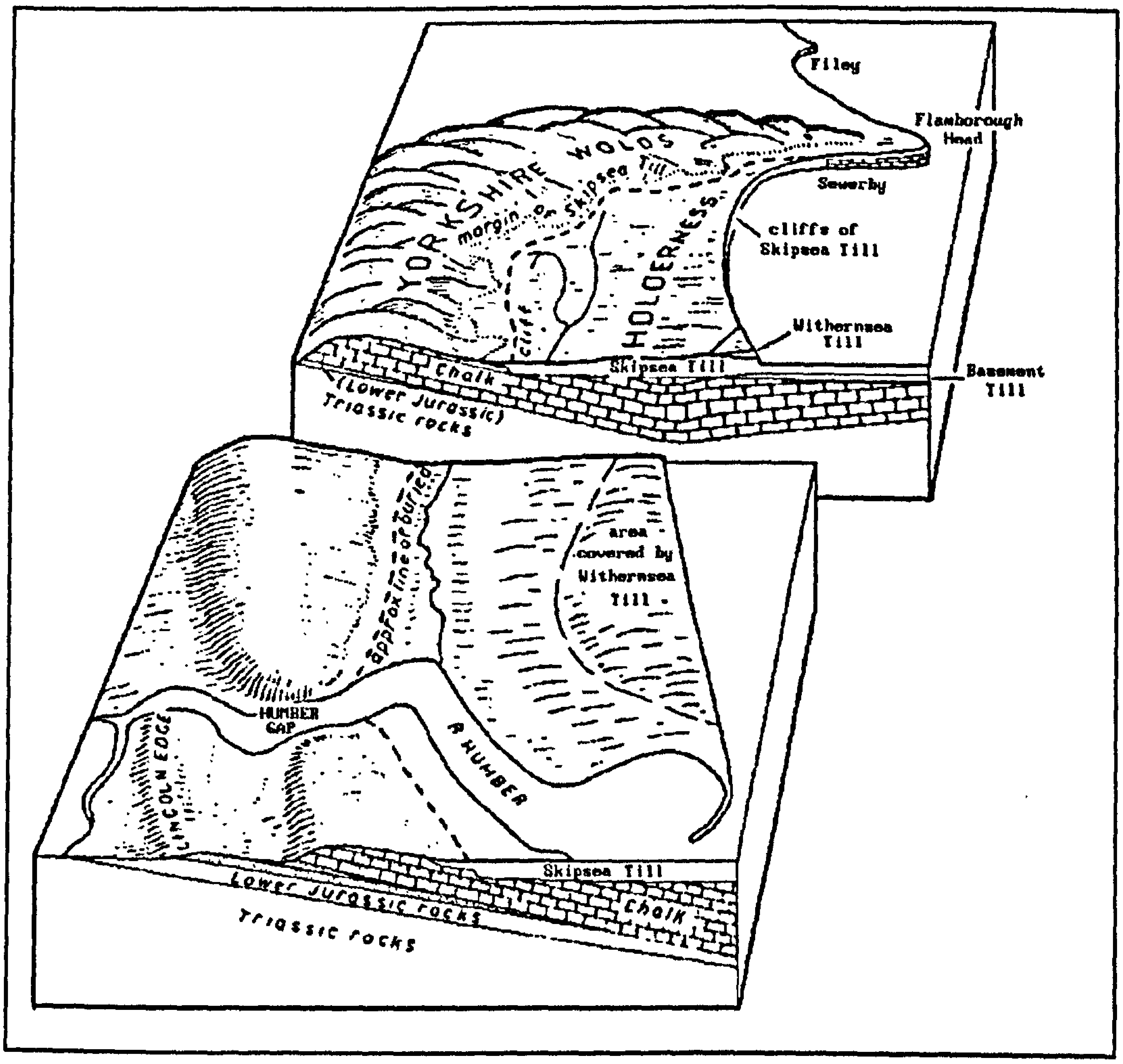


Figure 6.3 Block Diagram to show the geological structure of the region (Catt, 1990).



There are no Tertiary or early Quaternary deposits known anywhere in the Humber region. It is possible that early Tertiary beds once existed above the Chalk and have been completely eroded away. During the Tertiary and early Quaternary periods, the region was probably uplifted above sea level, tilted to the east and eroded mainly by streams.

6.1.3 Quaternary history of the Humber Estuary (after Pethick, 1990)

The coastline during the Ipswichian interglacial period is marked by a buried cliff line running approximately N - S along the eastern edge of the Yorkshire and Lincolnshire Wolds (Catt, 1990); see Figures 6.2 and 6.3. This coastline would have crossed the present Humber at the exact position of the Humber Bridge. Thus, during the Ipswichian period, between about 128,000 and 116,000 years BP, the Humber Estuary would have entered the North Sea some 45km westward of its present mouth at Spurn.

In contrast to the maturity of the inner estuary, the outer 45km reach of the Humber can only have been in existence for the past 3000 or 4000 years, that is since the present sea level was established during the Flandrian transgression (Gaunt and Tooley, 1974).

The extension of the Ipswichian estuary has been formed in the glacial tills of the Dimlington Stadial which constitute Holderness (Catt, 1990). As deglaciation proceeded in Holderness, the fluvial discharges from the Ouse and Trent cut across these tills, forming a deep channel within a wide shallow valley (Gaunt, 1981).

The northeasterly retreat of the ice front was temporarily halted along what is now the northern shore of the Humber, forming the Sutton moraine and forcing the river discharge to flow southeast, thus creating the distinct bend in the river marked by Skitter Point (Straw and Clayton, 1979). As the sea level rose (i.e. Figure 5.3a), this wide valley became flooded, forming a proto-Humber; sedimentation was extremely rapid in the inter-tidal area and the estuary width had halved by 2000 years BP. The depth of the central estuary channel, however, did not shoal appreciably, the underlying chalk being exposed in the present day channel in several places (McQuillin *et al.*, 1969).

The morphological changes in the Humber described above were initiated by the dramatic changes in sea level experienced during the Devensian and Flandrian periods. During the Quaternary, around 20,000 to 25,000 years BP, the lowest sea level attained appears to have been 150m below its present level (Carter, 1988). The onset of warmer conditions meant that sea level was beginning to rise rapidly by 13,000 years BP and evidence from the Humber suggests that it had risen to -18m OD (Ordnance Datum) by 8000 years BP (Gaunt and Tooley, 1974). During this period the Ouse and Trent incised deeply into the sediments of the inner Humber, producing a channel whose base lies at -20m OD in the Vale of York (Gaunt *et al.*, 1971 and Gaunt, 1981), while in the outer estuary a deep channel was incised into the glacial tills.

6.1.4 Drift geology

Later Quaternary deposits are extensive over both the Chalk and older rocks in the Humber region; most of them resulted from glaciation. There is firm evidence for only three glaciations of the area. The most recent resulted in the majority of the Quaternary deposits in Holderness and the Vale of York, and has been radiocarbon dated to between 18,000 and 13,000 years BP (Penny *et al.*, 1969 and Beckett, 1981). This period, the first part of the Late Devensian stage, is defined by Rose (1985) as the Dimlington Stadial. The name is derived from Dimlington Farm, southeast Holderness, where glacial sediments (boulder clay or till, and gravel) are over 30m thick and are underlain by lacustrine silts containing arctic moss remains dated to 18,240 (± 240) to 18,500 (± 400) years BP (Penny *et al.*, 1969).

An earlier glaciation resulted in a thick till (Basement Till) lying between the chalk and the moss-containing lacustrine deposits at Dimlington (Catt and Penny, 1966). The exact date of the glaciation has not yet been determined, but was probably during the Wolstonian 14,000 years BP. This very dark grey to olive grey Basement Till is seen in the foreshore and cliff foot between Kilnsea Beacon (TA 412176) and Hompton (TA 376237) on the southeast Holderness coast. The surface is at 2m to 6m OD and the base from -30m to -35m OD where it overlies chalk.

The Basement Till has a very patchy distribution in coastal areas of northeast England. It is presumed that it originally formed as a continuous sheet which was strongly dissected during the Ipswichian and earlier parts of the Devensian.

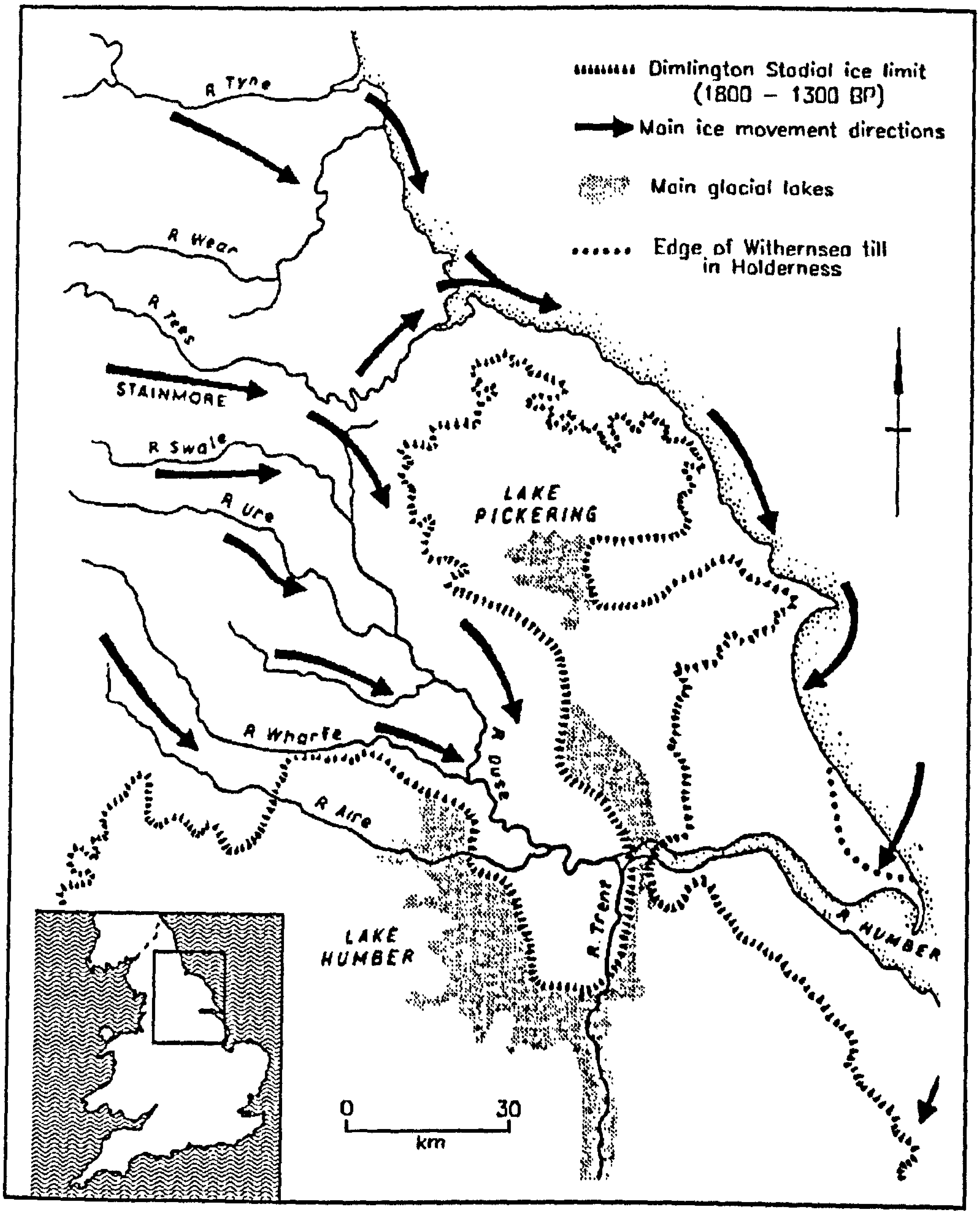
During the Dimlington stadial, ice approached the Humber from two different directions, north and northeast (Figure 6.4). Ice from the north (Vale of York glacier) came mainly from the Lake district and southwest Scotland, crossing the Pennines by way of the Stainmore Gap between the Vale of Eden and Teesdale. Ice from the northeast was on the western margin of a large lobe filling the western part of the North sea basin; this lobe had originated partly from the Stainmore ice stream (which divided to pass either side of the Cleveland Hills) and partly from ice spreading eastward across southeast Scotland and Northumberland and then moving southwards down the coast. At this time the North Sea area was largely dry land because, with so much water held in continental ice sheets over Europe and North America, the sea had fallen as low as 160m below its present level (OD).

Because the North Sea ice reached Holderness by two different routes it deposited two different tills, namely the Skipsea and Withernsea Tills of Madgett and Catt (1978). In Holderness the Skipsea Till (= Drab Clay of Bisat, 1939) is mainly very dark greyish brown and the overlying Withernsea Till (= Purple Clay of Bisat, 1939) is dark brown. The Skipsea Till extends throughout Holderness and the Lincolnshire Marsh, forming the core of the Ferriby moraine ridge, and thins to a feather edge on the eastern slopes of the Wolds.

The Withernsea Till is more restricted in distribution than the Skipsea Till, occurring as an arcuate area in southeast Holderness (Figure 6.3); it is visible in the coastal cliffs between Hornsea and Easington, extending inland no more than 10km (Madgett, 1975). Its erratics are mainly red Triassic sandstone and shale, grey Liassic and Carboniferous shales, chalk, magnesian limestone and Carboniferous limestone; igneous rocks are of rarer occurrence here than in the Skipsea Till, and come mainly from the Lake District (for example Shap granite).

The junction between the Withernsea and Skipsea Tills is usually sharp, with no evidence of weathering or disturbance, and only rare examples exist of incorporation of Skipsea Till within the basal Withernsea Till. The Withernsea Till

Figure 6.4 Features of the Dimlington Stadial Glaciation (after Catt, 1990).



is overlain by deposits infilling a kettle-hole at The Bog, Roos, which have been given a radiocarbon date of 13,045 ± 270 years BP (Beckett, 1981); this age, combined with the radiocarbon dates beneath the Skipsea Till, show that both tills were deposited in the space of 5000 years or less.

Many features suggest that the Skipsea and Withernsea Tills were deposited by a single ice sheet rather than two separate advances; a similar sequence can be traced northwards as far as the Tees estuary, the Skipsea Till probably correlating with the Lower Boulder Clay of County Durham (Smith, 1981).

Catt and Penny (1966), Madgett and Catt (1978) and Edwards (1981) have supported, in modified form, the suggestion of Carruthers (1953) that the glacier invading eastern Yorkshire was a composite ice sheet comprising superimposed tributary glaciers. This implies that the Skipsea Till was deposited by ice which originated in Northumberland and southern Scotland and moved southwards along the coast, whereas the Withernsea Till came from a Tees valley ice stream which overrode the coastal (Skipsea Till) ice near the mouth of the Tees and was then carried southwards on its back into eastern Yorkshire.

6.1.5 Previous geophysical surveys

A previous (McQuillin *et al.*, 1969) geological and geophysical survey of the Humber estuary was performed by the Institute of Geological Science (IGS) and included, where water depth permitted, a limited seismic investigation of Spurn Bight (Figure 6.5). Spurn Bight was also surveyed extensively using hand corers (maximum penetration 5ft/1.5m) to take sediment samples. Data collected by McQuillin *et al.* (1969), although peripheral to the UWB survey, provide geological information relevant to this project. In water depths less than 5 fathoms (9.2m), on the southern edge of Spurn Bight (Figure 6.6), boulder clay is exposed at the seabed surface and appears to be dipping to the northeast. Along the southern edge of the UWB survey area (Figure 6.6) the boulder clay appears to be approximately 2ft (0.61m) below seabed. The seabed sediments in this area are reported to be sand/mud and silt, becoming exclusively sand over occasional boulder clay further south in the main channel (Figure 6.7). Over the remainder of Spurn Bight, boulder clay was only confirmed in one core (and therefore at a depth of 1.5m or less beneath seabed) near the coastline northwest of Kilnsea.

Figure 6.5 Sparker/Boomer traverses performed by McQuillin *et al.* (1969) in the Humber Estuary.

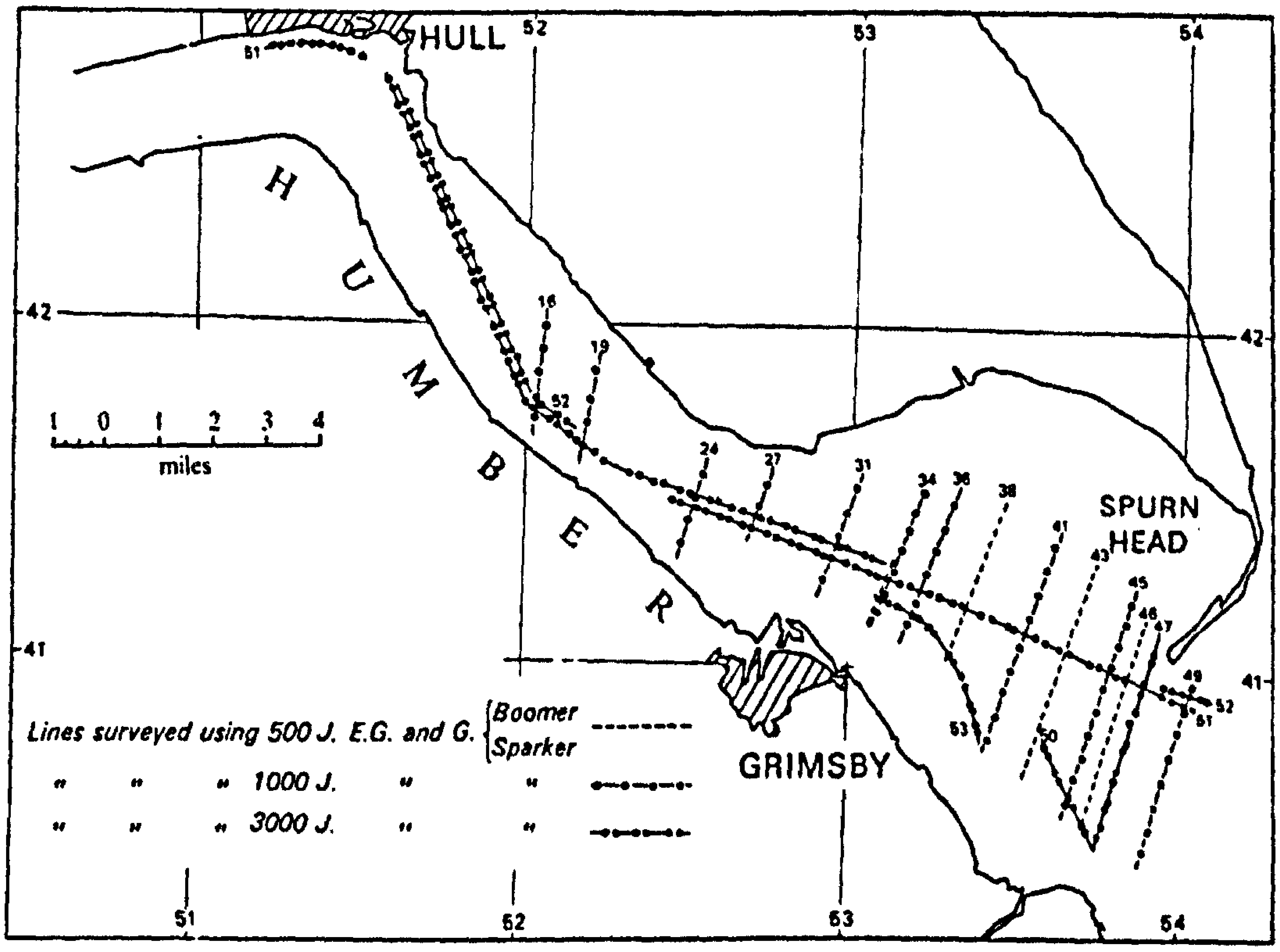
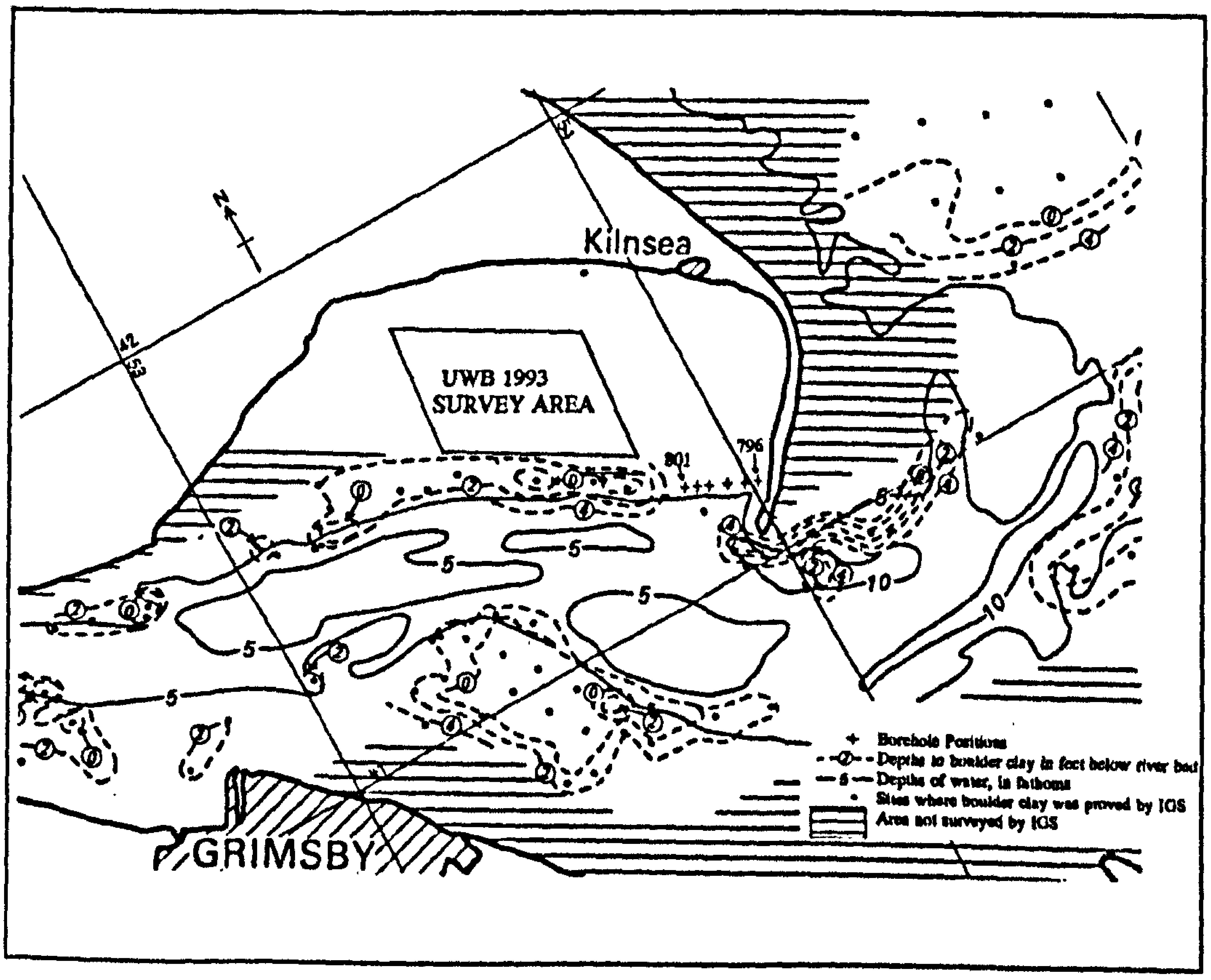


Figure 6.6 Depth to Boulder Clay as established by McQuillin *et al.* (1969) shown relative to UWB survey area and boreholes 796 - 801.



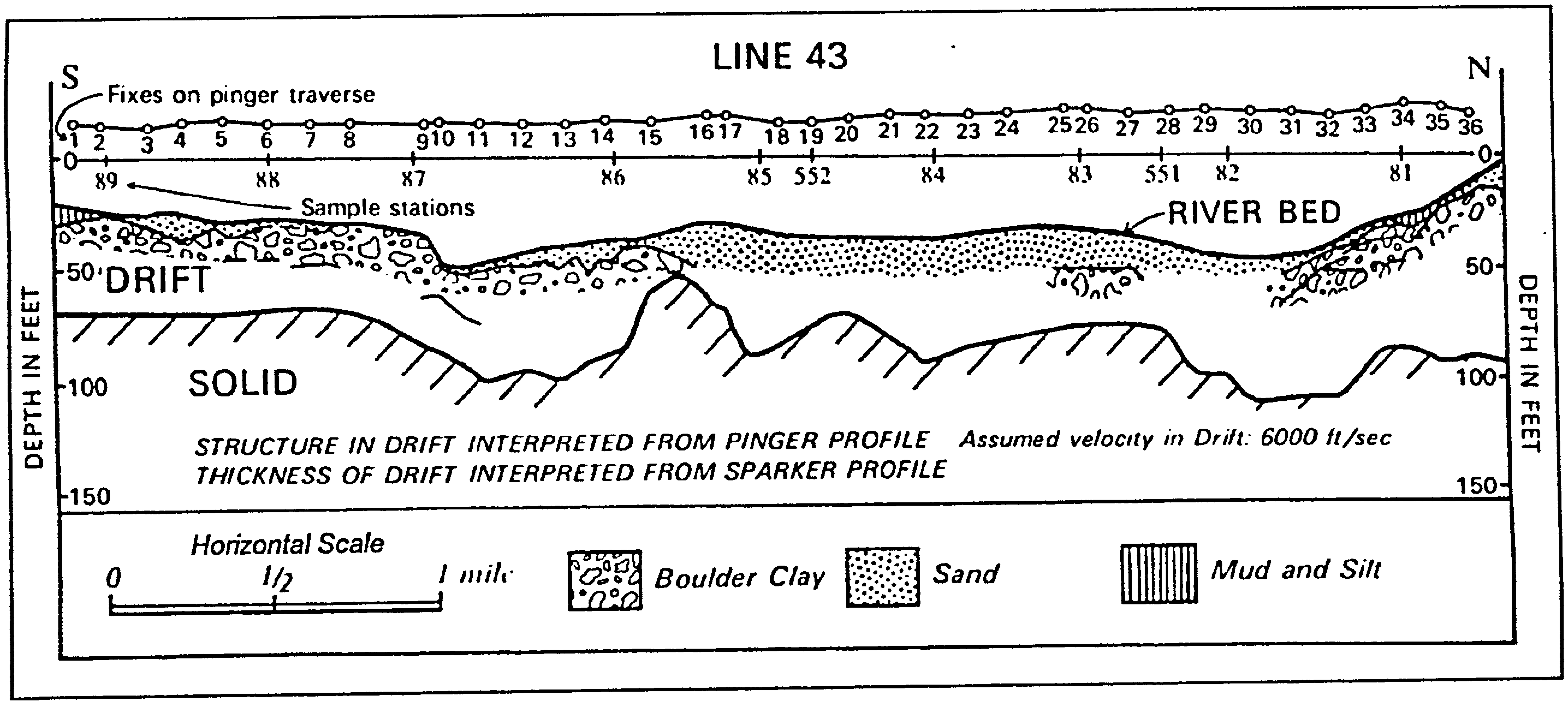


Figure 6.7 Interpreted geophysical section across the Humber Estuary. Line position as shown in Figure 6.5 (McQuillin *et al.*, 1969).

6.1.6 Borehole data

Available borehole records in the target area are scarce, however six borehole logs off Spurn Head (the positions of which are shown on Figure 6.6) were made available by the British Geological Survey (BGS) (Figure 6.8). These show surface deposits (of variable thickness) of sand offshore, grading into silt closer inshore. These units rest upon till at a depth of between -7m to -13m OD.

6.2 Marine seismic investigation

As per the Tees survey, part of this project was concerned not only with the testing of seismic stratigraphy principles in Quaternary sediments but also with developing methods of collecting analogue and digital seismic data in shallow water and the intertidal zone. Thus it is appropriate to include details on surveying procedure/logistics before presenting the data themselves.

6.2.1 Survey details

The Humber flats and marshes (Spurn Head to Saltend Flats) are a designated SSSI (Site of Special Scientific Interest), consequently permission to survey the area of interest was obtained by liaising with the Nature Conservancy Council for England (English Nature), Yorkshire Wildlife Trust (who own Spurn Head and much of the mud flats and foreshore of Spurn Bight), and the Spurn Heritage Coast Project. The major aim was to minimise disturbance and interference to any ongoing surveys and census of bird colonies being conducted in the area.

Permission was also obtained from the relevant landowners and occupiers to install trisponder stations and from the Humber Pilot station at Spurn to use their jetty for equipment loading and boat mooring.

Since the objectives of the work, as stated above, necessitated surveying in shallow water, a spring tide cycle is most favourable to maximise the working time for the underway marine survey. The spring tide chosen for the work was especially favourable as it had the potential to be one of the highest tides this century so providing maximum water access to the intertidal zone.

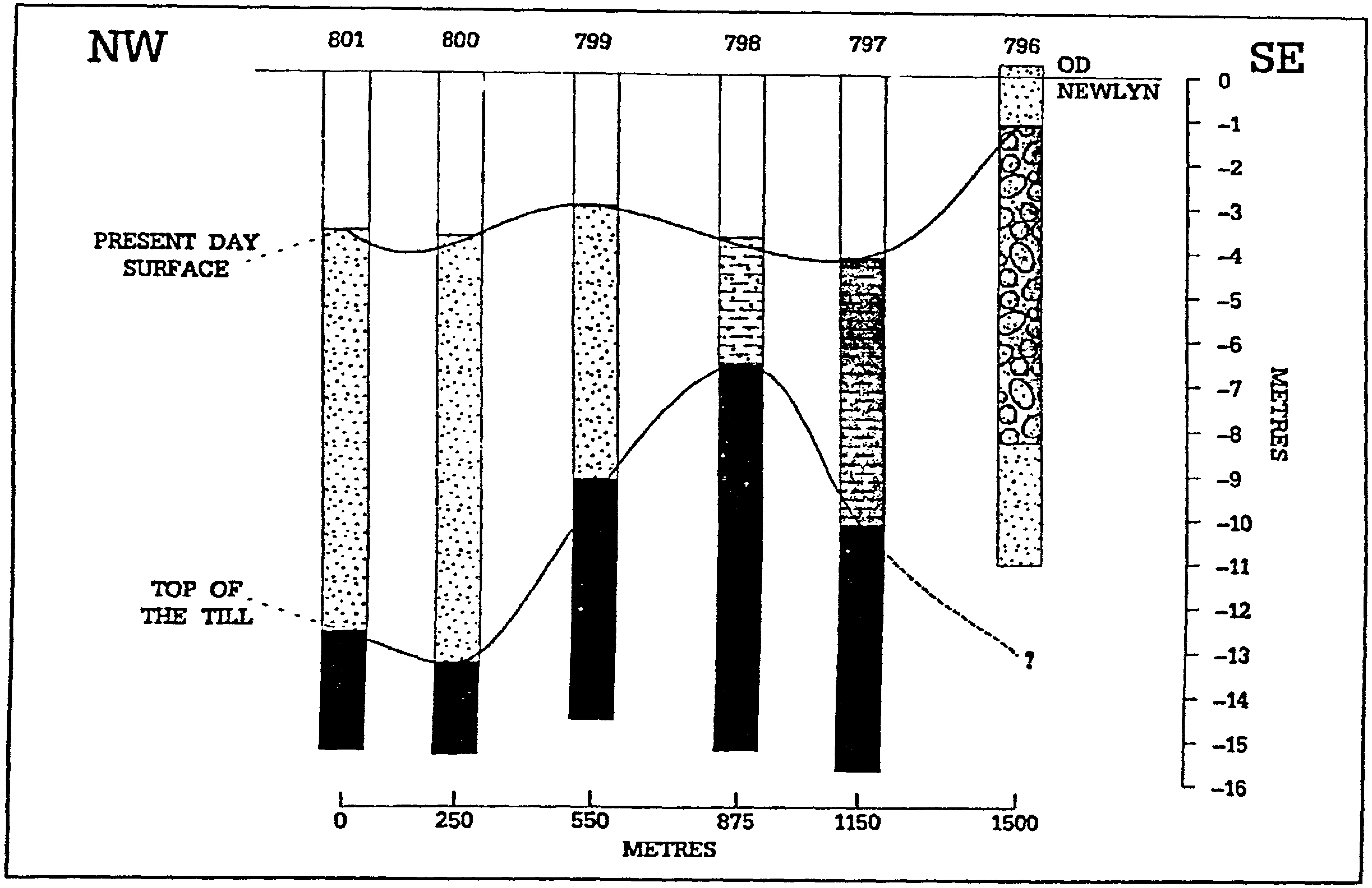


Figure 6.8 Borehole logs off Spurn Point (after Ciavola, 1993).

As well as attempting to achieve maximum inshore coverage of the survey area the survey line spacing was planned taking into account water depth, rate of change of water depth the size of the area to be surveyed and the density of survey lines. Complex geology will require a much more closely spaced seismic grid than a simple situation if it is to allow accurate mapping of subsurface conditions. The selection of a survey grid can be chosen pre-survey but must be open to re-evaluation once the complexity of the data has been assessed.

Taking in to account the factors discussed above and considering the further constraints of favourable weather forecasts[1] and budget constraints, the survey of Spurn Bight eventually consisted of 16 parallel N - S lines of approximately 3km length and 200m line spacing, and 4 WNW - ESE shore parallel cross lines of approximately 3.5km length and 500m spacing (Figure 6.9). This survey programme was performed over a five day period.

6.2.2 Equipment and survey vessel

The survey of Spurn Bight was originally attempted using the same vessel and equipment configuration as the survey in the Tees Estuary (chapter 5). After two aborted attempts it was proved that a bigger boat was required. The reasons for this were due mainly to safety and exposure of the area in that the 'Sandpebbler' could not safely transit between Grimsby marina (the only suitable launch site) and the survey area with the survey equipment onboard in poor weather conditions. It was also, after initial attempts, considered too dangerous to load equipment from the jetty at Spurn Head due to the rapidly changing tide level and high current speed. The vessel eventually used for all marine survey work was the 'Petroswift' (a hired-in Mitchell 38, with a 3'6" draft and a top speed of 18/20 knots), working from Grimsby marina. The greater speed of the 'Petroswift' over the original boat was also an advantage as access into and out of the marina in Grimsby is tidally limited to 2.5 hours either side of high water.

[1]When surveying in small boats, especially when using relatively bulky digital acquisition equipment, favourable weather reports are required both from a personal safety and data quality (which will affect resolution at the interpretation stage) point of view.

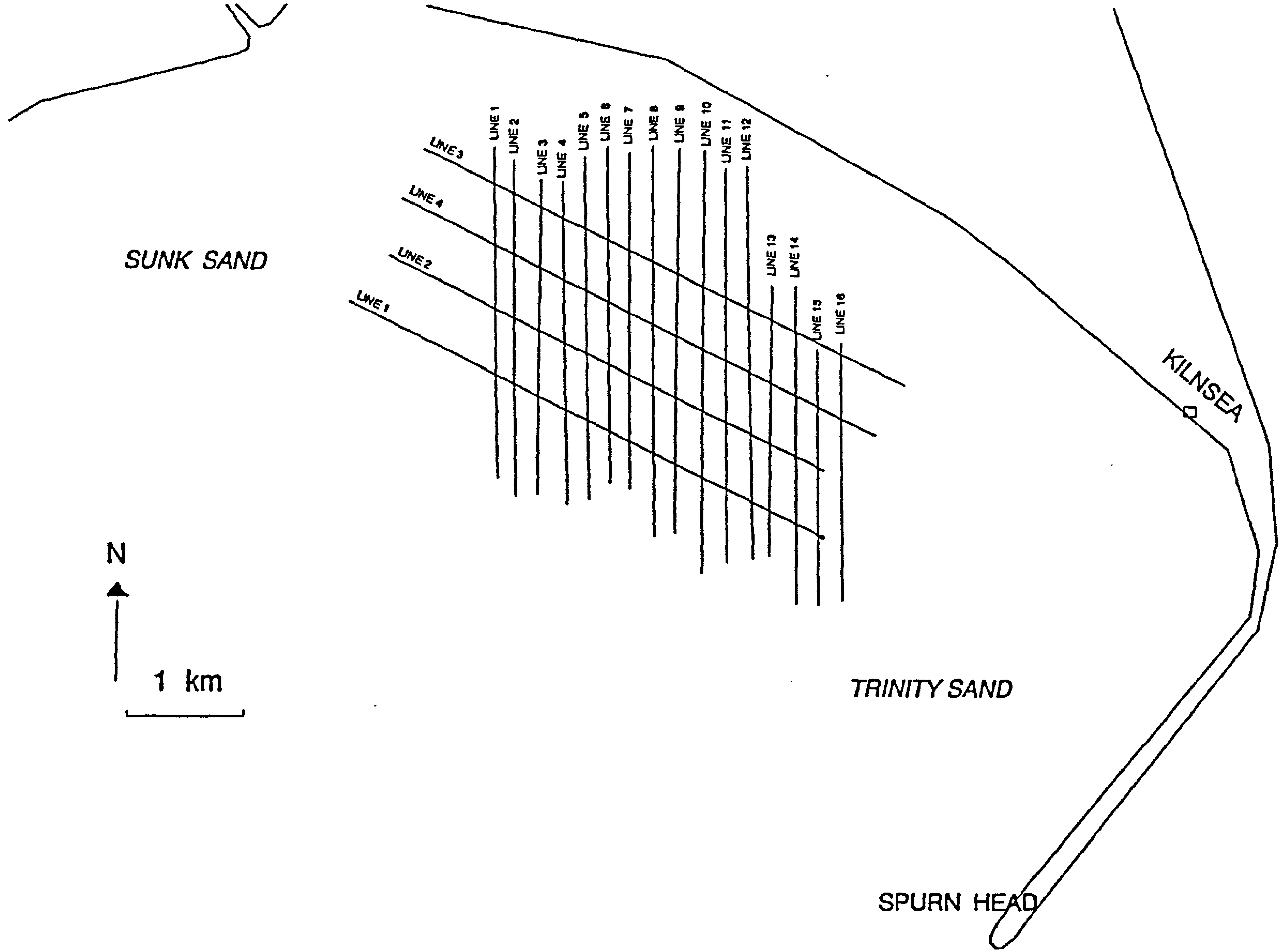


Figure 6.9 Survey programme within Spurn Bight.

Marine analogue data were output to a thermal printer. Digital data were recorded to magnetic tape via a Carrack digital seismic acquisition system. Post survey the digital data was found to be of poor quality, due to excessive noise, and it has therefore not been included in this study.

The following equipment was mobilised to site and used during the survey of Spurn Bight:

IKB Seistec
Geopulse power supply (Model 5420A)
Dowty (Waverly) thermal printer (model 3700)
Carrack Digital Seismic Acquisition System (SAQ V)
Del Norte 540 Trisponder System
Two generators (for onboard power)

6.2.2.1 Operating parameters

The Seistec (boomer) was towed behind the vessel from the port quarter making sure it was out of the wake throughout the survey. The layback between the trisponder antenna and the Seistec was 9m. The operating parameters of the Seistec and thermal printer were the same as in the Tees Estuary (chapter 5.2.2.1).

6.2.3 Position fixing

Because of accuracy constraints associated with GPS and the non-availability of a differential GPS system, underway position fixing was achieved using the Del Norte 540 Trisponder system, employing a mobile station on the survey vessel and three fixed shore based stations at:

Location	National Grid Reference
Easington	TA 539292E 417186N
Spurn Head	TA 539850E 410939N
Skeffling	TA 536932E 418341N

The system works by calculating a range from known stationary (slave) trisponder beacons. This is achieved by transmitting a microwave pulse from the master control unit on board the boat, and measuring the time interval until the slave responds with a second microwave pulse.

6.2.4 Navigation

The trisponder system was configured to give the vessel's position in national grid coordinates. This is achieved by measuring the range to each of the trisponder slave units and using the known grid coordinates of each of the slaves. The varying coordinates of the vessel were automatically logged on a PC at 5 second intervals. An accuracy of ±1m can be expected with the trisponder system provided that the positions of the trisponder slaves are accurately surveyed in, that the unit has been calibrated over a known range, and that the intersection angle of the ranges is between 30° and 150°. Accurate navigation was achieved by installing pre-determined track lines into the trisponder system in its 'Guidance Mode', and then allowing it to 'pilot' the vessel by providing the helmsman with graphical on/off track information. After limited practice straight courses can generally be steered, the only problem lying in compensating for the changing tidal current conditions. The trisponder system performed well during the survey, the only drawback to such a system being the need for manpower to maintain the power supplies (batteries) to the onshore slave units during surveys lasting a number of days.

6.3 Interpretation procedure

A number of the seismic profiles acquired during the survey are presented as data examples and for discussion in section 6.4. To assist in the interpretation and provide a 3D visual display contour maps have been constructed using data from the entire survey area. These plots illustrate bathymetry and subbottom reflectors. The data examples and contour plots have been constructed using the parameters discussed below.

6.3.1 Boomer interpretation

In the Interpretation of the boomer data an assumed seismic velocity of 1500m/s was used for seawater. An assumed seismic velocity of 1650m/s was used for sediment, this velocity, the same as that used in the Tees interpretation and provided by land seismic surveying (as discussed in chapter 5).

6.3.2 Tidal correction

Tide levels were not monitored during the survey. In order to correct for the variation in the water depth with time a tidal curve was generated from a simplified harmonic tidal prediction computer programme (NP159a) using Admiralty harmonics for Spurn Head. Although once again this did not take into account the meteorological conditions at the time of the survey, the fact that the weather was fairly stable throughout the survey period meant that such a correction could be considered sufficiently accurate for the purpose of this study.

6.3.3 Charting

Contour maps have been corrected to Ordnance Datum by adding a correction factor of 3.9m to tidally reduced water depths. This correction factor of 3.9m is quoted on Admiralty Chart 109 at Spurn Head and Grimsby as being the depth of Chart Datum (CD) beneath OD. Horizontal scales on the seismic sections have been calculated over average distances covered on individual seismic lines.

6.4 Seismic stratigraphic interpretation

A number of seismic profiles (the positions of which are presented in Figure 6.9) acquired during the survey are presented in Figures 6.10 to 6.12 as data examples. These examples illustrate unprocessed analogue data with a corresponding interpretation of significant reflectors (i.e. high amplitude reflectors) and events. Contour plots of units of interest have been presented (Figures 6.13 to 6.14) as well as a plot of present day bathymetry (Figure 6.15).

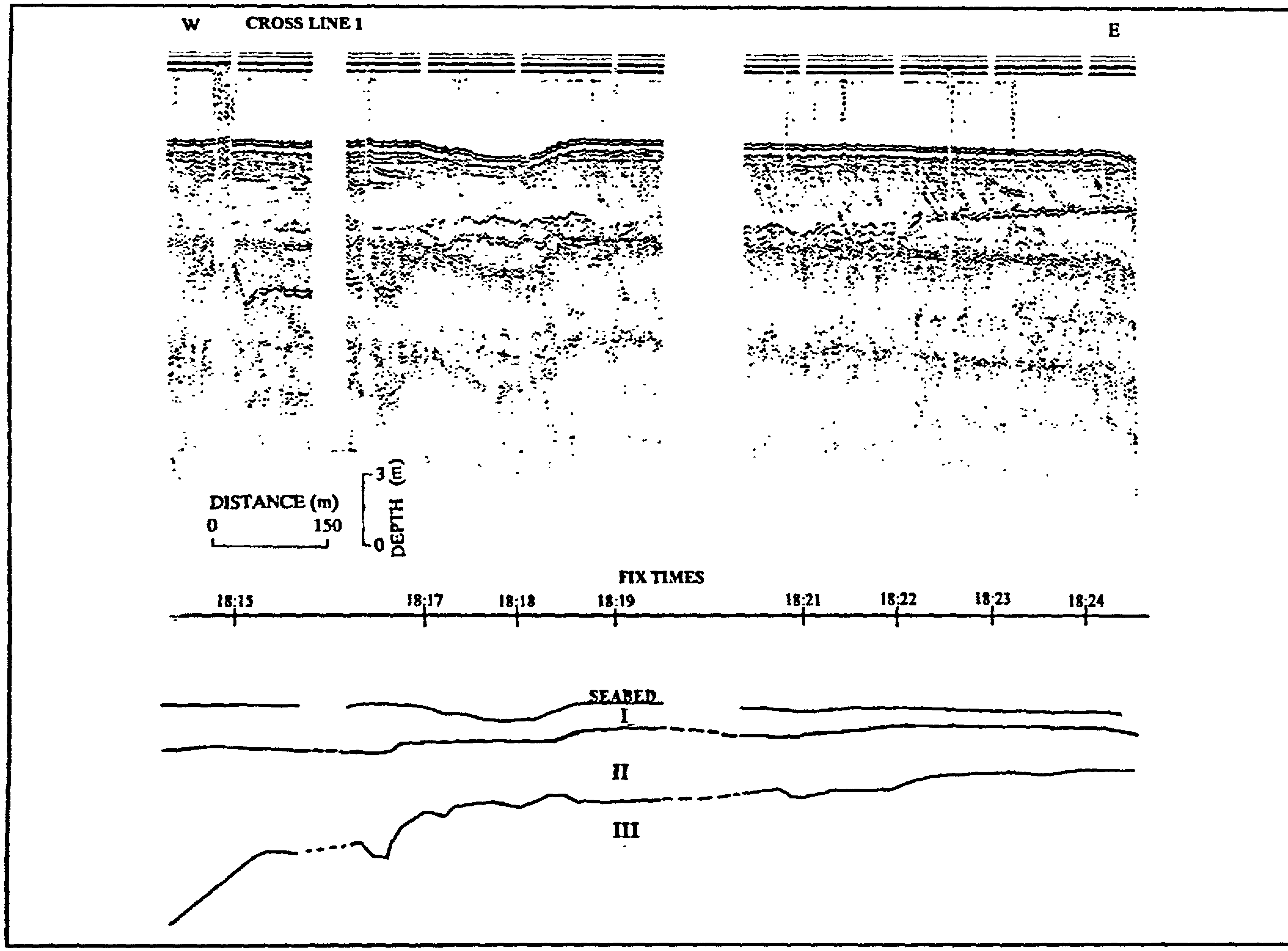


Figure 6.10 Unprocessed analogue marine data with interpretation showing significant reflectors (cross line 1).

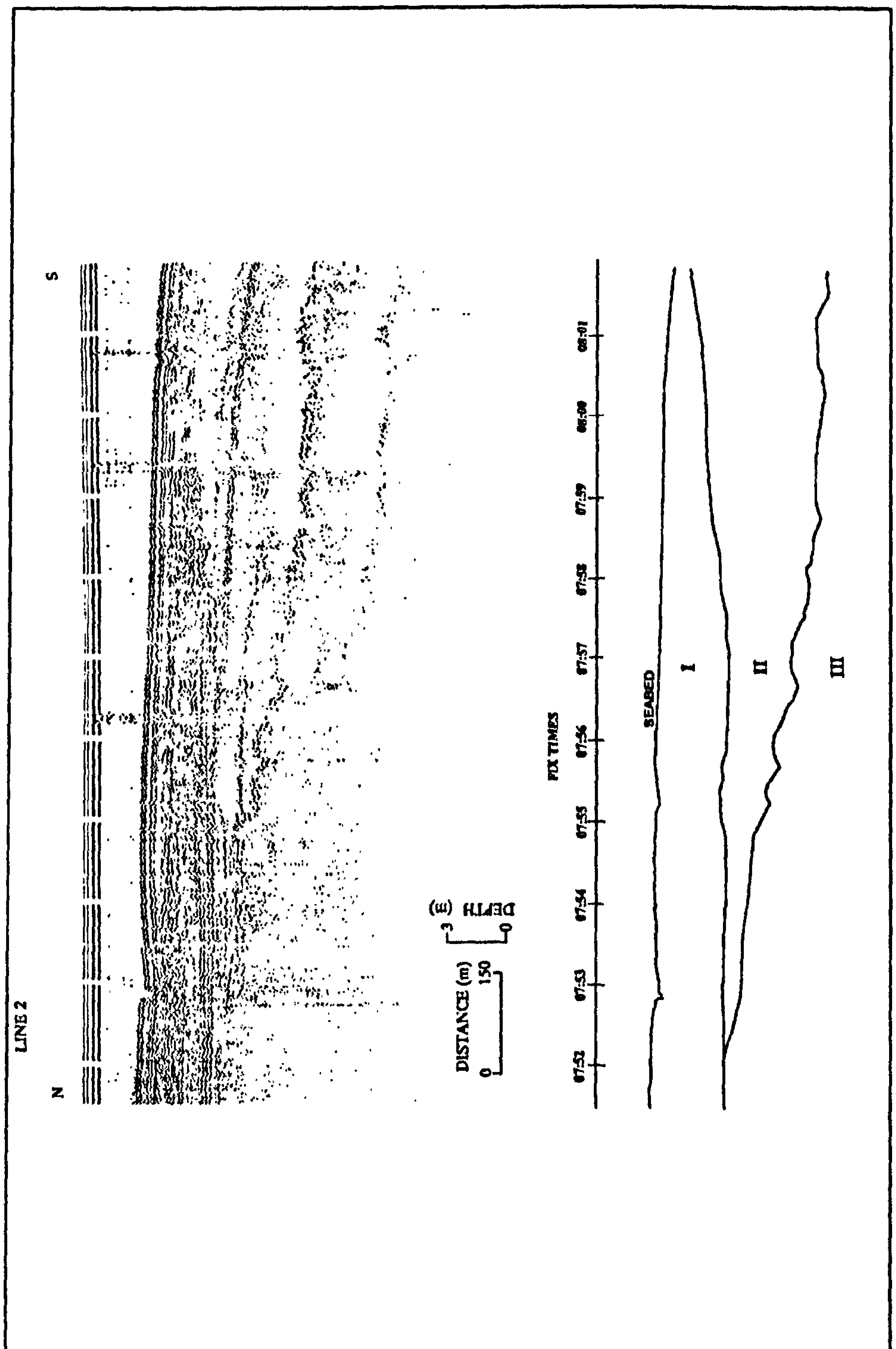


Figure 6.11 Unprocessed analogue marine data with interpretation showing significant reflectors (line 2).

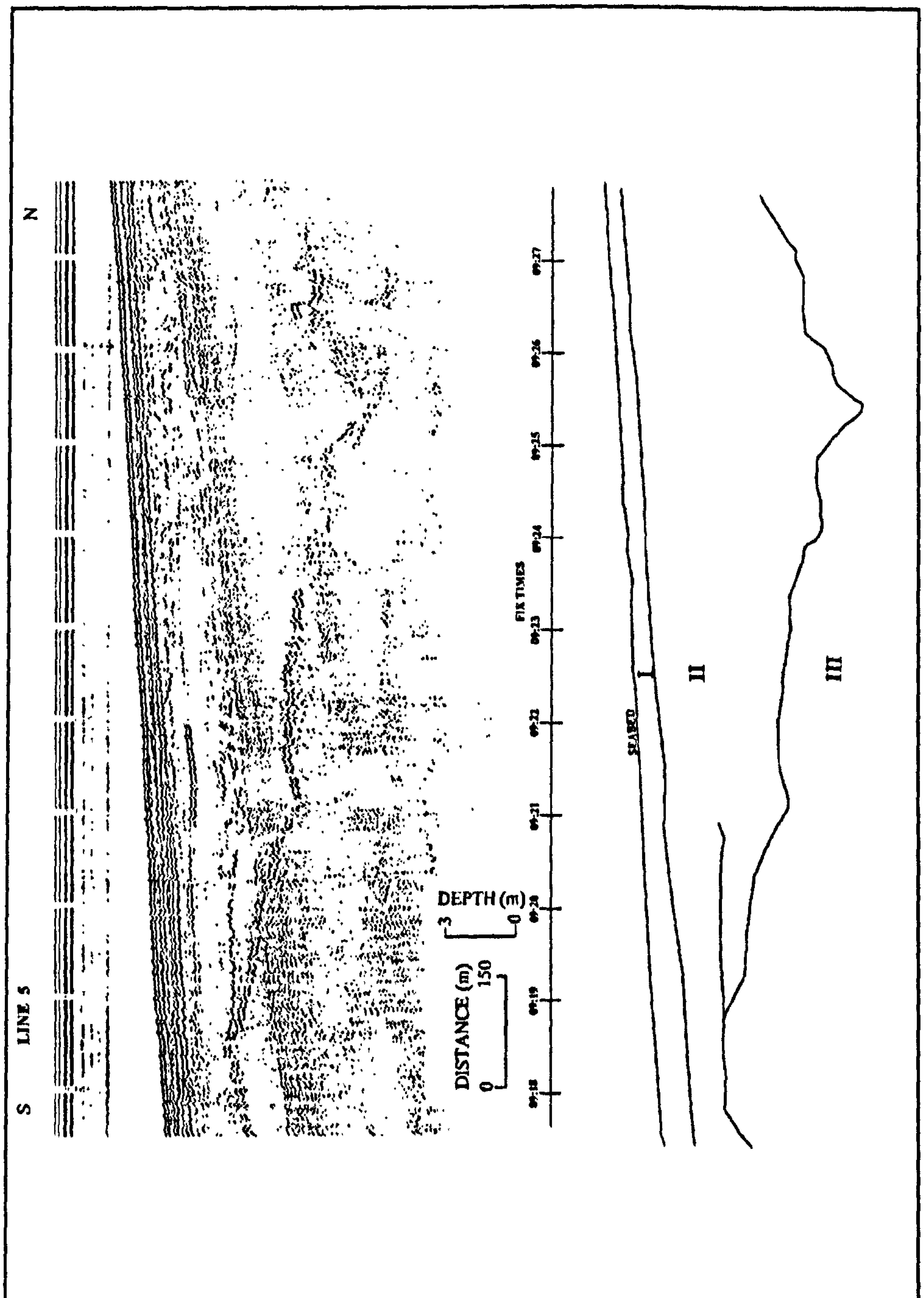


Figure 6.12 Unprocessed analogue marine data with interpretation showing significant reflectors (line 5).

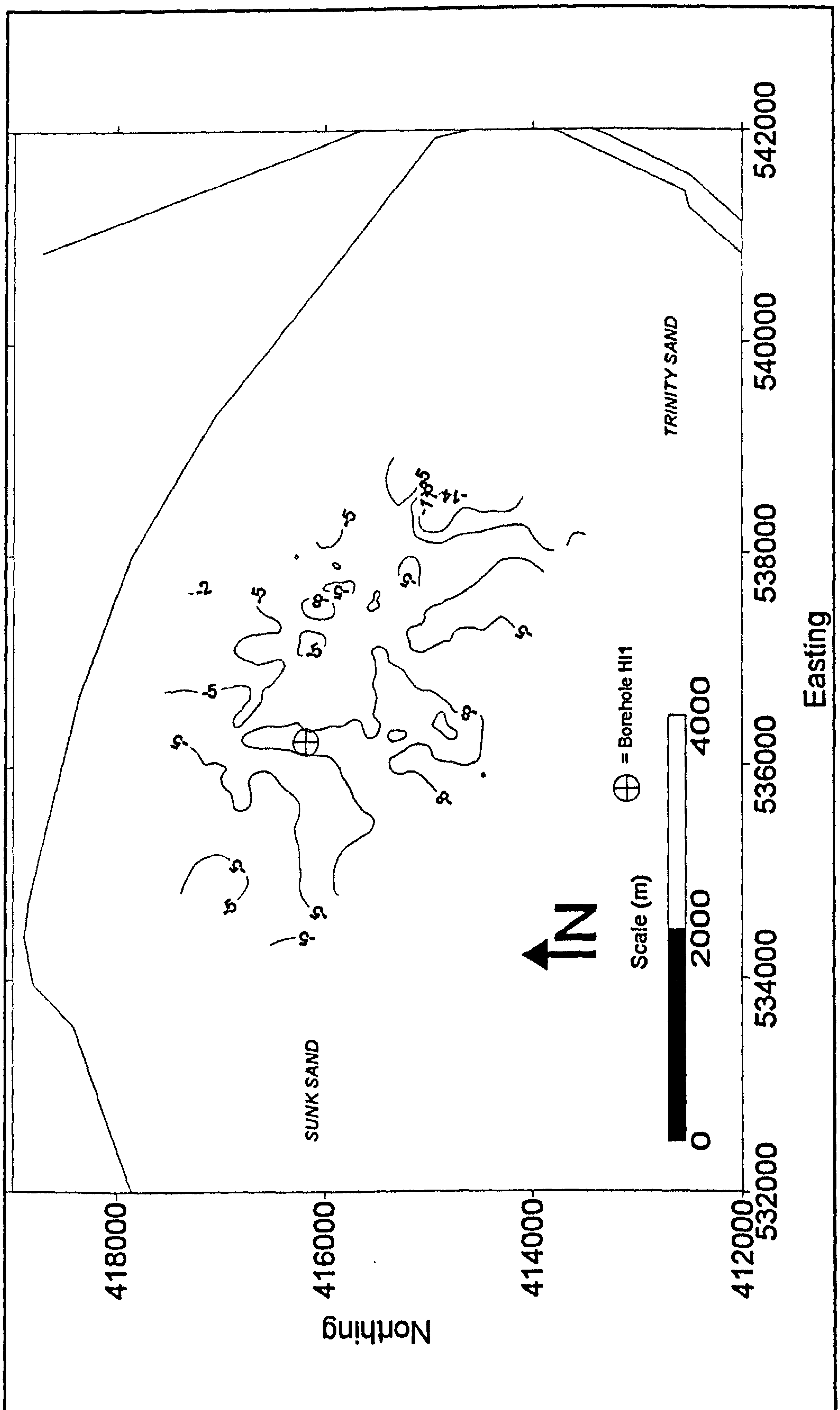


Figure 6.13 Contour plot, top of sequence III.

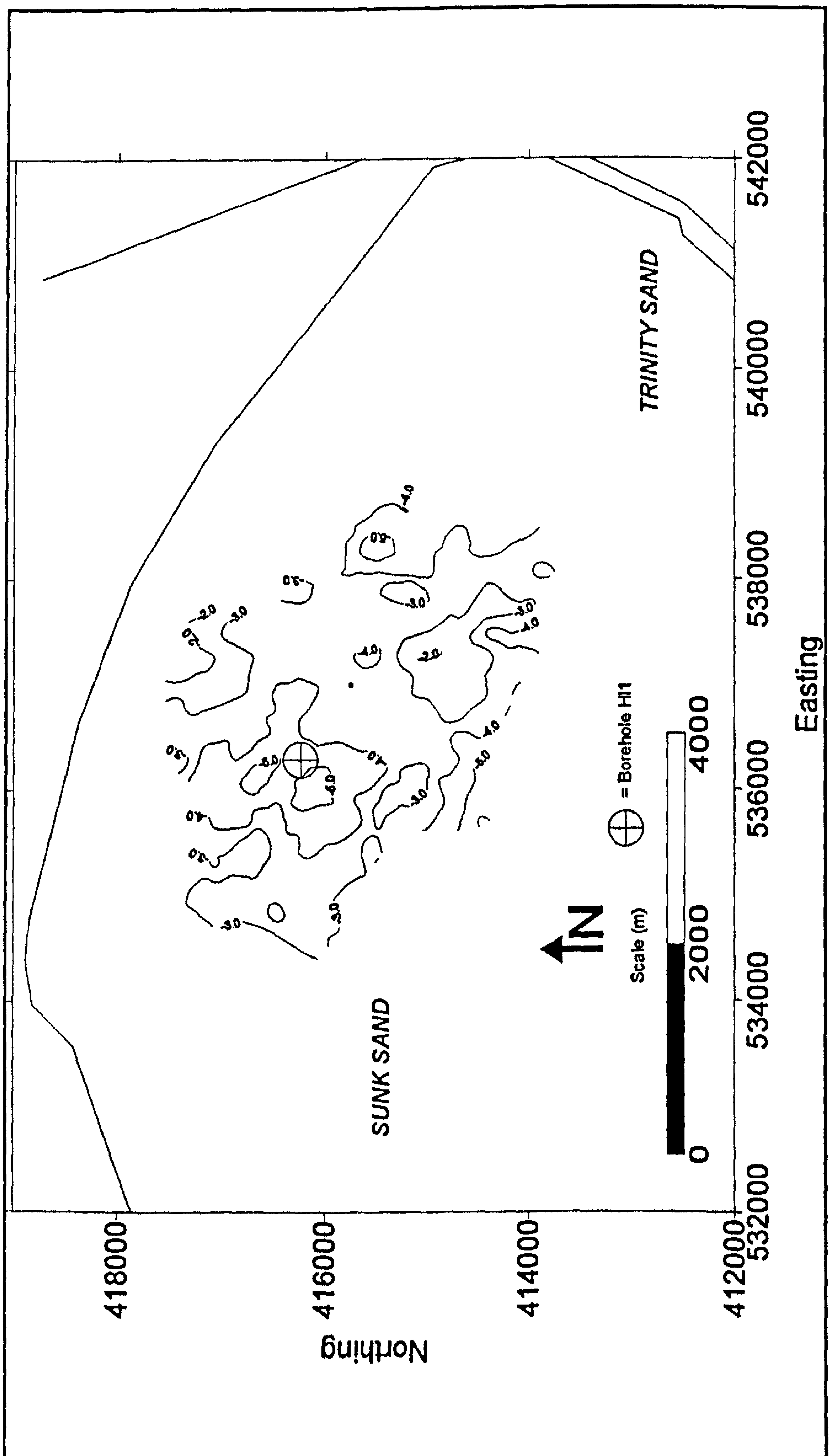


Figure 6.14 Contour plot, top of sequence II.

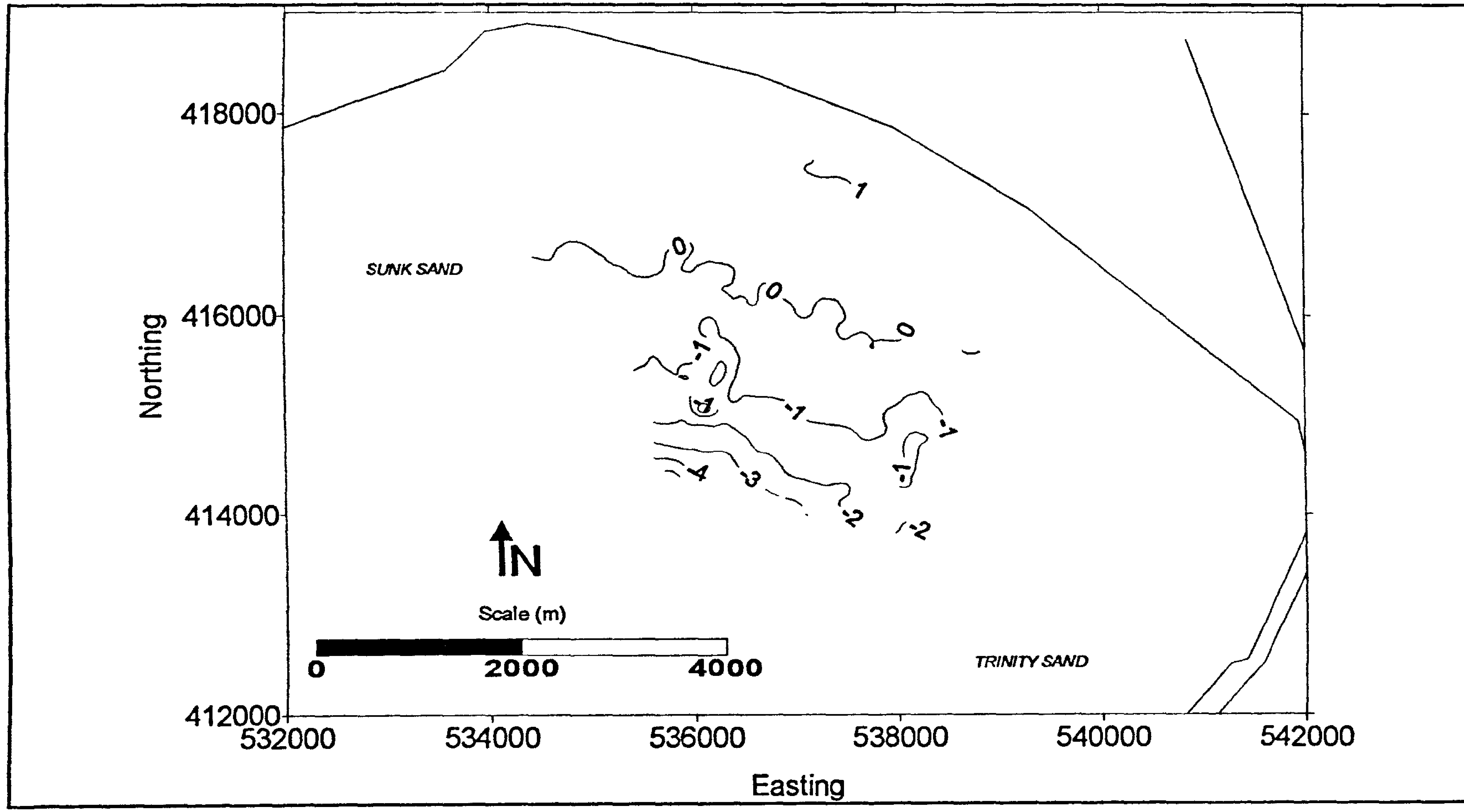


Figure 6.15 Bathymetry.

6.4.1 Seismic sequence analysis

The seismic data have been divided into three sequences by identifying discontinuities on the basis of reflection terminations. These sequences have been identified on the seismic data as being sequences I to III (Figures 6.10 to 6.12).

The evidence that allows these 'reflection packages' to be defined as sequences is as follows.

Sequence III, although having no observable structures on the seismic data, appears to be unconformably overlain by sequence II and has evidence of basal onlap. The base of sequence II shows some evidence of channelling.

Sequence I has been identified as a sequence due to it lying unconformably on the underlying sequence (II). The internal bedding of sequence I appears on the whole to be fairly horizontal but does have some evidence of channelling and onlaps sequence II (as seen in line 2, Figure 6.11).

Apart from this evidence it is difficult to see the 'bigger picture' regarding these sequences as they are not seen in their entirety. The subdivision of these sequences into systems tracts is therefore, using the criteria described in chapter 3, not possible.

6.4.2 Seismic facies analysis

Unit III shows no discernable internal structuring and appears unstratified and transparent. The reflector that delineates the upper surface of this sequence has a high amplitude (from inspection of the analogue data) and is a continuous coherent reflector mappable over the entire survey area. The data examples and 3D expression of this surface (Figure 6.13) reveal it to be a fairly irregular surface with two deep channel features. One of these channels, marked by the -8m contour, runs approximately NE - SW; the other channel, although less well defined, appears to run NW - SE and is marked by the -11m contour.

Based on the strength of the reflection, the palaeosurface that can be mapped from the surface it represents, the unstratified nature of the sequence it represents and regional geological knowledge, sequence III is interpreted to be glacial till. Such an interpretation ties fairly well into the survey of McQuillin *et al.* (1969)

Sequence II appears as an overall acoustically transparent layer with some lamination/bedding in places and with some, occasionally quite extensive (400m in length), reflectors of high amplitude within the sequence. The sequence appears to have a general trend of thickening towards the main channel of the Humber.

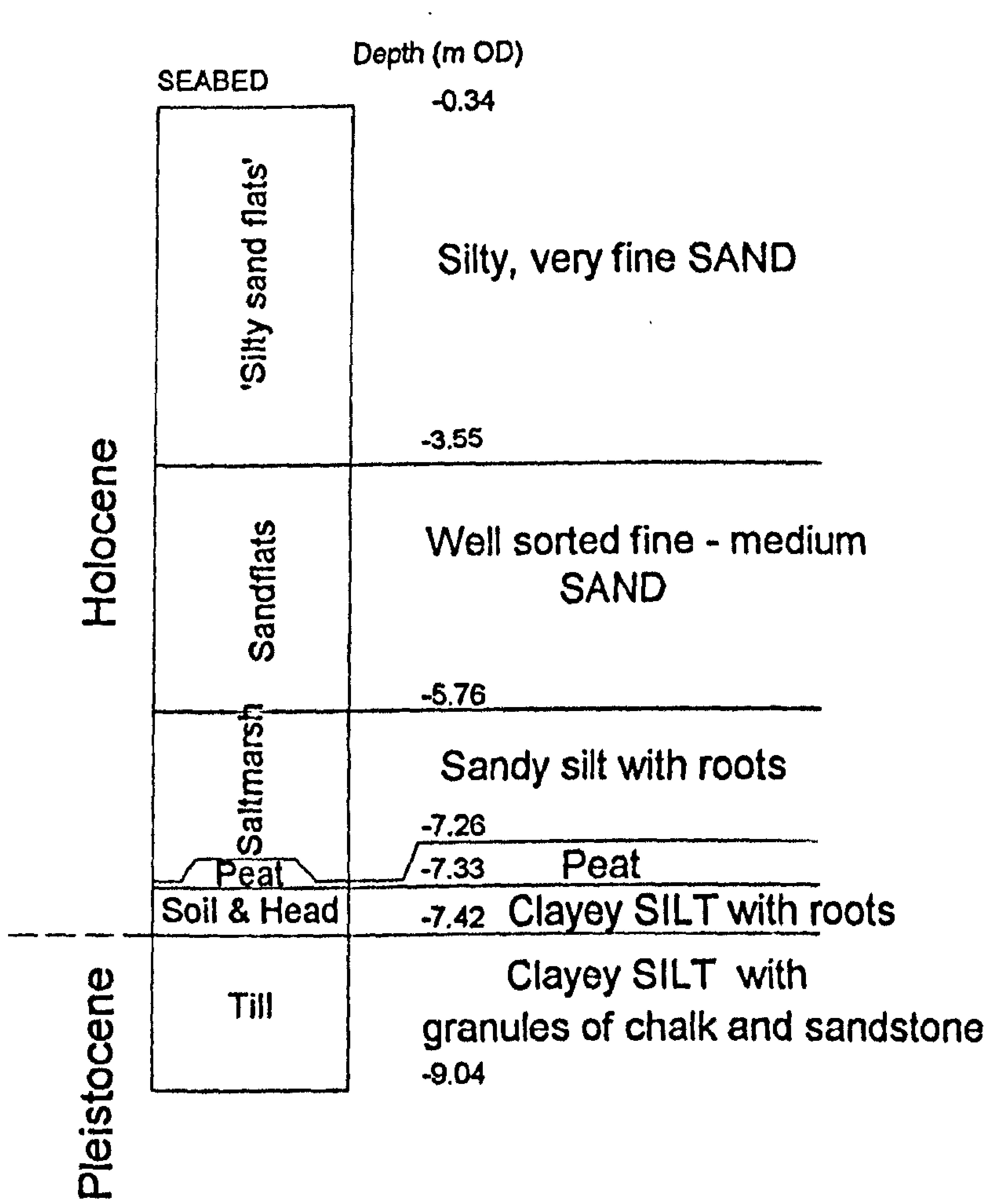
Sequence II has been interpreted as consisting of silts and sands. The surface of the sequence is fairly flat (Figure 6.14) indicating a possible conformable transition between sequences II and I with no substantial erosion.

Sequence I, the upper sequence, is well bedded with high amplitude reflectors with some structural features in places. It is of variable lateral thickness but with a general trend of overall thickening landward forming a shore parallel ridge which then thins landward. This bed has been interpreted as consisting of laminated/bedded sand and silt.

6.5 Discussion and conclusions

The geological interpretation based on facies analysis and published data from the surrounding area has been further confirmed by borehole data recently made available (Black, 1997). Borehole HI1 was collected for the RACS survey which was a continuation project of the LOIS programme. Borehole HI1 was collected in the middle of the UWB survey area. The borehole (Figure 6.16) indicates a silt and sand Holocene unit with peat and weathered till at its base overlying till. The Holocene sediments have been divided into a number of units on the basis of lithology. From the plot of the surface of sequence II (Figure 6.14) it would appear that the interface between well sorted fine to medium sand and sandy silt with roots at -5.76m OD that represents a transition between sandflats and saltmarsh is probably the interface between sequence I and II at the seismically derived height of approximately 5m.

Figure 6.16 Borehole HI 1.



The transition between silty sandflats and sandflats has not been readily recognised from the seismic data but could explain the high amplitude reflectors seen within sequence I.

The top of the till unit has been placed by borehole HI1 as being at -7.42m OD. This differs considerably from the seismic data which places this interface at approximately -9.1m OD. A possible explanation for this discrepancy could be attributed to the physical properties of the till. The layer of soil and head (weathered till) may extend deeper than indicated by the borehole. The reflection seen on the seismic data may represent the transition to unweathered till. Unfortunately this depth was not sampled by the borehole.

The till observed during the survey is likely to be the Skipsea Till of Madgett and Catt (1978). Catt (1990) showed the survey area to be extensively covered by this deposit (see Figure 6.3).

This case study has:

1) Identified three sequences on the basis of reflection terminations. However, as previously the sequences have not been able to be divided into component parts (i.e. systems tracts).

2) Shown that discrepancies can exist between lithological boundaries as identified by seismic and borehole data.

3) Shown that seismic facies analysis (with local geological knowledge) in determining lithology is fairly accurate. A fuller description and environmental interpretation of the area was however shown to be well described by a properly analysed borehole.

From these conclusions and the description and discussion of the sequences in the previous sections the interpretation of analogue data alone appears able to lead to a reasonable interpretation of the geology. However, the area may have benefitted from digital data processing due to its ability to identify lateral variability of lithology between sequences or differences in bed thicknesses, in this case of peat and head between sequences II and III. Such changes may have manifested themselves as tuning effects. The peat may also have been able to have been identified by a phase reversal (due to its low density) if it thickened above seismic resolution (approximately 0.25m).

CHAPTER 7

Menai Strait Case Study

7.1 Introduction

The Menai Strait was chosen as a suitable case study site for this project for a number of reasons. Previous marine geological and geophysical surveys in the region have identified predominantly metamorphic bedrock overlain by Quaternary sediments, with the thickness of Quaternary sediments reaching >10m in the area around Bangor Pier. The area, although subjected to strong oscillatory tidal currents, is relatively sheltered and not subjected to heavy sea swell. The protected nature of the survey area provides an environment that helps to optimise acquisition parameters and so improve data quality, it also allows the safe use of a small survey vessel allowing maximum intertidal coverage. Engineering work in the area (e.g. sewage outfall installation) has provided a sizable borehole data-base against which hypothesis and interpretation can be tested.

These factors would hopefully provide a further example of a complex Quaternary deposit that could be used to test the applicability of the seismic stratigraphic method to interpreting shallow water data using analogue and digital recording to identify depositional history and help to determine lithology and other physical attributes.

7.1.1 Setting/general area

The Menai Strait is the relatively thin body of water that divides Anglesey from mainland Wales (Figure 7.1a & b). It is approximately 27km long and ranges in width from between 250m to 2.5km. It is a very dynamic environment due to its complex hydraulic regime and experiences currents of up to 4 knots and a maximum tidal excursion of up to 6.8m.

The chosen survey target area was the NE end of the Menai Strait in the region around Bangor Pier (Figure 7.1b). The area has a wide intertidal zone of some 300m west of Bangor Pier and becomes wider to the NE over the Bangor Flats and wider still onto the Lavan sands, a surficial mixture of fine to very fine moderately sorted sands (Fouéré, 1966).

Figure 7.1a General area around survey site.

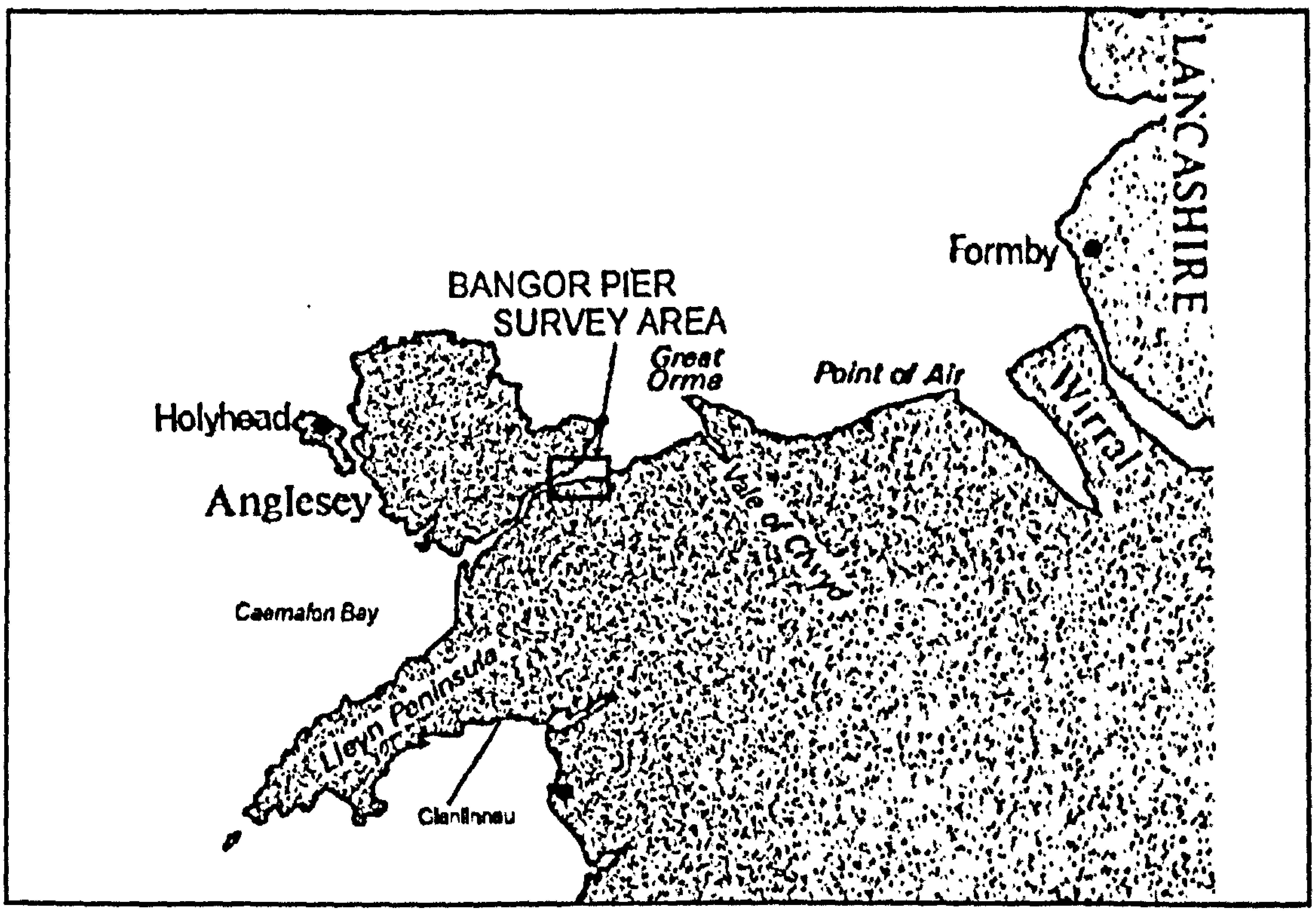
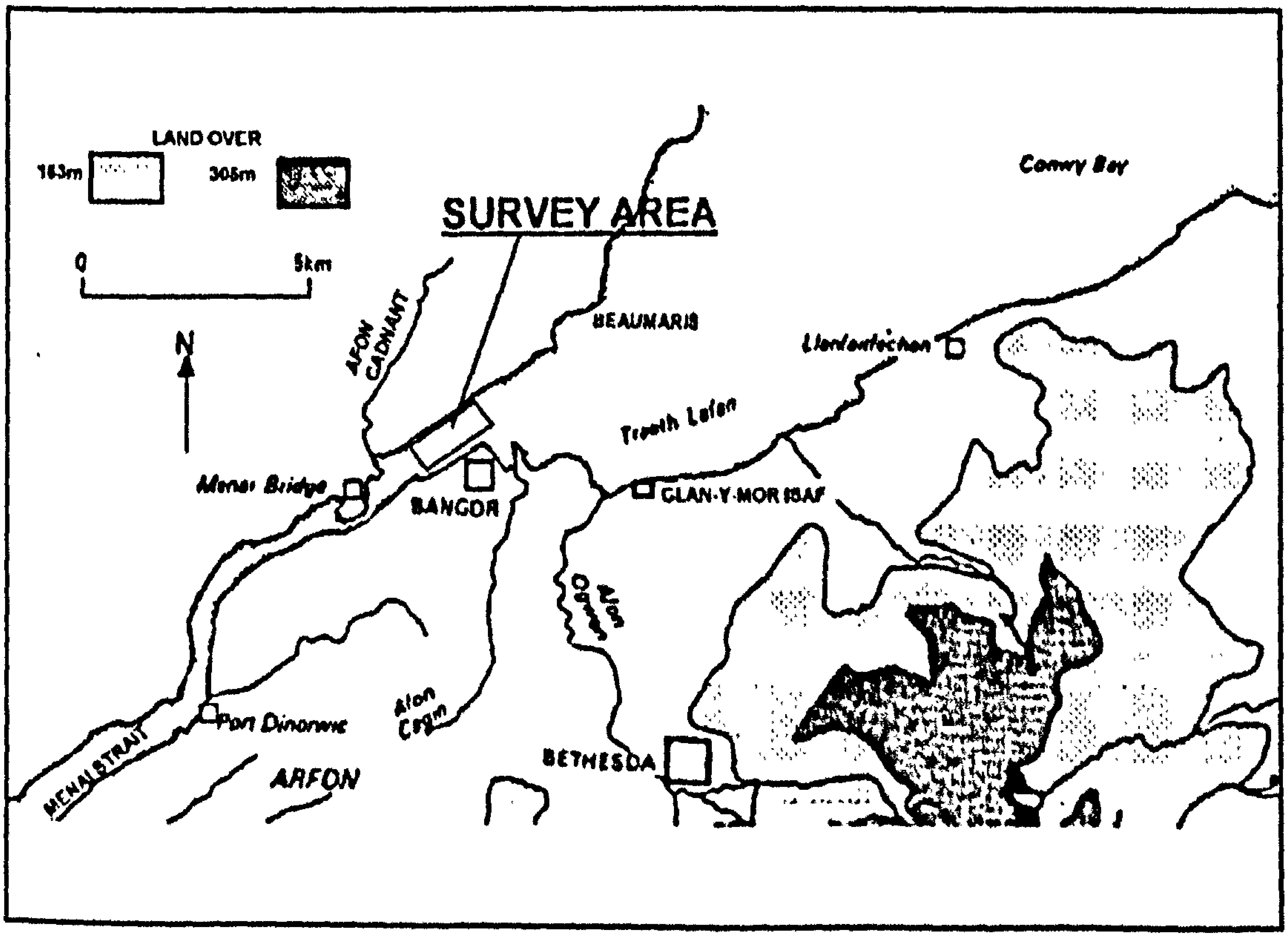


Figure 7.1b Local area around survey site.



The NE end of the Menai Strait has two distinct sedimentary environments: the well sorted sediments of the high energy environment of the mid channel, and the low energy environment of the intertidal zone characterised by more poorly sorted sediment (Fouéré, 1966).

7.1.2 Solid geology

The geology of the survey area, and indeed most of Anglesey, is dominated by the extensive Pre-Cambrian rocks of the Mona Complex and is described in detail by Greenly (1919). In the region between Menai Bridge and Beaumaris the solid geology consists of Gwna green-schist with spilitic lavas and albite diabases dissected by Palaeozoic dykes of dolerite and diabase.

On the mainland, around Bangor Pier, the Pre-Cambrian rocks take the form of the Bangor Ridge which stretches to Caernarfon. The ridge consists of the Bangor volcanic series (Greenly's Arvonian series) and comprises largely acid rhyolite lavas and quartz felsites with tuffs, agglomerates and grits.

7.1.3 Glacial and post glacial history

In his highly acclaimed geological study of Anglesey, Greenly (1919) demonstrated that Anglesey and Arfon were influenced by Irish Sea ice moving NE to SW on two occasions. Erratics, striations and what is described as a distinctive blue-grey Welsh till also show that in an early glaciation, ice from Snowdonia advanced rapidly into the Menai Strait fending off Irish Sea ice (Embleton, 1961). Following the retreat of the ice there would have been a period of periglacial, non-glacial climate during which weathering of these glacial deposits occurred (Whittow & Ball, 1970). Embleton (1964) then proposed that there was a second, final advance of Irish Sea ice.

Only circumstantial evidence for episodic glaciation in North Wales during the greater part of the Pleistocene exists and Addison (1990) argues that the principle evidence for the 'first' glaciation of North Wales must be of late Pleistocene age.

Embleton (1964) believed that the second ice advance was less extensive than the earlier one and thought it probably reached a depth of about 600ft because above this height he found a noticeable absence of contemporary meltwater channels. The maximum inland extent of Irish Sea erratics can be traced along the cols between Penmaenmawr to Moel Tryfan (Addison, 1990). The time bracket for this glaciation is probably Late Devensian; this time bracket is loose and relies on generally accepted timings for the British Isles as a whole.

7.1.3.1 Ipswichian Stage

The recognition of Ipswichian interglacial raised beaches in North Wales is tenuously based on the correlation of raised beach deposits at Porth Oer (Llyn) and Red Wharf Bay with the Pennard Stage (equivalent to Ipswichian) (Bowen *et al.,* 1985) in South Wales. Lacking the aminostratigraphy and speleotherm geochronology used in South Wales, the North Wales sites rely on the assumptions that they represent the higher sea-level of a pre-Holocene interglacial, and the overlying deposits are of a Devensian age.

7.1.3.2 Late Devensian Late Glacial (after Addison, 1990)

There is less uncertainty about the timing and rate of ice wastage and retreat due to a substantial number of pollen sites (some with radiocarbon calibration) supplemented by late glacial diatom records. In most respects the lithological and biogenic evidence for this interval conforms to the three-fold sub-division of the Scandinavian Late Weichselian (= Late Devensian) comprising a sequence of cold (Older Dryas), temperate (allerod) then cold (Younger Dryas) periods discussed below:

Older Dryas - The radiocarbon date of 14,460 ±300 years BP from a moss rich layer at Glanllnnau on the Cardigan Bay coast of Wales (Figure 7.1a) provides the earliest evidence of ice free conditions in the lowlands, and one of the earliest dates anywhere in Wales (Coope and Brophy, 1972 and Coope, 1977).

Progressively younger 'oldest dates' of 13,735 ±330 years BP at Llyn Goddionduon and 11,900 ±500 years BP (Burrows, 1975) and 11,260 ±220 years BP at Llanberis (Tinsley and Derbyshire, 1976) chart the retreat of ice into central Snowdonia.

Late-glacial (Allerod) Interstadial - At sites not previously occupied by Younger Dryas glaciers, there was a shift from minerogenic to biogenic sedimentation and an increase in *Juniperus* pollen around 13,000 years BP (Moore, 1977) indicative of continued climatic improvement that has been used to define the beginning of the late-glacial interstadial (Pennington, 1977).

Late Devensian late-glacial stadial: Younger Dryas (Loch Lomond Stadial) - Late-glacial stadial glaciers in the British mountains were restricted to cirque glaciation outside the limits of the Loch Lomond Ice Cap in Scotland. The climatic deterioration resulted in a return to minerogenic deposition and associated sparse tundra vegetation.

Where an absolute (radiocarbon) chronology is available (Switsur and West, 1973; Burrows, 1975; Tinsley and Derbyshire, 1976), the Younger Dryas in Snowdonia is placed between a maximum age of 11,125 ±265 years BP (Llyn Goddionduon) and a minimum of 9,400 ±200 years BP at Nant Peris.

7.1.3.3 The Holocene

The vegetation succession in North Wales during the Holocene reflects the development of temperate deciduous forest in response to climatic amelioration after the Younger Dryas. The early Holocene, starting at about 10,000 years BP, is frequently marked by an expansion in *Juniperus* and *Betula*.

7.1.4 Glacial deposits

Coastal erosion of a drumlin at Glan-y-Mor Isaf (Figure 7.1b) has exposed a complex sequence of sediments with the following succession (mainly after Pointon, 1990):

Unit	Description	Max observed thickness (m)
3	Irish Sea Till	4.0
2b	Silts, sands & gravels	1.5
2a	Silts and Sands	1.0
1b	Weathered Welsh Till	2.0
1a	Welsh Till	8.5

7.1.4.1 Welsh Till - Llwyd Diamicton

The till is light brownish grey to grey weathered to very pale brown in colour. Stone counts (8-16mm) show a lithological suite which includes limestone, mudstone, sandstone, gritstones, microgranite, tuffs, rhyolites and slates. Macrofabric results suggest ice flow from ENE.

Macrofabric results from Welsh till overlying Irish Sea till differ from those above and give ice flow directions of ESE - WNW and ESE - WNW. The surface of the unit at the eastern end is overlain by both gravels and Irish Sea till and is weathered. To the west of the section where Irish Sea till directly overlies Welsh till, the weathered horizon is absent.

Using this and other physical evidence Edge *et al.* (1990) suggest that the unit was deposited subglacially by a Welsh ice mass. Hart (1990) notes that the Llwyd Diamicton is homogenous at the base (interpreted as basal till) but grades upwards into a more chaotic gravel-rich facies which is interpreted as a deglacial sequence. Subsequent to retreat of the Welsh till and prior to deposition of upper sedimentary units, the deposit was exposed to sub-aerial processes and cryoturbation.

7.1.4.2 Silts, sands and gravels

Silts, sands and gravels are exposed at the eastern end of the section at Glan-y-Mor Isaf and are considered by Addison (1990) to be two separate channels cut into the Welsh till. Subsequent erosion of the cliff has exposed more of the deposit which can now be seen to be laterally continuous with hollows representing topographic lows in which sediments were deposited. According to Hart (1990), the diamicton represent small moraines and it is suggested that these are push moraines.

7.1.4.3 Irish Sea till

This deposit is the uppermost unit along most of the exposure. It ranges from a dark reddish brown to light reddish brown. The 8-16 mm gravel fraction contains mainly sedimentary clasts with some metamorphics and few volcanics. Of greater significance is the occurrence of red sandstone, Bunter pebbles and coal suggesting a northern provenance. Comminuted shell fragments found in the deposit also suggest an Irish Sea Basin origin.

The origin of the sequence at Glan-y-Mor Isaf has been summarised by Pointon (1990) as:

1) Glaciation by ice flowing out of the Conway valley which moved across the area from ENE to WSW depositing a lodgement till.
2) Retreat of the Welsh ice followed by sub-aerial weathering of the exhumed till surface.
3) Dissection and subsequent aggradation by fluvial processes.
4) Partial submergence perhaps by a proglacial lake and progradation of delta facies sediments.
5) Erosion of the land surface by an advance of ice from the North of the Irish Sea.
6) Deposition of an ablation sequence of till with intraformational glacifluvial sand lenses as the Irish Sea glacier waned and subsequently retreated.
7) Weathering of the exhumed surface and downslope transport of weathered material; exposure of the underlying Welsh till which in turn overrode the Irish Sea till.

7.1.5 Origin of the Menai Strait

Embleton (1964) considered the Menai Strait to be a composite valley cut low enough to allow its submergence in the Post Glacial, the final separation of Anglesey from the mainland occurring during the Flandrian transgression (6000 - 7000 years BP) forming the Menai Strait. Another 27m rise would unite Malltraeth Marsh and Red Wharf Bay and inundate other valleys. Each of these valleys has a watershead along its length. That of the Menai Strait rises to within 3m of low water, spring tide, between the bridges.

Greenly (1919) contends that pre-glacially, the 'Western' and 'Eastern' reaches of the Strait were two separate river valleys draining to Caernarfon and Conway Bays respectively (Figure 7.2). Joining the western reach and now partly represented by the 'Middle Reach' of the Strait which runs north-south, was the Afon Braint, while the exit of Arfon Cadnant at this time could only have been in the direction in which it is now, out into the sea beyond Beaumaris (Greenly, 1919). Greenly also considered that at a time in the late glacial the Ogwen glacier emerged far enough to block the drainage of the Eastern Reach, causing the formation here of a lake which overflowed to the SW into the old Braint valley (= the Middle Reach) and then to the western Reach and Caernarfon Bay. The spillway was eventually cut down far enough to be submerged in the post glacial.

Embleton (1964) disagreed with much of Greenly's hypothesis, and suggested that the Menai Strait developed in association with the down wasting of Irish Sea Ice in the region.

The Western and Eastern reaches of the Menai Strait are developed along outcrops of Upper Carboniferous and Carboniferous limestone respectively (Figure 7.3a), which Embleton considered likely to have existed as a pre-glacial (possibly interglacial) valley. At some time in the glacial period, the barrier dividing them was partially destroyed and cut down more than ten feet below present sea-level.

It is suggested by Embleton (1964) that the Cadnant was once the headstream of the river which once flowed generally SW along the Western Reach of the Strait. At Plas Cadnant, it crossed the line of an early Tertiary dyke, which provided a

Figure 7.2 Evolution of the Menai Strait according to Greenly (1919).

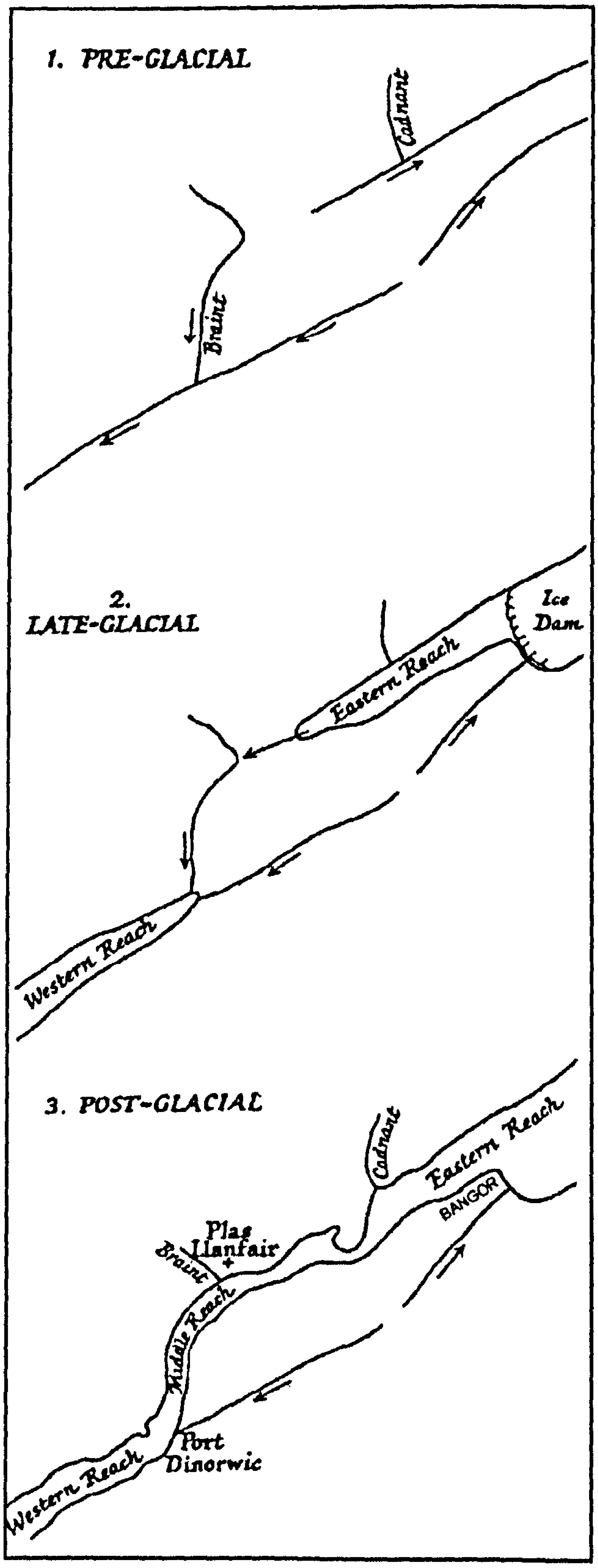
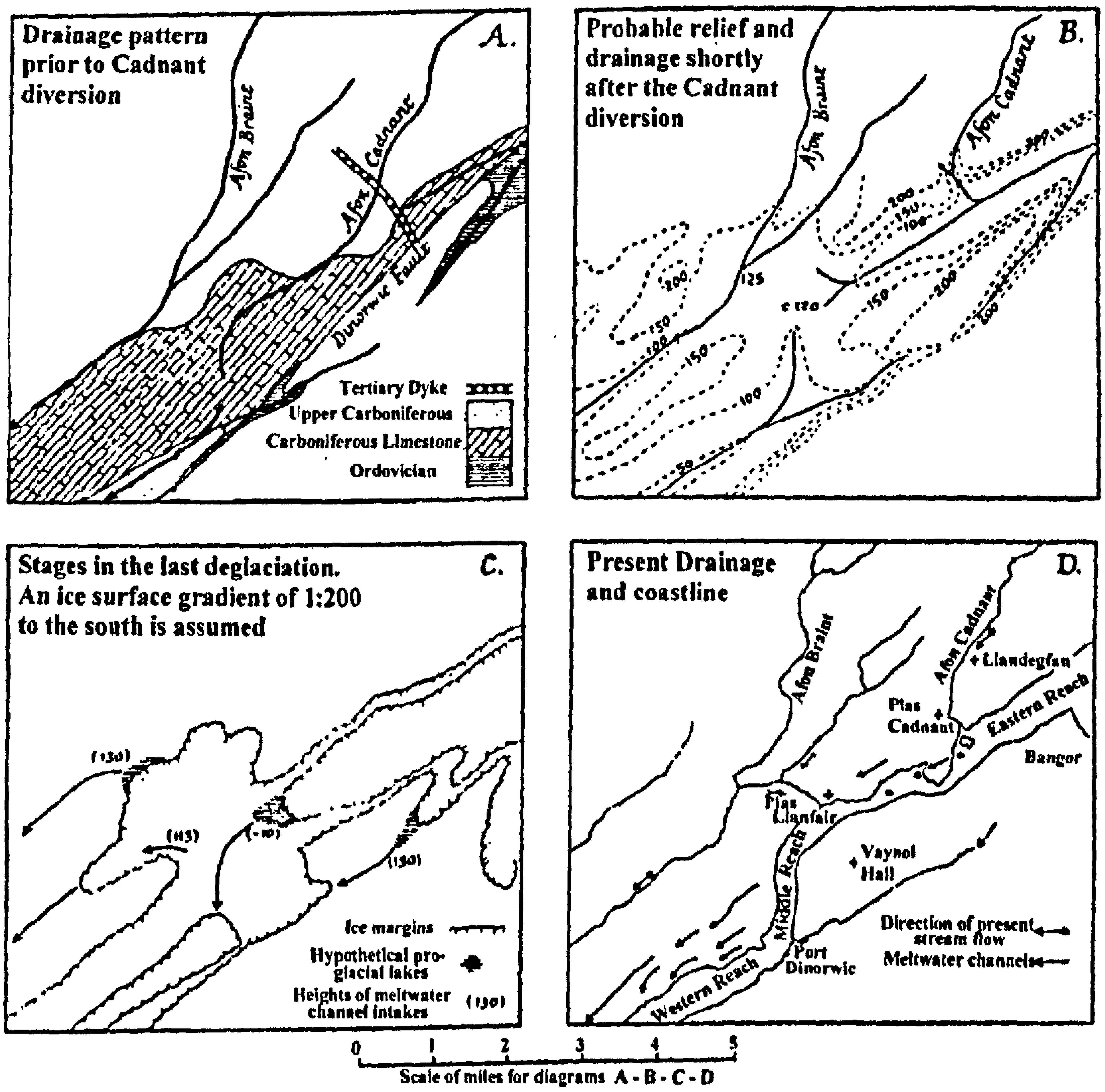


Figure 7.3 Evolution of the Menai Strait according to Embleton (1964)



line of weakness disrupting its path, the sharp angle the river now makes at this point indicating diversion by capture.

The probable river pattern after the Cadnant diversion is shown on Figure 7.3b. The date of this diversion is thought to be inter-glacial rather than pre-glacial.

The formation of the Menai Strait channel to its present form was considered by Embleton (1964) to have come about during the deglaciation of the Irish Sea ice. The generally north to south slope of the ice established by Embleton, which, combined with the incidence of local topographical features, means meltwater would escape to the SW.

As the ice surface wasted down, more and more of the buried topography would emerge. Tongues of ice would remain in the valleys, including the valleys now drowned to form the Eastern and Western reaches of the Strait. Two hypothetical stages of the deglaciation are shown in figure 7.3c; ice margins are based on a gradient of 1 in 200 from N to S.

In the first stage, meltwater cut two outlets to the southwest - the Gaerwen channel and the Bangor Dinorwic channel, both lowered to 130 feet before being abandoned. A tongue of ice also protruded down the Braint, the lower course of which was slightly overdeepened by meltwater.

By the second stage, the ice was no longer continuous from Conway to Caernarfon Bays. Meltwater was forced to carve a channel through the central divide standing at 120 feet and separating the Eastern and Western Reaches, a process which lowered it eventually below present sea level.

Alternatively Embleton contends that the Strait was formed in an earlier glaciation and subsequently re-occupied by ice.

Whittow and Ball (1970) have, as a result of a detailed study of the drift stratigraphy in North Wales, suggested the simple account given above is inadequate. They propose that the drift stratigraphy is the result of a complex ebb and flow of Northern and Irish Sea ice, and that this idea accounts for many of the anomalies associated with the picture of events described by Embleton.

The downwasting of the ice sheet was gradual and, as shown by evidence from Lleiniog (Campbell and Bowen, 1989) oscillated a number of times during its retreat. However, with each advance and withdrawal made by the ice a frontal moraine was deposited. It is one of these which is believed to have damned the north east flowing river and created a lake. When the lake eventually overspilled, an overflow channel was cut that connected to the southwestern flowing river. This is now represented by the double bend which runs north/south between the Britannia Bridge and Port Dinorwic. Subsequent changes in relative sea-level caused both the river's lake and meltwater channel to become submerged. This final separation of Anglesey from the mainland accounting for the landscape we see today.

7.1.6 Local sea level change

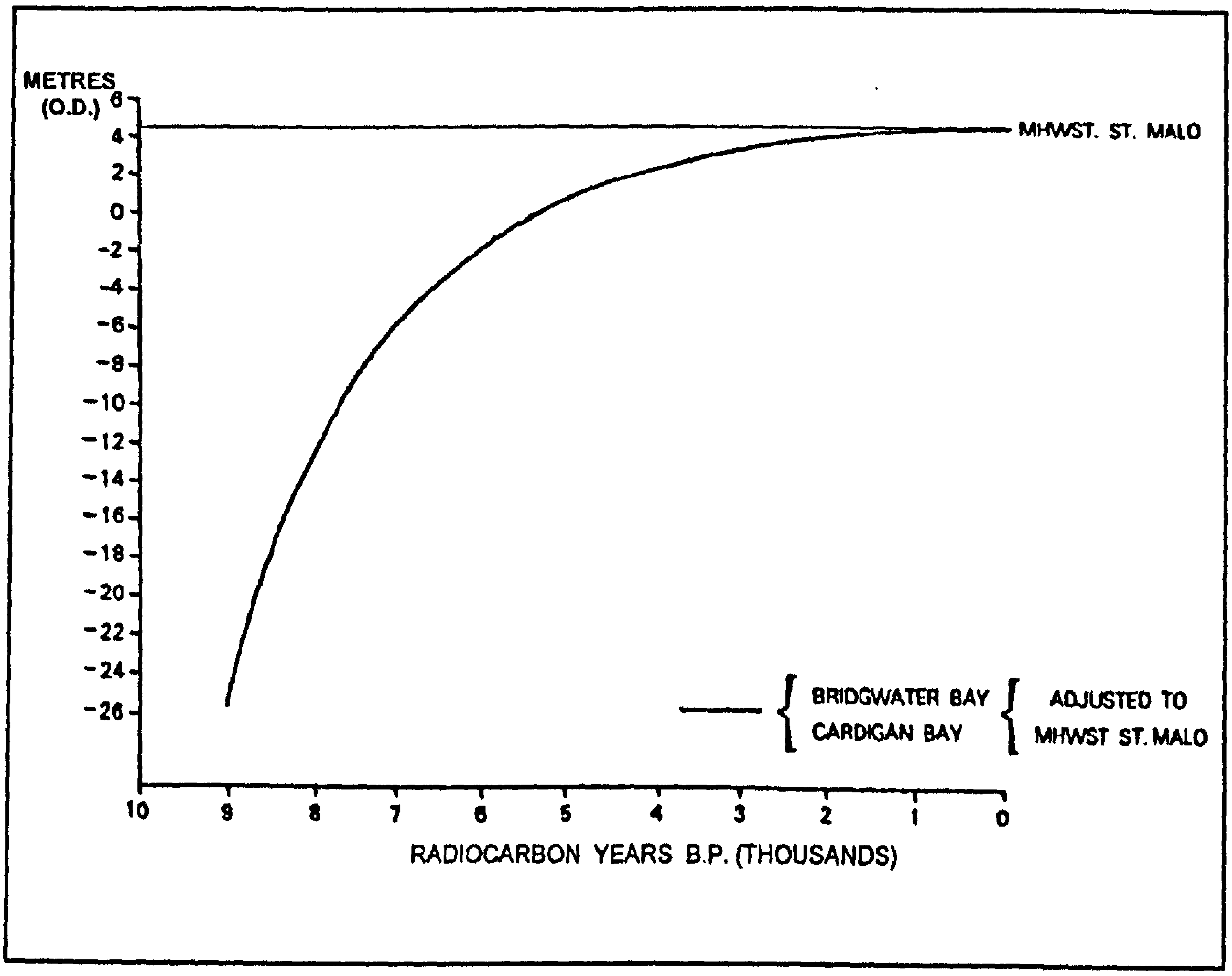
The identification of eustatic changes of sea level on the coast of Wales is, according to Heyworth and Kidson (1982), complicated by its location on a wide continental shelf and its subjection to great westerly storm belts. These factors and the errors involved in any measurements are also discussed by Heyworth and Kidson (1982).

Detailed investigation of the region of Cardigan Bay and Bridgewater Bay (Bristol Channel) (Kidson and Heyworth, 1973, 1978) reveal that they have an almost identical sea level curve. A combined sea level graph is presented in Figure 7.4.

Heyworth and Kidson (1982), using radiocarbon dates from Cardigan Bay, Bridgewater Bay and the Somerset Levels, concluded that no sea-levels higher than at present have occurred. In North Wales however, a difference did occur. Although only based on two measurements, the data appeared to suggest sea-levels higher than at present. This is thought to be due to isostatic uplift in the area as the order of uplift is that suggested by Kenna (1978). Shennan (1989) suggests slight uplift prior to 7000 BP for North Wales. Heyworth and Kidson (1982) rule out the suggestion of raised beaches by Whittow (1965).

Crustal linear downwarping has occurred throughout southern and south-eastern England and most of Wales for at least the last 4000 years. Glacio-isostatic

Figure 7.4. Sea Level curve (after Heyworth and Kidson, 1982).



processes have resulted in uplift in northern England and mainland Scotland. The rates of uplift have experienced exponential decay throughout the Holocene.

Data from the Tees estuary reveal slight uplift prior to 5000 BP, with essentially no trend since then, whereas most of the individual index points from the Humber estuary show subsidence (Shennan, 1989). The transition between uplift and subsidence on the east coast appears to lie between these two estuaries (Figure 7.5). On the west coast the transition between current uplift and subsidence (and therefore experiencing no relative isostatic movement) is around the Mersey and extends along the North Wales coast passing close to the Menai Strait survey area.

7.1.7 Borehole data

The area around Bangor Pier has been sampled by a considerable number of boreholes. Most of these boreholes have been drilled to assess the geological conditions prior to the installation of sewage pipes. The borehole logs reveal the geology around the survey area to generally consist of a Quaternary deposit of variable thickness comprising a mixture of clays and silts of varying proportions interbedded towards the base, with peat (Figure 7.5a). This overlies stiff silty clays.

7.1.8 Summary

From a study of geological and other literature about the Menai Strait and surrounding area it would appear that the overall history of the Menai Strait is not fully resolved and that the Quaternary geology is fairly complex. What does appear clear is that the area has been subjected to various periods of glaciation from different origins. These glaciers and the subsequent post glacial processes and marine inundation will have resulted in a complex sedimentary history which may help to be resolved with a detailed geophysical investigation.

7.2 Marine seismic investigation

Prior knowledge of the geological and environmental conditions in and around the survey area are essential at the planning stage of any survey regarding choice of

Figure 7.5 Estimated current rates of crustal movements (mm/yr) in Great Britain (after Shennan, 1989).

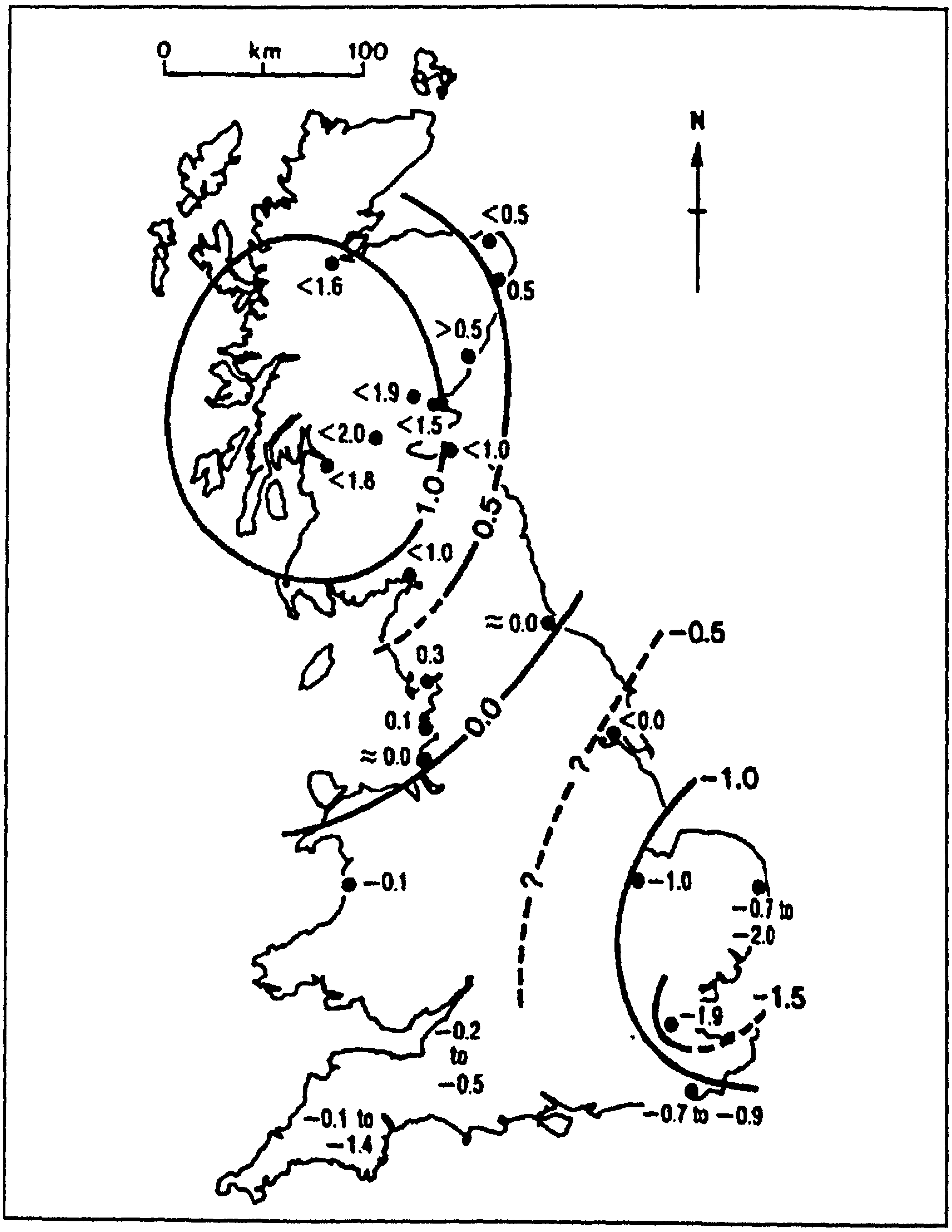
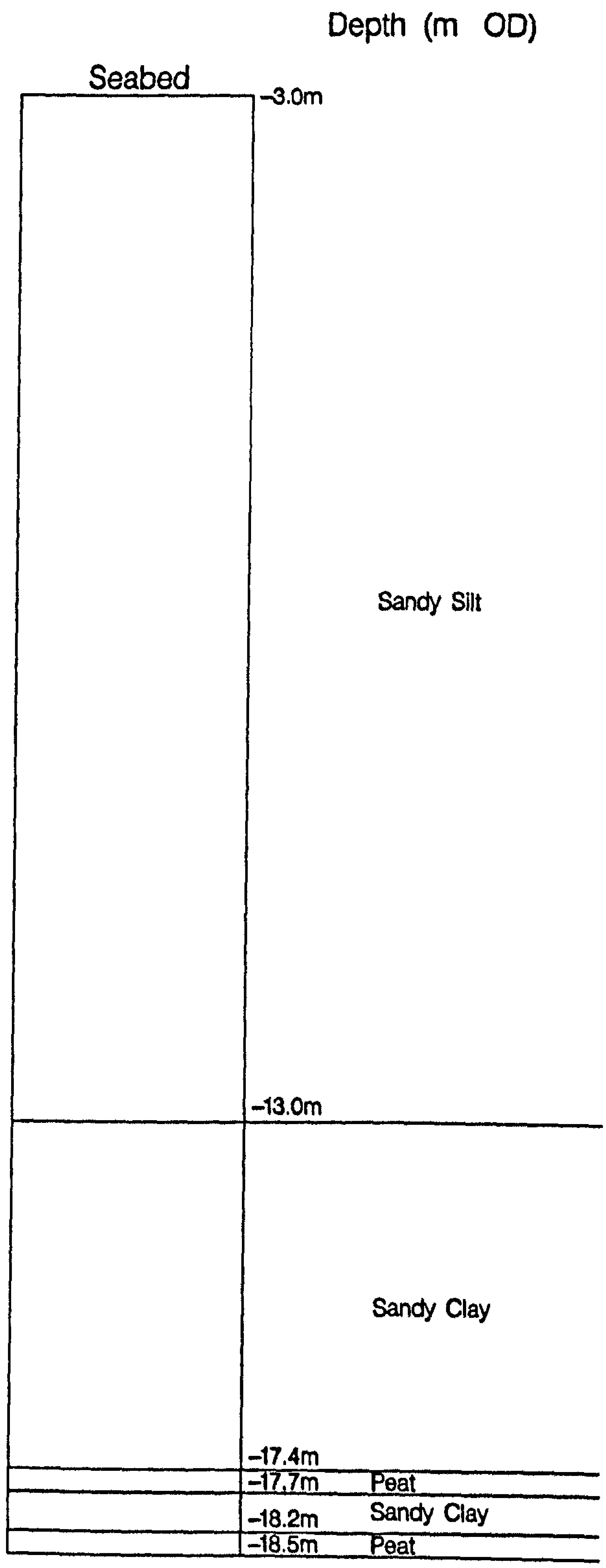


Figure 7.5a. Composite borehole log of typical sediments in the survey area around Bangor Pier.



Scale 1:1250

Menai Strait that any geophysical survey in the dynamic environment of the intertidal zone is planned with the local conditions in mind.

After considering these factors the method of conducting the survey that would best serve the objectives of this project was determined. A discussion of the survey method and equipment is described here.

7.2.1 Survey details

The intertidal area of the Menai Strait is a designated SSSI (Site of Special Scientific Interest). The area is of great interest for its marine communities; the strong tidal currents and shelter from wave action has created a rare habitat with very rich fauna. However, the restrictions imposed at the previously discussed Tees and Humber case study sites due to conservation projects and problems of access were not as problematic in the Menai Strait.

The area around Bangor Pier was surveyed on two different occasions. This was necessary due to problems encountered collecting digital data during the first survey.

The first seismo-acoustic survey was conducted from the 'Sand Pebbler' using the Seistec for seismic data acquisition, an echo sounder for bathymetry data, and a trisponder system for position fixing. The second survey was performed with the RV Prince Madog using a Uniboom source and single channel hydrophone array for seismic acquisition. This equipment was used as the Seistec was not available at the time of the survey. Position fixing and navigation onboard the Prince Madog was performed using differential GPS.

The survey programme during the two experiments is presented in Figure 7.6.

7.2.2 Sub-bottom profiling with the Seistec

The surveying performed with the Seistec concentrated on the intertidal zone around Bangor Pier as this area was known, from past experience and borehole data to consist of a thick accumulation of what are thought to be Quaternary sediments. A survey programme of 17 lines was run covering an area of

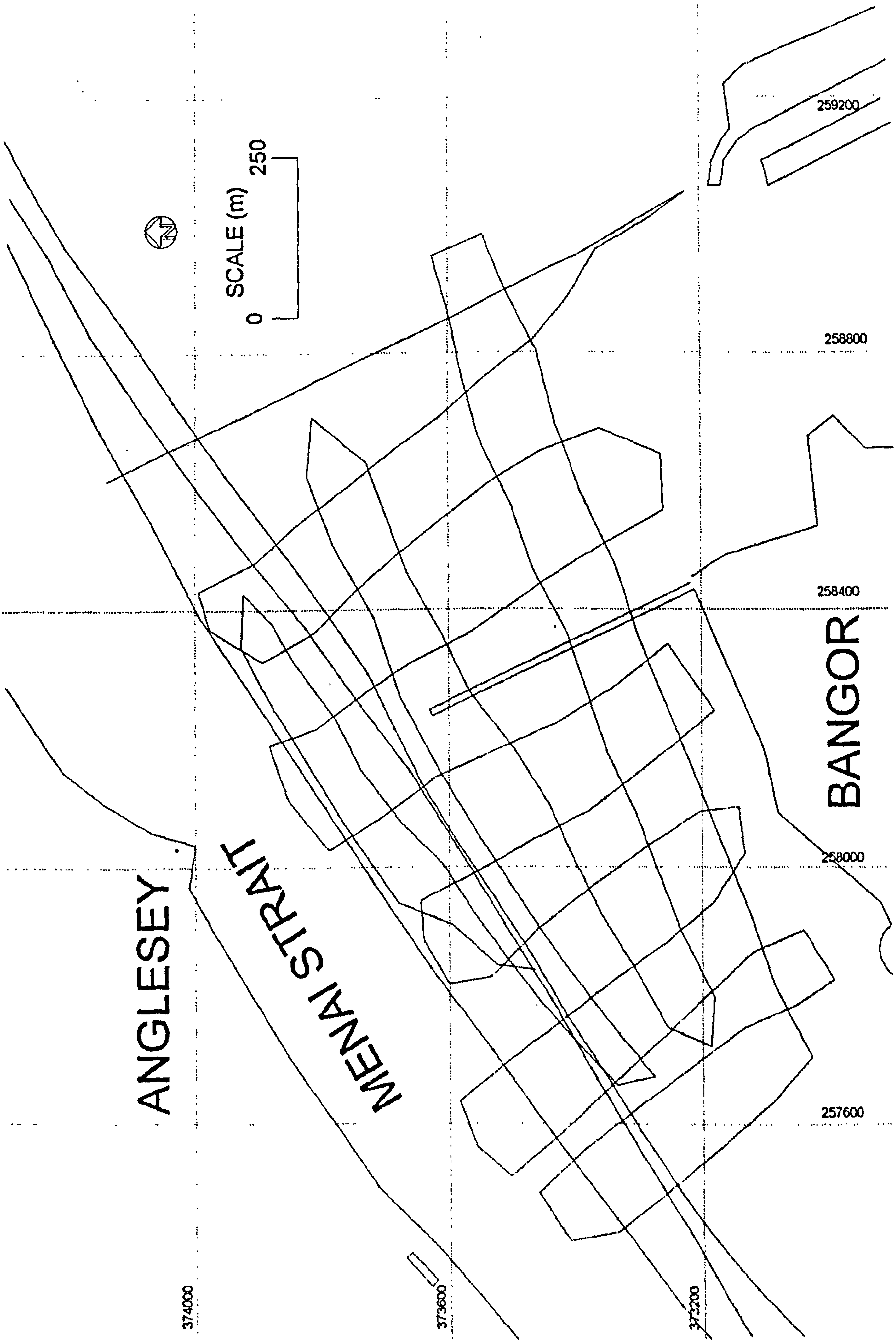


Figure 7.6 Survey lines run in the Menai Strait

approximately 1km^2. Surveying was carried out at high water to optimise the spatial coverage of the intertidal zone. The depths of water experienced during the survey ranged from 17m to 1.7m. The characteristics of the Seistec have already been described in section 5.2.2.1.

Seismic data were recorded as a hard copy to a thermal printer and to digital audio tape (DAT). The DAT tape was originally intended to be replayed to a digital acquisition system post survey. However, when this was attempted the tape was found to be corrupted hence requiring a re-survey of some of the area to acquire digital data.

Throughout the survey the Seistec and the printer used the same operating parameters as described in the Tees Estuary case study described in chapter 5. The survey equipment layout on board the Sandpebbler is presented in figure 7.7.

7.2.3 Sub-bottom profiling with the Uniboom

This survey was conducted to acquire a portion of the digital data not collected in the previous survey. The survey work carried out with the Uniboom was limited to the deep water channel of the Strait due to the draft of the Prince Madog. A total of three lines each approximately 3750m were run.

The EG&G 230-1 Uniboom comprises a sound source transducer mounted on a catamaran. Above the boomer plate is a 2" baffle to reflect and absorb energy directed towards the surface. Seismic energy is received using a separate multi-element single channel towed hydrophone array comprising 8 Aquadyne AQ-1 hydrophones with a common pre-amplifier.

The optimum deployment of both source and receiver plays an important part in data quality. The optimal towing arrangement is achieved by towing the source and receiver symmetrically and on opposite sides of the ship's wake. Such a configuration shields the hydrophones from the direct pulse thereby reducing its amplitude, and the scattering effect of the wake helps to reduce multiple strength. When surveying in shallow water it is especially important to reduce, if not eliminate, the direct pulse as it may mask the first arrival of seismic energy from the seabed and obscure important reflection data.

Figure 7.7 Survey equipment for the Seistec system on the Sand Pebbler.

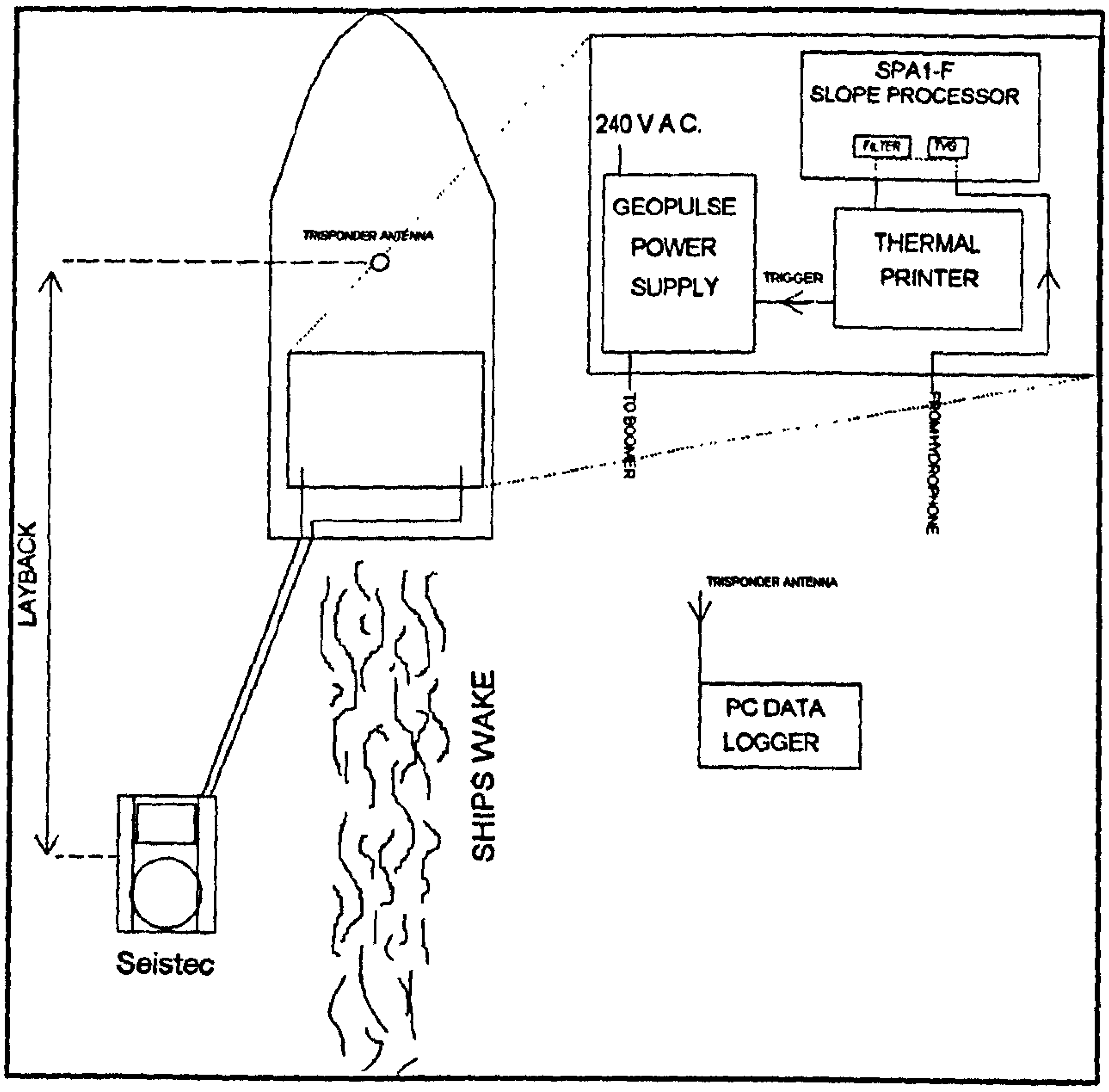
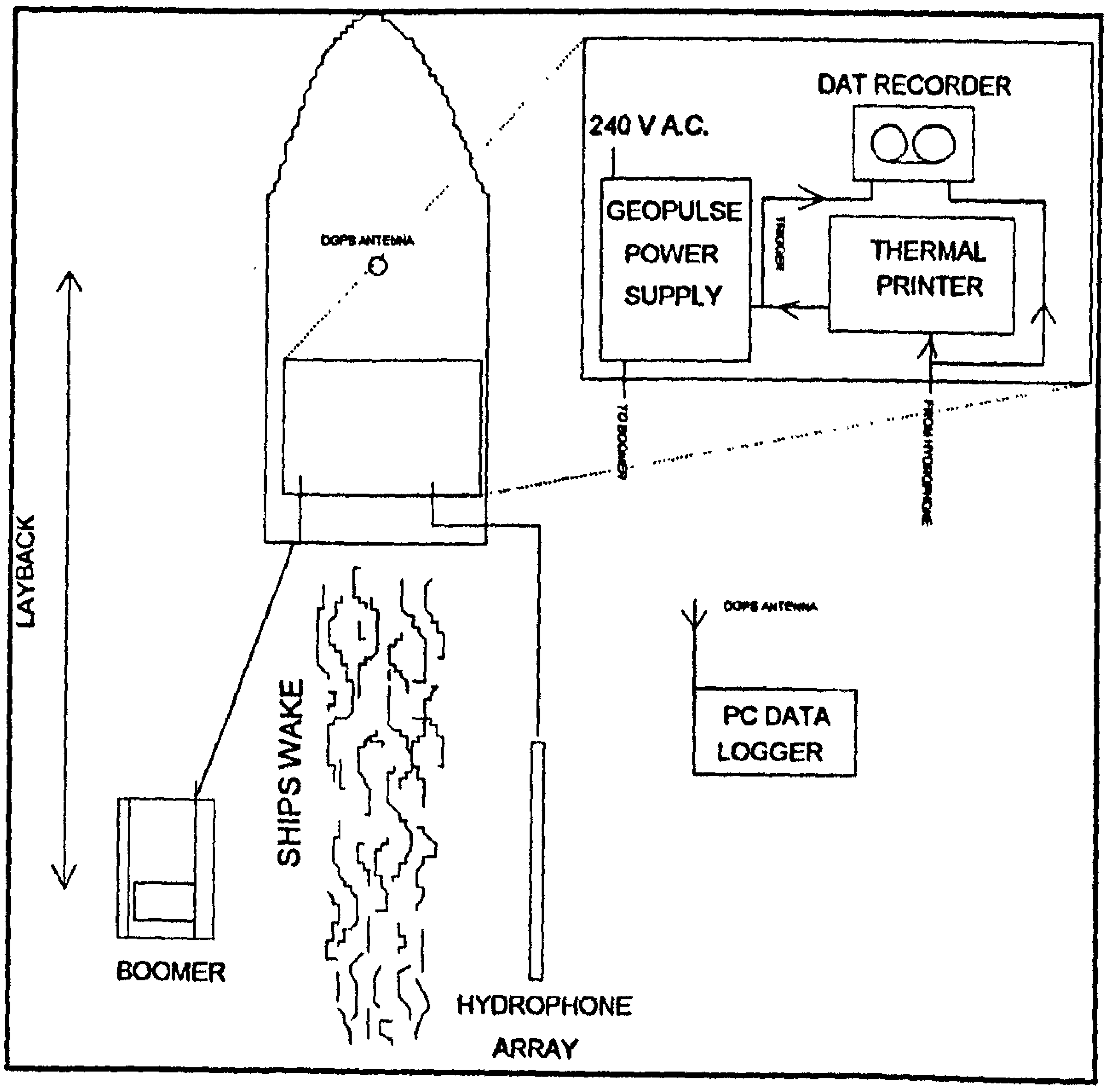


Figure 7.8 Survey equipment layout for the Boomer sub-bottom profiler system on the Prince Madog.



Throughout the survey the Seistec and the printer used the same operating parameters as described in the Tees Estuary case study described in chapter 5. The survey equipment layout on board the Prince Madog is presented in figure 7.8.

7.2.4 Digital data acquisition

Throughout the Prince Madog survey, data were recorded as a hardcopy to a thermal printer and to magnetic tape via a Sony DAT recorder. The recorder is routinely used as a back up to safeguard against data loss as it can easily be interfaced to the thermal printer to allow data playback. In this case it was also specifically utilised to record raw seismic and trigger data to allow post survey playback to a digital seismic acquisition system, the Elics-Delph 2. The data were recorded by the DAT recorder at a sampling frequency of 48kHz. The seismic data were eventually recorded to Exabyte tape in SEG-Y format to allow post survey data processing on a Sun Workstation.

7.2.5 Position fixing

Position fixing whilst surveying from the Sandpebbler was achieved by using the same Trisponder positioning system as used during the Humber survey (chapter 6). The Trisponder system was used as the vessel did not have a sufficiently accurate global positioning system (GPS) installed, and because the nature of the survey area, i.e. abundant terrestrial positions to install slave systems, readily lends itself to the use of a Trisponder system. The accuracy of the trisponder system can be expected to be ±1m.

The positional data were recorded in national grid coordinate format as an ASCII file to PC every 5 seconds.

For this survey the pre-calibrated slaves were deployed at the following fixed shore based stations:

Location	National Grid Reference
Glyn Garth	SH 258035E 374013N
Penryn	SH 259110E 373175N
Ynys Faelog	SH 256127E 372170N

During the survey with the Prince Madog, position fixing was achieved using a Trimble NavTrac differential global positioning system (DGPS). The differential GPS relies on error corrections transmitted from a reference station placed at a known location. The reference station calculates the error correction for the satellite range data and broadcasts these corrections to DGPS receivers in the vicinity. In differential mode the NavTrac has an accuracy in the order of 5m - 10m. The NavTrac GPS can output the navigation data via an RS-232 port. The navigation data were logged to PC every 2 seconds and, post survey, were converted from latitude and longitude to national grid coordinates.

7.3 Interpretative procedure

Examples of analogue and digital seismic data have been selected for presentation and discussion in the following section (section 7.4). To assist in the interpretation and provide a 3D overview of certain aspects of the data, contour maps have been constructed using the whole data set. These plots illustrate bathymetry and subbottom reflectors. The data examples and contour plots have been constructed using the parameters discussed. Layback on the Sandpebbler and Prince Madog were 9m and 27m respectively.

7.3.1 Seistec/boomer analogue interpretation

When surveying with the Uniboom, the boomer to hydrophone offset distance was 9.4m (calculated on the basis of the direct wave arrival time). This distance was used for practical considerations throughout the interpretation. It must be borne in mind however that this separation will have been subject to minor changes along survey lines due to the hydrophone array "snaking" in the water as it was towed, and would have been subject to greater changes on boat turns. Water and sub-bottom depths were worked out using non linear scales calculated using the following equation (7.1):

$$d = \sqrt{\frac{v^2t^2-x^2}{4}} \qquad (7.1)$$

Where: d = depth (m)

v = Seismic velocity (m/s)

t = Two way time (m/s)

x = Source-receiver offset (m)

In the interpretation of the boomer data an assumed seismic velocity of 1500m/s has been used for seawater. An assumed seismic velocity of 1650m/s was used for sediment, this is the same assumed velocity that has been used in the other case studies and was originally proved at Seal Sands, Teeside (chapter 5). Water depths were obtained from the simultaneously running, calibrated, echo sounder.

7.3.2 Boomer digital processing and interpretation

The digital data were acquired and processed for a number of purposes. An important aspect of seismic stratigraphy is seismic facies analysis. This, as previously discussed in section 3.4.3, can be assisted by examining the instantaneous attributes of seismic data. The production of instantaneous attribute plots can only be achieved using digital data. In this particular survey the availability of digitally recorded data also illustrated a point regarding data quality. During the survey an equipment problem resulted in a DC bias being applied to the data. This bias was able subsequently to be processed out with a resulting improvement of data quality (although the ability to perform such tasks should never be used as an excuse to not strive to collect the best quality data at the acquisition stage). The digital data have, in this case, also been subjected to different types of bandpass filtering to show its affect on data improvement. This was done to see if a particular filter may provide data that lends itself more favourably to a seismic stratigraphic interpretation.

Digital data acquired during the survey of the Menai Strait by the Prince Madog was initially recorded onto DAT tape and, post survey, replayed to the Delph acquisition system. In playback it was recorded as SEGY format ready for processing on a Sun workstation using ISX processing software.

Before any of the processing steps described in the previous sections could be accomplished, the data needed to be read from magnetic tape to the workstation and stored in a format recognised by the processing software. The data were read into Sierra Seis using the processing sequence shown in Figure 7.9.

The various pools and processes used in the sequence are as follows:

Segyin — This process reads trace sequential seismic data from tape in SEGY format. The interpreter need only specify the location of the file on the tape, and the number of files to read.

Bias — This process is used to remove or add DC bias to seismic trace data. In this case it was used to remove 100% of trace average calculated over first and last non zero samples from data acting as a sliding window over 1ms.

Wrpool — This process is used to write out traces to a pool, which in this case is the pool 'Pier'.

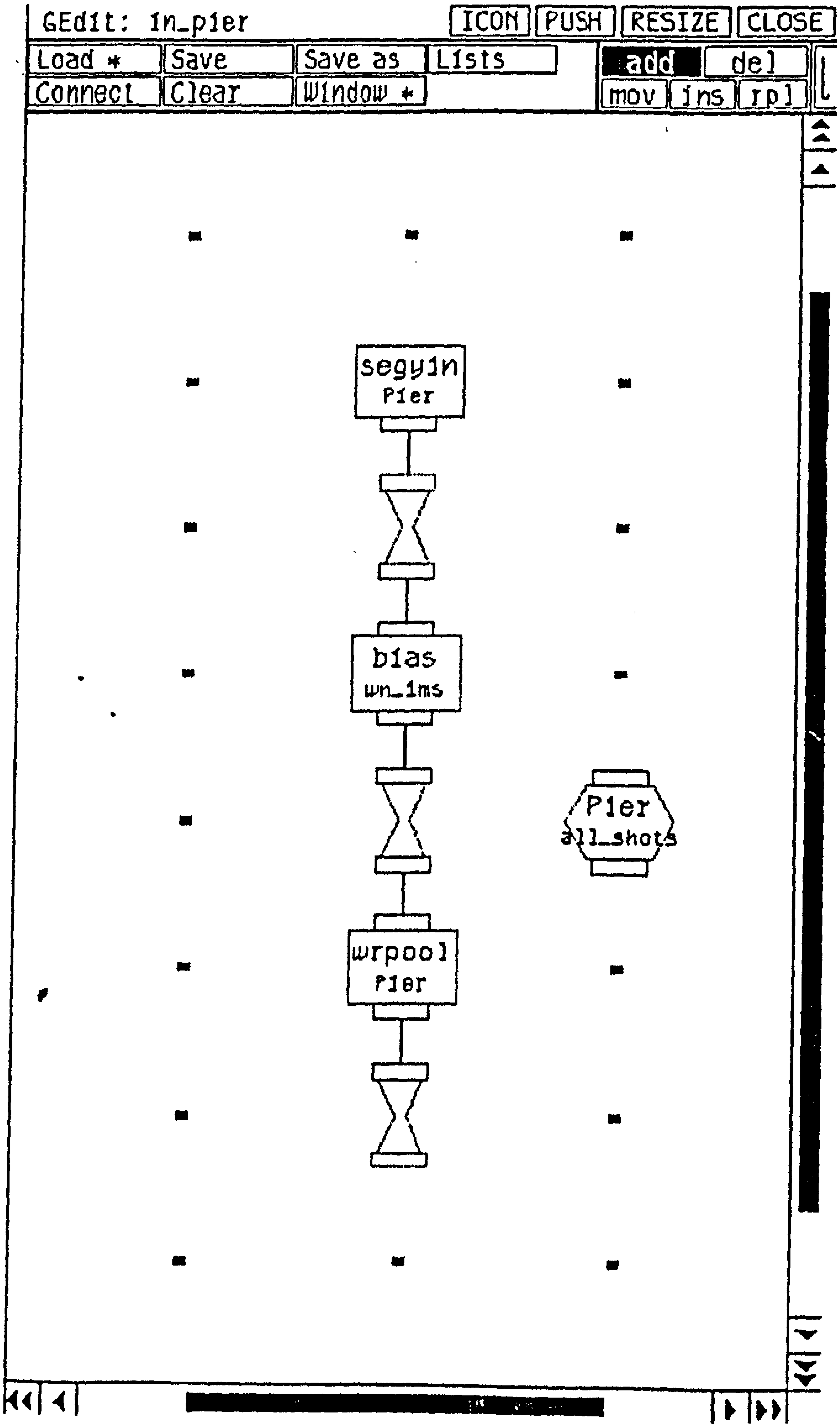
Pier — The pool 'Pier' is used as a store for the data.

Pipe — Pipes are simply data connections between processes containing only one trace at a time.

The affect that the Bias has on data quality can be seen by comparing Figures 7.10, 7.11 and 7.12 which show bias processed digital data, 'raw' digital data and analogue data respectively. In this case the Bias was necessary to remove DC offset from the data caused by a fault on the hydrophone pre-amp.

The type of data processing that can be carried out on single channel data is limited, and in this case was restricted to what Yilmaz (1994) has termed "preprocessing techniques".

Figure 7.9 Sierra Seis processing sequence used for reading digital sub-bottom profile data from magnetic tape and converting it to a format suitable for subsequent processing and display using Sierra Seis software.



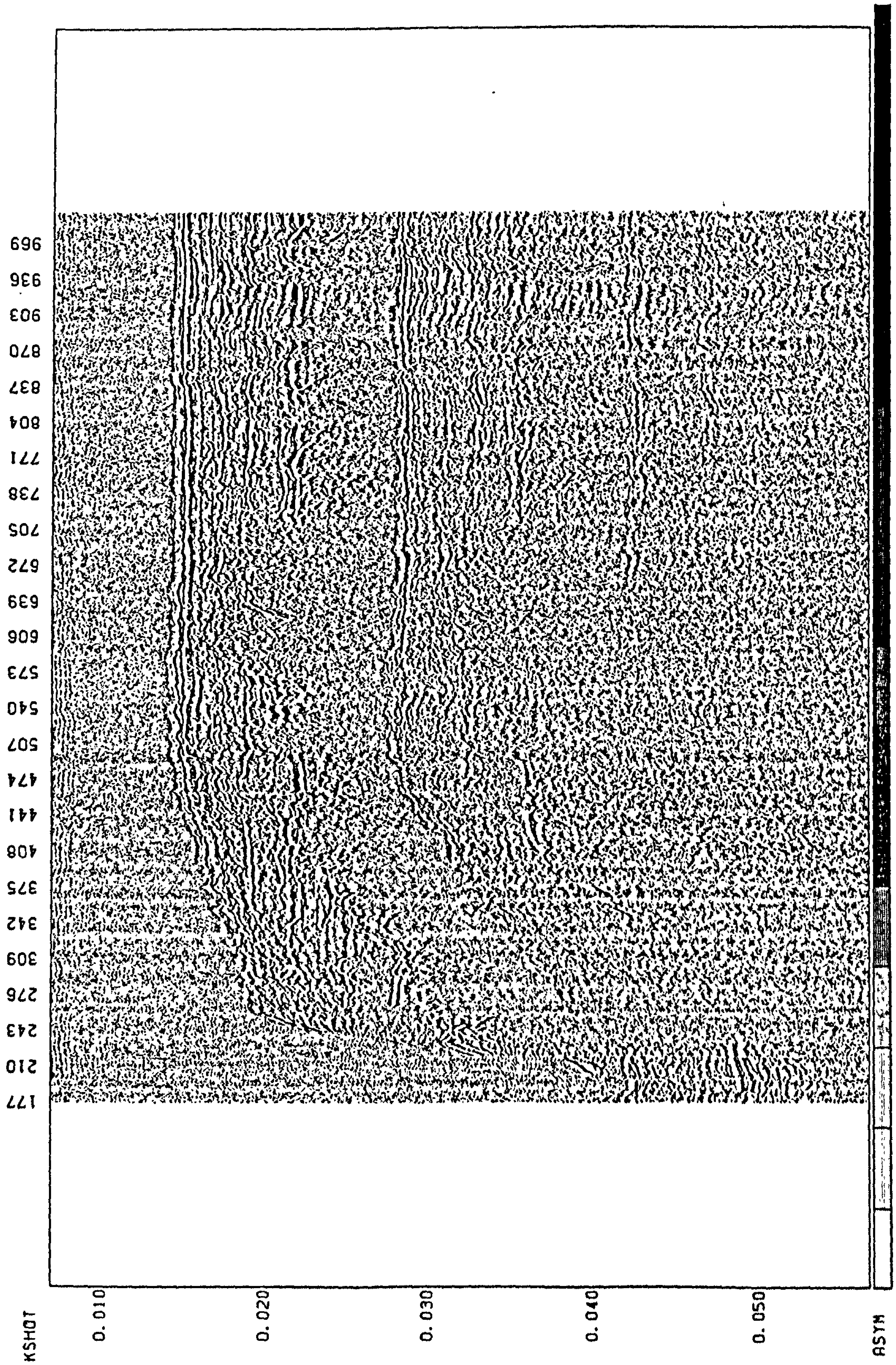


Figure 7.10 Digitally recorded data after 'Bias' processing.

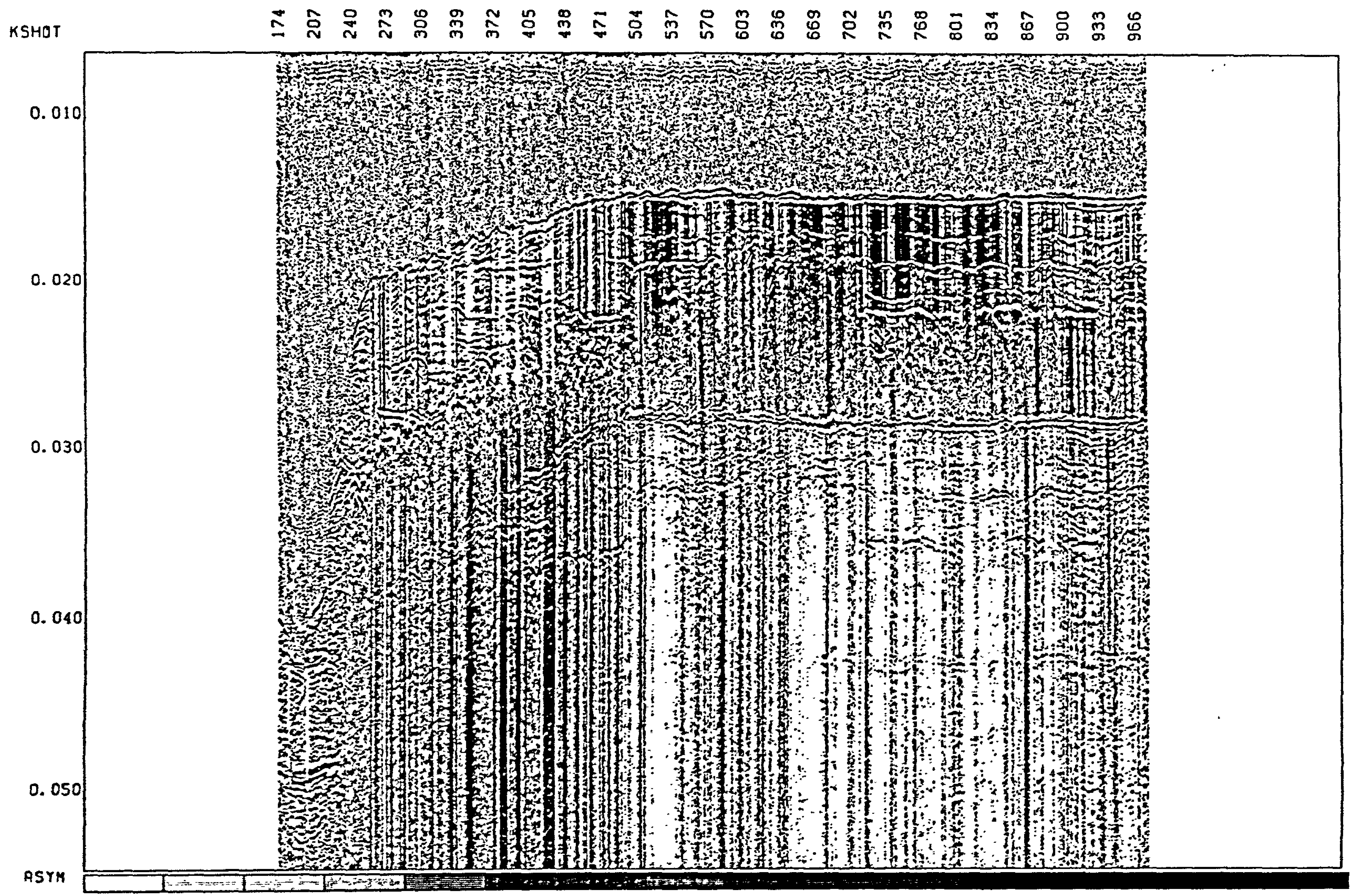


Figure 7.11 Digitally recorded data without 'Bias' processing.

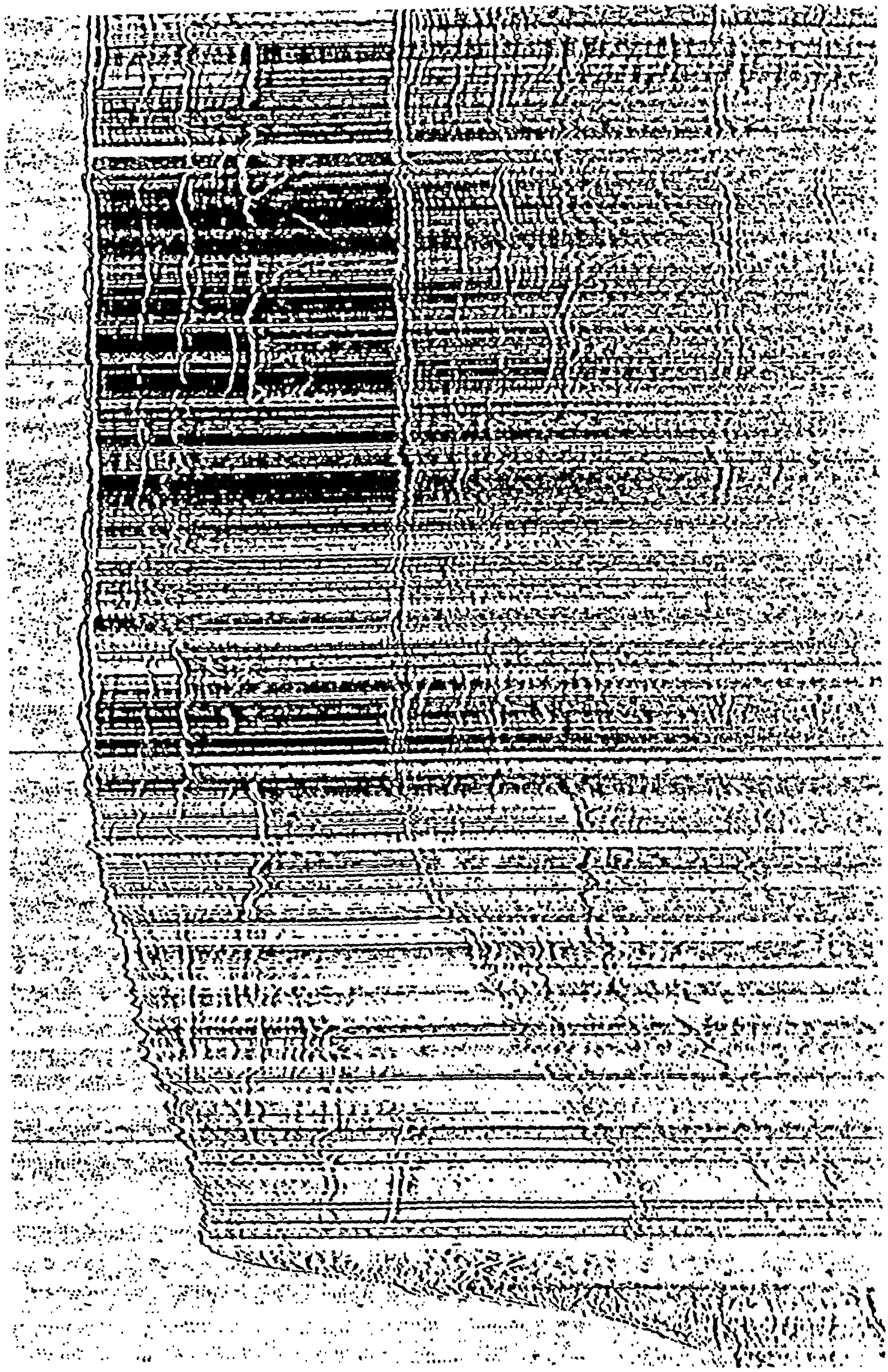


Figure 7.12 Analogue data.

However, one potential processing method for improving data quality is filtering. Unlike analogue data which will have had the filter settings and therefore appearance of the data determined at the acquisition stage, digital data recording allows a variety of filters to be applied post survey and their affect evaluated. In this case bandpass filtering was attempted, the results of which are presented in Figures 7.13 to 7.20 and which show the processed data and its associated Fourier transform graphs.

Fourier analysis in this context involves transforming seismic data from the time domain (Figures 7.13 to 7.16) to the frequency domain (Figures 7.17 to 7.20). The fourier diagrams display the amplitude spectrum of the component frequencies that the seismic data in the time domain consist of. It basically shows what frequencies exist in the seismic data and what amplitude these frequencies are at.

In this case, filtering did not appear to improve data quality, and may in fact make the data less useful for seismic facies analysis as subtle changes in acoustic character may be missed. Filtering was subsequently therefore not applied to the data before interpretation.

7.3.3 Tidal correction

Tide levels were not monitored during the survey. In order to correct for the variation in the water depth with time a tidal curve was generated from a simplified harmonic tidal prediction computer programme (NP159a) using Admiralty harmonic constants for the standard port of Menai Bridge. Although this does not take into account the meteorological conditions at the time of the survey, the fact that the weather was fairly stable throughout the survey period meant that such a correction could be considered sufficiently accurate for the purpose of this survey.

7.3.4 Charting

Contour maps have been corrected to Ordnance Datum (OD) by adding a correction factor of 3.8m to tidally reduced water depths. This correction factor of 3.8m is quoted on Admiralty Chart 1465 at Menai Bridge as being the depth of

Figure 7.13 Digitally recorded data without bandpass filter applied.

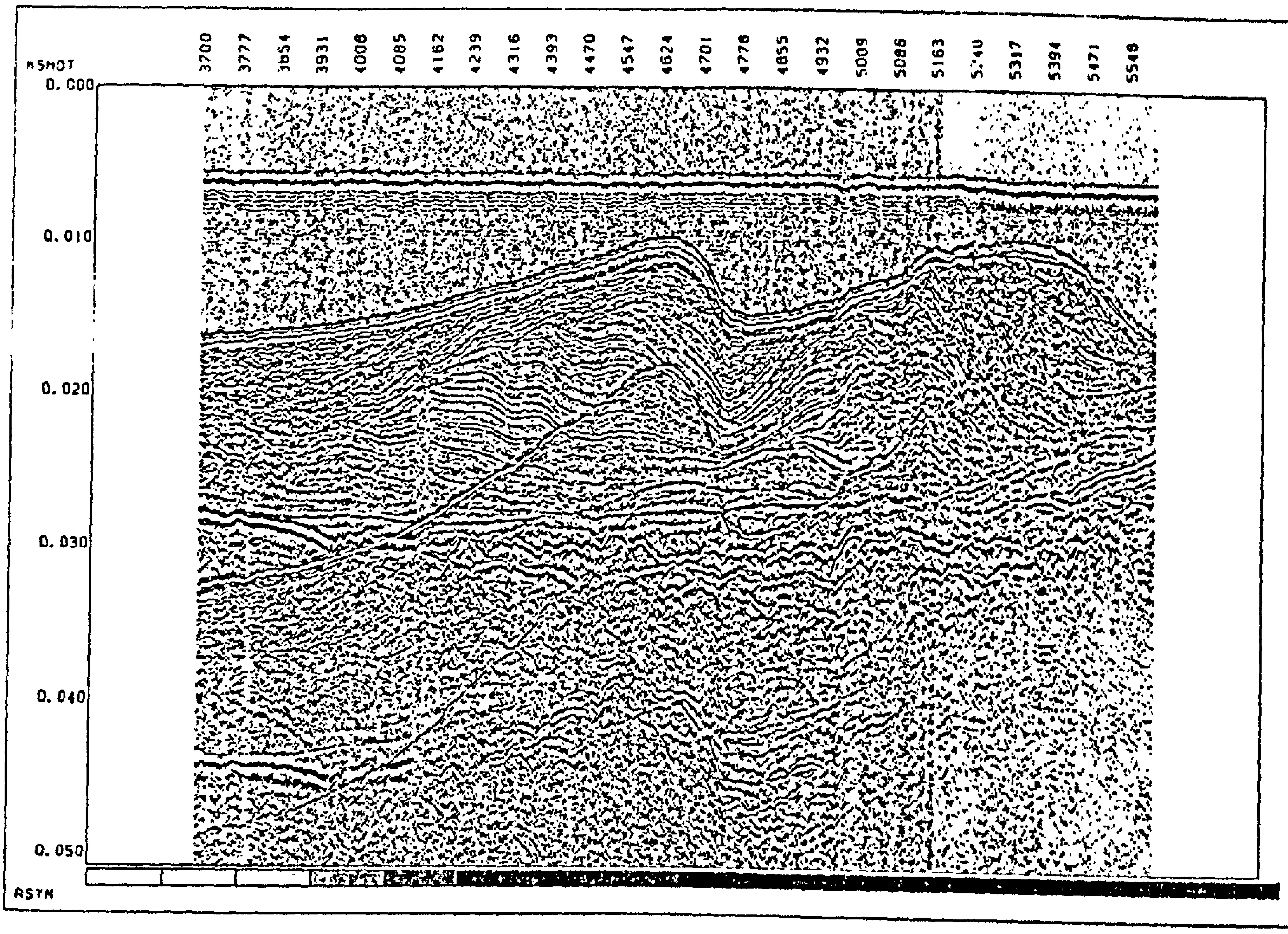


Figure 7.14 Digitally recorded data with bandpass (400 - 4000Hz) filter applied.

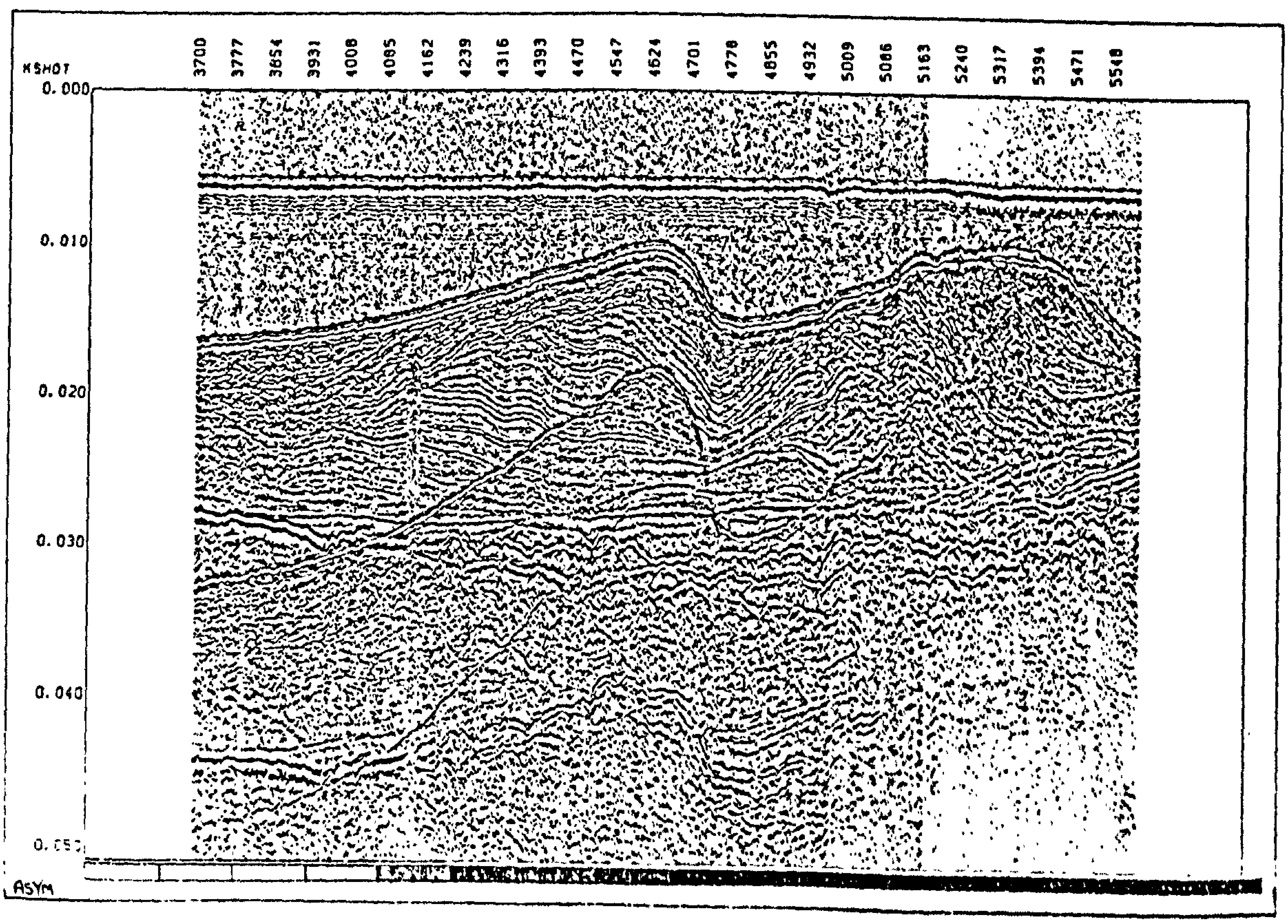


Figure 7.15 Digitally recorded data with bandpass (400 - 2000Hz) filter applied.

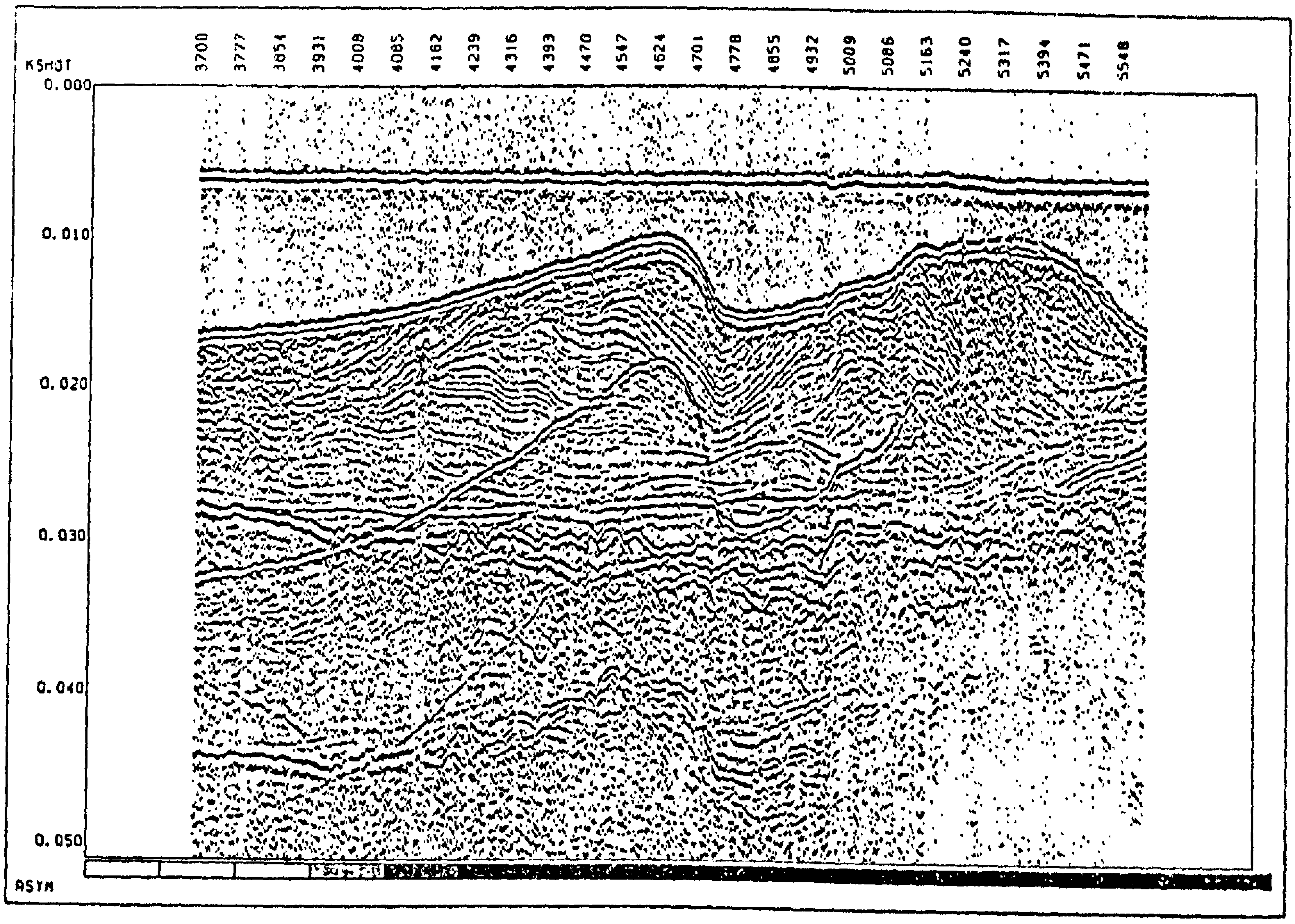


Figure 7.16 Digitally recorded data with bandpass (400 - 1000Hz) filter applied.

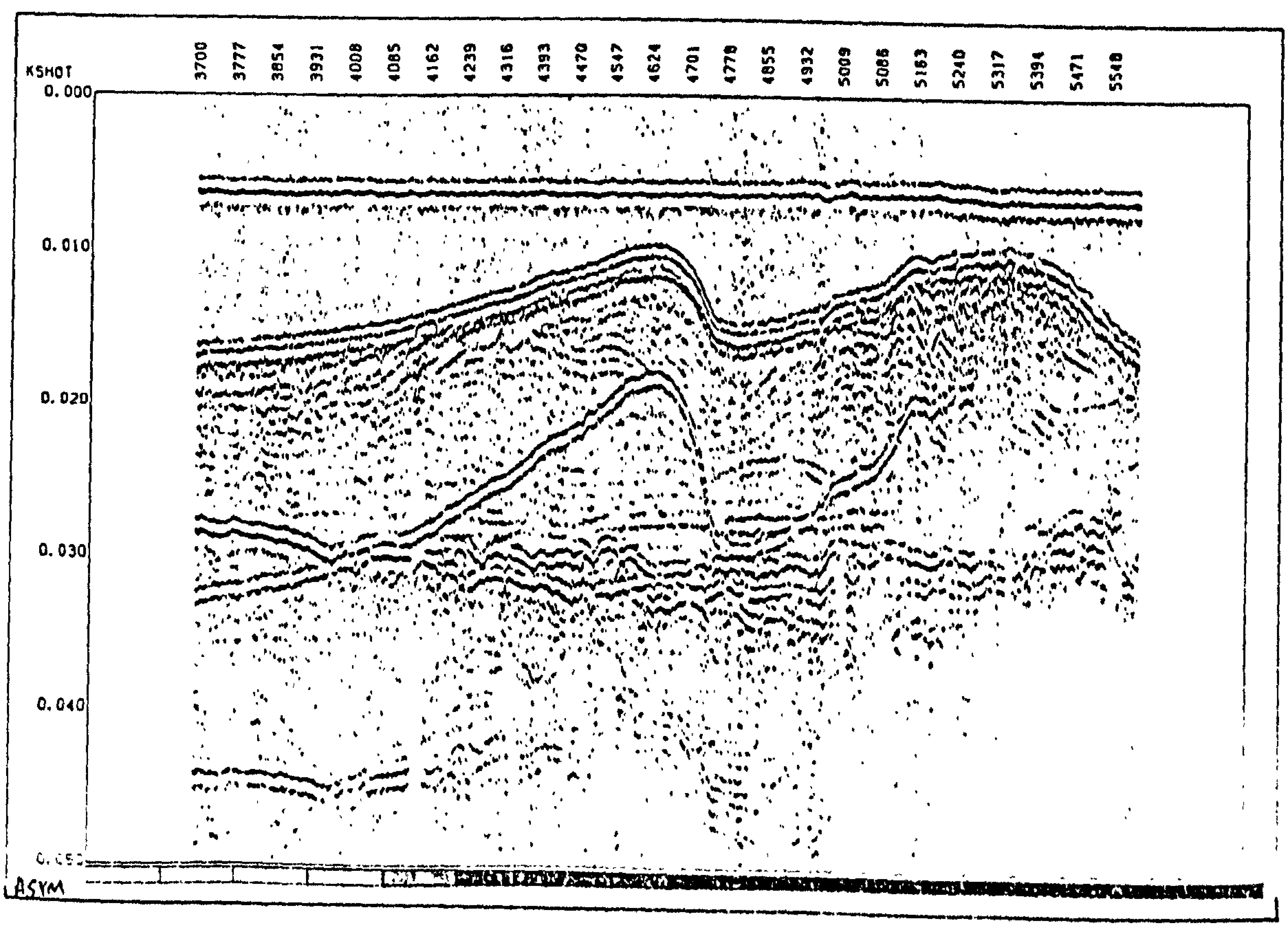


Figure 7.17 Fourier amplitude spectrum of digitally recorded data without bandpass filter applied.

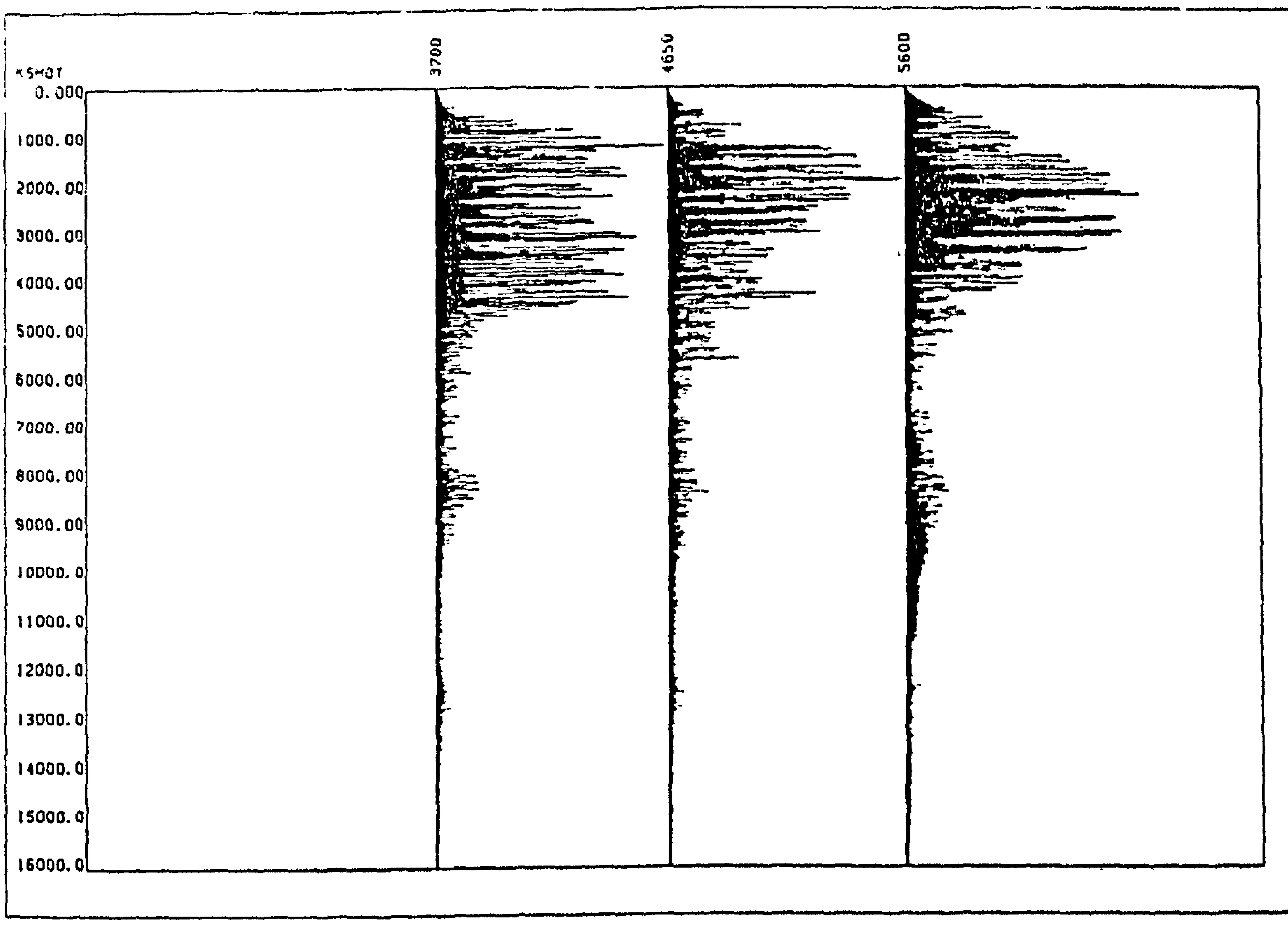


Figure 7.18 Fourier amplitude spectrum of digitally recorded data with bandpass (400 - 4000Hz) filter applied.

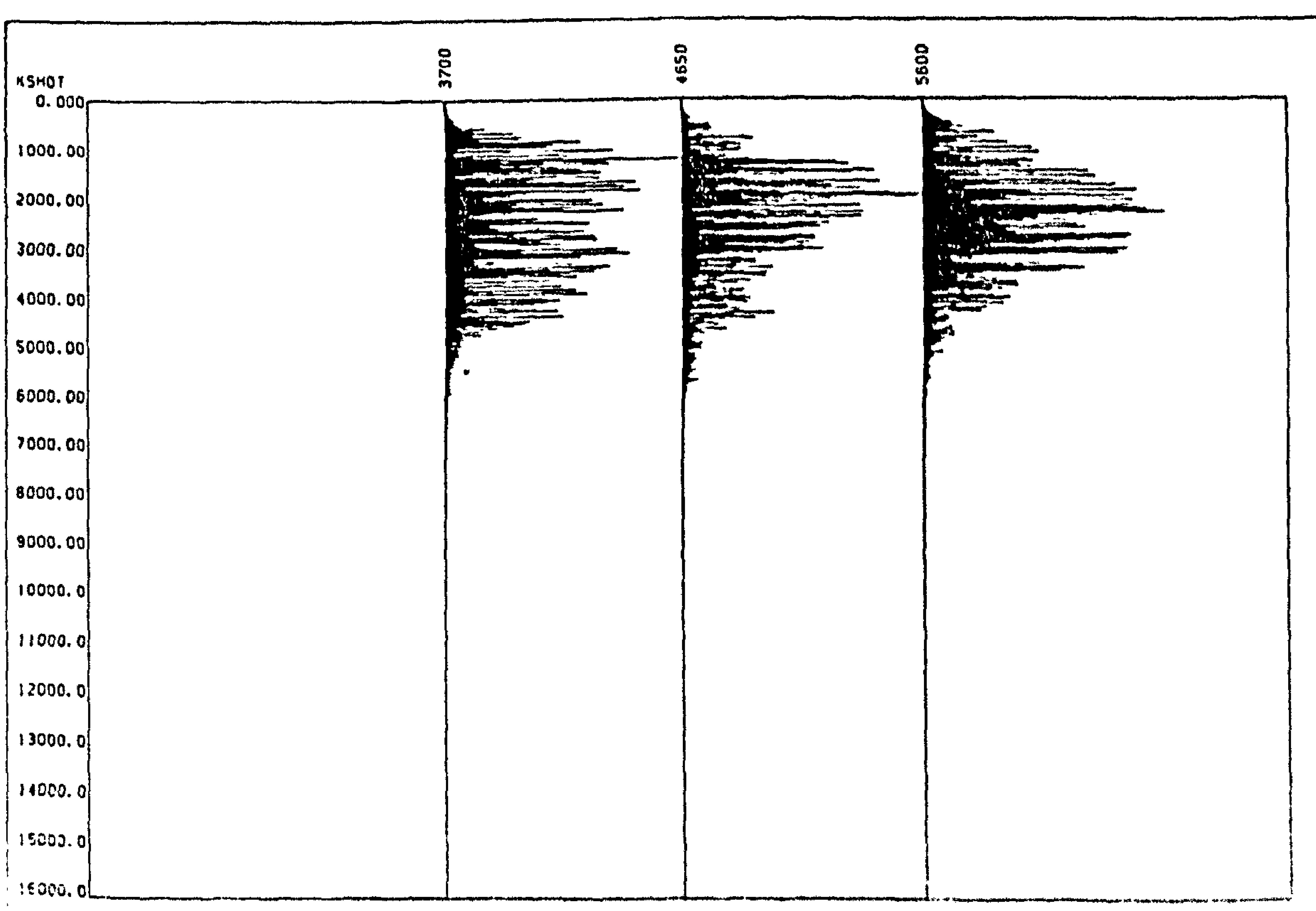


Figure 7.19 Fourier amplitude spectrum of digitally recorded data with bandpass (400 - 2000Hz) filter applied.

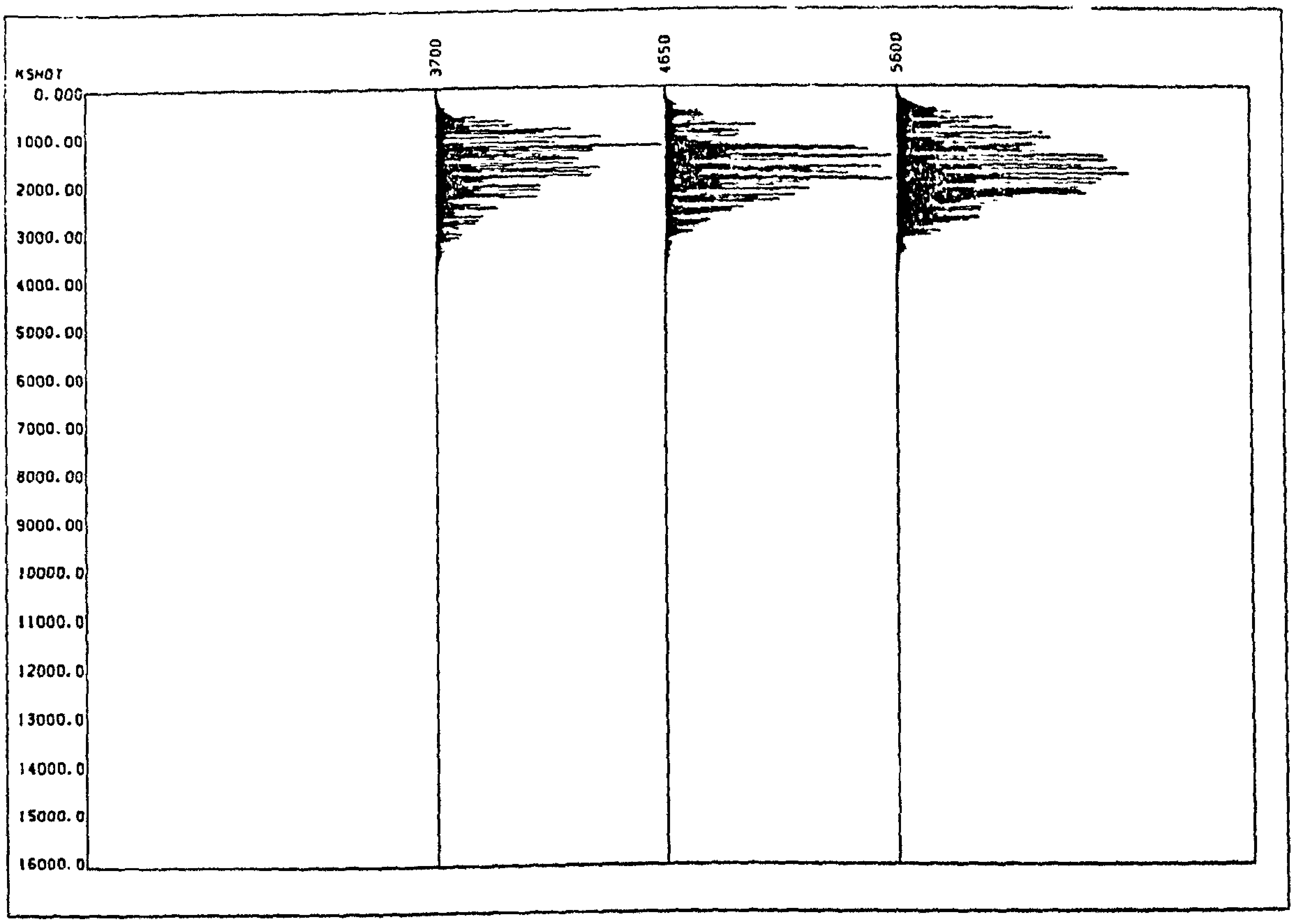


Figure 7.20 Fourier amplitude spectrum of digitally recorded data with bandpass (400 - 1000Hz) filter applied.

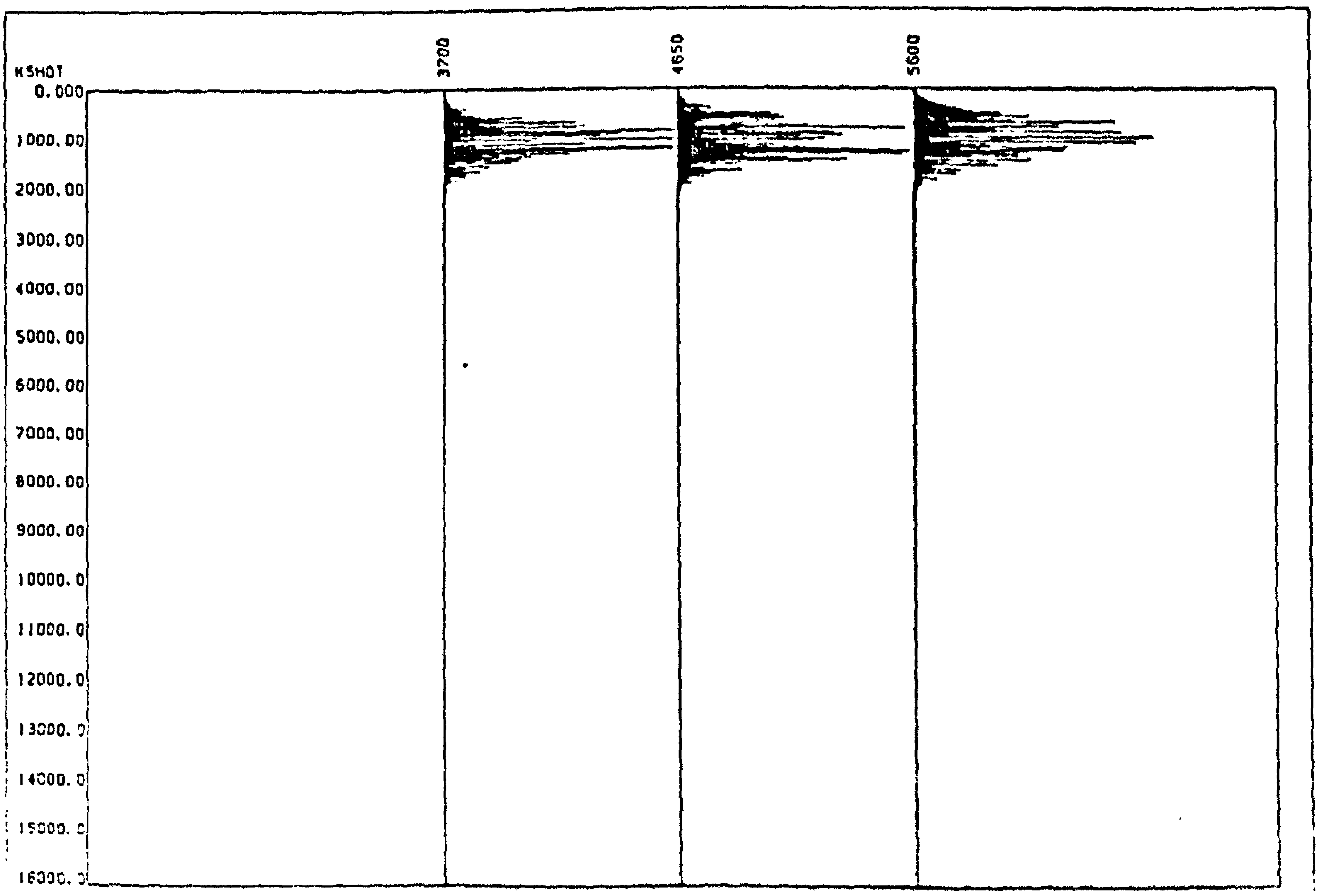


Chart Datum (CD) beneath OD. Horizontal scales on the seismic sections have been calculated over the average distance covered on the individual seismic lines.

7.4 Seismic stratigraphic Interpretation

A number of seismic profiles (the positions of which are shown in Figure 7.21) recorded during the survey are presented in Figures 7.22 to 7.26, 7.30 and 7.31 as data examples. These examples illustrate both unprocessed analogue and processed digital data with a corresponding interpretation of significant reflectors (i.e. high amplitude reflectors) and events highlighted. Two of the digital data examples (Figure 7.26 and 7.31) have also been displayed as instantaneous attribute plots (Figure 7.27 to 7.29 and 7.32 to 7.34 respectively). The various lithological units observed in the sections have been labelled (**A, B, D - I**) to identify them for discussion. The seismic profiles have been 'tied together' using cross lines to allow the lateral mapping and therefore common labelling of the seismic units on different lines. Contour plots of a sequence boundary and the bathymetry as well as a combined bathymetry and sequence boundary plot have also been presented (Figures 7.36 to 7.38 respectively).

7.4.1 Seismic sequence analysis

Ignoring background geological information for the moment (knowledge of which is not required at this stage of the seismic stratigraphic interpretation procedure), the seismic data can be discussed on its own merits. The data from the Menai Strait can be broadly broken down into two sequences on the basis of reflector termination patterns: a lower and upper sequence. The boundary between these two sequences is marked by an unconformity (a sequence boundary). The evidence for this unconformity is apparent erosional truncation (submarine or subaerial) of the lower parallel units that make up the lower sequence and the onlap of the units of the overlying sequence onto the lower sequence.

The unconformity has been mapped over the survey area, and is presented as a contour plot (Figure 7.36). The morphology of the unconformity surface reveals what appears to be two channels orientated NE - SW. These channels are now buried beneath more recent sediments that have accumulated to form the present bathymetry (Figure 7.37). The morphology of the subsurface channelling in

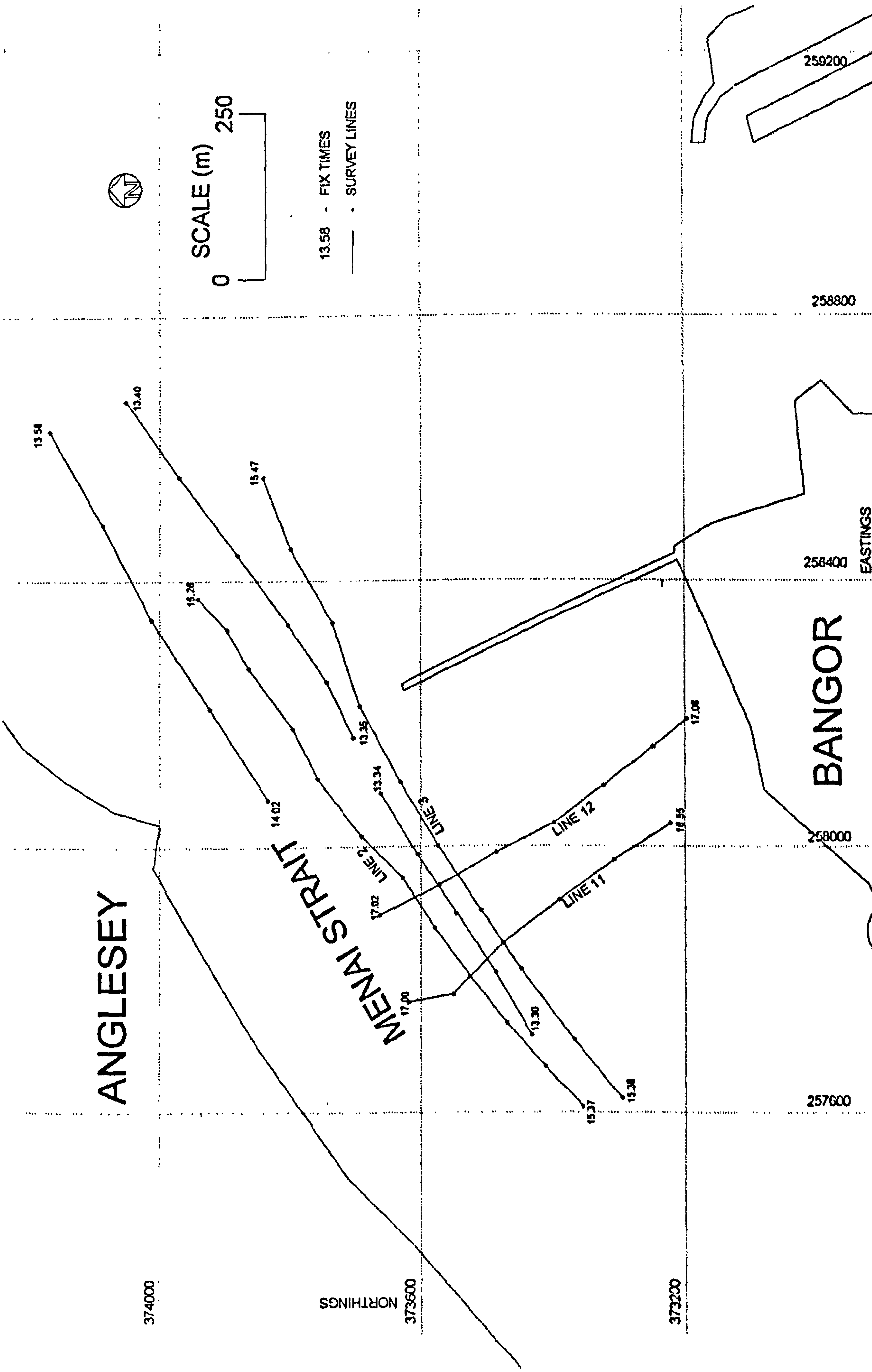


Figure 7.21 Positions of survey lines presented as data examples.

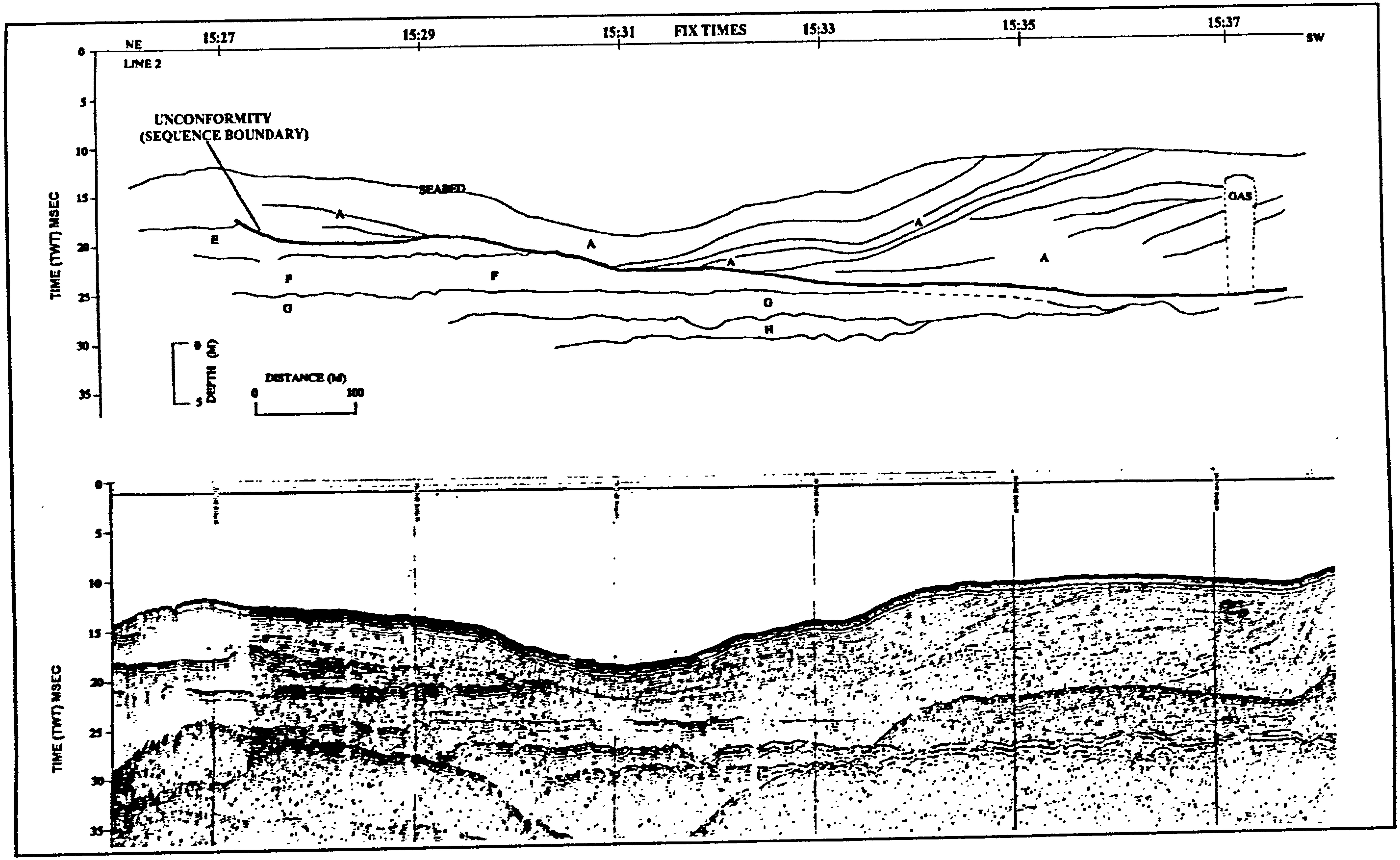


Figure 7.22 Unprocessed analogue data for line 2.

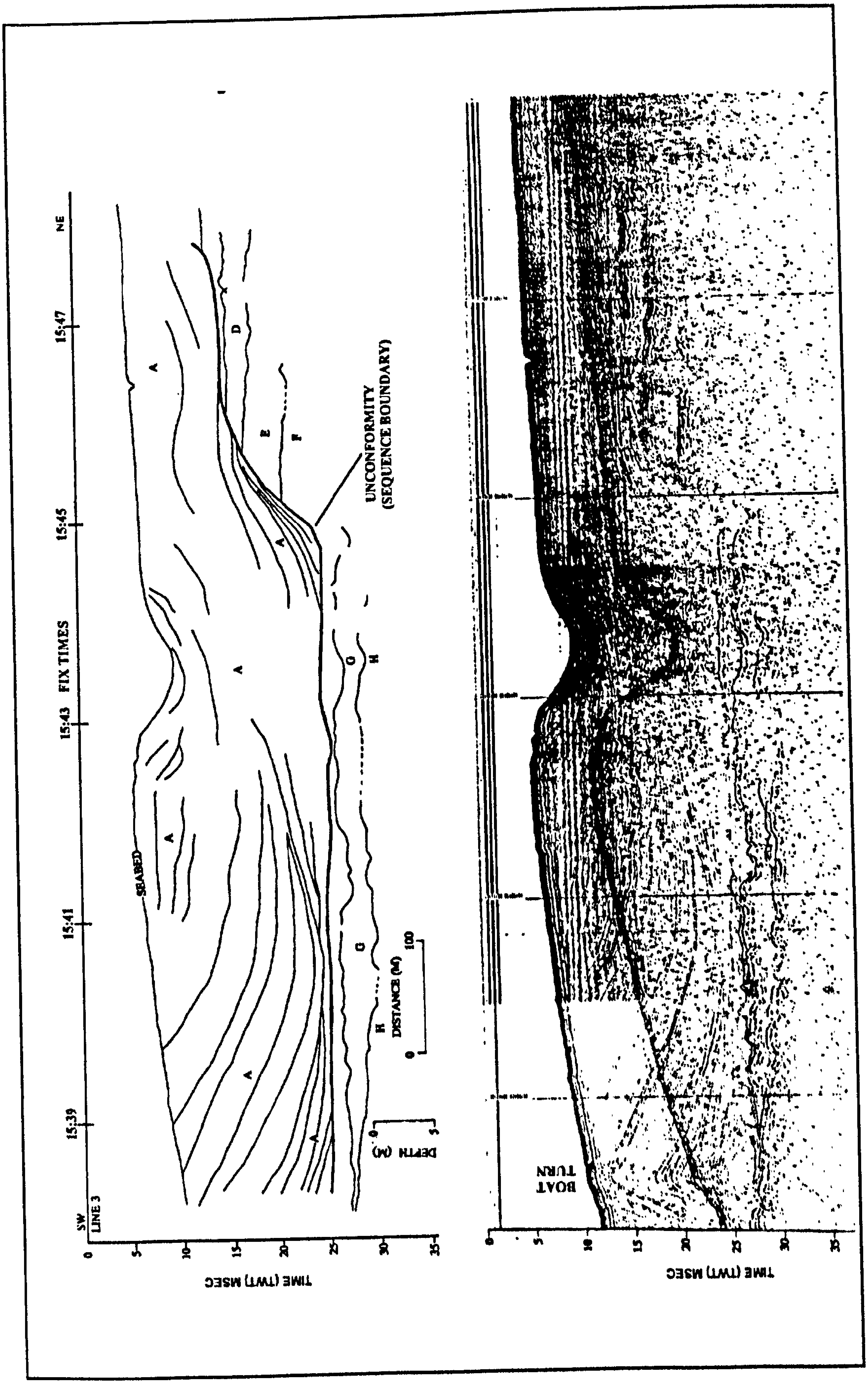


Figure 7.23 Unprocessed analogue data for line 3.

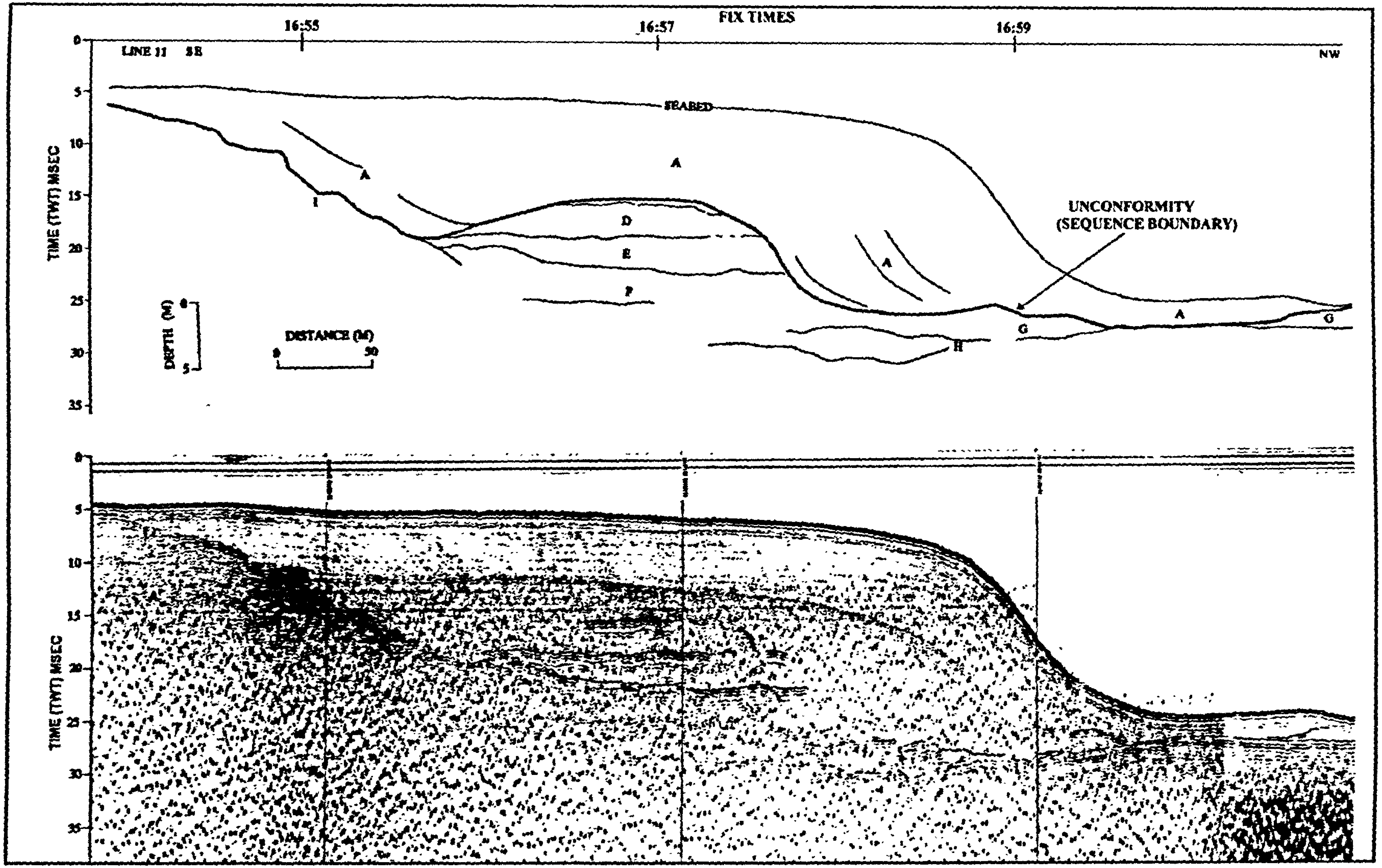


Figure 7.24 Unprocessed analogue data for line 11.

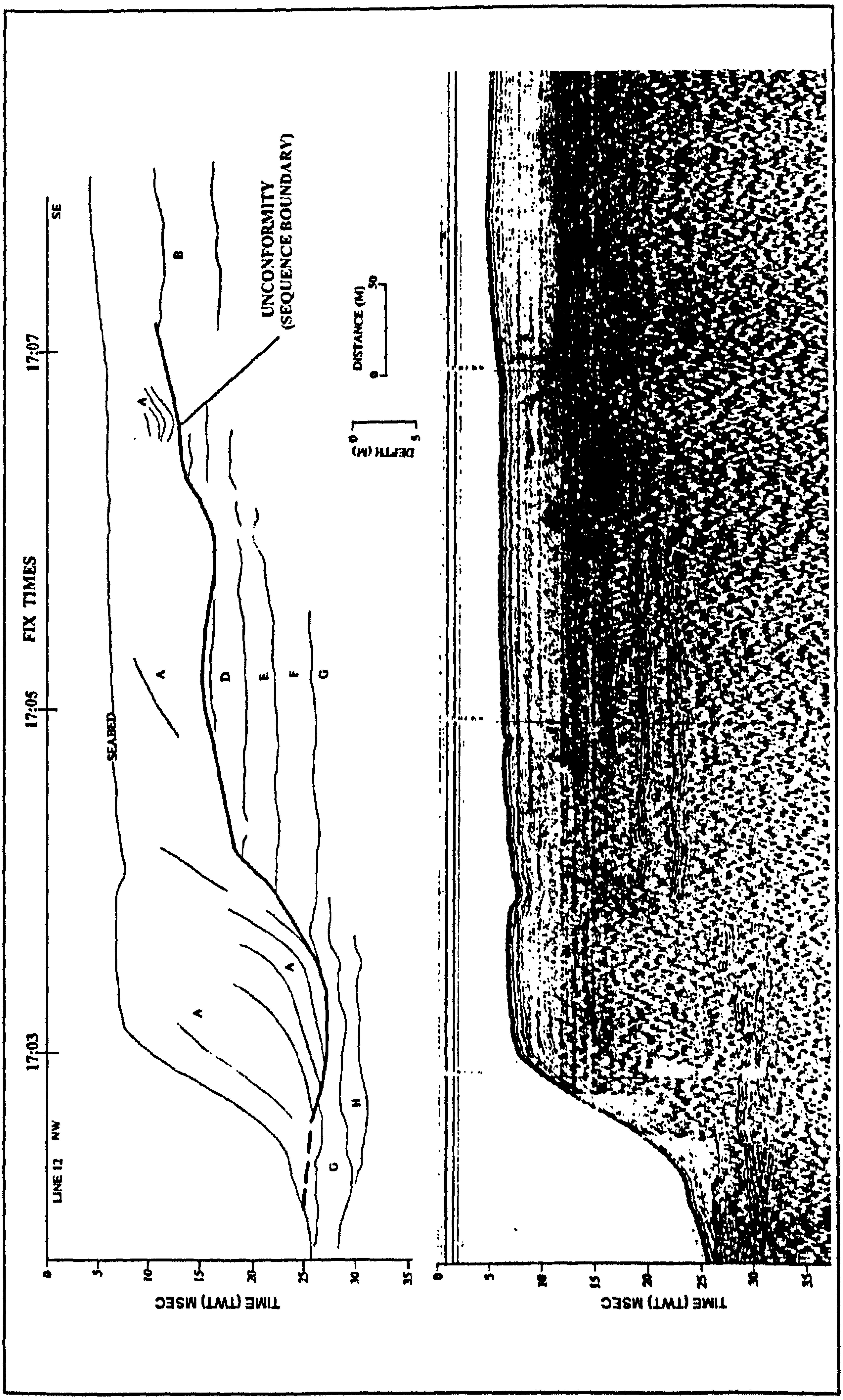
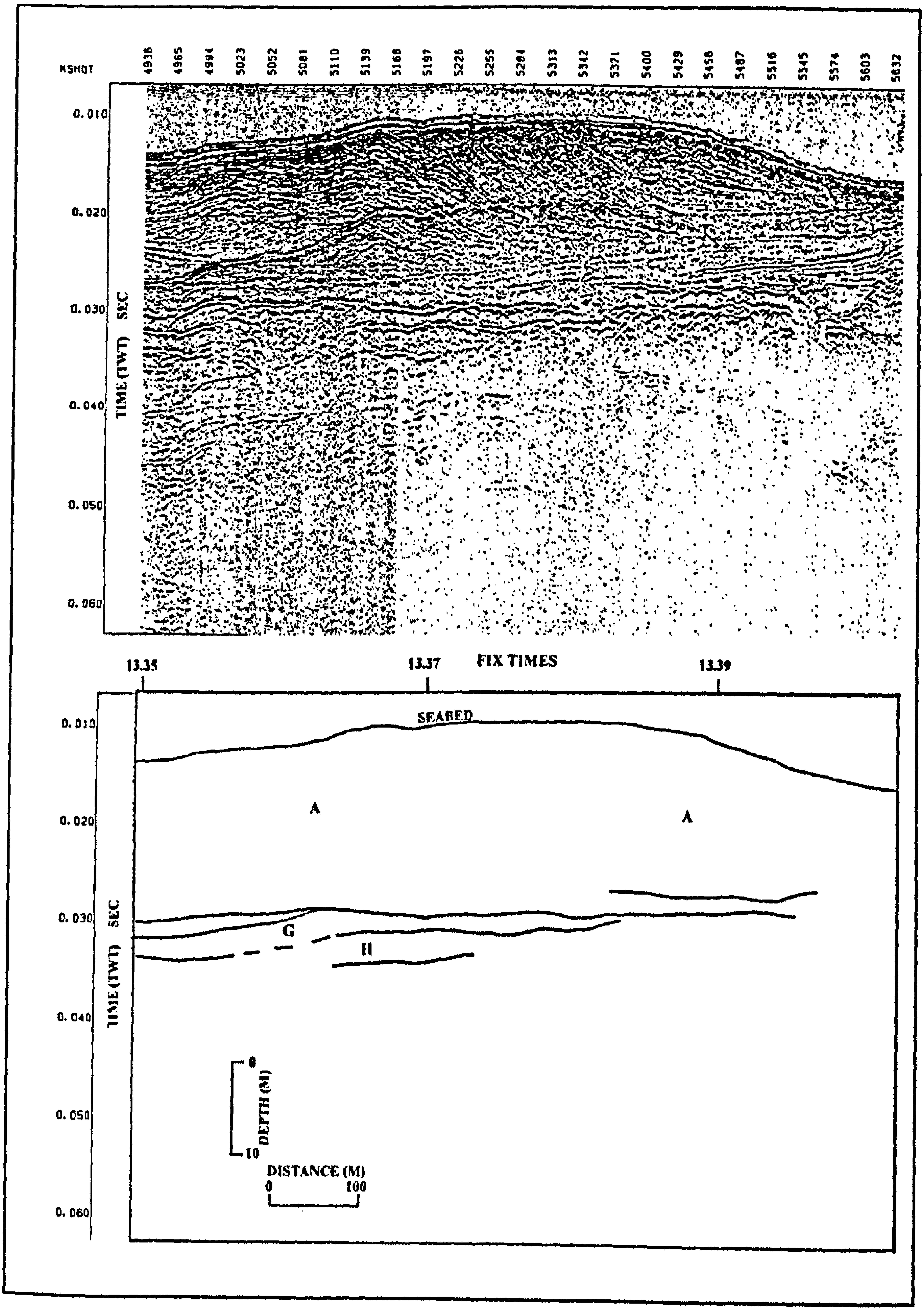


Figure 7.25 Unprocessed analogue data for line 12.

Figure 7.26 Processed digitally recorded data, fix time 13.35 - 13.40.



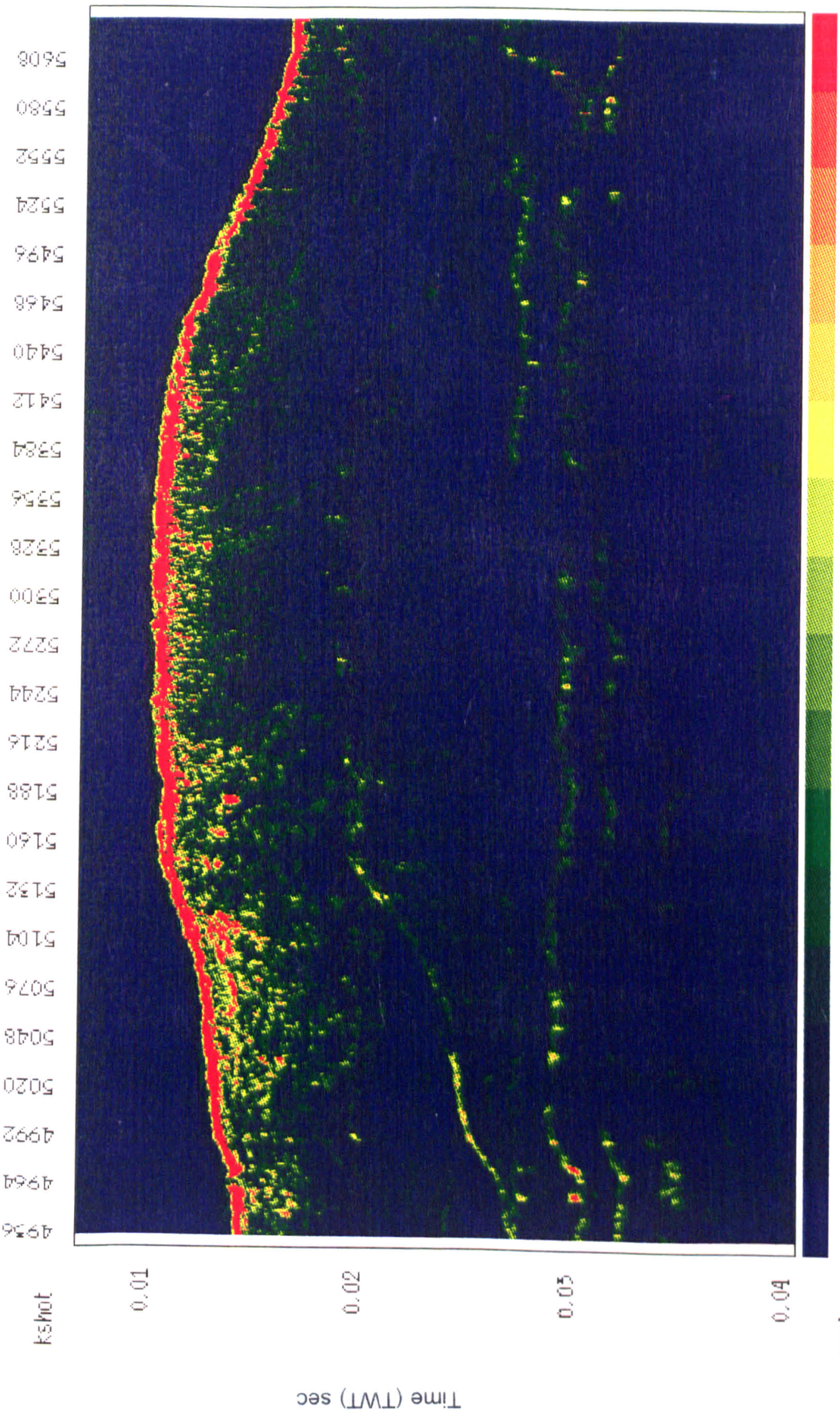


Figure 7.27 Instantaneous amplitude plot, fix time 13.30 - 13.34.

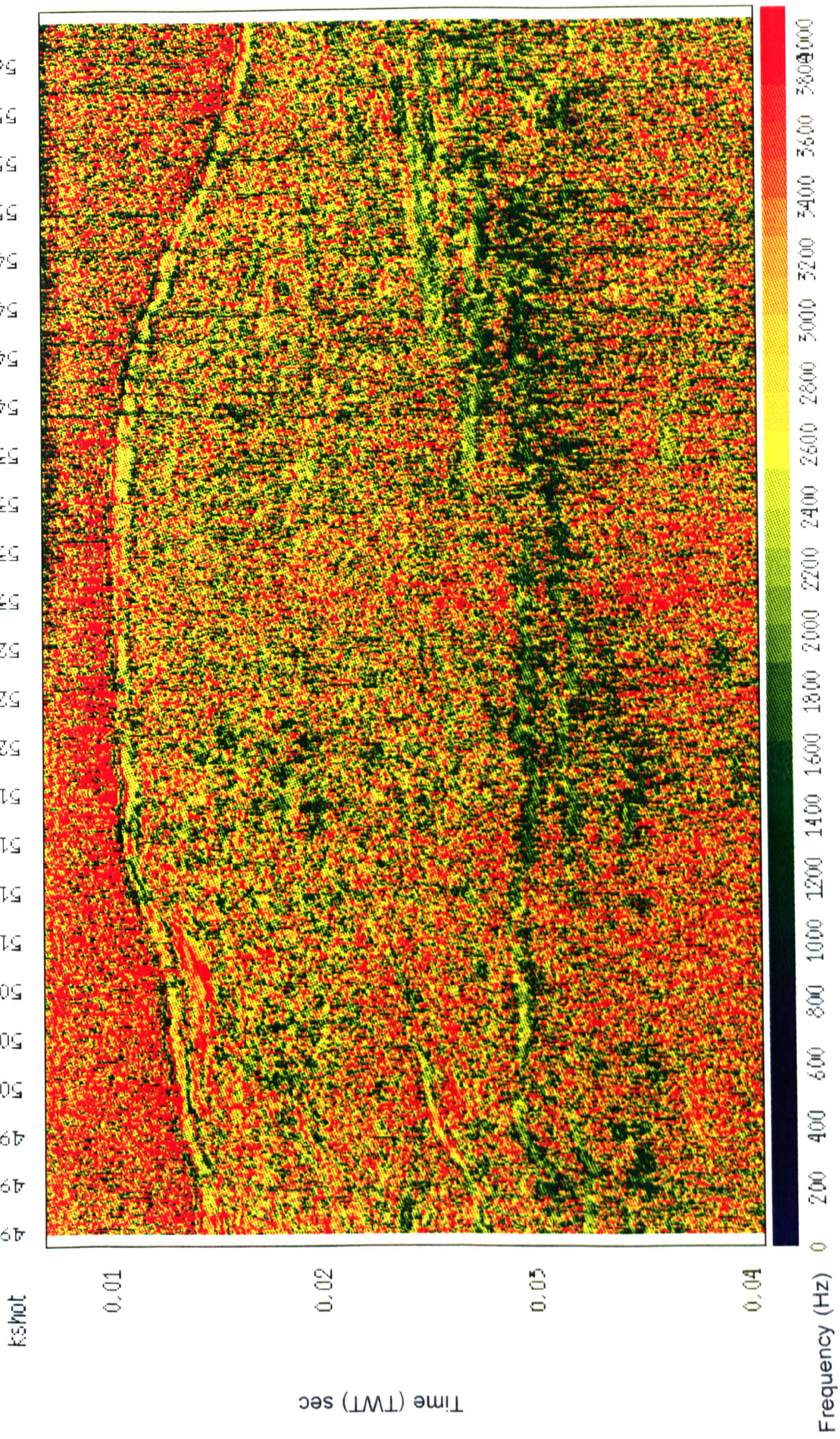


Figure 7.28 Instantaneous frequency plot, fix time 13.30 - 13.34.

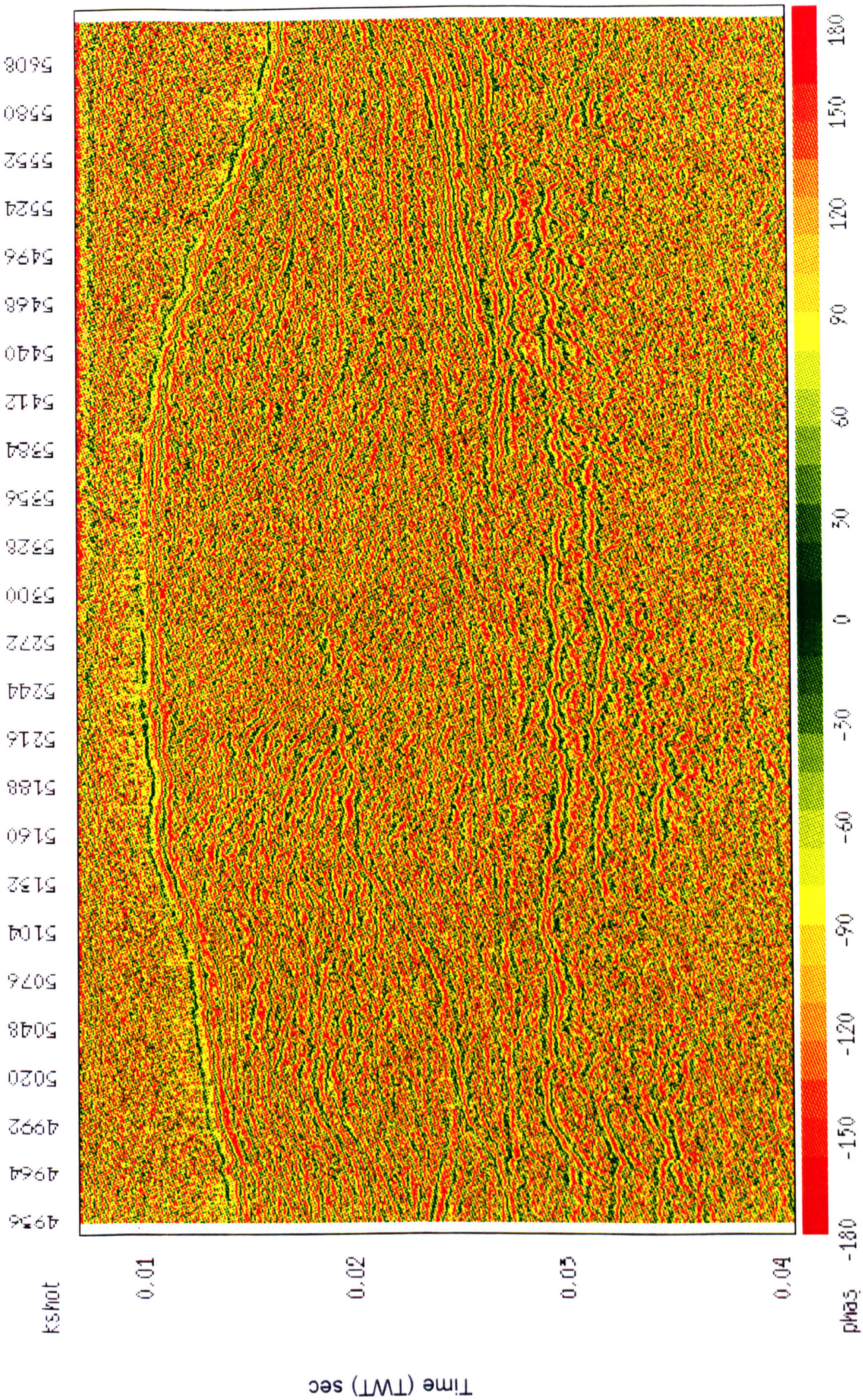


Figure 7.29 Instantaneous phase plot, fix time 13.30 - 13.34.

Figure 7.30 Processed digitally recorded data, fix time 13.30 - 13.34.

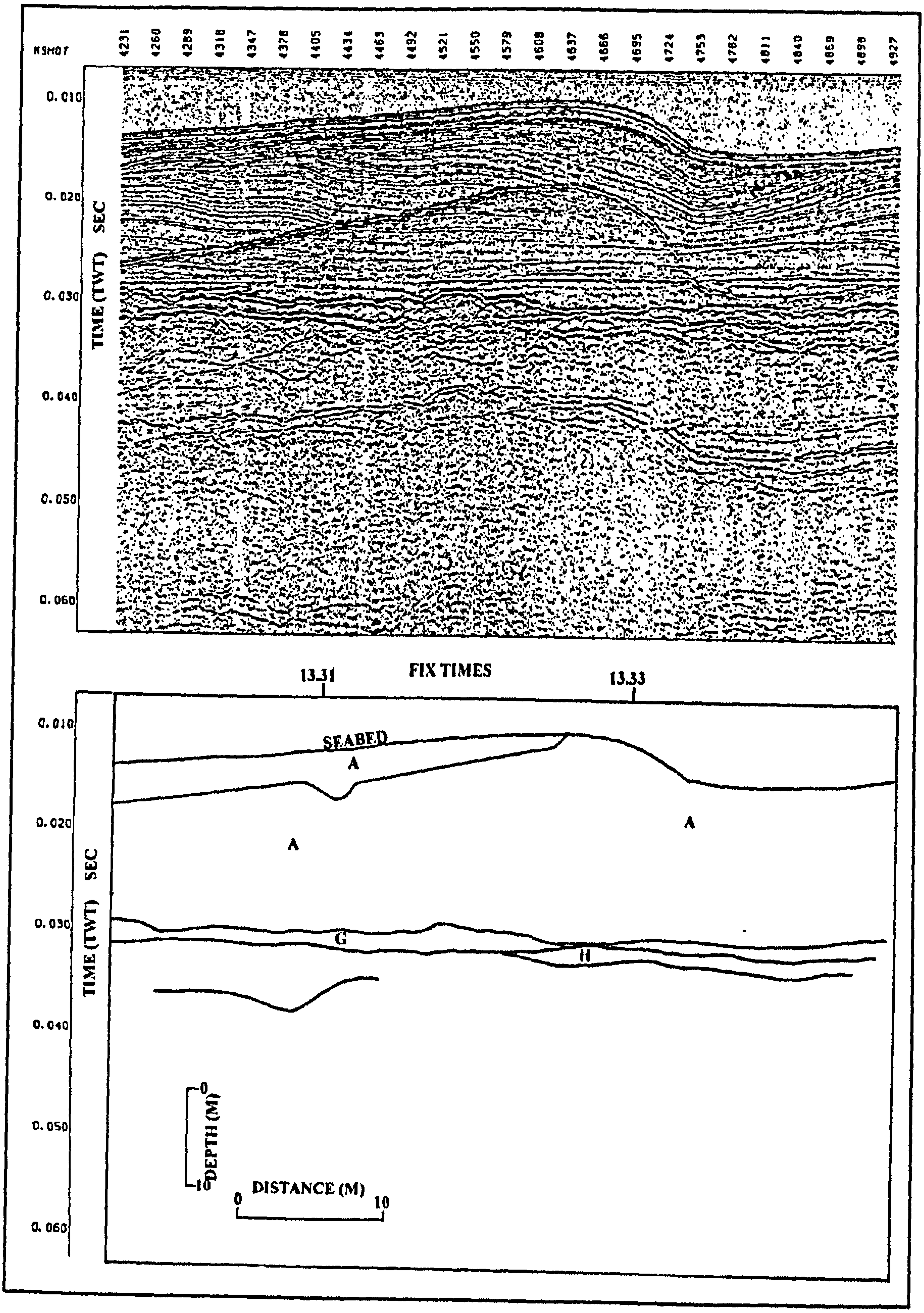
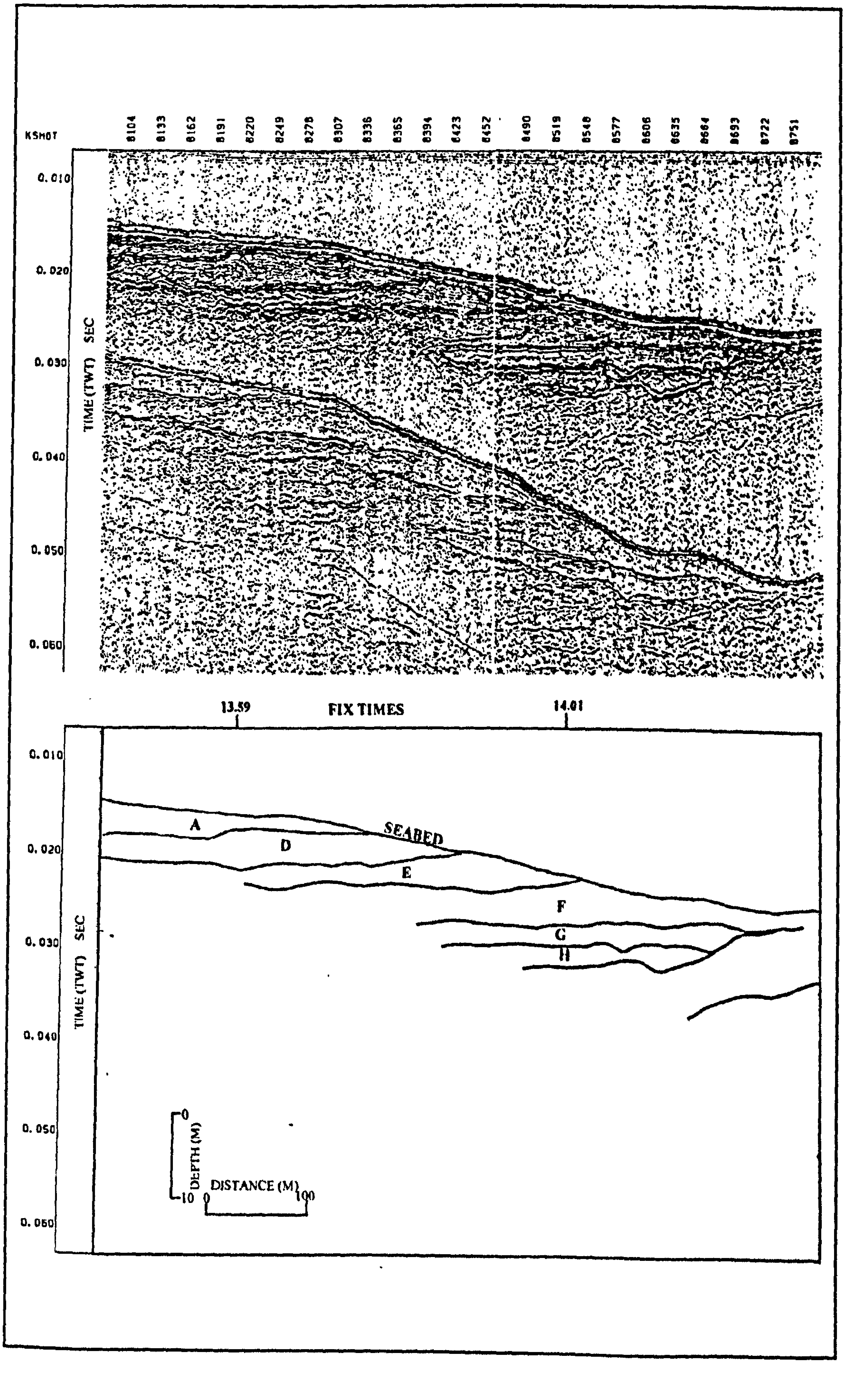


Figure 7.31 Processed digitally recorded data, fix time 13.58 - 14.02.



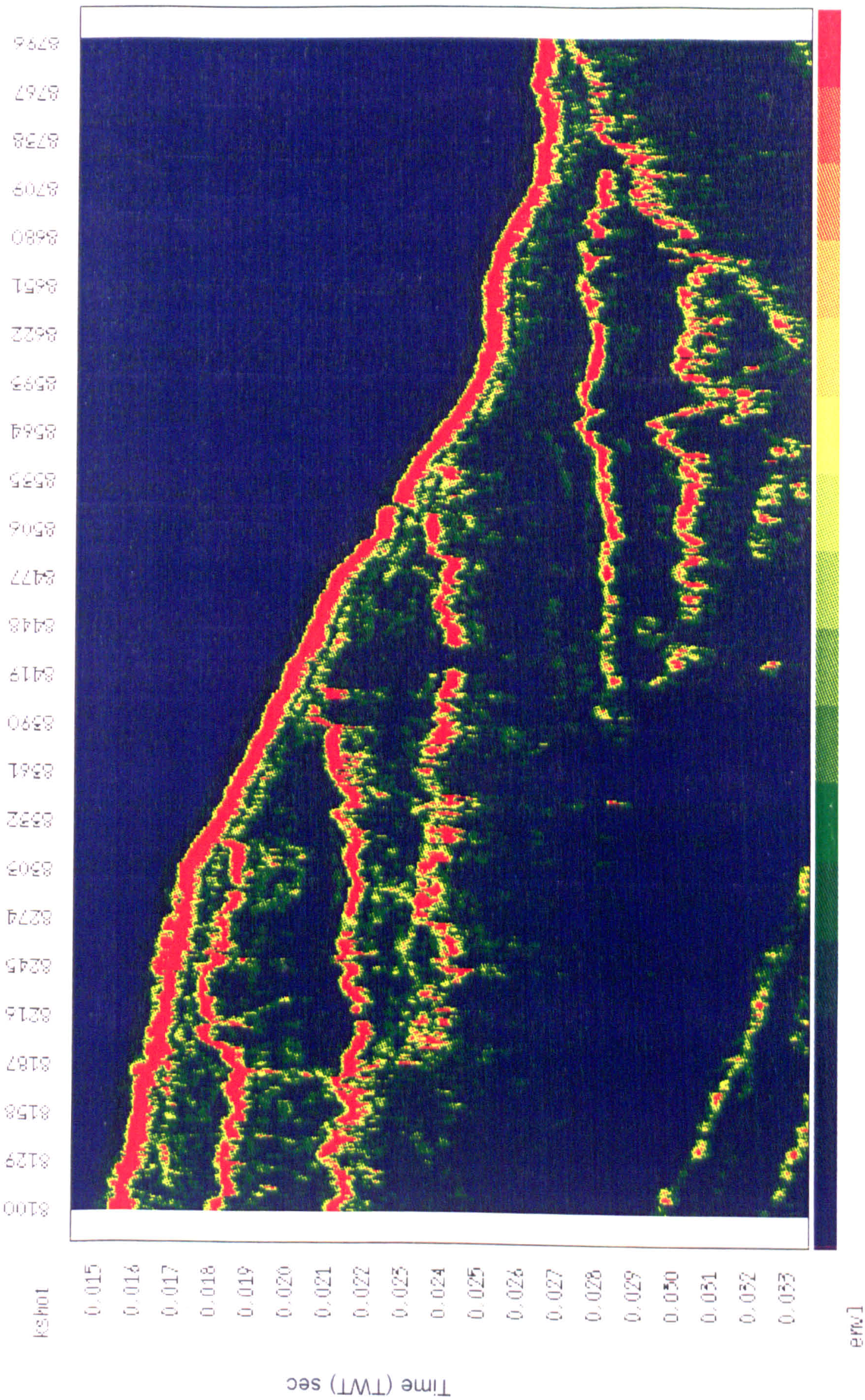


Figure 7.32 Instantaneous amplitude plot, fix time 13.58 - 14.02.

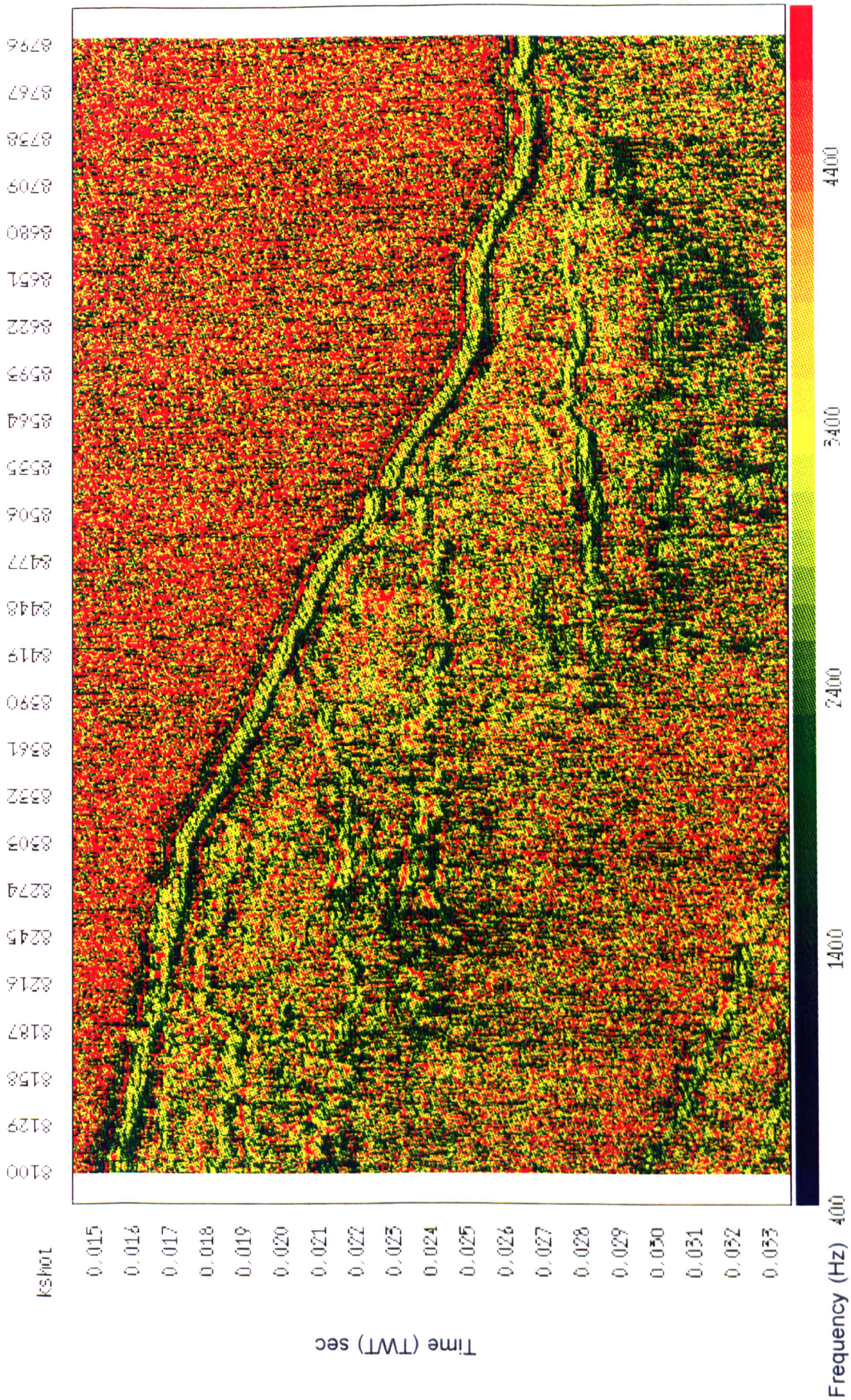


Figure 7.33 Instantaneous frequency plot, fix time 13.58 - 14.02.

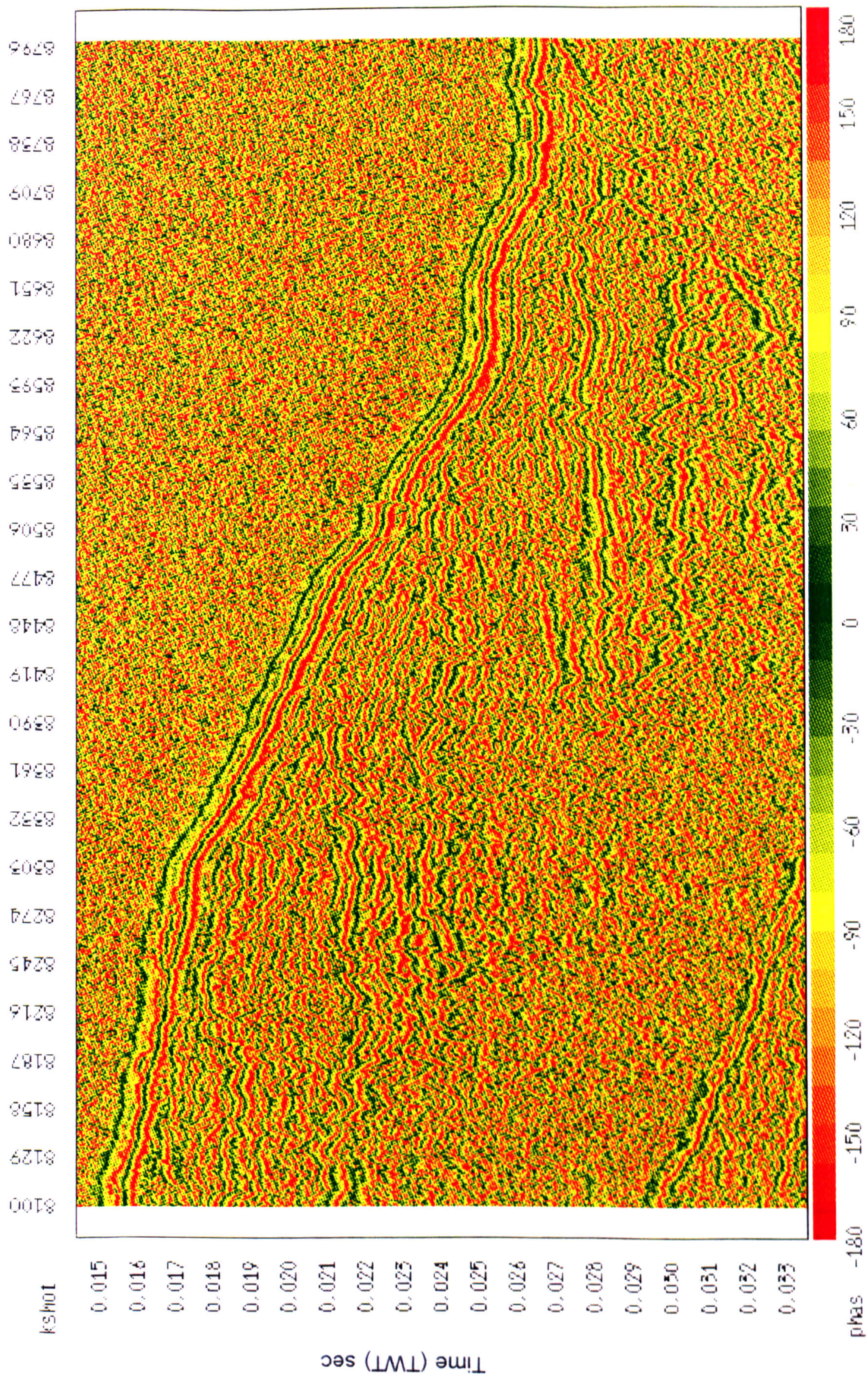


Figure 7.34 Instantaneous phase plot, fix time 13.58 - 14.02.

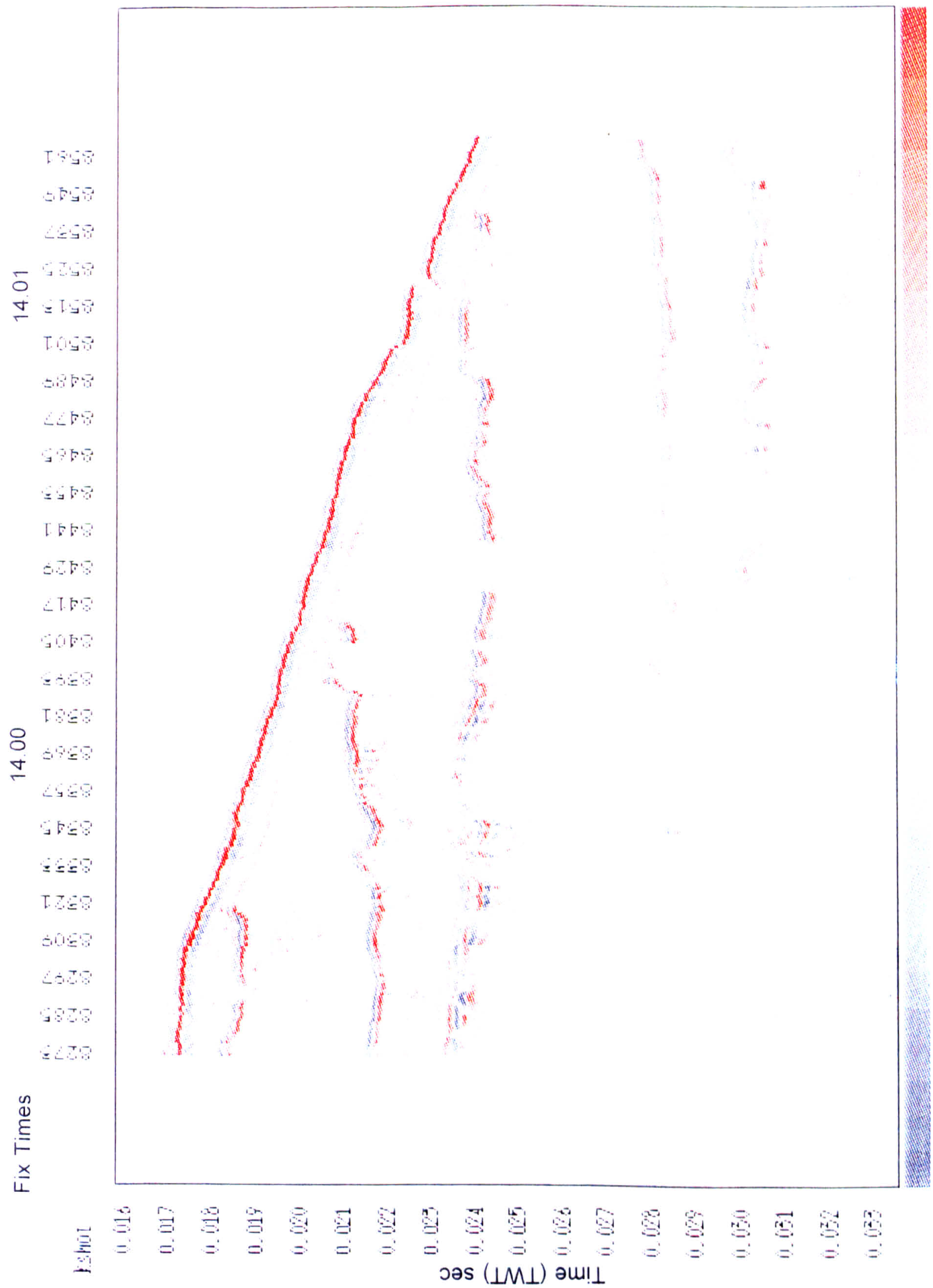


Figure 7.35 Colour variable area plot showing change in phase between seabed and sub-bottom reflectors.

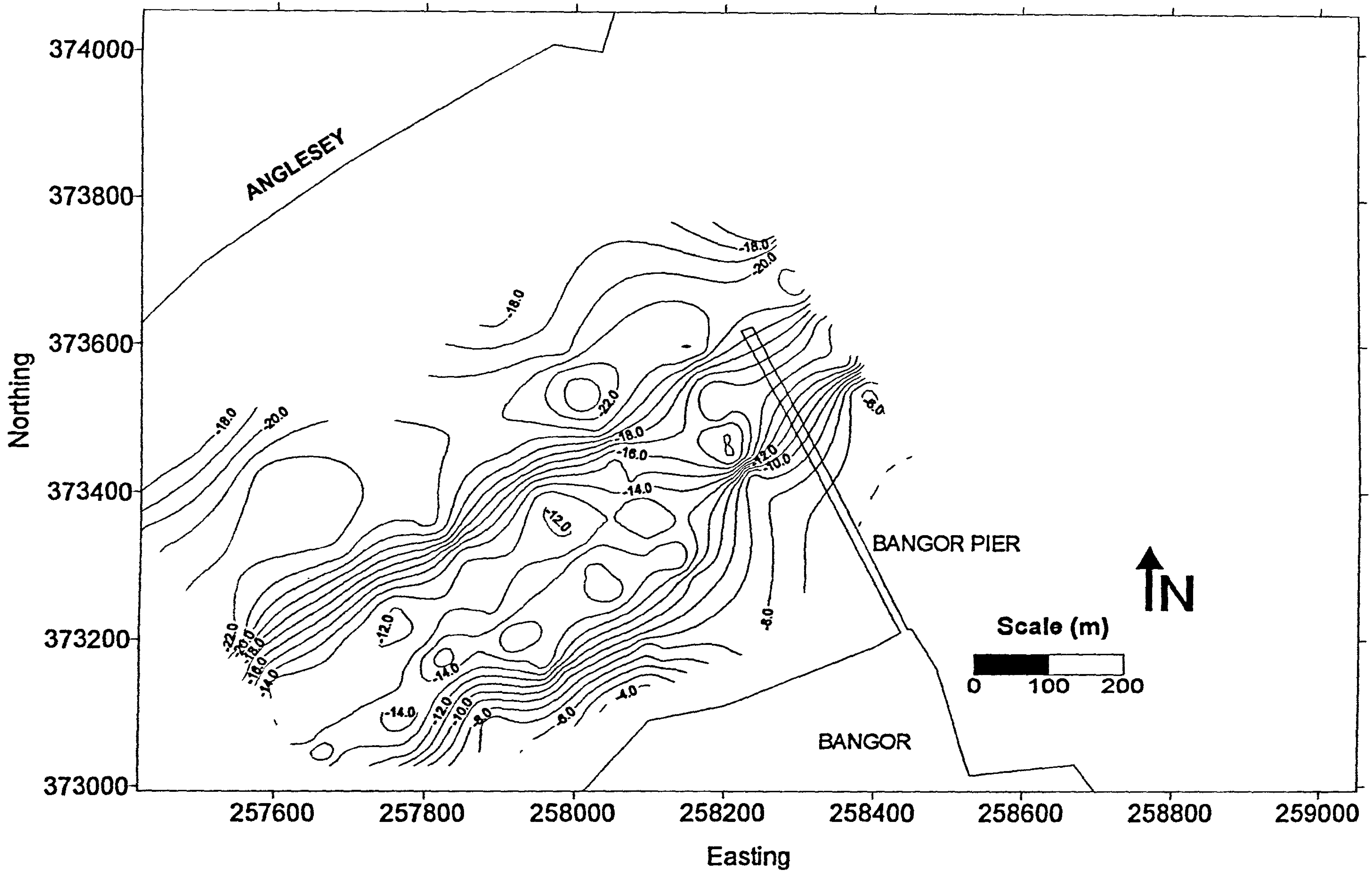


Figure 7.36 contour plot of unconformity/sequence boundary (m OD).

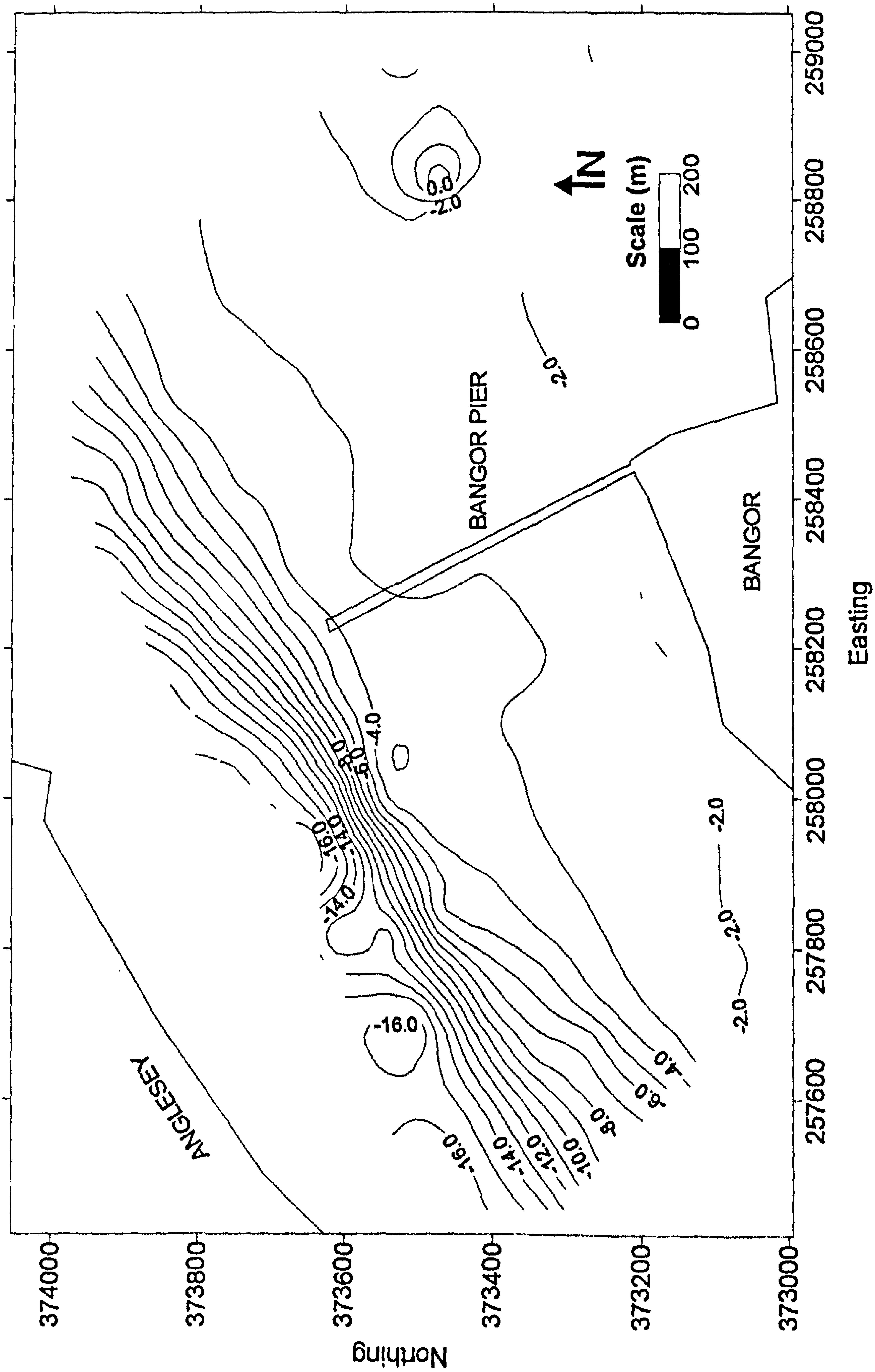


Figure 7.37 Contour plot of bathymetry (m OD).

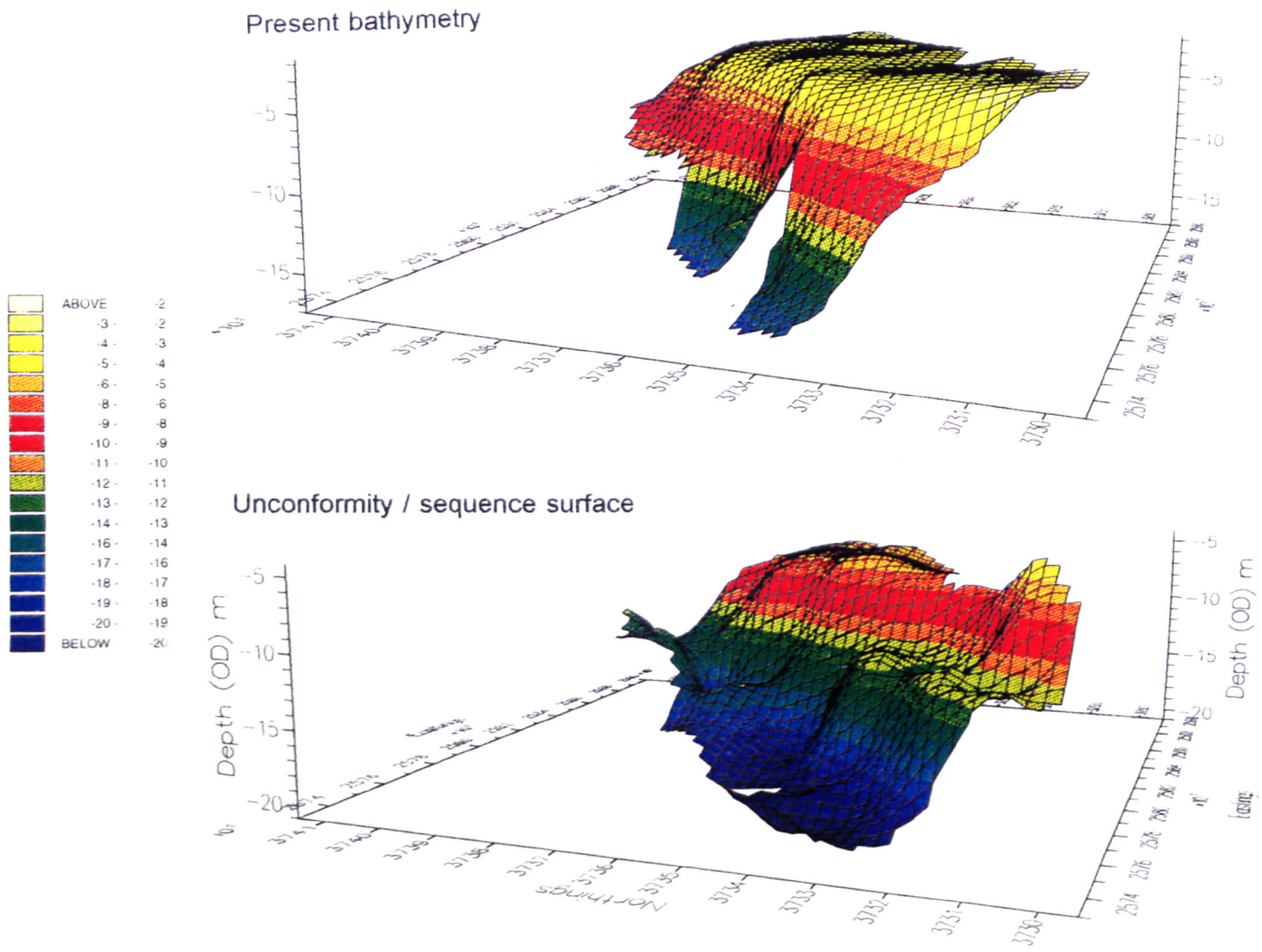


Figure 7.38 3D combined bathymetry/unconformity plot (vertical scale in metres relative to OD).

relation to present bathymetry is well illustrated as a combined 3D bathymetry/unconformity plot (Figure 7.38).

7.4.2 Seismic facies analysis of lower sequence

Over the survey area there are a number of significant reflectors within the lower sequence. These reflectors delineate a number of units which have been labelled **B, D-I**. The significant reflectors are parallel, laterally continuous (allowing the tieing of reflectors across the survey area using cross lines), high amplitude events. In places they have been subject to erosion producing a 'step like' effect where the limits of the units have been truncated. The lower of the units within the sequence (i.e. **G** and **H**) are the most extensive and appear to have been subject to least erosion.

The reflectors of the lower sequence appear to terminate due to erosion, either sub-seabed (seen in most data examples) or at the seabed itself (Figure 7.31); however on Line 11 (Figure 7.24) units **E** and **F** onlap **I**. Unit **I** is interpreted to be bedrock as it is seen on the seismic data to outcrop in areas where bedrock is exposed on the shores of the Menai Strait.

Following the rules of seismic sequence stratigraphy, the stratal components (i.e **E** and **F**) of a sequence form in response to the interaction between rates of eustacy, subsidence and sediment supply (Van Wagoner *et al.*, 1988 and Posamentier *et al.*, 1988), the fundamental control being short term eustatic change superimposed on longer term tectonic change.

Assuming that if it were not for erosion units **D**, **E** and **F** would also onlap onto bedrock (unit **I**), it would appear that a rise in sea level (ignoring for now the effect of any long term tectonic change, if any) with a continued supply of material has occurred allowing the sequence to develop as an apparently transgressive systems tract. Any downlap onto the transgressive surface (unit **I**), in a basinward direction (i.e. into deeper water), is not observed in the data, due to either problems of resolution, penetration or the fact that they exist beyond the limit of the survey area.

The significant reflectors identified that delineate the units D to G are parallel with roughly equal spacing. This, combined with a slight change in the seismic, and therefore possibly physical, character of the sediment (the seismic character within the units appears fairly homogenous but with a decrease in transparency to the top of the unit), suggests uniform rates of deposition (Mitchum *et al.*, 1977) in a rhythmic environment, the rhythmic changes themselves giving rise to a varying lithology.

7.4.2.1 Instantaneous attributes of lower sequence

The large amplitude of the significant reflectors of the lower sequence is emphasised in the instantaneous amplitude plots (Figure 7.27 and 7.32) which reveal none of the internal lower amplitude structure within the units seen for instance in Figure 7.31). The amplitude of the significant reflectors shows little lateral variation indicating a fairly consistent reflection coefficient and therefore laterally similar geology.

The instantaneous frequency plots (Figures 7.28 and 7.33) show that the significant reflectors are marked by low frequencies (relative to the instantaneous frequencies within the these units). The frequencies of these surfaces are between 1.6kHz and 2.6kHz (on Figure 7.28) and between 2.6kHz and 3.3kHz (on Figure 7.33). The difference in the range of frequencies between these two plots could be due to frequency dependent attenuation associated with transmission through sediment (discussed in section 2.3.2.3) resulting in lower frequencies with depth associated with Figure 7.28. The result of this effect being that the overburden in Figure 7.28 above units G and H has led to greater attenuation of the high frequency component of the signal.

The instantaneous phase display further emphasises the continuity of the significant reflectors. In Figure 7.28 it might be expected that a phase display would allow better lateral mapping of lower units such as G and H (as phase is independent of amplitude) which are observed over a short distance only. This loss of the reflector was originally thought to be due to the lack of penetration due to overburden. However, the inability to resolve the reflector using the phase display (Figure 7.34) may indicate that it either truncates or onlaps a unit of sufficiently low acoustic impedance contrast that it itself does not produce a significant reflection.

Figure 7.35 is a colour display of what is in effect a variable area display. It is included here to demonstrate the phase of some of the units of the lower sequence. It differs from the previously discussed phase displays in that it is amplitude dependant. As discussed in section 2.1.1 reflections at the surface of a medium of lower acoustic impedance than that above (due to either/or a lower velocity or density) will result in a phase reversal. In Figure 7.35 the first reflector is the seabed. The interface between the seawater and the seabed provides a positive reflection coefficient; this is illustrated by the colour sequence of the pulse (representing phase) being blue-red-blue; subsequent reflections in the section show predominantly negative reflection coefficients with a colour sequence of red-blue-red. This phase reversal could be caused by the peat deposits as they are essentially low density leading to a relatively reduced acoustic impedance.

7.4.3 Seismic facies analysis of upper sequence

It is interesting to note that, on the whole, there is no significant reflector that marks the sequence boundary itself. The position of the boundary has been determined by mapping the termination patterns of the upper sequence and apparent truncation of the lower units. This absence of a significant reflector would therefore suggest that the acoustic and therefore possibly physical properties of the upper and lower sequence are, on the whole, fairly similar.

Unlike the lower sequence the upper sequence has not been differentiated into component units. The layered sediments of the upper sequence are not separated by significant reflectors (i.e. they have relatively low amplitudes) as was the lower sequence, and this has been taken to indicate a fairly uniform lithology within the sequence. Thus the upper sequence has a quite different seismic character to the lower sequence.

The seismic lines that run shore parallel (i.e. Line 2, Figure 7.22 and Line 3, Figure 7.23) reveal a quite complicated bedding structure through the sequence as a whole. Although laterally continuous, the reflectors are of quite low amplitude and are very closely spaced (the minimum spacing observed was 0.25m, which appears to be the limit of seismic resolution). Overall, the most dominant reflection pattern is complex sigmoid oblique (see Figure 3.4) which implies strata with a history of alternating upbuilding and depositional bypass in the topset segment within a high energy depositional regime. There is evidence of this within the sequence of erosion and possible reworking of the units. There is variation in the angle of repose of the sediment and also in the source of sedimentation. This is clearly illustrated in Line 3 (Figure 7.23) where at the northeast end of the line the direction of sediment input is from the northeast and at the southwest end of the line the direction of sediment input appears to be from the southwest. This apparent conflict in the dominant direction of sedimentation from the northeast and southeast may still be apparent and is represented by the seabed trough, which runs obliquely to the 'banks' of the Menai Strait, around Fix Time 15:43.

7.4.3.1 Instantaneous attributes of upper sequence

The physical properties of the upper sequence appear from the instantaneous amplitude display (Figure 7.27) to be fairly similar. Evidence for this includes the fact that the bedding that is displayed on the corresponding variable area display (Figure 7.26) is not shown on the amplitude display. There is however some evidence of localised high amplitude reflections. In Figure 7.27 there is a high amplitude event at shot number 5076 immediately beneath the seabed. This high amplitude event also corresponds to a coherent area of very high instantaneous frequency (4.0kHZ) in Figure 7.28. This high frequency, high amplitude event is probably indicative of localised gas.

The instantaneous frequency of the remainder of the upper sequence appears very incoherent with frequencies varying between 1.6kHz and 4.0kHz. The instantaneous phase display of the upper sequence (Figure 7.29) further displays the bedding patterns seen in Figure 7.26.

7.5 Geological interpretation and environmental reconstruction

A suggested lithology for the units of the lower sequence, based in part on borehole and regional geological knowledge is of a seismically transparent silt or sandy clay overlain by relatively thick beds of clays, silts and sands with possible peat beds at the top of the units. There does not appear to be any material as coarse as cobbles or boulders as no point source diffractors associated with such deposits were observed. The strong reflection that marks the top and base of the units is likely caused by the coincidence of silt and sand/peat with their associated variations in physical properties being responsible for the high reflection coefficient and strong reflection.

The seismic facies information, combined with knowledge of borehole and regional geological knowledge, suggests that unit A is a sandy silt.

From the seismic and borehole data a simplified history of the survey area can be drawn up, namely:

1) Deposition of a fairly stiff silty sandy clay with occasional gravel (unit H). (Determined from borehole data)
2) Deposition of a number of units (B, D - G) clays, silts and sands with a possible peat bed at the top of each unit.
3) A period of erosion, marine or fluvial (forming the unconformity and sequence boundary).
4) Deposition of marine and fluvial deposits in what appears as one well bedded sequence.

Using this information and published literature for the area a more complete geological history can be hypothesised.

The last invasion of ice into the area was during the Late Devensian (Addison, 1990). This period could account for the stiff clays (lodgement till ?) observed as the lowest unit seen in the seismic data in all the example sections (Figures 7.22 - 7.34). Following the disintegration of the ice (14,460 ±300 years BP; Coope & Brophy, 1972) there followed a period of climate improvement and biogenic sedimentation followed by climatic deterioration and minerogenic sedimentation (because of low biological activity) (Loch Lomond Stadial). This was followed by climatic warming in the Holocene (10,000 years BP).

The situation in and around the present day positions of Menai Bridge and Bangor Pier at that time would have been one of a valley, with the river Cadnant draining to the east over the till surface. It has been suggested by Whittow and Ball (1970) that moraines left by the ice would facilitate lake formation. At this time, sea level would have been some -30m OD (Heyworth and Kidson, 1982) .

Assuming that units B, D-G are delineated by peat units it is possible that these peats started to form at the peripheral edges of the river Cadnant and on the clays left from the previously infilled lakes and local topographic depressions. These deposits themselves would have been subject to erosion by the draining Cadnant. The timescale available for such peat accumulation would have been over 3000 years. This figure reflects the time interval between the first occurrence of peat (and therefore marine free conditions) and the time of connection of the two reaches of the Menai Strait (6000 years BP). The lowest peat deposits are found at an altitude of -24m OD and are observed on all sections (unit G). From sea-level data in the area (Heyworth and Kidson, 1982), the sea did not reach this altitude until 9000 years BP.

The altitude of the uppermost peat deposit was some -12m OD (unit B, Line 12) which would suggest a last date of deposition before marine transgression of approximately 8000 years BP. These figures suggest that the peat deposits observed in the area only contain the peat accumulations of 1000 years. What other deposits existed, if they did at all, were presumably subsequently eroded.

As sea level rose, the valley would have changed from fluvial dominated to estuarine dominated. The area would be subjected to tidal scouring of peat deposits, and would become flood dominated and, by analogy with other estuaries in west Wales (i.e. Jago, 1980), subjected to tidal pumping of sediments into the estuary.

As sea level continued to rise this process would continue with salt marshes forming and sedimentation taking place at the sides of the estuary.

Approximately 6000 years BP, during the Flandrian transgression, sea level would have reached a sufficient height to allow the western and eastern reaches of the Menai Strait to connect. This would affect the dynamics of water movement in the Menai Strait. It is probable that the regime would change from flood to ebb dominant. This could represent the main phase of erosion of peats and alluvial sediments and be the main cause of the unconformity that is the sequence boundary and the deposition of the thick sequence of shelly silty sand that blankets most of the area. As an equilibrium was established sediment would be pumped out of what was the old estuary, this sediment helping to form the deltaic sediments of Lavan Sands.

7.6 Discussion and conclusions

In this case study the method of data collection worked well. It was unfortunate that the digital data from the intertidal segment of the survey was not able to be processed, but the method of recording raw seismic data to tape and then replaying it, post survey, to an acquisition system was proved to work in the latter study and so provides a 'hand portable' method of data recording.

As with the previous two case studies, it is relatively easy to suggest sequence boundaries but more difficult to differentiate the units within the sequence to systems tracts. In this case the reason may be due to the fact that the Menai Strait would be a difficult environment for sediments to behave in the manner that is assumed by Vail *et al.* (1977b) in that the arrangement of sediment source is complicated by the channel structure of the Menai Strait making the use of sequence analysis less confident (Thorne, 1992).

An unusual source of sediments could be considered for unit A. Sequence analysis usually assumes that sedimentation occurs by sediments carried from shallow water into deeper water and deposited on the intervening slope. However, in the case of the Menai Strait deposition could have occurred on what is now the sloping side of the channel and the gently sloping intertidal zone from a sediment source of mobile sediment within the main channel of the Menai Strait, sediment being deposited by alternating tides and periods of slack water as tides turn.

Instantaneous attribute and colour displays proved useful in helping to delineate the true extent of reflectors and identify proposed peat beds. The frequency and amplitude displays proved useful in identifying the variability of lithology and physical properties of beds. They also identified a possible area of very shallow gas.

From the seismic data it appeared impossible to differentiate between sandy clay and sandy silt (the proposed lithologies across the sequence boundary).

When working in the nearshore environment with high resolution data this case study has demonstrated that the use of seismic stratigraphy must remain flexible. In this case the occurrence of parallel bedding may in fact be derived *in-situ* and be organic. The apparent onlap demonstrated by units **B, D-G** onto the bedrock may therefore not have been caused by changes in sea level but by deposition of sediments into lakes and rivers and by *in-situ* production by peats.

CHAPTER 8

Liverpool Bay Case Study

8.1 Introduction

The Liverpool Bay site, the final area chosen for investigation, was selected for study on the basis of availability of geotechnical control data. Although being atypical relative to the other study sites in that it is situated away from the intertidal zone, lying in relatively deep water (max depth -31m CD) and having little variation in water depth over the area, the geology was known to be broadly similar in that the area has a significant covering of Quaternary sediments of glacial and post glacial origin. More importantly the area had fairly recently been surveyed for commercial purposes to allow the laying of pipelines to the oil and gas platforms sited in the area, and borehole and cone penetration test (CPT) data collected for these infield and export pipeline routes were kindly made available to the author (by Hamilton Oil) for research purposes.

It is now standard practice to collect CPT data when selecting pipeline (and cable) routes where the pipeline is to be trenched. CPT data are collected as they provide reliable *in-situ* measurements of lithology and geotechnical properties which allow selection of an appropriate plough and definition of appropriate depths of burial. CPT data are often supplemented with vibrocore data to provide a check on the CPT data. The spacing of CPT tests along a proposed route is variable and will be determined by expected lithology (estimated by seismic and sonar data), however a spacing of 1 CPT every kilometre with a vibrocore/gravitycore every ten CPTs is fairly standard. Over distances of thousands of kilometres (i.e. modern fibre optic cable lengths) the number of CPTs collected is considerable. The ability to use a remote sensing technique to determine the same or related geotechnical properties of sub-seabed conditions would provide a number of advantages to the pipeline/cable installation contractor in terms of time and money namely: (a) reduce number of required CPTs, (b) faster on-line interpretation without need to integrate CPT data and geophysical data except for calibration, (c) faster report turnaround.

This case study is unique within this project as it utilises CPT data to calibrate the seismic data allowing a more in-depth interpretation and discusses the effects that the physical and geotechnical properties of the marine sediments have on the instantaneous attribute displays of the seismic data en route to enhancing the role of geophysics in offshore site investigation.

8.1.1 Setting/general area

Liverpool Bay is situated in the SE part of the Irish Sea basin (Figure 8.1). The Irish Sea is semi-enclosed and is connected to the Atlantic ocean by the narrow entrances in the north (the North Channel) and the south (the St. Georges Channel). To take advantage of the available borehole and CPT data in the area the survey was conducted some 20km offshore in the geotechnically sampled region.

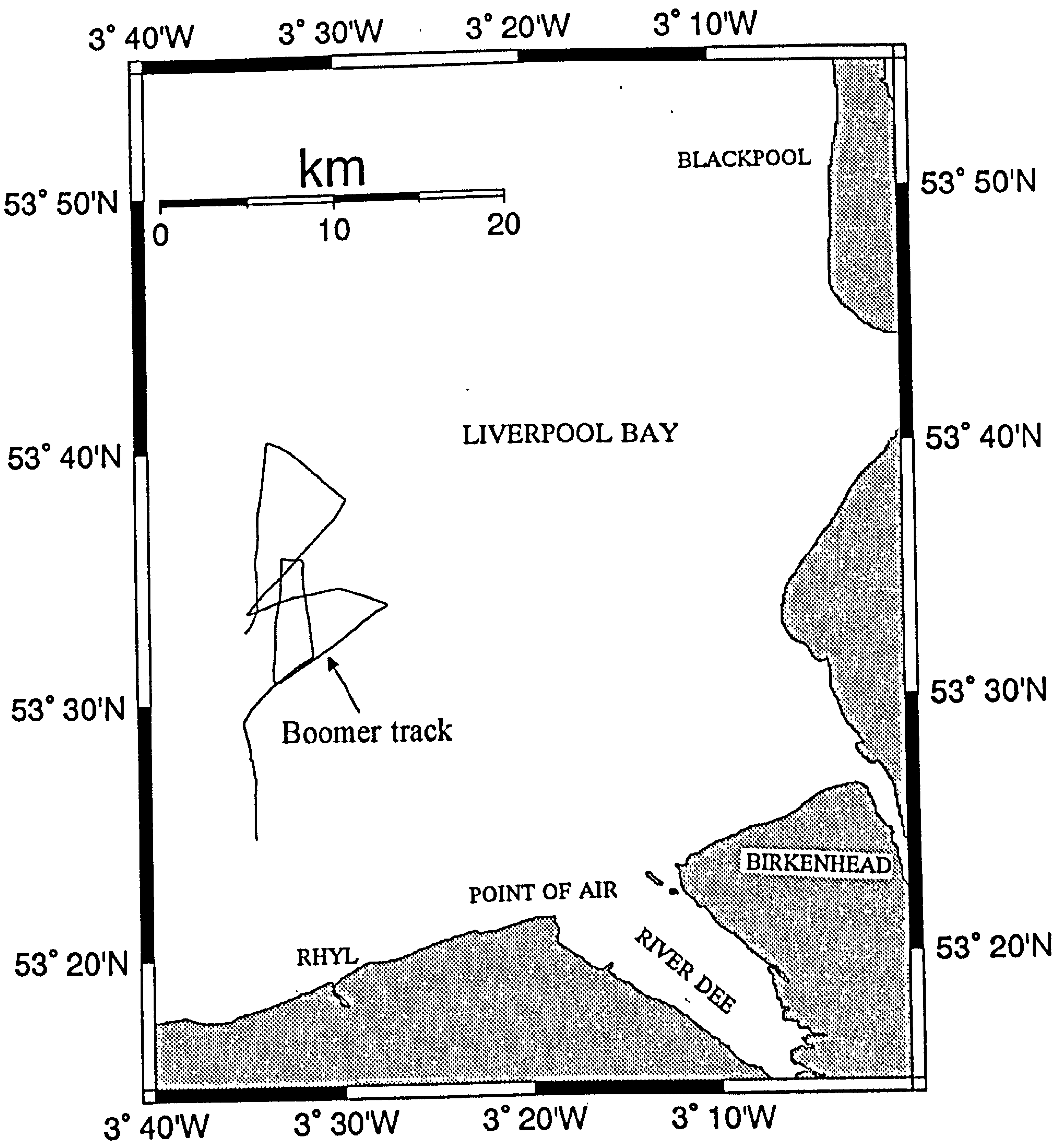
8.1.2 Solid geology

The geological setting of the area as a whole is of a Permo-Triassic basin infilled with more recent sediments. Seismic evidence indicates Carboniferous rocks exist almost everywhere beneath the Permo-Trias (British Geological Survey, 1978); these outcrop as coal measures (Westphalian) and Millstone Grit (Namurian) outside the survey area to the SE of the Isle of Man, and as a large subsurface syncline north of Anglesey.

The nature of geological control for the development of the Irish Sea Basin is considered by Dobson (1977) to be the downwarping block faulting and graben development of the Hercynian Orogeny.

In North Wales, the Carboniferous structures as far as Flintshire trend NNW-SSE, and near the Great Orme and throughout Anglesey they trend NE-SW. Large scale folding is geophysically recorded in the Carboniferous and Permo-Triassic in the Irish Sea.

Figure 8.1. Liverpool Bay. General area and geophysical survey track.



8.1.3 Quaternary sediments

Wright *et al.* (1971) carried out extensive geophysical and physical sampling over most of the Irish Sea. Seismic profiling was conducted using pinger and sparker seismic profilers. Maximum penetration, in excess of 500m, was achieved with the sparker at high energies while at lower energy levels it achieved penetration of 100m. The interpretation by Wright *et al.* (1971) grouped the seismic data into a top and bottom seismic layer. The bottom seismic layer was of Mesozoic and pre-Mesozoic (Permo-Triassic) age which, in the area relevant to this study, was interpreted as being red-brown sandstone and mudstone with a younger top layer of Quaternary, and in places possible Tertiary, sediments including sands, gravels and boulder clay.

The Permo-Triassic bedrock appears highly eroded and dissected and is typically overlain by glacial deposits including sands, gravels and boulder clay, which is overlain by proglacial water laid beds and these in turn by marine sediments (Wright *et al.*, 1971; Pantin, 1977). The thickness of the top layer is less than 40m over most of the Irish Sea but can reach 180m SW of the Isle of Man.

Grab samples, vibrocores and borehole data indicate that the marine sediments possess a considerably higher sand/mud ratio in Liverpool Bay than further north (Pantin, 1977). In Liverpool Bay, dominantly sandy sediments form the bulk of the assemblage with gravelly sediments in minor amounts.

The boulder clay resulted from melting and ablation of the Irish Sea portion of the Devensian ice sheet (Pantin, 1977). The proglacial water laid beds are reported as being less obvious over the survey area. These were probably laid down during the late Devensian, when deglaciation was partly completed; the bodies of water in which these beds were laid down may have included arms of the sea, lagoons with access to the sea restricted by ice or physical topography, or lakes. Pantin (1977) attributes the scarcity of macrofauna in these beds to indicate a low salinity as compared with the present day Irish Sea.

The age of the marine beds is thought to range from the Late Devensian to the Flandrian. Most of the beds are probably subtidal, but with some horizons of intertidal deposits formed on beaches or tidal flats.

The difference in bedding definition between the proglacial water-laid beds and the marine beds may result from the much greater efforts of bioturbation in the marine environment.

The apparent lateral passage between proglacial water-lain sediments and marine sediments, indicated by acoustic profiles, may well correspond to a significant real change in sediment facies (Pantin, 1977). If a change in bedding definition can result from a variation in the degree of bioturbation, the lateral transition could be due to the local appearance of large numbers of marine animals in response to a persistent saline wedge at the bottom of the water column. The form and extent of such a wedge would be determined by factors such as bottom morphology, distribution of glacial meltwater, strength and direction of tidal currents and direction of the prevailing wind.

The widespread core and pinger evidence of a lithological discontinuity between the water-laid beds and the overlying marine beds, together with the evidence of other discontinuities within the marine sediments themselves, indicate that phases of erosion could have occurred during the disintegration of the Devensian ice sheet. These phases could have resulted from changes in the tidal current regime, but could also have resulted from lowering of relative sea level. The occurrence of intertidal sediments interbedded with subtidal marine sediments or overlying proglacial lagoon beds, indicates one or more lowerings of relative sea-level.

The argument that the Flandrian transgression composed, particularly in its late phases, of a series of regressions and transgressions relating intercalating layers of terrestrial and marine sediments to actual changes in sea level was initiated by Fairbridge (1961). However, Shepard (1963) argued that the Flandrian transgression resulted from a smooth rise in sea level, initially rapid but decelerating progressively in the late Holocene (i.e. Figure 5.3a). Local geomorphic changes are attributed to differing rates of sea level rise, isostatic rebound and sedimentation.

8.1.4 Control data

As previously discussed, the area has been extensively investigated by Wright *et al.* (1971) using Shipek, gravity corer and vibrocorer sampling, and more recently by Hamilton Oil using vibrocore and CPT. The interpretation by Wright of the thickness of the surficial seismic layer and its lithology is presented in Figures 8.2 and 8.3 respectively. Borehole data and cone penetration test data acquired by Hamilton Oil for a proposed pipeline route will be discussed and presented later.

8.2 Marine seismic investigation

As previously mentioned, this project intends to test the seismic stratigraphic method in environments where it is not typically applied. It also hopes to test different methods and equipment configurations in the collection of these data. As such, some of the factors of equipment and logistics will be discussed here.

8.2.1 Survey details

The survey of Liverpool Bay was, from a logistical point of view, much simpler to organise and conduct than the previously discussed inshore surveys. The survey area is outside formal shipping channels and hence no special permission or notice was required to be given of survey intentions except for those that are routinely passed by the master of the boat to the coastguard.

The only survey constraint was the weather which, as discussed, will affect data quality. As such, the survey was conducted during a period of good weather and was completed in 12 hours steaming at an average speed of 4 knots.

The survey track is presented in Figure 8.1. The unusual line plan run during this survey was to gain optimum coverage of the available CPT and borehole locations (Figure 8.7).

Figure 8.2 Thickness of "top seismic layer" (Quaternary, in metres) after Wright *et al.* (1971). Surrounding 'shaded area' has a thickness less than 20m.

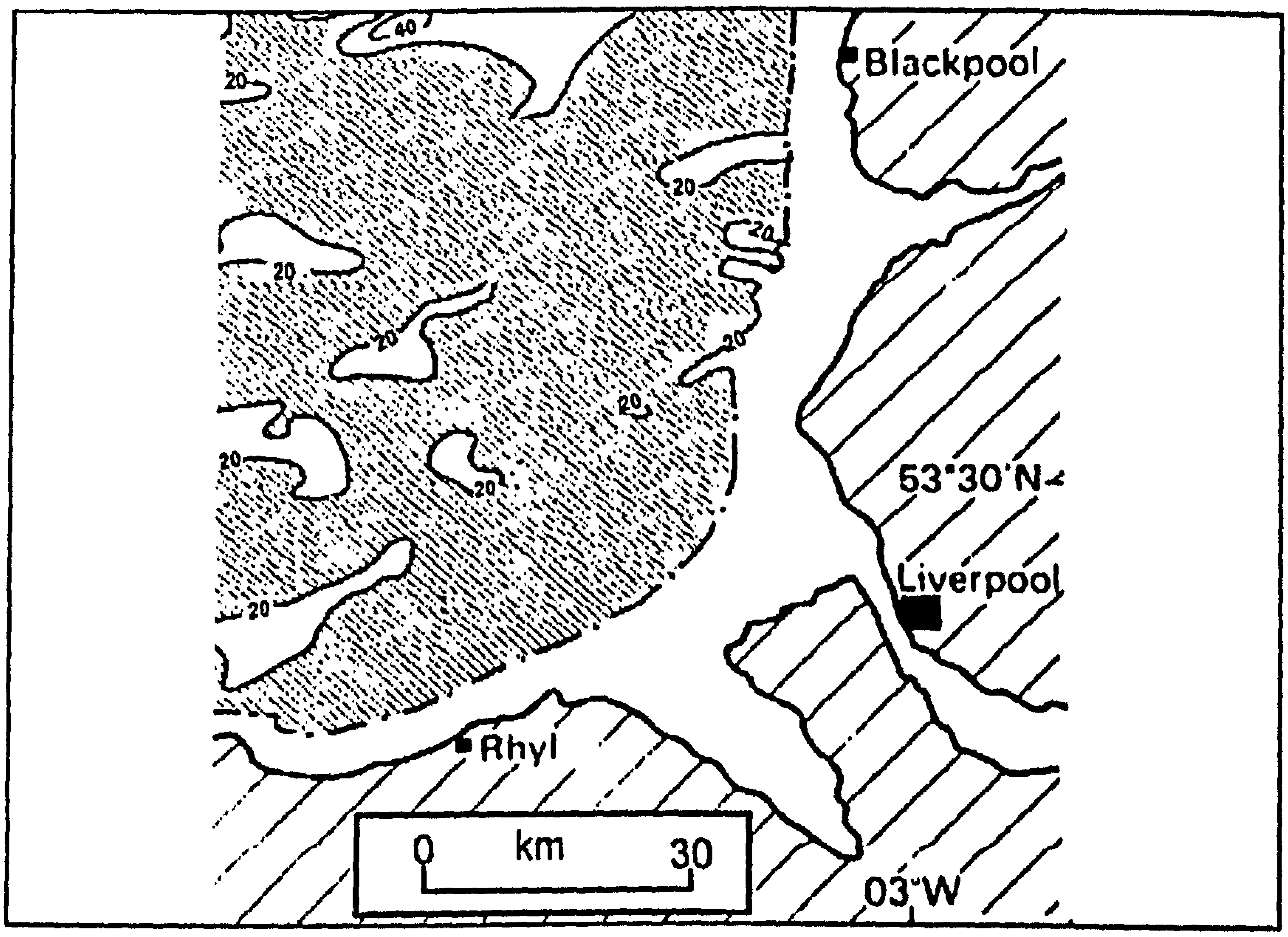
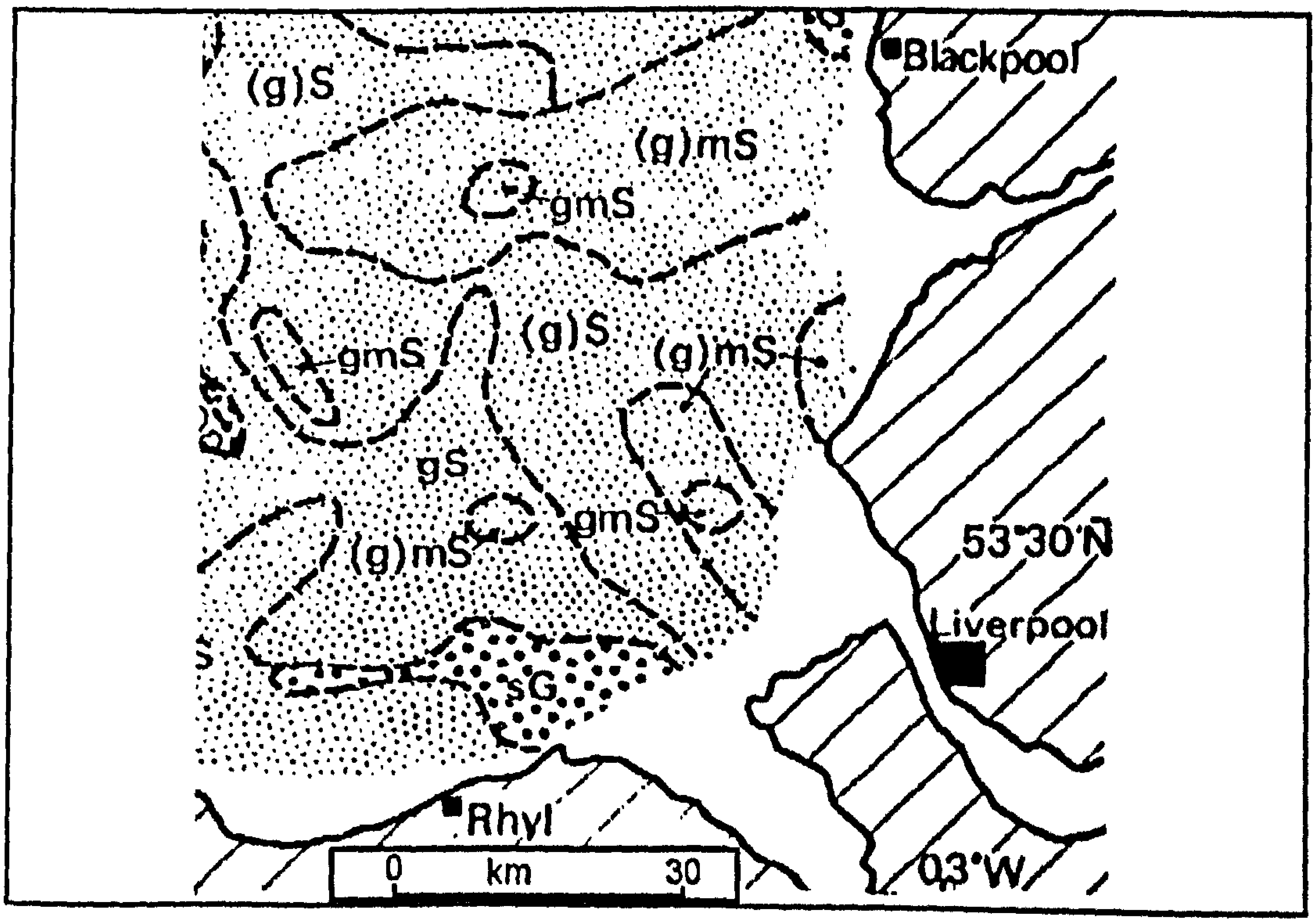


Figure 8.3 Sea floor sediment distribution (from Wright *et al.*, 1971). M - mud, S - sand, G - gravel. Based on Folk's classification.



8.2.2 Equipment and vessel

The vessel used for intertidal surveying in the other case studies was not suitable for working this distance offshore therefore the RV Prince Madog was used.

The survey tool initially deployed was the Seistec as, although designed as a shallow water survey tool, it is still capable of working in depths of up to 100m in calm conditions (Simpkin and Davis, 1993). However, due to a trigger problem a separate single channel hydrophone was deployed and used.

8.2.3 Analogue data acquisition

Analogue data recording was run simultaneous to the digital data acquisition. Data were recorded to thermal printer.

8.2.4 Digital data acquisition

Digital data were acquired using the Elics Delph2 system operating with the following parameters:

Shot interval	250msec
Sampling frequency	16kHz
High pass filter	480Hz
Low pass filter	4800Hz

The data were recorded to Exabyte tape in SEG-Y format for subsequent processing at UWB using the Sierra-Seis software. Backup data were recorded onto digital audio tape (DAT).

8.2.5 Position fixing and navigation

Position fixing was achieved using Trimble NavTrac differential global positioning system (DGPS) with a likely accuracy in the order of 5 - 10m. Navigation was achieved by following a number of waypoints programmed onto the ships auto-pilot.

8.3 Interpretation procedure

Examples of the seismic data have been selected for presentation and discussion in section 8.4. The main criteria for data selection were the proximity of ground truth control (Figure 8.7).

To assist in the interpretation and provide a 3D overview of certain aspects of the data, contour maps have been constructed using a portion of the data set. The data examples and contour plots have been constructed using the parameters discussed below.

8.3.1 Analogue interpretation

Data recorded from the hydrophone array have been interpreted using non linear depth scales to account for the offset between the source and receiver as discussed in chapter 7.3. Water depths were calculated from the boomer data using an assumed acoustic water velocity of 1500m/s. The assumed seismic velocity used to calculate sediment depth was 1650m/s; this value was assumed using published velocity information (i.e. as summarised in Sheriff and Geldart, 1995), from velocity data proved at Seal Sands (chapter 5) and the velocity found by Clark (1987) of 1640m/s for intertidal sediments at Point-of-Air on the north Wales coast. The assumed velocity also falls into the (rather high) assumed velocity used by Wright *et al.* (1971) of 1800m/s (±360 m/s) in the Irish Sea basin.

8.3.2 Digital data processing and interpretation

In this survey acquisition of high quality digital seismic data was the top priority. As previously mentioned seismic facies analysis can be improved with the use of instantaneous attribute displays of seismic data (chapter 3.4.3). Also, in this particular case study, the potential of integrating CPT and digital data was to be investigated.

Data were read into Sierra Seis using a standard processing sequence shown in Figure 8.4. The various pools and processes used in the sequence are as follows:

Figure 8.4 Sequence of commands to read seismic data from tape.

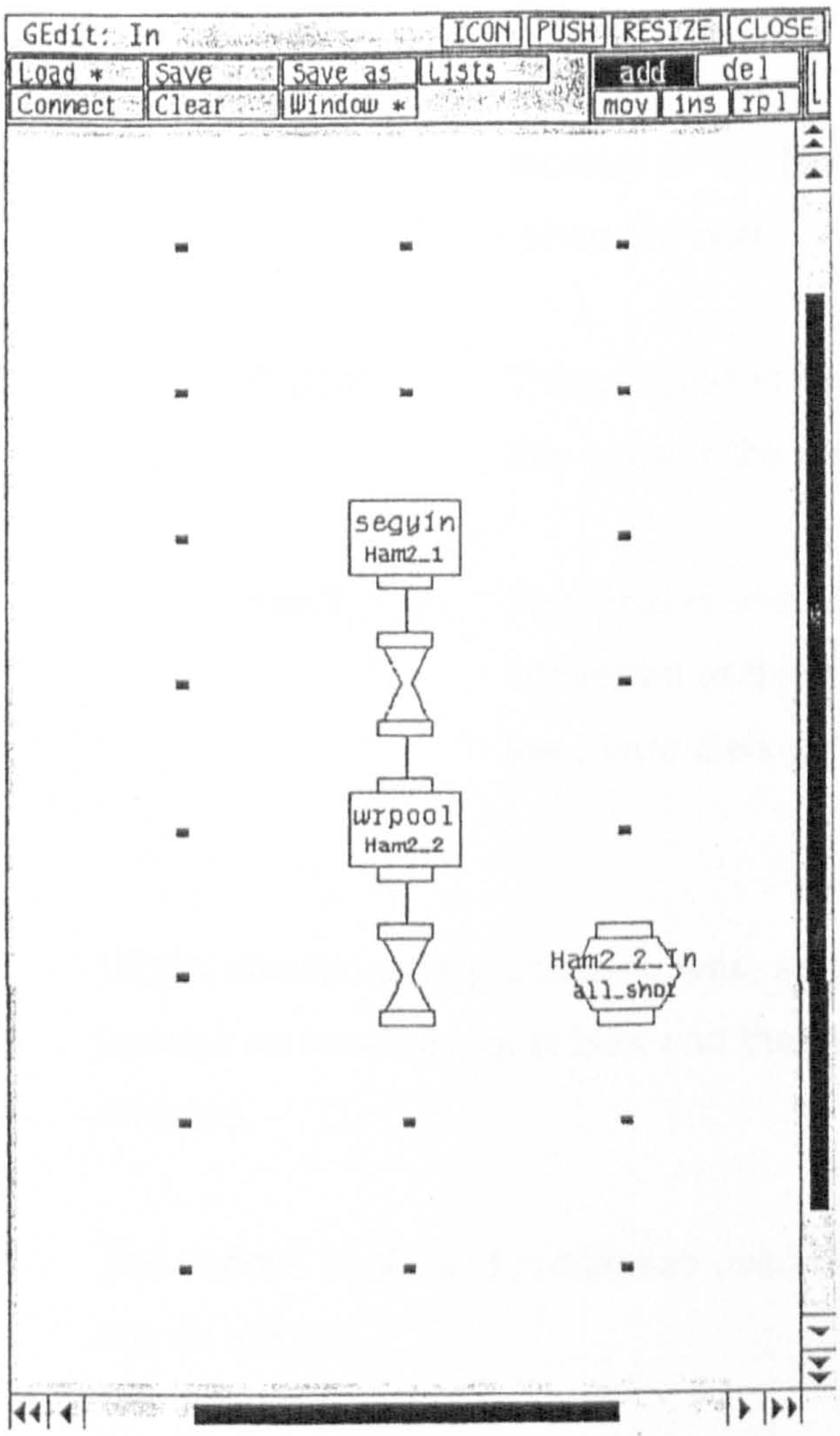
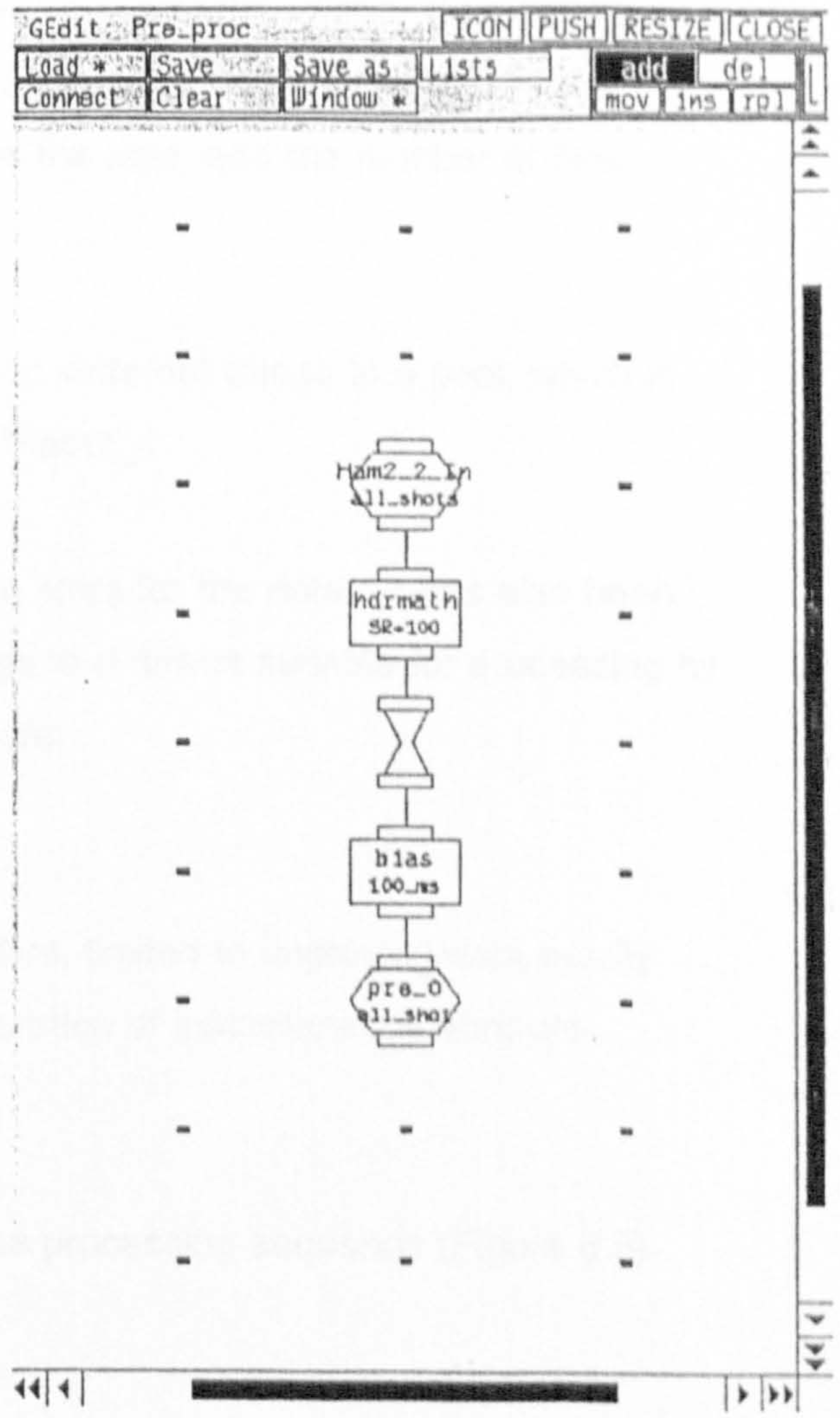


Figure 8.5 Sequence of commands to process seismic data.



Graph: GEdit: In

Segyin	This process reads trace sequential seismic data from tape in SEGY format. The interpreter need only specify the location of the files on the tape, and the number of files (shots) to read.
Wrpool	This process is used to write out traces to a pool, which in this case is the pool 'Ham2_1'.
Ham2_1_In	This pool is used as a store for the data. It has also been converted at this stage to a format suitable for processing by the Sierra Seis software.

Digital seismic data processing was, as before, limited to improving data quality through removal of signal bias and the generation of instantaneous attribute displays.

The various pools and processes used in the processing sequence (Figure 8.5) are as follows:

Graph:GEdit:Pre_proc

hdrmath	This process modifies existing trace attributes. In this case, being used to convert TWT from msec to seconds.
bias	This process was used to subtract DC bias from the signal.
Pre_0	This pool stores data that has been effectively 'cleaned up' by the previous processes.

An example of pre-processed data is presented in Figure 8.6; this can be compared with equivalent processed data discussed latter in this chapter (Figure 8.12).

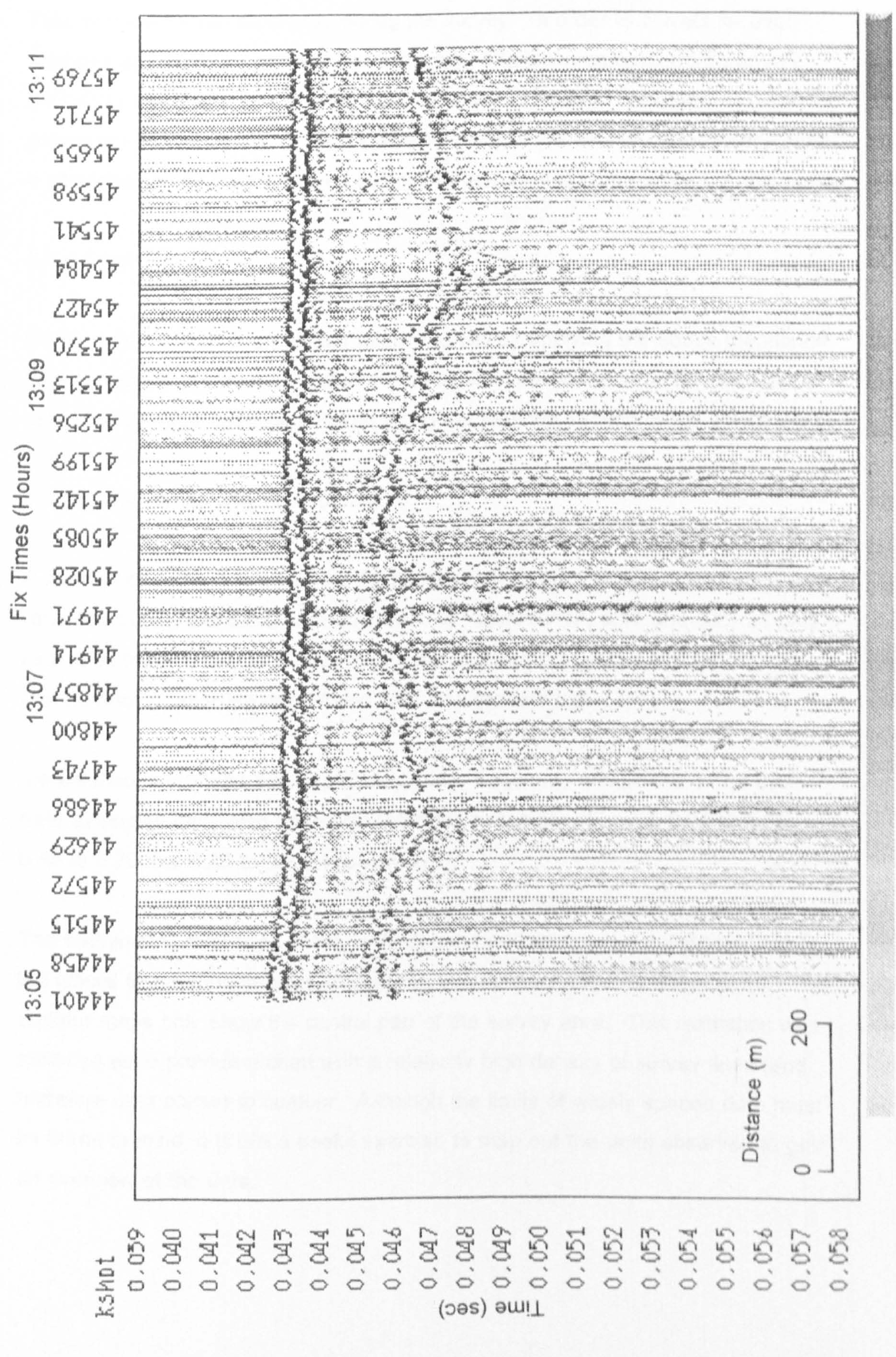


Figure 8.6 Pre-processed digitally recorded data (section A).

8.3.3 Tidal correction

Tide levels were not monitored during the survey. In order to correct for tidal changes as before a simplified harmonic tidal prediction computer programme (NP159a) was used applying Admiralty harmonic constants for Liverpool Bay. As previously the weather was fairly stable throughout the survey period hence such a correction could be considered sufficiently accurate for the purpose of this study.

8.3.4 Charting

Contour maps have been plotted relative to CD by applying the above mentioned tidal correction. Horizontal scales on the seismic sections have been calculated using the average distance covered along the relevant section of the seismic lines.

8.4 Seismic stratigraphic interpretation

A number of seismic profiles (the positions of which area as shown in Figure 8.7) recorded during the survey are presented in Figures 8.12, 8.17 and 8.22 as data examples for discussion. These examples illustrate processed digital data with a corresponding, appropriately scaled CPT or vibrocore log.

Instantaneous attribute displays of amplitude, frequency and phase of the three data examples have also been presented for discussion (Figures 8.13 to 8.15, 8.18 to 8.20 and 8.23 to 8.25 respectively).

The bathymetry, thickness of the surficial sand and gravel and palaeo-surface of the glacial till have been mapped over the survey area (Figures 8.8 to 8.10). The contour maps only show the central part of the survey area. This restriction was made so as to provide a chart with a relatively high density of survey lines (and therefore data points) to contour. Although the limits of widely spaced data must be borne in mind, it is still a useful exercise to map out the units observed to gain an overview of the data.

Figure 8.7 Chart illustrating parts of survey selected for discussion and location of vibrocore and CPT data.

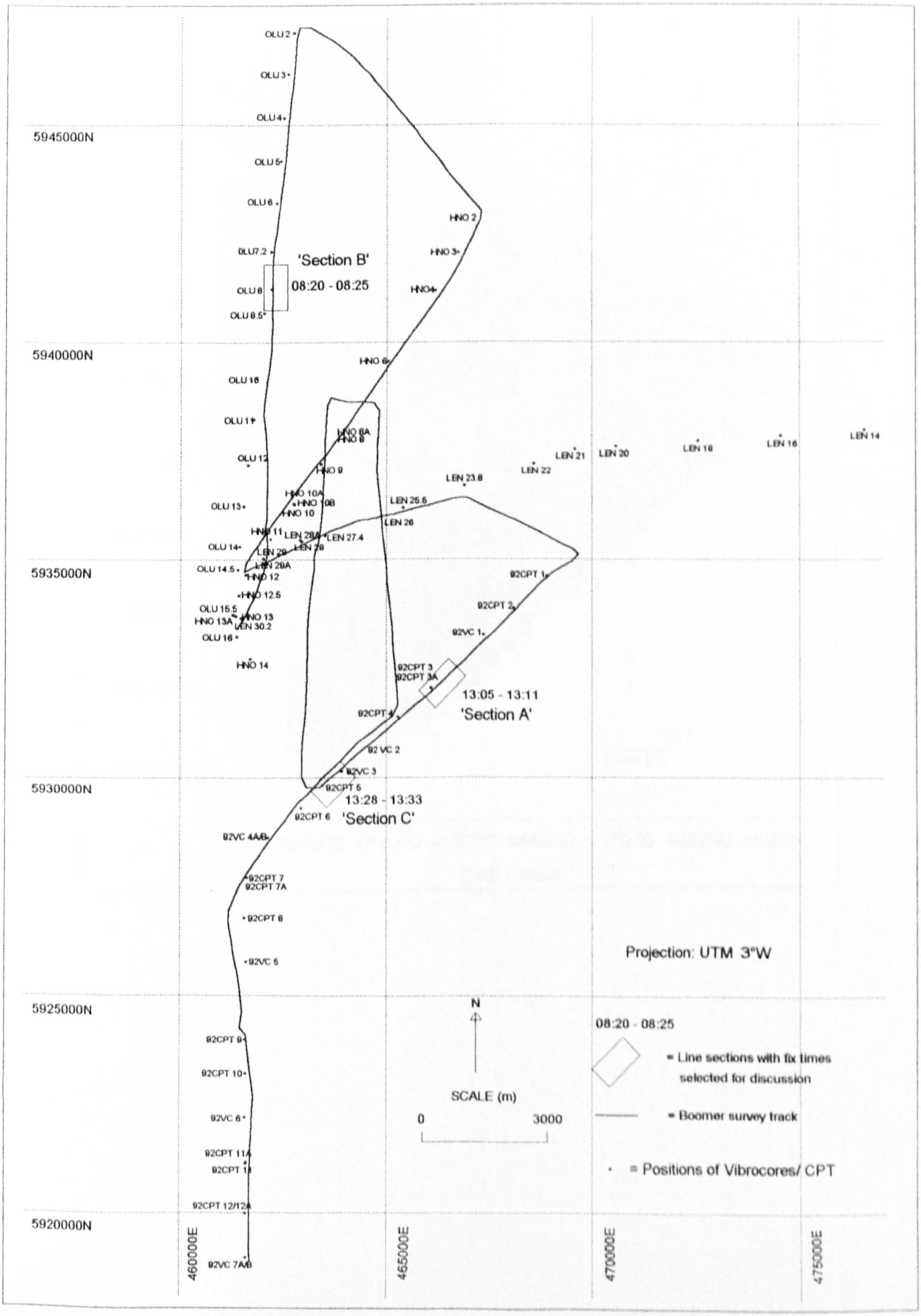


Figure 8.8 Bathymetry (m CD) of survey area (+ = fix point).

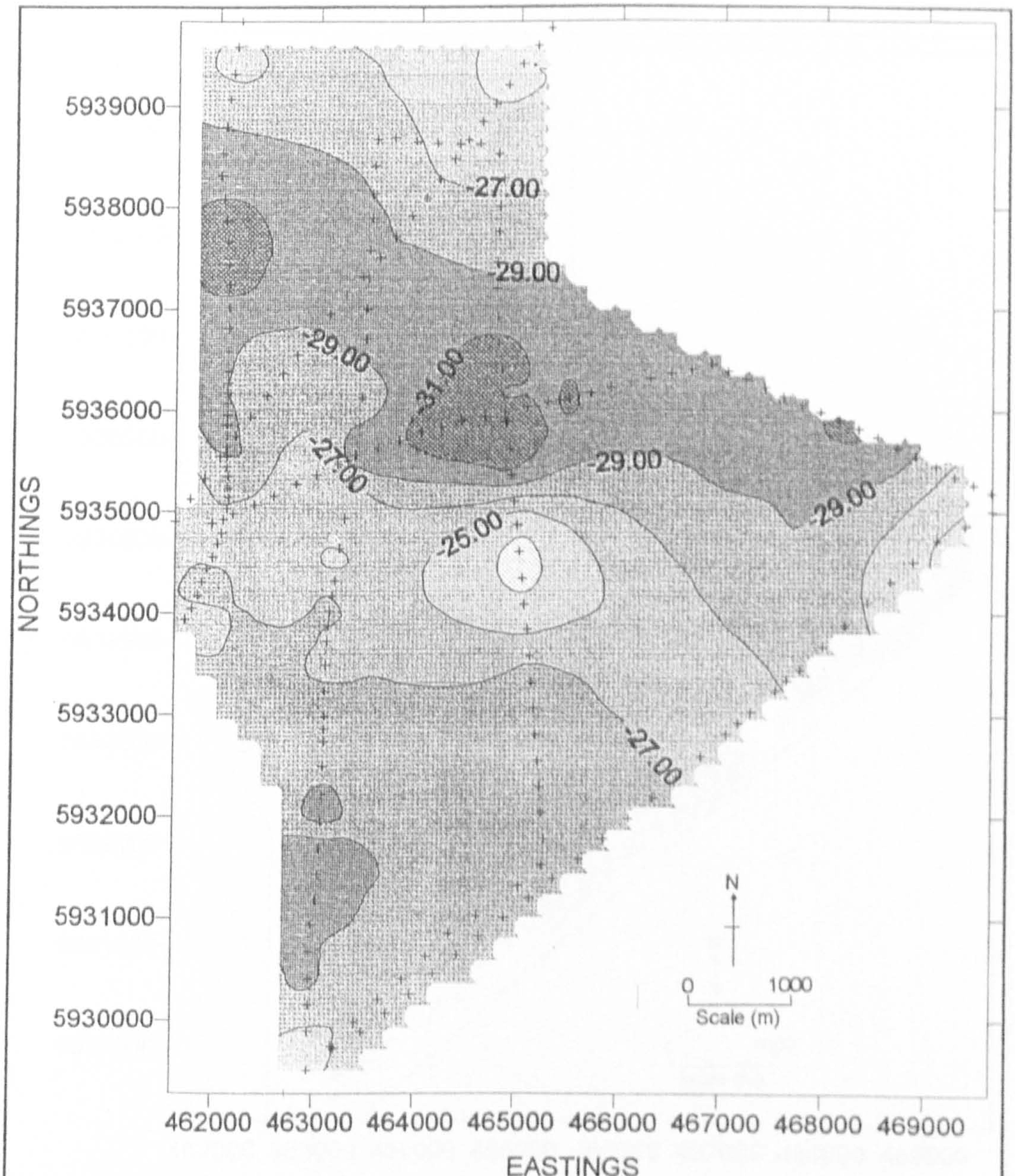


Figure 8.9 Thickness of surficial sand and gravel unit (m) of survey area based on boomer data (+ = fix point).

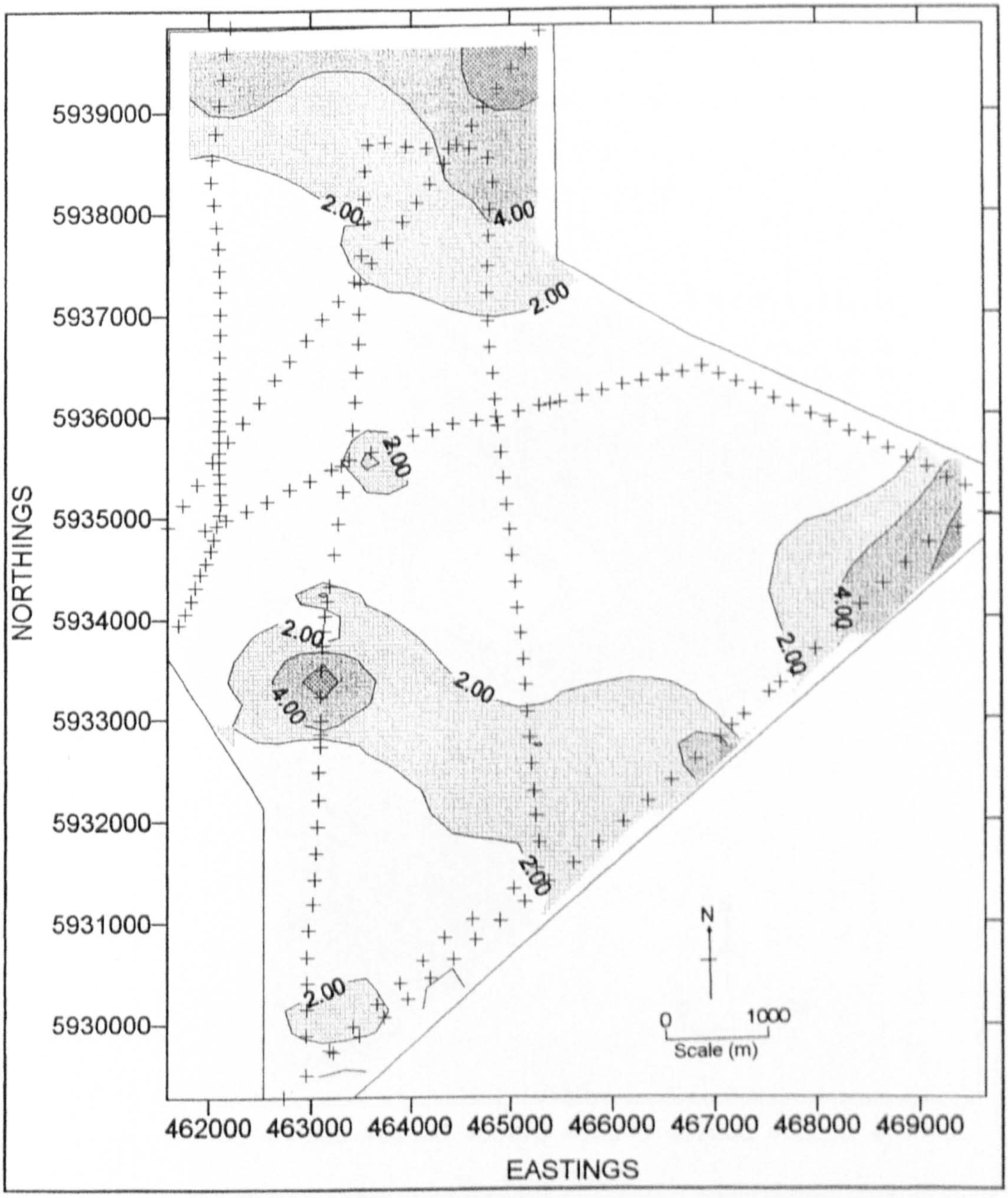
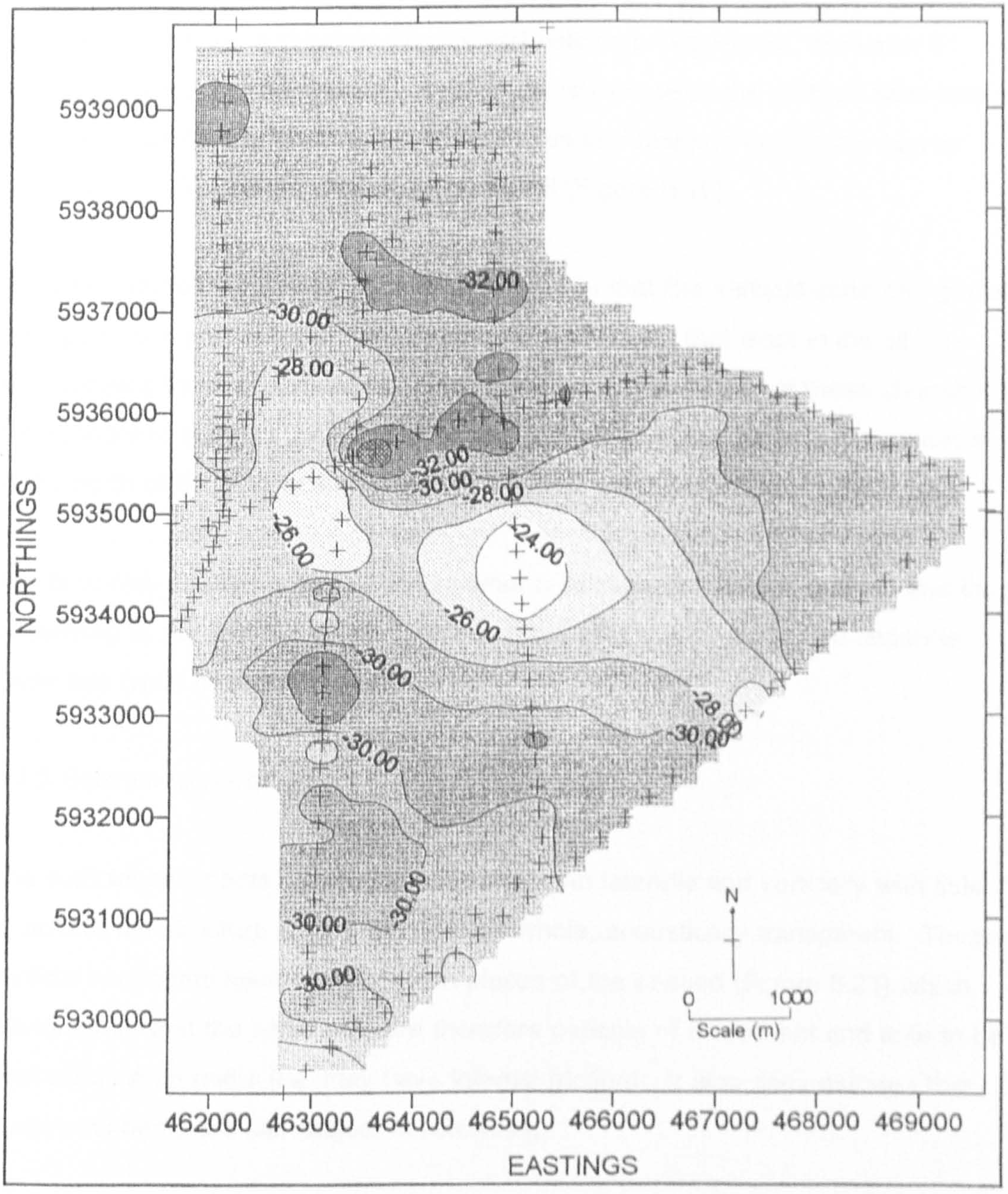


Figure 8.10 Palaeo-surface of glacial till (m CD) over survey area based on boomer data (+ = fix point).



8.4.1 Seismic sequence analysis

It is difficult in this data set to recognise discontinuities on the basis of reflection termination patterns and hence identify and delineate sequences. However it could be argued that a sequence boundary exists between the surficial sand and gravel unit identifiable on all the data examples and mapped across the survey area (Figure 8.9) and the underlying glacial till (Figure 8.10).

A comparison of Figures 8.8, 8.9 and 8.10 shows that the surficial sand and gravel unit appears in part to have been deposited in channels that exist in the till. It also appears that the surficial sand is not limited to just infilling of these channels but appears to account for areas of relatively shallow water, especially noticeable in the north of the survey area delineated by the -29m contour (Figure 8.8).

The boundary between the surficial sediments (although absent in places) and the underlying till represent a discontinuity as a possible period of erosion separate these two types of sediment.

8.4.2 Seismic facies analysis

The surficial sediments appear homogenous both laterally and vertically with little or no internal structure and appear, on the whole, acoustically transparent. These surficial sediments have sandwaves in places at the seabed (Figure 8.21) which demonstrate that the sediments are therefore capable of movement and able to be deposited on an angle (i.e. they have internal friction). It also demonstrates that these sediments are still subject to reworking.

The top of the till is marked by a high amplitude reflection. There is little evidence of internal structuring. This deposit appears on the whole to have higher internal backscattering. The seismic facies for these deposits, because of the lack of structure, is better described by their instantaneous attributes which in this case will also include a description of the parameters collected by the relevant CPT.

8.4.3 Discussion of CPT data and instantaneous attribute analysis

As discussed in chapter 4.3.3, the use of instantaneous attribute analysis provides a useful tool of seismic facies analysis. In this chapter selected examples of the data set will be presented as instantaneous attribute plots and their relative merits discussed relative to CPT data. The CPT data describe lithology and can provide an indication of geotechnical properties.

All depths unless otherwise stated are in metres below seabed.

8.4.3.1 Calibration of seismic data with 'CPT 3 1992'

CPT 3 1992 is presented in Figure 8.11. It collected data to a maximum depth of 5.20m. Estimated soil types of medium dense sand, sandy gravel and very stiff to hard sandy gravely clay (till) with an estimated undrained shear strength (Su) of 230-300kPa were encountered.

The uppermost unit (0.00m - 2.00m) is described as medium dense sand. Cone resistance increases from 0MPa to 1.8MPa in the first metre and remains at approximately 1.8MPa to the base of the unit at 2.00m. Skin friction through the sand unit remains low and does not exceed 0.03MPa. Pore pressure remains low through the unit at less than one bar. Relative density increases from about 30% to 55% in the first metre and remains at about 55% through the rest of the unit.

The sand rests on a thin (0.10m thickness) bed of sandy gravel. The gravel unit witnesses a sharp increase in cone resistance up to 8MPa. Skin friction remains fairly constant at a value typically less than 0.03MPa. Pore water pressure fluctuates between fairly low positive and negative values (negative pore pressures may be caused by a vacuum being created behind the tip of the cone). Relative density increases sharply to a maximum peak value of about 80%. The friction ratio remains at approximately 1 through the whole unit.

The final unit encountered (2.10m - 5.20m) is interpreted as very stiff to hard sandy gravelly clay. The cone resistance is greater than in the sand and is typically 5MPa with isolated areas where resistance peaks at 13MPa at 2.60m and 9.8MPa at 4.90m (due, probably, to relatively isolated patches of gravel).

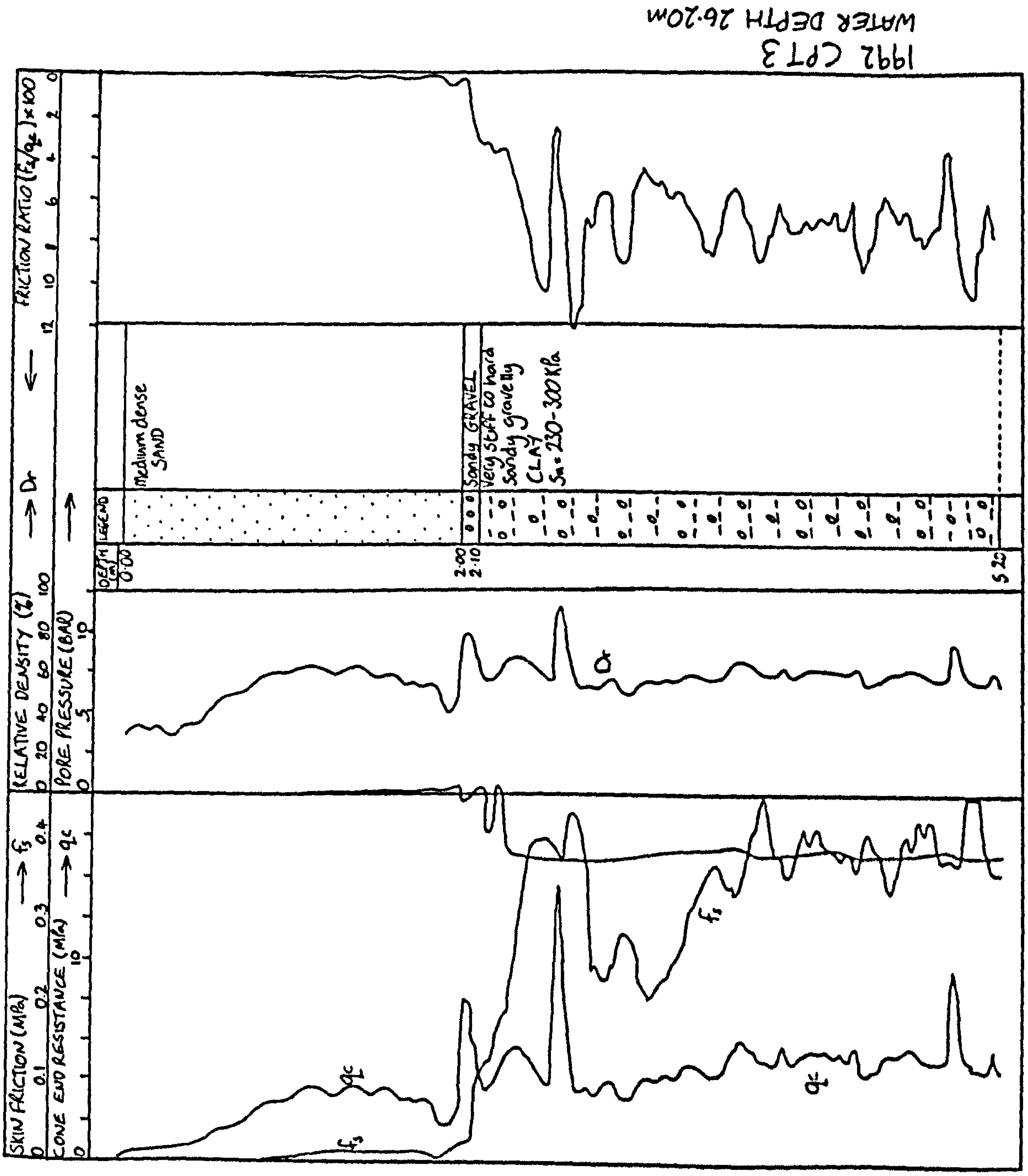


Figure 8.11 Data from '1992 CPT3'

Skin friction witnesses a sharp increase to 0.42MPa at the transition between sand and clay. This value fluctuates briefly before settling to an average value of 0.39 MPa. Pore pressure adopts a negative value of approximately -4 bar that, after initial fluctuation, settles and remains constant through the remainder of the unit. Relative density, although subject to slight variations, is fairly steady at 55%. The friction ratio increases with the transition from sand to clay, and although fairly variable is approximately 7.

There is an overall trend of increasing q_c with depth in the sand unit which indicates (as discussed in chapter 3) normally consolidated sediments. The clays, however, appear overconsolidated.

The lithological units predicted from CPT 3 have been presented, appropriately scaled, with the relevant variable density display of the seismic data for comparison (Figure 8.12). Figure 8.12 illustrates an excellent correlation between predicted lithological changes from the CPT and the occurrence of significant reflectors on the seismic data. Figure 8.12 is also presented as instantaneous attribute displays of instantaneous amplitude, frequency and phase which will be discussed below.

a) Amplitude

The Instantaneous amplitude plot (Figure 8.13) illustrates, in the form of a colour plot, the amount of energy reflected from a lithological interface which is, as discussed in chapter 2, dependent on the relative change in velocity and density across the interface between the two media. In this case the dominant impedance contrast is between the sand and sandy gravelly clay. This main subsurface interface appears to have a large impedance contrast value in the same order of magnitude as the seabed/water interface. The amplitude plot reveals some indication of lateral facies variations as the irregularity of the surface of the clay appears as discrete areas of high amplitude events. This may be caused by pockets of gravel resulting in the areas of stronger reflectors. Such patches are observed (to a certain extent) on the variable density plot, but are more obvious on the colour plot.

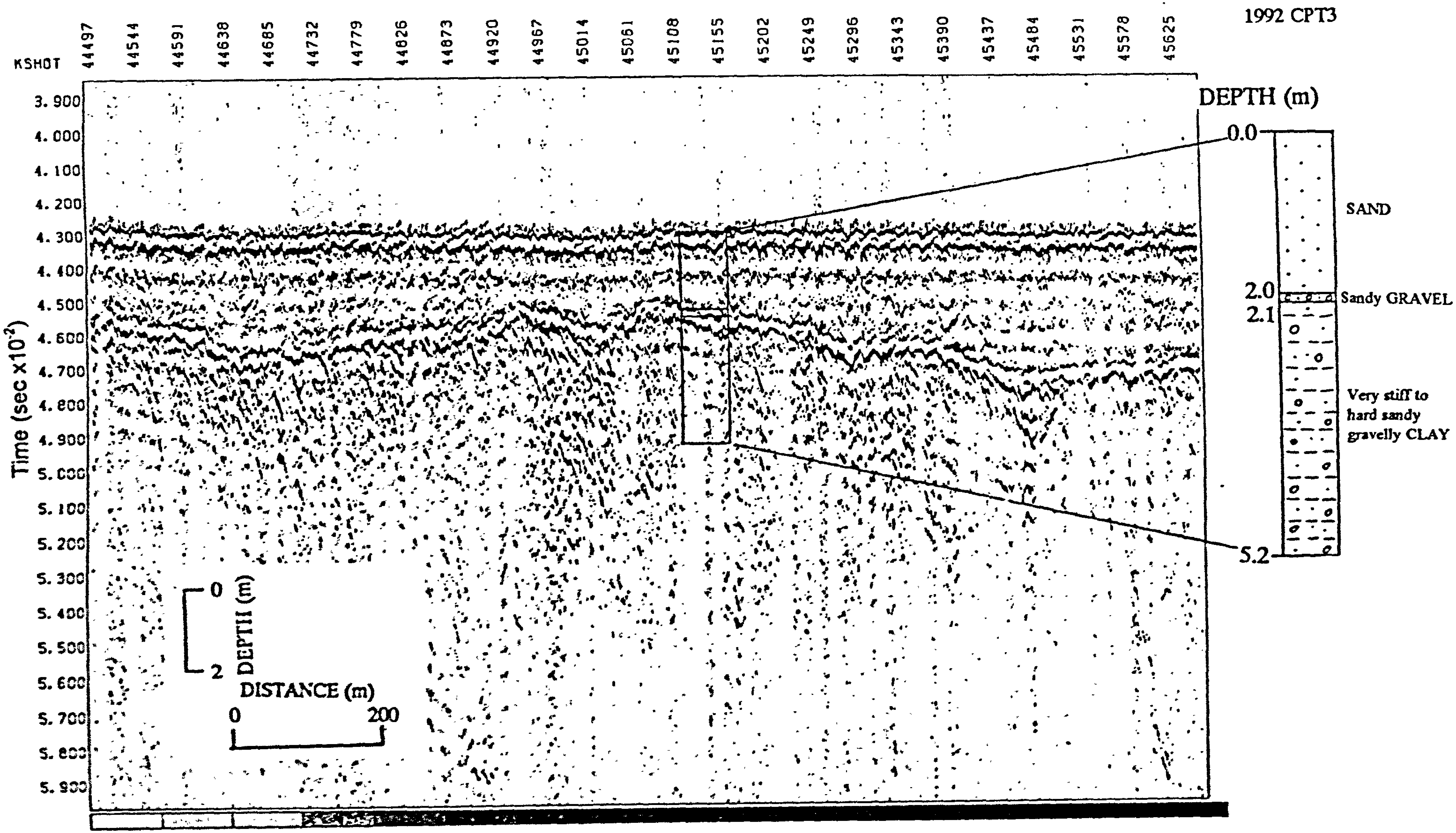


Figure 8.12 Processed digital data (section A) and 1992 CPT3

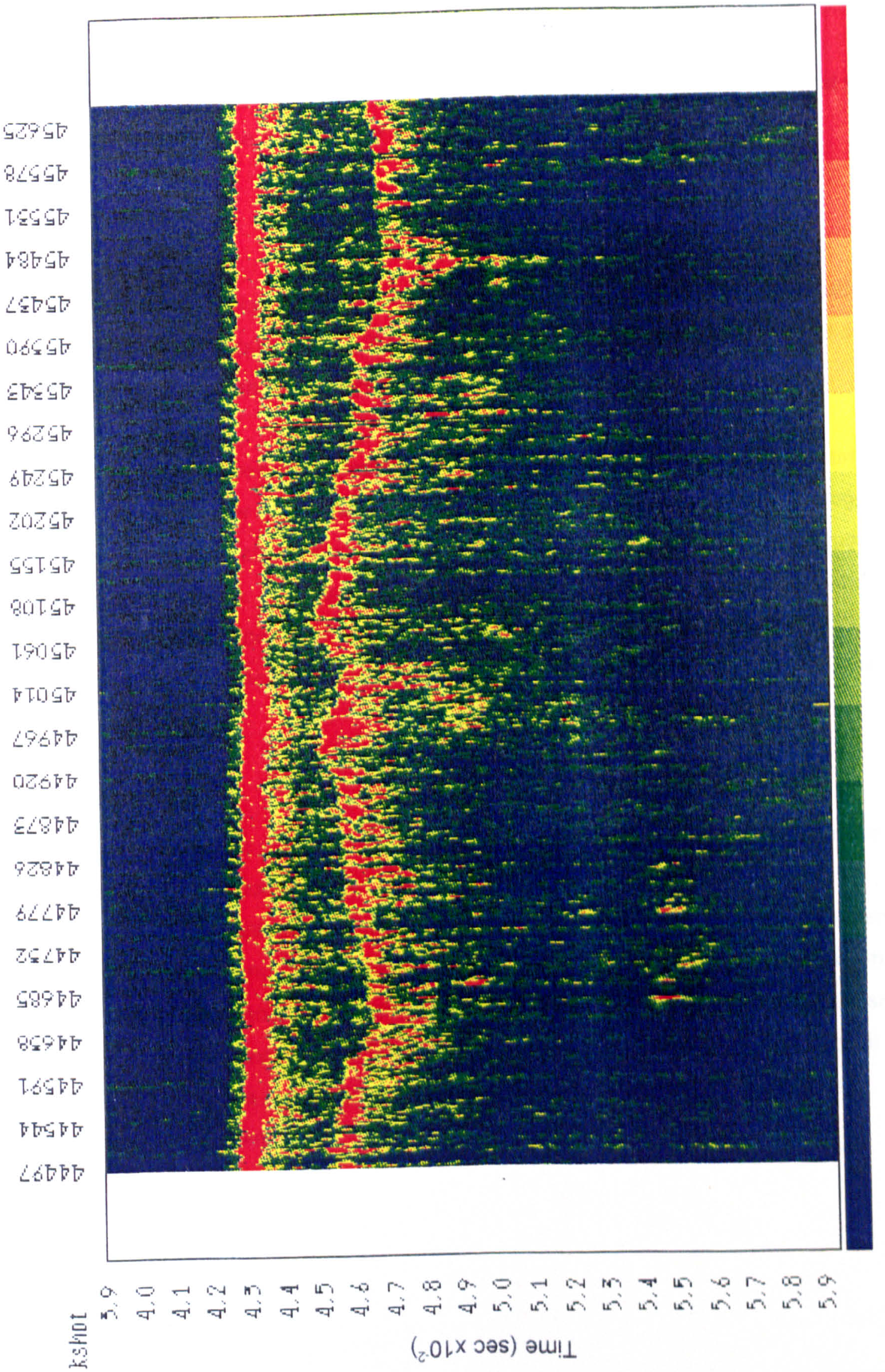


Figure 8.13 Instantaneous amplitude plot (section A).

The sand unit appears, from the lack of internal high amplitude events (indicating interfaces), to be essentially homogenous through the unit.

There appears to be a high amplitude event at the base of a small channel at fix 45460 which may be the result of a basal gravel deposit.

b) Frequency

The frequency display (Figure 8.14) shows a decrease in high frequencies with depth. Highest frequencies (4.2kHz) exist in the water column (noise ?) and at the first break of the seabed (3.0kHz).

The transition between the predicted major lithological units is shown as a fairly poorly defined layer of around 2.2kHz. The frequency response at the lithology boundary appears sharper in places where the 'thickness' of the high amplitude zone is at its least. This is probably due to tuning effects. A possible explanation for the poor definition of the top of the clay unit is potential variability of the thin sandy gravel unit resulting in a variable composite reflection from these two units.

c) Phase

The phase diagram (Figure 8.15) shows high internal backscatter where there are no laterally continuous seismic events. Phase plots are generally useful to delineate stratal patterns and continuity. Apart from the major interface between the sand and clay no other coherent boundaries are apparent. This suggests that the sand unit has no strong lamination patterns (at least within the limits of seismic resolution i.e approximately 0.25m) and that it is an essentially massive deposit . There is however a suggestion of internal layering within the clay (mudstone) although this is faint.

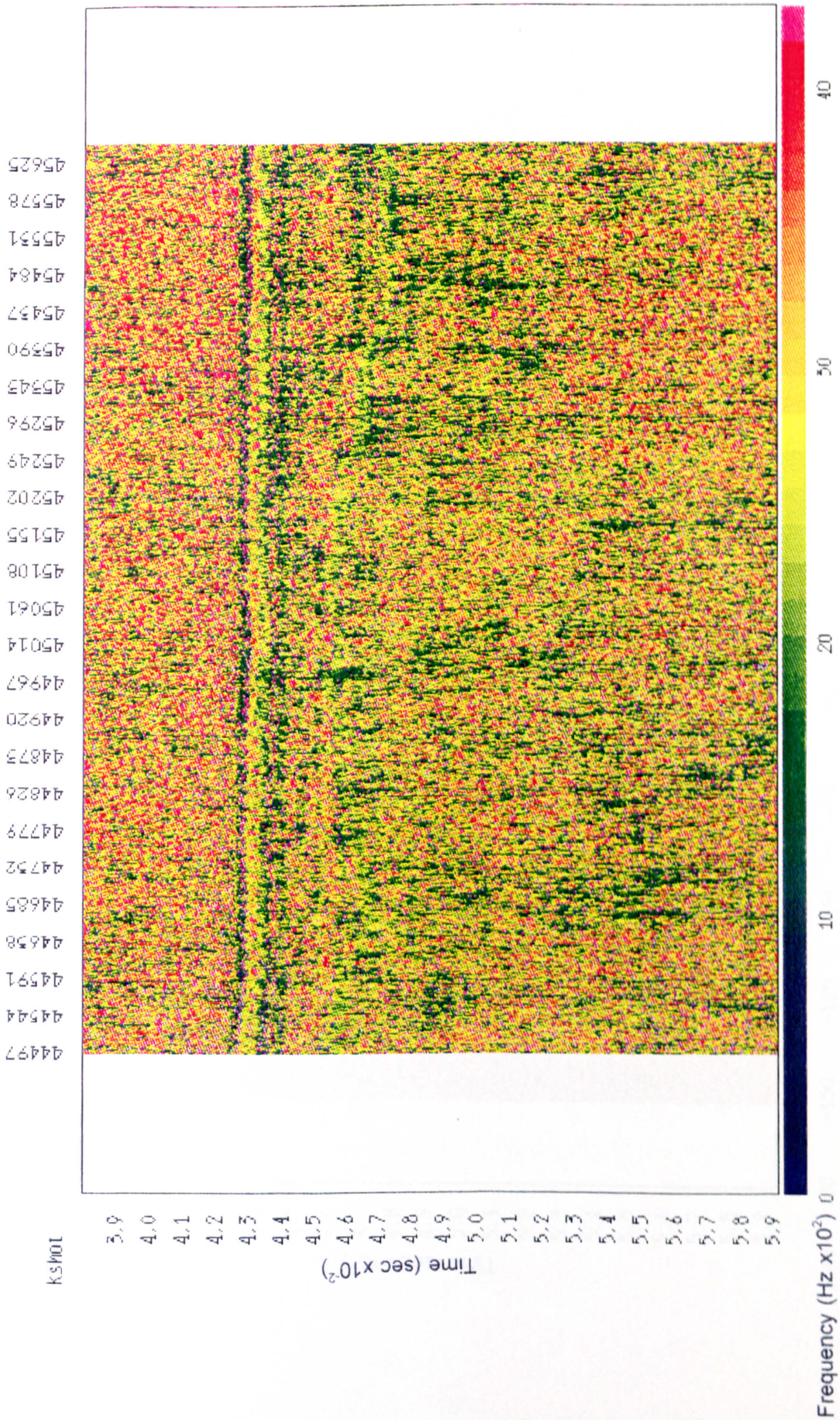


Figure 8.14 Instantaneous frequency plot (section A).

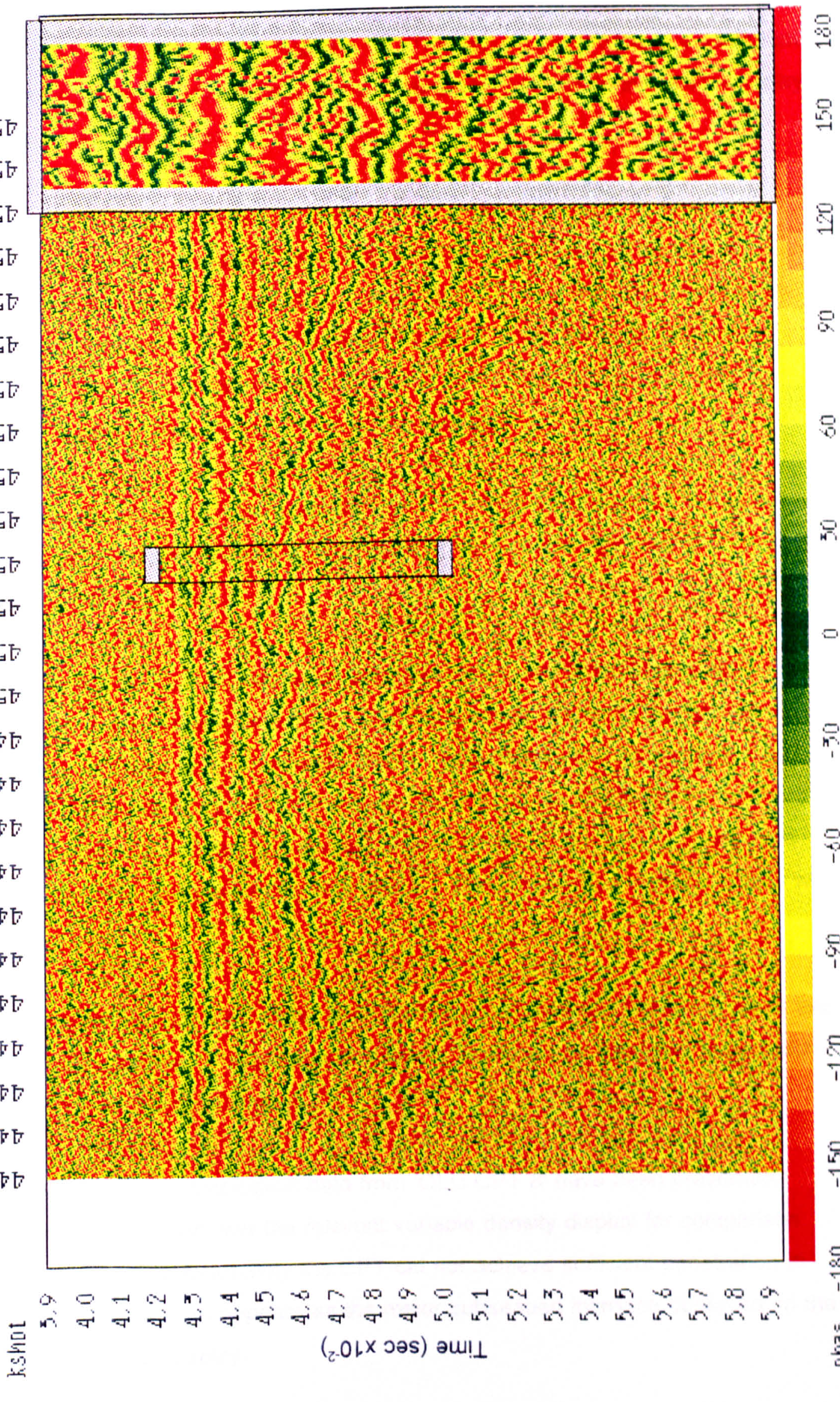


Figure 8.15 Instantaneous phase plot (section A).

8.4.3.2 Calibration of seismic data with 'OLU CPT 8'

OLU CPT 8 is presented in Figure 8.16. The test acquired data to a maximum depth of 3.26m. Estimated soil types of dense to medium dense sand and clayey sand were encountered.

The upper unit (0m - 1.28m) is described as a dense to medium dense sand. Cone resistance increases from 0MPa to 1MPa at the base of the unit but reaches up to 2.5MPa at a depth of 1.02m. Skin friction through the sand remains low throughout at a value of approximately 0.01MPa. Pore pressure increases steadily with depth to approximately 0.5 bar at the base of the unit. Friction ratio remains steady through the unit at approximately 0.5.

Relative density is fairly constant through the unit at approximately 0.7%, but at the base of the unit reaches a peak value of 48% before returning to 0.7% at the base of the sand unit.

The sand rests on what has been interpreted as a very loose clayey sand with an increase in clay towards the base. Cone resistance changes little through the profile, remaining at approximately 1MPa. Skin friction is approximately zero (reflecting the sand content of the clay). Pore pressure continues the trend of steady increase and reaches a value of about 1 bar at the limit of penetration (reflecting the increase of clay with depth). The friction ratio remains steady with a value of one.

The maximum undrained shear strength that could be expected in this lower unit is 25KPa - 33KPa. The actual value would, however, be expected to be much lower due to the sand content.

As previously, the lithological data from 'OLU CPT 8' have been presented, appropriately scaled with the relevant variable density display for comparison (Figure 8.17). Unfortunately the CPT did not achieve sufficient penetration to acquire data at what appears as the major subseabed interface observed on the variable density display.

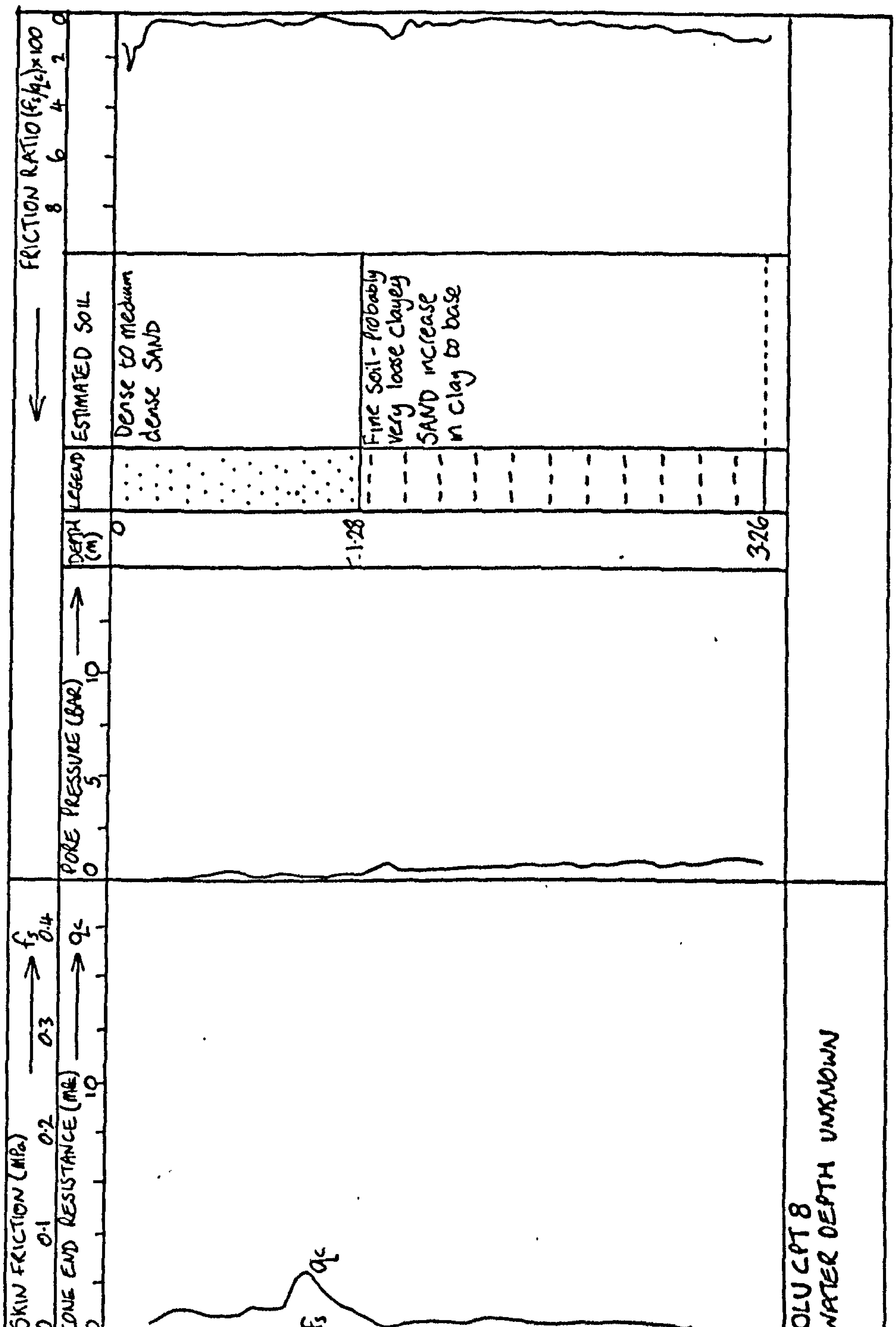


Figure 8.16 Data from 'OLU CPT8'.

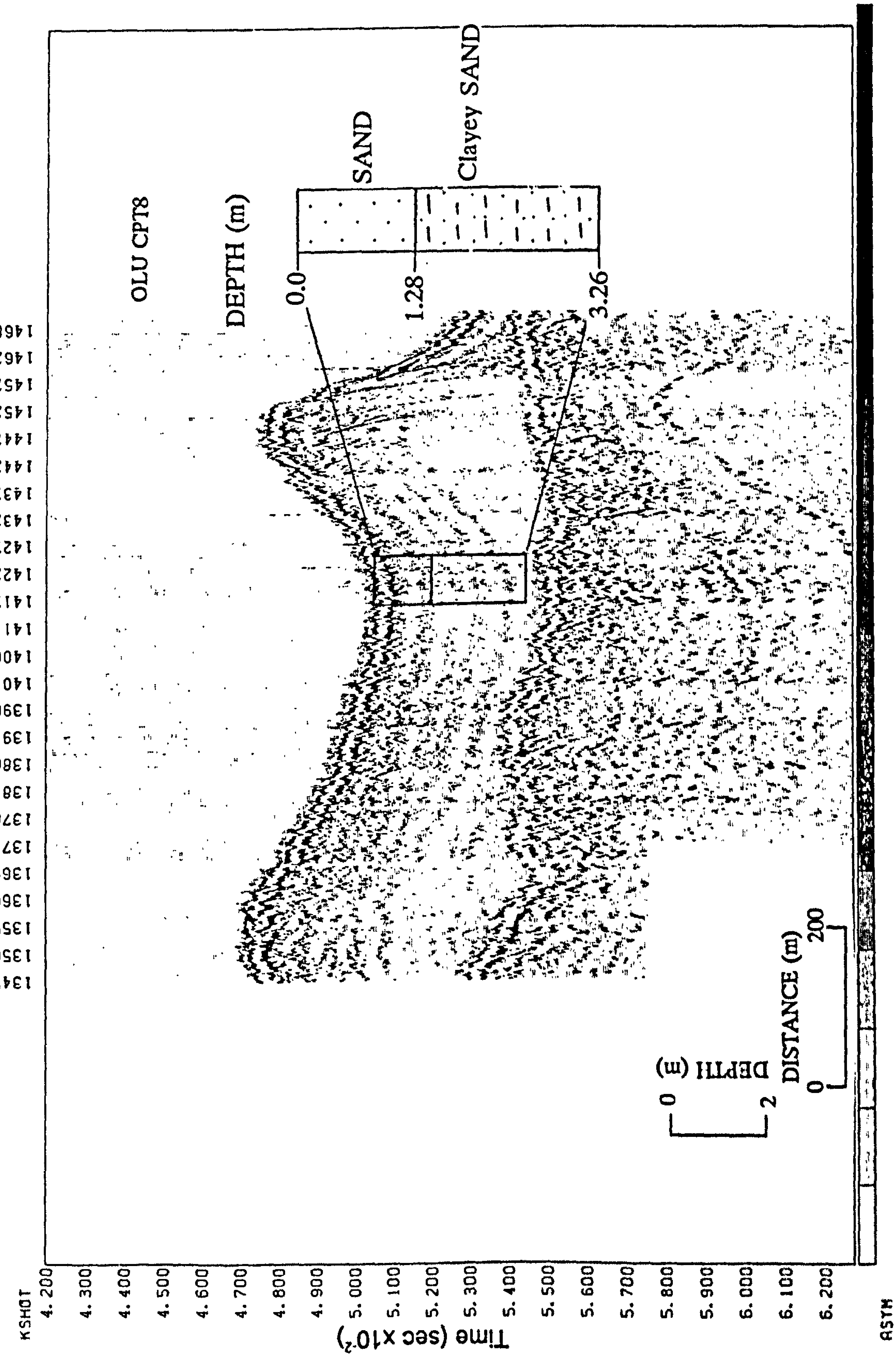


Figure 8.17 Processed digital data (section B) and OLU CPT8.

a) Amplitude

The data from Figure 8.17 have also been presented as an instantaneous amplitude plot (Figure 8.18).

Although a lithology change at 1.28m is inferred from the CPT data it is unlikely to result in an abrupt change in velocity or density. The change is more likely to be transitional and may result in a smearing effect on the seismic data. Consequently there appears to be no significant reflection at the boundary between the sand and clayey sand. There is, however, a marked reflector between the sand and clay as observed in 1992 CPT 3. In this case, as previously, the base of the sand appears to have a gravel lag producing a strong, high amplitude intermittent reflector which in this case appears more intermittent and of a lower amplitude than previously.

Where the high amplitude events are absent there is less of a change between the upper sand (with increasing clay content at its base) and the underlying sandy gravelly clay.

Shot number 14505 on what appears as the lee slope of a sand wave or ridge appears to be slumping within the sand unit. High amplitude reflections are observed which may be the result of either the edges produced by the slump causing diffractions or the slip surface itself.

The amplitude of the subsurface reflection does not seem to be greatly attenuated by the thickness of the sand above it. The amplitude of shot number 14223 at 54msec with approximately 3.5m of sand above it is the same as shot 14673 with 0.5m of sand above it.

As previously, there appears to be some channelling in the mudstone and discrete high amplitude events indicating possible gravel areas.

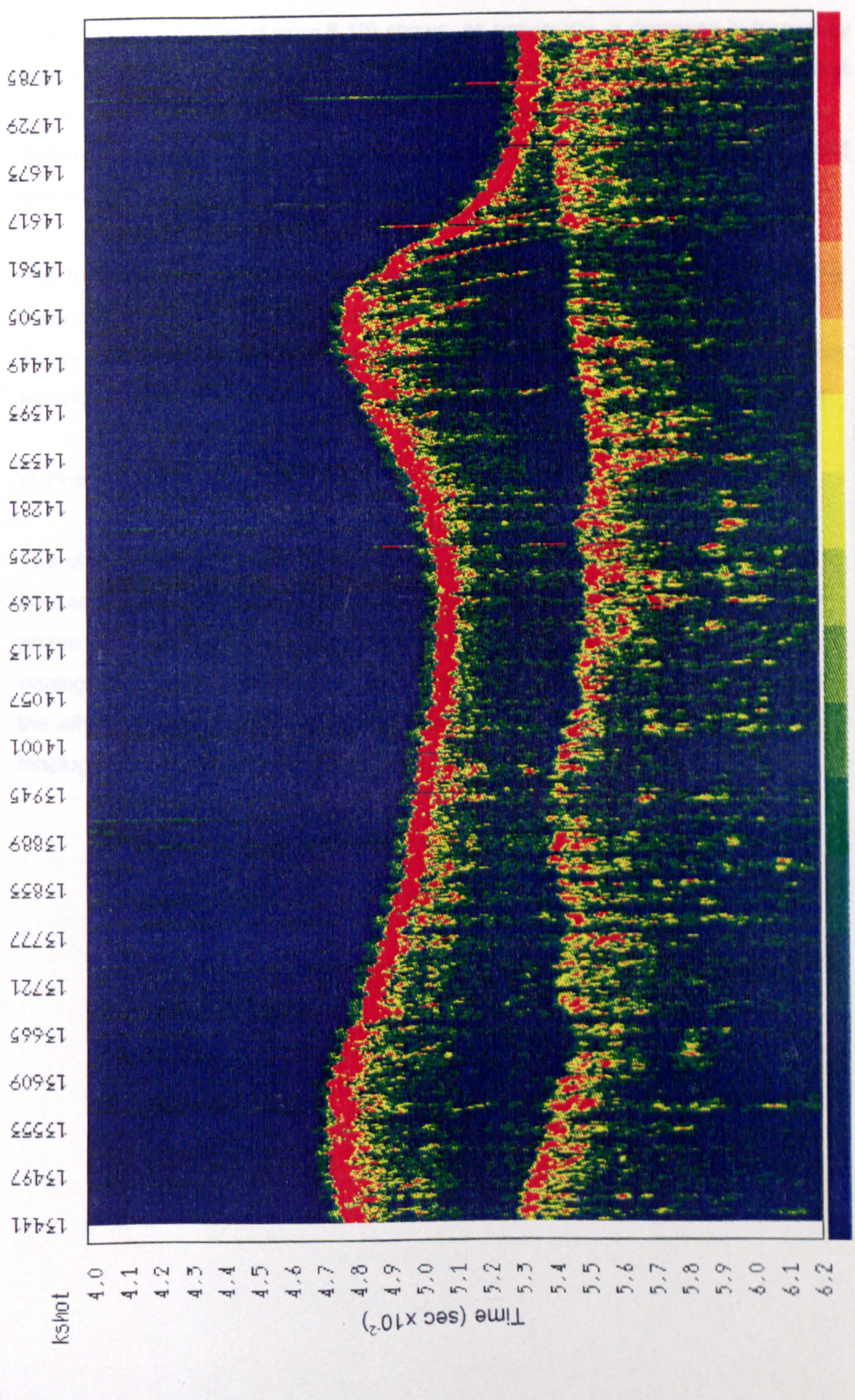


Figure 8.18 Instantaneous amplitude plot (section B).

b) Frequency

The frequency display (Figure 8.19) shows, as previously, a decrease in frequency with depth. Highest frequencies (4.2kHz) exist in the water column and at the first break of the seabed. The frequency content of the sand unit has a marked decrease in high frequencies which is more pronounced in the clay (frequencies of around 2.4kHz).

The transition between the main lithological units is fairly obvious with a frequency response at around 2.2kHz which is notably less where the thickness of sand above the boundary is thinner. The frequency plot shows an obvious change with acoustic facies between the predominantly sandy layer and underlying clay layer.

c) Phase

The phase diagram (Figure 8.20) appears, as before to have high internal backscatter. However, the main lithological boundary is fairly well defined. The phase plot does have the unfortunate effect of increasing the coherency of the ringing affect of the pulse as it is a non amplitude dependent attribute. This has the effect of obscuring any subtle changes that may have come about in a lithological variation within the sand unit.

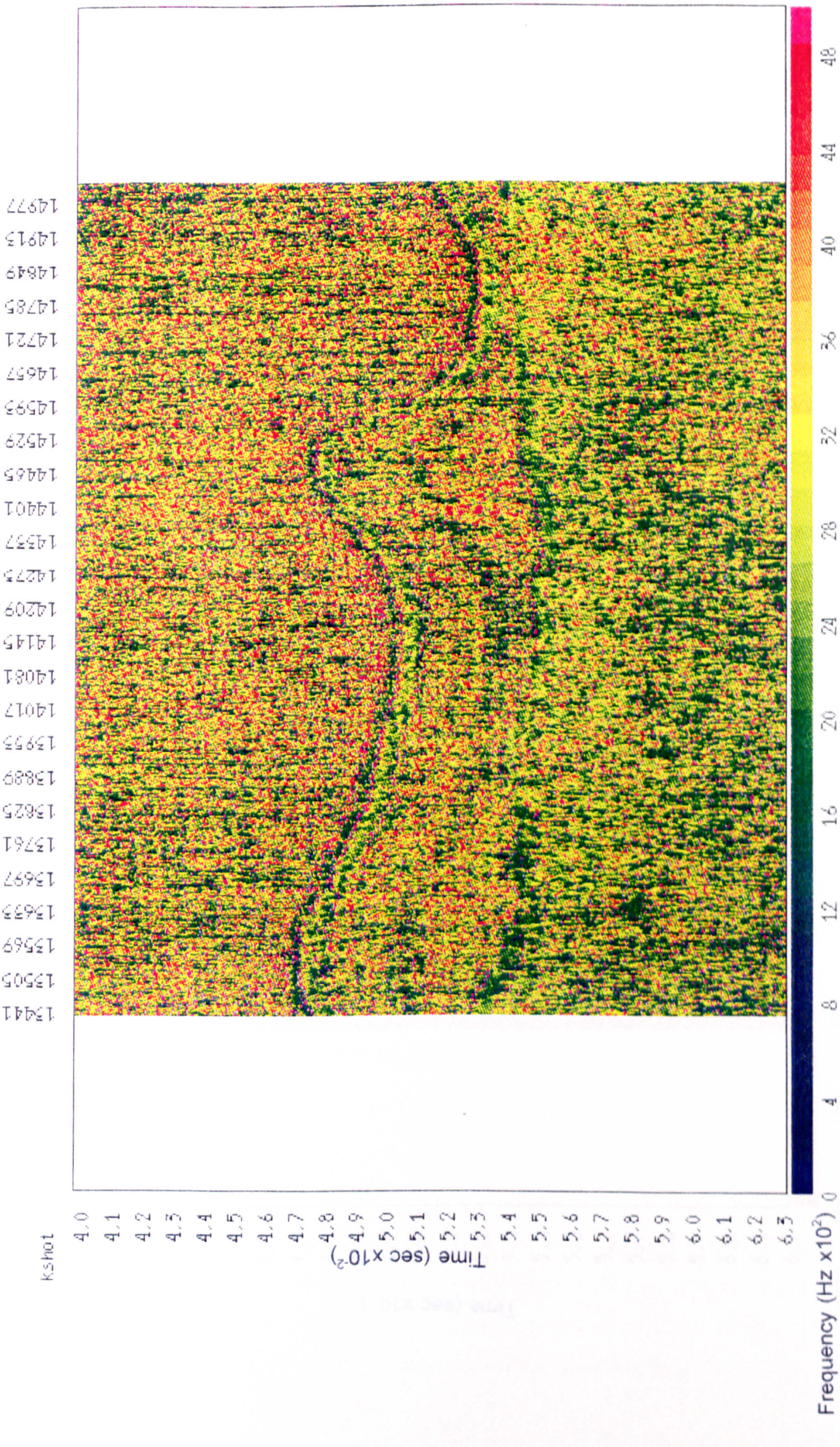


Figure 8.19 Instantaneous frequency plot (section B).

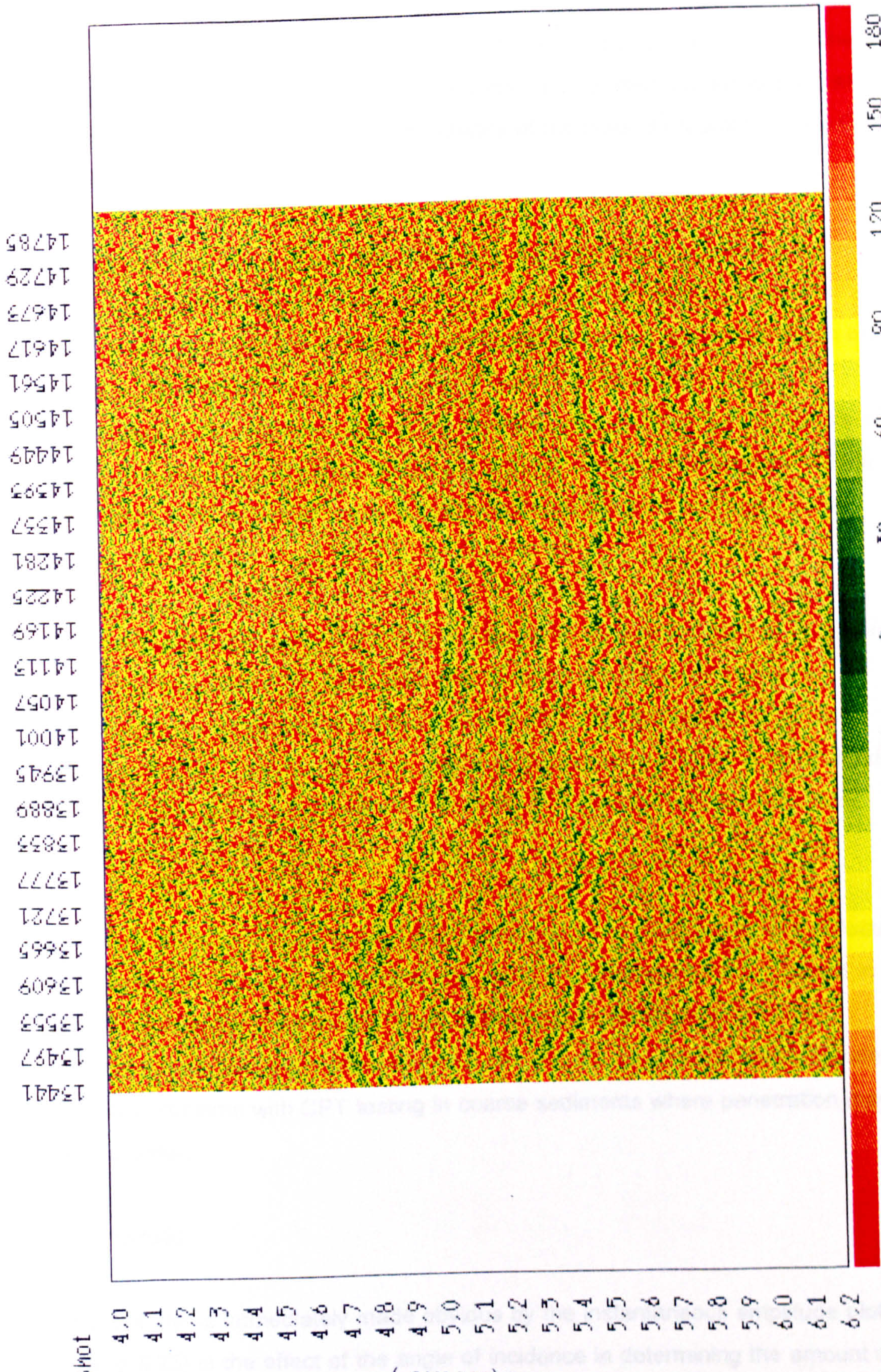


Figure 8.20 Instantaneous phase plot (section B).

8.4.3.3 Calibration of seismic data with '1992 CPT5 & 1992 VC3'

'CPT5 1992' is presented in Figure 8.21. The test acquired data to a maximum depth of 1.50m below seabed. Estimated soil types of medium dense sand and gravel were encountered. The characteristics of the units, as found from the CPT, will be discussed below.

The upper of the two units is described as a medium dense sand (0m - 1.45m). Cone resistance increases fairly regularly through the unit from 0MPa to 8MPa and appears normally consolidated. Skin friction increases with depth within the unit but only reaches a maximum value of 0.01MPa. Pore pressure is approximately zero bars throughout the unit (reflecting the well drained nature of sand). Relative density increases fairly constantly with depth from 30% to 75%. The friction ratio generally increases with depth but does not achieve a value greater than about 1.

The sand unit rests upon what has been described as gravel 0.05m thick (1.45m - 1.50m). The gravel is marked by a rapid increase in cone friction up to a maximum value in excess of 32MPa. Skin friction also increases rapidly and reaches a value of 0.08MPa. Pore pressure decreases markedly to approximately -3 bar and relative density increases to 115%. The friction ratio remains fairly steady at around 0.3.

The variable density plot (Figure 8.22) shows good comparison between reflectors and lithological boundaries identified with the CPT. Vibrocore data collected in the area have also been presented. Both sampling techniques show a good correlation both with each other and with the seismic data. It also demonstrates potential problems with CPT testing in coarse sediments where penetration may be prevented.

a) Amplitude

One fact that is immediately made obvious by the instantaneous amplitude plot (Figure 8.23) is the effect of the angle of incidence in determining the amount of energy that is reflected. The angle of incidence on the slope of the sand wave results in a low return of energy. There is therefore less energy available for

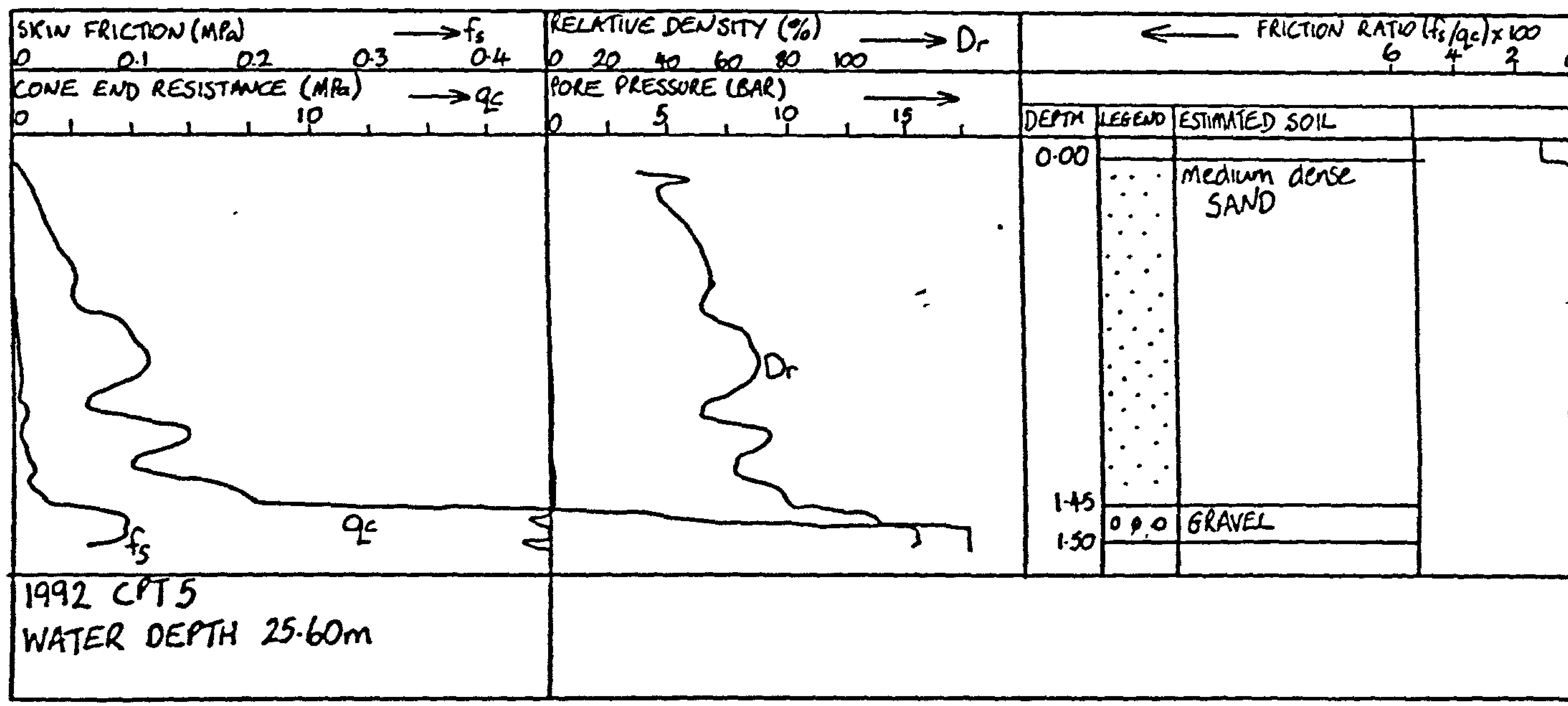


Figure 8.21 Data from '1992 CPT5'

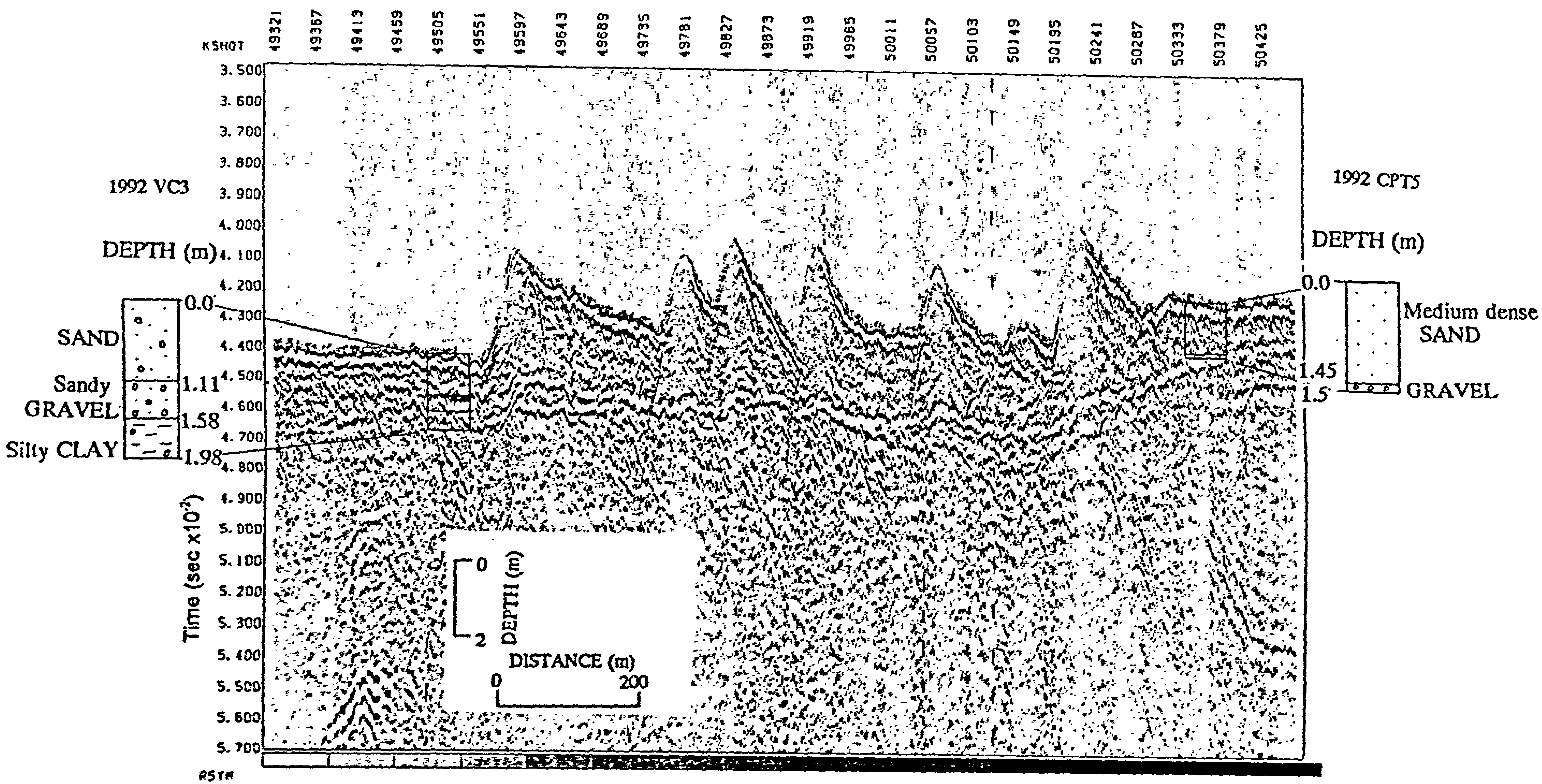


Figure 8.22 Processed digital data (section C) and 1992VC3 and 1992CPT5.

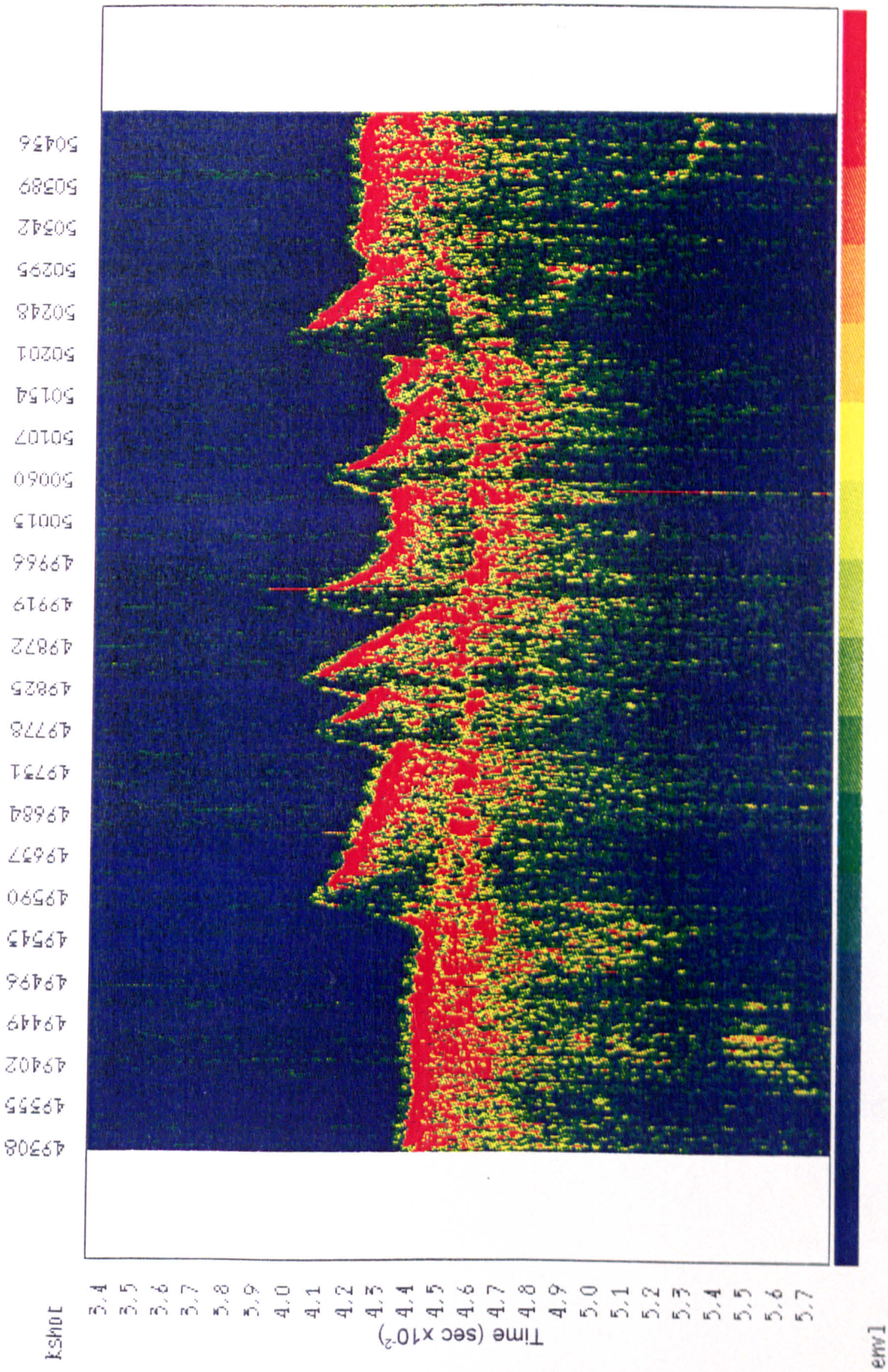


Figure 8.23 Instantaneous amplitude plot (section C).

subsurface penetration which is more obvious on the instantaneous amplitude plot than on the variable density plot. This manifests itself as areas of low amplitude at the next significant lithological boundary.

The instantaneous amplitude plot (Figure 8.23) reveals considerable information regarding lithological information. CPT 5 appears to show a fairly abrupt lithological transition between sand and gravel. This transition is illustrated on the instantaneous amplitude plot as a fairly discrete area of high amplitude at this boundary.

The data from VC3 (vibrocore data) indicates a lithological transition that is more gradual i.e. sand to a sandy gravel to a silty clay. The transition between these varying units is difficult to define on the amplitude plot as the seismic data are smeared.

b) Frequency

The frequency plot (Figure 8.24) appears fairly confused as a result of the high angles of incidence associated with the sand waves. Frequency values appear to be lowest (2.0kHz) in areas were the seabed is flattest and in areas where gravel beds pinch out.

c) Phase

The phase plot (Figure 8.25) shows coherency only where the seabed is flat or on the gentler slopes of the sandwaves. The main subsurface reflectors appear fairly coherent and the low return of energy from the maximum slopes of the sandwaves is further emphasised. There appears to be an almost total lack of reflected energy on these slopes as the phase plot, which is not amplitude dependant, does not show them.

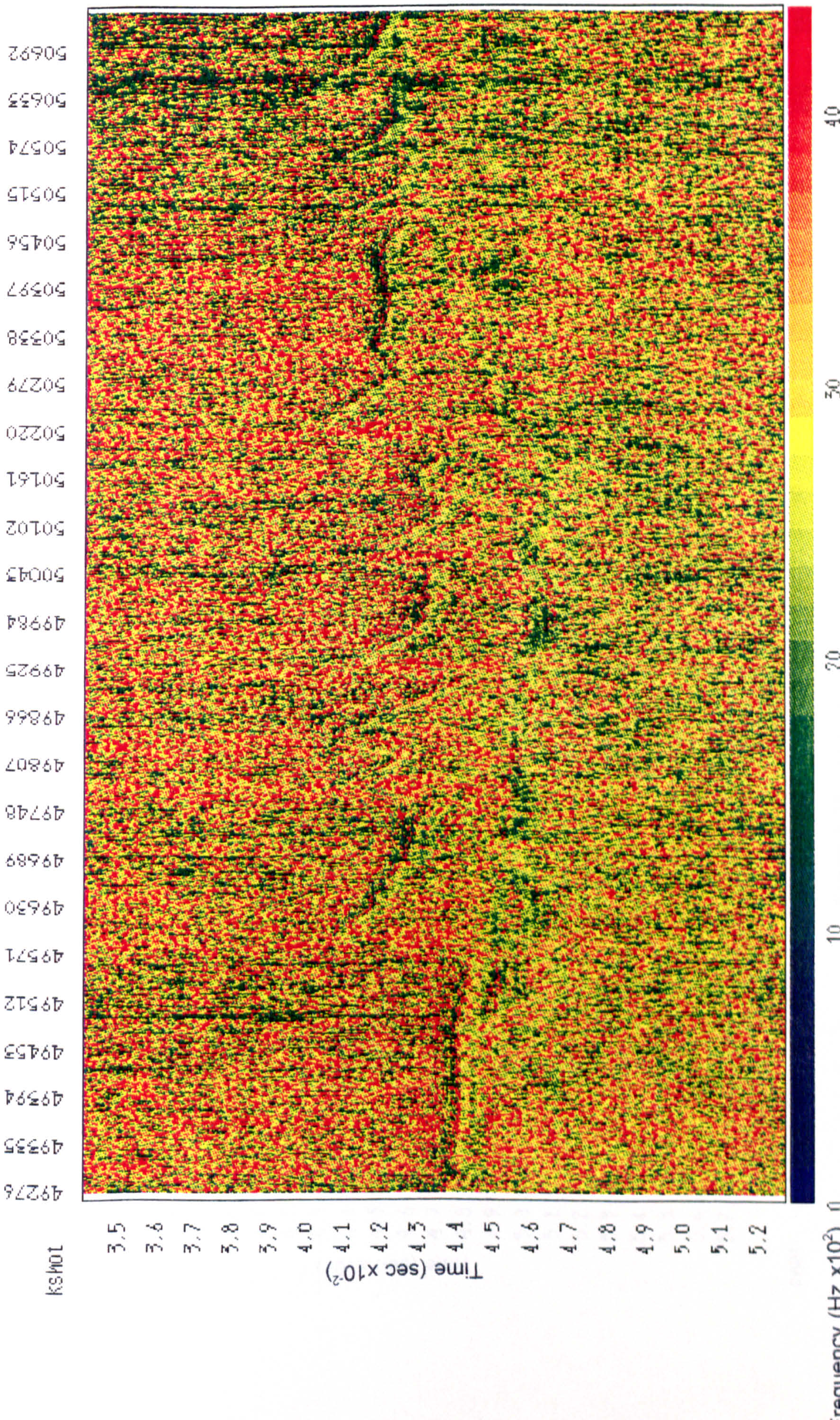


Figure 8.24 Instantaneous frequency plot (section C).

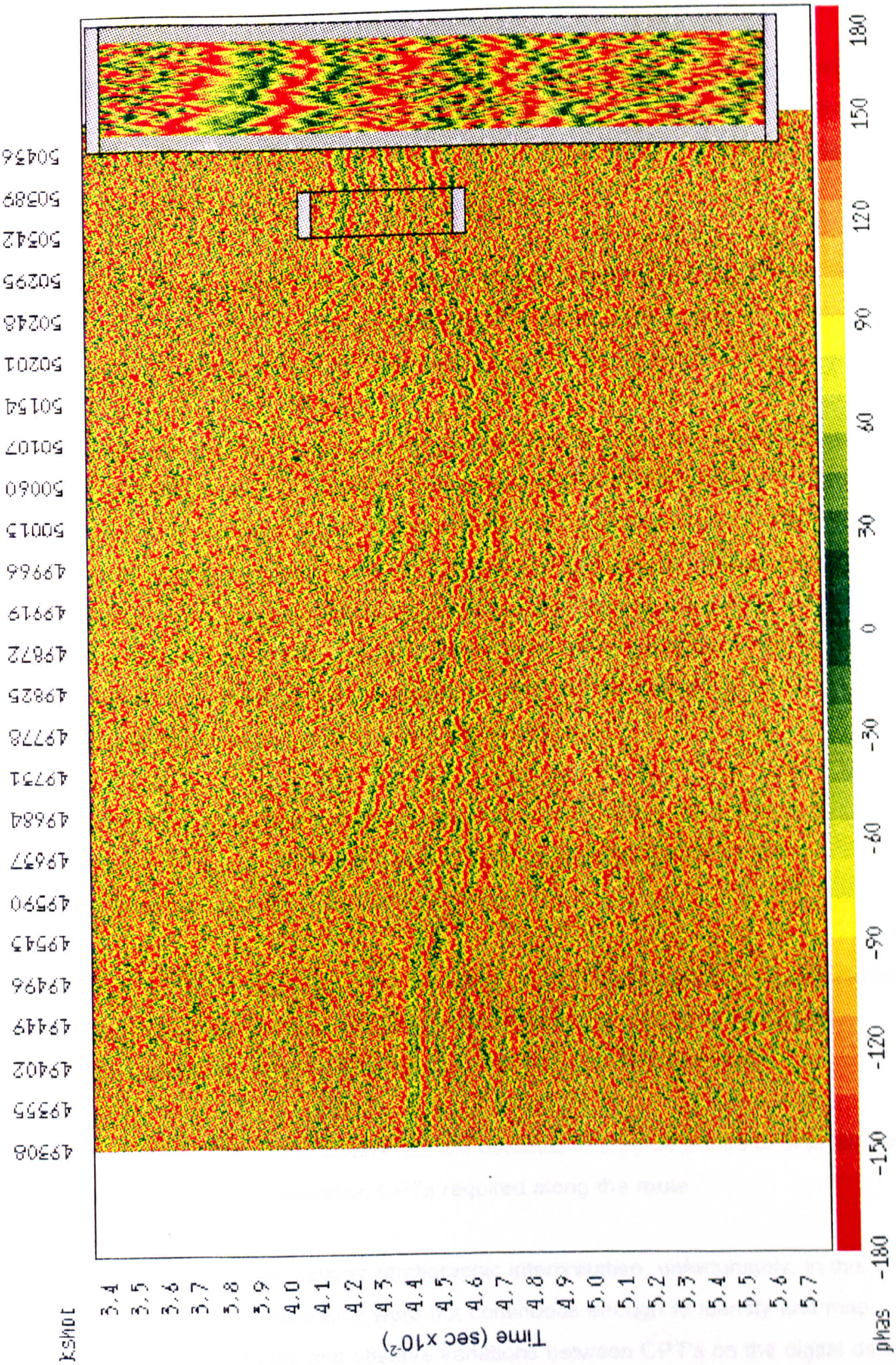


Figure 8.25 Instantaneous phase plot (section C).

8.5 Discussion and conclusions

The thickness of the sand and gravel unit (as proved by groundtruth data) resting on the glacial till (Figure 8.9) in the survey area varies from between less than 1m to 6m. There is a marked thickening in the north and middle of the survey area but over much of the area the thickness is less than 1m.

The overall thickness of the Quaternary deposits reported by Wright *et al.* (1971) of up to 20m (Figure 8.2) in the survey area were not found during this survey, the base of the glacial till was not observed due to limited penetration.

The palaeo-surface contour plot (Figure 8.10) shows the subsurface position of the top of the till relative to CD. This surface has been derived by plotting outcropping till and the subseabed interface between the sand and gravel unit and till. The till surface is fairly undulating ranging in elevation from between -24m to -34m CD. When compared with the thickness of the surficial sand cover and present bathymetry it can be seen that the ancient channelling and erosion has provided areas for accumulation of sand and gravel and that the present bathymetry is still influenced to a certain extent by this channelling.

Comparing geophysical and geotechnical data sets, in this study the good agreement between CPT's and seismic data to identify lithological and geotechnical boundaries has been proven.

Clearly, CPTs in geophysical surveys may be better than boreholes to groundtruth data as they quickly provide a description of lithology and the geotechnical parameters that will determine the acoustic response of the sediment.

The digital seismic data clearly has the potential to provide a means of predicting change with fewer calibration CPTs required along the route.

In relation to general seismic stratigraphic interpretation, unfortunately, in this study the surficial sediments were not continuous enough to identify and map lateral facies changes and observe variations between CPT's on the digital data.

It is difficult to find in this data set a common response and variation of the instantaneous attributes, as achieved for instance by Breitzke and Spieß (1992) (discussed in section 3.4.3.4). However some relationships were observed. In Figure 8.22 1992CPT5 indicates medium dense sand over gravel and 1992VC3 shows a predominantly sand unit over a sandy gravel. The gravel bed is marked by a discrete high instantaneous amplitude event in Figure 8.23 and the sandy gravel appears as a chaotic high amplitude event with no discrete boundary. The chaotic reflections become more coherent as there is a lateral variation in facies and the gravel pinches out. Although this affect can be observed to a certain extent on the analogue data it is clearer on the instantaneous amplitude plot.

As the methodology of extracting geotechnical information from seismic data progresses and is developed into a routine method conducted on line, the ability of CPTs to produce fast and efficient calibration and confidence checks on the interpretation has been shown to be well suited.

CHAPTER 9

Summary discussion

9.1 Introduction

This chapter aims to bring together and summarise previous findings and discussions included in the case studies, and to analyse them in the context of Quaternary seismic stratigraphy.

9.2 Methodology

The marine seismic survey methods used to investigate the intertidal zone for the purpose of this project i.e. to implement seismic stratigraphic analysis, were largely successful; in particular, the IKB Seistec proved an excellent system for very shallow water work and provided excellent data quality where conditions permitted.

At the Tees estuary, the parallel use of land survey methods to provide multichannel seismic data in the intertidal zone proved useful. It provided velocity information able to be input to the marine seismic interpretation, and provided data in a suitable format to display instantaneous attributes; it also has the potential to provide quantitative information (seismic attributes) suitable for making inferences on geotechnical properties. It did however prove to be a slow method of data collection. At the Tees site a useful correlation between the marine and land based data was achieved although it must be noted that there were differences between the two data sets; the resolution of the land based survey was 2m at best whereas the resolution of the marine survey was typically 0.25m. The investigated penetration depths varied between a maximum value of approximately 20m for the marine method and 40m for data acquired using the land method. The collection of land based data, and subsequent integration with marine data allows the interface zone between land and marine environments to be investigated and also aids continuation of the seismic interpretation landward.

At the other two coastal sites discussed, logistics prevented any land based seismic studies; the main problem was soft mud, this preventing a good coupling being obtained between the seismic source and the ground. However, based on the advantages afforded by the collection of land based data, i.e. instantaneous attribute displays and velocity information leading to a more confident interpretation of the marine data, the parallel collection of multi-channel data, where possible, is recommended.

When ever attempting the type of investigation discussed in this thesis, the research should, where ever possible, be conducted in an area that has or will have groundtruth data available. In particular the value has been highlighted of the quite sophisticated interpretation available by combining seismic data with CPT and vibrocore results.

The recording of digital data in underway marine seismic surveys has, traditionally, relied on using quite large and sensitive pieces of equipment. Although significant progress has been made in the design of acquisition instruments for use at sea, in this study problems were encountered, especially in the Humber estuary, operating this equipment in a small boat. Although digital acquisition equipment is becoming more compact, if space is at a premium the recording and post survey replay of digital audio tape (DAT) has been shown to be a practical alternative.

9.3 Seismic stratigraphy

The seismic stratigraphic method, although conceived for use at scales suitable to hydrocarbon exploration, i.e. 100s of metres, should still be applicable at any scale i.e. 10s of metres. Although sequence analysis has been successfully applied by others to what are essentially "preserved" features in Quaternary sediments in the Mediterranean (i.e. Chiocci, 1994), facies analysis of Quaternary sediments has been shown to be unreliable without access to adequate groundtruth data (Stoker *et al.*, 1992). The use of seismic stratigraphy as applied to modern sedimentary structures in the Quaternary, a period of time that is still ongoing and that has been subjected to complex sedimentation processes caused by rapidly varying sea level (resulting in laterally and vertically variable sediments), especially using the additional tool afforded by digital methods, in very shallow waters around the UK, remains largely untested.

Seismic stratigraphic analysis has been demonstrated to be of some significant use in the various environments to which it has been applied in this research project. Much of the information that can be gathered about the geological history (of whatever age) of an area can be gained from sequence analysis and stratal architecture. However, for this to be most effective it requires reflectors to terminate so that units can be placed within the context of an overall depositional environment. Such termination patterns were not apparent in the majority of areas studied in this research project. This could be due to terminations either lying outside the survey area or being truncated (eroded) by modern channelling.

In the case studies discussed it is relatively straight forward to suggest sequence boundaries but more difficult to identify and differentiate the units within the sequence into systems tracts. A possible explanation for this may be found in the fact that many of the case study sites would effectively represent difficult environments for sediments to behave in the manner that is assumed by Vail *et al.* (1977b) in traditional sequence analysis; that is in that the arrangement/location of sediment source is complicated by the presence of adjacent deep water channels (some of which are estuarine with their potential for increased sedimentation) and that some sediments can be attributed to a glacial origin. Sedimentation in all the investigated areas, apart perhaps for Liverpool Bay, is also currently being controlled primarily by alternating tides and periods of slack water. These factors make the use of sequence analysis less confident (Thorne, 1992).

Seismic facies analysis has been proven in this case study to be a particularly useful tool in seismic interpretation. It has provided strong evidence, mostly through an examination of reflector strengths, to help identify and delineate the various lithological units and has allowed comment on their specific composition and variability as well as helping identify possible geotechnical boundaries. The majority of reflecting boundaries interpreted from the seismic data on the basis of facies/sequence analysis have been correlated to borehole logs and proven to be lithologically significant.

However, some lithological boundaries, such as those sampled by boreholes in the Humber estuary, show that some lithological transitions e.g. the transition between silty sand and sand, are not readily recognised from the seismic data, if seen at all. Also in the Humber estuary, there was a further problem in placing the position of the till unit: a discrepancy of approximately 1.5m was observed which is significant in terms of the seismic resolution capability. A possible explanation for this discrepancy could be in the physical properties of the till. The layer of soil and head (weathered till) most likely extends deeper than indicated by the borehole (of which boundaries may have been visually delineated). The reflection seen on the seismic data may represent the true transition to unweathered till (as far as the physical properties that determine the acoustic response are concerned). Unfortunately, this cannot be physically proven as the required (as estimated by the seismic method) depth was not sampled by the borehole.

In the Menai Strait case study, it appeared impossible to differentiate between sandy clay and sandy silt on the basis of the seismic data (the proposed lithologies, based on borehole and facies analysis, straddling the sequence boundary).

As mentioned previously, the use of Instantaneous attributes was originally developed as a tool for hydrocarbon indication. The principle application for the attributes of amplitude, frequency and phase are for lithological variation along bedding (Taner *et al.*, 1979) and as such are potentially useful in the complex Quaternary sediments for sequence and facies analysis.

Instantaneous amplitude provides an indication of the magnitude of change in acoustic impedance (velocity and density) at the reflecting interface; high reflection strength is often associated with major lithological changes between adjacent sediment layers. It is also useful in distinguishing reflections from massive interfaces (which remain constant laterally) and reflections arising from the interference of several separate reflections (which vary laterally). Instantaneous phase displays emphasise the continuity of events and are therefore helpful in delineating bedding and identifying certain physical properties (such as helping to identify gas). Instantaneous frequency is sensitive to interference patterns between closely spaced reflections. It is sensitive to changes in bedding and useful in identifying where stratigraphic changes occur (Sheriff, 1980).

Instantaneous attributes as colour displays have proved useful in helping to delineate the true extent of reflectors and in the case of the Menai Strait study, to identify possible peat beds. The frequency and amplitude displays proved useful in identifying variability of lithology and physical properties of beds, and in identifying possible areas of shallow gas.

Clearly, when working in the nearshore environment with high resolution data, this research project has demonstrated that the use of seismic stratigraphy must remain flexible (to not do so has been identified as a major failing by Posamentier and James, 1993). For instance, in some investigations the occurrence of parallel bedding, a feature generally attributed to uniform rates of deposition on a uniformly subsiding shelf (section 3.4.1), may in fact be derived *in-situ* and be of organic origin. Apparent onlap demonstrated by some units may therefore not be directly attributable to changes in sea level but to deposition of sediments into lakes and rivers and by *in-situ* production by peat formation.

9.4 Calibration of seismic data

Comparing geophysical and geotechnical data sets, the research has shown good agreement between CPTs and seismic data making it possible to identify lithological and geotechnical boundaries using an integrated approach (seismic and CPT) to site investigation.

Clearly, CPTs may in some cases be better than boreholes for groundtruthing geophysical survey data as they quickly provide a description of lithology and geotechnical parameters; further, it can be shown that the same lithological variants/geotechnical properties will determine the acoustic response of the sediment. On this basis digital seismic data clearly have the potential to provide a means of predicting broad changes in the properties of sediment possibly using only a few calibration CPTs along a given route survey.

As the methodology of extracting geotechnical information from seismic data progresses and is perhaps developed into a routine approach conducted on line, the ability of CPTs to produce fast and efficient calibration and confidence checks on the interpretation should be increasingly recognised.

CHAPTER 10
Conclusions

10.1 Introduction

This project has tested the method of seismic stratigraphy as an approach for the identification of the environment of deposition and estimation of lithology of Quaternary sediments in selected areas around the UK. It has demonstrated that the collection of digital data and use of instantaneous attributes as part of seismic facies analysis is applicable to the intertidal zone.

The application of sequence stratigraphy has however been limited in these particular studies of Quaternary sediments as identified sequences appear limited in their extent and thus present only relatively small "snapshots in time". Although it is possible to make some limited comment on local sea level change using the data collected during this research global sea level changes cannot be predicted. Sequences have mostly been identified by discontinuities; it was invariably not possible to view the whole shape of the sequence or identify systems tracts, and hence not possible to use this information to help determine environmental settings and assist in facies determination, particularly of a sediment column that is still undergoing change.

Although seismic stratigraphic analysis of high resolution seismic profiles for the Quaternary has previously been conducted with some success in the Mediterranean (i.e. Chiocci, 1994), the extent of the success is difficult to assess in comparison with the current study as the Mediterranean work relied entirely on analogue data and concentrated on sequence analysis with limited attention placed on seismic facies analysis. The environmental conditions in the Mediterranean clearly differed from those in the UK throughout the Quaternary: Chiocci's Mediterranean study site and the sediments themselves were never subjected to glacial activity and therefore can be assumed "less chaotic". Also, where the approach was used, it was applied to sequences now occurring in water depths greater than 30m. The majority of the sediments examined in these deep water conditions could be considered "preserved" as they are no longer active in the sense that they are no longer influenced by intertidal processes. In contrast, the sediments examined in the current research are either essentially "modern" or are of a glacial origin.

This project has demonstrated that:

1) With the correct equipment high resolution boomer records can be routinely acquired in the intertidal zone.

2) Digital data can be acquired (if only recorded as raw data for subsequent replay to an acquisition system) using the smallest of survey vessels capable of deploying seismic equipment.

3) Single channel high resolution digital seismic data have great potential for providing a means of mapping out sediment physical and geotechnical properties. The interpretation can be significantly improved by determining real sediment velocity from land survey work when operating in the intertidal zone.

4) The theory of seismic stratigraphy is applicable to Quaternary sediment investigations in as much as some of the principles can be seen to be successfully applied to typical Quaternary deposits of the UK coastal margin.

5) The integration of digital seismic and CPT data has the potential to provide a powerful method for rapid mapping of geotechnical properties of sea floor sediments. The parameters that are used to predict lithological boundaries on CPT data appear to correlate with boundaries recognised (significant reflectors) on seismic data.

Seismic facies analysis would be greatly enhanced by the routine extraction of geotechnical parameters from seismo-acoustic data which, with technological advances, has or is becoming practically feasible (Haynes *et al.*, 1993b).

10.2 Suggestions for further work

It would be interesting to collect a grid of CPT data in an area of thick (at leat 5m) Quaternary sediments in zones known to display subtle changes in lithological and geotechnical properties of the soil in order to finely correlate CPT parameters with instantaneous attributes; similar studies have been conducted in the laboratory at higher frequencies by Breitke and Spieß (1992).

It would also be extremely valuable to collect deep cores at the case study sites to conduct an in-depth physical investigation of lithology and geotechnical parameters, and then to relate these to the seismic data. Although a lot of core logs were made available to the author they were mostly limited to descriptions of lithology and hence restricted the extent of the validation exercise.

The study sites were typically restricted to a relatively small survey area. It would be useful to extent the survey limits in an attempt to provide data at a more regional scale and to then see if the application of seismic stratigraphy is improved.

CHAPTER 11

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