

**Architecture & Stratigraphy of Neogene & Quaternary
sediments
off the Island of Terschelling, the Netherlands**

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Abbreviations

km	kilometres
m	metres
ms	milliseconds
Ma	million years before present
TWT	two-way time

<i>BGS</i>	<i>British Geological Survey</i>
<i>HGS</i>	<i>Halliburton Geophysical Services Ltd.</i>
<i>NOPEC</i>	<i>Norwegian Petroleum Consultants</i>
<i>RGD</i>	<i>Rijks Geologische Dienst</i>
<i>SIPM</i>	<i>Shell Internationale Petroleum Maatschappij</i>
<i>SEPL</i>	<i>Shell (U.K.) Exploration & Production Ltd.</i>
<i>SNSP</i>	<i>Southern North Sea Project</i>

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Abstract

The Neogene to Quaternary sedimentary succession of the southern North Sea Basin, which is generally considered to consist of deltaic sediments, has been studied in an 80 by 170km area off the north-west coast of the Netherlands. The total thickness of the succession here varies from 450 to 1,200m, and is thickest at the southern end of the North Sea Central Graben.

The sediments were studied using about 2500km of regional seismic data, 58 commercial well logs and 7 high resolution, site investigation, reflection seismic data-sets, the latter covering areas no larger than 6km². From this database a preliminary litho-stratigraphic scheme for the study area has been constructed. This has been fully integrated with existing, offshore stratigraphic schemes. The limited bio-stratigraphic data available has been used to give age estimates of the units which make up the succession. Only sediments deposited between the Netherlands' Praetiglian and the Waalian stages (late Pliocene to early Pleistocene, 2.5 to 1.4Ma) can be assigned ages with any confidence.

The base of the Neogene to Recent succession is marked by an unconformity generated by a minor phase of late Oligocene to early Miocene inversion. The oldest part of the succession is made up of 80m of clay, deposited along the southern end of the North Sea Central Graben axis during the ?early to middle Miocene. Following this, there was a major depositional hiatus lasting from ?middle Miocene to ?Brunsumman (middle Pliocene) times. This hiatus, which is marine, is an important marker horizon in both well and seismic data. Sedimentation resumed in the ?early Reuverian (middle Pliocene) in the north-east of the study area, and gradually expanded westward across the hiatal surface to cover the entire study area by the middle of the Tiglian (late Pliocene, ~1.9Ma). Outer shelf, clay deposition dominated at first, shallowing to middle/inner shelf, coastal and fluvial sedimentation from the beginning of the Praetiglian onward. After a large transgression in the middle Tiglian, a major regression occurred in the late Tiglian (latest Pliocene, ~1.8Ma), possibly displacing the sea to the far north-west of the study area. Estuarine and fluvial environments probably dominated the study area from then until the ?mid "Cromerian" (~0.5Ma). A combination of glacial and marine conditions dominated deposition from ?Elsterian times (0.3-0.4Ma) to the present, resulting in large scale erosion and in very complex depositional architecture for sediments of this age.

Although coarsening upward and regressive overall, the proportions of sand and clay fluctuate on a scale of ~0.1Ma during the late Pliocene (~2.7 to ~1.8Ma). This is likely to represent changes in relative sea level, sediment supply to the basin and energy of the basin, and may be related to global climatic fluctuations. One, over 60m fall in relative sea-level has been identified, which is of probably late Eburonian age (early Pleistocene, ~1.5Ma).

The architecture of the Pliocene part of the succession is clinoform, or delta-like, in pattern. Fore-set slopes vary from less than 1° to around 2.2° and face west to south-west. Top-set and toe-set surfaces are gently convergent westward with the Miocene-Pliocene hiatal surface. The architectural styles recognised within the clinoforms do not conform with all previously published observations of clinoform architecture.

Glacial channels of ?Elsterian age show alignment with Pliocene slope break positions. Their regional location seems to be related to the position of deeper structure within the sediment pile. Thermogenic and, possibly, biogenic gas may have had a significant influence upon both their depositional patterns and those of the older parts of the Neogene and Quaternary succession.

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CHAPTER 1:
INTRODUCTION

1: INTRODUCTION

1.1: Thesis Background

It has long been known that the Miocene to Recent succession of the Netherlands locally reaches over 1000m in thickness, including over 500m of "Quaternary" (*sensu* Zagwijn, 1992) sediment alone (Van Montfrans, 1975; Van Staaldunin *et al.*, 1979). However, more recent work in the North Sea area shows that up to 2000m of sediment accumulated there over the same period (Bjorslev Nielsen *et al.*, 1986), with "Quaternary" sediment possibly reaching half that thickness (Caston, 1977). These sediments, which are the most recent part of the thermal phase of basin subsidence in the North Sea area, seem to make up an unusually large thickness of the North Sea Basin sediment pile, even allowing for the effects of reduced compaction (Kooi *et al.*, 1989; Kooi & Cloetingh, 1989).

The *British Geological Survey (BGS)*, in association with its Dutch equivalent, the *Rijks Geologische Dienst (RGD)*, undertook to survey and map the "Quaternary", upper part of this succession in the late 1970's, much of this work having now been published in 1:250,000 scale maps (Balson & Cameron, 1985; Laban & Cameron, 1984). However, many of the basic questions about both the correlation of offshore and onshore successions remained unanswered by this body of work. In addition, nothing has been published on the stratigraphy of the older, pre-"Quaternary" parts of the succession and the whole succession is generally regarded as unprospective.

In 1989, using funding from the *Commission of European Communities (CEC)*, the *Southern North Sea Project (SNSP)* was set up in order to correlate the "Quaternary" part of this succession over the whole of the Southern North Sea area, coördinating Quaternary geologists from many different disciplines in countries that border the Southern North Sea; Belgium, Denmark, Germany, Great Britain, and the Netherlands (Fannin, 1989). Participants included sedimentologists, palaeontologists, palaeo-magnetists and seismic stratigraphers. Funding was also provided for the drilling of several, potentially 250m boreholes within the offshore sectors of the various countries (Thompson *et al.*, 1992) and for the acquisition and processing of high resolution seismic data linking these boreholes to facilitate correlation.

In the same year, funding was given by the *Natural Environment Research Council* and *Shell (U.K.) Exploration & Production Ltd. (SEPL)* for two postgraduate research projects, to be undertaken in association with the *SNSP*, these being awarded to Christine Kay and the present author respectively. These studentships

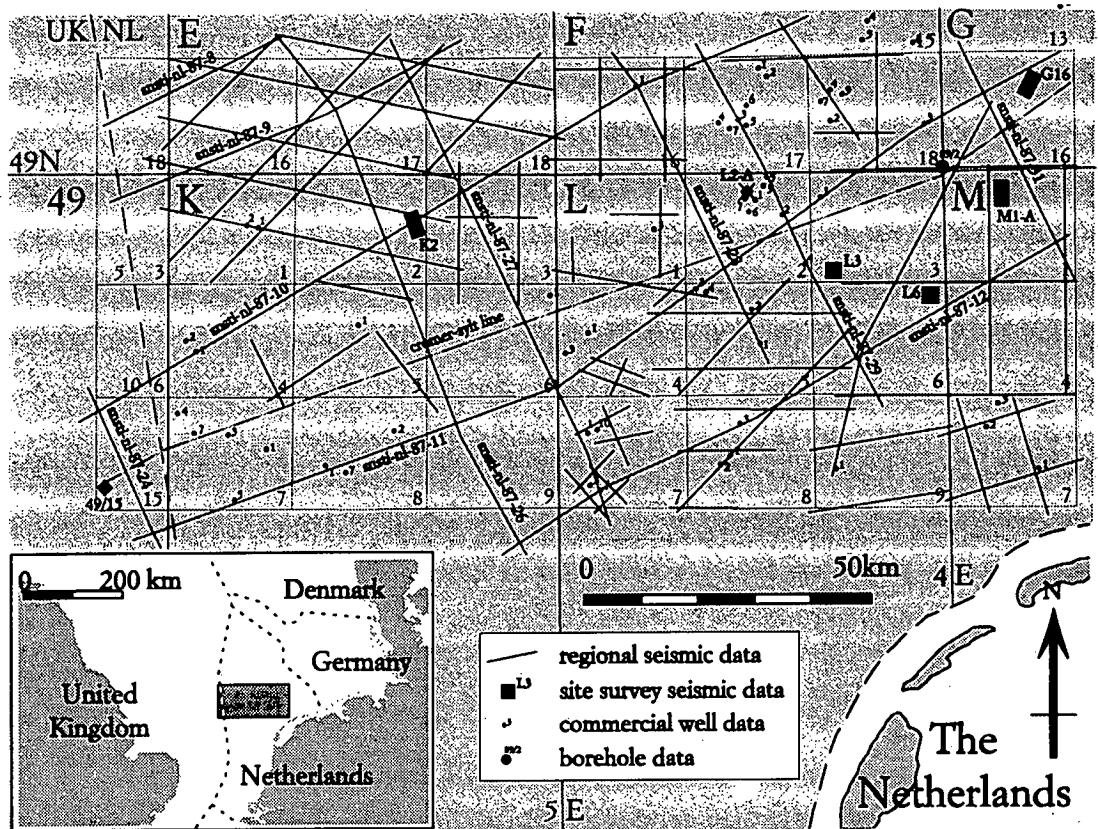


Fig. 1.1: The present study area, including the data-sets used in this study. NOPEC regional seismic lines and the "Cromer-Sylt" regional seismic line are indicated.

were originally intended for the study of high resolution seismic data covering only the upper, "Quaternary" part of the succession over the Southern North Sea area, the study thence to be incorporated into the *SNSP* correlation programme. This would allow a reconstruction of the basin-wide patterns of sediment deposition and of basin subsidence. The original scheme was subsequently extended to include all the late Miocene and Pliocene sediments above a prominent unconformity surface seen on both well and seismic data, which is commonly called the "mid-Miocene" or "mid-Tertiary" unconformity. All these late Miocene to Quaternary sediments, hereafter described as "late Cenozoic" in age, are together known as the "Upper North Sea Group" in the Southern North Sea area and the "Nordland Group" in the central and northern North Sea area (Deegan & Scull, 1977; *NAM & RGD*, 1980; Knox & Holloway, 1992). Christine Kay's project covered the whole of the Southern North Sea area at a low spatial resolution (Kay, 1993) whilst the present study focused upon a 170 by 80 km area off the NW coast of the Netherlands (see fig. 1.1).

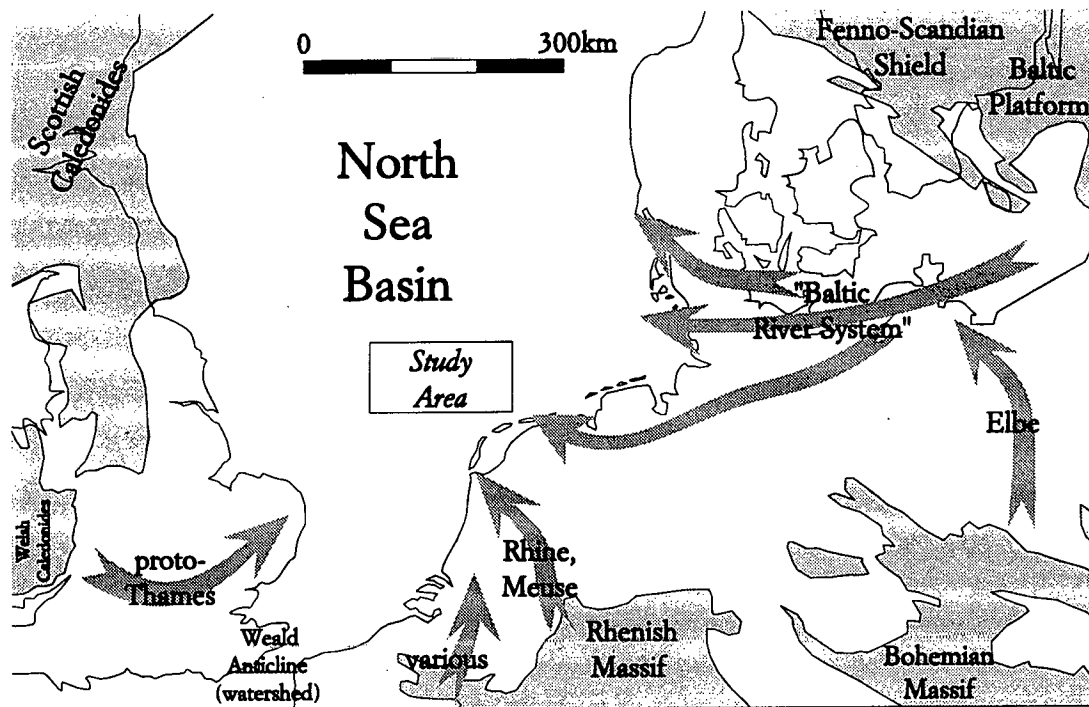


Fig 1.2: Map of the major source areas of sediment for the North Sea Basin during the late Cenozoic, including the major rivers supplying the basin at this time. Shaded areas indicate exposed basement rocks which were the source of sediment during the late Cenozoic (after Gibbard, 1988).

Before outlining the specific objectives of this study, the following review is presented in order to give a brief summary of the background and the current state of knowledge about the late Cenozoic sediments of the southern North Sea Basin. This review is largely based upon published work, but includes many of the preliminary findings of the *SNSP*, as outlined in the unpublished, European Commission report of Fannin *et al.* (1991).

1.2: Geological Setting

1.2.1: Geological Background of the Study Area

The study area is situated within the southern part of the North Sea Rift Basin. According to Glennie (1990), this area was originally uplifted during the early Devonian, Caledonian Orogeny, due to the closure of the Iapetus Ocean to the NW. However, the area then became part of a basin during the Devonian to Carboniferous closure of the Proto-Tethys Ocean to the south, which ultimately resulted in the late Carboniferous, Variscan Orogeny. The area underwent active rifting in the late Triassic and Jurassic, during an early stage of the opening of the North Atlantic Ocean to the west, thus generating the present North Sea Basin. After rifting of the basin ceased in the Cretaceous, thermal subsidence took over, allowing the accumulation locally of a further 3500m of sediment up until the present day.

The following overview is a summary of the pre-Miocene history of the study area. It is based upon the reviews of Ziegler & Louwerens (1979), Van Wijhe (1987a, b) and the work of Clark-Lowes *et al.* (1987).

Palaeozoic and Older Rocks

The basement within the study area is of Caledonian age and older (Ziegler & Louwerens, 1979). These basement rocks are at present exposed around the North Sea area in the Fenno-Scandian Shield to the NE, the Variscan Massif to the SE and the Caledonides to the west and NW (Ziegler & Louwerens, 1979). These basement areas make up much of the source material for the sediments that have filled the North Sea Basin (see fig. 1.2).

The Variscan Orogeny, to the south of the North Sea area, and the resulting W-E oriented foredeep which it generated, caused renewed sedimentation after the early Devonian closure of the Iapetus Ocean. The fore-deep fill includes Devonian clastic sediments and carbonates (Ziegler & Louwerens, 1979). These are overlain by the regressive, Carboniferous succession, resulting from the progressive uplift of the Variscan Massif, which ultimately generated paralic sedimentation in the Southern North Sea "Coal Measures" (see fig. 1.3a) and subsequent continental sedimentation in the "Barren Measures". The top of this succession is marked by an unconformity and represents the end of the Variscan Orogenic phase. The thickest part of this succession, including the "Barren Measures", trends east-west across the study area (Van Wijhe, 1987a). The "Coal Measures" are the major source of gas

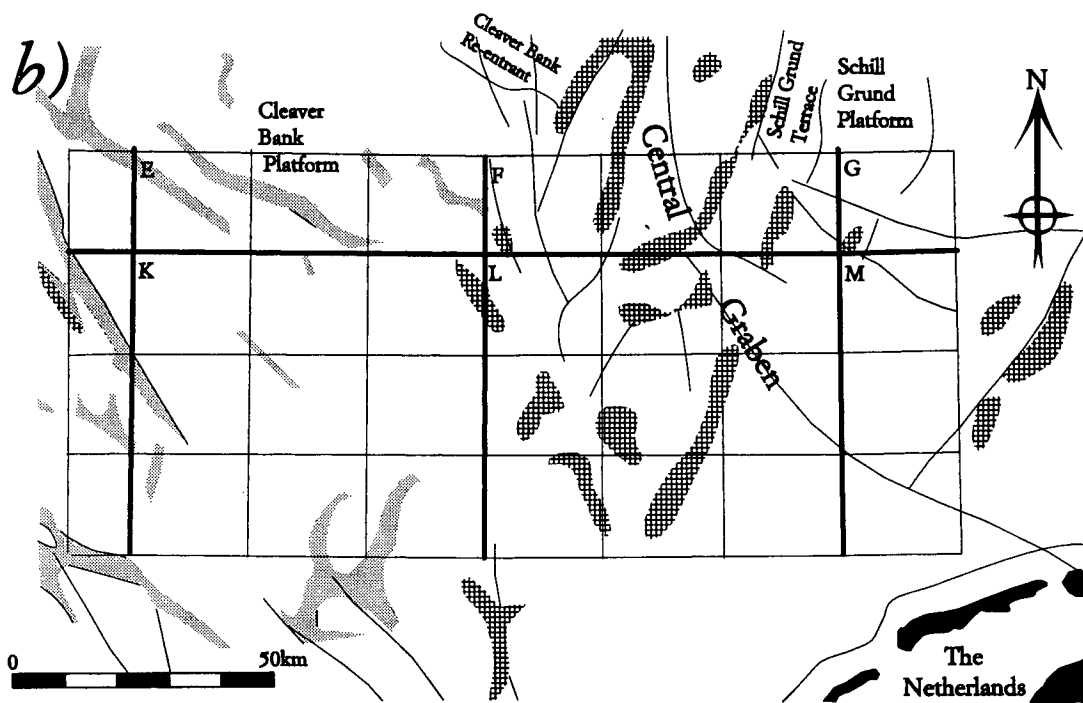
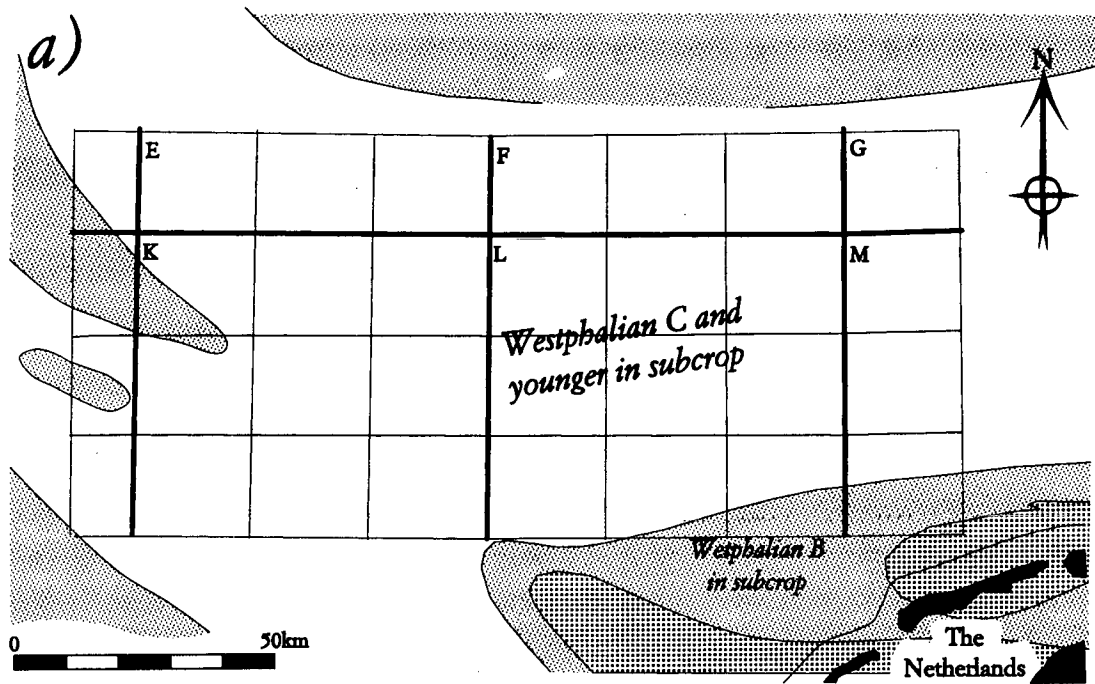


Fig. 1.3: Geological maps of the study area: a) showing the Carboniferous sediments lying immediately below the Variscan unconformity surface, b) showing major tectonic fault trends and salt diapirs apparently active at the end of the Cretaceous (after Clark-Lowes *et al.*, 1987; Van Wijhe, 1987a; 1987b; Oudmayer & De Jager, 1993).

in the southern North Sea Basin, being mature throughout the study area (Van Wijhe, 1987a).

Subsequently, renewed subsidence enabled gentle, Permian sedimentation to follow along the same, east-west oriented, depositional axis within the "Southern Permian Basin" (Clark-Lowes *et al.*, 1987). This phase was dominated by deposition of the Zechstein evaporites (Van Wijhe, 1987a) but, within the study area, also includes slightly older, aolian and fluvial deposits (Clark-Lowes *et al.*, 1987).

The Mesozoic

The beginning of the Triassic period heralded the start of rifting in the Central Graben (see fig. 1.3b) and rapid differential subsidence of the Broad Fourteens Basin (Van Wijhe, 1987b, Kooi *et al.*, 1989). Sedimentation began with isolation of the basin (Ziegler & Louwerens, 1979) and fluvial deposition resulted from influx of sediment during uplift of the London-Brabant Massif to the south (Clark-Lowes *et al.*, 1987). This gave way, with decreasing sediment supply and rising sea levels, to deposition of non-marine shale and evaporites (Clark-Lowes *et al.*, 1987) and, finally, to deposition of open marine clay (Van Wijhe, 1987a). Salt movement and diapirism of the Permian evaporites were also first triggered in the Triassic by the commencement of rifting (Ziegler & Louwerens, 1979; Clark-Lowes *et al.*, 1987).

Marine clay deposition, although in progressively shallower waters, continued into the Early Jurassic (Clark-Lowes *et al.*, 1987; Van Wijhe, 1987a). However, doming of the Central Graben to the north of the study area in both the Middle and Late Jurassic (the mid- and late Kimmerian) caused extensive erosion of these sediments, especially on the graben flanks (Clark-Lowes *et al.*, 1987). This doming was locally associated with the deposition of paralic and continental sediments, punctuating the continuing marine clay sedimentation. These are again only preserved within the graben (Clark-Lowes *et al.*, 1987; Van Wijhe, 1987a). The Broad Fourteens Basin continued to subside rapidly at this time, associated with the development of the Texel-IJsselmeer high to the west, this movement being due to trans-tensional forces associated with rifting (Van Wijhe, 1987b).

Although thick, paralic sediments were deposited throughout the Early Cretaceous in the Broad Fourteens Basin, (Van Wijhe, 1987b), deposition of marine clay continued in the Central Graben. This pattern changed in the Late Cretaceous, when a major rise in sea level, coupled with the end of rifting and the commencement of regional, thermal subsidence, caused clastic sediment starvation and the deposition of a thick chalk succession over the North Sea. This chalk succession can be over 1km

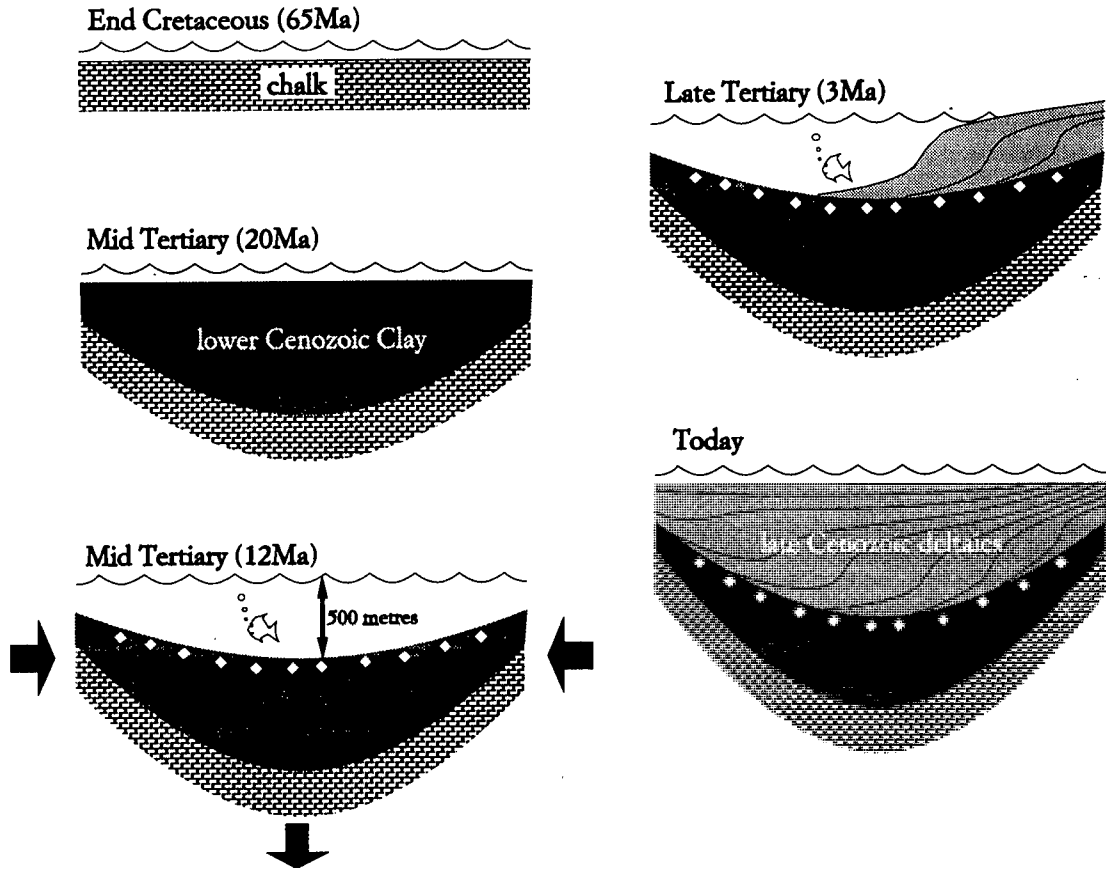


Fig. 1.4: Conventional model of the history of the southern North Sea Basin from the end of the Cretaceous to the present, including rapid subsidence at the end of the Miocene, due to compression (after Cameron *et al.*, 1987; Gramman & Kockel, 1988; Kooi *et al.*, 1989).

thick in the west of the study area, although absent it is from block F17 in the NE of the study area (Van Wijhe, 1987a).

Towards the end of the Early Cretaceous, Alpine movements caused local transpression and inversion of the North Sea sediments (Clark-Lowes *et al.*, 1987). Although initially minor, this inversion culminated in the Palaeogene with extensive uplift and erosion of areas which had previously been grabens, aided by the movement, or halokinesis of the lubricating Permian salt (the "Laramide Orogeny"). This inversion was generally weak in the Central Graben, although strongly affecting the Broad Fourteens Basin and other basins to the south.

The Palaeogene

With the continuation of thermal subsidence, clay deposition resumed at the end of the Palaeocene, punctuated only by minor inversion at the end of the Eocene (the "Pyrenian" Event) which hardly affected the Central Graben (Van Wijhe, 1987a). Clay deposition and subsidence was, for an unknown reason, rapid during the early

Eocene, compared with the Cretaceous, but decreased markedly during the Oligocene and Miocene (Kooi *et al.*, 1989). Regional faulting occurring within some parts of the study area at this time was probably largely due to halokinesis (Van Wijhe, 1987).

In general, the whole of the depositional record, since the commencement of North Sea rifting in the early Mesozoic, has been dominated by background clay deposition, interspersed with externally forced events, related either to global or regional forces, which have generated temporary changes in basin conditions.

1.2.2: Neogene to Recent Basin Development

Miocene and younger sediments reach a thickness of more than 1500m in the southern North Sea Basin, half the total Cenozoic sediment thickness (Gramman & Kockel, 1988). This represents a marked increase in subsidence rate compared with the Palaeogene part of the North Sea succession (Kooi *et al.*, 1989). Subsidence rates for the Quaternary alone are estimated to have been up to 0.5 millimetres per year (Caston, 1977). Cloetingh *et al.* (1990) attributed this subsidence rate increase to compression, possibly associated with plate reorganisation around the North Atlantic margins, as most basins around the North Atlantic show increased subsidence from the Pliocene onward. Older structural lines are still possibly present within the basin (Caston, 1977), and a new rifting phase in the North Sea Basin has even been suggested (Thorne & Watts, 1989).

Sediment supplied to the basin throughout Miocene to Recent times came from the Palaeozoic, Fenno-Scandian Shield and western Baltic Platform via the now extinct "Baltic River System" (Bijlsma, 1981), from the Variscan Massifs (the Rhennish and Bohemian Massifs) via the Rhine, Scheldt and Meuse (Zagwijn & Doppert, 1978), and from the Palaeozoic, British Caledonides, the major supply in the south being via the precursors of the Thames that ran through East Anglia (Whiteman & Rose, 1992; see fig 1.2).

Miocene

A phase of increased sediment supply to the southern North Sea started in the Early Miocene, probably resulting from renewed uplift and erosion of the Fenno-Scandian Shield and Variscan Massifs. This erosion generated active, although fine grained, alluvial fan and paralic sedimentation from the "Baltic River System" in Germany (the "Brown Coal Sands"; Bijlsma, 1981) and from the Rhine in the SE Netherlands (the "Lower Rhine Brown Coal"; Zagwijn & Hager, 1987).

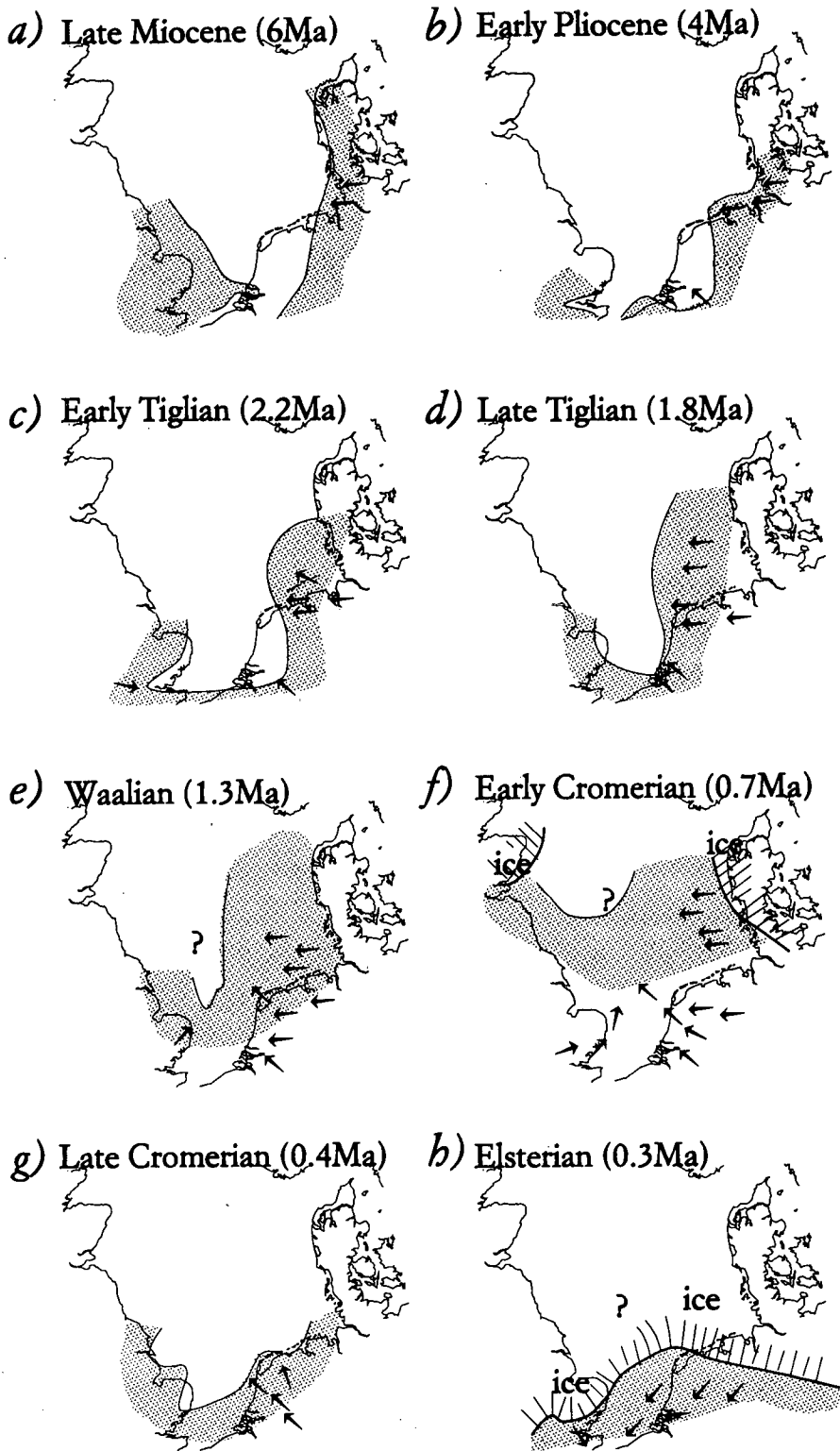


Fig. 1.5: (figures "a" to "h") Coastline changes in the southern North Sea from Miocene times to the present, showing the gradual displacement of the sea from the area of the southern North Sea Basin (after Zagwijn & Doppert, 1978; Zagwijn, 1979; Bijlsma, 1981; Cameron *et al.*, 1987; Long *et al.*, 1988).

A major transgression occurred at the end of the Middle Miocene ("Reinbekian" to "Langenfeldian"), which marks the base of the late Cenozoic succession (see fig. 1.4). This is represented by condensation of the late Middle Miocene succession in Germany, Denmark and the Netherlands (Gramman & Kockel, 1988; Zagwijn & Doppert, 1978; Zagwijn & Hager, 1987), by outlying remnants of the transgression preserved in Southern Flanders (Zagwijn & Doppert, 1978) and, probably, by Miocene shark's teeth in the basal gravel of younger formations in East Anglia (Balson, 1993a). This transgression is also suggested to be the cause of the 300 to 500m rise in sea level indicated by the height of Miocene clinofolds seen in seismic data from the North Sea (Gramman & Kockel 1988). There is no evidence for a southern linkage of the North Sea to the Atlantic at this time, the Lenham Beds of Kent being considered to be part of a separate basin (Balson, 1993b; see fig 1.5a).

A second phase of regression commenced in the Late Miocene and generated coarsening upward, prograding sedimentation on the eastern margin of the North Sea Basin (Gramman & Kockel, 1988). In the southern Netherlands, fine grained and paralic sedimentation continued for a while, but was soon replaced by coarse grained, fluvial sedimentation which prograded NW (Zagwijn & Hager, 1987). Ice rafting of sediments had possibly already commenced at this time (Ehlers *et al.*, 1984).

Brunsummanian to Reuverian

At the beginning of the Pliocene (Brunsummanian), NW Germany and Denmark underwent another transgression (Gramman & Kockel, 1988). Although not mentioned by authors in the Netherlands, sedimentation became fine grained there at this time (Zagwijn & Doppert, 1978). In Britain, this transgression is either represented by the "box-stones" of East Anglia or by the overlying Coralline Crag; tidal sediments which certainly record a rise in sea level and, by analogy with the Holocene, may also indicate a southern, marine connection of the North Sea to the Atlantic (Balson, 1989; 1993a).

Possible further uplift of the Baltic hinterlands later in the Brunsummanian caused the resumption of coarse, fluvial sedimentation in Germany and Denmark. This fluvial sediment prograded westward to reach the eastern part of the Netherlands (Gramman & Kockel 1988; Bijlsma, 1981; see fig. 1.5b). Coarse sedimentation in the eastern Netherlands had waned by the end of the overlying Reuverian stage, with only fine sand reaching the Netherlands at this time. However, sedimentation in the southern Netherlands changed little throughout the Brunsummanian and Reuverian (Zagwijn & Doppert, 1978).

Erosion of the deeply weathered, Baltic hinterlands towards the end of the Reuverian caused increased deposition of kaolinite in the North Sea Basin (Fannin *et al.*, 1991 *unpub.*), associated with the first definite evidence of unlithified sediment block transport by ice (Ehlers, 1983; Ehlers *et al.*, 1984).

Praetiglian to Waalian

Regional, annual temperatures started to both decrease and fluctuate more rapidly from the Praetiglian onward in both Germany (Ehlers, 1983) and Holland (Zagwijn, 1974; De Jong, 1988; see fig. 1.6). However, no associated increase in clastic sedimentation can be seen in the Praetiglian deposits at least, with only paralic and lacustrine sediments seen in NW Germany (Bijlsma, 1981), and tidal forces dominant on the rivers supplying the southern Netherlands (Kasse, 1990a; see fig. 1.5c). East Anglia was also subjected to strong tidal erosion and sedimentation at this time (Mathers & Zalasiewicz, 1988).

Coarse grained sedimentation in braided river environments commenced near the end of the Tiglian (TC4), both on the continent (Bijlsma, 1981; Gibbard 1988) and in Britain (Whiteman & Rose, 1992). This caused rapid progradation of coastlines westward across the Netherlands and into the present North Sea area (Zagwijn & Doppert, 1978; Bijlsma, 1981), and, possibly, slight shoreline advance eastward from East Anglia (Cameron *et al.*, 1987; see fig. 1.5d). These regressions may have been due to uplift of the hinterlands (Bijlsma, 1981). However, sea level dropped temporarily and the regional temperature decreased markedly at this time, with the earliest documented permafrost conditions in the southern Netherlands (Vandenburge & Kasse, 1989; Kasse, 1990a). It is therefore possible that fully glacial conditions inland caused major erosion of the hinterlands. This suggestion is supported by the increased presence of abundant, fresh feldspar in the late Tiglian gravel of the Baltic River System, suggesting the removal of most of the highland weathering profiles (Bijlsma, 1981). The course of the Lower Rhine river system was also forced northward into a line along the Netherlands Central Graben by this and by later sea level falls, to be replaced in the southern Netherlands by sediments predominantly from the Scheldt river system (Kasse 1986; 1990b).

A pattern of sedimentation, with cold conditions, including regression and permafrost, followed by warm conditions with transgression, continued from the end of the Tiglian until the end of the Waalian (Zagwijn & Doppert, 1978; Vandenburge & Kasse, 1989; Zagwijn, 1989), by which time, due to the continuing advance of shorelines and the confluence of the various rivers around the southern

part of the North Sea, the sea had retreated far to the north (Cameron *et al.*, 1987; Stoker & Bent, 1987; Fannin *et al.*, 1991 *unpub.*; see fig. 1.5e).

Menapian to Cromerian

Much colder conditions occurred during the Menapian (De Jong, 1988), causing erosion, continued development of braided river systems, both in the present onshore and offshore areas, and permafrost, which included cryo-hydrostatic up-doming (Vandenburge & Kasse, 1989). The Menapian stage also marked the decay of the "Baltic River System", at least from the area of the Netherlands (Bijlsma 1981), to be replaced by the rivers draining the Variscan Massifs to the south, including the Rhine and Scheldt (see fig. 1.5f). The limited Scandinavian sediments represented in the Menapian include the "Hattem Layers" of the northern Netherlands. These layers are made up of unweathered, Variscan boulders along with heavily weathered, Scandinavian boulders, which could only have been brought to the area by ice or ice rafting (Bijlsma, 1981; Zagwijn, 1985).

The disappearance of Baltic-derived sediment from the succession could indicate the presence of an ice sheet in the Baltic area, which destroyed the river course of the "Baltic River System" and eroded the Baltic depression (Bijlsma, 1981). However, no evidence of a Menapian ice sheet has been found (Ehlers *et al.*, 1984). A less dramatic possibility is that inland ice on the Fenno-Scandian Shield may have reached equilibrium with the underlying, unweathered rocks, causing a marked decrease in erosion rates, a situation which was not to occur in the Variscan Massifs until much later.

The precursors of the Thames were also carrying less sediment by the end of the Bavelian stage, although this is attributed to a decrease in the size of the catchment area, due possibly to glacial erosion of the upper reaches of the river system (Whiteman & Rose, 1992).

Temperature fluctuations became more extreme during the Cromerian, and ice sheets were almost definitely present in the Baltic area by Cromerian Glacial "C", when glacio-fluvial boulders of Scandinavian origin were deposited in the "Weerdinge Beds" of the northern Netherlands (Ehlers *et al.*, 1984; Zagwijn, 1986). A till deposit in Denmark may well also be of Cromerian age (Lundqvist, 1986), and could be part of the same glaciation.

Although northward advancing shorelines are estimated to have reached the latitude of southern Scotland by the Cromerian stage (Stoker & Bent, 1987), reduction of sediment input to the basin resulted in large scale marine transgression,

reaching as far south as the Netherlands, between the middle and the end of the Cromerian (West, 1980; Zagwijn, 1985; Gibbard *et al.*, 1991; see fig. 1.5g). The reduction in sediment supply could again have been caused by the equilibration of inland ice in the south with the underlying rocks of the Variscan Massifs, causing a marked decrease in erosion rates. Whatever the cause, the Cromerian transgression effectively marked the end of the phase of regression which had been continuing in the North Sea Basin since the Miocene.

Elsterian to Present

Further deterioration in climate in the Elsterian stage finally caused large ice sheets to form around the margins of the North Sea Basin, centred upon the Caledonides and Scandinavia. These ice sheets grew large enough to coalesce in the centre of the North Sea, much of which had been sub-aerially exposed due to glacial lowering of sea level. Ultimately, they extended as far south as 53°N, reaching the north coast of East Anglia and the Netherlands (Long *et al.*, 1988; see fig. 1.5h). This glaciation locally resulted in extensive erosion of much of the underlying succession, and in the deposition of glacio-fluvial and glacio-lacustrine sediments beyond the southern limit of the ice sheet. The subsequent history of the North Sea area has been of repeated transgression in warmer times, followed by regression and re-advance of ice sheets in colder times (Cameron *et al.* 1987, Long *et al.*, 1988).

River Supply to the Study Area

Although the study area is fairly centrally positioned with the southern North Sea Basin, one river system, the now extinct "Baltic River System", is thought to have dominated deposition to this area throughout the whole of the late Cenozoic from the Miocene up until the Middle Pleistocene (Menapian stage; Zagwijn, 1985). Even then, although sediments from this river system stopped appearing in the Netherlands then, there is some evidence to show the continued dominance of this river system further north until some time later (Fannin *et al.*, 1991 *unpub.*). However, in the south, the sediments of the Baltic River System were replaced by sediments supplied via the Rhine river, which at that time flowed northwest through the northern Netherlands.

Although the source of the Baltic River System was to the west of the study area, at least some of the river system's sediments were delivered to the study area from the southeast, via the northern part of the present day Netherlands (Zagwijn

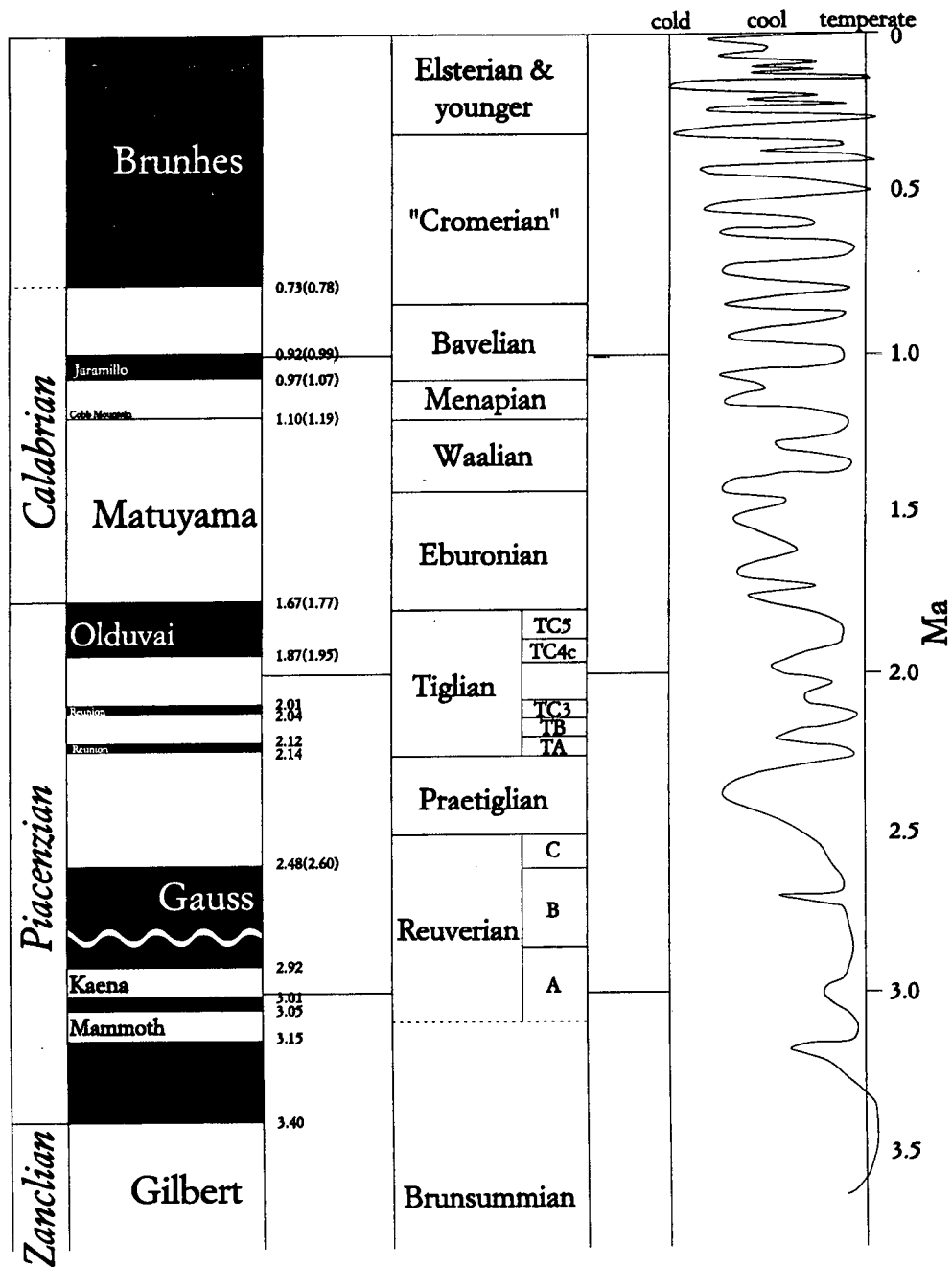


Fig. 1.6: Comparison of magneto-stratigraphy for the last 3.5Ma (after Shackleton *et al.*, 1990; Harland *et al.*, 1989) with the stratigraphy and pollen-based temperature curve from the Netherlands (Zagwijn, 1989; 1992).

& Doppert, 1978; Gibbard, 1988). Because of the potentially identical southeastern supply direction for both the Baltic and Rhine rivers to the study area, it may, therefore, be impossible, on purely seismic architectural grounds, to distinguish between the deposits of the two rivers. However, it is thought, on the basis of work done on the SNSP boreholes, that almost all of the sediment before Elsterian (glacial) times was derived from the catchment of the Baltic River System (Fannin *et al.*, 1991 *unpub.*).

1.2.3: Stratigraphy of the late Cenozoic Succession

The Concept of the "base Pleistocene"

The base of the Pleistocene in NW Europe has been traditionally marked as being the first significant indication of late Cenozoic, climatic deterioration. This occurs at the base of the Netherlands Praetiglian stage (NAM & RGD, 1980; Zagwijn & Doppert, 1978). It was assumed that this horizon would correlate with the first, significant deterioration in climate elsewhere. However, this assumption was found to be incorrect.

It is now known that the base Praetiglian, which is close above the Gauss-Matuyama palaeo-magnetic chron boundary, has an age of between 2.3 and 2.4 Ma (Gibbard *et al.*, 1991; Zagwijn, 1992; see fig 1.6). This boundary is therefore somewhat older than the internationally accepted level of the base Pleistocene, which is near the top of the Olduvai palaeo-magnetic sub-chron, within the Matuyama chron, with an age of between 1.6 and 1.8 Ma (Aguirre and Pasini, 1985).

It is highly likely that the internationally accepted, Pliocene-Pleistocene boundary lies on or near the Tiglian-Eburonian boundary of NW Europe (De Jong, 1988; Gibbard *et al.*, 1991). However, the exact position is still not known. It is therefore advisable to avoid using the terms "top Pliocene" and "base Pleistocene", and, instead, to use the local stage names "Reuverian", "Praetiglian", "Tiglian" and "Eburonian" for denoting sediments of this age range in the southern North Sea Basin.

Offshore Stratigraphy

The following description of the late Cenozoic stratigraphy of the Southern North Sea succession, hereafter referred to as the Nordland Group after the definition of Deegan & Scull (1977), is based largely upon the work of Cameron *et al.* (1984a; 1984b, 1986; 1989) and Jeffery (1989; 1993; see fig. 1.7). Although it is arguable that these authors have assigned too many formation names to this succession, this will not be considered further here. The Southern North Sea stratigraphic framework of NAM & RGD (1980) does not discuss the offshore stratigraphy of this late Cenozoic succession in any detail.

The Base of the Nordland Group: This is often marked on well logs by a high gamma peak, corresponding with the presence of a phosphatic or glauconitic lag, and upon

seismic data by a clear unconformity surface (Gramman & Kockel, 1988; Cameron *et al.*, 1989). According to Cameron *et al.* (1987), this unconformity probably covers a large age range in the British sector of the southern North Sea Basin. However, Oudmayer & de Jager (1993) give this unconformity a base Miocene age, whilst Gramman & Kockel (1988) suggest a base Middle Miocene age, additionally mentioning that there is a lower, base Miocene unconformity in the German sector of the North Sea Basin. The base of the Nordland Group is ill-defined in the stratigraphy of NAM & RGD (1980), although it corresponds approximately with the base of the Upper North Sea Group.

The Brielle Ground Formation: This formation consists of perhaps over 180m of shelly, marine, slightly glauconitic sands and clays in the east of the area (Cameron *et al.*, 1986). It is currently considered to be made up of all the sediments of the Nordland Group older than the Westkapelle Ground Formation, excluding the offshore parts of the Red Crag Formation and the "Coralline Crag" (Cameron *et al.*, 1984b; 1986; Jeffery *et al.*, 1989; 1993). It is, therefore, a litho-stratigraphic subdivision of convenience, and should be seen as such. Additionally, there is no documented palaeontological evidence for a suggested Reuverian age (Cameron *et al.*, 1984a; 1986; Jeffery, 1989) in sediments near the top of this formation, and it is difficult to find the source of this data. Its upper age range is, therefore, unreliable (T. D. J. Cameron, *pers. comm.*).

The offshore Red Crag Formation & "Coralline Crag" : These are outliers of the Brielle Ground Formation, situated offshore from East Anglia (Cameron *et al.*; 1984a), and are all outside the area of study. They should not be considered further here except as indicators of the maximum age of the overlying formations.

The basal section of borehole 89/5, to the NW of the study area, includes around 10m of glauconitic, sandy mud, which show normal magnetic polarity and are probably of Reuverian age, deposited during the Gauss chron (Thompson *et al.*, 1992). However, it is unknown whether this section represents part of an outlier, filling a halokinetic depression, as suggested in Fannin *et al.* (1991 *unpub.*), in which case a Reuverian age poses no problem, or whether it is the lateral continuation of a known offshore formation which has previously been considered younger than the Reuverian. The latter situation may explain the reasoning of Jeffery (1989; 1993), who states, without supplying evidence, that some of the Westkapelle Ground Formation is of Reuverian C age and that it partially correlates with the onshore Red Crag Formation, also locally of Reuverian age. An alternative suggestion, although

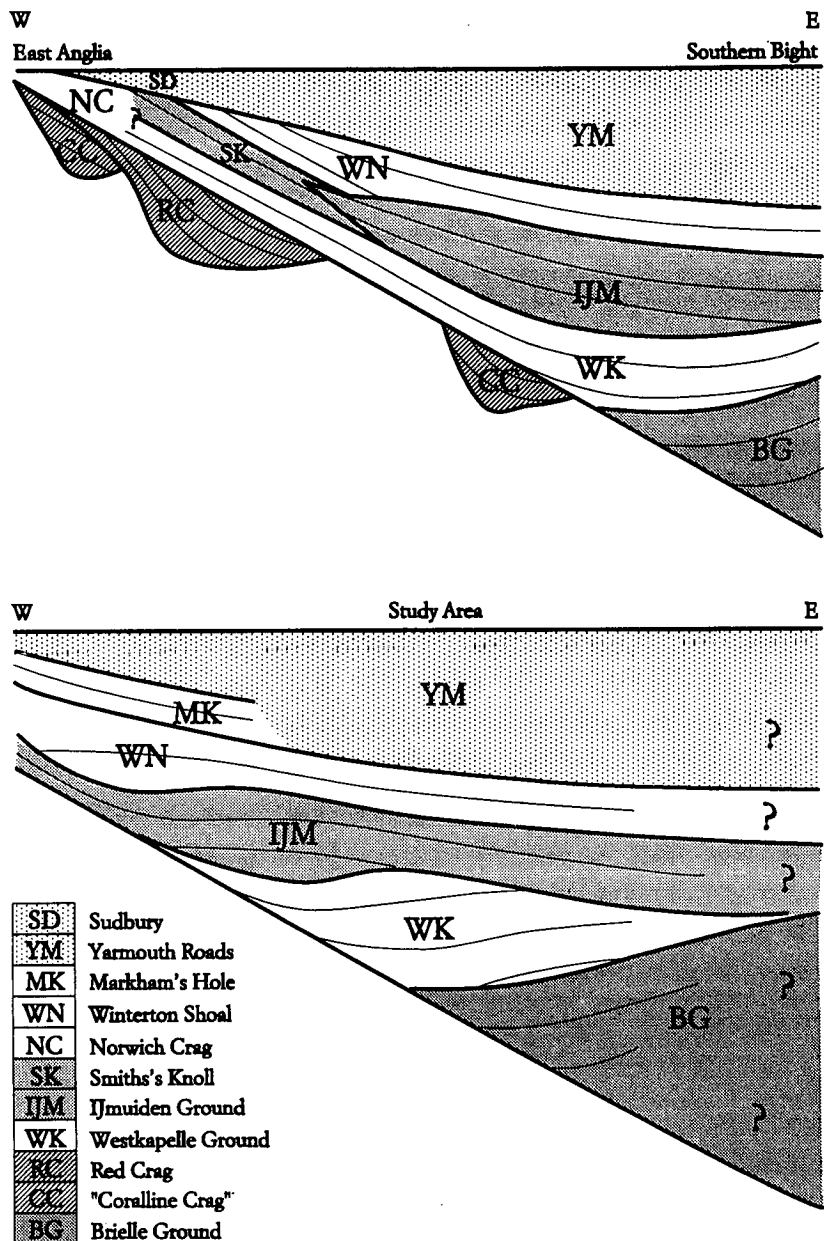


Fig. 1.7: The stratigraphy of the "Nordland Group" in: a) East Anglia and the Southern Bight, both to the SW of the study area, b) the study area. Formation names given are taken from the work of Balson (1993a; 1993b), Cameron *et al.* (1984b; 1986), Jeffery (1990; 1993), Mathers & Zalasiewicz (1988) and Whiteman & Rose (1992).

unlikely, according to Fannin *et al.* (1991, *unpub.*), is that the basal sediments of borehole 89/5 are not Pliocene at all, the faunas having been reworked, and that the normal Palaeo-magnetic event near the base of the borehole is the short-lived Reunion event of the Matuyama chron, which would make the base of late Cenozoic succession lower or middle Tiglian in age in borehole 89/5.

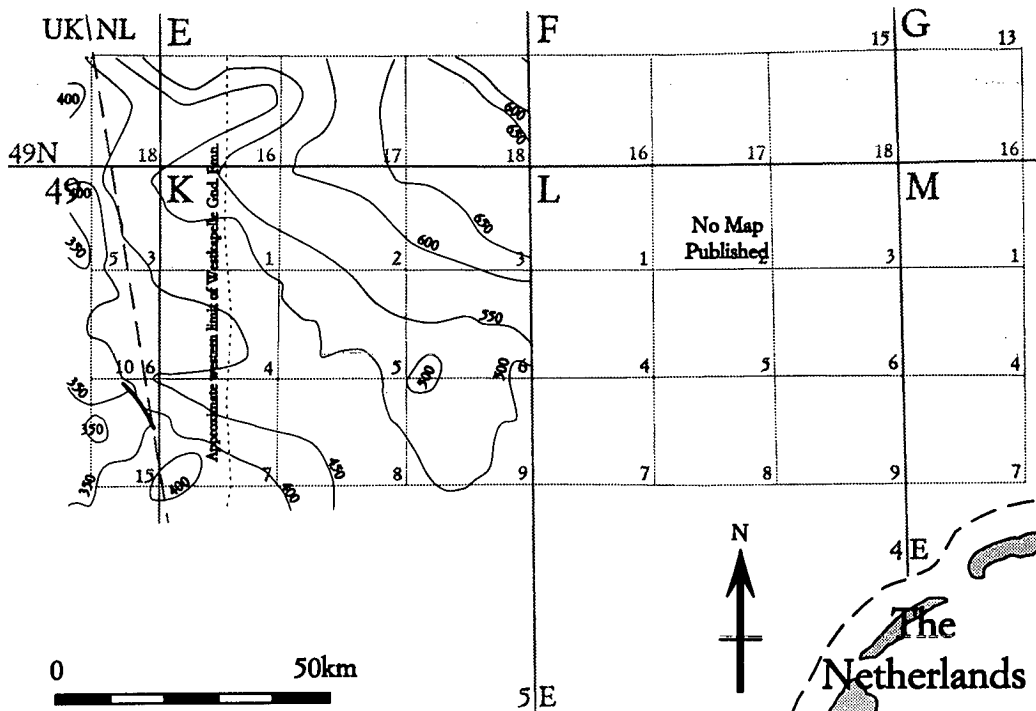


Fig. 1.8: Depth to the base of the Westkapelle Ground Formation where mapped within in the study area, using depth estimates based upon an assumed interval velocity of between 1750 and 1800m/s. Where the formation is absent, the depth shown is to the base of the “Nordland Group” (after Cameron *et al.*, 1986; Jeffery, 1993).

The Westkapelle Ground Formation: This is the oldest formation to have been comprehensively studied in the late Cenozoic succession of the southern North Sea Basin. It is a very low to low energy, slightly coarsening upward, marine interval of clay and fine grained, sparsely shelly and glauconitic sand, and reaches a thickness of up to 250m (Cameron *et al.*, 1984b; 1986). On seismic data in the west it is made up of weak to moderate amplitude, gently dipping, sub-parallel events (Cameron *et al.*, 1989). In the study area these sediments dip to the west and unconformably overlie pre-Nordland Group sediments. However, they rest conformably on the Brielle Ground Formation in the east (Cameron *et al.*, 1984b; 1986; 1989). The formation is absent from the western margin of the study area (see fig. 1.8).

Palynological investigation of this interval, to the SW of the study area, has indicated that it was deposited in slightly cold conditions. A Thurnian or, possibly, Baventian British stage correlation is implied (Cameron *et al.*, 1984a). These are probably respective equivalents of the Netherlands Tiglian B and Tiglian C4 sub-stages (Gibbard *et al.*, 1991). However, citing no reasons, Jeffery (1989; 1993) has assigned a late Reuverian to Praetiglian age to equivalent deposits in “E” quadrant to the north (see above).

The IJmuiden Ground and Smith's Knoll Formations: The IJmuiden Ground Formation, along with its British-derived equivalent, the Smith's Knoll Formation, consists of up to 200m of fine to fine-medium grained, locally shelly and glauconitic, muddy, marine sand, which includes increasingly large amounts of silt and clay toward the centre of the basin (Cameron *et al.*, 1984a; 1984b). Although conformable with the underlying Westkapelle Ground Formation in the SW, the base of the formation is obviously unconformable toward the centre of the basin to the NE, the Westkapelle Ground Formation being thin or absent there (Cameron *et al.*, 1984a; 1984b; 1986). In seismic data, the IJmuiden Ground Formation consists of strong, sub-parallel events dipping to the west and NW (Cameron *et al.*, 1984b; 1986; Jeffery, 1989).

The Smith's Knoll Formation, which only occurs to the SW of the study area, was deposited in warm conditions and probably correlates with the British, Antian stage, according to Cameron *et al.* (1984a). This probably corresponds to Netherlands Tiglian C1-4b (Gibbard *et al.*, 1991), although a late Tiglian age was suggested by Cameron *et al.* (1984b). Micro-fauna in the IJmuiden Ground Formation, where sampled, are also said to suggest an Upper Tiglian age (Cameron *et al.*, 1989). However, due to the fact that the Smith's Knoll Formation is said to partly wedge out underneath the IJmuiden Ground Formation (Cameron *et al.*, 1989), the two formations may, at least in part, be of slightly different ages.

The Winterton Shoal Formation: This is a unit of fine to medium grained, shelly sand and sandy or silty clay, generally of finer grain size to the NW, which reaches up to 150m in thickness (Cameron *et al.*, 1984a; Jeffery, 1993). It rests unconformably upon the IJmuiden Ground Formation or on older sediments below (Cameron *et al.*, 1984b). In the SW, its upper surface is truncated by the Yarmouth Roads Formation above (Cameron *et al.*, 1984b; 1989). The formation records a change in sediment progradation direction from the west to the north and NW (Cameron *et al.*, 1989) and, although largely featureless on seismic data at the top, includes strong, westward and NW dipping reflectors near the base (Cameron *et al.*, 1989). To the north it is partly of the same age as the Yarmouth Roads Formation (Cameron *et al.*, 1986).

Analysis of several boreholes suggests that this formation may have been deposited during the cool, British, Baventian stage (Cameron *et al.*, 1984b; Gibbard *et al.*, 1991). Although this stage would correlate with the Netherlands Tiglian C5, according to Gibbard *et al.* (1991), some authors suggest an early Eburonian age for

the formation (Funnell, 1987; Cameron *et al.*, 1989). However, palaeo-magnetic evidence from borehole 89/5 would suggest that it can be no younger than the Tiglian (Thompson *et al.*, 1992; Jeffery, 1993; see below).

The Markham's Hole Formation: This formation consists of fine to medium grained, glauconitic, muddy sand with some clay (Thompson *et al.*, 1992; Jeffery, 1993). Although reaching up to 150m to the north of the study area, it is perhaps less than 60m thick within the study area and is generally featureless on seismic data (Cameron *et al.*, 1986). The Markham's Hole Formation is the lateral equivalent of part of the Yarmouth Roads Formation in the south and west (Cameron *et al.*, 1986).

Although dates as late as Waalian or Menapian have been suggested by Cameron *et al.* (1986) and Jeffery (1989), palynological and palaeo-magnetic evidence from borehole 89/5, including the presence of the Olduvai sub-chron (Thompson *et al.*, 1992), suggests an age no later than the early Eburonian and possibly as old, in part, as the latest Tiglian.

The Yarmouth Roads Formation: This formation reaches up to 250m thickness to the north but is perhaps no more than 150m thick in the study area (Cameron *et al.*, 1986; Jeffery, 1989). However, the base of the formation, although clearly truncating underlying sediments to the SW, is diachronous within the study area, and time equivalents include the Winterton Shoal and Markham's Hole Formations in the north (Cameron *et al.*, 1984a; Cameron *et al.*, 1986). It consists of fine to medium grained, characteristically de-calcified, sand, with some pebbles of flint and quartzite as well as intra-formational mud and peat clasts (Cameron *et al.*, 1984a; 1984b; 1989; Jeffery, 1989). Additionally, bands of micaceous, perhaps lagoonal clay are present near the base (Jeffery, 1989; 1993). Worn shells and lignite are locally common (Jeffery, 1989; 1993). Jeffery (1989) suggests a gradual upward transition from marine to fluvial sand, followed by a return of marine conditions near the top. On seismic data, events are weak and chaotic in appearance, although occasional channels can be discerned (Cameron *et al.*, 1984a; 1986; Jeffery, 1989).

Suggested ages for this thick and highly reworked formation are, quite reasonably, very varied, ranging from Waalian in the south, based upon limited palynological evidence (Cameron *et al.*, 1984b), to Elsterian in the north (Jeffery, 1989). Palaeo-magnetic evaluation (Thompson *et al.*, 1992) certainly suggests that a Bavelian or early "Cromerian Complex" age for the youngest deposits is not unreasonable.

Comparison with Pre-Glacial, Onshore Stratigraphic Schemes

Three of the countries bordering the Southern North Sea have stratigraphies which can be directly compared with the sediments of the study area: these are Britain, the Netherlands and Germany (see fig. 1.9). However, the exact relationships of these stratigraphic schemes are uncertain and are discussed below.

British Stratigraphy: It is probably fair to say that, at present, it is easier to correlate the offshore formations of Cameron *et al.* (1984a; 1986) with the present onshore British stratigraphy than with the stratigraphic schemes of NW Europe, largely because the existing offshore classification covers almost exactly the same time period as that in which the onshore sediments were deposited (Funnell, 1987). However, the majority of the British succession, which is almost entirely contained within East Anglia, is no older than the Netherlands' Reuverian B or C, so that correlation is impossible with the as yet unstudied, older sediments present further offshore (Hunt, 1989; Gibbard *et al.*, 1991). In addition, the whole onshore succession is condensed, being no more than 90m thick, in comparison with over 600m of sediment of similar age in the centre of the southern North Sea Basin (Mathers & Zalasiewicz, 1988; Jeffery, 1989). This is largely due to the marginal nature of East Anglia to the North Sea Basin, and the resulting, large sedimentation gaps present in East Anglia (Shotton, 1986).

The British onshore stratigraphy has been quite largely reviewed and simplified over the last few years, so that six pre-glacial formations now encompass the vast majority of the sediments there. These formations are the "Coralline Crag", "Red Crag", "Norwich Crag" and "Cromer Forest Bed" marine or estuarine formations, and the "Sudbury" and "Colchester" fluvial formations (Gibbard & Zalasiewicz, 1988; Mathers & Zalasiewicz, 1988; Whiteman & Rose, 1992), the last two of which were formerly known as the "Kesgrave Gravel" (Rose & Allen, 1977). Having a similar litho-facies, it is highly likely that the Red Crag Formation is of much the same age, onshore and offshore (Cameron *et al.*, 1984a). However, along with other outliers of the Nordland Group, including the Coralline Crag Formation, it is not particularly useful for correlation except in defining the maximum age of overlying sediments.

Cameron *et al.* (1989) suggest that the base of the Westkapelle Ground Formation marks a major transgressive event which may well have originally reached East Anglia. The formation has certainly been partly correlated with the onshore Norwich Crag Formation (Hopson *et al.*, 1991) and, as suggested by Gibbard

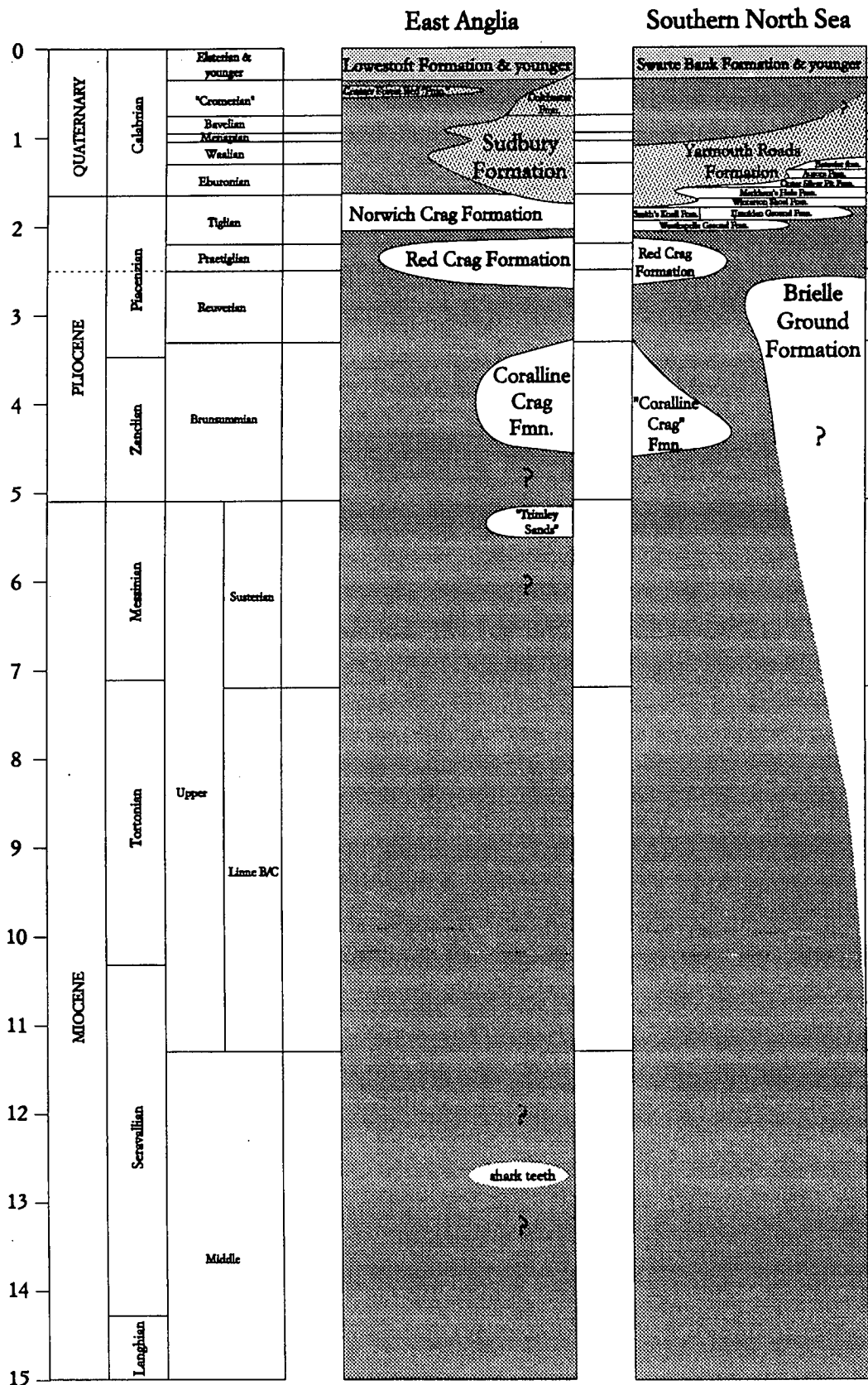
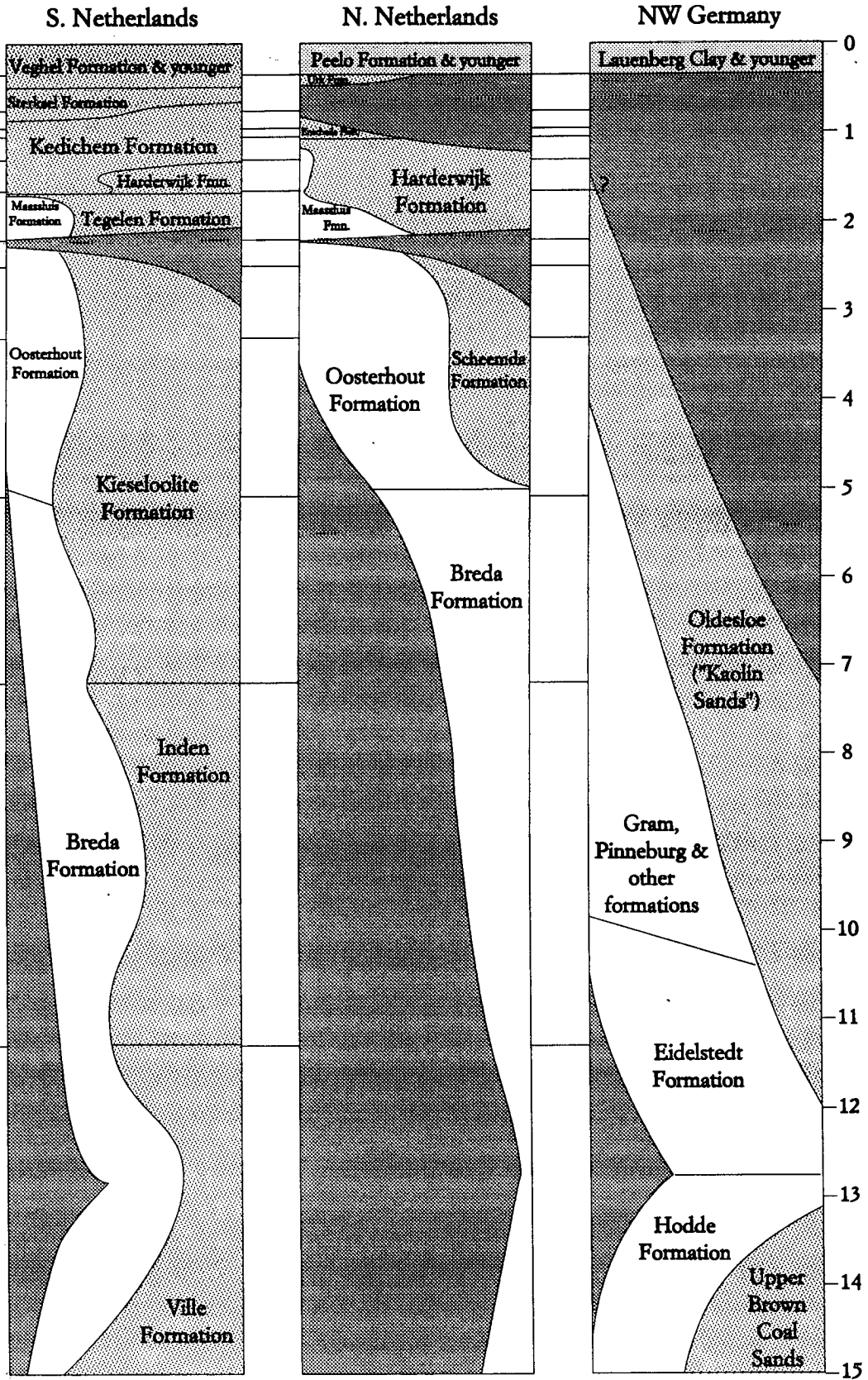


Fig. 1.9: Table comparing the middle Miocene to Recent stratigraphic schemes of the southern North Sea, Britain, the Netherlands and NW Germany (after Van Staalduinen *et al.*, 1979; West, 1980; Cameron *et al.*, 1984b; 1989; Zagwijn, 1985; Zagwijn & Hager, 1987; Mathers & Zalasiewicz, 1988; Balson, 1989; 1993a; Whiteman & Rose, 1992; Hinsch, 1993, and Jeffery, 1993).



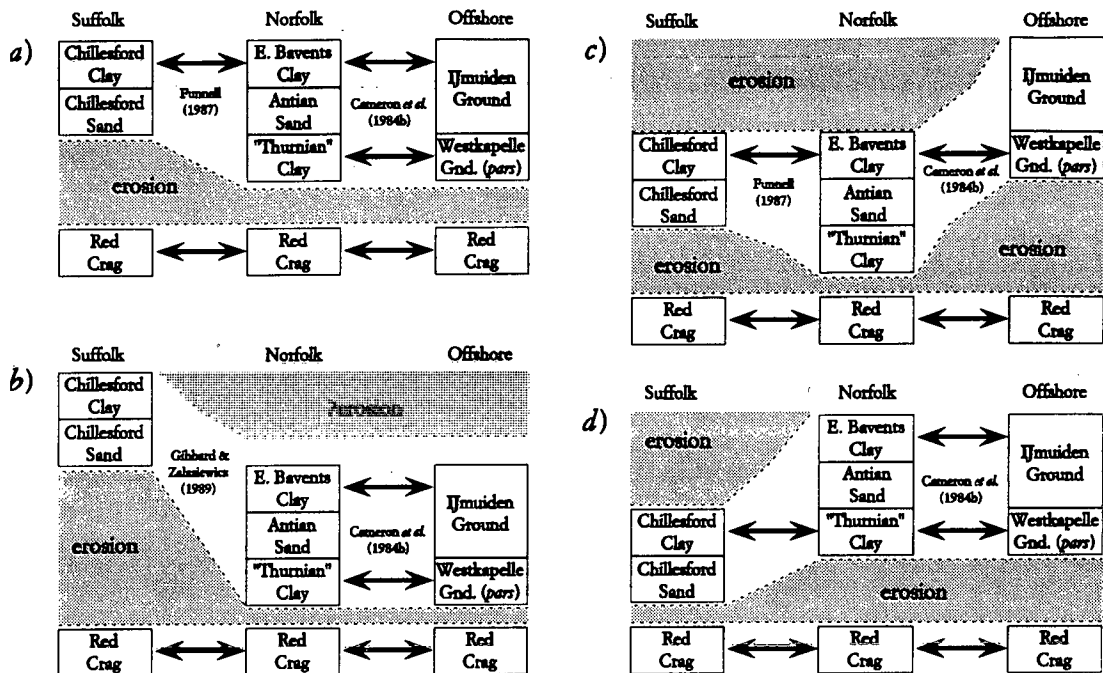


Fig. 1.10: Various potential correlation schemes for the late Pliocene deposits of East Anglia and the southern North Sea, utilising the interpretations of Cameron *et al.* (1984a), Funnell (1987) and Gibbard & Zalasiewicz (1988). Correlation “a” is the most simple, least problematic correlation scheme.

et al. (1991), perhaps correlates partly with either the Easton Barents Clay or with the “Thurnian Clay” (Lu 2) of the Ludham borehole (after West 1961; 1980; see fig. 1.10). Although unlikely, it may instead correlate with the Chillesford Clay of Mathers & Zalasiewicz (1988). However, Funnell (1987) was of the opinion that depositional equivalents of the Westkapelle Ground Formation do not occur onshore.

According to Cameron *et al.* (1989), the Smith’s Knoll Formation, the offshore British equivalent of the IJmuiden Ground Formation, may have extended into the area of East Anglia at the time of its deposition. Jeffery (1993) also suggested that age equivalents of the Smith’s Knoll Formation may be present within the Norwich Crag Formation.

The presence of the Winterton Shoal Formation in East Anglia is more doubtful. Although Cameron *et al.* (1984a) suggested that it is likely to have been removed from East Anglia by erosion, Cameron *et al.* (1989) stated that this is the youngest offshore formation in which British provenance can be recognised, and that its presence there cannot be ruled out.

Jeffery (1993) suggested that the break in deposition recognised in the middle of the Ormesby borehole succession of East Anglia (Harland *et al.*, 1991) may correlate with the unconformity seen at the base of the Yarmouth Roads Formation in the SW part of the southern North Sea Basin. Correlation of the Yarmouth Roads Formation with the sediments of East Anglia is generally assumed, although not

necessarily well understood (Funnell, 1987; Gibbard *et al.*, 1991; Jeffery, 1993). It is probable that the Yarmouth Roads Formation just offshore from East Anglia correlates with the Sudbury Formation of Whiteman & Rose (1992).

Dutch Stratigraphy: The late Cenozoic succession of the Netherlands, in contrast to that of Britain, is almost 1km thick, and is punctuated by far fewer gaps in sedimentation (Zagwijn, 1989). Although the stratigraphy of the Netherlands can be quite complicated, especially in sediments of Praetiglian age or younger, this problem is largely due to the complex relationship between deposits of the different river systems in the south of the Netherlands. In the northern part of the Netherlands, where comparisons with the study area should be made, this problem is relatively minor, due to the dominance, at the expense of other river systems, of the now extinct Baltic River System. Therefore the pre-glacial sediments of the study area should be compared exclusively with the "Breda", "Oosterhout" and "Maasluis" marine formations, and with the "Scheemda", "Harderwijk", "Enschede" and "Kaolin Sand" fluvial formations, the "Kaolin Sands" only being present in the east. At present, little has been published on the late Cenozoic geology of the northern part of the Netherlands and little attempt has been made to apply these formation names to the offshore succession.

There are a number of regional markers within the deposits of the Tiglian stage which may possibly be useful for correlation purposes. Zagwijn (1974; 1989) and Zagwijn & Doppert (1978) talk of a "base Pleistocene" unconformity, although this may be divisible into both a "base Praetiglian" and a "base Tiglian" unconformity. Additionally, a major regressive event is known to occur across the Netherlands in the Tiglian C4c sub-stage, and there is little evidence of marine deposition in the area of the Netherlands following this until the end of the "Cromerian Complex" stage, save for minor incursions in the Waalian and Bavelian (De Jong, 1988; Zagwijn, 1992). The sediments of the IJmuiden Ground Formation are said to reflect the influx of large amounts of Rhine-type sediment into the area, and may therefore be of Tiglian TC4c age or younger (Cameron *et al.*, 1984a; 1989).

German Stratigraphy: In NW Germany, the succession equivalent to the Nordland Group is fairly thick and well known (Gramman & Kockel, 1988), but is not particularly useful for stratigraphic correlation here, partly because of its distance from the study area but, more importantly, because the vast majority of the German succession of Miocene to early Pliocene age, and is therefore significantly older than the sediments of the study area. This contrast is due to the westward prograding nature of the Nordland Group. Additionally, much of the younger, Plio-Pleistocene part of the Nordland Group succession has been removed by glacial action here, and tend to be preserved only within halokinetic depressions (Ehlers, 1983).

The basal unconformity surface of the Nordland Group is fairly well defined as being of either Reinbekian or Langenfeldian age (Seravalian), as this hiatus was of far smaller duration in Germany than in the centre of the Southern North Sea (Hinsch, 1990). This would make the unconformity of late Middle Miocene age, in contrast to the age suggested by Gramman & Kockel (1988).

Comparison of Onshore and Offshore Glacial Deposits

The offshore, Elsterian to Recent succession is highly complex and includes many formations, some very localised in their distribution (Cameron *et al.*, 1986; 1989; Joon *et al.*, 1990). This succession records at least three phases of glaciation; the Elsterian or Anglian, the Saalian, and the Weichselian or Devensian. It is perhaps only the oldest of these, the Elsterian, that need be considered further, as it is the only glaciation which has an influence easily visible in regional seismic data. This glaciation has caused the erosion of up to 500m deep channels into the pre-glacial sediment, these channels being present in a broad, W-E trending band which runs from the northern tip of East Anglia, through the northern part of the Netherlands, into NW Germany and eastward toward Russia (Van Staaldunin *et al.*, 1979; Hopson *et al.*, 1991; Ehlers *et al.*, 1984). The fill of this channel system is represented by the Swarte Bank Formation offshore (Cameron *et al.*, 1986). In the Netherlands it is represented by the Peelo Formation and in Germany by both Elsterian tills and by the Lauenberg Clay (Van Staaldunin *et al.*, 1979; Ehlers *et al.*, 1984). In Britain, contemporary deposition is represented by the various deposits of the Anglian Glaciation (Hopson *et al.*, 1991).

1.3: Study Rationale & Layout

1.3.1: Architecture of late Cenozoic, Offshore Deposits

The apparently delta-like nature of seismic architecture in the late Cenozoic formations of the southern North Sea Basin has been observed by several authors (Blok & Dongelmans, 1986; Cameron *et al.*, 1987; Jeffery, 1993). This architecture includes westward dipping seismic facies interpreted as pro-delta, delta-front and delta-top facies by Cameron *et al.* (1987). The deltaic analogue is further suggested by the overall regressive nature of the late Cenozoic succession, as shown by the available borehole data (Bjorslev Nielsen *et al.*, 1986; Cameron *et al.*, 1984a; Knudsen & Asbjörnsdóttir, 1991; Thompson *et al.*, 1992), as well as by the upward change from marine to continental facies seen in equivalent deposits of the various countries bordering the Southern North Sea (Zagwijn & Doppert, 1978; Gramman & Kockel, 1988; Gibbard & Zalasiewicz, 1988).

Because this architecture is currently held by some authors to be indicative of large scale, deltaic conditions within the southern North Sea Basin, attempts have been made (Cameron *et al.*, 1987) to apply the principles of seismic, stratigraphic analysis, as outlined by Vail *et al.* (1977) to this succession. For this reason, it is worth explaining the principles of seismic, stratigraphic interpretation at this point.

Genetic Seismic Interpretation

Since the publication of AAPG Memoir 26 in 1977, seismic stratigraphy has been a source of much controversy. This controversy has been centred around the genetic interpretations of successions including progradational, clinoform architecture in seismic data. In this study, the term "Clinoform Architecture" is used to indicate the result of iteration, by lateral migration normal to strike, of a horizontal or gently dipping depositional surface including a relatively steep section. In sedimentation, this will result only from the lateral migration, perpendicular to strike, of environments including a depocentre; for example, progradation of the delta-front in deltaic environments.

In deltaic environments, the position of the slope break, the top of the steeply dipping component of the progradational, clinoform architectural unit, is largely controlled by the position of the sea surface. In AAPG Memoir 26, Vail *et al.* (1977) assumed that the slope break is always controlled by the sea surface, and first suggested that slight changes in the patterns of this architecture with progradation

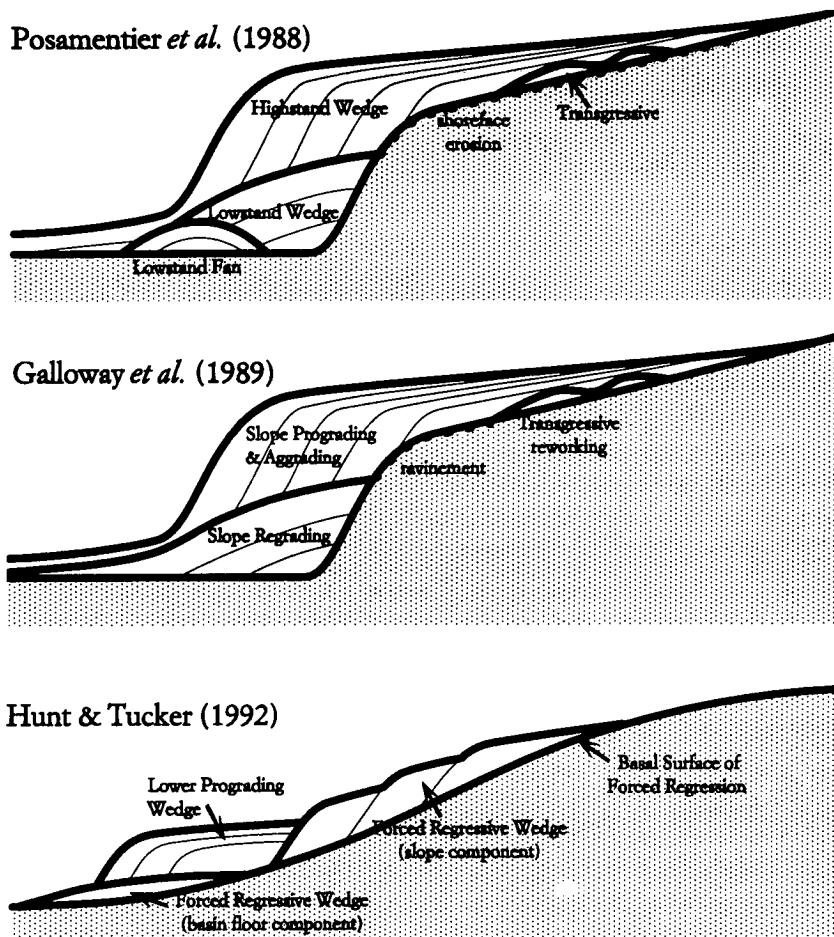


Fig. 1.11: Different seismo-stratigraphic models for the clinoform depositional architecture seen in seismic and well data. The models of Posamentier *et al.* (1988) and Hunt & Tucker (1992) are based upon the assumption of a predominant relative sea level control upon the observed architecture.

might be related to fluctuations in relative sea levels at the slope break. This paradigm was updated by Posamentier *et al.* (1988), who stated that progradational, clinoform architecture can be divided into different “systems tracts”, which represent deposition at different stages in a cyclically oscillating, eustatic sea level controlled regime. These include “lowstand wedge”, “transgressive-” and “highstand” systems tracts (see fig. 1.11).

Galloway (1989) argued that the transgressive architecture seen in progradational, clinoform successions could be generated by an interplay of eustatic sea level rise, accelerated subsidence and sediment starvation. He extended his argument to show that, in a subsiding basin, the generation of the “lowstand wedge” and “lowstand fan” systems tracts need not necessarily be through eustatic sea level fall at all, and that these facies could be generated simply by the natural regrading of sediment slopes after transgression, due to a relative sea level rise or to sediment

starvation. As relative sea level rise can be generated easily within a basin by subsidence, this rules out any need for eustatic sea level control at all.

However, recent evidence has been presented for the existence of sediment wedges resulting exclusively from relative sea level falls. These are referred to as "forced regressions" or the "forced regressive wedge" systems tract (Posamentier *et al.* 1992, Hunt & Tucker 1992). These differ from the "lowstand wedge" of Posamentier *et al.* (1988) in recording sub-aerial exposure. However, these systems tracts have only been identified in wells, outcrops and high resolution seismic data, and it is doubtful whether they would be recorded in normal seismic interpretations.

Several problems might arise from the application of these assumptions to the southern North Sea Basin. The first is that, apart from the "forced regression", the above models are designed for application to passive, shelf margins, which slope uniformly toward the continental shelf edge. In contrast, the North Sea Basin is an epeiric sea-way, with no obvious, preferred slope direction. Additionally, tidal and storm related forces have probably played a major rôle in the shaping of environments in the basin over the last few million years (Kasse, 1986; Mathers & Zalasiewicz, 1988; Balson, 1989). The models of Posamentier *et al.* (1988) and Galloway (1989) should therefore be used with caution, as they may be neither applicable nor relevant.

1.3.2: Correlation of the Data-sets

Regional Seismic and Well Data-sets

There were a number of problems in the correlation of the regional seismic and well data-sets. These problems included:

- 1) A lack of previously established tie horizons between the two data-sets.
- 2) The lack of bio-stratigraphic control in the well data.

Only one horizon could initially be identified in both regional seismic and well data-sets. This horizon was the hiatal or unconformity surface at the base of the Nordland Group succession, often known as the "mid-Miocene unconformity", which has obvious characteristics in both of the data-sets, and has been approximately dated in a number of wells (see chapters 2 and 3). This was used as an important marker in the establishment of a velocity profile for the study area (see the section on "Velocity Profile" below).

The initial interpretation of the internal geometry of the Nordland Group was carried out using the regional seismic data-set only. The methodology for this interpretation was to select a number of widely spaced seismic horizons within the Nordland Group succession. The horizons chosen are indicated by the presence of reflector terminations along them (see fig. 1.12), and are somewhat more obvious than other seismic horizons, generally being marked by high amplitude seismic events. These horizons were then correlated throughout the regional seismic data-set. Correlation was done, as is suggested in Vail *et al.* (1977) by the method of "loop-tying" throughout the seismic grid.

Once this seismic horizon correlation had been achieved, the positions of the interpreted seismic horizons were marked onto the well data (where wells were on or close to the available seismic lines). The seismic horizon interpretation was applied to the chrono-stratigraphic interpretation of the well data-set using the assumption that seismic horizons marking surfaces of reflector termination are chrono-stratigraphically significant (Vail *et al.*, 1977) and, therefore, that this information would help in the chrono-stratigraphic interpretation of the well data. The marking of seismic horizons onto the well data was done by using a standard velocity function (derived largely from the well and high resolution, site survey seismic data-sets, as information from the regional seismic data-set was found to

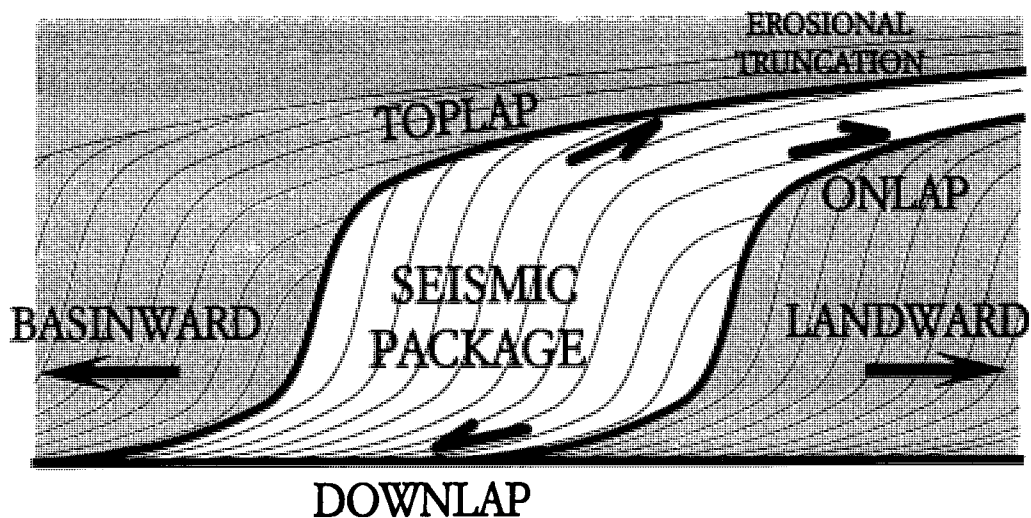


Fig. 1.12: Types of reflector termination distinguished in this study, together with other terms used for describing the seismic data in this study.

give insufficiently precise values; see below) to convert the seismic time information to depth information. Because of the marked consistency of the velocity profile over the whole of the study area, no significant anomalies were found using this method.

All the available well data were then compared, in order that a complete correlation of the well data throughout the study area could be achieved. This correlation was done by comparison of all the available electric log characteristics, using the information from the interpreted seismic horizons as a guide. Where there was apparently strong support for a well correlation which did not match the seismic interpretation, the regional seismic data interpretation was reassessed. If, because of this, the seismic interpretation, upon re-examination, was found to be interpretable in a way which was more consistent with the well data, then re-interpretation was undertaken. Ambiguities in the correlation of the well data were resolved by interpreting additional seismic events within the seismic data, although, again, only reflector termination surfaces were used.

It is apparent from this study that 60 or more seismic packages (i.e. sediments bounded by apparent seismic unconformities) can be identified in the Nordland Group succession of the study area, using the available regional seismic data. With this number of packages, it was decided not to trace out each seismic unconformity within the succession but, instead, to discuss the individual seismic packages and their complex relationships by reference to those seismic horizons already interpreted. It should, therefore, be realised that the interpreted seismic horizons are no more significant than any other reflector termination surface, and should not be seen as such. The resulting seismic interpretation is therefore an interpretation of 23

reflector termination surfaces (out of more than 60), separating up 23 arbitrary seismic intervals within the Nordland Group.

Site Survey Data-Sets

Because of the awkward positioning of the site survey data (few of the survey positions coincided with well or regional seismic data), it was decided that these data-sets should be interpreted independently, due to the inaccuracy of any correlation that could be made between these data-sets and the regional seismic and well data-sets (see chapter 4). On the other hand, toward the upper parts (i.e. top 400 metres) of the eastern site survey data-sets, correlation was possible from one site survey to another, without recourse to the other data-sets, due to the lateral consistency of the high resolution seismic facies seen at this level. This resulted in the site survey data-sets resolving parts of the Nordland Group stratigraphy in the shallow parts of the succession which were not resolvable at all in the majority of the regional seismic and well data, due to the poor quality of the latter data-sets at this level. In this respect, the site survey data-sets should be seen as an additional, complementary source of information, and are kept separate from the main interpretation. However, an attempt has been made to correlate the site-survey data-set interpretations with the regional seismic and well data interpretations of chapters 2 and 3.

Velocity Information

The processing of multi-fold seismic data requires the calculation of a velocity versus "two way time" curve, which can be derived from the raw seismic data. As a by-product of the processing, the final paper displays of seismic data contain the resulting velocity information in "velocity boxes" at the top of the seismic section. These are present in both the regional and the high resolution, site survey seismic data-sets, and allow the calculation of time versus depth curves from the seismic data (see fig. 1.13). However, these time/depth curves are commonly inaccurate, and it is preferable to use well data in order to establish improved time versus depth curves.

The method of establishing time/depth curves from well data is to use the "marker ticks" which are sometimes present on the composite well log. These marker ticks are only present where a down-hole sonic log profile has been recorded (see chapter 3). The separation of the marker ticks on the composite log (using the

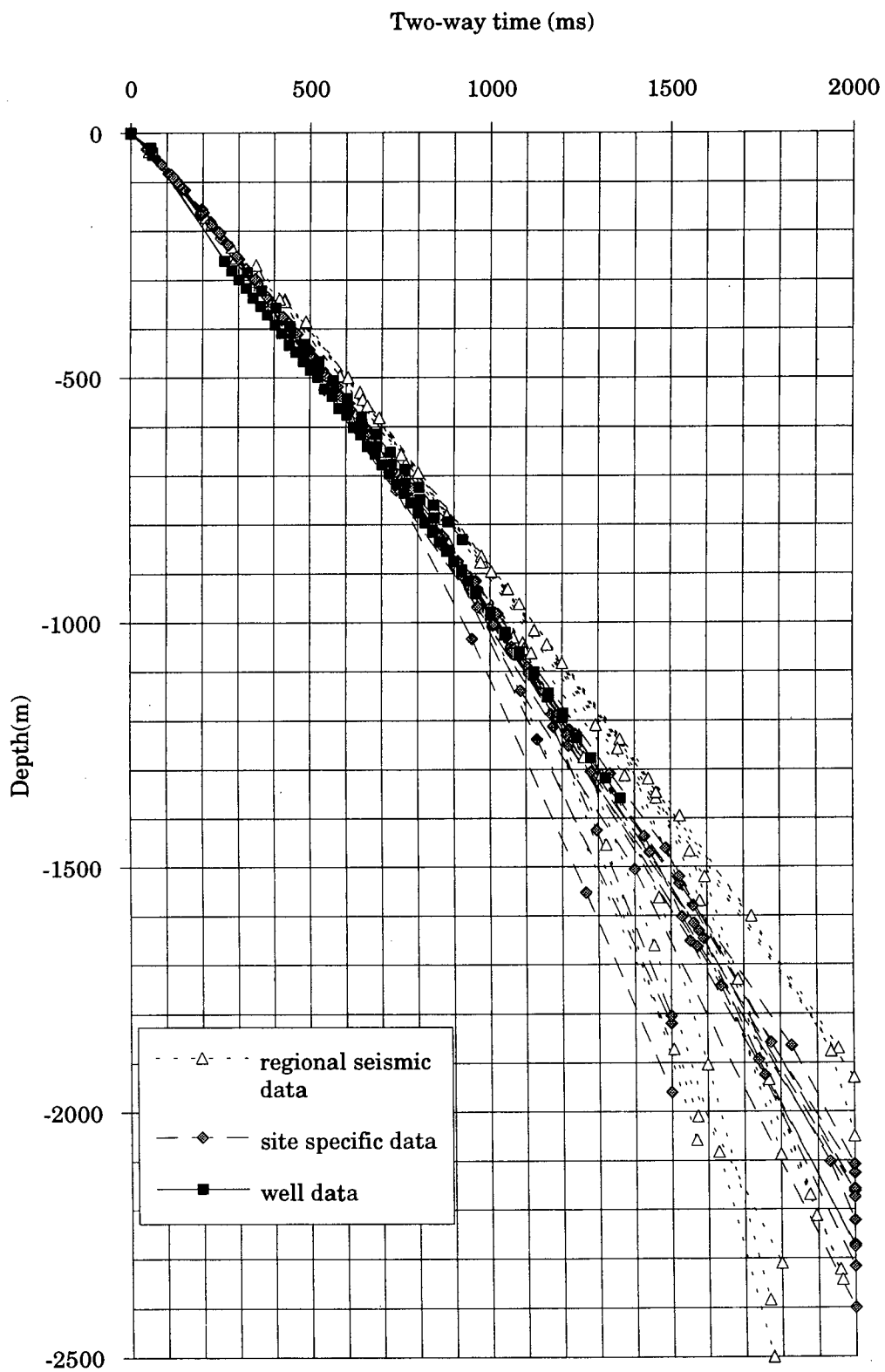


Fig. 1.13: velocity versus depth curves for the three data-sets. Note the divergence of the velocity curves as they enter the chalk field in the deeper part of the curve.

composite log scale given) records the vertical distance of rock or sediment within the hole through which it would take a sound wave ten milliseconds to travel one way. Because the sonic log is not recorded up to the sea bed, these marker ticks do not extend to the top of the composite log, presenting problems in the upper part of the section.

Using an independently correlated marker horizon seen in both well and seismic data, in this case the base of the Nordland Group succession ("mid-Miocene unconformity"), the marker tick information can be used to construct velocity versus depth curves for the wells. Well velocity information was taken from selected wells which are known to coincide with seismic lines, and where the "mid-Miocene unconformity" is easily picked in both the well and the seismic data.

The standard velocity profile for the whole study area was, in the end, based upon both the well and the high resolution, site survey seismic data-sets, which have very similar time/depth profiles over the whole of the study area. The regional seismic data-set was deemed unsuitable for incorporation into the standard velocity profile, due to the consistently low depth values it gives by comparison with the other two data-sets. For the computer-generated, interpreted depth sections, a best-fit polynomial equation was used in the depth conversion programme, to convert the two way time data to depth data.

1.3.3: The Thesis Plan

In the following chapters I attempt to incorporate detailed interpretation from the study area into the existing geological framework, as described above. Chapter 2 deals with the regional seismic stratigraphic framework into which the data from the following chapters is incorporated. The relationship of this stratigraphy with the existing offshore stratigraphy, as outlined by Cameron *et al.* (1989), Balson (1993a) and Jeffery (1993), is also considered. Problems with the existing depositional models for the area are discussed.

Chapter 3 details the lithological database available, including the proprietary well data and existing borehole data. This database is integrated with the seismic stratigraphic framework of chapter 2, to derive a litho-stratigraphic framework. The chapter also discusses the problems of correlating this framework with the onshore stratigraphic schemes.

Chapter 4 is an attempt to glean more detailed information from high resolution, site specific data, not in order to improve the stratigraphy, but to derive a better understanding of the sedimentary environments of deposition. This data also allows a better definition and the resolution of some problems of interpretation which are present in the regional seismic data set but, due to the low resolution of the regional data, which are not easily explained.

Finally, Chapter 5 is an attempt to generate a litho-stratigraphy for the study area which can be correlated with current onshore schemes, and which supplements the existing offshore data. Additionally, models are presented for the deposition of the sedimentary packages seen, including a consideration of climatic effects on these environments. Suggestions for probable sedimentary environments are made.

CHAPTER 2:

**REGIONAL
SEISMIC DATA**

2: REGIONAL SEISMIC DATA.

2.1: Introduction

Despite the large amount of proprietary seismic data covering the whole of the Dutch sector of the North Sea, little has been published on the seismic stratigraphy of the late Cenozoic succession here, owing to its perceived lack of commercial potential. The most important seismic stratigraphic interpretation work in the area is that published by Cameron *et al.* (1984b; 1986) and Jeffery (1989), as part of the joint, regional mapping programme by the *BGS* and *RGD*. These authors set up the widely used seismic stratigraphy for the Quaternary part of the succession in E, K and P quadrants of the Dutch sector. Their work also demonstrated the westward migration of sediment depocentres across the area during the Quaternary. Cameron *et al.* (1987) interpreted the reflector packages seen in terms of deltaic environments because of a natural facies division by the slope of reflectors, and they defined basin floor, delta slope and delta top facies, amongst others. Other work includes the unpublished study of Blok & Dongelmans (1986), who mapped out individual packages in E and K quadrants in order to establish a sea level based stratigraphy for the whole of the Nordland Group.

However, the above interpretations have used only the survey data-sets of the *BGS* and *RGD*. Using proprietary seismic data from the German sector, Gramman & Kockel (1988) estimated that water depths at the time of deposition were up to 500m, based on the height of the observed fore-sets.

The aim of this chapter is to establish a seismic stratigraphic framework for the whole of the Nordland Group succession within the study area, both for the correlation of available well and borehole data, and for the establishment of regionally traceable seismic stratigraphic units within the area. This study uses proprietary data for the majority of the interpretation.

2.1.1: *The Seismic Data Available*

The data discussed in this chapter are of two types only (see fig. 2.1). Each data-set has its own limitations, and arbitrary definitions of these are given here. The *resolution* of the data is an estimate based on the closest vertical distance between two reflecting horizons such that they are distinguishable. This is normally accepted to be three-eighths of the wavelength of the seismic data at best. The *interpretation range*, the time window over which the data is interpretable, is dependant on the

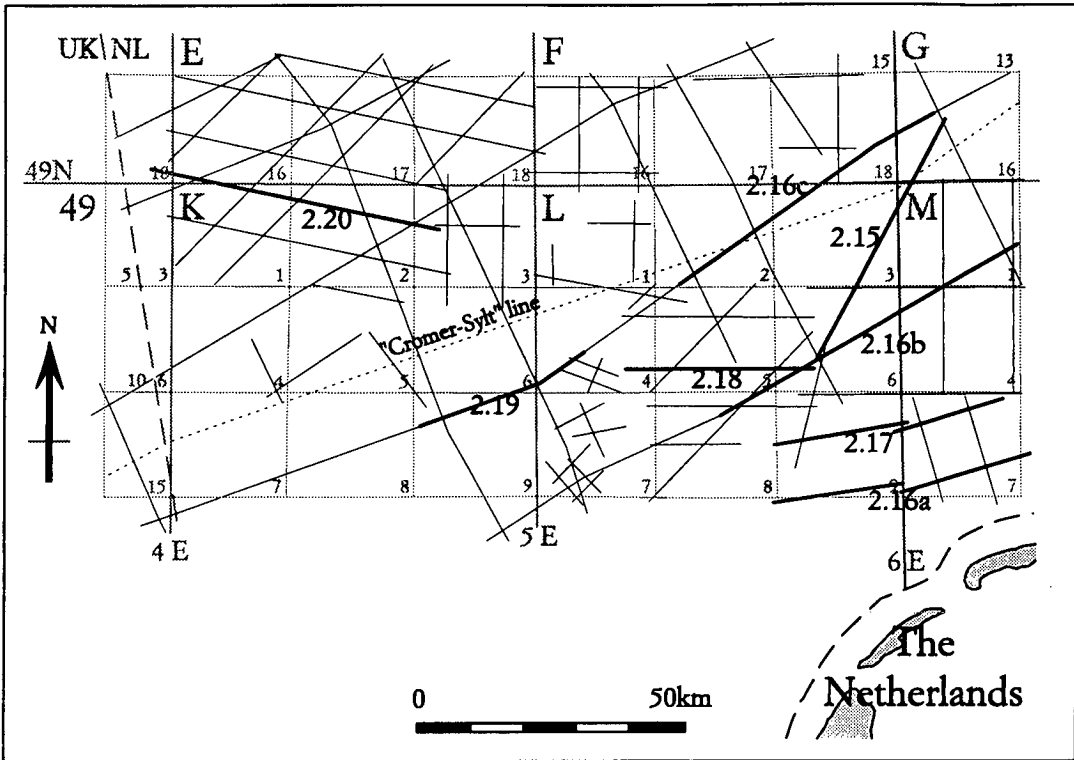


Fig. 2.1: Map of the regional seismic database used in this study and discussed in this chapter, including the “Cromer-Sylt”, high resolution, regional seismic line. The map also includes the locations of interpreted sections, together with their figure numbers.

processing parameters applied to the data, for example trace muting and deconvolution, and upon the depth of penetration of the seismic source signal. The *trace separation* is the horizontal distance between consecutive seismic traces. The *fold* of the data is the number of seismic traces that make up one seismic trace as seen on a seismic section. Theoretically, increasing the fold of the data improves the signal to noise ratio of the data.

Proprietary data

Resolution: 16ms TWT (~ 10m)

Interpretation Range: greater than 250ms TWT (~ >220m)

Trace Separation: 12.5m

Fold of Data: 60

Although this type of data is of low resolution, it has the advantage that there is a dense, commercial database of lines covering the entire Dutch sector of the North Sea. The data used here has been obtained from two major sources: *NOPEC* kindly supplied regional lines across all sectors of the southern North Sea for use by the

SNSP. These lines are part of the *Southern North Sea Tie Infill (SNSTI)* survey, acquired between 1986 and 1987. Some of these lines fall within the present study area, and were used to make the initial, regional interpretations of the late Cenozoic succession. Additional data were obtained from *HGS* to extend the interpretation to regions within the study area not covered by the *NOPEC* regional data-set. However, coverage in the SW of the study area is relatively poor.

The "Cromer-Sylt" line

Resolution: 3ms TWT (~ 3m)

Interpretation Range: 0-700ms TWT (~ 0-650m)

Trace Separation: ~ 6.25m

Fold of Data: 6

This line was digitally acquired in 1987 by the *RGD*. Processing was subsequently carried out by the *BGS*, as discussed by Cameron *et al.* (1993). Although of rather poor quality below about 700ms TWT, due to the poor penetration of the water-gun source used, this high resolution seismic line has the advantage that it can be incorporated into the regional interpretation based upon the lower resolution, commercial seismic data. This allows a better understanding of some features with ambiguous geometry on the commercial lines, and enables a check to be made on the accuracy of well correlation made using the regional interpretation.

2.2: The Regional Seismic Data-set

2.2.1: The “Pre-Nordland Group” Succession

A succession almost entirely made up of clay (NAM & RGD, 1980; see section 3.2.1), and sometimes greater than 1km thick, separates the Cretaceous and Paleocene chalks of the Chalk Group below from the Nordland Group above. This was named the Hordaland Group in the central North Sea by Deegan & Scull (1977), and ages of its sediments probably range from Upper Paleocene to Middle Miocene (see section 1.2.1). The base of the succession is usually marked on regional seismic data by a very high amplitude, positive polarity event, corresponding to the upper surface of the chalk, or to the top of older sedimentary successions where the chalk has been removed. The top of the succession is a conspicuous unconformity surface, corresponding to the “mid-Tertiary” unconformity, and hereafter referred to as seismic horizon “H₀”. The succession is locally very thin or absent around areas of salt induced uplift.

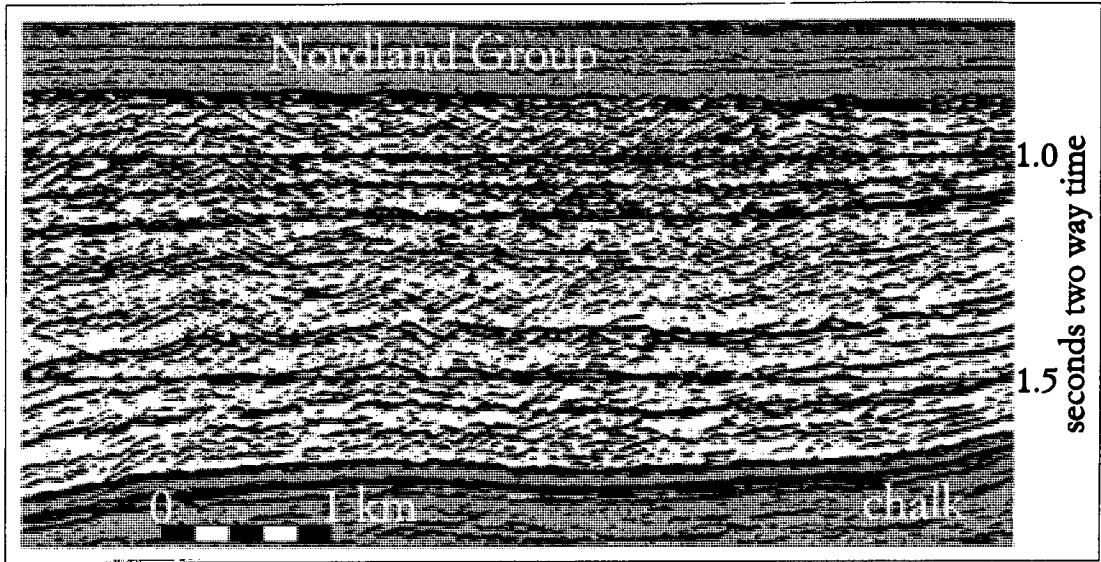
Despite the lack of lithologic variation seen in well data from this succession (see section 3.2.1), internal events of both normal and reverse polarity can be picked out which possibly represent variations in the cementation, and the water and gas contents of the clay. These events are especially well imaged in the regional seismic data provided by HGS, allowing the following features to be observed:

Character of the “mid-Tertiary” unconformity

This horizon (H₀) is often marked by a very high amplitude, negative polarity event. This implies a reduction of velocity and density downward, across this boundary, possibly due to slight over-pressure in the underlying sediments. Although this event shows very slight disruption and faulting over the whole of the study area, in certain areas this disruption can become intense, with individual fault displacements of up to 20m and lateral fault separations of 250m (e.g. fig. 2.2a). This intense disruption seems to be localised, but never coincides with points of maximum salt uplift (see fig. 2.3a).

Locally, horizontal, stepped, negative polarity reflector patterns are observed at the “mid-Tertiary” unconformity surface on the NOPEC grid of regional seismic lines (see fig. 2.4a), although these are not imaged in the HGS regional seismic data.

a)



b)

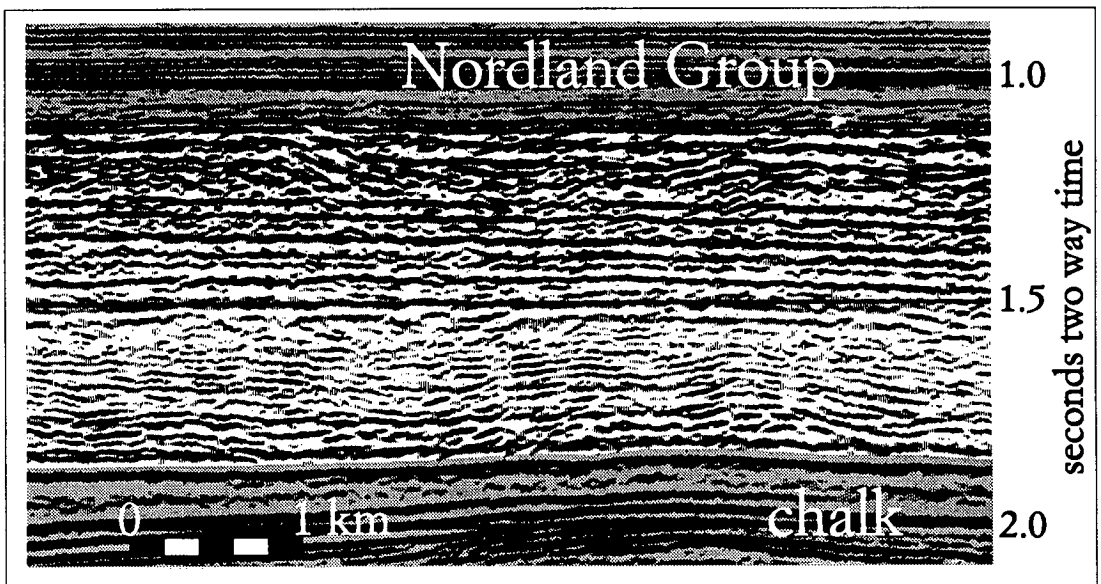


Fig. 2.2: Examples of seismic textures in the lower Cenozoic clay succession. a) Apparent disruption superimposed upon laterally traceable seismic events within the clay. This may be due to out-of-plane reflector interference. b) Possible de-coupling of the clay sequence from the chalk below (seismic data courtesy of HGS Ltd.).

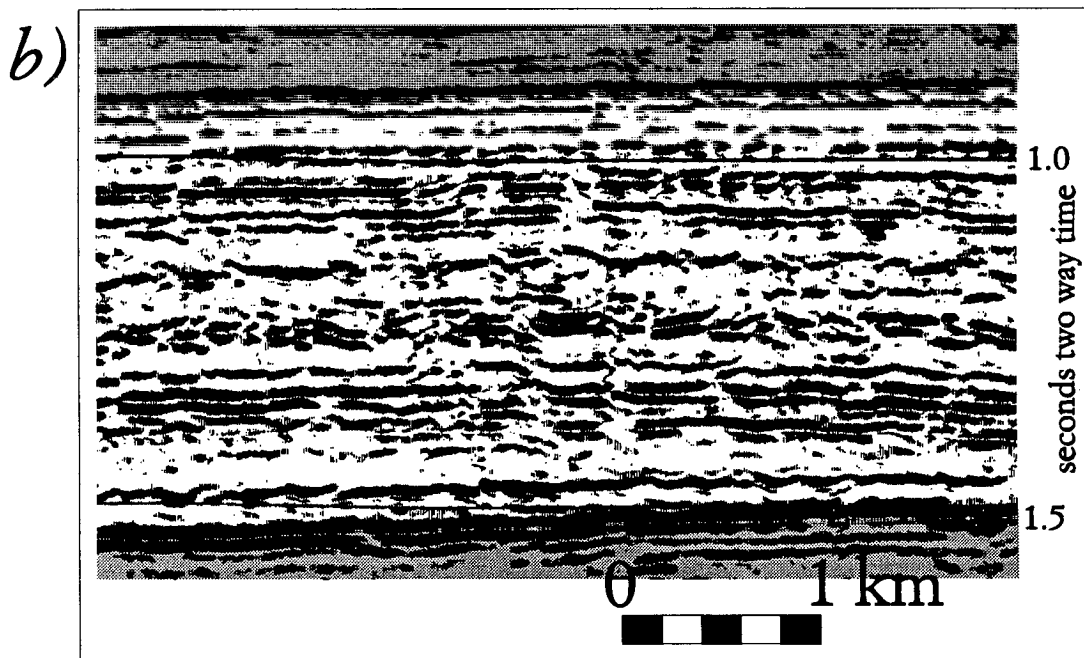
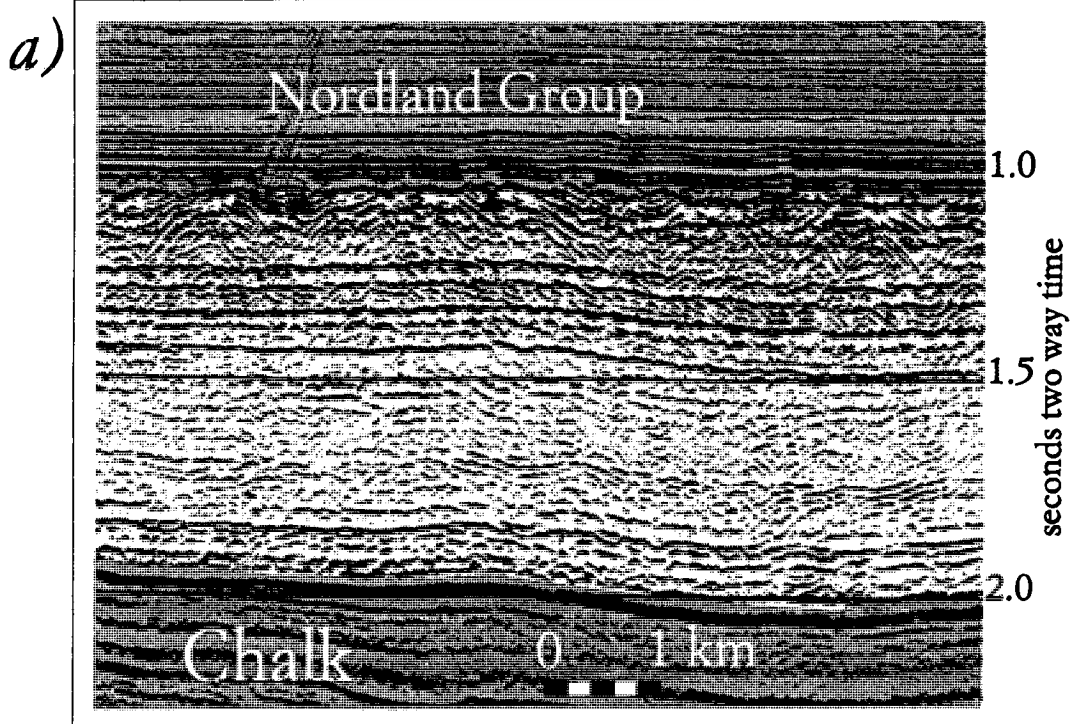


Fig. 2.2: (continued) c) Pervasive faulting within the clay succession, together with complex diffraction patterns near the top of the succession which may be due to diapirism. d) More "brittle" fault textures in clays from the east of the study area. Note how in "c" and "d", fault styles are different for different levels within the succession (seismic data courtesy of HGS Ltd.).

Internal unconformities

Only two unconformity surfaces have been previously recognised within the Lower Cenozoic succession of the southern North Sea, those of the Eocene with the Oligocene and of the Oligocene with the Miocene, these being derived from lithologic data (NAM & RGD, 1980). However, several hiatal surfaces can be seen within this succession upon inspection of the seismic data, the ages of which are unknown, and which are largely beyond the scope of this study. Similar surfaces have also been noted by Clausen & Korstgård (1993a), in sediments of the same age from the Danish Central Graben.

Regionally, internal reflector patterns within the Late Cenozoic succession closely mimic the largely salt controlled structure of the underlying chalks; no marked structural changes having occurred during deposition of the succession. However, an angular unconformity, here called Horizon "H_x", is apparently present up to 70ms below the top of the succession in the east of the study area. In the west of the study area, Horizon "H_x" laps out against Horizon "H_o" above, such that the angular unconformity is here coincident with Horizon "H_o" (see fig. 2.5). Events within the interval between the two horizons are apparently concordant with Horizon "H_o" above, and show onlap onto Horizon "H_x" below. Horizon "H_x" may correspond approximately with the base of well interval "X" (see section 3.2.1).

Internal character

The Lower Cenozoic succession often has a broken appearance on seismic data, due to the presence of small scale faults at all levels throughout (see fig. 2.2c & d). This faulting is intra-formational, as it does not extend into the chalk succession below and is truncated at the "mid-Tertiary" unconformity surface above. The lateral separation of the faults is between 300 and 1000m, these usually appearing to show extension with apparent, normal displacements of around 30m. However, there may be some reverse fault movement around salt domes.

The faults apparently have highly variable down-throw directions; there being, at best, only a weak preferred down-throw direction to the west. Also, different levels within the succession show quite different fault patterns and scales of faulting, which may depend upon the material properties of the clay (see fig. 2.2b to d & 2.6). A total loss of event continuity can be seen locally at certain levels, suggesting complete disruption. The succession appears to show de-coupling, both of the base of the succession from the Chalk below and of individual levels from each

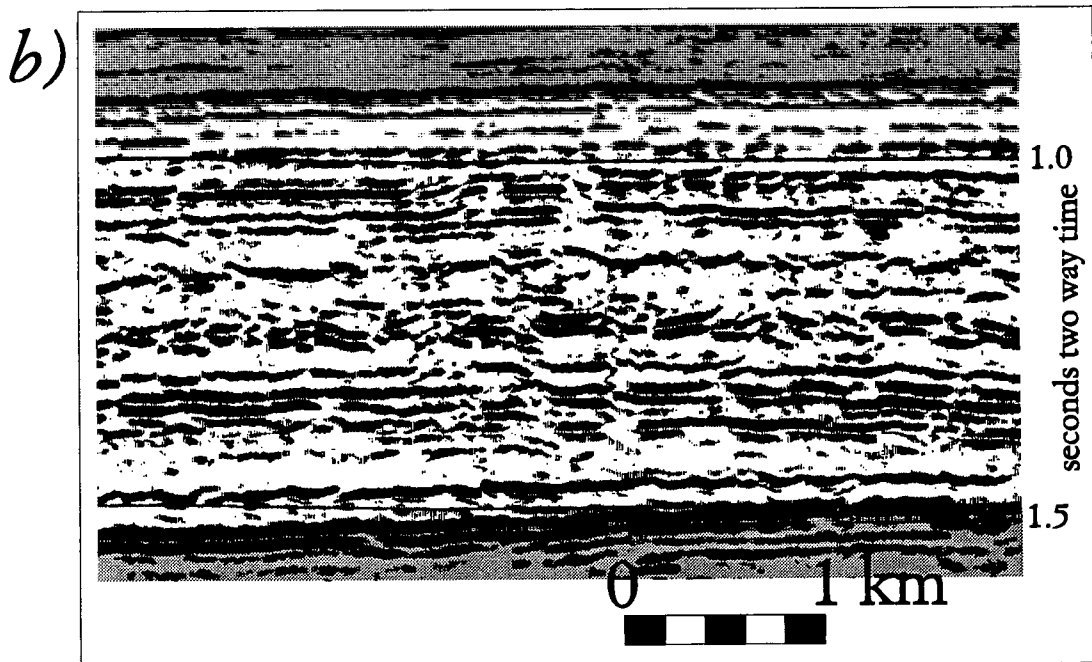
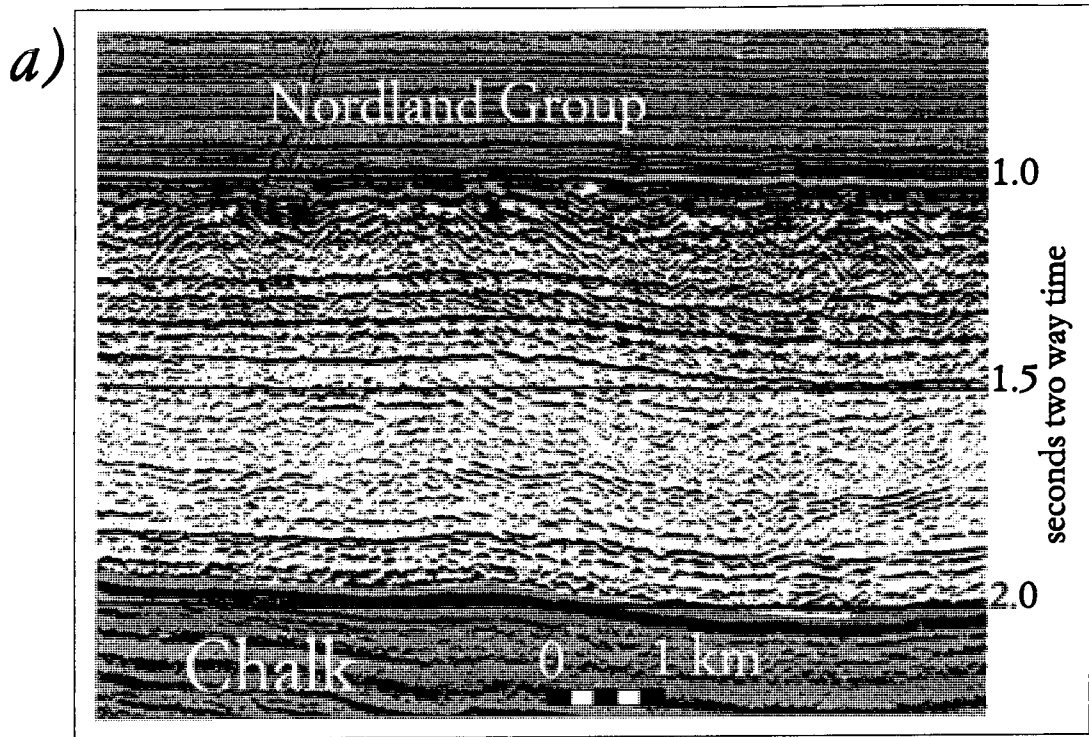


Fig. 2.2: (continued) *c*) Pervasive faulting within the clay succession, together with complex diffraction patterns near the top of the succession which may be due to diapirism. *d*) More "brittle" fault textures in clays from the east of the study area. Note how in "*c*" and "*d*", fault styles are different for different levels within the succession (seismic data courtesy of HGS Ltd.).

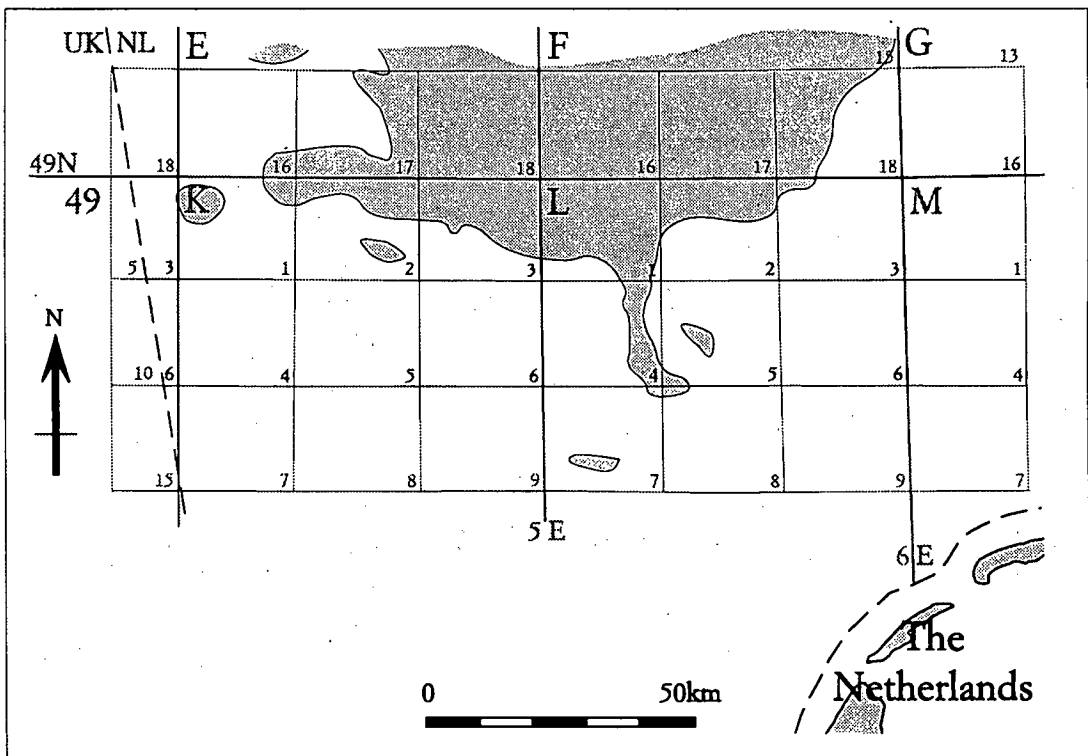
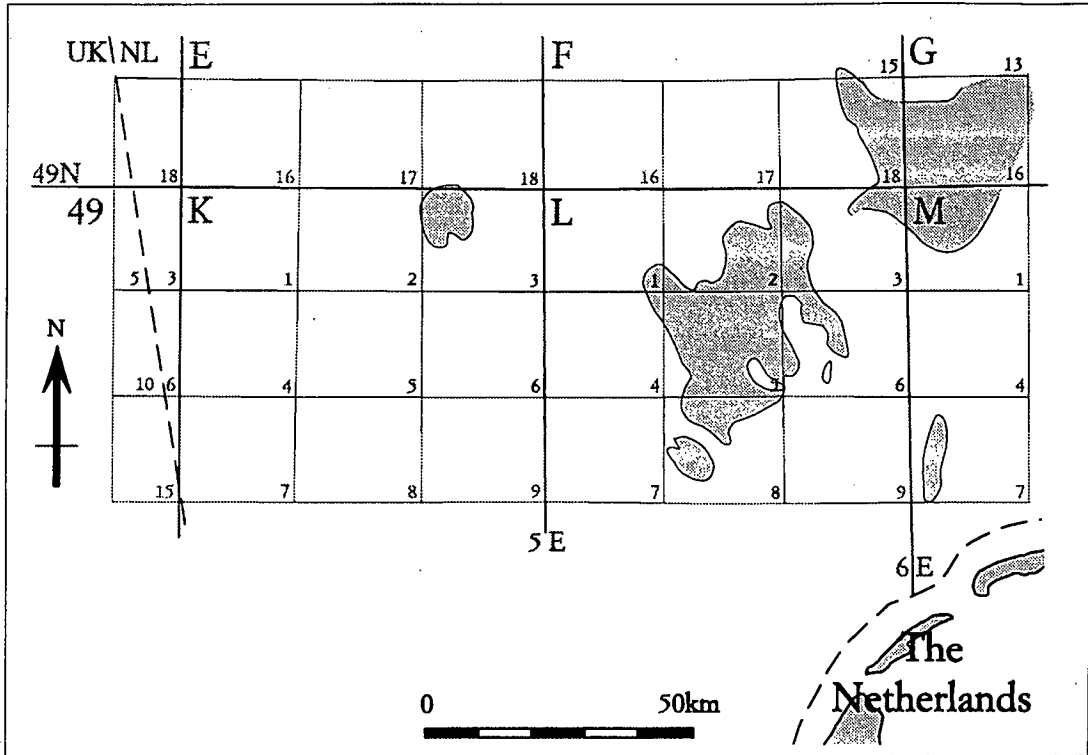
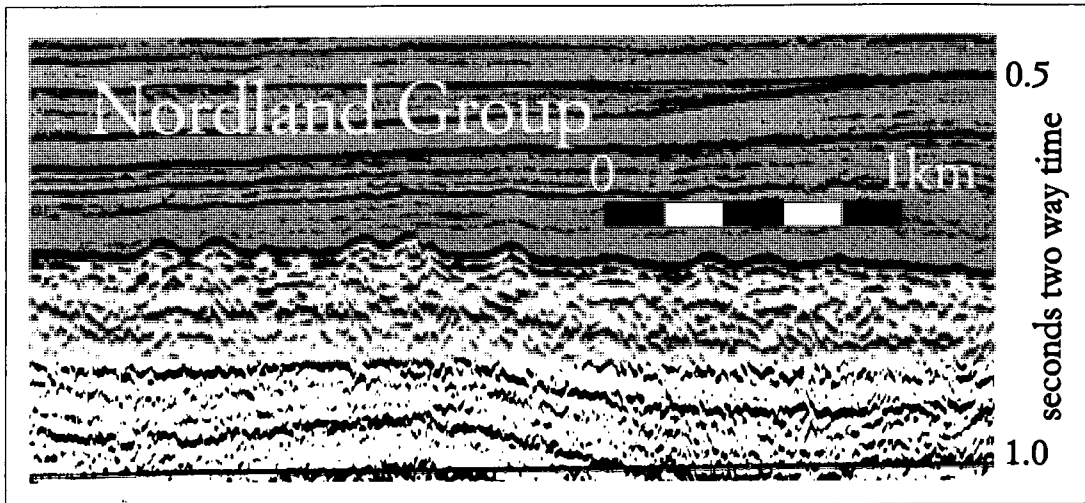


Fig. 2.3: Maps of: a) disruption distribution on seismic horizon "H₂". Compare with figure 2.8a to see the absence of disruption above salt domes; b) distribution of "diapiric" disruption near the top of the clay succession.

a)



b)

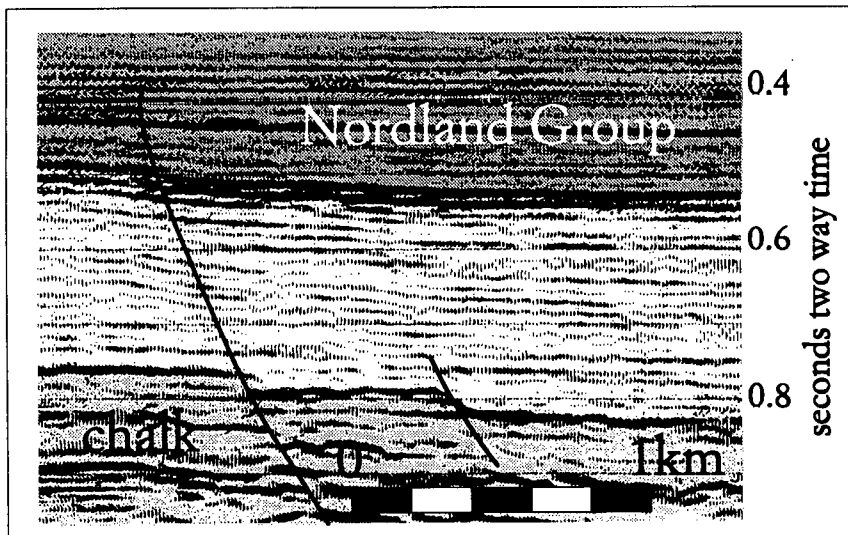


Fig 2.4: Examples of seismic textures around horizon "H₀". a) Horizontal, stepped events at the level of horizon "H₀", possibly due to the presence of a gas-water contact. b) Doming of horizon "H₀", possibly due to diapiric movement of the underlying clay (seismic data courtesy of NOPEC Ltd. and HGS Ltd.).

other. Where seismic sections show only weak faulting, this could be due to the lack of visible structure in the plane of section along which the seismic sections were recorded. However, this needs to be analysed further, using dense grids of seismic data.

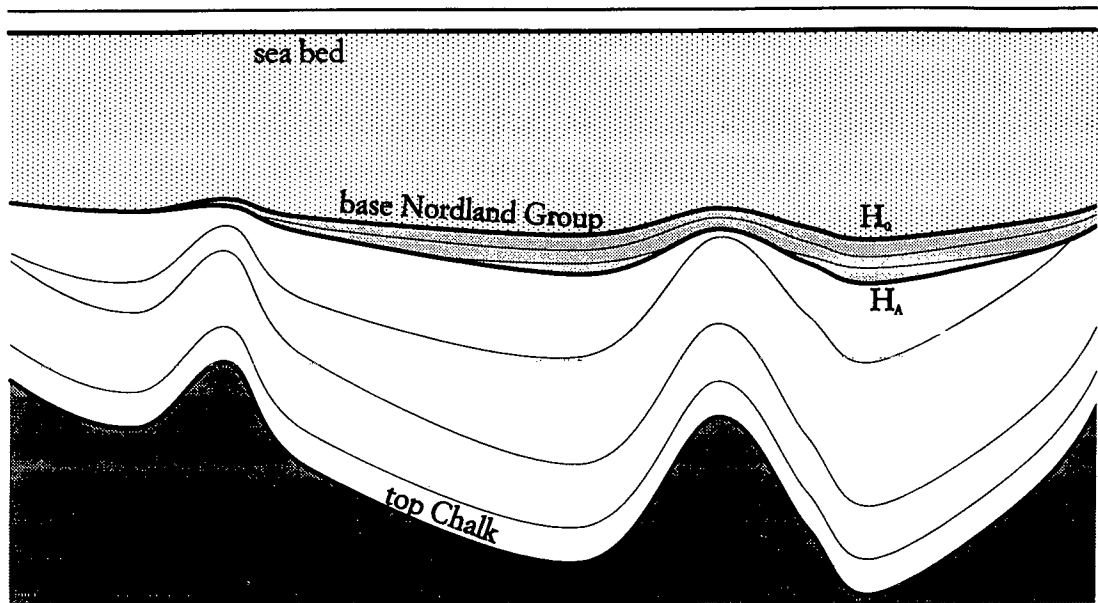


Fig. 2.5: Possible stratigraphic configuration of seismic horizons "H_n" and "H_x", suggesting the more significant nature of the unconformity defined by horizon "H_x".

In the north of the study area, where the succession is most pervasively disrupted, high amplitude, negative polarity, dish-shaped and diffractive packages of events can be seen at the top of the succession (see fig. 2.2c). Each package can be over 100m thick and up to 1km across. The tops of these packages are usually truncated along Horizon "H_n", events showing dips relative to the horizon of up to 10°. However, in the NW of the study area they are associated with doming of the horizon (see fig. 2.4b), and this doming has also affected some of the basal packages of the Nordland Group. The distribution of this disruption seems to correspond approximately with the distribution of well interval "X" (see fig. 3.5), near top of the lower Cenozoic succession, and with sediments above Horizon "H_x" (see fig. 2.3b).

Cusate structures reminiscent of de-watering or de-gassing also occur locally in areas below major mass flows in the overlying Nordland Group (see figs. 2.7a-c & 2.8). These not only pervade the whole Lower Cenozoic succession within such areas but also apparently affect the underlying chalk (see also the discussion on mass flows in section 2.3.2).

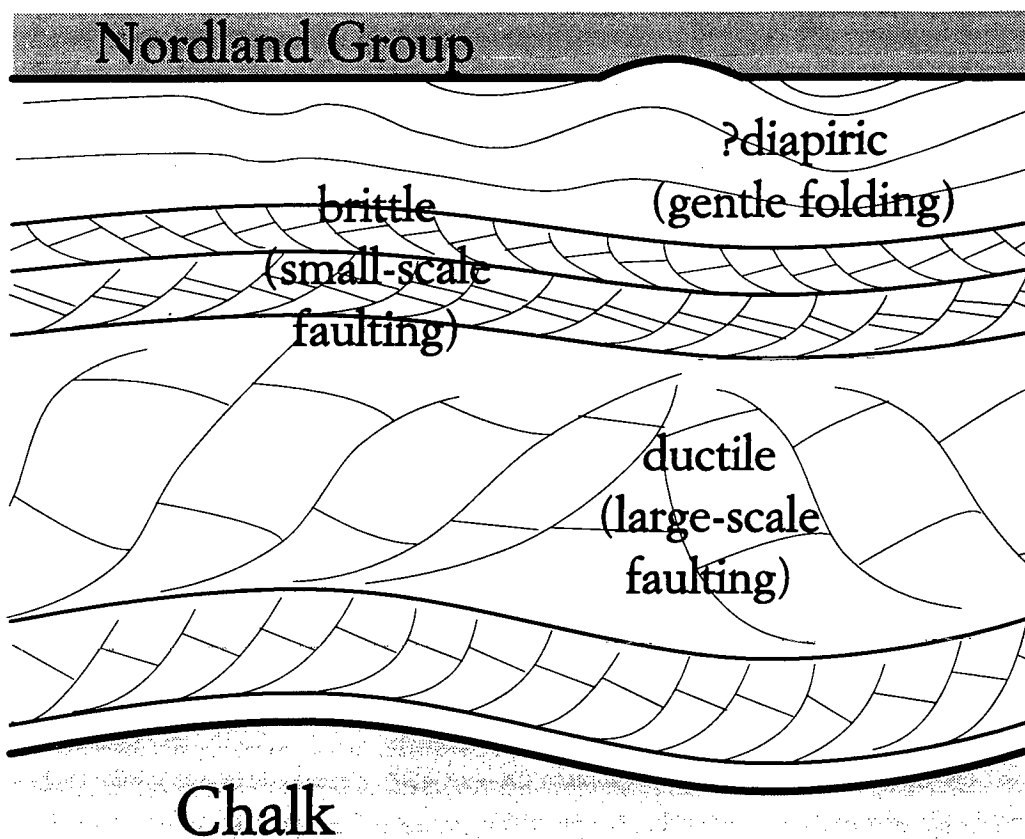


Fig. 2.6: Possible internal structure of the lower Cenozoic “pre-Nordland Group” succession, showing vertical stratification of fault patterns within.

2.2.2: The Nordland Group Succession

All intervals described from the Nordland group succession have been labelled “A” to “X” in order of decreasing age, separated by seismic horizons “0” to “22”. Within each interval, packages have been labelled A₁, A₂, etc., again in order of decreasing age.

Intervals were correlated with the existing nomenclature of Cameron *et al.* (1986) and Jeffery (1989) by comparison of interpretations made in this study with the interpreted sections and contour maps presented in both of the above, along with additional information from Jeffery (1993).

Reference is made to “landward” and “basinward” onlap within this section, using the assumption of an eastern source area, via the Baltic River System, for the sediments of the Nordland Group within the study area (cf. Bijlsma, 1981), as little sediment apparently was supplied from western margin of the southern North Sea throughout this time.

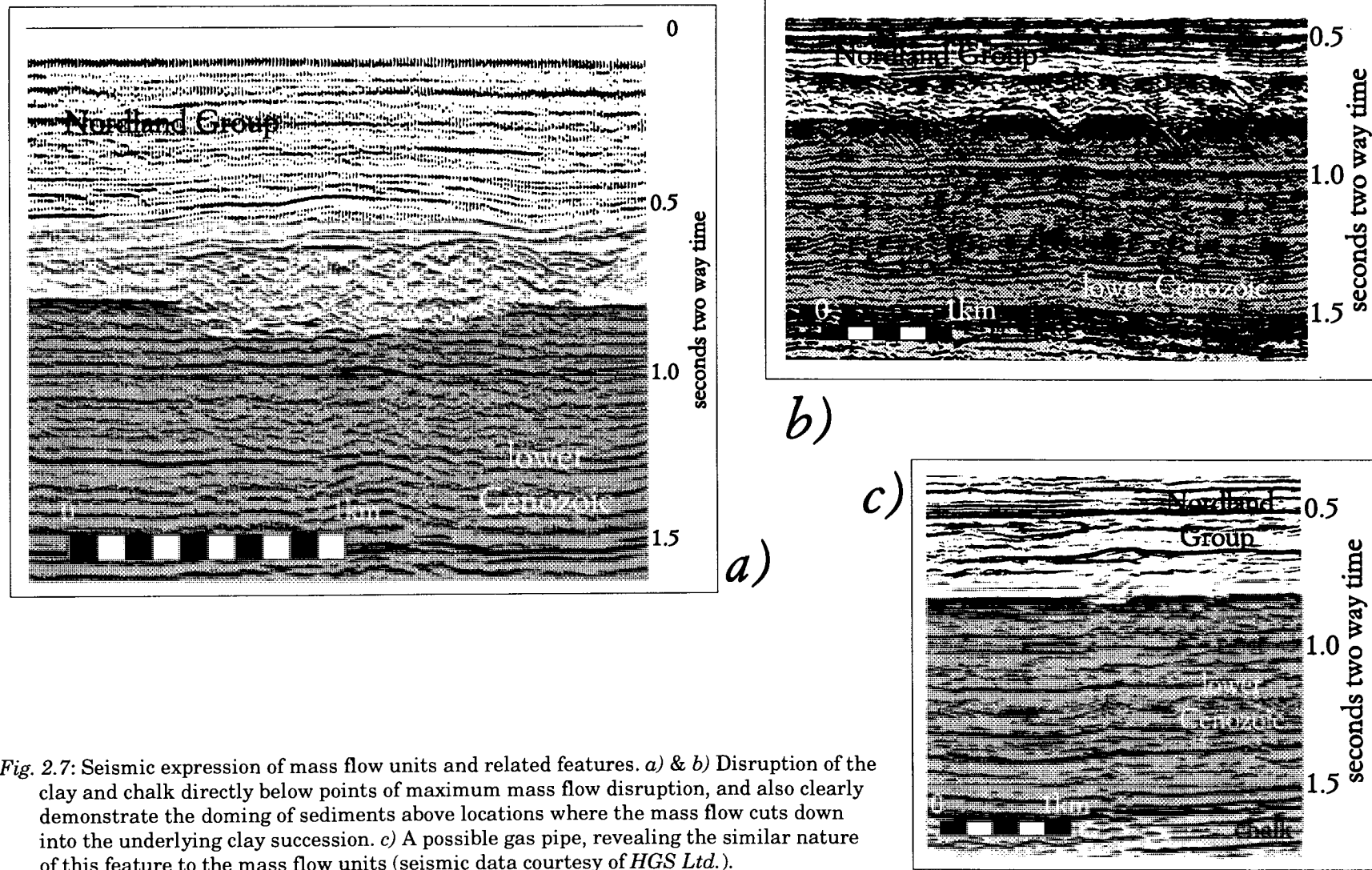
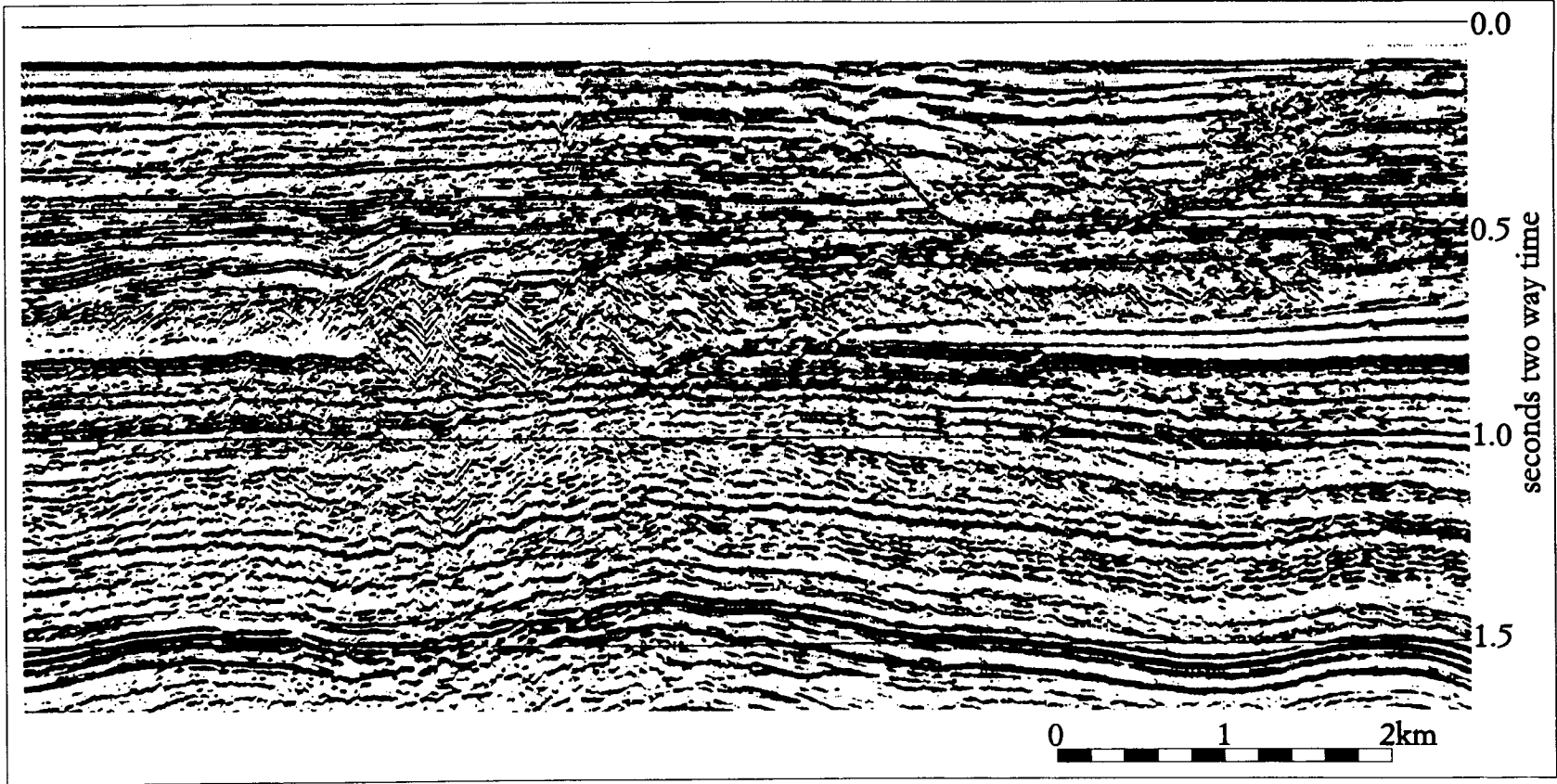


Fig. 2.7: Seismic expression of mass flow units and related features. *a)* & *b)* Disruption of the clay and chalk directly below points of maximum mass flow disruption, and also clearly demonstrate the doming of sediments above locations where the mass flow cuts down into the underlying clay succession. *c)* A possible gas pipe, revealing the similar nature of this feature to the mass flow units (seismic data courtesy of HGS Ltd.).



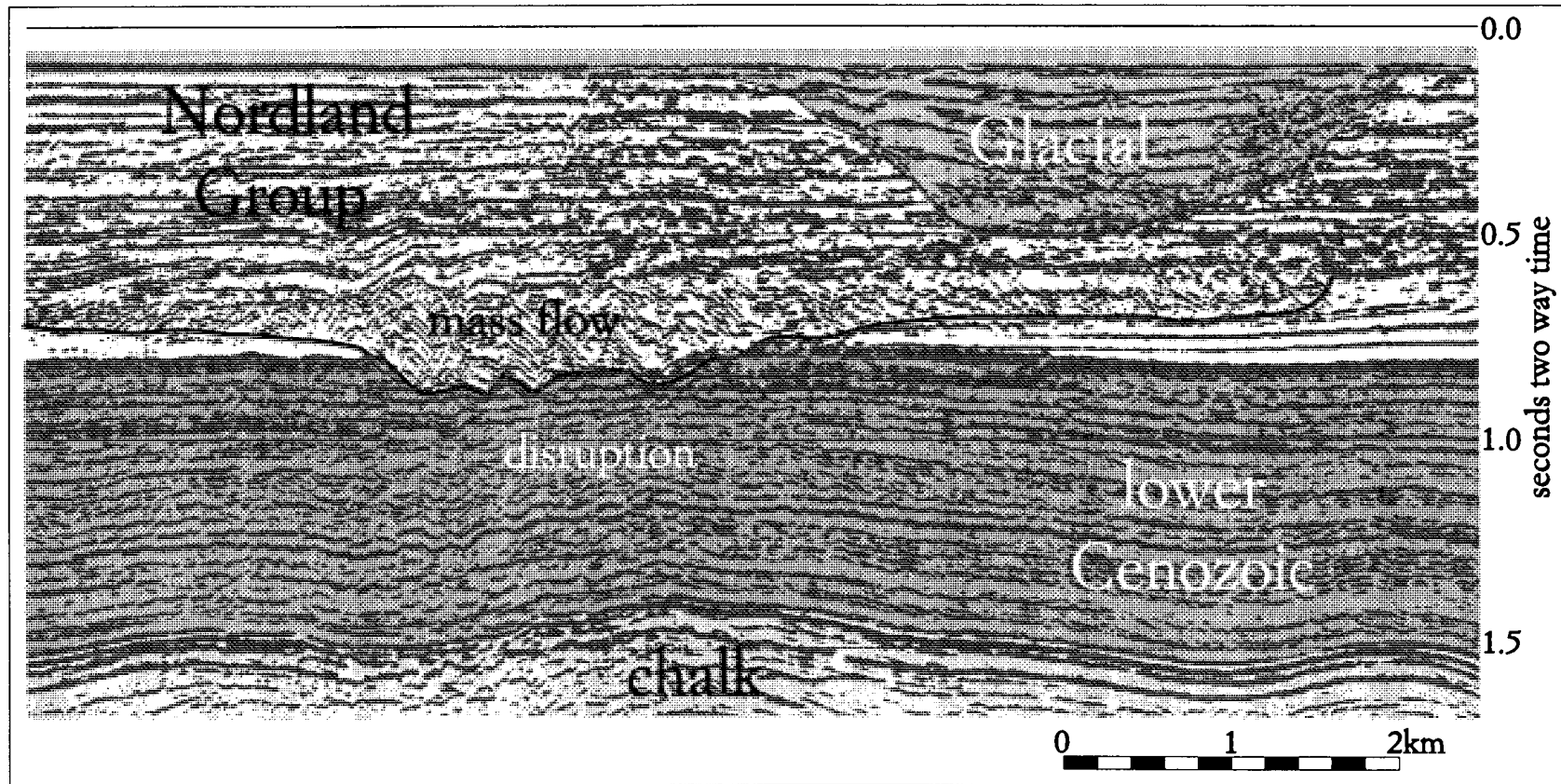


Fig. 2.8: ("a" and "b") Seismic section, interpreted and uninterpreted, showing individual fault blocks resolved within the structure of the mass flow unit. These fault blocks apparently extend all the way to the mass flow failure point at the right-hand side of the seismic line. Note also the disruption pattern of both the clay and chalk beneath the point of maximum mass flow disruption, the possibly irregular nature of the base of the flow where it cuts down into the underlying clay succession, the doming of the sediments above the mass flow maximum and the large glacial channel near the top of the Nordland Group (seismic data courtesy of HGS Ltd.).

Brief interpretations are given at the end of each of the interval descriptions, based purely upon study of the seismic data-set. As such, they are only guides, and are not necessarily indicative of the true history of the succession.

TWT maps of horizons "H₁" to "H₂" are illustrated in figures 2.11a to v. TWT isopach maps of intervals "A" to "W" are illustrated in figures 2.12a to v. The relationships and the internal structure of intervals "A" to "X" are illustrated in figures 2.13 and 2.14.

The "mid-Tertiary" unconformity (H₁)

This horizon is the lowest to be interpreted in detail in the seismic data study, and its character has been documented in the previous section. The TWT contour map of this surface (see fig. 2.9) shows the relief on this event to be around 750ms within the study area, whilst the deepest point is at 1090ms TWT, approximately 1100m below sea level. The major axis of subsidence is the southernmost part of the North Sea Central Graben. A structural line has also been identified in the west of the study area, running NW-SE across the area, which marks a sharp change in subsidence rate, higher subsidence rates occurring to the NE of the line. This may be related to deeper tectonic control (cf. Clausen & Korstgård, 1993a). Salt induced uplift has also affected this horizon, generating the only large faults to break it, and locally producing relief of up to 400m. An W-E trending, linear salt uplift structure shows collapse features along its apex in the NW corner of the area.

Isolated mounds

At two locations within the study area, in the NW and in the NE, small, isolated sediment mounds, up to 2km across and 50m high, occur on the "mid-Tertiary" unconformity surface (see fig. 2.10). These are apparently associated with salt collapse structures or trough erosion. Internal reflectors within the mounds are parallel with the upper surface of the mounds and show downlap onto the "mid-Tertiary" unconformity surface. The ages of these mounds are unknown. Unusually, the overlying sediments are concordant with the upper surface of each mound, this influence being traceable up to 300m above the mound. Better examples of these features are seen to the north of the study area (C. J. Kay, *pers. comm.*).

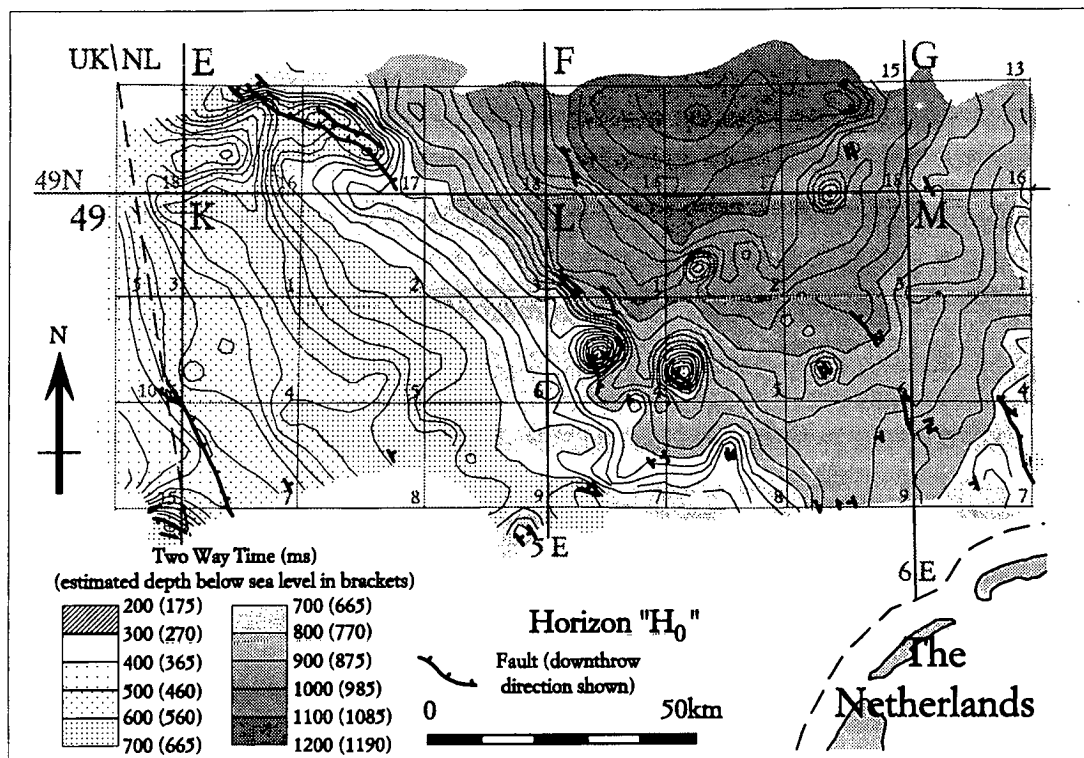


Fig. 2.9: TWT map, in ms, of horizon "H₀", the base of the Nordland Group, showing observed fault distributions.

Interval A (H₀-H₁)

This interval occurs only in the NE corner of the study area, its fore-sets dipping to the WSW. Its upper limit is largely defined by the top of a mass flow feature (see fig. 2.15). The interval is up to 350m thick in the study area alone, but possibly includes sediments deposited over a wide age range. A division into four packages can be made.

Package A, gently dips and is complex, as it probably includes the toe-sets of many depositional packages better developed to the NW of the study area. It has undergone mass flow deformation of its upper surface, obscuring its internal structure. The upper three packages have much steeper fore-sets with dips of up to 1.5°. Package A, slightly back-steps, showing basinward onlap onto package A. Package A, progrades again, showing landward onlap onto the preceding fore-sets of package A. Package A, again back-steps. The upper fore-set and top-set geometry of these packages is unknown, being developed out of the study area. Also, the exact relationships of the upper packages are obscure due to the mass flow deformation of the upper surface. Where the interval is undisturbed, internal events are weak and discontinuous.

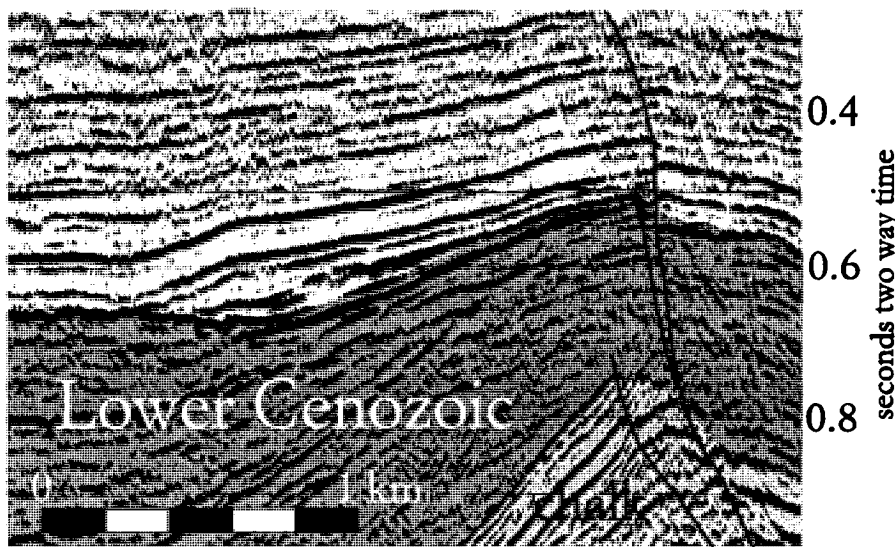
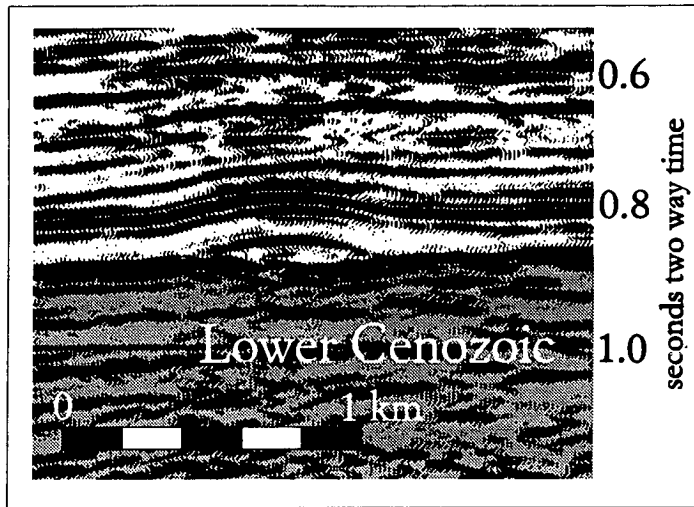


Fig. 2.10: Seismic expression of domed sediment packages resting upon horizon "H". Note the presence of troughs cut into the underlying, lower Cenozoic clay succession below the domes (seismic data courtesy of HGS Ltd.).

Interval B (H₁-H₂)

This interval is around 190m thick and oversteps interval "A" to the SW. Fore-sets all face SW, with slopes of up to 1.5°. The upper surface of the interval is defined by a moderate to high amplitude, continuous event over most of the area (see fig. 2.15). Toe-sets are only moderately developed. Six packages are present within this interval. Package B, back-steps and onlaps interval "A" landward, with no top-sets. Package B, is transgressive, back-stepping further, and shows thick top-set

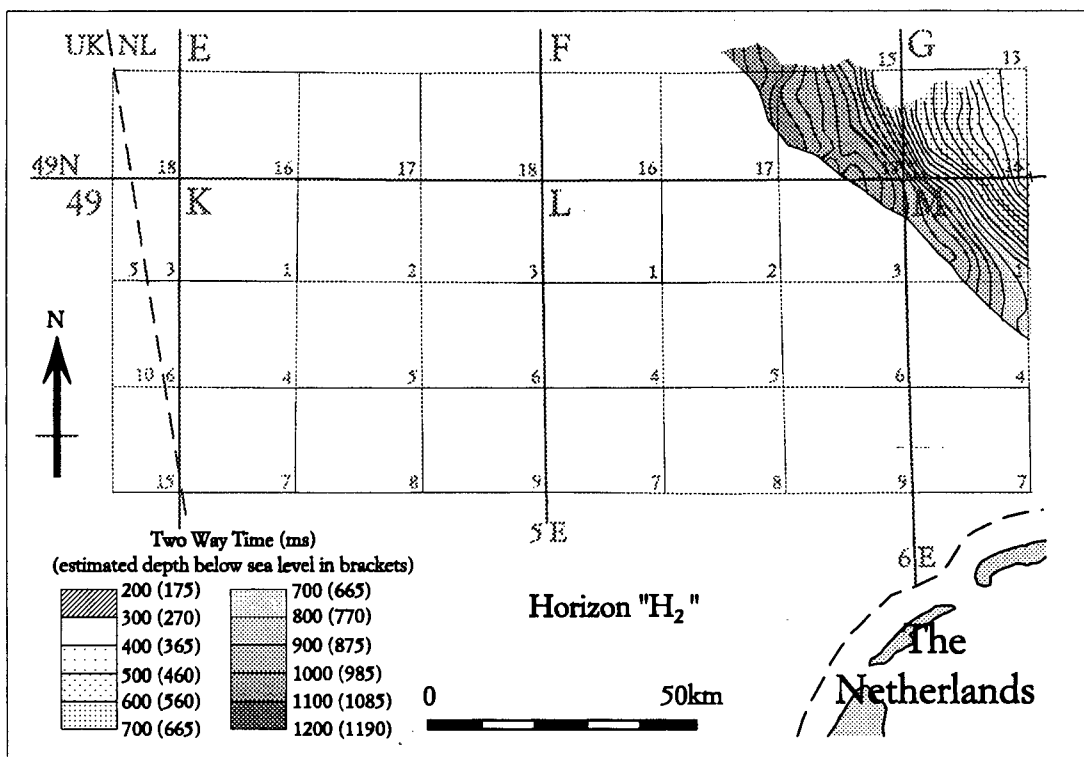
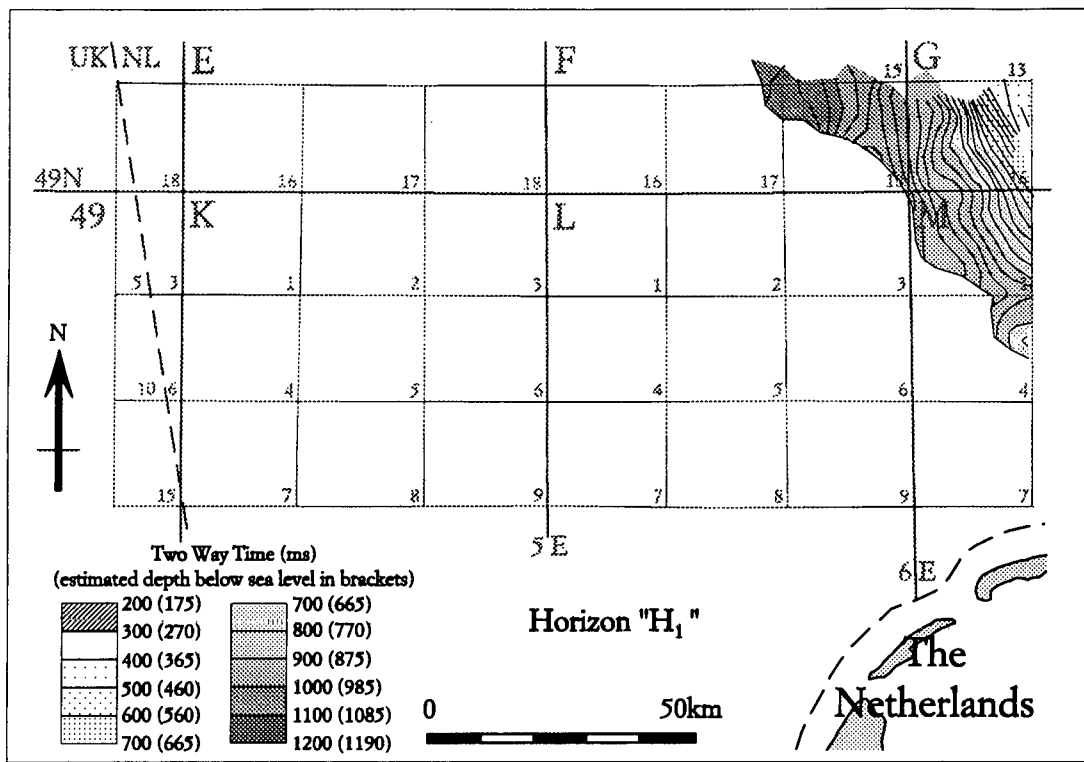
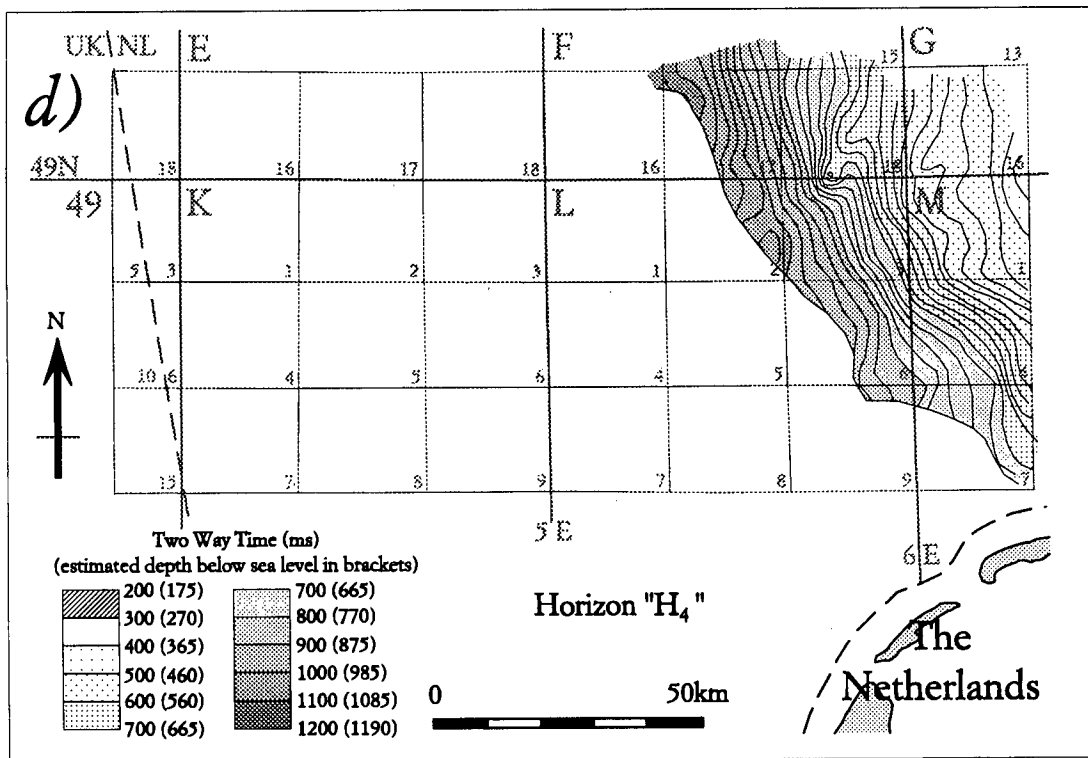
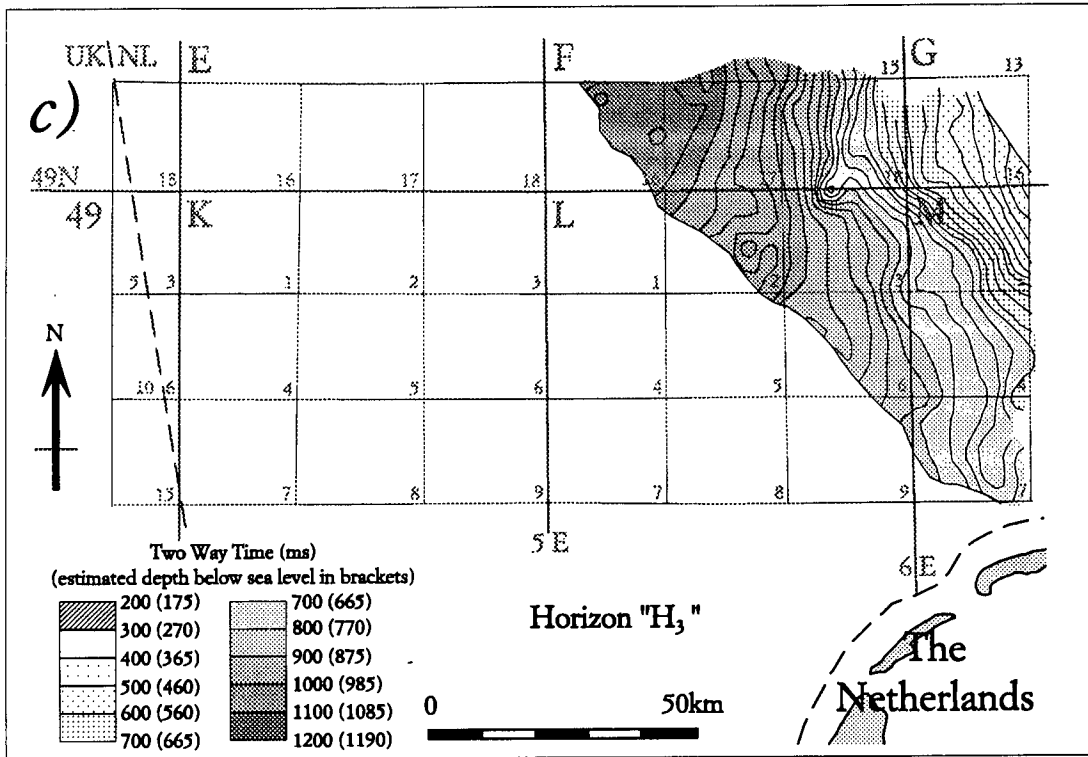
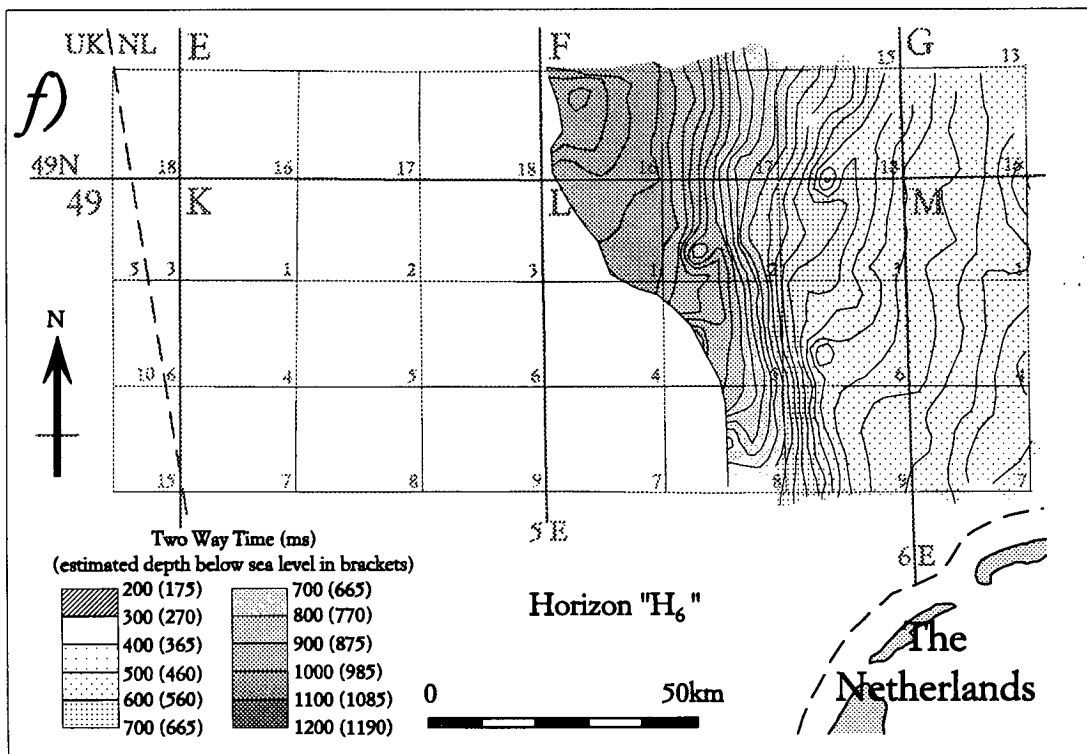
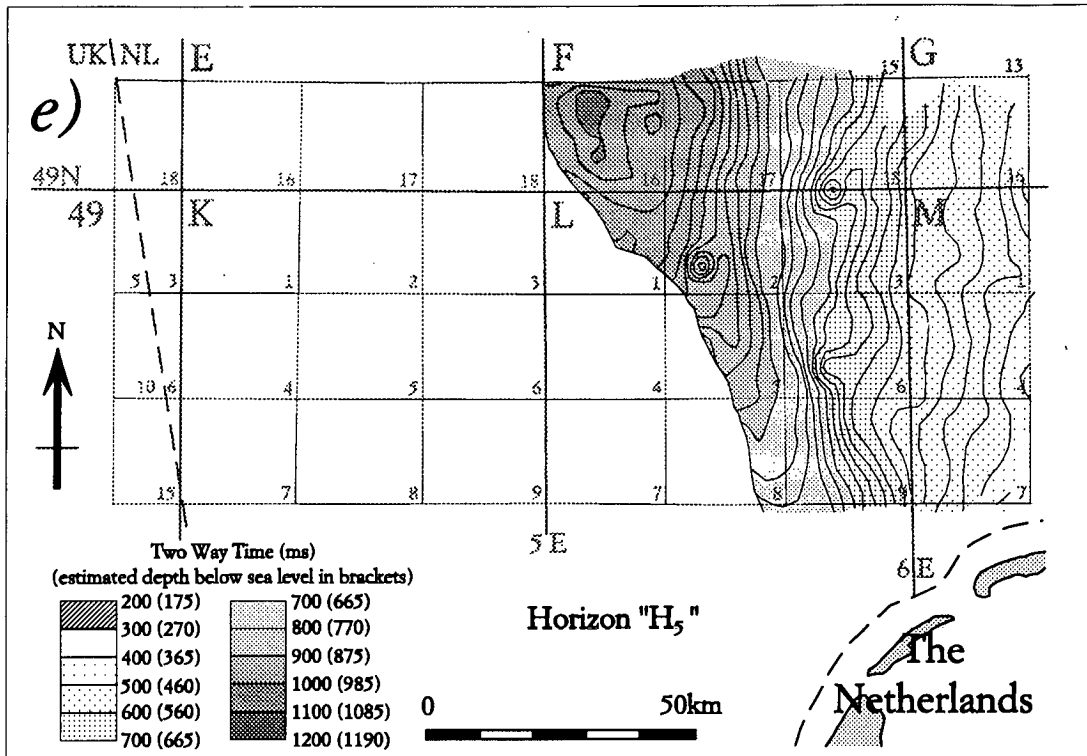
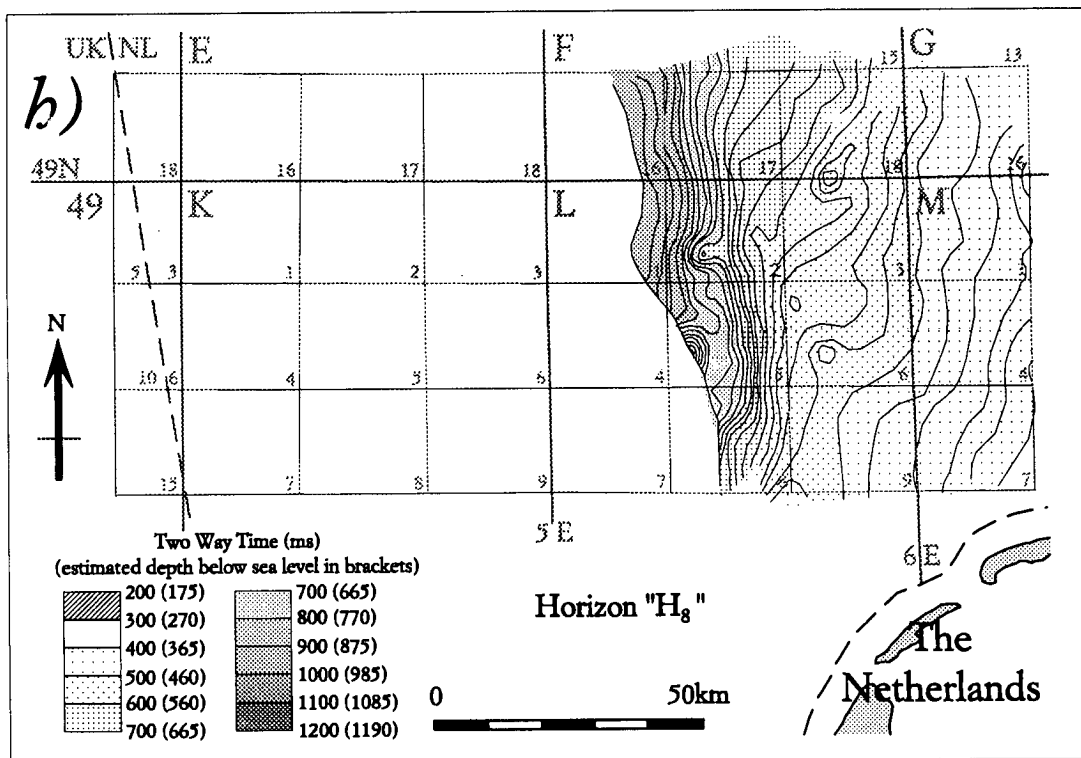
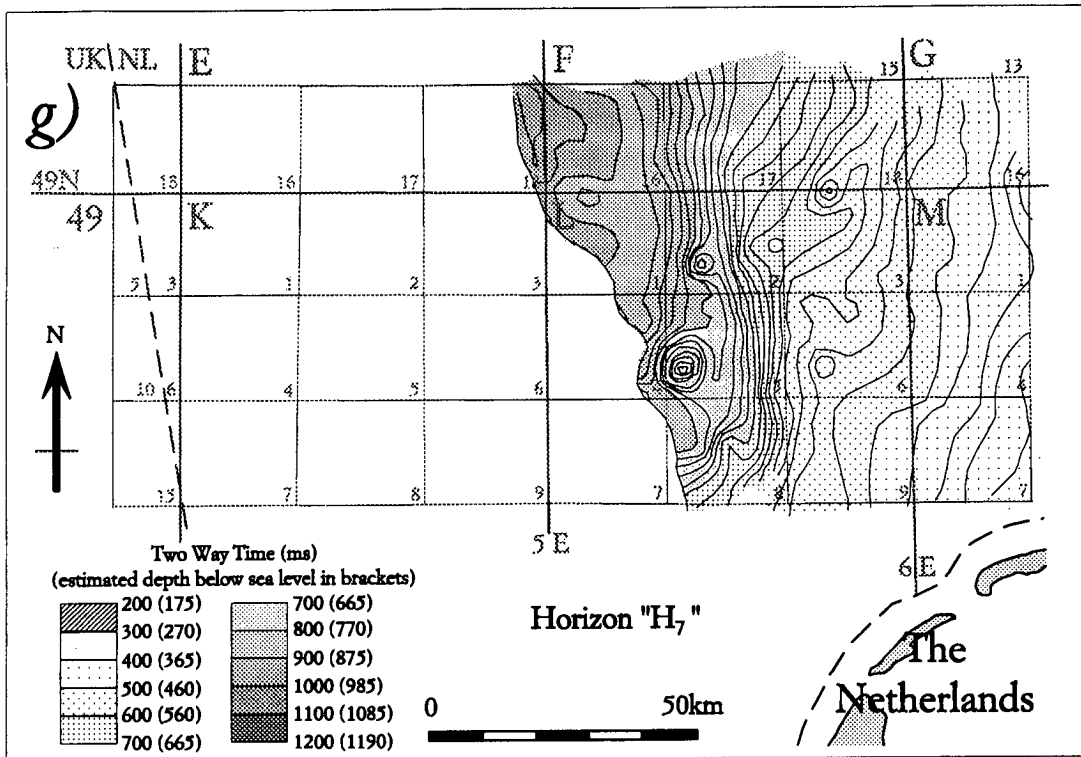
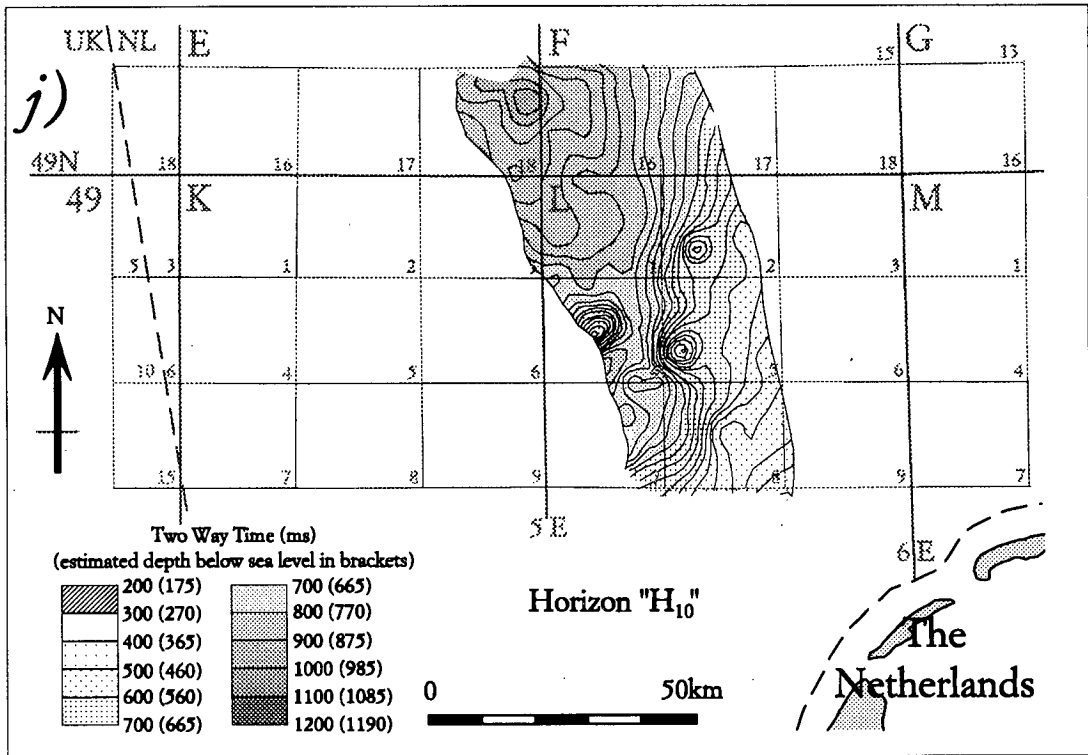
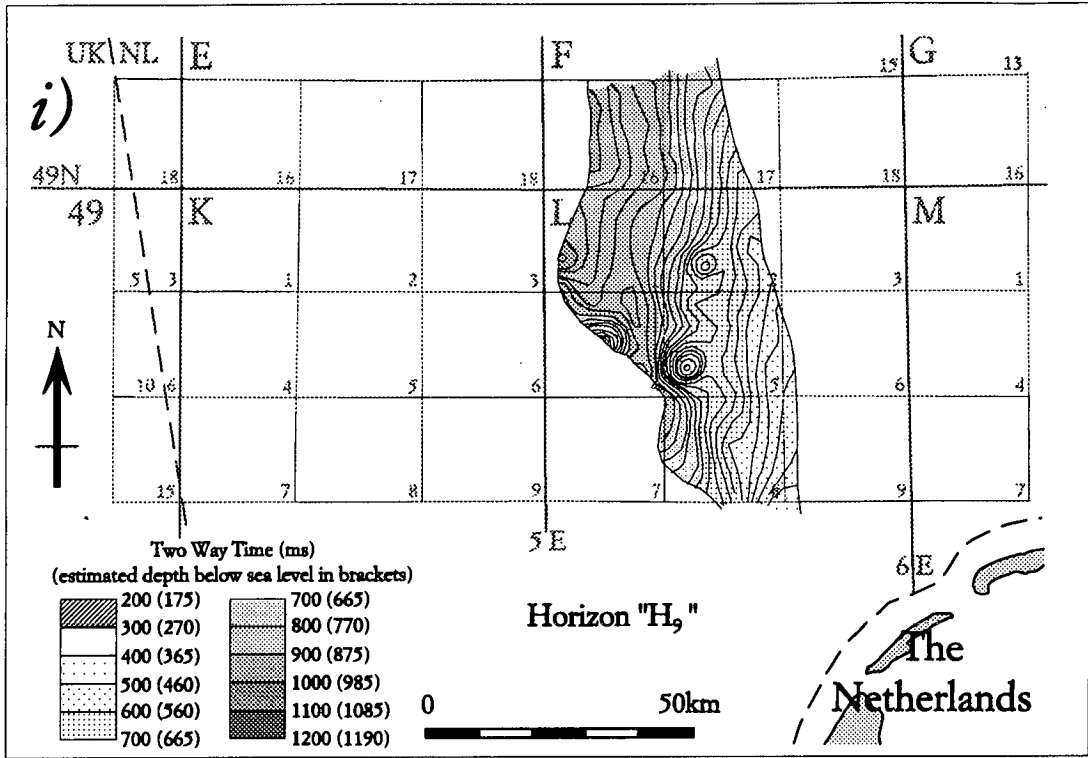


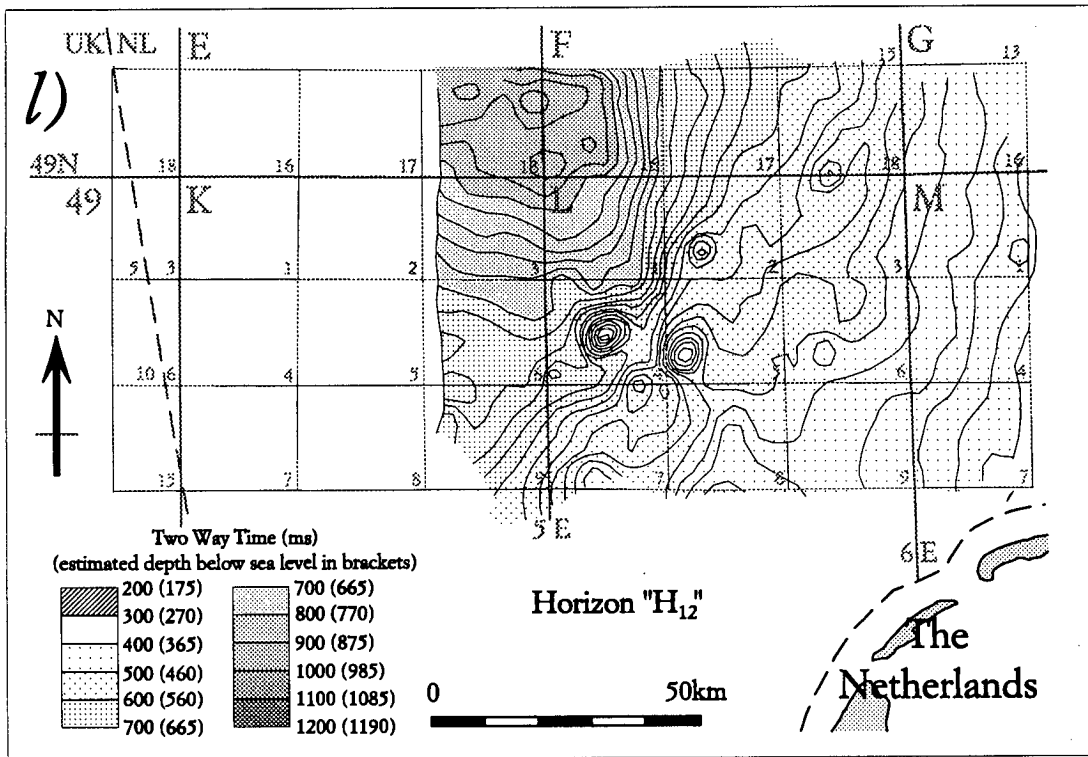
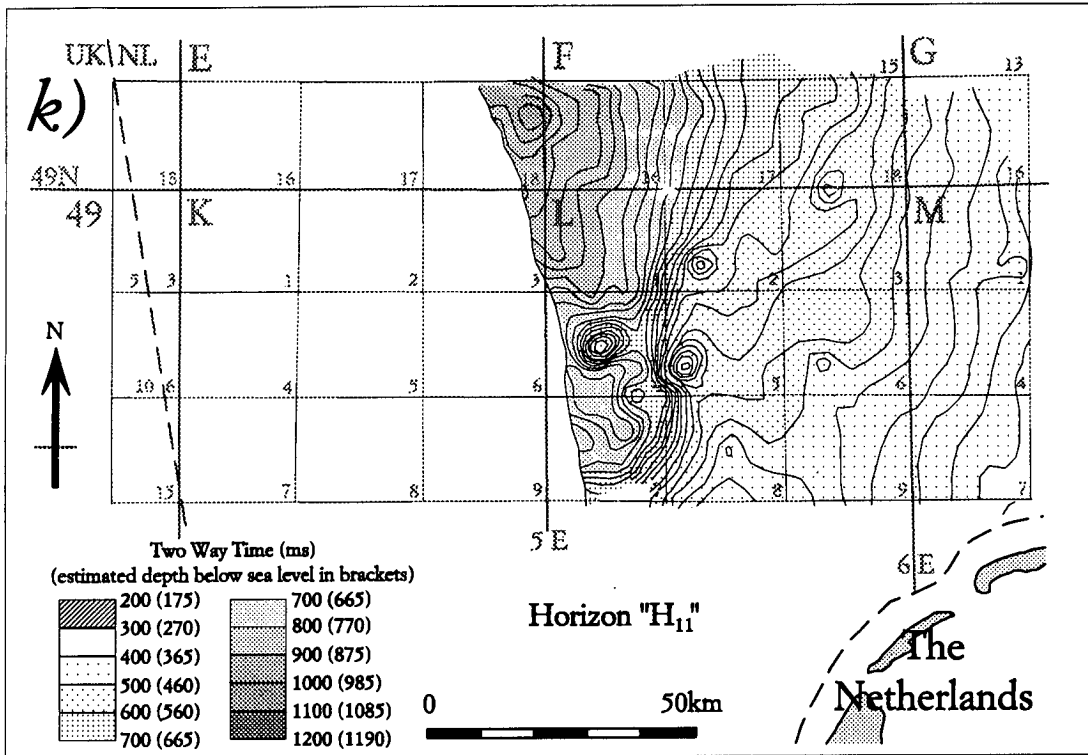
Fig. 2.11: ("a" to "v"; drawn on pages 51 to 61) TWT maps, in ms, of horizons "H₁" to "H₂₂", showing the progressive expansion of depositional area first to the SW, then to the west.

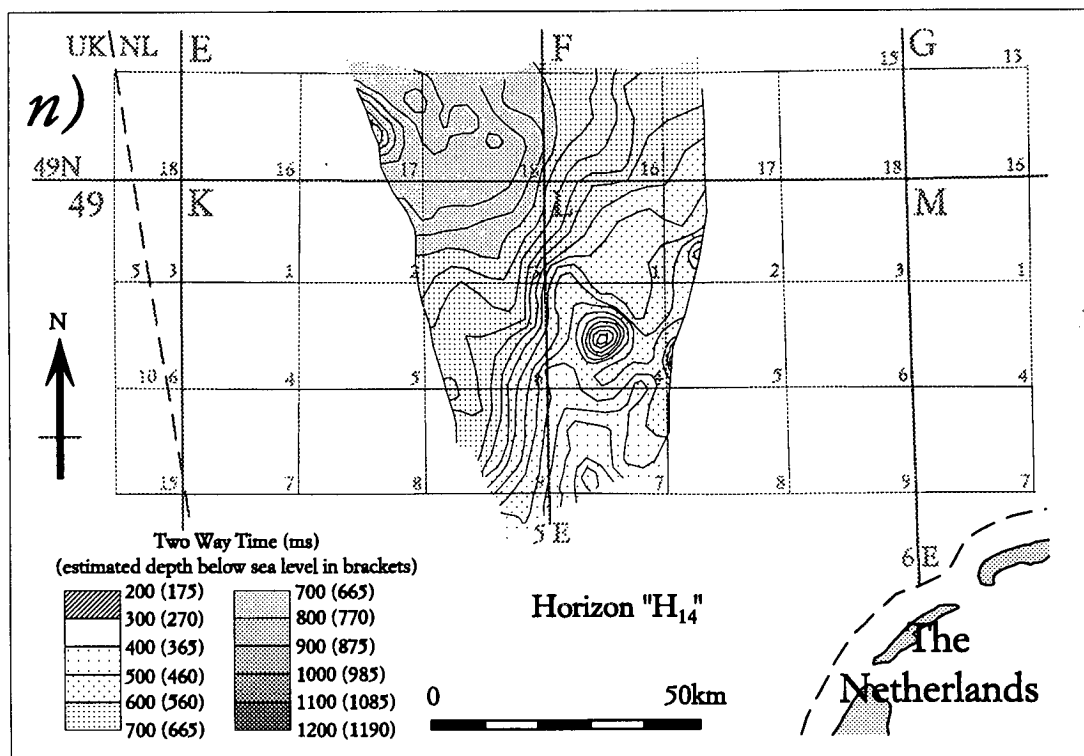
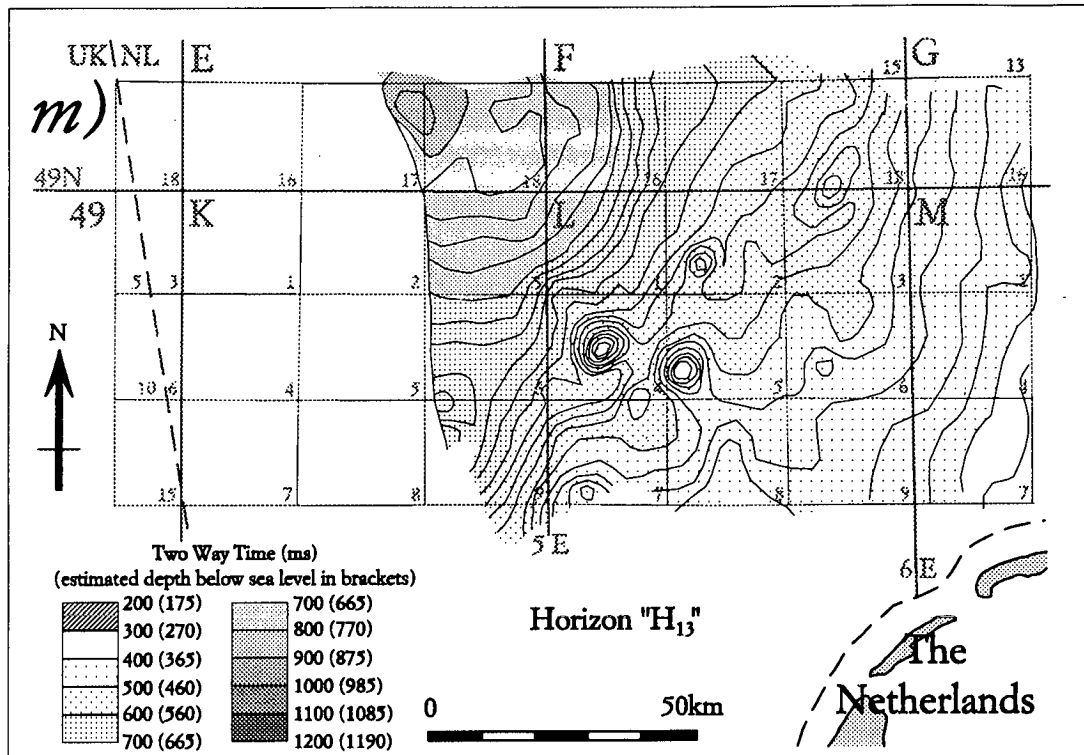


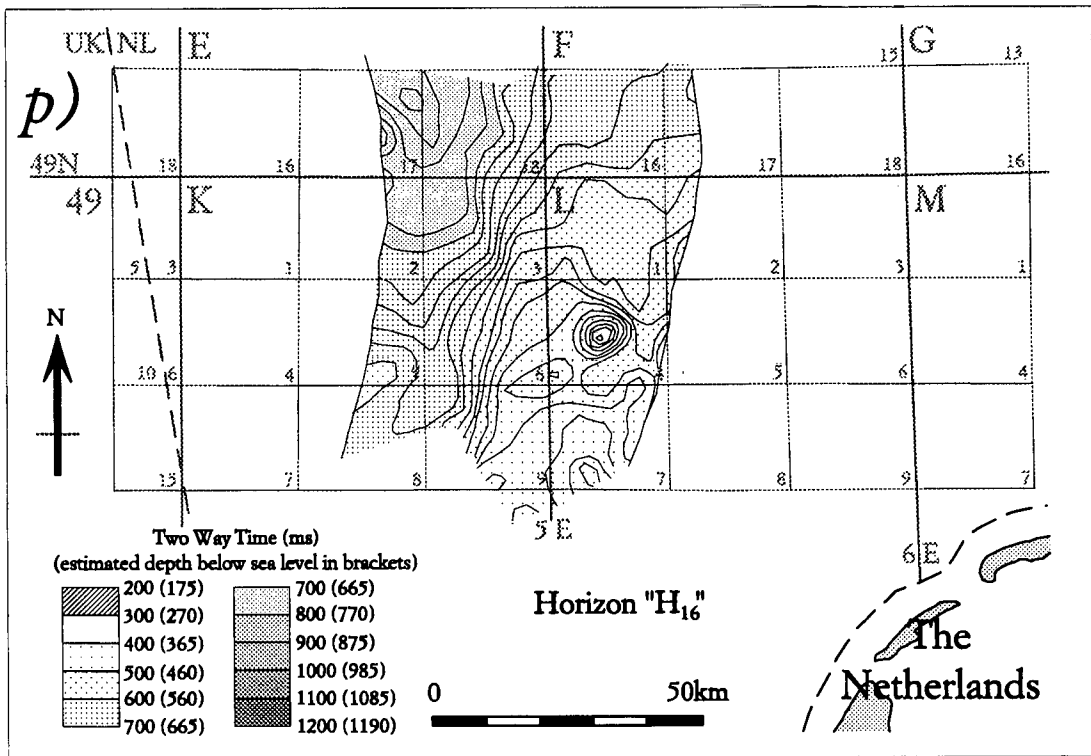
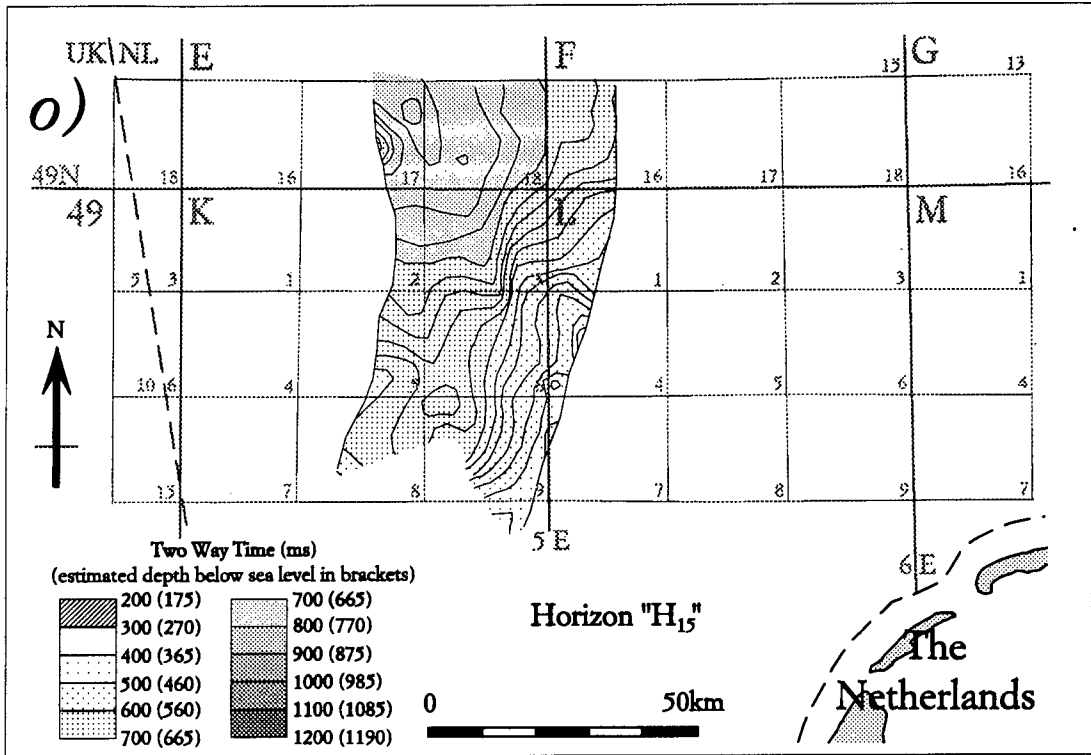


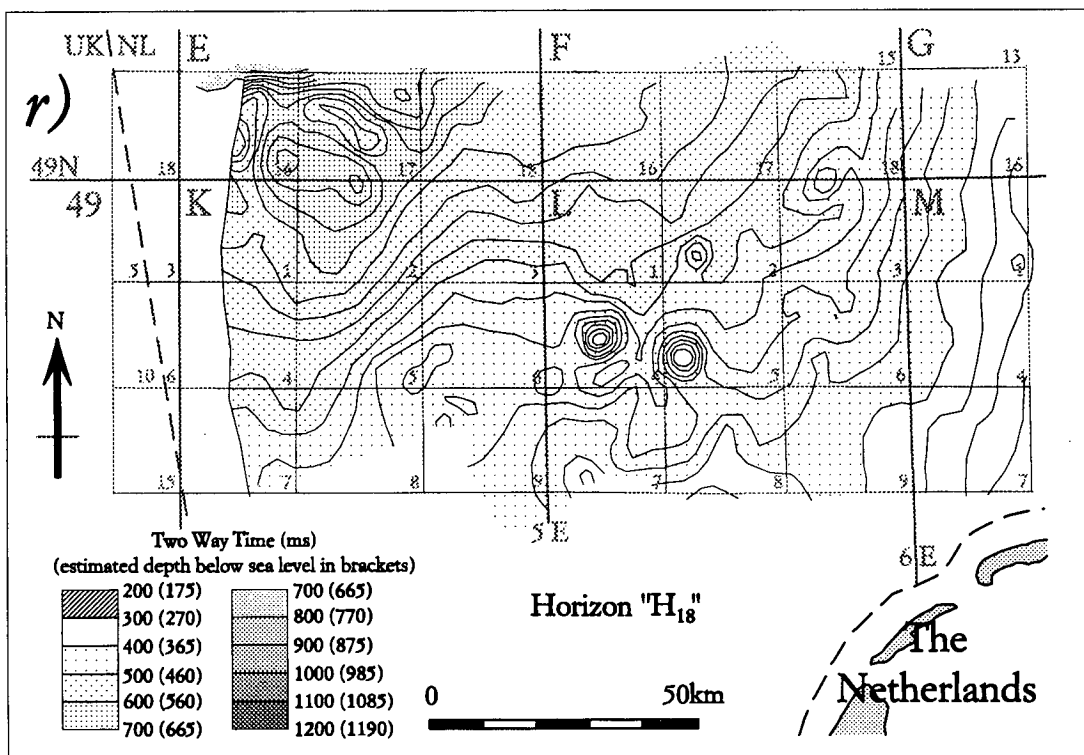
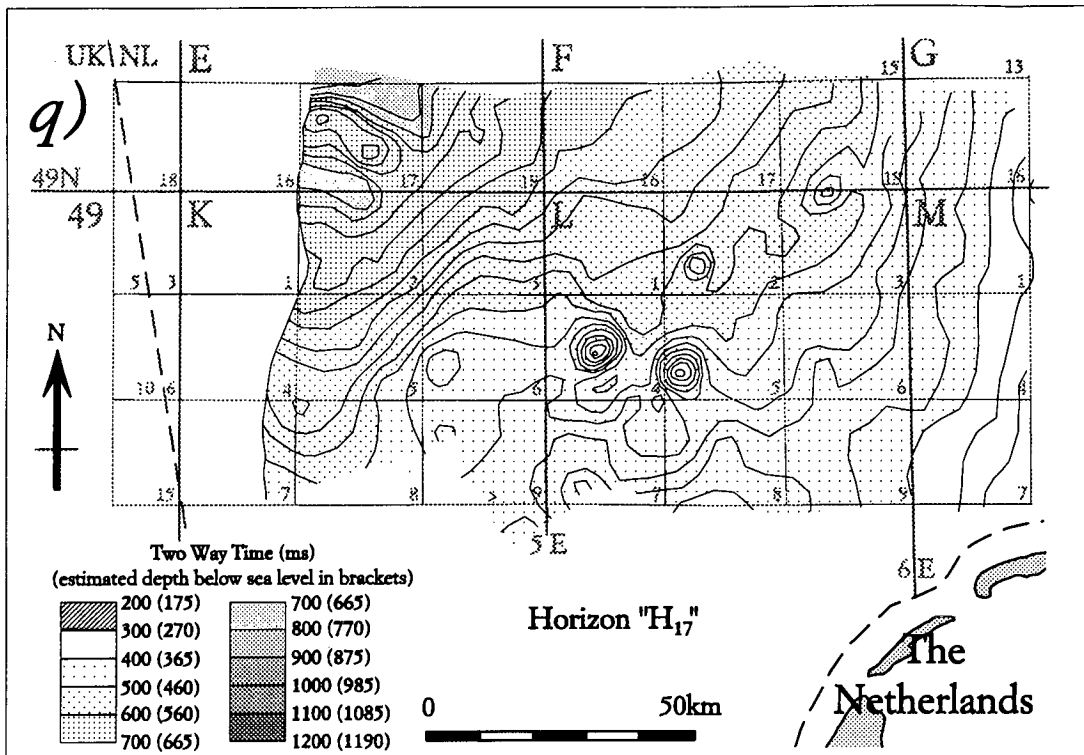


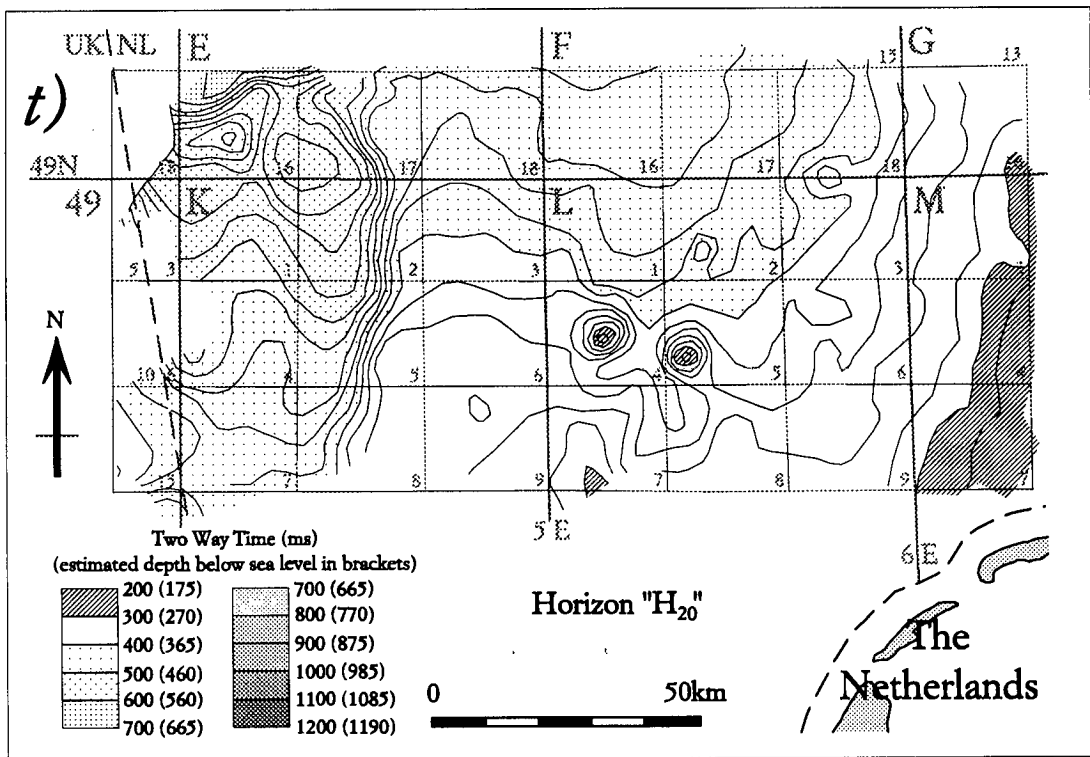
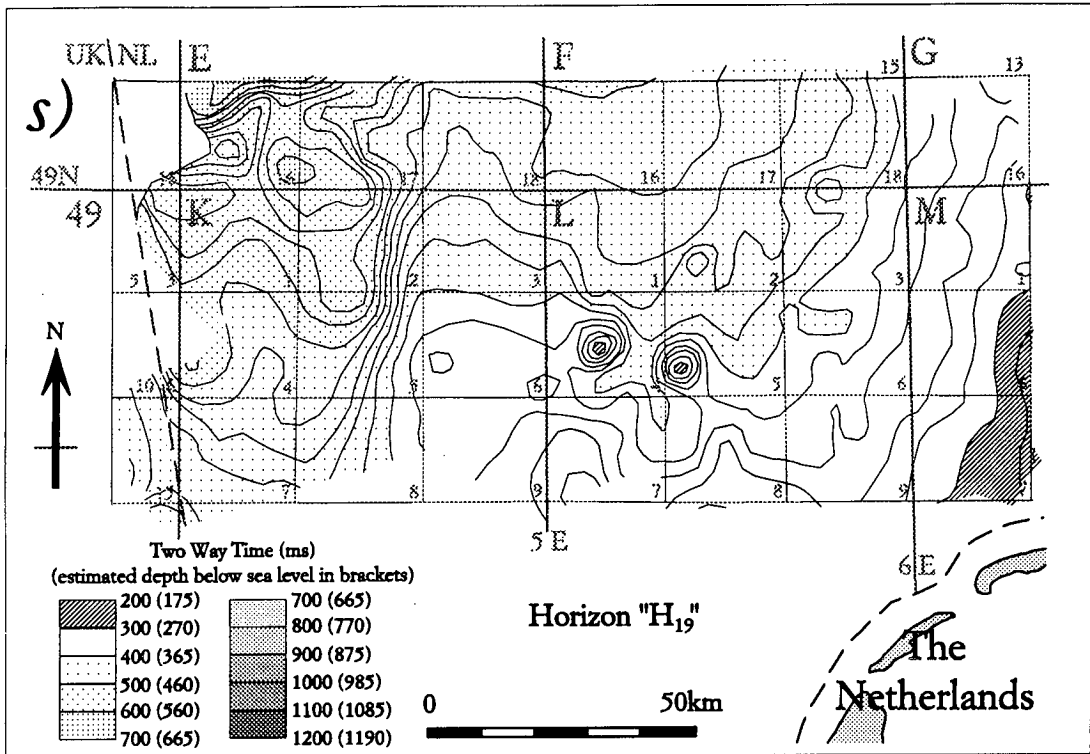


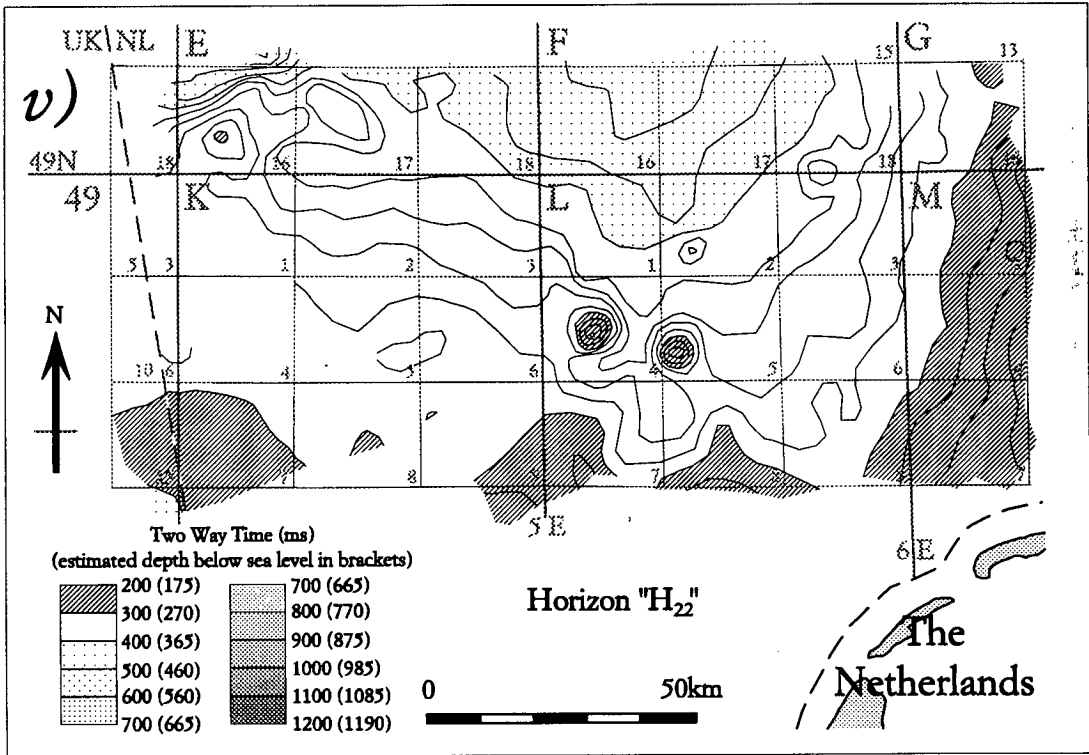
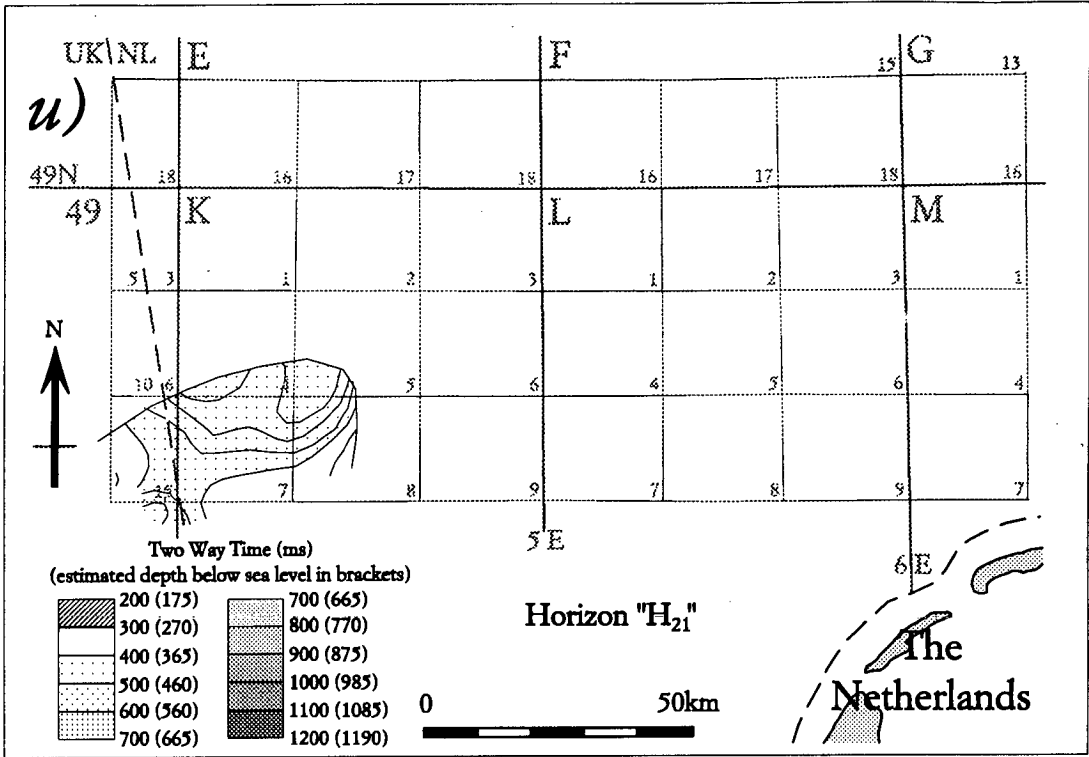












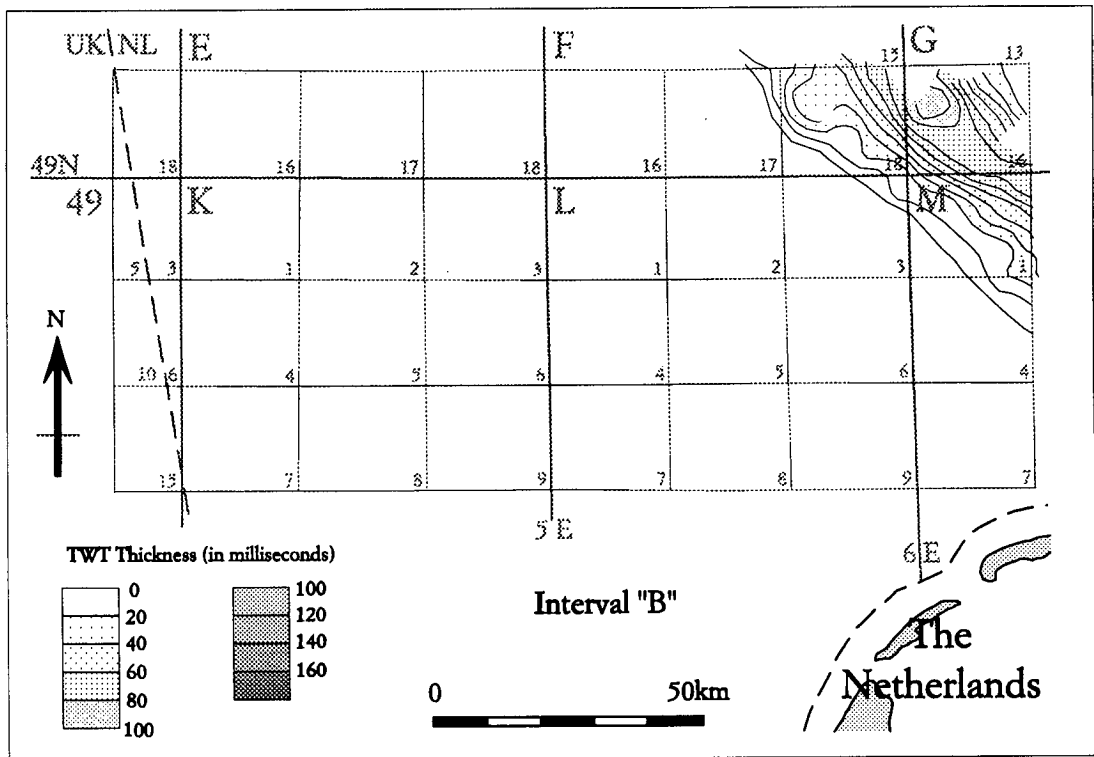
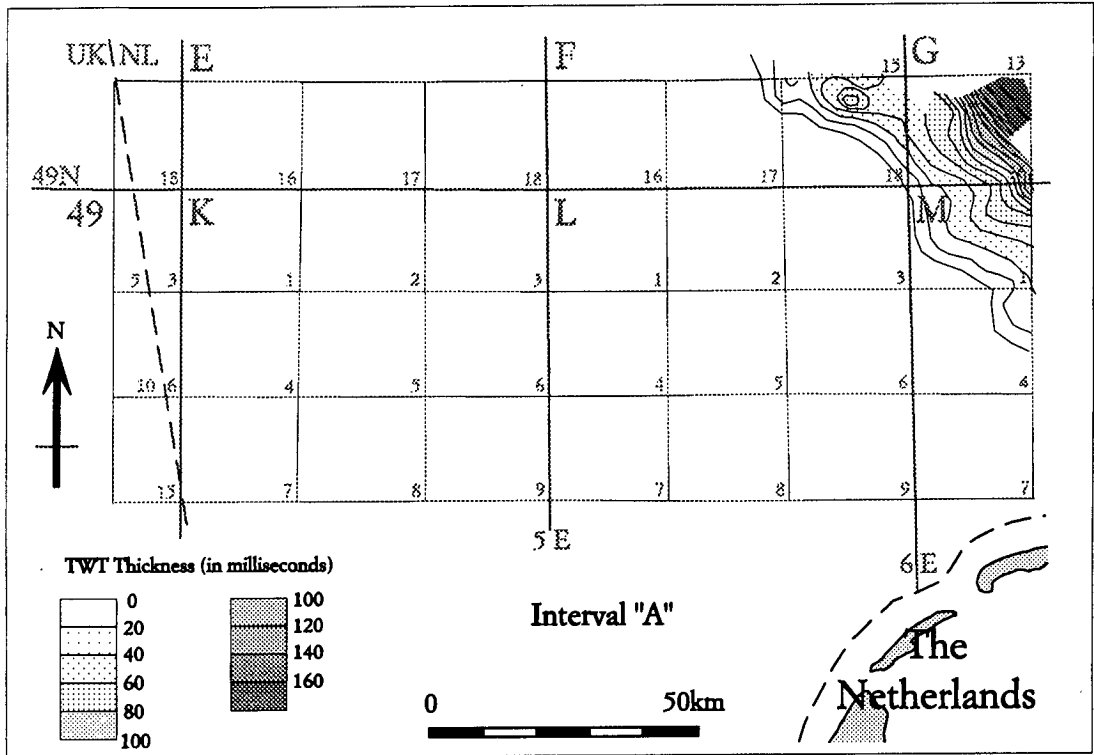
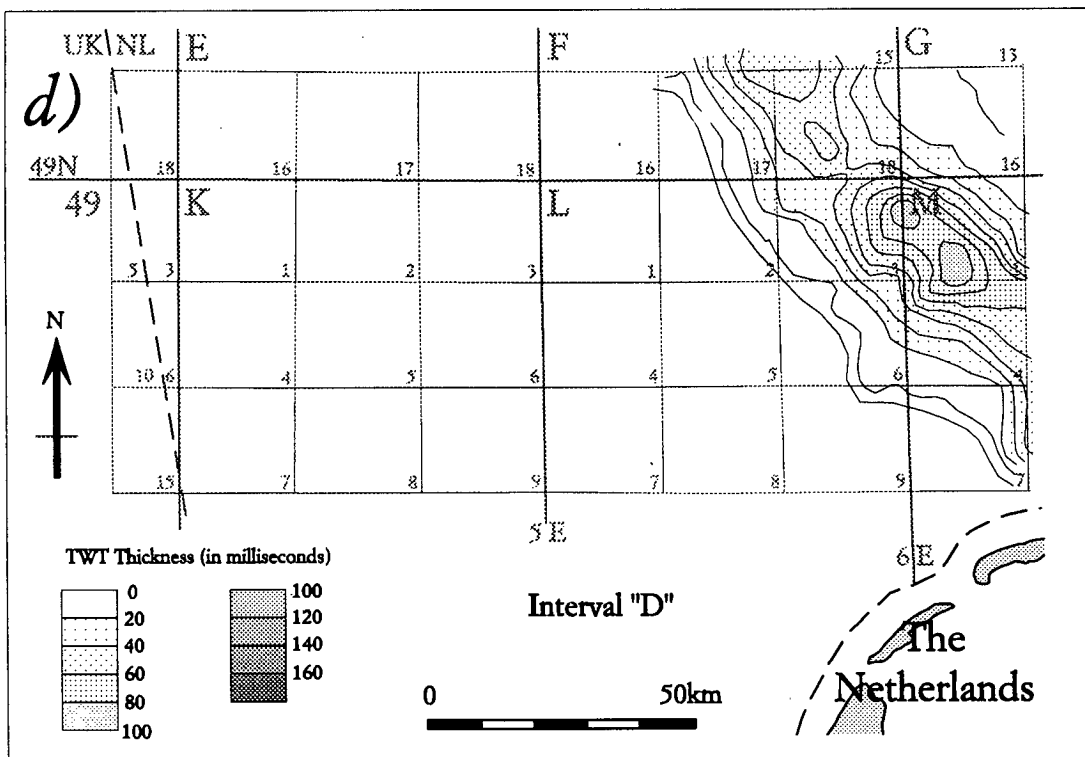
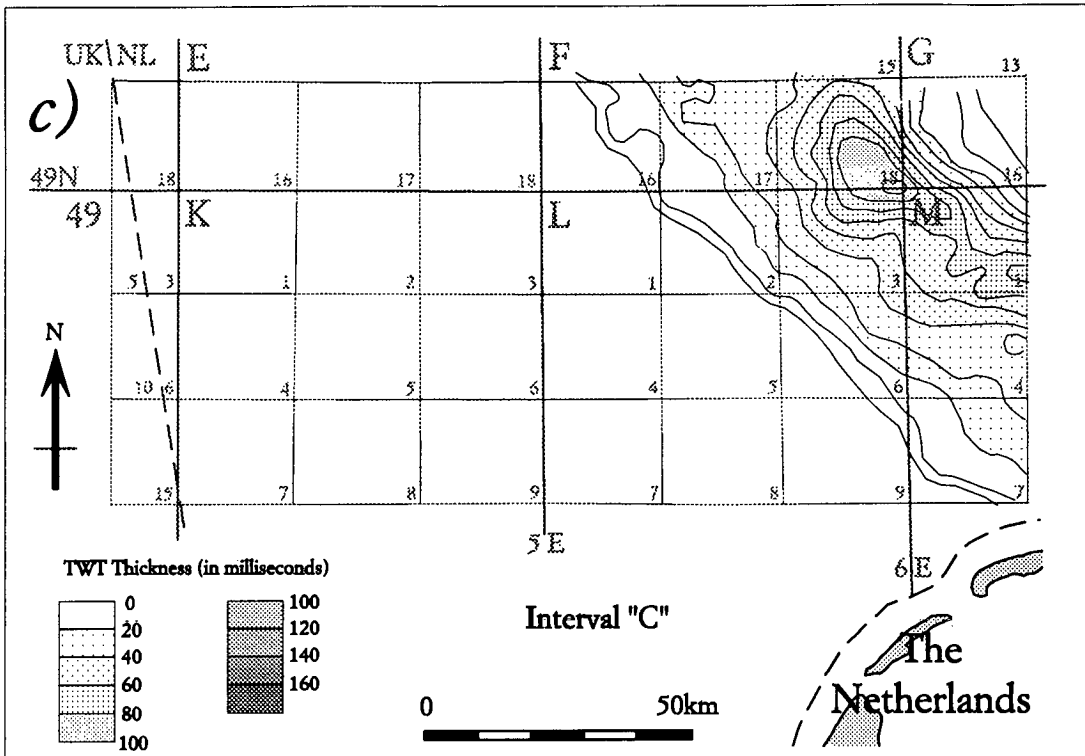
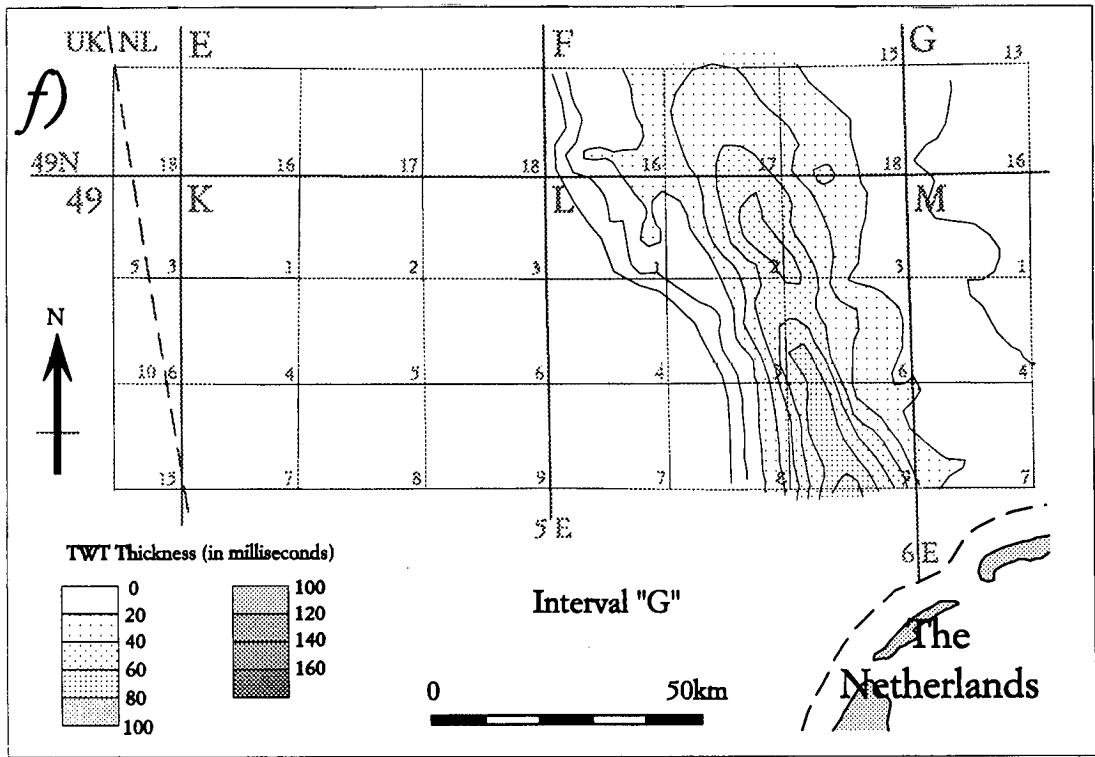
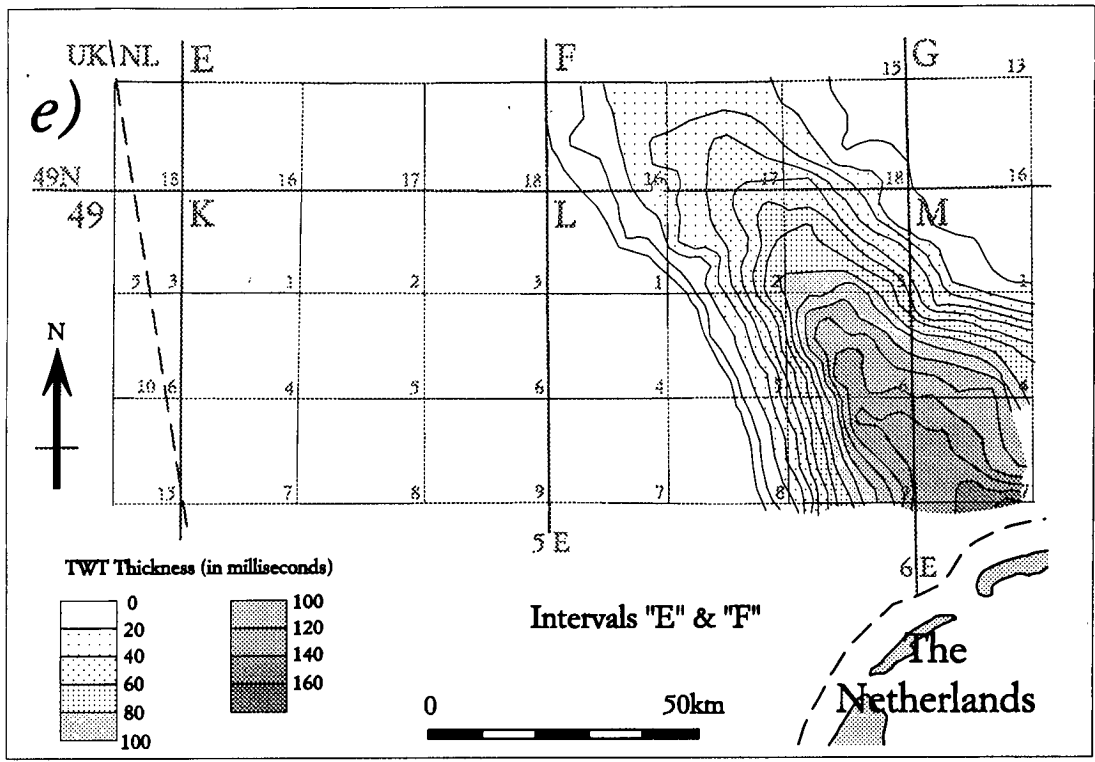
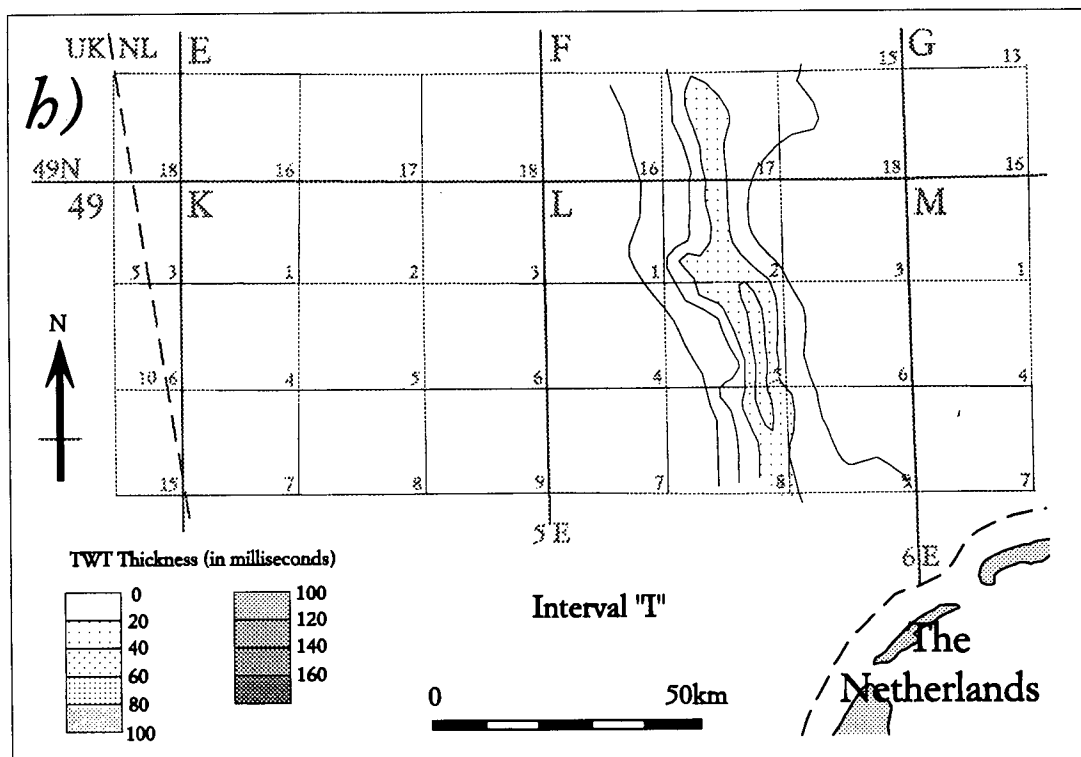
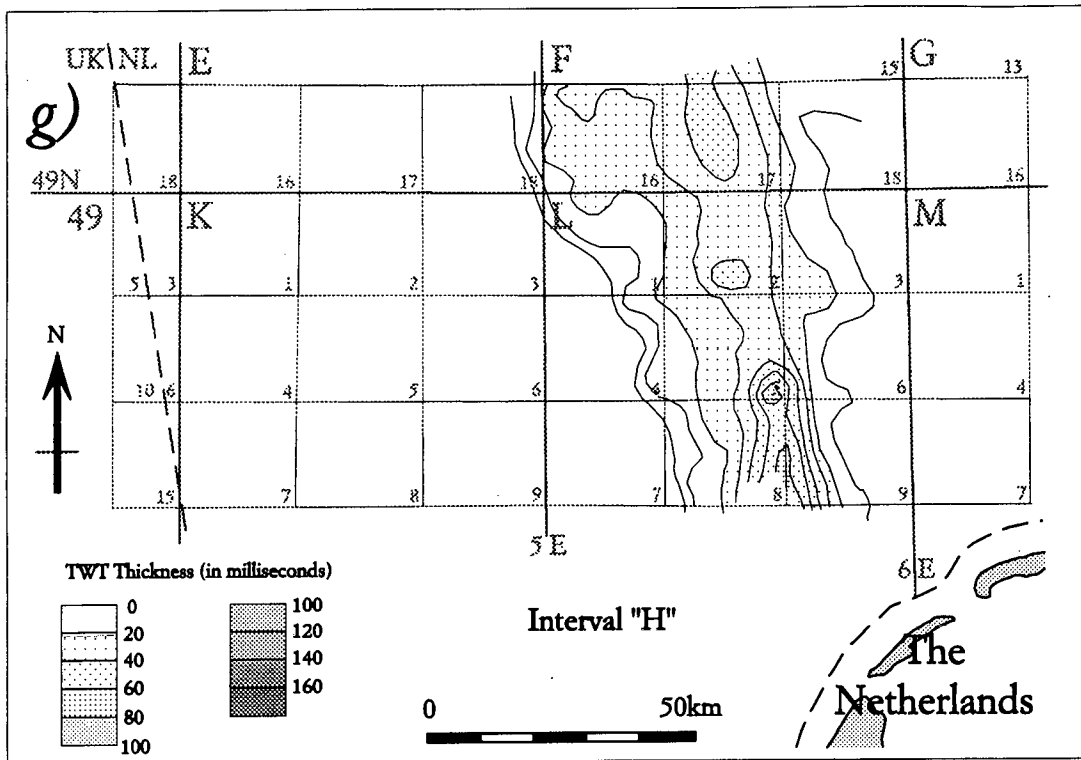
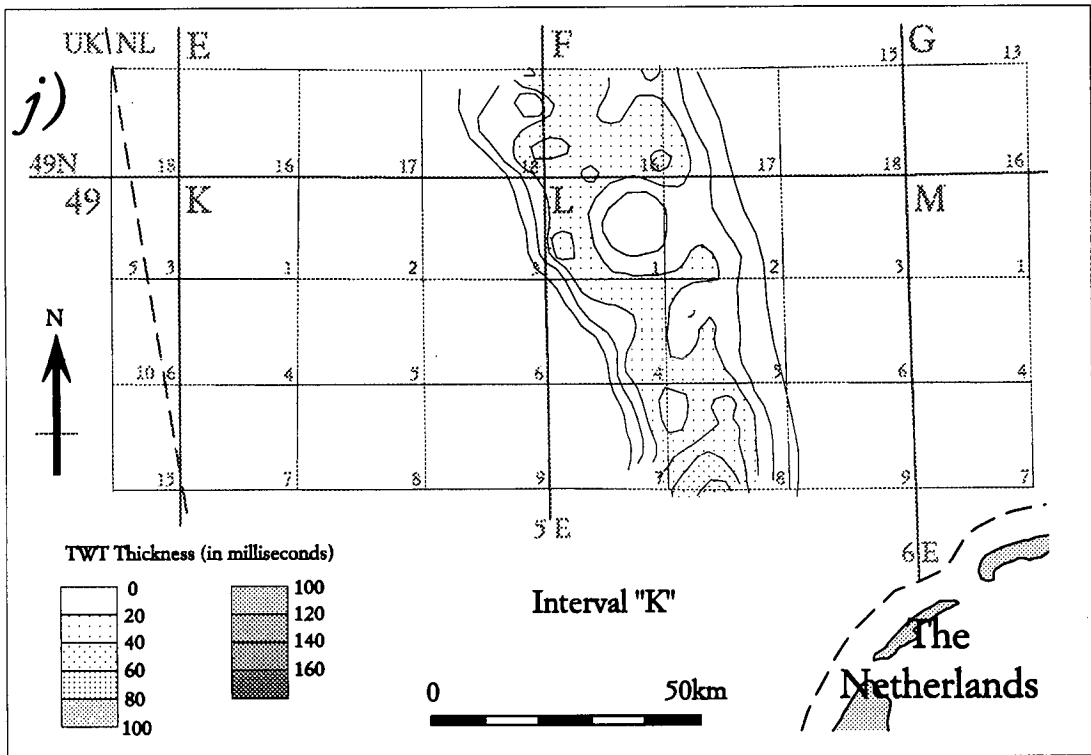
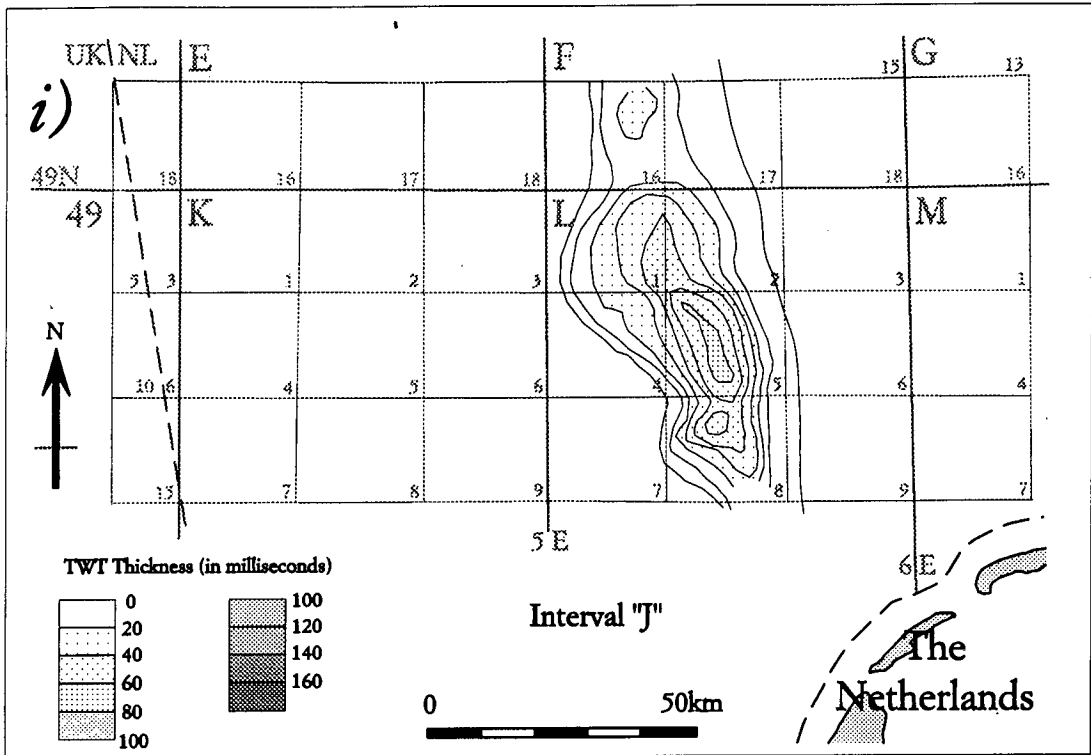


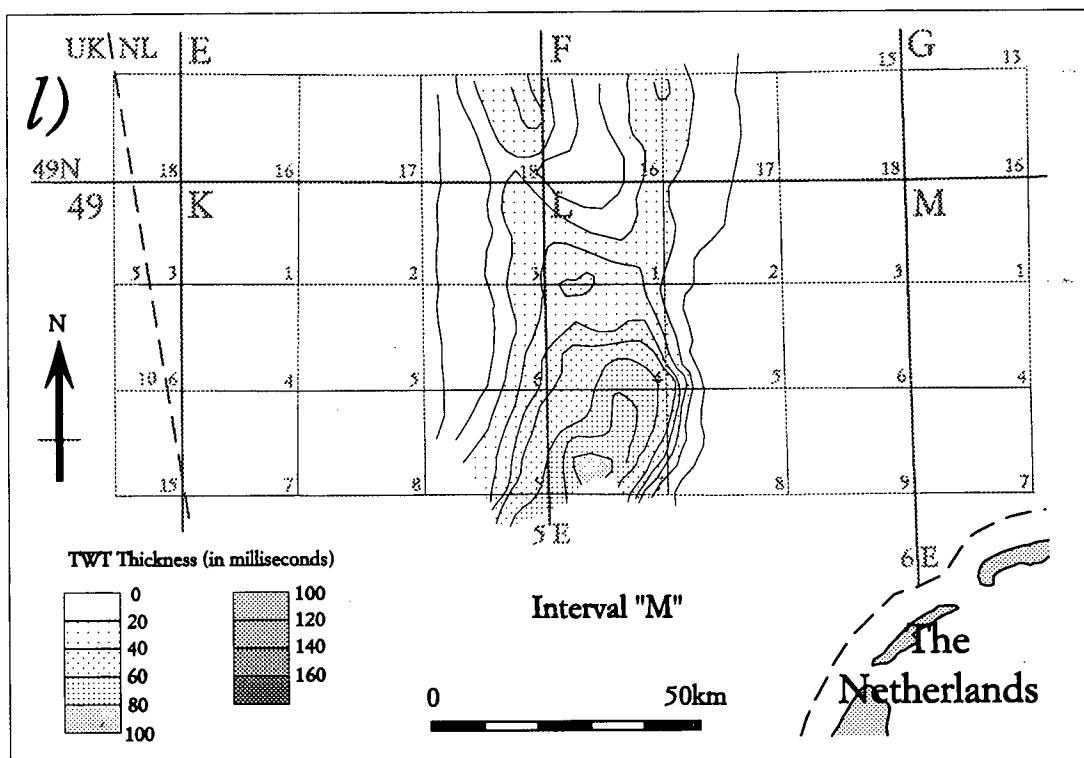
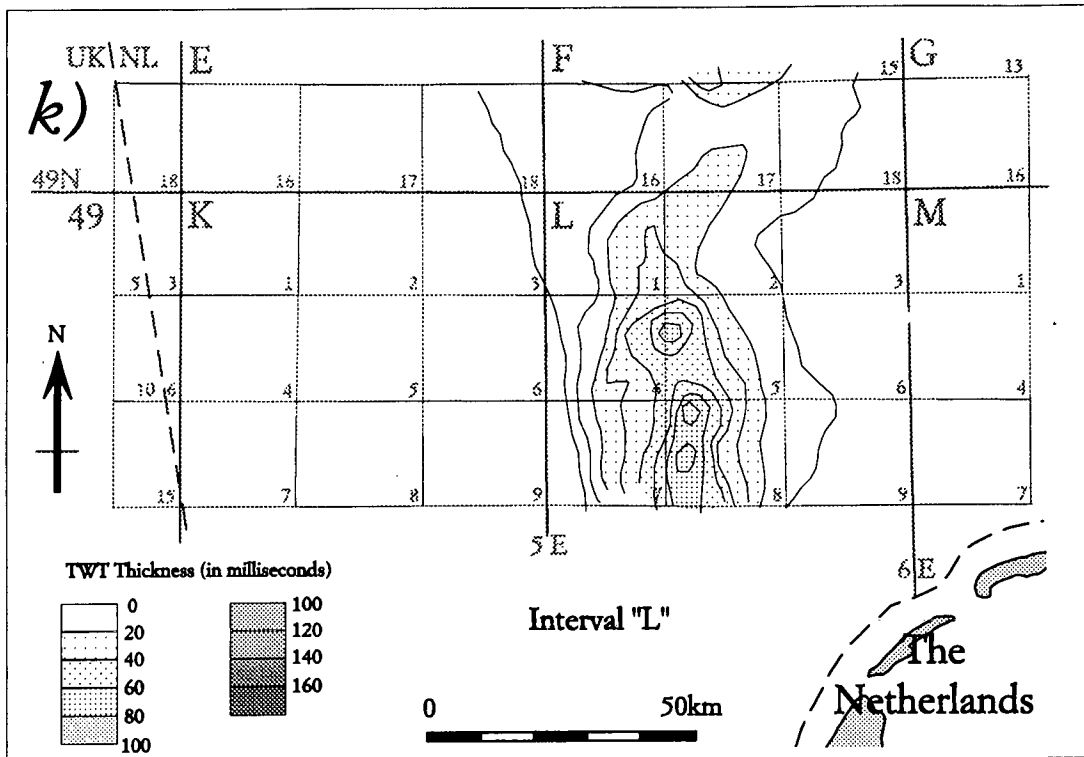
Fig. 2.12: ("a" to "v"; drawn on pages 62 to 72) TWT thickness maps, in ms, of intervals "A" to "W", showing the migration of the sediment depocentre from the NE to the west.

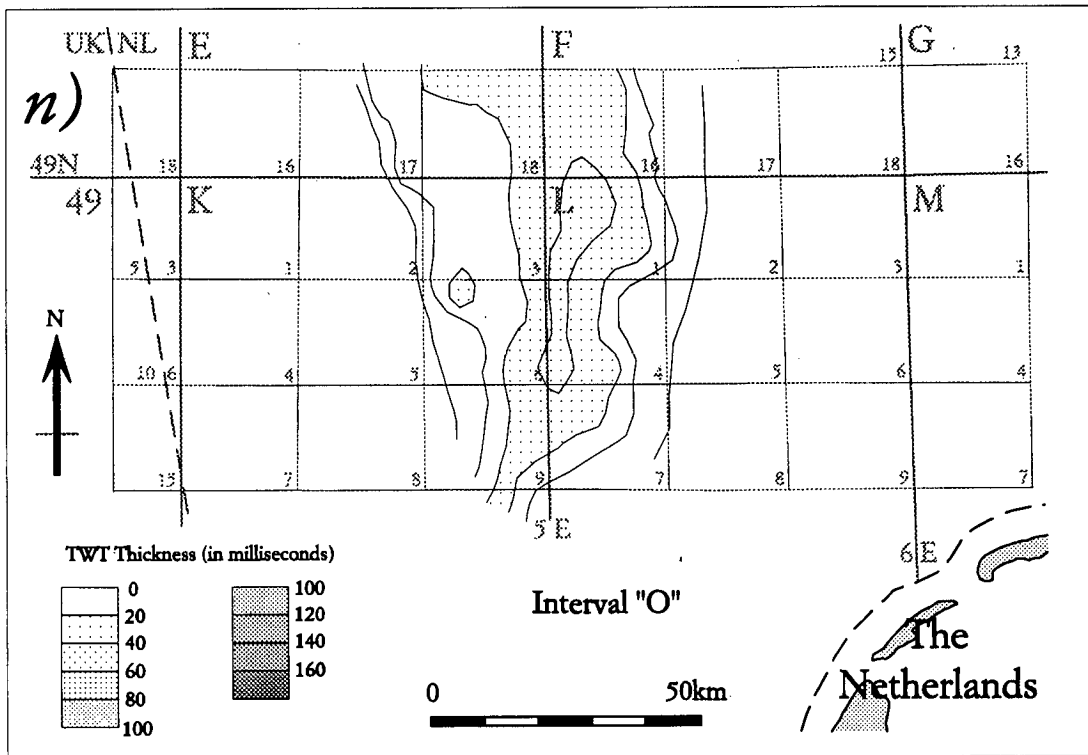
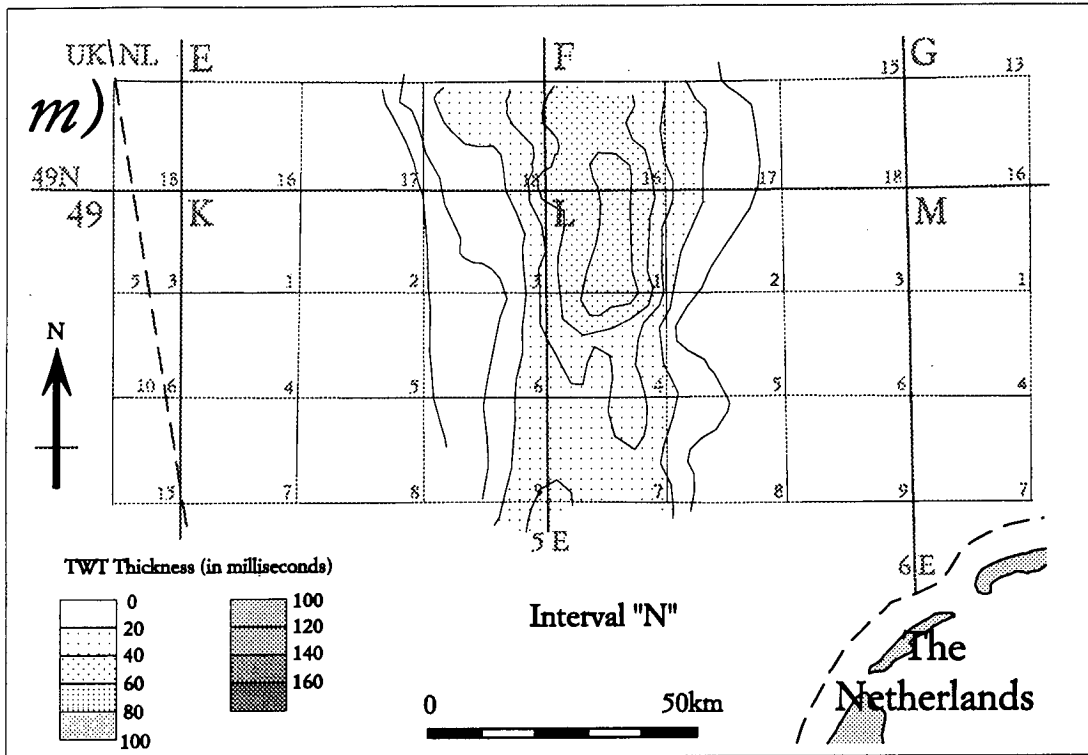


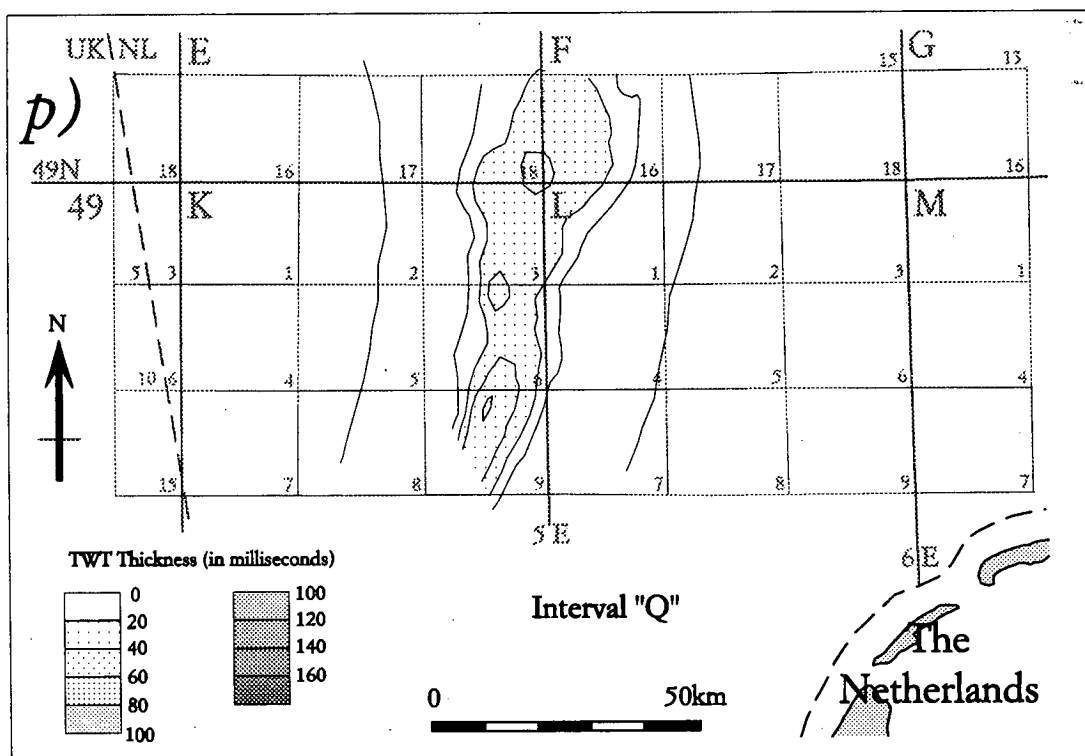
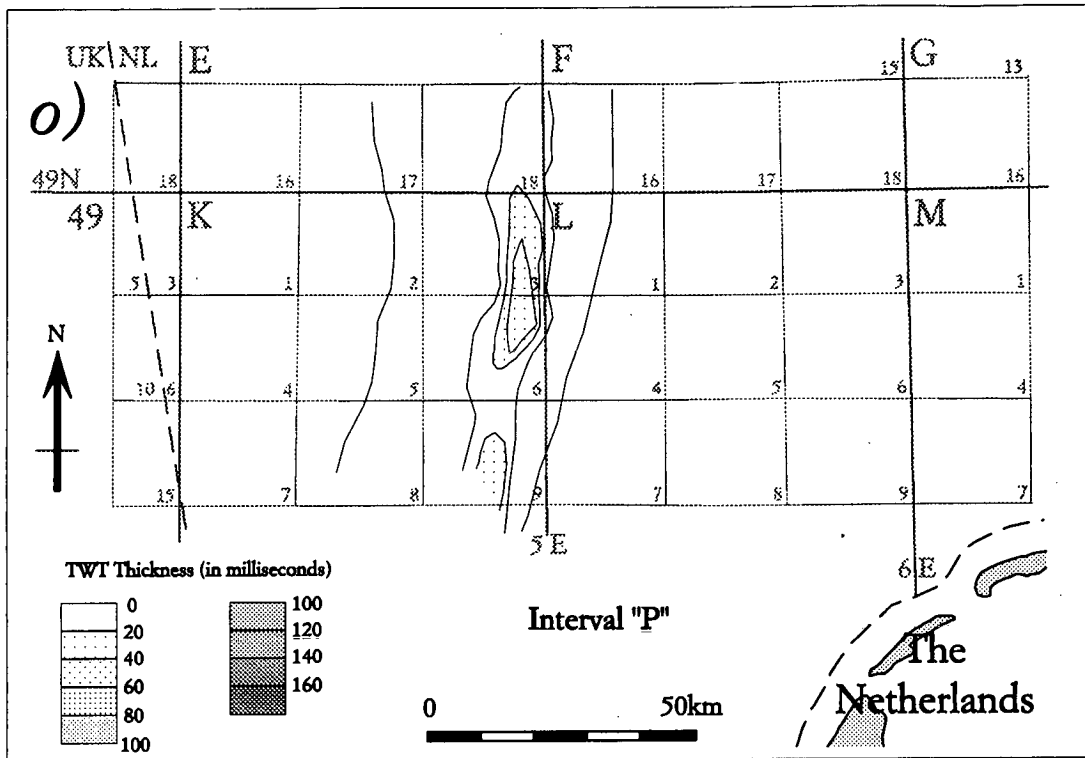


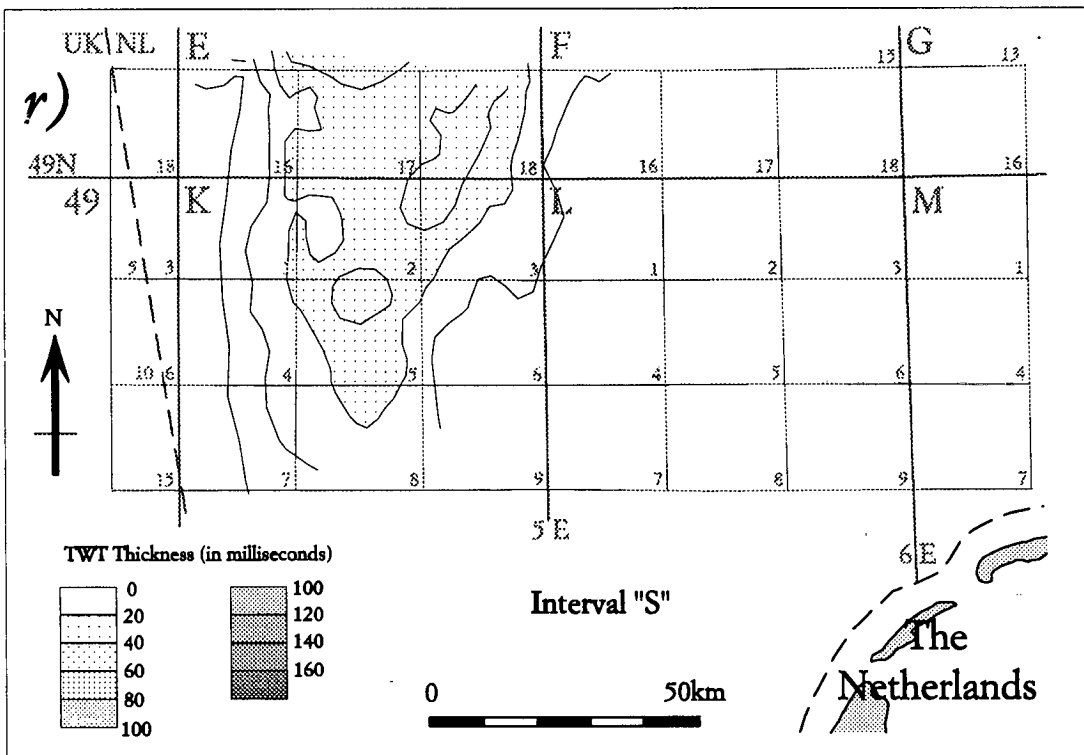
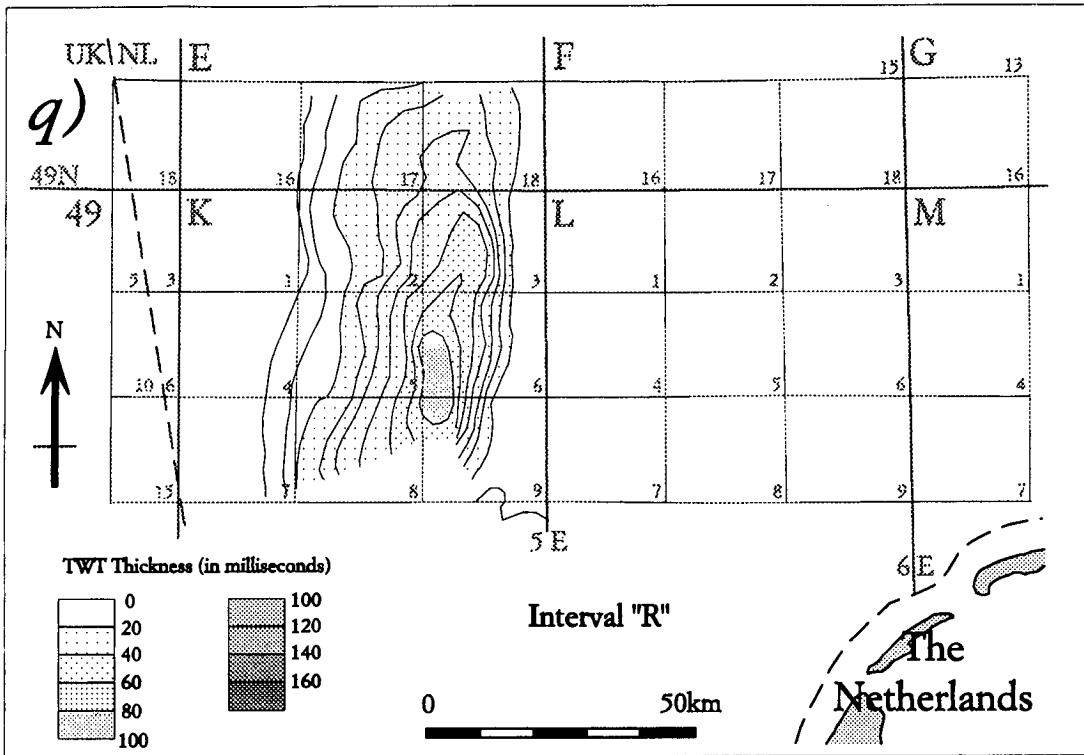


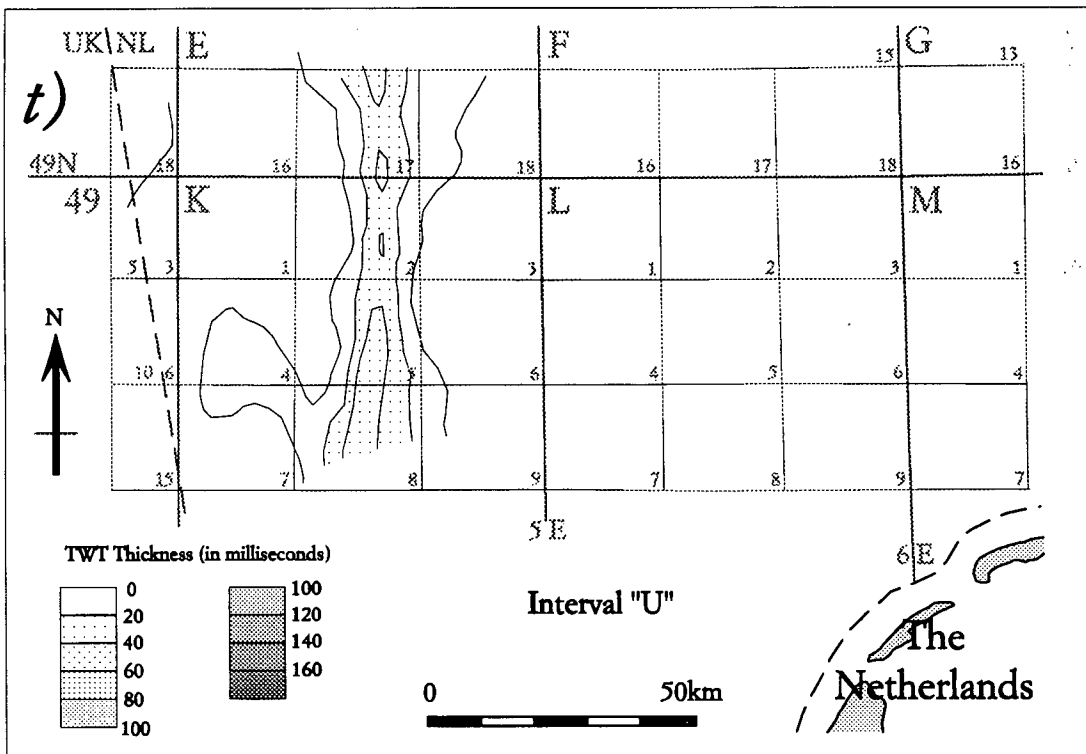
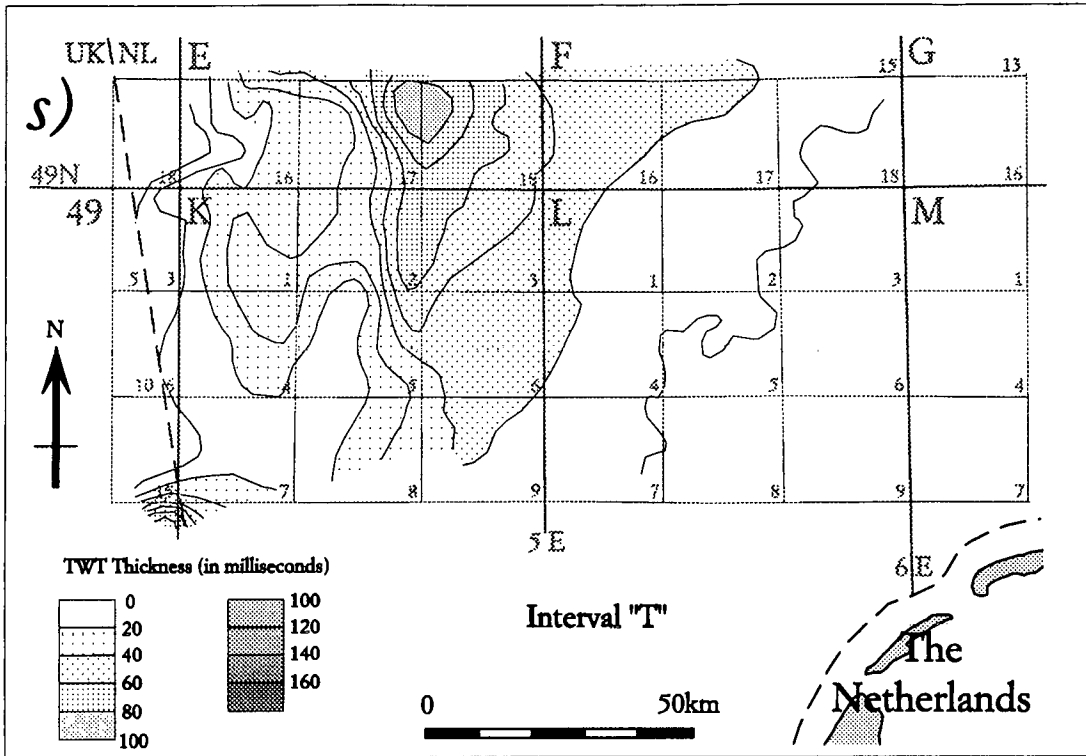


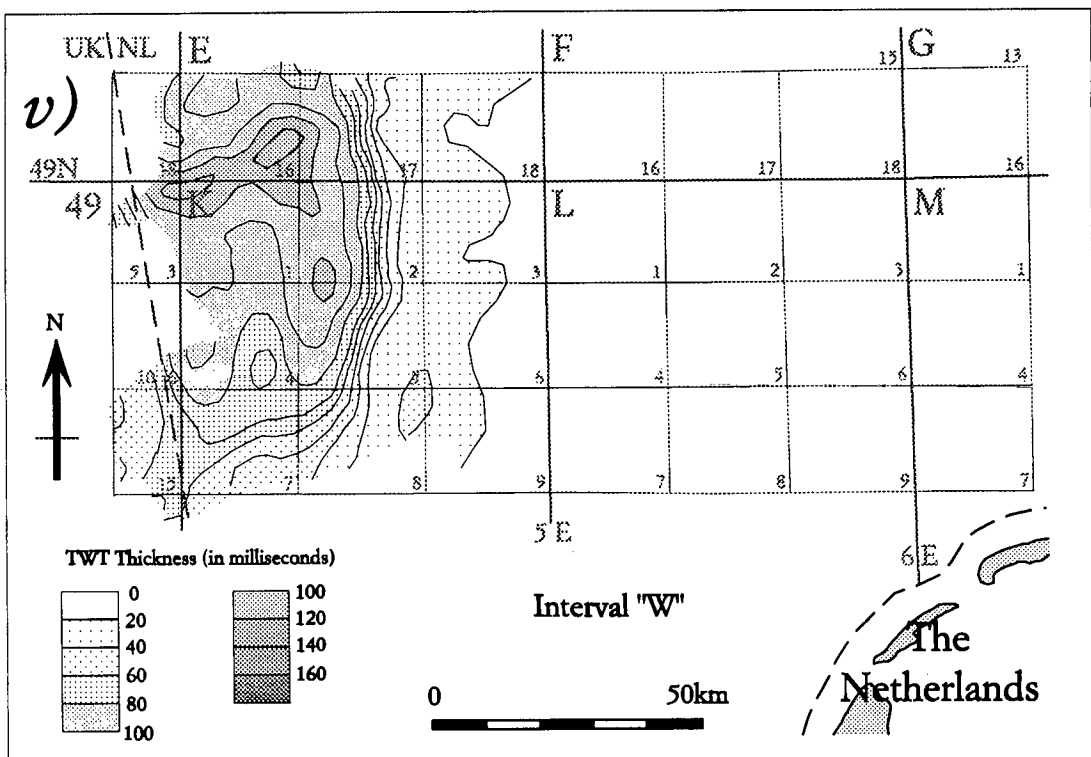
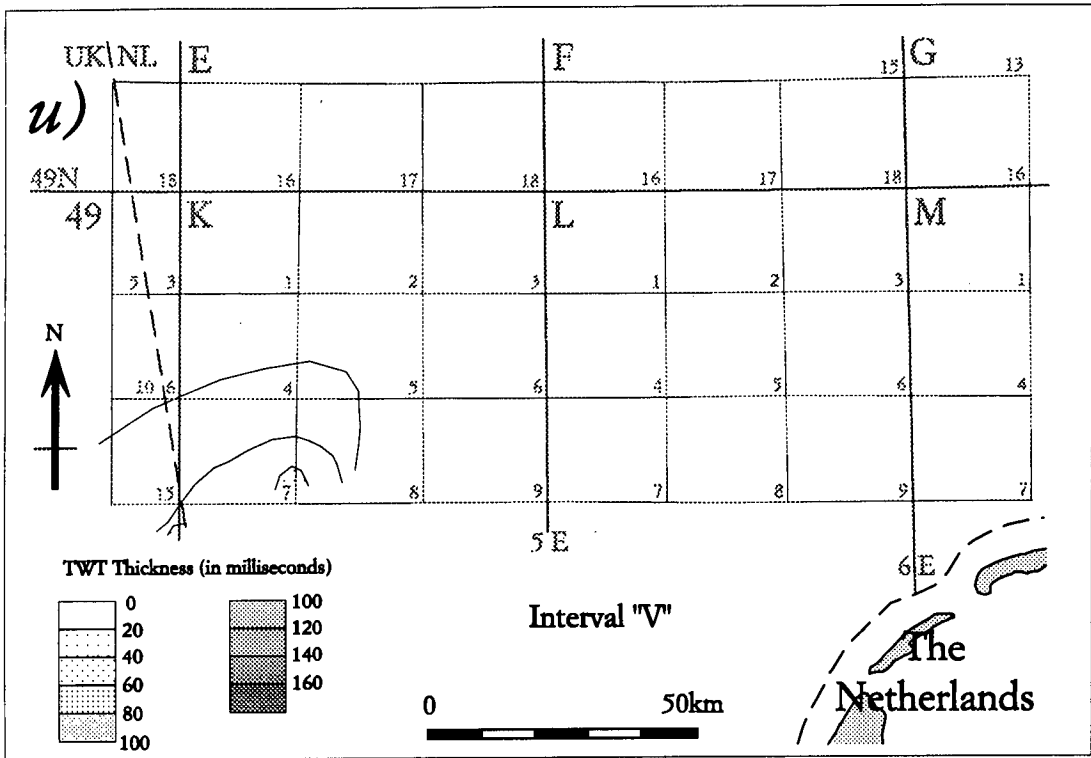












Interval B (H₁-H₂)

This interval is around 190m thick and oversteps interval "A" to the SW. Fore-sets all face SW, with slopes of up to 1.5°. The upper surface of the interval is defined by a moderate to high amplitude, continuous event over most of the area (see fig. 2.15). Toe-sets are only moderately developed. Six packages are present within this interval. Package B₁ back-steps and onlaps interval "A" landward, with no top-sets. Package B₂ is transgressive, back-stepping further, and shows thick top-set development. Packages B₃ to B₆ above are progradational, and show successive downward shifts of landward onlap. A SW facing, fore-set erosion surface, dipping 1.5°, is present at the base of package B₆, maximum erosion occurring at the basinward margin of this surface. The top Interval "B" shows toplap and is possibly truncated. Events within the interval are of weak to moderate amplitude and moderate continuity, although amplitudes increase toward the top of the interval. Up-slope directed slump-scars are locally developed within the interval.

Interval C (H₃-H₄)

This interval is up to 180m thick and shows continued advance to the SW. The top of the interval is again locally defined by the top of a mass flow, but elsewhere is also of "chaotic" appearance (see fig. 2.15). Unlike interval "B", there is no top-set development. However, toe-sets are widely developed across the NE of the study area. Fore-set slopes are shallow, generally less than 1°. All the packages in this interval save the highest show landward onlap against the preceding package. A fore-set erosion surface is present, along with intra-formational channelling, in fore-sets near the top of the interval. The youngest package of the interval shows back-stepping and basinward onlap onto previous packages, and toplap at its upper surface. Seismic events within interval "C" are generally of low amplitude, and are absent within the toe-sets.

Interval D (H₅-H₆)

This interval can be over 200m thick, its upper surface again locally defined by the top of a chaotic deformation feature, but otherwise indistinct. Fore-sets are directed SW, although the sediment depocentre is now located in the SE. This suggests a slight reorientation of the fore-set slope direction to the WSW. All sediments in this interval show downlap onto interval "C" (see fig. 2.15). The lowest package of the

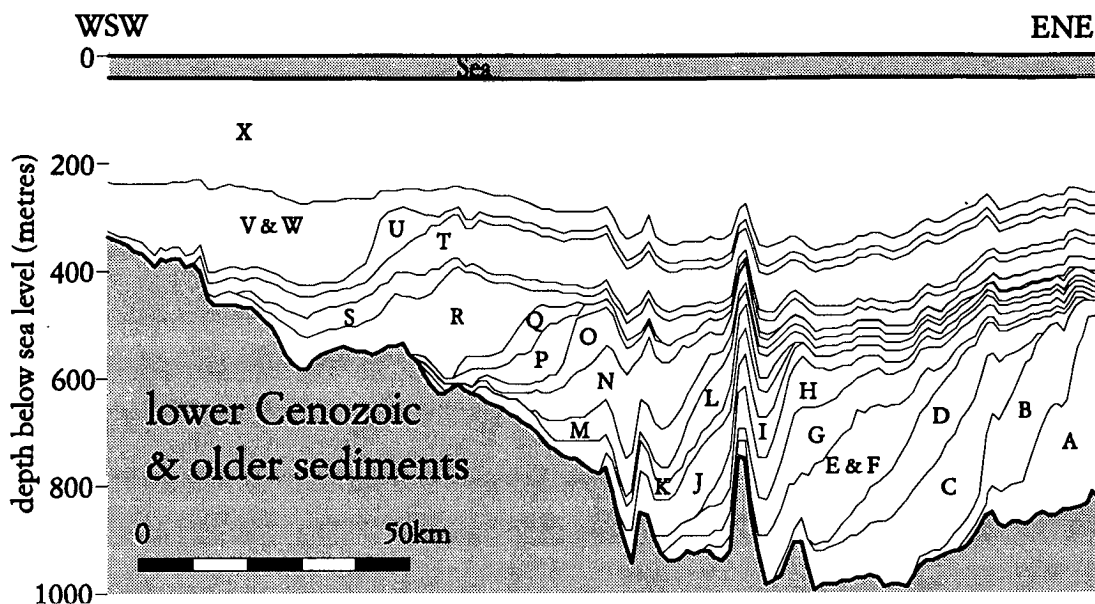


Fig. 2.13: Regional relationships of intervals "A" to "X", based upon interpretation of a depth converted section of the "Cromer-Sylt" seismic line within the study area.

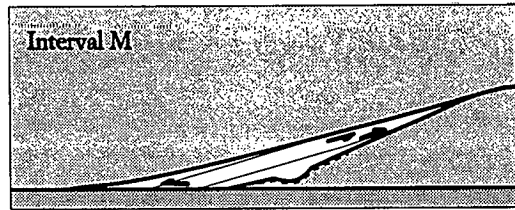
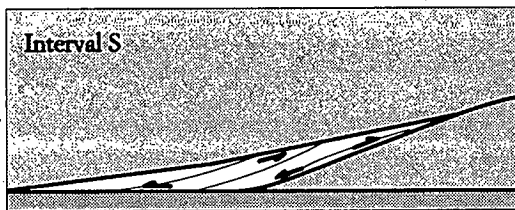
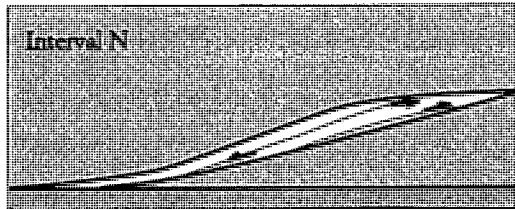
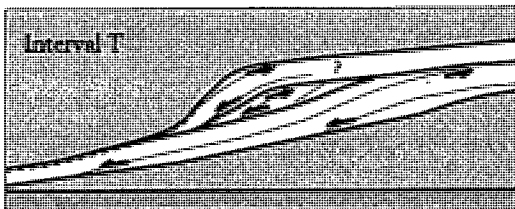
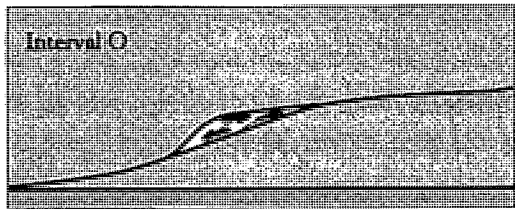
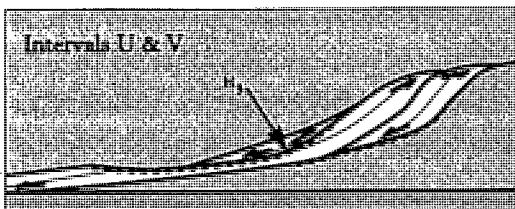
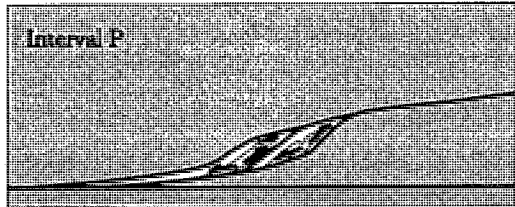
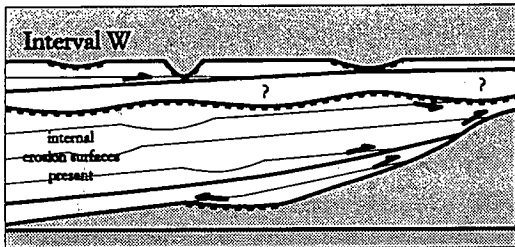
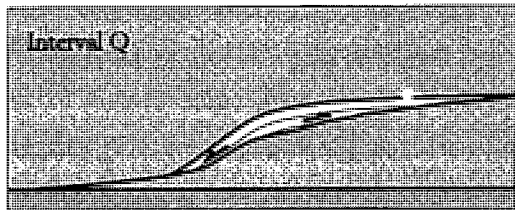
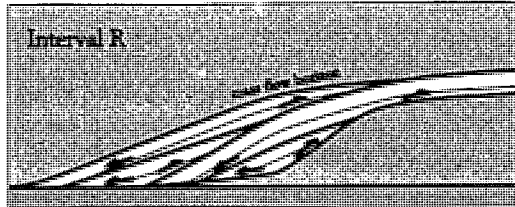
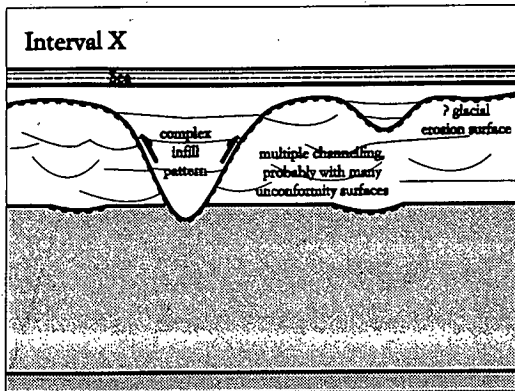
interval, D₁, is a SW facing, back-stepping, transgressive package with thick top-sets. This package makes up the majority of top-set deposition within interval "D". It also apparently includes landward directed slump-scars.

Packages D₁ and D₂ are unlike those seen before. Package D₁ back-steps landward, whilst package D₂ is built out in front of D₁. Both packages onlap basinward onto package D₁, and show toplap, possibly truncation, at their upper surfaces, with no top-set development. These packages steepen the average fore-set slope to around 1.3°. Package D₁ is only locally distributed, is of low energy and is chaotic internally, whilst its distal component is of moderate amplitude, and moderate continuity. Package D₂ is acoustically weak to transparent.

Package D₃ uniformly drapes D₁ and D₂. It also shows landward onlap, although top-sets are very thin and probably do not extend far landward. It is again weakly reflective but with good continuity. Package D₄ is only locally developed beyond the slope-break and shows landward onlap. It is of low energy and includes moderate continuity events.

Intervals E & F (H₁-H₂)

Sediment fore-sets change direction from facing SW, as in interval "D", to facing WSW in this interval. Because of the complexity of packages, these are best divided into two separate intervals for consideration here. The lower interval, "E", is up to



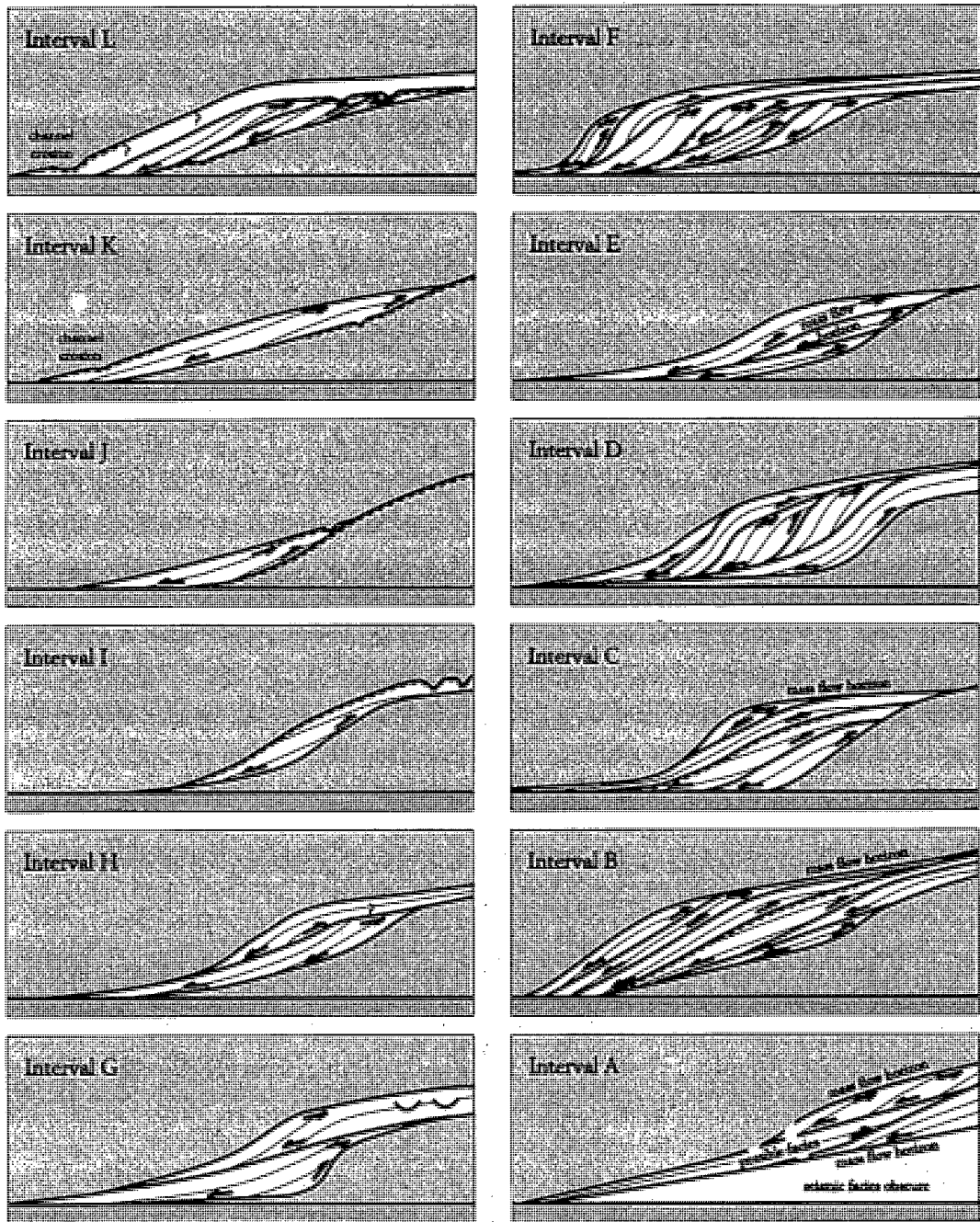
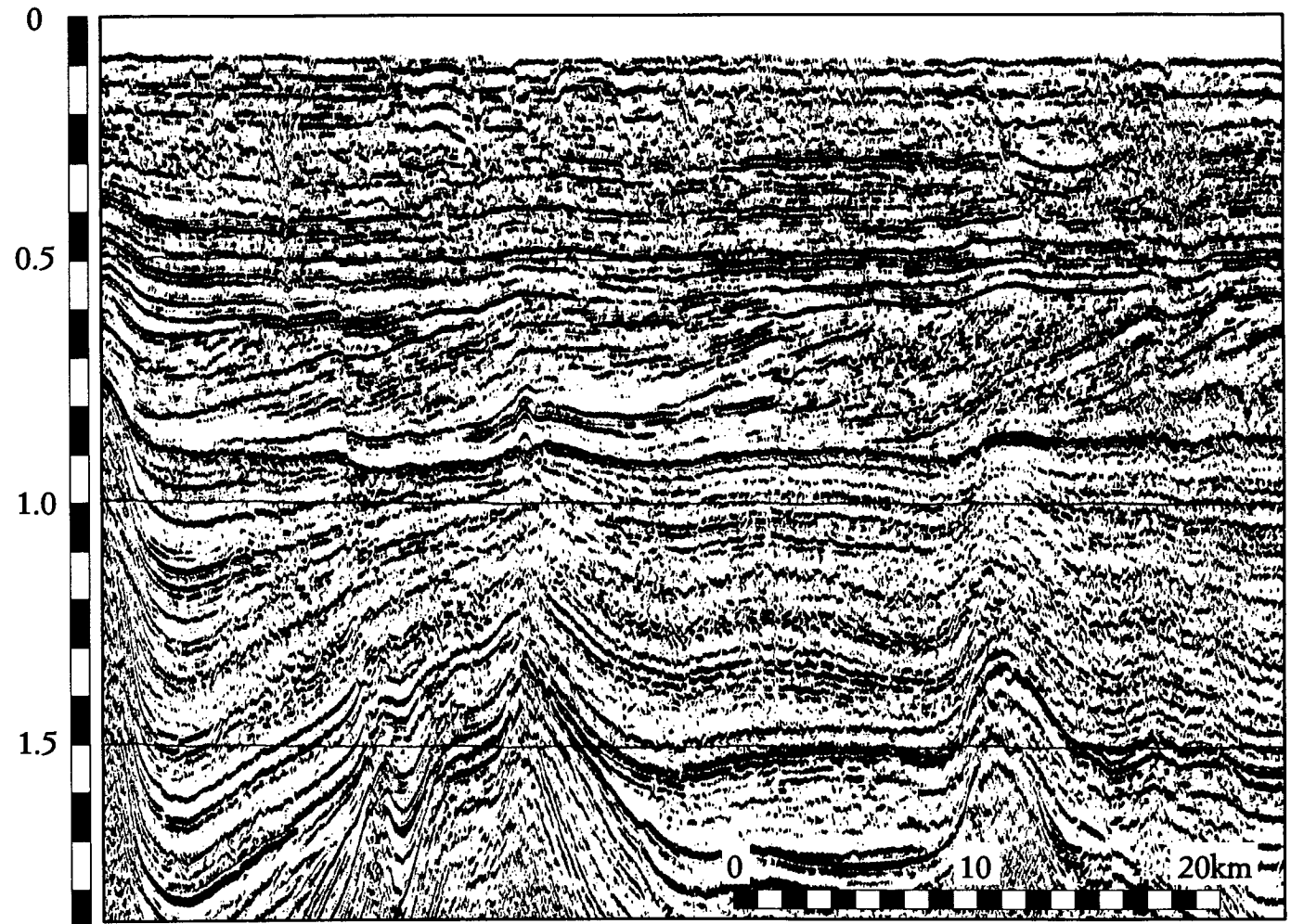


Fig. 2.14: Internal architecture of intervals "A" to "X", compiling all the packages observed into one schematic cross-section for each interval. However, not all packages are necessarily to be found in any one section through any interval. These diagrams are largely concerned with fore-set and toe-set architecture, as package relationships within the top-sets are impossible to resolve using regional seismic data.



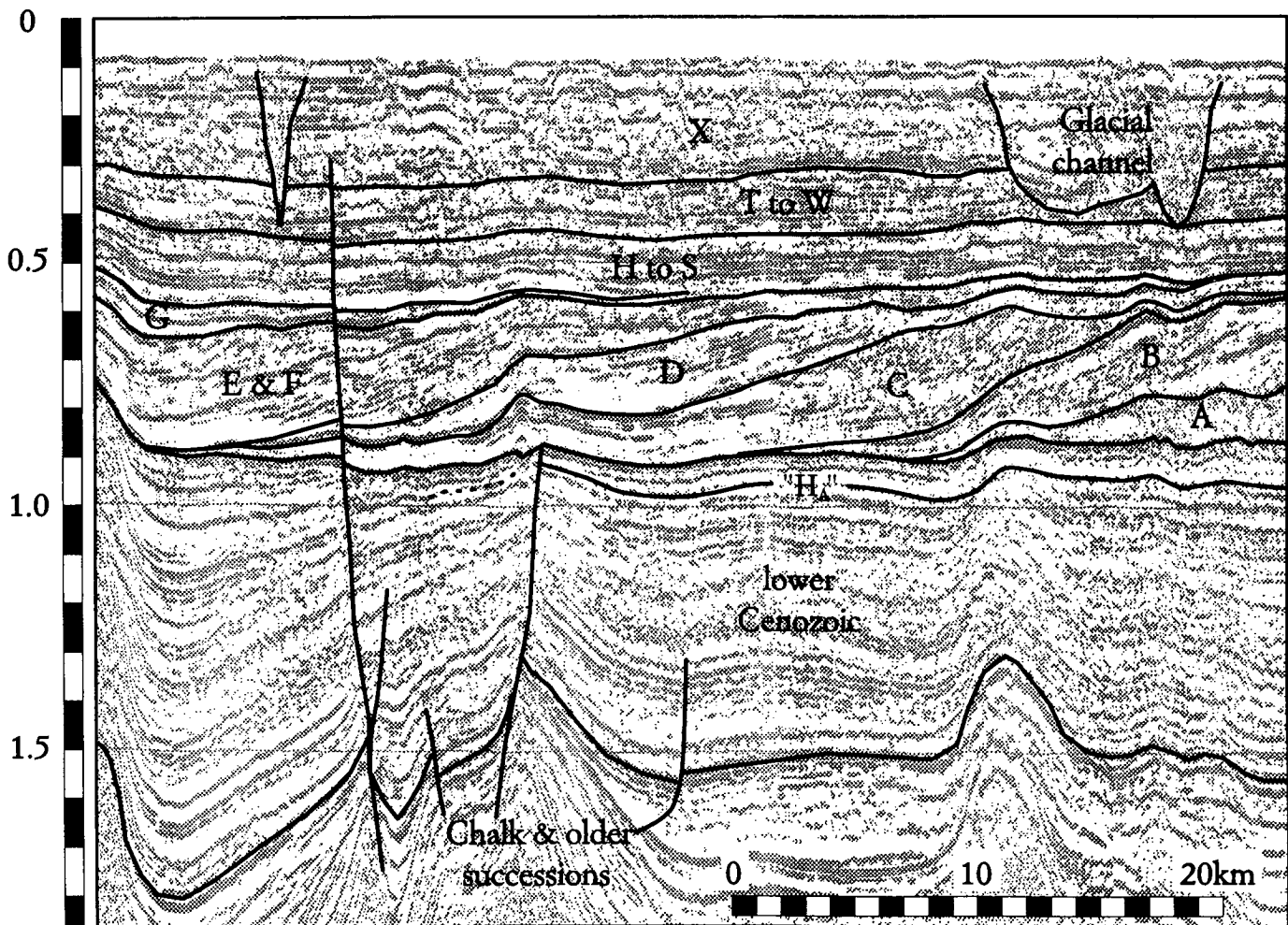
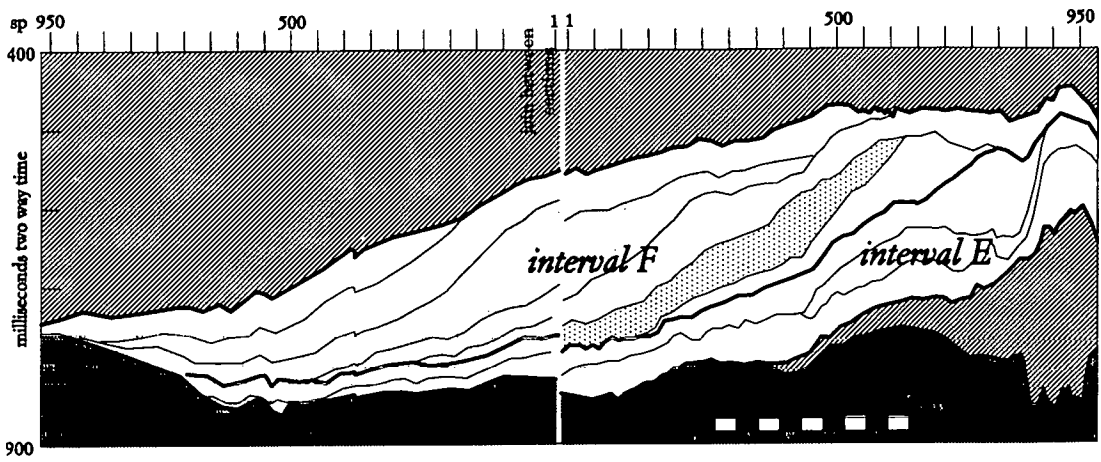
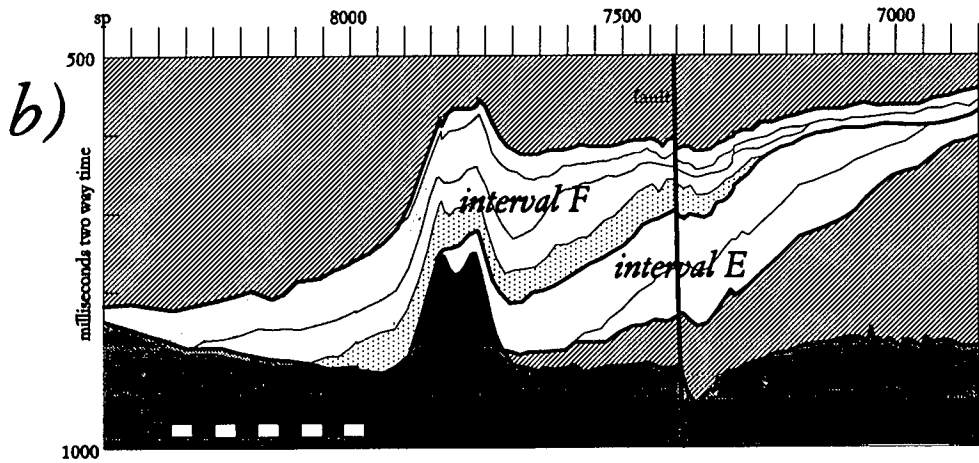


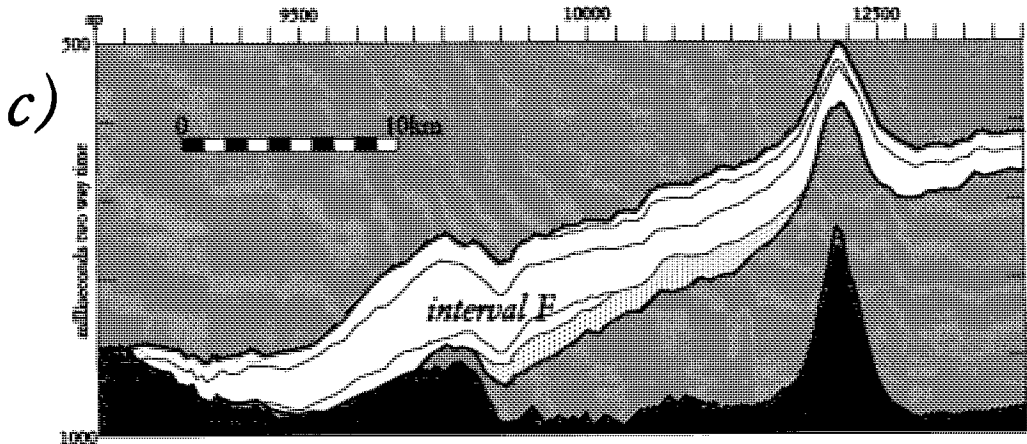
Fig. 2.15: Seismic section (interpreted and uninterpreted; see fig. 2.1 for location), from the NW corner of the study area, illustrating the fore-set relationships of the lowest interval in the Nordland Group succession. Also note channeling near the top of intervals "T" to "W", the high amplitude reflector near the base of interval "X" in the east and the glacial channels (seismic data courtesy of HGS Ltd.).



a)



b)



c)

Fig. 2.16: Digitised TWT sections, oriented WSW-ENE, through combined intervals "E" and "F", bounded by horizons "H₁" and "H₂". These show the along strike variations to be seen within these intervals. a) from the SE of the study area. b) from the middle of the eastern part of the study area. c) from the NE of the study area (see fig. 2.1 for locations of sections).

180m thick, and represents the continuation of the sedimentation style seen in previous intervals. It is only present in the SE of the area (see fig. 2.16). The basal sediments of interval "E" consist of two back-stepping packages, E₁ and E₂, locally disrupted by mass flow at their top (see fig. 2.17). These show gradual landward onlap, though without top-sets. Packages E₁ and E₂ are overlain by package E₃, a weakly developed, progradational package showing progradation showing landward onlap. This package also shows toplap at its upper surface, with no development of top-sets. Package E₃ is locally disturbed in the toe-sets. Events in all three packages are generally weak, except in regions of toplap and at the interfaces of the depositional packages.

Interval "F" is up to 250m thick. Its lowest package, F₁, is only locally developed in the SE (see fig. 2.16). It shows oblique prograding clinof orm architecture (*sensu* Vail *et al.*, 1977), downlapping onto the sediments of interval "E", and lapping out at its upper surface without either top-set or toe-set development (see fig. 2.17). The base of this package also shows diffraction tails and may be erosive. Packages F₂, F₃ and F₄, which, although thickest in the SE, are developed across the whole depositional front, show steady progradation over the sediments of interval "E". Each package laps out at its upper surface, and only F₄ includes top-sets.

Packages F₂ and F₃ are again weakly developed in the north, due possibly to both a lack of sedimentation and erosive reworking. Package F₂ back-steps, and is transgressive, with extensive top-set development. Package F₃ is very localized, shows landward onlap and toplap at its upper surface. Events within interval "F" are of moderate amplitude and are discontinuous. Distally, the interval is of low energy. This could relate to differences in sand to shale ratio in the distal and proximal parts of the interval.

Interval G (H₁-H₂)

This interval is up to 110m thick, and shows progradation to the WWSW. Two packages are developed, package G₁ exhibiting coastal onlap and weakly prograding over previous intervals, but also lapping out on its upper surface, with little or no top-set development. Package G₂ back-steps and is transgressive, with very thick top-sets (see fig. 2.17). Channels up to 30m deep locally incise the top of package G₂ near the slope break. Landward directed slump-scars can be seen near the top of the interval (see figs. 2.17 & 2.18). Events within interval "G" are of moderate amplitude and are fairly continuous, except for a high amplitude event marking the contact between the two packages.

Interval H (H₁-H₂)

WWSW directed progradation continued in this interval, which is up to 120m thick, and can be divided into two packages. Package H₁ shows basinward onlap onto interval "G" and slight progradation, but laps out at its upper surface and has no top-sets. It is not clear from the data whether this package shows landward onlap onto the previous fore-set slope. The package is locally affected by landward directed slumping (see fig. 2.18).

Package H₂ is transgressive, showing back-stepping, basinward onlap onto package H₁, and well developed top-sets. Internal events within the interval are weak to moderate, being weakest toward the top, and they are of low continuity. The top of interval "H" is defined by a moderate amplitude event.

Interval I (H₂-H₃)

Interval "I" is around 60m thick and reflects the continuation of WWSW progradation. The top of this interval is always marked by a moderate to high amplitude, positive polarity event (see fig. 2.18). In the fore-sets, this event dips at around 2°, and forms a major marker horizon within the succession. Interval "I" shows basinward onlap onto package H₂, shows landward onlap and has well developed top-sets. Channels up to 30-40m deep are locally cut into the top of the interval at the slope break, and fore-set erosion is sometimes evident. Events within interval "I" are mainly weak and discontinuous, but distally they can be of moderate to high amplitude.

Interpretation: This interval records the waning of sediment supply, and the uppermost sediments of the interval may be extensively eroded. The high amplitude event that defines horizon "H₃" could be the seismic expression of a hardground.

Interval J (H₃-H₄)

This interval, which is present only beyond the slope-break, is rather unevenly distributed, showing landward onlap across most of the previous fore-set slope. It shows very slight basinward onlap onto interval "I". Interval "J" up to 120m thick in the middle of the area, but is thin or absent to the north and south. The top of the interval is again locally incised by channels which are in the same locations as those on horizon "H₃". Interval events within the interval are of high amplitude near the base, decreasing to low amplitude at the top. The whole interval is often disrupted by landward directed slumping (see fig. 2.18).

Interval K (H₉-H₁₀)

This interval, which is up to 100m thick, shows uniform landward onlap across the fore-set slope, but thins over topographic highs on horizon "H₉". It also progrades, with basinward onlap onto interval "J" and onto horizon "H₉". Interval "K" laps out just below the slope break, without development of top-sets. Internal events within the interval are very weak, with rare moderate amplitude reflectors of low continuity.

Interval L (H₁₀-H₁₁)

This complex interval is well developed in the south, reaching a thickness of up to 150m, but thins to around 40m in the north, suggesting a southward shift of depocentres at this time. Progradation was to the WNW by the end of deposition of this interval. Interval "L" is made up of three packages.

Package L₁ is complex, with hummocky clinoform reflectors, and shows WNW directed basinward onlap onto interval "K". Intra-formational erosion surfaces are occasionally present. The package shows toplap at its upper surface. Internal events are generally of low amplitude but strengthen upward, and a high amplitude event defines the top of the package. The basal reflector of the package is diffractive, and possibly results from erosion. This facies is only present in the southern half of the area.

Package L₂ shows basinward onlap onto both package L₁ and horizon "H₁₀". It shows slight landward onlap, with little top-set development. Internal events are variable in nature, tending to be weak and of low continuity, and decreasing in amplitude basinward. Package L₃ is thin, its base defined by a strong reflector which shows basal erosion with up to 15m of relief. It has extensively developed top-sets, and shows basinward onlap onto horizon "H₁₀". Its internal events are of weak to moderate amplitude.

Interval M (H₁₁-H₁₂)

This interval again has its depocentre, including over 200m of sediment, in the south, as opposed to less than 60m the north. The interval shows landward onlap, with fore-set slopes dipping at around 0.5°. There are no top-sets, and its upper surface shows toplap and may be slightly truncated. Channel levee systems are locally present, possibly associated with submarine erosion. Rarely, the upper surface of its toe-sets is locally disturbed, completely obscuring the geometry of the

sediments beneath. Internal events within interval "M" are of low amplitude and moderate continuity.

Interval N (H₁₂-H₁₃)

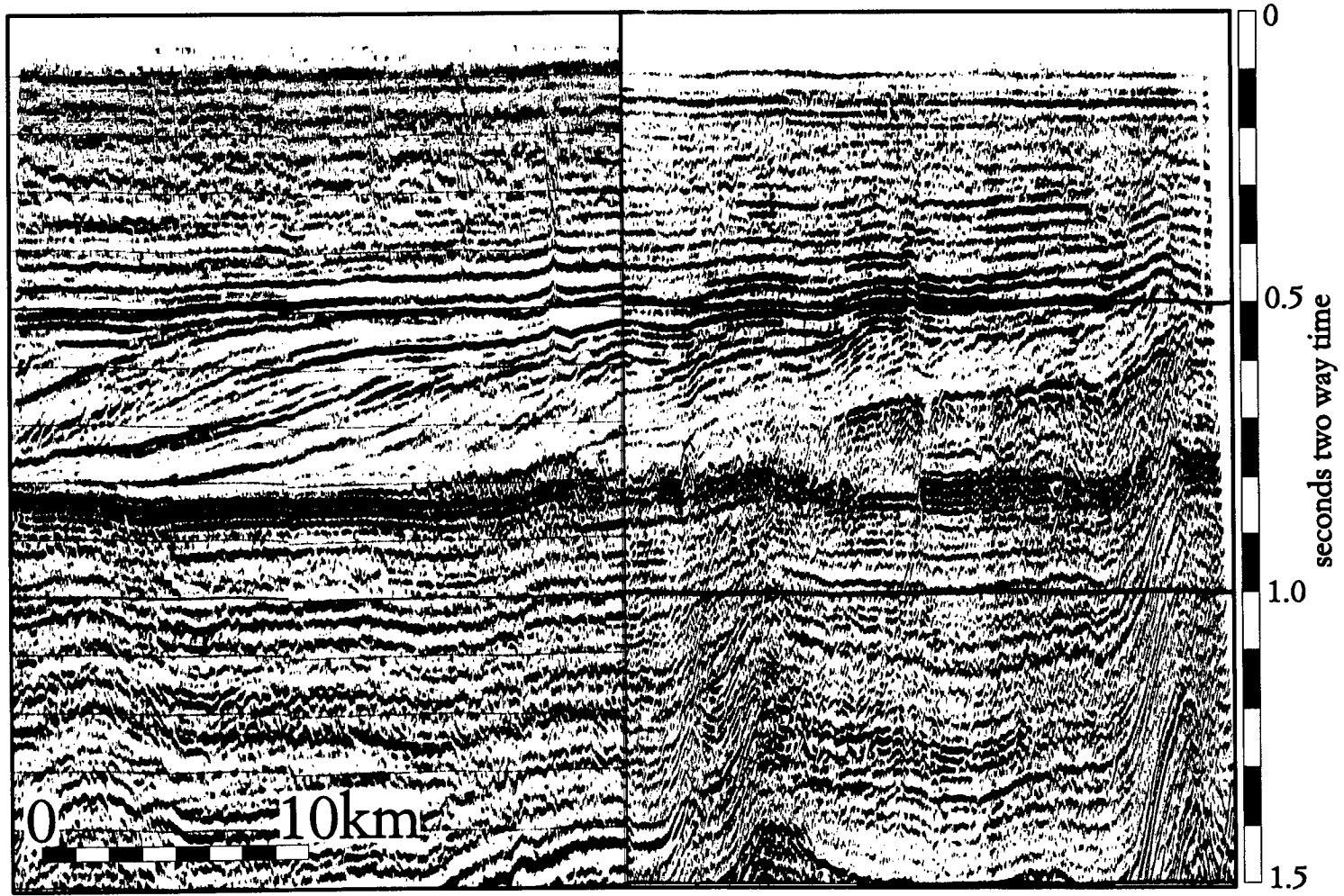
During deposition of interval "M", there was a northward shift of sediment depocentres. Sediment thicknesses are up to 100m in the north, but are less than 60m in the south. Planar fore-sets face WNW at the top of the interval, with slopes of around 0.5°. The interval shows landward onlap and toplap, with no top-sets. It shows basinward onlap onto both interval "M" and horizon "H₆". Levee channels have also been observed. Internal events within the interval are of moderate to high amplitude, but low continuity.

Interval O (H₁₃-H₁₄)

This interval is up to 90m thick, and it occurs only as fore-sets showing basinward onlap onto interval "N". In the south of the area, interval "O" is of oblique prograding facies, with progradation directions are to the WNW. Fore-sets here are steep and hummocky, and the amplitudes and continuity of events are low (see fig. 2.19). In the north of the area, fore-sets are less steep, show landward onlap, and do not lap out at the upper surface of the interval. Events in the north are of moderate to high amplitude, and show greater continuity.

Interval P (H₁₄-H₁₅)

This interval is poorly developed, being present only beyond the slope break and reaching a thickness of no more than 80m. It is made up of two WNW facing fore-set packages (see fig. 2.19). These onlap basinward onto interval "N" and show landward onlap, package P₁ being developed beyond P₂. Package P₁ has a slightly erosive base, whilst package P₂ shows slight toe-set development. Events within interval "P" are of low amplitude, although high amplitude channel events up to 30m deep do occur in the package P₁. In the north, fore-sets of interval "P" again dip less steeply than in the south, and could be conformable with interval "O".



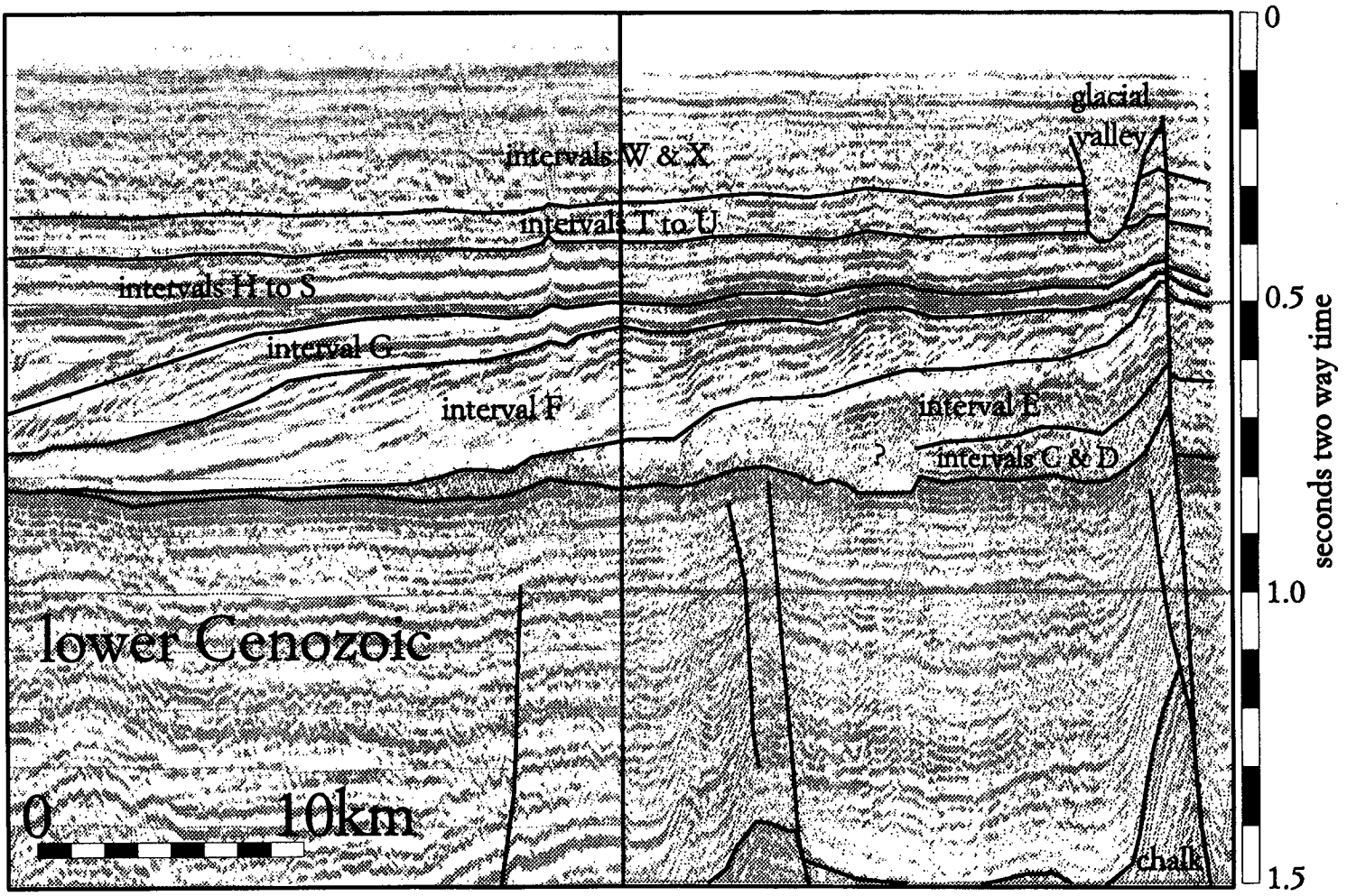
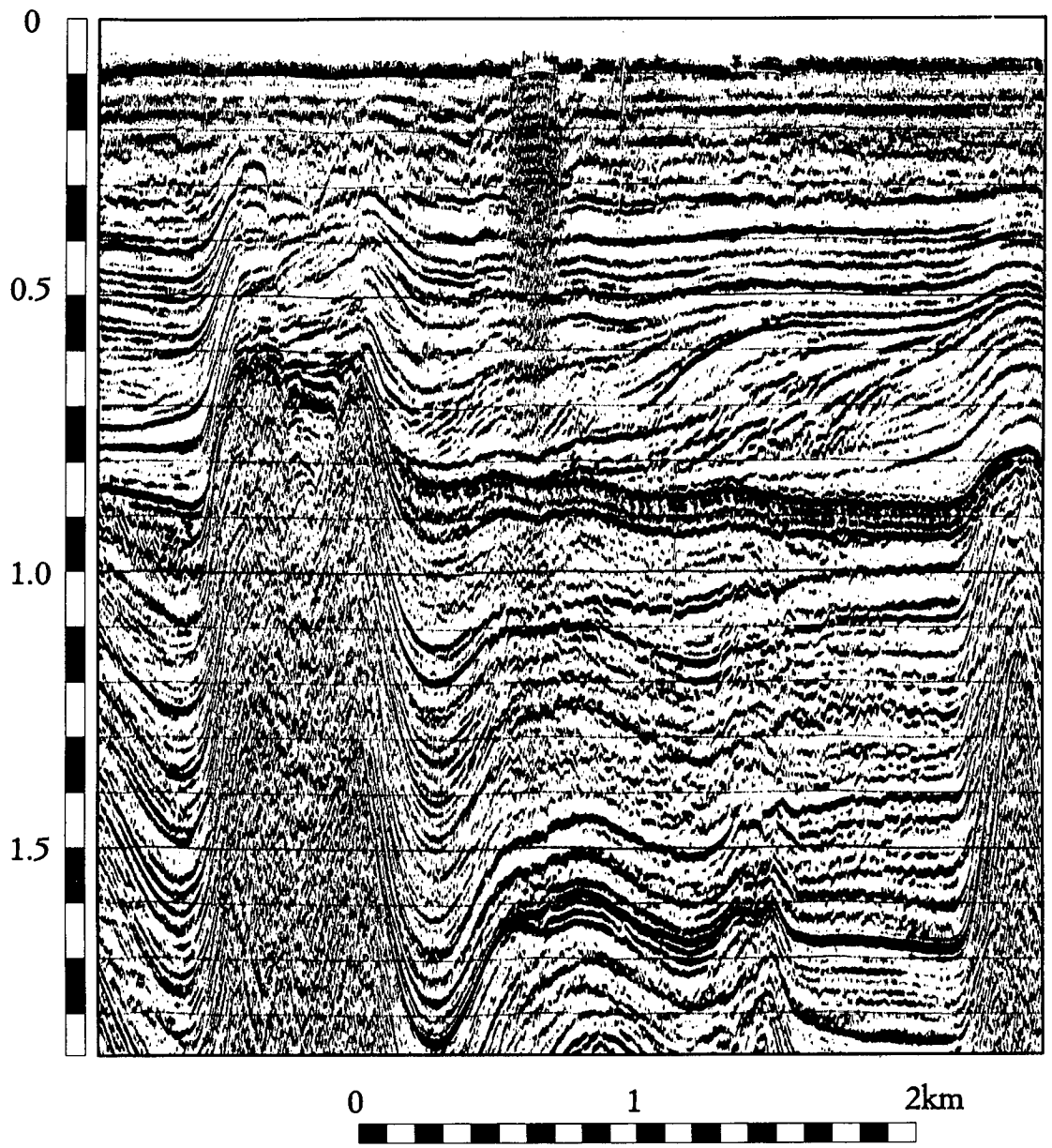


Fig. 2.17: Two line, combined seismic sections (interpreted and uninterpreted; see fig. 2.1 for location), from the SW corner of the study area, illustrating the fore-set relationships of intervals "E" to "G" in the Nordland Group succession. Also note the mass flow disruption of interval "E", the disturbance of interval "G" and the glacial channel at the eastern end of the section (seismic data courtesy of HGS Ltd.).



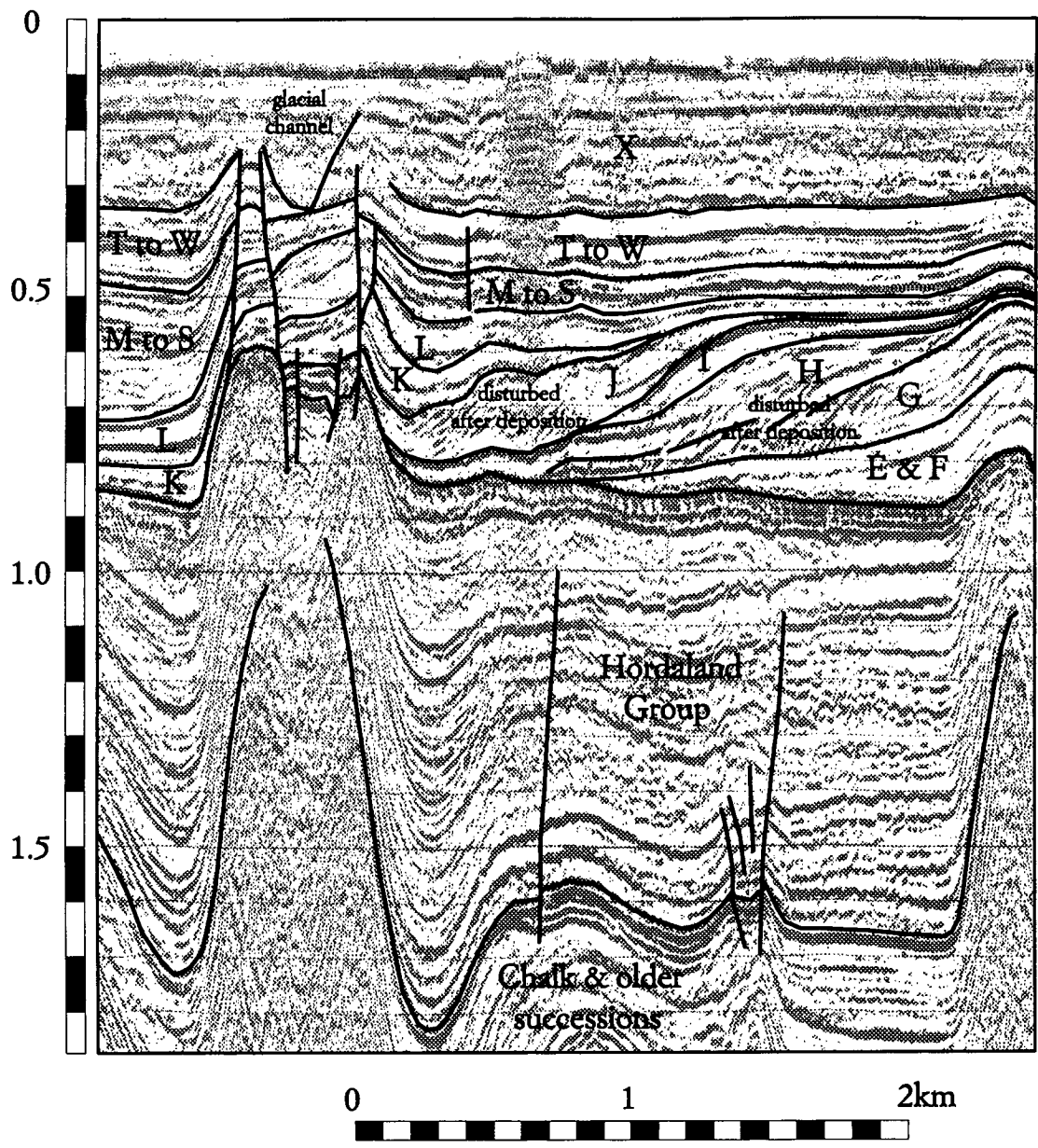


Fig. 2.18: Seismic section (interpreted and uninterpreted; see fig. 2.1 for location), from the centre of the study area, illustrating the fore-set relationships of intervals "G" to "L" in the Nordland Group succession. Also note the disturbance of intervals "G", "H" and "J", the salt related faulting of the Nordland Group succession and the zone of blanking at the top of the section (seismic data courtesy of HGS Ltd.).

Interval Q (H₁₅-H₁₆)

This is another thin, WNW facing interval, up to 80m thick. Interval "Q" is transgressive, showing basinward onlap onto interval "P". It has limited top-set development, and its fore-sets sometimes show strongly reflective bounding surfaces, of negative polarity at the top and of positive polarity at the base (see fig. 2.19). Internally, interval "Q" is acoustically weak, although in the north, occasional moderate amplitude, continuous reflectors are present.

Interval R, top Brielle Ground to base Westkapelle Ground Formation (H₁₆-H₁₇)

During deposition of this interval, which is up to 160m thick, there was a regional change in progradation direction to the WNW. The oldest of four packages, R₁ is only developed in the south, where it shows landward and basinward onlap onto the preceding intervals. Package R₁ is transgressive, with extensive top-sets, and again shows basinward onlap onto the preceding intervals. The base package R₂ is very uneven and is associated with diffraction tails, suggesting erosion.

Packages R₁ and R₂ have extensive toe-sets, which onlap basinward onto horizon "H₁₆" (see fig. 2.20), and onlap landward with little or no top-set development. Package R₃ apparently shows gentle basinward onlap onto R₂. The top of interval "R" locally exhibits mass flow disruption (see fig. 2.19 & 2.30).

Interval S, top Westkapelle Ground Formation (H₁₇-H₁₈)

This interval is relatively thinly developed, reaching only 60m (see fig. 2.20). Its reflector geometry is similar to that of the previous package, continuing the WNW advance, and it shows gentle basinward onlap and landward onlap onto interval "R" and westward development of very extensive toe-sets. Interval "S" shows toplap at its upper surface.

Interval T, base IJmuiden Ground Formation (H₁₈-H₁₉)

This interval is relatively complex, as it was apparently deposited during a major, regional transgression. Its top-sets alone reach over 60m in thickness across much of the study area. Maximum thickness of the interval, within the fore-sets in the NW, is about 160m. In the south, the equivalent fore-set succession is thin, and the intervals reflector geometry displays an overall return to westward progradation.

The base of the interval, horizon "H₁₈", marks a strong upward increase in reflector strength in the west of the study area (see fig. 2.20). In the east, the horizon is marked by a strong top-set reflector.

The interval is made up of three packages. Package T₁ is very widespread and makes up much of the thickness of both the toe-sets and top-sets of the interval. Reflectors are largely parallel within the top-sets, except near the slope break where they dip down to the west and gently downlap onto the preceding top-set surface. These downlap terminations are directed WSW in the lower part of the package, but change direction markedly to the WNW at the top. This suggests that two sediment sources were present, although the architecture and inter-fingering of the resulting sediments is not clear from the seismic data. However, a high amplitude, continuous event is present within package T₁, and this may separate two sub-units with different sources.

Package T₂ is developed only as fore-sets. It has oblique prograding architecture, and largely shows basinward onlap onto package T₁. Package T₂ does not extend far landward, and shows toplap at its top surface. Package T₃ is apparently transgressive, showing basinward onlap onto T₂, and has well developed top-sets. However, the base of these top-sets is apparently erosive, truncating the top of both package T₁ and T₂. Interval events within interval "T" are of moderate amplitude in the west but of low amplitude in the east.

Interval U, intra IJmuiden Ground Formation (H₁₉-H₂₀)

This interval marks continued westward progradation, with constant sediment thicknesses and regularity of facies along strike. This regularity could be due to along-slope reworking of the sediments. The interval reaches no more than 60m in thickness, and it is composed of two packages, U₁ and U₂. These are of low amplitude and moderate continuity internally, and are separated by a moderate to strong reflector.

Package U₁ shows simple onlap and extensive toe-set development. Package U₂ is similar, but shows toplap. The two packages are separated by an erosion surface of possibly marine origin, which has locally removed the whole of package U₁ in two elongate depressions along the base of the fore-sets (see fig. 2.20). The larger depression is about 40km long and 10km wide, whilst the smaller depression is probably around 10 by 4km. Both depressions trend approximately N-S, and are around 20m deep. A similar erosion surface locally marks the top of interval "U". Fore-set slopes, which have been steepened by this pattern of erosion, dip at around 2.2°.

The upper surface interval "U" is always defined by a high to very high amplitude reflector beyond the slope break. This reflector is often also present within the top-sets of the succession. Locally, stepped, horizontal, negative polarity reflectors occur along this upper horizon, suggesting the possible presence of a gas-water contact.

Interval V, intra IJmuiden Ground Formation (H_m-H_n)

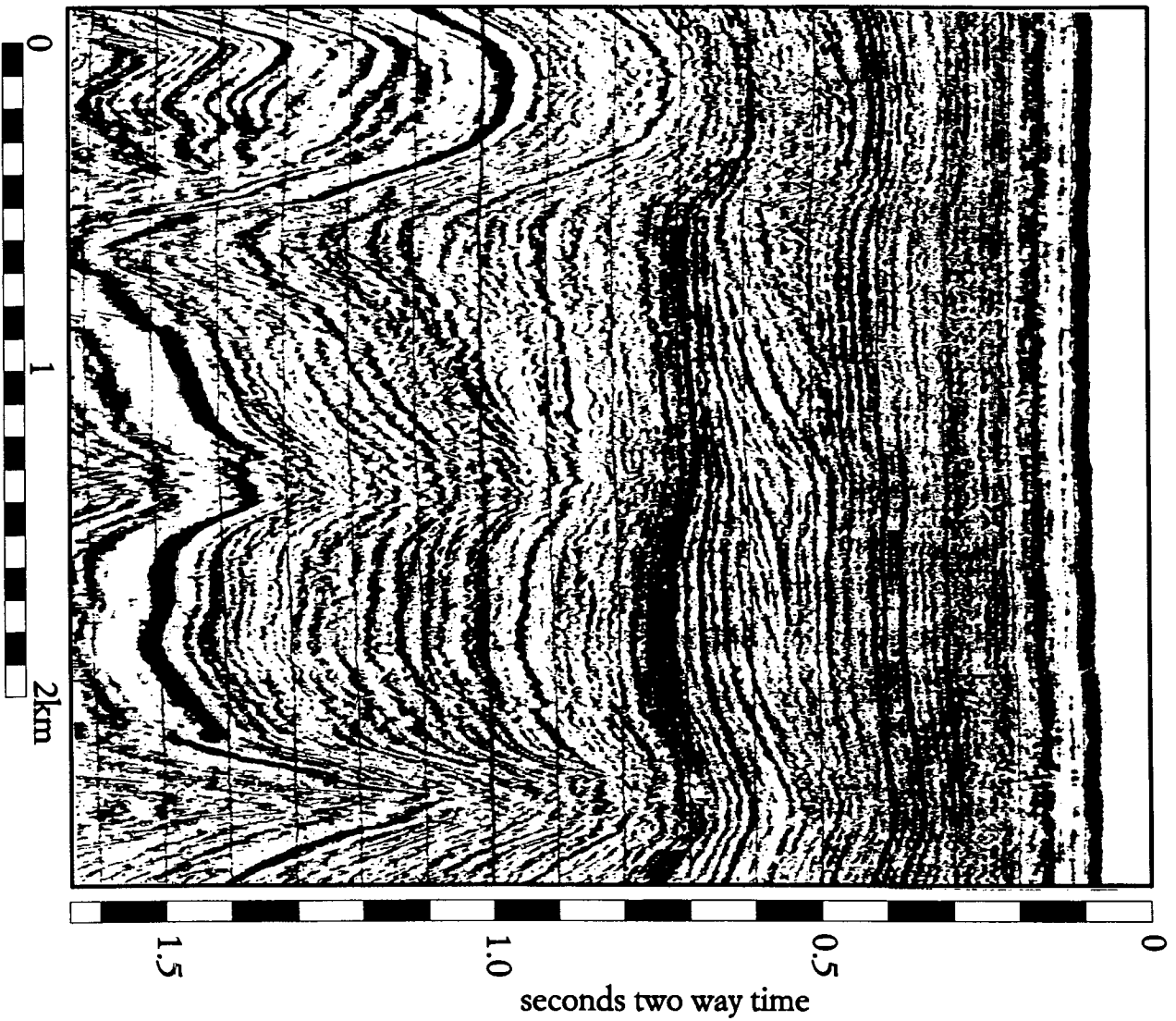
This interval, which is no more than 40m thick, is only very locally present in the SW of the area. It is developed above the sediments of interval "U", and beyond the pre-existing slope break, showing landward onlap onto the fore-set slope. Interval "V" apparently thins out rapidly to the north or NW. This is possibly due either to the southern position of its depocentre or to the nature of the erosion surface that forms its upper limit. The interval is acoustically transparent.

Interval W, top IJmuiden Ground to base Winterton Shoal Formation (H_n-H_m)

This interval reaches 220m in thickness, and the majority of it seems to have been deposited during a distal reworking phase, as dips are generally very gentle (see fig. 2.20). Slightly steeper fore-set development is present at the top of the interval in the very NW corner of the study area. The interval is here divided into four packages. Package W₁ dips to the west and its character is similar to that of interval "V". Events within are of very low amplitude, and a moderate amplitude event defines its top. There are no top-sets. Sediments show uniform onlap from north to south across the pre-existing fore-set slope. Package W₁ shows basinward onlap only onto preceding intervals "U" and "V".

Package W₂, the thickest of the interval, shows landward onlap and is probably only developed basinward of previous fore-sets. Internally, events are regular, of low to moderate amplitude, continuous, and are concordant with the top of interval "U". However, most of these internal events locally describe low angle erosion surfaces similar to those seen in interval "T". Each of these surfaces forms a broad, erosive basin or channel up to 15m deep and tens of kilometres wide, and slightly truncates the events below. Events above the erosion surfaces show onlap onto both sides of the eroded basins..

Package W₃ is around 40m thick and probably makes up most of the top-sets of interval "W". Internal events are indistinct, having low amplitude and continuity. However, they seem to describe small scale channel features against which package



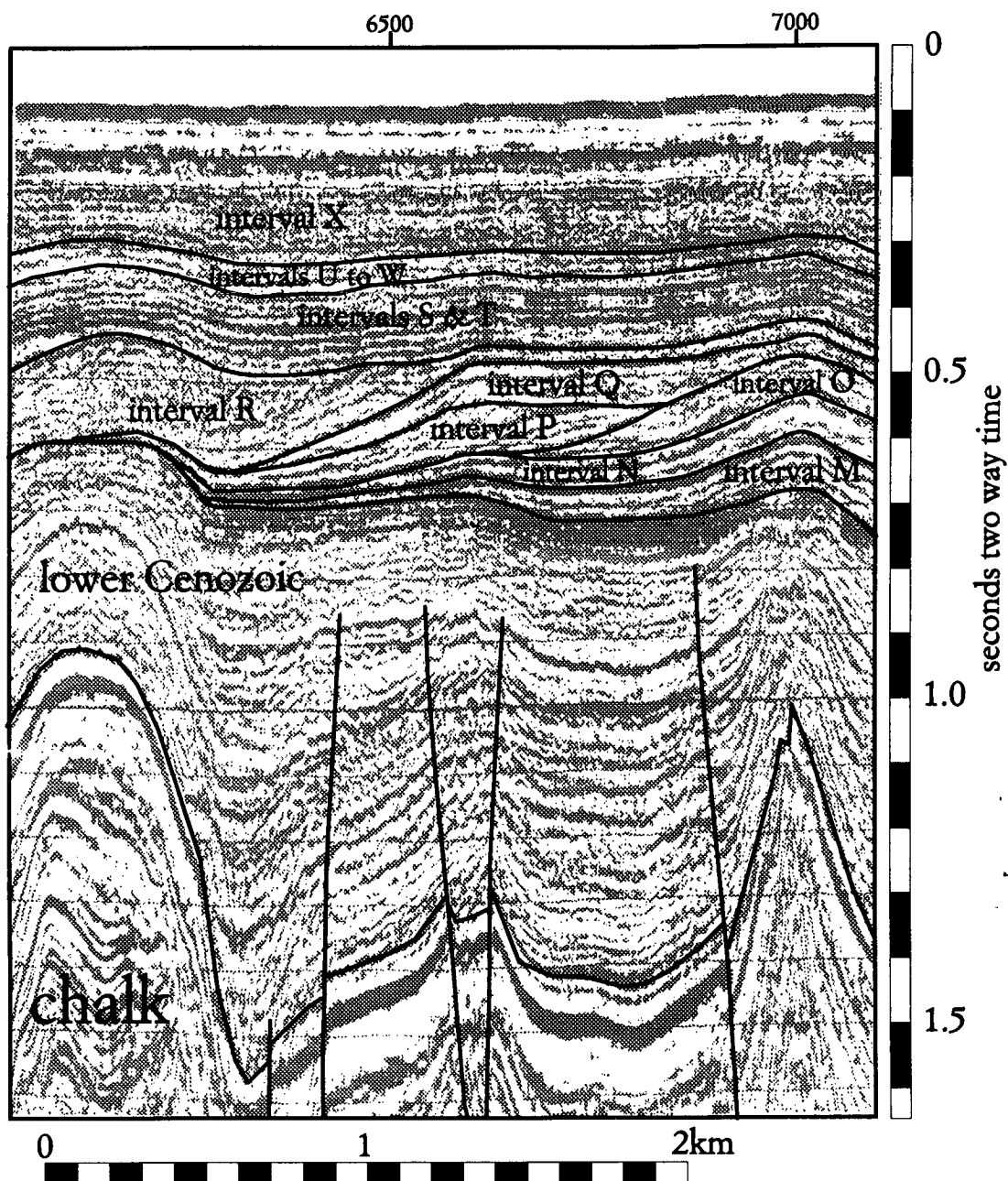


Fig. 2.19: Seismic section (interpreted and uninterpreted; see fig. 2.1 for location), from the centre of the study area, illustrating the fore-set relationships of intervals "O" to "R" in the Nordland Group succession. Also note the mass flow disturbance of interval "R" (seismic data courtesy of NOPEC Ltd.).

W₂ shows very subtle truncation. This truncation could be due to post-depositional tilting.

Package W₃, which is only developed in the NW corner of the study area, shows onlap onto package W₂. However, its distal sediment relations are unknown as they fall outside the study area. Events within this package are of low to moderate amplitude.

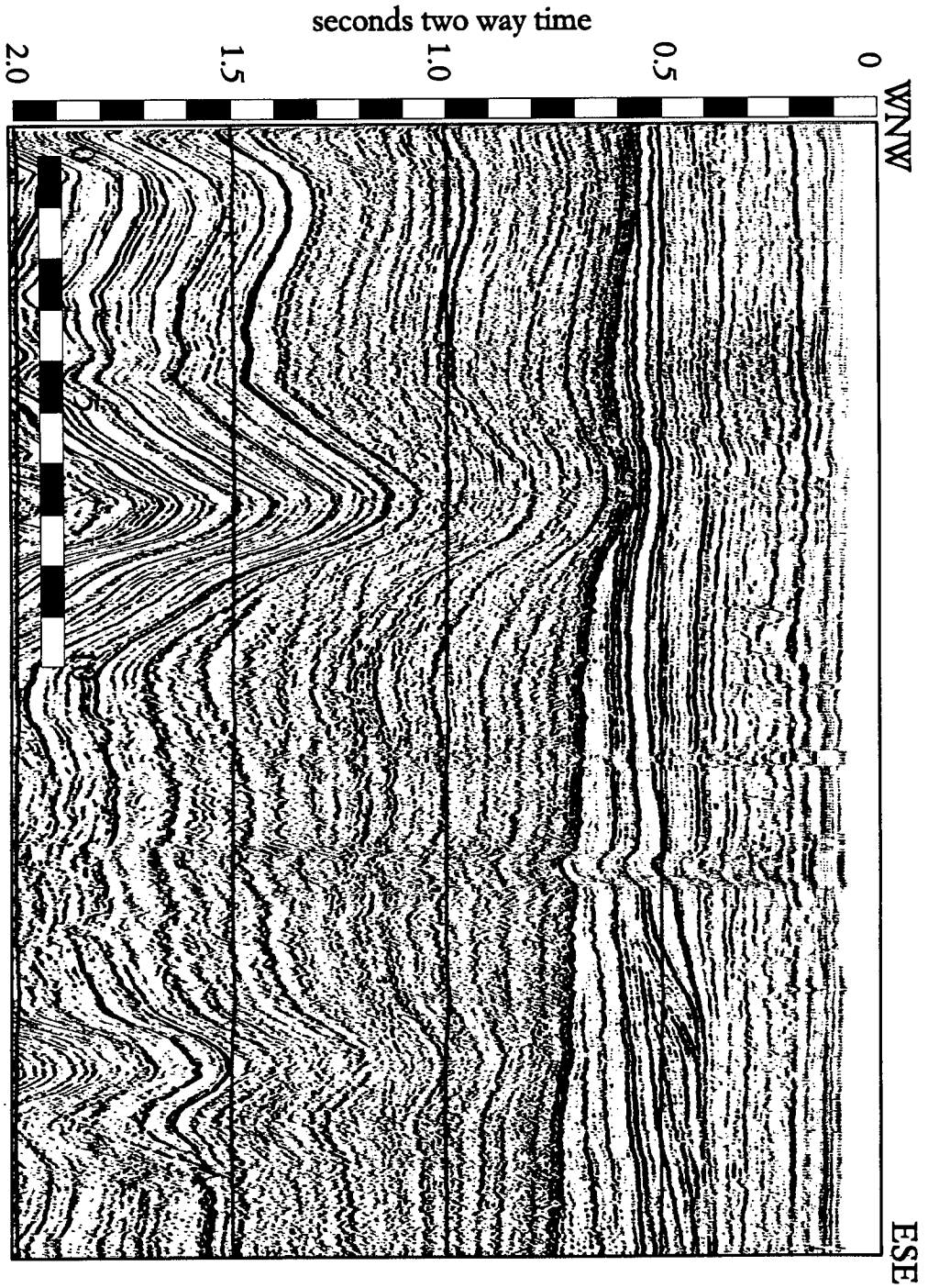
Interval X, Winterton Shoal & younger formations (H₂ to sea-bed)

This is the most complex of all of the intervals, reaching a thickness of up to 400m. The interval can be divided into two separate packages. In package X₁, few horizons can be traced laterally for any great distance, and it is probable that intra-formational channelling is extensive. Events within this package are generally of low to moderate amplitude, with low to very low continuity. Rarely, in the east, a single, high amplitude event can be traced for several kilometres about 20ms above the base of the package (see fig. 2.15). Those channels that can be defined occasionally reach depths of more than 30m. This seismic facies pattern is diagnostic of the Yarmouth Roads Formation (Cameron *et al.*, 1986).

The base of package X₁ is defined by massive, erosive channel forms, up to 400m deep (e.g. figs. 2.8, 2.15, 2.17, 2.25c), which cut into much older sediments, including the Eocene clays in the study area. When mapped out, these channels are seen to be elongated N-S to NW-SE across the study area, shallow toward both ends, and can show widths of up to 10 km (see fig. 2.21a). Sediments above this erosion surface usually show onlap onto the channel sides, although more complex relationships of events are common.

In the NW of the study area (see fig. 2.21a), events are present close below sea floor, characterised by high amplitude, negative polarity, a loss of reflector continuity beneath them and, sometimes, by the presence of velocity pull-down of up to 50ms below the centre.

The sea-bed reflector is often lost through data processing, so that first events occur on seismic data at around 80ms TWT. However, an elongated depression, up to 50m deep can be seen on the sea-bed in the NW corner of the study area (see fig. 2.21a).



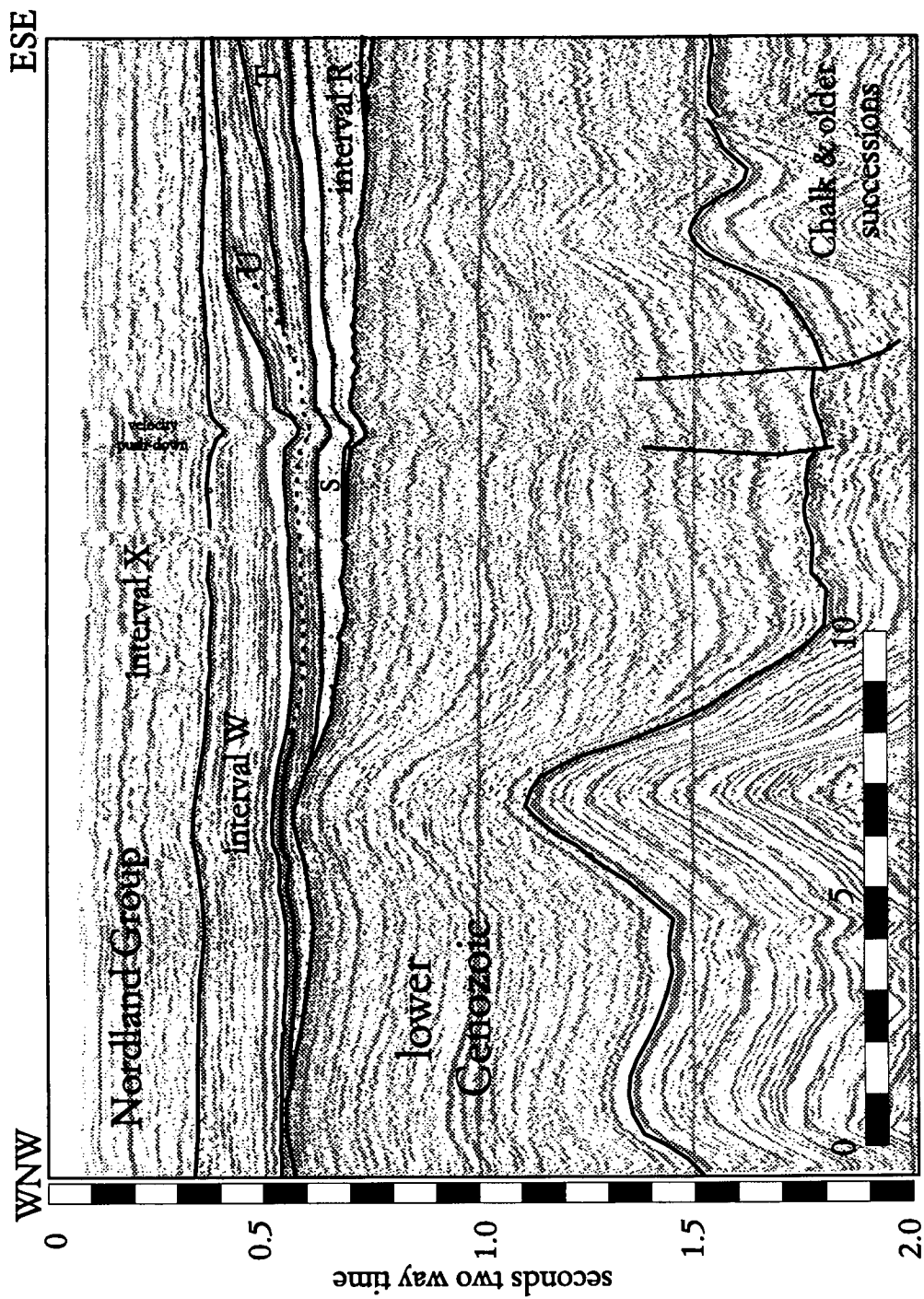


Fig. 2.20: Seismic section (interpreted and uninterpreted; see fig. 2.1 for location), from the NW of the study area, illustrating the fore-set relationships of intervals "T" to "W" in the Nordland Group succession. Also note the channelled fore-set erosion surface within interval "U" (seismic data courtesy of HGS Ltd.).

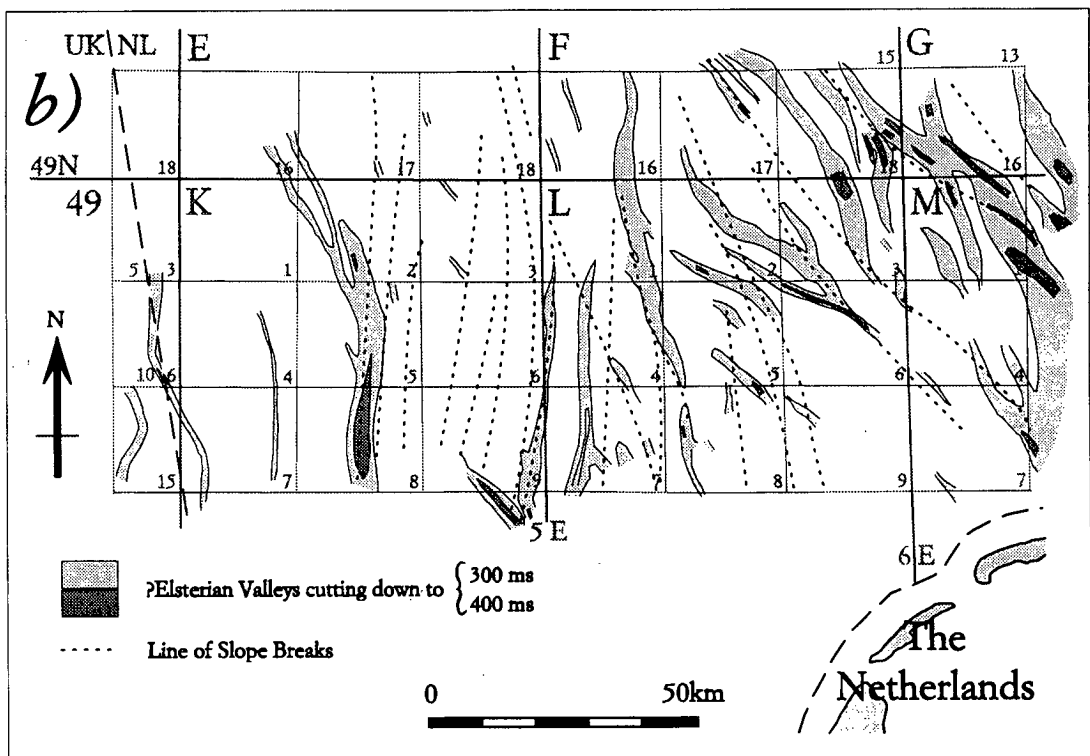
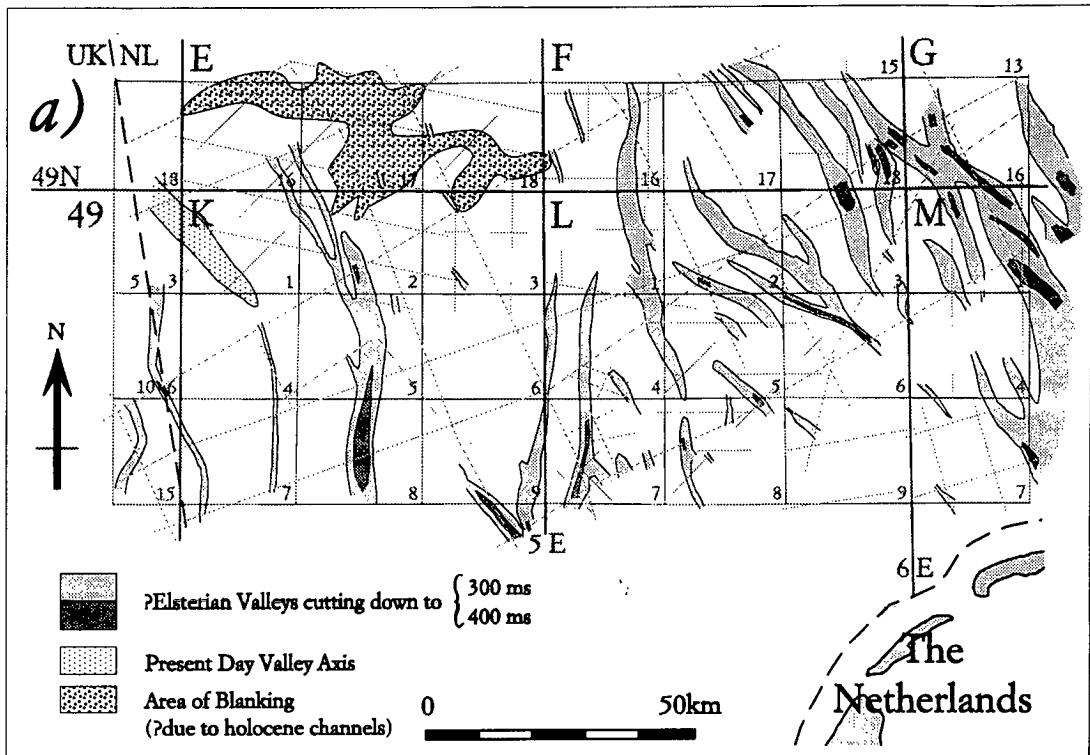


Fig. 2.21: Maps of: a) Elsterian and Weichselian channel distributions within the study area, as interpreted by the author. Note the general N-S to NW-SE trend for the Elsterian channel axes; b) The comparison of pre-glacial Nordland Group slope break positions and the positions of Elsterian channels, showing good correlation to the west, away from the North Sea Central Graben axis.

2.3: Discussion

2.3.1: The “pre-Nordland Group” Succession

Faulting Elsewhere in the lower Cenozoic

The structures seen in the lower Cenozoic succession of the study area can be compared with similar structures seen in clays of the same age elsewhere in the North Sea Basin.

Belgian North Sea: Equivalent deformation within the lower Cenozoic clay succession, including both faulting and diapirism, has been recognised in Ypresian (Eocene) clay from the southernmost, Belgian part of the southern North Sea Basin by Henriët *et al.* (1989; 1991). These authors attribute the deformation to under-compaction of the clay, caused by its rapid deposition. Because water loss and compaction only occurred at the base and at the top of the clay, causing water to drain into sand layers above and beneath, these confining clay layers became impermeable barriers to the further escape of water from the middle of the clay succession. Differential loading on the whole succession later caused de-stabilisation and fluidization of much of the succession.

Danish Central Graben: Clay dominated, lower Cenozoic sediments in the Danish part of the North Sea Central Graben were shown by Clausen & Korstgård (1993b) to have been affected by largely extensional faulting. Their estimates of extension vary, across the area, from less than 5% to more than 10%. Additionally, the authors recognised localised compression, largely above the axis of a Cretaceous fault line. The authors interpreted the patterns of faulting to be indicative of flexural bending of the clay succession around its upper surface, and suggested that this may have been due to deep, basement fault re-activation.

Outer Moray Firth: Here, Higgs & McClay (1993) recorded extensional faulting, which is again truncated at the “mid-Tertiary” unconformity. Down-throw in the Outer Moray Firth is toward the basin-margin, and again occurs in clay dominated sediments of the lower Cenozoic age. The authors presented a model relating the faulting to basinward tilting during deposition, and without the need for a basal decollement separating the clay succession from older units below. The interpreted fault styles, with individual faults traceable throughout the lower Cenozoic succession, are not similar to those seen within the present study area, and this would suggest

entirely unrelated faulting processes. However, apparently random joint and fault patterns have been imaged in 3D seismic data within this succession (fig. 8 of Newton & Flanagan, 1993; Cartwright, 1994). This indicates that similar structures to those in the Southern North Sea are actually present within the same, lower Cenozoic succession of the Outer Moray Firth, and that the latter also contains fault patterns of a non-tectonic origin.

Origin of Faulting

The generally normal style of faulting in the lower Cenozoic succession suggests lateral extension of the succession (cf. Clausen & Korstgård, 1993b). Several alternative reasons can be suggested to account for this phenomenon:

Mass flow movement: this could cause the extensional features seen if mass flow movement occurred throughout the deposition of the lower Cenozoic succession. This mass flow movement might be expected to have been directed toward the basin centre. However, no preferred direction of extension is seen within the lower Cenozoic clay succession of the study area (cf. figure 8 in Newton & Flanagan, 1993; Cartwright, 1994). Additionally, as indicated by Clausen & Korstgård (1993b), extension should be concentrated above extensional, tectonic fault lines, causing localised mass flow movement or gravity collapse, rather than the observed compression in these locations.

Tectonic movement: The absence of the lower Cenozoic faults from the chalk succession below precludes the possibility of the faults representing the upward continuation of older fault trends. Clausen & Korstgård (1993b) suggested that the cause of the fault patterns seen in the Danish Central Graben is the bending of the partially cemented clays over active fault scarps on the upper surface of the chalk there. However, the apparent compression seen above these fault lines in the top of the chalk (Clausen & Korstgård, 1993b) actually implies that the clays bent not over the fault-related, chalk topography, which would generate extension in the lower Cenozoic succession above the faults, but that they bent around the “mid-Tertiary” unconformity surface, which acted as a neutral surface. This problem requires further consideration.

Clay compaction: This has been suggested by both Henriët *et al.* (1989; 1991) and Cartwright (1994). In this model, the clay succession was sealed at an early stage, both at the base and the top, by well compacted, impermeable layers. This sealing

process prevented further escape of water from the middle of the clay succession. Eventually, with continuing deposition above the clay succession, sufficient differential stresses were set up within the succession to de-stabilise the under-compacted and, possibly, over-pressured clay. The upper clay seal ruptured and water was rapidly released from the interior of the clay succession. Cartwright (1994) suggests that this may have happened several times during the deposition of the lower Cenozoic clay.

Timing of Faulting

The faulting seen within the lower Cenozoic clays of the southern North Sea may have resulted from processes which continued throughout deposition of the lower Cenozoic clay succession, for example mass flow movement or multiple fluid-expulsion events (Cartwright, 1994). Alternatively, if the faulting was due to a single event, then it was caused by a middle Miocene or younger deformation phase, as it affects sediments right up to the “mid-Tertiary” unconformity surface.

The “lower Cenozoic” style of deformation also locally affects sediments within the lower part of the Nordland Group succession, and similar disruption patterns are locally seen within the mass flows above the “mid-Tertiary” unconformity. If this is the case, then it is unlikely that the tectonism of the lower Cenozoic succession can be attributed to one tectonic event.

Gas Within the lower Cenozoic

Bright Spots: The flat, stepped, high energy, negative polarity events at the “mid-Tertiary” unconformity surface may be due to a gas-water contact resulting from the presence of trapped gas beneath the surface. If so, this indicates that the “mid-Tertiary” unconformity surface may be, or may be overlain by, an impermeable layer of sediment, preventing the upward migration of water or gas.

Diapirism: Major, apparently ductile deformation occurs in the north of the study area at the top of the succession. This deformation is probably due to diapirism in the younger, less well lithified parts of the lower Cenozoic succession. Although the reasons for clay diapirism are not obvious, a possible mechanism involves the de-stabilisation of the clays by either thermogenic or biogenic gas, as has been observed off Norway (Hovland, 1990; 1991). Similar, diapiric structures have also been recorded offshore from Belgium at the top of the lower Cenozoic succession by Henriët *et al.* (1989).

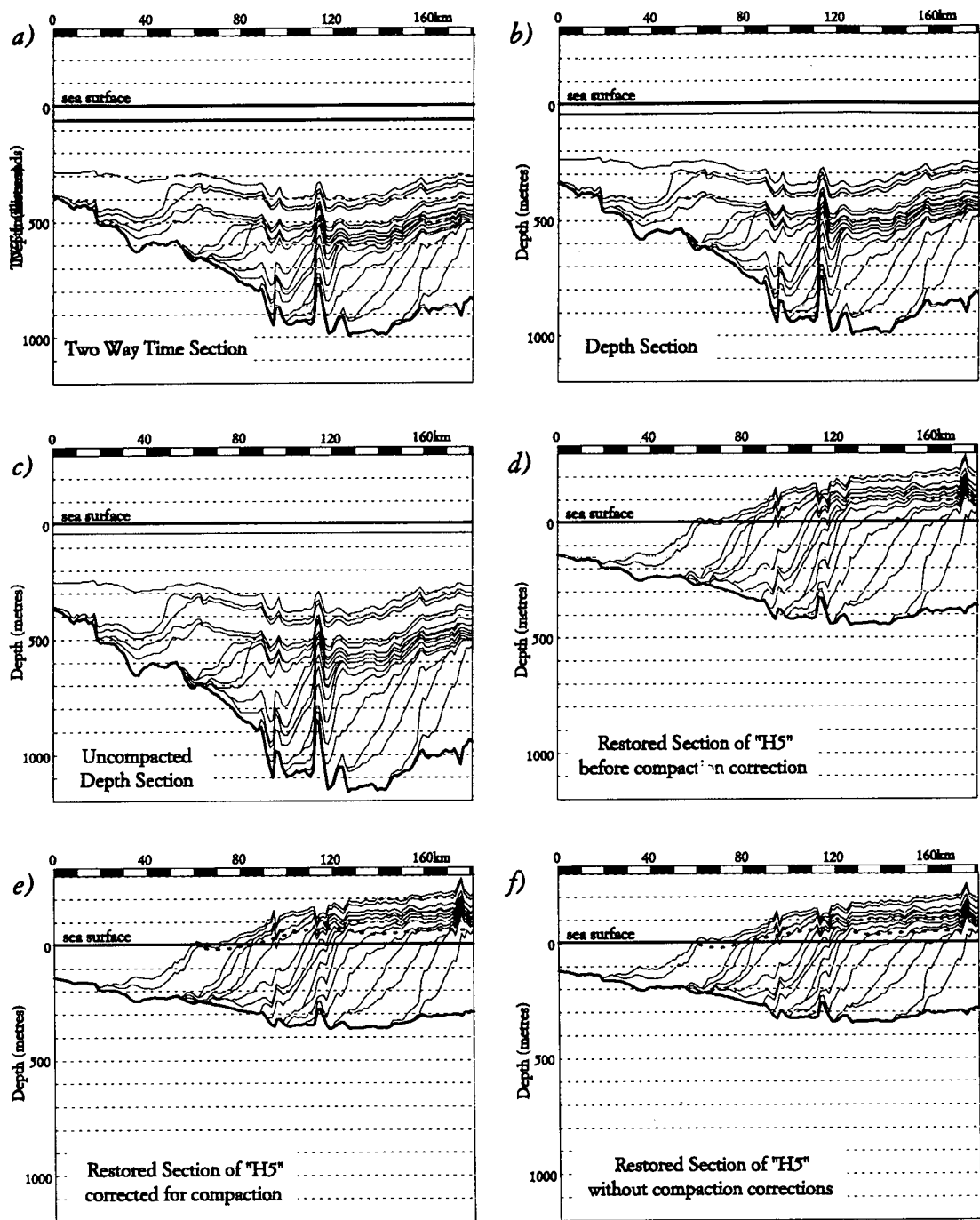


Fig. 2.22: Attempted restoration of the architecture of the Nordland Group succession at the time of deposition of seismic horizon "H₅", using the assumption of non-variable subsidence rates across the basin and of sea level control upon the position of the slope break. Two restorations of the section have been done, one with corrections for compaction and the other with no correction for compaction, to show that the overall architecture of the succession is not substantially altered by taking compaction into consideration. For both the compaction corrected and un-corrected sections, the line joining successive slope breaks dips to the west. Also, during deposition there has been net top-set aggradation.

2.3.2: The Nordland Group Succession

Subsidence Patterns During Deposition

The Nordland Group succession of the study area, when looked at in depth converted cross-section, has the appearance of a standard, deltaic architecture, individual fore-sets indicating potential water depths of up to 400m during its deposition. Generally, this interpretation is accepted by most authors (Cameron *et al.*, 1987; 1993; Gramman & Kockel, 1988).

The simplest scenario is that differential subsidence did not occur during the deposition of the Nordland Group succession (i.e. at any geographical point, assumed subsidence rates for the Nordland Group at any time are proportional to the current depth of the base of the Nordland Group below present sea level at that point). Using this scenario, individual palaeo-sections across the study area can be worked out, using simple, velocity based estimates for present porosity within the succession, and hence its degree of compaction. This procedure has been undertaken here for the section along the Cromer-Sylt seismic line (see fig. 2.22).

A palaeo-section for the time of deposition of seismic horizon "H₁" is shown here, using the assumption that the slope-breaks observed within the cross-section of the Cromer-Sylt line are due to sea-level control (cf. Vail *et al.*, 1977), and were, therefore, once at or near sea level. This palaeo-section has the appearance of a typical cross-section for a delta prograding into water up to 400m deep. If a line is drawn connecting the slope breaks of all the previous depositional surfaces shown on the palaeo-section, this line dips to the west. This implies that relative sea level in the basin steadily dropped by as much as 80m over the time between deposition of the oldest slope break observed in the section and the deposition of the sediments at the level of seismic horizon "H₁". Using a simplified model, without correcting for compaction effects, this sea level drop is reduced to around 50m, but the sign remains unchanged.

Large-scale aggradation of the Nordland Group succession occurred during this apparent relative sea level fall, up to 100m of sediment being deposited as top-sets. If this architecture is compared with the predicted, sea level controlled sequence models of Posamentier & Vail (1988; see fig. 2.23), it clearly does not fit the models, as large-scale top-set aggradation is associated with the generation of vertical accommodation space due to a relative sea level rise.

This contradiction can be overcome by removing the assumption of uniform subsidence along the line of section. Instead, it is necessary for the major axis of subsidence to have migrated or expanded across the area from east to west

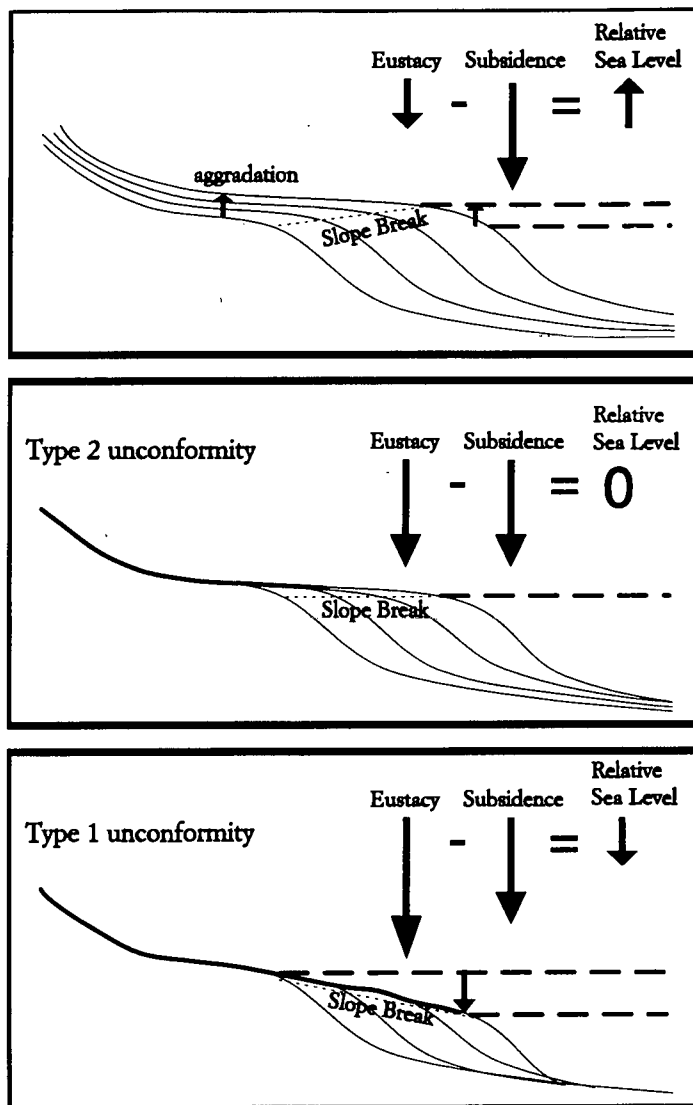


Fig. 2.23: Schematic diagrams of the architecture produced by varying relative sea level changes, after Posamentier *et al.* (1988). Using these models, aggradation of top-sets can only occur during a relative sea level rise.

throughout deposition of the Nordland Group succession. This model avoids the need for a continuous, relative sea level fall throughout the time of deposition.

Clinoform Geometry

Four types of steep, clinoform seismic facies can be seen in the lower part of the Nordland Group (see figs. 2.24 & 2.25), although only three of these have been identified within study area. They are described here, using the terminology of Vail *et al.* (1977).

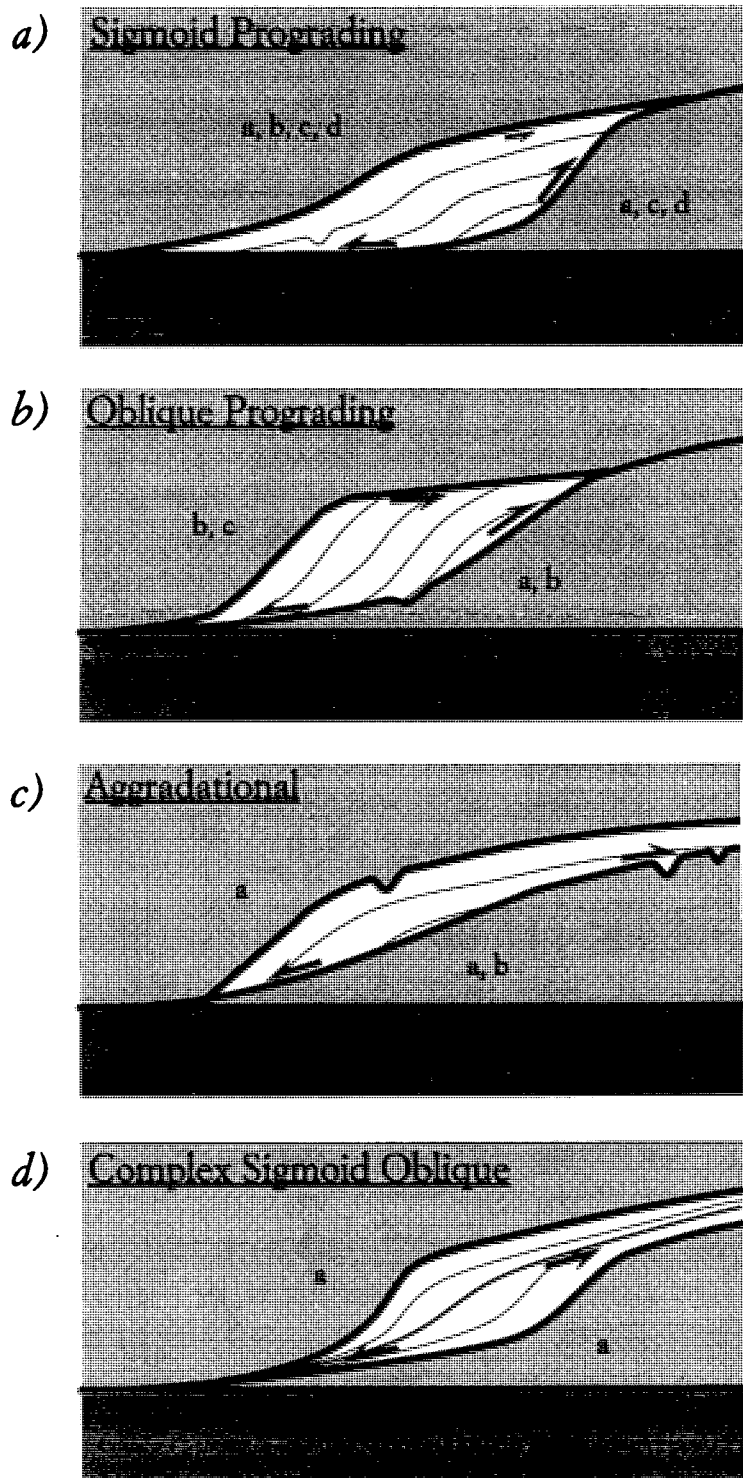
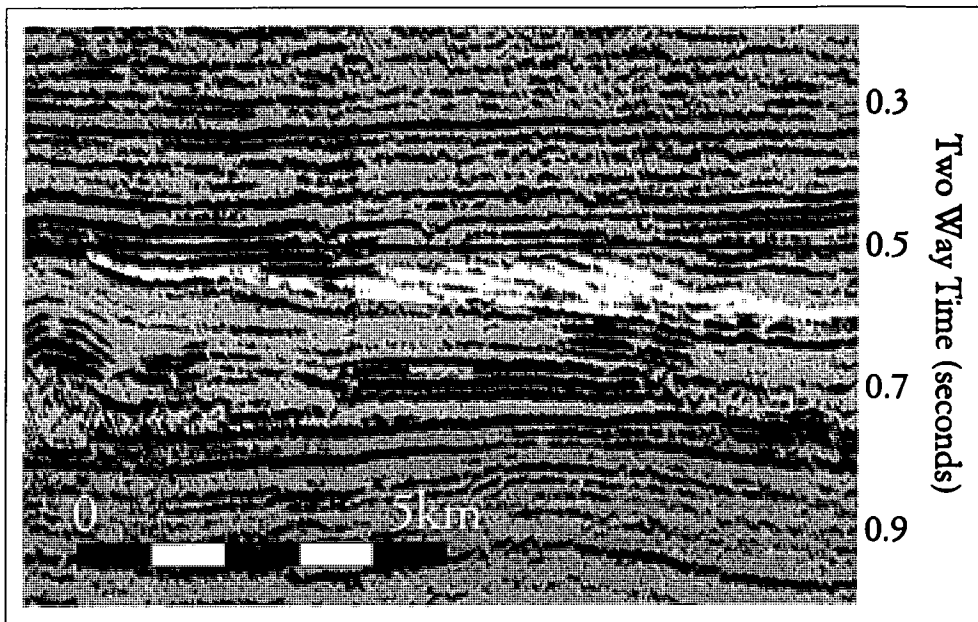
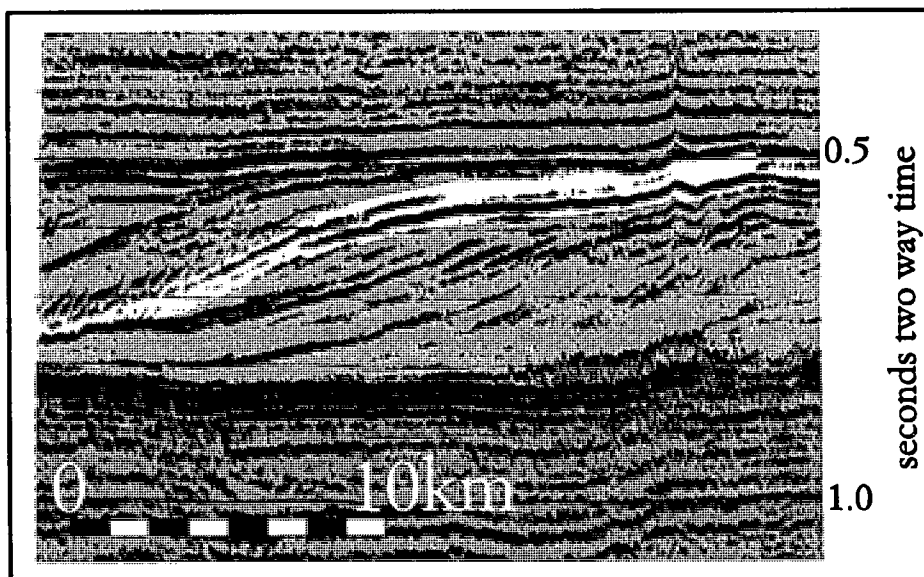


Fig. 2.24: Types of clinoform architecture observed within seismic data of the Nordland Group in the study area, not including the complex, transgressive architecture of seismic interval "T".



a)



b)

Fig. 2.25: Seismic sections of the Nordland Group, illustrating the forms (in regions without stipple) of: a) "Oblique Clinoform" seismic facies, which shows top-lap and no top-set development, and b) "Aggradational" seismic facies, which shows almost as thick top-sets as fore-sets. "Sigmoid Clinoform" seismic facies, which have little variation in character in clinoform facies, are seen underlying the "Oblique Clinoform" seismic facies in "a" (seismic data courtesy of HGS Ltd.).

“Sigmoid Prograding” Facies: This facies is developed basinward of the slope break and shows landward onlap onto the slope front. It is the principle unit of progradation, having extensive toe-sets, and makes up most of the clinof orm part of the succession. Dip directions and distribution of sediments are generally uniform across the entire depositional front, whilst dips are generally no more than 1.5°. Fore-set heights can be up to 400m in the areas where the Nordland Group is thickest. Upper surfaces of the clinof orms very occasionally show toplap or are cut by channels. Fore-sets occasionally show extensive erosion surfaces, as well as large channels (see fig. 2.26a), and scour features which are possibly tidal. Events are of low to moderate amplitude and are fairly continuous in undisturbed sediments.

This facies overlies “aggrading” or “complex sigmoid oblique” facies, and is overlain by any of the other three facies. It is equivalent to seismic facies *a* and *b* of Cameron *et al.* (1987), and also seems to be equivalent depositional style of the “lowstand wedge systems tract” of Posamentier *et al.* (1988) and the slope regrading package of Galloway (1989). “Sigmoid prograding” facies are attributed to low energy conditions by Vail *et al.* (1977).

“Oblique Prograding” Facies: This facies is also developed beyond the slope-break, but it often lacks toe-sets, as it shows basinward onlap distally onto preceding toe- and fore-sets. It is only locally developed at the depositional front, where it has variable fore-set dip directions and dips of up to 2.5°. Fore-set heights are generally less than 150m. Individual packages show toplap and top-sets are usually absent. Older packages within the Nordland Group have tangential oblique architecture, whilst younger packages are often parallel oblique. Erosion of underlying facies is often present at the base of this facies. Internally, the facies is made up of very variable amplitude and moderate to low continuity events, and sometimes shows chaotic structure. This facies occurs in intervals “D”, “F”, “L”, “O”, “P”, “T” and, possibly, “A”, “C” and “H”. It is usually overlain by “transgressive” facies.

This facies normally overlies “sigmoid prograding” facies, rarely “aggrading facies”, and is overlain by “aggrading” facies. It is equivalent to seismic facies *c* of Cameron *et al.* (1987). Although this facies does not match any of the systems tracts described by Posamentier *et al.* (1988), it could represent the “forced regression” facies of Posamentier *et al.* (1992). “Oblique prograding” facies were associated with high energy by Vail *et al.* (1977).

“Aggrading” Facies: This facies often has extensive top-set development and shows coastal onlap, but thinly drapes or shows basinward onlap onto previously deposited,

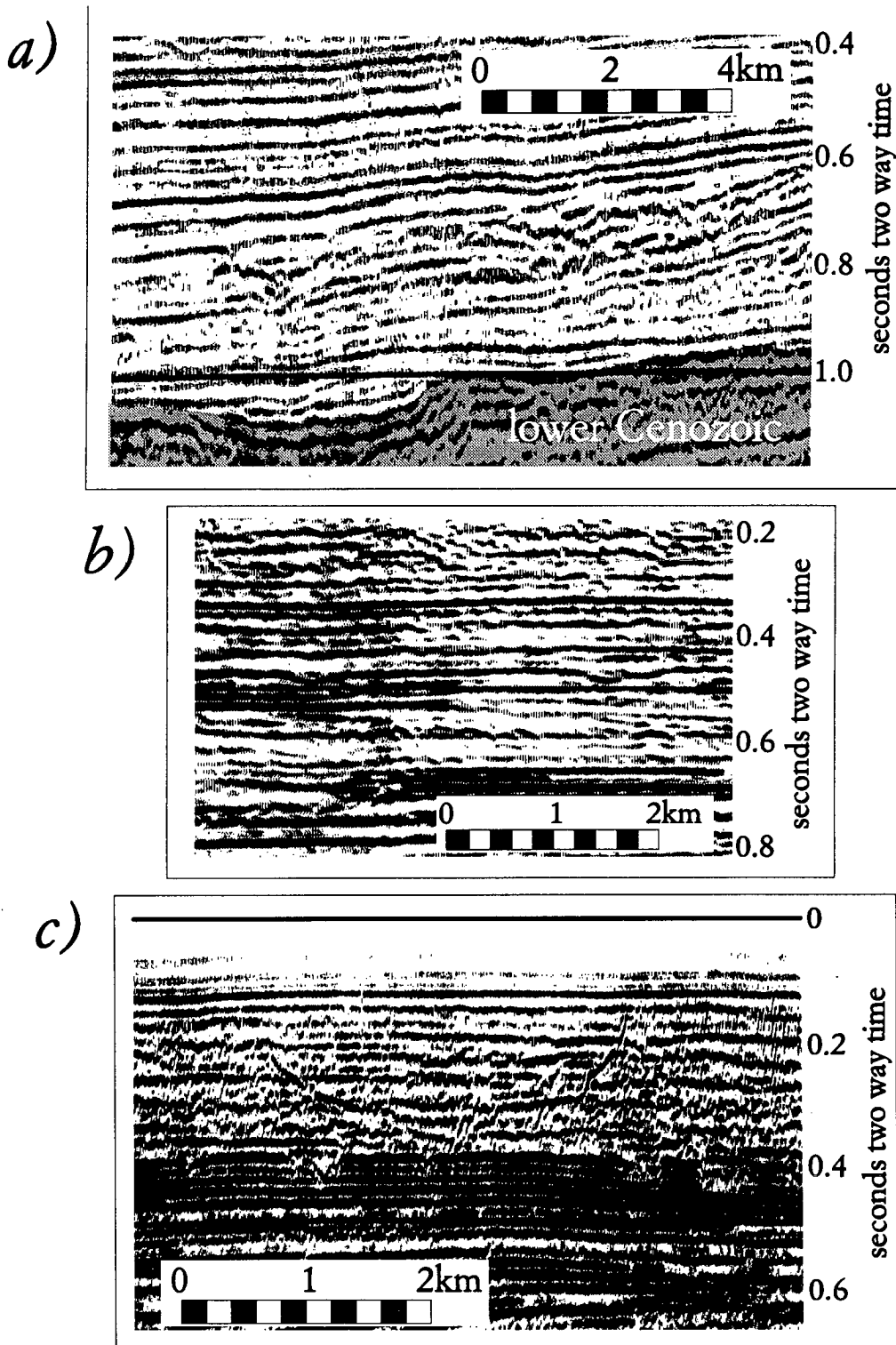


Fig 2.26: Seismic sections of the Nordland Group, illustrating: a) Channel development within fore-sets (top interval "C"); b) Channel development at the break of slope; c) Channel development within the top-sets, both as small, possibly fluvial channels, and as large, glacial channels (seismic data courtesy of HGS Ltd.).

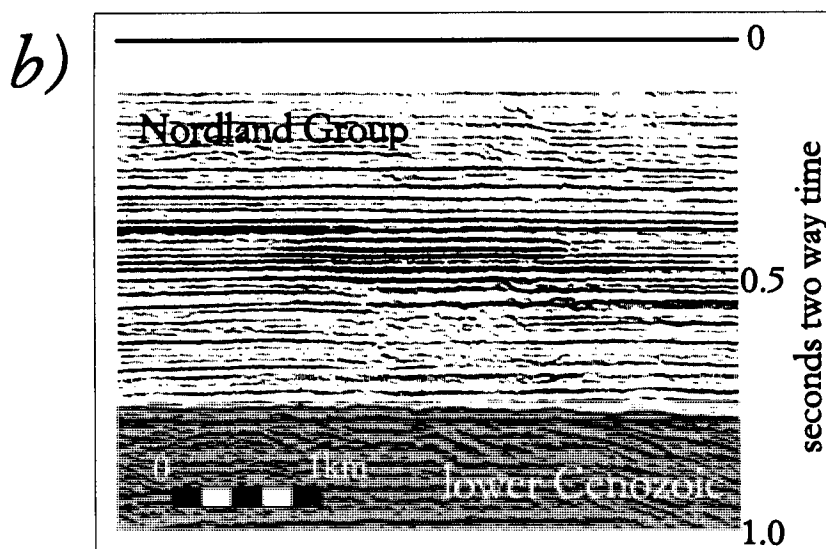
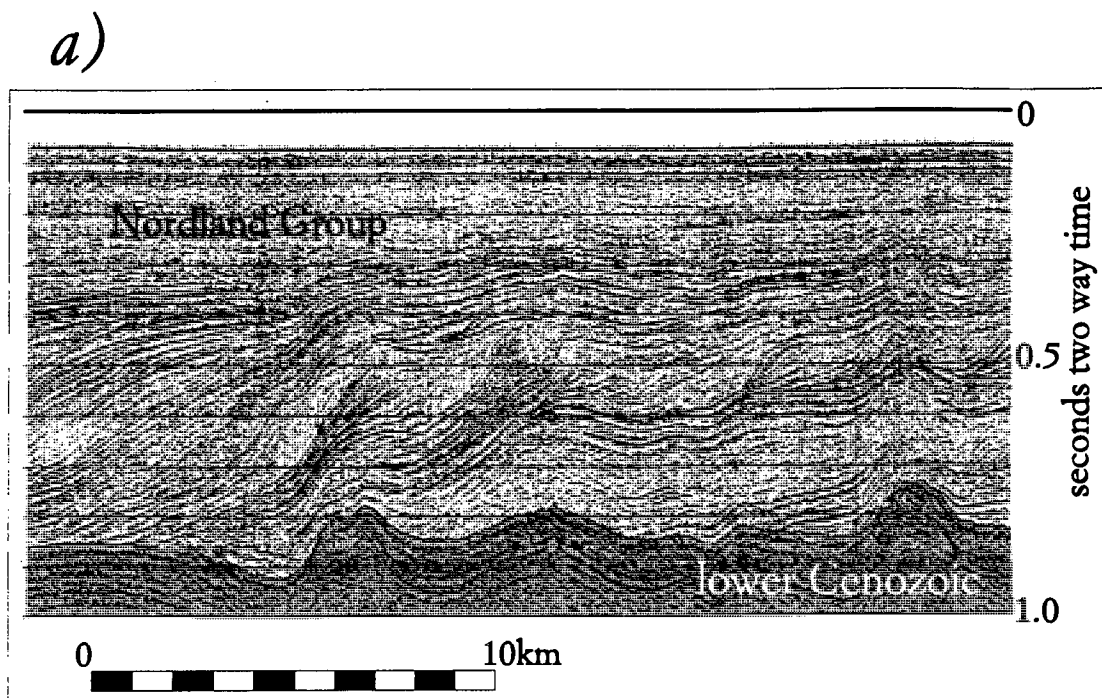


Fig 2.27: Seismic sections of the Nordland Group, illustrating: a) "Complex Sigmoid Oblique" Facies in the "Cromer-Sylt" seismic line to the NE of the study area in the German sector; b) Shallow gas trapped within the succession (seismic data courtesy of BGS & RGD and HGS Ltd.).

distal sediments without significant progradation. The base of the facies often truncates the underlying sediments in the west of the study area. "Aggrading" facies are present in intervals "B", "D", "F", "G", "H", "I", "L", "Q", "R", "T" and "W", and often overlie "oblique prograding" facies where the latter are present.

This facies is developed above "oblique prograding" facies where the latter is present. Otherwise, it is developed above "sigmoid prograding" facies. It can be overlain by either "sigmoid prograding" or "oblique prograding" facies. The facies does not match those previously observed well, although it can possibly be considered as equivalent to the "highstand systems tract" of Posamentier *et al.* (1988).

"Complex Sigmoid Oblique" Facies: This facies is developed to the east of the study area in the German sector and in the eastern part of the Dutch sector (see fig. 2.27a). It is similar to the "oblique prograding" facies, in showing steepening of fore-set slopes. However, whilst toplap surfaces can be seen within the facies, there is also considerable aggradation, with thick top-sets. Additionally, toe-sets are often well developed. Internal structures are chaotic within the fore-sets of the facies. However, moderate to high amplitude reflectors can be seen in both the toe and top-sets.

Although not identified within the study area, this facies may be present only between periods of "sigmoid prograding" facies development. It is similar to the "highstand systems tract" of Posamentier *et al.* (1988) and the "slope prograding and aggrading" facies of Galloway (1989).

Fore-set Erosion Surfaces: These are erosion surfaces which have apparently steepened fore-set slopes by preferentially eroding the basinward part of the fore-sets. The generation of steeper fore-set slopes by erosion is unusual. They have been noted within the succession at four different levels:

- + Within interval "C"
- + Within interval "D"
- + At the top of interval "I" ("H₁")
- + At the top of interval "U" ("H₂₀")

The first three of these are often formed within clay dominated parts of the succession (see section 3.2.2). Steepened fore-set slopes in a clay succession have also been noted in a re-interpretation of the work of Asquith (1970) in the Western Interior Sea-way of Wyoming by Van Wagoner *et al.* (1990). Possible origins for these surfaces are (see fig. 2.28):

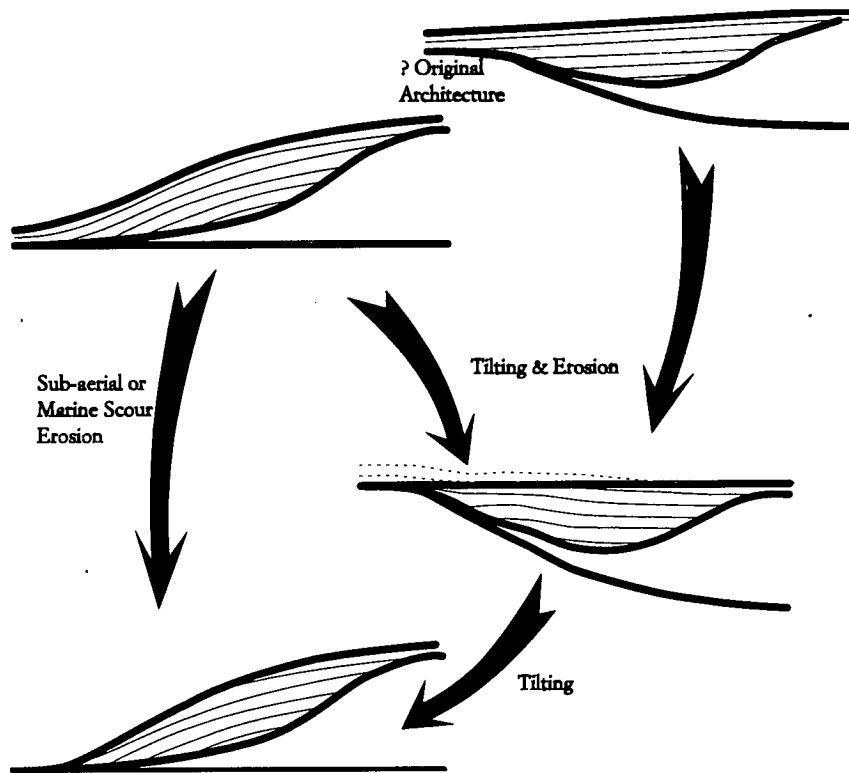


Fig. 2.27: Possible mechanisms for the formation of the fore-set erosion surfaces seen in seismic data.

+ Eastward tilting of a westward dipping surface to horizontal, followed by erosion and subsequent westward tilting of the surface to approximately its original attitude. This method does not obey the principle of parsimony.

+ Marine erosion of dipping fore-sets due to a decrease in sediment input. Such erosion could include slumping of fore-sets as a result of wave or tidal influence, and reworking of the slumped sediment. This is certainly possible for the erosion surface at the top of interval "U". However, there is little evidence for slumping and reworking associated with the older erosion surfaces.

This mechanism is problematic, due to reworking and regrading of slopes normally having the effect of reducing, and not increasing the angle of the slope. It may be that erosion by contour currents along the base of the fore-set slope could generate this erosion pattern.

+ Sea level fall beyond the slope break. This also presents problems, both for the reasons mentioned in "2", and because of the amount of sea level fall required for the slope break to be exposed sub-aerially, which may be very large.

It is possible that any of these processes could have acted independently or in combination to produce the fore-set erosion surfaces seen. Nevertheless, the origin of this feature remains a problem.

Top-set Geometry

The architecture of the top-sets is fairly uniform throughout the succession. All top-set events dip to the west relative to horizon "H₆". Only package T₁ of interval "T", which is a major transgressive unit, shows morphological complications. Events within this less than 40m thick package dip more steeply to the west, showing downlap onto the top-sets of interval "R" below, and they show toplap against the base of package T₂ of interval "T".

Events within the top-sets are generally of variable amplitude and continuity. Near the base of the top-set succession, they can be continuous and of low to moderate amplitude. At higher levels, top-sets tend to become very variable in amplitude, possibly due to frequent lithology changes or hardground and soil development. Their variable continuity may be due to channelling (see fig 2.26b). Near the top of the succession, top-set events are of low amplitude and continuity. However, isolated events are present which can be of very high amplitude, with negative polarity, and fair to good continuity. These might be clay or peat layers within predominantly sandy, possibly fluvial sediments.

At the base of the top-sets, near or at the slope break, rare, large channels up to 50m deep and 300m wide can be seen (e.g. within interval "G", and on horizons "H₇" and "H₈"). These channels cannot be traced between adjacent seismic lines and they are therefore very localized features. such channels could be related to slope regrading (see fig. 2.26b).

Sediment Doming

This occurs within the Nordland Group in two forms:

+ As isolated sediment mounds resting on the "mid-Tertiary" unconformity surface in locations where the "mid-Tertiary unconformity is defined by a slight depression, the uppermost layers of the lower Cenozoic clay succession having apparently been eroded and removed. Sediment packages lying above these mounds are also domed, showing no onlap onto the upper surface of the dome, but doming becomes less pronounced upward.

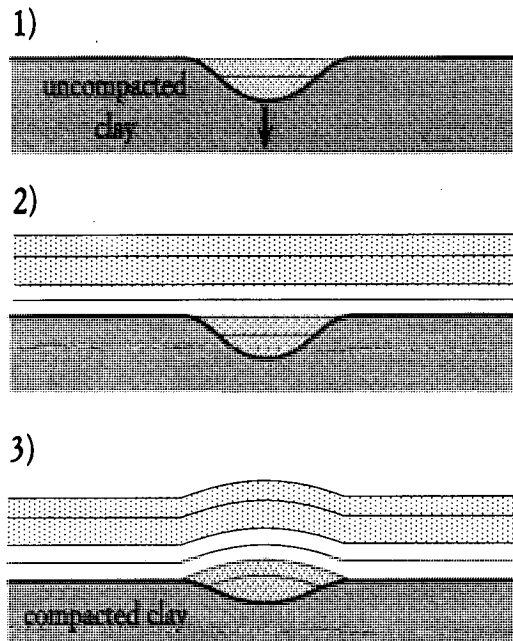


Fig. 2.28: Probable origin of "domed" sediment packages within and at the base of the Nordland Group.

+ As doming of sediment above the maximum disturbance in mass flow units. As above, this doming occurs only directly above locations where the base of the mass flow unit is cut into the underlying, lower Cenozoic clay succession, and doming becomes less pronounced upward.

The doming is therefore apparently related to the removal of the uppermost layers of the lower Cenozoic clay succession, due either to their incorporation into mass flow units or to some other erosion mechanism prior to the deposition of the Nordland Group succession. Additionally, the concordance of the sediment packages above the mounds and mass flow units suggests that this present geometry formed some time after the sediments were originally deposited.

It is suggested here that the doming is likely to be an inversion effect, due to the differential compaction of the lower Cenozoic clays, compared with the material that replaced them where they were removed (see fig. 2.29). Although the sediment within the isolated mounds has not been sampled, the lithology of the sediments in which the mass flow units occur is entirely clay dominated (see section 3.2.2). This suggests, at least for the mass flow units, that the sediment filling the spaces left by removal of the lower Cenozoic clay is also clay dominated. This implies, therefore, that the lower Cenozoic clays were less compacted than the clay dominated infill of the depressions, and that the subsequent compaction of the upper layers of the lower Cenozoic succession caused the inversion of the sediments above the depressions.

Mass Flow Disturbance

Mass flow units occur at several places within the study area, although they are largely located in the east (see fig. 2.30a). Ten mass flow units have been identified, and are, in ascending stratigraphic order:

- + Flow I (middle of "A"): highly erosive
- + Flows II & III (top of "A"): highly erosive
- + Flow IV (top of "C"): complex flow, highly erosive
- + Flow V (top of "D"): complex flow, highly erosive
- + Flows VI & VII (middle of "E"): highly erosive
- + Flow VIII (top of "E"): weakly developed in toe-sets only
- + Flow IX (top of interval M): very poorly developed in toe-sets only
- + Flow X (top of interval R): very erosive

In the study area, mass flow seismic facies are characterized by the following properties (see figs. 2.7, 2.8, 2.31a):

+ Where the mass flow is developed within the toe-sets, it has a "rubbled", uneven upper surface with many diffraction tails (see fig. 2.31a). This may be the seismic expression of an uneven erosion surface in most places. Primary events in the packages underlying this surface units appear to be obliterated in many sections. This could be due either to mass flow disturbance of the underlying sediments or to the obscuring of events in these sediments by diffraction energy.

+ An up-slope separation point, occurring on the fore-set slope, which defines the land-ward limit of disturbance.

+ Rotated fault blocks and slumping in the top-sets and fore-sets. This does not occur in flows "VIII" and "IX", which are only developed within the toe-sets. Fault blocks reach sizes of up to 500m wide and 200m thick. They are usually very localised in areas with dimensions of up to 5 by 10km, their long axes along strike. Fault blocks only occur near or at the head of the mass flow. Their rotation and movement directions are entirely consistent with the depositional slopes indicated by the fore-set slopes. They are always on, or just landward of the slope maximum. The original structure of the undeformed sediments is often preserved within the individual

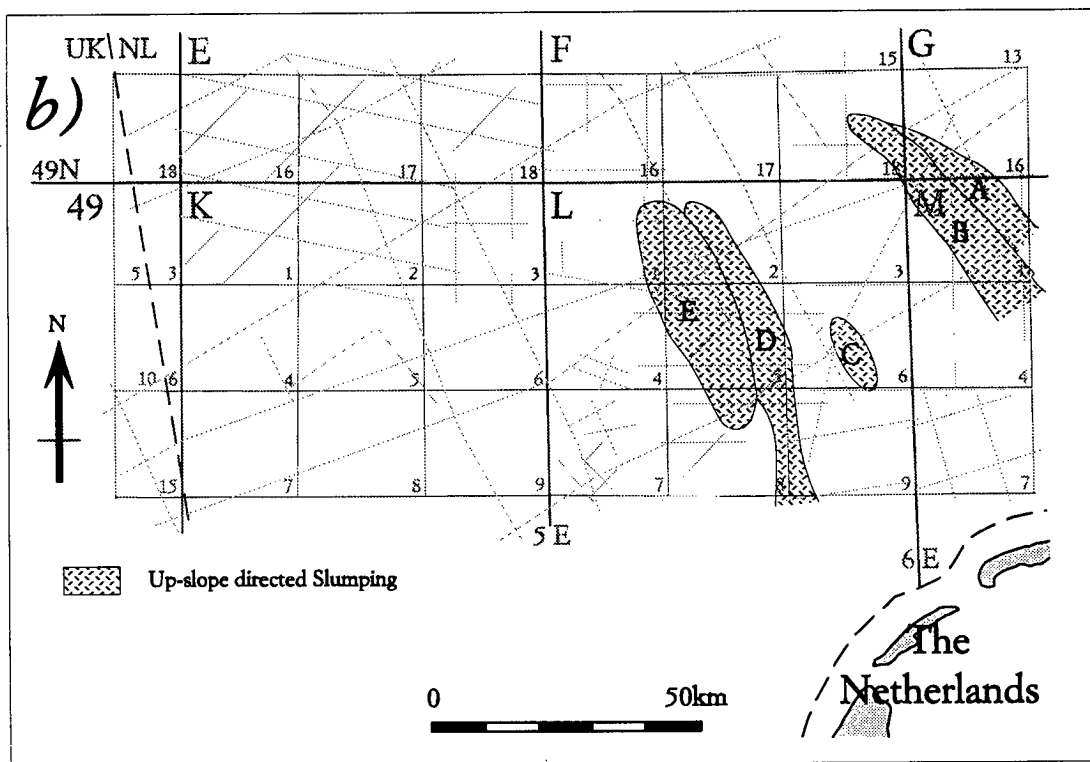
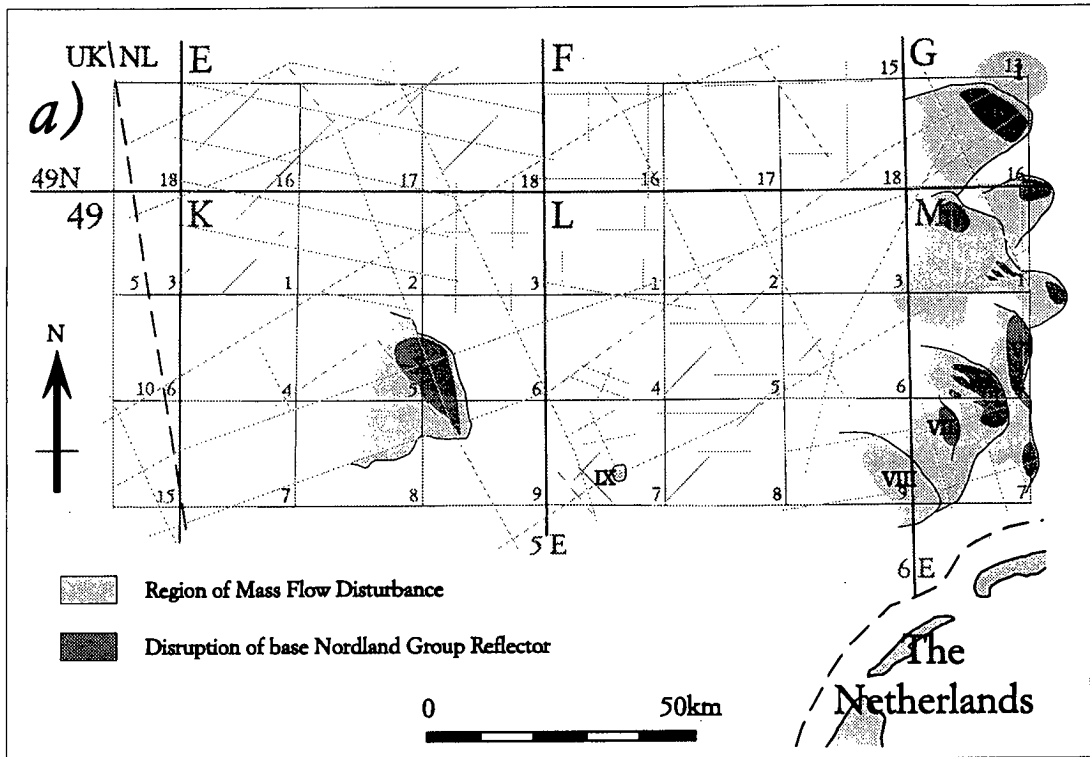


Fig. 2.29: Maps showing: a) the location of mass flow units and related disturbance within the study area; b) the location of "up-slope slump-scars" within the study area.

blocks, although their seismic reflectors generally have higher amplitude than for the same sediment packages elsewhere.

Where fault blocks are present, the basal decollement surface of the mass flow slump scar often cuts down into lower Cenozoic sediments, and results in the disappearance of the "H₁" reflector. When traceable within the lower Cenozoic clay succession, this decollement surface appears to be irregular, as if individual fault blocks are actually embedded in the clay. Additionally, sediments at these locations are domed above the mass flow (see discussion on doming in this section). There is often show post-slump, onlapping infill above the foot-wall blocks, with slight erosion of the foot-wall crests.

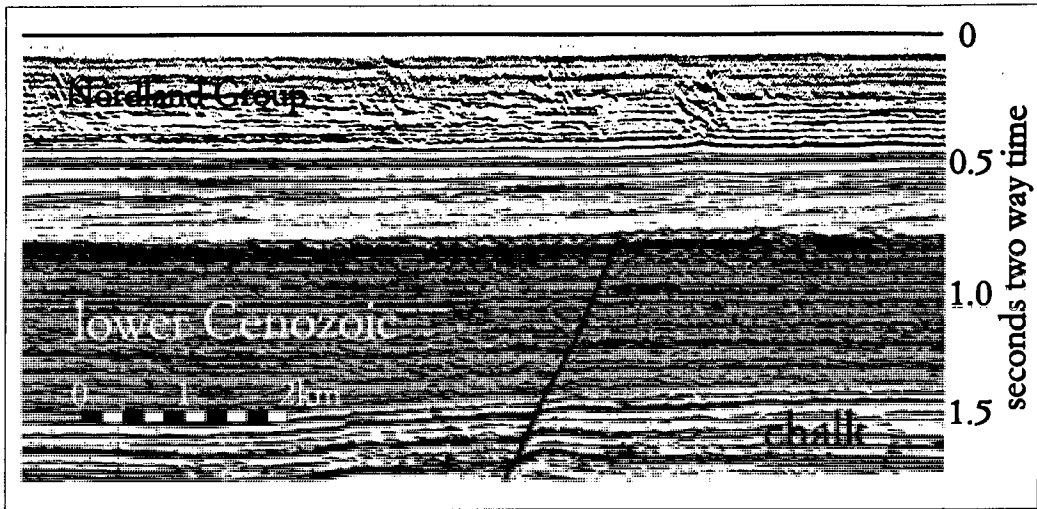
+ High amplitude events at the top of the flow. These are negative polarity events at the top of the mass flow package, and are often associated with the apparent disappearance of a reflector at the level of the "mid-Tertiary" unconformity.

The overall geometry of the flows is of slight elongation down the fore-set dip. They extend for some distance into the basin, and are often well developed in the toe-sets. The flows may show lines of maximum erosion perpendicular to fore-set strike, but there is insufficient information to confirm this. These lines of maximum erosion are defined by multiple, steep sided, channel like erosion surfaces, with depths of up to 30m, and widths of around 200m.

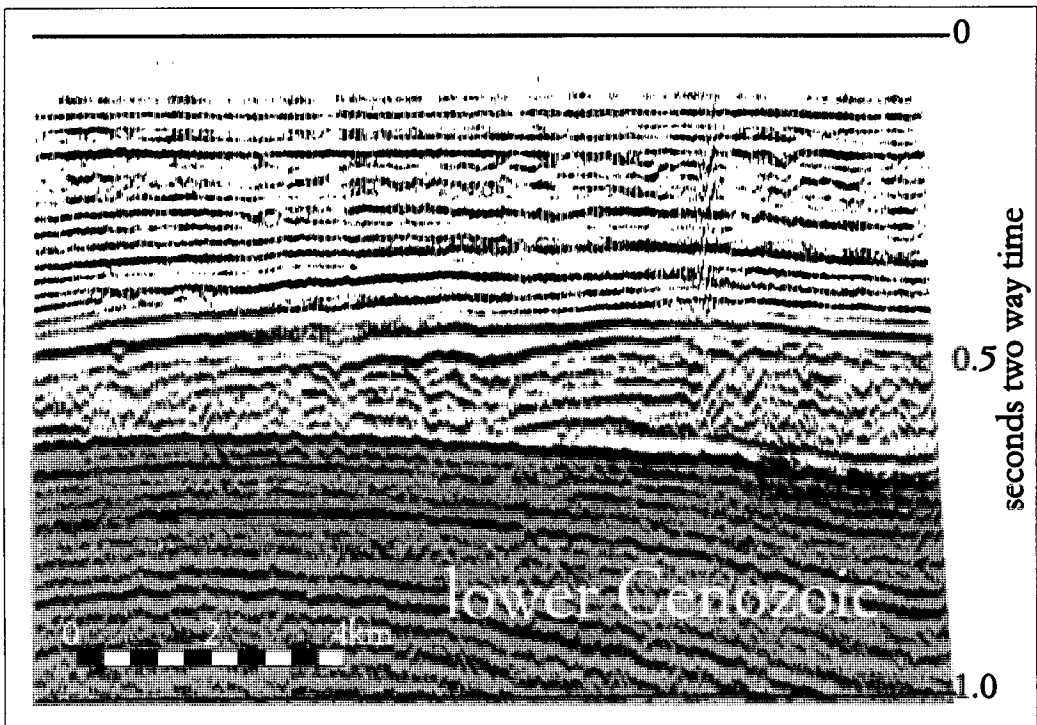
Mass Flow Locations: Flows "I" to "VIII" are all formed along a N-S line in the eastern-most part of the study area, around the 5°12'E line of longitude. Oldest flows here occur in the north, the youngest in the south. Mass flows were apparently triggered as each sediment package prograded SW across this line. The reasons for this alignment could include:

+ Uplift to the east, along an old structural trend, possibly the southern limit of a high that defines the eastern limit of the North Sea Central Graben within the study area. This might cause the sediments over-steepen locally, triggering mass flow. The principle argument against this mechanism is that many of the mass flow units have their up-slope detachments in areas which should be stabilised by local subsidence patterns, such that sediments in these areas were sloping at lower angles than they would have normally.

a)



b)



Figs. 2.30: Seismic sections showing unusual mass flow character. a) “rubbling” of a seismic event. This is commonly associated with fully developed mass-flow units, but is here isolated. There may be some connection between this seismic texture and the location of the underlying fault. b) Mass flow structure in flow “XI”, at the top of interval “R” (seismic data courtesy of HGS Ltd.).

+ The invasion of the sediments along this axis by fluids or gas, causing weakening and failure of the sediments. It has been noticed in certain places that the point of maximum disturbance, usually at the point of fault rotation, overlies older, apparently chaotically disrupted lower Cenozoic sediments and that the upper surface of the chalk is also disrupted in these locations (see fig. 2.7; see section 4.3.1 & 4.3.2).

Up-slope Directed "Slump-Scars"

Apparent, intra-formational, slump-like features are seen at several levels in the succession, in zones of disruption up to 5km wide 30km long, running parallel to strike along the base of fore-set slopes. These "slump-scars" are located in two different zones within the study area (see fig. 2.30b):

NW slump zone	Slump A (within interval "B") Slump B (tentatively identified, top interval "C")
Central slump zone	Slump C (tentatively identified, interval "F") Slump D (top interval "G") Slump E (top interval "J") Slump F (? top interval "K")

At first sight, this deformation appears to be high amplitude, shingled clinoform reflectors (*sensu* Vaile *et al.*, 1977), prograding westward within the fore-set succession. On closer inspection, it can be seen that each of these reflectors belongs to the same seismic event, which has been broken by regularly spaced faults (see fig. 2.32). The faulting includes both normal and reverse styles, although possible thrusting occurs only at the up-slope end of the disrupted zone. Individual "fault-blocks" are about 250m wide, and about 50 to 100m thick.

The upper surface of the disrupted zone has sometimes been eroded before subsequent deposition, and individual "fault-blocks" are often truncated, suggesting that the faulting is syn-depositional. Also, the faults do not extend to any depth, and basal decollements are tentatively identified just 50 to 100m below the upper surface of individual "slump-scar" packages. These packages are not associated with any regional or larger scale fault patterns developed in the succession.

The pattern of down-throw in these "slump-scars" is apparently toward the east or ENE. This is approximately 180° away from the expected depositional dip direction, as deduced from fore-sets slopes in the seismic data. If these are gravity-influenced slump scars, then their up-slope directed down-throw directions suggest that the slope upon which they now rest has an opposite dip direction to that existing when the slumping occurred.

Regionally, the "slump-scar" packages normally occur in paired zones (see fig. 2.32) above and below steep (greater than 2°), high amplitude clinoform surfaces

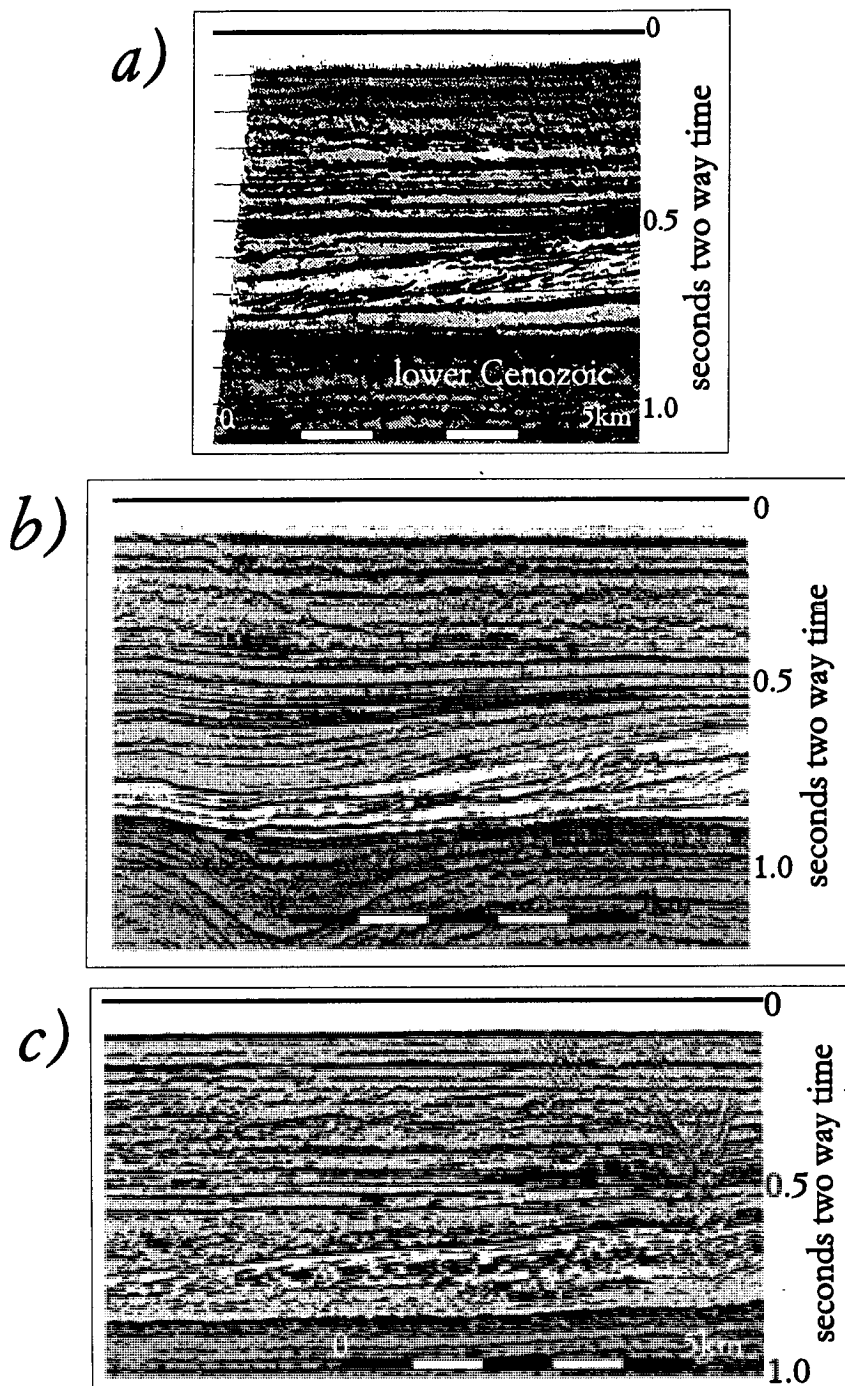


Fig. 2.31: Seismic sections showing “up-slope directed slump-scars”. a) From interval “G” (slump C). b) From interval “J” (slump D), showing possible reverse faulting. c) From interval “B” (slump A; seismic data courtesy of HGS Ltd.).

(e.g. horizons “H₂”, “H₃”). They are also associated with fore-set erosion surfaces, although no causal relationship is suggested here. These features have also been observed in data from the northern end of the North Sea Central Graben.

Gas Within the Nordland Group

Zones of acoustic blanking and velocity pull down are observed to start just below the sea-bed in the NW corner and the centre of the study area (see fig 2.21b). Similar features have been demonstrated to be channel systems in 3D data from just to the south of the study area (D. Praeg, *pers. comm.*). These features are seen only in the locations of salt uplift, and they may be fluvial channel systems, picked out by the presence of shallow gas, which has leaked from deeper in the sediment pile and is now trapped within the channel fill.

Gas is also present at deeper levels within the Nordland Group, and is revealed by the presence of stepped, flat events, each of which indicates a gas-water contact. Such events have already been described at the base of the succession in the lower Cenozoic succession, just below horizon "H₁", the "mid-Tertiary" unconformity (see fig 2.4a), but they are also present at certain horizons within the succession (see fig. 2.27b). Some, if not all of these horizons are at locations where high amplitude events are locally absent from beneath "H₁", for example where mass flow disruption has occurred. This suggests that, at these locations, the "mid-Tertiary" unconformity ceases to be a barrier to upward gas migration, gas only becoming trapped at shallower levels.

Glacial & Fluvio-Glacial Channels

Three possible phases of channelling can be discerned within package X₁ of interval "X":

+ The oldest phase of channelling defines the base of package X₁, an erosion surface with relief of up to 400m (see figs. 2.8, 2.15, 2.17, 2.26c). Channels on this erosion surface are oriented N-S to NW-SE (see fig. 2.21a), and usually decrease in depth toward both ends. They are therefore unlikely to be fluvial in origin. In the study of Cameron *et al.* (1986) these channels were said to define the base of the Swarte Bank Formation, and to be of Elsterian age. Their origin is generally attributed to sculpting by glacial melt-water at the margin of an ice sheet (Boulton & Hindmarsh, 1987; Ehlers, 1989; Wingfield, 1990) and, in this case, they were probably formed at the southern margin of Elsterian ice sheet (Long *et al.*, 1988).

A correlation has been noted between the orientation of individual channel orientations within this channelling phase and the orientations of some slope breaks within the pre-glacial part of the Nordland Group succession (see fig. 2.21b).

However, this correlation is not universal, and some valleys show patterns which may instead be indicative of tectonic control upon their location, especially within the North Sea Central Graben axis to the west of the area. Additionally, the valleys are not uniformly distributed, but are seen to be concentrated especially toward the eastern margin or the NE corner of the study area.

+ The second phase of possible channelling, which occurs in the NW of the study area (see fig. 2.21a) is defined upon seismic data by zones of acoustic blanking, occasionally associated with velocity push-down, just below the sea bed. Although not resolvable on regional seismic data as channel-like in form, time sections from 3D seismic data over this area have revealed the channel-like pattern of this acoustic disturbance (D. Praeg, *pers. comm.*), which may be picked out by gas charging of the sediments. This channelling may be glacial or glacio-fluvial channelling. The channels may be of Weichselian age and are possibly part of the Botney Cut Formation (Cameron *et al.*, 1986).

+ The final phase of channelling in the study area is defined by one elongate depression in the NW of the study area (see fig 2.21a), commonly known as the Botney Cut. This is said to be a glacial channel of Weichselian age, partly filled by sediments of the Botney Cut Formation by Cameron *et al.*, (1986). It may relate to the maximum expansion of the Devensian ice sheet offshore from Britain (Long *et al.*, 1988).

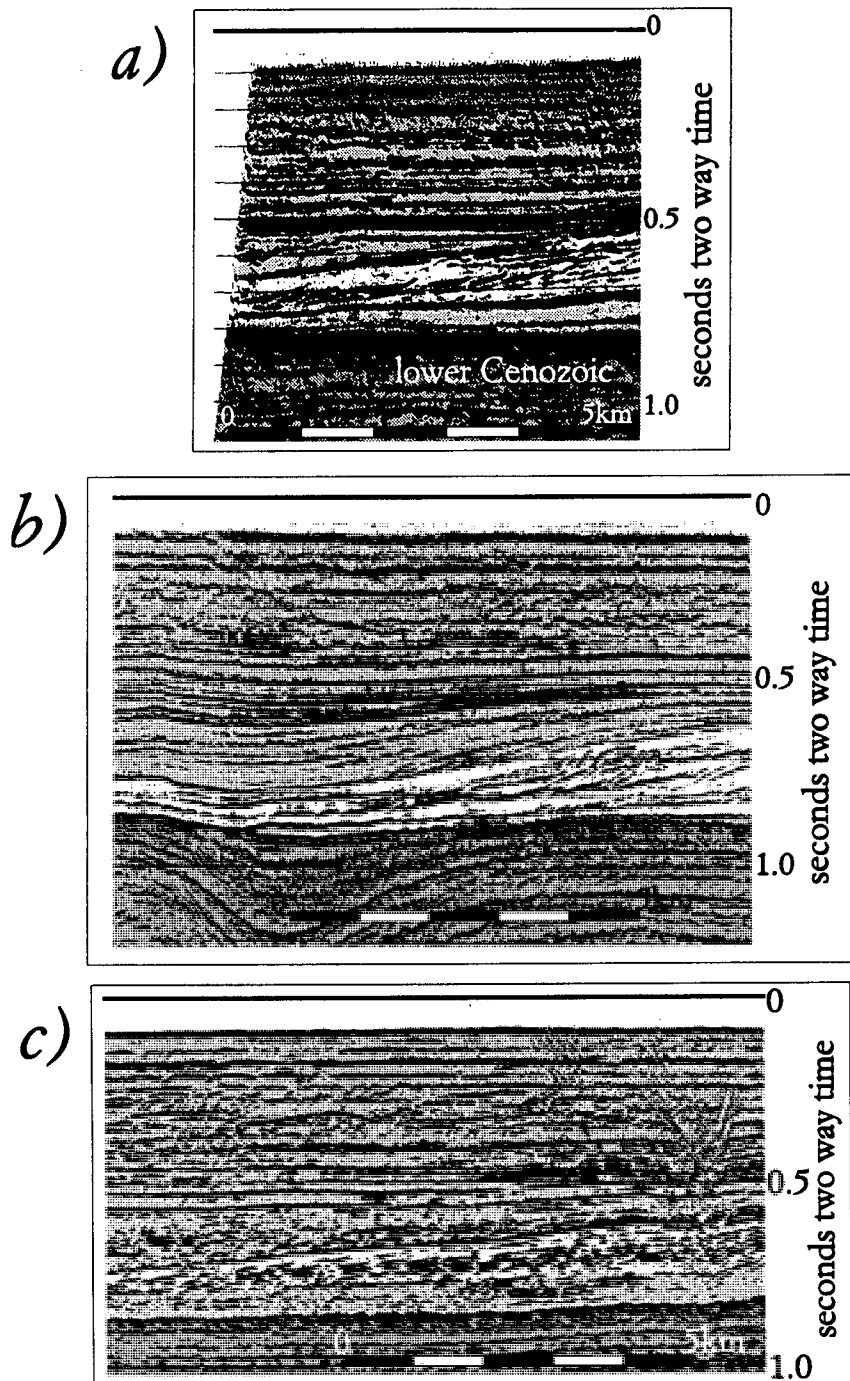


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CHAPTER 3:

WELL & BOREHOLE DATA

3: WELL & BOREHOLE DATA

3.1: Introduction

Until now, the late Cenozoic sediments of the southern North Sea Basin have not been put into a comprehensive litho-stratigraphic framework. Equivalent sediment sequences have been studied extensively in Britain (Rose & Allen 1977; Zalasiewicz & Mathers 1985; Zalasiewicz *et al.* 1988; Harland *et al.* 1991), the Netherlands (Van Staalduinen *et al.* 1979; Doppert 1980; Kasse 1990a) and Germany (Gramman & Kockel 1988; Hinsch 1990), and attempts have been made at synthesis of this data (Bijlsma 1981; Gibbard *et al.* 1991; Zagwijn & Doppert 1978). However, there has been a lack of similarly detailed litho-stratigraphic studies offshore. Those attempts that have been made to correlate parts of the offshore succession with onshore schemes (*NAM & RGD*, 1980; Cameron *et al.*, 1984a; Funnell, 1987; Thompson *et al.*, 1992) have had mixed results.

The scheme proposed by Cameron *et al.* (1984b; 1986) established a stratigraphy for the upper, post-Reuverian sediments of the southern North Sea Basin as far east as a longitude of 4°E which, whilst tentatively correlated with onshore successions, remains independent of them (see section 1.2.3). Although their scheme is, in large part, a seismic stratigraphy, boreholes have penetrated most of the units described and lithological descriptions of these boreholes have been made. The formal stratigraphic nomenclature of the Netherlands, compiled by *NAM & RGD* (1980) does not effectively extend above the top of the Miocene within the North Sea area, although it correlates many onshore, post-Miocene sediment units in some detail.

The recent borehole correlation work of the *SNSP* has, at the time of writing, resolved few of the questions raised and, unfortunately, no attempt has been made to incorporate this new data into the existing, offshore nomenclature (Fannin *et al.*, 1991 *unpub.*; Thompson, *et al.*, 1992). The current state of knowledge on the Pliocene and Early Quaternary stratigraphy of the southern North Sea Basin therefore remains incomplete.

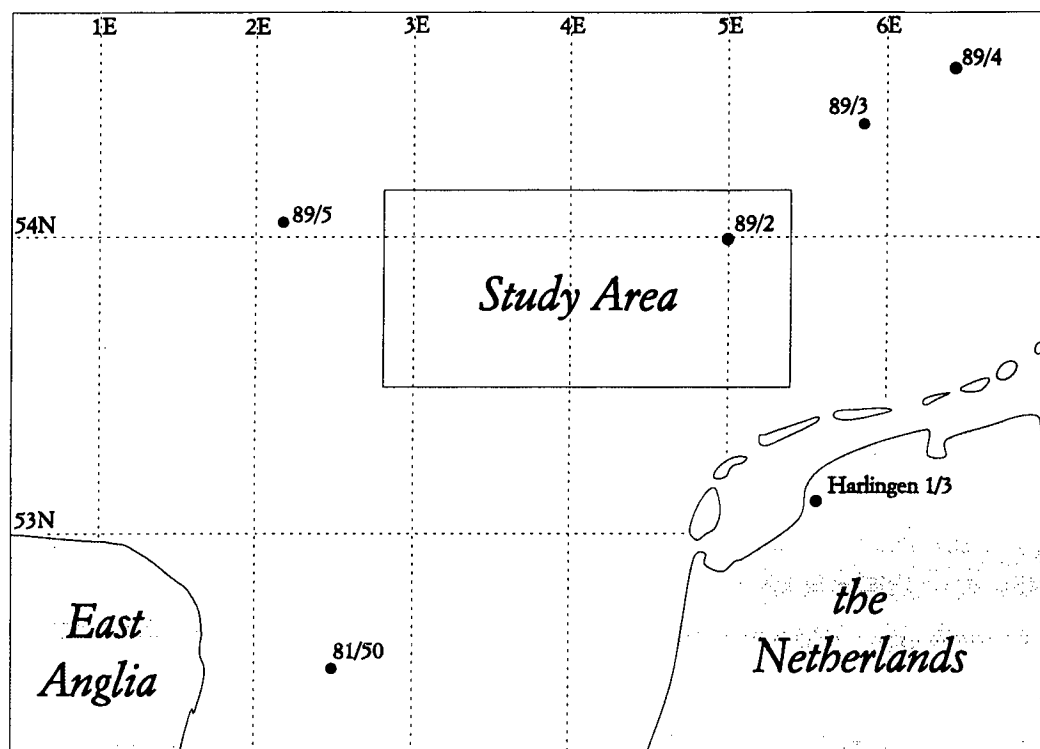


Fig. 3.1: Location map of boreholes used in this study.

3.1.1: Data Sources

Shallow Borehole Data

The shallow borehole data used in the study have been acquired by both the *BGS*, during its continental shelf reconnaissance programme, and by the *SNSP*. All these boreholes were drilled to depths of between 175 and 300m below the sea surface. Commercial borehole data, acquired during geotechnical investigations of the seabed, generally reach a depth of little more than 100m below the sea surface, and are of little use in the context of this study.

Borehole data is the most important source for detailed magneto-stratigraphic, bio-stratigraphic and lithological information on the Nordland Group succession. However, due to the high proportion of unconsolidated sand within the succession, core recovery can be poor, and sandy sections have yielded less useful magneto- and bio-stratigraphic information than might have been hoped. There is only one well-dated and accessible borehole within the area (see fig. 3.1):

89/2 (with 89/2A): drilled in 1989 as part of the *SNSP*. This composite borehole reached a depth of around 260m below sea level (Thompson *et al.*, 1992). However, the Nordland Group succession extends a further 600m below the base of the borehole in this area.

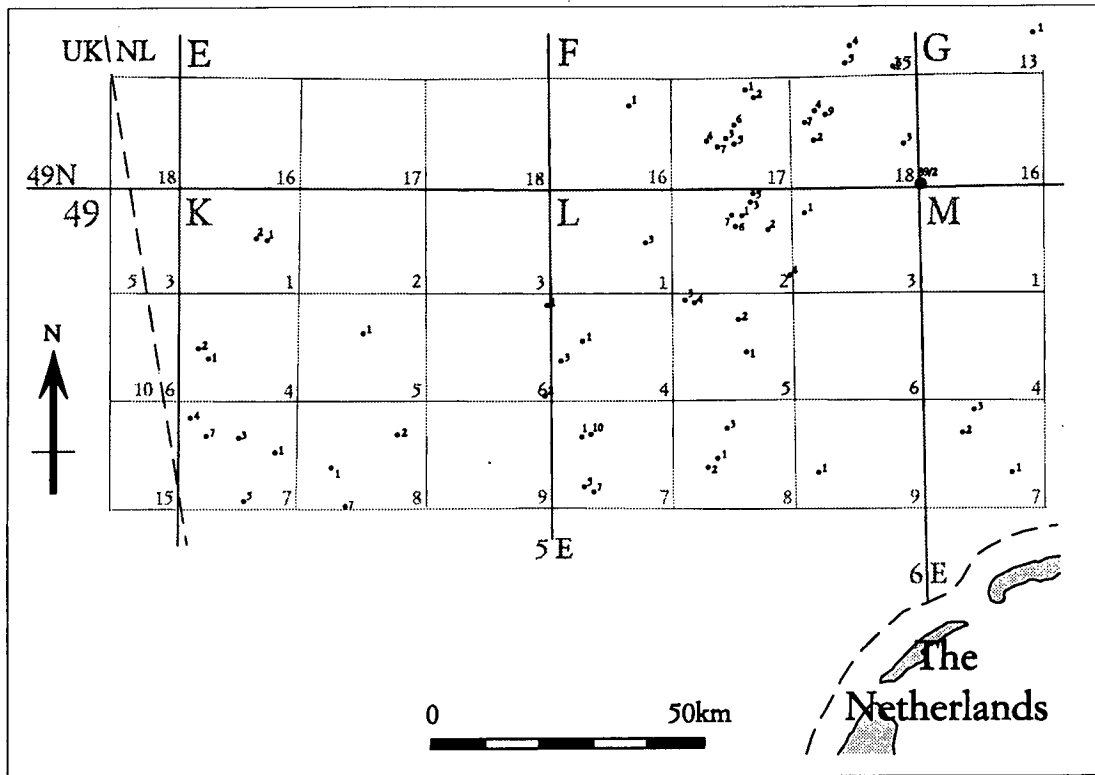


Fig. 3.2: Location map of commercial wells used in this study.

Several boreholes have been drilled outside the study area which, because of the presence of high resolution seismic data linking these boreholes to the area, can be correlated with the succession to provide additional information on the ages of the sediments. These include (see fig. 3.1):

81/50 (with 81/50A): drilled in 1981 by the BGS (formerly the *Institute of Geological Sciences*). This composite borehole is to the SW of the study area, in the British sector of the Southern North Sea, offshore from the East Anglian coast. The borehole reaches a depth of 175m below the sea surface, penetrating the entire Nordland Group succession, and reaching Eocene clay at its base.

89/3 & 89/4 (with 89/4B): drilled as part of the *SNSP*. Both boreholes were acquired to the NE of the area of study in the German sector of the Southern North Sea. The boreholes reached depths of 306 and 250m below the sea surface respectively (Thompson *et al.*, 1992), but neither boring reached the base of the Nordland Group.

Additional to these, two wells, *Harlingen 1 & 3*, in the NW of the Netherlands (Ter Wee, 1976), provide some additional petrological and stratigraphic data.

Commercial Well Data

A total of 58 commercial well logs from the Dutch sector of the Southern North Sea, have been used in this study (see fig. 3.2). Copies of these were obtained from the *RGD*, Haarlem, in the Netherlands. Because the Nordland Group succession is unconsolidated, and because commercial well objectives are at much greater depths, study of the late Cenozoic interval of the well data has the following limitations:

- 1) No cores have been taken within the Nordland Group.
- 2) No representative samples can be taken in unconsolidated sediments. Sand content is always under-represented because of the ability of loose sand grains to pass through the “shakers”, the filters which are used to collect samples. Samples are often contaminated by sediments from higher levels, due to “caving” of the well during drilling.
- 3) The Lithologic (Mud) logs at this level are notoriously unreliable, if they are available at all, due to the lack of commercial interest in the upper sediments of the wells.
- 4) Only a limited range of wire-line logs are recorded near surface. The principle logs available are Gamma Ray, Sonic and Induction logs. Whilst all three can be recorded, sonic and induction logging tools are rarely turned on at less than 300 to 500m from the surface. Sometimes these logs are not recorded at all within the interval. However, it is rare for no gamma log recording to be taken from this interval.
- 5) The gamma log response can be affected by the rate of withdrawal of the logging equipment during recording. Because the wire-line equipment can sometimes be withdrawn faster near surface than at depth, this can result in unnaturally low gamma-ray readings, and its quantitative use at this level is not advisable. Also, because of the lack of consolidation of the sediments, thick casings are also necessary for stability of the hole. Casing changes are frequent near surface, each causing a change in hole diameter, and each of these has to be corrected for.

3.1.2: Commercial Well Data Handling

Wire-line Digitisation

All wire-line logs obtained from the study area have been processed to a standard format. After digitising, these have then been corrected for the following:

1) Kelly Bushing, which is the height above average sea level from which all depth measurements are taken. This is so that all wells can be compared using mean sea level as the 0m reference depth.

2) scale differences, due to recording scale changes and casing thickness changes. It is often apparent that there are variations in log scale between different wells, which must normally be due to recording conditions but are occasionally due to mistakes in scale annotation. This effectively means that all well logs should be used qualitatively rather than quantitatively.

The Gamma Log

Gamma logs record the natural gamma radiation from sediments, and are often used to estimate vertical changes in sand to clay ratios (see fig. 3.3). This is possible because of the normal absence of radioactive minerals from clean sand, in contrast to the highly radioactive nature of clay minerals in muddy sediments. However, this general picture is complicated by the lack of radioactivity in peat and clean limestone. Conversely, high radioactivity can be shown by sand rich in radioactive minerals such as glauconite, apatite, feldspar and mica. Initial observations of well data from the area show that three relative radioactivity levels are common. These are:

1) Low radioactivity intervals, representative of clean sand, possibly with some lignite. The presence of clean limestone is unlikely, given the climatic and environmental conditions of the basin during the late Cenozoic. This radioactivity level is referred to here as “Gamma Sand” facies.

2) High radioactivity intervals, probably almost pure clay intervals, although occasional misinterpretations can occur where sands are radioactive. High radioactivity intervals are referred to as “Gamma Clay” facies.

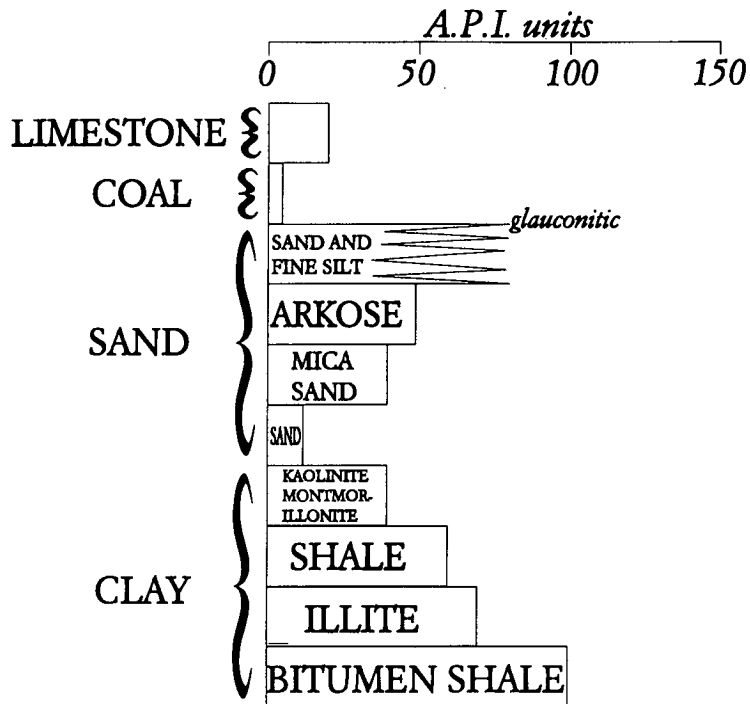


Fig. 3.3: Gamma ray log response of different sedimentary lithologies.

3) Very high radioactivity intervals, probably resulting from mineralisation or bitumen contents. These intervals could be of either sand or clay, although it is more likely that they are of clay. This type of response is referred to here as “High Gamma” facies.

The differences between these responses are complex, and descriptions such as “Gamma Silt” and “Very High Gamma” facies are also referred to here. Change in radioactivity with depth will be described in terms of fining and coarsening upward or unchanging, block-like patterns in the well description.

The Sonic Log

This type of log has proved difficult to interpret, especially within the upper part of the sequence. Sonic logs are normally most useful in detecting peat and limestone horizons, picked out by low and high velocities respectively. In practice, limestone is unlikely to be present within the late Cenozoic sequence and no peat horizons have been unambiguously identified. Sand and clay in unconsolidated sediment sequences are not necessarily distinguishable from each other. In this respect the sonic log should act only as a complement to the Gamma log.

Within the Nordland Group, variations in water content and consolidation may be represented in the sonic log responses. In the lower, older part of the succession, where clay is predominant over sand, velocity changes can be correlated easily from well to well. However, these changes become erratic in the upper parts of the succession in all wells, regardless of the depth of burial. As is to be expected in increasingly compacted sediments, velocities generally increase downward.

The Induction (Resistivity) Log

This is normally used as a measure of water and gas contents within sand intervals. Porous sand normally shows an increase in resistivity values over non-porous clay. However, this trend is appears to be reversed in the Nordland Group succession, high porosity sand being indicated by low induction log values and *vice versa*. The reason for this is unknown.

The Lithologic Log

Although derived from analysis of cutting samples, lithologic logs are usually very unreliable, but can still be informative if used carefully. Indications of sand to clay ratio are usually unhelpful, but can be assessed independently using wire-line data. The lithologic logs often record other features such as the occurrence of shell debris, glauconite, pyrite, mica, bitumen and lignite. Once again, such data have to be used with caution, but well comparison can be a good guide as to the validity of individual logs. The most useful guides in the sequence are:

- 1) The last upward occurrence of large amounts of glauconite. This normally occurs at the base of the Nordland Group and, as such, represents a major regional stratigraphic marker.
- 2) The first upward appearance of shell debris within the Nordland Group. Unlike the appearance of glauconite, this is a diachronous marker, having been traced at several different, chrono-stratigraphic levels within the sequence. This is presumably related to a diachronous, facies change.
- 3) The first upward appearance of mica within the Nordland Group. The usefulness of this marker is currently uncertain.

3.2: The Lithologic Data-set

Well Correlation

Correlation between wells has been achieved through independent interpretation of both the available seismic and well data. However, as many wells are separated by distances of over 20 kilometres, correlation of these is impossible without reference to the seismic data-set.

Comparison of velocity information from several different wells revealed a broad similarity in velocity changes with depth across the study area. Using a standard velocity function derived from selected well velocity data, interpreted seismic horizons were superimposed at their depth-converted positions on the well logs. The information was then compared from well to well to see if a reasonable match could be obtained between the correlation based on seismic and well data. Seismic re-interpretation was performed in some cases where an obvious discrepancy between the two data-sets occurred, such as when two wells showed an obvious correlation which did not match the seismic interpretation.

3.2.1: Pre-Nordland Group Sediments

The sediments that lie directly below the Nordland Group in the study area range in age from Eocene through to Miocene. These sediments are almost entirely made up of clay which, especially within the Eocene sequence, can be of very monotonous character. However, four separate intervals have been distinguished directly below the Nordland Group succession on the basis of well log correlation (see fig. 3.4). These have been designated well intervals "W" to "Z" in ascending stratigraphic order.

Interval W

Interval Thickness: possibly up to 800m.

Lithologic Log: A grey-brown to dark grey, slightly glauconitic, rarely silty, calcareous clay. This interval is probably Eocene in age (NAM & RGD, 1980).

Electric Logs: A monotonous "gamma clay", rarely of "gamma silt" grade. Sonic logs are largely uniform, recording low interval velocity. Induction logs are also uniform and have low values.

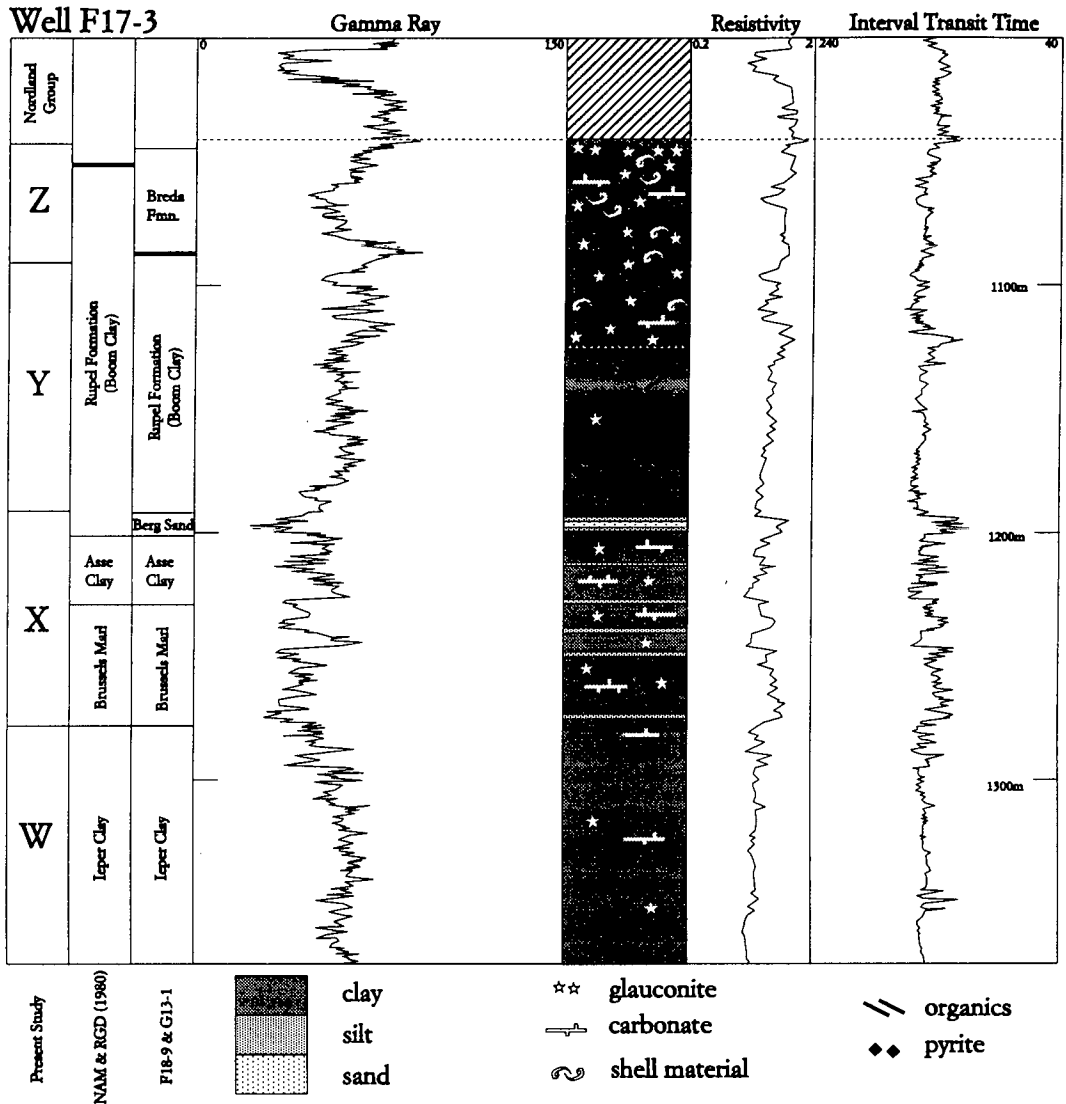


Fig. 3.5: Electric and lithologic logs for the Upper Eocene to Miocene succession in well F17-3.

Interval X

Interval Thickness: up to 70m. This interval is absent in the far west.

Lithologic Log: The lower part is of light green-grey, silty to sandy, soft to fairly hard, very calcareous claystone or shale, sometimes including chalky limestone. This part is sometimes pyritic and can it be glauconitic toward the base of the interval. Commercial well dating generally assigns well interval “X” an Eocene age. The whole interval is often referred to the Brussels Marl Member although, according to *NAM & RGD (1980)*, the top of the interval includes the Barton/Asse Clay (Upper

Eocene) and the base of the Boom Clay (Oligocene). This interpretation has been amended in two recent, *NAM* wells (F18-9, G13-1), where the Oligocene top of the interval is called the Berg Sand. The presence of mineralisation within the base of the interval could be due to a hiatus separating the Eocene and Oligocene.

Electric Logs: The gamma log response of this interval is generally quite low, of “gamma silt” grade, although it often shows one 20m layer of “gamma clay” grade about 10m below the top of the interval, which has been called the Barton (Asse) Clay in two wells (F18-9, G13-1). Sonic log velocities are variable, but are generally higher than those of intervals “W” and “Y”. This is possibly due to the abundance of carbonate within the interval. Induction logs again show erratic but generally high values.

Interval Y

Interval Thickness: less than 10m up to 150m. The sequence achieves its maximum thickness in block L7. This interval is thin or absent in certain areas, such as in block M7.

Lithologic Log: This interval is of light green to green-grey, soft shale alternating with light yellow-brown, soft, slightly micaceous shale. In thicker sequences, glauconite content is relatively high. Some carbonaceous fragments are present. Well interval “Y” is normally assigned by well operators either to the Barton Clay (Eocene) or, according to *NAM & RGD* (1980), to part of the Rupel Formation (Boom Clay; Oligocene).

Electric Logs: Gamma logs show a sudden upward increase in gamma values to “gamma clay” at the base, and show “gamma clay” values throughout. Sonic logs show a sudden decrease in interval velocity at the base, with only a slight upward increase in values, if any. Westward, this increase becomes more abrupt. Induction log response, which also starts at the base with a sharp drop in values, can show a gradual increase in values upward.

Interval Z

Interval Thickness: 0 to 80m, reaching its maximum thickness in well F16-1, but thin or absent in the SW (see fig. 3.5).

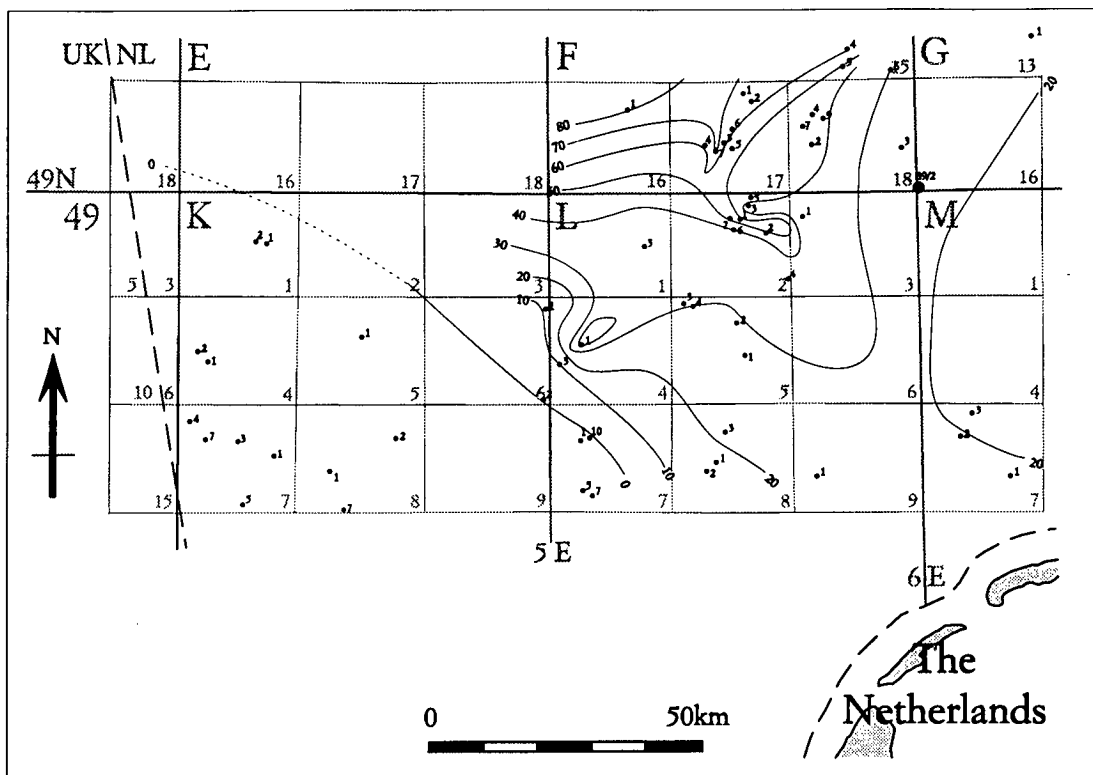
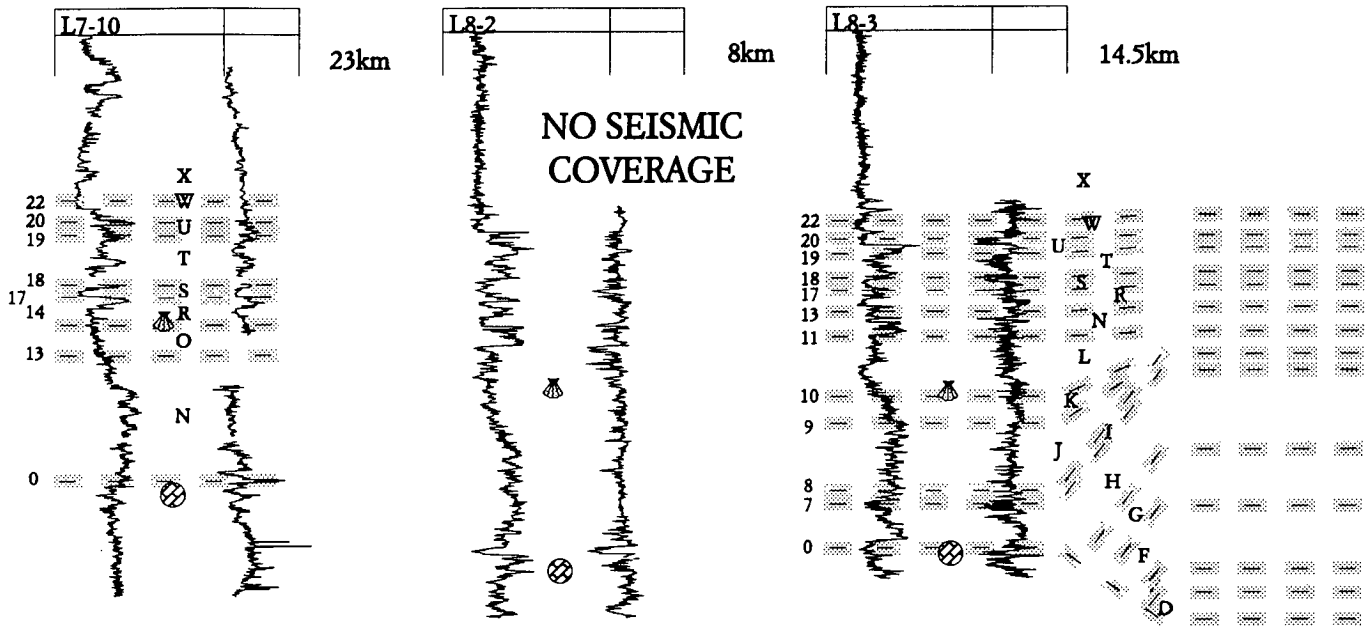


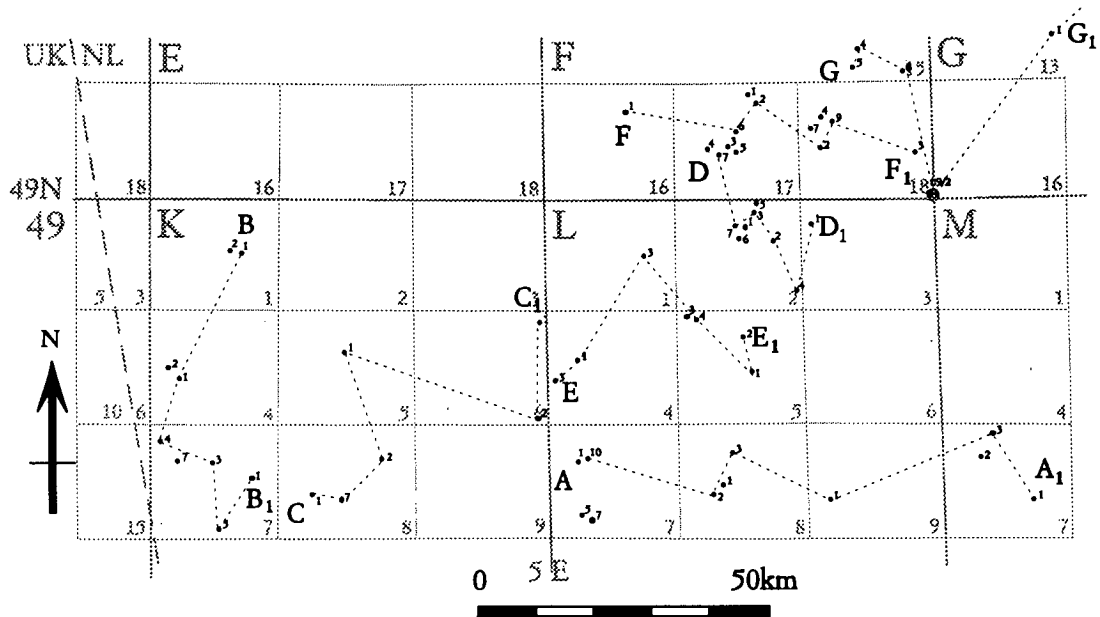
Fig. 3.6: Isopachs, in metres, of interval "Z" within the study area, based upon available well information.

Lithologic Log: A dark, olive-grey to dark brown-grey, slightly silty and micaceous, calcareous, hard, pyritic claystone, which includes fossil fragments and carbonaceous material. The interval also contains glauconite, which becomes increasingly abundant towards the top of the interval. Interval "Z" is assigned to the Rupel Formation (Oligocene) or to both the Rupel and Breda formations (Miocene) by well operators. *NAM & RGD* (1980) refer the majority of well interval "Z", save the upper 10m, to the upper part of the Rupel Formation (Oligocene). However, two recent *NAM* wells (F15-6, G13-1) assign the upper half of the interval a Miocene age.

Electric Logs: On gamma logs the base of this interval is defined by a "high gamma", occasionally "very high gamma", spike. The remainder of the interval is of "gamma silt" to "gamma clay", occasionally showing minor, "high gamma" spikes within. The top of interval "Z" is usually marked by a second, "very high gamma" spike. The high radioactivity of these horizons is probably caused by an unusually high proportion of micaceous, glauconitic and phosphatic material within the clay. On sonic logs this interval shows low interval velocities. Because these velocities are lower than those within the basal Nordland Group sequences, it is probable that this contrast is the cause of the high amplitude, negative polarity seismic event at the base of the Nordland Group. Induction log values are variable.



A



Last downward occurrence of shells in Nordland Group



First major downward occurrence of glauconite

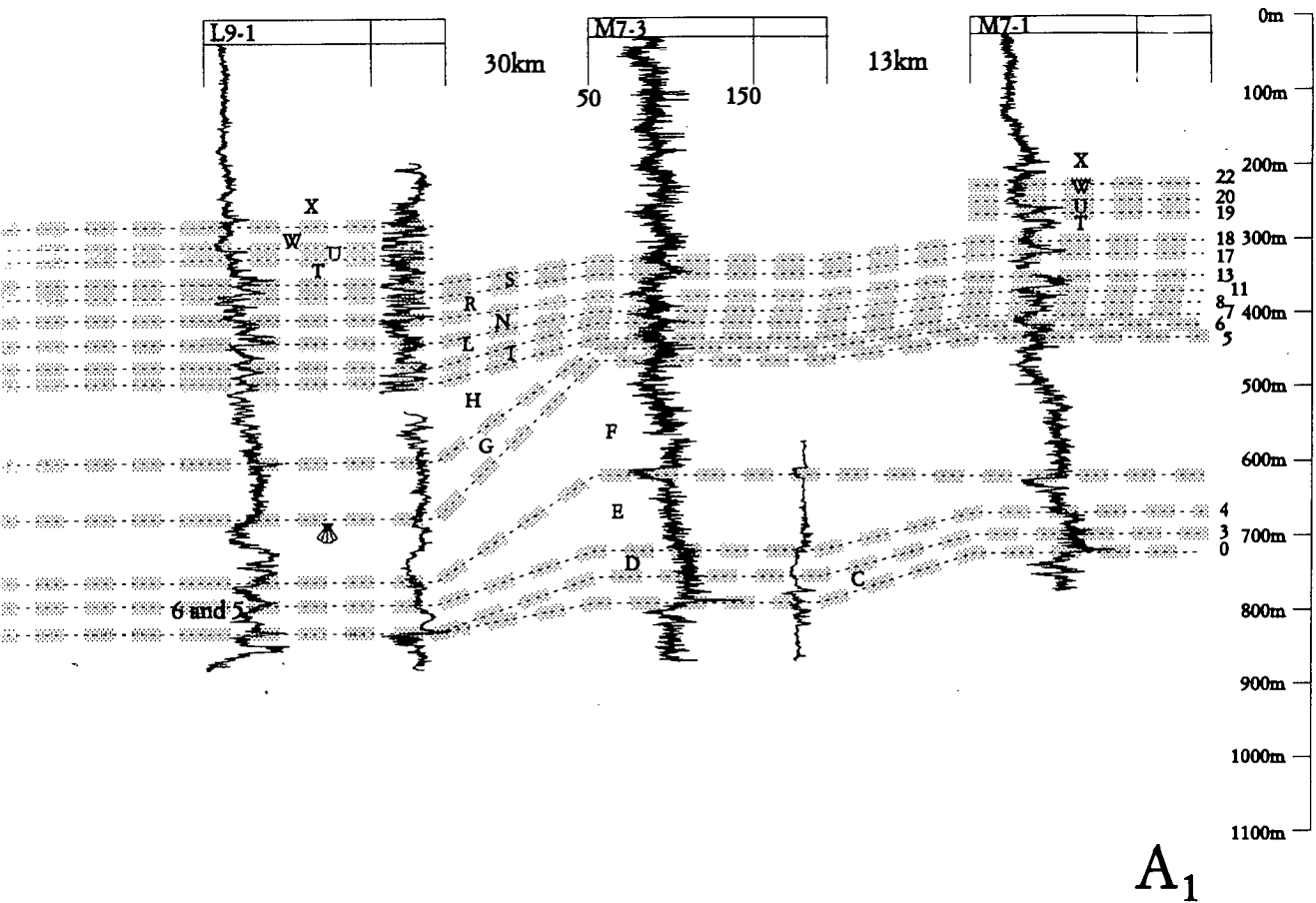
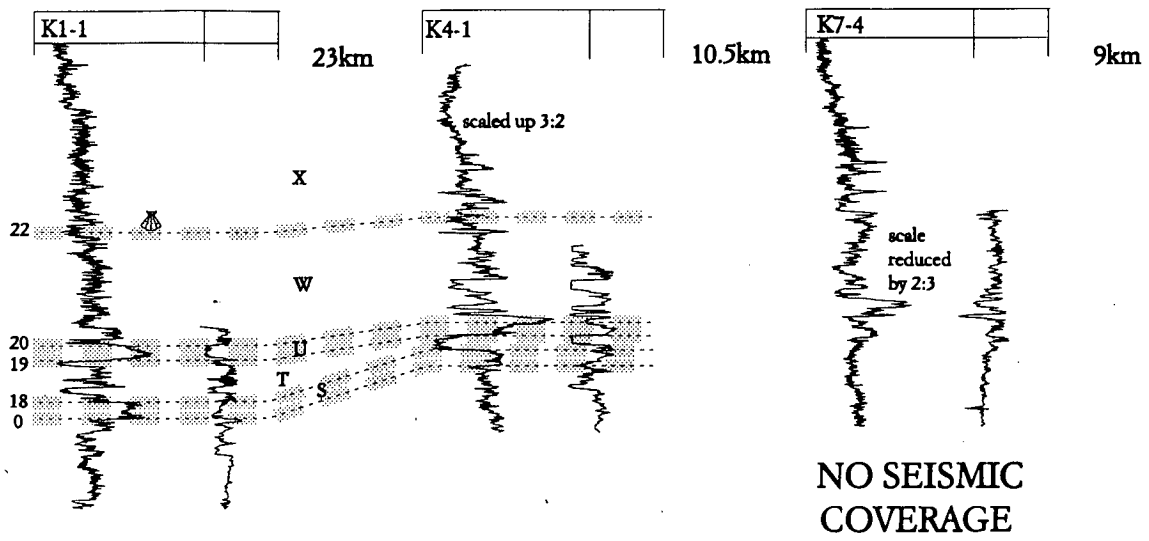


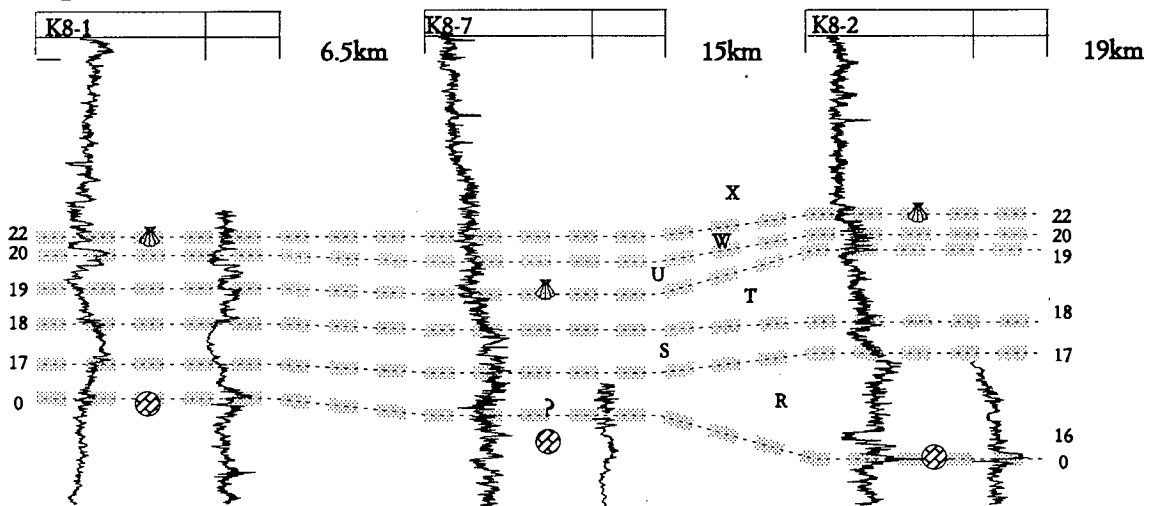
Fig. 3.6: (sections "a" to "g") Correlation diagrams for the well data within the study area, with the seismic interpretation of chapter 2 superimposed. Location of each section is shown in the accompanying map. Gamma log response for each well is on the left hand side (scale bars represent 0 and 150 API units unless otherwise stated). Sonic log response is on the right hand side (scale bars represent 180 and 100 ms/ft). The upper horizontal line in each well represents present day sea level, whilst the line beneath represents the present sea bed. The vertical resolution of the seismic data is no finer than 10 metres, and the shading around each seismic horizon is representative of this uncertainty.

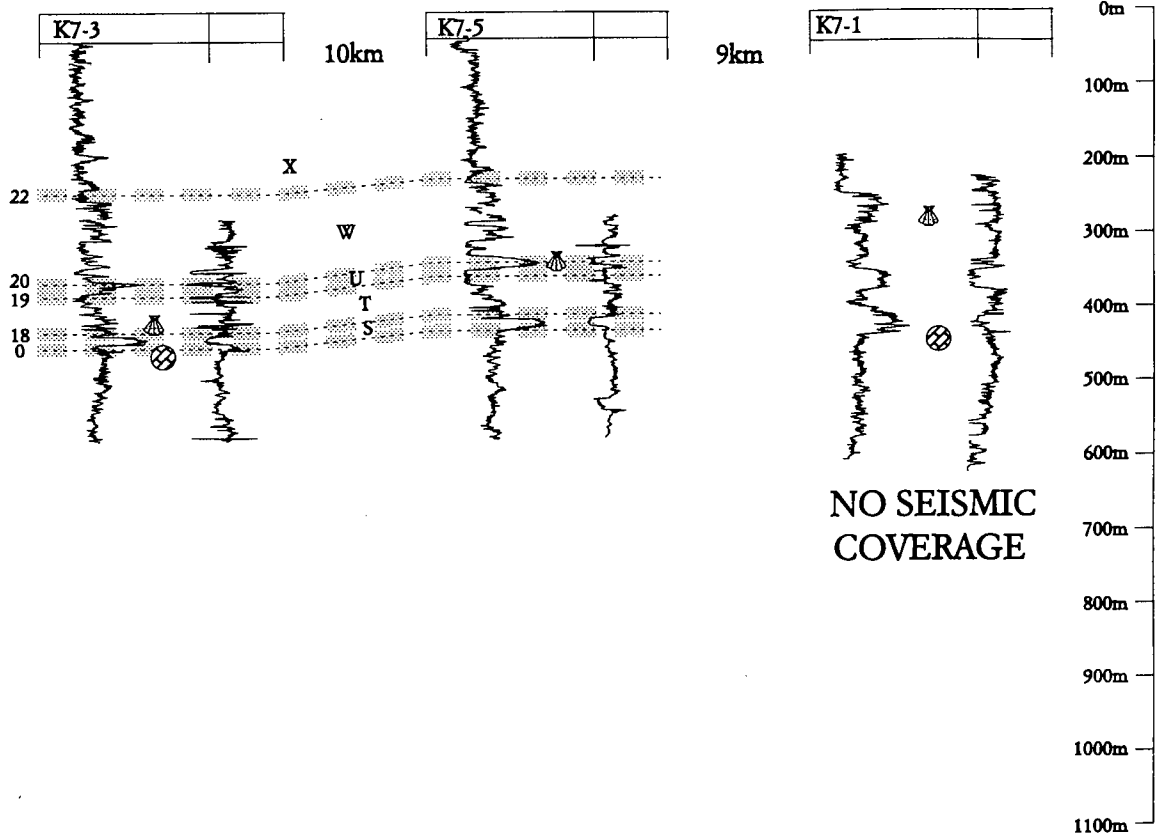
The values given between each log are the distances between wells. Not all wells used in the correlation scheme are shown here. Unfortunately, no well data were obtained from "E" quadrant.



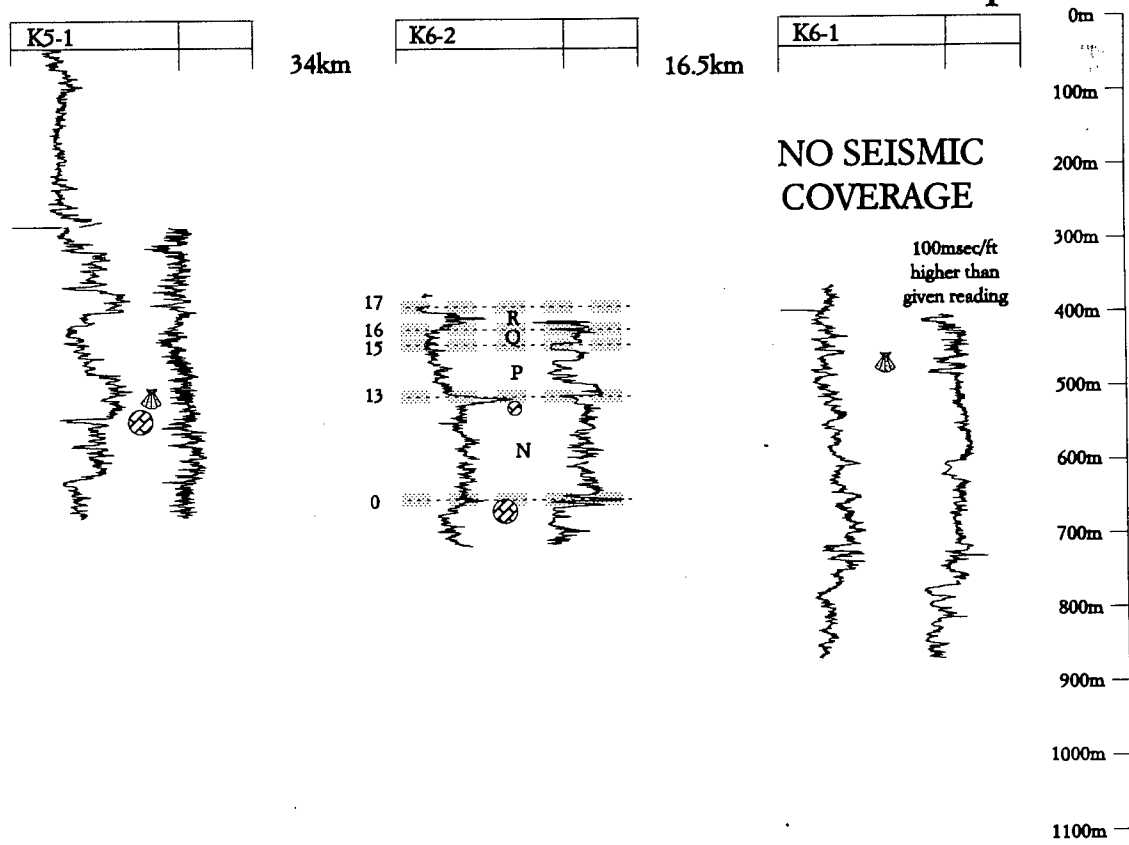
B

C





B_1
 C_1



F17-7

11km

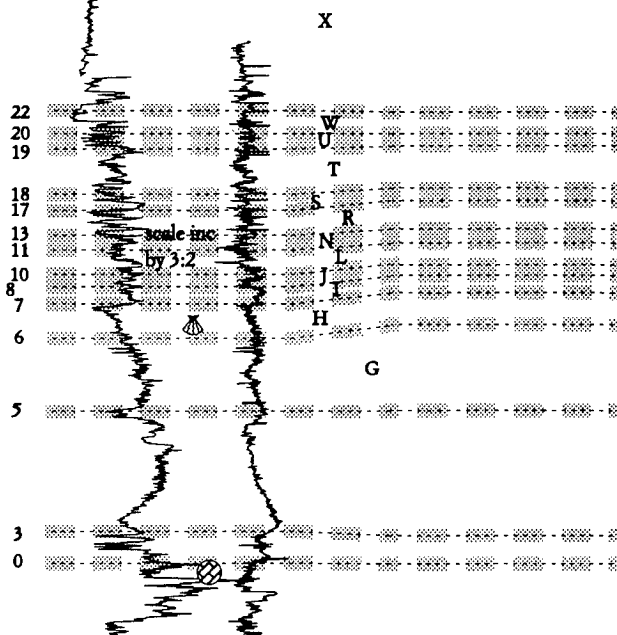
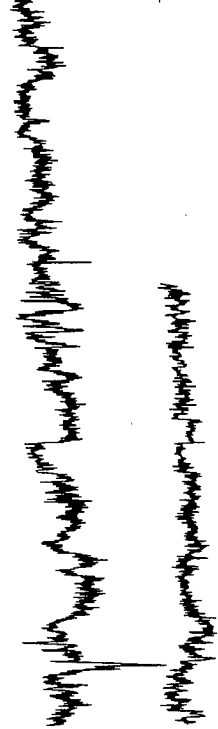
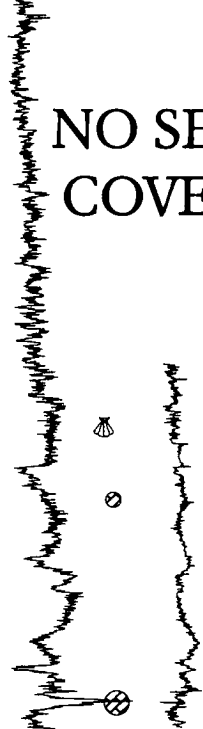
L2-7

4.5km

L2-3

6km

NO SEISMIC
COVERAGE



D

E

L4-3

4.5km

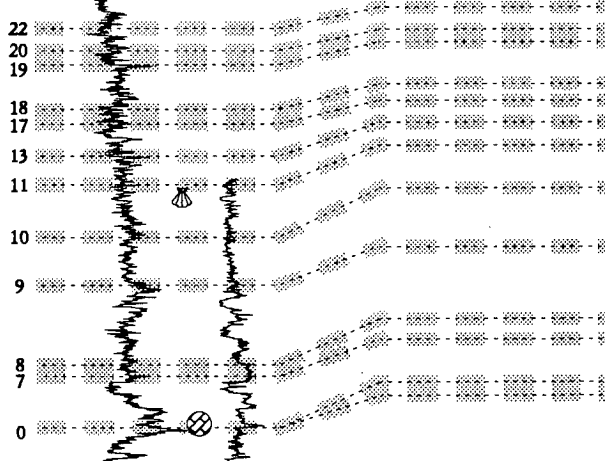
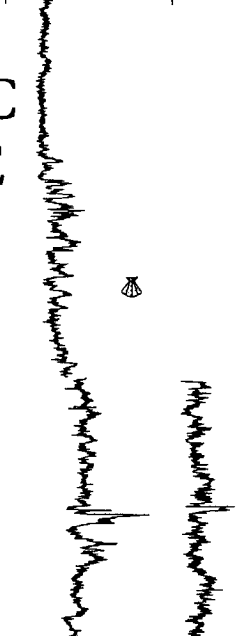
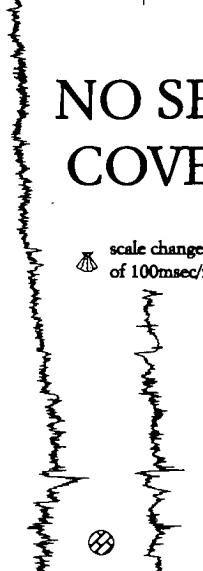
L4-1(a1)

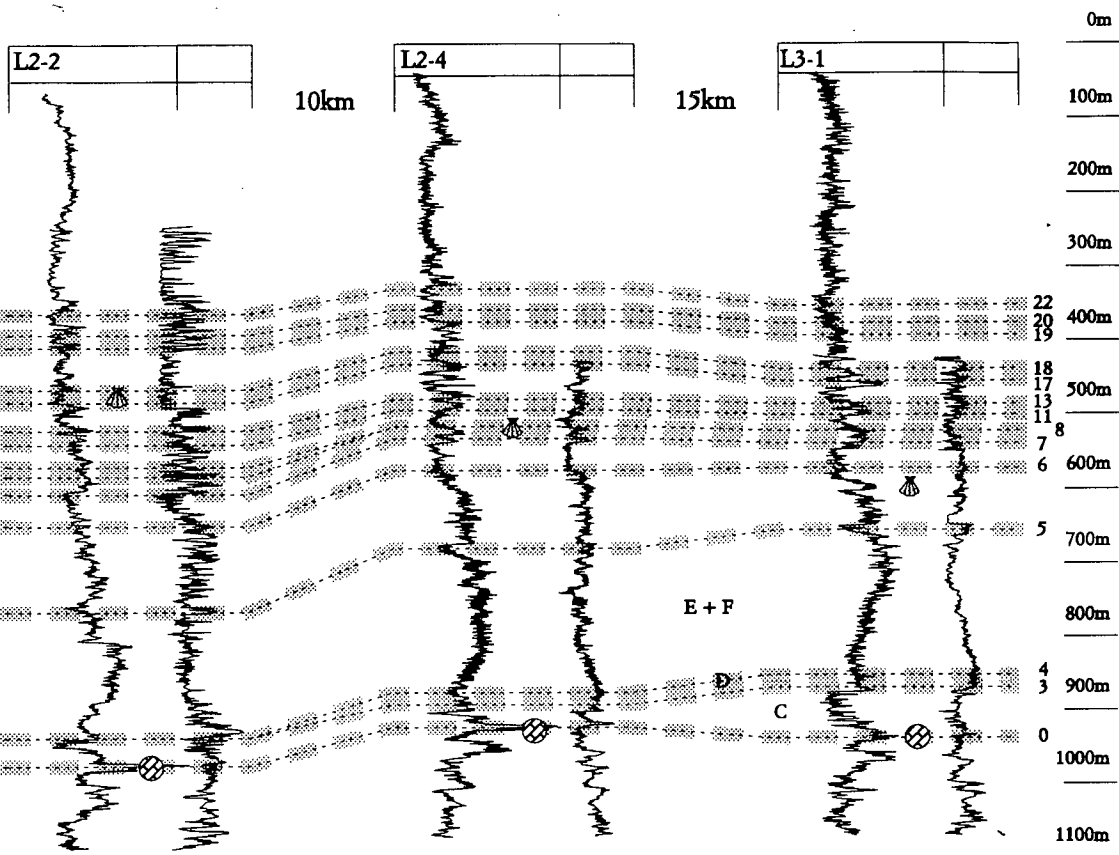
22km

L1-3

14km

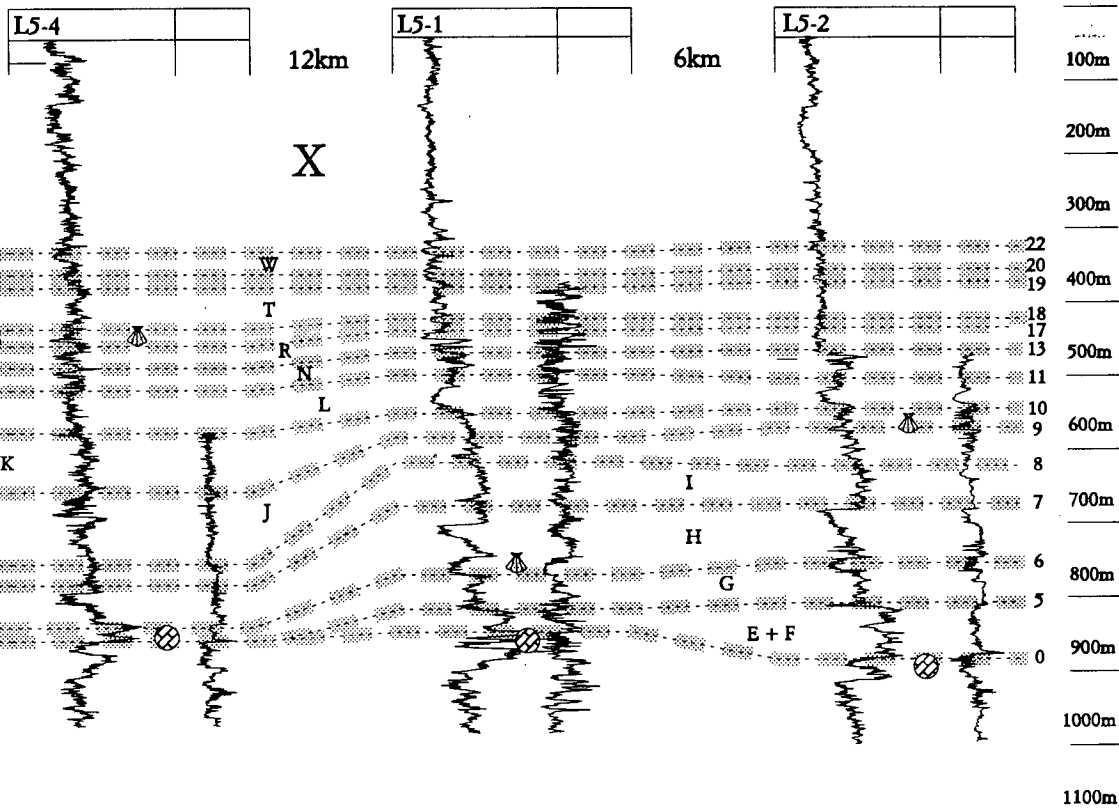
NO SEISMIC
COVERAGE





D₁

E₁



X

F16-1

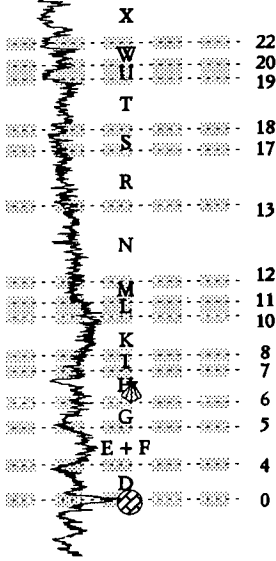
21km

F17-6

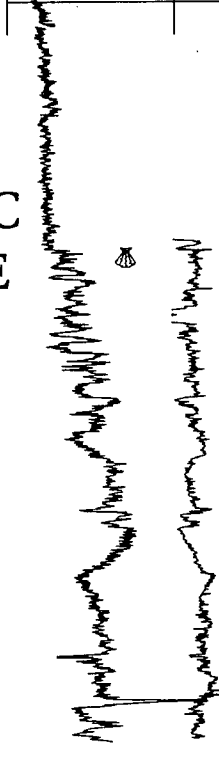
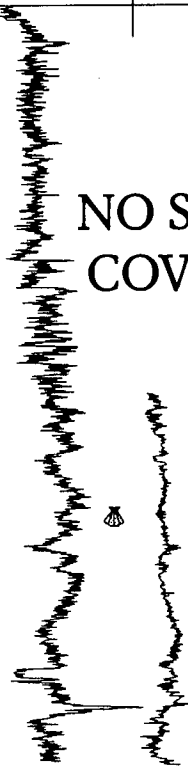
5.5km

F17-2

14.5km



NO SEISMIC COVERAGE



F

G

F15-5

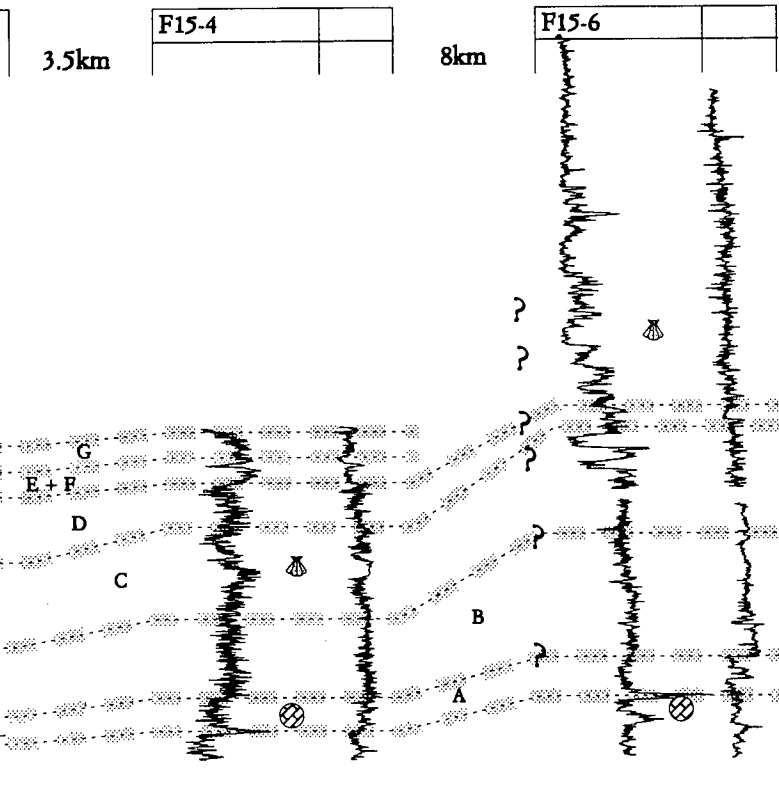
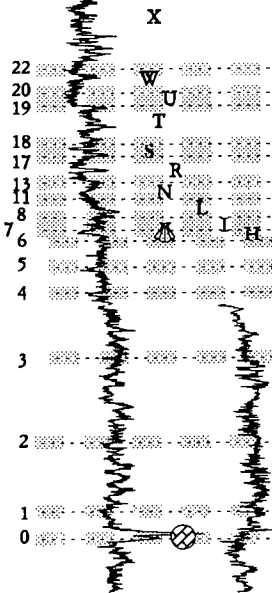
3.5km

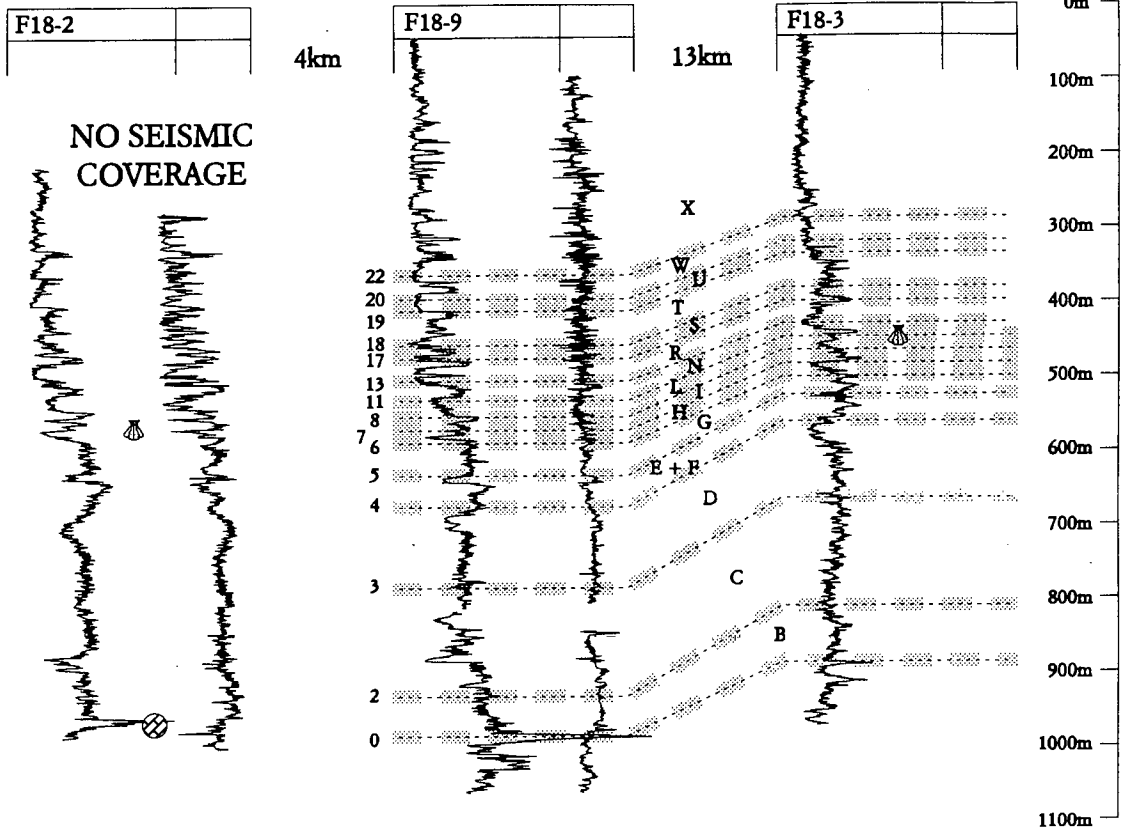
F15-4

8km

F15-6

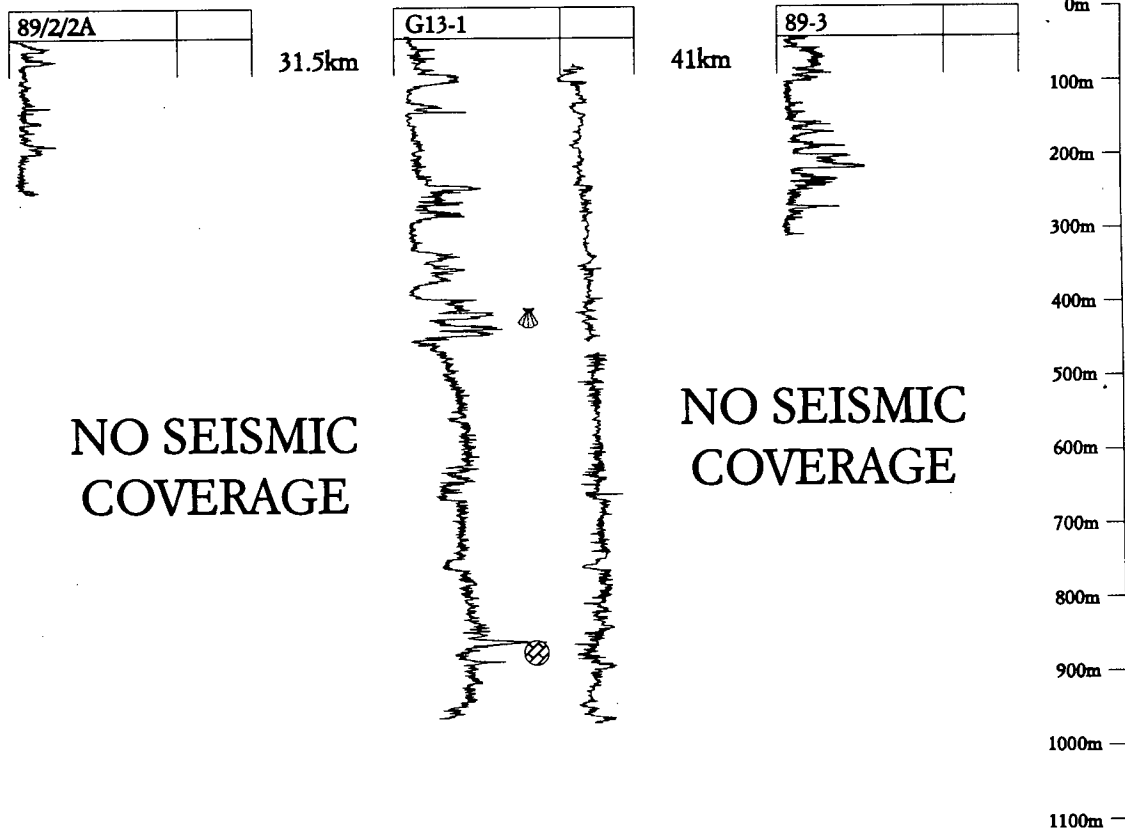
21km





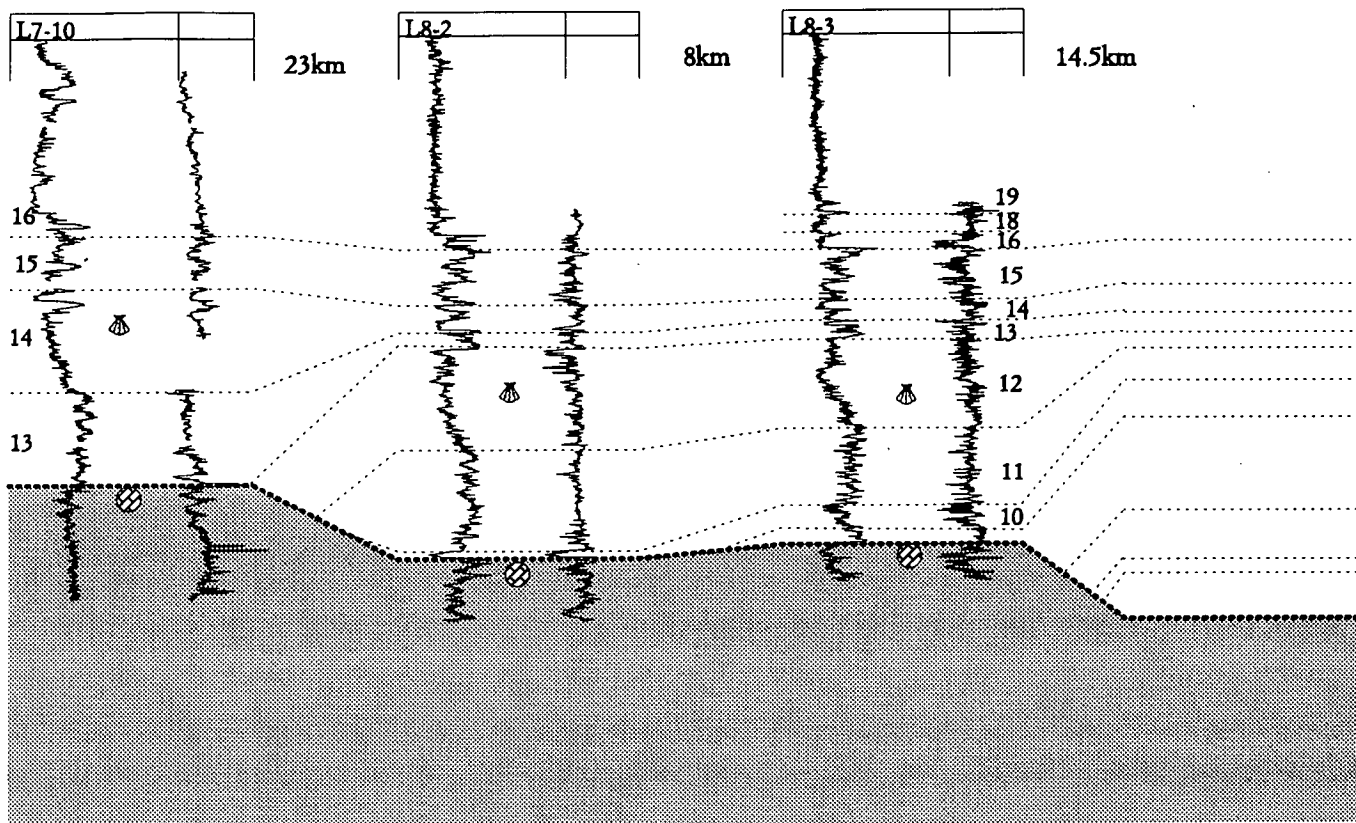
F₁

G₁

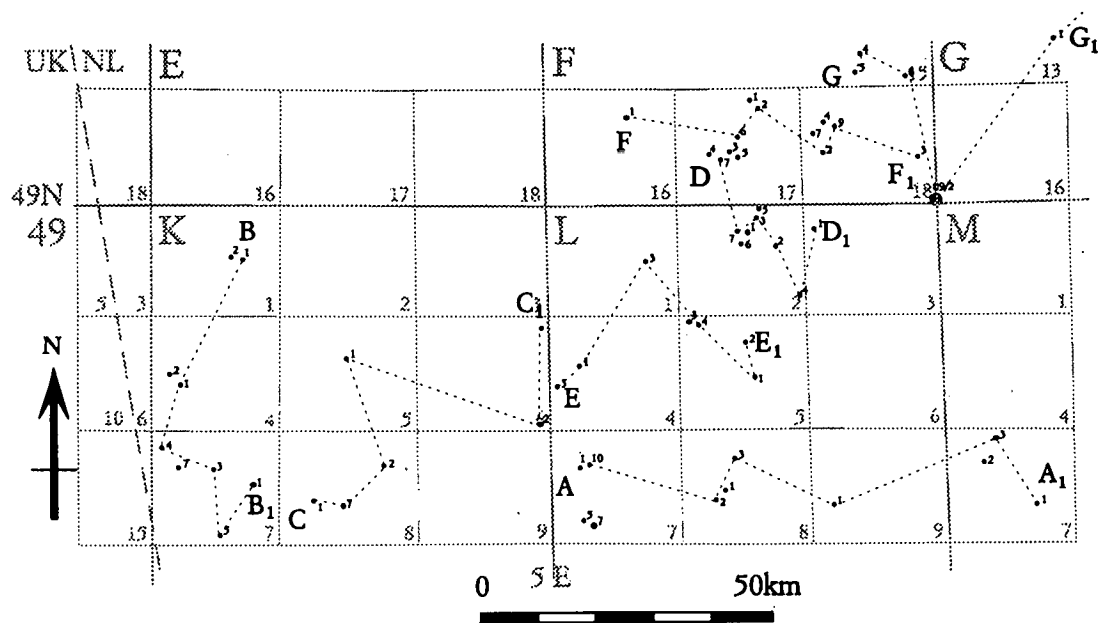


NO SEISMIC
COVERAGE

NO SEISMIC
COVERAGE



A



☉ Last downward occurrence of shells in Nordland Group

⊗ First major downward occurrence of glauconite

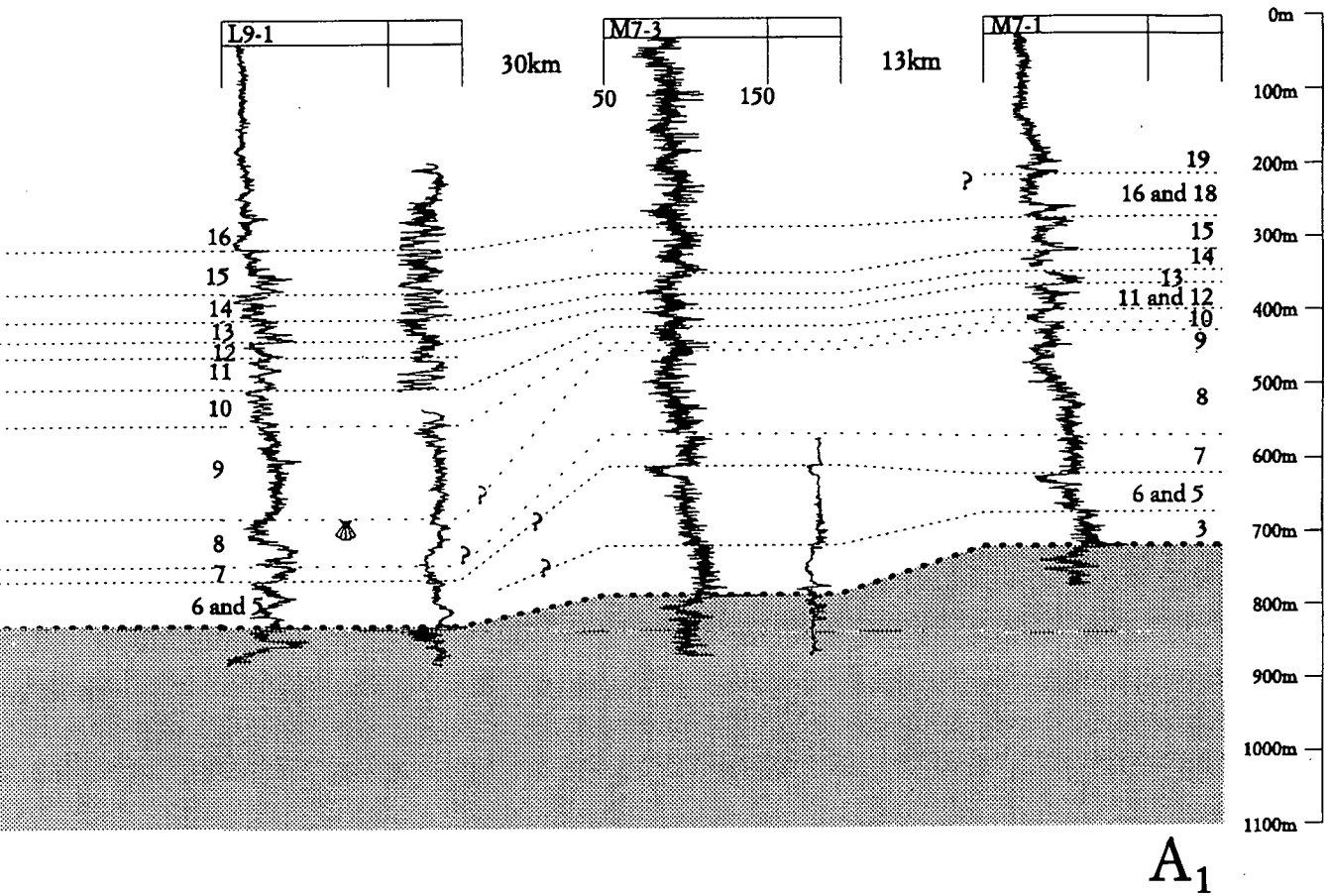
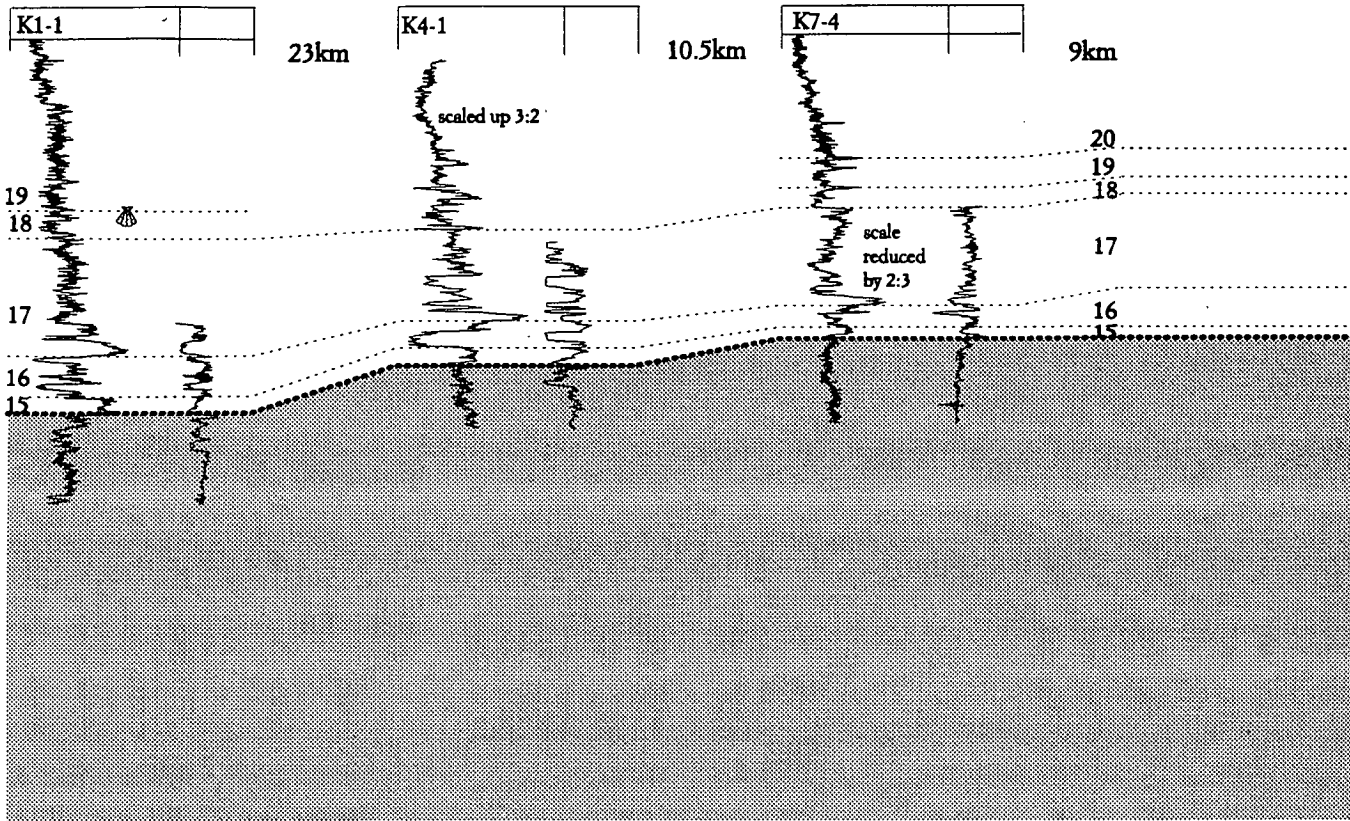
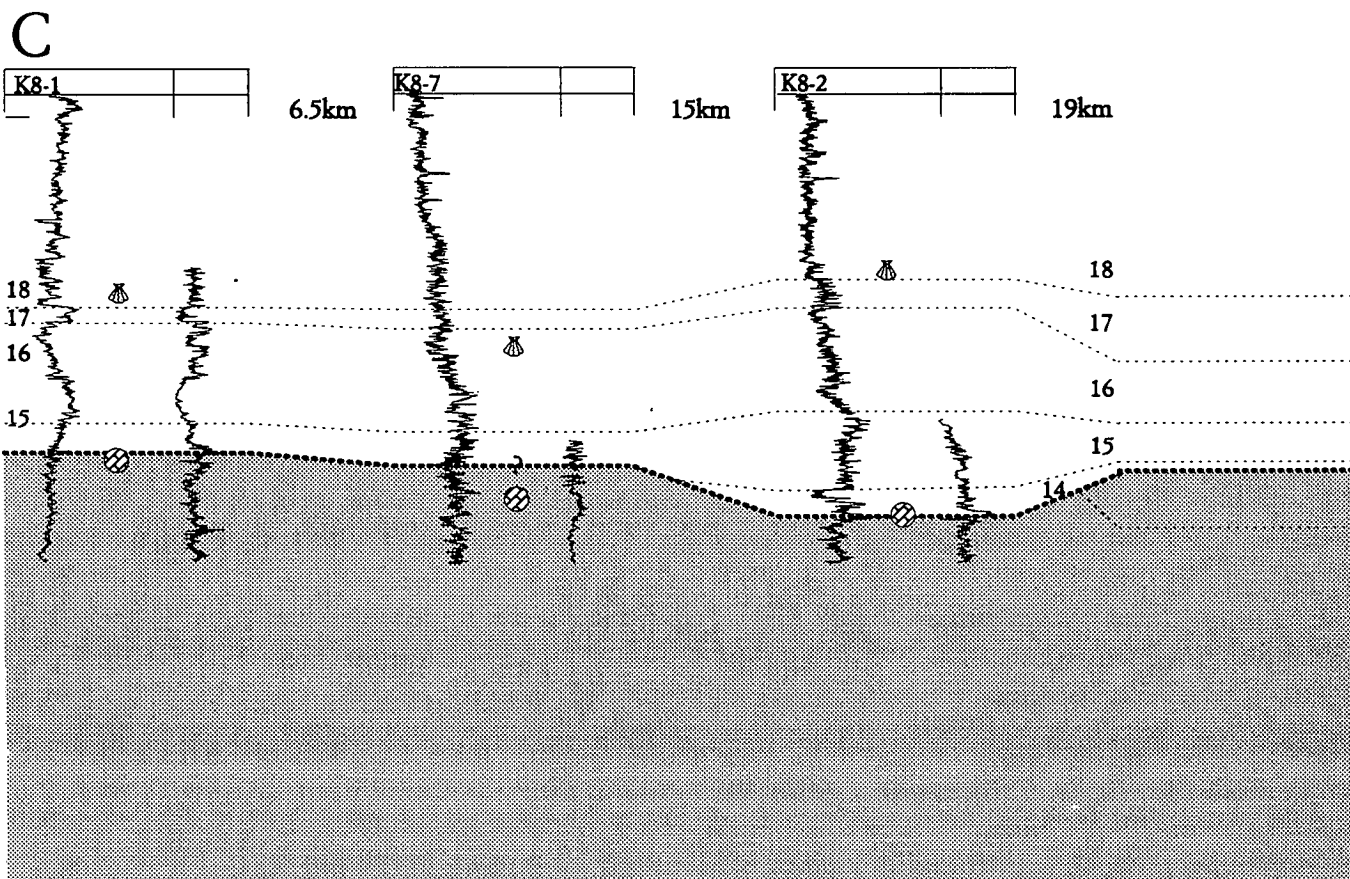


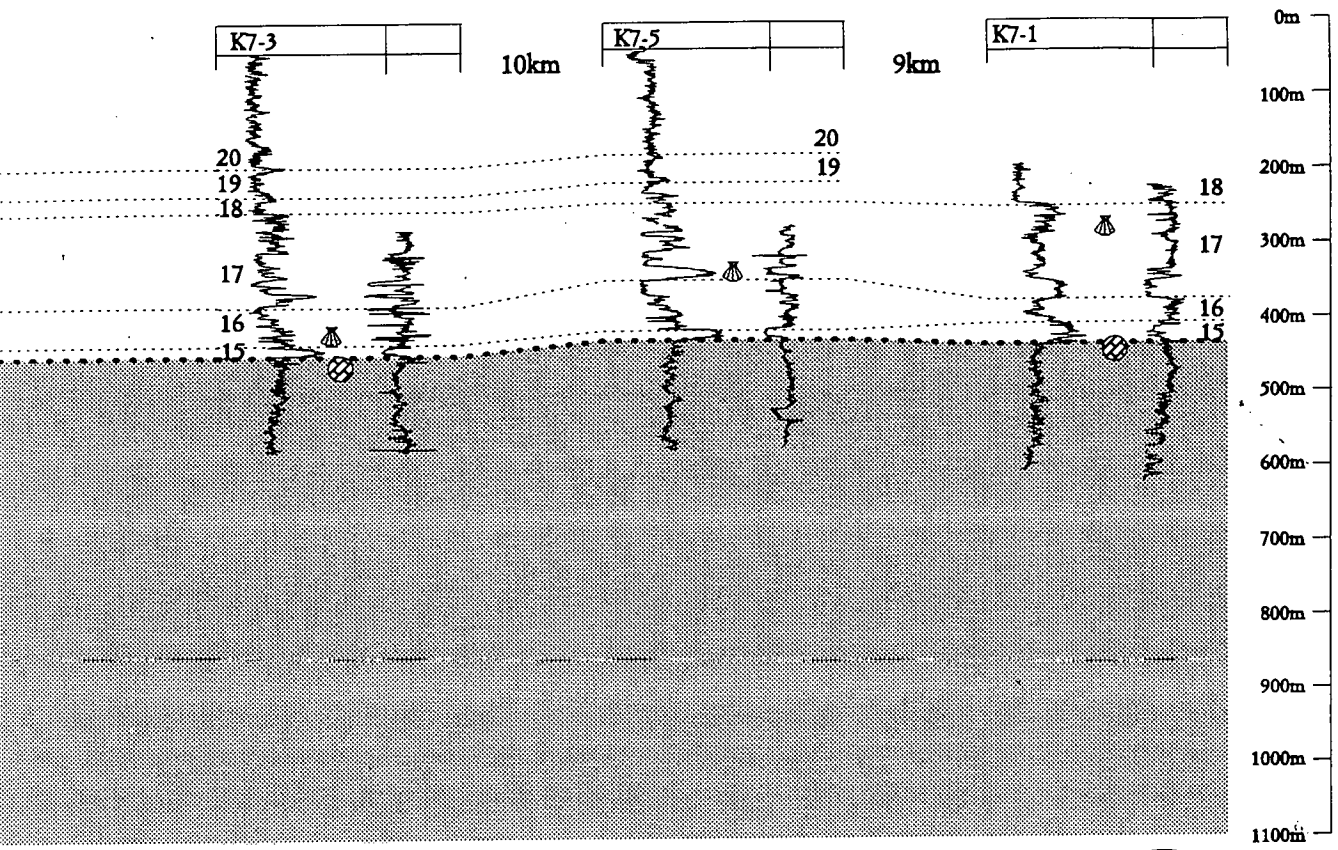
Fig. 3.7: (sections "a" to "g") Correlation diagrams for the well and borehole data within the study area (also including information from well G13-1 and borehole 89/3). Location of each section is shown in the accompanying map. Sediments older than the Nordland Group are marked by grey stipple. The glacial succession within the Nordland Group (interval "21") is not generally distinguished. All other details are as for figure 3.7.



B

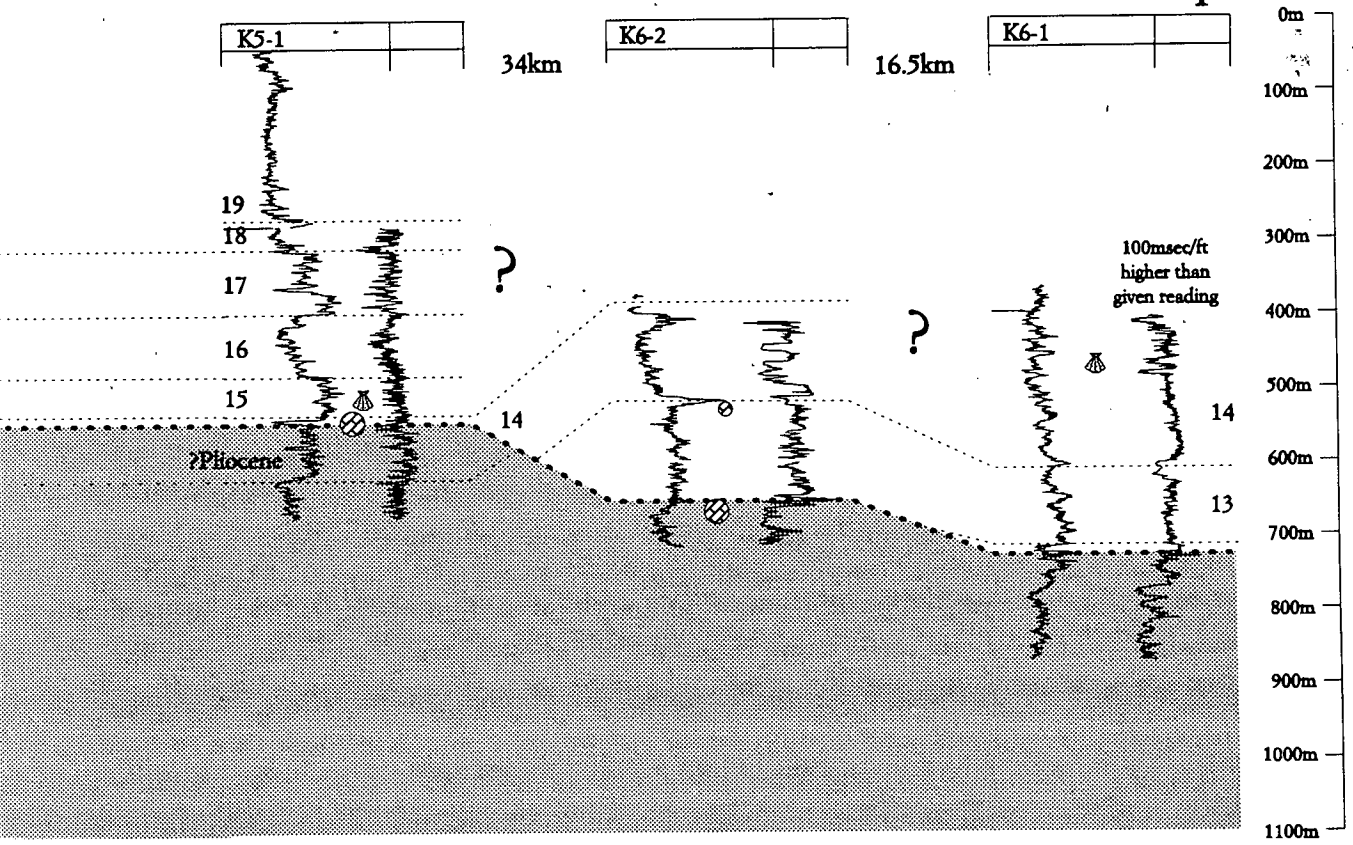


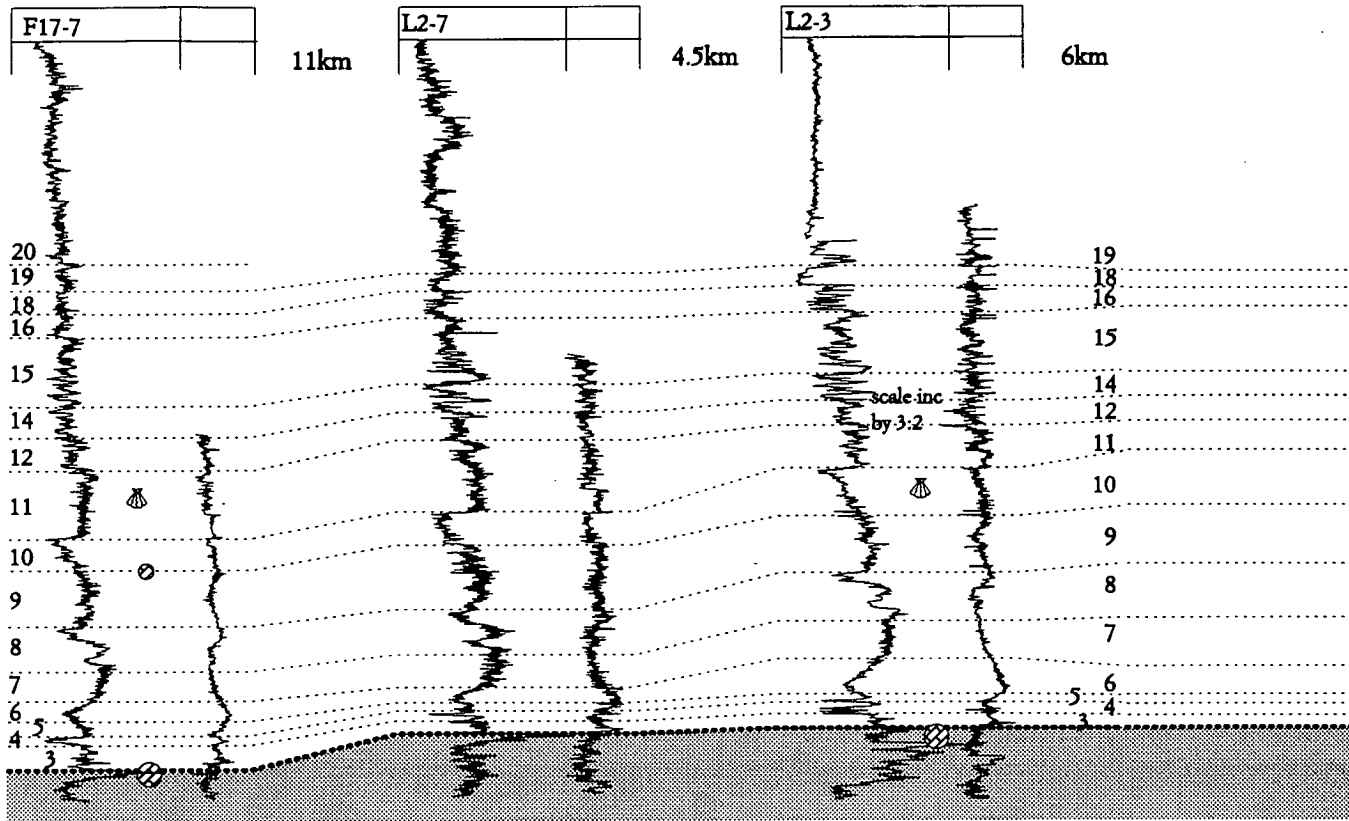
C



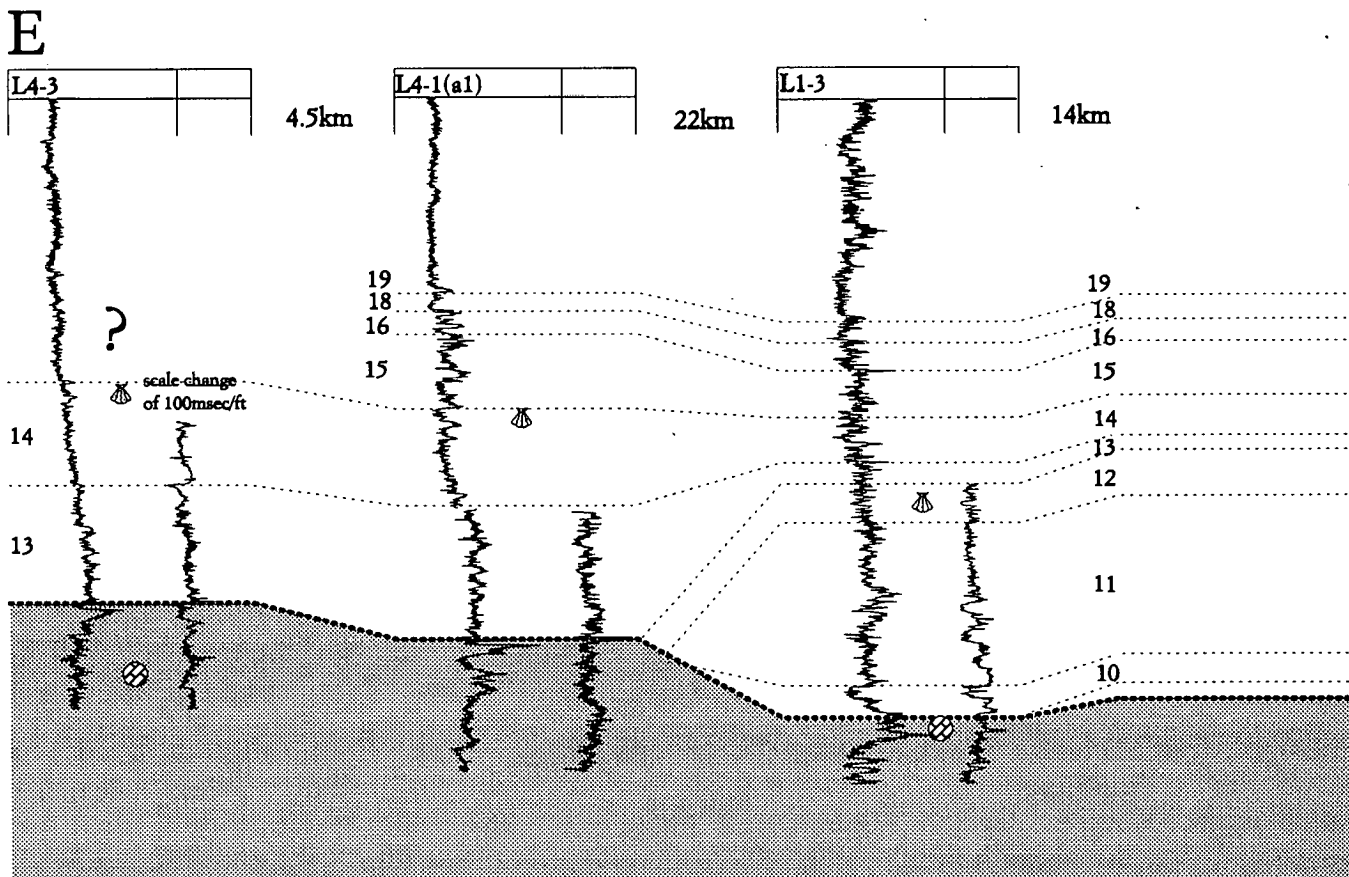
B₁

C₁

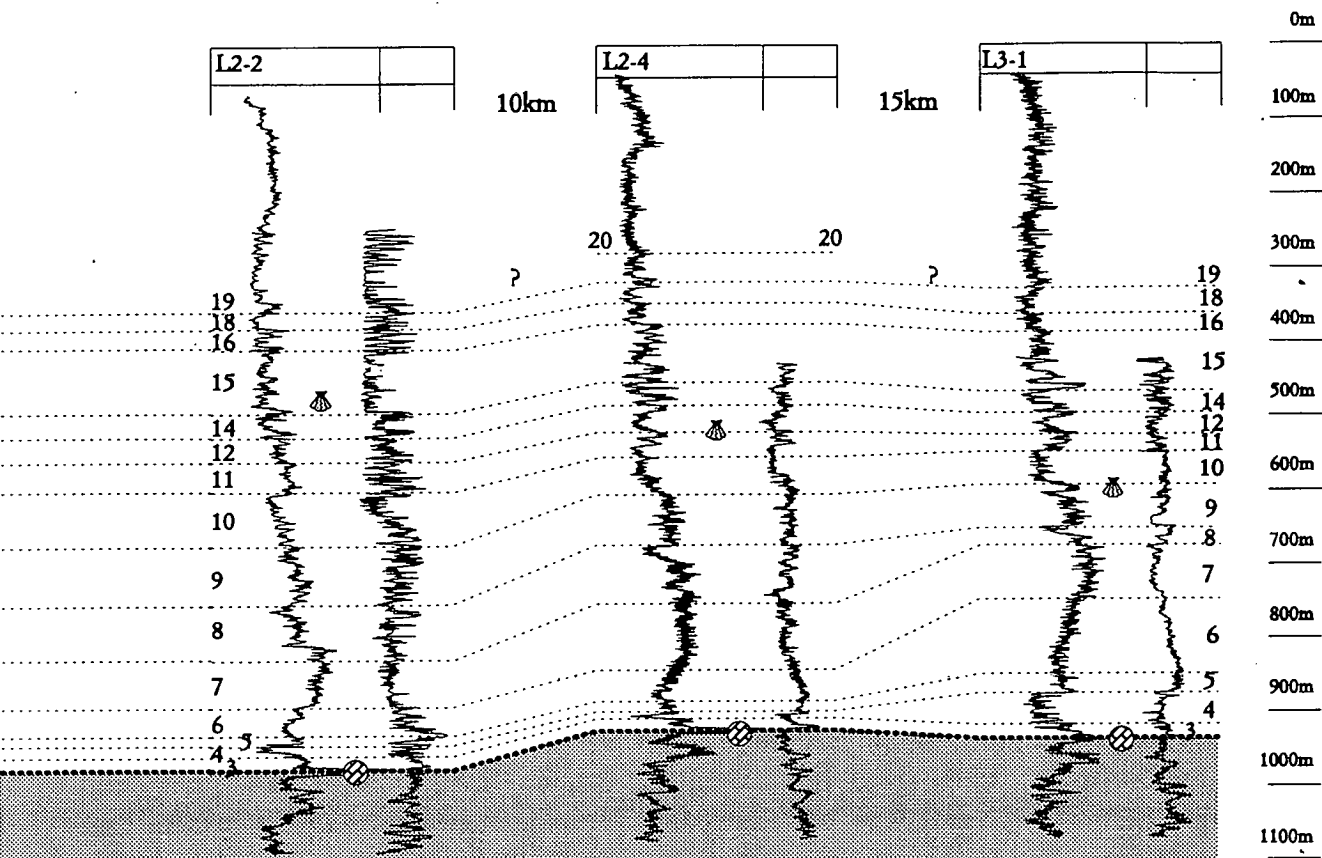




D

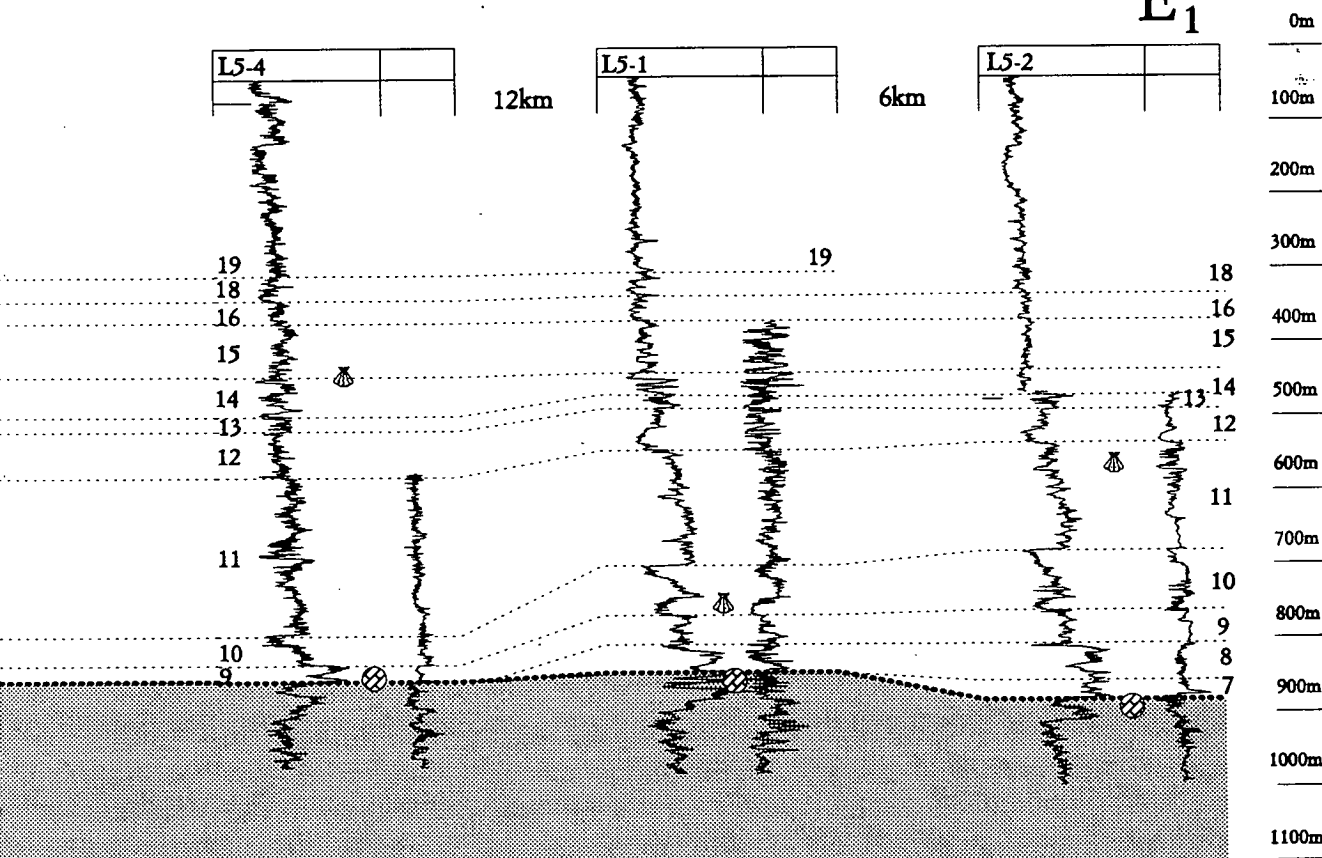


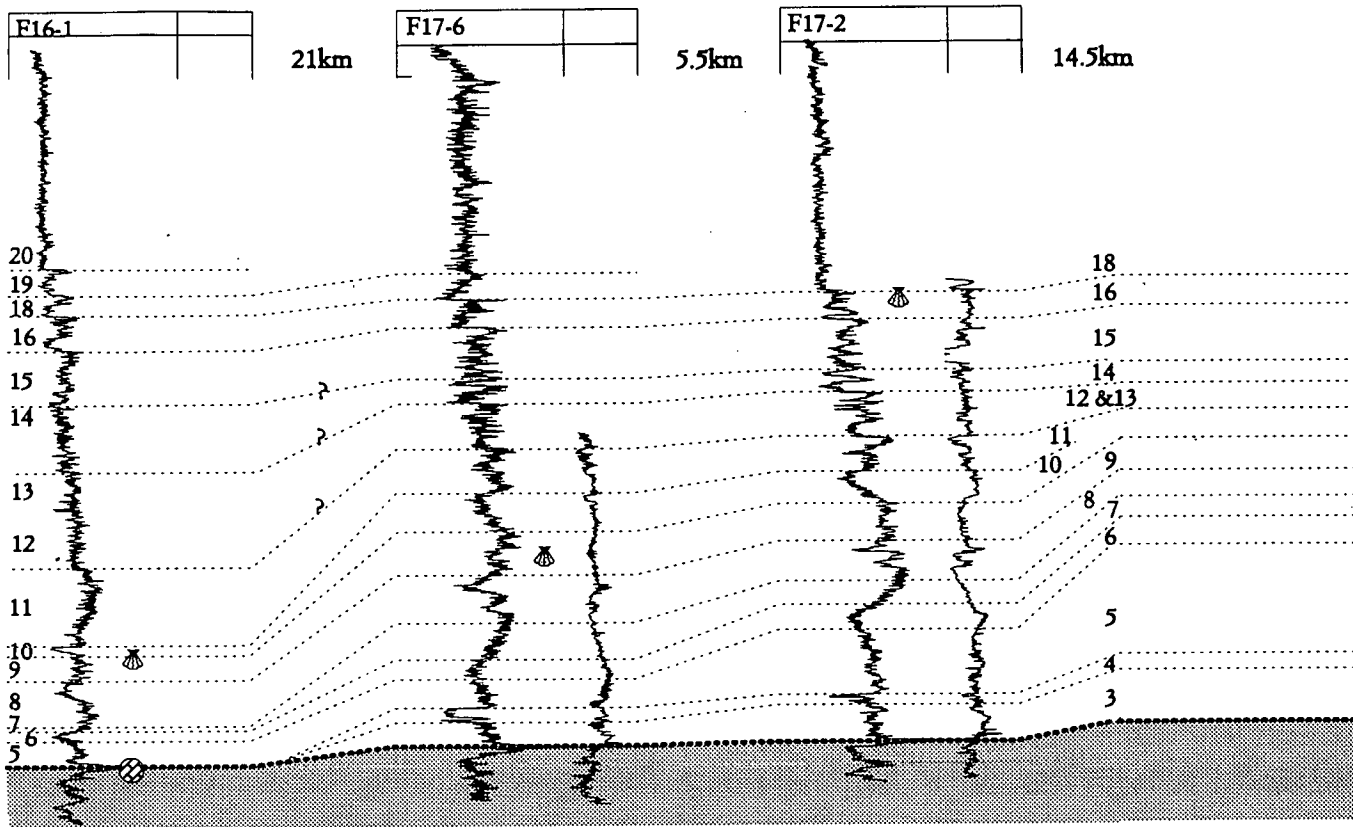
E



D₁

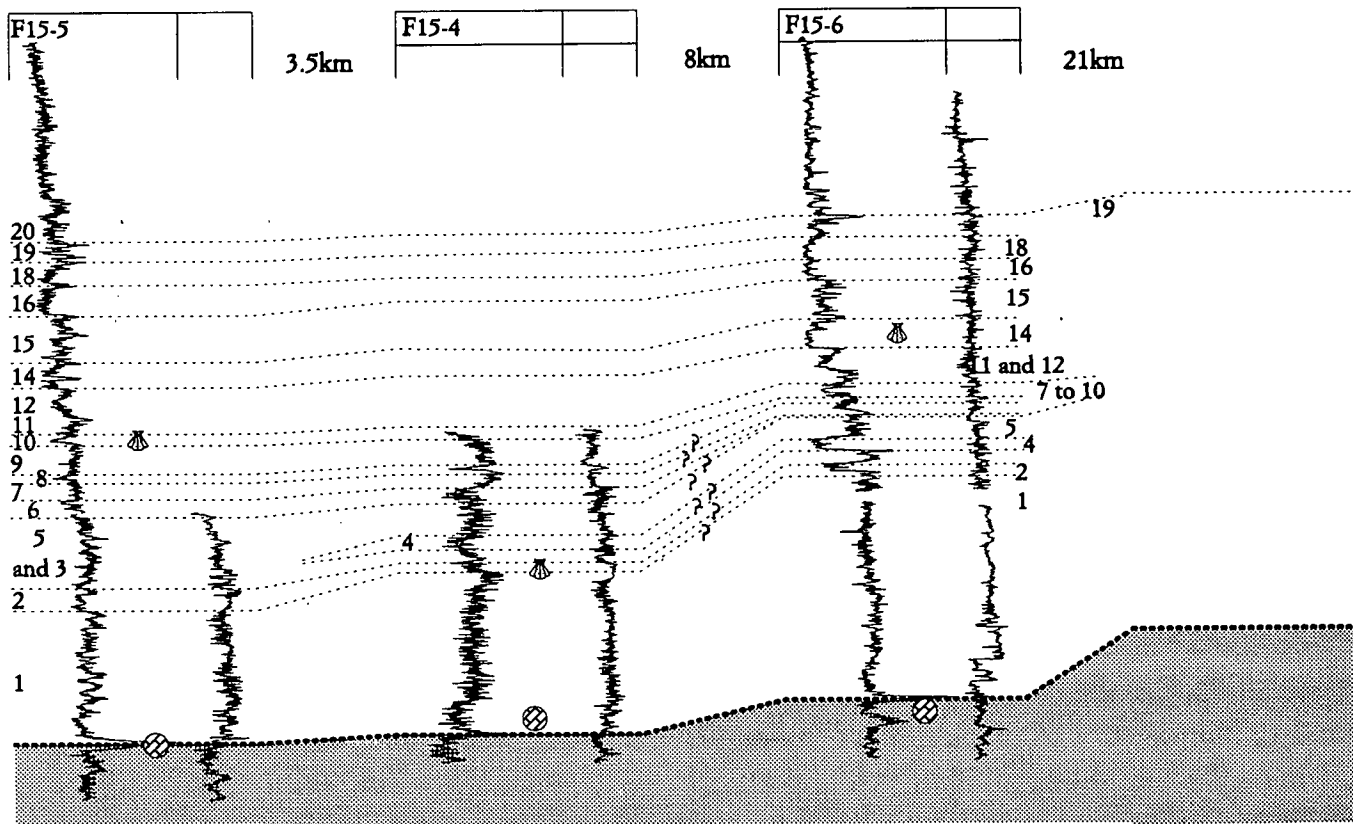
E₁

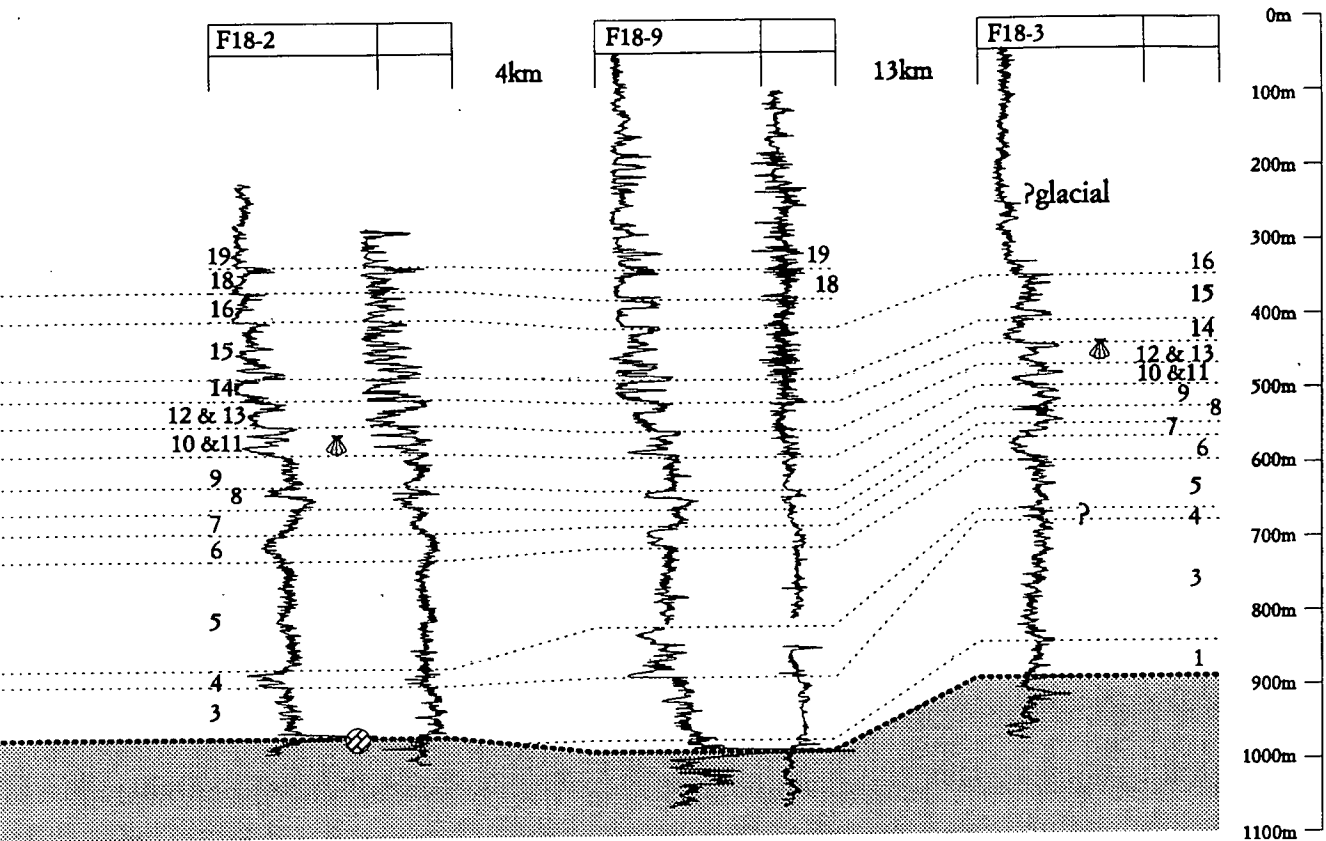




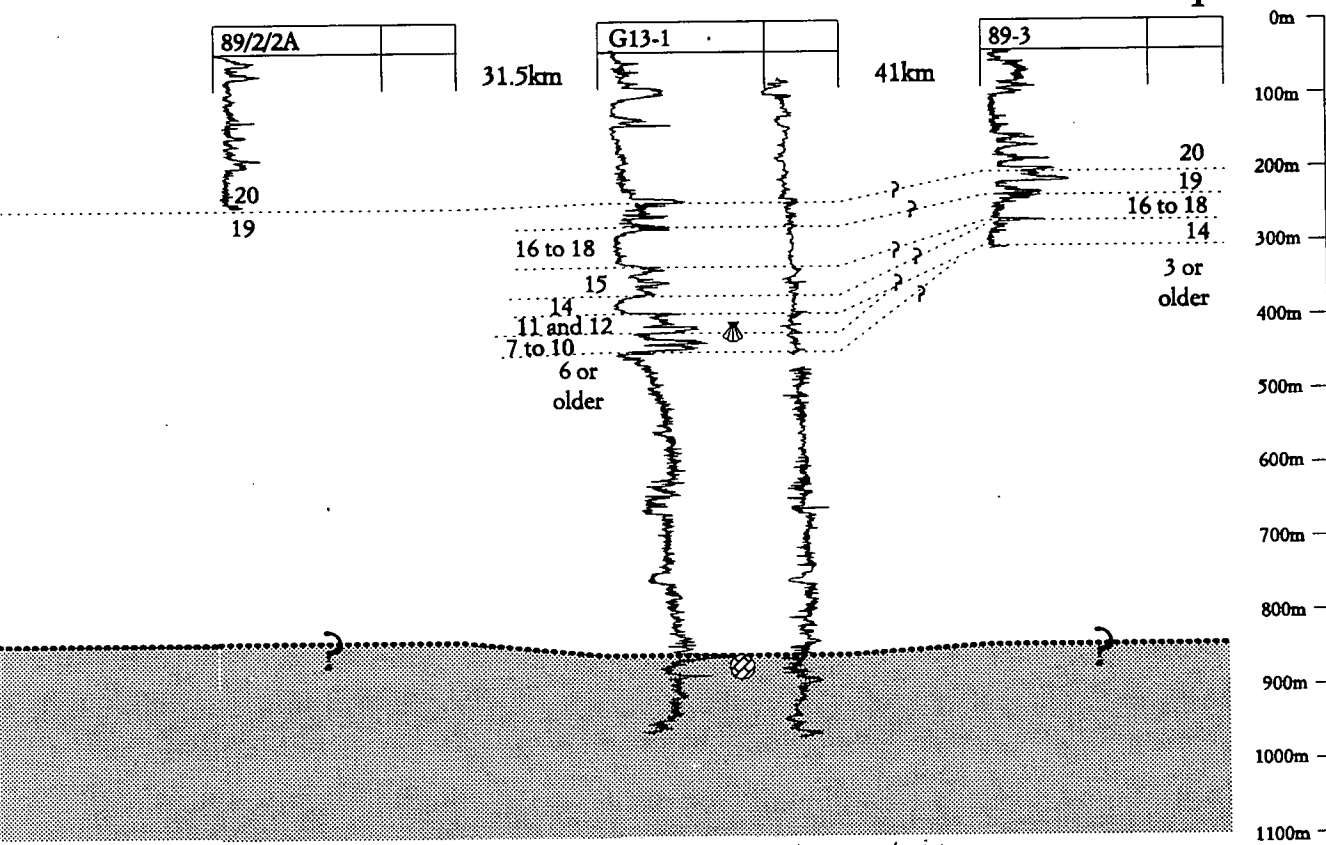
F

G





F₁
G₁



3.2.2: Nordland Group Sediments

Based partially upon the seismic correlation of chapter 2, and partially upon the character of the electric logs (e.g. gamma log response; see fig. 3.6a to g.), the following well intervals, “1” to “21” (see fig. 3.7a to g), have been distinguished. Alternate intervals generally correspond to alternating “gamma clay” and “gamma silt” or “gamma sand” sections. Boundaries are not always clear in the lower part of the succession where clay is predominant. As with seismic intervals, the oldest well intervals are best developed in the NE and the east of the area. Each successive interval has its depocentre slightly to the west of that preceding it. The following intervals are described in ascending stratigraphic order.

Interval 1

Interval Thickness: up to 375m, top-set thicknesses unknown

Lithologic Log: This is described as a grey to dark grey, rarely calcareous, silt streaked clay interval.

Electric Logs: Gamma logs show a monotonous, “gamma clay” containing rare, up to 40m thick layers of gamma silt. The basal beds of the interval also give slightly lower gamma readings. The low gamma layers have significantly lower interval velocities, suggesting high porosity. This could indicate the presence of porous, sandy units resulting from rapid deposition, possibly by turbidity currents.

Interval 2

Interval Thickness: up to 70m, top-set thickness unknown, possibly around 10m.

Lithologic Log: This interval is a silty clay, very rarely with shell fragments, and possibly includes carbonaceous material.

Electric logs: This is generally of “gamma clay” to “gamma silt”, though having distinctly lower gamma values than those of interval “1”. The interval becomes increasingly difficult to distinguish basinward.

Interval 3

Interval Thickness: up to 130m, top-set thickness less than 10m.

Lithologic Log: This interval is made up of light olive grey to light yellow-brown, soft to moderately hard, blocky or shaly clay. It also includes some pyrite and lignitic material and becomes quite glauconitic distally. One well (F17-3) records the presence of dolomite near the top of the interval.

Electric Logs: The gamma log suggests a fining upward continuation of the sedimentation pattern of interval "2". It is entirely of "gamma clay"; the top of the interval gives the highest gamma values. There are few sonic logs through interval "3", and the induction log shows no distinguishing features, except perhaps for slightly low readings.

Interval 4

Interval Thickness: up to 80m, top-set thickness unknown. Top-sets possibly not represented. This interval is only developed in the NE of the study area.

Lithologic Log: This interval is poorly described in logs, but is pale yellow-brown, continuing the colour of the underlying interval, and silty, sometimes showing fine to medium sand (L2-4), sometimes no sand at all (e.g. L2-3, L2-5). It is calcareous and has been recorded in one well (F17-4) as very calcareous.

Electric Logs: Interval "4" is characterised by highly variable, rapidly changing responses between "gamma sand" and "gamma clay", especially in the toe-sets. No overall trends can be seen within the interval and it has a generally blocky appearance. Mapping out of the extent of the "gamma sand" facies within the interval indicates their localised distribution in the NE corner of the area, in a location within the seismically defined basin floor (see fig. 3.8a).

Sonic logs show no distinguishing characteristics for the interval, whereas induction log readings approximately mimic those of the gamma log, with large negative responses. In the toe-sets this interval is equivalent to the somewhat diffractive, upper surface of seismic interval "C". The interval was probably deposited by turbidity currents resulting from a mass flow in the NE.

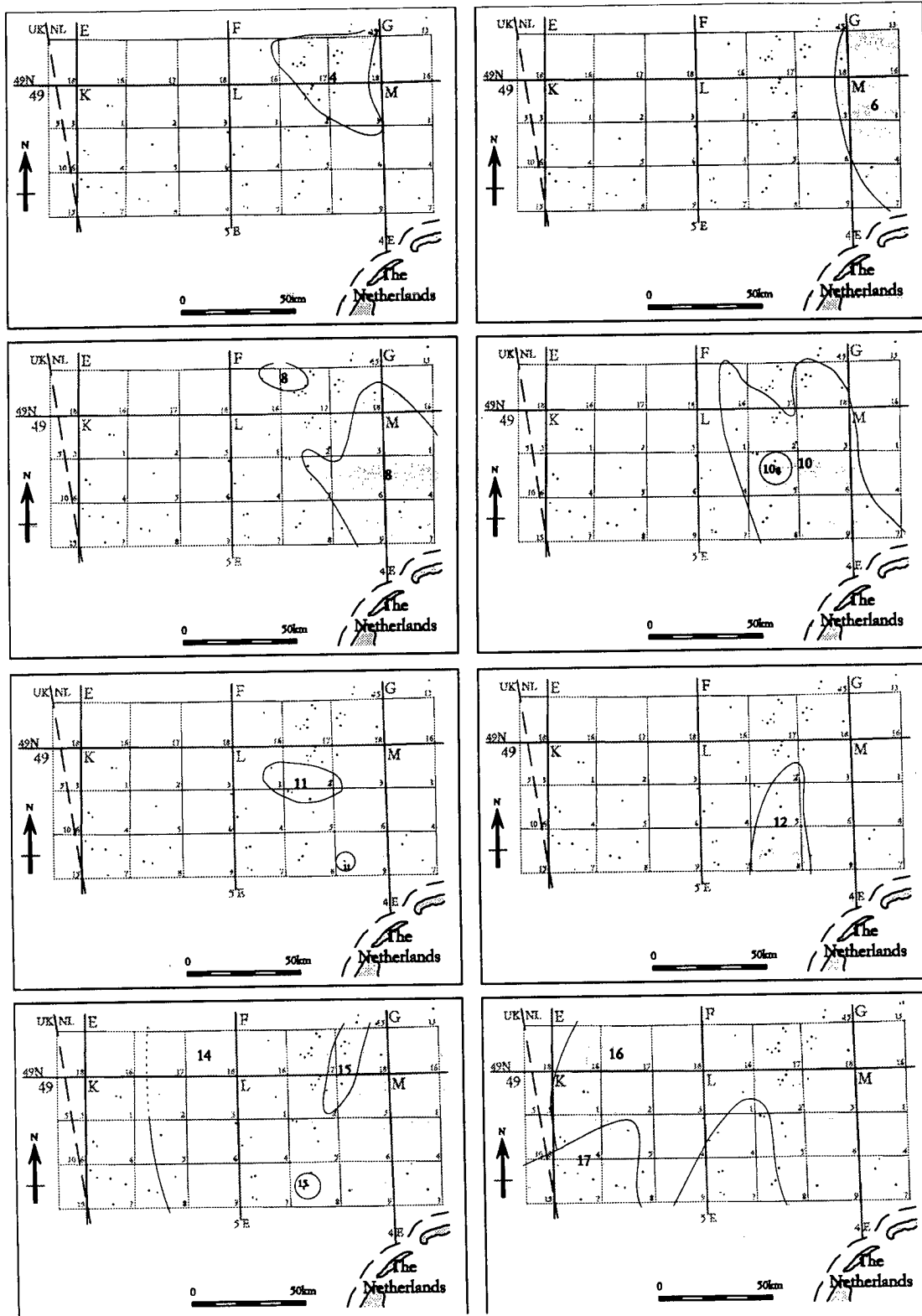


Fig. 3.9: ("a" to "j") Maps of "gamma sand" distribution within individual intervals of the Nordland Group, based upon available well data. Numbers on individual "sands" refer to the well interval in which they are found (body "10a" is the lower "gamma sand" in well interval "10").

Interval 5

Interval Thickness: up to 140m, top-set thickness less than 10m.

Lithologic Log: A green-grey to brown-grey, silty clay, with possible rare pyrite, mica and carbonaceous material. This is the lowest recorded occurrence of mica within the Nordland Group.

Electric Logs: The gamma log shows a uniform "gamma clay", possibly with a "gamma silt" layer around the middle of the interval. The sonic log response is characterised by a slightly higher interval velocity than interval "4", but is otherwise featureless. The induction log is also featureless.

Interval 6

Interval Thickness: up to 100m, top-set thickness unknown, possibly less than 10m.

Lithologic Log: Interval "6" is comprised of green-grey to brown-grey, calcareous and micaceous clay with fine to coarse grained, rounded sand. In block M7 in the SE, a thin, fully developed sand bed is present at the top of the interval, containing clear, fine grained, sub-angular quartz. From analysis of seismic facies in block L6, which is without commercial well coverage but shows the presence of an oblique prograding wedge of sediment, it is suspected that some parts of this unit are predominantly sandy.

Electric Logs: Gamma logs record a clear upward coarsening, followed by fining upward within interval "6". Gamma values are, at minimum, of "gamma silt" grade. In block M7 there is a clearly defined, 10m thick "gamma sand" of block-like appearance at the top of the interval. Mapping out of the distribution of "gamma sand" facies within the interval indicates their presence in only the eastern extreme of the area (see fig. 3.8b).

Sonic logs show a similar trend to that of the gamma log, but in reverse, with highest interval velocities in the middle of the unit. The "gamma sand" is represented on sonic logs by low interval velocity. Induction log values are sometimes low, suggesting locally increased porosity.

Interval 7

Interval Thickness: up to 100m, being thickest in the SE. Top-set thickness up to 10m.

Lithologic Log: This is a green-grey to medium-grey, slightly silty, slightly pyritic and micaceous clay, possibly containing streaks of organic mud.

Electric Logs: The gamma log shows a simple, upward increase in gamma response from "gamma silt" to "gamma clay" values. Sonic logs show upward decreasing interval velocity. The sonic log for well L2-6 records a very large reduction of velocity within this interval which, if real, could possibly represent over-pressure. All electric log trends are consistent even within the top-sets. Induction logs are uniformly high.

Interval 8

Interval Thickness: up to 120m in SE, but commonly less than 50m thick. Top-set thickness up to 15m.

Lithologic Log: Interval "8" is generally a silty clay with calcareous sand. However, in blocks L9 and M7 it is a grey, soft, sandy clay, coarsening upward into a sand which includes abundant shells and traces of pyrite. It can also include organic streaks.

Electric Logs: The gamma log normally consists of two gamma troughs, of "gamma clay" below and "gamma silt" above, separated by a thin, "high gamma" layer. Beneath these, there is a "high gamma" spike, which may be a radioactive clay layer. In the SE of the study area, the upper gamma trough is of "gamma sand" facies. "Gamma sand" is best developed in the extreme SE corner, where the interval is thickest, and the gamma log here shows a coarsening upward response (see fig. 3.8c). However, these sands may not correspond exactly with the sand described above, and could, in fact, be beneath the "high gamma" clay layer.

The gamma response is once again mimicked in reverse by the sonic log, which shows high values at the gamma troughs. The upper gamma trough is sometimes matched by an irregular, low induction log value, suggesting occasional, patchy, high porosity. No good sonic or induction logs are available for the interval in the SE of the study area.

Interval 9

Interval Thickness: up to 50m, top-set thickness up to 5m.

Lithologic Log: This is a green-grey to medium grey, soft, silty to sandy, micaceous and calcareous clay containing rare shell fragments and carbonaceous material.

Electric Logs: This is a moderately uniform, "gamma clay" interval. The limited variation in gamma ray value either represents changes in grain size or proportions of radioactive minerals in a mainly clay sequence. The sonic log is generally uniform, except for low values recorded at the base of the interval in the NE of the area (e.g. F18-2, L2-2 & 4, L3-1). The induction log gives high values, suggesting low porosity.

Interval 10

Interval Thickness: up to 80m, top-set thickness up to 15m.

Lithologic Log: A very fine to fine grained, sub-angular to sub-rounded, clear, poorly sorted quartz sand containing some medium grey clay. Coarse grains and rounded gravel have also been recorded locally, as well as rock fragments (L1-3). Shell fragments and pyrite are almost always present. The middle of interval "10" has been recorded as glauconitic in two wells (F17-7, L2-6). This interval records a major increase in shell material.

Electric Logs: The electric logs of this interval together comprise the most distinctive and recognisable unit within the succession. The coarsening upward, "gamma silt" to "gamma sand" pattern is clearly traceable as far as the western limit of interval "10". Mapping of "gamma sand" facies within the interval shows its distribution in a NNW-SSE trending band across the eastern part of the study area (see fig. 3.8d). In block L5, at the base of this interval, a second, block-like "gamma silt" or "gamma sand" is present. The contact between intervals "9" and "10" may be diachronous.

The sonic log shows no sudden change in interval velocity from that of interval "9" below, but shows increasing velocity upward. Near the top of interval "10", the sonic log sometimes includes a thin, low velocity layer. This character is also shown by the induction logs which show an upward increase in porosity just below the top of the interval. The combination of log responses may be due to a high porosity sand layer near the top of the interval.

Interval 11

Interval Thickness: up to 120m, top-set thickness up to 10m.

Lithologic Log: This is a medium grey to light grey-brown and, rarely, grey-green, soft, sometimes blocky, calcareous, slightly micaceous and silty clay. It contains increasing shell fragments upward and is slightly lignitic. Sand is recorded in only one well (L9-1).

Electric Logs: A relatively uniform gamma response gives values between “gamma clay” and gamma silt. The general impression is of slight fining upward, although this trend is temporarily reversed, with a “gamma silt” spike near the top of the interval in some wells. A localised “gamma sand” is present across the north end of “L” quadrant (see fig. 3.8e). This is beyond the seismically defined slope break and may be turbidite sand facies.

Sonic logs record a sudden upward decrease in velocity about 20m above base. This could be due to the presence of a hiatal surface at this level. Induction log values decrease upward slightly, suggesting a corresponding, upward increase in porosity.

Interval 12

Interval Thickness: up to 190m, top-set thickness up to 25m.

Lithologic Log: A very fine, sub-angular to sub-rounded quartz sand. Moderately sorted, with trace rock fragments, interbedded with light to medium grey, slightly micaceous clay.

Electric Logs: This interval is very variable from well to well and can be difficult to correlate within the fore-set succession, especially from north to south. The gamma log is distally irregular in blocks L1 and the NW part of block L5, showing multiple fining upward cycles which go from “gamma silt” to “high gamma” values. This could be related to turbiditic sedimentation.

“Gamma sand” facies are present along a N-S line running through blocks L2, L5 and L8, and cutting across the line of the seismically defined slope break see fig. 3.8f). This “gamma sand” is sometimes capped by a 30m thick layer showing higher, blocky “gamma silt” values, possibly due to an increase in clay content. In block L8, where the “gamma sand” is thickest, the interval shows increasing upward gamma response, going upward from “high gamma” to “gamma sand” values.

Top-sets generally show block-like or coarsening upward, “gamma silt” values. Sonic and induction logs reflect the coarsening upward patterns of the gamma log in large part, showing low values where gamma values are low. However, both the sonic and induction logs are not smooth, and rapid fluctuations in response occur in both logs.

Interval 13

Interval Thickness: up to 150m, with top-set thickness up to 10m. Top-sets absent in the extreme NE, possibly due to the presence of a slight angular unconformity at the base of interval “14”.

Lithologic Log: A light grey to green-grey, generally soft and swelling clay, which has small amounts of silt, carbonaceous material, carbonate and mica. Interval “13” also contains some very fine grained, sub-angular to sub-rounded sand with rock fragments. The interval becomes increasingly silty, shelly and lignitic upwards. In two wells (K6-1 & 2) a highly calcareous layer occurs about 20m below the top of the interval. Glauconite is also recorded throughout the interval in one well (K6-2).

Electric Logs: This interval shows no general trend within the gamma logs, oscillating between “gamma clay” and “high gamma” values throughout. The variations are regular however, and allow correlation within the thickest parts of the interval. The top part of the interval, which can be up to 30m thick, is of homogeneous gamma clay. A “very high gamma” spike is present at the top of the interval in one well (K6-2), possibly related to the presence of glauconite. Sonic log values are fairly high throughout, but decrease sharply near the top of the interval, at the level of the “high gamma” spike.

Interval 14 “top Brielle Ground Formation”

Interval Thickness: up to 140m, top-set thickness up to 40m.

Lithologic Log: A slightly shelly, fine to medium, sometimes very coarse grained, quartz sand, together with some medium grey to light grey-brown clay. Sand grains are sub-rounded to rounded, rarely sub-angular. Rock fragments have been recorded (L5-1). This interval is often lignitic at the top. Glauconite is recorded at the top of the interval in one well (L2-3).

Electric Logs: Gamma logs show a general coarsening upward trend from “gamma silt” to “gamma sand” grade within the fore-sets of this interval, punctuated near the top by a “high gamma” spike. Where this interval is present, it always includes “gamma sand” facies and, within the top-sets, is predominantly of “gamma sand” (see fig. 3.8g). Interval “14” includes discontinuous, thin “gamma clay” layers in the top-sets which sometimes make it difficult to distinguish the interval from interval “15” above. Sonic logs show high interval velocities at the base in some wells. There are sporadic layers of low velocity throughout the interval.

Interval 15 “Westkapelle Ground & base IJmuiden Ground Formation”

Interval Thickness: up to 170m, top-set thickness up to 80m. Interval thins to the NE and, if the seismic correlation is correct, is possibly less than 5m thick in borehole 89/3 to the NE of the study area. This may be due to the presence of an angular unconformity at the base of interval “16”.

Lithologic Log: According to borehole sources in the west (Cameron *et al.*, 1984a; Cameron *et al.*, 1989) this is distally a coarsening upward unit, being of slightly silty and glauconitic, olive-grey to grey-brown clay at the base but predominantly of fine grained, slightly shelly, muddy sand at the top.

In well cuttings, interval “15” is a medium grey to light grey-brown, soft, shelly, lignitic, slightly calcareous, slightly micaceous, silty clay with fine to medium sand beds near the base. Five wells (K5-1, K8-1 & 7 & L2-1, L7-7) record pyrite within this interval, especially in the upper levels of the top-sets. In one well (L7-1) the interval is abundantly shelly, whilst a second well (L8-1) records up to 40% shell material near the base of the interval, which may represent a coquina.

Electric Logs: This interval generally shows a slight fining upward trend, largely ranging from “gamma silt” to “gamma clay” and, distally, when it has thinned to less than 25m, it includes “high gamma” values throughout. Within the top-sets, one or more 10m thick, “gamma clay” spikes may sometimes be present at or near the base of the interval. Other events within the top-sets can be highly discontinuous. Locally, in the NE of the study area, a NNE-SSW trending line of “gamma sand” facies can be traced near the base of the interval (see fig. 3.8h). Sonic logs show a reversal of gamma trends for the interval, interval velocities being very low at levels of high gamma radiation.

Interval 16 "base IJmuiden Ground Formation"

Interval Thickness: up to 170m, top-set thickness up to 25m.

Lithologic Log: Cameron *et al.* (1984a) recorded that the equivalent sediments from offshore East Anglia, part of the Smiths Knoll Formation, are of olive green, fine grained, muddy sand, glauconitic and locally micaceous, with between 1 and 10% shell gravel. However, unlike the study area, these sediments were derived largely from the British mainland.

In well cuttings this is a clay rich, slightly calcareous, fine, rarely coarse sand. This sand includes shell fragments which become less abundant westward. Lignite is common within the interval, especially at the base. The clay is light grey to green-grey. Pyrite is increasingly present westward. Traces of glauconite are also present in one well (L2-3). In another (M7-1) the sand is cemented by an iron rich cement.

Electric Logs: On gamma logs this is a rather complex interval, showing stacked, coarsening upward packages, ranging from "gamma clay" to "gamma sand", in the fore-sets but showing fining upward or block-like patterns in the top-sets of the NE. However, near the base, thin "gamma sand" or "gamma silt" layers are present. Although, where present, this interval includes "gamma sand" facies almost everywhere, they are absent around blocks L4, L5, L7 and L8 (see fig. 3.8i). This may be due to salt induced uplift in this area, which can be seen in the seismic TWT map (see fig. 2.11, horizon "H₁₀").

Near the top of the interval there is sometimes a low interval velocity spike, together with a low induction log value at the same level.

Interval 17 "top IJmuiden Ground Formation"

Interval Thickness: up to 140m, top-set thickness up to 20m. Top-sets possibly absent in the NE.

Lithologic Log: A medium grey to light grey-brown, soft, slightly sandy, sometimes very shelly clay. Distally, as the interval thickens, it also includes silty or sandy beds, and is calcareous and dark grey near the base. In some western wells (K7-1 & 3, K8-2), this interval marks the uppermost occurrence of large amounts of mica within the succession.

Electric Logs: On gamma logs within the top-set succession, this interval is represented by a thin, "gamma silt" or "gamma clay" layer. However, distally, where the interval is thick, three separate components can be distinguished: 1) a basal, "high gamma" unit up to 20m thick, 2) a variable, "gamma sand" to "gamma clay" unit up to 70m thick with lowest gamma values at the base and top, and 3) a fining upward, "gamma silt" to gamma clay unit up to 60m thick. When mapped out, the "gamma sand" facies of the second unit is seen to be distributed only in the SW corner of the study area, beyond the seismically defined slope break (see fig. 3.8j).

Sonic logs for the interval show that the basal component has a very low interval velocity. Interval velocities for the other two components are higher but more variable. Induction log values for the second component are low within the sandier levels, suggesting high porosity. The one induction log recorded for the top component displays a slight decrease in values toward the top.

Interval 18 "Winterton Shoal Formation"

Interval Thickness: up to 30m in top-sets. No fore-sets are present within the studied well logs.

Lithologic Log: Cameron *et al.* (1984a) observed that, in the west, these sediments are olive green, fine or medium grained, shelly sand with minor, silty clay. Jeffery (1993) recorded bioturbated, calcareous, sandy mud, with glauconite and granules of monosulphide, partially altered to pyrite further north in the British sector of the North Sea.

This is a very sandy interval in well cuttings, with medium grey, shelly, lignitic and pyritic, loose sand. Glauconite is recorded at the top of the interval in one well (L2-2)

Electric Logs: Gamma logs record a variable response throughout this interval. However, it is generally of "gamma sand", rarely "gamma silt" grade, and either fines upward or has a blocky appearance. Two available sonic logs in "K" quadrant (K5-1, K7-1) show a low velocity layer about 10m thick at the base of the interval.

Interval 19 “?Markham’s Hole Formation”

Interval Thickness: around 40m in top-sets. No fore-sets are recorded within the area.

Lithologic Log: In the British sector, this is recorded by Jeffery (1989) as being made up of muddy, fine grained sand, slightly glauconitic and calcareous with partings of clay, becoming coarser, and less glauconitic and calcareous upwards in fore-sets.

In well cuttings, interval “19” includes fine grained, slightly shelly, sub-rounded to rounded, muddy sand, becoming more gravel rich toward the base. Lithologies can be variable between nearby wells. Pyrite is recorded in two wells (L2-1 & 5). A light grey-brown to light grey, very lignitic and pyritic clay is sometimes present at the base, and a thin brown coal could be developed locally. The top of this interval was penetrated near the base of borehole 89/2 & 2A.

Electric Logs: This interval has a very variable gamma response, ranging from “gamma clay” to gamma sand. A “gamma clay” spike can sometimes be observed at the base, whilst a second, better developed spike can often be seen at the top of the interval.

Interval 20 “Yarmouth Roads Formation”

Interval Thickness: up to 300m in top-sets. No fore-sets are recorded within the area. This interval is often removed by glacial erosion.

Lithologic Log: According to Cameron *et al.* (1984a) and Jeffery (1989), this interval is a grey-green, very fine to medium grained, non calcareous sand with variable clay laminations. Lignite is often present, especially near the base. The basal sediments also include pebbles of chert and quartzite, and worn shell material, with many layers of stiff, micaceous clay. Shell material is present throughout.

In well cuttings, this is a loose, fine to coarse grained, sub-rounded to rounded, rarely sub-angular, poor to well sorted sand. The sand is slightly feldspathic, sometimes gravel rich, and includes shell fragments and lignite. Occasionally, light grey to brown-grey, amorphous clay is present, which is slightly silty, sandy and calcareous, with lignite and shell fragments. Shell fragments become increasingly abundant upward. Pyrite is locally recorded within the interval and is reported to be abundant in one well (L2-1). A thin brown coal may be developed locally near the base of the interval.

Electric Logs: Gamma log trends within this interval are very variable, values ranging from “gamma sand” to “gamma clay”, with coarsening and fining upward, as well as blocky trends all represented. “Gamma sand” tends to be more abundant toward the base of the interval. In some wells to the east, a 15m thick “gamma silt” band is present about 60m above the base of the interval. Where recorded, sonic logs give generally low values, and there is a sharp decrease in velocity at the base of the interval in two wells (F15-6, G13-1).

Interval 21 “Swarte Bank & younger formations”

Interval Thickness: very variable, ranging between 25 and 450m. Its base is a seismically defined erosion surface, which cuts down to the level of interval “15” in some wells.

Lithologic Log: No attempt can be made to distinguish glacial sediments properly. This is partly because the glacial interval often consists of material reworked from the underlying sediments and it shows no apparent differences in lithologic texture from those intervals beneath. However, interval “21” can sometimes show an abundance of lignite, shells and coarse pebbles, including metamorphic and chert fragments, at the base, and it often contains large thicknesses of clay.

Electric Logs: There is no systematic way of distinguishing the glacial sediments from those beneath in individual well logs. However, as noted above, clay is far more abundant within this interval, as revealed by common “gamma clay” values. Thick, glacial sequences are best revealed in electric logs by noting anomalies in electric log responses at depths where the normal, pre-glacial succession can be predicted from comparison with other wells. Unlike in the underlying succession, correlation of logs responses between wells is difficult for this interval.

Isolated Sediment Packages

At the base of the Nordland Group in well K5-1, there is a 70m thick package of glauconitic, silty clay. This package has been given a Pliocene age by the operators. In the gamma log it is predominantly of “gamma silt” to “gamma clay” grade, although two “gamma sand” spikes occur toward the top of the package. This package is likely to correspond to the fill of an isolated depression seen in the seismic data adjacent to the well, although its relationship to other intervals defined within the Nordland Group is unknown.

3.3: Discussion

3.3.1: Pre-Nordland Group Sediments

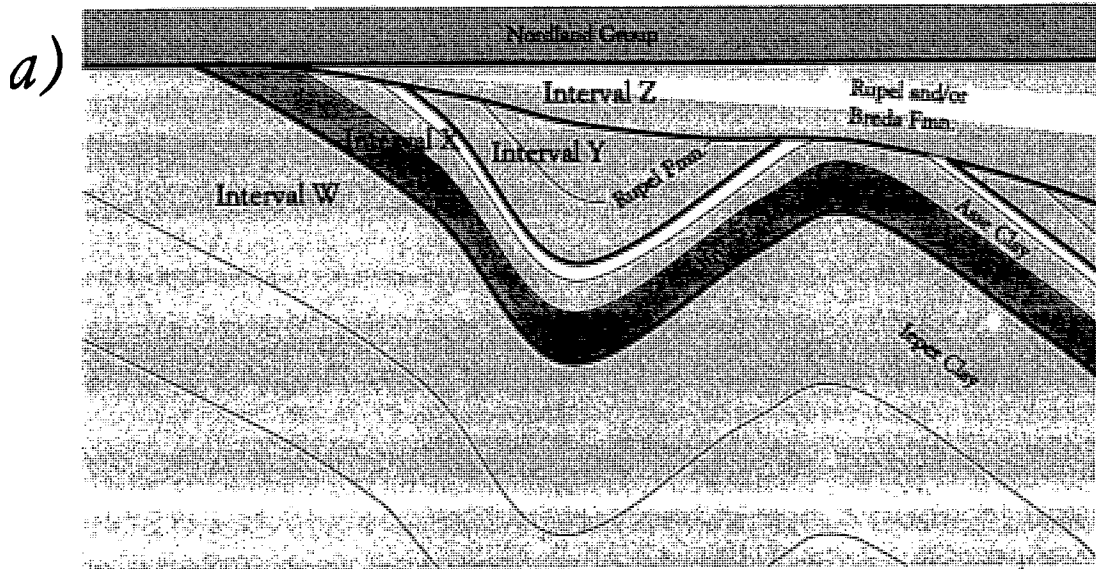
Ages of Unconformity Surfaces

Deegan & Scull (1977) assigned all the clay dominated, Cenozoic sediments below the middle Miocene, "mid-Tertiary" unconformity to the "Hordaland Group" in the Central and Northern North Sea. However, *NAM & RGD* (1980) divided the Cenozoic succession into three groups, the "Lower", "Middle" and "Upper North Sea" groups, in the Southern North Sea, separated by two major unconformities, the "top Eocene" and the "top Oligocene". This would place the "mid-Tertiary" unconformity above the base of the Upper North Sea Group, and therefore implies that there are actually three potential major unconformity surfaces developed within the Cenozoic of the southern North Sea Basin (see fig. 3.9a, 3.10):

- 1) Top Eocene-Base Oligocene: between the Lower and Middle North Sea groups.
- 2) Top Oligocene-Base Miocene: between the Middle and Upper North Sea groups.
- 3) Intra Middle Miocene: between the Hordaland and Nordland groups.

According to the well data, there are possible unconformities developed near the middle of, and at the top of the Oligo-Miocene interval "Z". If the interpretation of *NAM & RGD* (1980), that interval "Z" is almost entirely Oligocene, is correct, then a fourth, previously unrecognised, "mid-Oligocene" unconformity has to be present near the middle of interval "Z" (see fig. 3.9b). This is possible, although a simpler scenario may be that the upper half of interval "Z" is actually Miocene, as is suggested in many composite logs, thus removing the need for a fourth, major unconformity surface.

Seismic horizon "H_x" (see section 2.2.1), which lies beneath the "mid-Tertiary" unconformity ("H_o"), is likely to be at or near the base of interval "Z". This therefore leads to the possibility that Horizon "H_x" may, in fact, be the base Miocene unconformity surface.



b)

	Deegan & Scull (1977)	NAM & RGD (1980)	Major Hiatuses	Scenario 1	Scenario 2
Pliocene to Recent	Nordland Group	Upper North Sea Group			
Miocene				Z	Z
Oligocene	Hordaland Group	Middle North Sea Group			
Eocene		Lower North Sea Group			

Fig. 3.10: Stratigraphic relationships in the lower Cenozoic succession. a) Schematic representation of the relationships seen in the succession. b) Possible unconformity surfaces developed, based upon the information from Deegan & Scull (1977), NAM & RGD (1980) and the present study.

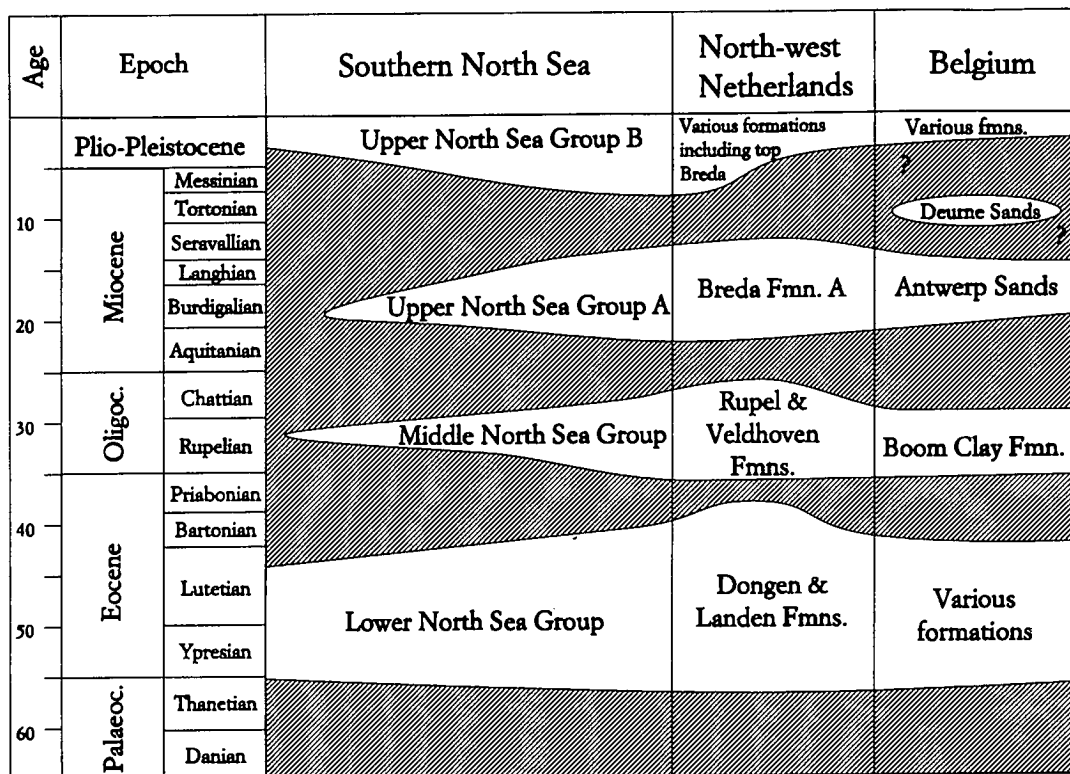


Fig. 3.11: Suggested correlation scheme for the lower Cenozoic of the southern North Sea.

Diapirism Below the "mid-Tertiary" unconformity

The fact that interval "Z" is thickest in the middle of the northern part of the study area, in the place where apparent diapirism just below the "mid-Tertiary" unconformity is most effective (see section 2.2.1), may indicate that interval "Z" is, in part, equivalent to this "diapiric" layer. However, interval "Z" is of greater extent than the diapiric layer in the east of the study area, and it seems apparent that diapirism is usually present only where interval "Z" is greater than 30 or 40m thick.

3.3.2: Nordland Group Sediments

Well log correlation of the Nordland Group succession has been aided by the surprising degree of lateral continuity within the succession, especially in the transition from top-sets to fore-sets across the slope break. A particularly good example of this is in intervals “6” through to “10” (see fig. 3.11) which, in the north of the area, can be traced over a distance of 45km from the top-sets through the fore-sets out into the toe-sets, where they eventually lap out westward against the “mid-Tertiary” unconformity surface, without a significant change in gamma log response.

Correlation reveals that, except for glacial interval “21”, which will not be discussed further, the succession can be divided into alternating sand-rich and clay-rich packages (see fig. 3.12a & b). However, the succession is regressive overall, increasing in gross sand content upward. The sediments show certain uniform electric and lithologic characteristics and vertical changes for the different seismic facies of the clinoform succession. These interval characteristics are detailed in the following discussion (see figs. 3.13a to c).

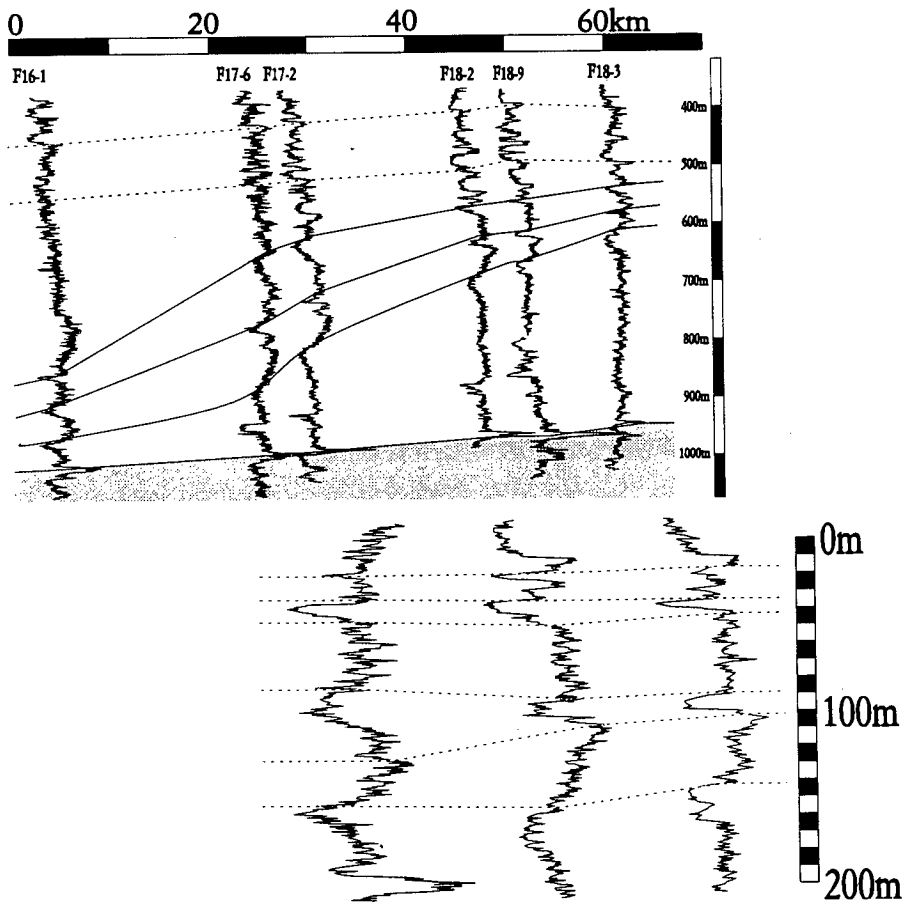


Fig. 3.12: Lateral gamma log correlation of intervals “6” to “10” from the top-sets into the toe-sets of the Nordland Group in the NW of the study area, showing the lack of marked change in electric log character across the slope break.

Top-sets

Sand-Rich Intervals: These are generally represented on gamma logs by blocky intervals between 25 and 30m thick, which have sharp tops and bases, and generally low gamma values. Interval velocities are highly variable, but are sometimes slightly lower than for the sediments above and below. The sediments of these intervals vary between pure sand and sandy clay. Their sands are generally well sorted, and medium to very fine grained, but locally include coarse material. Lignite and pyrite are often present within the sand, and there are occasionally quantities of glauconite near their upper surface.

Sand bodies toward the base of the top-sets sometimes show slight coarsening upward trends. However, fining upward trends are normal at higher levels. The sand rich intervals are probably erosive based, channel sand deposits. Near the top of the Nordland Group succession, sandy top-sets dominate to the almost total exclusion of clay.

Clay-Rich Intervals: Although these intervals can be up to 30m thick toward the base of the top-set succession, they can be less than 5m at higher levels. They are indicated on gamma logs by high gamma values, but are difficult to resolve in sonic logs.

Interval "15", a very sandy clay, is unlike other clay-rich intervals within the top-sets, being up to 60m thick, with an irregular fining upward trend. This trend is probably due to its unusual, possibly transgressive nature, as seen in seismic data (see section 2.2.2, interval "T"). Where present, in combination with interval "14" it forms a major, fining upward marker unit in the top-sets of the study area.

Fore-sets

Sand Rich Intervals: These are locally up to 150m thick, and have a gross coarsening upward appearance on gamma logs, occasionally with more than one coarsening upward cycle present. Tops of intervals usually show a rapid transition into clay facies above. A decrease in interval velocity is apparent near the top of many intervals, possibly related to high porosity values within the top of the sand. The bases of coarsening upward intervals can be quite sharp and, with seismic evidence, suggests that they may be erosion surfaces.

Sand-rich fore-sets are characterized by fine to coarse grained, sub-angular to sub-rounded, poorly sorted, quartz sands, sometimes with abundant shells and

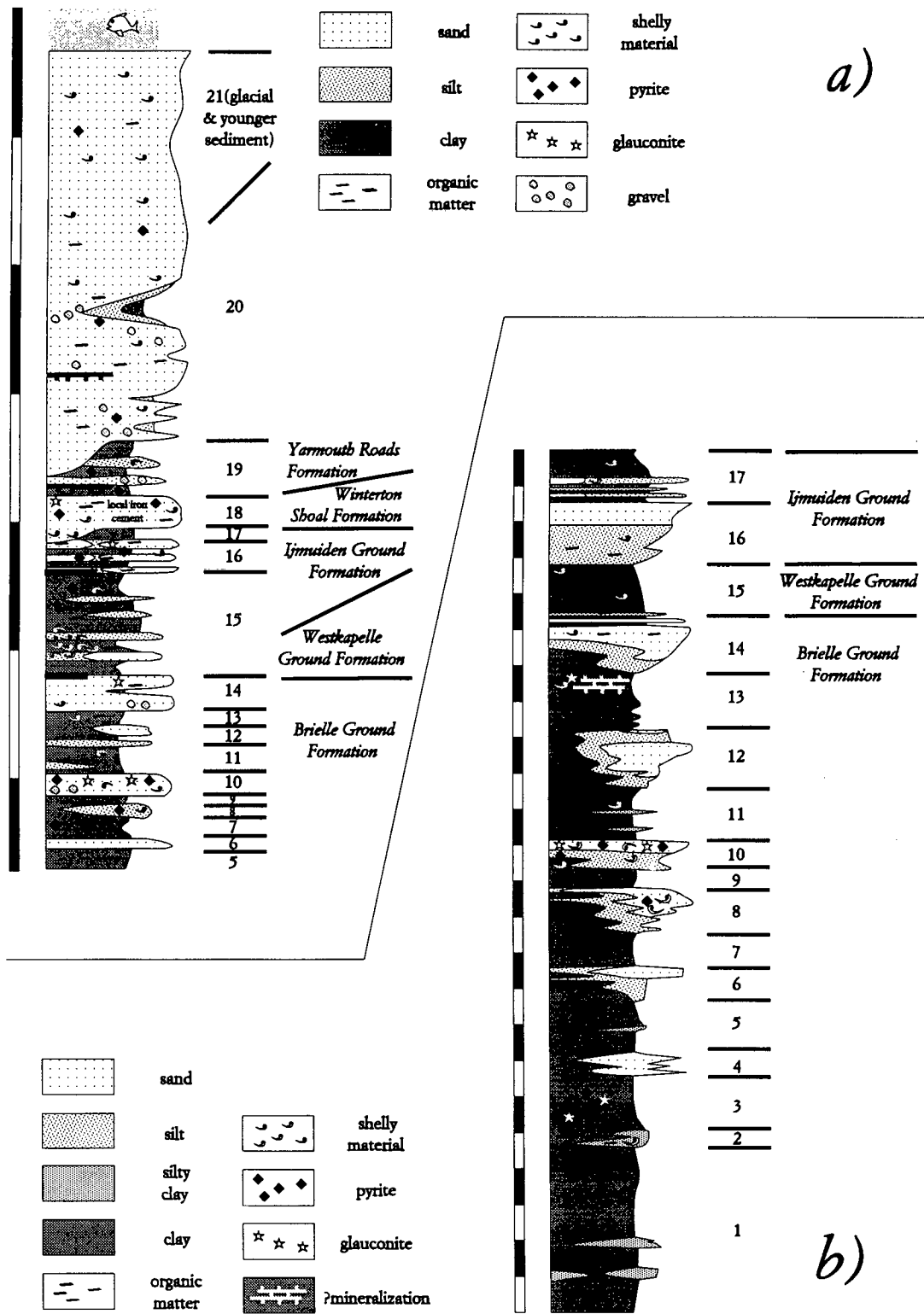
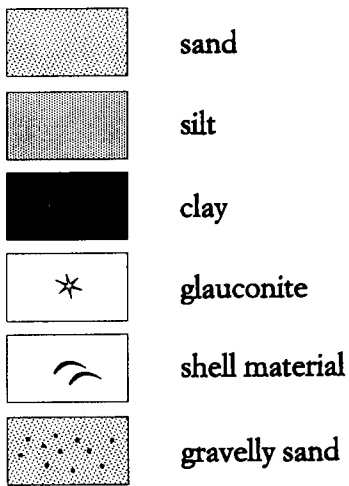
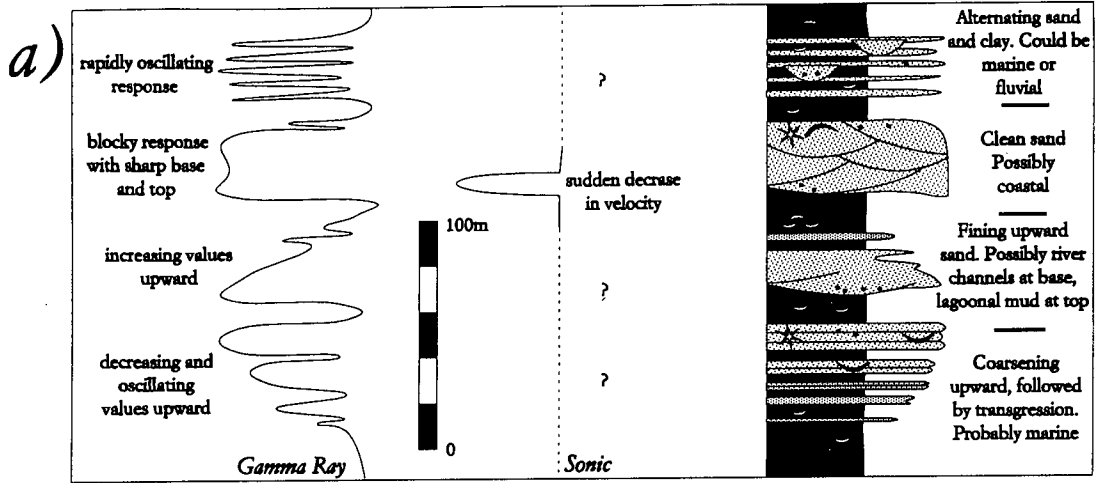


Fig. 3.13: Suggested vertical litho-stratigraphy of the Nordland Group. a) Within the top-sets. b) Within the fore-sets. Vertical scale bars are marked at 100m intervals.



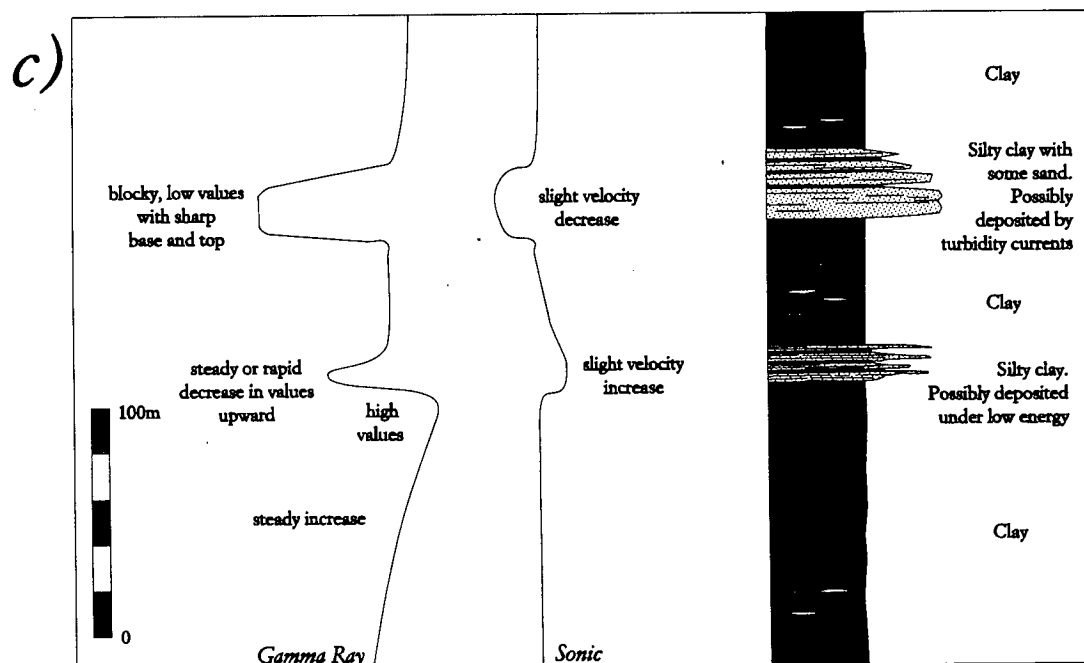
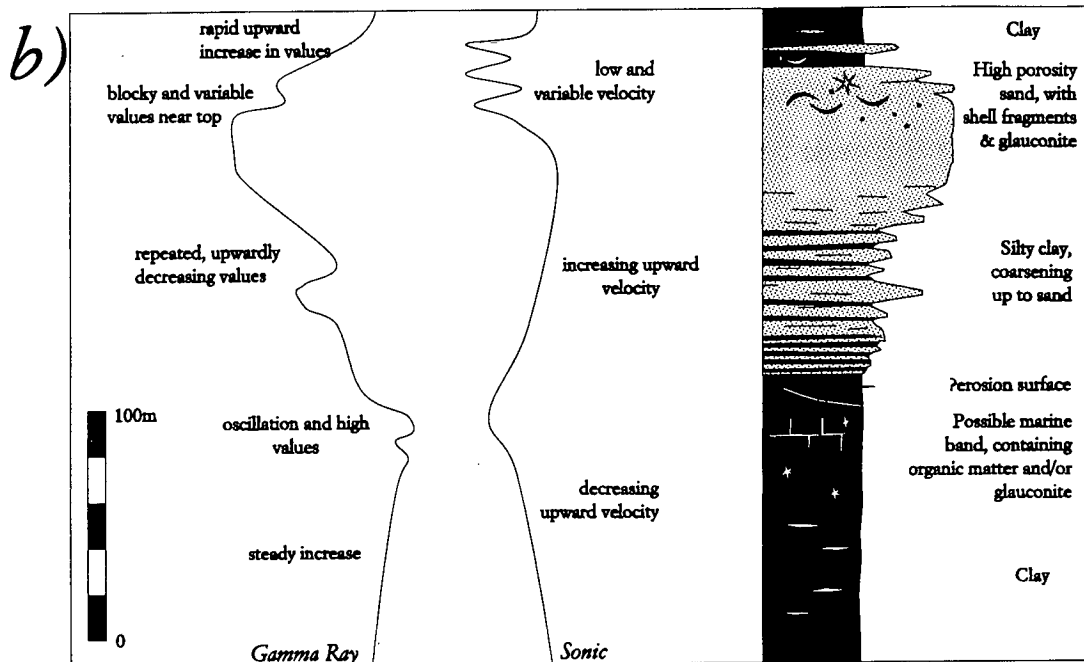


Fig. 3.14: Suggested vertical changes in sediment character in the Nordland Group. a) Within the top-set succession. b) Within the fore-set succession. c) Within the toe-set succession.

gravel. Correlation with the seismic data suggests that these intervals are related to “oblique prograding” and “aggrading” seismic facies (see fig. 3.14).

Clay-Rich Intervals: These intervals, which can be up to 200m thick, usually show a slight increase in gamma values upward, especially toward the top, in combination with a slight upward reduction in interval velocity. The upward increase in gamma response may be due to the increasing presence of radioactive minerals such as glauconite and phosphate, or bituminous layers, and the top of the intervals are possibly maximum flooding surfaces (cf. Galloway, 1989). The upward reduction in interval velocity may be the result of reduced compaction toward the top of the interval. Correlation with seismic data suggests that clay-rich fore-set intervals are related to “sigmoid prograding” and “aggrading” seismic facies (see fig. 3.14).

The basal intervals of the Nordland Group succession show an almost total absence of sandy intervals. The detailed vertical changes in electric log response within these clay dominated intervals are not well understood.

Toe-sets

Sand-Rich Intervals: These are 50m thick or less, with sharp bases and tops, and they often lap out basinward onto the basal unconformity surface. Although always represented by low gamma values, they show variable character in sonic logs. This possibly relates to the energy of deposition and the porosity of the resulting sand body. Correlation with seismic data suggests that sand-rich toe-set intervals are often related to “aggrading” seismic facies.

At some levels within the Nordland Group succession (e.g. intervals “4”, “11” and “17”), sand bodies are present within the toe-sets and the fore-sets which have no sandy equivalents in the top-set succession. These can be very variable in thickness and are laterally discontinuous. These sand bodies are apparently preserved within sediments showing “sigmoid prograding” seismic facies, although this may be due to the resolution of the seismic data.

Clay Rich Intervals: These are similar to clay-rich intervals of the fore-sets, and are difficult to distinguish in well data. Correlation with seismic data suggests that these intervals are again related to “sigmoid prograding” seismic facies.

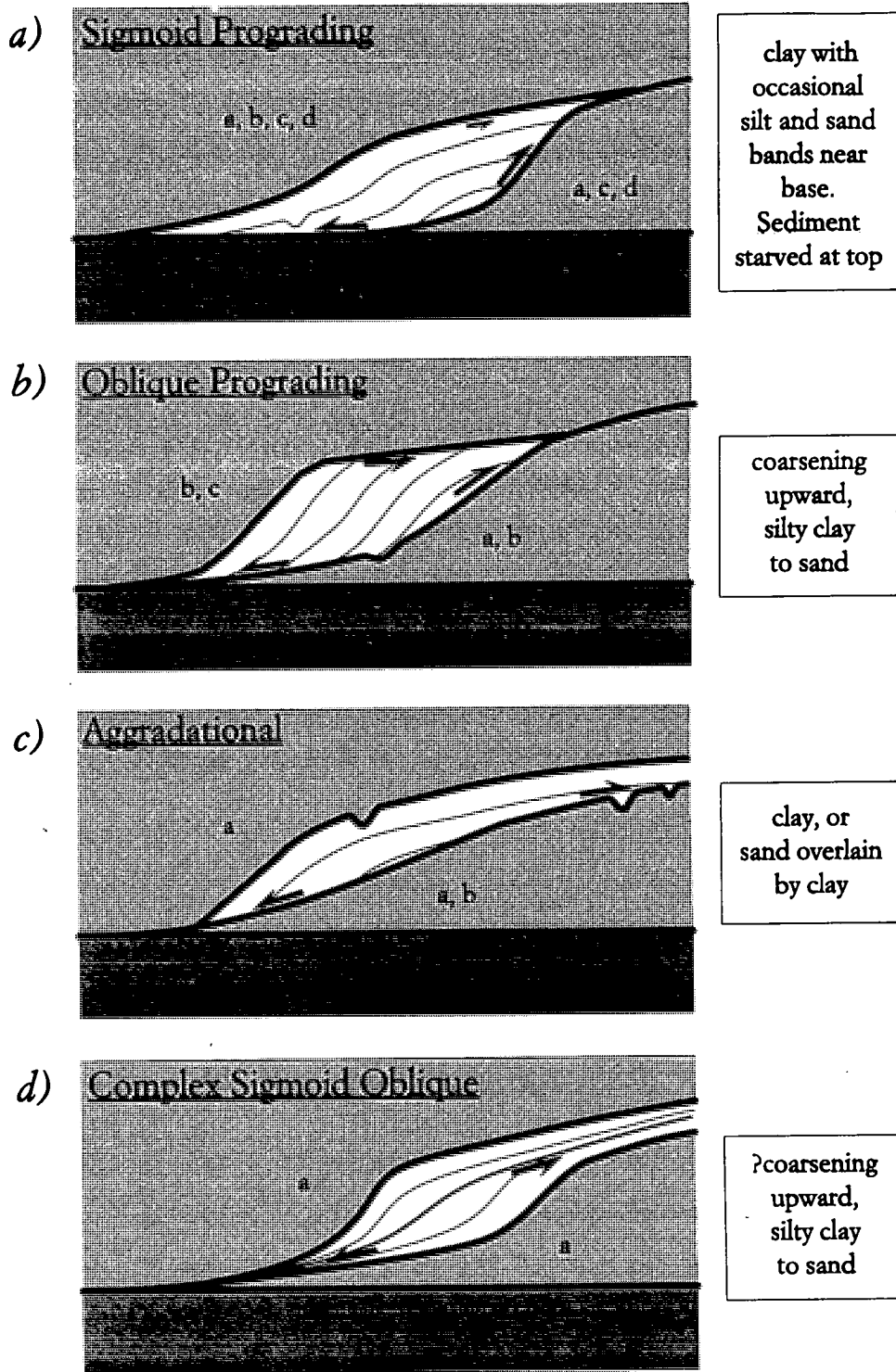


Fig. 3.15: Possible lithologies seen within seismic architectural units of chapter 2 (based upon fig. 2.24)

Distribution of "Gamma Sand" Facies

Tectonic Influence: It is interesting to note that the majority of "gamma sand" facies within the study area are concentrated around the southernmost extreme of the North Sea Central Graben axis (see figs. 1.3b, 3.8). This suggests a possible topographic control upon the distribution of sand bodies within the sequence. This is further illustrated by the absence of "gamma sand" facies from areas of salt induced uplift in well interval "16".

Influence of the Slope Break: Three different types of sand distribution related to the slope break are noted:

1) Distribution only beyond the slope break (e.g. in well intervals "4", "11" and "17"). These may, in some cases, be basin floor, turbidite sands.

2) Distribution showing slope break influence. Two examples of this are present, in well intervals "8" and "10". These two sand bodies are distributed right across the top-sets, fore-sets and toe-sets. However, when traced NNW, the "gamma sand" facies is seen to disappear first over the slope break. This may indicate preferential deposition away from the slope break or the local erosion, during reworking, of the slope break in the north.

3) Distribution showing no slope break influence. Although there are several examples of "gamma sand" facies showing no slope break influence, only one of these straddles the seismically defined slope break. This is the "gamma sand" of well interval "12". Reasons for this apparent lack of influence are unknown.

Influence of Sediment Supply: It is apparent from the distribution of "gamma sand" facies that sediment supply is likely to have been from the SE rather than the NE, the direction of sediment progradation. It may be that the major supply of sediment to the study area actually came via deltas in the current location of the NW Netherlands. This sediment may have been directed NW either by a depression formed by the tectonic control of the North Sea Central Graben axis or by along shelf reworking and movement of sand (cf. Swift *et al.*, 1987).

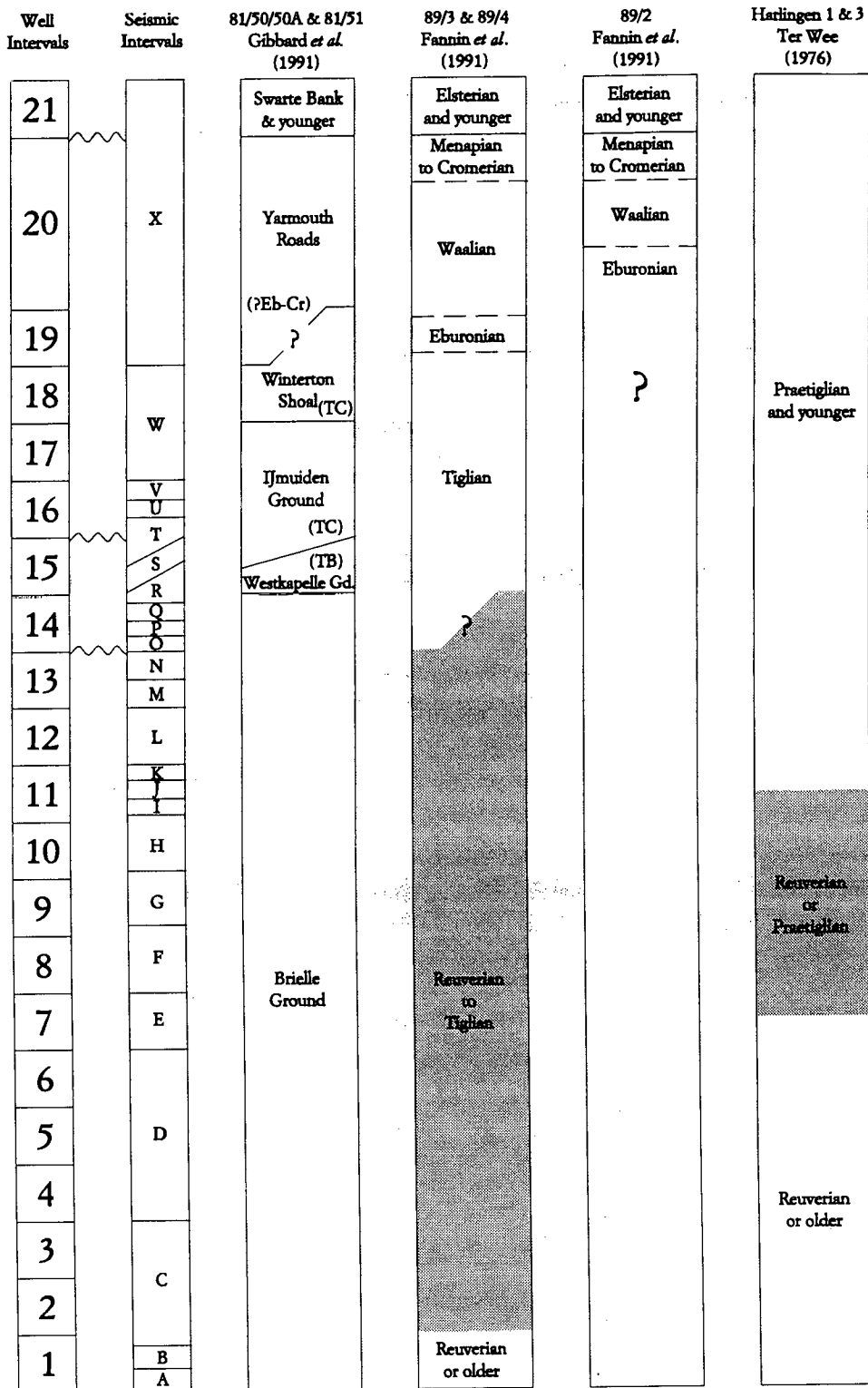


Fig. 3.16: Correlation chart, comparing the seismic stratigraphic scheme of chapter 2 with the litho-stratigraphy of this chapter, and comparing both with available bio-stratigraphic information from borehole data.

Correlation of Data

All electric log events were originally correlated using seismic and well data. No bio-stratigraphic correlation could be undertaken within the area, as there is little palaeontologic control. However, the following discussion is an attempt to incorporate the limited available bio-stratigraphic information into this study, and to suggest ages for the interpreted sedimentary packages (see fig. 3.15). Because of the possible presence of a diachronous unconformity between seismic intervals "R" and "T", these intervals are shown as diachronous on the correlation chart. However, even if this inference is incorrect the correlation is not considerably affected.

Unconformities: Three major unconformity surfaces have been recognised on the basis of regional seismic data and well log interpretations. These are at the base of well intervals "14", "16" and "23". The unconformity at the base of interval "14" is also seen clearly on the "Cromer-Sylt" seismic line in the German sector of the North Sea, east of the study area, where it truncates sediments over a wide age range. However, this unconformity is quite subtle within the study area. The unconformity at the base of interval "16" is more obvious from well data, and is also seen on the "Cromer-Sylt" seismic line.

The unconformity at the base of interval "23" is the base of the glacial succession and is present both in the regional seismic and well log data. This unconformity surface is very likely to represent the base of the Elsterian, therefore all sediments below this are probably Cromerian or older.

Base Praetiglian: In the interpretation of the regional stratigraphy by Cameron *et al.* (1986) this horizon was estimated to be at the base of the Westkapelle Ground Formation, which is here interpreted to be at the base of well interval "15". However, Gibbard *et al.* (1991) suggesting that the Westkapelle Ground Formation is of Thurnian age, equivalent to Tiglian "B" in the Netherlands. This casts doubt upon the interpretation of Cameron *et al.* (1986), implying that, unless the majority of the Praetiglian is absent from the study area, the base Praetiglian should probably be found at a lower level in the succession.

Resolution of this stratigraphic problem by the use of the *SNSP* drilled boreholes has proved largely unsuccessful (Fannin *et al.*, 1991 *unpub.*). Borehole 89/2 & 2A, the only project borehole drilled within the study area, did not reach the base of the Praetiglian. In both boreholes 89/3 and 89/4 & 4B, in the German sector of the North Sea to the east of the study area, the Nordland Group succession is too

condensed, and many horizons picked in this study could potentially be correlated with the base Praetiglian as recorded in the boreholes (e.g. fig. 3.16).

Another complication relates to the ambiguity of the age data from the basal sediments of borehole 89/3 (Fannin *et al.*, 1991 *unpub.*). This is the nearer borehole to the study area, with the less condensed succession of the two German boreholes. According to pollen analysis, the top of the Reuverian was not reached in this borehole. This is partially corroborated by clay mineralogy of a clay layer near the borehole base, which was more typical of sediments deposited after the beginning of the Praetiglian. However, gravel analyses suggest that the basal sediments of 89/3 are of Reuverian age, although evidence of reworking is present. Magnetostratigraphic data has, if anything, suggested that the base of the Praetiglian is higher in the 89/3 borehole succession (Thompson *et al.*, 1992). Hence, this data has not resolved the problem.

A possible additional source of data is the *Harlingen 1* and *3* wells, drilled onshore and documented by Ter Wee (1976). Although no direct correlation is possible between these and the study area, because there is no seismic tie-line, the base of the Praetiglian was placed at the base of an over 100m thick, coarsening upward, shelly sand. By analogy with the intervals seen within the study area, this could only have formed as part of the fore-set succession. Because of the positions and progradation directions of the fore-sets seen within the study area, it is very likely that the base of the fore-sets seen in the Harlingen borings correlate with one of the well intervals somewhere between "7" and "11". This would make the base of the Praetiglian very much lower within the succession than the level suggested by Cameron *et al.* (1986).

Base Eburonian: Although Cameron *et al.* (1989) suggested that the base of the Eburonian may be older than the Winterton Shoal Formation, below well interval "18", Gibbard *et al.* (1991) give this formation a possible Tiglian "C" age, which would make the top of the Tiglian slightly higher in the offshore stratigraphy.

Although probably not reached by borehole 89/2 & 2A, the base of the Eburonian is found at around 142m below sea bed in borehole 89/3 (Fannin *et al.*, 1991 *unpub.*). This level is probably equivalent to the base of well interval "19", the top of the Winterton Shoal Formation, and therefore fits well with the conclusions of Gibbard *et al.* (1991).

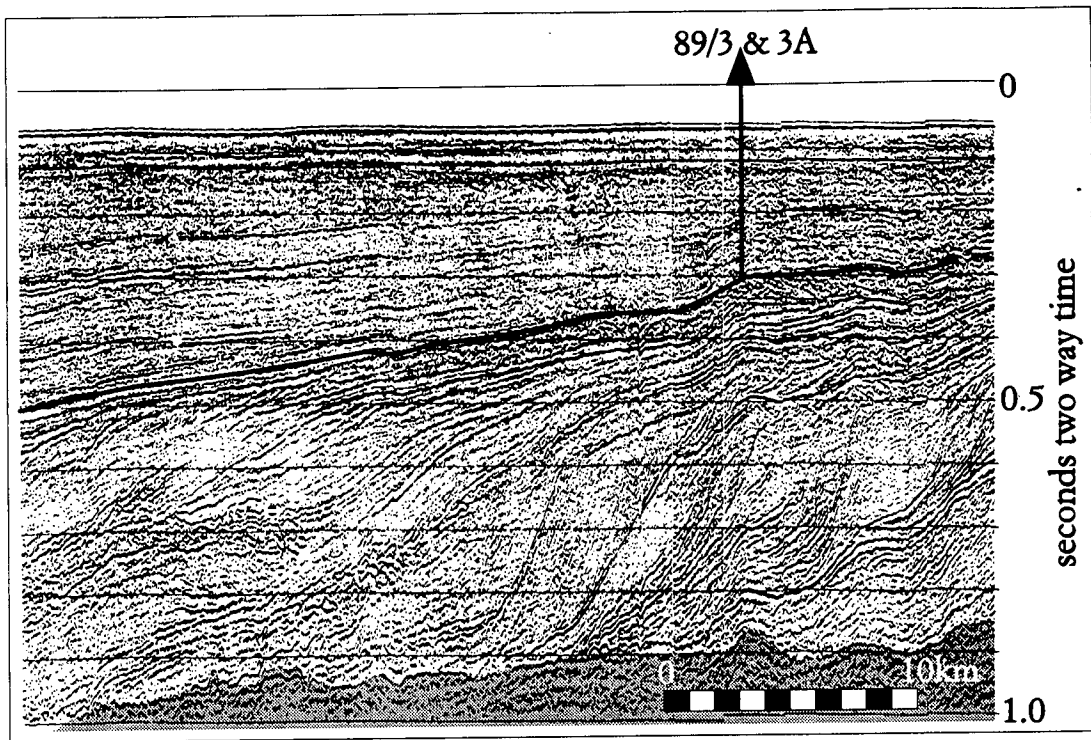


Fig 3.17: Part of the "Gauss" seismic line, showing the relationship of the seismic line to borehole 89/3, and demonstrating the wide range of correlations possible with the base of the borehole (courtesy of the SNSP).

Base Waalian: Unfortunately, it has not proved possible to resolve the evidence from the two sources of information here, boreholes 89/2 & 2A and 89/3. The two levels suggested in Fannin *et al.* (1991 *unpub.*) appear, based upon regional seismic data, to be at two separate chrono-stratigraphic levels within the succession.

CHAPTER 4:

**SITE SURVEY
SEISMIC DATA**

4: SITE SURVEY SEISMIC DATA

4.1: Introduction

Because of the many problems associated with the establishment of stable drilling rigs in certain areas of the North Sea, it is common for oil exploration companies to carry out geo-technical surveys of the sea bed within the drilling area. These surveys usually include 4 to 8km² grids of high resolution seismic surveys, providing geological information down to 1½ or 2 seconds TWT, occasionally augmented by boreholes, drilled to depths of up to 60m. Whilst the boreholes are largely too shallow to be of interest here, much of the seismic data, especially that acquired within the last few years, is of very high quality and has great potential for resolving stratigraphic problems within the shallow successions of the North Sea.

Paper copies of seven, high resolution seismic surveys have been kindly donated for the purposes of this study, all within the area of investigation (see fig. 4.1). Six of these have been donated by *SIPM*, the Hague, and one by *SEPL*, London.

Use of Site Investigation Data

Because of the lack of cores over 70m deep available from most of the Nordland Group, it is difficult to establish the environments of deposition of the sediments that make up the succession from the currently lithologic data. The contribution of regional seismic data in helping to resolve some of these questions cannot be underestimated. However, this gives only a broad-brush approach to the interpretation of the origins of the sedimentary packages. Furthermore, regional seismic data do not allow investigation of the intricacies of three dimensional relationships of sediment bodies.

Site investigation data, although only covering individual survey areas of no more than 8km², can enable the detailed mapping of geological features in three dimensions, due to a typical line spacing of between 100 and 200m. In addition, because the data is of high resolution, resolving units as thin as 5m, it displays small-scale features not apparent on the regional data, allowing these to be incorporated into the interpretation.

Methods of Lithological Interpretation

Interpretations of the site investigation seismic data have been based upon a number of assumptions and methods, outlined here:

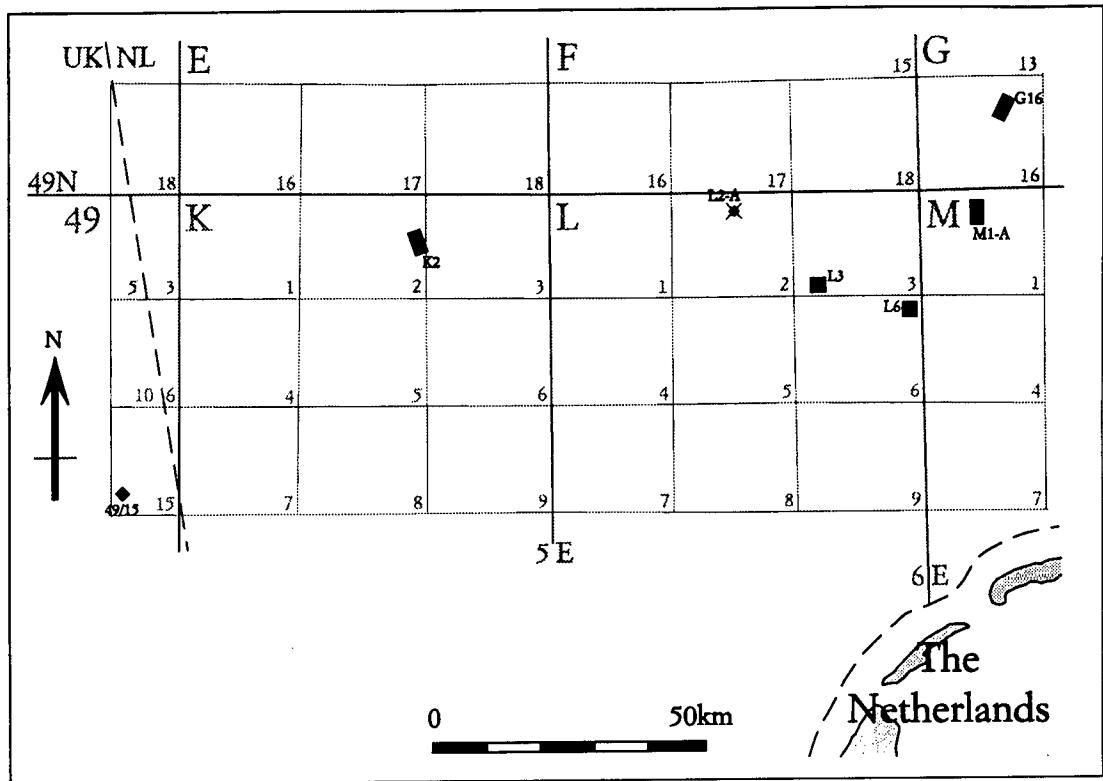


Fig. 4.1: Location of site survey data-sets within the study area.

Well data: Although this is useful, especially in site survey L2-FA-1, where two wells are actually present within the area of the survey, it is very important that not too much reliance is put upon the regional seismic and lithologic interpretations of chapters 2 and 3, in order to prevent misinterpretation of the high resolution seismic data.

Seismic representation of instability: Where purely depositional processes are seen in seismic data, it is sometimes useful to introduce some form of “instability” concept in their interpretation, analogous to the “clay prone” and “sand prone” facies of Vail *et al.* (1977). For example, if clays are deposited slowly and uniformly in a low energy, marine or lacustrine environment, it is normal for this to be recorded in seismic data as low amplitude, parallel banded, high continuity events without obvious hiatal surfaces. Conversely, in high energy, variable or “chaotic” environments, which may include sand, clay or gravel, it is reasonable to expect these to be recorded in seismic data as very variable, poor continuity, dipping, diffractive and chaotic seismic facies, possibly with many unconformities.

However, factors other than depositional processes may cause the instability recorded in seismic data. These include faults, which are often only discernible in uniformly deposited clays. This is due to the contrast between the chaotic zone of fault disruption and the regular layering of the clay succession. Hence, faults are not necessarily visible in chaotically deposited sediments because of lack of contrast in seismic facies across the fault zone. Conversely, if sediments are deformed in situ after deposition, for example by sub-glacial, metamorphic or compaction processes, then it is quite reasonable to expect a uniformly deposited clay succession to be recorded in seismic data by chaotic seismic facies.

Palaeo-geomorphology: The upper part of the Nordland Group succession records the former presence of ice sheets in the southern North Sea area. These eroded channels to depths of up to 400m into the underlying, pre-glacial part of the succession. These depressions have all subsequently been filled in by younger sediments. Whilst the exact reasons for the presence of these channels are still a matter for debate, their morphology reveals much about the sediments that they are cut into, contrary to the opinions of Wingfield (1990). Hard, erosion-resistant horizons, such as clay layers, tend to cause terrace formation at the channel margins. These are indicated in seismic profiles by the flattening out of channel profiles at these clay horizons. Conversely, the sandy parts of the succession, which are loose and unconsolidated, tend to be easily eroded, and are indicated on seismic profiles by a steepening of the channel margins.

Lithologic Velocity Contrasts: These can be quite difficult to assess, due to the known variations in induration and compaction with depth of identical lithologies within the Nordland Group. However, a negative polarity event, indicating a downward decrease in velocity, is probably the result of the reflection of acoustic energy from the upper surface of either a peat layer or an under-compacted, more water-rich or gas-rich layer. The latter situation is often due to the presence of an upward permeability barrier, for example a transgressive clay overlying a porous sand.

A normal polarity event, indicating a sharp, downward increase in velocity, could possibly represent the reflection from an unconformity surface where some erosion and removal of sediment has occurred before resumption of sedimentation. Alternatively, it could be due to reflection from the interface of an overlying, under-compacted unit with an underlying, normally compacted unit, for example the downward transition from porous, over-pressured sand to clay. However, seismic response to velocity changes should generally be treated with caution, due to reflector interference.

Noise: A common problem in seismic data is the distinction of noise from real, geological information. The commonest example, the water bottom multiple, can usually be distinguished easily in seismic sections. However, on equalised sections in zones of low primary reflectivity, such as low energy clay intervals, random noise can become dominant in the section, giving these intervals an overly “chaotic” appearance. This is especially common in both the Lower Tertiary part of the section and in the deeper parts of the Nordland group succession, where poor signal to noise ratio is to be expected in any case, due to depth from the surface.

“Braided” Seismic Events: This term is occasionally used within this chapter to describe events which can be followed for some distance laterally, but which show continuously changing character along their length. It is likely that these events are due to the presence of rapid lateral changes of lithology, largely beyond the resolution of the seismic data, within a regionally significant lithologic unit.

Nomenclature of Successions

Due to the lack of any good correlation between the stratigraphy of each of the various site survey data-sets, each survey area is discussed separately in order to avoid unnecessary comparison being made. However, for simplicity, each site survey interpretation is stratigraphically divided into three sections; the “pre-Nordland Group” succession (T), the “pre-glacial Nordland Group” succession (P) and the “glacial Nordland Group” succession (G), as the two unconformities separating these three sub-divisions, the “mid-Tertiary” unconformity and the channelled, Elsterian unconformity, are generally assumed to be correlateable over most of the Southern North Sea area. Whereas the pre-glacial and glacial Nordland Group successions is described in detail for each survey area, the pre-Nordland group succession is only described in generally terms here.

Each sub-division has been broken down and described in terms of numbered intervals, each interval being arbitrarily chosen for ease of description. Where possible, tentative litho-stratigraphic names have been assigned to these intervals. For the pre-Nordland Group succession, these are simply stratigraphic Group names, based upon the Dutch, offshore nomenclature of *NAM & RGD* (1980). In the case of the Nordland Group successions, both pre-glacial and glacial, an attempt has been made to assign formation names to the intervals by correlation with the southern North Sea, offshore stratigraphic scheme of *Cameron et al.* (1986) and Joon

et al. (1990). Where no formation name is applicable, for example in the older parts of the pre-glacial Nordland Group succession, none has been assigned. No correlation is implied between intervals of similar name described in separate survey areas.

The "Seismic Outer Line Box": For the five complete surveys provided for this study, the display of the seismic data has been achieved by horizontally compressing the outer seismic lines, and displaying them together where they intersect in such a way that they form a complete seismic loop. This allows the majority of stratigraphic features to be shown within one diagram for each survey data-set. Where additional features of interest are present within the survey area, these are presented as separate diagrams.

4.2: Survey 49/15A

This survey is located in the SW corner of the study area (see fig. 4.1). Its interpretation is based upon a complete, 4km² survey, made up of 22 lines, provided as both true and relative amplitude plots.

4.2.1: The pre-Nordland Group Succession

This succession has been divided into three intervals for discussion here.

Interval 49/15-T1 (Chalk Group)

Top of Interval: 720 to 940ms TWT, largely dipping to the SW, away from a NW-SE trending, salt induced high in the NE of the area. Relief generated by Tertiary salt movement.

This interval is characterized by low frequency, low to moderate amplitude and good continuity events. Where disturbed by salt movement, continuity becomes very poor. The top of this interval is everywhere defined by a high amplitude, normal polarity event. Interval "T1" is locally faulted around a major salt uplift structure.

Interval 49/15-T2 (Lower North Sea Group)

Top of interval: between 460 and 550ms TWT, dipping to the SW. Relief due to Tertiary salt movement.

This is a very low amplitude, very poor continuity interval with rare fault displacements, all of less than 20m. The top of interval "T2" is defined by a positive polarity, high amplitude event. Two continuous events are traceable within the interval; a negative polarity, moderate to high amplitude event, about 50ms above the base of the interval, and a positive polarity, moderate, locally high, amplitude event about 40ms below, and concordant with the top of the interval. The latter event probably represents an unconformity surface as, locally, there are small, weak diffraction tails beneath it. Events below this also have a slightly chaotic appearance. This is in contrast to those events at the top of the interval, which have higher continuity. However, the majority of the stratification within the interval is obscured by multiple energy. Traces of events can be distinguished occasionally, and

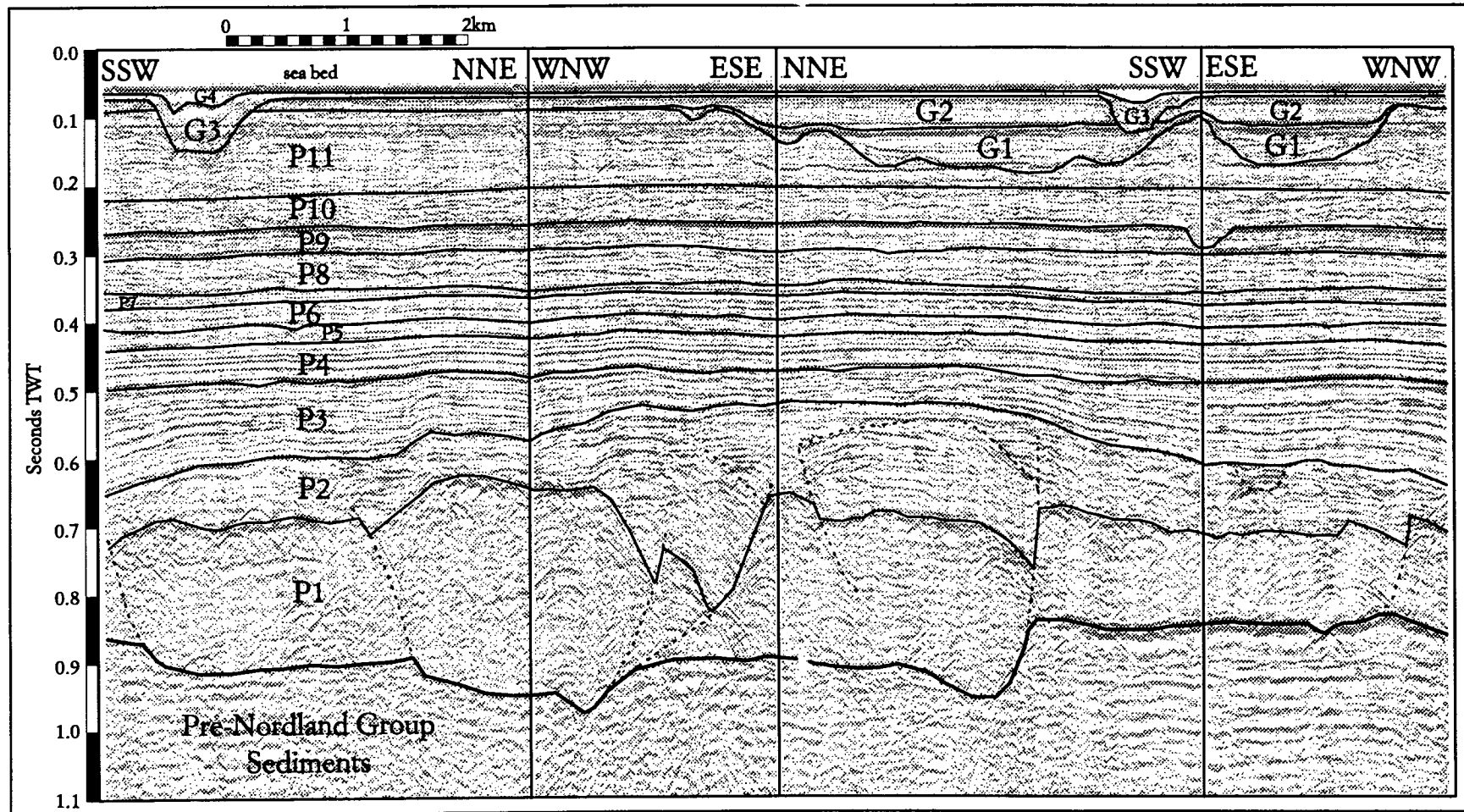
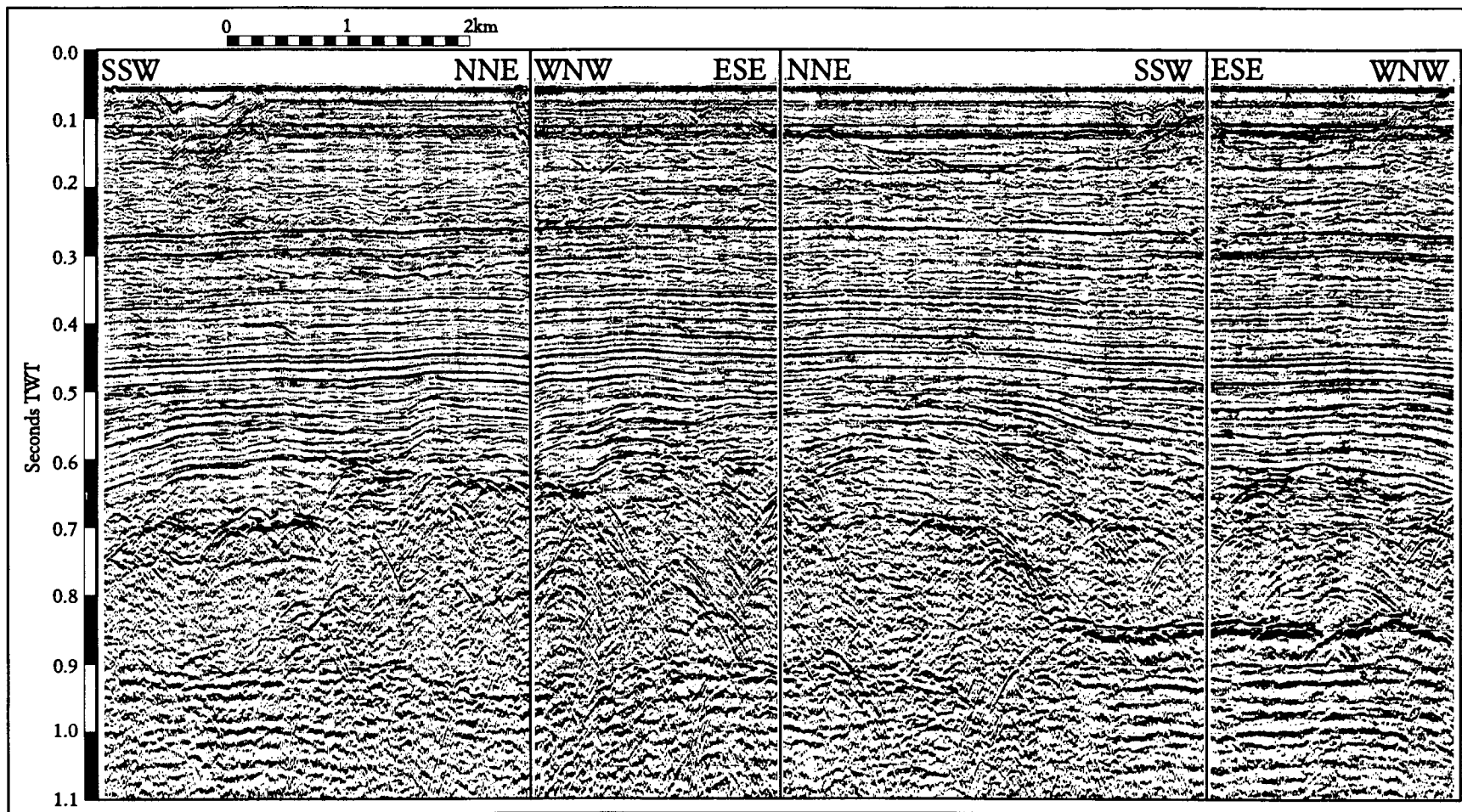


Fig. 4.5: "Seismic outer line box" (interpreted and uninterpreted) of survey G16-FA down to 1100ms TWT, showing the intervals from the Nordland Group succession described in the text, as well as the structure related to a mass flow near the base of the Nordland Group succession (data courtesy of SIPM).



4.3: Survey G16-FA

This is perhaps the most interesting survey out of the seven studied. It is located in the NE corner of the study area (see fig. 4.1), within an area of mass flow disturbance (mass flow “II” of chapter 2), providing a rare opportunity to study the architecture of this feature (see fig. 4.5). The survey has been studied in detail, as it may give an insight into the mechanisms behind mass flow generation.

4.3.1: The pre-Nordland Group Succession

This succession is here divided into two intervals.

Interval G16-T1 (Chalk Group)

Top of Interval: 1420 to 1470ms TWT, slightly domed and faulted.

Only the upper 100ms of this interval has been recorded on the profiles of this dataset. Here, the interval consists of high amplitude events of low frequency and with either normal or reverse polarity. The top surface of the interval is domed in three places within the study area, apparently dipping away toward the edges of the survey area (see fig. 4.6a). Faults with throws of up to 40ms cut this surface, exhibiting widely varying trends and, at the resolution of the data, no faults are seen to continue across the area.

Interval G16-T2 (Lower to base Upper North Sea Group)

Top of Interval: 830 to 950ms TWT. Relief on this surface caused by erosion associated with emplacement of a mass-flow unit at the base of the Nordland Group.

This interval is only weakly reflective and internal events are rarely traceable. However, where present, they are generally concordant with the top of interval “T1” below, indicating a continuation of structural styles. Interval “T2” seems to be characterized by zones of vertical disruption above the faults of the interval below.

A moderate to high amplitude event is present at around 920ms TWT, about 80ms below the base Nordland Group reflector. This event is slightly faulted but essentially sub-horizontal. The basal decollement of a Nordland Group mass flow unit often soles out just above this event.

channel, probably due to compaction, and the interval may be predominantly made up of clay.

Interval 49/15-G2 (? intra Swarte Bank Formation)

Top of interval: between 150 and 210ms TWT.

This interval is characterized by low amplitude, low continuity events that are concordant with the top of interval "G1". The top of this interval is defined by a negative polarity, low to moderate amplitude event, which is locally mounded. When mapped out, these mounds form a series of ridges no more than 5m in height and up to 400m in length which, although slightly sinuous, run W-E, perpendicular to the axis of the channel (see fig. 4.4b). These ridges may be push-moraines, related to the presence of ice, or may be related to axial water flow within the channel system.

Interval 49/15-G3 (?top Swarte Bank & younger formations)

Top of interval: sea bed

Interval "G3" is of low amplitude, moderate continuity events, although high amplitude, continuous events occur near the top. Near the base of the interval there is a weak but continuous reflector. Both this event and the base of the interval define passive onlap surfaces. All subsequent events are parallel bedded.

The presence of terraces on the glacial erosion surface at the top of interval "P1" and at around 350ms TWT, suggests the presence of erosion resistant clay layers at these levels. Otherwise, interval "P1" may be of sandy clay.

Interval 49/15-P2 (?Winterton Shoal Formation)

Top of interval: unseen due to glacial erosion. Minimum two way time around 240ms TWT.

This interval has a highly variable seismic facies, showing low to high amplitudes and low to moderate continuity, but its internal reflectors are sub-parallel. Diffraction energy is commonly seen at the base of the interval, suggesting the presence of an erosion surface. This interval is probably more sandy than interval "P1".

4.2.3 The Nordland Group Succession (glacial)

A glacial channel system is eroded into the underlying succession of survey area 49/15A from 240 down to 430ms TWT, and trends N-S (see fig. 4.4a). Although neither channel margin is seen within the survey area, this channel may be over 2km wide. Below the bottom of the channel in the south of the area there is development of local faulting at between 45° and 90° to the channel axis. These faults may have been formed while ice occupied the channel system, causing disruption of the underlying sediments. The succession within the channel system is subdivided into three intervals.

Interval 49/15-G1 (base Swarte Bank Formation)

Top of Interval: between 180 and 230ms TWT. Relief possibly due to compaction.

This interval is generally made up of very low amplitude and poor continuity events, and shows a chaotic texture. Depositional patterns for this interval are unknown. The top of the interval, which is an unconformity surface, is marked by a very high amplitude, normal polarity event throughout the area. One high amplitude event can be traced locally, up to 25ms below the top of the interval along the channel axis. However, this event, which is deepest along the channel axis and plunges to the north, is truncated by the upper surface of the interval toward the channel margins and in the south. The top of the interval partially mimics the relief of the base of the

these are generally concordant with the base of the interval.

Interval 49/15-T3 (?Lower to Middle North Sea Group)

Top of Interval: between 400 and 440ms TWT, except where removed by glacial channel. Dips gently to the SW. Relief probably due to Tertiary salt movement.

The relationship of this interval with interval "T2" below is unclear, and there may be no unconformity separating the two. Events seen within interval "T3" are largely multiple energy and primary events within the interval are generally of low amplitude and poor continuity (see fig. 4.2). These are concordant with the base of the interval.

4.2.2 The Nordland Group Succession (pre-glacial)

The basal unconformity of this succession, which shows an angular relationship with the underlying succession here, is marked by a complex, continuous, largely unbroken, very high amplitude, negative polarity event. The pre-glacial Nordland Group succession shows no obvious depositional breaks, but is divided into two separate intervals here for simplicity (see fig. 4.2).

Interval 49/15-P1 (?top IJmuiden Ground Formation)

Top of Interval: between 280 and 310ms TWT except where removed by glacial channel.

At its base, this interval is characterized by moderate to high amplitude, continuous and parallel events, concordant with the basal unconformity surface. These events decrease in amplitude and continuity upward, although remaining parallel. A 300 by 100m ridge, perhaps less than 5m thick, can be seen near the middle of the interval, due to the weakness of events here (see fig. 4.3a). This feature is elongated W-E and occurs in the south of the area. Its origin is unknown.

A series of W-E trending, vertical discontinuities is present throughout the lower half of the interval, extending down through the basal unconformity surface. These have the appearance of either small scale faulting or very gentle folding (see fig. 4.3b). These are unlikely to be velocity effects associated with the overlying glacial succession, due to the difference in orientation. However, they may be due to glacio-tectonic effects associated with later ice movement.

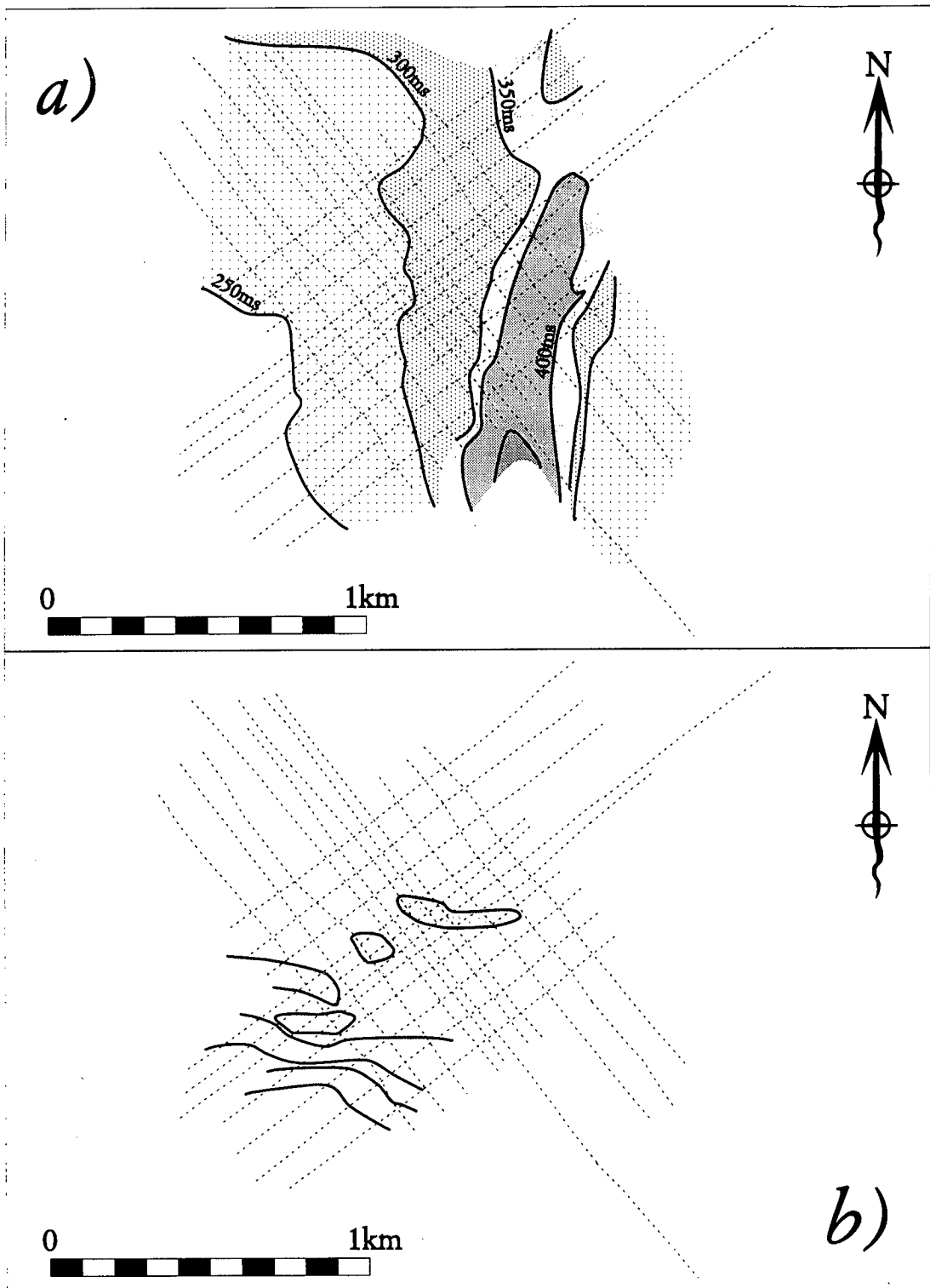


Fig. 4.4: Maps from survey 49/15A: a) TWT contours of the base of the glacial channel system; b): W-E trending ridges, possibly moraines, on the upper surface of interval "49/15-G2".

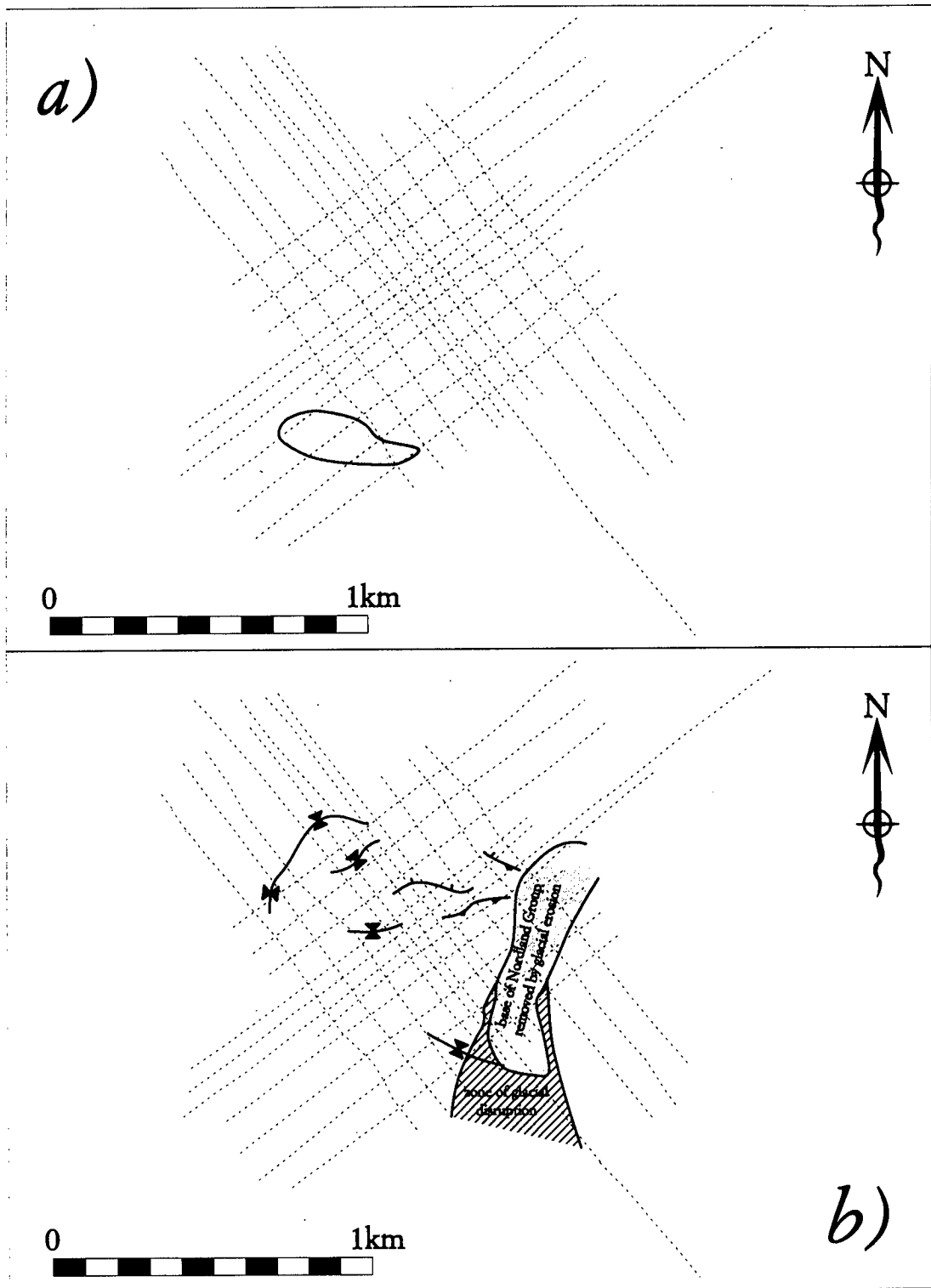


Fig. 4.3: Maps from survey 49/15A: a) a W-E trending ridge within the basal part of interval "49/15-P1"; b) folding and faulting within the basal part of interval "49/15-P1". This may, in part, be glacio-tectonic.

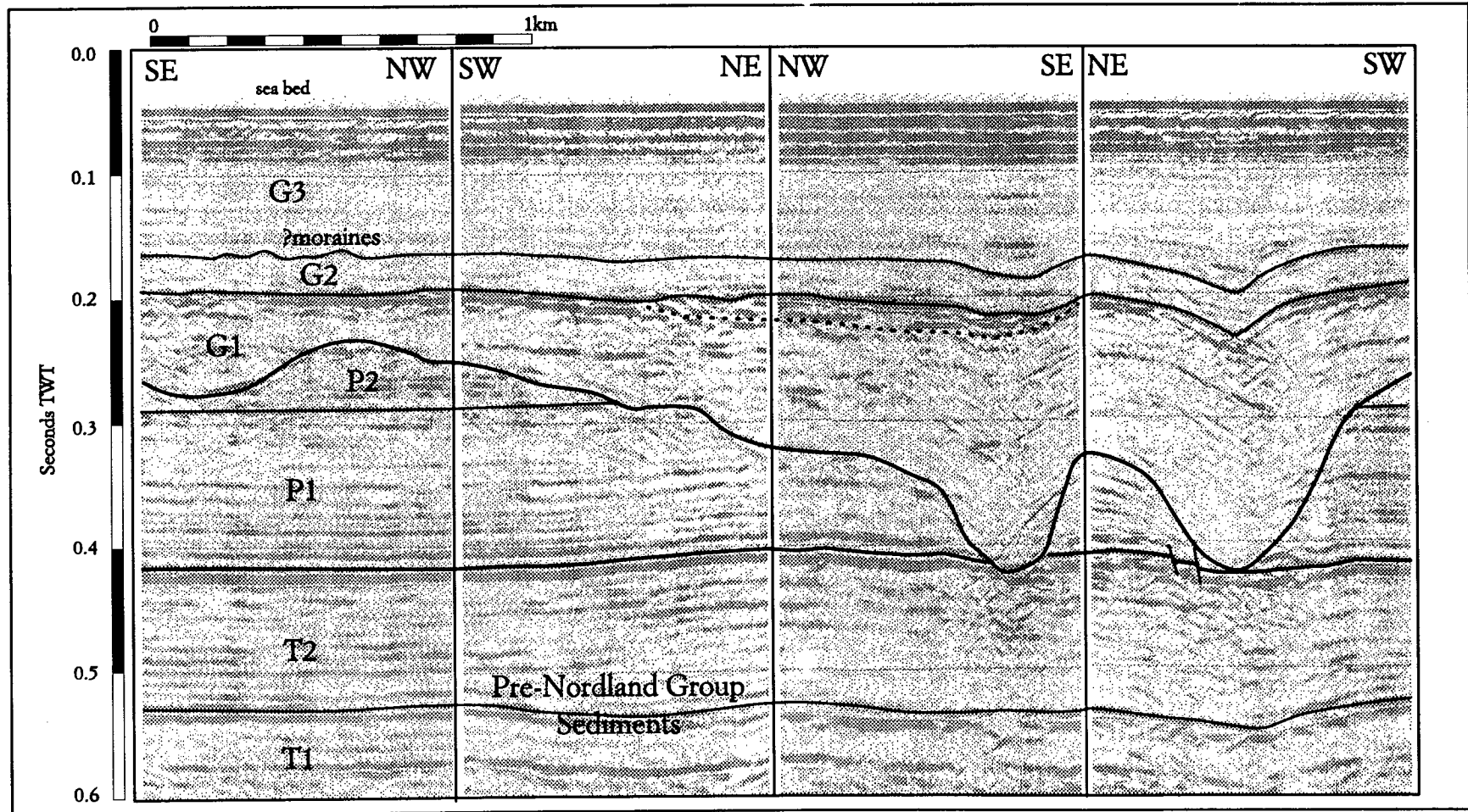
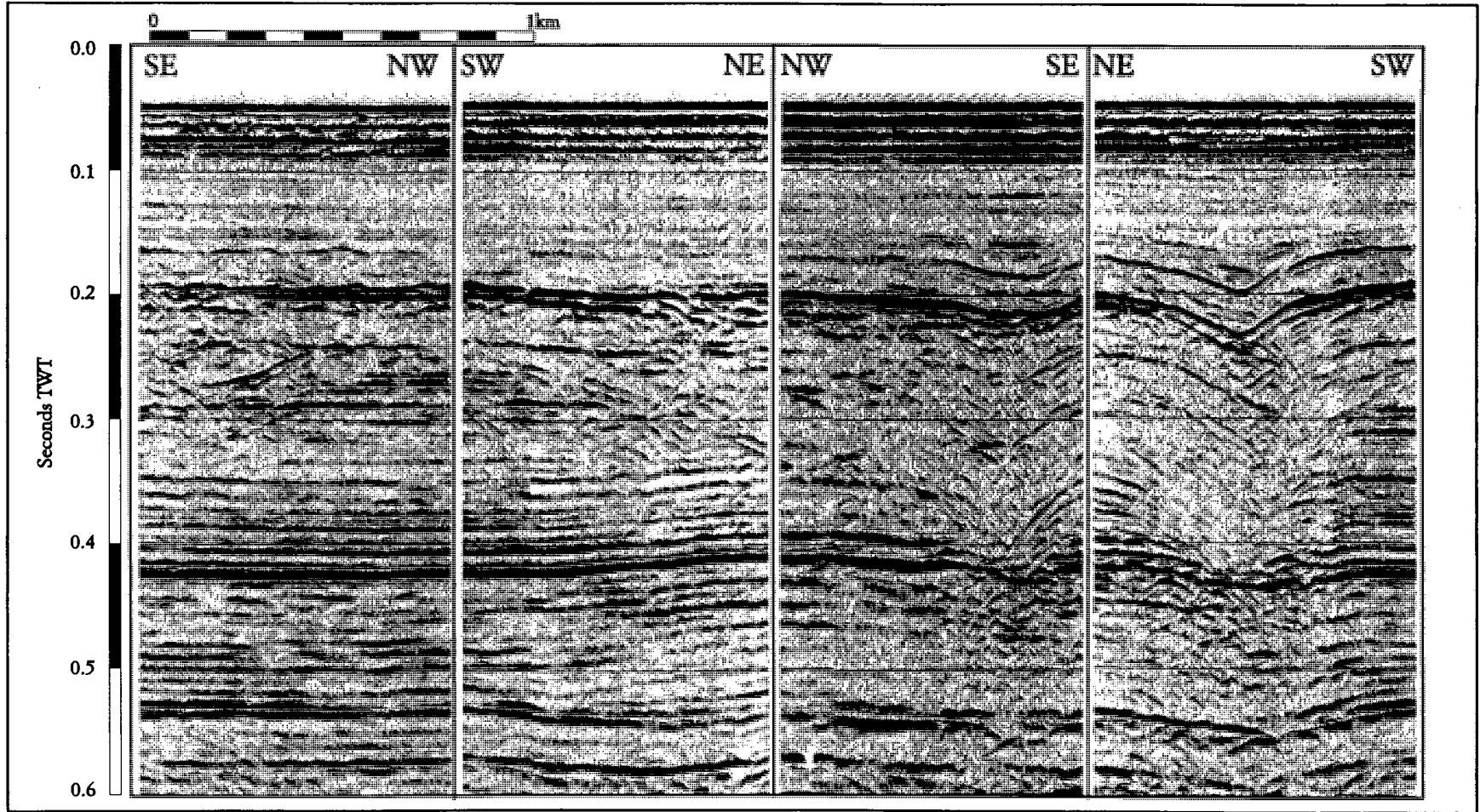


Fig. 4.2: "Seismic outer line box" (interpreted and uninterpreted) of survey 49/15A down to 600ms TWT, showing the intervals described in the text (data courtesy of SEPL).



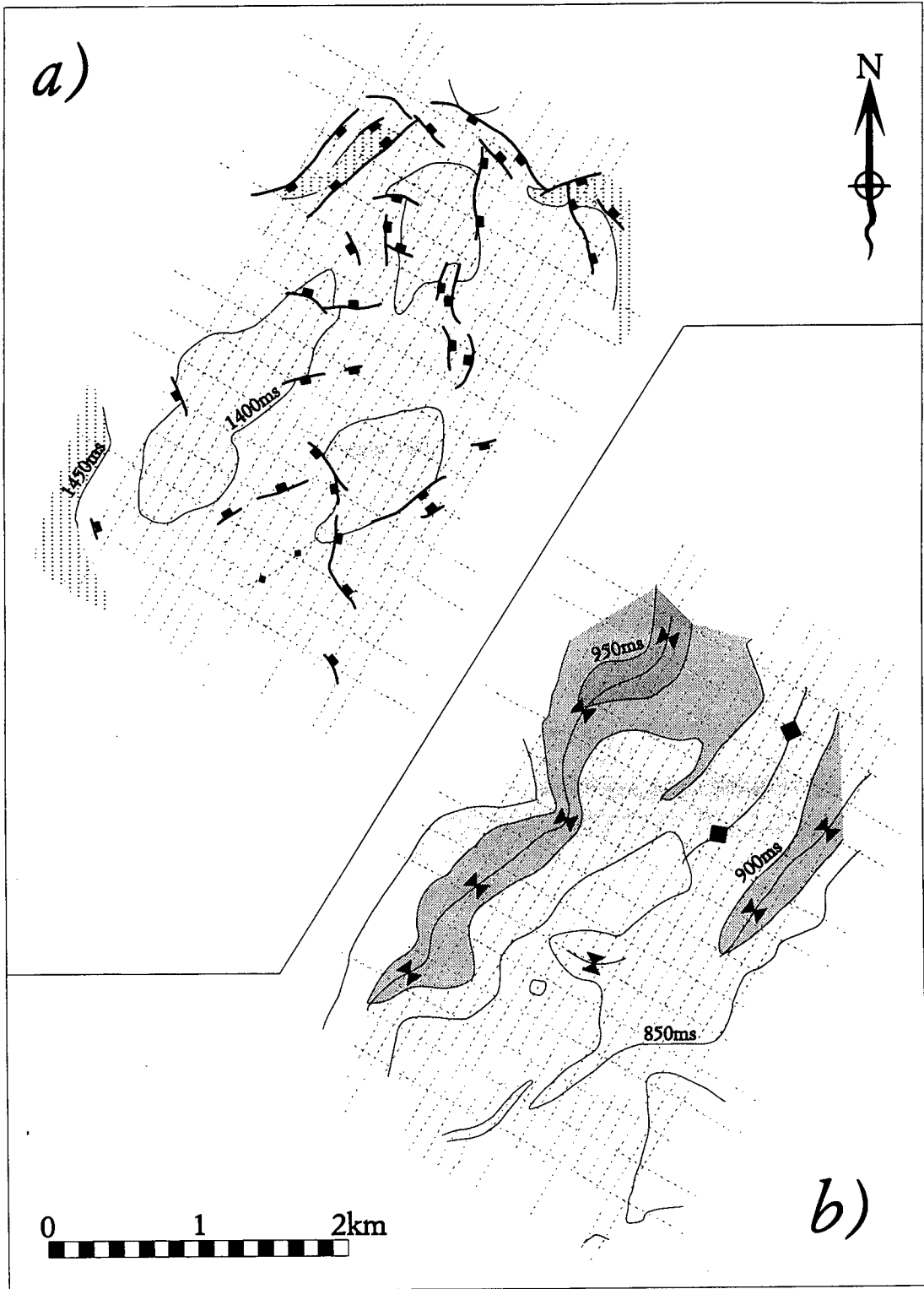


Fig. 4.6: Maps from survey G16-FA: a) TWT contours of the upper surface of interval "G16-T1", the top of the Chalk Group; b) TWT contours of the erosion or decollement surface at the base of the mass flow, showing similarities with the structure of the top of the Chalk Group below.

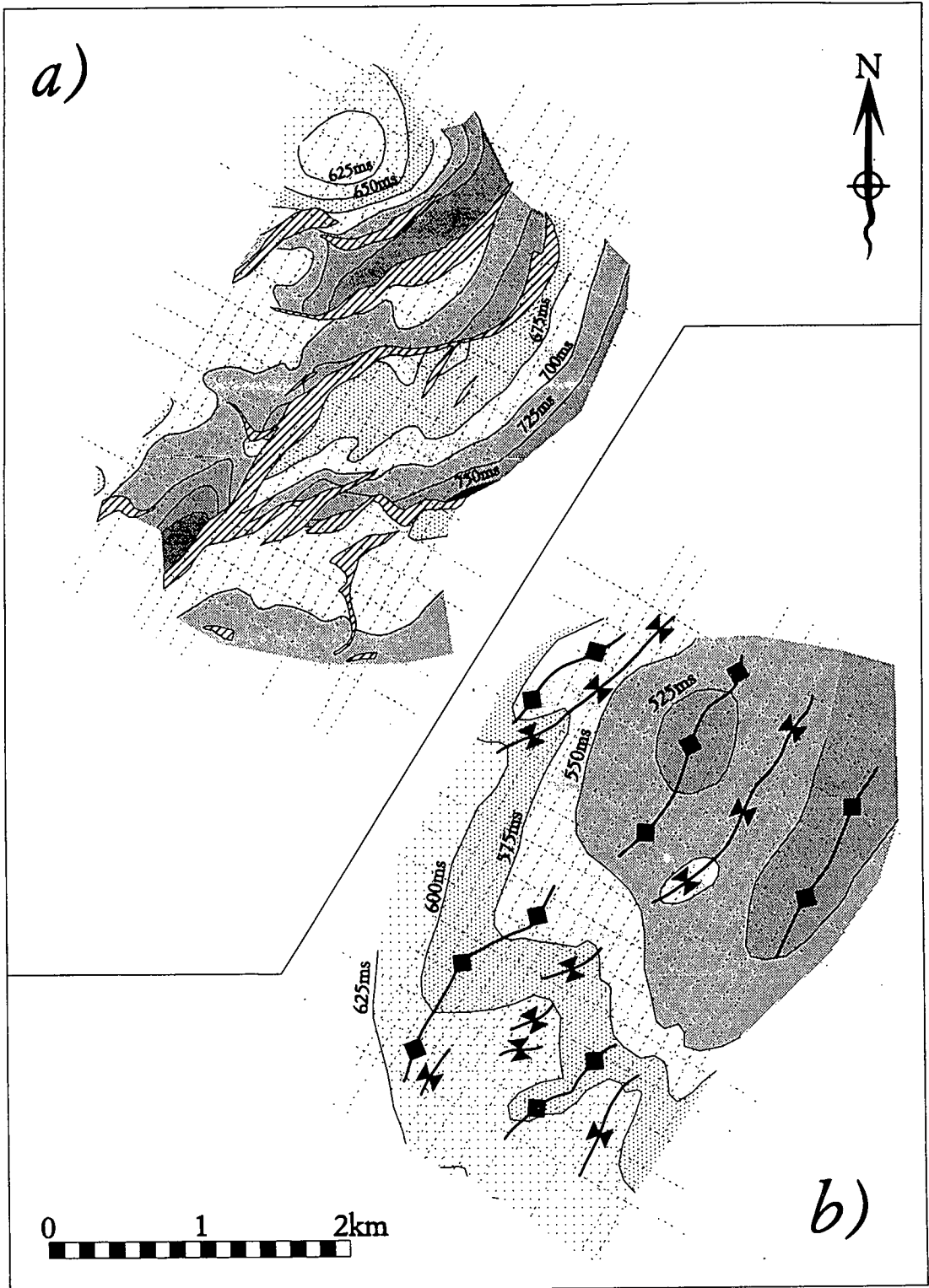


Fig. 4.7: Maps from survey G16-FA: a) TWT contours of the upper surface of interval "G16-P1", revealing the faulted nature of the surface and the structure present within the mass flow blocks which disrupt the surface; b) TWT contours of the base of interval "G16-P3", showing the development NNE-SSW trending fold axes on the WSW dipping surface.

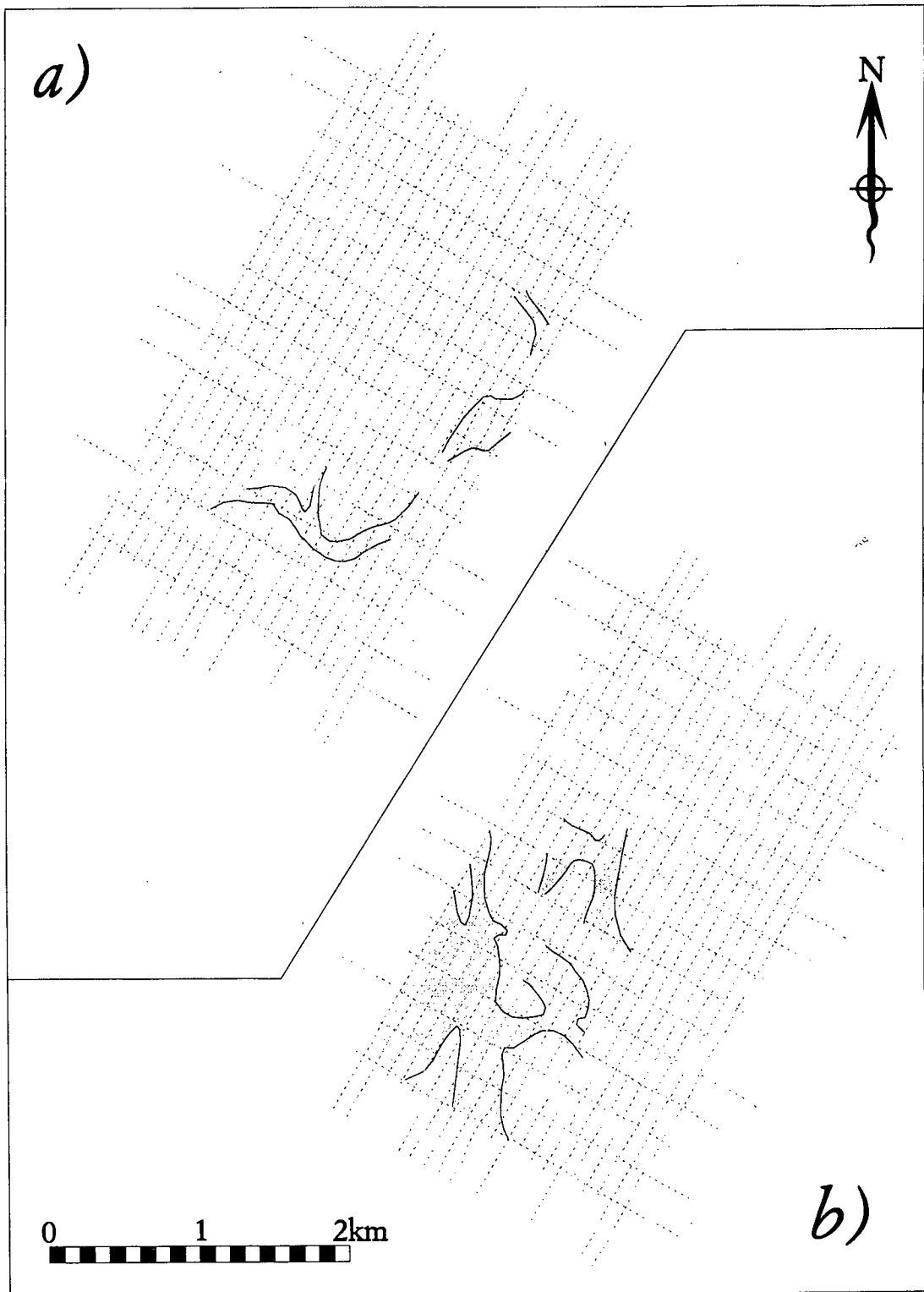


Fig. 4.8: Maps from survey G16-FA: a) a possible meandering channel within interval “G16-P4”, picked out by the local absence of a strong event at around 455ms; b) possible channels and ridges at the base of interval “G16-P5”, picked out by the local absence of a strong event.

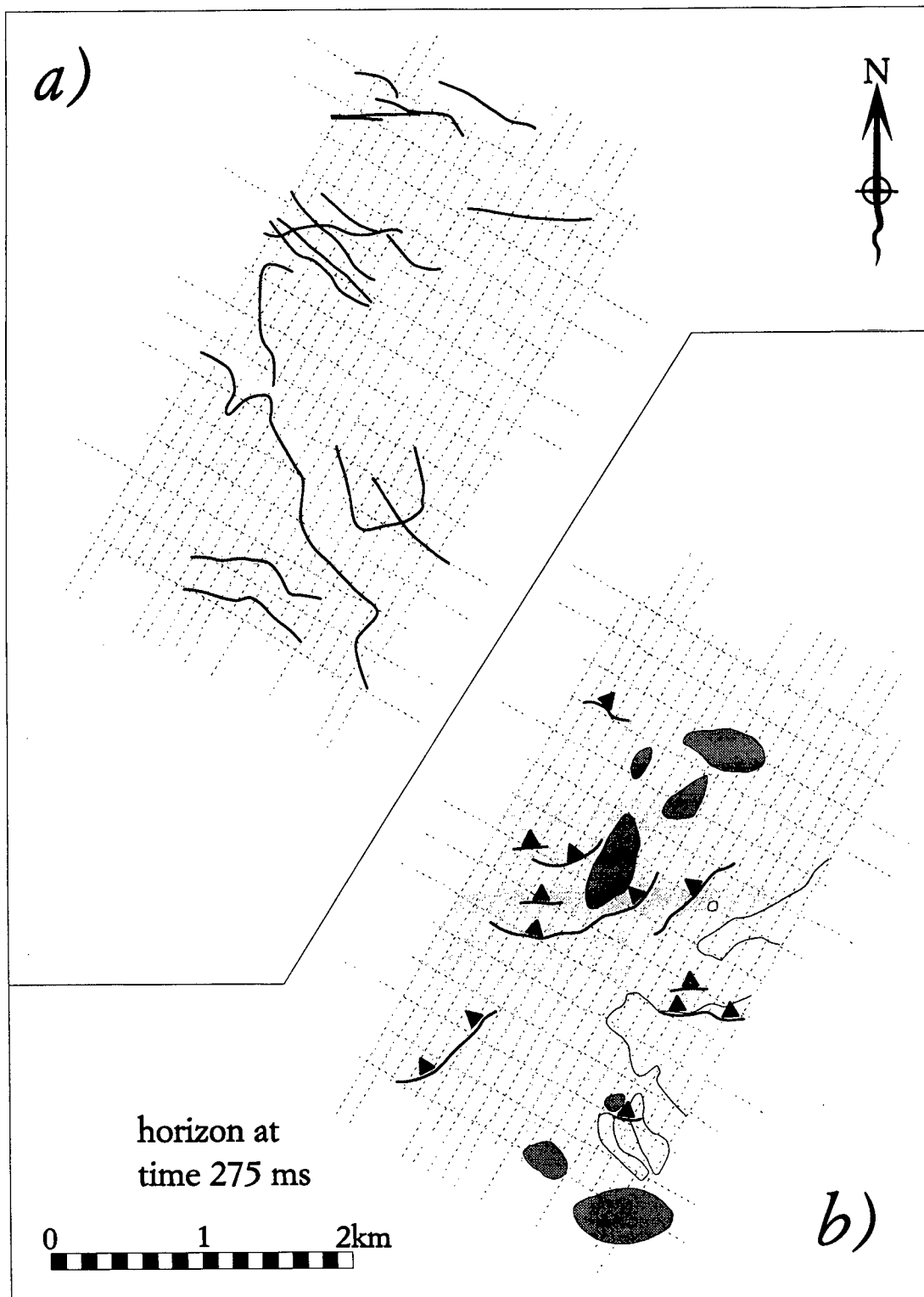


Fig. 4.9: Maps from survey G16-FA: *a)* trends within interval "G16-P8". The shaded area, which indicates preservation of most of interval "G16-P7" below, shows the NW-SE trending, basal channel axis of the interval. Other lines indicate the trends of other channels within the interval; *b)* features on the base of interval "G16-P10". Dark areas are eroded hollows, which may be fluviially reworked, peri-glacial features. Light areas record the presence of preserved terraces below a deep valley system. Lines with dip arrows indicate the dip direction of surfaces within the base of the valley fill.



Fig. 4.10: Maps from survey G16-FA: a) horizon within the valley fill of interval "G16-P10". Shaded areas show the extensive absence of an event at this level, possibly indicating areas extensively reworked by channelling. Black, branching forms indicate local absence of the event, and may be "crevasse splay-like" features; b) rare trends, traced within interval "G16-P11" of survey G16-FA. These may be both fluvial and marine features.

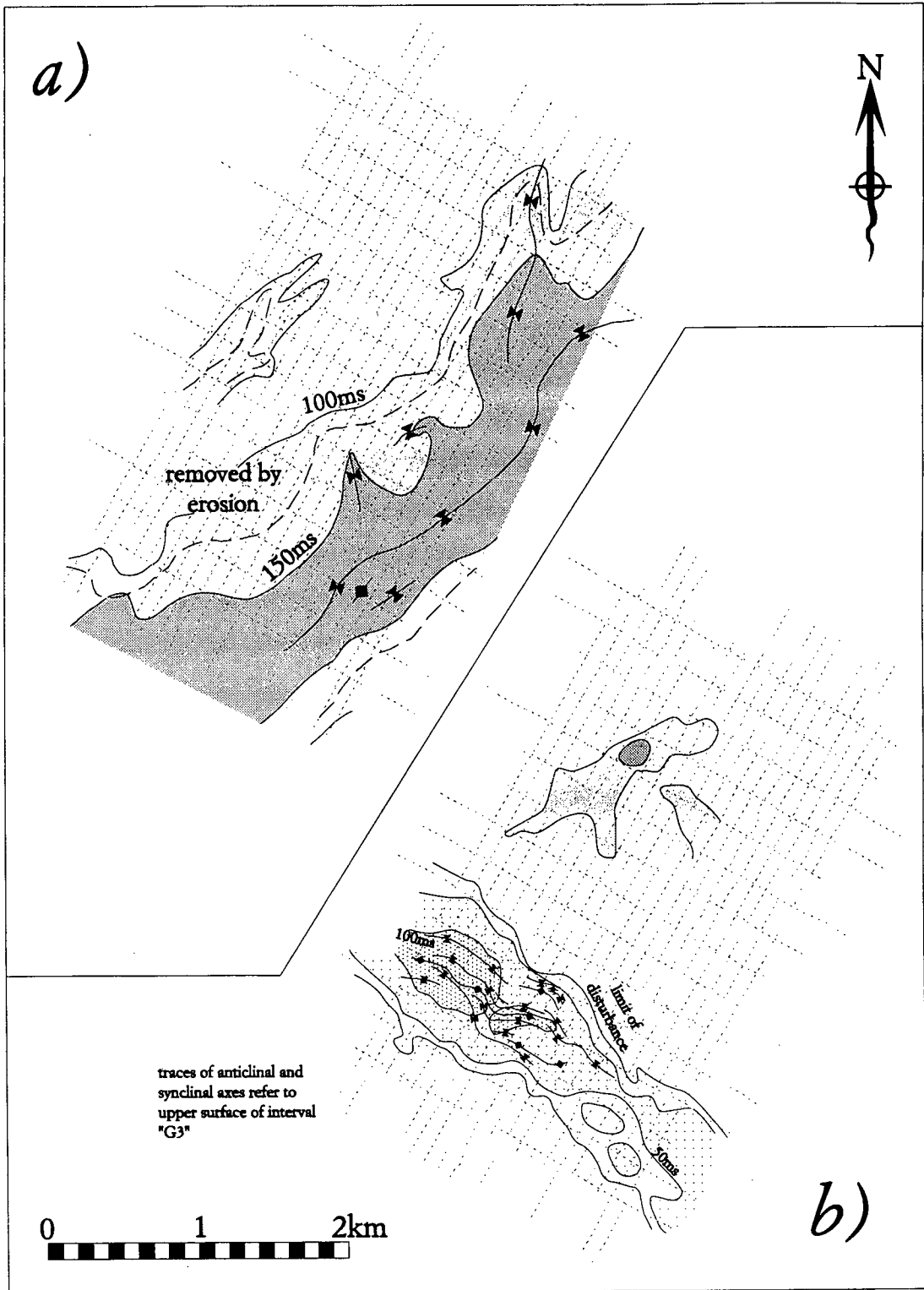


Fig. 4.11: Maps from survey G16-FA: a) TWT contours of the base of the lower glacial channel system. Dotted line indicates the extent of the event at the top of glacial infill interval "G16-G1"; b) the southern part of this map shows TWT contours of the base of the upper glacial channel system, also showing the axes of synclinal and anticlinal ridges at the top of interval "G16-G3". The feature to the north is a channel-like depression centred around a gas escape chimney (darker shading).

4.3.2 The Nordland Group Succession (pre-glacial)

The pre-glacial Nordland Group succession has been divided into 11 separate intervals for the purposes of discussion here (see fig. 4.5). The basal unconformity of this succession is locally defined by a sub-horizontal, high amplitude, negative polarity event between 840 and 850ms TWT. This reflector has relief of around 15 to 20ms and associated diffraction tails are common, suggesting that it is faulted at the scale of tens of metres. However, this event has been removed by mass flow erosion in the north of the area, only surviving in the extreme south.

The mass flow itself shows maximum deformation in the NW of the area. It seems to consist of several listric fault blocks showing predominant down-throw to the NW. This faulting has caused rotation and re-orientation of beds, so that they now dip to the SE. Roll-over anticlines may also be present. Both intervals "P1" and "P2" have been faulted and heavily disrupted, although much of the disruption within interval "P1" may be due to an older mass flow (mass flow "I" of chapter 2), which is better developed to the NE of survey "G16-FA".

The basal decollement surface of the mass flow extends down to 120ms below the normal, high amplitude, base Nordland Group event, and hence cuts into Oligocene, Miocene and possibly older sediments below (see fig. 4.6b). Oddly, this basal surface is not smooth, and it is difficult to visualize its operation as a decollement plane unless some fluidization and diapirism of the underlying, Lower Tertiary clays occurred as a mechanism of sediment removal from beneath the fault blocks.

Interval G16-P1

Top of Interval: 680 to ?850ms TWT. Highly variable relief due to intense, mass flow related faulting.

Interval "P1" is of low to moderate amplitude and of very poor continuity. No primary events can be traced internally and only diffraction tails can be seen. The upper surface of the interval is often defined by a high amplitude, negative polarity event, which is also highly diffractive (see fig. 4.7a). The presence of this high amplitude event at places where the base Nordland Group event has been eroded out suggests that these two surfaces are perhaps major permeability barriers to the upward escape of water or, more likely, gas. Interval "P1" may be predominantly made up of clay.

Interval G16-P2

Top of Interval: 530 to 650ms TWT, sloping to the WSW. Relief due to both mass flow movement and depositional processes within the interval.

This interval is generally of low to moderate amplitude and poor continuity, although events can be discerned internally. It is extensively deformed by the development of fault blocks related to mass flow movement. The movement of these blocks has generated extensional depressions between the crests of the tilted fault blocks. Despite the faulting present within, the upper surface of the interval is smoothed, due both to onlapping sediment infill in the extensional depressions between fault blocks and to subsequent erosion where sediments were uplifted by fault block rotation. This summary is probably an over-simplification. However, there is no obvious evidence of multiple phases of movement between the fault blocks. This interval is interpreted to consist predominantly of clay, possibly including some sand in the depressions near the top.

Interval G16-P3

Top of Interval: 470 to 500ms TWT, sloping gently to the WSW.

This interval is of low to moderate amplitude, internal events showing fair continuity. The base of the interval shows landward onlap onto interval "P2" below, and there is little evidence of upward fault propagation from below. Other surfaces of landward onlap are almost undoubtedly present within the remainder of this interval. The upper surface of the interval shows truncation of events along a clear unconformity surface.

Although events generally dip to the SW, a series of NE-SW trending anticlines and synclines are superposed upon this at wavelengths of between 400 and 750m (see fig. 4.7b). This folding has strong similarities with the structure on the basal decollement surface of the mass flow below, although exact relationships are obscure. This perhaps implies continuation of fault movement. The interval may be made up of silty or sandy clay.

Interval G16-P4

Top of Interval: 415 to 435ms TWT, sloping gently to the WSW.

This interval, apart from its base, which is probably channelled, includes low to moderate amplitude, good continuity events. The fold ridges present within interval "P3" below are only very weakly developed above the unconformity surface at the base of interval "P4". Three continuous, moderate amplitude events are present within the interval, the highest defining its upper surface. Just below each of these, events are slightly more chaotic in appearance, showing "braided" patterns. The three events may define flooding surfaces, clays above separating sands or silts below. The channels at the base of the interval are rather poorly defined, but may be up to 15m deep. Additionally, a vague NE-SW trend can be mapped, possibly related to channelling at the base of the middle sand. Near the top of the interval, where rare diffraction tails and occasional reflector breakdown occur, a possible meandering channel axis can be mapped (see fig. 4.8a).

Interval G16-P5 (top Brielle Ground Formation)

Top of Interval: 390 to 410ms TWT.

Events within this interval are of poor continuity and weak to moderate amplitude. Where events are seen, they are of "braided" character, dipping, and of high relief, possibly indicating channel or ridge deposits. Variations in amplitude at the base of the interval seem to indicate N-S trending features, which could be sand waves. There is also possible evidence of a channel like feature cutting one of these (see fig. 4.8b). The top of the interval is sometimes defined by a moderate or high amplitude event. Interval "P5" is interpreted to be composed predominantly of sand.

Interval G16-P6 (Westkapelle Ground & ?base IJmuiden Ground Formations)

Top of Interval: 360 to 380ms TWT.

This interval is of moderate continuity and moderate amplitude. Events are generally of low relief, although some apparently "braided" patterns are present. Interval "P6" includes possibly both sand and clay. Sand waves may well be present at the base of the interval, making it difficult to define its basal surface in some places.

Interval G16-P7 (intra IJmuiden Ground Formation)

Top of Interval: 345 to 360ms TWT, defined by erosion surface.

This interval, although perhaps only 15m thick, is best described separately. It is a moderate amplitude interval of good continuity, and its events are of markedly higher frequency than those above and below. This interval may represent clay containing laterally continuous layers of sand or silt.

Interval G16-P8 (top IJmuiden Ground & Winterton Shoal Formations)

Top of Interval: 285 to 305ms TWT, defined by erosion surface.

This interval includes low, medium and high amplitude, discontinuous, dipping events of high relief. Some diffraction tails are present near its base, which is highly erosive in the east, possibly cutting down 20m. When mapped out, the basal erosion surface describes channelling running NNW-SSE (see fig. 4.9a). This has the curious effect of making the base of the interval flatter, relative to the sea bed, than its top. Near the top of the interval a 20m deep channel complex can be traced running NW-SE to W-E (see fig. 4.9a). The whole interval is probably largely made up of fluvial sands.

Interval G16-P9 (Markham's Hole Formation)

Top of Interval: 255 to 270ms TWT, except where removed by erosion.

This interval, which is largely defined at both the base and top by high to very high amplitude, normal polarity, continuous events, is internally of low to moderate amplitude and low continuity. Where events are seen, they are generally dipping, with apparently random dip directions. The basal high amplitude event has been partially removed by erosion along a N-S line in the eastern corner of the area. The very high amplitude event at the top of the interval can be clearly seen on regional seismic data. This interval is interpreted as being made up of sand or sandy clay, whilst the top and base may be of clay.

Interval G16-P10 (base Yarmouth Roads Formation)

Top of Interval: 205 to 215ms TWT.

Interval "P10", which is of both highly variable amplitude and continuity, is perhaps the most complex seen, and has not been fully resolved by mapping. Mapping suggests that much of this interval is actually part of the valley fill complex, which may have been more than 40m deep. This valley complex may trend NE-SW to NNW-SSE, although this has been difficult to map. Where preserved, the sediments eroded out to form the valleys are acoustically transparent, and are probably largely of clay. The base of the valley complex is locally marked by many diffraction tails, indicating a rough surface.

Two major, eroded hollows are present at the base of the valley complex, cutting down through most of interval "P9" and reaching a depth of up to 30m (see fig. 4.9b). However, these are not channels, as they are oval in plan, being up to 300 by 500m in diameter. The best possible analogue for these features seems to be fluviually reworked, peri-glacial pingo remnants, as seen in the Eocene London Clay of SE England (Hutchinson, 1980).

A series of dipping surfaces up to 15m high overlies, and is the uppermost infill of these hollows (see fig. 4.9b). These generally dip to the N and NW at angles of up to 5°, and they may be formed as a result of river migration within individual valleys. Alternatively, they may be part of a lacustrine delta system.

Whilst the majority of reflectors are almost chaotic in appearance near the base of interval "P10", suggesting sandy deposition, the upper part of the interval includes many flat events of fair continuity. The lack of good continuity is probably due to channel erosion and this part of the interval may be part of a flood-plain environment (see fig. 4.10a). This interval is perhaps composed of silt or clay, with local, sand filled channels, and may include discontinuous peat layers.

Interval G16-P11 (top Yarmouth Roads & ?base Swarte Bank Formation)

Top of Interval: 80 to 180ms TWT, defined by the depth of glacial erosion.

This interval is generally of low to moderate amplitude, very poor continuity events. Just below the first water bottom multiple it is difficult to distinguish primary from multiple energy. Events which have been traced, which are few, suggest NW-SE and, rarely, NE-SW trending features within the sediments (see fig. 4.10b), although what these features are is unknown. It is possible that the trends represent

the line of both channels and sand waves. Channel forms are certainly seen on individual seismic lines. Rare, sub-horizontal events have been observed locally at around 100 and 130ms TWT. Interval "P11" is likely to be dominated by sand, with only very local clay or silt horizons.

Immediately below the first water bottom multiple, many high amplitude diffraction tails can be seen. This might be due to the presence of a horizontal erosion surface at the level of the first water bottom multiple. However, the diffraction instead may simply be an artefact of the data, due to the presence of the multiple enhancing and overemphasizing real events.

4.3.3 The Nordland Group Succession (glacial)

The glacial succession of this area fills two channel systems. The lower system, which follows a NW-SE trend, has its shoulder at 85ms TWT, and erodes down to about 175ms TWT (see fig. 4.11a). This system also has tributary axes, running N-S, at its margins. The upper channel system has a WNW-ESE trend and cuts the lower channel system (see fig. 4.11b). It has a shoulder depth of around 60ms TWT, and erodes down to 155ms TWT.

Interval G16-G1 (?base Swarte Bank Formation)

Top of Interval: 95 to 125ms TWT, except where cut by later, glacial erosion.

This interval forms the basal fill of the lower channel system and includes low to moderate amplitude, fair continuity events which onlap the channel base. The base of the interval is generally marked by a moderate amplitude, normal polarity event without diffraction energy, suggesting a smooth surface. Locally, several low to moderate amplitude events are present just above, and concordant with the base, separated from the overlying sediments by a moderate amplitude event. These events may represent an early phase of infill, deposited while the channel was still being used as a conduit.

The top of the interval is always marked by a very high amplitude, negative polarity event. This event is usually very flat across the centre of the channel system, at around 120ms TWT. However, as this event is also present on the channel walls, it is unlikely to be due to gas, and may represent a peat layer. High amplitude, fairly continuous events are locally present just below this horizon.

Interval "G1" is probably composed of a mixture of sand and clay. Apart perhaps from its basal sediments, the interval is possibly dominated by passive infill of the channel system after glacial retreat. The tributary axes of the channel system were clearly formed before the final stages of deposition of interval "G1", as they influence the morphology of sediment layers in the upper part of the interval (see fig. 4.11a). However, it is not clear whether they originated synchronously with the formation of the channel system.

Interval G16-G2 (?top Swarte Bank Formation)

Top of Interval: 75ms TWT, except where cut by later, glacial erosion.

This interval, which makes up the remaining fill of the lower channel system, is almost acoustically transparent, although amplitudes increase slightly upward, and some events can be discerned at the top of the interval. These events are gently dipping, and indicate the development of weak clinoforms. The whole interval may therefore represent coarsening upward, deltaic deposition. There is also possible evidence, from dipping reflector development, of small fan deposits along the walls of the channel.

Interval G16-G3 (?Clever Bank Formation)

Top of Interval: 70 to 110ms TWT.

This interval represents the lower fill of the younger channel system. The base of this system is highly uneven, as demonstrated by the abundance of diffraction tails. It is also of very variable depth along the channel axis, and there is no development of tributary axes. Although interval "G3" is of generally low amplitude; sporadic, high amplitude, smooth, dipping events are seen along the channel margins. This part of the channel fill possibly represents sheared, clay rich sediments.

The top of the interval is marked by a high amplitude, normal polarity event, that undulates over numerous ridges and troughs with wavelengths of as little as 50m (see fig. 4.11b). These features are not channels, as they run parallel to each other, and they are probably caused by folding and deformation of the upper part of the interval. This channel may have been formed by ice push from the north or south.

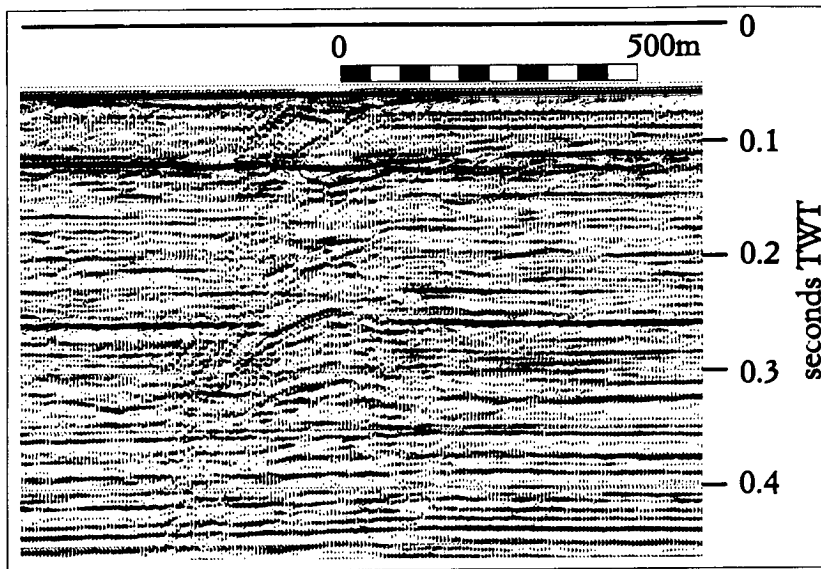


Fig. 4.12: Gas escape chimney within the upper part of the Nordland Group succession in survey G16-FA, along with an associated, infilled crater just below the sea bed (data courtesy of SIPM).

Interval G16-G4 (?Eem and younger formations)

Top of Interval: sea bed.

The base of this interval defines the outline of a relatively small basin within the younger channel system, reaching down to 110ms TWT. Outside this basin, the interval forms a 10 to 15m thick sediment layer over the whole area. Interval "G4" is acoustically weak, except where it reaches its maximum thickness within the channel system basin. Here, the lower half of the interval includes fairly continuous events which indicate that it onlaps interval "G3" below. However, the relief of sediments is clearly influenced by the underlying topography, and some deformation and compaction may have occurred within interval "G3" at this time. Interval "G4" may be made up of both clay and sand.

There is a filled, 10m deep, elongate, channel-like depression close below the sea bed in the north of the area (see fig. 4.11b). This depression is associated with a vertical zone of sediment disturbance, extending down at least to 350ms TWT, that is probably a gas escape chimney, as it occurs directly above a local high seen clearly at around 550ms TWT (see fig. 4.12). The depression could be the crater left from the escape of gas at the sea bed.

4.4: Survey K2-B

This survey is located in the west of the study area (see fig. 4.1). Relative amplitude plots of only 6 of the 30 lines that make up the survey have been supplied for this study, along with one true amplitude plot. Three-dimensional facies and geometric analysis have therefore not been undertaken.

4.4.1: The pre-Nordland Group Succession

This succession has been divided into two intervals here.

Interval K2-T1 (Chalk Group)

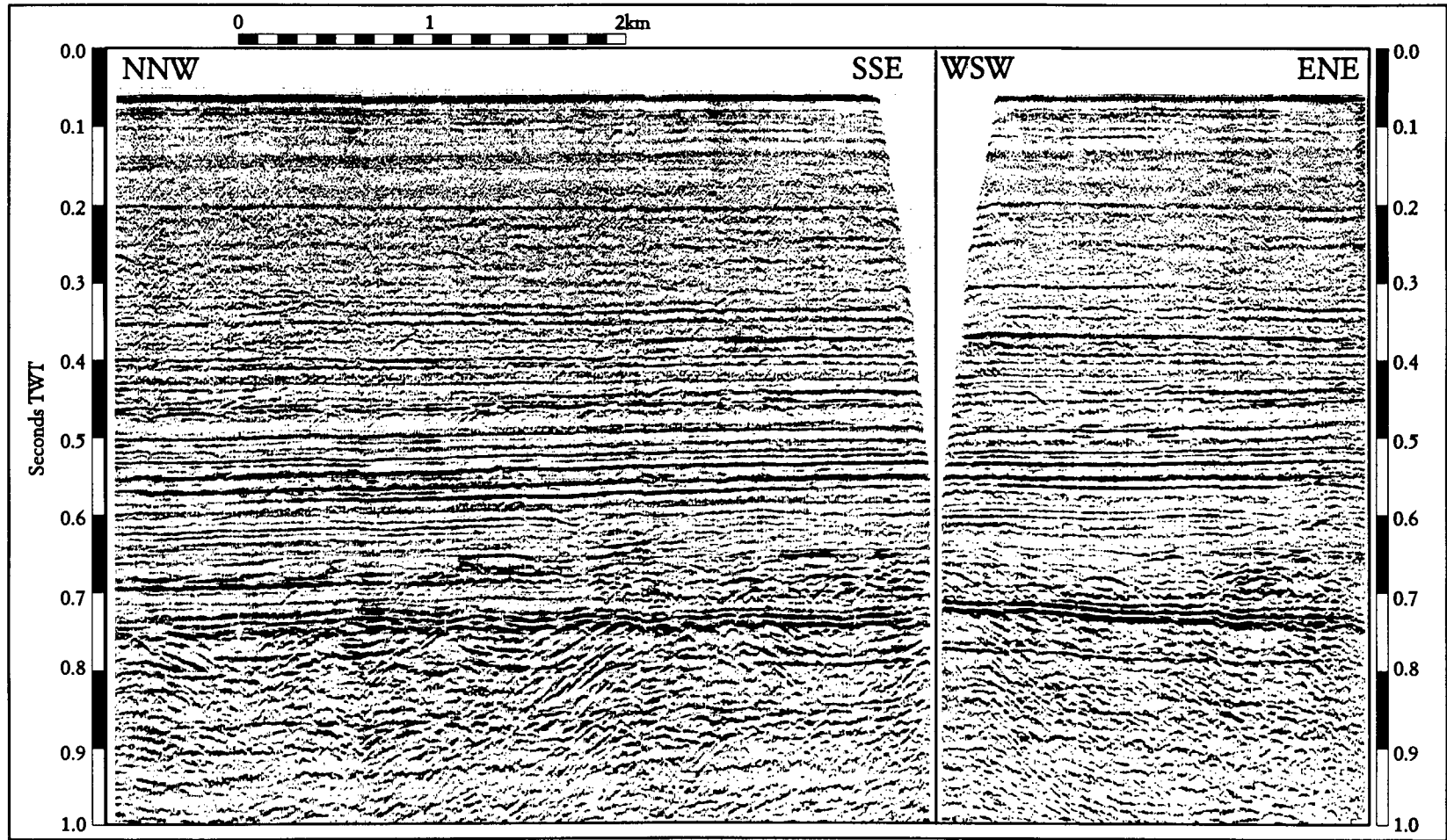
Top of Interval: 1490 to 1650ms TWT.

The seismic character of this interval is not well resolved, due to poor signal to noise ratio. However, the top of the interval is seen to be a high amplitude, continuous, normal polarity event. This event is occasionally broken by faults with offsets of up to 60m.

Interval K2-T2 (Lower to ?Middle North Sea Group)

Top of Interval: 730 to 760ms TWT, gently dipping NE

This interval again suffers from poor signal to noise ratio. Internal events are largely untraceable, being of very low amplitude and continuity. However, occasional events can be traced, for example at about 1050 and 1250ms TWT. These are locally broken, showing fault offsets of up to 40ms. These faults cannot be traced vertically, do not show similarities with those observed at the top of interval "T1" below, and are probably intra-formational, being restricted to certain levels within interval "T2". The top of interval "T2" contains many moderate to high amplitude reflectors of poor to fair continuity. Many of these events dip steeply and they cannot be related to structural trends within the underlying succession. The whole interval shows signs of disturbance after sediment deposition.



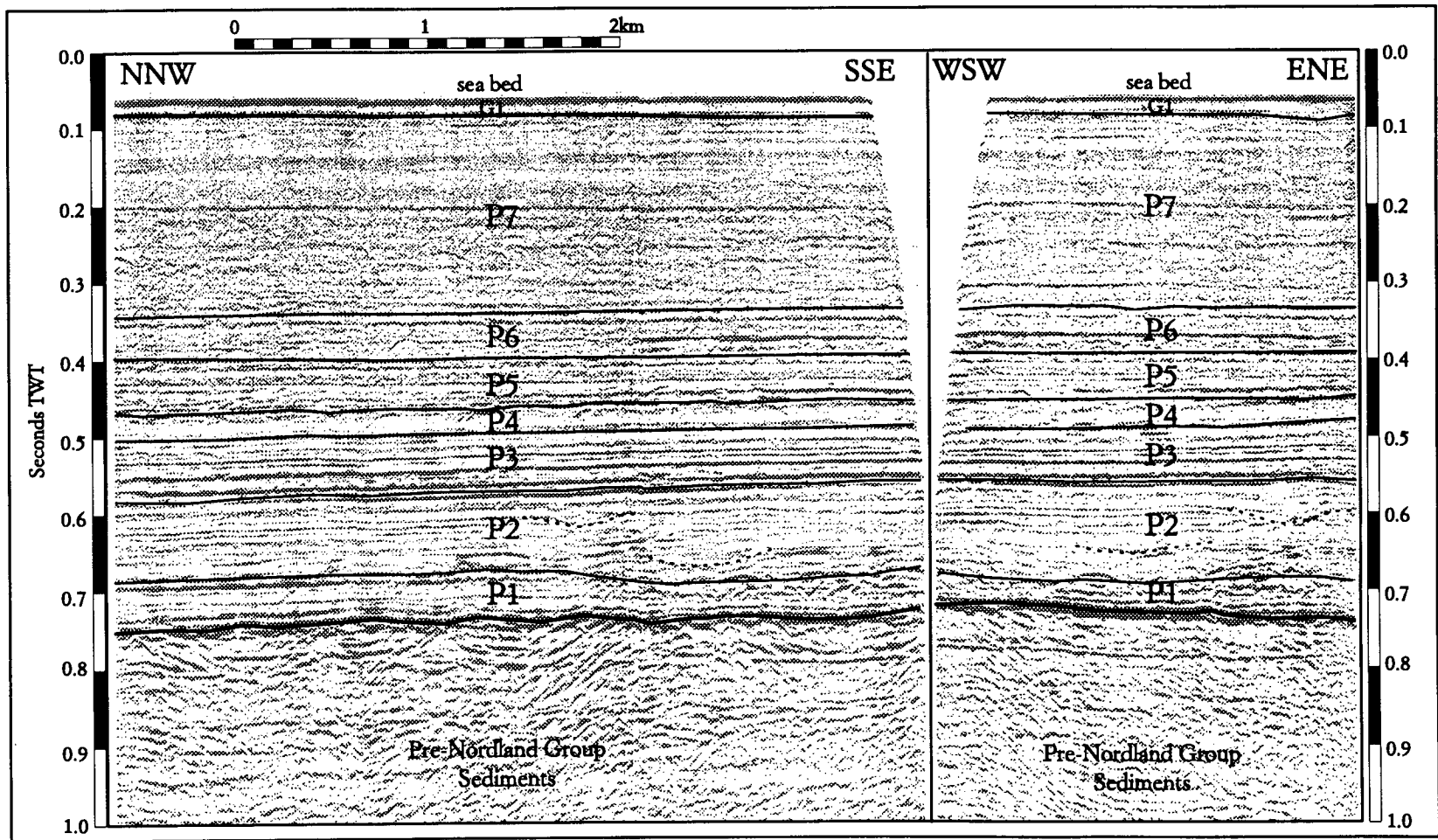


Fig. 4.13: Seismic lines (interpreted and uninterpreted) from survey K2-B down to 1000ms TWT, showing the intervals from the Nordland Group succession described in the text (data courtesy of SIPM).

4.4.2 The Nordland Group Succession (pre-glacial)

This succession has been divided into 7 intervals for the purposes of discussion here (see fig. 4.13). The base of the succession is defined by a high amplitude, negative polarity event, and shows clear, angular unconformity with the underlying units. This surface also shows fault offsets of less than 10ms, spaced at 100 to 150m intervals.

Interval K2-P1 (?top Brielle Ground Formation)

Top of Interval: 670 to 690ms TWT.

This interval is characterized by low to moderate amplitude, fair to good continuity events. However, in the southern part of the area continuity is poor, and many dipping and diffractive events are seen toward the top of the interval. These are related to erosion at the base of the interval "P2" above. The top of interval "P1" is defined by a high amplitude, negative polarity event, except where represented by an erosion surface. Where undisturbed, seismic facies suggest low energy depositional conditions within this unit.

Interval K2-P2 (Westkapelle Ground Formation)

Top of Interval: 550 to 580ms TWT, dipping very gently ENE.

This interval is made up of low amplitude, poor to fair continuity events. The base of the interval is defined in the south of the area by the base of a W-E trending channel, which is over 40m deep and perhaps over 3km wide. This channel base includes much diffraction energy. A moderate amplitude event is traceable at around 600ms TWT over the survey area. This is locally eroded by smaller channels, perhaps 15m deep and no more than 500m wide. These trend W-E and SW-NE. Seismic facies suggest variable energy, possibly submarine slope conditions within interval "P2".

There is slight inversion of sediments above the channel at the base of interval "P2". This is possibly due to reduced compaction around this area, due to the possible presence of higher proportions either of sand or of flow de-watered clays within the channel.

Interval K2-P3 (base IJmuiden Ground Formation)

Top of Interval: 470 to 510ms TWT.

This interval includes moderate to high amplitude, fair to good continuity events. Toward the top of the interval, events decrease in continuity and amplitude.

Interval K2-P4 (intra IJmuiden Ground Formation)

Top of Interval: 440 to 470ms TWT.

This is an approximately 25 to 30m thick interval of very low amplitude, poor continuity facies. The interval may be composed of clay.

Interval K2-P5 (top IJmuiden Ground Formation)

Top of Interval: 390 to 410ms TWT.

This interval contains variable, low to high amplitude and variable polarity, moderate to poor continuity events. Some diffraction tails are present at the base of the interval suggesting local erosion and a possible unconformity with the underlying sediments. Near the top of the interval both the amplitude and continuity of events become relatively low. Seismic facies suggest that interval "P5" is a coarsening upward unit, interbedded sand and clay being replaced upward by sand. The top of the interval is sometimes marked by a complex, moderate, rarely high amplitude event which is locally of negative polarity.

Interval K2-P6 (Winterton Shoal and ?Markham's Hole Formations)

Top of Interval: 330 to 350ms TWT.

This interval is largely of low amplitude and poor continuity seismic facies, and is possibly dominated by sand. The middle and top of the interval are locally marked by moderate to high amplitude, sub-horizontal events which could be clay partings. Where absent these events may have been eroded by channels. Where the mid-interval event is of high amplitude and negative polarity, diffractive and channel-like reflectors can usually be seen just below it .

Interval K2-P7 (Yarmouth Roads Formation)

Top of Interval: normally at 80ms TWT, except where eroded by glacial channels.

This interval is of low amplitude and poor continuity events, and may be composed predominantly of sand. Locally, moderate amplitude, slightly dipping events are recorded, and these could be due to channelling. One dipping event may describe the margin of a 60m deep valley which has eroded down from 230ms TWT. A negative polarity, continuous, sub-horizontal event is present at approximately 200ms TWT. This may represent a clay layer. Other bands of improved continuity within the interval, at around 240 and 310ms TWT, could also be due to clay layers.

4.4.3 The Nordland Group Succession (glacial)

There is little evidence for a thick glacial succession within the area of survey K2-B (see fig. 4.13). One small channel, its base rarely defined by high amplitude reflectors, is present in the north of the area, possibly trending SW-NE to WSW-ENE. This has a shoulder depth of around 85ms TWT and cuts down to around 140ms TWT. Due to its geographical location, the age of this channel is likely to be Elsterian, making the channel fill part of the Swarte Bank Formation.

Interval K2-G1 (Swarte Bank & younger formations)

Top of Interval: sea bed.

The interval, which comprises the fill of the channel system and all subsequent deposits, is made up of moderate amplitude and fair continuity events. However, it is difficult to assess whether all these events are primary.

4.5: Survey L2-FA-1

Survey L2-FA-1 is located in the NE of the study area (see fig. 4.1). The interpretation of this data-set is based upon a complete survey grid of six lines. These are all relative amplitude plots, although one true amplitude plot has been used to estimate amplitude variations.

Two commercial wells, well L2-1 & 7, have been drilled within the survey area, and their electric logs allow a prediction of the correct lithologies to be found within the succession, acting as a useful control on the interpretation of other site survey lithologies, as interpreted from seismic characteristics. This is supplemented by velocity information from the wells, allowing calibration of the velocity data obtained from the commercial well data with that from the site survey seismic data.

4.5.1: The pre-Nordland Group Succession

Interval L2-T1 (?Chalk or base Lower North Sea Group)

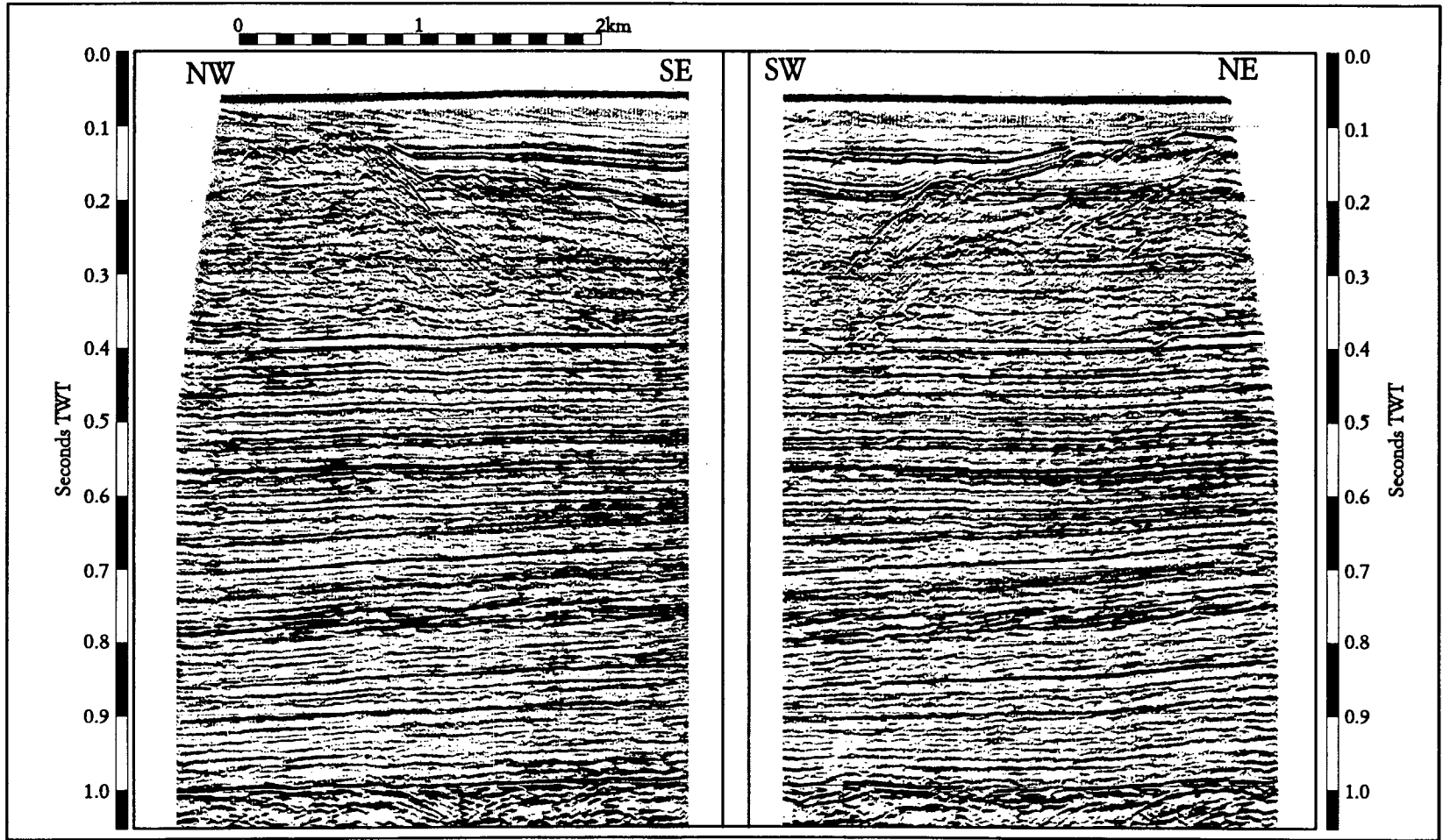
Top of Interval: 1530 to 1630ms TWT, dipping gently to the west.

Primary events within this interval are difficult to resolve, due to poor signal to noise ratio. However, the top of the interval can be picked out as a single, strong event, unusually, for the top Chalk event, of apparently negative polarity. Concordant events are recorded below this, although these may be multiple energy. If faults are present within this interval they have very small offsets and are not resolved on the seismic profiles.

Interval L2-T2 (?base or intra Lower North Sea Group)

Top of Interval: 1120 to 1180ms TWT.

This interval is of low amplitude and may be of low continuity, although signal to noise ratio of the interval is poor, making primary and multiple events difficult to distinguish. No primary events have, therefore, been unequivocally identified.



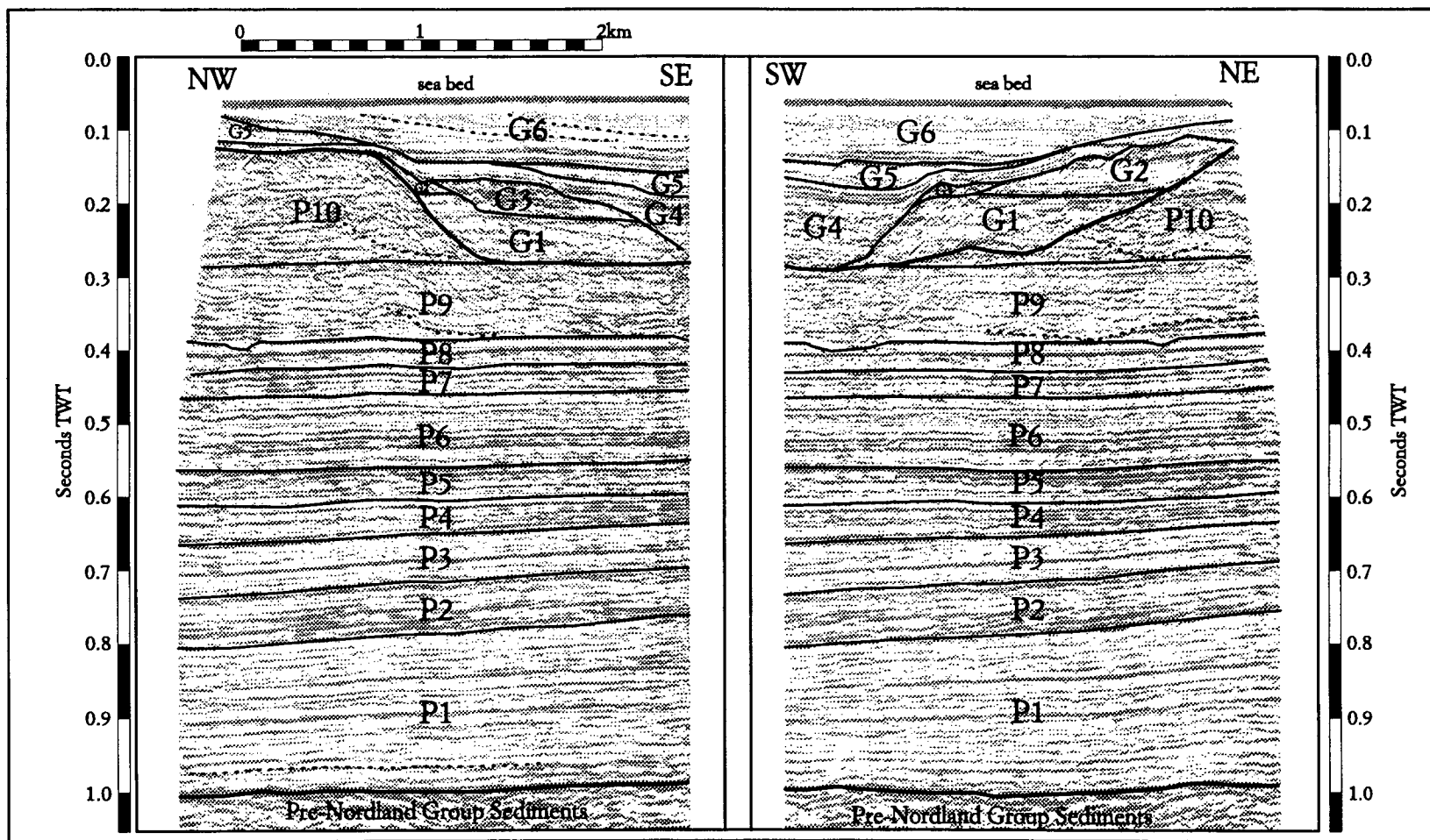


Fig. 4.14: Seismic lines (interpreted and uninterpreted) from survey L2-FA-1 down to 1050ms TWT, showing the intervals from the Nordland Group succession described in the text (data courtesy of SIPM).

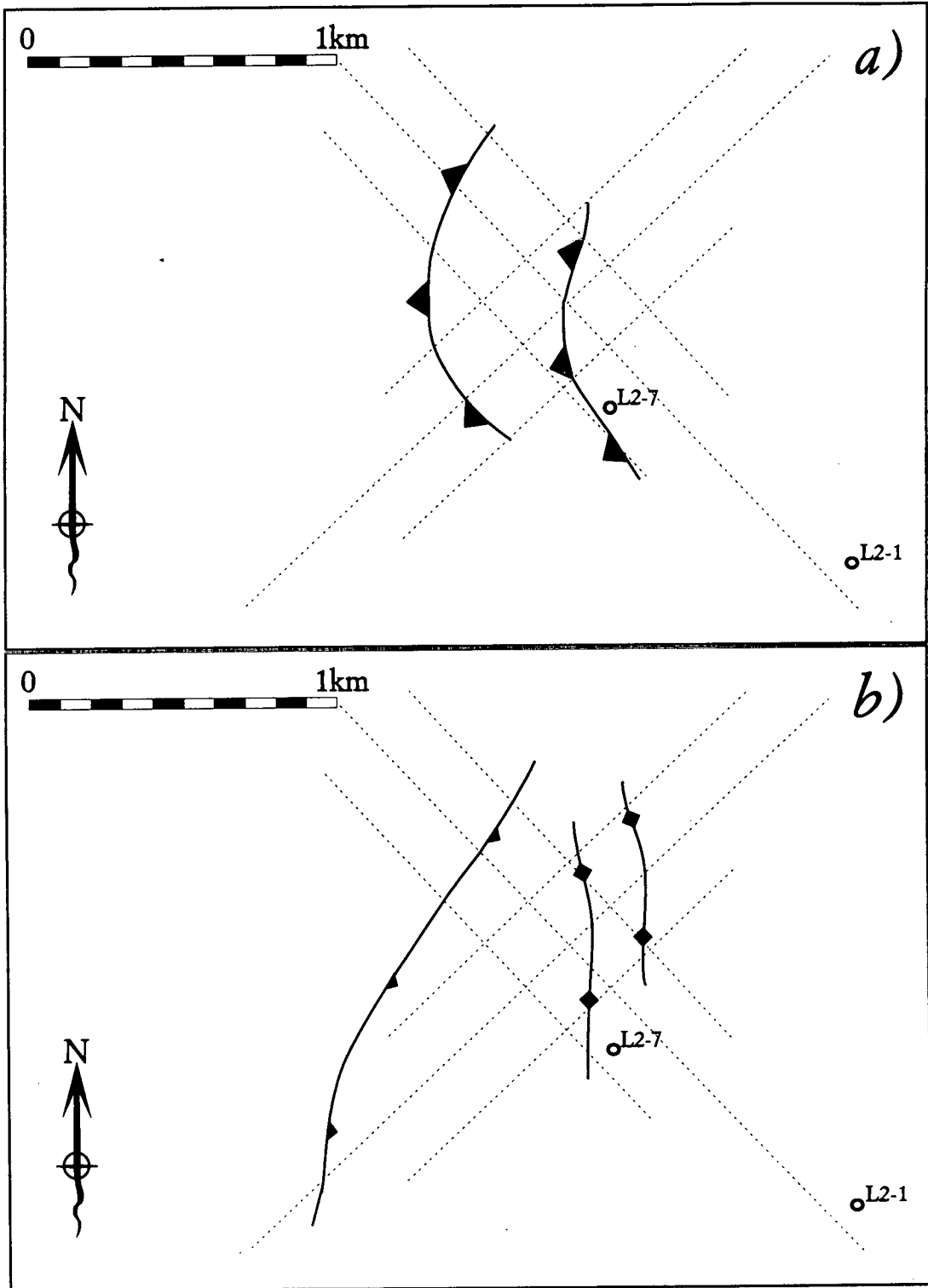


Fig. 4.15: Maps from survey L2-FA-1: a) Arcuate, possibly deltaic fore-sets, developed within interval "L2-P2", sectioned at 750ms TWT; b) Possible sand ridges developed within interval "L2-P4". The westernmost lineation represents the eastern margin of what is possibly a very large sand ridge.

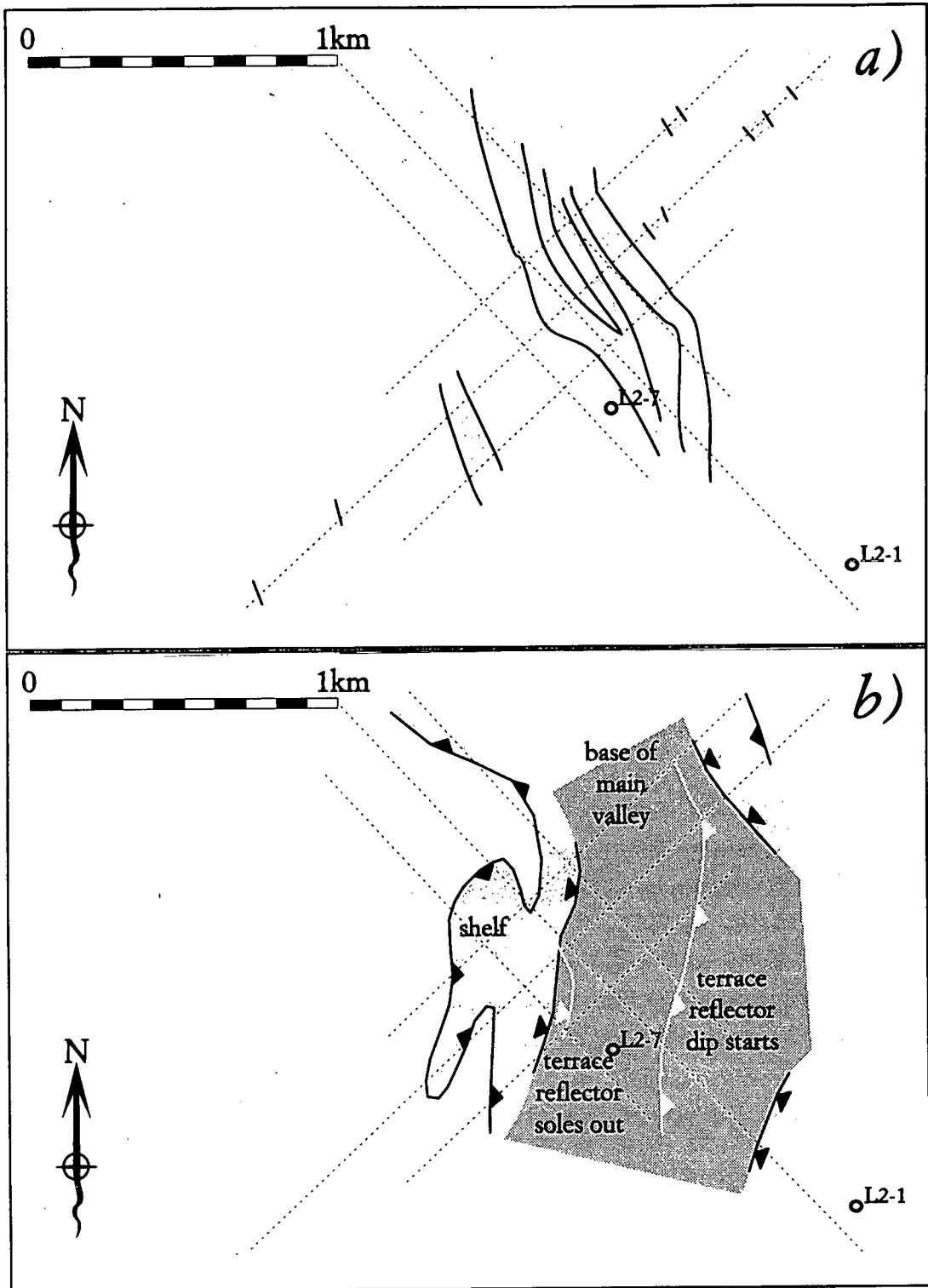


Fig. 4.16: Maps from survey L2-FA-1: a) Lineations, mapped out by the absence of an event, at the base of interval "L2-P8". These may be either channels or sand ridges; b) The N-S trending valley system developed within interval "L2-P9". A basal terrace is developed at the western margin of the valley, possibly over a clay horizon. Dipping reflectors within the valley fill show the eastward migration of smaller channels within the valley.

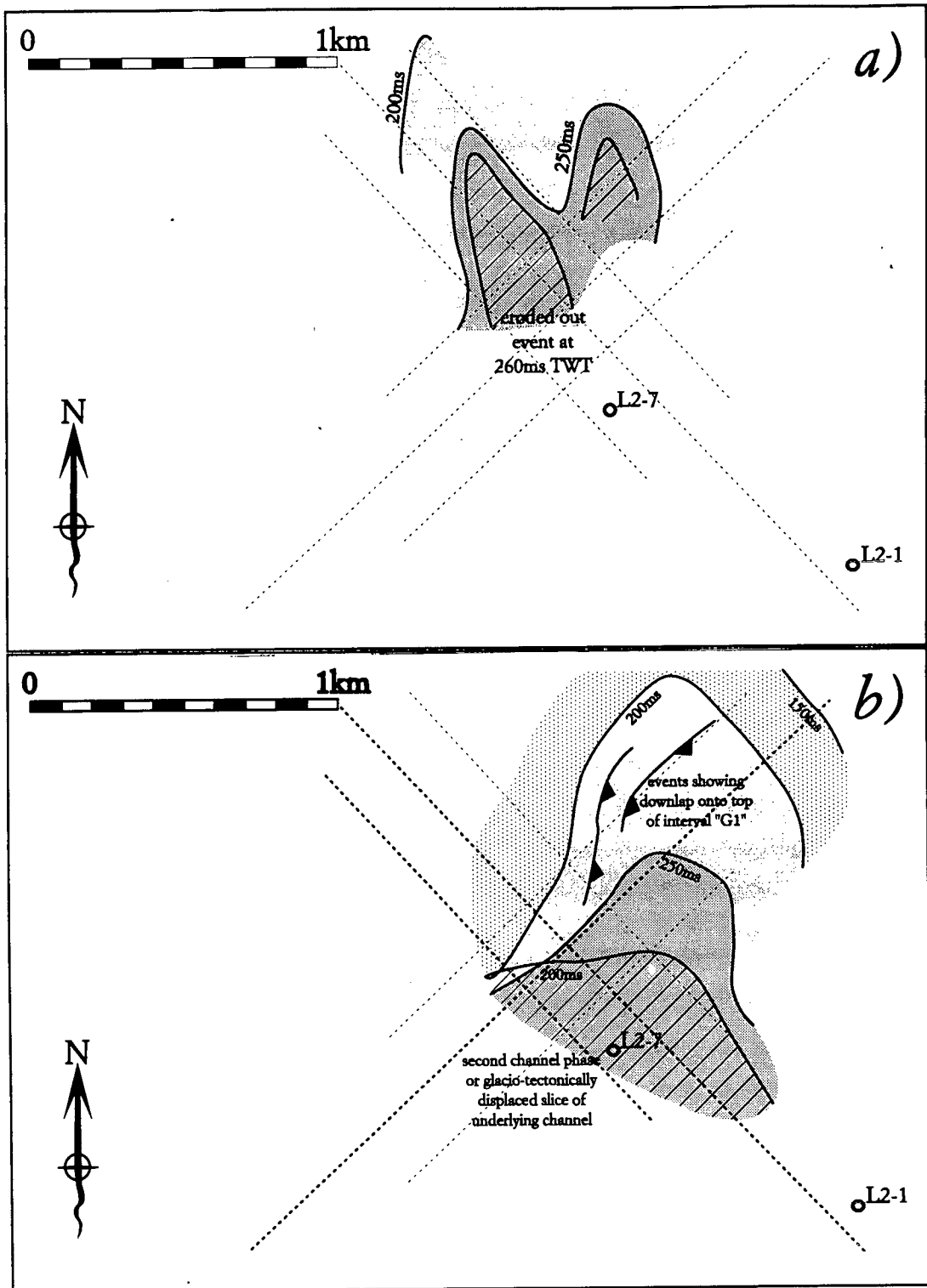


Fig. 4.17: Maps from survey L2-FA-1: a) Tentative mapping of an erosion surface within interval "L2-P10". The apparent enclosure to the north of the resulting valley may indicate the glacial origin of this feature; b) TWT contours of the base of the oldest, definite glacial channel system. The hatched area to the south indicates the presence of the second channel system below 200ms TWT. However, this may be a glacio-tectonic slice of the channel system below.

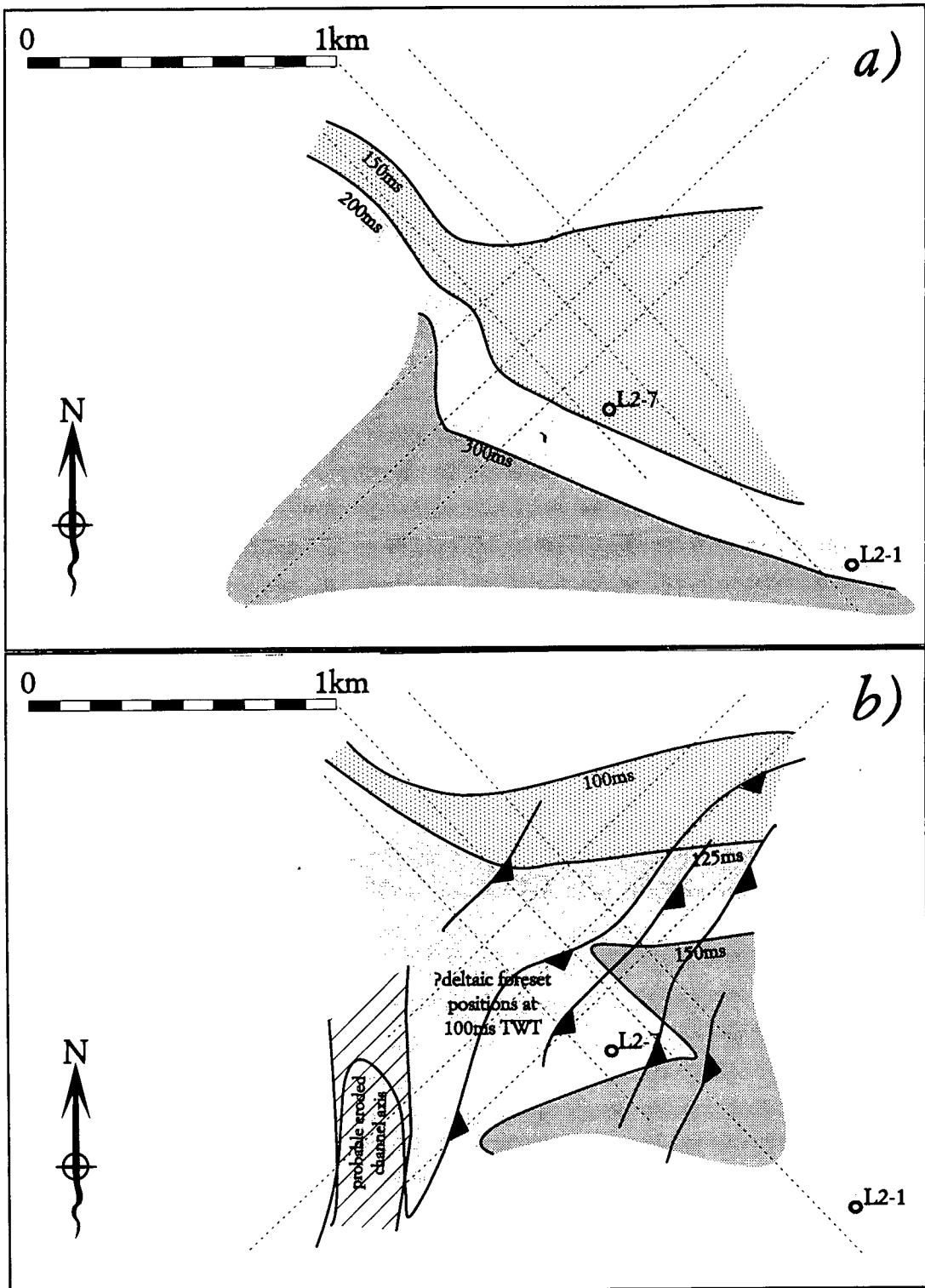


Fig. 4.18: Maps from survey L2-FA-1: a) TWT contours of the base of the third glacial channel system; b) TWT contours of the base of the youngest glacial channel system. Superimposed upon this are the fore-set directions of the channel fill, interval "L2-G6", fore-sets being marked where they cross the 100ms TWT contour. A probable channel is seen within this fill to the SW.

Interval L2-T3 (top Lower to base Upper North Sea Group)

Top of Interval: 995 to 1005ms TWT, essentially sub-horizontal.

This interval includes moderate to high amplitude, low continuity, diffractive events, some of which show anomalous dips in relation to the top and bottom of the interval. Because of this, it is difficult to determine the relationship of the interval with interval "T2" below. The difference in seismic facies between the two intervals could simply reflect disturbance within the latter. The base of interval "T3" is often marked by a continuous, high amplitude, negative polarity event.

4.5.2 The Nordland Group Succession (pre-glacial)

The base of the Nordland Group is a sub-horizontal, negative polarity event, showing angular unconformity with the underlying succession. This event may be cut by faults throughout the survey area, although, if real, these faults have throws of no more than 5m. This succession is divided into 10 intervals for the purposes of discussion here (see fig. 4.14)

Interval L2-P1

Top of Interval: 770 to 810ms TWT. This surface dips gently WSW.

Interval "P1" is characterized by low to moderate amplitude, fair continuity seismic facies. Events are sub-parallel, although gently dipping to the WSW. A thin unit, apparently showing subtle downlap at its base, is present at around 880 to 900ms TWT. The presence of apparent onlap just above this unit is possibly caused by the interference of primary and multiple events. Commercial well data suggest that interval "P1" is predominantly composed of clay, with minor silt and sand layers near the middle and base of the interval. These layers possibly correspond with slightly higher amplitudes recorded on the seismic data at certain levels within the interval.

Interval L2-P2

Top of Interval: 720 to 740ms TWT.

This interval is of variable seismic facies, changing upward from high amplitude, moderately continuous facies, events exhibiting apparent downlap at the base of the interval, to low amplitude, low continuity, “braided” looking events at the top. The top of interval “P2” is defined by a moderate amplitude, continuous, negative polarity event. Commercial well data indicate the coarsening upward nature of the interval, sandy clay coarsening upward into porous sand at the top, and this interval probably corresponds with well interval “10”. Interval “P2” has a “deltaic” appearance of the seismic data, with both fore-sets and top-sets present and seismic facies being diachronous. When mapped out, fore-sets show an arcuate pattern, with dip directions varying from WNW to SW (see fig. 4.15a).

Interval L2-P3

Top of Interval: 640 to 660ms TWT.

This interval is characterized by low to moderate amplitude, fair continuity, parallel banded seismic facies. The base the interval is often of low amplitude, poor continuity, “braided” looking events. Interval “P3” is known to be dominated by clays from the commercial well data. However, the “braided” events near the base may represent continued sand deposition and, although not mapped out, could represent sand ridges. In the middle of the interval is a high amplitude, continuous, normal polarity event. This event does not correspond with any lithology change in the wells, but may be related to a sharp downward increase in interval velocity recorded within wells L2-1 and L2-7 in well interval “11”. This interpretation would suggest that the lower half of the interval is better compacted or more indurated than, or unconformable with its upper half.

Interval L2-P4

Top of Interval: 610 to 620ms TWT.

Interval “P4” is characterized by moderate amplitude, fair to good continuity events, especially near the top and base of the interval. Commercial well evidence records

the interval to be sandy clay with a “medium-gamma” response, and, based upon seismic facies, this may be rhythms of sand and clay. Within interval “P4”, there is an upward change from WSW dipping to essentially horizontal events. This transition occurs within the middle of the interval in a unit of low amplitude, low continuity, “braided” seismic facies up to 20ms thick. The upper surface of this facies is sometimes represented by convex upward, moderate amplitude reflectors which, when mapped out, appear to form a series of ridges running N-S and NNE-SSW (see fig. 4.15b). Dimensions of these ridges range from 5m in height and 200m width to 20m in height and 500m width. The largest ridge has the appearance of a sand bar in the seismic data.

Interval L2-P5 (top Brielle Ground Formation)

Top of Interval: 560 to 570ms TWT.

This interval is of low to moderate amplitude, poor to fair continuity seismic facies. Although some events within the interval are smooth and planar, many are both “braided” and wavy in appearance. The top of the interval is defined by a sub-horizontal, high amplitude, negative polarity event, which could indicate a contact between a porous sand and an overlying clay horizon. Commercial well data, which has fairly low gamma values, indicates that this interval is composed of sand, with minor clay layers.

Interval L2-P6 (Westkapelle Ground and base IJmuiden Ground Formations)

Top of Interval: 450 to 470ms TWT.

This interval is characterized by moderate, rarely high amplitude, fair to good continuity seismic facies. However, thin units, containing “braided” events, are also present. Highest amplitudes are represented by continuous seismic events at between 515 and 535ms TWT. Convex upward reflectors up to 5ms in height can again be seen locally just above this level. Attempts at mapping these events have given ambiguous results, although ridge trends running WNW-ESE are suggested. Interval “P6” is indicated to be composed of sandy clay in the commercial well data.

Interval L2-P7 (top IJmuiden Ground Formation)

Top of Interval: 420 to 430ms TWT.

This interval is made up of low to moderate amplitude, poor to fair continuity events. The interval is indicated to be composed of variable sand and clay facies in commercial well data. The top surface of the interval is of moderate to high amplitude. On well data it has a higher gamma response and is probably a clay horizon.

Interval L2-P8 (Winterton Shoal Formation)

Top of Interval: 380 to 390ms TWT.

This interval is predominantly of low amplitude, low continuity seismic facies, although the top part of the interval is of higher amplitude and good continuity. Commercial well data suggest the sandy nature of the interval, although the top part is of higher gamma response and is probably a clay layer. The local absence of events in interval "P7" below reveals trends varying from NNW-SSE to N-S when mapped out (see fig. 4.16a). These may be channels, although little erosion of underlying units in interval "P8" can be detected. Alternatively, these may be sand ridge features. A SE dipping event near the top of the interval, which is probably a channel, has also been mapped out, revealing a NNE-SSW trend.

Interval L2-P9 (?Markham's Hole & Yarmouth Roads Formations)

Top of Interval: around 290ms TWT.

This interval records the first major evidence of lateral facies variations within the Nordland Group. Although predominantly of low amplitude, poor continuity facies, moderate to high amplitude, sub-horizontal events are present locally near the base of the interval. Commercial well data indicate the largely sandy or silty nature of the interval. Zones of erosion of the base of interval "P9" can be mapped out as 250m wide, over 5m deep, high sinuosity features of no preferred orientation. These are almost undoubtedly the result of channel cutting.

Other horizontal events at higher levels within interval "P9" are of limited extent, due to subsequent erosion, enabling the mapping of a major valley system

running N-S (see figs. 4.16b, 4.35). This valley is up to 80ms deep from shoulder to base, almost the thickness of the whole interval, and may be several kilometres wide, as it extends outside the survey area. The valley profile is not uniform, a terrace being present on the western side. This suggests that the sediments near the base of interval "P9" include moderately consolidated clay horizons.

The fill of the valley system is complex, although two weak, eastward dipping events have been mapped in the western half of the valley. These are also seen to truncate underlying events, and are probably the bases of later, smaller channels running N-S. These features suggest progressive bank-full channel migration to the east as the major valley system filled. Another event can be seen near the top of the valley fill, trending NE-SW.

Interval L2-P10 (Yarmouth Roads & ?Swarte Bank Formations)

Top of Interval: defined by the base of glacial erosion, although present as high as 130ms TWT.

This interval is of similar seismic facies to interval "P9" below, also being recorded as sand in the commercial well data. Diffraction energy from the base of the glacial succession locally obscures its internal events. The base of interval "P10" is defined by a sub-horizontal, continuous, moderate amplitude event, and concordant, moderate amplitude reflectors are locally present just above this. Erosion surfaces occurring within this event suggest uniform, N-S trending channels at least 400m wide. These erosion surfaces, although suspected to be part of the Yarmouth Roads Formation due to their irregularity, and the nature of seismic facies within, could actually be part of the glacial succession, as they seem to plunge toward the south and may be blind-ended (see fig. 4.17a). However, they are provisionally consigned to the pre-glacial succession here.

4.5.3 The Nordland Group Succession (glacial)

The glacial succession of survey L2-FA-1, excluding the possibly glacial channelling of interval "P10", records at least three, and maybe four phases of channel erosion, and is divided in 6 intervals here for the purposes of discussion (see fig. 4.14). The oldest channel system, elongated NNE-SSW, is estimated to be over 1.5km wide, is enclosed to the north, and flattens out at the base of interval "P10" around 290ms TWT (see fig. 4.17b). The second channel system has been largely removed by

subsequent erosion, although it may have been oriented WNW-ESE. However, its status as a separate channel fill is dubious, and it may be a glacio-tectonic slice of the oldest channel system.

The third channel system, which is elongated NW-SE and is estimated to be at least 2km wide, again flattens out at the base of interval "P10" around 290ms TWT, with a channel shoulder depth of around 130ms TWT (see fig. 4.18a). The fact that two channel systems flatten out at the same level suggests the presence of a dense clay horizon at a depth of around 290ms TWT in the underlying succession.

The youngest phase of channel erosion reaches down to around 160ms TWT, its channel shoulder being at around 80ms TWT (see fig. 4.18b). Based upon available evidence, this channel system trends approximately ENE-WSW, plunging to the east, and may be 3 or 4km wide.

Interval L2-G1 (?base Swarte Bank Formation)

Top of Interval: 160 to 190ms TWT, although generally very flat at around 190ms TWT.

Interval "G1" comprises the basal fill of the lowest channel system. The channel base is locally defined by high amplitude, negative polarity diffraction events. Internally, the interval is of low amplitude, low continuity seismic facies. The upper surface of the interval is marked by a moderate to high amplitude, negative polarity, sub-horizontal event. Interval "G1" has been sampled in commercial well L2-7 and, although no lithology information is available, it has a low gamma response, suggesting that it may well be composed of sand.

Interval L2-G2 (intra Swarte Bank Formation)

Top of Interval: defined by the level of subsequent glacial erosion. Highest point at 110ms TWT.

Interval "G2" comprises the remainder of the oldest channel fill and is of low amplitude, moderate continuity events. The basal part of the interval also includes moderate amplitude, more continuous events. Along the western channel margin, these events show ESE directed downlap onto the base of the interval. This could represent lateral, fan fill of the channel, although the conditions under which these sediments were deposited is unknown. Terrace development in the third channel,

just above this lateral fill, indicates that it may be largely composed of clay. Conversely, channel slopes cut through the upper part of the interval are relatively steep by comparison, suggesting the sandier nature of the upper fill.

Interval L2-G3 (intra Swarte Bank Formation)

Top of Interval: defined by the level of subsequent glacial erosion. The interval is only represented between 180 and 230ms TWT.

Interval "G3" is the only remnant of a possible second channel fill, and, where present, is of low to moderate amplitude, low continuity seismic facies. Near the top of the interval, a high amplitude, negative polarity event is rarely preserved. This event is of irregular depth, possibly being faulted, with diffraction tails, and may have been slightly disrupted during the formation of the overlying channel system. The base of the interval is smooth and is often defined by a moderate amplitude, fairly continuous event. The terrace developed above interval "G2", at the base of the third channel, also extends along the top of this interval, suggesting that the upper part of this interval is also made up of clay. This is confirmed by the high gamma readings seen in well L2-7 at this depth.

An alternative origin for interval "G3" is that, rather than being the infill of a channel system which has been almost entirely removed by the erosion of channel three, it is, in fact, a glacially displaced slice from channel one below. This may explain the faulting present within, and the similarity of the high amplitude event with that seen at the top of interval "G1".

Interval L2-G4 (intra Swarte Bank Formation)

Top of Interval: 110 to 210ms TWT.

This interval, which forms the basal fill of the third channel, changes upward in internal character from low amplitude, poor continuity events to moderate to high amplitude, moderate continuity, sometimes diffractive events. The top of the interval is defined by continuous, normal polarity, moderate amplitude events. These events drape the underlying topography, being present on the channel walls where the rest of the interval is absent, and may be composed of clay deposited from suspension.

Interval L2-G5 (intra Swarte Bank Formation)

Top of Interval: 140 to 150ms TWT. A fairly flat surface

This interval, which is the upper part of the third channel fill, is of low to moderate amplitude and poor continuity seismic facies. It is only present near the axis of channel three, possibly due to erosion at the base of the youngest channel system, which has removed much of the interval away from the channel axis. This fill is rarely seen to downlap onto the top of interval "G4" below.

Interval L2-G6 (?top Swarte Bank & younger formations)

Top of interval: sea bed

This interval represents the fill of the youngest channel and all subsequent sediments in the area. The base of the interval is a moderate amplitude, continuous, normal polarity event which is seen everywhere within the third channel fill. Just above this are up to 20m of moderate amplitude, continuous events, which show onlap onto the base of the interval at the channel margin. These are overlain by low amplitude, moderate continuity seismic facies, including dipping events which downlap to the SW, with dips of up to 3°. Coherency of events decreases upward, and there is limited evidence for a channel near the top of the interval. The whole interval is possibly a coarsening upward, deltaic succession of sandy clays and sands.

4.6: Survey L3-E

This site survey is located in the west of the study area (see fig. 4.1), and includes a complete survey data-set of 36 lines. One relative amplitude plot has also been provided, and has been used for amplitude determination.

4.6.1: The pre-Nordland Group Succession

This succession has been divided into two intervals for the purposes of discussion here.

Interval L3-T1 (Chalk Group)

Top of Interval: ?1530 to 1630ms TWT.

The top of this interval is defined by a moderate to high amplitude event, which is sometimes of negative polarity. Interval "T1" is characterized by discontinuous, moderate amplitude, low frequency, sub-parallel events.

Interval L3-T2 (Lower to base Upper North Sea Group)

Top of Interval: 910 to 930ms TWT, slightly faulted but essentially sub-horizontal. An apparent eastward dip is probably due to lateral velocity contrasts within the overlying glacial succession.

This interval is of low amplitude, poor continuity seismic facies. Where resolved, discontinuous events sometimes show excessively steep dips. One moderate amplitude, sub-horizontal event is traceable across the survey area near the top of this interval between ?1040 and 1060ms TWT.

4.6.2 The Nordland Group Succession (pre-glacial)

This succession has been subdivided into 9 separate intervals (see fig. 4.19). The base of this succession is defined by a high amplitude, negative polarity event which is slightly faulted, with offsets of up to 10ms. These faults exhibit clear diffraction tails.

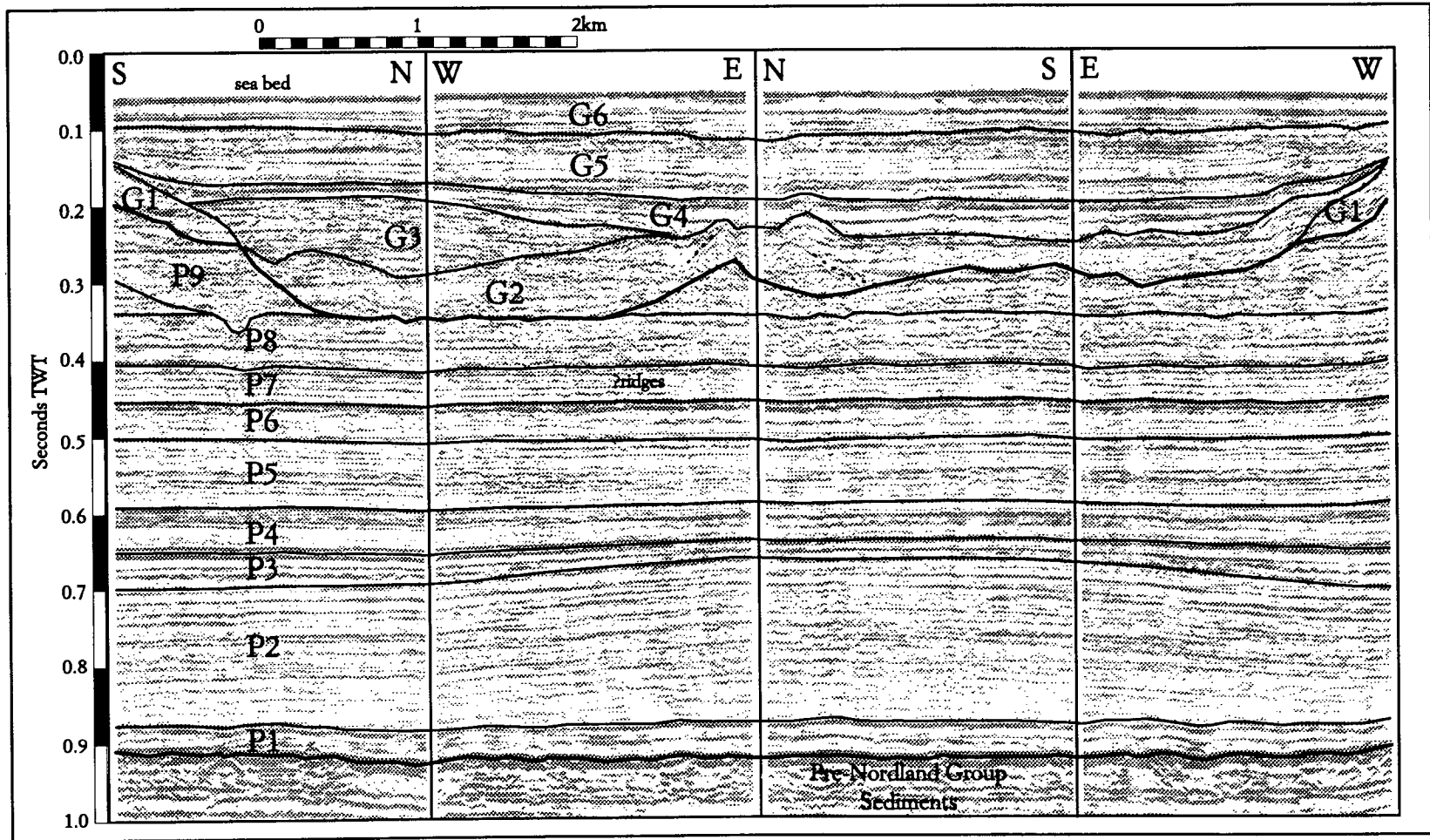
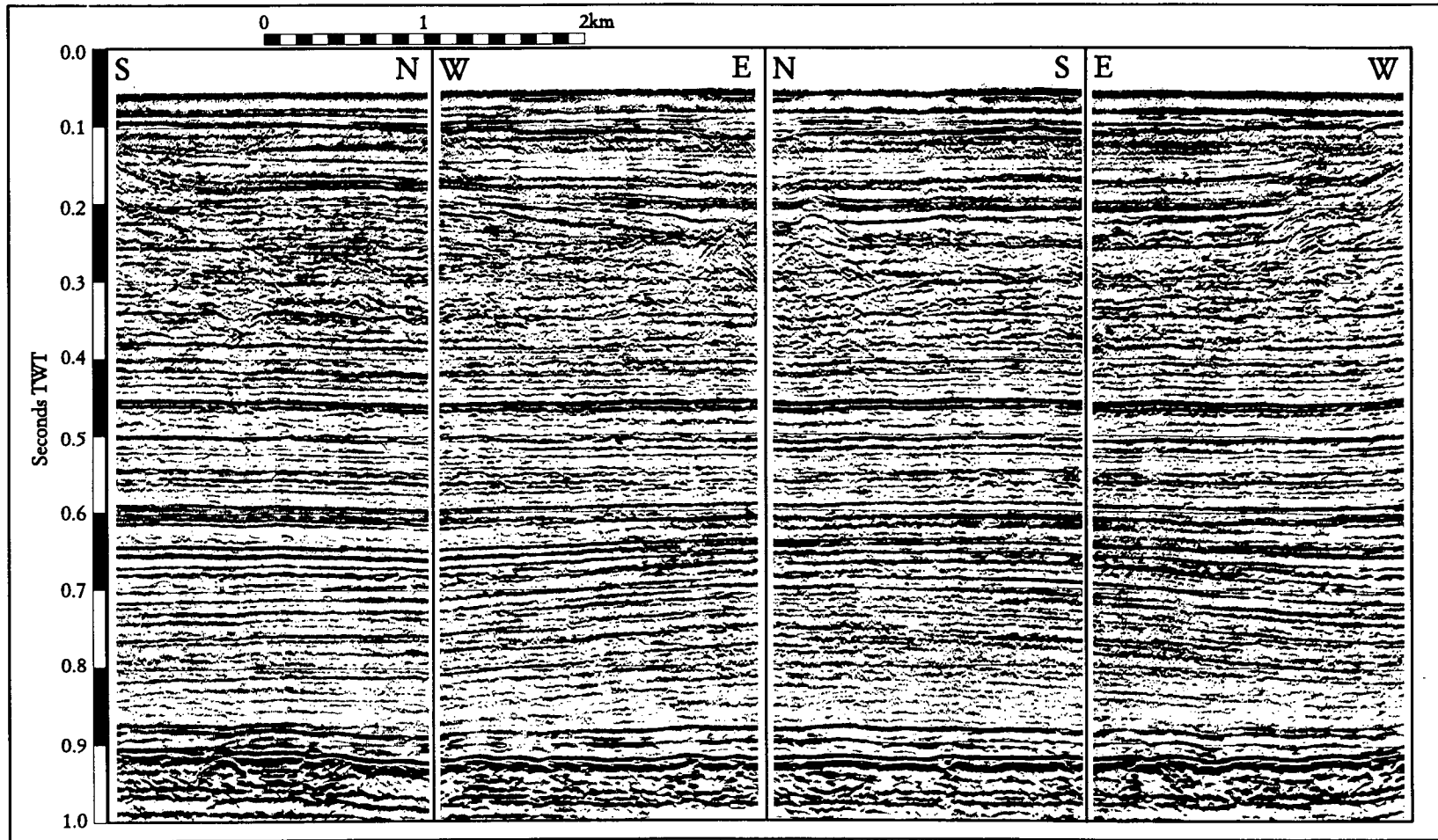


Fig. 4.19: "Seismic outer line box" (interpreted and uninterpreted) of survey L3-E down to 1000ms TWT, showing the intervals from the Nordland Group succession described in the text (data courtesy of SIPM).



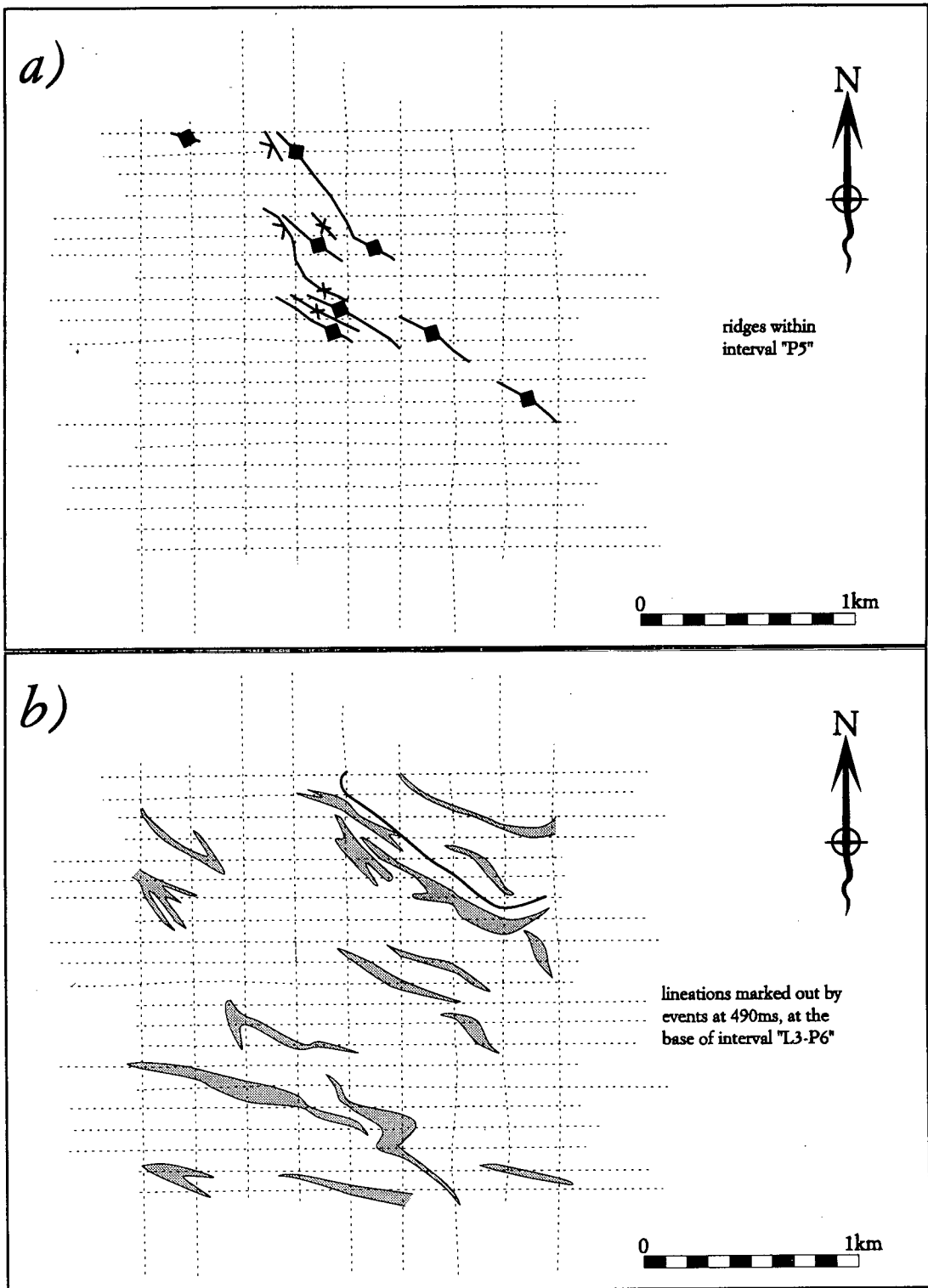


Fig. 4.20: Maps from survey L3-E: a) Anticlinal and synclinal axes of possible sand ridges within interval "L3-P5"; b) Reflector distribution defining WNW-ESE trends at the base of interval "L3-P6". These may be sand ridge trends.

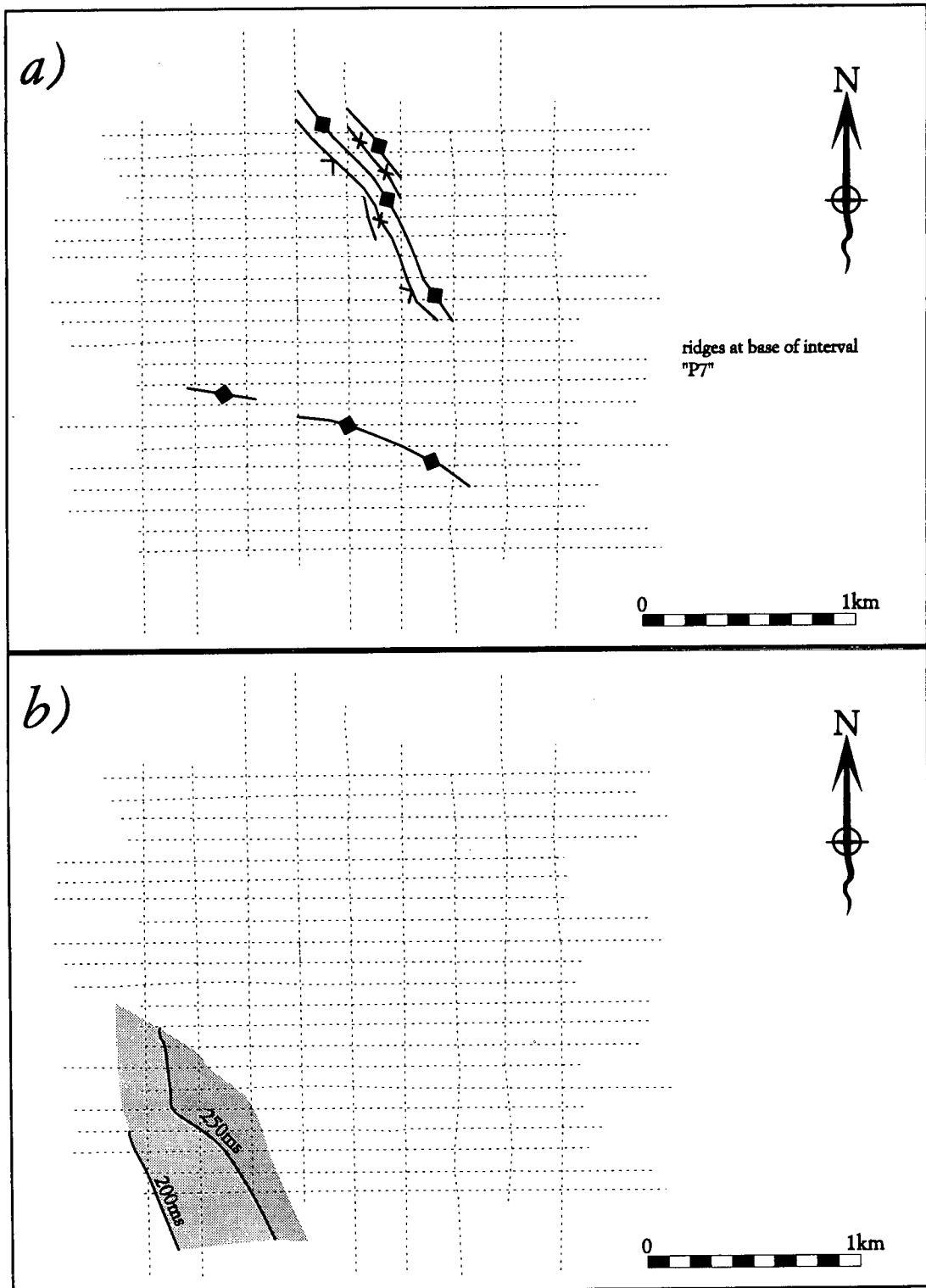


Fig. 4.21: Maps from survey L3-E: a) Anticlinal and synclinal axes of possible sand ridges at the base of interval "L3-P7"; b) TWT contours of the base of the oldest glacial channel.

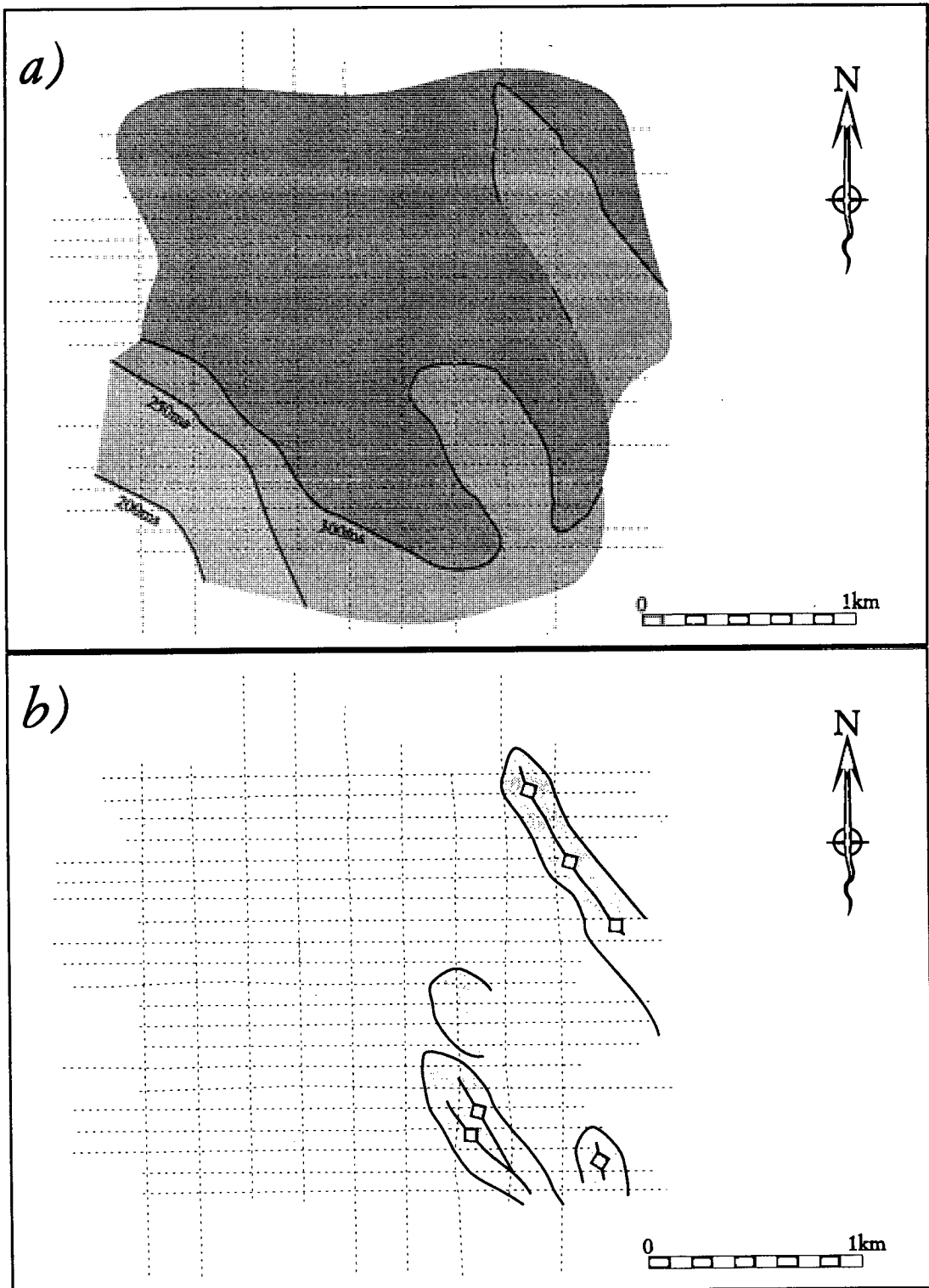


Fig. 4.22: Maps from survey L3-E: a) TWT contours of the base of the second glacial channel, showing preserved ridges within the base of the channel; b) Ridges, possibly drumlins, on the upper surface of interval "L3-G2", the lowest fill of the second glacial channel.

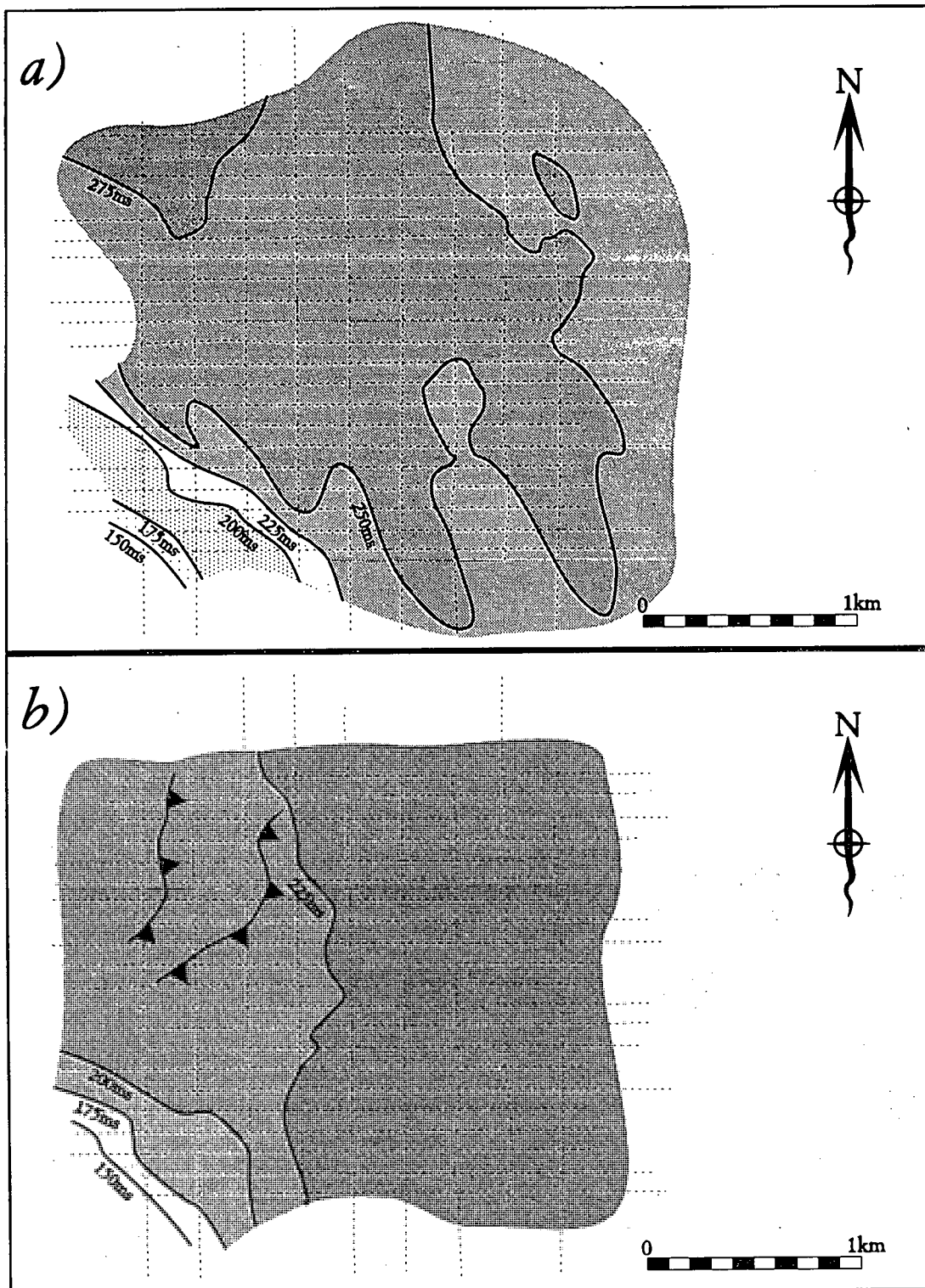


Fig. 4.23: Maps from survey L3-E: a) TWT contours of the upper surface of interval "L3-G2", showing plunge to the NW; b) TWT contours of the eastward dipping base of the third glacial channel. Also shown are the eastward dipping reflectors of interval "L3-G3". Note the presence of the remnant older topography of glacial channel two in the SW corner of the area.

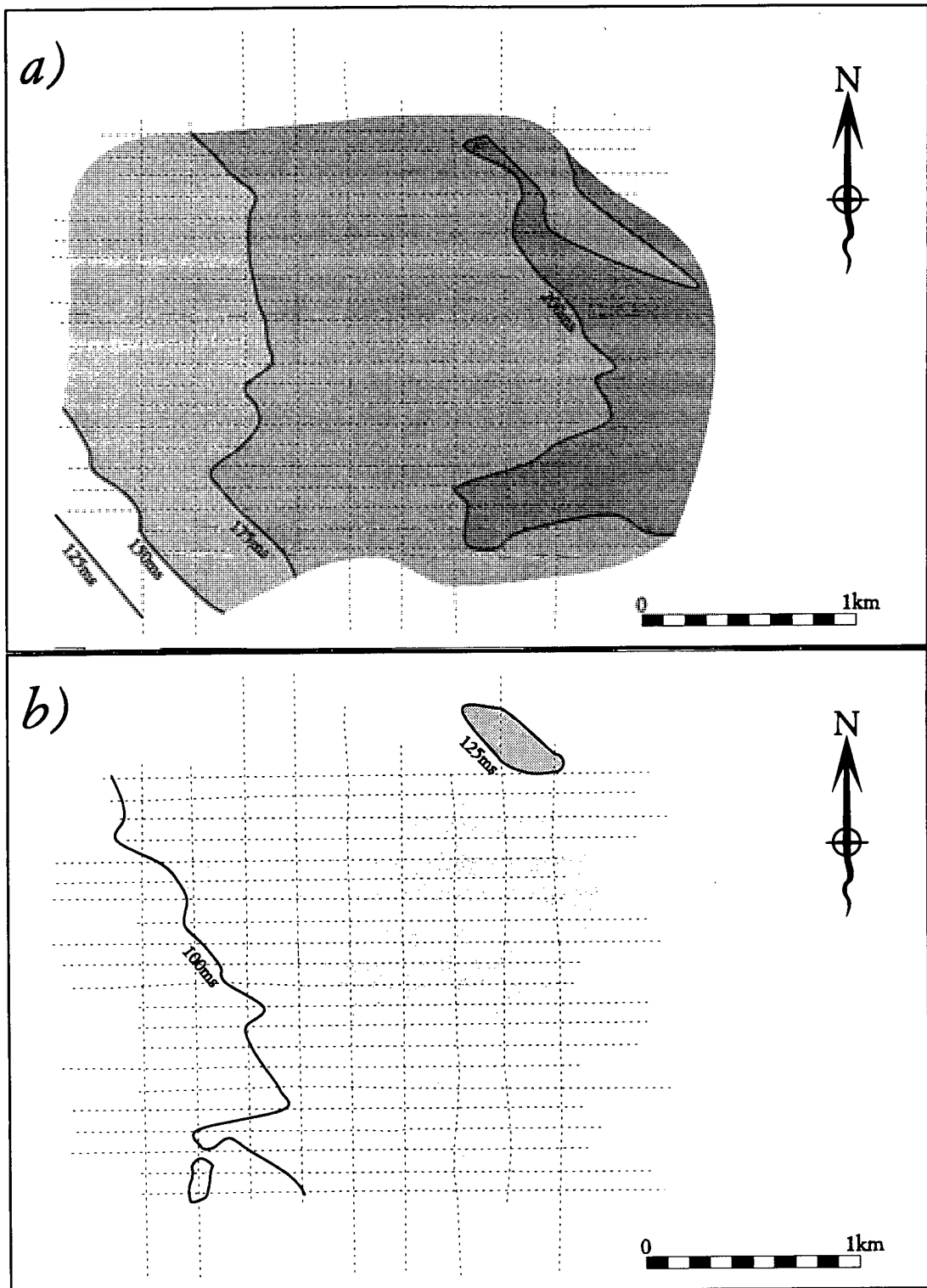


Fig. 4.24: Maps from survey L3-E: a) TWT contours of the base of interval "L3-G5", showing eastward dip, except in the SW corner of the area; b) TWT contours of the base of the fourth glacial "channel".

Interval L3-P1

Top of Interval: 870 to 880ms TWT, slightly faulted. Eastward dip due to lateral velocity changes within the glacial succession.

This interval thins marginally to the west, and is composed of moderate to high amplitude, fair continuity, parallel banded seismic facies. No downlap can be distinguished at its base. The upper surface of the interval is represented by a moderate to high amplitude, normal polarity event, which perhaps represents a marine erosion or hardground surface. The sediments within this interval are most likely to be clay dominated. High amplitude, negative polarity reflections within the interval may be due to differences in porosity, due either to the variable water content of the clay or to the presence of thin bands of sand or silt.

The whole interval, including the base Nordland Group event, has been folded gently into a series of domes and depressions without obvious elongation or preferred orientation. These folds are not present within interval "P2" above, or within any of the younger part of the Nordland Group succession. Some faulting may also be present within the interval.

Interval L3-P2

Top of Interval: 660 to 710ms TWT, dipping uniformly to the WSW.

This interval is of low amplitude and fair to poor continuity. Amplitudes are slightly higher toward the top of the interval, but otherwise, where of low amplitude, this interval also suffers from poor signal to noise ratio and multiple energy on equalised sections. All recognisable events within the interval are roughly concordant with its upper surface and show apparent downlap at its base.

Interval L3-P3

Top of Interval: 630 to 650ms TWT, dipping uniformly to the WSW.

This interval is of moderate amplitude, fair continuity seismic facies, its top locally marked by a high amplitude, negative polarity event. The interval shows eastward directed onlap onto the underlying intervals. Local diffraction tails can be seen internally, especially near the base of the interval, although these have not been mapped. This leads to the alternative possibility that, rather than the base of this

interval being a surface of onlap, an angular unconformity surface may lie just above the base of the interval and events within the seismic data may simply appear to show onlap. Interval "P3" probably consists of interbedded sands and clays, and may include porous sand at the top.

Interval L3-P4

Top of Interval: 590 to 600ms TWT. Sub-horizontal.

This interval is of variable seismic facies, showing low amplitude, moderate continuity events at its base but increasing amplitudes and decreasing continuity, with diffraction tails often present, toward the top. This facies change could represent a transition from clay at the base to interbeds of sand and clay near the top of the interval. The base of the interval may be either a surface of eastward onlap or a slight angular unconformity.

Interval L3-P5

Top of Interval: 500 to 510ms TWT. Sub-horizontal.

This interval is of low amplitude, with very poor continuity of events. However, near the middle of the interval, at around 550ms TWT, amplitudes are slightly higher, and a single, moderately continuous, positive amplitude event can be distinguished. This event may well be the same as that seen in interval "L2-P3", there corresponding with a sharp downward increase in velocity in the middle of well interval "11". Moderate amplitude, convex upward events, between 5 and 10ms thick and with associated diffraction tails, can be seen just above this event (see fig. 4.20a). Although possibly representing erosion, when mapped out, these form ridges running NW-SE to WNW-ESE, with their crests about 100m apart. These features may be sand waves. Toward the top of interval "P5", continuity increases and amplitudes are slightly higher, even allowing for the possible presence of interference from multiple energy. The whole interval is probably clay dominated, although sand content may become slightly higher toward the top.

Interval L3-P6 (top Brielle Ground Formation)

Top of Interval: 460 to 465ms TWT. Sub-horizontal.

This interval, which is around 45m thick, is defined at the base by a sharp, high amplitude, normal polarity event, and at the top by a sharp, sometimes very high amplitude, negative polarity event. This suggests that the interval has a lower seismic velocity than those above and below. Thus, interval "P6" is thought to be made up largely of highly porous, wet sand, perhaps containing some gas. Internally, events are of low amplitude and moderate to poor continuity, some events dipping slightly. When mapped out, some events near the base of the interval show WNW-ESE trends (see fig. 4.20b). These could be related to the development of sand waves. The base of interval "P6" locally shows slight relief of less than 5m, and may be an erosion surface.

Interval L3-P7 (Westkapelle Ground and base IJmuiden Ground Formations)

Top of Interval: 405 to 410ms TWT. Sub-horizontal.

This interval, which is about 50m thick, is of low amplitude and continuity at the base, changing to moderate amplitude and continuity toward the top. Convex upward events are present at the base of this interval, with relief of up to 10ms. When mapped out, their crests trend NNW-SSE and WNW-ESE (see fig. 4.21a). As with interval "P5", these features may be sand waves.

Interval L3-P8 (top IJmuiden Ground & Winterton Shoal Formations)

Top of Interval: around 340ms TWT. Sub-horizontal.

This interval is made up of low to moderate amplitude events with poor continuity. The base of the interval shows relief of around 5m. The distribution of a moderate to high amplitude event at this level gives a NE-SW trending axis, which may represent the line of a channel. Just below the top of the interval there is a high amplitude, negative polarity event, possibly due to a downward transition from clay to sand. The base of a glacial channel system soles out at the top of the interval, suggesting that there may be clay at this level. A second, similar event occurs at between 475 and 490ms TWT, and this could also represent a clay layer. However, the rest of the interval is probably dominated by sand.

Interval L3-P9 (Yarmouth Roads Formation)

Top of Interval: between 250 and 265ms TWT, except where removed by glacial erosion.

This interval is made up of low to high amplitude, poor continuity events. Much of the lower half of the interval forms the infill of a ?NNW-SSE trending valley system which may have cut down to depths of 50m or more and potentially has a width of several kilometres. This valley system cuts through a locally preserved succession of low to moderate amplitude, poor to moderate continuity events which may represent sandy clay. The valley system contains a terrace at around 310ms TWT, possibly indicating the presence of an underlying clay layer. In the base of the valley system in the east of the area, cutting down into interval "P8" below, is a 20m deep, roughly circular depression about 300m in diameter, which, as with similar structures in interval "G16-P10" of survey G16-FA, may be a permafrost related pingo.

The upper half of the interval "P9" is defined at its base by a flat, high amplitude event at around 250 to 265ms TWT. Above this event, at around 220 to 225ms TWT, is a second, moderate amplitude, sub-horizontal event. Both events define terrace levels for glacial erosion and may be the tops of clay layer. Otherwise, interval "P9" is interpreted to be dominated by sand.

4.6.3: The Nordland Group Succession (glacial)

This glacial succession of survey L3-E comprises the entire fill of one major channel system, which has probably been shaped by four or more individual phases of channel erosion. The oldest channel, where preserved, reaches down to perhaps no more than ?250 to 260ms TWT (see fig. 4.21b). From the limited available evidence, this channel probably followed a NNW-SSE axis, although its original width and depth are unknown, due to its destruction by the erosion of the second channel. This runs along a NW-SE axis and cuts down to approximately 330ms TWT, the axis plunging and deepening to the NW (see fig. 4.22a). This channel may have been more than 6km wide, although neither margin lies within the survey area. The base of this channel includes at least two NNW-SSE trending, preserved ridges. This may be the result of either multiple-phase channel incision or the confluence of several channel axes. The latter possibility is not ruled out by evidence from the regional data-set. However, evidence from cross-cutting relationships suggests multiple-phase channel erosion, successive channels migrating to the NE. The fill of this channel plunges

axially to the NW.

The third channel is wide and broad. Its base is at 250ms TWT, and, although neither channel margin is seen within the survey area, its axis, which runs N-S, is beyond the eastern edge of the survey area (see fig. 4.23b). The formation of this channel apparently resulted from the filling, from the west, of channel two below by eastward dipping sediments. Conversely, there may also have been erosion of the infill of channel two in the south and west of the area. Interestingly, evidence of possible drumlins, formed during the readjustment of the channel system, suggests that ice may have occupied the channel system at this time.

The uppermost erosion surface or channel cut is shallower than the others, reaching only down to 120ms TWT (see fig. 4.24b). Although the margins of the channel cut are again not seen within the survey area, the erosion axis probably runs along a NW-SE to NNW-SSE line. The whole glacial succession has been divided into 6 separate intervals here for the purposes of detailed discussion (see fig. 4.19).

Interval L3-G1 (base Swarte Bank Formation)

Top of Interval: 130 to 250ms TWT, defined by the level of subsequent glacial erosion.

This interval, which is all that remains of the lowest channel fill, is of low amplitude and poor continuity. Its base, which is often difficult to determine, flattens out at around 250ms TWT, possibly above a clay layer in the pre-glacial sediments underlying the channel system.

Interval L3-G2 (intra Swarte Bank Formation)

Top of Interval: 230 to 300ms TWT (see fig. 4.23a). A channel-like upper surface, although with an axial plunge to the NW, except where eroded by the third channel.

This interval, which forms the basal fill of the second channel, is also of low amplitude and poor continuity seismic facies. The base of this interval is generally poorly defined. This suggests the similarity of acoustic properties between the sediments of this interval, which are likely to be sands, and of those directly beneath them.

Locally, the upper surface of this interval defines straight, elongate ridges up to 250m wide and 15m high (see fig. 4.22b). These are only present where the base

of channel two is raised, causing localized thinning of interval "G2", and they may be due to lithological differences within the interval. Oddly, these apparently erosion resistant features are maintained, without being removed, within the basal topography of the third channel. This suggests they may have been related to processes acting during the formation of channel three. Their morphology is reminiscent of glacial drumlins, and ice may have been present within the channel system during the formation of channel three.

Interval L3-G3 (intra Swarte Bank Formation)

Top of Interval: 190 to 250ms TWT (see fig. 4.23b).

Interval "G3", which forms the remaining fill of the second channel during its evolution into channel three, is of low to moderate amplitude, fair continuity and eastward dipping events. The interval may be made up of both sand and clay. The contact between interval "G3" and "G2" below is only defined by a contrast in seismic facies. However, it seems unlikely that the two are chrono-stratigraphically equivalent.

Interval L3-G4 (?intra Swarte Bank Formation)

Top of Interval: 120 to 210ms TWT, generally dipping gently eastward (see fig. 4.24a).

Interval "G4", which forms the basal fill of the third channel, is generally of low amplitude and fair continuity seismic facies, which show basal onlap. The basal surface of the interval itself is usually defined by the truncation of events within the underlying sediments. However, the upper surface of the interval is a good continuity, moderate amplitude, negative polarity event. A moderate amplitude, normal polarity event is also present 10 to 15ms below the top of the interval. Interval "G4" may be largely made up of sandy clay. However, in the SW, near the margin of the channel, the interval is of relatively low amplitude and poor continuity and may be a more sandy facies.

The relief of events within "G4" is influenced by the shape of base of the third channel. This may be due to draping sediment fill and to post-depositional compaction.

Interval L3-G5 (?top Swarte Bank Formation)

Top of Interval: 90 to 110ms TWT, defined by the base of erosion by the uppermost channel (see fig. 4.24b).

This interval, which comprises the fill of the upper part of the third channel, is generally of low amplitude and poor continuity, although it includes events of moderate amplitude and good continuity. Although such events are rare, they suggest lateral downlap onto interval "G4" and may represent a passive infill stage within the channel.

Interval L3-G6 (?Clever Bank & younger formations)

Top of Interval: sea bed.

Interval "G6", which is of low to moderate amplitude and fair to good continuity, extends across the entire L3-E survey area, and is made up by the fill of the uppermost channel and all subsequent sediments. The basal reflector of the interval is a high amplitude, normal polarity event with much diffraction energy, possibly suggesting the rough nature of the erosion surface. Flat, high amplitude, negative polarity events are occasionally seen at the top of the interval, just below the sea bed. The origin of these is unknown.

4.7: Survey L6-A

The interpretation of this site survey data-set, which is located in the west of the study area (see fig. 4.1), is based upon a complete relative amplitude survey data-set of 29 lines, together with one true amplitude line for amplitude estimation.

4.7.1: The pre-Nordland Group Succession

This succession has been divided into 2 intervals here for the purposes of discussion.

Interval L6-T1 (Chalk Group)

Top of Interval: 1480 to 1620ms TWT. Slightly domed in the NW corner of the area.

The top of this interval is defined by a high amplitude, negative polarity event. Because of poor signal to noise ratio within the interval and the effect of dip filtering on the data, it is difficult to tell which of the events seen within are primary. The interval is probably characterized by low amplitude seismic facies. The top surface of the interval is slightly faulted, faults trending NW-SE.

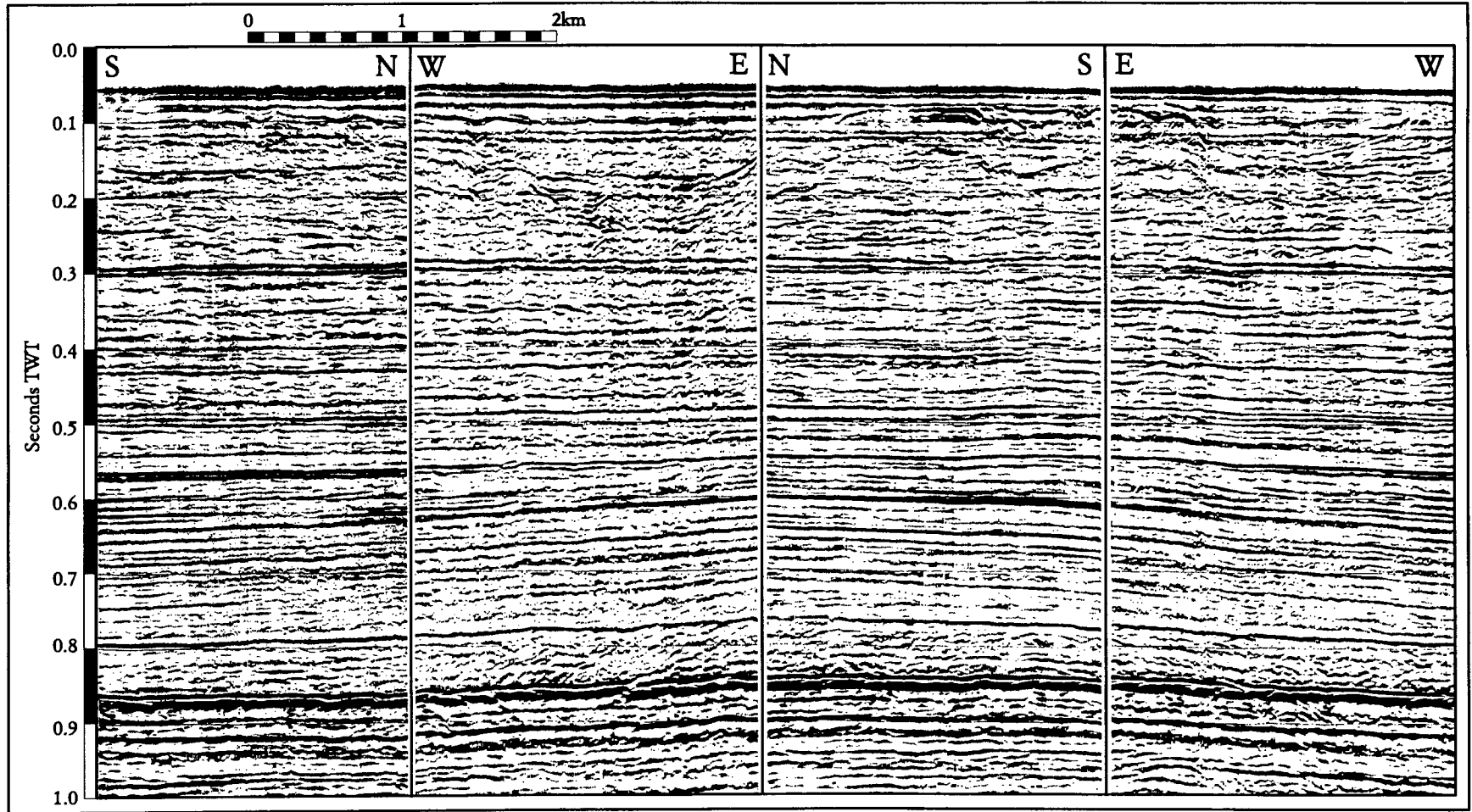
Interval L6-T2 (Lower to base Upper North Sea Group)

Top of Interval: 840 to 870ms TWT, dipping very gently to the west.

This interval, which is difficult to resolve, is of low amplitude and, probably, of low continuity seismic facies.

4.7.2: The Nordland Group Succession (pre-glacial)

The pre-glacial Nordland Group succession has been divided into 8 separate intervals for the purposes of discussion here (see fig. 4.25). The base of the succession, which is defined by a very high amplitude, negative polarity reflector, is locally heavily faulted. The Nordland Group succession sometimes includes vertical disruption features up to 100m wide and sometimes affecting all levels. These features could be artefacts of data acquisition, although the absence of disruption near the top of the seismic data suggests that they are real features. The disruption is most likely to be associated with vertical, water or gas escape through the sediment pile.



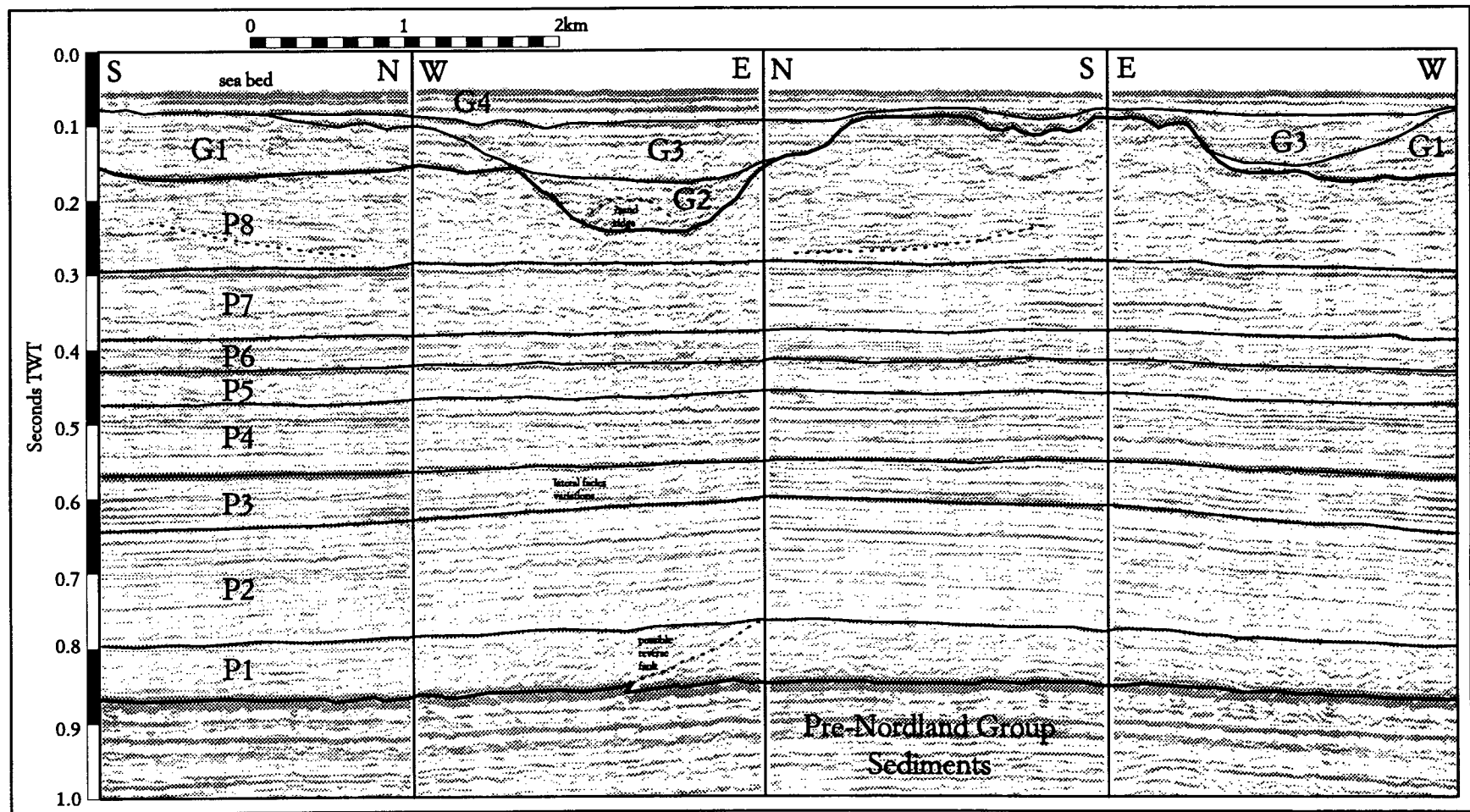


Fig. 4.25: "Seismic outer line box" (interpreted and uninterpreted) of survey L6-A down to 1000ms TWT, showing the intervals from the Nordland Group succession described in the text (data courtesy of SIPM).

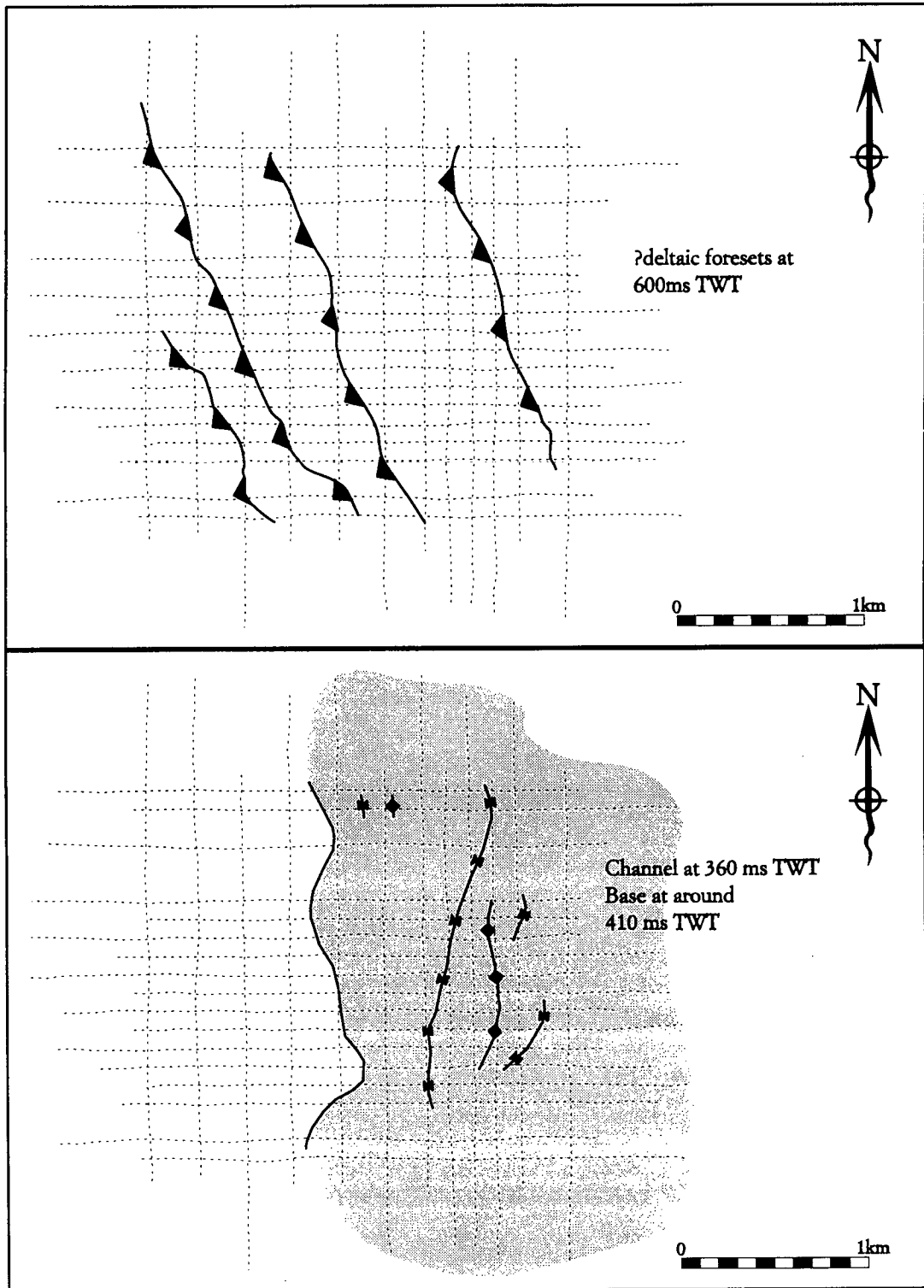


Fig. 4.26: Maps from survey L6-A: a) Position of dipping reflector surfaces at 600ms TWT, within interval "L6-P3". Note their straight nature by comparison with similar reflector surfaces seen in survey L2-A; b) 50m deep valley cut seen within interval "L6-P7", at around 360ms TWT, showing axes of ridges related to channels within the valley cut.

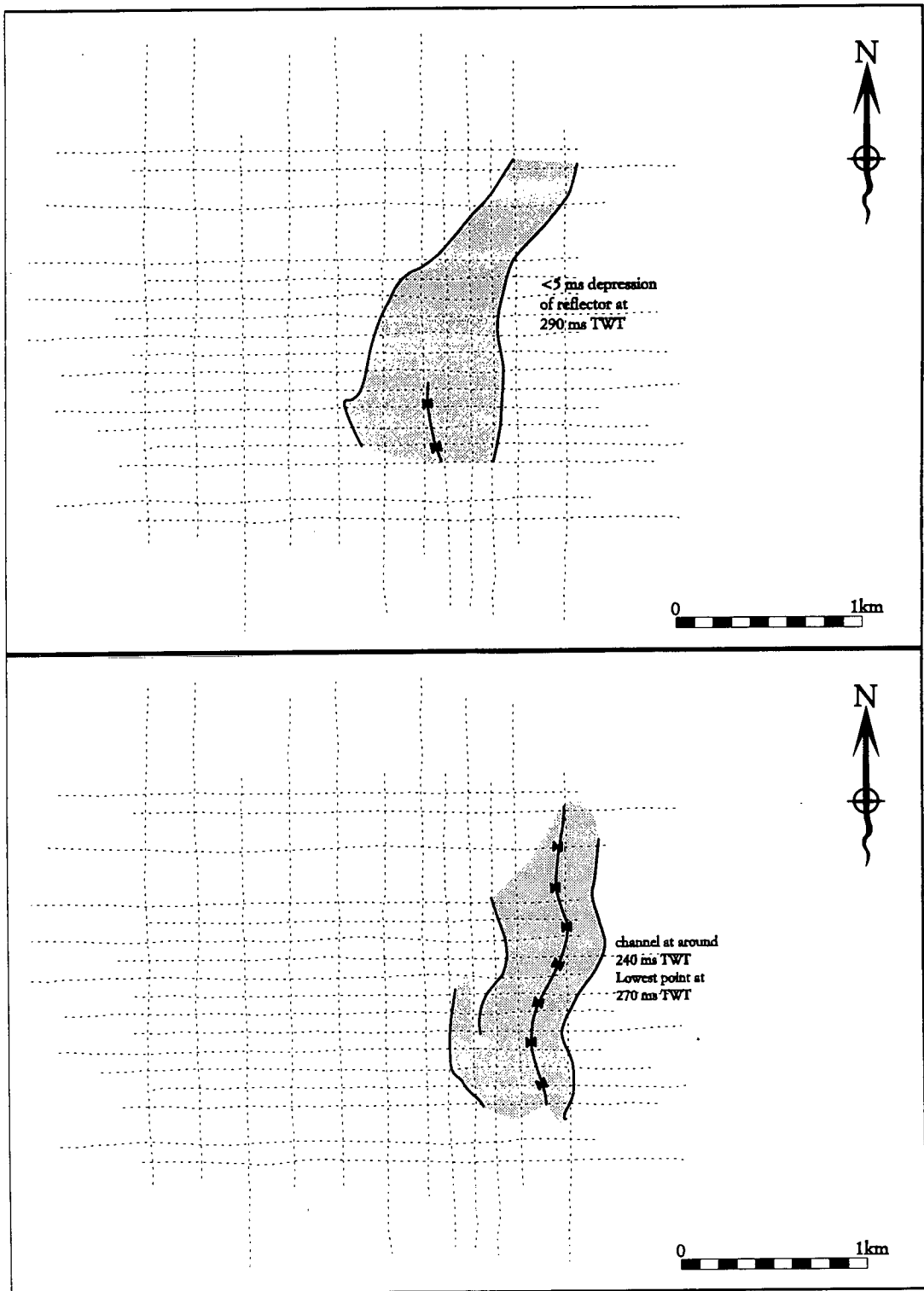


Fig. 4.27: Maps from survey L6-A: a) A 5m deep channel cut at the base of interval "L6-P8", revealed by depression in the upper reflector of interval "L6-P7" below; b) A 30m deep channel, again within interval "L6-P8".

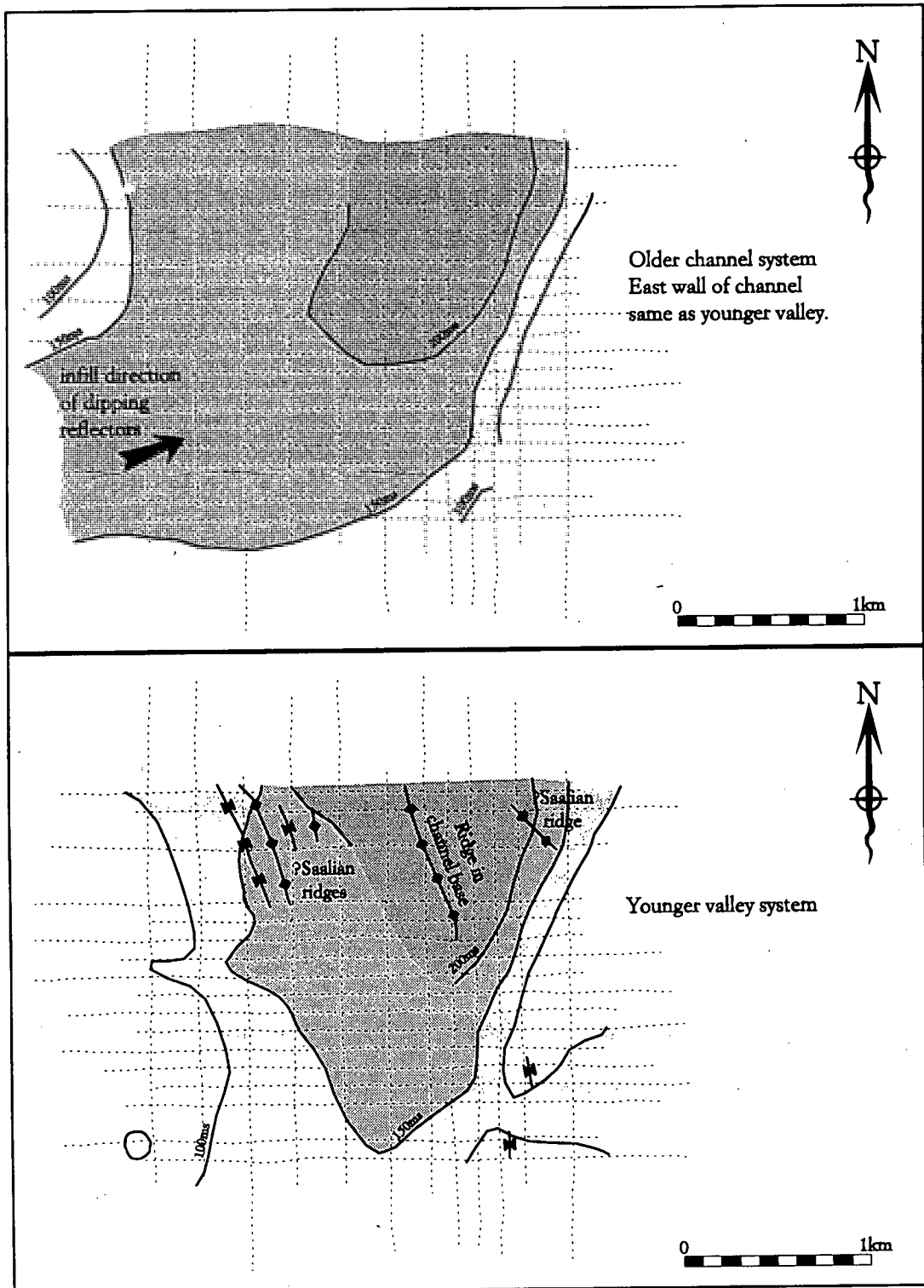


Fig. 4.28: Maps from survey L6-A: a) TWT contours of the older glacial channel of the survey. The western wall of the valley may have been reshaped by the younger channel system; b) TWT contours of the younger glacial channel of the survey. The axis of the valley contains a NNE-SSW trending ridge which may be a channel sand or esker. The other ridges indicated are at the base of interval "L6-G4" and may be due to more recent, perhaps Saalian, glacio-tectonics.

Interval L6-P1

Top of Interval: 760 to 800ms TWT, dipping slightly to the west.

This interval is of low amplitude, low to moderate continuity seismic facies. Locally it is apparently chaotic. On close inspection, low angle events can be traced within this chaotic facies, these events dipping generally to both the ENE and WSW. These dipping events define reverse fault planes cutting the base, but not the top of the interval; the latter defined by a continuous, moderate amplitude, normal polarity event (see fig. 4.29). This suggests that the majority of disruption of the interval took place before deposition of subsequent sediments. The lithology of the sediments is uncertain, although it is probable that they are dominantly composed of clay.

Interval L6-P2

Top of Interval: 590 to 640ms TWT, dipping to the WSW.

This interval is of low amplitude, poor to fair continuity seismic facies. Events show possible WSW directed downlap onto, or convergence with the top of interval "P1" below, but are otherwise parallel, showing uniform dip directions to the WSW. One moderate amplitude event is locally present between 710 and 670ms TWT. Another moderate amplitude, continuous event at a shallower level is probably a multiple. The top of the interval is defined by a moderate, locally high amplitude event of variable polarity. Interval "P2" is probably dominantly composed of clay.

Interval L6-P3

Top of Interval: 540 to 570ms TWT, dipping gently to the WSW.

This interval is of variable and laterally diachronous seismic facies. The top part of the interval is of very low amplitude and poor continuity facies. This grades downward into moderate amplitude, fair continuity facies. This latter facies rarely exhibits downlap onto the base of the interval. Dip directions are to the WSW and remain uniform throughout (see fig. 4.26a). The top of the interval is marked by a moderate to high amplitude, negative polarity event. Interval "P3" is probably made up of sandy clays, coarsening up to sands.

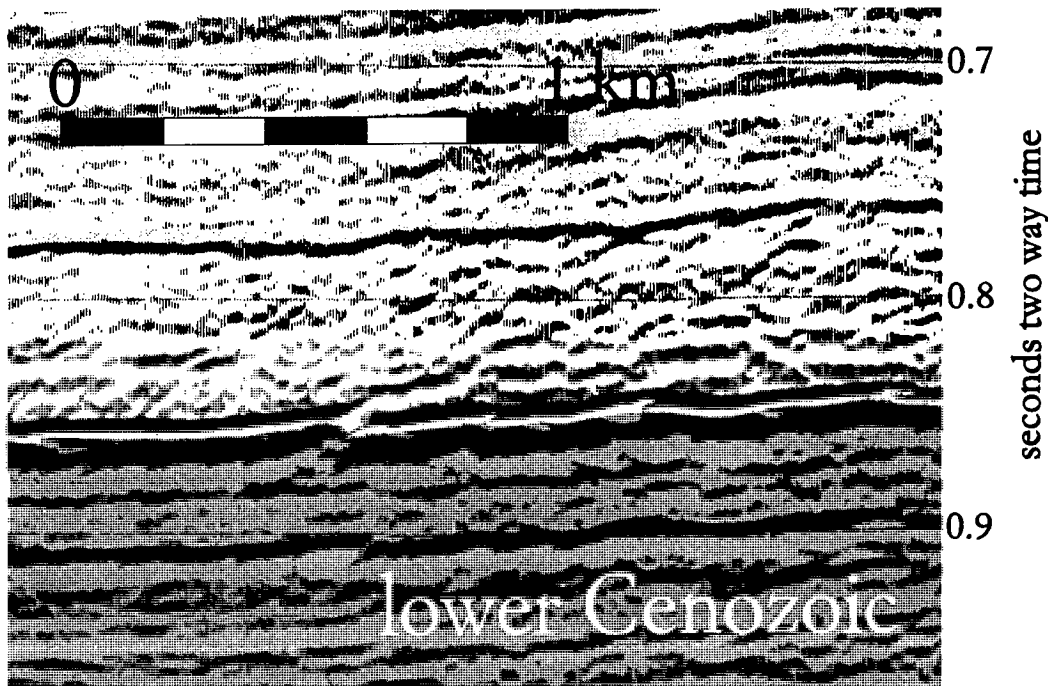


Fig. 4.29: Possible reverse faulting within basal interval "L6-P1" of survey L6-A. Note the lack of disturbance in the intervals above. It is unknown whether the intervals below are disturbed (data courtesy of SIPM).

Interval L6-P4

Top of Interval: 450 to 480ms TWT, gently dipping to the WSW.

This interval is composed of two main facies, alternately banded with each other to form four units, numbered here from 1 to 4 upward. Units 1 and 3 are of low amplitude, moderate to good continuity, parallel banded seismic facies, and these possibly represent clay. The top of unit 3 is often of a high amplitude event. Units 2 and 4 are of moderate amplitude, moderate continuity seismic facies, which might suggest interbedded sand and clay. Unit 2 is probably the sandier unit of the two, as it locally includes poor continuity and slightly chaotic reflector configurations. The whole interval possibly represents two coarsening upward cycles.

Interval L6-P5 (top Brielle Ground Formation)

Top of Interval: 410 to 430ms TWT, dipping very gently to the WSW.

This interval is of low amplitude, low continuity seismic facies. Its internal reflectors show apparently random orientations, and thus cannot be mapped. The base of the

interval has a variable nature, suggesting a slight erosion surface with less than 5m relief. The top of the interval is a fairly high amplitude, negative polarity, continuous event. Interval "P5" is probably made up largely of sand.

Interval L6-P6 (Westkapelle Ground & base IJmuiden Ground Formations)

Top of Interval: 370 to 390ms TWT, dipping very gently to the WSW.

This interval is composed of moderate amplitude, poor to fair continuity seismic facies, and is largely parallel banded. Although weakly dipping events can be seen within, none has been mapped.

Interval L6-P7 (top IJmuiden Ground to ?Markham's Hole Formations)

Top of Interval: 290 to 300ms TWT.

This interval is again of low amplitude, poor continuity seismic facies. Its base is erosive, but shows relief of no more than 5m. One valley-like feature has been mapped out within the basal half of the interval (see fig 4.26b). This feature is 50m deep, at least 1500m wide, and trends N-S. Secondary, channel-like features can be seen within the banks of this valley. The largest of these, around 750m wide and 20m deep, shows a NNE-SSW trend. The top of the interval is defined by a high amplitude, continuous, negative polarity event. Interval "P7" is probably largely made up of sand, the channels suggesting that much of this sand is fluvial in origin. The top part of the interval, above the channels, could be composed of clay.

Interval L6-P8 (Yarmouth Roads Formation)

Top of Interval: up to 100ms TWT, defined by the base level of glacial erosion.

This interval is of low to moderate amplitude, low continuity seismic facies, and parallel events are absent. Moderate amplitude events and very weak truncation of the basal, high amplitude event allow mapping of channel axes near the base of the interval. These are up to 1km wide, 30m deep valleys with approximately N-S trends (e.g. fig. 4.27a & b). The interval is probably sand dominated and, at least near the base, includes fluvial sediments. Occasional, moderate amplitude, fair continuity events within the lower half of the interval could be the remnants of partially eroded clay horizons.

4.7.3: The Nordland Group Succession (glacial)

The glacial succession in survey L6-A has been divided into 4 units for the purposes of discussion here (see fig. 4.25). The base of the succession is defined by a major erosion surface cut into the underlying sediments. This erosion surface is found between 90 and 250ms TWT, and defines the base of a valley system trending between SW-NE and N-S. This system is somewhat complex, essentially being made up of two channel phases. The older channel trends SW-NE, is wide and shallow, probably reaching down to around 210ms TWT, and runs across the centre of the survey area (see fig. 4.28a). A wide, flat terrace, which forms much of its base, is very likely to be the result of the channel largely failing to cut down through a clay layer at about 180ms TWT in the underlying, pre-glacial succession.

The upper channel is comparatively deep, cutting down to 250ms TWT, and, although of similar trend to the first, is deeper in the north of the survey than the older channel (see fig. 4.28b). This channel may have evolved directly from the first by breaching of the pre-glacial clay layer at 180ms TWT, causing rapid deepening of the valley system in the NE, with concomitant infill of the older channel in the SW. The base of the younger channel soles out at 250ms TWT, presumably above another clay layer at this level within the underlying, pre-glacial succession.

Interval L6-G1 (?base Swarte Bank Formation)

Top of Interval: 90 to 160ms TWT, depending on the level of subsequent glacial erosion.

Interval "G1" comprises the entire fill of the older channel. The base of the interval is typically defined by a high amplitude, planar, negative polarity event. Generally the interval is of low amplitude and low continuity seismic facies, although events near the top of the interval is partly obscured by the first water-bottom multiple event. However, weak to moderate amplitude, ENE dipping events can be seen near the western margin of the channel. The geometry of these dipping surfaces suggests that the channel was gradually filled in axially from the SW, possibly during the genesis of the younger channel (see fig. 4.28a).

Interval L6-G2 (intra Swarte Bank Formation)

Top of Interval: 140-180ms TWT. Only present within younger channel.

This interval, which comprises the basal fill of the younger channel, includes low to moderate amplitude, poor continuity events. The top of the interval is defined by a negative polarity event. The base is often ill defined, but locally marked by high amplitude, negative polarity, diffraction events which mask the texture of the seismic facies below. Along the middle of the channel there is a zone of low amplitude which seems to define a NNW-SSE trending ridge feature, slightly oblique to the channel axis (see fig. 4.28b). This feature could represent the form of a sand filled channel within the younger channel system, possibly having a domed upper surface due to compaction of the surrounding sediments. Alternatively it could represent an esker ridge associated with the formation of the younger channel system.

Interval L6-G3 (?top Swarte Bank Formation)

Top of Interval: 80-105ms TWT. Only present within younger channel.

This interval, which comprises the remaining fill of the younger channel, is generally made up of low amplitude, poor continuity events. Local high amplitude events are present in the NW of the area but these are probably due to localized shearing of sediment, as the upper surface of the interval has been subsequently disturbed here. The interval may therefore be composed of clay.

Interval L6-G4 (?Cleaver Bank and younger formations)

Top of Interval: sea bed.

This interval, which is distributed over the whole area of survey L6-A, includes low amplitude, fair continuity events at the base, passing upward into high amplitude, good continuity events at higher levels. This could represent sandy clay passing up to sand. The base of the interval, which is of normal polarity, locally includes NNW-SSE to NW-SE trending troughs and ridges which are probably glacio-tectonic in origin, perhaps related to SW directed ice movements (see fig. 4.28b). However, it is not known whether these features are associated with the original, glacial channel system or are the result of deformation during a later glacial phase.

4.8: Survey M1-A

This survey is located in the far west of the study area (see fig. 4.1). Due to the supply of only 7 relative amplitude plots and one true amplitude plot of lines from this survey, three-dimensional facies analysis of this survey area is limited.

4.8.1: *The pre-Nordland Group Succession*

This succession has been divided into two intervals for the purposes of discussion here.

Interval M1-T1 (Chalk Group)

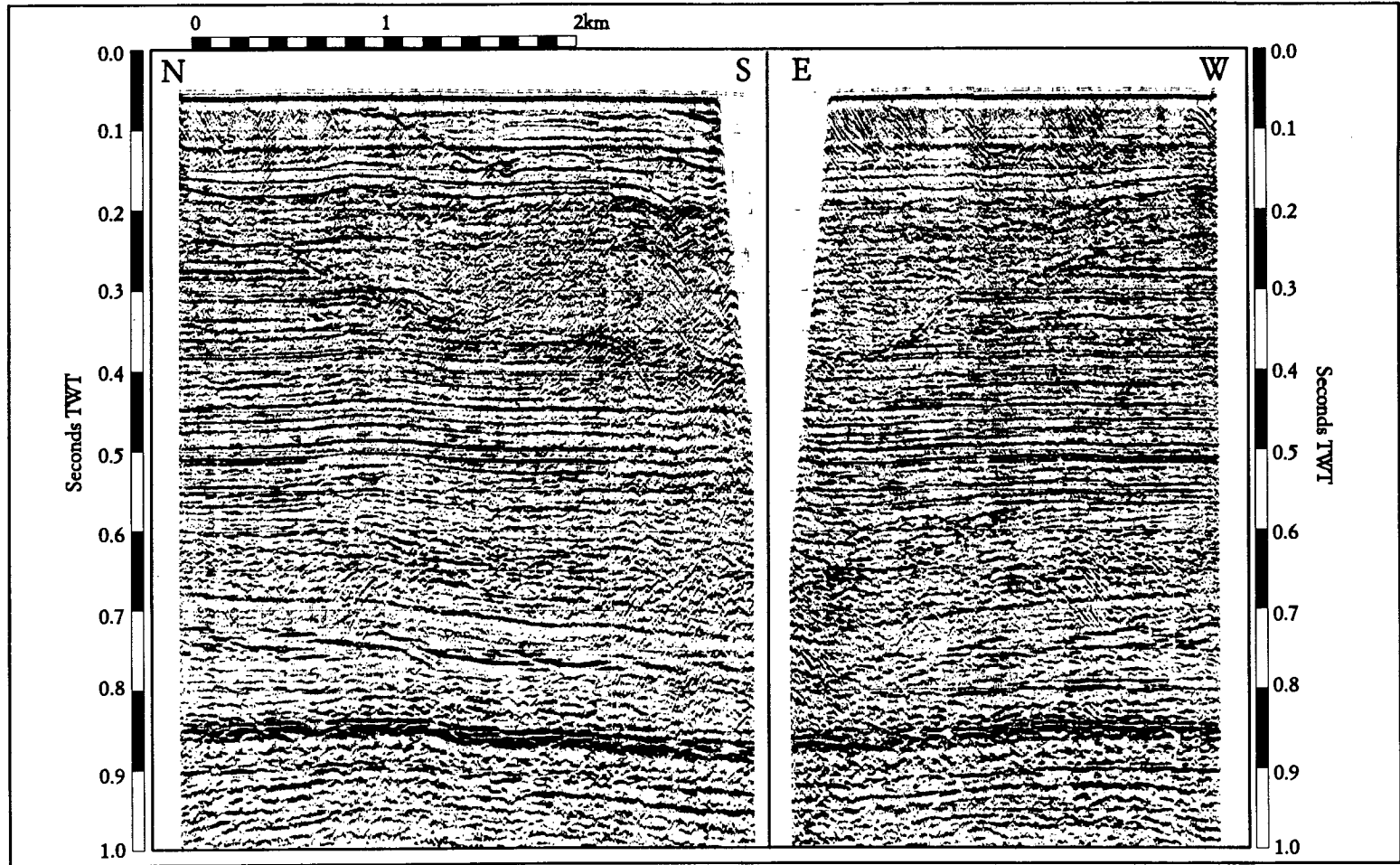
Top of Interval: 1500 to 1380ms TWT, in the form of a weak, possibly salt uplift related dome, slightly to the NE of the centre of the area.

Signal to noise ratio is poor at this level. However, the top of the interval is distinguished by a high amplitude, positive polarity event. This event is rarely affected by faults with offsets of up to 30ms.

Interval M1-T2 (Lower to base Upper North Sea Group)

Top of Interval: 840 to 870ms TWT. A gentle anticline, plunging to the SW.

This interval is again of poor signal to noise ratio, with multiple energy obscuring much of its character, especially near the top. Generally, the interval is of low amplitude and continuity. Two events are traceable about 60 and 250ms above the base of the interval, and are concordant with it. Toward the top of the interval higher amplitude, discontinuous events are present, but the exact nature of these events is unclear. A normal polarity event can be distinguished at between 960 and 1000ms TWT. Rare, low to moderate amplitude, discontinuous events are present throughout the interval showing excessively high dips by comparison with the upper and lower surfaces of the interval. However, these dipping events cannot be traced laterally.



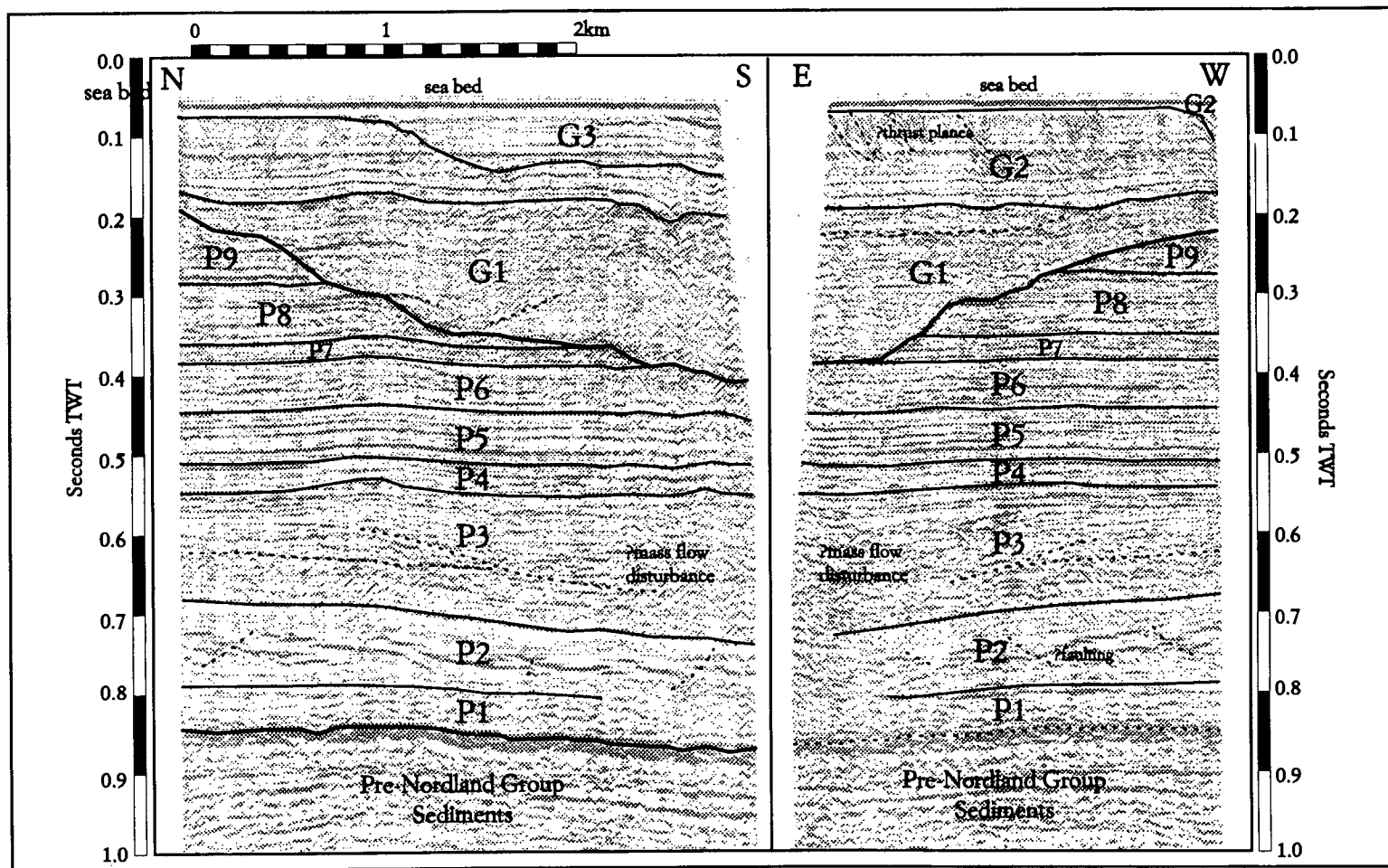


Fig. 4.30: Seismic lines (interpreted and uninterpreted) from survey M1-A down to 1000ms TWT, showing the intervals from the Nordland Group succession described in the text (data courtesy of SIPM).

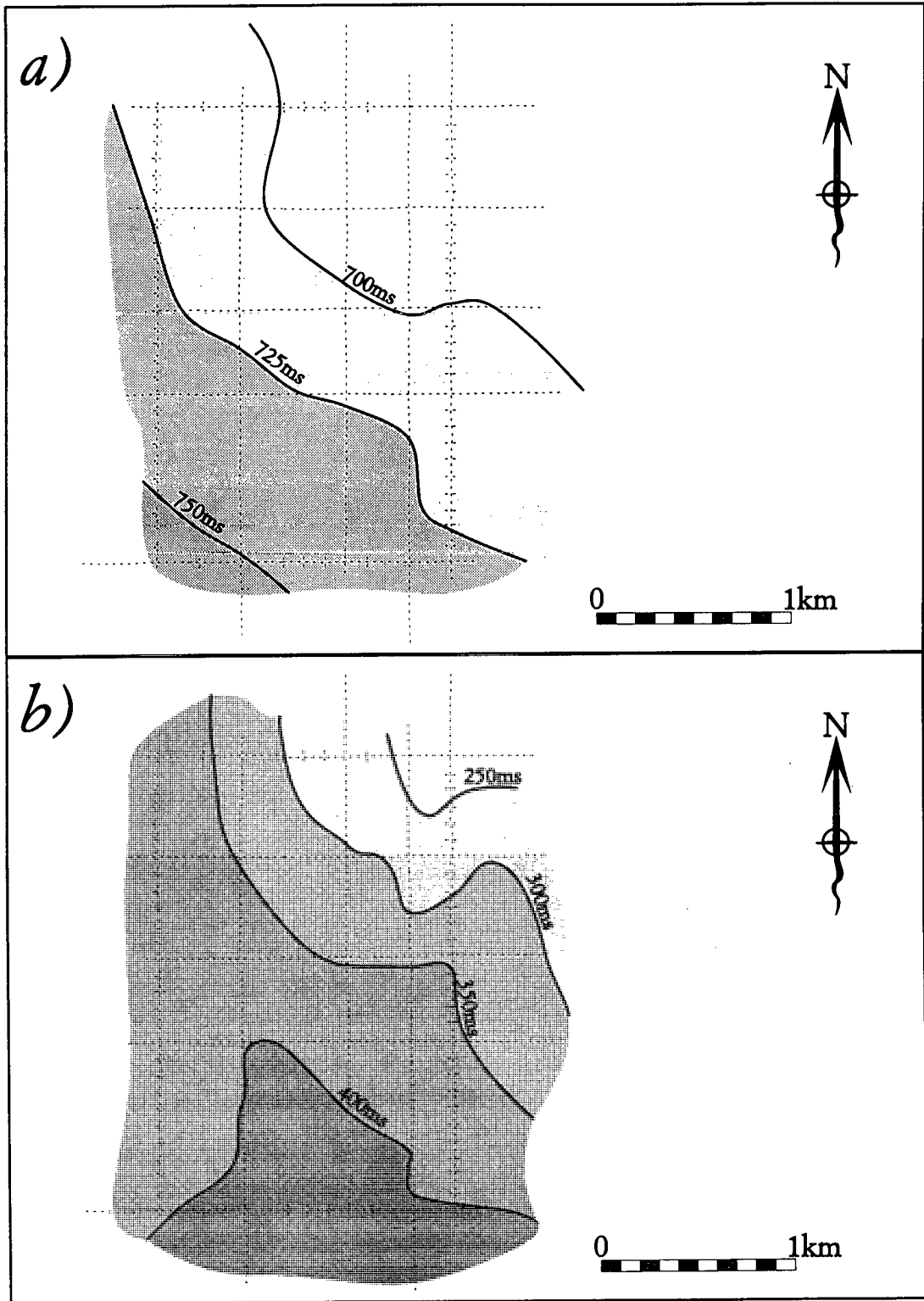


Fig. 4.31: Maps from survey M1-A: a) TWT contours of the upper surface of interval "M1-P2", showing gentle folding on a SW dipping surface. This folding is unlikely to be due to velocity effects within the glacial succession; b) TWT contours of the base of the lower glacial channel system.

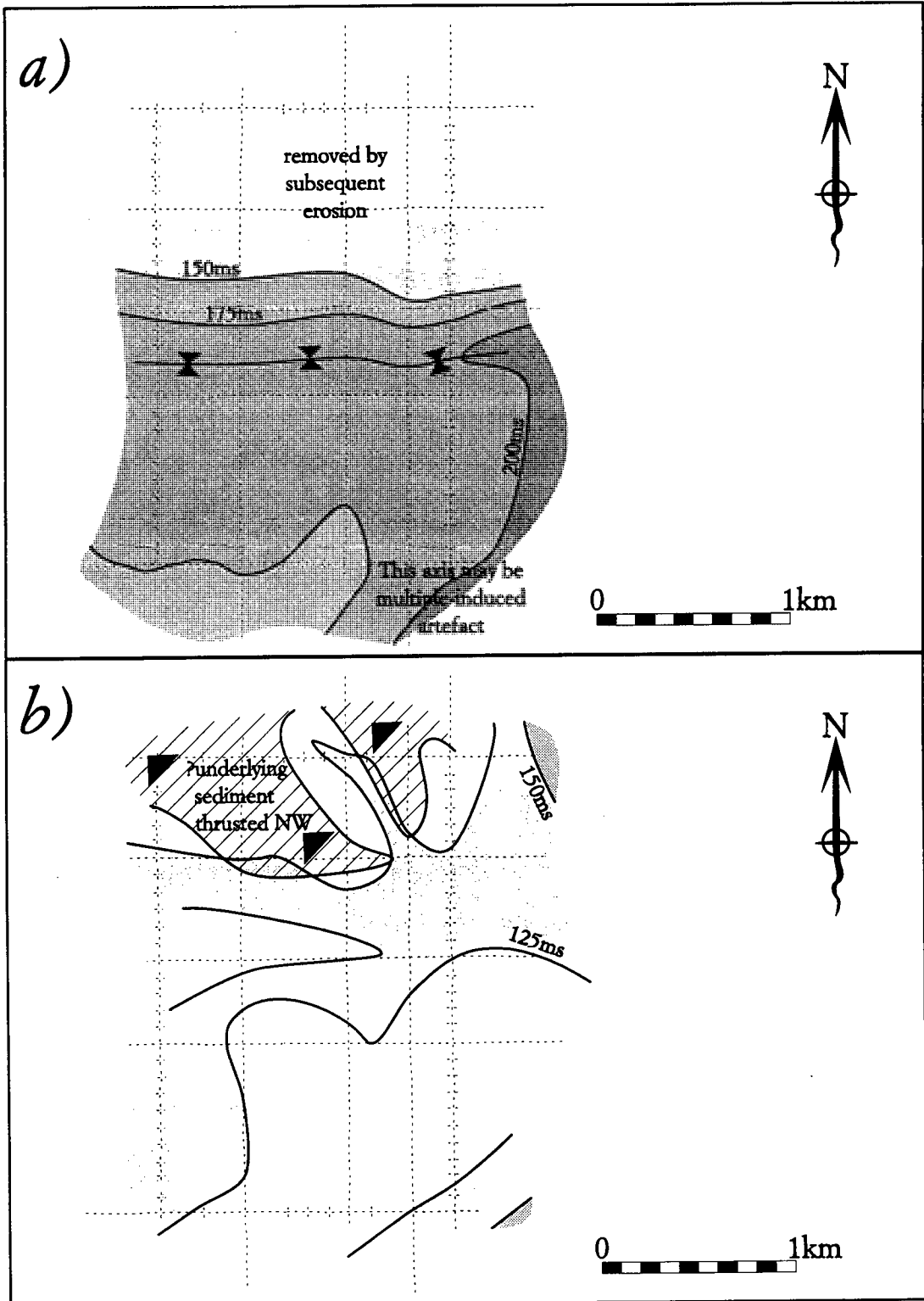


Fig. 4.32: Maps from survey M1-A: a) TWT contours of the base of the upper glacial channel system; b) TWT contours of the depressions within the top of the upper glacial channel system, showing their lack of channel-like form. Also shown are the zones of disturbance within the upper part of interval "M1-G2", which are probably of similar age.

4.8.2: The Nordland Group Succession (pre-glacial)

The base of this succession is marked by a very high amplitude, negative polarity event. This is made up of a series of planar events which show sudden changes of level of as much as 10m, and may either represent gas-water contacts or faulting. Some diffraction tails are also present, associated with the edges of these events. This succession has been divided into 9 intervals for the purposes of discussion here (see fig. 4.30).

Interval M1-P1

Top of interval: 790 to 810ms TWT.

This interval contains low to moderate amplitude, low continuity events which often show diffraction tails and dip excessively with respect to the base of the interval. The interval is probably slightly disturbed, and could be the distal equivalent of a mass flow unit.

Interval M1-P2

Top of interval: 680 to 750ms TWT. Dip to the WSW, although, slightly folded along a SW-NE axis, which is unlikely to be a velocity effect (see fig. 4.31a).

This interval contains very low amplitude, poor continuity events. However, in the middle of the interval, at between 720-740 and 820-840ms TWT, there is a thin unit of moderate to high amplitude, positive polarity events which show fair to poor continuity. This unit has a broken appearance, each event present often being only 150m long and approximately horizontal. However, groups of these events define the tops of much larger, separated packages dipping SW. Although evidence is somewhat ambiguous, these packages could represent the “up-slope slump-scars” seen on regional seismic data in slump unit “A” (see section 2.3.2). The horizontal events which define the top of the packages may therefore be due to gas entrapment, and a gas-water contact at this horizon. Interval “P2” may be predominantly made up of clay, although the higher amplitude packages within may be sandier.

Interval M1-P3

Top of Interval: 540 to 570ms TWT.

This interval is locally highly disturbed, and has been difficult to interpret because of the lack of three dimensional control available from the supplied lines. Internal events are of moderate, rarely high amplitude but are generally broken looking and hence of poor continuity. This broken appearance is probably due to major internal disruption of the interval. Where locally undisturbed, some events are seen to be continuous. The majority of the disturbance occurs in the SW of the area. Here, there is evidence for intra-formational, rotational fault block development, with fault throws apparently to the SW. A possible decollement or erosion surface, perhaps associated with this faulting, is present between 675 and 710ms TWT, and is indicated by a zone of diffraction tails. This surface has cut down at least into interval "P2" and, possibly, into interval "P1", but has not disrupted the base Nordland Group reflector. It is not known how far up the effects of faulting extend within the interval, although there is no evidence of faulting at its upper surface. Interval "P3" is again probably composed largely of clay.

Interval M1-P4

Top of Interval: 500 to 520ms TWT.

This interval includes low to moderate amplitude, fairly continuous, parallel events, which show no obvious, distinguishing features. The base of the interval is locally an unconformity surface. High amplitude events are present around the middle of the interval locally, appearing to describe depressions up to 5m deep. These depressions show basal diffraction tails and are probably the result of erosion. However, they cannot be traced across the survey area using the available data-set. The top of the interval is marked by a high amplitude, negative polarity event. Interval "P4" is probably made up of clay with some sand layers.

Interval M1-P5

Top of Interval: 430 to 450ms TWT.

The events within this interval are mostly of moderate, rarely high amplitude, parallel, and show fair to good continuity. However, units of poor continuity can also be distinguished. Interval " P5" possibly contains both clay and sand layers.

Interval M1-P6 (top Brielle Ground to base IJmuiden Ground Formations)

Top of Interval: 380 to 390ms TWT, except where top eroded by glacial valley system.

This interval is generally made up of low amplitude and poor continuity packages separated by moderate amplitude, fair continuity events. In the middle of the interval, low to moderate amplitude, good continuity, high frequency events can also be distinguished. The poor continuity, low amplitude facies possibly represent sand bodies, and there is certainly evidence for channels of over 5m in depth within the interval.

Interval M1-P7 (?intra-IJmuiden Ground Formation)

Top of Interval: 350 to 370ms TWT, except where eroded out by glacial channel system.

This interval contains moderate to low amplitude, continuous, parallel events. These events are sometimes eroded by channels of both the overlying interval and the glacial succession. The basal erosion surface of the glacial channel system has a stepped form, the upper surface of the interval forming a terrace level which is apparently resistant to erosion. This suggests that at least the upper part of the interval could be of clay.

Interval M1-P8 (top IJmuiden Ground & Winterton Shoal Formations)

Top of Interval: 275 to 280ms TWT, except where eroded out by glacial channel system.

This interval is of generally low amplitude and poor continuity. However, moderate amplitude events are occasionally present toward the base of the interval. These events are wavy in appearance and are possibly channelled surfaces. The base of the interval is erosive, although showing relief of no more than 10m. About 30ms below the top of the interval is a moderate amplitude, continuous event, marking a horizon apparently resistant to glacial erosion, and is associated with terrace formation within the glacial channel. Most of interval "P8" is probably composed of sand, although the moderate amplitude event perhaps corresponds with a clay horizon.

Interval M1-P9 (Markham's Hole to Yarmouth Roads Formation)

Top of Interval: 200ms TWT, defined by the level of glacial erosion.

The base of this interval, where present, is marked by a horizon resistant to glacial erosion, and is denoted by a high amplitude, negative polarity, continuous event. This event probably represents the contact between a clay and an underlying sand layer. About 15ms above the base of the interval there is another event of moderate amplitude that has been eroded from much of the survey area. Apart from this, remnants of interval "P9" have only locally been preserved from glacial erosion, and resolution of this seismic facies is poor.

4.8.3: The Nordland Group Succession (glacial)

The glacial succession of survey M1-A comprises the fill of two channel systems and has been divided into three intervals for the purposes of discussion here (see fig. 4.30). The base of the lower channel system ranges in depth from 200 to 420ms TWT (see fig. 4.31b). It is oriented NNW-SSE, plunging to the SSE, and is estimated to be over 6km wide from shoulder to shoulder. Its basal surface is picked out in the channel axis by high amplitude diffraction events which mask events in the underlying sediments, but it can only be distinguished elsewhere by the level of erosion of continuous, horizontal events from the underlying succession. The lower part of the infill plunges to the NNW, whilst the upper infill is essentially sub-horizontal.

The second channel system, which reaches down to 150ms TWT and is oriented W-E, with secondary axis running SW-NE, cuts the lower channel system in the south of the area. The top of this channel system shows evidence of glacio-tectonic deformation, directed NW, and of small, SE-NW oriented, elongate basins down to 110ms TWT (see fig. 4.32b).

Interval M1-G1 (base Swarte Bank Formation)

Top of Interval: 170 to 210ms TWT.

This is a very low amplitude, poor continuity interval, that forms the lower fill of the older channel system, showing onlap onto the walls of the channel system. The top of the interval is often defined by a very high amplitude, negative polarity event, which has reduced event energy beneath it. This event locally shows flat spots, which could be due to the presence of a gas-water contact at this level. Near the deep, SSE end of the valley system, the top of the interval has apparently collapsed, forming a series of ridges. High amplitude, negative polarity, diffractive events at the base of the interval in the channel axis could represent a rough basal surface.

A moderate amplitude facies can also be distinguished locally at the top of the interval in the channel axis. However, this facies appears to be laterally contiguous with the normal, low amplitude facies toward the valley margins and does not necessarily represent a separate unit. Due to its very poor continuity on seismic data, the whole of interval "G1" may have been disrupted after deposition, and the collapse of the upper surface of the interval above the channel axis may be due to subsequent compaction.

Interval M1-G2 (?top Swarte Bank Formation)

Top of Interval: up to 70ms TWT, defined by the erosive base of the overlying interval.

This interval, which is the upper fill of the older channel system, is characterized by low to moderate amplitude, fair continuity events which are concordant with interval "G1" below. However, a moderate to high amplitude, normal polarity event, present about 30ms above the base of the interval, is apparently an onlap surface. Continuity of events decreases toward the top of the interval.

High amplitude, SE dipping, steep, negative polarity events are occasionally present at the top of the interval, where it has not been eroded extensively by the formation of the upper channel system. These dipping events apparently cut across other events at this level, and they may be glacio-tectonic in origin, perhaps marking thrust surfaces, related to NW directed ice movement (see fig. 4.32b). These probably relate to the later stages of interval "G3" above. Channelling, defined at its base by high amplitude, diffractive events, is locally present within the lower half of the interval.

Interval M1-G3 (?Clever Bank & younger formations)

Top of Interval: sea bed

The interval is made up of the infill of the second channel system. Its base is marked by a moderate amplitude, normal polarity event with much diffraction energy. Events within interval "G3" are of low to moderate amplitude and are fairly continuous. A second phase of channelling within this channel system, running SE-NW, but obviously influenced by the first channel, is defined at its base by a high amplitude, normal polarity reflector (see fig. 4.32b).

4.9: Discussion

4.9.1: *The pre-Glacial Nordland Group*

Correlation of Data

Figures 4.33 & 4.34 illustrate the suggested correlation of intervals between the different site survey data-sets. This correlation has been achieved largely through the comparison of site survey seismic data with the regional seismic interpretation of chapter 2. However, in the east of the study area, where the majority of the survey data-sets are located, correlation between top-set sequences has often been possible without recourse to the regional seismic interpretation. For example, well interval “14”, the top of the Brielle Ground Formation, was independently recognised as a good regional marker horizon before the site survey data-sets were compared with regional data.

Two horizons, corresponding to the base and top of well interval “19”, appear to be very similar and can easily be wrongly identified, as both show characteristics suggestive of thick clay horizons. These two horizons possibly correspond with the base and top of the Markham’s Hole Formation.

Fore-set sequences could not be correlated independently. This is because they occur within parts of the succession characterized by rapid lateral facies, hence displaying different seismic facies in each of the various site survey areas.

Sand Waves

Possible sand waves have been recognised at three levels within the top-sets (see fig. 4.34):

- 1) A tentative possibility of waves at the base of well interval “11” (L2-FA). Trends for these waves are unknown.
- 2) Near the top of well interval “11” (L2-FA, L3-E and L6-A). These waves may be developed at more than one horizon. Commercial well data suggest that well interval “11” is increasingly sand rich in the SE of the study area, toward the Dutch coast (e.g. L9-1), and this may be due to the presence of increased numbers of sand waves there. Trends for the waves mapped are ?N-S (L2-FA), and NW-SE to WNW-ESE (L3-E).

3) Near the base of well interval “14”, the top of the Brielle Ground Formation (G16-FA, L3-E), which is dominated by sand, and may be composed of multiple sand waves (e.g. G16-FA). Where seen, mapped trends at this level run N-S to NNW-SSE (G16-FA, L3-E), and WNW-ESE (L3-E).

4) At the base of well interval “15”, the base of the Westkapelle Ground Formation (L2-FA, L3-E and, possibly, G16-FA). Trends for these waves are WNW-ESE to NW-SE (L2-FA, L3-E).

It is tempting to assume that these features may be tide or storm generated. If so, then the whole succession from the base of well interval “11” to base of well interval “15” may represent a coarsening upward, tide or storm dominated shelf sequence. The possibility of this environment continuing throughout the deposition of well interval “15” cannot be ruled out. However, similar features have not been seen above the base of this interval.

Channelled Facies

At least seven phases of channel erosion have been recorded within the top-sets of the pre-glacial Nordland Group on the site survey seismic data (see fig. 4.34). These are:

1) At the base of well interval “8” (G16-FA, M1-A). Channels cut down by as much as 15m. However, such channels are only seen in the extreme NE of the study area, and no orientations have been mapped.

2) At the base of well interval “10” (G16-FA), again in the extreme NE of the study area. One channel, possibly with a NE-SW trend, is recorded in survey G16-FA. This erosion surface may also be present to the SW, represented by diffraction tails, in survey L3-E.

3) At the base of well interval “16”, within the IJmuiden Ground Formation (G16-FA, M1-A, L6-A, L3-E, L2-FA and K2-B). This is perhaps the most widespread erosion surface, being present everywhere except in the extreme west of the study area. Channel orientations range from NNW-SSE and NNE-SSW (G16-FA, L2-FA, L6-A) except in survey L3-E, which shows a NE-SW orientation.

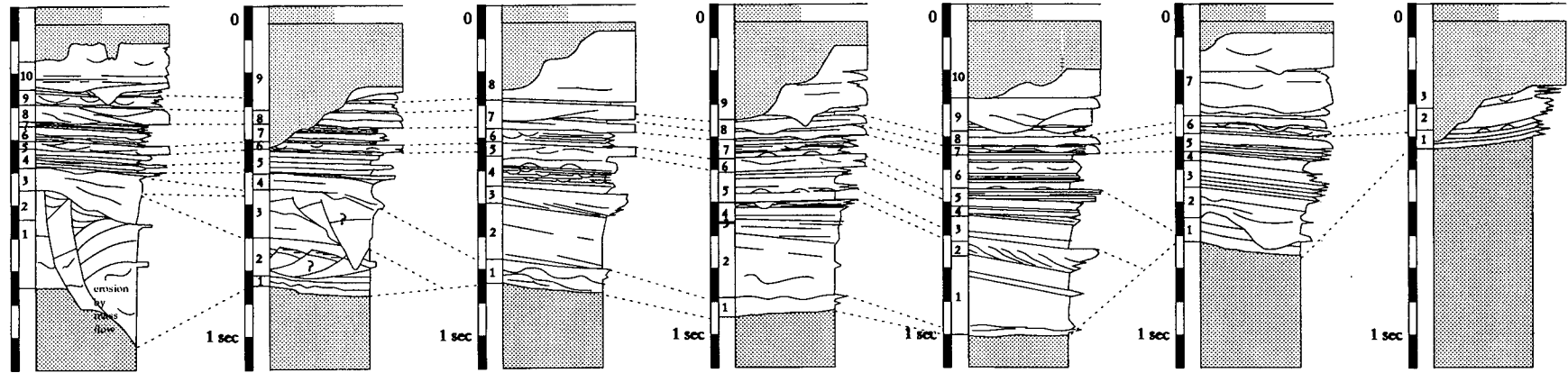


Fig. 4.33: Cartoons of the suggested lithologic changes within the pre-glacial Nordland Group succession of the various site survey data-sets studied here, together with their suggested correlation (dark grey tone at base is pre-Nordland Group sediment, light grey tone at top is glacial Nordland Group sediment).

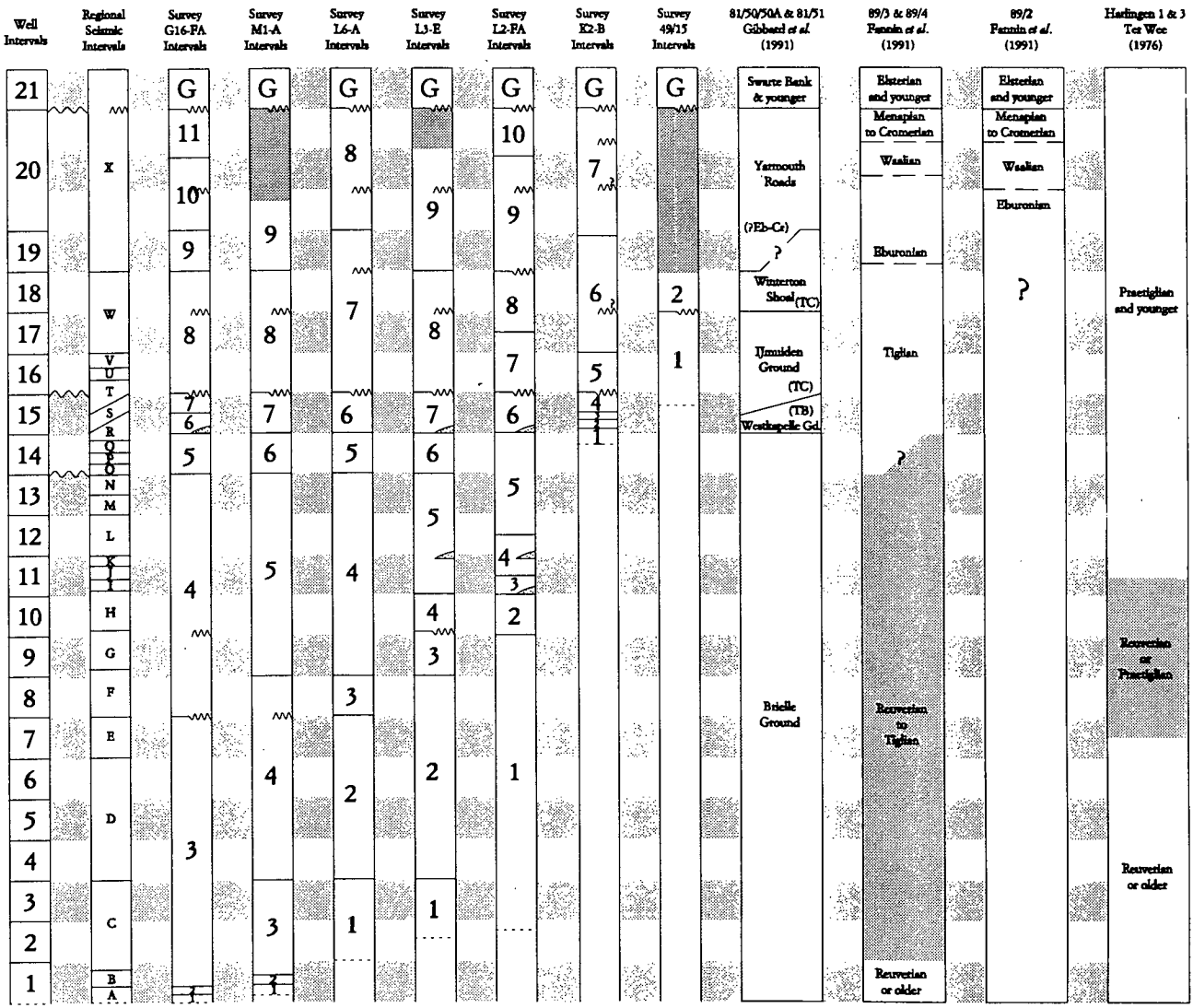


Fig. 4.34: Suggested correlation, for the pre-glacial Nordland group succession, between the site survey data-sets, the lithological and regional seismic stratigraphic schemes presented in chapters 2 and 3, and the published data of various authors. Also shown is the evidence of probable erosion events and sand waves within the site-survey data-sets.

4) At the base of well interval “18”, near or at the base of the Winterton Shoal Formation (G16-FA, M1-A, L3-E, K2-B and, possibly, 49/15). Only in survey G16-FA has a channel orientation been mapped, running NW-SE.

5) Near the base of well interval “19”, which is possibly part of the Markham’s Hole Formation (G16-FA, L6-A, L2-FA). Channelling within this interval is quite rare, probably reflecting the more clay rich nature of the sediments at this level compared with those above and below. Channel orientation is N-S in G16-FA, although a meandering form has been mapped in survey L2-FA.

6) Within the lower half of well interval “20”, in the Yarmouth Roads Formation (G16-FA, L2-FA, L3-E, ?L6-A, K2-B). This has cut valleys which are up to 70m deep over much of NW part of the study area (e.g. in fig. 4.35). It also contains possible large-scale cryoturbation features, which may be eroded pingo remnants (G16-FA, L3-E). Valley orientations are NNW-SSE and NE-SW in G16-FA, N-S in L2-FA and L6-A, and ?NNW-SSE in L3-E.

The lower half of well interval “20” includes a large, intra-Eburonian stage hiatus in *SNSP* boreholes 89/2 & 2A, and 89/3, as stated in Fannin *et al.* (1991 *unpub.*). The valley system may, therefore, be of Eburonian age, whilst evidence from the same report suggests that the valley system’s infill could be of late Eburonian to Waalian age.

7) In the upper half of well interval “20”, again within the Yarmouth Roads Formation (G16-FA, K2-B and L2-FA). This not likely to be one channelling event but rather the continued reworking of the whole interval by channelling. Channel orientations may be fairly uniform, trending NW-SE (G16-FA) or NNW-SSE (L2-FA).

Interestingly, despite the probably erosive nature of the basal surface of well interval “14”, little evidence has been found of associated channelling at this level. The erosion may, therefore, be tide or storm related.

Base of Fluvial Facies: The Nordland Group succession is known to be regressive, and to include fluvial sediments near its top, especially following the Tiglian TC4c regressive event of Zagwijn (1974). However, at what levels fluvial sediments occur within the succession is difficult to ascertain without detailed sedimentological and palaeontological input.

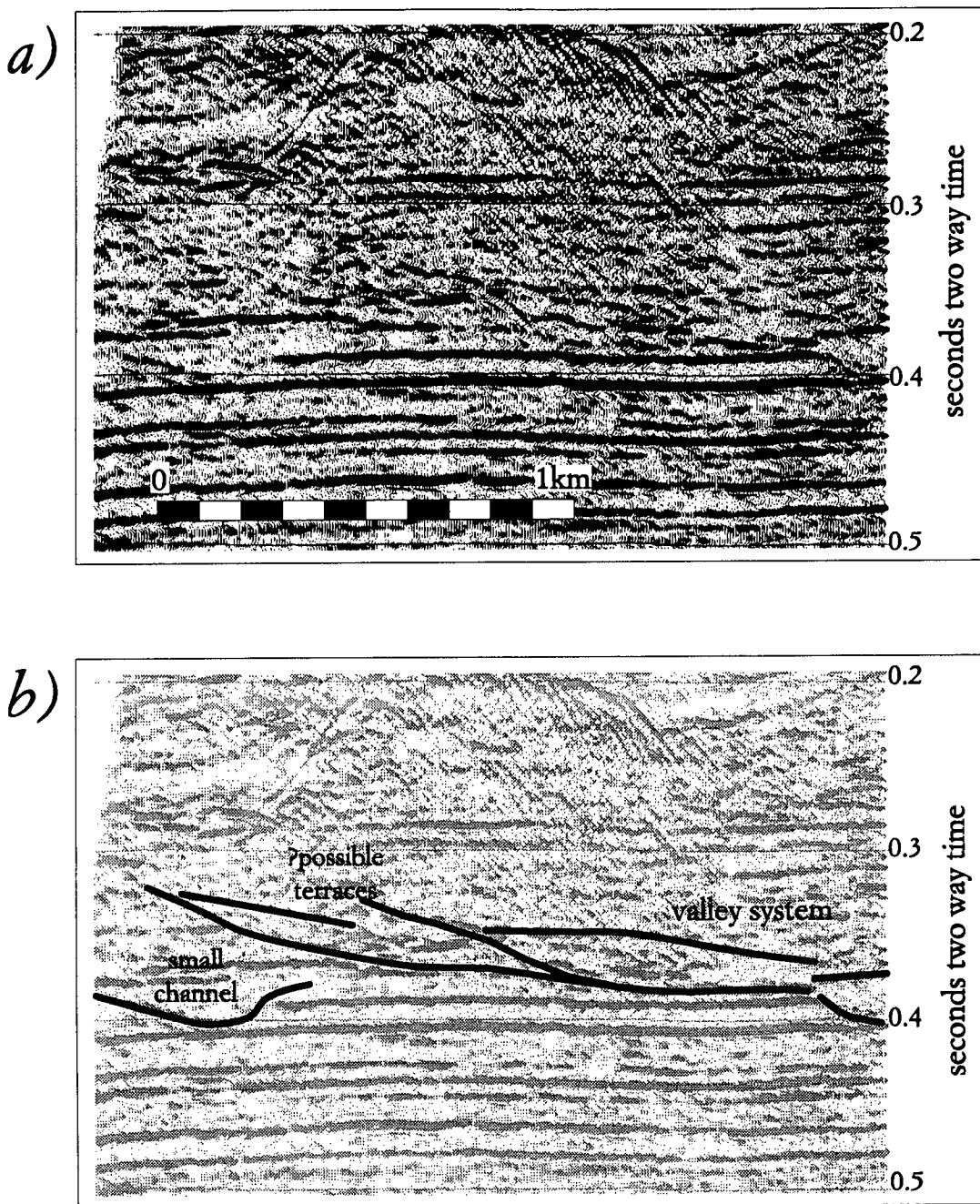


Fig. 4.35: Seismic sections taken from site survey data-set "L2-FA-1", showing: a) uninterpreted, and b) interpreted sections through half of a deep valley system. This valley system apparently includes "terrace-like" depositional packages within it, and may be of fluvial origin.

It is difficult to be confident about the environments in which channelling occurred at the base of well intervals "8" and "10". However, it is quite probable that channelling from well interval "16" upward is fluvial in origin, due to its patterns of erosion. This possibly allows the placement of the base of the fluvial sequence somewhere within either well interval "16" or "18", depending on the location within the study area.

Channel Orientations: It is interesting to note that the mean orientation of channel axes is not perpendicular to the western “shelf edge” seen on regional data from the study area, but is instead N-S. This trend is parallel to the N-S subsidence axis of the Offshore Central Graben which could have controlled the flow of rivers at times of low sea level, as suggested by Kasse (1990b).

The Valley Facies Model: The valley system in the lower half of well interval “20” is quite unlike anything seen below, as individual valleys are up to 70m deep. *SNSP* borehole 89/2 & 2A has sampled the fining upward valley fill of this system, and proved it to be of fluvial origin, as stated in Fannin *et al.* (1991 *unpub.*). Because of its depth, it is highly likely that this was cut during a major relative sea level fall, perhaps during a global period of glaciation.

A tentative mechanism for the formation of this valley system is suggested here (see fig. 4.36). The valley system may have been cut during the onset of a major, global glaciation event, possibly coupled with regional uplift of the southern North Sea Basin’s centre, causing a rapid fall in relative sea level of perhaps more than 70m. This resulted in valley incision, with valley axes, which largely run N-S, directed toward the shelf edge, which was, by then towards the north, or being controlled by the axis of the Offshore Central Graben (cf. Kasse, 1990b). At maximum glaciation, there was little sediment delivered to the southern North Sea Basin, and the exposed base of the valley was subjected to permafrost conditions and cryoturbation, with the resulting formation of “pingo-like” structures.

With the onset of deglaciation, as relative sea level started to rise, coarse grained clastics were initially deposited in a fluvial environment. This was due to release of sediment from ice sheets, an increase in river energy, and the generation of fluvial accommodation space by the sea level rise (Posamentier and Vail, 1988), causing the valley to be partially filled.

After deglaciation, but before marine incursion, sediment input decreased and fine grained clastics were deposited in flood-plains and meander belts, perhaps with increased growth of vegetation, causing peat generation. Finally, with marine incursion, estuarine or transgressive marine silts were deposited, forming the uppermost component of the valley fill.

The presence of single valley walls from this valley system in almost all of the eastern site survey data-sets is rather hard to explain, as it might be expected that, in some surveys, there would be no evidence of the valley system, in others, both valley walls would be outside the area of the seismic data-set, and in others still, both

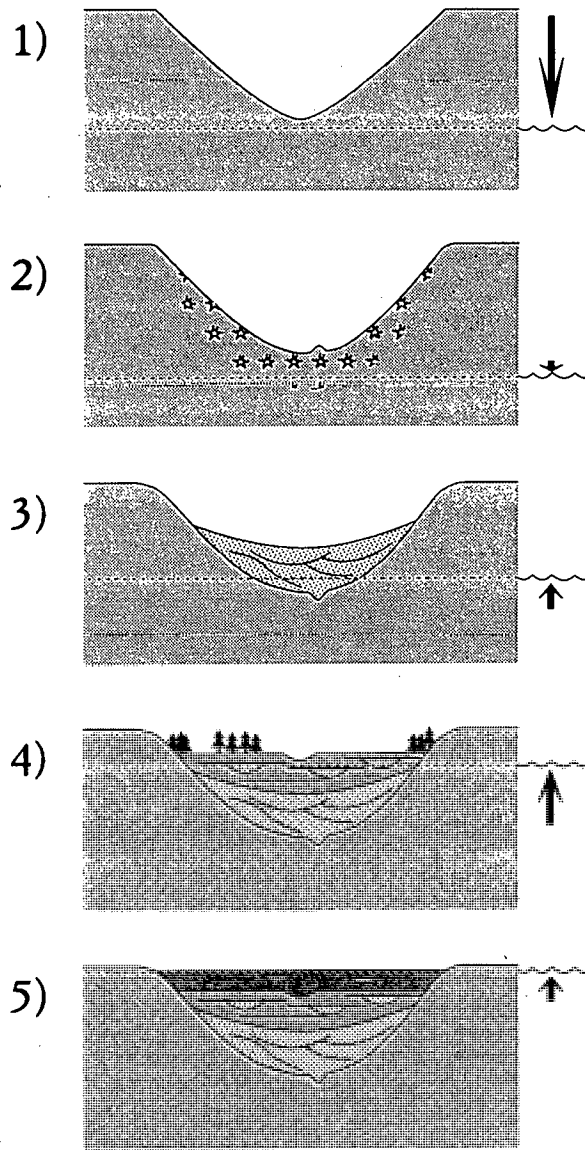


Fig. 4.36: Possible evolution of the valley system within well interval "20", near the base of the Yarmouth Roads Formation, related to relative sea level fluctuations and climate change through time. Stars in part "2" indicate permafrost conditions.

valley walls would be present within the seismic data-set. This might be explained by considering the valley system as undergoing constant lateral migration, causing the removal of extensive tracts of older sediment and the continuous, lateral infill of disused parts of the valley system.

Late, Fine Grained Facies

Several good continuity horizons can be resolved in the eastern site survey data-sets (G16-FA, K2-B, L2-FA-1, L3-E, L6-A and M1-A), within the poor continuity seismic facies of well interval "20". These horizons are usually the levels of terrace formation at the base of the glacial succession above, and are probably more resistant to erosion than the sediments above and below. They probably represent silt or clay facies within the generally sandy facies of the interval.

In each survey area, only one or two of these horizons is ever observed. However, it is suggested here that at least three may have originally been deposited, these being present at about 60, 80 and 140m above the base of the interval. The lowest of these is also recorded in well data, and in *SNSP* borehole 89/2 & 2A (Thompson *et al.*, 1992). These fine grained events may reflect either marine incursion or lagoonal environments.

Oblique Cliniform Seismic Facies

Oblique cliniform seismic facies, within diachronous facies patterns suggesting delta-like, coarsening upward trends, are seen in the fore sets of two of the site survey data-sets. They occur in interval "L6-P3", which is well interval "8", and in interval "L2-P2", which is well interval "10". Oblique cliniform facies have been seen in seismic interval "F", which is equivalent of interval "L6-P3", in regional seismic data. However, they have not been observed from the regional equivalent of interval "L2-P2", and this may be due to the poor development of the facies within well interval "10", such that this facies is simply not seen in the lower resolution, regional seismic data.

Mass Flows

Salt influence on mass flow genesis: In survey G16-FA, there is a clear relationship between salt induced features, as seen in the Palaeogene and older succession, and the distribution of faulting within the mass flow package of the overlying Nordland Group succession here (see fig. 4.6). Two different causes can be suggested for this relationship:

- 1) Doming or salt withdrawal causing localized steepening of slopes and destabilization within the Nordland Group succession. This model seems unlikely, given the

extremely flat nature of the events immediately underlying the base of the Nordland Group in survey area G16-FA. However, it is possible that, after localized, salt-induced uplift or subsidence, resulting in mass flow, this horizon returned to its original, sub-horizontal shape.

2) Upward gas invasion along faults within the Chalk and the Palaeogene succession, causing weakening and failure of the sediments directly underlying the Nordland Group succession. This model requires that these sediments were neither well lithified nor well compacted.

Doming above mass flows: It has been noted within the regional data-set that doming characteristically exists above the mass flows of the Nordland Group succession (see Chapter 2). However, this doming has been analysed in three dimensions in survey G16-FA. Here, the relationship is seen to be more intricate, with anticlinal ridges present above synclinal troughs on the basal decollement surface and *vice versa* (see figs. 4.6b & 4.7b). This suggests that either:

1) Individual fault blocks in the mass flow unit continued to move and rotate after the major mass flow event, causing the continued development of “roll-over anticline” forms.

2) Sediments above the mass flow were inverted, due to differential compaction. This differential compaction cannot simply be related to the de-watering and partial compaction of the fault blocks during mass flow as the development of domes only occurs where the basal decollement surface cuts into pre-Nordland Group sediments. This suggest that inversion has to be related to under-compaction in the pre-Nordland Group sediments, such that the mass flow removed lower Cenozoic sediment that was actually less compacted than the Nordland Group sediments within the mass flow blocks. Thus, the more lower Cenozoic sediment that was eroded by the mass flow, the greater the degree of inversion due to differential compaction. This concept will be discussed further in chapter 5.

Faulting Within Toe-sets

Within two of the interpreted surveys (L3-E and L6-A), the basal toe-set packages and the "mid-Tertiary" unconformity surface have apparently been subjected to pervasive faulting, although the overlying sediments have undergone little or no faulting at all. In both cases, the geometry of this faulting suggests that it may have been generated by lateral compression. In survey L3-E, the compression has caused slight bending and doming of each faulted block, indicating that the blocks have been pushed together. In L6-A, a possible thrust surface can be observed on line "L6-A-1" (see fig. 4.26).

Faulting in the two survey areas occurs at the same stratigraphic level, within well intervals "3" and "4", extending upward only to the top of well interval "4". The presence of sharply defined faulting suggests a considerable time gap between sedimentation and fault disruption, and the top of well interval "4" may be an extensive hiatal surface.

It is possible that the faulting is due to a single, compressive tectonic phase in the history of the basin between deposition of well intervals "4" and "5". The faults may otherwise be the result of some sedimentary process; for example, compression at the base of a slump feature. However, no slump feature is known from this vicinity and these two areas are unlikely to have been affected in the same way by the same slumping event. It is unknown whether any other horizons within the Nordland group succession show similar, deformational features within their toe-sets.

4.9.2: The Glacial Nordland Group

The glacial channel systems seen within the site survey data-sets are complex phenomena, which remain difficult to interpret because of the lack of data available on the changes occurring along the axes of individual glacial channel systems. It is also doubtful, based upon the regional mapping of the glacial channel systems (see section 2.2.2), whether any channel system is recorded by more than one site survey data-set within the study area. However, several features resolved by the site survey data are seen to be common to the different channel systems.

Glacial Channel Morphology

Glacial channel systems, due to the fact that they are probably ice marginal features (Boulton & Hindmarsh, 1987; Wingfield, 1989), may not be the result of one channel cutting event, but rather of numerous channel shape changes, involving both erosion and simultaneous infill, superposed upon each other. The architecture of glacial channel systems and their fill may, at least in part, be a function of the following:

- 1) The bank-full capacity of each channel within the system, assuming that each channel was, at some time, a fully occupied conduit for either ice or water.

- 2) The gradual process of channel deepening or reshaping, in order to improve the efficiency of the channel, hindered by the resistance to erosion of different layers within the pre-glacial substrate.

- 3) The geographical position of the ice margin with respect to the channel system at any one time.

Some examples are given to explain this:

- a) The lateral migration of a channel, without an increase in capacity, may cause one wall of the channel to be eroded whilst the other wall accumulates sediment. This is equivalent to normal channel migration and the generation of epsilon cross-bedding, although such bedding has not been seen in the site survey seismic data.

- b) An expanding channel eroded into uniform sand will, as it enlarges, generate an efficient, concave channel profile, due to the lack of downward resistance to erosion.

However, if the channel, with enlargement, encounters an erosion resistant layer, such as a clay horizon (see fig. 4.37a), then the channel will probably widen and flatten out above this horizon, due to the lower resistance to erosion of the sand, compared with the clay horizon (e.g. L2-FA-1, channels 1 and 3). This profile will therefore become increasingly inefficient. Eventually, if the clay horizon is breached, renewed erosion will take place at the base of the channel, and the widened channel margins will infill, as this profile is far more efficient for the channel transport (e.g. L3-E, channel 1 changing to channel 2).

Similarly, the breaching of the erosion resistant clay at the base of the channel, and the deepening of the channel profile, may cause the channel's length to decrease, due to the improvement in efficiency of the channel, and cause the infill of the ends of the channel (e.g. L6-A, channel 1 changing to channel 2).

c) A decrease in the discharge of a channel may cause partial filling of the valley both at the base and sides (e.g. L3-E, channel 2 changing to 3). The pattern of this fill will reflect the changing shape of the channel as discharge decreases. This pattern will be approximately concordant with the initial channel and will not be horizontal or overlapping.

The Elsterian channels seen within the study area generally have axes running N-S (see chapter 2). These channels, all of which have a boat shaped longitudinal profile, are very likely to be related to the W-E oriented margin of the Elsterian ice sheet, centred to the north of the study area (Cameron *et al.*, 1987; Wingfield, 1990). Therefore, if the ice margin retreated northward then the ice marginal channels would migrate northward. This would cause erosion and the northward extension of the pre-existing channel systems and the successive infill of the moribund parts of the channel systems in the south. Many of the Elsterian valleys in the west of the study area are known to contain large, northward dipping clinoforms, or "back-fill" (Praeg, 1993), which may be due to this infill mechanism. However, examples of similar infill styles are seen in the lower fill of channels in some site survey datasets (49/15A; L3-E, channel 2; M1-A, channel 1; possibly L6-A).

If the marginal deposits of the channel systems are the result of changing channel shape in a fluid conduit, then they are likely to be of sand or coarse, rock and shell gravel, due to the necessarily high energy conditions of the channels at this time. However, if the channel was shaped by ice then these marginal deposits could well be of clay or till. This could be an important distinction, as it might reveal whether

these channel systems developed beneath ice sheets as a result of esker-like processes (cf. Boulton & Hindmarsh, 1987) or as a result of large scale, fluid outflow at an ice margin (cf. Wingfield, 1989).

Glacial Channel Infill

Glacial channels often show two different seismic facies types on high resolution seismic data (e.g. Wingfield, 1989). These are the basal, “chaotic” fill and the upper, “passive” fill facies.

“Chaotic” Channel Fill: This facies is generally of low amplitude and poor continuity, including rare, sporadically high amplitude events. The upper surface of this facies often being of negative polarity. This lower unit is usually suggested to be of sandy facies, possibly of glacial or fluvio-glacial origin. Whilst this is probably often the case (e.g. L2-FA-1, channel 1; possibly L3-E, channel 2), it is equally possible that the “chaotic” nature of this lower facies may be due to post-depositional deformation, for the following reasons.

1) There is often a marked angular unconformity between the “chaotic” and the “passive” fill, suggesting erosion before renewed deposition (e.g. 49/15A; M1-A, channel 1; ?L3-E, channel 2). There is no intermediate facies, suggesting sudden, rather than gradual change from “chaotic” to “passive” infill.

2) On regional, low resolution data, this lower facies is usually seen to be marked by numerous, traceable events (D. Praeg, *pers. comm.*), suggesting that it is not, in fact, chaotically deposited at all.

3) In two surveys (49/15A; M1-A, lower channel), a thin, acoustically transparent unit with a normal polarity top overlies, and is concordant with, the “chaotic” fill. In survey 49/15, W-E trending ridges, possibly moraines, are seen directly above this thin unit. The unit is overlain by “passive”, onlapping sediments which infill the previous topography, suggesting compaction before subsequent deposition.

Below this unit, the top of the “chaotic” fill is often of negative polarity. This includes flat spots which suggest the presence of trapped gas at this level, below a permeability barrier.

Two possible explanations are suggested for the deformed nature of this infill. Firstly, that after sediment deposition, the ice sheet over-rode the channel system and deformed the sediments present within (see fig. 4.37b). This explanation is supported by the presence of possible moraines in survey 49/15A, and the thin unit just below these features may be a till. However, on its own, glacial deformation seems insufficient to deform all the sediments within the channel system, without noticeably having deformed those within the pre-glacial succession.

The second explanation, which may not be incompatible with the first, is that the lower fill of the channel system may, in some places, be predominantly composed of clay. This clay compacted and partially liquefied, causing the loss of reflector continuity within. This explanation is backed up by the collapse, possibly due to dewatering, of the upper surface of the "chaotic" fill in two surveys (49/15A; M1-A, lower channel). Additionally, the presence of trapped gas at the top of the "chaotic" fill of survey M1-A would suggest that fluidization due to over-pressuring within the fill could have been possible.

"Passive" Channel Fill: This facies includes moderate to good continuity, low to high amplitude events, which are often attributed to glacio-marine or glacio-lacustrine deposition of clay, silt and sand (Cameron *et al.*, 1987). Four types of passive fill have been recognised:

1) Draping fill is distributed across all not only the axis of the channel, but is also present on the channel walls. This is probably due largely to sedimentation of clay particles from suspension in a very low energy, possibly lacustrine environment. Draping fill is normally characterized by parallel banded events which are concordant with the underlying relief (e.g. L2-FA-1, channel 3). However, draping fill is sometimes marked by a high amplitude, negative polarity event (e.g. G16-FA, lower channel), which may be the representation of a peat layer within the channel. This latter situation may arise because of sub-aerial exposure, again with very low sedimentation rates (see fig. 4.37c).

2) Onlapping sub-horizontal fill is usually confined to the channel axis, and may represent higher energy conditions, with sedimentation of both clay and sand (e.g. 49/15A; G16-FA, lower channel; L2-FA-1, channel 3; L3-E, channel 3; L6-A, upper channel; M1-A, lower channel). Environments of deposition could be highly variable, ranging from fluvial to marine conditions, and may be reflected in the variable continuity of events with this fill (e.g. within G16-FA, lower channel).

3) Downlapping, marginal fill may be due to filling of the channel from the channel margin via marginal fans (e.g. G16-FA, lower channel; L2-FA-1, channel 1). This fill may be due to channel margin collapse.

4) Downlapping, "Deltaic" fill, with progradation at least partially along the channel axis, and coarsening upward of sediments from clay or silty clay at the base to channelled sand at the top (e.g. L2-FA-1, upper channel; possibly G16-FA, lower channel). This filling pattern may be due to high energy, marine environments.

Evidence of Ice Within Channels

Although there is generally little evidence of the direct action of ice within the channel systems seen, and the base of most valleys, as recorded on the site survey data-sets, appears to be remarkably smooth, some evidence suggest that ice may have played an important rôle in the shaping of many glacial channel systems:

1) The possible presence of glacial moraines within the channel system of survey 49/15A may indicate, at very least, the re-advance of an ice sheet into the area of the glacial channel system.

2) Some apparently displaced and faulted sediments beneath valleys in surveys 49/15A and L2-FA-1 may have been affected by glacio-tectonic action. There is also good evidence for the presence of local glacio-tectonism in blocks 49/12 & 17, to the west of the study area (D. Praeg, *pers comm.* and own work).

3) Possible drumlins are present within the fill of the second channel system in survey L3-E. If genuine, these would indicate not only the presence of ice within the channel system but also its effect in shaping the channel system.

Channel Orientation and Underlying Structure

In four of the six survey data-sets which include glacial successions (L2-FA, L3-E, L6-A and M1-A) there is an approximate correlation between the orientation of the main channel axis and the orientation of the fore-set strike direction in the underlying Nordland Group succession. In the case of survey 49/15A there is no obvious fore-set strike direction, so that little comparison can be made. However, no alignment can be found between this channel axis and any underlying structure.

Survey G16-FA shows no fore-set correlation, channel axes in the lower channel system running NNE-SSW and fore-set strike directions in the Nordland Group running NW-SE. However, glacial channel axes follow the trend of mass flow induced ridges developed on the fore-set surfaces. This may indicate that the alignment of the glacial channels with fore-set strike directions is more than coincidental. However, the pre-glacial sediments which overlie the fore-sets are generally sub-horizontal and a reason has to be given why older sediments which are not in contact with the channels, and have no apparent architectural influence upon them should affect their distribution.

The presence of a shallow, perhaps less than 10m deep channel-like depression just below the sea bed at the top of interval "G16-G4", again in survey G16-FA, may provide a possible answer. This depression is related to a gas chimney, extending down to a structural high at around 550ms TWT which is again related to the ridges within the fore-sets. Whilst this depression is almost undoubtedly a gas escape "crater", its channelled form could be due to current orientations within the water column. Therefore the location and orientation of individual channels within the glacial channel system may in part be related to gas escape from the underlying sediments.

?Saalian Erosion

An unusual, high relief erosion surface, sometimes containing clearly developed, channel-like forms, occurs at the top of many of the survey data-sets in the NE of the area (L3-E, L6-A, M1-A, G16-FA and, possibly L2-FA-1). Unlike the lower erosion surface which defines the base of the glacial succession, this upper surface shows clear signs of tectonism within each survey. In survey M1-A, possible thrust planes, dipping to the SE, are developed in the underlying sediments. In G16-FA and L6-A, apparent fold ridges are present, trending NW-SE in both cases. In all surveys this surface, which is of normal polarity, is highly diffractive, possibly suggesting its irregular nature. Fully formed channels are present on this surface in surveys G16-FA and M1-A, oriented respectively WNW-ESE and W-E, whilst a weak channel form, directed NW-SE, is present in survey L3-E. The channel in survey G16-FA, which has a highly abnormal channel-form, is also filled by sediment which has probably been tectonized, and the channel may itself have been formed by ice push towards either the SSW or the NNE, gouging out this large depression. The channel in L2-FA-1, which is directed approximately NW-SE, shows few of the features seen in the others, and may be of Elsterian age.

All these structures are likely to be related to the rather poorly defined, Saalian glacial phase of the southern North Sea. This glaciation only reached the eastern half of the study area and it is known to have generated many glacio-tectonic features (Joon *et al.*, 1990), showing totally different erosion styles to the earlier, Elsterian glaciation. Ice advance directions for the Saalian glaciation, based upon information obtained from the site survey data, are highly variable, although, together, they suggest a north to NW movement direction. This is in broad agreement with the interpretation of Joon *et al.* (1990).

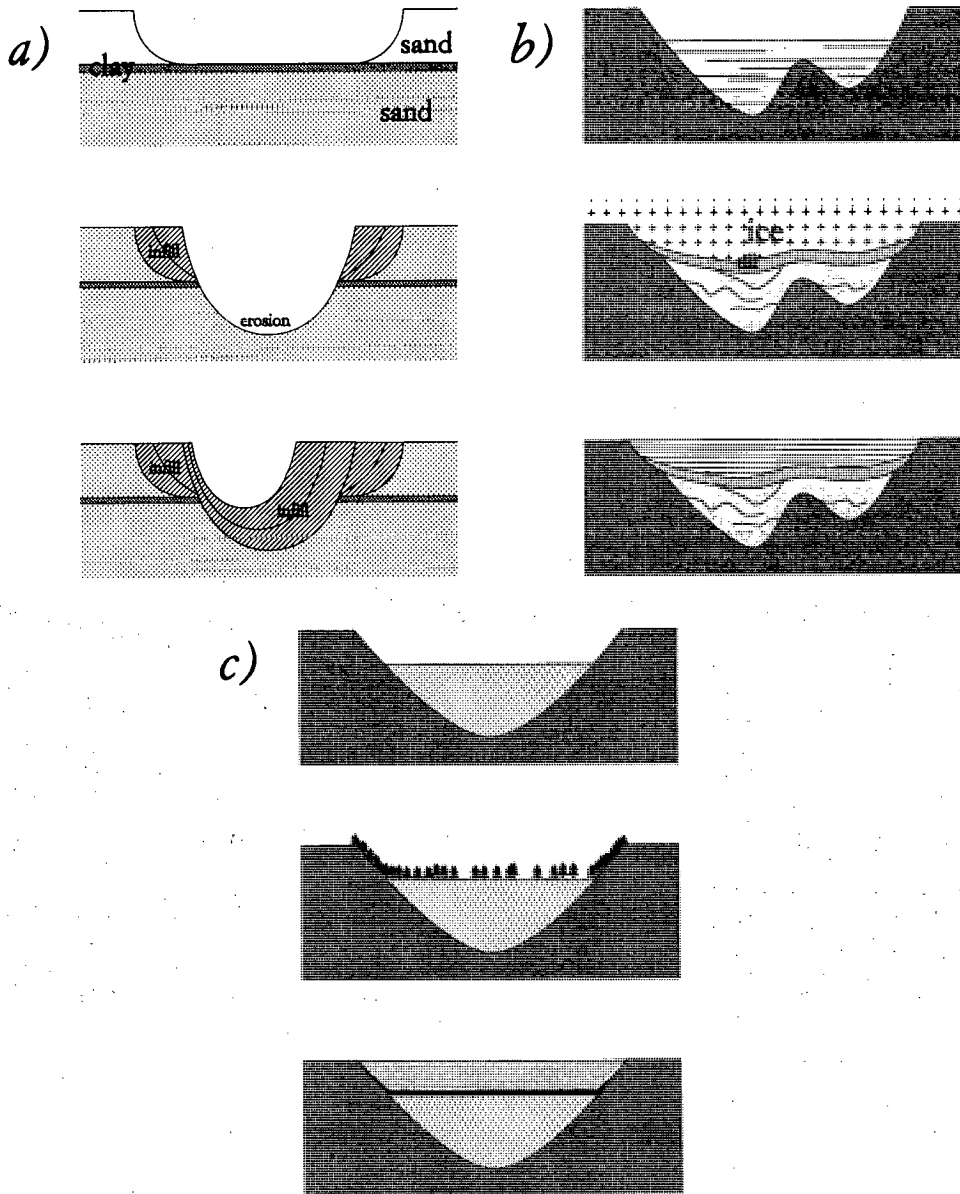


Fig. 4.37: Possible mechanisms for the generation of some glacial channel infill architecture: a) Changes in resistance to erosion of the substrate and variations in channel bank-full capacity, b) Re-advance of ice into the channel area, over-riding and deforming earlier channel infill, c) Passive infill of the channel, including sub-aerial exposure.

CHAPTER 5:
DISCUSSION
&
CONCLUSIONS

5: DISCUSSION & CONCLUSIONS

5.1: Introduction

The following discussion is an attempt to generate a geological framework for the late Cenozoic sediments of the study area using the information presented in chapters 1 to 4. This framework will then be incorporated into a review of the geological setting of the southern North Sea area during the late Cenozoic. This procedure necessitates discussion of the stratigraphy of the succession within the study area, the environments of deposition of its sediments, and the history of the study area, including the influence upon sedimentation of deteriorating climate in NW Europe throughout this time. Additionally, processes involved in the formation of sediment body geometry are tentatively suggested.

5.2: Correlation of Successions

The stratigraphy of the Cenozoic, silici-clastic succession within the study area is discussed here in terms of the lower Cenozoic (Palaeocene to Middle Miocene) “pre-Nordland Group” and the late Cenozoic (middle Miocene to Recent) “Nordland Group” successions.

5.2.1: *The lower Cenozoic Succession*

This succession, which extends from the top Chalk horizon up to seismic horizon “H₀”, the “mid-Tertiary” unconformity, is characterized by its broken appearance on seismic data. Only two sediment packages have been distinguished in the present study, based upon the available seismic and well data. These packages are separated by seismic horizon “H_A”, which is an angular unconformity surface (see sections 2.2.1, 3.3.1 & figs. 2.5, 3.10).

Package 1: This lower package consists predominantly of clay, and is equivalent to combined well intervals “W”, “X”, and “Y” (see section 3.2.1). According to the stratigraphic scheme of *NAM & RGD* (1980), it can be subdivided into the Paleocene to Eocene “Lower North Sea Group” and the basal part of the Oligocene “Middle North Sea Group”, the two being separated by an unconformity. It is suggested here that package “1” is likely to include the whole of the “Middle North Sea Group”.

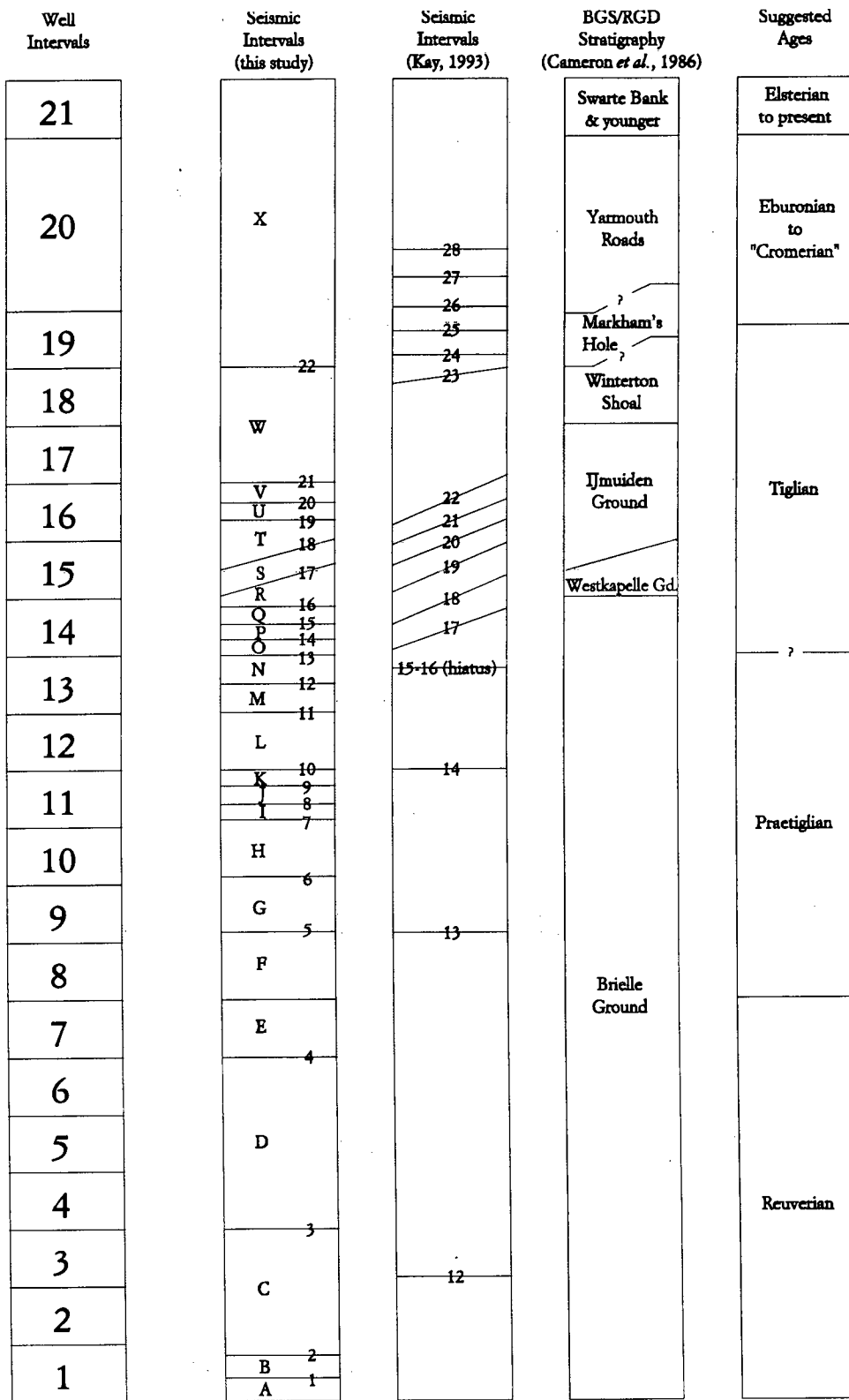


Fig. 5.1: Correlation diagram, showing the suggested correlation for the various different stratigraphic schemes, including the regional seismic and well log correlation schemes of this study, the stratigraphic framework of Cameron *et al.* (1986) and the basin-wide, regional seismic correlation scheme of Kay (1993).

Package 2: This is up to 80m thick in the study area, consists of clay, and is equivalent to well interval “Z” (see section 3.2.1). According to *NAM & RGD* (1980), this package forms the upper part of the Oligocene “Middle North Sea Group” and only the basal, Lower to Middle Miocene sediments of the “Upper North Sea Group”. It is suggested here that package “2” is likely to include only the basal sediments of the “Upper North Sea Group”, and that it therefore incorporates only the Lower to Middle Miocene sediments of the Miocene “Breda Formation”.

Horizon “H_A”, which forms an angular unconformity surface across much of the study area (see section 2.2.1), possibly represents an Upper Oligocene or Lower Miocene phase of tectonic inversion in the southern North Sea Basin. This may correspond with the final, Cenozoic inversion phase recorded by Becker (1993). In contrast, there is little evidence within the study area of a major tectonic event associated with Horizon “H₀”. Sediments at the level of Horizon “H₀” are highly glauconitic, possibly also with phosphate, but there is little evidence of truncation of underlying units. Horizon “H₀” is likely to represent a hiatal surface, with minor erosion and winnowing, and may correlate with a major transgression, of possibly late Middle Miocene (?Seravallian) age, seen in NW Germany (Hinsch, 1990). In the western half of the study area, Horizon “H₀” merges with Horizon “H_A” below (see section 2.2.1), and a single unconformity surface is present here.

5.2.2: The Nordland Group

In the absence of good bio-stratigraphic control for the late Cenozoic succession of the southern North Sea Basin, the following techniques have been used, in order of significance, to correlate the local stratigraphy of the study area with the existing, onshore and offshore stratigraphic schemes:

- + Bio-stratigraphy (where available) and litho-stratigraphy.
- + Correlation of unconformity surfaces.
- + Comparison of published map data.
- + Comparison of litho-facies.

A summary correlation diagram is presented for the various correlation schemes in figure 5.1, whilst a possible litho-stratigraphic scheme for the study area is given in figure 5.2 and in the Supplement, including suggested correlation with British and Dutch stages, and applying the existing offshore nomenclature. The time scale is based upon Harland *et al.* (1989) and Shackleton *et al.* (1990).

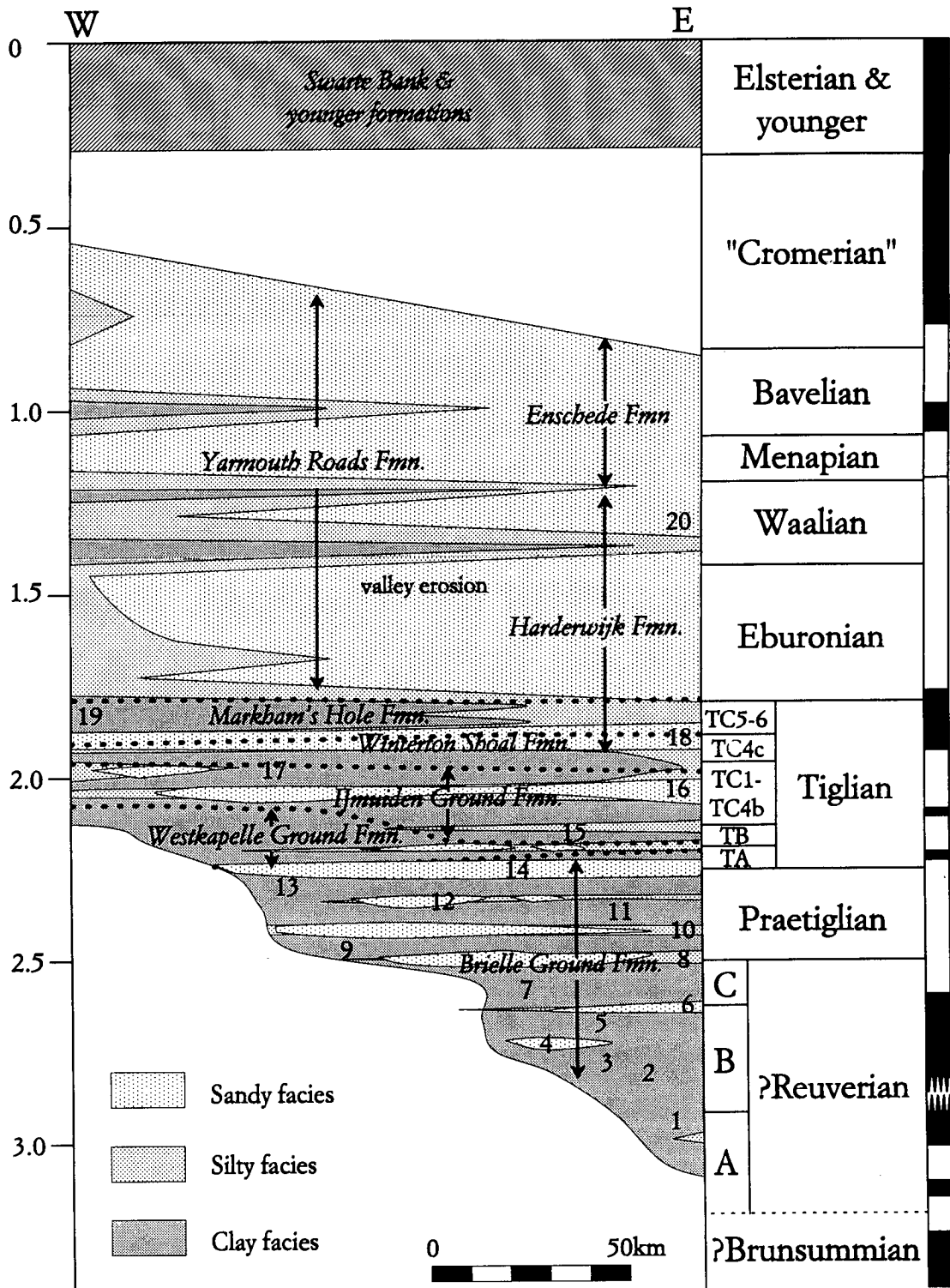


Fig. 5.2: Simplified litho-stratigraphy of the study area, giving tentatively suggested ages for the different sediment bodies in the succession. The diagram also includes the stratigraphic nomenclature of Van Staalduin *et al.* (1979) and Cameron *et al.* (1986) and the well intervals of chapter 3. The unconformity surfaces seen throughout the succession are not shown on this diagram, but are shown in the detailed supplement at the back of the thesis (Time-scale based upon Zagwijn, 1989; Shackleton *et al.*, 1990. Additional age data from Harland *et al.*, 1989).

Bio-stratigraphy

Although bio-stratigraphic data for the study area are limited, ages of individual units have been assigned with reasonable confidence for well intervals “15” through “19”, using available information from boreholes both within and outside the study area. The data are taken from Cameron *et al.* (1984a), Gibbard *et al.* (1991), Thompson *et al.*, (1992) and Fannin *et al.* (1991 *unpub.*). However, bio-stratigraphic data of adequate resolution were unavailable for other levels within the succession (see section 3.3.2).

Correlation of Unconformities

Based upon stratigraphic relationships, several unconformities have been identified by Zagwijn (1974; 1989) within the post-Reuverian succession of the Netherlands. Although most of these are of limited areal extent, three regionally significant unconformities may be present in the NW Netherlands: at the base of the Praetiglian stage, at the base of the Tiglian stage, and near the base of the Elsterian stage.

The “base Praetiglian” unconformity: Two alternative horizons may represent a base Praetiglian unconformity surface within the study area. These horizons occur at the bases of well intervals “8” and “10”, which, based upon seismic data, are known to be unconformities in the east of the area (see section 4.9.1). The base of well interval “8” is the more marked unconformity surface of the two, and may be the “base Praetiglian” unconformity. However, this writer considers that a major, base Praetiglian unconformity surface may not actually be present within the NW Netherlands.

The “base Tiglian” unconformity: The base of well interval “14” is correlated with this unconformity for two reasons. Firstly, this horizon is one of the most significant regional unconformity surfaces present within the study area. It is represented by a marked angular unconformity on sections of the “Gauss” seismic line in the German sector to the NE, where the whole of the Praetiglian may be missing (see fig. 3.16).

Secondly, the sediments at the base of well interval “15” have been dated as probably Tiglian TB, based upon bio-stratigraphic evidence (Cameron *et al.*, 1984a; Gibbard *et al.*, 1991; Fannin *et al.*, 1991 *unpub.*; see section 3.3.2). A base Tiglian age is therefore reasonable for the sediments of well interval “14”.

The “base Elsterian” unconformity: This unconformity, which represents the base of regional glacial erosion within the southern North Sea Basin (Cameron *et al.*, 1987), is defined on the regional and site survey seismic data-sets by a deeply channelled erosion surface (the base of package X₂; see sections 2.3.2 & 4.9.2).

Additionally, a fourth major unconformity surface can be seen upon the site survey seismic data-sets within well interval “20”, at a depth of between 150 to 250m below sea level. This unconformity is defined by valleys up to 70m deep, and probably represents a fluvial erosion surface associated with a large, relative fall in sea level (see section 4.9.1).

The base of the valley system is clearly observed in borehole 89/2 & 2A as a major erosion surface at around 240m below sea level, above which is a thick, fining upward, Eburonian to Waalian succession (Fannin *et al.*, 1991 *unpub.*), which is probably the valley fill. The unconformity surface is therefore probably of late Eburonian age. An equivalent unconformity has not, apparently, been recorded in the Netherlands.

Comparison of Horizon Maps with Onshore Map Data

Cameron *et al.* (1986) suggested that the base of the Praetiglian stage is represented by the base of the Westkapelle Ground Formation in the west of the present study area (see section 1.2.3). However, this horizon could not be directly correlated with the onshore map of the base Praetiglian in the Netherlands, published by Zagwijn & Doppert (1978), as the base of the Westkapelle Ground was not originally mapped across the eastern half of the present study area, leaving an around 80km gap between the published maps.

Although there is also a gap of around 10km between the maps compiled for the study area and the published maps of the Netherlands, this gap is insignificant on a regional scale. It has therefore been possible to deduce the range of seismic horizons which, when depth corrected, might potentially correlate with the base of the Praetiglian in the Netherlands. The interval between seismic horizons “H₄” and “H₅”, equivalent to well intervals “7” to “9”, is therefore most likely to include the base Praetiglian (see fig. 5.3). Other horizons, including the base of the Westkapelle Ground Formation (equivalent to seismic horizon “H₁₇” in the east of the study area), are unlikely to correlate, unless there is a major, structural discontinuity running between the coast of the Netherlands and the study area.

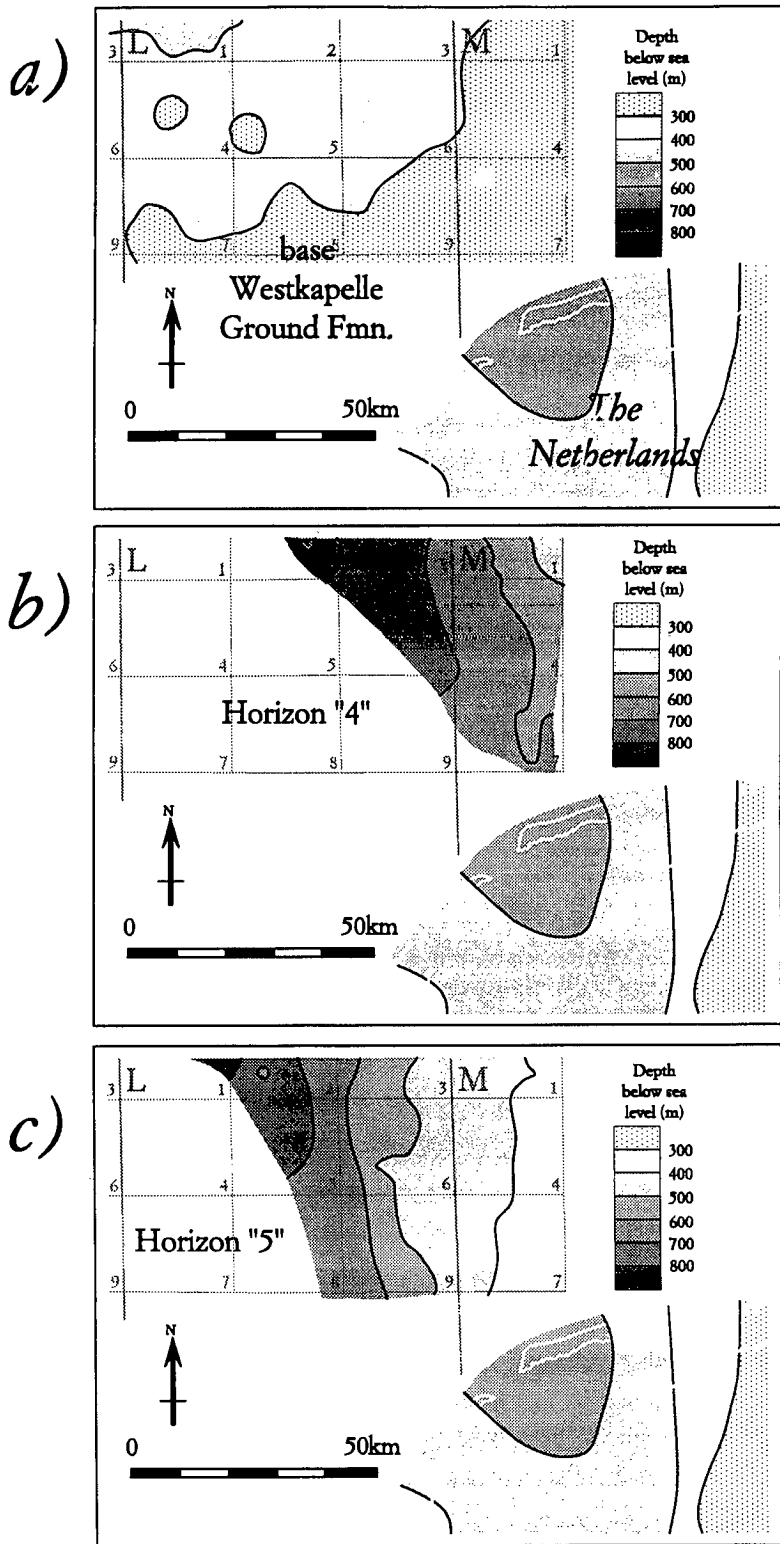


Fig. 5.3: Comparison of the data from the published map of the depth to the base Praetigian in the Netherlands (Van Staalduinen *et al.*, 1979), with maps of the approximate depth to various interpreted horizons within the study area: a) the base of the Westkapelle Ground Formation ("H₁"); b) Horizon "H₁", around the top of well interval "6"; c) Horizon "H₁", within well interval "9". This comparison reveals that the base of the Praetigian is unlikely to be near the base of the Westkapelle Ground Formation, but is instead likely to be present between seismic horizons "H₁" and H₂".

Based upon the earlier observation that the base Praetiglian unconformity is likely to be either the base of well interval “8” or “10”, the conclusion that the base of well interval “8” is approximately the base of the Praetiglian is reinforced.

Comparison of Litho-facies

Clay bands within well interval “20”: Up to three, clay dominated horizons are present within the predominantly sandy facies of well interval “20”, based largely upon evidence from the site survey seismic data-sets (see section 4.9.1). It is suggested tentatively that these horizons may be equivalent to marine incursions recorded in the Netherlands during the Waalian and Bavelian interglacial stages (Zagwijn, 1989; 1992).

Reuverian & older litho-facies: Although little information has been published about the litho-facies of Reuverian and older sediments in the NW Netherlands, it is possible that all of the thick, clay dominated succession of well intervals “1” to “7” may be equivalent to the Reuver Clay of the southern Netherlands (Van Staalduinen *et al.*, 1979). However, the similarity in litho-facies cannot justify the correlation of the two successions.

Correlation with the Stratigraphic Scheme of Kay (1993)

Preliminary work has been undertaken on the correlation of the seismic stratigraphy of Kay (1993) with the work of this study (see fig. 5.1). This correlation has revealed some minor discrepancy between the two schemes which cannot be resolved without further comparative work, especially between horizons “17” to “22” of Kay (1993) and seismic horizons “H₁₄” to “H₂₀” of this study. However, the following conclusions can be drawn confidently:

- + Horizon “1” of Kay (1993) lies within well interval “Z” of this study
- + Horizon “2” of Kay (1993) correlates with seismic horizon “H₀”, the “mid-Tertiary unconformity within the study area.
- + Horizons “3” to “10” of Kay (1993) are not represented within the present study area, as they lap out and disappear to the east of the area.

- + Horizons “15” and “16” of Kay (1993) are represented by one surface within the study area, this surface lying between horizons “H₁₂” and “H₁₃” of this study. This suggests that a significant hiatal surface may exist between horizons “H₁₂” and “H₁₃”. The hiatal surface could correspond with the locally glauconitic layer near the top of well interval “13”.
- + Horizons “24” to “28” of Kay (1993) all lie above horizon “H₂₂” of this study, within interval “X” (package X₁).
- + Horizon “13” of Kay (1993) approximates to the base Praetigian, using the suggested chrono-stratigraphy of this study.

Stratigraphic Revision

Neither a new formal stratigraphy nor stratigraphic revision of published stratigraphic schemes are suggested here for the following reasons:

- + There is still insufficient biostratigraphic control to allow accurate regional correlation. This problem is compounded by recent doubts about the chrono-stratigraphic validity of the unconformity surfaces observed in seismic data (Christie-Blick, 1991; Cartwright *et al.*, 1993)
- + It is only a matter of time before the stratigraphy of the NW Netherlands, which is itself largely based upon well and borehole data, is extended offshore. Until such time, it seems sensible to continue using the existing stratigraphic schemes of the *BGS & RGD* (Jeffery, 1993), Van Staalduinen *et al.* (1979) and *NAM & RGD* (1980), in the areas where each scheme seems most appropriate.

However, the present author considers that the stratigraphic scheme of the *BGS* (Jeffery, 1993) is overly complex, and that formation status has been assigned to individual sediment packages based upon insufficient bio-stratigraphic or lithologic data. Additionally, in some cases, there is insufficient stratigraphic information given in order to apply this stratigraphic scheme to new data-sets.

The base Westkapelle Ground Formation: This horizon (seismic horizon “H₁₈”) is an excellent seismic marker. It is an apparent unconformity surface, truncating underlying, westward dipping events, and with westward dipping events downlapping upon it (see sections 2.2.2 & 2.3.2). However, well interval “15” (see section 3.3.2) includes strata both above and below this marker horizon, being above horizon “H₁₈” in the east of the study area and below it in the west. Three possibilities are suggested to explain this:

- + Well interval “15” may include sediments of two different age ranges, separated by a non-diachronous unconformity surface.
- + Horizon “H₁₈” is a diachronous unconformity, with sedimentation in two separate areas at any one time (cf. Christie-Blick *et al.*, 1990).
- + Horizon “H₁₈” is only an apparent unconformity, due to the thinning, beyond seismic resolution, of individual packages at the level of the apparent unconformity (cf. Cartwright *et al.*, 1993).

The resolution of this problem ultimately requires the accurate dating of the sediments above and below the apparent unconformity surface.

5.3: Depositional and Stratigraphic Framework of the Nordland Group

The epeiric sea-way of the North Sea Basin was heavily influenced by tidal forces in the south during the Pliocene, as evidenced by tidal deposits in East Anglia and northern Belgium (Kasse, 1986; Gibbard & Zalasiewicz, 1988; Zalasiewicz *et al.*, 1988). The majority of sediments deposited on the southern North Sea shelf within the study area were of clay during Nordland Group times. However, occasional, thick, sand bodies were also deposited, largely at the extreme southern end of the North Sea Central Graben axis, which shale out to the north (e.g. well intervals “8” & “10”, see fig. 3.9).

The Nordland Group succession is regressive overall, with marine sediments making up the majority of the succession, and fluvial deposits predominant toward the top, just below the glacial and interglacial sediment complex of Elsterian to Recent times. The following discussion is intended in order to elucidate the depositional history of the succession, and to suggest a sequence stratigraphic framework for it.

5.3.1: Quaternary Analogues

In an effort to find analogues for the sandier intervals of the Nordland Group, comparison is made here with studies of late Quaternary successions from the western Mediterranean, off the Tyrrhenian Margin of Italy (Chiocci, 1994; Chiocci & Normark, 1992; Trincardi & Field, 1991) and in front of the Rhône delta, off France (Tesson *et al.*, 1993). These successions have all been studied using single channel, unprocessed, high resolution data-sets. All have been interpreted as having formed during the last glacial-interglacial cycle, and comprise interpreted lowstand wedges which have been subsequently flooded during the Holocene sea level rise, and are now either partially or wholly covered by what have been interpreted as transgressive and highstand sedimentary wedges.

The Lowstand Wedge

This is an isolated wedge of possibly sandy sediment, its location ranging from the middle shelf to just beyond the shelf margin. According to Tesson *et al.* (1993), it can be considered as equivalent to the “forced regressive wedge” of Posamentier *et al.* (1992). The sediment wedge has a roughly linear shape, and runs approximately parallel to the shelf bathymetric contours. Where is it present beyond the shelf

margin, and can be up to 90m thick, although it is no more than 10m thick when deposited on the shelf.

In the thicker wedges formed beyond the shelf margin, their internal geometry can be discerned. They are seen to downlap seaward onto previous sediments, occasionally showing channelled erosion, and show toplap at their upper surfaces. The wedges are therefore bounded by non-deposition (omission) or unconformity surfaces. It is thought likely that these wedges coarsen upward. Where the wedges are absent from the shelf, a contiguous, erosional unconformity surface can be seen, separating deposits older than the lowstand wedge from those younger than it. This unconformity is thought to be related both to sub-aerial erosion at the time of lowstand wedge deposition, and to subsequent ravinement during transgression.

Occasionally, the lowstand wedges include channel forms within them. These are thought to be small river courses, formed in deltaic conditions during sea level lowstand, and related to nearby river sources (Tesson *et al.*, 1993). These gullies may also be present on the shelf unconformity surface, where no lowstand wedge deposition has taken place (Chiocci & Normark, 1992). Where no river courses are evident within the lowstand wedge, these deposits have been interpreted as beach-shoreface complex sediments deposited during the lowstand (Trincardi & Field, 1991).

In sequence stratigraphic terms, the base of the lowstand wedge defines a sequence boundary, using the definition of Van Wagoner *et al.* (1990), as sub-aerial exposure and erosion is assumed to have occurred on the shelf at the start of lowstand wedge deposition. On the other hand, the top of the lowstand wedge is thought to be a ravinement surface, and is interpreted therefore as a marine flooding surface, and hence a parasequence boundary (*sensu* Van Wagoner *et al.*, 1990). This means that, where no lowstand wedge has been deposited, the sequence boundary and parasequence boundary must coincide at the level of the shelf unconformity surface.

The Transgressive and Highstand Wedges

These deposits, which are immediately above the lowstand wedge in the succession, tend to show a non linear depositional geometry, and are thought to be related to point source deposition from rivers in the hinterlands. On occasion, these deposits can be entirely absent, this resulting in the vertical stacking purely of successive lowstand wedges. Highstand and transgressive wedges are thought to be made up almost entirely of fine grained sediments, although, where there is strong deltaic input, highstand deposits may be thicker, and contain coarser material.

Comparison with the Nordland Group

Much of the Nordland Group succession is considerably older than the deposits described above, and it is unlikely that eustatic sea level changes were as extreme during most of Nordland Group times as they have been over the last few glacial-interglacial cycles. Nonetheless, the following comparisons can be made.

The Lowstand Wedge: Where it is deposited at the shelf margin, this appears to be very similar to the sand dominated “oblique prograding clinoform” seismic facies of the Nordland Group. Although the resolution of seismic data over the Nordland Group is generally lower than that of the study conducted in the Mediterranean, the two sediment packages are still seen to share the following features (see chapters 2 and 3):

- 1) Downlap of their internal reflectors onto sediments below, occasionally associated with slight erosion.
- 2) Top-lap at their upper surfaces
- 3) Isolation of the wedge at the shelf margin.
- 4) The occasional presence of channel forms within them.
- 5) Their often marked linear geometry overall (e.g. the “oblique prograding clinoform” seismic facies associated with the sandy well intervals “14” and “16”, see chapter 3)
- 6) The possibly sandy nature of the sediments they contain.

Where the “lowstand wedge” occurs on the shelf top, this may be equivalent to the sand ribbons seen within the top-sets of the Nordland Group (e.g. the “gamma sands” of well intervals “12” and “15”, see fig. 3.8). These sand ribbons again show marked linear geometry, as do the “lowstand wedges” on the Tyrrhenian Shelf (e.g. Trincardi & Field, 1991). Additionally, in well interval “12”, the shelf top sand ribbon is seen to be lateral equivalent of the sandy sediments of the “oblique prograding clinoform” facies in the fore-sets.

If the interpretation of Tesson (1993) and Trincardi and Field (1991) is correct, then the deposits of the “oblique prograding clinoform” facies and the sand ribbons of the Nordland Group top-sets may be the result of “forced regression” (*sensu* Posamentier *et al.*, 1992) and represent coastal and near-shore marine (beach-shoreface complex) deposition during sea level lowstands in the Pliocene and Pleistocene. As such, the bases of these packages would define sequence boundaries and, in some cases, their upper surfaces may define parasequence boundaries.

The Transgressive Wedge: In the sediments of the Mediterranean, this wedge is usually extremely thin (less than 10m thick) and, if it exists, it is unlikely to be recognised or resolvable in the regional seismic data of the Nordland Group.

The Highstand Wedge: This package may be equivalent to the “aggradational” seismic facies of the Nordland Group, as both of these packages are the major aggradational units of their respective successions. However, this analogue is by no means perfect, as the “aggradational” seismic facies of the Nordland Group may occasionally be made up predominantly of sandy sediments (e.g. seismic packages “R₂” and “T₃”), whereas the highstand wedge is predominantly fine grained.

The “aggradational” seismic facies of the Nordland Group can only be formed during times of shelf accommodation space generation, due to a rise in relative sea level on the shelf. If this occurs relatively rapidly (e.g. by a rapid eustatic sea level rise), then the resulting shelf accommodation space may be filled slowly in a fine grained, distal marine setting, as is suggested for the “highstand wedge” of Chiocci (1994) and others. However, if sedimentation can either keep pace with or outstrip the rate of accommodation space generation (e.g. during conditions of slow subsidence and constant or gently falling eustatic sea level), then deposition of sands (either sub-aerially or in proximal marine settings) may occur across the entire shelf. This may sometimes be the case in the Nordland Group.

It is, at present, difficult to see where the “sigmoid prograding clinoform” seismic facies of the Nordland Group, which is clay dominated, but is developed exclusively beyond the slope break, fits into the above scheme. It may be that these deposits do exist within the Mediterranean, but are unrecorded in the high resolution surveys that have been conducted. In normal seismic stratigraphic terms, this facies is part of the “Lowstand Fan” or “Lowstand Wedge” (Posamentier *et al.*, 1988), although its genetic interpretation is open to question.

5.3.3: A Sequence Stratigraphic Framework?

Because of the lack of environmental, sedimentological and biostratigraphic information contained within the data-base used in this study, it is not possible to present an accurate history of the nature of relative sea level changes during the deposition of the Nordland Group. Therefore, it is impossible to confidently apply any sequence stratigraphic framework to the sediments of the Nordland Group at the present time. However, In this section, some suggestions will be made for a provisional sequence stratigraphic scheme to the sediments of the Nordland Group, based upon the evidence that is available from the three data-sets.

Seismic Stratigraphic Scheme

Using the principles of Vail *et al.* (1977), the succession of the Nordland Group can be divided into at least 12 “seismic sequences”, which are shown in figure 5.4. These are defined on the basis of at least eleven surfaces of non-deposition which can be identified within the top-sets of the Nordland Group (for the purposes of this discussion, seismic packages “A₁” to “B₅” will not be considered, as their top-set configurations are not fully understood). Each non-deposition surface (or “seismic sequence boundary”) is identified due to the presence of distally developed seismic packages, occurring either exclusively beyond the slope break or having only limited development within the top-sets. In a seismic stratigraphic framework, the position of the “seismic sequence boundary” in the fore-sets occurs at the base of the lowest, distally developed seismic package associated with each surface of non-deposition.

The Significance of Regional Unconformities

The Nordland Group succession contains only three significant unconformity surfaces which can be plainly observed on seismic data (see chapter 2). These are:

1) the basal, “mid-Miocene unconformity”, which, on regional seismic data, shows some evidence for the localised truncation of underlying seismic reflectors. This unconformity surface may have either a tectonic or eustatic origin, and may well be a sequence boundary. However, it is not known whether this surface was sub-aerially exposed anywhere, so the possibility of this surface being a sequence boundary cannot be proved. However, based upon well characteristics (e.g. high gamma values, see chapter 3), it is highly possible that a marine flooding surface is either coincident with, or lies just above this unconformity surface.

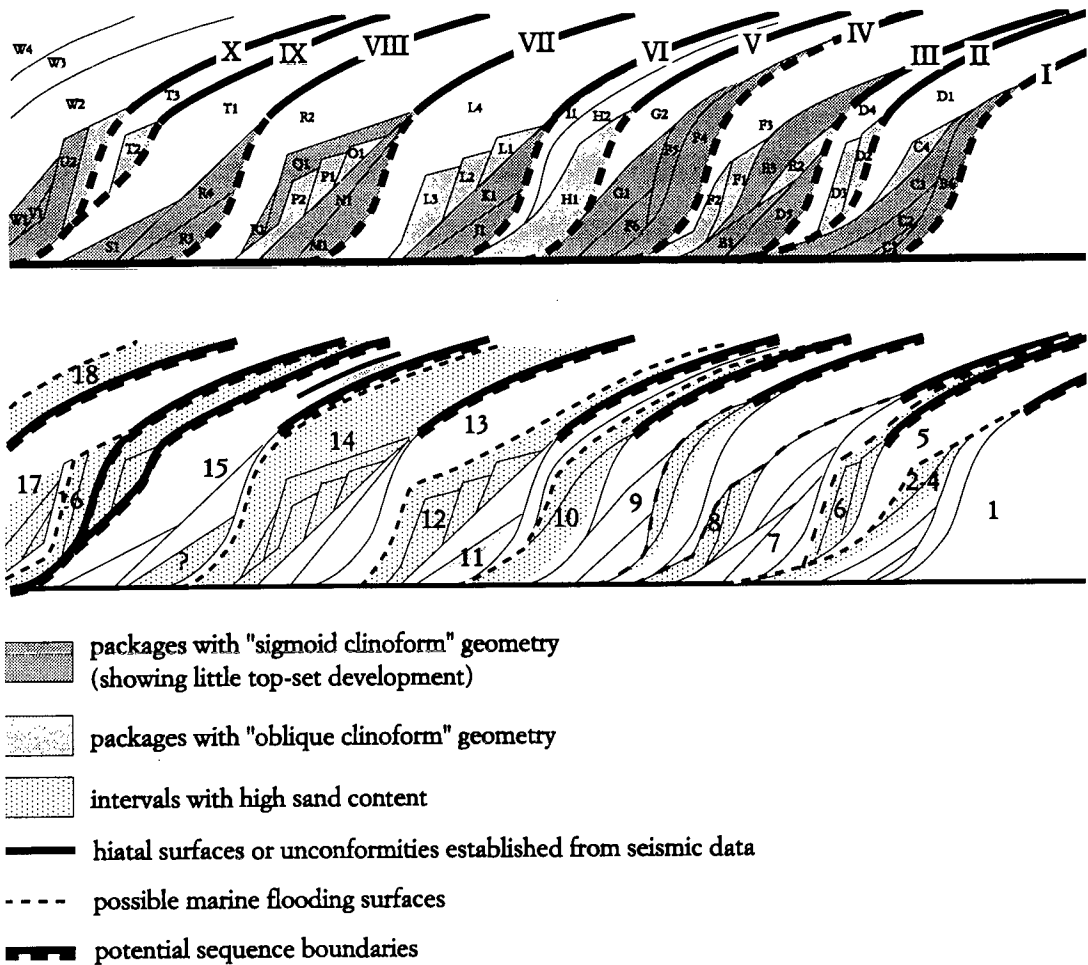


Fig. 5.4: The architecture of the Nordland Group within the clinoform succession, showing at the top the simplified relationship of the seismic packages of chapter 2 to each other. This reveals the more significant hiatal or unconformity surfaces within the succession, which are numbered from "I" to "X" (also see supplement). Below, the relationship of the well intervals of chapter 3 to the seismic packages is shown, revealing those packages which have a high sand content. Super-imposed upon this are potential sequence stratigraphic surfaces that may be present within the succession.

2) the 70m relief erosion surface within well interval "20" observed in a number of site survey data-sets, and dated as of approximately Eburonian age (see section 5.2.2). Because this interval has been cored by several SNSP boreholes, and the erosion surface is known to be fluvial in origin, this unconformity can be fairly confidently called a type-1 sequence boundary (*sensu* Van Wagoner *et al.*).

3) the glacial erosion surface, near the top of the succession, formerly dated as of Elsterian age (Cameron *et al.*, 1987), which has resulted in the deep, channelled erosion of much of the earlier Nordland Group succession. Using current sequence stratigraphic terminology, this surface has no sequence stratigraphic significance.

Apart from these three surfaces, there are no obvious, major erosional unconformities within the regional seismic data-set of Nordland Group succession. However, there are the eleven surfaces of non-deposition present within the top-sets of the Nordland Group (see section above). Any of these surfaces could potentially represent sub-aerial exposure surfaces, and could, therefore, be genuine sequence boundaries.

Evidence for erosional truncation, one indicator of the possible presence of a true sequence boundary, is almost totally absent from both the regional seismic and well data-sets. However, there is some evidence for regionally significant erosional truncation within the top-sets on certain horizons within the site-survey data-sets (probably corresponding with the bases of well intervals “16” and “18”, and to a lesser extent, with the bases of well intervals “8” and “10”, see chapter 4), all of which correspond with non-deposition surfaces seen in the regional seismic data-sets. The lack of major erosional truncation associated with these non-deposition surfaces may result from erosion only being active for relatively short periods of time.

Finally, the presence of isolated, sand dominated wedges beyond the shelf break (the “oblique prograding clinoform” facies of chapter 2), which are contiguous with some of these non-deposition surfaces, fits the description of a “forced regressive wedge” (*sensu* Posamentier *et al.*, 1992) as applied by authors such as Tesson *et al.* (1993), although the origin of these wedges cannot be proven to have resulted from sub-aerial exposure of the shelf. Therefore, at least some, if not all of the seismic non-deposition surfaces seen may, in fact, be genuine, although rather weakly developed, sequence boundaries.

It is comparatively easy to see where each potential sequence boundary occurs within the top-sets of the succession. However, unlike the “seismic sequence boundary”, beyond the shelf break there are a number of alternative horizons to choose from, each of which separates the various distal sediment packages. This problem does not occur when the lowest of these packages shows oblique clinoform architecture (cf. the “forced regressive wedge” of Posamentier *et al.*, 1992), as the base of this package is assumed to be the sequence boundary horizon. If this is not the case, then the position of any potential sequence boundary is open to question, as the deposits below the lowest “oblique clinoform” wedge, which are all “sigmoid clinoform” wedges, could be related either to sedimentation during falling sea level (cf. the “lowstand fan” of Posamentier *et al.*, 1988) or to shelf front erosion during sea level high-stands (cf. the “slope regrading” phase of Galloway, 1989).

There may be a number of regionally significant unconformities within the sandy sediments of well interval “20”, all of which could be potential type-1 sequence boundaries. There is certainly much evidence for multiple channel formation events in the high-resolution data-sets, and a number of erosional unconformity surfaces

have been recorded in the *SNSP* borehole data, most of which have been correlated regionally on sedimentological and biostratigraphic grounds (Fannin *et al.*, 1991 *unpub*). However, it is not appropriate to establish an unconformity-based stratigraphy for this part of the succession using the information from this study.

Marine Flooding Surfaces

The positions of marine flooding surfaces (and hence “parasequence boundaries”) cannot be found from seismic data alone, except to say that these surfaces are likely to occur only within seismic packages which have considerable top-set development. For this purpose, it is therefore necessary to turn to the electric log data-set.

Marine flooding surfaces tend to be found at the upward transition in well logs from sand to (marine) clays. Although not proven, the majority of clays within the Nordland Group succession (those below well interval “20”) are probably marine in origin, judging by the presence of glauconite and shell material (see chapter 3). It is, therefore, likely that the majority of upward transitions from “gamma sand” to “gamma clay” in the Nordland Group are marine flooding surfaces. This is in accord with the fact that all, or almost all of these transitions occur within “aggradational” seismic packages.

On this basis, it is estimated that there are at least 10 parasequence boundaries within the Nordland Group succession (below well interval “20”), separating at least 11 parasequences. These parasequences are large, by comparison with those commonly found in the literature, but this may be explained by the exceptionally high sediment accumulation rates estimated here (each of these “parasequences” includes sediments that may have been deposited over periods of only around 0.1Ma). Alternatively, many minor, marine flooding surfaces may not have been recognised at the scale of the data analysis.

Potential flooding surfaces within the upper parts of the Nordland Group (i.e. within well interval “20”) may be easier to recognise than individual sequence boundaries. There are at least three upward transitions from sand to clay, marking potential marine flooding surfaces within the pre-glacial succession. However, it is possible that some of the clay dominated facies may be non marine, which makes recognition of parasequence boundaries within the succession very much harder. It is perhaps beyond the capabilities of this study to resolve this problem. Within the post-glacial succession there are thought to be anything up to four marine flooding surfaces (Cameron *et al.*, 1986). However, these are at a finer scale than can be resolved by the present data-set.

5.4: Depositional History of the Cenozoic Succession

5.4.1: *The lower Cenozoic*

After an early Paleocene, depositional hiatus which marked the end of Chalk deposition in the southern North Sea Basin, large amounts of muddy sediment were deposited within the study area. This depositional phase continued throughout most of the Eocene, culminating in the deposition of silty sediments (the “Brussels Marl”). The end of the Eocene was marked, in parts of the southern North Sea Basin, by significant inversion, although there is little evidence of this within the study area. Clay deposition resumed during the Oligocene, although Oligocene sediments are generally thin within the study area.

A second inversion phase may have occurred at the end of the Oligocene or the beginning of the Miocene, marked by the formation of an angular unconformity across the whole of the study area (seismic horizon “H₀”). Following formation of the unconformity, Lower to Middle Miocene, onlapping, muddy sediments were slowly deposited in the study area along the axis of the North Sea Central Graben (see fig. 5.5).

A major transgression at the end of the Middle Miocene generated a widespread, glauconitic, hiatal surface across the study area (the “mid-Tertiary” unconformity; seismic horizon “H₀”), which probably extends across much of the southern North Sea Basin and into the central North Sea Basin. It is suggested here that this hiatus resulted in some minor erosion, although this may have been due to a change in marine conditions within the basin.

5.4.2: *The Nordland Group*

The Brunsummanian to Reuverian Stages

Uplift and erosion of the Fenno-Scandian Shield at the end of the Miocene, and its drainage into the North Sea Basin via the “Baltic River System” (Bijma, 1981), caused the deposition of a thick, SW advancing (Cameron *et al.*, 1993), possibly deltaic succession to the NE of the study area in either the late Brunsummanian or the early Reuverian Stage. However, following this, coarse grained sediment supply started to wane, resulting in the deposition of a thick, SW advancing, clay dominated succession, possibly resulting from the erosion of kaolinite-rich sediment from the Fenno-Scandian Shield. The succession prograded into the NE part of the study area (see fig. 5.6), perhaps in the middle Reuverian Stage (well intervals “1” to “5”). This

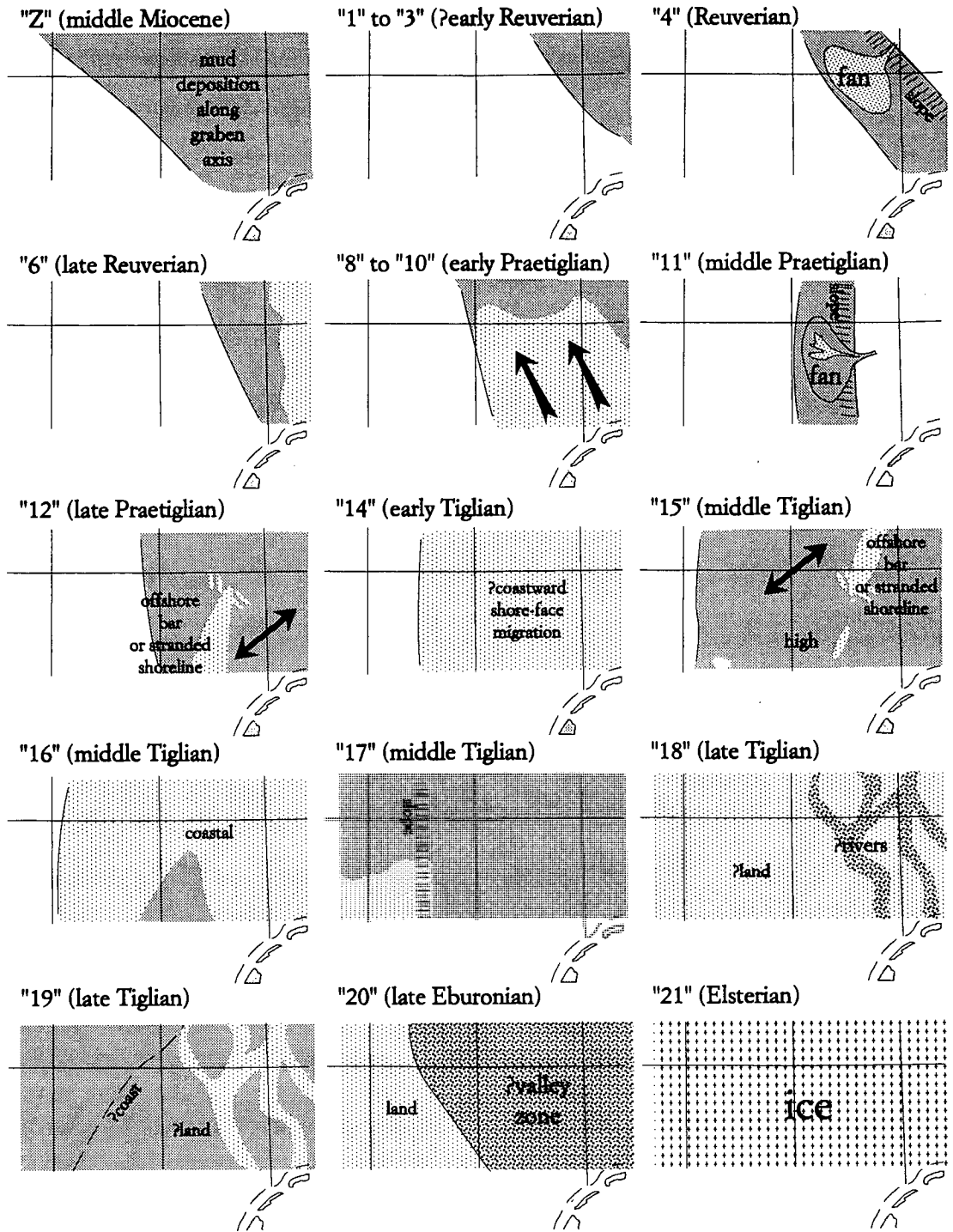


Fig. 5.5: Summary maps of the study area, showing the evolution of the Neogene to Pleistocene succession through time, illustrating the complex changes in sediment body geometry and the overall change from clay dominated, marine conditions to sandy, possibly fluvial conditions with time.

depositional phase was punctuated throughout by mass flow events, possibly associated with periods of sediment starvation and reworking. The input of turbiditic sand to the area (well intervals "4" and "5") may have coincided with the steepening of the fore-set slope during deposition, possibly related to a sea level fall. NW-SE trending contour currents may also have operated along the graben axis during this time.

Coarser grained sedimentation returned, possibly near the end of the Reuverian Stage (well interval "6"), with sand deposition across the eastern edge of the study area. Sediment progradation directions were still to the SW, and the "Baltic River System" is very likely to have remained the main sediment supplier. This change in sedimentary regime may have been due to minor glaciation, causing increased, coarse grained sediment input from the Fenno-Scandian Shield and, possibly a fall in relative sea level. A major transgression occurred, possibly at the end of the Reuverian Stage (well interval "7"), which caused the almost complete cessation of coarse clastic sedimentation in the study area, and resulted in the deposition of anoxic shale along the North Sea Central Graben axis.

The Praetigian Stage

At the beginning of the Praetigian an extensive sand sheet was deposited along the southern end of the North Sea Central Graben. This sand was probably delivered to the area from the SE, via one of the outflows of the "Baltic River System" flowing through Germany to the eastern Netherlands (well interval "8"). The increase in coarse grained sedimentation may have been influenced by the markedly colder conditions prevailing in the hinterlands at this time or by changing basin or hinterland conditions.

After a period of reduced coarse sediment supply (well interval "9"), a second extensive, sandy unit, again derived from the SE, was deposited at the southern end of the North Sea Central Graben axis (well interval "10"). The N-S trending fore-sets again became steepened at this time, and were extensively reworked, possibly in late Praetigian times, during a period of low coarse sediment input to the area (well intervals "11" to "13"). Evidence of a possible sea-level lowstand may be recorded by a NNE-SSW trending sand body (well interval "12"), associated with some erosion of earlier sediments, which could represent the result of a "forced regression".

An unconformity surface covering the western half of the study area, and cutting down into possibly Reuverian sediments in the east, probably marks a major phase of relative sea level fall at the end of the Praetigian. This was associated with

the input of large amounts of sandy sediment into the basin, which prograded westward, out into the western half of the study area, lapping out westward onto the “mid-Tertiary” unconformity surface. Coastal environments are likely to have reached the east of the study area at this time.

The Tiglian Stage

Following a brief transgression (base “Westkapelle Ground Formation”), there was another hiatus, associated with the deposition of a minor, NNE-SSW trending sand body, on the shelf. This sand body may be another “forced regressive wedge”, resulting from a brief sea level fall.

Following this, there was a second, major transgression during the early part of the Tiglian (TB), resulting in the large-scale migration of coastal environments back out to the east of the study area. This transgression is unlikely to have been due to a global sea level rise, as climatic conditions at this time are indicated to have been quite cold (Cameron *et al.*, 1984a). It is more likely that clastic sediment supplies were diverted or that there was reduced hinterland erosion. The lack of sediment input therefore caused transgression as the basin subsided. With the return of fine grained sediment input, a thick, clay succession was deposited (well interval “15”; top “Westkapelle Ground Formation”, base “IJmuiden Ground Formation”), which extended right across the study area, and may have reached East Anglia (the “Ludham Clay” of West, 1961).

Sandy conditions returned to the basin toward the end of the middle Tiglian (well interval “16”; lower to middle “IJmuiden Ground Formation”). This change was probably coupled with the re-advance of coastlines into the east of the study area, and may be associated with the first occurrence of fluvial environments there. This change may also have been associated with a relative lowering of sea level and a narrowing of the basin into a N-S oriented, channel-like depression in the west of the study area at this time. This could have caused the amplification of tidal currents along the now narrowed southern North Sea, as is suggested by the presence of wide, possibly contour current eroded, N-S trending channels within toe-sets, and the along-slope reworking of depositional fore-set surfaces in the west of the area.

Another transgression, again of possible middle Tiglian age, caused the deposition of a thin clay layer across the study area, and clay deposition may again have reached East Anglia (the “Bavents Clay” of West, 1980; ?the “Chillesford Clay” of Mathers & Zalasiewicz, 1988). This transgression was followed by extensive sediment reworking beyond the slope break (well interval “17”; top “IJmuiden Ground Formation”), coupled with sand deposition in the SW of the area.

A major regression then caused the deposition of sandy, fluvial sediment across at least the eastern half of the area, and possibly over much of the west of the area, during the Tiglian TC4c regressive event (well interval "18"; the "Winterton Shoal Formation"). By this time, the sediment depocentre had moved out of the area to the west and NW (Cameron *et al.*, 1986; Jeffery, 1993). This regression was almost undoubtedly caused by glacial conditions pertaining in the eastern hinterlands, coupled with global lowering of sea level at this time. The regression was followed by another transgressive, clay dominated phase at the end of the Tiglian (well interval "19"; base "Markham's Hole Formation"). Coastlines migrated back into the eastern part of the study area, and transgression may have been even more extensive for short periods.

The Eburonian Stage

A long phase of predominantly sandy deposition across the study area (base well interval "20"; base "Yarmouth Roads Formation"), started possibly at the beginning of the Eburonian. Although much of the sediment from this depositional phase has been eroded from at least the eastern part of the area, it may have included fluvial and coastal depositional facies. Fluvial environments probably reached the NW corner of the study area at this time.

During the middle or late Eburonian, relative sea level dropped by up to 70m, causing the incision of deep, approximately N-S trending, fluvial valley systems across the western half of the area. The fall in sea level was coupled with permafrost conditions and sediment starvation, and there may have been extensive glaciation in the highlands around the southern North Sea at this time. The erosion of these valleys might also have resulted in the deposition of large-scale, sandy, lowstand deltas far to the north of the study area. Renewed input of coarse grained sediment, coupled with warmer conditions and rising sea levels, caused the start of valley filling at the end of the Eburonian.

The Waalian to Cromerian Stages

Sediment, although increasingly fine grained, continued to be delivered to the study area during the beginning of the Waalian Stage. This, together with the continued rising of sea level, caused the complete filling of the Eburonian valley system, and ultimately resulted in transgression across much of the study area. This transgression possibly reached the NW Netherlands.

Following this transgression, renewed coarse grained input resulted in regression and sand deposition in fluvial and coastal environments right across the whole study area. This depositional pattern continued possibly until the middle of the “Cromerian” Stage, punctuated by two fine grained, transgressive depositional episodes, of possibly late Waalian and early Bavelian age (Zagwijn, 1989; 1992). The position of the coastline by the middle of the “Cromerian” Stage may have been well to the north of the study area. Climate throughout this time fluctuated from cold glacial to warm temperate conditions (Zagwijn, 1989).

It is possible that the sediment source during the Menapian changed from the Fenno-Scandian Shield, its sediments supplied by the “Baltic River System”, to the Rhennish Massif, its sediments supplied by the Rhine, as is apparently the case in the Northern Netherlands (Zagwijn, 1985). However, no evidence of this change has been found in the *SNSP* boreholes (Fannin *et al.*, 1991 *unpub.*), and it is, therefore, also possible that the “Baltic River System” remained as the major sediment supply up until the “Cromerian” Stage.

It is not known whether any sediments are preserved within the study area from the later part of the “Cromerian” Stage. However, onshore data suggest that coarse grained sediment supply may have all but ceased by the end of the “Cromerian”, resulting, with continuing basin subsidence, in transgression right across the study area and into the NW Netherlands (Zagwijn & Doppert, 1978).

The Elsterian Stage to the Present

Deteriorating climate during the Elsterian glacial stage resulted both in global sea level falling and in the expansion of NW European ice sheets out into the area of the North Sea Basin. These ice sheets covered the study area, eroding and removing extensive tracts of the uppermost, sand dominated, pre-glacial parts of the succession, and cutting channels up to 10km wide and 500m deep. By the time of ice retreat from the area towards the end of the Elsterian Stage, these channels were almost completely filled with glacial sediment. However, the depressions remaining probably continued to exist as lakes for a time, before melting ice sheets and sea level rise caused transgression of the sea across the area.

Another glacial event, currently attributed to the Saalian glacial stage, may have been responsible for a second, basin-wide regression, and the glacio-tectonic deformation seen in the eastern half of the study area (Joon *et al.*, 1990). This deformation may have been due to the localised, north or NW advance of an ice sheet lobe from the area of the Netherlands during the “Older Saalian” glaciation (Ehlers, 1990). The glaciation was again followed by transgression.

During the most recent, Weichselian glacial stage, advancing ice reached the NW corner of the study area, eroding a 50 to 100m deep glacial channel into the underlying succession. This channel still forms the Botney Cut depression. Small-scale channels in the NW of the study area may have been cut in glacio-fluvial environments at the end of the Weichselian.

The most recent transgression across the study area was during the Flandrian (Holocene) Stage, and the whole of the study area is currently between 20 and 100m below sea level.

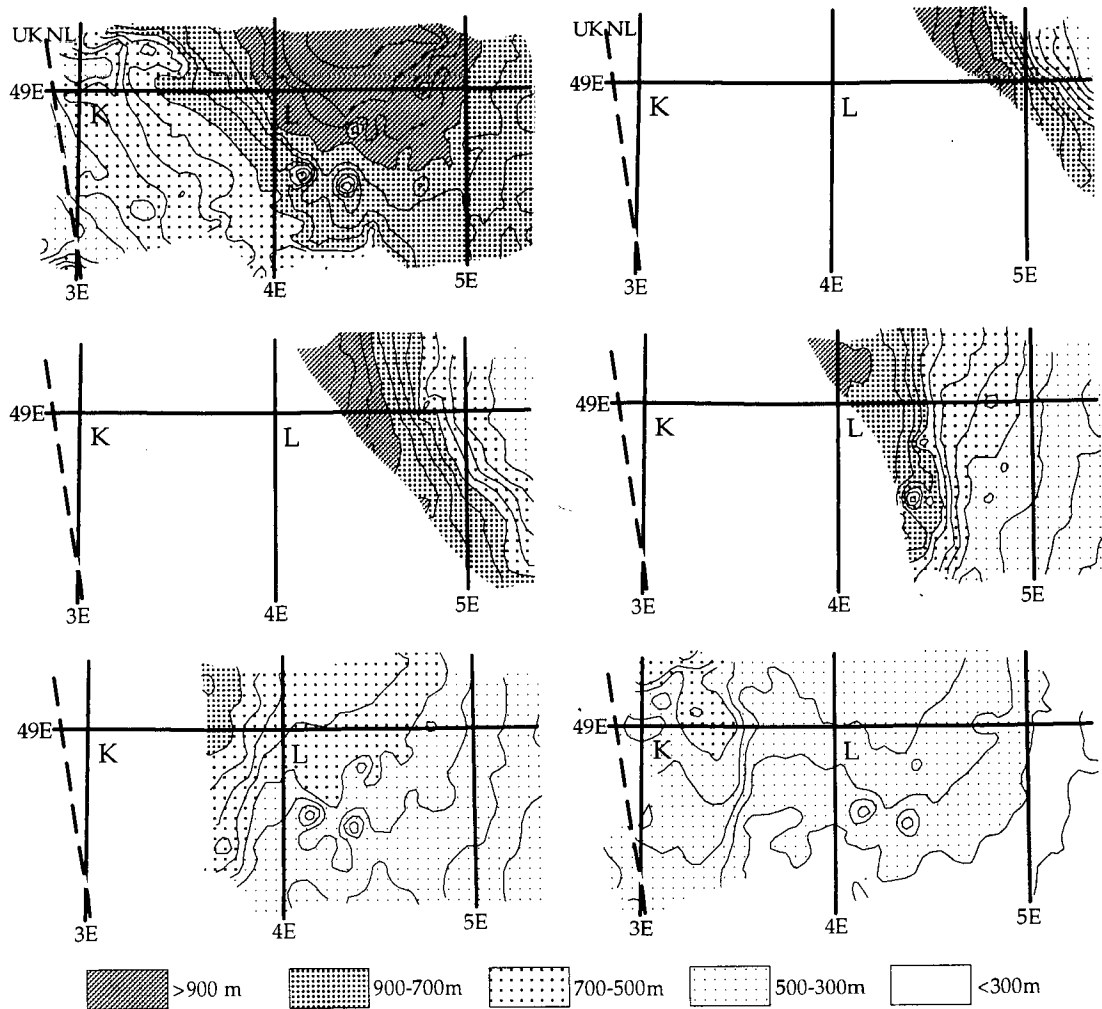


Fig. 5.6: Summary maps of depths from the sea surface to individual horizons within the Nordland Group, showing the expansion of the sediment depositional area to the SW and west.

5.5: Problems of Sediment Geometry

5.5.1: Mass Flow Facies

Mass Flows Elsewhere

In order to understand better the nature of mass flow facies seen within the Nordland Group, they are here compared to slope failure features seen on the Mississippi shelf, as studied by Coleman *et al.* (1983). These authors divided the slope failure features seen there into the following categories:

Mud Flow Gullies: These are between 20 and 1500m wide gullies, which may reach depths of tens of metres. Up-slope, they consist of a slump-scar zone which extends down-slope into a narrow chute, presumably for the removal of material, in the form of both sediment blocks and disaggregated sediment, from the slump zone. Sediment is deposited at the down-slope end in overlapping sediment lobes. Mud flow gully systems on the Mississippi shelf coalesce to form a general zone of gully formation beyond the Mississippi river mouth.

Growth Faults: These are isolated faults with lateral continuities of up to 10km. Offset of the faults increases with depth (from 5m near surface to 80m at depth), and it is obvious that they have been active over some period of time. The faults are usually concave upward and sole out at depths of around 700 to 800m. Rollover anticline formation on the down-throw side of the fault is common. Growth fault propagation is thought to be associated with the de-watering and/or de-gassing of the sediment in which the fault is present.

Massive Shelf-Edge Failures: These are extremely large features, which are occasionally seen at the shelf margin of the Mississippi shelf. Where the shelf margin has failed (in one case leaving a scar which cuts through 500m of sediment), the resulting depression has been filled by oblique prograding sediment wedges which successively decrease in dip upward. The material that makes up these wedges is clay dominated. Massive, shelf-edge failures on the Mississippi shelf are interpreted by Coleman *et al.* (1983) to have been formed during the last sea level lowstand.

Submarine Canyons: The particular example of a submarine canyon sited by Coleman *et al.* (1983), the Mississippi Canyon, is around 10 km wide and more than

700m deep in places. This canyon is interpreted to have been formed by successive sediment failures, migrating up-slope, with the removal of the slumped sediment down along the canyon axis out into the shelf slope and basin floor. The canyon is, therefore, essentially formed by slope failure.

Comparison with Nordland Group Slope Failures

The slope failures of the Nordland Group are of two basic types (see chapter 2), those which show down-throw of slumped blocks toward the basin floor (“mass flows”) and those which apparently show slump block down-throw toward the shelf top (“up-slope slump-scars”).

Mass Flows: The dimensions of the Nordland Group mass flows, which are several kilometres in area and up to 400m thick, and their location in shelf margin settings, makes these flows more comparable with the “massive, shelf-edge failures”, rather than with other features on the Mississippi shelf. However, the internal make up of the Nordland Group mass flows is perhaps most similar to the rather smaller scale, “mud-flow gullies”, which occur on the shelf of the Mississippi. Both contain at their up-slope end a zone of slumping, with essentially intact blocks of sediment, and at the distal end of the Nordland Group mass flows, the diffractive reflector patterns may be due to the deposition of lobes of sediment from debris flows in rather the same way as is seen in the “mud flow gullies”. However, in the mass flows of the Nordland Group, there is no obvious development of a chute in between these two sediment geometries, and the mass flows have a much less elongate geometry than do the “mud flow gullies”.

Although comparisons can be made between the growth faulting of the Mississippi delta and the Nordland Group mass flows, including the soling out faults at depth, and the presence of roll-over anticlines, the Nordland Group mass flows so evidence which suggests that they were formed by a single slope failure event, and fault offsets are roughly constant at the bottom and the top of fault planes (see chapter 4), whereas the growth faults of the Mississippi shelf show evidence of movement over long periods of time.

Up-slope slump-scars: If these features are truly the result of faulting with down-throw directions toward the shelf, then there is no slope failure type comparable with them on the Mississippi shelf. However, an alternative possibility exists that these features may, in fact, be similar to “massive shelf-edge failures”, which are of a similar scale. If this is the case, then the reflector configuration of the faulted

blocks should be re-interpreted as shingled clinoforms (similar to the oblique prograding wedges of the Mississippi failures). This would certainly remove the problem of the slump direction anomaly. However, there is no evidence for the existence of the large depositional lobe on the basin floor which would be expected to have resulted from the original slope failure. Additionally, the interpreted slump-scar reflectors of the Nordland Group are developed at the base of the present fore-set slope, and it is the authors opinion that the reflector configuration is, as is suggested in chapter 2, the result of faulting.

Mass Flow formation

In this section, a model is suggested for the formation of the “mass flow” units observed within the Nordland Group succession. This is put forward for discussion, and based upon available evidence. It is not stated as fact, as there is, at present, insufficient information either to confirm or reject it.

Mass flow units are seen to occur in a N-S trending, diachronous band at the eastern margin of the study area, although one large scale mass flow unit is also present in the west (see section 2.3.2). They always occur within clay dominated packages of sediment and, presumably, the mass flows were triggered only during times of fine grained sediment accumulation at these sites.

Regional and site survey seismic data (see sections 2.3.2 & 4.3.2), have revealed a remarkable correlation between fault lines on the upper surface of the Chalk Group at depth, and in the position and orientation of the fault blocks within individual mass flow units. These structures do not always appear to be directly connected.

Additionally, the basal decollement surfaces of some mass flow units, where they breach the “mid-Tertiary” unconformity, are seen to be irregular in such a way that it is difficult to imagine how individual fault blocks, which now seem to be embedded in the lower Cenozoic clay, could have moved along such a decollement (see sections 2.3.2 & 4.3.2).

In the suggested model, the assumption is made that faulting within the lower Cenozoic clay succession occurred first near the base of the succession, and finally at the top of the succession, as a result of several episodes of water release and compaction of the succession (cf. Henri^et *et al.*, 1989; Cartwright, 1994). The last of these phases of water release, compaction and faulting occurred during the deposition of the Nordland group succession.

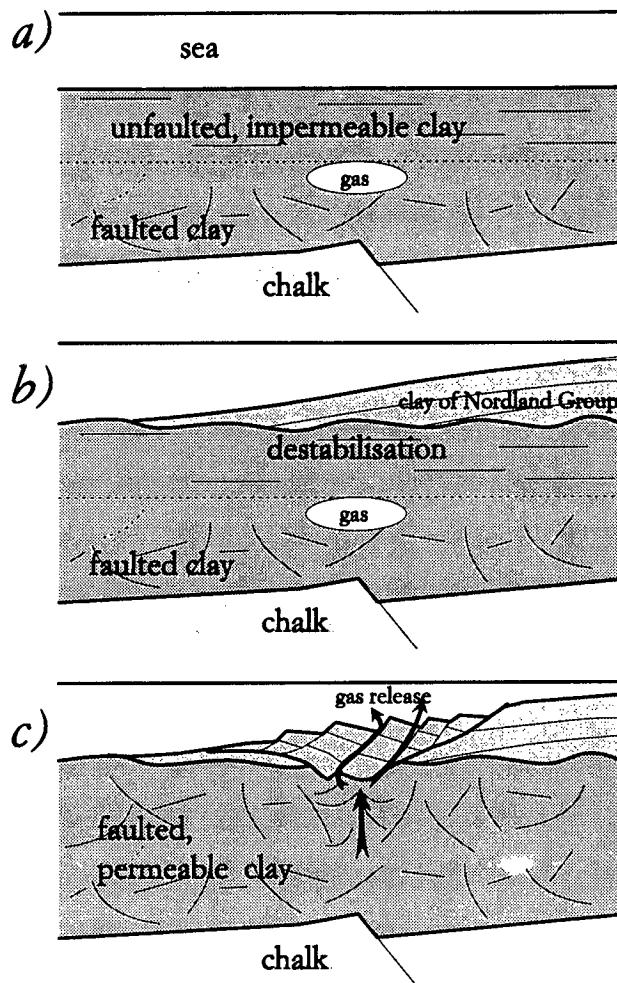


Fig. 5.7: Possible mechanism for mass flow formation, involving the influence of deep, thermogenic gas. Gas, delivered via faults in the top of the chalk, is kept in store within the lower Cenozoic clay succession. Subsequent destabilisation by Nordland group sedimentation, and resultant faulting, allows the migration upward and escape of the gas, causing major disruption in the process.

The distribution and morphology of mass flow units was controlled by locations of escape of thermogenic gas from deeper within the sediment pile, via faults cutting the Chalk Group succession. The gas migrated to the base or middle of the lower Cenozoic clay succession, perhaps through faulted, high permeability clays at the base of the lower Cenozoic succession (cf. Oligocene shale in Texas; Capuano, 1993), and became trapped beneath an impermeable boundary defining the base of unfaulted, low permeability clays in the upper part of the lower Cenozoic succession (see fig. 5.7; see section 2.3.1). This gas build-up may have occurred over a significant period of time. Only where the Nordland Group succession was dominated by low energy sedimentation was the top of the lower Cenozoic clay succession sufficiently undisturbed that the gas remained trapped below this horizon.

Eventually, the build up of differential sediment loading on the “mid-Tertiary” unconformity surface, possibly associated with other, unknown causes, caused the spontaneous faulting of the upper part of the lower Cenozoic clay succession (cf. Henri^{et al.}, 1989), rupturing of the clay seal. The sediments at the top of the lower Cenozoic succession were rapidly invaded by gas and were fluidized. These fluidized sediments acted as lubricants for fault propagation in the Nordland Group sediments and escaped to the surface along the faults. The loss of sediment volume beneath the Nordland Group sediment pile caused its localised break-up and collapse into the top of the lower Cenozoic clay succession.

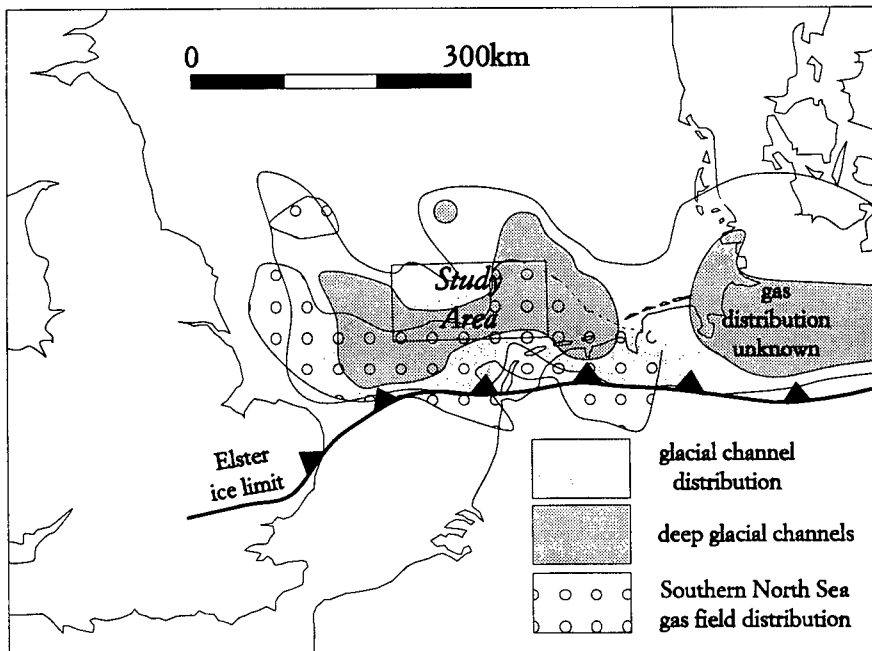


Fig. 5.8: Map of Elsterian glacial channel distribution in the southern North Sea channel belt, together with known distribution of southern North Sea gas fields and the southern limit of the Elsterian ice sheet. Note a possible structural control upon the distribution of both gas field and channel distributions (based upon Ehlers *et al.*, 1984; Cameron *et al.*, 1986; Long *et al.*, 1988; Wingfield, 1989; Glennie, 1990; Jeffery, 1989; 1993, with unpublished data from RGD and from chapter 2).

5.5.2: Controls upon Elsterian, Glacial Channel Locations

Glacial channels of Elsterian age are present over the whole of the study area. However, they are not ubiquitous across the North Sea Basin, being largely concentrated in a WSW-ENE trending belt, over 100km wide, its southern margin running from northern East Anglia in the west, across the northernmost part of the Netherlands and into northern Germany (see fig. 5.8; Van Staalduinen *et al.*, 1979; Ehlers, 1983; Wingfield, 1989). This channelled belt is generally assumed to be the result of glacial erosion at the southern, WSW-ENE trending margin of the NW European, "Elster" ice sheet (Long *et al.*, 1988; Wingfield, 1989). Current models for glacial channel formation (e.g. Boulton & Hindmarsh, 1987; Ehlers & Linke, 1989; Wingfield, 1990) require that the individual channels were cut by glacial melt-water, and were oriented perpendicular to this ice margin.

Regional mapping of the individual channels within the study area reveals orientations varying between N-S and NW-SE (see fig. 2.21a), which is in agreement with existing formation models. However, these orientations are, in some areas, broadly in line with those seen for the pre-glacial Nordland Group slope breaks, and individual channels are often cut in locations above the positions of individual slope breaks (see fig. 2.21b). The apparent correlation be due to one or a combination of the following causes:

Control of deep structure upon surface topography: In this scenario, compaction by ice of sediments above deep structure, such as slope breaks or fault lines, may have caused the surface topography to mimic this underlying structure. Although the topographic effect would be small, the influence could have been sufficient to cause preferential migration and concentration of melt-water in compaction-related, topographic depressions (D. Praeg, *pers. comm.*). This model, which requires fine control upon melt-water flow, is incompatible with the catastrophic, melt-water outbursts of Wingfield (1990).

Influence of deep structure upon melt-water flow patterns: In this model, glacially derived ground-water was concentrated along sub-surface structural lines by distortion of the hydrostatic field by sub-surface aquifer shape. This melt-water concentration then caused localised increases in hydrostatic pressure.

The upper 200m of the pre-glacial succession is generally of sand within the study area, and would be expected to act as a good aquifer. However, ground-water flow over surfaces even at depths of as little as 200m (shallower than the depth of

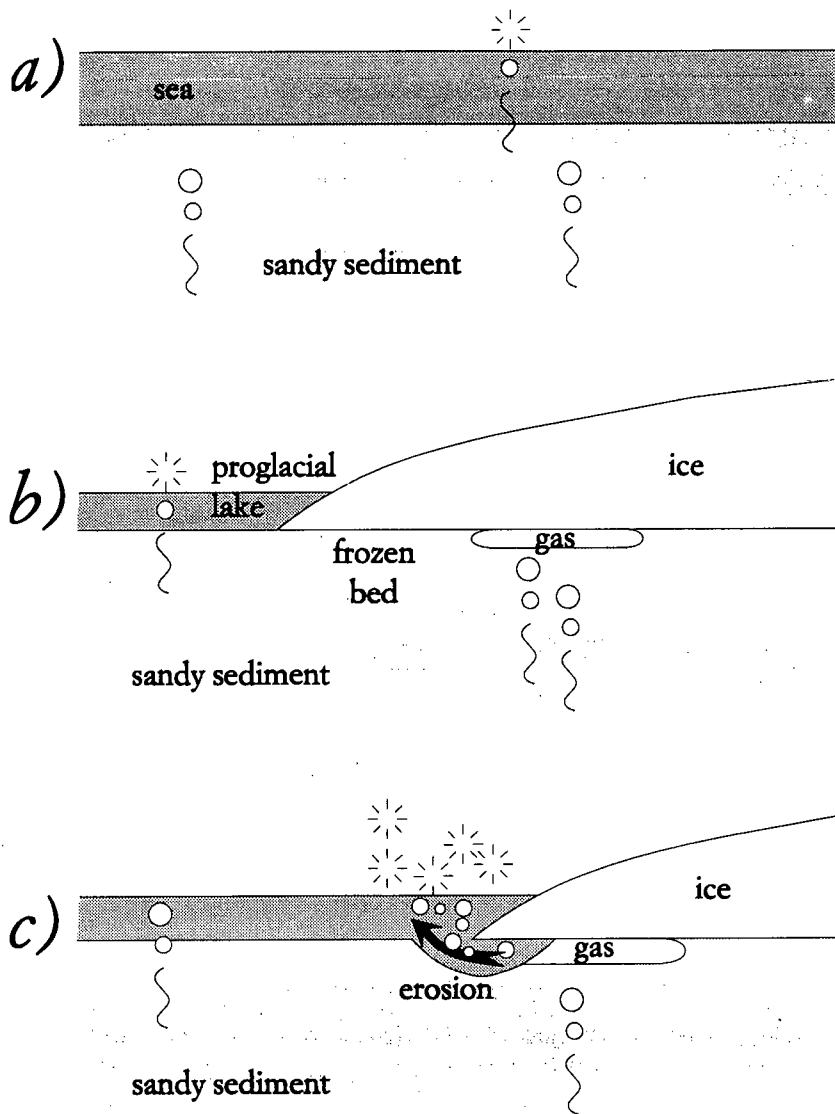


Fig. 5.9: Possible mechanism for the generation of deep, glacial channels within the Southern North Sea "channel belt". a) Interglacial conditions, with steady gas release from the sediment pile into the atmosphere. Note the preferential location of gas release sites. b) Maximum glacial conditions, with gas build-up beneath the ice sheet. c) Deglaciation and ice sheet retreat, causing rapid release of gas from beneath the ice sheet. The gas enhances natural erosion processes at the ice sheet margin during ice margin retreat.

any slope break within the study area) is unlikely to have had a major effect on flow near the base of the ice sheet (P. Caban, *pers. comm.*).

Enhancement of melt-water erosion by thermogenic gas: There is a noticeable, if imperfect correlation between the areal extent of the southern, Elsterian glacial channel belt and that of the Southern North Sea gas fields (see fig. 5.8), and it seems that the same structural controls may have affected the distribution of both. In

addition, the majority of very large channels are concentrated at the western edge of the study area (see fig. 2.21a). This is in the same location as the majority of the mass flow units in the study area (see fig. 2.30a), which are strongly suspected to have been triggered by thermogenic gas (see section 5.5.1). This channel concentration also runs contrary to the model of Boulton & Hindmarsh (1987), which predicts that channels should be found at approximately an equal spacing along the (W-E oriented) ice front.

Additionally, two channels in two different site survey data-sets (see chapter 4, surveys "49/15" & "M1-A") have evidence for trapped gas within the lower "chaotic" fill (seen as bright spots), this gas having locally escaped, fluidizing and causing collapse of the top of the "chaotic" fill.

The following hypothesis is suggested for the role of gas in the formation of these channels. During warm conditions in the Southern North Sea area, thermogenic gas, derived from the deep, Westphalian Coal succession, migrated upwards and escaped from the top of sediment pile into either the water column or directly into air (see fig. 5.9).

The advent of glacial conditions in the Southern North Sea area, and the resulting extension of an ice sheet across the study area, caused the entrapment of the gas beneath the ice sheet, possibly in the form of gas hydrates, generated by the high pressure and reduced temperature beneath the ice sheet. Due to the long residence time of the ice sheet in the area, large quantities of gas built up beneath the ice. With increasing temperatures, and the resulting melting and withdrawal of the ice sheet, gas was released and rapidly escaped. During its escape, the gas expanded, generating zero effective stress in the sub-glacial sediment, and combined with glacial melt-water and sediment to generate a fluid of high erosive capability. This had an effect similar to, but greater in magnitude than the "piping" of Boulton & Hindmarsh (1987), causing the movement of large amounts of sediment "slurry" locally from beneath the ice sheet margin out into a zone beyond the margin.

This effect should be seen to be localised to geographical locations where seeping gas normally comes to the surface, such as along fault lines and the fronts of steep sediment belts such as fore-sets. Therefore, evidence for gas seepage should be expected where large, glacial channels are seen. This does not mean that large, glacial channels should necessarily be expected in glaciated areas where there is evidence of gas seepage, as ice sheet residence times and rates of gas seepage could be important factors. This hypothesis remains to be tested by further study.

Ultimately, all these models can only be tested by further study of channel distribution and orientations in other parts of the North Sea and other basins.

5.6: Further Work

5.6.1: Stratigraphy

The lower Cenozoic Clay Succession

Although the stratigraphy of the Palaeocene and Early Eocene, silici-clastic succession in the central North Sea area is well documented (e.g. Knox & Holloway, 1992), relatively little work has been published on post Early Eocene stratigraphy of these areas, and upon the lower Cenozoic succession of the southern North Sea area.

Much work needs therefore to be done to understand the detailed stratigraphy of this thick, clay dominated succession, not only to understand the changes in depositional environment throughout this time but also to allow a framework for mapping out the distribution of individual sediment packages.

The Nordland Group

Studies of the stratigraphy of the whole of the North Sea area during Nordland group times are still in their infancy. Although various stratigraphic schemes have been established for onshore deposits around the North Sea Basin of equivalent age, these are in no way integrated into a larger framework which will enable the understanding of the whole basin in a regional context. There need to be many more interdisciplinary studies, like those of Gibbard *et al.* (1991) and the SNSP (Fannin *et al.*, 1991 *unpub.*), before this larger framework can be erected.

It would be unwise here to try to extend the application of the local stratigraphic scheme presented in this thesis, even to the other parts of the offshore Netherlands, as there is little information available on how the stratigraphic units recognised change outside the present study area. Additionally, there has been virtually no bio-stratigraphic or litho-stratigraphic analysis undertaken on the late Cenozoic deposits of the southern North Sea Basin, an essential pre-requisite for any regional stratigraphic scheme. The work undertaken in this study is therefore seen as the first of what I hope may be many similar studies of the Nordland Group succession throughout the North Sea Basin.

5.6.2: Architecture

Applications of 3D Seismic Data

The lower Cenozoic clay sequence commonly shows highly complex fault patterns which cannot be traced adequately using conventional grids of seismic data. However, such complex patterns could be easily mapped using 3D seismic data, a good example of this being shown by figure 8 of Newton & Flanagan (1993), a horizon slice showing the patterns of deformation in lower Cenozoic clay from the outer Moray Firth.

Additionally, interpretation of 3D seismic data-sets could allow the understanding of the complex fault patterns involved in both mass flow units and slumps from the pre-glacial Nordland Group succession, and also elucidate the origins of these features. Similar work, using 3D seismic data-sets, is already being undertaken on the nature of the infill and morphology of the largest glacial channels in the glacial Nordland Group succession (D. Praeg, *pers. comm.*).

Basin-wide Depositional Patterns

Although reconnaissance work has been done on mapping the geometry of regional sediment bodies by Bjørnslev Nielsen *et al.* (1989), Clausen & Korstgård (1993a) and Kay (1993), much work remains to be done on the changes in morphology of late Cenozoic sediment bodies further north and with the morphology of lower Cenozoic sediment bodies in the whole of the North Sea Basin. Only then might it be possible to make significant conclusions about the nature of regional changes in sediment body distribution throughout the Cenozoic era.

Pliocene and Pleistocene, especially in the east of the study area, have had a significant effect upon sediment body architecture during both the

11) Migration of thermogenic gas from deeper in the sediment pile to the surface may

the area, and their location may have been influenced by deeper structure. been mapped across the study area. These do not show uniform distribution across

10) Using regional seismic data, up to 400m deep, Pleistocene glacial channels have

significant fall in relative sea level. surface is defined by over 60m deep valley incision, and is probably due to a

succession of the study area from high resolution, site survey seismic data. This

2) An early Pleistocene (Brunnian) unconformity surface is recognised within the

Figure 1

sediment in the Cenozoic succession north of at the end of the Pliocene (middle or late

8) Bio-stratigraphic and well data suggest that sand replaced clay as the dominant

causes cannot be ruled out

period, the origin of which may be due to global sea level fluctuations, although other

late Pliocene sediments of the study area. These have an approximate 100,000 year

1) Cycles of sand and clay sedimentation are recognised from well data within the

westward onto the "mid-Tertiary" basal surface (see fig. 2.10)

area from the NE to the west during the Pliocene, showing progressive onlap

3) Mapping of regional seismic data shows that sedimentation expanded across the

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Supplement: A diagram showing the detailed stratigraphic relationships of the pre-glacial (pre-Elsterian) Nordland Group sediments, together with suggested stage ages for the sediments (based upon various sources quoted in the text). The diagram includes all of the seismic packages and well intervals discussed and used in chapters 2 and 3. A simplified version of this diagram is contained in chapter 5 (fig. 5.2).

Seismic packages "A1" to "W4" are all defined on the basis of minor hiatal surfaces between each of them. These hiatal surfaces are not shown here, as they would overly complicate the diagram. Although this diagram purports to show a W-E section through the study area, all N-S variations in facies have also been incorporated (seismic packages "F1 to "F3", which do not occur in the northern part of the area, are shown here). Numbers given in roman numerals refer to the unconformity surfaces discussed in chapter 5 (section 5.3.2).

Environmental interpretations and numbers relating to SNSP boreholes 89/2 & 2A are taken from the work of the *Southern North Sea Project* Working Group report (Fannin *et al.*, 1991). The formation names are taken from the mapping work of Cameron *et al.* (1986).

