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Stratigraphy and palaeobotany of Middle Pleistocene interglacial deposits in the North Sea.

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STRATIGRAPHY AND PALAEOBOTANY OF MIDDLE PLEISTOCENE INTERGLACIAL DEPOSITS IN THE NORTH SEA

BY

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Dedicated to the memory of the

Late HAFIZ NOOR-UL-HASAN ANSARI (author's father)

(1915 - 1986)

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ABSTRACT

This study presents a detailed palynological investigation of Middle Pleistocene interglacial sediments from the North Sea. A borehole and three vibrocores from the Inner Silver Pit area of the southern North Sea, and a borehole from the Devil's Hole area of the central North Sea, have been investigated. The palynological investigation has been supplemented by micropalaeontological and sedimentological analyses and also by seismic data.

The sequence recovered in borehole 81/52A from the Inner Silver Pit presents a depositional record from the mid-Anglian to the Wolstonian glacial stage.

Glacigenic sediments overlying Cretaceous Chalk correlate with the Lowestoft Till (Anglian).

The depositional history of the interglacial cycle indicates that during the pre-temperate substage extensive erosional activity occurred in coastal areas causing a large proportion of reworked pollen and a very low amount of contemporaneous pollen to be deposited. The sequence preserves a good vegetational record of the early-temperate (HoII), late-temperate (HoIII) and post-temperate (HoIV) substages. The pollen assemblages representing HoIII and HoIV are very similar to the pollen assemblages of these substages from Marks Tey, Essex. The pollen assemblage representing HoII is different from Marks Tey in having a high proportion of *Picea;* as such it shows similarity with

the pollen assemblages found at Nechells, Birmingham.

The sequence of the sands and gravels can be correlated with the Wolstonian sands and gravels at Tottenhill in the Nar Valley, North Norfolk and with Saalian sediments in the Dutch sector of the North Sea.

Three vibrocores, 53/00/962, /1103 and /1104, from the Inner Silver Pit area provide additional data and represent various parts of the Hoxnian interglacial stage.

Pollen data from borehole 81/34 from the Devil's Hole area suggests that the sequence representing the Ling Bank Formation does not represent a single interglacial stage but rather two interglacial stages (separated by a cold stage) within the Cromerian Complex.

Chapter I

Introduction

I.1. Aims of the study

Over the past decade it has become apparent that throughout the Quaternary the North Sea Basin has acted as a depositional trap for glacial and interglacial sediments derived from the surrounding land masses. Consequently, a more complex and complete record of Quaternary events is preserved in the basin than is found on the peripheral land areas.

In the British sector of the North Sea Basin, regional mapping studies by the British Geological Survey (BGS) indicate that the Quaternary succession thickens eastwards. The Quaternary sequence is present in a linear trough trending north-northwest down the centre of the North Sea Basin (Fig. I.1). The Quaternary succession in this area has been subdivided into a number of seismostratigraphic formations which are thought to range from Early Pleistocene to Holocene in age. These units can be correlated over a large part of the North Sea, but their palaeoenvironmental implications and age relationships are relatively unknown.

The main aim of this study is therefore to contribute to the effort to establish a Quaternary stratigraphic framework for the North Sea.

The Hoxnian (Holsteinian) interglacial has been extensively investigated in the landmasses surrounding the

North Sea, and its presence has also been reported from the Dutch sector of the North Sea. Pollen analyses of four samples (Fisher *et al.*, 1969) collected by the University of Hull using gravity corers in 1964 in the Inner Silver Pit suggested the presence of Hoxnian deposits offshore in the British sector. In 1981 the British Geological Survey (BGS) sited a borehole in the vicinity of the Inner Silver Pit in order to confirm the correlation of offshore seismostratigraphic units with the land based stratigraphy. This 50 metre borehole penetrated to the Cretaceous Chalk (Fig. III.3), and recovered a Quaternary stratigraphic succession which shows a close similarity with the stratigraphic sequence reported from the Nar Valley (Ventris, 1985; Fig. I.13). On the basis of this comparison, and the pollen analyses of the four samples of silty-clay from the Inner Silver Pit (Fisher *et al.*, 1969 and see also section I.4) a major aim of the project was to test the hypothesis that the silty-clay* sequence in this borehole could be correlated with the Hoxnian interglacial on palynological grounds.

In borehole 81/52A, a sequence of sand and gravel overlies the silty-clay. Tappin (1991) has named this the Egmond Ground Formation correlated it with the Egmond Ground Formation of the Dutch sector which represents the Holsteinian interglacial stage. Tappin's interpretation

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* Tappin (1991) has named this silty-clay sequence as the Sand Hole Formation.

indicates that both the Sand Hole and Egmond Ground Formations were deposited during the Holsteinian (Fig. III.1.). The lithologies of the two formations are extremely different. The Hoxnian sites in the Nar Valley (Ventris, 1985) indicate that the youngest marine record in the Nar Valley is HoIIIb (late-temperate substage). Ventris interprets this (absence of marine record of HoIV) as a result of marine regression. This raises the hypothesis that the sand and gravel of the Egmond Ground Formation might correlate with the post-temperate substage (HoIV) of the interglacial.

In the British sector of the central North Sea BGS borehole BH 81/34 (Stoker *et al.*, 1985b) penetrated to a depth of 230 metres below seabed. Stoker *et al.* (1983) carried out a palaeomagnetic investigation of this borehole. They divided the sequence into a number of formations (Stoker *et al.*, 1985b) and correlated them adopting the stratigraphic scheme proposed by Holmes (1977). According to Stoker *et al.* (1985b) the thick silty and sandy sequence between 55 and 142 metres below seabed in this borehole can be correlated with the Ling Bank Formation. Harland (1988) has examined the dinoflagellate cyst assemblages from this borehole. Though he has not been able to provide any precise correlation he suggests the whole length of the succession between 55 - 142 m represents a single temperate cycle. Knudsen (in prep., Fig. V.6) has carried out foraminiferal analysis on the same borehole, (BH 81/34). The results of her analyses show that the sequence between 55 - 142 m does not represent a single interglacial cycle but rather two warm phases separated by a cold phase.

In the Quaternary of NW Europe palynology has played a very significant role; the zones of interglacial stages are defined almost exclusively on vegetational characters as pollen analysis has been the dominant technique in most investigations. "Pollen analysis does appear to offer greater scope for correlation within the Quaternary offshore, despite the problems encountered in using the assemblages from marine sediments to interpret regional palaeoclimate" (Cameron *et al.*, 1987). Another aim of this study is to undertake pollen analysis of samples from the warm phases present in the Ling Bank Formation in an attempt to achieve a correlation with terrestrial sequence.

A greater understanding of pollen sedimentation and taphonomy in the marine environment is an essential pre-requisite for the terrestrial-marine correlation of the Quaternary sequence in NW Europe. This project was designed to address this problem in the context of the highly distinctive Hoxnian pollen signature.

This study therefore presents a detailed investigation of a borehole and three vibrocores (Fig. III.2) from the area of the Inner Silver Pit in the southern North Sea (Fig. I.5), and a borehole from the vicinity of the Devil's Hole in the central North Sea (Fig. V.1). The main tool used in this investigation is palynological analysis supported by micropalaeontological and sedimentological investigations.

In addition, the interpretation of seismic surveys of the areas provides information on the lateral distribution of the deposits encountered in the boreholes and vibrocores.

These data are compared with the various Hoxnian sites in Britain, the correlative Holsteinian of continental European and the Gortian of Ireland, particularly as the interglacial sediments are represented here by marine deposits. A detailed comparison with the Nar Valley sequence is presented.

Main aims of this study can be summarised as follows:

1. To establish the age of the silty-clay sequence of the Sand Hole Formation of Tappin (1991) recovered in BH 81/52A from the Inner Silver Pit area of the southern North Sea.

2. To establish the status of the sand and gravel of the Egmond Ground Formation of Tappin (1991).

3. To establish the status of the Ling Bank Formation of Stoker *et al.* (1985b). Does it represent a single interglacial stage, as indicated by the dino cyst analysis (Harland, 1988), or two warm periods separated by a cold period as suggested by the foraminiferal data (Knudsen, in prep., Fig. V.6)?

I.2. Geological history of the North Sea

The Quaternary isopach map has been constructed by Caston (1977; Fig. I.1). He used information obtained from 188 wells drilled throughout the North Sea. Although his data is questioned, according to Stoker *et al.* (1985a), the conspicuous feature of this map is the considerable thickness of the Quaternary present in a linear trough trending north-northwest. According to Caston (1977), this linear trough corresponds approximately in position to the underlying central graben which has been identified as a major structural feature of Mesozoic and Tertiary age (Kent, 1975). This major structural feature contains at least two closed basins in which maximum Quaternary thickness exceeds 1,000 m. This suggests that, in general, sedimentation throughout the Quaternary followed the tectonic setting of the North Sea.

a) Summary of tectonic history of the North Sea

During its geological evolution, according to Ziegler and Louwerens (1979), the North Sea area was occupied by a number of genetically different sedimentary basins, each of which developed in response to a different megatectonic setting (P.A. Ziegler 1975, 1977; W.H. Ziegler 1975). Thus the history of the North Sea can be subdivided into several more or less distinct tectono-depositional cycles.

Ziegler and Louwerens (1979) suggest that the North Sea basin came into existence as a structural entity during the Early Tertiary, but the geometry of the Tertiary and

ISOPACH MAP, NORTH SEA

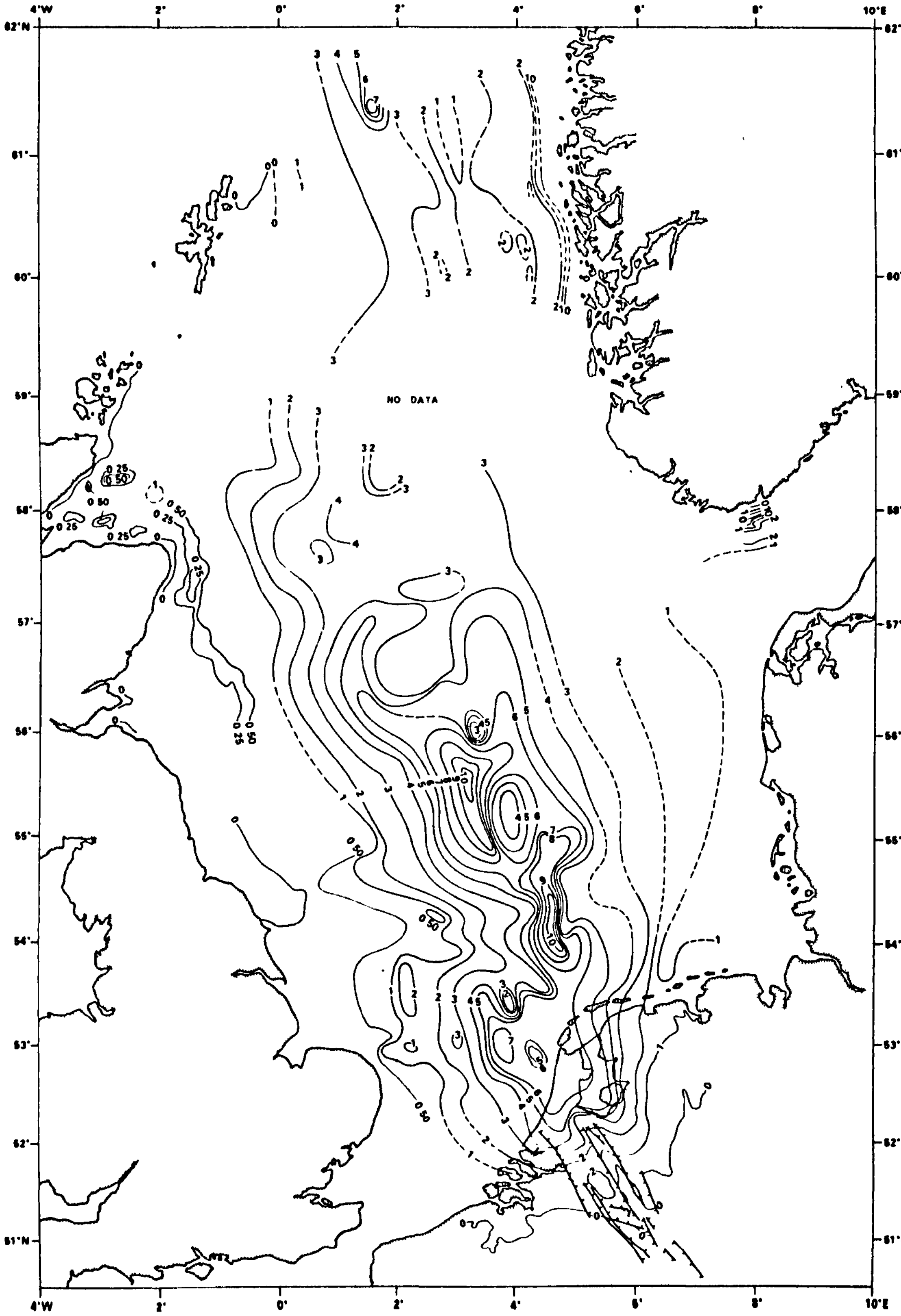

Fig. I.1. Isopach map of total Quaternary thickness in North Sea based primarily upon data from 188 wells. Isopachs at intervals of 100 m, except locally of the UK coast where the 25 and 50 m contours have been added (from Caston, 1979).

Quaternary North Sea basin has been strongly influenced by earlier events in the Late Palaeozoic and the Mesozoic.

The Saxonian and Thuringian development of NW Europe was characterised by the subsidence of two large basins (P.A. Ziegler, 1978; Ziegler and Louwerens, 1979). The Northern Permian Basin extends from the Moray Firth to the Oslo Graben and is separated from the Southern Permian Basin by the Mid North Sea - Ringköbing - Fyn trend of highs (Fig.I.2) which came into existence during the Late Carboniferous and early Permian. The Southern Permian Basin extends from Poland to England over a distance of some 1500 km.

Their model suggests that the Mesozoic development of the North Sea is characterised by the subsidence of a complex graben system. The main element of the Jurassic - Cretaceous rift system is the North Sea Rift and development of the N-S trending Viking Graben and Central Graben that breached the E-W oriented Mid North Sea - Ringkobing - Fyn High (Fig.I.3).

With the onset of the Late Cretaceous sedimentation in Northwestern Europe changed from shales and clastics to carbonates (Hancock and Scholle, 1975), (Fig.I.4). The upper Cretaceous are the most extensive Mesozoic deposits in the North Sea, being present almost everywhere except over the inversion axes in the Southern North Sea Basin. The average thickness is not more than 500 m, but in grabens and marginal troughs it reaches 1000 - 1600 m. In the southern

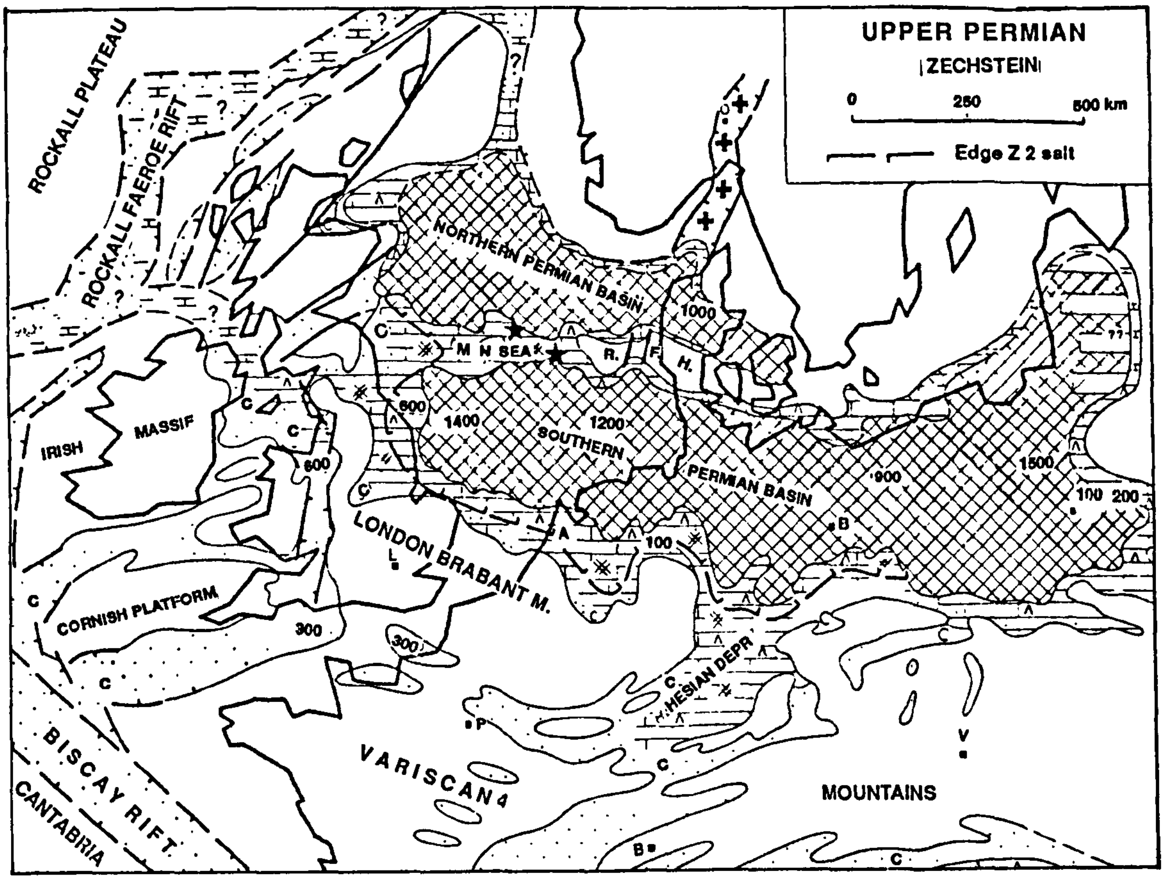

Fig. I.2. Zechstein palaeogeography showing the Northern Permian Basin and Southern Permian Basin (from Ziegler, 1978).

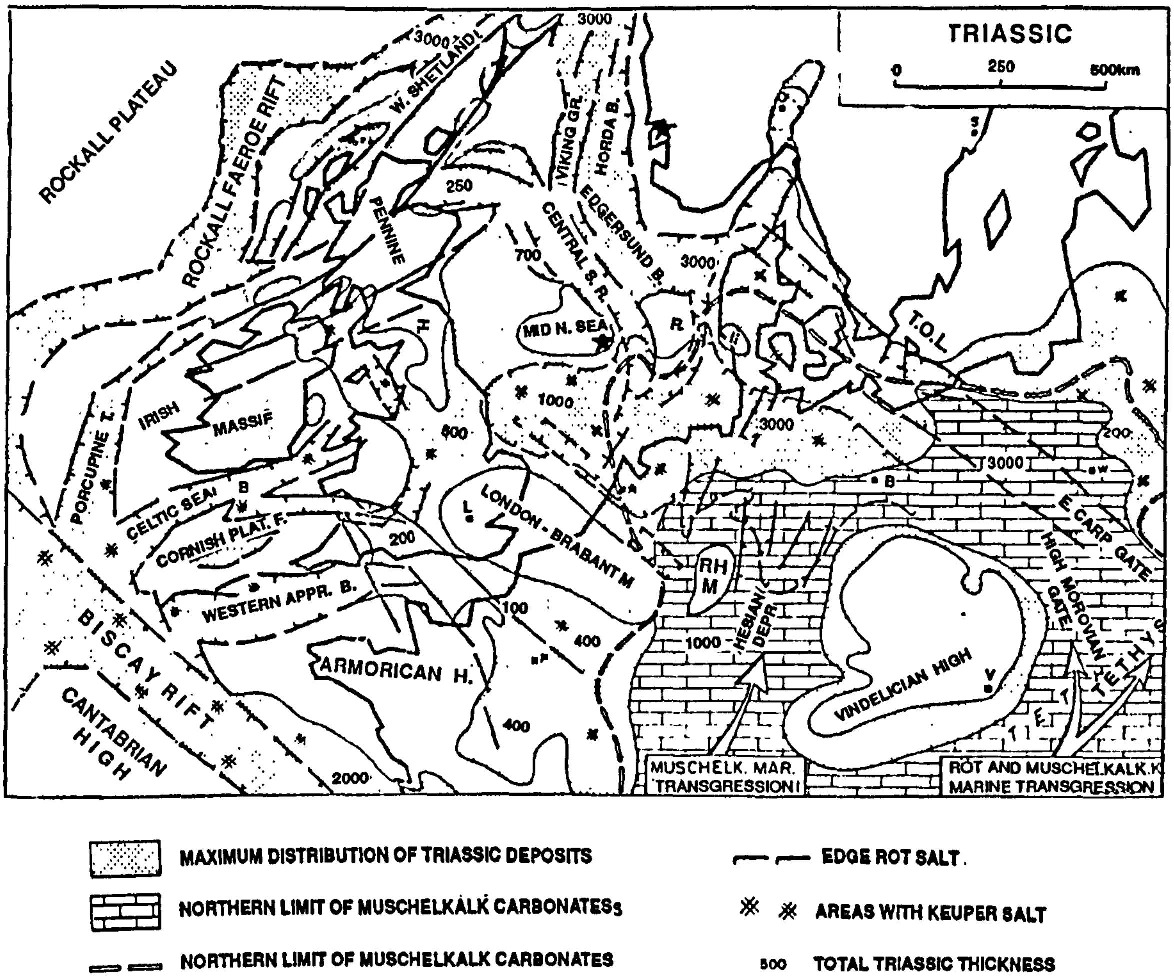

Fig. I.3. Triassic palaeogeography showing the Viking and Central Graben (from Ziegler, 1978).

North Sea the Upper Cretaceous is mostly pure chalk, but northwards in the Central Graben the chalk becomes slightly argillaceous. In the Viking Graben the chalk almost disappears and the succession consists of clay which becomes silty northwards. The Chalk is a distinctive limestone chiefly because it was deposited as low-magnesian calcite. The purity of the chalks and limestones is an indication of the extent to which the Late Cretaceous seas had inundated the highs flanking the North Sea area. The Chalk sequence consisting mainly of coccolith oozes, reaches thicknesses of some 1200 m in the Central and the Southern Viking grabens (P.A. Ziegler, 1975; Ziegler and Louwerens, 1979; Hancock and Scolle, 1975).

During the Tertiary the entire North Sea area was dominated by regional subsidence which apparently continues as demonstrated by the great thickness of Quaternary strata (Caston, 1977; Fig. I.1).

The Palaeocene - Eocene transitional period in the North Sea was influenced by the volcanicity of the Scottish Tertiary (Jaqué and Thouvenin, 1975), with the scattering of tuffaceous material over much of the North Sea area resulting in the deposition of the almost basin wide Early Eocene tuff marker. In the central and southern North Sea the Palaeocene and Eocene are represented mainly by clays and silts (Parker, 1975).

The Oligocene is marked by a regional hiatus at its base and top. These breaks in sedimentation are thought to be caused by eustatic sea-level changes rather than by local tectonic events.

According to P.A. Ziegler (1978), Miocene and younger strata consist of shallow marine and paralic sands and clays as well as of Quaternary glacial material. Neogene and Quaternary sediments attain a maximum thickness of 2000 m in the central North Sea. Generally, Oligocene and younger time stratigraphic units expand in thickness from the margins of the North Sea basin towards its centre (Ziegler and Louwerens, 1979). The axis of this basin coincides with the axes of the Mesozoic Viking and Central Grabens (Ziegler and Louwerens, 1979). Pleistocene uplifting of the Fennoscandian shield resulted in the truncation of the north-east edge of the Tertiary North Sea Basin, and the scouring-out of the sea-bottom relief of the Skagerrak and Norwegian Trough is attributed to glacial activity (Holtedahl and Bjerkli, 1975).

The saucer-shaped subsidence pattern of the North Sea Basin, according to Ziegler and Louwerens (1979), can be explained in terms of the cooling and resorption into the upper mantle of a rift cushion or asthenolith underlying the North Sea rift system during the Jurassic and Cretaceous (P.A. Ziegler, 1975, 1978). These workers believe that, in contrast to the North Sea rift systems, the inverted Mesozoic troughs and grabens and their surrounding areas remained stable throughout the Tertiary.

I.3. Bathymetry

Bathymetric map of the North Sea is presented in Fig. I.5 (from Caston, 1979). Caston (1979) has presented the detailed history of hydrographic surveys undertaken in order to construct this map. He has divided the map into four principal areas: i) shelf edge; ii) Norwegian Channel; iii) northern North Sea and iv) southern North Sea. The area from the British coast and the western edge of the Norwegian channel from 56°N northwards to the edge of the continental shelf has been defined as the northern North Sea whereas the southern North Sea includes the area from 56°N south. This means that there is no distinctive bathymetric province for the "central" North Sea.

This study concerns the central and the southern North Sea southwards from 58°N. The central North Sea is defined as the area between 56°N and 58°N.

BGS surveys have been primarily directed towards the production of geological maps at a scale of 1:250,000 on the basis of sheet areas measuring 1° latitude by 2° longitude, with separate maps illustrating solid geology, Quaternary geology and sea bed sediments. Most of these maps are now published or in press. These maps also include bathymetric information.

Two of these sheets are directly relevant to this study, the Spurn sheet from the southern North Sea and the Devil's Hole sheet from the central North Sea. The bathymetry for these two areas are presented in the relevant chapters.

BATHYMETRY, NORTH SEA

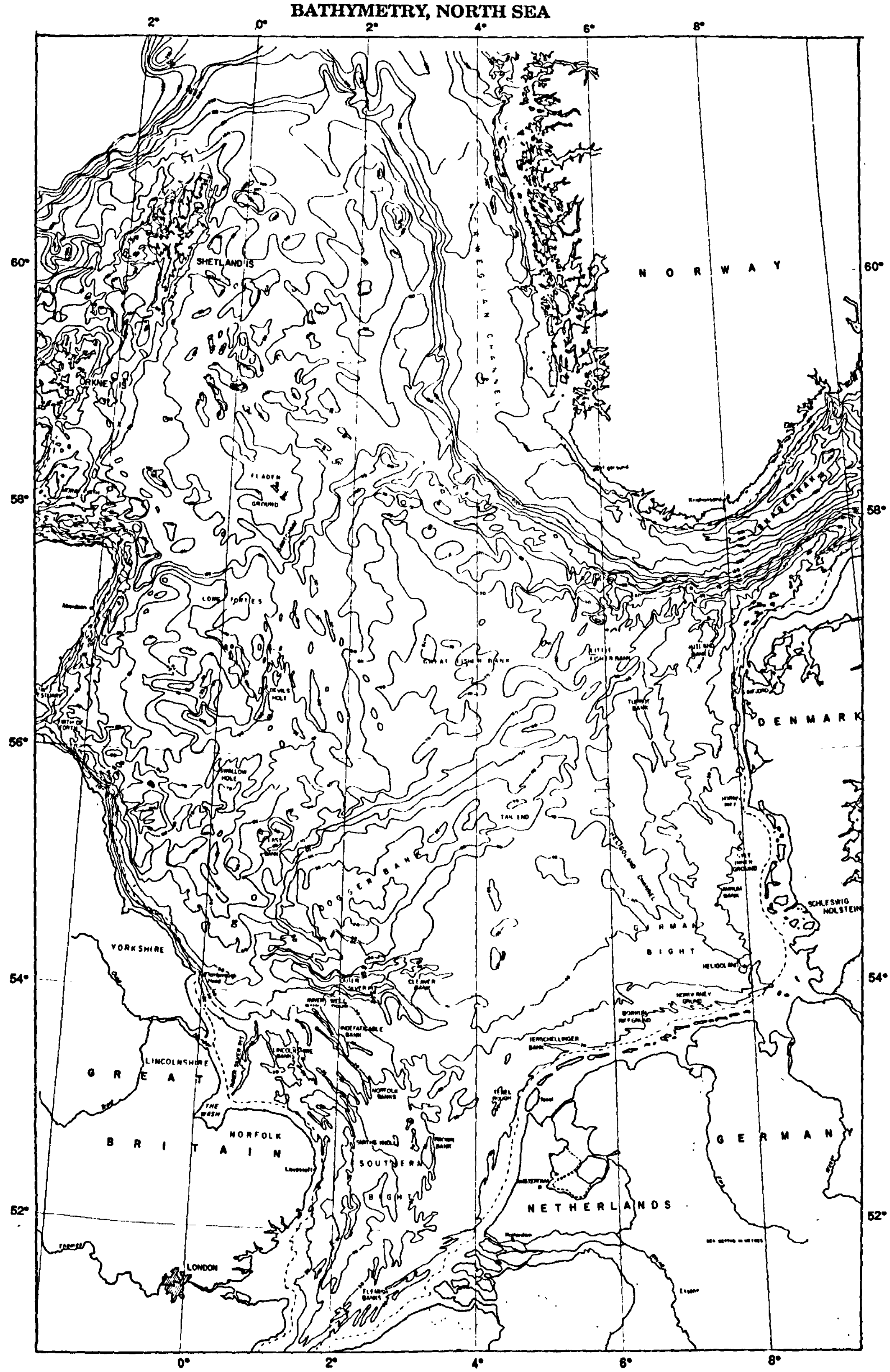

Fig. I.5. Bathymetric map of the North Sea. Isobaths nominally at intervals of 10 m to 100 m, 20 m to 100 m at greater depths. (from Caston, 1979).

I.4. Quaternary stratigraphy

The Quaternary is characterised by a series of climatic fluctuations that have long served as the basis for stratigraphic subdivision. Historically the possibility of significant climatic change was first realised in the terrestrial environment from the recognition of glacigenic sediments in areas not currently affected by glacial activity. More recently marine records have become increasingly important with the availability of ocean sediment cores and techniques of oxygen isotope and palaeomagnetic analysis (Shackleton and Opdyke, 1973, 1976). Despite these major advances based upon deep-ocean marine sediments, relatively little is known about continental shelves which offer the potential of linking the deep ocean and terrestrial records.

The standard sequence of the Quaternary of NW Europe (Table I.1 & 2) is based on the recognition of end moraine systems and correlative till beds, and on fossil assemblages associated with terrestrial, lacustrine and marine deposits (Sibrava *et al.*, 1986, Ehlers *et al.*, 1991a). Three main glacial stages are widely recognised in continental Europe: the Elsterian, Saalian and Weichselian separated by the Holsteinian and Eemian interglacials respectively (Sibrava *et al.*, 1986). In Britain these glacial stages are represented by the Anglian, Wolstonian and Devensian glacial stages separated by the Hoxnian and Ipswichian interglacial stages (Ehlers *et al.*, 1991a). Much of NW Europe was

Table I.1. Correlation of European, British and Irish Middle Pleistocene sequences showing suggested equivalence with deep sea stratigraphy. DS = deep sea stages; Int. = Interstadial; --- = Palaeomagnetic reversal (from Ehlers *et al.*, 1991b).

BRITAIN	IRELAND	EUROPEAN	DS
Ipswichian		Eemian	5e
Wolstonian	Munsterian	Warthe Substage	6
		Interstadial	7
		Drente Substage	8
		Wacken/Hoogeveen	9
		Fuhne Stadial	10
Hoxnian	Gortian	Holsteinian	11
Anglian		Elsterian II	12
		Miltitzer Int.	
		Elsterian I	
Cromerian s.s.		Cromerian IV	
Beestonian (part)		Glacial C	
		Cromerian III	
		Glacial B	
		Cromerian II	
		Glacial A	
---------------		Cromerian I 788 ka	19

Table I.2. Middle Pleistocene stratigraphy in NW Europe.

Britain	Netherlands		Germany		North Sea
Wolstonian cold stage	Saalian cold stage	Bentega Ints. Hoogeveen Ints	Saalian cold stage		Saalian cold stage
Hoxnian temperate stage	Holsteinian temperate stage		Holsteinian temperate stage	Domnitz Intg. Fuhne Gla. Holstein Intg.	Holsteinian temperate stage
Anglian cold stage	Elsterian cold stage		Elsterian cold stage		Elsterian glacial stage
Cromerian Stage	Cromerian Complex		Cromerian Complex		Cromerian Complex?

repeatedly covered by continental ice-sheets. Glacial-tectonism, diapirism, repeated erosion with accompanying unconformities, and scarcity of fossils make correlation of glacial sequences particularly difficult (Sibrava, 1986; Ehlers *et al.*, 1991a). The number of glacial and interglacial cycles in Europe between the Brunhes/Matuyama boundary and the Elsterian (Anglian) is uncertain. At present it is believed that the post-Elsterian interglacial sequence is probably correct (e.g. Ehlers *et al.*, 1984) and that the pre-Elsterian sequence is fragmentary.

Preliminary data from BH 81/52A and BH 81/34 indicate the presence of sequences of Middle Pleistocene age. A brief review of the Middle Pleistocene is therefore presented below.

a) Middle Pleistocene climatic stages

i) Britain

The type site for the Anglian stage is at Corton in north east Suffolk. The deposits of this cold stage are represented by two glacial advances (Shotton, 1985; Ehlers, *et al.*, 1991c) which deposited two different types of till. An early advance from the northeast across the North Sea deposited Cromer Till (North Sea Drift), whereas the later advances from northwest Britain deposited the Lowestoft Till (Chalky Boulder Clay). Tills of the Lowestoft glaciation are the most extensive in eastern England reaching as far south as the area of north London. The stratigraphic position of the Anglian glaciation is well defined and clearly observable at many sites in East Anglia (Lewis *et al.*, 1991). The upper boundary of the Anglian glaciation is marked by the presence of Hoxnian biogenic deposits overlying Lowestoft Till. Hoxnian deposits at Hoxne (West, 1956), Marks Tey (Turner, 1970), in the Nar Valley (Ventris, 1985), and at several other sites, rest directly on till of Anglian age. Hoxnian deposits are mostly found in basins and troughs formed on the early deglaciated land surface (Wingfield, 1990a & b). The most complete Hoxnian sequence found so far is from Marks Tey in Essex (Turner, 1970). The deposits here cover the complete interglacial cycle (Turner, 1970). The associated eustatic rise in sea level deposited marine sediments on land (Ventris, 1985; section VII.3). The sediments at East Winch in the Nar Valley indicate that by pollen zone HoIIIb the sea-level reached at least +23 m O.D. (Ventris, 1985; discussion in Chapters VI and VII).

The glacial stage between the Hoxnian and Ipswichian has been defined as the Wolstonian stage from a type-site at Wolston in Warwickshire (Shotton, 1953; Shotton and West, 1969; Mitchell *et al.*, 1973). Since Sumbler (1983a,b) stated that the Wolston type sequence might actually belong to the Anglian stage, the limit and indeed the existence of any Wolstonian ice, and the status of this stage have been a matter of active debate (Gibbard, 1991; Rose, 1991). Shotton (1983, 1986) revised the Pleistocene sequence of the Midlands and pointed to further stratigraphic evidence from two localities in the Birmingham area, Nechells and Quinton.

Similarly, in East Anglia, the presence of Wolstonian deposits has been a matter of discussion. However, glacial-fluvial deposits of Wolstonian age have been described and discussed by Ventris (1985), Gibbard *et al.* (1991a) and Rose (1991).

Further north in Britain the Early and Middle Pleistocene record is rather fragmentary, and accurate dating and correlation of various glacial and interglacial events on the basis of stratigraphy is apparently impossible. The most detailed record occurs in northeast Scotland where the Kirkhill site presents a complex sequence of deposits which pre-date the preserved last interglacial (Connell *et al.*, 1982; Connell and Hall, 1987; Hall and Connell, 1991). There is no direct dating on any of the Kirkhill sequence but on the simplest interpretation of stratigraphy, basal periglacial fluvial sands and gravels containing erratics have tentatively been correlated with the Anglian (Connell and Hall, 1987). Developed in these basal sands and gravels is a soil horizon with an overlying organic layer. This organic layer contains pollen eroded from a land surface with a temperate soil and vegetation cover (Connell, 1984; Lowe, 1984). This deposit has been correlated with the Hoxnian. This organic layer is overlain by a till deposit, now weathered. This till relates to a glacial incursion from the northwest and has been correlated with the Wolstonian glaciation.

ii) Continental Europe

Elsterian cold stage - In the continental part of NW Europe during the advance of the Elsterian ice the drainage system was completely rearranged. Rivers draining towards the Baltic Sea were partly dammed by the advance of the ice sheet and forced to flow west or east (Lüttig and Meyer, 1974). A characteristic feature of this glaciation are buried channels. Recent studies in the Netherlands (Ter Wee, 1938a), Lower Saxony (Ortlam and Vierhuff, 1978; Kuster and Meyer, 1979), Hamburg (Grube, 1979; Linke, 1983), Schleswig-Holstein (Hinsch, 1979), and east Germany (von Bülow, 1967; Cepek, 1968) have revealed that the subsurface is dissected by a net-like system of deep channels, the direction of which trend radially away from the centre of the ice mass towards the margin (Fig. I.6). Seismic investigations have shown that these are continuous with similar features in the North Sea (Borth-Hoffmann, 1980).

Apart from Elsterian till the most common glacigenic sediments are glaciolacustrine clays, principally the Lauenburg Clay (Table I.3; cf. Ehlers *et al.*, 1984). When the Elsterian ice melted large ice-dammed lakes were formed in glacially-eroded channels in which silt, clay and fine sand were deposited. The changes in composition reflect the progressive decay of the Elsterian ice. Older layers are rich in dropstones and mixed with sand. The sorting increases towards the top where a varve-like sequence of laminated sediments is found. The upper part of this sequence is characterised by an arctic-boreal fauna

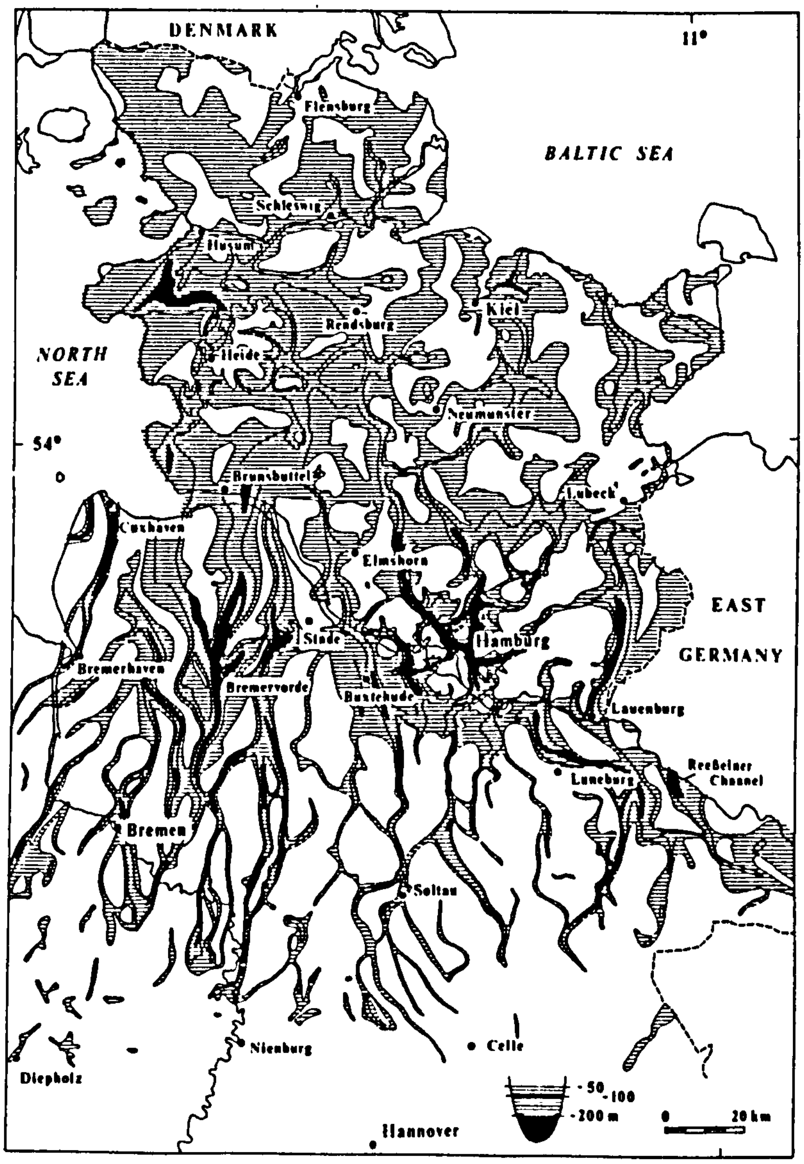

Fig.I.6. The Elsterian buried channels of North-West Germany (from Ehlers *et al.*, 1984).

Table I.3. Correlation table of the Saalian and Elsterian sequences in NW Europe (from Ehlers *et al.*, 1984).

The Netherlands	Denmark	Schleswig-Holstein	Hamburg	Lowe Saxony	eastern Germany
			EEMIAN		
					S-3-Till (?) Interval (?)
		Warthe 2 (Hennstedt Till)	Fuhlsbuttel Till	Warthe (Vastorf Till)	S-2-Till
			Interval		
	Warthe	Warthe 1 (Vaale Till/ Kuden Till)	Niendorf Till sandy base	Drenthe-2-Till sandy base	Interval
			Interval		
Drenthe	Drenthe	Drenthe (Burg Till) (Hindorft Till)	Red Drenthe Till Drenthe Till	Red Drenthe-1 Till Drenthe-1-Till	S-1-Till
			HOLSTEINIAN		
Potklei Clay		Lauenburg Clay	Lauenburg Clay	Lauenburg Clay	
Till (?)	2 Elsterian Tills	2 Elsterian Till (?)	Elsterian Till	Till of East Baltic facies "normal" Elsterian Till	Younger Elsterian Till Miltitzer Interval Older Elsterian Till
			CROMERIAN		

representative of an early marine transgression (Knudsen, 1976; Strehl, 1983).

The maximum extent of the Elsterian glaciation is presented in Fig. I.7. Figure shows that in the Netherlands, these glaciolacustrine clays are represented by the 'potklei' (Table I.3); in the northern part of the country near Noordbergum a considerable thickness of 'potklei' has been proved by drilling (Ter Wee, 1983a). However, the advance of the Elsterian ice over the Netherlands has yet to be positively proved. Elsterian tills have so far only been found as two thin layers (Ehlers *et al.*, 1984).

In the south of Germany the Elsterian channels terminate at a line which runs roughly from Diepholz via Nienburg to Celle (Fig. I.6). The thrust sequence of the Rehburger end moraine, exposed west of the Weser River, does not contain Elsterian till (Meyer, 1970). In contrast, the presence of blocks of Tertiary material indicates that the Elsterian ice did not extended beyond this line.

In the southern areas of eastern Germany the Elsterian sediments were not overridden by Saalian glaciation and consequently enable a convincing reconstruction of the maximum extent of the Elsterian glaciation (flint line), though some uncertainty still exists.

Till fabric measurements in the Elbe-Weser triangle showed a direction of ice movement from north to south or from north-west to south-east during the Elsterian glaciation (Höfle, 1976). The Elsterian tills of northwest Germany are normally dark brown or grey in colour. In the

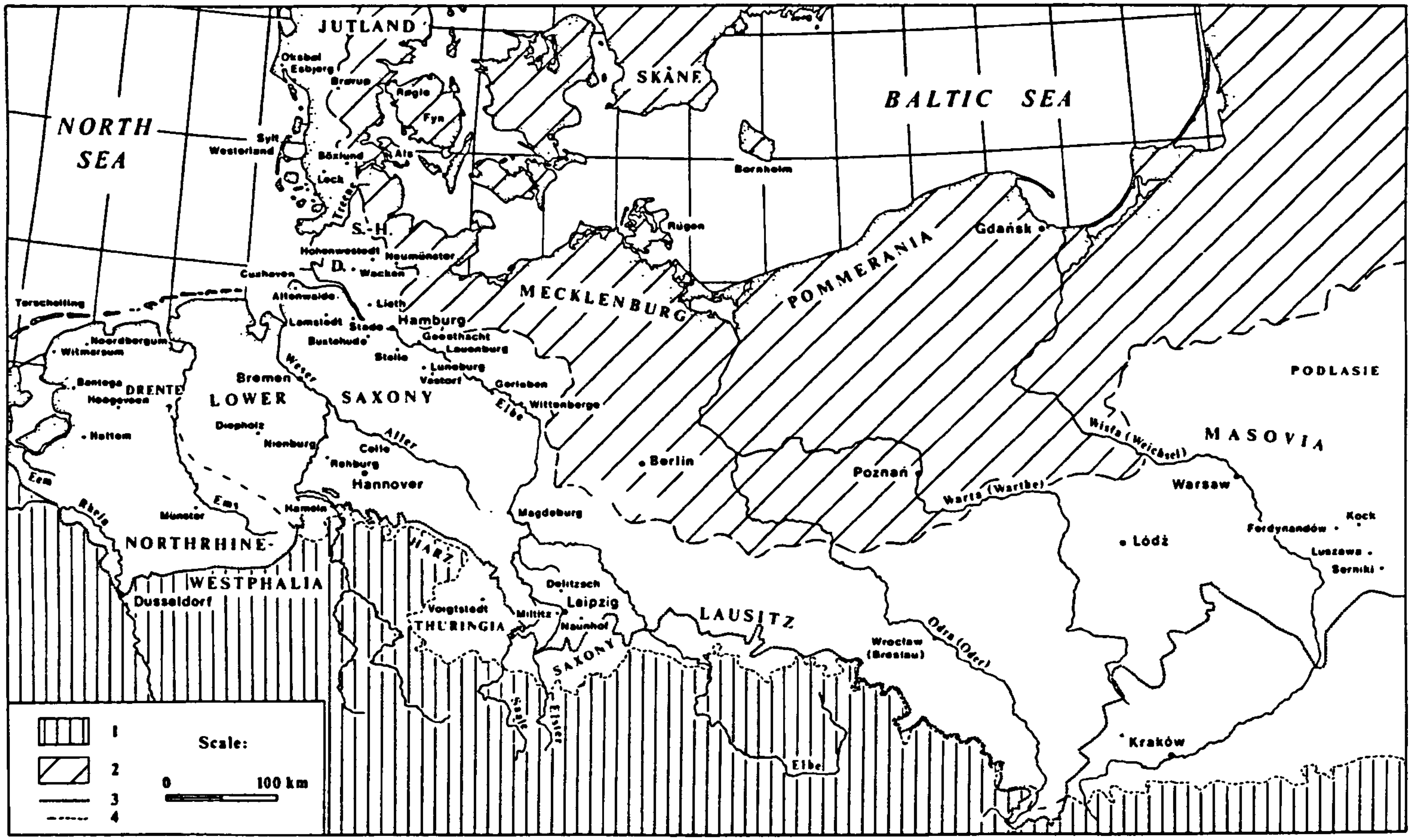

Fig. I.7. Extent of the three Quaternary glaciations and places, mentioned in the text: 1=unglaciated area; 2=area of the Weichselian Glaciation; 3=maximum extent of the Saalian Glaciation; 4=maximum extent of the Elsterian Glaciation (in Western Lower Saxony estimated) (from Ehlers *et al.*, 1984). S.-H=Schleswig-Holstein; D=Dithmarschen.

area east of Hannover an exposure of red-brown Elsterian till lies conformably on the more usual dark grey Elsterian till (Jordan, 1975). In contrast to other Elsterian tills it contains a high proportion of East Fennoscandian erratics.

In Denmark the results of drilling indicate that two Elsterian tills exist (cf. Ehlers *et al.*, 1984). It is believed that one ice sheet advanced from the north and later a second ice sheet advance from the Baltic region which reworked rhomb porphyries from the Oslo area with a higher amount of flint and Palaeozoic limestone (Sjorring, 1981).

Holsteinian temperate stage - The temperate stage which separates the Elsterian from the Saalian on the continent is known as Holsteinian; it is widely accepted that this correlates with the Hoxnian in Britain. This temperate stage has been extensively investigated on palaeobotanical grounds (cf. Sibrava *et al.*, 1986). Like the Hoxnian, the Holsteinian is considered a single interglacial cycle, in Germany it is recognised as a complex (Table I.2) containing two interglacial phases separated by a cold phase. In the former German Democratic Republic, the Holsteinian complex is represented by Holstein Interglacial (*sensu stricto*) and Dömnitz * interval of deglaciation separated by the Fuhne glacial period (?) (Cepek, 1967, 1968, 1986). Recent studies

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* Equivalent of the Dömnitz interval in the former Federal German Republic is known as the Wacken (Menke, 1968).

(Turner 1975; Gibbard and Turner, 1988; Gibbard, 1991) suggest that the younger interglacial included within the Holsteinian complex does not represent the Holsteinian but constitutes an early interstadial of the Saalian cold stage. They believe that the Dömnitz/Wacken interglacial episodes of the Holsteinian complex may be the correlative of the Hoogeveen Interstadial of the Netherlands.

Saalian cold stage - The phase between the Holsteinian and Eemian in continental NW Europe is known as the Saalian cold stage. Although this stage was originally recognised in Germany, much of the detail of events during this stage have been established in the Netherlands (Grube, 1981; Ter Wee, 1983b; Ehlers *et al.*, 1984).

Though the deposits of the Saalian are known in much more detail than the Elsterian, the stratigraphy of the Saalian is more complicated than the Elsterian. It comprises two major advances; the older is known as the Drenthe Substage and the other Warthe Substage separated by a deglaciation phase of the Drenthe advance (see below).

The Saalian started with a prolonged interval of cold climate punctuated by interstadial conditions. Zagwijn (1973) has recognised two interstadials (Hoogeveen Interstadial and Bantega Interstadial) below the Drenthe Substage. These two interstadials are separated from the Holsteinian by a short cold stadial period of ground ice development.

During the Drenthe Substage an expansion of glacial ice reached its maximum extent in the central Netherlands. This major advance is interpreted as the most extensive in the Saalian. This Substage was followed by an extensive recession during which most of continental northern Europe was characterised by deglaciation. This deglacial period was followed by a second advance, the Warthe Substage. During this Substage the ice advance was less extensive than in the Drenthe and only reached as far as central Germany.

Ehlers *et al.* (1984) have identified the following sequence of landscape development during the Saalian :

1. At the beginning of the Saalian (Stadial I) permafrost, cryoturbations, large ice wedges and boulder pavements developed. There was a sparse vegetation with *Betula, Artemisia* and *Juniperus.*

2. In the following Hoogeveen Interstadial re-forestation took place with the development of *Picea* forest with *Alnus* and *Carpinus*.

3. During Stadial II there was a considerable decline in vegetation and an open landscape once again prevailed but without extensive permafrost.

4. In the relatively cool Bantega Interstadial only *Betula-Pinus* forest developed with *Alnus, Corylus*

and some *Quercus*.

5. During the following Stadial III* the continental ice sheet developed. Widespread permafrost features occurred in non-glaciated areas.

b) North Sea

i) Stratigraphy

The Quaternary sediments of the UK sector of the North Sea have been subdivided into various seismic-stratigraphic units. The units have been described from seismic records and their age and environmental significance assessed from micropalaeontological evidence. The stratigraphy has been described in detail on BGS maps, in separate reports by Laban *et al.* (1984) and by Stoker *et al.* (1985a) for the southern and central North Sea respectively, and in a joint IKU**/BGS map of the northern North Sea by Rise *et al.* (1984). Cameron *et al.*, (1987) attempted to integrate these data in a regional study of the history of Quaternary sedimentation in the North Sea. The stratigraphy and suggested correlation of the sedimentary units in the North Sea are illustrated in Fig. 2 in Long *et al.* (1988), modified in Fig. VII.1), and the geological relationships of these sedimentary facies within the North Sea Basin are

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* Beginning of Stadial III represents the beginning of the Drenthe Substage of the Saalian cold stage.

** Institute for kontinentalsokkerundersokelser (IKU).

shown in Fig. I.8.

A) Southern North Sea

The southern North Sea has been investigated in more detail than the central and northern North Sea. In particular, the joint study by BGS and IKU has provided considerable detail about sedimentation in the southern North Sea. Laban *et al.* (1984), Balson and Cameron (1985), Cameron *et al.* (1987), Balson and Jeffrey (1991) and Tappin (1991) have discussed climatic history and sedimentation in the southern North Sea. The stratigraphy and the suggested correlation of the sedimentary units in the southern North Sea are illustrated in Fig. I.9.

B) Central North Sea

In the central North Sea the thickness of the sequence varies from 0 in the extreme west to greater than 200 m in the northeast. Consequently, a more complete record of Pleistocene sedimentation is preserved in the eastern part. Stoker *et al* (1985b) have proposed a sequence based on the widespread recognition of ten major Quaternary formations and have revised the stratigraphic nomenclature adopted by Holmes (1977) and Thomson and Eden (1977). Table I.4 shows the new names proposed together with those of the earlier nomenclature, and the general stratigraphic relationships of the Quaternary formations is presented in Fig. I.10.

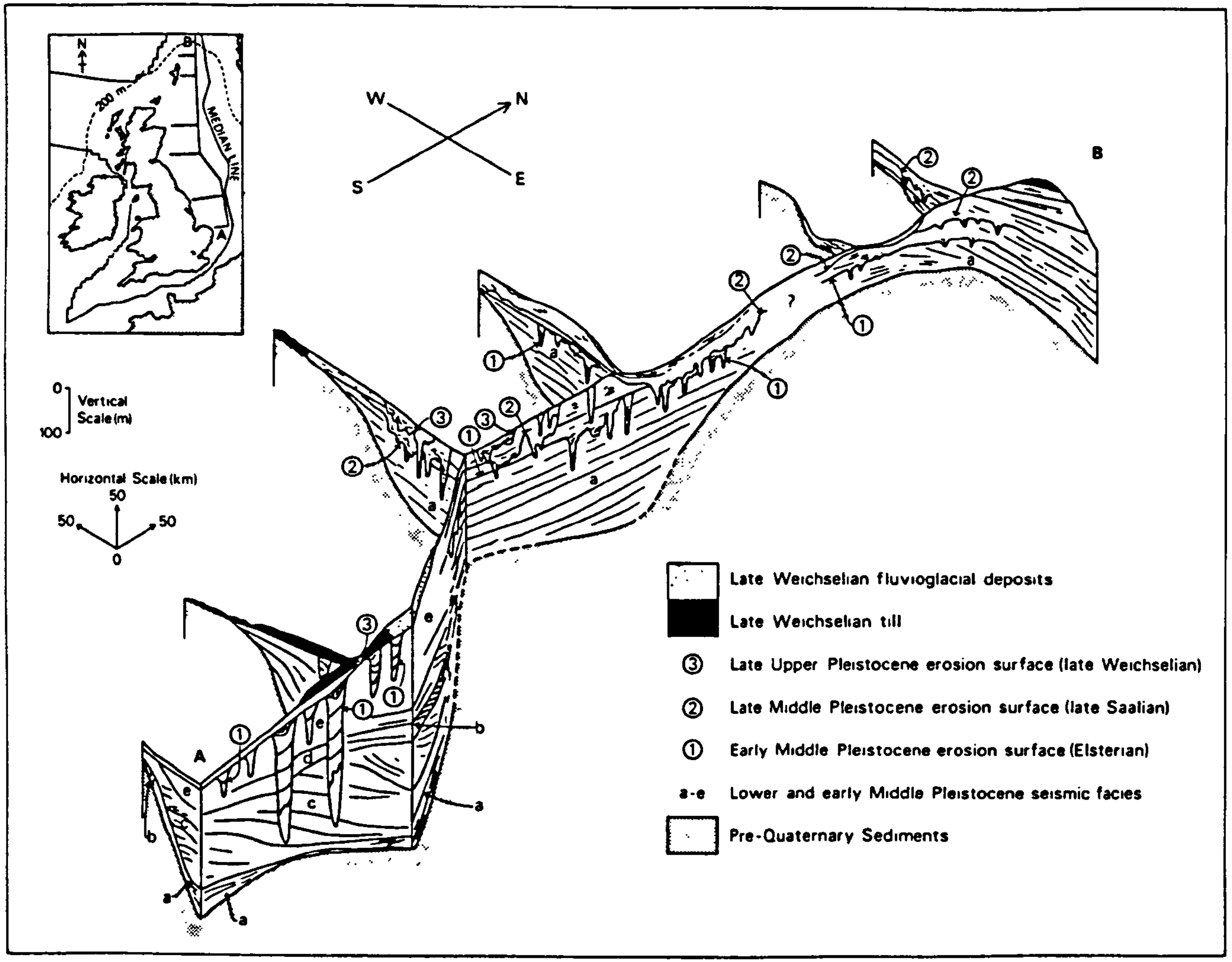
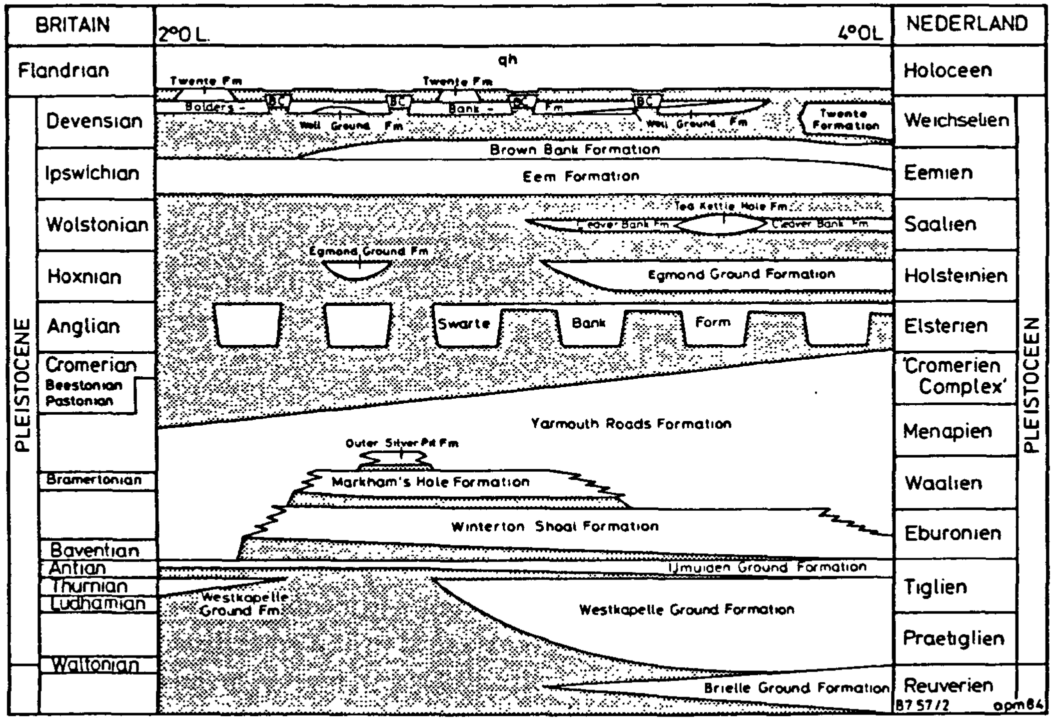


Fig. I.8. Schematic fence diagram of the Pleistocene deposits in the North Sea; the sections are along the lines indicated on the inset map (Cameron *et al.*, 1987).



BC = Botney Cut Formation

Fig. I.9. Correlation of the Pleistocene formations in the southern North Sea with the Quaternary Stages of Britain and The Netherlands (from Long *et al.*, 1988). See Gibbard *et al.* (1991b) for the latest correlation for the Lower Pleistocene.

Table I.4. Table to show new and old stratigraphic terminology (from Stoker *et al.*, 1985b).

Previous nomenclature (Holmes 1977; Thomson & Eden 1977)		New terminology (this report)	
Forth Beds	Middle & Upper Forth Beds	Forth Formation	St. Andrew's Bay Member
	Lower Forth Beds		Largo Bay Member
Upper Channel Deposits	Upper Series		Whitethorn Member
	Middle Series		Fitzroy Member
Witch Ground Beds		Witch Ground Formation	Glenn Member
			Witch Member
			Fladen Member
St. Abbs Beds		St. Abbs Formation	
Marr Bank Beds		Marr Bank Formation	
Upper Swatchway Beds		Swatchway Formation	
Wee Bankie Beds		Wee Bankie Formation	
Upper Channel Deposits-Lower Series Upper Swatchway Channel Deposits		Coal Pit Formation	
Lower Swatchway Beds Fisher Beds		Fisher Formation	
Lower Channel Deposits		Ling Bank Formation	
Aberdeen Ground Beds		Aberdeen Ground Formation	

Table I.5. Explanation of abbreviations for the sedimentary formation names.

qh = Superficial sediments
BDK = Bolders Bank Form.
SH = Sand Hole Formation
YM = Yarmouth Roads Form.
IJ = IJmuden Ground Form.
tk = Undivided

BCT = Botney Cut Formation
EG = Egmond Ground Formation
SBK = Swarte Bank Formation
WM = Winterton Shoal Form.
WK = Westkapelle Ground Form.

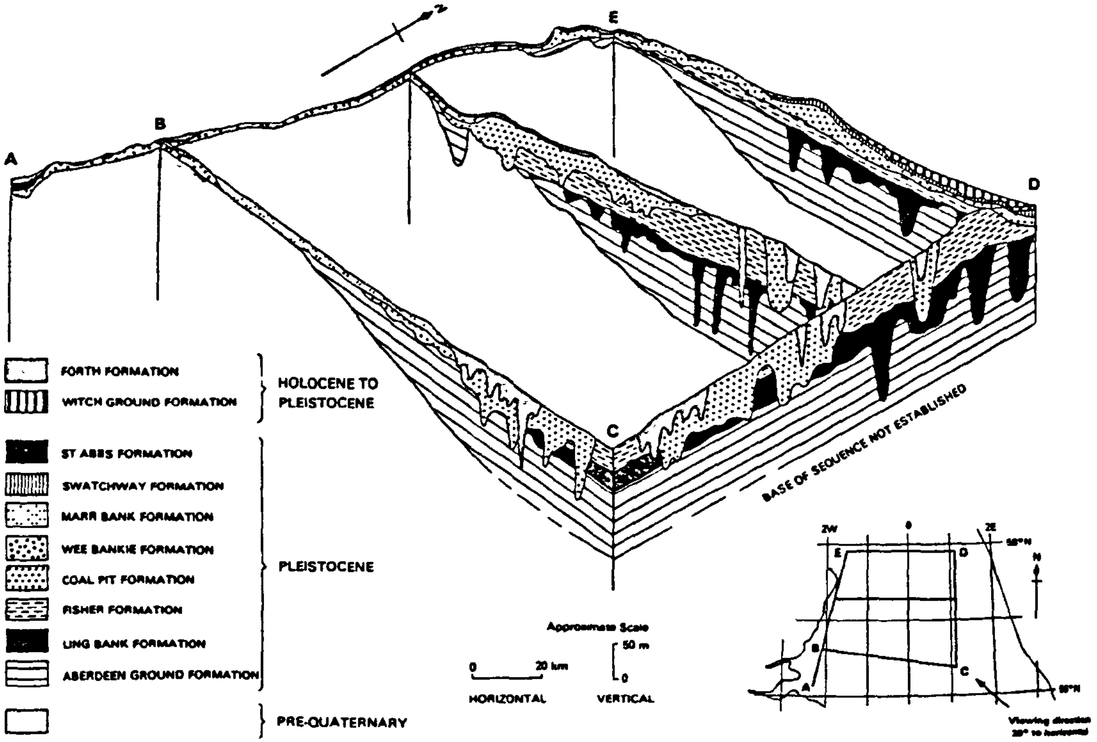


Fig. I.10. General stratigraphic relationships of the Quaternary formations (from Stoker *et al.*, 1985b).

I.4. Incisions and interglacial sediments

Sedimentation in the North Sea Basin has been dominated by glacial erosion and deposition since mid-Quaternary times. A characteristic feature of the three glaciations offshore is the development of systems of subglacially eroded valleys (Fig. I.11). Interglacial sediments are usually found in these valleys and basins. Origin of these features is discussed in section VII.2,a).

I.5. Interglacial pollen biostratigraphy

Palynological investigations of different interglacials show a strong parallelism in vegetational development but with significant regional and temporal differences. This parallelism reflects an equally strong parallelism in climatic development throughout NW Europe. Turner and West (1968) proposed a standard zonation scheme with the aim of standardising procedures and enhancing interglacial correlation on palynological grounds. They suggested a subdivision of four substages for each interglacial stage, so that the distribution of taxa could be defined in relation to zonal boundaries for different interglacials. West (1980) has discussed the four substages in each Pleistocene interglacial in southern England.

Interglacial substage I

This substage is known as the 'pre-temperate' substage and is characterised by the development of forest vegetation

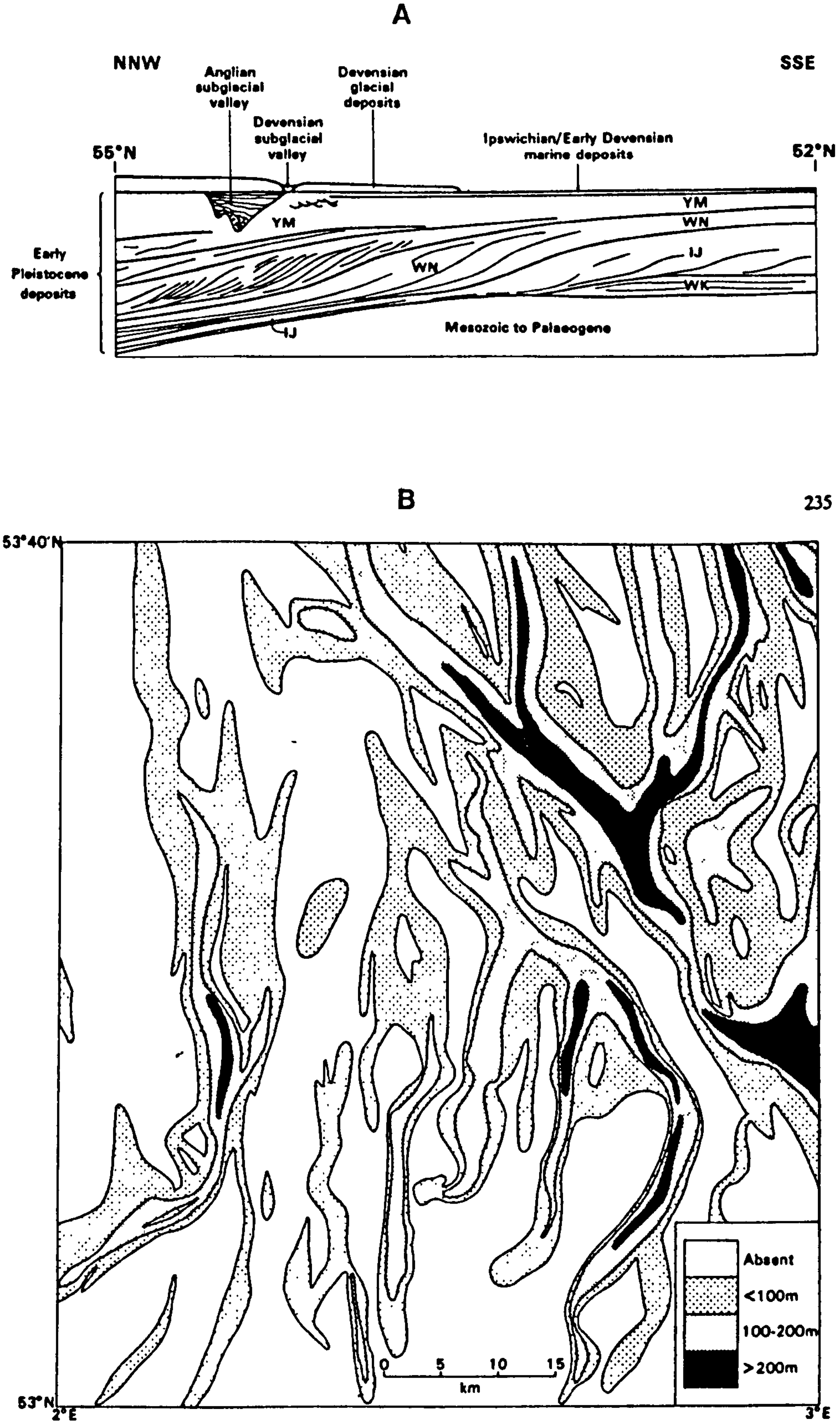


Fig. I.11. Showing incisions in the North Sea (from Balson and Cameron, 1985): A) Schematic profile along the axis of the Early Pleistocene sedimentary basin showing the general relationships of the formations identified in the seismic profiles (see Table I. for formation abbreviations). B) Isopachyte map of the Anglian deposits in the subglacial valleys of the north-eastern part of the area.

following late glacial period of open herbaceous vegetation. Though containing high frequencies of herbs and shrubs, boreal trees, particularly *Betula* and *Pinus*, are significant.

In the Cromerian (Fig. I.12) this substage, CrI, is divided into two phases, CrIa shows the spread of *Betula-Pinus* forest, with the presence of *Ulmus, Alnus,* and *Picea*, whereas in CrIb *Pinus* pollen reaches its highest frequency and *Betula* frequencies fall. *Alnus* and *Picea* occur in low frequencies, and *Ulmus* is strongly represented.

In the Hoxnian (Fig. I.13), at Marks Tey, Turner (1970) has not subdivided this substage (HoI) which is characterised by the high frequency of *Betula*. Plant communities at this time included *Hippophaë,* and herb taxa, particularly Gramineae. The *Betula* frequency decreases and *Pinus* increases during the later part of the substage but it never exceeds the value for *Betula*. Thermophilous tree genera appear in this substage, including *Quercus, Acer, Alnus, Tilia (cordata)*, *Ulmus* and *Quercus*. The later part of this substage is marked by a fall in *Betula* pollen frequencies and a rise in *Quercus*, indicating the replacement of birch forest by oak-dominated forest.

In the Ipswichian (Fig. I.14) this substage (IpI) is divided into two phases. IpIa shows a high frequency of *Betula* pollen and a rapid rise in *Pinus*, with a significant presence of *Ulmus*. IpIb shows a continued rise *Pinus* frequencies but a fall of *Betula* associated with the

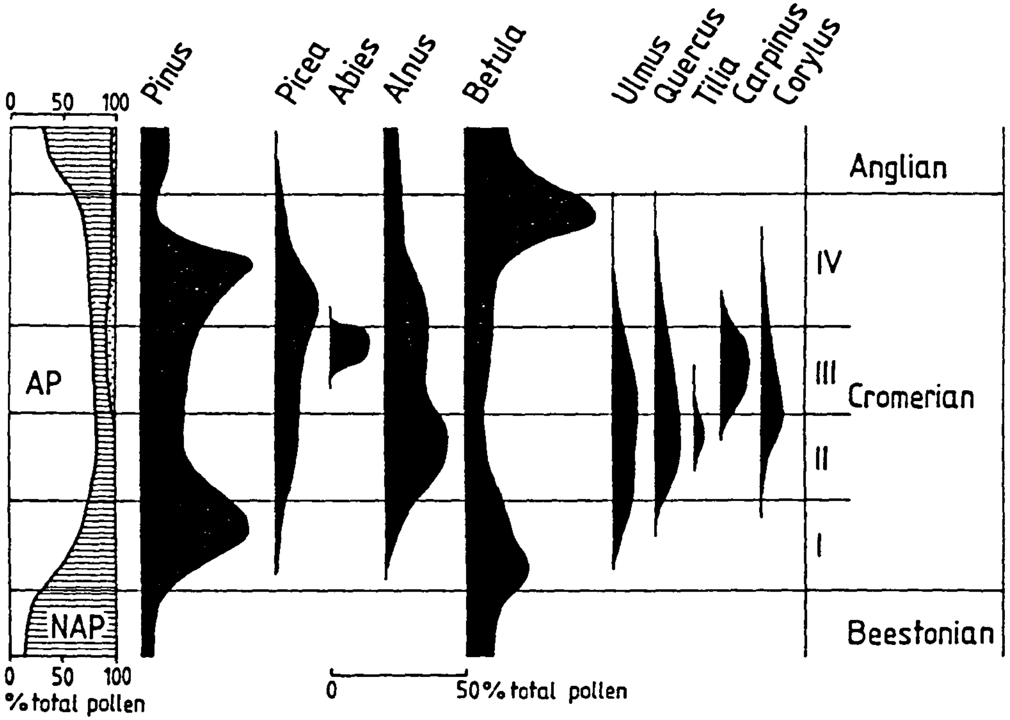


Fig. I.12. Pollen diagram of the Cromerian (from West, 1980).

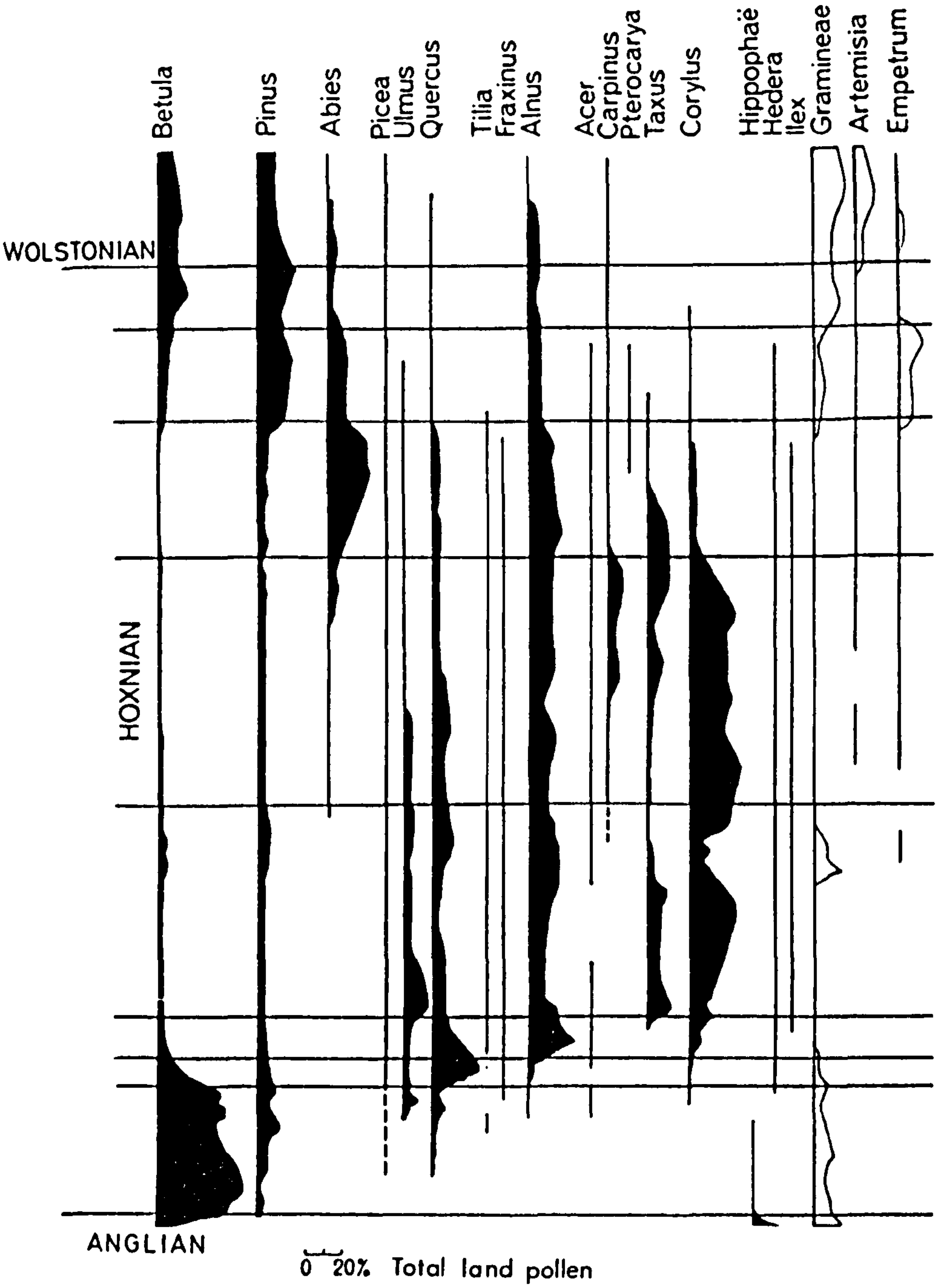


Fig.I.13. Pollen diagram of the Hoxnian at Marks Tey, Essex (from Turner 1970).

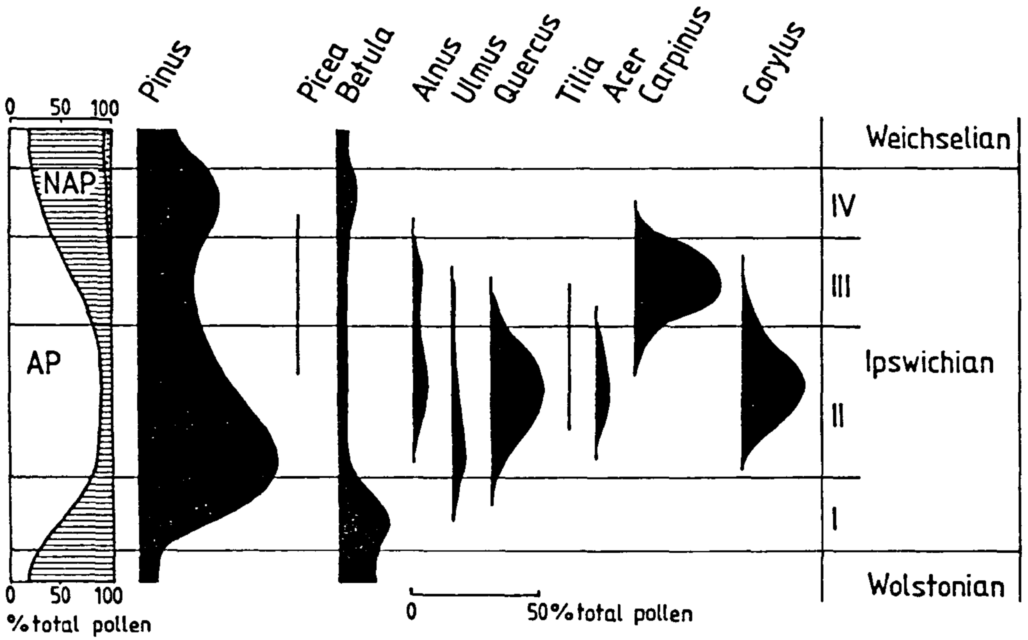


Fig. I.14. Pollen diagram of the Ipswichian (from West, 1980).

appearance of *Quercus* and a rise in *Ulmus* frequencies.

Interglacial substage II

This substage is known as the 'early-temperate' stage and is represented by the establishment and expansion of mixed oak forest vegetation. Typical trees of this substage include *Quercus, Ulmus, Fraxinus* and *Corylus*. During this period the forest achieves its maximum density and luxuriance. In the Cromerian and Ipswichian this substage is divided into two phases whereas in the Hoxnian at Marks Tey, it has been divided into three phases (Turner, 1970).

In the Cromerian, CrIIa shows significant rises in *Quercus, Alnus* and *Picea* pollen and falls in *Betula* and *Pinus* with *Ulmus* remaining constant. The later part of this phase shows the appearance of *Tilia*. CrIIb is characterised by the highest values for *Corylus, Quercus, Tilia* and *Alnus*, and low values for *Pinus* and *Betula,* but with an increasing frequency of *Picea* pollen. The upper half of this phase shows the appearance and increase of *Carpinus*.

In the Hoxnian HoIIa is characterised by sharp increase in the frequencies of *Quercus*. HoIIb is defined by increases in the frequencies of *Alnus, Tilia and Ilex*. Both *Tilia cordata* and less frequently *T. platyphyllos* are represented. The deneseness of the forest is reflected in the low values of herb pollen at this time. In the third phase, HoIIc, *Ulmus* and *Taxus* are represented by pollen frequencies as high as *Corylus*. This phase appears to be the longest of HoII, and demonstrates a period of stable temperate forest.

In the later part of HoIIc, temporary disturbance of the forest, registered by lower frequencies of tree pollen and higher frequencies of herb pollen has been recorded at several sites. The detail is best seen at Hoxne (West, 1956) and Marks Tey (Turner, 1970), where *Alnus* appears to be the least affected tree taxon. Later the pollen of the forest taxa rise in frequency as regeneration occurred. It seems probable that the regional upland forest suffered a calamity which must have been very widespread in East Anglia. Turner (1970) suggests that a major forest fire occurred. Preece *et al.* (1990) have also found some evidence to support this view.

In the Ipswichian, IpIIa includes the highest frequency values of *Pinus* and *Ulmus* and marked decline of *Betula*. *Corylus, Alnus* and *Acer* are present in the upper half of the phase. IpIIb shows expansion of true temperate forest with highest values for *Corylus, Quercus, Acer* and *Alnus*. *Taxus* and *Tilia* (*cordata*) are present in low frequencies.

Interglacial substage III

This substage has been called the 'late-temperate' substage and is characterised by the decline of the former mixed-oak forest dominants and the expansion of the late-immigrating tree taxa *Carpinus, Abies* and sometimes *Picea*. In the Cromerian and Hoxnian this substage is further subdivided into two phases.

In the Cromerian, CrIIIa begins with rise in *Carpinus* pollen frequencies. *Pinus, Alnus, Quercus, Ulmus* and *Corylus* remain well-represented, but *Tilia* frequencies fall. *Picea* shows a low but continuous curve. The end of the phase is characterised by the appearance of *Abies*. In CrIIIb *Abies* becomes well represented and with *Carpinus* forms a characteristic assemblage. *Quercus, Ulmus, Tilia* and *Corylus* pollen frequencies fall but *Pinus* and *Picea* pollen frequencies rise.

HoIIIa is characterised by the appearance and expansion of *Carpinus*. The values of *Quercus* and *Ulmus* decrease in frequency whereas *Alnus, Taxus* and *Corylus* remain unaffected. Turner (1970) calculated the length of HoIIIa as 2000 years based on the laminations in sediments at Marks Tey. In HoIIIb *Carpinus* and *Corylus* decline and are replaced by *Abies* with subsidiary *Alnus*. *Taxus* declines later, with *Pinus* becoming more abundant with the spread of *Abies*. *Buxus, Vitis* and *Ilex* pollen also occur indicating that these shrubs were locally present. The forest vegetation of the later part of substage HoIII indicates an oceanic climate. The forest was dominated by Abies, with *Pterocarya* possibly associated with the low-lying forest, a habitat preferred by *P. fraxinifolia*, the species most closely resembling the fossil material.

In Ipswichian diagrams the late-immigrating forest is characterised by the complete absence of *Abies* and the only significant taxa is *Carpinus* which replaces *Corylus, Quercus, Acer* and *Tilia*. *Picea* is consistently present but with low frequencies.

Interglacial substage IV

This substage is known as the 'post-temperate' substage and shows the return of boreal forest represented by the dominance of *Betula* and *Pinus*. This is accompanied by thinning of the forest and the gradual development of open communities, especially damp heathland. Ericaceous heaths are particularly characteristic of this substage but they often persist into the succeeding early glacial period. In the Cromerian and Hoxnian interglacial stages this substage is further subdivided into three and two phases respectively.

In CrIVa the major forest components are *Pinus, Picea, Alnus* and *Betula*. *Abies* and *Carpinus* disappear in the earlier and later half of the phase respectively. The frequencies of *Ulmus, Quercus* and *Corylus* decline. CrIVb shows the highest frequencies of *Pinus* and a sharp rise in the frequency of *Betula* with reduced values for *Picea* and *Alnus*. *Ulmus* disappears by the middle of the phase, and *Quercus* shows very low frequencies. In CrIVc *Betula* becomes the dominant forest taxon with lower *Pinus, Picea* and *Alnus* frequencies.

HoIVa is characterised by the development of grassland and *Empetrum* heath. *Pinus* becomes more important, *Betula* declines and *Abies* remains dominant. Thermophilous forest genera are very sparse, but *Pterocarya* remains in low frequencies. The later part of HoIVb is defined by a decline of *Abies* and *Alnus* with a rise in *Betula*, at the same time as an expansion of grassland and a restriction of *Empetrum* heath. These changes may have been caused by a change to a drier and colder climate than in the earlier part of the substage.

In IpIV *Pinus* is the major component of the forest replacing *Carpinus*. *Picea* and *Alnus* disappear with *Carpinus* in the later half. *Betula* is represented by high frequencies.

I.6. Summary of the Nar Valley Section

The lithological log of BGS borehole BH81/52A (this study - Fig. III.3) shows a close similarity with the stratigraphy within the Nar Valley which has been investigated by Stevens (1960) and Ventris (1985). A summary of this sequence (Fig. I.15) is presented below.

Woodlands Farm Till

This blue-grey till consists of silty-clay with considerable quantities of sand and clasts of chalk, Kimmeridge Clay and flint. The till rests on the Mesozoic bedrock and is interpreted as a lodgement till. Evidence from the fabric and erratic content at Bawsey indicates that ice movement was from the north-north-east.

Bawsey Calcareous Till

This pale cream to buff, highly chalky till containing chalk and round flint clasts is set in a comminuted chalk

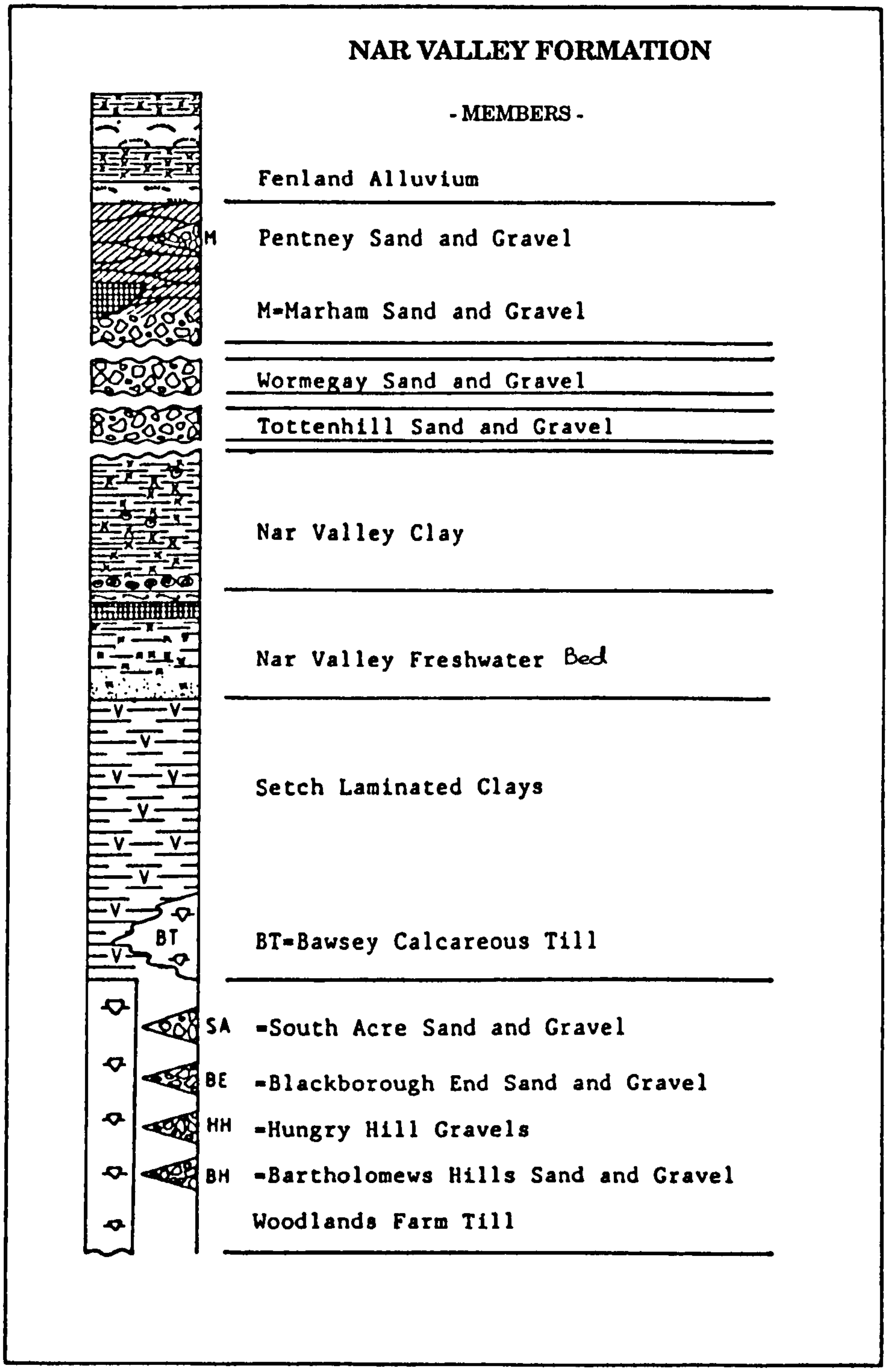


Fig. I.15. The lithology of the Nar Valley Pleistocene deposits (from Ventris, 1985).

matrix. The base of the unit rests on the Woodlands Farm Till with a sharp contact. Fabric studies by Evans (1975) led him to suggest that the ice depositing the Bawsey Calcareous Till ice had entered the region from a north-westerly direction.

Setch Laminated Clay

The name of this unit is derived from the Setch Borehole where it rests conformably on the Woodlands Farm Till. These laminated clays were deposited in a turbid, proglacial lake which existed during a fairly late phase of the Woodlands Farm Till glaciation.

Nar Valley Freshwater Member

This consists of a series of blue-grey silty sands containing a rich freshwater Mollusca fauna that fine into silty- clay and wood peat. In the lower Nar Valley this unit rests conformably on the Setch Laminated Clays. In the site described by Stevens (1960) the Freshwater Member overlies till that she correlated with the Lowestoft Till.

Nar Valley Clay

The base of this unit is defined as the contact with the underlying Nar Valley Freshwater Member. However, the Freshwater Member does not always occur below the clays and in some localities the clay rest directly on bedrock. The distribution of this unit reflects deposition in the overdeepened 'tunnel valley' passing through East Winch, south of East Walton to West Acre, South Acre to West Lexham.

Tottenhill Sand and Gravel

This unit consists of a lower matrix-supported flint gravel overlain by clast supported gravels of similar lithology. At the type-site the unit rests unconformably on the Nar Valley Clay but elsewhere these sands and gravels are known to rest on both till and Kimmeridge Clay. The lithology suggests fluviatile rather than marine deposition. This unit has recently been investigated in detail by Gibbard *et al.* (1991a).

Wormegay Sand and Gravel

This unit has been identified mainly from surface mapping. Throughout the Valley this unit follows the course of the overdeepened 'tunnel valley' and always occurs as a thin mantle of sands and gravels overlying the Nar Valley Clay. Young (1972) described some Nar Valley Clay sections and ascribed the overlying gravels to solifluction. The basal contact with the Clays shows some evidence of cryoturbation and this may have disturbed any primary sedimentary structures making the gravels appear massive and unsorted.

Ventris has demonstrated both the Tottenhill and Wormegoy Sand and Gravel units to be post-Hoxnian and pre-Ipswichian in age, and has therefore correlated them with the Wolstonian stage.

I.7. Glacial-marine sediments

The term "glacial-marine" was first used by Philippi (1910) to describe till-like sediments dredged from the sea floor of Antarctica. Andrews *et al.* (1980) defined "glacial marine sediment" as any marine deposit which bears evidence of having been deposited by floating ice. Whereas Andrews and Matsch (1983), and Powell (1984), have defined "glacimarine sediments" as made up of debris deposited in the marine environment after release from either grounded or floating glacial ice (Dowdeswell, 1987).

From the North Sea, particularly from the southern North Sea, glacimarine deposits have been described by Balson and Cameron (1985), Cameron *et al.* (1987) and Tappin (1991).

Borehole 81/52A includes approximately 3 metres of glacigenic sediment which have been investigated along with the overlying interglacial sediments. Foraminiferal and dino cyst results are available and samples have been examined for pollen analysis.

CHAPTER II

METHODS

II.1. Offshore surveying and coring

a) Surveying

The British Geological Survey (BGS) has developed sampling and drilling technology appropriate to the range of geological conditions and locations investigated on the UK continental shelf. The Continental Shelf Division of BGS is responsible for producing a series of maps at 1:250,000 scale comprising magnetics, gravity, bathymetry, sea bed sediments, Quaternary geology and solid geology. They began the systematic mapping of the UK continental shelf in 1966, involving geophysical traversing, sampling, drilling and laboratory testing and analysis. Since 1967, approximately 150,000 km of multiple seismic profiles have been run, some 2500 sample stations occupied and 463 boreholes have drilled (Ardus *et al.*, 1982).

Geophysical work has been carried out with a grid pattern survey at approximately 5 km traverse line spacing using a suite of equipment comprising magnetometer, gravimeter, precision depth recorder, side-scan sonar, high resolution profiling systems (pinger, boomer and deep tow boomer), sparker and air gun.

b) Coring

The BGS rotary drilling system can penetrate up to 300 metres below seabed and sites have been planned to achieve lithological, stratigraphical and geotechnical control for seismic interpretations in the compilation of the regional geological map series. The boreholes examined in this thesis, sites BH 81/52A and BH 81/34, were sunk in 1981, when the borehole programme was carried out from the Heerema drill ship "D/S Mariner". Drilling techniques utilised a Christensen marine wire line system modified by the BGS. Downhole gamma logging was carried out using a Mount Sopris 2500 portable logger.

Vibrocorers are employed for unconsolidated sediments and soft rocks. The present BGS vibrocoring system produces relatively undisturbed cores, 85 mm in diameter and up to 6 metres long, and can be operated in water depths up to 1,000 metres. The vibrocorer incorporates a core barrel of 100 mm outside diameter containing a C.A.B. (cellulose acetate buterate) transparent plastic liner of 85 mm inside diameter.

Vibrocore samples are contained in plastic liner tubes within the core barrels extracted on deck, cut into one metre lengths and then capped top and bottom. The core and liner are then split into halves lengthwise. One half is designated as the 'archive' half with the other available for testing and subsampling. Sections are photographed prior to geological logging and geotechnical testing (Plate II.1).

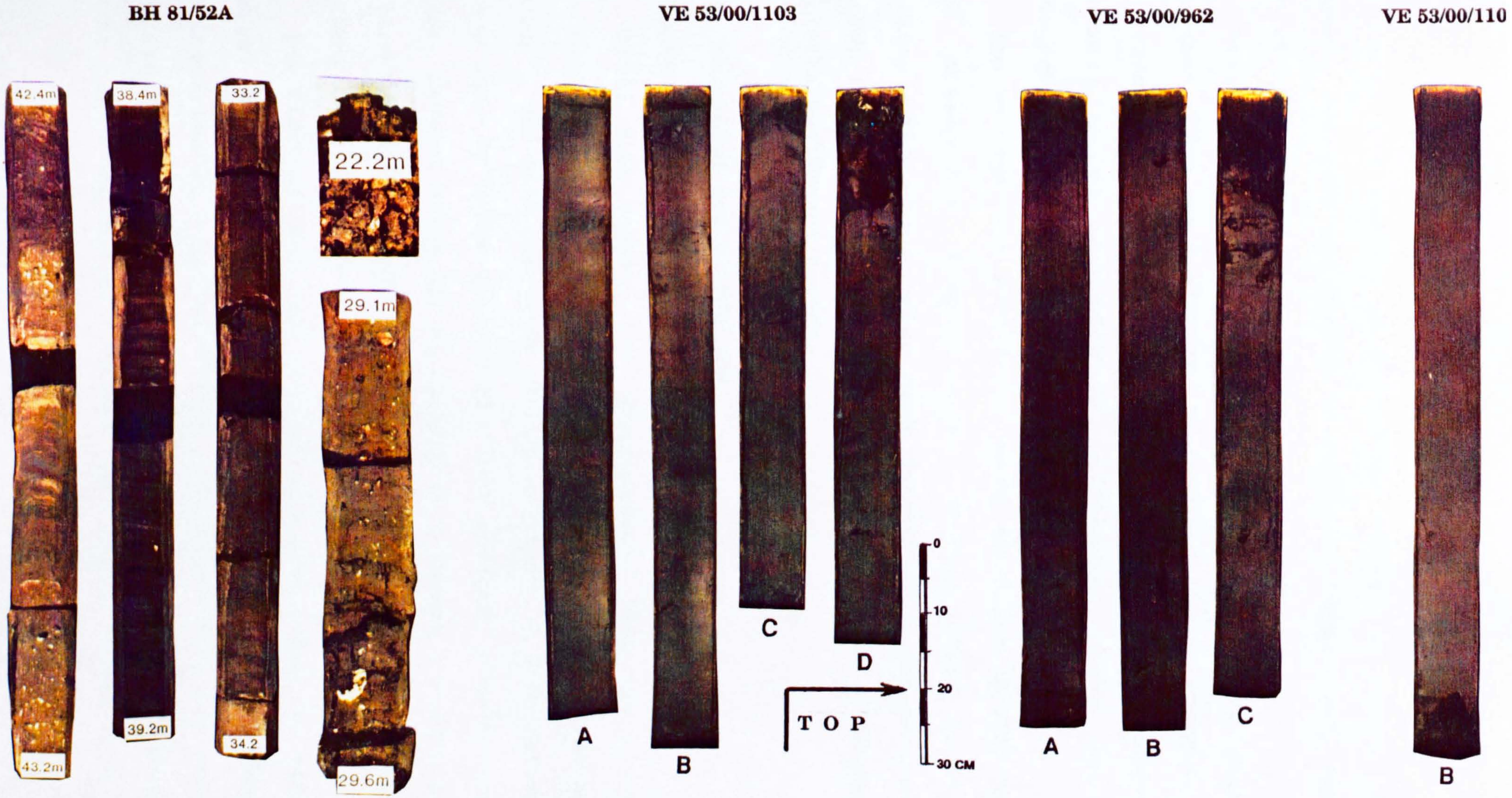


Plate II.1. BGS Borehole and vibrocores from the Inner Silver Pit, southern North Sea.

The cores are sealed in polythene tubing in order to preserve moisture and placed in cardboard boxes which are then stored.

Drill cores are handled in a manner similar to that described above but longitudinal slicing is not undertaken. The cores are cleaned of drilling mud and trimmed to allow examination of undisturbed sediments. Cores were photographed prior to any detailed analysis.

The surveys were positioned using satellite navigation with interactive doppler sonar and Main Chain Decca. Drilling sites were located using Main Chain Decca and the precise position subsequently verified using the Magnavox Satellite Navigation system.

II.2. Boreholes and vibrocores

a) Registration of boreholes and vibrocores

Drill site numbers run consecutively from the first site drilled by 'D/S Mariner' in 1981, and being prefixed by 'BH 81/'. The site number is therefore unique. A site refers to the hole or holes drilled from one acoustic positioning beacon. Several holes may be drilled at a single locality by pulling the drill string above the seafloor and offsetting the ship some distance from the previous hole.

The first or only hole drilled at a site takes the site number. Additional holes at the same site are further distinguished by a letter suffix. The first hole has only the site number, the second has the site number with suffix A, the third has the site number with suffix B and so on.

For example, if site 52 had three holes drilled, they should be referenced as Site BH81/52 (first hole), Site BH81/52A (second hole), and Site BH81/52B (third hole). It is important, for sampling purposes, to differentiate the holes drilled at a site since the recovered sediments or rocks usually do not come from equivalent positions in the stratigraphic column at different holes.

Site number for vibrocores also run consecutively but are prefixed with 'VE' and include latitude and longitude references; VE stands for vibrocore. For example site VE 53/00/1103 and site VE 53/00/1104 represent vibrocore sites /1103 and /1104 respectively which have been collected from locations between 53 and 54°N, and 0 and 1°E.

b) Core description

Cores were trimmed, carefully examined and logged in detail. The logging has been summarised in the core description. As far as possible the lithological data for the main lithologies presented in the following order:

- Sediment or rock type;
- Colour name and Munsell code*;
- General description of core, sedimentary structures including disturbance and other special features;

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* All colour descriptions presented here are estimations based on the 1954 edition of the Munsell Soil Colour Charts. These charts are available in the UK from Tintometer Ltd., Salisbury, Wilts.

- Sediment composition, including fauna and flora and assessment of carbonate content;
- Visual classification of sediment grainsize (Folk system).

Many cores contain important minor lithologies and these have been described wherever possible.

c) Drilling disturbance

When the cores were split many showed signs that the sediments had been disturbed since deposition. Such disturbance structures include inclined or convex upward deformation affecting the original bedding plane (Plate II.2), and the chaotic mixing of lumps of different lithologies (Plate II.1; contact between silty-clays and overlying recent sediments at the top of sections D & C in vibrocores 53/00/1103 & /1104). Variable lithologies are usually found disturbed. It seems reasonable to suppose that many of these core disturbances occurred during or after the cutting of the core. Three different processes which may have caused stresses sufficient to alter sediment physical characteristics from those of the *in situ* state are: cutting, retrieval and handling.

Unconsolidated sediments are nearly always disturbed and/or deformed by the rotary drilling/coring technique (sand and gravel sequence in BH 81/52A recovery in Plate II.1). Consolidated sediments and rocks seldom show much

BGS VIBROCORE 53/00/1102
INNER SILVER PIT
BRITISH SECTOR, SOUTHERN NORTH SEA

Plate II.2. BGS Vibrocore 53/00/1102 from the Inner Silver Pit of the southern North Sea.

internal deformation but are usually broken by drilling into cylindrical pieces of varying lengths (Plate II.1 - BH 81/52A). There is frequently no indication of whether adjacent pieces in the core liner are actually contiguous or whether intervening sediment has been lost during drilling. That is why samples from two opposite faces are not recommended for microfossil analyses.

Megascopic sedimentary structures were apparent in many of the cored sediments. These include primary features such as laminations (Plate II.2) and graded bedding as well as secondary features such as microfaulting and bioturbation (Plate II.2; at depth 55 cm). Very careful examination was undertaken to distinguish whether the features were real or the product of coring disturbance. A specific problem is the production of pseudo-lamination by coring disturbance. This disturbance structure is caused by discs of sediment rotating with the drill bit causing drilling mud to penetrate through the entire core; these pseudo-laminations can be detected fairly easily by eye by examining the distribution of the drilling mud. A characteristic feature of these pseudo-laminations is the similarity of their thickness. Some times this penetration of the mud causes to increase the length of the core recovered to be longer than the actual thickness of the sequence (Dr C.D.R. Evans, *pers. comm.*).

Subsampling was carried out very carefully and at least 0.5 cm of the outer material was routinely discarded. Plate II.1 demonstrates that cores from BH 81/52A are contained in a "liner" which is in fact drilling mud rather than liner. Plate II.3 presents a photograph of two semi-discs from site BH 81/34 in the central North Sea. 'A' has been taken from depth of 81.0 m and 'B' from 82.5 m. Contamination by drilling is very clearly shown by the presence of ca. 0.5 cm of different coloured drilling material. This situation becomes more severe when drilling material is found not only at the margins but penetrating throughout the core (see the dark coloured material in the rectangular cavity of A). Extra care is needed when the colour of the actual core material and the drilling mud is similar (see B in Plate II.3). In this case only very careful examination is able to distinguish the difference between the two materials.

II.3. Pollen analysis

a) Subsampling

Samples for pollen analysis were collected routinely every 10 cm and for palaeontological analysis every metre. However, additional samples were taken where distinct lithological changes were observed. Samples were stored in carefully labelled tubes in a dark cold store. At all times care was taken to avoid any possibility of contamination. If there was any doubt concerning the purity of a sample it was not prepared.

Samples selected were prepared using the standard procedure of the School of Ocean Sciences, University College of North Wales. This procedure eliminates the use of

Plate II.3. Two semi discs from BH 81/34 in the Devil's Hole area, central North Sea.

hydrofluoric acid (HF) and involves the use of the heavy liquid zinc chloride ($ZnCl_2$). A comparison between the two methods is presented by Bjorck *et al.* (1978).

b) Laboratory preparation

A 2 to 4 gm subsample was placed in a centrifuge tube. Two tablets containing a known quantity of exotic *Lycopodium* spores were added and treated with 10% hydrochloric acid until effervescence ceased. This procedure was accelerated by placing the sample in a warm water bath. The samples were washed several times, centrifuged and the supernatant decanted. 10% sodium hydroxide (NaOH) was then added and the tubes were placed in a boiling water bath for 10 minutes*. This stage breaks down organic debris and disaggregates inorganic sediments. After boiling, samples were diluted to twice the volume and sieved through a 120 µm mesh and the residue examined for macrofossils. The filtrate was then sieved through a 10 µm mesh** with water and two or three drops of liquid detergent. Washing was then continued until the supernatant was clean. The residue was then rinsed from the mesh into a centrifuge tube.

Zinc chloride ($ZnCl_2$) solution (density of at least 1.8 g/cm^3) was then added and stirred thoroughly to prevent the pollen trapping amongst the inorganic particles, followed by

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* The solution should not become concentrated by evaporation.

** With large samples it is advisable to add the sample slowly to the mesh to prevent clogging.

centrifugation at 3,000 r.p.m. for 10 minutes. The supernatant containing the pollen was then decanted into another tube. Water was then added to 4 times the volume and the mixture centrifuged at 2,500 r.p.m. for 3 minutes*. The sample was then washed with 10 % hydrochloric acid to prevent the formation of zinc hydroxide ($ZnOH_2$). Samples were then acetolysed using Erdtmans reagent (9 parts of acetic anhydride to 1 part concentrated sulphuric acid) and washed with glacial acetic acid to remove the soluble cellulose acetate products of acetolysis. The samples were then washed with distilled water and sieved again through 10 µm mesh**. The samples were then dehydrated in tertiary butyl alcohol, stained with aqueous safranin stored in silicone oil (viscosity ≈2,000 cs).

Slides for microscopic counting were prepared by evenly distributing a drop of well stirred sample on a clean glass slide and sealing with a square glass coverslip using nail varnish.

c) Counting

Counting was carried out along regular traverses of prepared microscope slides across the whole area of the

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* Following this stage centrifuging speed must not exceed 2,500 r.p.m. as this will cause the destruction of pollen, particularly saccates grains.

** Every process after acetolysis must be carried out very carefully as the risk of loosing pollen is greater because of the lightness of the extracted pollen.

coverslip to avoid the problem of differential pollen distribution as a function of size (Brooks and Thomas, 1967). Pollen grains were counted at a magnification of x400 using ZEISS microscope with x10 periplan oculars and a x40 apochromatic objective. Critical determinations were made using an oil-immersion (anisole) objective at x 1,000 magnification.

Except site BH 81/34, a minimum of 500 total pollen and spores were counted at each level. In almost every sample the proportion of land pollen (ΣP, see section f below) exceeding 90 %. At site BH 81/34 a minimum of 300 land pollen (ΣP) were counted for each level.

d) Identification

The pollen grains were identified by comparison with modern taxa using the reference collections of the School of Ocean Sciences, University College of North Wales, and Sub-department of Quaternary Research, University of Cambridge. Pollen and spore type conventions mostly follow the schemes of Faegri and Iversion (1975) and Birks (1973). Botanical nomenclature follows Clapham *et al.* (1962). Unidentifiable grains were recorded as indeterminable; this category has been subdivided into corroded, degraded, crumpled, broken, or concealed types (Birks, 1973). Reworked pollen and spores were not studied in detail but recorded as pre-Quaternary taxa.

i) Notes on selected pollen and spore types:

Abies: No attempt was made to identify the grains of this genus species level, but most probably the species is *A. alba* (Turner, 1970; West, 1980). The diagnostic characteristics of the bisaccate grains of *Abies* are the thick (> 5 µm) proximal part of the exine (crest) and the semiglobular shaped air-sacs with obvious constriction.

Picea: The very blunt proximal entry angle of air-sac without any constriction distinguishes *Picea* from *Abies*. The proximal part of exine (crest) is less than 5µm thick.

Pinus: The bisaccate grains of *Pinus* are similar to *Abies* and *Picea* but far smaller, ca. 50 µm in size. The proximal part of the exine is less than 5 µm, as in *Picea*, but the proximal entry angle of the air-sacs is not as blunt as *Picea*. There is a saccate constriction as in *Abies*.

Bisaccate: Individual sacs of *Abies* and *Picea*, and some complete grains not satisfactorily able to be included with *Abies* or *Picea* were categorised as 'Bisaccate'.

Pterocarya: Stephenoporate grains of this genus are usually characterised by 5-7 unringed pores on the equatorial plane. Grains are quite spherical with a smooth to very faintly sculptured exine. Grains of *Pterocarya* can be distinguished from *Juglans,* which possesses pores on one half of the spherical grain, and from *Carya* which is triangular in shape and possesses three pores not exactly on the equatorial plane.

Empetrum: The triangular tetrads of *Empetrum* are thick walled, psilate, and with a very short well-defined furrow. Grains of this genus have been divided into two taxa: *E. nigrum* and *E. hermaphroditum.* These two species can be distinguished by size; *E. nigrum* ranges between 25-36 µm whereas *E. hermaphroditum* is larger, between 30-47 µm. (Clapham *et al.*, 1962).

Carpinus: This stephanoporate grains are oblate in shape and more than 40 µm in size. The pores protrude and the equatorial limbs are more or less circular. The microsculpturing is faintly rugulate with minute spinules.

Acer: Tricolpate grains of this genus are oval or round, and thick walled. They possess three wide, open furrows. Sculpturing is fine, distinctively striate, and predominantly meridional. The grains are usually bigger than 30 μm.

Menyanthes: The oval shaped grains of *Menyanthes* are distinguishable from the thick walled *Acer* in possessing three nipped pores with three furrows (tricolporate). They have coarse 'crisscross' striations.

Taxus: Grains of this genus are round/oval/rounded triangular and medium walled. There is no visible pore or furrow but part of the wall is characteristically split. Gemmate sculpturing with concentration of gemmae. Grains are often folded, collapsed or crumpled and subfossil grains commonly lose the outer part of the wall so appearing smaller than ca. 20 μm; actual size is nearer ca. 24 μm.

Populus: Rounded, very thin walled grains without any pore or furrow. Sculpturing is a frustillate spotty chenille on a bright ground. When collapsed the grain has a sharp stiff fold as opposed to the crumple characteristic of *Taxus*.

Juniperus: The grains of this genus are round or oval in shape, thin walled and possess one small poorly defined pore. Usually these grains are split and folded in a distinctive way, pointed like a tea leaf. They are usually not crumpled.

Fagus: The tricolporate grains of *Fagus* are scabrate. They are characterised by circular limbs, convex intercolpium and short slit furrows with pores. Well-defined annuli around the pores. The edges of the pores are not protruding, and the endopore is meridionally elongated. The size of the pore and meridionally elongated endopore differentiate this taxon from *Rumex*.

Corylus/Myrica: No attempt has been made to separate the triporate grains of *Corylus* and *Myrica* in view of the low numbers encountered.

Tilia: The grains of *Tilia* are round, triangular in polar view, and oblate in equatorial view. They possess three very short furrows surrounded by coarsely sculptured area. *T. platyphyllos* is characterised by large polar mesh area with central spot and a funnel shaped lumen. *T. cordata* has a smaller mesh and no centre spot.

Hippophaë: The tricolporate thin-walled grains of this genus are characterised by a vestibulum, long slit-shaped furrows and small, round protruding pores with transparent thickening.

Frangula: This taxa is oblate, thin-walled, triangular in polar view, has a faintly granular surface and a long slit furrow with neat pore.

Rosaceae: No attempt was made to identify pollen of this family to species or genus level, except the grains of *Filipendula*, in view of the very low numbers encountered.

Quercus/Ranunculus: Both pollen grains of these two genera are tricolpate. *Quercus* is characterised by scabrate sculpturing, a tectum without perforation and distinct and uniform columellae, whereas in *Ranunculus* sculpturing is verrucate and the columellae are distinct but partly absent.

Osmunda: The spores of this genus have been divided into two species. *O. regalis* is thick-walled with dense processes often joining, appearing as blunt spikes. The spores of this species are ca. 57 µm, whereas *O. claytoniana*, is about 30 µm in size, thin-walled and the processes are jointed.

Filicales: This group includes spores of various families which are characterised by a bean-like shape and possess a single furrow. They are usually plain and shiny, the outer sculptured cover having broken away.

Trilete: All trilete spores which were not satisfactorily identified to species or genus level were included in this group.

e) Pollen concentrations

Pollen concentrations were determined by adding tablets of exotic *Lycopodium* spores to all samples. The exotic spores were counted along with the fossil pollen, the concentrations being calculated using the standard formula :

$$Pollen_{concentration} = \frac{Spores_{added} \times Fossils_{counted}}{Spores_{counted} \times Weight\ of\ sample}$$

Benninghoff (1962) was the first to introduce the method of determining fossil pollen concentrations by adding exotic pollen, and Matthews (1969) and Bonny (1972) have described the method more comprehensively. Stockmarr (1971) was the first to introduce the use of the tablet method.

In percentage diagrams the counts of a given pollen type in a sample are expressed as proportions of some specified pollen sum. This means that the frequencies are wholly interdependent, thus the real value of concentration diagrams lies in the independence of the various taxon curves. In percentage diagrams the conversion of taxa into percentage proportions introduces a constraint into the data which is not present in nature, whereas concentration information can help in the accurate characterisation of sediments and as an additional source of information relating to the concept of palynofacies. In addition concentration information has been found of great assistance during routine counting for deciding whether or not to count a particular level. The quick calculation of the pollen concentration after counting between five and ten traverses reveals whether the level is above or below what can be termed the 'concentration threshold' (Scourse, 1991). A threshold of 4,000 identifiable grains per gram was chosen in this study. Levels with concentrations of below 4,000 grains per gram were not counted to the 500 grain level; such levels are extremely difficult to interpret, and often of little value.

f) Data presentation

The pollen count data has been reproduced as percentage and concentration pollen diagrams. Following the recommendation of Faegri and Iversen (1975) concerning the percentage diagrams, all pollen types are included in the calculation sum on which their percentage frequency is based. The pollen sums used in the calculation of these percentages are as follows:

Pollen of all trees, shrubs and land herbs (total land pollen) = ΣP

Pollen of aquatic herbs (excluding Cyperaceae) ΣAq = $P + Aq$

Lower plants (Pteridophytes and *Sphagnum*) ΣLo = $P + Lo$

Indeterminable grains (ΣI) = $P + I$

Pre-Pleistocene Taxa (ΣPPT) = $P + PPT$

Dinoflagellate cysts ($\Sigma Dino$) = $P + Dino$

Notes concerning the percentage calculations and pollen diagrams

1. The horizontal scales used on the diagrams are the same, rendering each curve directly comparable.

2. The lithological column at the left hand margin of the diagram was constructed using the sediment symbols scheme adopted by BGS and has been presented in the composite log of every borehole.

3. The total number of dry land pollen grains (calculation sum ΣP) and the number of taxa encountered for each level is shown immediately following the herb taxa and preceding the aquatic taxa on the diagrams.

4. The herbs, aquatic and pteridophyte taxa are

presented on the diagram in the order of families given in Clapham *et al.* (1962).

5. On the large diagrams taxa that have only one isolated occurrence, at a low percentage, are represented by a unique abbreviation at the appropriate level.

6. A summary diagram showing the relative frequencies of trees, shrubs and herbs is given on the far right of the diagrams; this gives an immediate impression of the pollen changes through the sequence.

7. The symbol '+' represents a pollen representation of less than 1% at the level concerned.

The calculations and the pollen diagrams were constructed using the VAX mainframes computer of the University College of North Wales by running the programme written by Dr H.J.B. Birks and Dr B. Huntley (modified by Dr J.R.M. Allen) and stored in the file 'Mpolldata'.

g) Zonation of the pollen diagrams

The number of fossil taxa represented, the number of stratigraphical levels analysed, and the numbers of individual fossils counted at each level make the pollen diagram a very complex method of data presentation. In order to describe the diagram adequately and comparison with other diagrams it is generally necessary to subdivide the pollen diagram into smaller units. The most useful unit of subdivision of the vertical or time dimension of a pollen diagram is the 'pollen zone'. The diagrams are therefore split into vertical units and these units can be recognised as pollen zones. A 'pollen zone' has been defined as "a body of sediment with a consistent and homogeneous fossil pollen and spore content that is distinguished from adjacent sediment bodies by difference in the kind and frequencies of its contained fossil pollen and spores" (Gordon and Birks, 1972).

Turner and West (1968), West (1970), Gordon and Birks (1972), Birks and Birks (1980) and Birks and Gordon (1985) have fully discussed the basis and practice of the zonation of pollen diagrams. A 'pollen zone' as a biostratigraphic unit should be defined and described according to the recommendations of the International Stratigraphic Guide (Hedberg, 1976).

Pollen assemblage zones are defined purely on the basis of the fossil pollen and spores at one particular site; they are therefore local pollen assemblage zones (l.p.a.z.). Similarities in the local pollen assemblage zones thus constructed between adjacent sites of similar ages can be identified and grouped into regional pollen assemblage zones (r.p.a.z.) which may be significant over a large area.

The study of interglacial deposits has emphasised the strong parallelism of climatic and vegetational development during each of the three most recent interglacial stages. Iversen (1958) and Andersen (1966) considered this parallelism and proposed a scheme of descriptive terms for the stages within an interglacial cycle. Later, Turner and West (1968) discussed comprehensively the climatic and vegetational development of interglacial stages and suggested that during each stage a series of four distinct sub-stages of vegetational development can be recognised and regarded as natural biostratigraphic zones based on the pollen assemblage characters. The sub-stages suggested are: Zone I, the pre-temperate zone, dominated by boreal trees and light-demanding herbs and shrubs;, Zone II, the early-temperate zone, showing establishment and expansion of mixed oak forest vegetation; Zone III, the late-temperate zone, dominated by the expansion of late-immigrating temperate trees, and Zone IV, the post-temperate zone, again dominated by boreal trees, thinning of the forest and gradual development of open communities, particularly damp heathland. These four substages allow broad comparisons to be drawn between sites, although substage boundaries are not regarded as isochronous (West, 1980). The substages I, II, III and IV are prefixed by an abbreviation for the particular interglacial stage, and are themselves subdivided on the basis of the changes in pollen frequencies e.g. HoIIIa and HoIIIb, where Ho stands for Hoxnian and IpIIb where Ip represents Ipswichian. The Turner and West (1968) scheme is presumed to have regional significance and the four substages based on pollen assemblages are therefore of regional pollen assemblage zone status.

Over the past decade there has been increasing use of quantitative methods in Quaternary palynology. Primarily, pollen data are invariably recorded in numerical form as the number of different types of pollen grains and spores are counted in a sample. Recently computer-based techniques have been used to compare stratigraphic levels within a pollen diagram to effect its division into zones (Gordon and Birks, 1972; Pennington and Sackin, 1975), to compare several diagrams within a region (Gordon and Birks, 1974; Birks and Peglar, 1979), to compare surface pollen spectra (Prentice, 1978; Lamb, 1984) and to compare modern and fossil spectra (Birks, 1980; Lamb, 1984).

The biostratigraphic units produced using numerical techniques accord more closely to the recommendations for stratigraphic subdivision and classification of Hedberg, (1976), than do the subjective subdivisions used at present. These procedures provide a rigorous and precise technique for the subdivision of biostratigraphic assemblages. However, they provide strictly defined local assemblage zones significant only at the site under investigation. In defining interglacial vegetational history it is at present necessary to correlate these units with the broader regional zones of Turner and West (1968).

Three numerical methods were used in the present study. These were the constrained clustering agglomerate procedure

CONSLINK and the constrained divisive techniques SPLITINF and SPLITLSQ (Gordon and Birks, 1972). All the analyses were carried out using the programme ZONATION, written in FORTRAN IV by A.D. Gordon, H.J.B. Birks and B. Huntley. The analyses were undertaken on mainframes and workstations in the Computer Centre of the University College of North Wales.

h) Plant macrofossil analysis

Sediment samples for pollen analysis were washed in 10 % HCl until effervescence ceased and then sieved early in the preparation process. The filtrate was then prepared for pollen analysis and the material on the sieve was routinely examined for the presence of plant macrofossils.

II.4. Loss-on-ignition

Organic sediments sampled for palynological analysis were also subjected to loss-on-ignition in order to determine their organic and carbonate carbon content.

Sub-samples of about 3 grams of each sample were taken and dried overnight at 105°C and weighed . The samples were then combusted for about 8 hours at 550°C. The weight loss after this ignition reflects the organic carbon content of the samples. The samples were then recombusted for a further 8 hours at 950°C. Evolution of Co_2 from the calcium carbonate begins at about 800°C (700°C for dolomite) and as the organic matter has already been removed, any weight loss after this ignition reflects the carbonate content of samples (Dean, 1974).

Dean (1974) stated that the 950°C ignition can remove significant quantities of lattice water from argillaceous sediments and hence over-representation of the carbonate carbon content may result.

II.5. Dinoflagellate cyst analysis

No special sample preparation was carried out for dinoflagellate cyst analysis, and the slides prepared for pollen counting were used for this purpose. Dinocyst data have been obtained in three ways:

First, dinoflagellate cysts were counted along with pollen and spores. The total number of dino cysts have been presented in each pollen diagram to give an impression of marine influence.

Second, detailed dinocyst analysis was carried out for each vibrocore*. Levels which were found to have an inadequate number of dinocysts were not included in the diagram (more detail in section IV.2,6 below).

Third, for site BH 81/52A from the southern North Sea and BH 81/34 from the central North Sea, the diagrams have been constructed using data from Harland (1988; Appendix

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* In pollen counting a mininum number of 500 total grains were counted but in dinocyst counting such a limit was not attained. The concentration of dinocysts has been found to be very variable. However, counts of exotic *Lycopodium* have been used to achieve a data set in a manner that can be used for statistical analysis. A limit of 300 total *Lycopodium* spores was fixed and dinocysts were counted until the number of *Lycopodium* reached this limit.

II).

a) Identification

Reid (1972) and Harland (1983, 1988, 1990) have been the main texts used in the identification of dinoflagellate cysts.

b) Data presentation

Data have been presented in percentages where counts of a given species in a sample are expressed as proportions of the dino cyst total. Percentages of species were calculated from the total count of dinoflagellate cysts. Diagrams have been constructed in a way that has been adopted by Harland (1988) to assist comparison.

II.6. Particle size analysis

Samples were first separated into coarse and fine fractions*, by wet sieving through a 63 µm screen. The sand fraction was then dried at 40°C** before cooling to room condition in a desiccator and weighing.

a) Sieving for coarse fraction

Most of the samples contained less than 5 % sand

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* 'Coarse fraction' has been defined as the weight-percentage of material coarser than 63 µm whereas 'fine fraction' as the weight percentage of material finer than 63 µm. Fine fraction incorporates both 'silt' and 'clay'.

** Drying at higher temperatures was avoided because the fractions were used for counting of foraminifera.

(fraction coarser than 63 µm). Only a few samples from the sequence of diamicton between 41.5 m and 43.2 m contained more than 5 % sand. The sand fraction was not therefore further sieved.

b) Sedigraph for fine fraction

Fine fractions were analysed using a Micrometric Sedigraph. This machine employs X-rays and provides a very detailed frequency distribution of sediments finer than 63 µm. The machine also produces results very quickly and quite accurately provided the material is cleaned and well dispersed. Particular care was taken to remove the cementing agents commonly present, as this helped dispersion prior to running the samples on the sedigraph.

i) Removal of organic matter

The procedure presented by Jackson (1969) has been used for the removal of organic matter. This procedure seldom removes all the organic matter but is nevertheless very helpful in dispersing sediments. Samples of low organic content were placed in a beaker and 6 % H_2O_2 added. After stirring well they were left overnight. Beakers were then covered and heated to 40°C for 1 hour, and then brought to a brief boil at the end of the heating period to remove excess H_2O_2. It should be mentioned that this procedure is for samples with little organic matter. Samples with high organic content were treated with 30 % H_2O_2 and heated for only 10 minutes at 40°C (Carver, 1971). Sample were centrifuged and washed with distilled water.

ii) Removal of carbonate

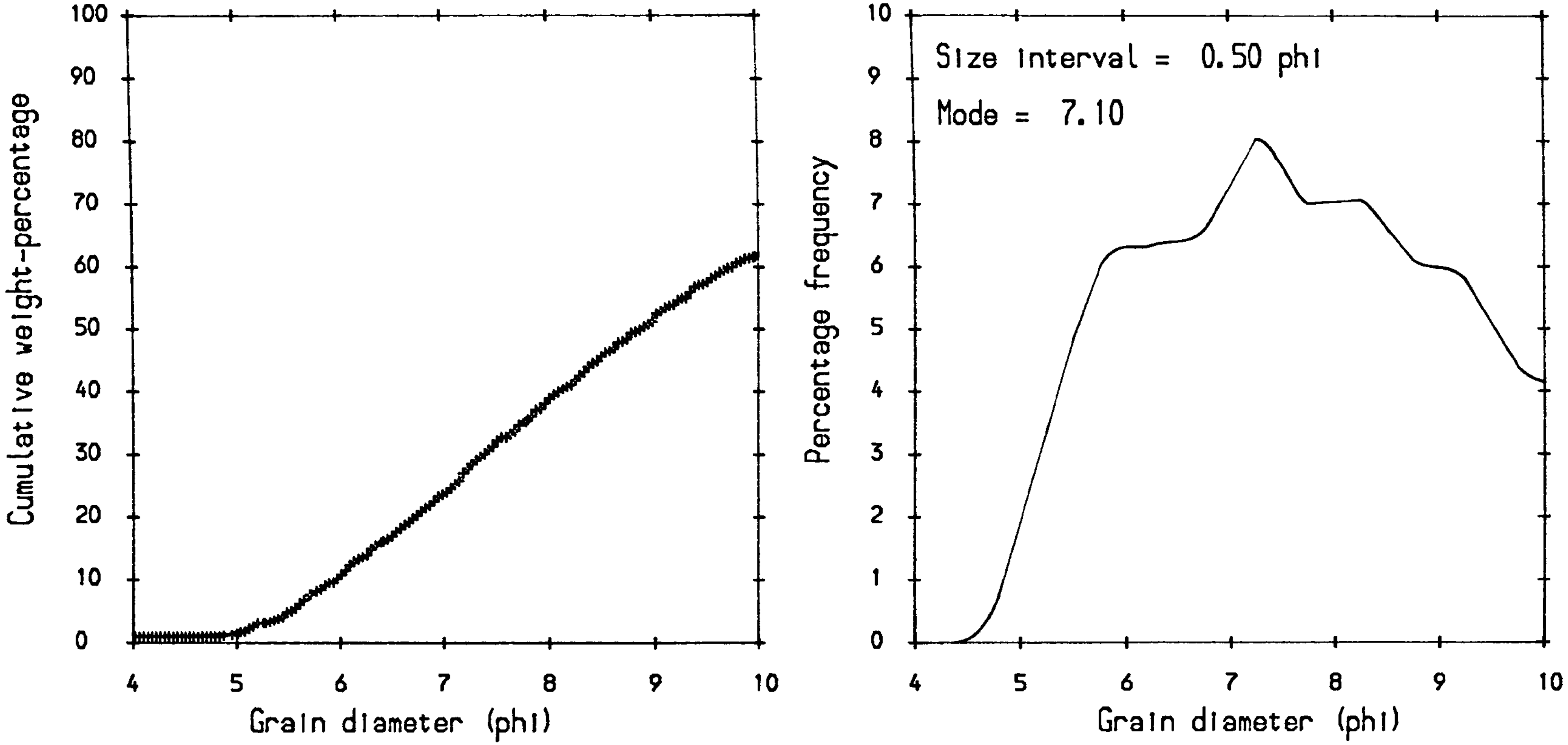
Samples were soaked in distilled water and then 10 % HCl was added until effervescence ceased. Richly calcareous samples were not soaked in distilled water but 10 % HCl was slowly added immediately and left overnight. Samples were then centrifuged and washed twice, first with 0.1 % HCl and then with distilled water.

A comprehensive FORTRAN grain-size analysis package (written by Dr Sarah Jones) has been developed and adopted as a standard procedure in the School of Ocean Sciences. This package combines raw sieve or fall-tower and pipette or sedigraph data. It also incorporates fine - particle analysis using the Micrometric Sedigraph through an IBM-PC interface.

This programme facilitated the processing of converted and combined data using the following procedure:

1. Fitted a smooth curve through all the data points (Fig. II.1).

2. If required for incompletely determined distribution this curve was extrapolated to 0 %, assuming normally distributed tails, following the method suggested by Folk (1966).



SAMPLE IDENTIFIERS

Date ... 1981

Area ... Inner Silver Pit

Site ... BH 81/52A

Sample number PS43/1988

(PHI)	MOMENTS	FOLK
Mean	9.480	9.402
Sorting	3.169	3.197
Skewness ...	0.946	0.299
Kurtosis ...	3.341	0.934

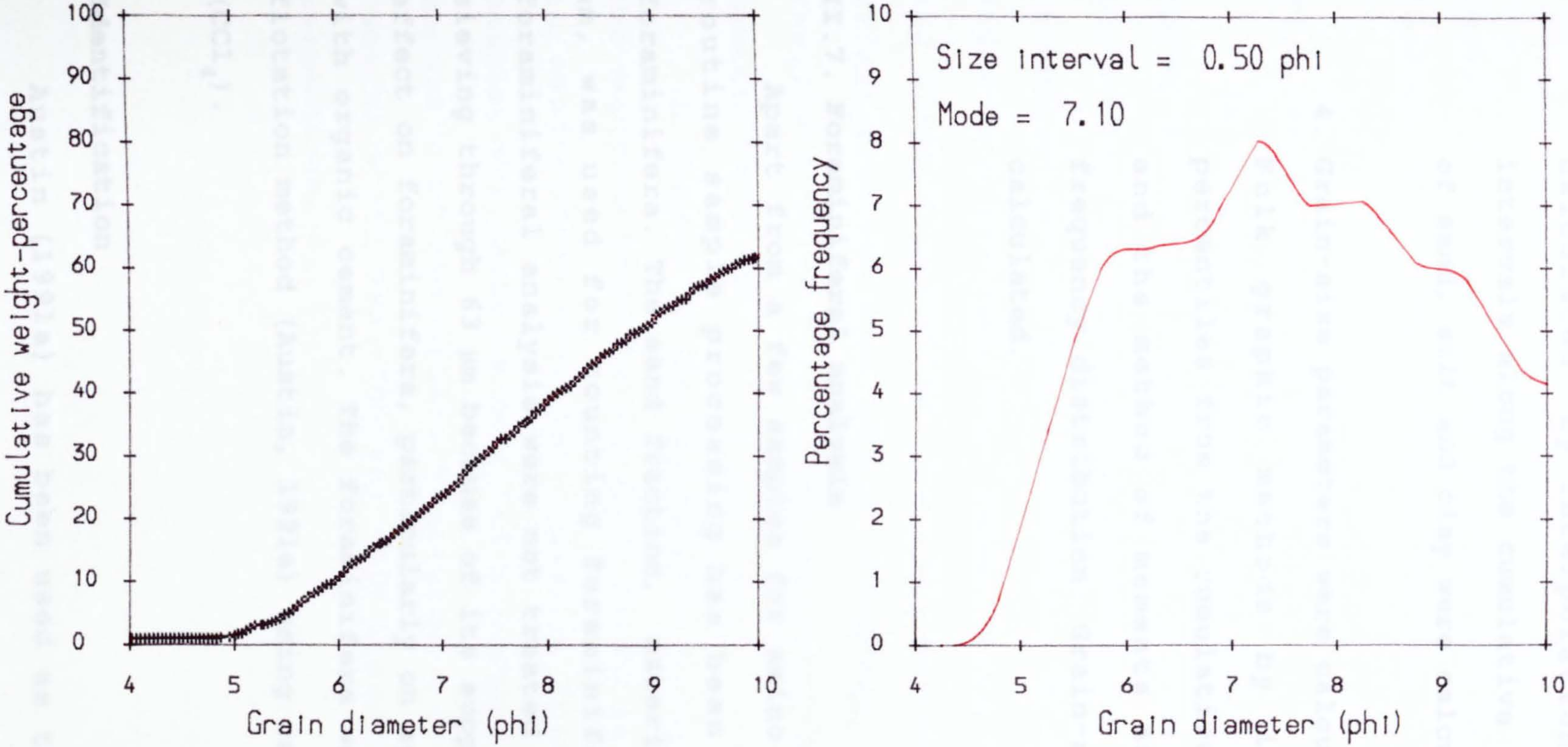
WENTWORTH CLASSIFICATION

% gravel 0.0, % sand .. 1.0

% silt .. 37.9, % clay .. 61.1

fine-skewed,
very poorly sorted,
clay.

Fig. II.1



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WENTWORTH CLASSIFICATION
% gravel 0.0, % sand .. 1.0
% silt .. 37.9, % clay .. 61.1
fine-skewed, very poorly sorted, clay.

Fig. II.1

3. A weight percentage frequency distribution was calculated by interpolation and diffraction intervals along the cumulative curve. Percentages of sand, silt and clay were calculated.

4. Grain-size parameters were calculated based on the Folk graphic methods by interpolation of percentiles from the cumulative frequency curve, and the method of moments analysis from the frequency distribution. Grain-size mode was also calculated.

II.7. Foraminiferal analysis

Apart from a few samples for amino acid analysis, no routine sample processing has been carried out for foraminifera. The sand fraction, material coarser than 63 µm, was used for counting foraminifera. Samples for foraminiferal analysis were not treated with H_2O_2 prior to sieving through 63 µm because of its supposedly destructive effect on foraminifera, particularly on agglutinated species with organic cement. The foraminifera were separated by a flotation method (Austin, 1991a) using carbon tetrachloride (CCl_4).

Identification

Austin (1991a) has been used as the main basis for identification of foraminifera. *Elphidium excavatum* forma *clavata* was chosen for amino acid analysis.

The amino acids analysis was carried out by Dr W.E.N. Austin in the laboratory of Prof. H.P. Sejrup, Department of Geology, University of Bergen, Norway.

II.8. Presentation of results

In Chapter III results from site BH 81/52A from the Inner Silver Pit area of the southern North Sea are presented and briefly discussed; in Chapter IV, investigations of three vibrocores, VE 53/00/962, /1103 and /1104 from the same area (Inner Silver Pit) are presented and their correlation with the sequence recovered in BH 81/52A from the same area is discussed. Chapter V presents results from BH 81/34 from the Devil's Hole area of the central North Sea.

In Chapter VI the depositional history (environment) of the deposits found in the Inner Silver Pit area is discussed in conjunction with the evidence from the Nar Valley. Chapter VII presents detailed environmental history of the deposits of the Middle Pleistocene in the southern and central North Sea. Chapter VIII presents conclusions and suggestions.

CHAPTER III

Site Borehole 81/52A

Inner Silver Pit, Spurn Area

British sector, southern North Sea

III.1. Quaternary Stratigraphy

a) Onshore stratigraphy (East Anglia)

It is widely accepted that during the Pleistocene East Anglia was twice affected by glaciation, during the Anglian and during the Devensian (Ehlers *et al.*, 1991c; Hart and Boulton, 1991; Straw, 1991). During the Devensian the ice sheet only reached the coastal areas of northwest Norfolk (Catt, 1980; Straw, 1991). Some authorities believe this area was also glaciated during the Wolstonian (Baden-Powell, 1948; Straw, 1965). Although the existence of the Wolstonian glaciation in the area is still a matter of debate (Gladfelter, 1975; Gibbard, 1991; Rose, 1991), Wolstonian deposits have been reported and discussed by Ventris (1985), Gibbard *et al.* (1991a) and Rose (1991).

During the Anglian, ice advanced as far south as the northern margin of London. Much of the marginal areas of the Anglian glaciation of East Anglia were characterised by intensive subglacial meltwater activity. During this glaciation, three different facies of till were deposited in East Anglia (Table III.1); these can be clearly distinguished as the 'Cromer Till' ("North Sea Drift"), the 'Lowestoft Till' ("Chalky Boulder Clay") and the 'Marly Drift'.

Table III.1 Till stratigraphy in the East Anglia

Till facies	**Responsible ice sheet**
Marly Drift	British Ice Sheet
Lowestoft Till (Chalky Boulder Clay)	British Ice Sheet
Cromer Till (North Sea Drift)	Continental Ice Sheet

The sediments of northeast Norfolk contain a number of distinct tills of 'North Sea Drift' lithofacies. There are also a number of glacially-derived landforms, which include the Cromer Ridge end moraine which is thought to represent a long-term glacial still-stand position (Ehlers *et al.*, 1991c; Hart and Boulton, 1991). Associated with these features are kame-like ridges and mounds, and an esker south of Blakeney (Sparks and West, 1964; Boulton *et al.*, 1984). One of the main problem in the East Anglian till stratigraphy results from the fact that the different till types rarely occur in superposition. However, there are a few sites where North Sea Drift, Lowestoft Till, and Marly Drift end members of the lithofacies assemblage can be seen in relationship to each other. The Corton section is one of the best of this type and for this reason it was designated as the type site of the Anglian Stage (Mitchell *et al.*, 1973).

At Corton there are both North Sea Drift (Cromer Till) and Lowestoft Till facies in the sequence, separated by sands called the Corton Beds (Pointon, 1978; Bridge, 1988). These Beds are thought to be an outwash sand sequence, possibly a series of distal fans, related to the North Sea Drift glacier (Bridge and Hopson, 1985). The base of the North Sea Drift is a laminated deposit and evidence suggests that this was deposited by an ice advance from the northeast (Banham, 1970). Overlying the North Sea Drift, the Lowestoft Till is more homogeneous, and a study of the pebble orientation from this till member indicates that it was deposited by an ice advance from the southwest* (West and Donner, 1956). It is thought that the Lowestoft Till ice sheet eroded the Fenland basin (Perrin *et al.*, 1979) and spread out over East Anglia. This relationship (Table III.1) of North Sea Drift to Lowestoft Till can also be seen near Aylsham and at Scratby (Bristow and Cox, 1973; Hopson and Bridge, 1987) and in the basin of the River Waveney (Bridge and Hopson, 1985).

The Marly Drift is not regarded as the result of any third advance. Some workers believe it represents chalky

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* This direction of the ice sheet advance should be regarded as direction representing local movement of the ice sheet. Actual advance of the British Ice Sheet is from northwest of the country (Britain).

facies of the Cromer Till whilst most designate it as chalky rich facies of the Lowestoft Till. In the sand pit at Bawsey, Evans (1976), Ventris (1985) and Straw (1991) have found Marly Drift directly overlying the Lowestoft Till.

i) Till of the Anglian glaciation

A) Cromer Till (North Sea Drift)

This Till, also known as the North Sea Drift, is sandy and outcrops in the coastal cliff sections of northern Norfolk and southern Suffolk between Lowestoft and Weybourne. This Till was first reported by Reid (1882). The Cromer Till contains comparatively little chalk and flint, a relatively high proportion of quartz and quartzite (from reworked periglacial sands and gravels) and about 1 % of far-travelled erratics among which some Norwegian indicator rocks occur (rhomb porphyries and larvikites) (cf. Ehlers *et al.,* 1991c). It is believed that the Cromer Till is certainly not a facies of the Lowestoft Till, (section B below) and that it represents an ice sheet (continental ice sheet) advance from a different (northeastern) direction (Ehlers *et al.,* 1991a).

B) Lowestoft Till

The most widespread till in East Anglia is the Lowestoft Till. The term Lowestoft Till was introduced by Baden-Powell (1948). Harmer (1902) interpreted the deposition of this 'Chalky Boulder Clay' to be the result of his 'Great Eastern Glacier' from the northwest. The Lowestoft Till occurs as a largely continuous till sheet, especially in the more southerly areas of East Anglia. The distinctive blue-grey colour is thought to be the result of the reworking of considerable quantities of Jurassic (Kimmeridge) clays, strongly suggesting westerly to northwesterly source areas (Ehlers *et al.*, 1991c). The Till is dominated by sedimentary rocks of English origin, especially chalk which distinguishes it from the Cromer Till. This Till was deposited by an ice sheet (British ice sheet) advancing from the northwest. Norwegian erratics are occasionally found, but they may be reworked from older deposits.

C) Marly Drift

In northwest Norfolk extremely chalk-rich tills occur and the term 'Marly Drift' was first used for these deposits by Boswell (1914, 1916). For a long time it was unclear whether this till was a chalk-rich variety of the 'North Sea Drift' (Boswell, 1914, 1916) or chalk-rich Lowestoft Till (Chalky Boulder Clay) (Harmer, 1928; West and Donner, 1956).

The distribution of the Marly Drift has been variously delineated by different authors (Harmer, 1909; Banham *et al.*, 1975; Ehlers *et al.*, 1987; Straw, 1965, 1991). Where Marly Drift occurs, in some cases it directly overlies the bed rock (chalk). More often, however, Ehlers *et al.* (1991c) have found a thin layer of glaciofluvial sediments between the till and underlying substratum. "This layer, which often has a thickness of just a few centimetres, records the role of meltwater during ice advance. The presence of this sand and gravel layer also demonstrates that glacial erosion of the underlying Chalk was not an aerial process but was restricted to escarpments and protrusions" (Ehlers *et al.*, 1991c).

It is now believed that Marly Drift till also represents an ice sheet (British ice sheet) advance from the northwest (Ehlers *et al.*, 1991a). This facies was deposited at a later stage of the ice advance.

b) Offshore stratigraphy (Offshore East Anglia)

The distribution and relationship of offshore sedimentary units (presented in Fig. III.1) are based on the interpretation of seismic profiles, where the formations are seen to be generally separated by reflectors (Balson and Cameron, 1985; Cameron *et al.*, 1987; Tappin, 1991)). Most of the reflectors are seen to represent erosion surfaces or sub-parallel unconformities, but in some instances they represent changes in sedimentary facies (Fig. III.2 & 16). Names for the offshore formations are taken from some of the adjacent sheets notably California (Lott, 1986), Indefatigable (Cameron *et al.*, 1986) and East Anglia (Hopson *et al.*, in press). The formations have been sampled largely in vibrocores and gravity cores and more rarely, in shallow

CORRELATION OF SEDIMENTARY FORMATIONS

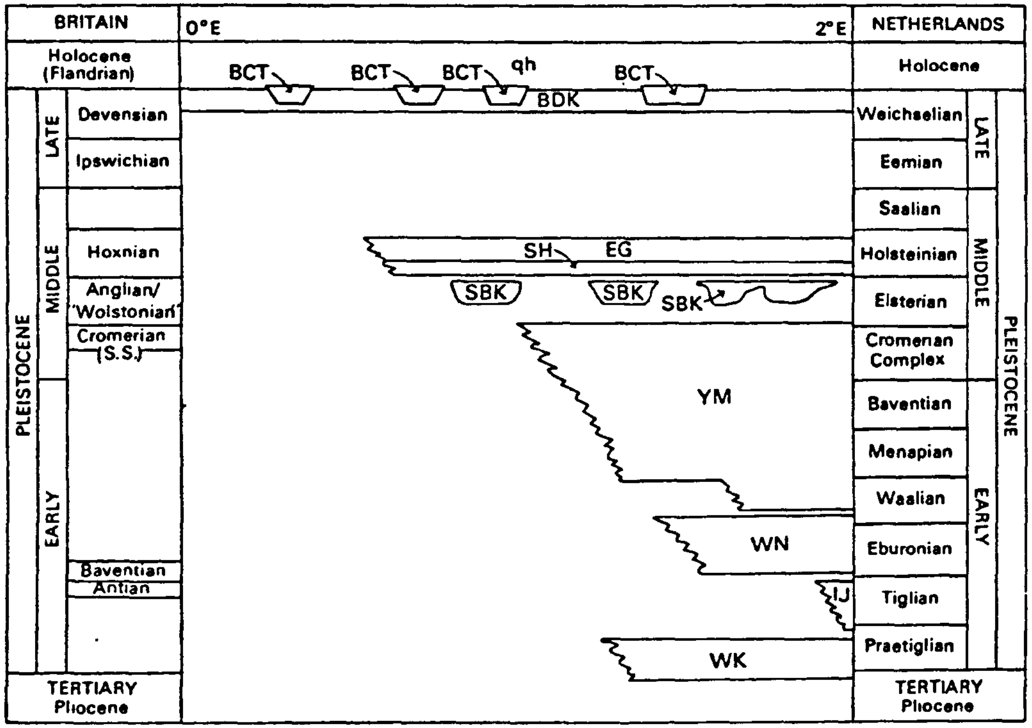


Fig. III.1. Correlation of sedimentary formations with the Pleistocene stages of Britain and the Netherlands (from Tappin, 1991). See Table I.5 for abbreviations. It should be noted that this diagram contains a number of mistakes (e.g. Baventian in Dutch sequence should read Bavelian) and does not conform to the most recent stratigraphic synthesis (Gibbard *et al.*, 1991b).

rotary cores. The ages of the formations are based upon microfossil assemblages of borehole samples from the Spurn (this thesis: Fig. III.3) and adjacent sheets, and have also been interpreted from general seismostratigraphic relationships. Depth and thickness on the geological cross-sections have been calculated from seismic sections. The stratigraphic units have been described, in detail, by Lott, (1986), Cameron *et al.* (1986), Hopson *et al.* (in press) and Tappin (1991). A brief account on the description of these units of the Middle Pleistocene is presented below.

i) **Yarmouth Road Formation** (? Waalian-? Early Elsterian)

On seismic records this Formation is either structureless, or is of a chaotic character, but with recognisable channel features indicative of erosion and infill. The Formation penetrated in boreholes in the Indefatigable sheet (of the BGS map series) to the east (Cameron *et al.*, 1986) where the sediments consist of fine- and medium-grained sands, often decalcified, with interbedded silty clay, local intercalations of marine shell sand and partings of reworked peat. These sediments are interpreted as having being deposited in a fluvial or deltaic environment. On the Spurn sheet this Formation is confined to the eastern part. The Yarmouth Road Formation, whose maximum thickness is 120 m, thins westward.

ii) **Swarte Bank Formation** (Anglian/Elsterian)

Conspicous channelised features are commonly recognised

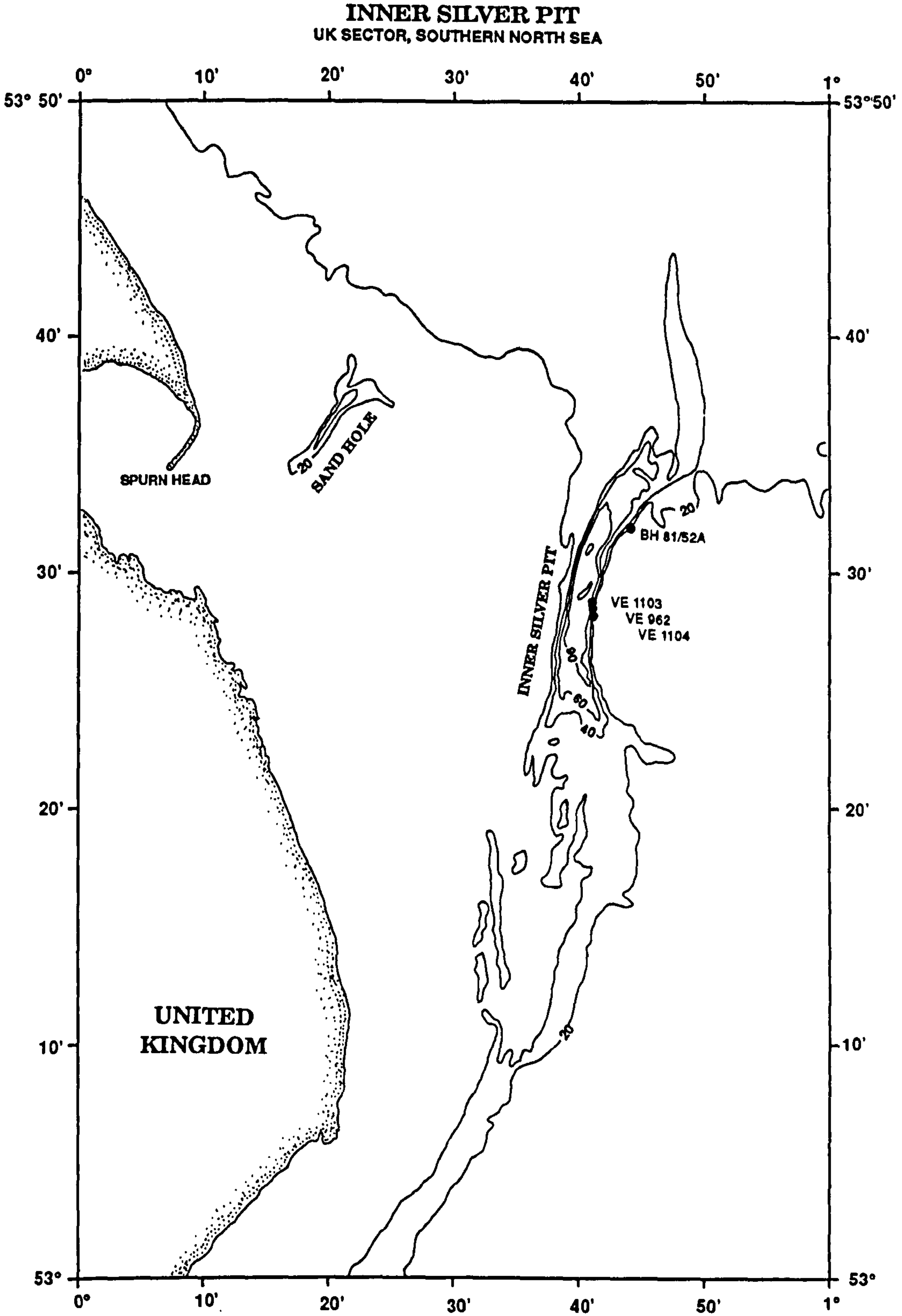
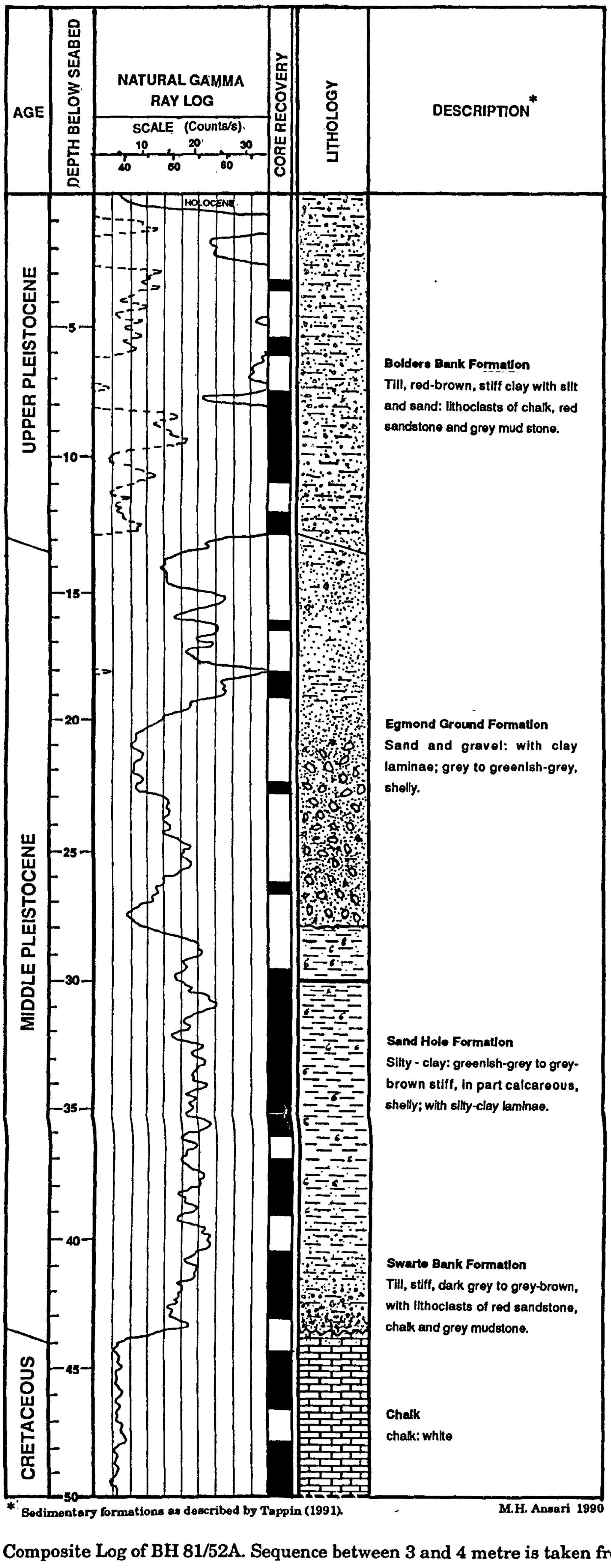


Fig. III.2. The Inner Silver Pit and Sand Hole bathymetric features, and locations of borehole and vibrocores in the area. Contours in metres.


BGS BOREHOLE 81/52A
INNER SILVER PIT
BRITISH SECTOR, SOUTHERN NORTH SEA

Bolders Bank Formation
Till, red-brown, stiff clay with silt and sand: lithoclasts of chalk, red sandstone and grey mud stone.

Egmond Ground Formation
Sand and gravel: with clay laminae; grey to greenish-grey, shelly.

Sand Hole Formation
Silty - clay: greenish-grey to grey-brown stiff, in part calcareous, shelly; with silty-clay laminae.

Swarte Bank Formation
Till, stiff, dark grey to grey-brown, with lithoclasts of red sandstone, chalk and grey mudstone.

Chalk
chalk: white

* Sedimentary formations as described by Tappin (1991).

M.H. Ansari 1990

Fig. III.3. Composite Log of BH 81/52A. Sequence between 3 and 4 metre is taken from BH 81/52.

on shallow seismic profiles. These features represent deeply incised valleys cut into Pleistocene and older sediments (Balson and Cameron, 1985; Cameron *et al.*, 1987; Tappin, 1991). Sediments of the Swarte Bank Formation are usually associated with the infills of these subglacial valleys cut during the Anglian/Elsterian glaciation (Balson and Jeffrey, 1991). These valleys occur in NNE to SSW trend and form an anastomosing complex which penetrates through the Middle and Early Pleistocene into Tertiary and Mesozoic sediments. Geometrically the valleys are up to 100 m deep and 4 km wide.

Sediments filling these valleys can be ascribed to three different facies*: i) The basal infill of the valleys is characterised by chaotic reflectors on seismic profiles (Balson and Cameron, 1987; Balson and Jeffrey, 1991; Tappin, 1991). This unit of poorly sorted, gravelly, coarse-grained sands and diamictons (representing resedimented tills) is thought to be deposited penecontemporaneously with the incision of the valleys. ii) The sediments overlying the basal infill are characterised by parallel to sub-parallel reflectors which drape over underlying irregularities, infill the uppermost parts of the valleys and in some cases extended onto the adjacent valley shoulders (Tappin, 1991). These sediments are thought to

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* These three facies are different from three types of till recognised in East Anglia (described in section III.2,a,i. above)

represent quiet water, probably glacio-lacustrine, conditions. iii) In places an upper unit characterised by cut-and-fill structures and inclined reflectors is incised into the underlying beds. It is considered that this is a product of shallow, relatively high energy, glacial-marine sand and mud sedimentation (Tappin, 1991).

iii) Sand Hole Formation* (Hoxnian/Holsteinian)

This formation, recently named by Tappin (1991; Figs. III.1 and III.3), has only been identified in the area of the Inner Silver Pit (Fig. III.6; Appendix I). The formation was penetrated in borehole 81/52A and 11 m of stiff, grey, partly calcareous, laminated silty-clay was sampled underlying the Egmond Ground Formation (Fig. III.3).

On seismic profiles these silty-clays are represented by closely spaced, parallel and even reflectors of moderate amplitude (Tappin, 1991). The clays have been interpreted as being of marine origin and appear to be localised in occurrence (Balson and Jeffery, 1991; Tappin, 1991; Figs. III.5 & III.16). On the basis of preliminary micropalaentological data and seismostratigraphic records, Tappin (1991) has correlated this Formation with the Holsteinian Egmond Ground Formation of Laban *et al.* (1984) in the Dutch sector of the southern North Sea.

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* This name is based on the Sand Hole bathymetric feature (Fig. III.2) off Spurn Head (Dr D. Tappin, *pers. comm.)*

iv) Egmond Ground Formation (?Wolstonian/Saalian)

Seismically this Formation (Fig. III.1) is characterised by low-amplitude, parallel and even reflectors. In the south-east of Spurn sheet, the base of the Formation is represented by a conspicuous seismic reflector which truncates the upper part of the Swarte Bank Formation (Tappin, 1991). The Formation was penetrated in BH 81/52A (Fig. III.3) and is represented by 16 m of grey-brown, fine to medium grained 'sands and gravels' of marine origin. On the basis of seismic record Tappin (1991) suggests that this sandy sequence typifies lithologies found elsewhere on adjacent sheets and correlates the Formation with the Egmond Ground Formation of Laban *et al.* (1984) which represents the Holsteinian temperate stage in the Dutch sector (Fig. III.1).

III.2. Present status of the Middle Pleistocene

The glaciation of the Anglian/Elsterian stage is widely accepted to be the most extensive of the Pleistocene in NW Europe. Since its deposits were later overridden by younger glaciations, much of the sedimentary record has been lost and there is only fragmentary evidence for reconstructing the glacial climate history of the stage. This is discussed in detail in Chapter VII. A brief account is presented below:

1. The deposits of the Anglian/Elsterian cold stage are best preserved beyond the margin of later

advances. Eastern England and adjacent offshore regions include extensive deposits and features formed during this stage.

2. During the Anglian glaciation East Anglia experienced ice sheet advances from two directions. First the continental (Scandinavian) ice sheet advanced from the northeast and later the British ice sheet advanced from the northwest.

3. In a series of papers Banham (1968, 1971, 1975, 1977) described and interpreted coastal exposures of Anglian sediments. He recognised three stratigraphically distinct till units deposited by oscillation of an ice lobe that entered the area from the southern North Sea basin.

4. Sandy tills below Lowestoft Till have been reported from several areas (Harmer, 1928). Ehlers *et al.* (1987) and Evans (1976) assumed that these tills are older than the Lowestoft Till at Bawsey. Ehlers *et al.* (1991c) interprets these tills as the result of North Sea ice advance and they correlate them with the Cromer Till (North Sea Drift).

5. There was a gap before and after the interaction of the two (continental and British) sheets which

acted as a corridor in which the Corton Sands were deposited (cf. Ehlers *et al.*, 1991c). An investigation of plant remains within silt bands in the Corton Sands by West and Wilson (1968) showed that they were of full glacial affinity.

6. The British ice sheet advanced from the northwest and deposited the Lowestoft Till (Chalky Boulder Clay).

7. Continued withdrawal of the North Sea ice sheet or advancing British ice sheet* over the relatively high ground of the chalk escarpment and down into the Fenland Basin led to the deposition of chalky-rich 'Marly Drift' grading into more typical Lowestoft Till in the vicinity of Bawsey.

8. By the middle phase of the Anglian glacial stage British ice covered the UK sector of the southern North Sea (discussed below). During and following this period the valleys, tunnels, deeps and shallow basins were created (Wingfield, 1991; section VII.2,a. below). These valleys and basins were later filled by Anglian glacigenic sediments.

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* Withdrawal of the continental ice sheet is not regarded representing later phase of the Anglian glaciation. It may represent fluctuation in the glacial condition or strength of the British ice sheet.

9. During the early phase of the following interglacial stage, with the improvement of the climate, clay and silty-clay began to accumulate in those valleys which remained incompletely filled by Anglian glacial deposits (Ventris, 1985) and on the seafloor of the North Sea (Fig. I.9). Hoxnian deposits have been reported from palaeovalleys on land and on the North Sea floor (Balson and Cameron, 1985; Tappin, 1991; this thesis).

10. Sediments of the Hoxnian interglacial stage are overlain by glacial-fluvial sand and gravel of the Wolstonian glacial stage (Ventris, 1985; Gibbard, 1991; Rose, 1991).

11. In the Spurn area Tappin (1991) has described three sedimentary units. Glacigenic sediments overlying Cretaceous Chalk have been correlated with the Swarte Bank Formation of Anglian age (Fig. III.1). He has correlated overlying silty-clay of the Sand Hole Formation with the Egmond Ground Formation of Laban *et al.* (1984) in the Dutch sector of the southern North Sea. Tappin has also correlated sands and gravels overlying the Sand Hole Formation with the Egmond Ground Formation of Laban *et al.* (1984).

Detailed discussion of the climate and deposits of the Middle Pleistocene is presented in Chapter VI.1.

III.3. Location

The area investigated, the Inner Silver Pit, lies within the British sector of the southern North Sea. The Silver Pit area is divided into two; the Outer Silver Pit and the Inner Silver Pit (Fig. I.5). This investigation concerns the Inner Silver Pit which lies within the 'Spurn sheet' of British Geological Survey offshore series.

There are several trench-like closed basins in the southern North Sea east of the Humber and the Wash, the longest being the Inner Silver Pit. BGS borehole 81/52A, was located on the eastern side of the Inner Silver Pit, close to its margin (Figs. III.2 & III.5) at 53° 31.855' N (longitude) and 0° 44.291' N (latitude) in a water depth of 20.20 metres.

The Inner Silver Pit, is over 50 kilometres long (Fig. III.2, up to almost 4 kilometres wide and over 70 metres deep below the adjacent seafloor. Donovan (1973) believed that tidal scour may have played a major role either in the creation of the pit or in modifying the form of pre-existing subglacial valleys during the Flandrian marine transgression (discussed in section VII.2,a).

New Sand Hole* (Fig. III.2) is another important relief

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* The Sand Hole Formation is named after this bathymetric feature (section III.1,b,iii)

feature, parallel-sided trench about 0.9 km wide, 9 km long and 18 m deep, and 44 m at its greatest recorded depth (McQuillin *et al.*, 1969). During (University of Hull cruise, Donovan, 1971) cruises only coarse sand was recovered in the New Sand Hole but at one location the core cutter showed chalky smears and may have touched chalk without retaining a sample. It is therefore believed that the New Sand Hole cuts through till, probably to chalk below. Other trench like features include Sole Pit and Coal Pit. These features are believed to be of similar origin (section VII.2,a).

Borehole 81/52A (Fig. III.3) penetrated up to 50 metres below the sea bed and the recovered sequence include deposits of chalk, till, silty-clay, sand and gravel, and till of Cretaceous and Pleistocene age.

III.4. Bathymetry

The bathymetry of the area is shown in Fig. III.4. Data quoted in the text is derived from Balson (1990). Depths are given below lowest astronomical tide (LAT). The level of LAT on this sheet is approximately 3.90 metres below Ordnance Datum (Newlyn) at Immingham and -3.75 metres at Skegness.

The offshore area is relatively shallow with water depth mostly less than 30 metres. An extensive nearshore area where the water depths are less than 10 metres e.g. off the North Norfolk, Lincolnshire and Holderness coasts, have not been surveyed in detail.

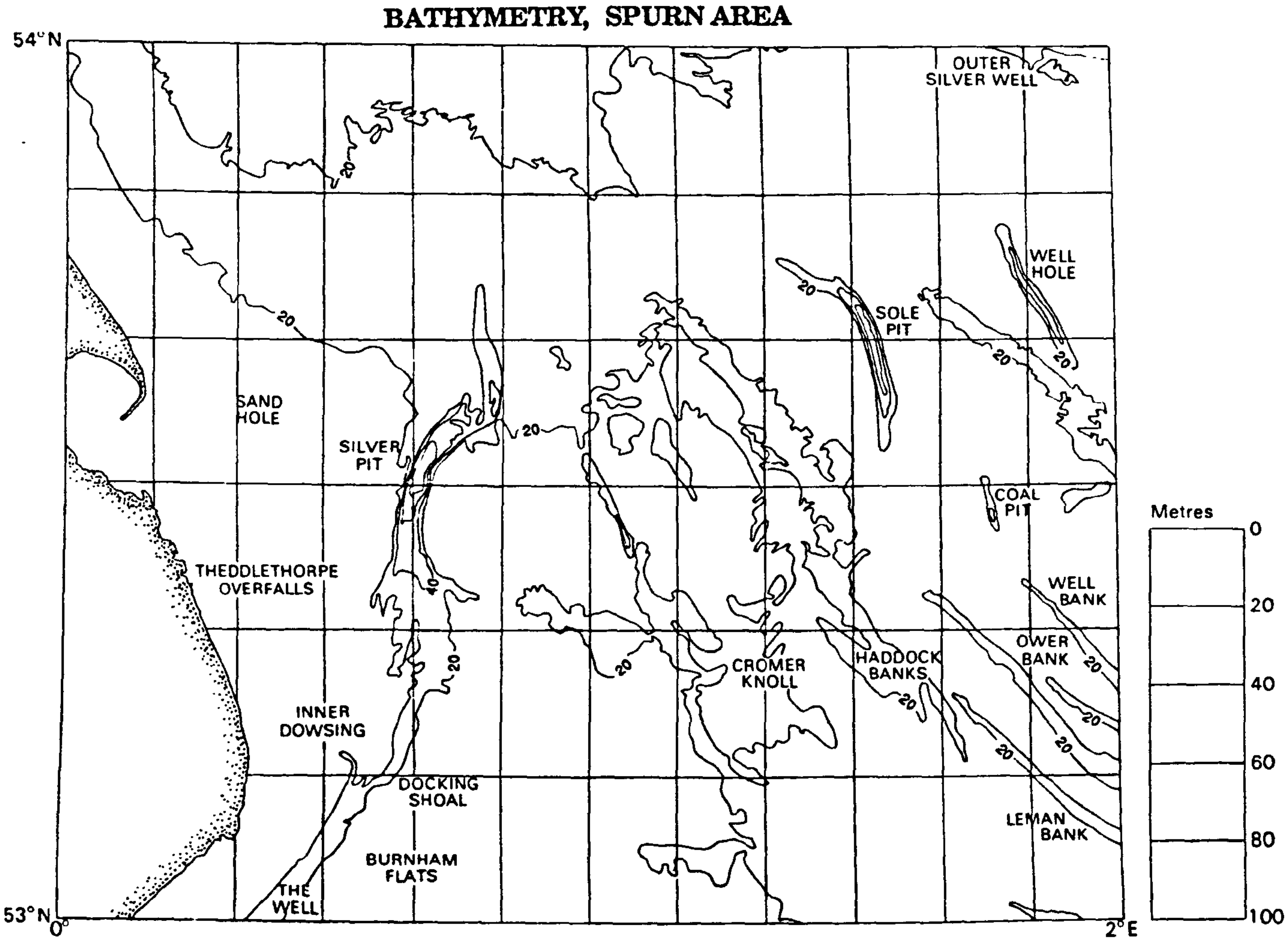

Fig. III.4. Bathymetric map of the Spurn area. Contours in metres: below lowest astronomical tide.

The area appears to be subject to strong tidal currents that have swept mobile sediment into nearshore areas of sediment accretion, such as the Wash and large offshore sandbanks. Most of the seafloor is covered by coarse, winnowed lag deposits and is relatively flat with the exception of the elongated valleys or 'pits' described above among which the Inner Silver Pit is the largest one. The pits are believed to have been excavated by meltwater beneath the southern edge of an ice sheet during the last glaciation (Wingfield, 1990a & b; Jeffery, 1991; Wingfield, 1991; section VII.2,a).

A major system of sand banks occurs offshore and parallel to the Norfolk coastline (Houbolt, 1968, Caston and Stride, 1970, Caston, 1972). Well Bank, which is one of the largest of these, is 58 kilometres long and in places over 25 metres high. These sand banks are characterised by up to 7° northeast slopes. The banks are believed to have initially formed around 7800 B.P. (Jelgersma, 1979). Sandwaves occur elsewhere in the area associated with smaller banks such as Skegness Middle (Dugdale *et al.* 1978). These sandwaves have a wavelength ranging from 75 metres to single isolated examples and have amplitudes generally up to 8 metres although locally they may reach 13 metres.

III.5. Trend of current sediment distribution

With the exception of accumulations within the sandbank and sandwave fields, modern sediments are thin, generally only a few centimetres thick (Balson, 1990). It is believed that very little sediment is supplied into this area, or indeed anywhere in the North Sea, from fluvial sources at the present time (Veenstra, 1971). Most of the sediments were probably already present prior to the Flandrian transgression which began to inundate the area after approximately 9000 B.P. (Jelgersma, 1979). A terrestrial peat in the vicinity of Lemen and Ower Banks has been radiocarbon dated to 8425 +170 B.P. (Godwin, 1960). The main source of sediment at the present time is erosion of the Holderness cliffs north of Spurn Head where cliff recession is up to 2 metres/year (Valentin, 1971). It is estimated that total loss from these cliffs during last 100 years has been $100x10^6cm^3$ (c. $200x10^6t$) of which only $3x10^6cm^3$ (c. $6x10^6t$) has been deposited on Spurn Head (Valentin, 1971).

The gravel component comprises a mixture of lithologies dominated by carbonaceous sediments and limestone, together with igneous rock types including dark-coloured porphyries with rectangular phenocrysts believed to have been derived from the Cheviots in north-east England (Veenstra, 1971). Flint pebbles, although numerous, do not form a dominant component of the gravels as compared with farther south in the North Sea (cf. Balson, 1990). Other components include Permian and Devonian sandstone and quartzite (Robinson, 1968). The assemblage reflects derivation from the Palaeozoic formations of northern England and southern Scotland, and the gravels are believed to have arisen as lag deposits derived from moraines or outwash fans (Robinson, 1968; Veenstra, 1971).

Some gravel may also be derived as a result of reworking of till that underlies most of the offshore areas and is being actively eroded by wave activity from the cliffs along the Holderness coast north of Spurn Head. Some of the gravel-sized sediment is transported southward by longshore drift to form the sand and shingle spit of Spurn Head, and some may be transported offshore to the area of the Banks (De Boer, 1964).

The sands, like the gravel, is believed to have come mostly from glacially-derived sediments (Houbolt, 1968) and is presently mobile in the strong tidal currents. Most sand-sized sediment has accumulated to form the sand banks or has been transported shoreward into areas of sediment accretion such as the Wash.

III.6. Geometry of the deposits recovered in BH 81/52A

The geometry of the deposit suggests that the marine silty-clays (Sand Hole Formation, Fig. III.3 & III.5) were deposited in a shallow basin. It is 33.75 km wide along a NW-SE section (Fig.III.6) and 25.00 km along a NE-SW section (Appendix I). In contrast it reaches a depth of only 90 m.

The NW - SE seismostratigraphic section suggests that there was a very shallow basin in existence prior to the deposition of these sediments. The processes which formed this basin are not clear but it is believed to be a feature created during the Anglian glacial stage. Its dimensions clearly suggest a rather different and perhaps simpler

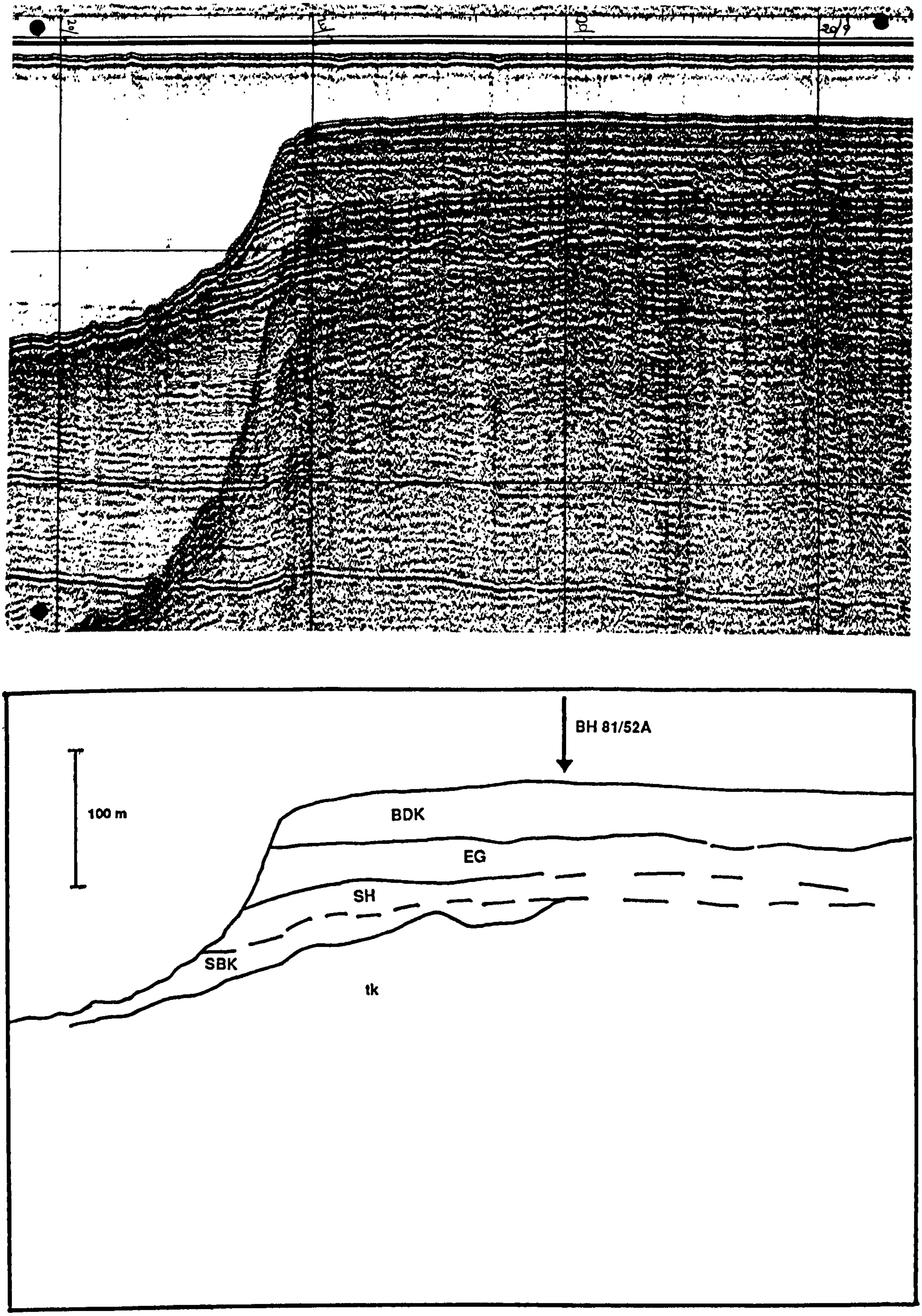

Fig. III.5. Seismic results showing the general relations of the sedimentary formations. A, Photography of seismic record from sparker line BGS 81/01/20 B, Interpretation by Dr D.R. Tappin. Arrow indicates nearest position from BH 81/52A.

origin than the events responsible for the deep palaeovalleys, very common features in the southern and central North Sea (Wingfield, 1990b; Jeffery, 1991; Wingfield, 1991; section VII.2,a).

III.7. Sediment description

29.67 - 29.99 m

'Hammer sample' from plugged bit

Grey-brown (5y4-5/1), silty-clay (Fig. III.3) with diffused laminae. Laminae are fine and more distinct at the top. The sediments are micaceous and contain shell fragments. Two samples were collected: one from the top and one from the bottom. The upper sample was used for pollen analysis whereas the lower one was analysed for organic and carbonate content.

30.00 - 30.08 m

Dark brown (10YR 4/3) silty-clay with shell fragments. Unfortunately this part of the core was not available so the 5 cm thick organic rich sediment layer within this part mentioned in the BGS composite log (Fig. III.3) was not found.

30.09 - 30.24 m

Dark brown (10YR 4/3), stiff silty clay with a few small chalk granules. Shell fragments present. This part of

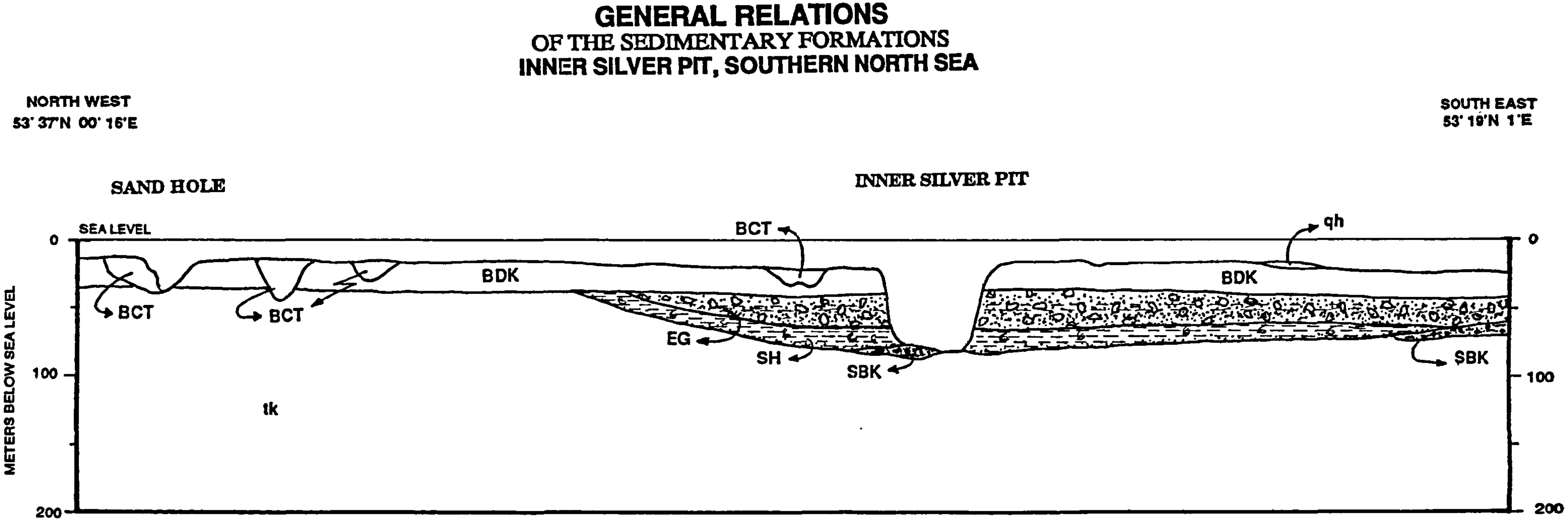

Fig. III.6. Section showing the general relations of the sedimentary formations. (Drawn from Tappin (1991). See Table I.5 for abbreviations.

the core is not well preserved and was avoided during subsampling with the exception of a single sample taken from the top used for pollen analysis.

30.25 - 31.70 m

Dark greyish-grey (2.5Y 4/2) silty-clay with a few small chalk granules. Shell fragments and ferruginous concretions present.

31.71 - 32.70 m

Olive-grey (5Y 4/2) silty-clay with a few chalk granules. No lamination except coring pseudolamination present. Shell fragments and ferruginous concretions present.

31.44 - 32.20 m

Olive-grey (5Y4/2) silty-clay with a few small chalk granules. No laminae except coring pseudolamination present. Ferruginous concretions present.

32.21 - 33.20 m

Olive-grey (5Y4/2) silty-clay, desiccated and hard at the time of subsampling. Occasionally greenish. No chalk granules. No visible lamination except coring pseudolamination present. Ferruginous concretions present.

33.21 - 34.20 m

Light brownish-grey (10YR 6/2) silty-clay without chalk granules. Occasionally greenish shed is seen and two or three ferruginous concretions present. Some coring pseudolamination.

34.21 - 35.20 m

Dark greyish-brown (10YR 4/2) silty-clay, some very small chalky inclusions.

35.21 - 36.20 m

Dark greyish-brown (10YR 4/2) silty-clay, some rock fragments in the lower part of this section.

36.21 - 37.11 m

No recovery.

37.12 - 38.12 m

Dark greyish-brown (10YR 4/2) silty-clay, with traces of chalk. Green mottles in the centre of this section.

38.13 - 39.20 m

Dark greyish-brown (10YR 4/2) silty-clay. Chalk granules and ferruginous concretions present.

39.21 - 40.57 m

No recovery.

40.58 - 40.67 m

Greyish-brown (10YR 5/2) silt-clay, chalky granules present.

40.68 - 41.70 m

Light brownish-grey (10YR 6/2) diamicton. Finely laminated at the base. Scattered chalk granules.

41.71 - 42.56 m

Dark grey (2.5Y 4/0), grading down into dark brown diamicton. Chalky granules increase towards the base, and the sequence between 42.47 - 42.56 m is grey brown in colour with abundant chalk granules and rock fragments.

42.57 - 43.20 m

Grey-brown diamicton similar to the Lowestoft Till of East Anglia. The upper part is clast free. However, the basal 43 cm contains chalk granules and Jurassic and Permo-Triassic rock fragments.

III.8. Pollen analysis

The silty-clay sequence between 29.67 - 43.00 m drilled depths in the borehole was chosen for pollen analysis. This decision was made for the following reasons:

1. The silty-clay sediments were considered

potentially good for pollen analysis.

2. The deposits of coarser material showed poor recovery (Fig. III.3) and contamination was suspected.

3. Silty-clay deposits from the Inner Silver Pit area have already produced an interesting palynological and micropalaeontological record (Fisher *et al.*, 1969).

a) Palaeobotany

The pollen diagrams from the silty-clay sequence of borehole 81/52A are presented in Figs. III.7 & III.9. Samples for pollen analysis were taken with a 10 cm sampling interval but extra intervening samples were taken where significant lithological changes were observed. The BGS composite log indicated that 33 cm of the sequence was represented by a disturbed sequence taken from the plugged bit and described as a 'hammer sample'. This was clearly an important potential source of contamination. However the pollen spectrum from this sample did not indicate any serious contamination and this level (topmost level) has been included in the diagram (Figs. III.7 & III.9).

The sequence of 9.53 metres between 29.67 m and 39.20 m yielded well preserved pollen spectra. The pollen

PERCENTAGE POLLEN DIAGRAM
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA

Fig. III.7. Results of the palynological analysis from the Sand Hole Formation, Inner Silver Pit, southern North Sea. See Fig. III.3 for detailed lithologies.

concentrations are not particularly high but the sequence does presents a fairly complete history of three out of the four substages of an interglacial cycle (Turner and West, 1968). The pollen assemblages show a series of floristic changes which enable the diagram to be divided into four major pollen assemblage zones and ten further subzones. This zonation has been confirmed using the numerical ZONATION (Gordon and Birks, 1972) programme (see Fig. III.8). The taxa included in the zonation procedure were *Abies*, *Picea*, *Alnus*, *Fraxinus*. *Taxus*, *Quercus*, *Corylus*, Gramineae and *Empetrum*. The pollen assemblage zones are presented in Table III.2.

i) Pollen assemblage zones (p.a.z.)

ISP*p.a.z.1

This pollen assemblage zone is characterised by thermophilous tree taxa although *Pinus* and *Picea* are dominant throughout. On the basis of fluctuations in the frequencies of *Quercus*, *Alnus*, *Taxus* and *Corylus* this zone has been divided into three subzones.

ISP p.a. subzone 1a (39.20 - 38.91 m)

Pinus-Picea-Quercus p.a. subzone

This subzone is dominated by *Pinus* and *Picea* but high frequencies of *Quercus* define this subzone. *Quercus* frequencies decline upwards from 16 % at the base to 4 % at

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* ISP stands for Inner Silver Pit

ZONATION DIAGRAM
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA

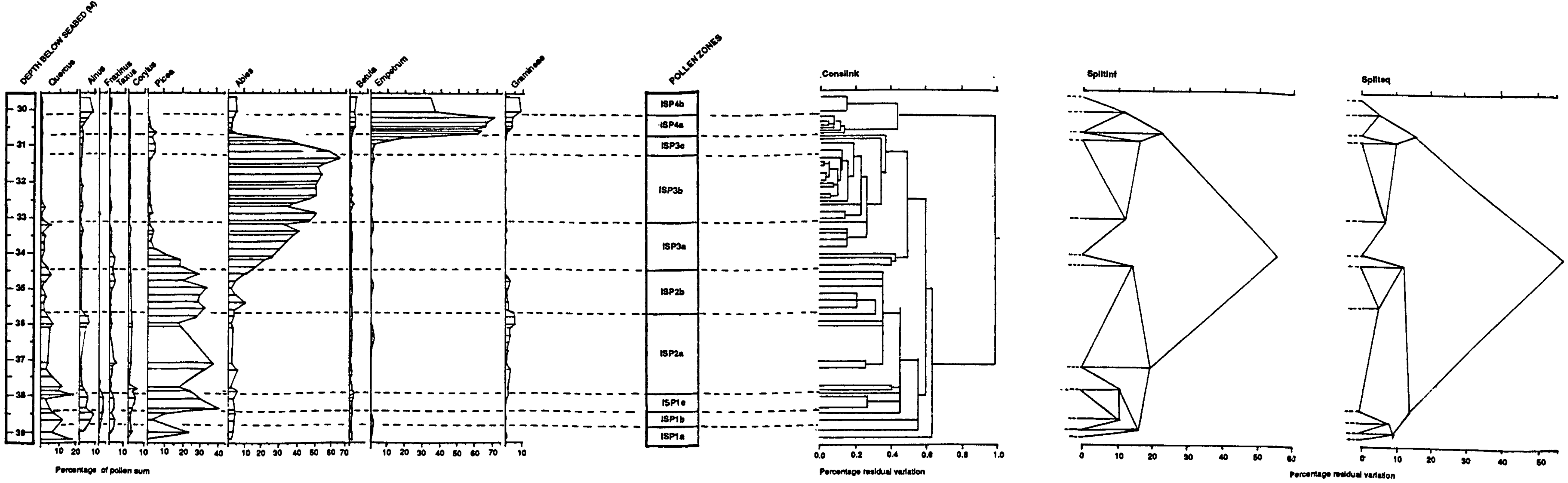

Fig. III.8. Results of the numerical zonation from the Sand Hole Formation, Inner Silver Pit, southern North Sea.

Table III.2. Pollen assemblage zones - Borehole 81/52A

Site pollen assemblage zones	**Depth (M)**	**Pollen assemblage**
ISP4b*	30.24 - 29.67 m	*Pinus-Betula*-Gramineae-*Empetrum*
ISP4a	30.70 - 30.25 m	*Pinus-Alnus*-Gramineae-*Empetrum*-Ericales
ISP3c	31.39 - 30.71 m	*Pinus-Abies-Empetrum*
ISP3b	33.10 - 31.40 m	*Pinus-Abies*
ISP3a	34.40 - 33.11 m	*Pinus-Abies-Quercus*
ISP2b	35.70 - 34.41 m	*Pinus-Abies-Picea*
ISP2a	38.00 - 35.71 m	*Pinus-Picea-Quercus-Corylus*
ISP1c	38.70 - 38.01 m	*Pinus-Picea-Taxus-Quercus*
ISP1b	38.90 - 38.71 m	*Pinus-Picea-Alnus*
ISP1a	39.20 - 38.91 m	*Pinus-Picea-Quercus*

*ISP stands for Inner Silver Pit pollen assemblage zone the top. High percentages of indeterminable (corroded and degraded) and reworked pollen and spores also characterise this subzone. *Pinus* is represented by very high values, ranging from 55 % to 69 %. Frequencies for *Picea* are high in the upper part, but low towards the base. *Corylus* shows a rise in values from 0.8 % at 39.2 m to 3.2 % at 39.0 m. Other significant tree taxa of this zone include *Alnus* with 2 % and *Abies* at lower frequencies. *Betula* ranges from 1 % to 2 %.

The most important shrub taxa is *Juniperus* and significant herbaceous taxa include Gramineae, Compositae, *Empetrum* and Ericales (excluding *Calluna* and *Empetrum*). Gramineae reaches 1.5 % towards the base. *Compositae* reaches a maximum of 0.8 %. *Sphagnum* and Filicales constitute the spore total. Filicales shows frequencies ranging from 4 % to 6 %. and *Sphagnum* is present in the upper part with low percentages.

ISP p.a. subzone 1b (38.90 - 38.71 m)

Pinus-Picea-Alnus p.a. subzone

This subzone is characterised by high values for *Pinus* and *Picea* in association with thermophilous tree taxa such as *Alnus, Fraxinus, Taxus, Quercus* and *Corylus*. The frequencies of *Alnus* comprehensively differentiate this subzone from subzone 1a and range from 3.7 % to 9.9 %. Frequency ranges for *Fraxinus, Taxus, Quercus* and *Corylus* are 2 - 3.7 %, 3 - 5.6 %, 3 - 11.1 % and 1.5 to 2.3 %

CONCENTRATION POLLEN DIAGRAM
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA

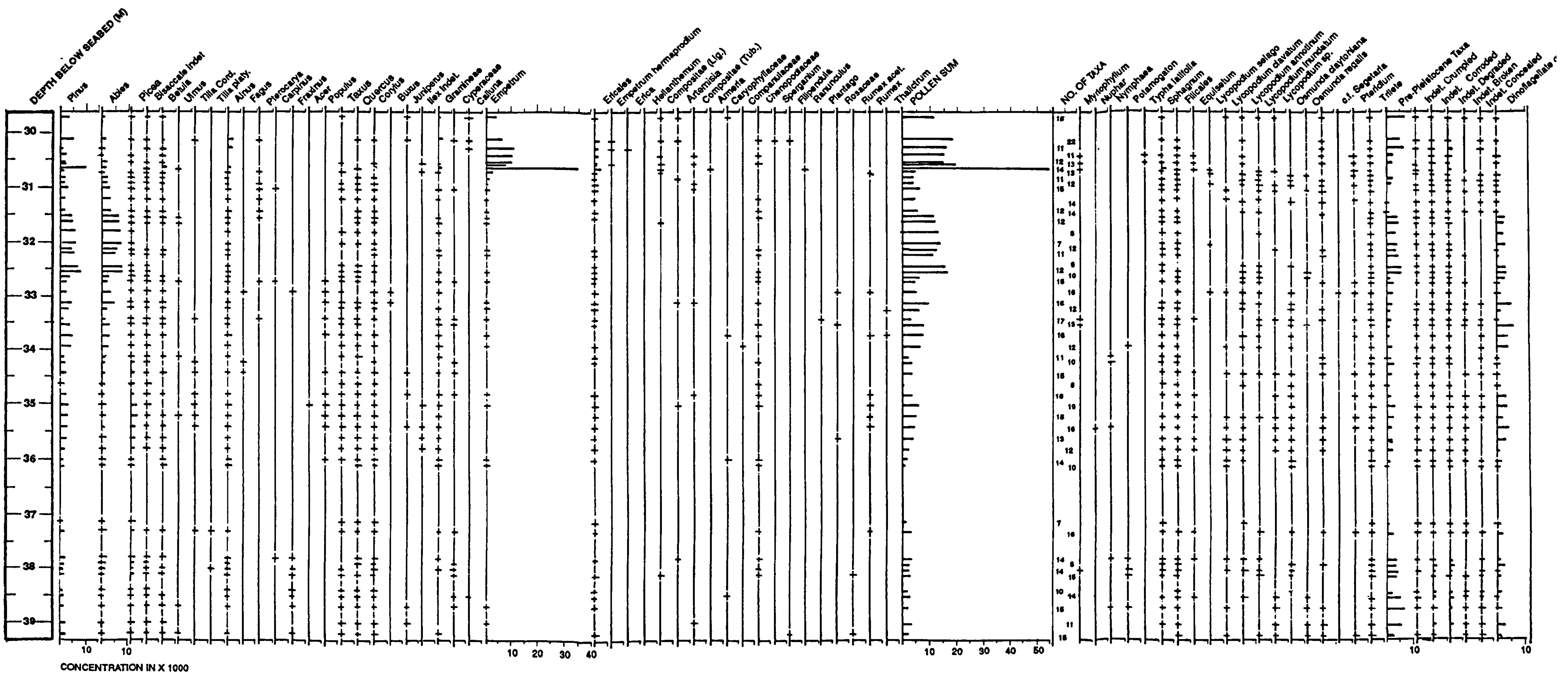

Fig. III.9. Concentration pollen diagram of the palynological analysis from the Sand Hole Formation, Inner Silver Pit, southern North Sea.

respectively. *Pinus* is represented by the highest frequencies among the tree taxa with percentage ranges between 33 % and 58 %. *Picea* shows quite low frequencies at the base (3 %) but rises sharply to 41 % at the top.

Cyperaceae represents a significant herbaceous taxon accompanying Gramineae, and the spores are dominated by Filicales, *Sphagnum* and *Osmunda* (mostly *O. regalis*).

ISP p.a. subzone 1c (38.70 - 38.01 m)

Pinus-Picea-Taxus-Quercus p.a. subzone

This subzone is characterised by the continuing dominance of *Pinus and Picea*, and the continued presence of *Quercus, Alnus, Fraxinus* and *Corylus*, but shows the highest percentages of *Taxus* and *Quercus* in the diagram. *Pinus* and *Picea* range from 23 to 46 % and 24 to 30 % respectively. *Quercus* shows a sharp increase at the top of the zone from 1.5 to 19.9 % and the highest value for *Taxus* occurs at the top of the subzone at 38.0 m. *Corylus* and *Fraxinus* range from 4 to 5.9 % and 0.7 to 3.4 % respectively. Other minor tree taxa include *Abies* and *Betula* with very low frequencies.

Spores are represented by Filicales, *Sphagnum*, *Osmunda* and various species of *Lycopodium*.

ISP p.a.z. 2

This zone is defined by the dominance of *Pinus* and *Picea* and the decline in the significance of the thermophilous tree pollen characteristic of ISP p.a. 1. This pollen assemblage zone is divided into two subzones:

ISP p.a. subzone 2a (38.00 - 35.71 m)

***Pinus-Picea-Quercus-Corylus* p.a. subzone**

This subzone is dominated by *Pinus and Picea* but associated with the moderate and consistent presence of *Alnus, Taxus, Quercus* and *Corylus. Pinus* shows a consistent presence with high values ranging from 42 % to 63 % upwards. *Picea* is the most distinctive taxa of this subzone and ranges from 17 to 37 %. *Quercus* has higher frequencies in the lowest part of the subzone (ranging from 1.9 to 11.7 %). *Alnus* and *Taxus* range from 0.2 to 5.8 % and 1.2 to 5.4 % respectively. *Corylus* has high frequencies only towards the bottom of this subzone, 8.3 % at 37.9 m; this is the highest *Corylus* frequency at the site. *Abies* is represented by very low values.

A varied range of herbaceous taxa is present, represented by Ericales (excluding *Empetrum* and *Calluna*), *Empetrum, Calluna,* Compositae Liguiliflorae and a consistent presence of Chenopodiaceae. Aquatic taxa include *Nymphaea* with 0.4-0.5 % and *Potamogeton,* which ranges from 0.5 to 0.9 %. Gramineae is represented by fairly high percentages.

The spore taxa are dominated by *Sphagnum,* Filicales, *Equisetum, Polypodium, Osmunda* and various species of *Lycopodium.*

ISP p.a. subzone 2b (35.70 - 34.41 m)

Pinus-Abies-Picea p.a. subzone

Pinus is the dominant taxon throughout this subzone. Its frequencies are very high, ranging from 50.7 % to 60.2 % of total tree pollen. This zone is characterised by a low but consistent presence of *Abies* which rises to a maximum of 10 % at 35.4 m followed by a decrease and then a renewed increase in its frequencies. *Picea* is also a persistent and dominant tree taxon in this subzone, ranging from 29.9 to 35.5 %, but its value decreases to 19.5 % at 34.80 m at the top of the subzone. *Taxus* and *Quercus* both show increases in the upper part of this subzone, *Taxus* from 2 % to 7 % and *Quercus* from 1.5 % to 4 %. *Corylus* shows a similar pattern to *Taxus* and *Quercus*, and is characterised by an increase in frequencies towards the top of the subzone.

Herb taxa include Gramineae, Cypraceae, Ericales (including *Empetrum* and *Calluna*), Compositae, Rosaceae and Chenopodiaceae, but all are represented by very low values.

The spore spectrum consists of *Sphagnum*, Filicales, and *Osmunda*, particularly *Osmunda regalis*, which reaches up to 4%.

ISP p.a.z. 3

Pinus shows high frequencies throughout this zone, and *Picea* is well represented in the lower part, but this zone is in particular characterised by a very distinct frequency curve for *Abies*. This assemblage zone can be divided into three subzones:

ISP p.a. subzone 3a (34.40 - 33.11 m)

Pinus-Abies-Quercus p.a. subzone

Though this subzone is dominated by the presence of *Pinus*, it shows a comprehensive and gradual increase in the frequencies of *Abies* and a decrease in the frequencies of *Picea*. *Abies* rises from 16.7 % to reach 43.2 % at 33.4 m, whereas *Picea* declines from 16.9 % to 2.9 % at 33.7 m. *Alnus* and *Taxus* show persistent but low frequencies. *Quercus* remains an important taxon and reaches nearly 8 % at 33.2 m. *Fagus* is present at 35.2 m and 35.4 m. *Corylus* is represented by low but consistent values throughout.

The herb spectra includes Gramineae, Cyperaceae, Ericales (including *Empetrum* and *Calluna*), Caryophyllaceae and Chenopodiaceae, all represented by low frequencies.

ISP p.a. subzone 3b (33.10 - 31.40 m)

Pinus-Abies p.a. subzone

This p.a. subzone is characterised by the comprehensive dominance of *Abies*, although *Pinus* is present throughout the subzone in high values. This subzone is characterised by the highest values for *Abies* at the site which range from 35.8 to 63.9 %. The top of this subzone is marked by the beginning of the decline in *Abies* values.

Picea is also present but with very low percentages. *Alnus* does not show any significant changes apart from a maximum at 32.1 m, and *Quercus* maintains its consistent presence. *Carpinus* appears in low frequencies and *Fagus* is present at 32.9 m, albeit with low values.

Chenopodiaceae is present throughout the subzone. Other herbaceous taxa include Gramineae, Cyperaceae and Ericales (including *Empetrum* and *Calluna*).

ISP p.a. subzone 3c (31.39 - 30.71 m)

***Pinus-Abies-Empetrum* p.a. subzone.**

This subzone represents a transitional zone between ISP p.a.z. 3 and ISP p.a.z. 4 in which the dominance of *Abies* and *Pinus* decline with the rise in *Empetrum*. *Pinus* decreases from 45 % to 23 % and *Abies* declines from 57 % to 30 %. *Picea* is represented by slightly higher values than in ISP p.a. subzone 3b as is *Alnus*. Other important tree taxa are *Carpinus, Quercus, Pterocarya* and *Taxus*.

A varied spectra of herbaceous taxa is dominated by *Empetrum* and Ericales (excluding *Calluna*). At the top of this subzone *Empetrum* shows a sharp increase in its values to reach 19 % at 30.88 m. Ericales also shows a gradual increase.

ISP p.a.z. 4 Zone

This zone is defined by the dominance of non-tree pollen types, particularly *Empetrum* and Gramineae. The zone shows very high vales for *Empetrum*, reaching up to 77 %, with much reduced values for *Abies*. On the basis of changes in the frequencies of *Empetrum*, Gramineae, *Betula* and *Pinus* this zone is divided into two subzones:

ISP p.a.subzone 4a (30.70 - 30.25 m)

Pinus-Alnus-Gramineae-Empetrum p.a. subzone

This subzone is characterised by very high values for *Empetrum*, and begins with a sharp increase from 19 % at the top of ISP p.a. subzone 3c to 60 % at the bottom of this subzone. *Empetrum* continues to rise to the top of this subzone and reaches its highest value of 72 % at 30.25 m, the top of the subzone. Other taxa significant in the definition of this subzone include *Betula*, Gramineae and *Alnus*. *Betula* and *Alnus* reach 3.4 % and 6.9 % respectively at the top of this subzone. *Pinus* is also present but with declining levels throughout the subzone, its values decreasing from 23 % to 4 %. *Abies* is represented by very low values.

ISP p.a. subzone 4b (30.24- 29.09 m)

Pinus-Betula-Gramineae-Empetrum p.a. subzone

This subzone is characterised by the decline in *Empetrum* and significant increases in the values for *Pinus, Betula* and Gramineae. *Pinus* increases from 4 % at 30.25 m to 34 % at 39.95 m, *Betula* continues rising from 3 % (at 30.25 m) to 4.1 %, and Gramineae reaches 9.1 % at 30.10 m, but declines slightly to 5.5 % at the top of this subzone. *Alnus* decreases from 9.8 % to 5.5 % at 30.10 m. *Abies* is represented by low values ranging between 4.7 % and 5.9 %.

b) Correlation with standard interglacial stages

i) Taphonomic note

It is clear from foraminiferal and dinoflagellate analyses (see below) that this sequence is marine in origin. Before fossil pollen assemblage zones (p.a.z.) and vegetational history from marine sequence can be discussed, pollen taphonomy must be taken into consideration. There has been much discussion on the value of vegetational, palaeoclimatic and biostratigraphic inferences drawn from pollen analysis from different sediment types (Faegri and Iversen, 1989; Birks and Birks, 1980; West, 1980). In marine environments water currents and turbulence are of great importance in distributing pollen. There is a tendency for winged conifer pollen to be over-represented through flotation (Muller, 1959; Stanley, 1969) and to be transported for a long distances in the atmosphere (Traverse and Ginsburg, 1967). Samples of air taken over the oceans many hundreds of miles from land contain pollen grains (Nichols *et al.*, 1978). Detailed discussion of this problem is presented in the relevant sections.

This sequence in BH 81/52A in the Inner Silver Pit area is estuarine/sub-tidal with probable fluvial influences. The pollen assemblages therefore reflect a large regional source area and contrast with sites away from fluvial influence in the central North Sea (BH 81/29, Ekman, *Pers. comm.* ; BH 81/34, Chapter V in this thesis) more detail in section iii, below.

ii) General correlation

The sequence investigated for pollen provides a pollen spectra which clearly represents a temperate stage. Pollen data combined with lithological and stratigraphical evidence suggests correlation of this interglacial with the Hoxnian. The correlation of Quaternary seismic stratigraphic units in the North Sea is generally based on micropalaeontology, palynology and amino acid stratigraphy (Cameron *et al.*, 1987).

High frequencies of *Picea, Abies* and *Empetrum*, and the presence of *Pterocarya,* make correlation of this pollen diagram with the Ipswichian interglacial stage unlikely. Correlation with either the Cromerian or Hoxnian interglacial stages is more likely.

The main problem in correlating with the Hoxnian is the high values for *Picea* because neither the deposits at Hoxne or Marks Tey show such high values, neither do the marine deposits from the Nar Valley (Ventris, 1985). However the Hoxnian deposits at Nechells do show high values for *Picea* (Kelly, 1964).

The temperate interglacial stage found in this sequence correlates very convincingly with the composite pollen diagram of the Hoxnian temperate stage from Marks Tey (Turner, 1970). The BH 81/52A sequence does not show vegetational record of a complete temperate cycle, but it does show the presence of three (presence of two or three substages is discussed in section below) out of the four interglacial substages. The site is located offshore of the Humber and the Wash, and the pollen diagram represents vegetational changes on the adjoining land area as recorded in an outer estuarine - subtidal context (see section III.12 & III.13 below). In addition, very high values for *Abies* have so far only been associated with the Hoxnian interglacial. The very high frequencies of *Empetrum* provide strong supporting evidence for correlation with the Hoxnian.

The pollen diagram of borehole 81/52A shows a close similarity with the widely cited pollen diagram of the Hoxnian interglacial from Marks Tey (Turner, 1970). However, in correlating pollen spectra of this site with Marks Tey (Turner, 1970) there are two options:

Option 1: the 81/52A pollen diagram represents only two out of the four substages (late- and post-temperate substages) of the Hoxnian interglacial stage.

Option 2: the 81/52A pollen diagram represents three out the four substages, (early-, late- and post-temperate substages) of the Hoxnian interglacial stage.

Option 1 involves simpler and easier interpretation with the conclusion that HoI and HoII are represented by the non-polleniferous sequence between 40.67 m and 39.20 m, and that the whole sequence between 29.67 m and 39.20 m represents only half of the interglacial cycle. A disadvantage of this option is the lack of any satisfactory interpretation of the lower part (ISP1 & 2) of the sequence. In this case persistent domination of *Picea* in the upper part (ISP2b) and thermophilous trees such as *Quercus, Alnus, Taxus* and *Corylus* in the lower part (ISP1 & ISP2a) remains unexplained. If they are included within part a of the late-temperate substage (HoIIIa) then their presence can perhaps be explained as a minor variation within vegetational composition.

It is perhaps significant that *Picea* is impersistently dominant in the lower part of the diagram, and the absence of *Picea* in the lowermost level, in which nearly three hundred (267) land pollen grains were counted, suggests that the whole sequence between 34.60 m and 39.30 m is not representative of HoIIIa.

Option 2 involves an interpretation of a longer history of the interglacial cycle. The major problem here is the poor pollen concentrations (Fig. III.9) representative of HoII, making subdivision of this zone less reliable and clear, and a temptation to over-interpret the pollen diagram.

A major problem is the absence of *Carpinus* which characterises the middle part of HoIIIa. This sequence appears to demonstrate the abundance of *Picea* at the expense of *Carpinus*. Nevertheless, comparison between the two options makes 2 the more convincing option.

The high frequencies of reworked pre-Pleistocene taxa in ISP1 and ISP2 might suggest that the thermophilous

Pleistocene taxa are similarly reworked in these zone, however, there was a clear distinction in the degree of preservation between the Pleistocene and pre-Pleistocene populations.

iii) Correlation of substages

The pollen diagram clearly indicates the presence of Hoxnian substages HoIII and HoIV. Hoxnian substage HoII* is also present but must be viewed critically because the section of the sequence which represents HoII is of very low pollen concentration. Substage HoI is absent**.

A) Hoxnian early-temperate substage

(HoII, Turner and West, 1968)

The early-temperate substage of the Hoxnian is represented by vegetation of mixed-oak forest and has been divided into three subzones. Subzone HoIIa of Turner (1970) is characterised by the highest peak of *Quercus* found in the pollen diagram of the Inner Silver Pit in p.a. subzone ISP1a. Substage HoIIb, which is characterised by a peak of *Alnus*, is represented by ISP1b. Substage HoIIc, which is defined by the peak in *Taxus*, is represented by ISP1c at

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* Subzone HoIIa is represented by the peak of *Quercus* at 39.20 m. This represents the middle part of subzone HoIIa at Marks Tey.

** Absence of substage HoI does not mean erosion or non-deposition below HoII. In fact sequence below HoII has not been recovered (except 9 cm recovery, see section III.7) and as substages of interglacial stages are recognised on pollen, presence of HoI is not stressed.

this site.

B) Hoxnian late-temperate substage
(HoIII, Turner and West, 1968)

This substage is characterised by the late immigrating thermophilous trees *Carpinus* and *Abies*. This substage has been divided, by Turner (1970), into two parts: the lower one is represented by the beginning of the persistent presence of *Carpinus* and *Abies* whereas the upper one is characterised by the dominance of Abies. In the Inner Silver Pit pollen diagram the lower part (HoIIIa) is represented by ISP3a. Although the *Abies* curve can be easily correlated in this way, the *Carpinus* curve is rather different. This difference may be explained as follows:

1. The pollen diagram suggests that *Betula* is under-represented.

2. *Carpinus* is morphologically similar to *Betula*, and may also therefore be under-represented..

3. *Carpinus* has the extra disadvantage that its size, and perhaps also weight too, is greater than *Betula*, resulting in even greater under-representation than *Betula*.

As far as the upper part 'b' of the substage (HoIII) is concerned, the Inner Silver Pit pollen diagram provides a very strong correlation. The *Abies* curve is extremely similar to the *Abies* curve in Turner (1970).

C) Hoxnian post-temperate substage

(HoIV, Turner & West, 1968)

This substage at Marks Tey is characterised by the dominance of *Empetrum*, Gramineae, *Betula, Pinus*, and *Alnus*. In this pollen diagram this substage, HoIV, is represented in relatively condensed form by ISP4. At Marks Tey this substage has been divided into two; the lower part is represented by the dominating peak of *Empetrum* whereas the upper part is represented by the highest peak of Gramineae. The pollen diagram from the Inner Silver Pit provides a convincing correlation with Marks Tey. Similar vegetation is present with the important exception of *Betula*. Although *Betula* is under-represented the form of its curve is similar to HoIV at Marks Tey.

Comparison of the pollen diagrams from Marks Tey (Fig. I.11) and the Inner Silver Pit (Fig. III.7) suggests that the silty-clay sequence of the Sand Hole Formation from the Inner Silver Pit records an almost complete Hoxnian interglacial cycle.

III.9. Age of the interglacial deposit

This borehole is being considered for detail chronostratigraphic investigation (Dr J.D. Scourse, *pers. comm.*). However, one sample was analysed as part of this project. In an attempt to provide some amino acid data a sample from the silty-clay sequence of the Sand Hole Formation was chosen. The sample was selected from 34.16-20 m depth which represents bottom of the ISP3b which represents part 'b' of the late-temperate substage of the interglacial. This sample has yielded an aIle/Ile ratio of 0.29 from a monospecific sample of 200 small specimens of the benthic foraminiferal species *Elphidium excavatum* (Terquem) forma *clavata* Cushman. This ratio supports the correlation of the sequence with the Hoxnian. Although the ratio is anomalously high for the Hoxnian, as Knudsen and Sejrup (1988) quote a typical ratio close to 0.145 for their Holsteinian group 3, it is too low for correlation with the Cromerian. It is interesting to note that *E. excavatum* species used is a typical constituent of shallow arctic assemblages, though it is interpreted here to be responding to lowered salinities (Austin, 1991b). As the pollen evidence strongly suggests correlation with the Hoxnian the high amino acid ratio may be the result of reworking (Austin, 1991a & b). The age of the Hoxnian interglacial is discussed in Chapter VII.

III.10. Vegetation

During zone ISP p.a.z. 1 the vegetation shows established mixed-oak forest characterised by *Quercus, Alnus, Taxus* and *Fraxinus*. During subzone ISP1a Quercus expanded considerably, probably associated with an understorey of *Corylus*.

In ISP p.a. subzone 1b *Alnus* spread to become the dominant tree pollen producer. With the expansion of *Alnus* further changes took place in the composition of the forest. A decline in *Quercus* accompanies the rise in *Alnus,* and *Fraxinus, Taxus* and *Ulmus* appear to have become part of the forest structure. Though *Pinus* and *Picea* are represented by very high percentages they were probably not dominant components of the vegetation (Taphonomic note in section 8,b,i). The shrub understorey continues to consist of *Corylus* whereas herbaceous vegetation is represented by Cyperaceae, *Calluna,* Ericales, and Caryophyllaceae. Aquatic plants include *Potamogeton* and *Nymphaea*.

Further changes in forest composition took place in subzone ISP1c. *Quercus* and *Alnus* dominated the forest canopy with a significant *Corylus* understorey. In pollen diagrams of many temperate sites the abundance of *Corylus* at the time of forest maturity is remarkable (West, 1956; Kelly, 1964; Turner, 1970, Ventris, 1985) and also in certain Irish postglacial pollen diagrams (Mitchell, 1976, 1981; Watts, 1964, 1967). Normally *Corylus* represents an understorey shrub to mature forest and subordinate in pollen production to the canopy-forming trees. *Pinus* and *Picea* continue to be abundant but were probably not dominant within the forest.

Zone ISP2 shows the emergence of the dominance of *Picea* accompanied by the decline of the mixed-oak forest. The upper part of subzone ISP2b shows the immigration of *Abies* into the forest and the decline in *Alnus*. *Taxus* appears to be the most significant of the thermophilous tree group.

During ISP3 the *Picea* and mixed-oak forest community were replaced by *Abies*, which appears to have increased rapidly to reach forest dominance. During ISP3a the dominance of the vegetation transferred from *Picea* to *Abies*. *Tilia cordata* appears to represent a consistent minor constituent of the forest. For the first time the trees *Fagus* and *Pterocarya* occur.

During ISP3b the vegetation appears to be completely dominated by *Abies*. The top of this subzone is characterised by quite high percentages of *Pterocarya*, and *Buxus* is also present; *Buxus* is often associated with *Abies* forest in Central Europe. *Abies* is noted as a low pollen producer in comparison with other conifers, and the abundance of its pollen can only mean that it was present in large quantities on the adjacent onshore areas (also see section 8,b,i).

There is some evidence for open habitats. There was little grass pollen but *Plantago*, Compositae and other herbs were present and there is continuing evidence of heathland vegetation with *Empetrum* and Ericales.

Subzone ISP3c shows major changes in vegetation composition, with the tree community being replaced by non-tree taxa. This is explained by a fairly rapid decrease in the contribution of *Abies*, which has been dominating the forest, and an increase in *Empetrum* which represents the herbaceous community. During this subzone thermophilous tree taxa give way to *Empetrum* heath.

The vegetation in ISP4 is dominated by herbs rather than trees. Within the tree community there is replacement of thermophilous trees by boreal trees such as *Pinus* and *Betula*. During ISP4a thermophilous forest gave way to grassland and, in particular, to *Empetrum* heath. *Pinus* became the forest trees (see Fig. III.7 & 9) although *Abies* was still present, with the additional presence of *Betula, Alnus* and *Pterocarya*.

Generally the vegetation shows increased open habitats in ISP4b with the significant expansion of grassland, particularly at the expanse of *Empetrum* heath. In contrast to ISP 4a calcicolous plants dominated these communities. Not only do pollen values for *Empetrum* fall but also those for *Calluna*, Ericales and the spores Filicales and *Sphagnum*. Among the wide variety of herbaceous plants present were Compositae, Caryophyllaceae, *Ranunculus, Umbelliferae, Plantago media, P. maritima, Potentilla, Rumex acetosa, Polypodium, Pteridium, Lycopodium and Osmunda regalis*.

III.11. Duplicate recovery

Sediment description of borehole 81/52A (section III.7) shows that there is a duplication of a one metre sequence between 32.5 - 31.50 m. The investigated cores were recovered in two attempts. One recovered the sequence between 0.0 - 32.70 metres whereas the other recovered from 31.44 to 50.0 metres below seabed. Consequently there is recovery overlap between 31.44 and 32.70 m. The boreholes were close to each other and the same sediments were expected in both holes (Dr Peter Balson, *pers. comm.*). Pollen analysis confirmed this expectation (Fig. III.7 & 10a). The main pollen diagram (Fig. III.7) was constructed using the 31.44 - 50.00 m sequence representing the older sediments and only 29.67 - 31.50 m from the younger sequence. The complete pollen results from the younger sequence are presented in Fig. III.10a.

To confirm this samples were taken from the duplicate recovery of both the sections; samples between 31.50 - 32.50 m from the lower section and the same depth between 31.50 - 32.50 m from the upper section were also tested for loss-on-ignition. The results (Fig. III.10b) confirm the recovery of the same sediments at the same depth.

III.12. Dinoflagellate cyst analysis

The dinoflagellate cyst data for this borehole, 81/52A, has been kindly provided by Dr R. Harland of the BGS (Appendix II). Samples from the silty-clay sequence between 29.9 m to 40.97 m drilled depth contained a rich and diverse dinoflagellate flora, Fig. III.11). The dinoflagellate cyst assemblage is, however, rather mixed comprising *Operculina centrocarpum* (Deflandre and Cookson), which represents warm conditions, and *Bitectatodinium tepikiense* (Wilson) which are indicative of cold water. The assemblages are characterised by high proportions (ca. 60%) of *Spiniferites*

DUPLICATE CORE RECOVERY
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA

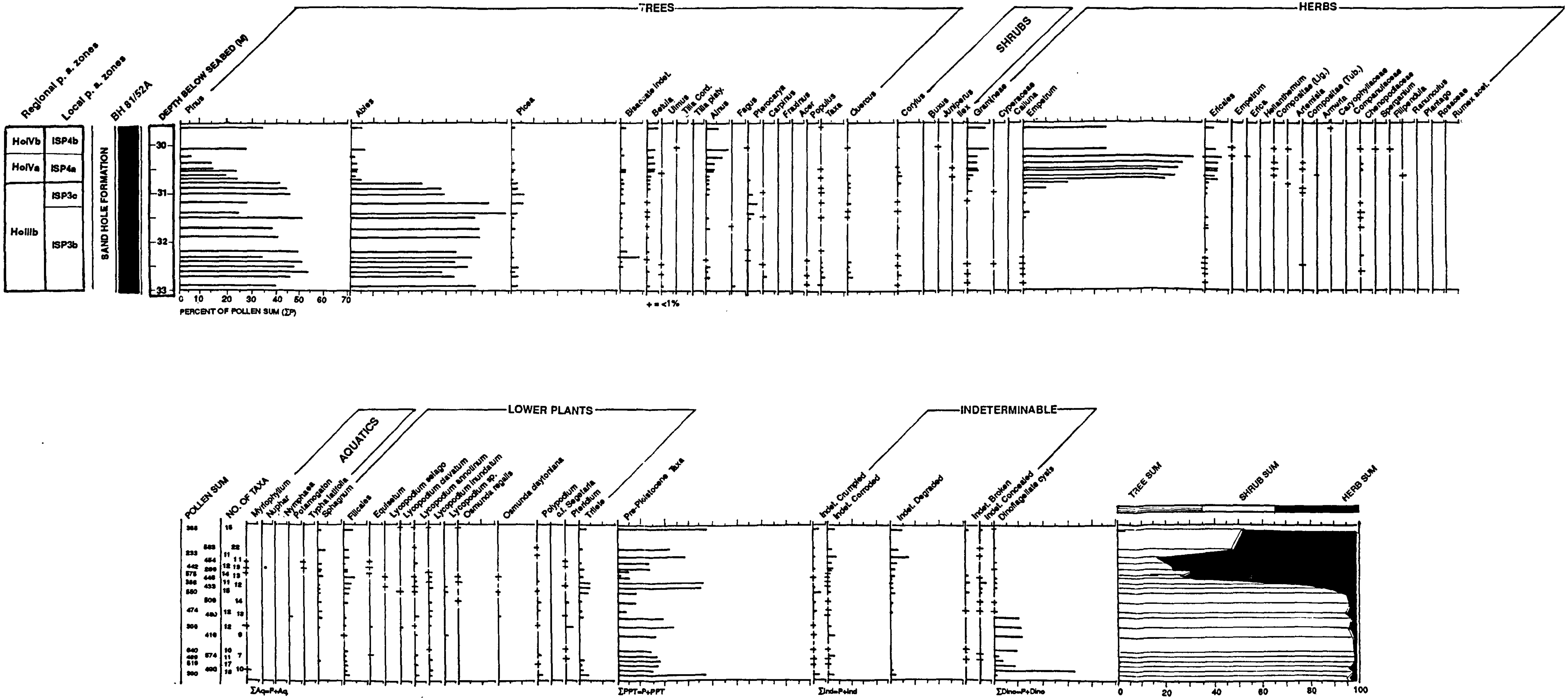

Fig. III.10a. Results of the palynological analysis from the duplicate core recovery of BH 81/52A, Inner Silver Pit, southern North Sea. See Fig. III.3 for detailed lithologies.

Analysed by M.H. Ansari 1989

DUPLICATE CORE RECOVERY
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA

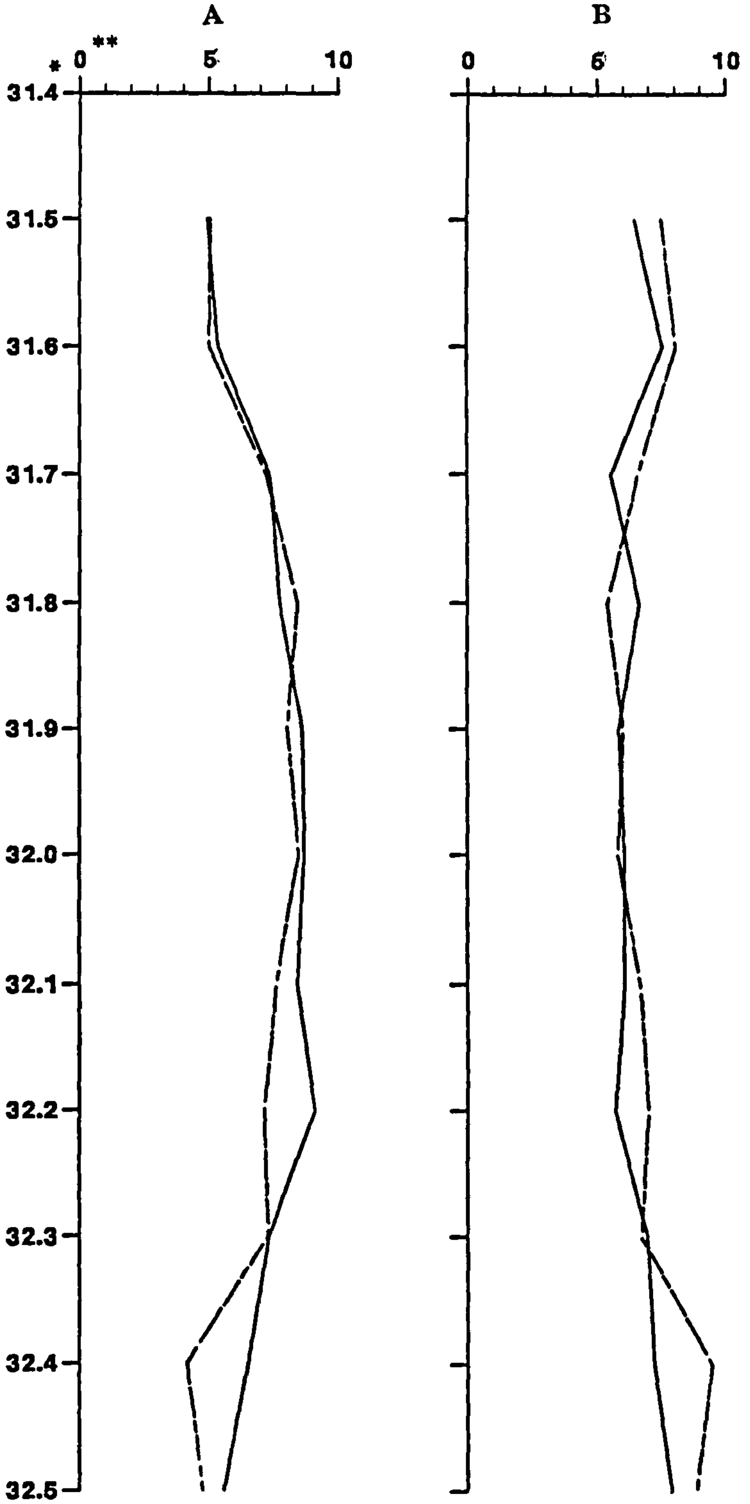

Fig. III.10b. Results of the loss-on-ignition from the duplicate core recovery of BH 81/52A. A, Organic content. B, Carbonate content. *, Depth below seabed (M). **, Percent of dried sample weight.

spp. including *Achomosphaera andalousiensis* Jan du Chene, Appendix II).

a) Dino cyst assemblage zones*

The dinoflagellate cyst spectra can be divided into two zones, with the division at 36.03 m. The lower part (D1) of the diagram is dominated by *Bitectatodinium tepikiense*. The frequencies of *Operculodinium centrocarpum* and *Spiniferites spp*. are also high. The curves are stable and consistent.

The upper zone (D2) is dominated by *Achomosphaera andalousiensis* and by *Spiniferites* spp. This upper part is characterised by very unstable curves (see standard deviation for these species in Appendix III - D2). This pattern is followed by every species.

The older part of the sequence can be further divided into two subzones, D1a and D1b. Subzone D1a is dominated by *B. tepikiense*. which ranges from 14 % at 40.97 m to 26 % at 38.08 m, whereas *O. centrocarpum* ranges from 13 % at 40.97 m to 16 % at 38.03 m. *Protoperidinium* spp. range from 8 % at 40.97 m to 7 % at 38.03 m. The characteristic feature of this subzone is instability in the frequency changes, particularly at the bottom and top of the subzone. The values for *Spiniferites* spp. are quite high and this is the only curve that is stable.

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* Data about dinoflagellate cyst provided by Dr R. Harland is presented in Appendix III.2 and mentioned in text. However dinoflagellate zones are presented within this project.

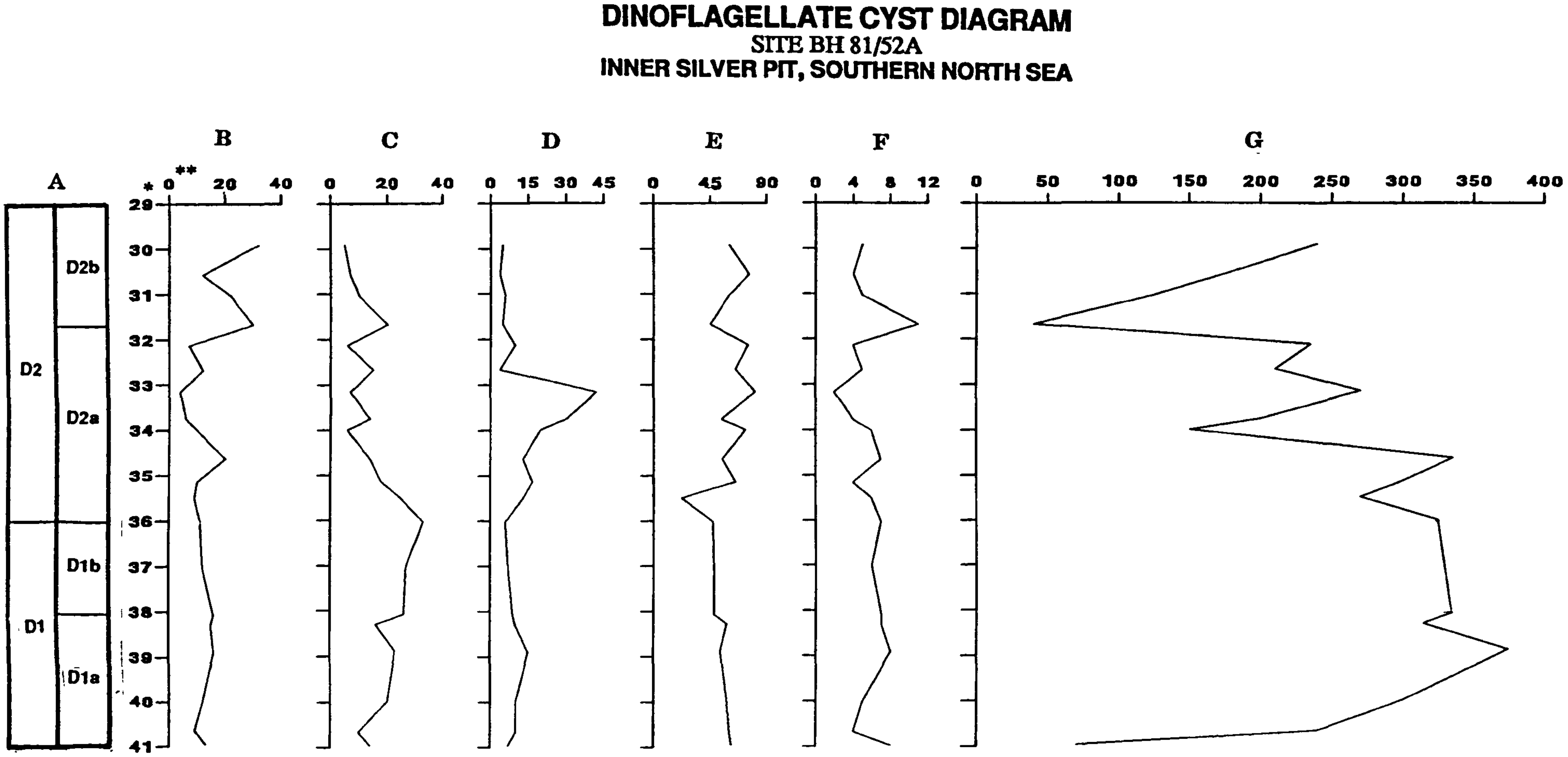

Fig. III.11. Dinoflagellate cyst biostratigraphy from the Sand Hole Formation, Inner Silver Pit, southern North Sea (Data from Appendix II). A, Dino cyst zones. B, *Operculina centrocarpum* (Deflandre and Cookson) Wall. C, *Bitectatodinium tepikiense* Wilson. D, *Achomosphaera andalousiensis* Jan du Chene. E, *Spiniferites* cysts. F, *Protoperidinium* cysts. G, Cysts/Slide. *, Depth below seabed (M). **, Percent of total cysts.

Subzone D1b is also dominated by *B. tepikiense* but the frequencies for *B. tepikiense* are higher and for *O. centrocarpum* and *Protoperidinium* spp. they are lower than in D1a. The features which characterise this subzone are the stability of the frequency curves and the decline in frequencies for all species except *B. tepikiense*.

As the upper part of the sequence, Zone D2 can also be divided into two dino cyst subzones, D2a and D2b. The lower subzone, ISP d.a. subzone 2a, covers the longer sequence and shows large fluctuations in frequency values. All levels and species in this subzone show fluctuating frequency values. This subzone is dominated by *Achomosphaera andalousiensis* and *Spiniferites* spp. Frequencies of *Spiniferites* spp. are higher throughout and range from 55 % at 34.64 m to 65 % at 32.67 m. *Achomosphaera andalousiensis* increases from 13 % at 34.64 m to 42 % at 33.16 m. *O. centrocarpum, B. tepikiense* and *Protoperidinium* spp. show the opposite pattern.

The upper subzone is defined by the low and declining values of every species except *Spiniferites* spp. which dominate the subzone. The characteristic feature of this subzone is the return of stability to the frequency values. The uppermost level is apparently slightly different from the others.

b) Palaeoenvironmental interpretation

The sequence investigated contains a rich and diverse dinoflagellate flora indicative of an ameliorative episode of interglacial status (Harland, 1988, Appendix II).

The high number of total dino cyst and higher proportion of *Operculina centrocarpum* and *Spiniferites* spp. are main elements in this amelioration*. High numbers of cysts per gram of sediment is interpreted as a reflection of high recruitment because of rich availability of meoplankton species and good environmental conditions (Harland, 1990).

The rich and diverse assemblage, dominated by *O. centrocarpum,* is comparable with the present-day North Atlantic assemblage (Harland, 1983, 1988). The major amelioration episode is represented by *Operculina centrocarpum*. According to Wall *et al.* (1977) *O. centrocarpum* is found within a range of estuarine, coastal and transitional coastal-oceanic environments in temperate and subtropical latitudes. Its relative abundance tends to increase offshore.

Around the British Isles, sediments rich and diverse in dino cyst assemblages are commonly associated with the high production of *Spiniferites* spp. (Harland, 1988, 1990). However, in this diagram the curve for this group shows significant improvement at the optimum phase of the interglacial stage.

The high proportion of *Bitektatodinium tepikiense* is extraordinary. This is a species common in north-temperate

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* Trend showing decrease in proportion of total dino cysts, *Spiniferites* spp. and *O. centrocarpum,* or an increase in proportion of *B. tepikiense* reflects deterioration. Similarly opposite trend in the change of frequencies of the species indicates amelioration or improvement in the marine environment.

to arctic environments across the North Atlantic with an area of concentration between Iceland and Scotland. This species is generally regarded as indicative of cool climates and commonly shows a reciprocal relationship with *O. centrocarpum* which is representative of temperate interglacial climates.

Evidence from Quaternary sequences investigated around the British Isles (Harland, 1988, 1990) indicates that amelioration is represented by *O. centrocarpum* while deterioration in the climate is represented by *B. tepikiense*. The high proportion of *B. tepikiense* in this diagram may be the result of depressed salinity (section III.9 above; Austin, 1991b).

Protoperidinium spp. includes several species (Appendix II), including *P. conicum, P. divaricatum, P. pentagonum, P. subinerme, P. (P. sect Quinquecopis)* sp. indet and *Protoperidinium* spp. (round brown cysts). According to Harland (1990) this poorly defined group generally shows a fairly cosmopolitan temperate to tropical, coastal to outer neritic/oceanic distribution. Nevertheless *P. conicum* (Gram) Balech, and *P. subinerme* (Paulsen) regularly appear in offshore areas.

c) Discussion

The most dominant component in the dino cyst spectra are the various species of *Spiniferites*. The assemblage is characterised by approximately 60 % of representatives of this genus (Fig. III.11). This abundance of *Spiniferites,* associated with *Achomosphaera andalousiensis,* is undoubtedly an indicator of climatic amelioration.

The total dinoflagellate curve from 40.67 m upwards shows the persistence of favourable marine conditions. The major ameliorative episode became established at 38.90 m (curve of total cyst) and lasted until 31.67 m. The curve of total dino cysts shows that after the fluctuation at 31.67 m the climate again improved, but deterioration in the climate can be discerned after about 31.57 m. This upper part of the sequence is dominated by *B. tepikiense*.

The nature and duration of the interglacial cycle, well defined by pollen analysis, is supported by the dino cyst data. In addition the curves for *B. tepikiense* indicate the involvement of oceanographic factors such as salinity and current activity

The frequency curve for *O. centrocarpum* shows the establishment of ameliorative conditions at 38.90 m and their subsequent improvement. The peaks at 31.67 m and 34.67 m represent the peak of the interglacial. The curve for *B. tepikiense* supports this interpretation, and its low values between 31.67 m and 34.00 m coincide with the peak of the interglacial. Its high frequencies are associated with the lower half of the interglacial.

The palaeoecology of *A. andalousiensis* is not very well known but its frequencies suggest that it is associated with the climatic optimum of the interglacial stage.

The high concentration of *B. tepikiense* in the lower part of the sequence led Harland (1984) to assume the influence of cool water, but the pollen data (see above) indicates warm climatic conditions. The high frequencies of *B. tepikiense* may be caused by the involvement of some other oceanographic factor such as lowered salinity or current activity. A similar situation is found in the foraminiferal assemblages from this sequence (see below).

III.13. Foraminiferal analysis

The foraminiferal data for this borehole (Fig. III.12) have been kindly provided by Dr D. Gregory of the BGS (Appendix IV). She found diverse fossil assemblages throughout the sequence, though the lower part (between 42.20 m and 35.51 m) shows lower diversity.

The samples from the silty-clay sequence between 29.67 m and 42.20 m contained a rich and diverse foraminiferal fauna. The characteristic feature of the assemblage is the abundance of *Nonion orbicularae*[*] in the lower part and *Bulimina marginata* combined with several other Quaternary species (see ISP f.a.z.[**]3 below) in the upper part. As in other Quaternary sites in the North Sea, the foram assemblages of this site are dominated by the abundance of *Elphidium excavatum*, which ranges from 52.6 % at 32.63 m to

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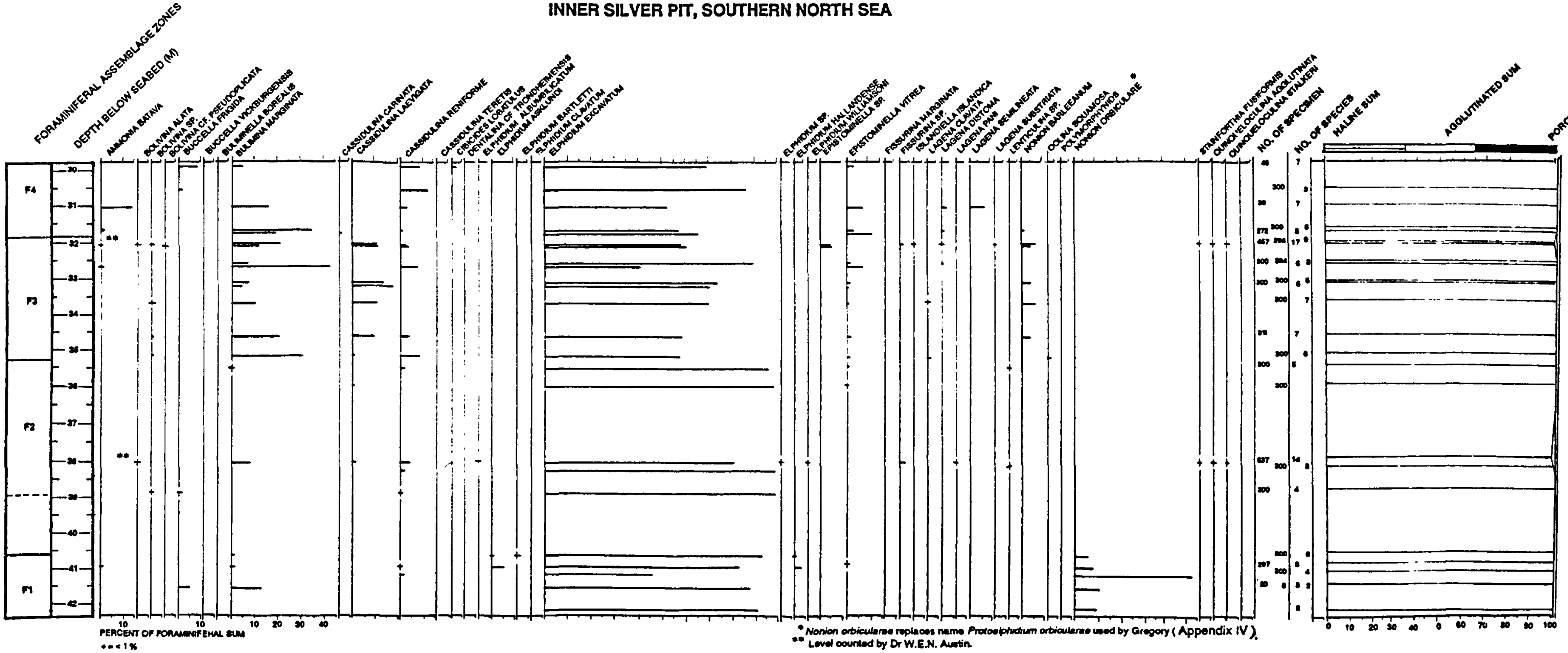
[*] This species has now replaced *Protoelphidinium orbicularae* commonly found in literature concerning the North Sea.

[**] ISP f.a.z. stands for Inner Silver Pit foraminiferal assemblages zone.

FORAMINIFERAL DIAGRAM
SITE BH 81/52A
INNER SILVER PIT, SOUTHERN NORTH SEA



* *Nonion orbicularae* replaces name *Protoelphidium orbicularae* used by Gregory (Appendix IV).
** Level counted by Dr W.E.N. Austin.

Fig. III.12. Foraminiferal biostratigraphy from the Sand Hole Formation, Inner Silver Pit, southern North Sea (Data from Appendix IV).

99 % at 36.03 m. Only the samples from 32.67 m and 41.20 m have percentages lower than 50 %.

a) Foraminiferal assemblage zones (f.a.z.)

On the basis of visual changes in faunal assemblages the foraminiferal spectra can be divided into four zones, ISP f.a.z 1 (F1 in Fig. III.12) to ISP f.a.z. 4 (F4) in ascending stratigraphic order. Some of the characteristic features of the assemblages in each zone are given below:

ISP f.a.z. 1 - (F1, 40.67 - 42.20 m)

***Nonion orbicularae* - *Elphidium excavatum* f.a.z**

This foraminiferal assemblage zone is characterised by *Nonion orbicularae* which reaches a peak of 52 % at 41.20 m. Other important species in this zone include *Elphidium hallandense, E. asklundi and Buccella frigida, Bulimina borealis* and *Cassidulina reniformis*.

ISP f.a.z. 2 - (F2, 35.51 - 40.66 m)

***Elphidium excavatum* f.a.z.**

This zone is characterised by the domination of *E. excavatum* which ranges from 81-99 %. There is no significant presence of any other species in this zone. The abundant species of ISP f.a.z. 1, including *N. orbicularae* and *E. asklundi* have disappeared and *Buccella frigida* and *Cassidulina reniformis* show no significant presence.

ISP f.a.z. 3 - (F3, 31.67 - 35.50 m)

Bulimina marginata, Cassidulina laevigata, C. reniforme, Epistominella vitrea and Nonion barleeanum f.a.z.

This zone shows a very diverse foraminiferal assemblage characterised by *B. marginata, C. laevigata, C. reniformis, N. barleeanum and E. vitrea*. *B. marginata* reaches 43 % at 32.67 m. High frequencies of *C. laevigata* between 32.07 - 34.64 m are associated with the presence of *Nonion orbicularae*. *C. reniforme* and *E. vitrea* show low but consistent presence throughout the zone.

ISP f.a.z. 4 - (F4, 29.90 - 31.66 m)

Ammonia batava, B. marginata, C. reniforme, Epistominella vitrea and Nonion orbicularae and Legena semilineata f.a.z.

This zone represents the upper part of the sequence and is dominated by *C. reniforme* and *E. vitrea*. Other important components include *A. batava,* with a high value (13 %) at 31.03 m, *B. frigida* which reaches 8.7 % at 29.9 m and *C. semilineata*. Species which characterised the middle part of ISP f.a.z.3, such as *C. laevigata* and *N. orbicularae,* are totally absent from this zone.

b) Palaeoenvironmental interpretation

The sequence between 29.67 m to 42.20 m represents a series of changes in depositional environment. Climate appears to have deteriorated between 40.67 m and 42.20 m, ameliorated between 38.9 m and 31.67 m, with a subsequent deterioration at the top.

In the dino cyst assemblages ameliorative conditions are represented by *O. centrocarpum* and deterioration by *B. tepikiense;* in the foraminiferal assemblages *Bulimina marginata* indicates amelioration whilst *Nonion orbicularae* represents deterioration. Changes in the frequency of *N. orbicularae* therefore reflect the marine climate.

Assemblage zone F1

The faunal assemblages between 42.20 m to 40.67 m are mainly arctic in character. The dominance of *N. orbicularae* in conjunction with *Elpidium excavatum* suggests a glacial marine environment. This interpretation is supported by the presence of *E. asklundi* and *E. hallandense*. Faunal diversity of fauna is quite low in this zone.

The sequence between 42.20 - 41.58 m is characterised by the highest proportion of *Nonion orbicularae* and indicates inhospitable conditions. Diversity is very low and only *E. excavatum* second species is present in any quantity. At 41.20 m these appears to be some improvement in the environment within this glacial (glacial-marine) stage where *N. orbicularae* is represented by very high values. Further improvement in the environment occurs above 41.20 m.

Assemblage zone F2

Increased diversity between 35.51 - 38.90 m suggests improved environmental conditions though no one taxon dominates. This interpretation is supported by the absence of *N. orbicularae* and the presence of *B. alata, Bolivina sp., Bolivina cf. pseudoplicata, Cassidulina laevigata* and *E. albumblicatum* .

Assemblages zone F3

The presence of high percentages of *B. marginata, C. laevigata, Nonion barleeanum, C. reniforme* and *E. vitrea* between 31.64 m and 35.6 m suggest strong amelioration. This assemblage suggests the existence of a stable, fully marine, sublittoral environment (Culver and Banner, 1978). This zone contains the highest diversity of foraminifera within the sequence. Towards the top of this zone the percentages of *Ammonia batava* indicate similarity with the modern North Sea fauna, and its occurrence here suggests open marine conditions.

Assemblage zone F4

The assemblages between 29.67 - 31.03 m indicate a deterioration in the climate. The characteristic feature of this zone is the disappearance of species which represent fully marine conditions. At the top of the zone the abundance of *B. frigida* and *N. orbicularae* suggests a return to cold conditions.

III.14. Textural analysis

Samples from the silty-clay sequence between 33.40 m and 29.67 m were not analysed for textural analysis because during pollen preparation it was apparent that the samples did not contain a significant amount of coarse (sand) material.

On the basis of textural analysis (Fig. III.13) the sequence between 43.10 m and 33.4 m can be divided into two units T1 and T2 in ascending order.

The detail of the curves in T1 enable the unit to be divided into four sub-unit. The sequence between 43.2 m and 42.5 m (T1a) shows low percentages of coarse sediment in the upper part: percentages of sand and silt are lower whereas clay shows higher proportion.

The sand percentages in T1b show a narrow range between 12.6 % at 42.00 m and 15.8 % at 42.50 m. The sequence between 40.67 m and 41.80 m, T1c, is characterised by relatively low sand content and higher percentages of silt and particularly clay. Sub-units T1d between 40.67 m and 39.20 m shows higher percentages of sand and silt and lower percentages of clay.

Unit T2, between 39.10 m and 33.4 m, shows very low percentages for sand and higher percentages for silt and clay.

a) Palaeoenvironmental interpretation

The sequence between 43.20 m and 33.40 m investigated for textural analysis comprises both glacial and interglacial sediments. The sequence between 43.20 - 40.67 m represents glacigenic sediments (diamictons/glacial-marine

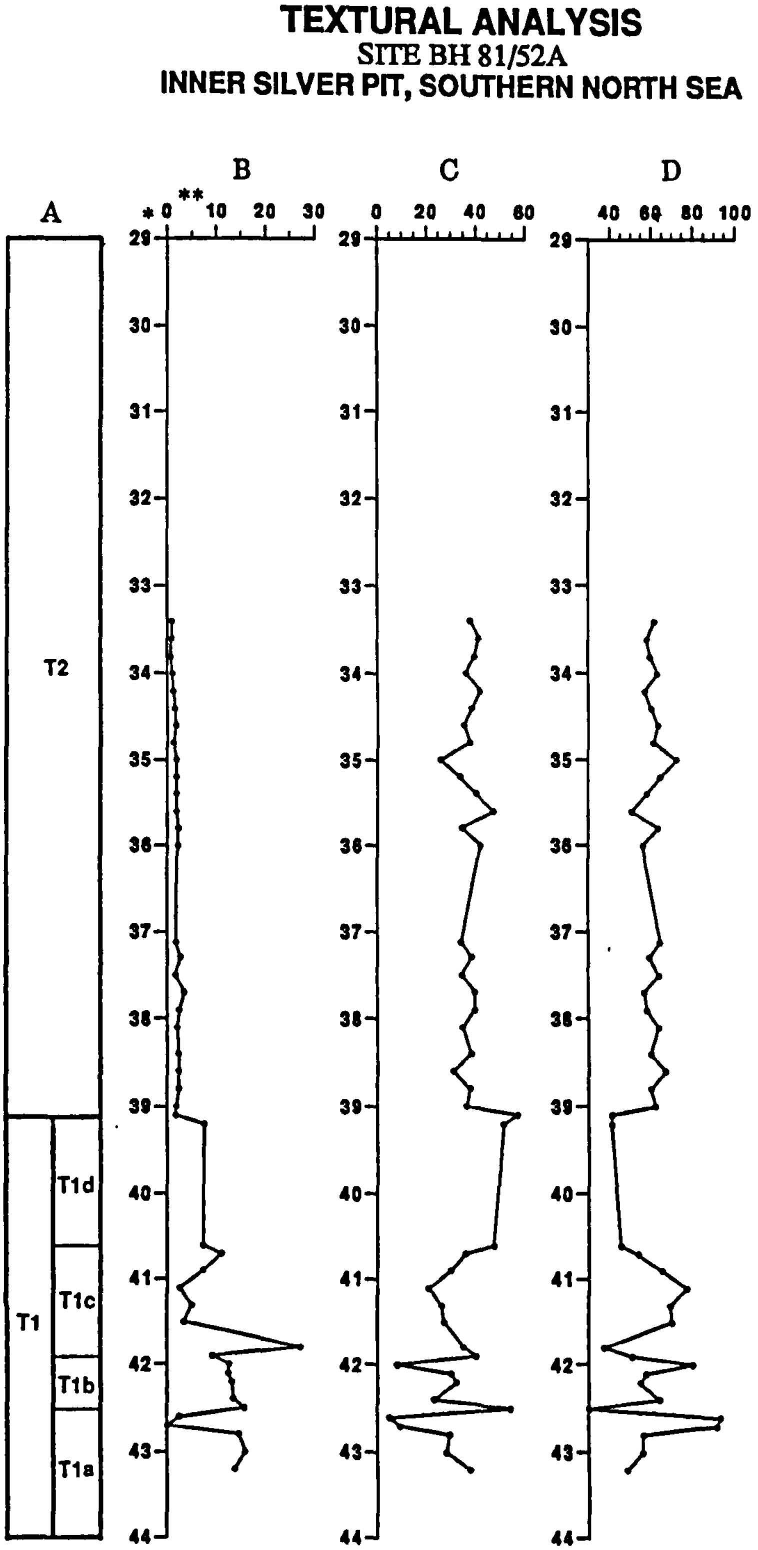


Fig. III.13. Results of the textural analysis from the Sand Hole Formation, Inner Silver Pit, southern North Sea. A, Textural Units. B, Sand (%). C, Silt (%). D, Clay (%). *, Depth below seabed (M). **, Percent of dried sample weight.

sediments) whereas the sequence between 40.67 - 33.40 m represents interglacial sediments (marine sediments).

The results from the glacigenic sediments between 43.20 - 40.67 m suggest that the sequence can be divided into three distinct units. The sequence in sub-unit T1a is represented by relatively higher and varied proportion of sand and is unfossiliferous. This suggests that this unit represents relatively high energy marine condition.

The sequence in sub-unit T1b is represented by a very homogeneous distribution of sand fraction (standard deviation in Appendix V - D). This unit is fossiliferous and is characterised by a high proportion of *Nonion orbicularae* in a low diversity foram assemblage. This may mean this unit represents an early and cold phase of glacial-marine conditions.

The sequence represented by sub-unit T1c is characterised by unstable environmental conditions but it also contains *N. orbiculare* and is thought to be glacial marine in origin.

Sub-unit T1d comprises fossiliferous marine silty-clays. During this phase of deposition it is thought that extensive erosional activity on the adjacent coast would have provided a supply of reworked glacial sediment causing the poor concentration of pollen and spores.

III.15. Loss-on-ignition

Samples were combusted at 550C° and 950C° to provide outline data on the content of organic matter and carbonate (Dean, 1974).

The results of loss-on-ignition from the sequence between 29.67 m and 43.20 m (Fig. III.14) shows a series of changes which, as in the textural analysis, enables the sequence to be divided into two main parts. The lower part extends between 43.20 m and 36.10 m, and the upper from 36.10 to 29.67 m.

The lower part shows highly irregular curves for both organic matter and carbonate content. This sequence can be divided into five sub-units (L1a - L1e):

1. Sub-unit L1a represents the sequence between 43.20 m and 42.50 m where both the organic matter and carbonate content curves are highly irregular.

2. L1b represents the sequence between 42.50 m and 41.80 m where the values for organic matter and carbonate are low but stable. The carbonate curve is particularly stable between 42.5 m and 41.8 m.

3. The sequence between 40.67 m and 41.80 m is represented by subzone L1c and characterised by higher values for both organic matter and carbonate.

4. Sub-unit L1d shows stable curves for both organic

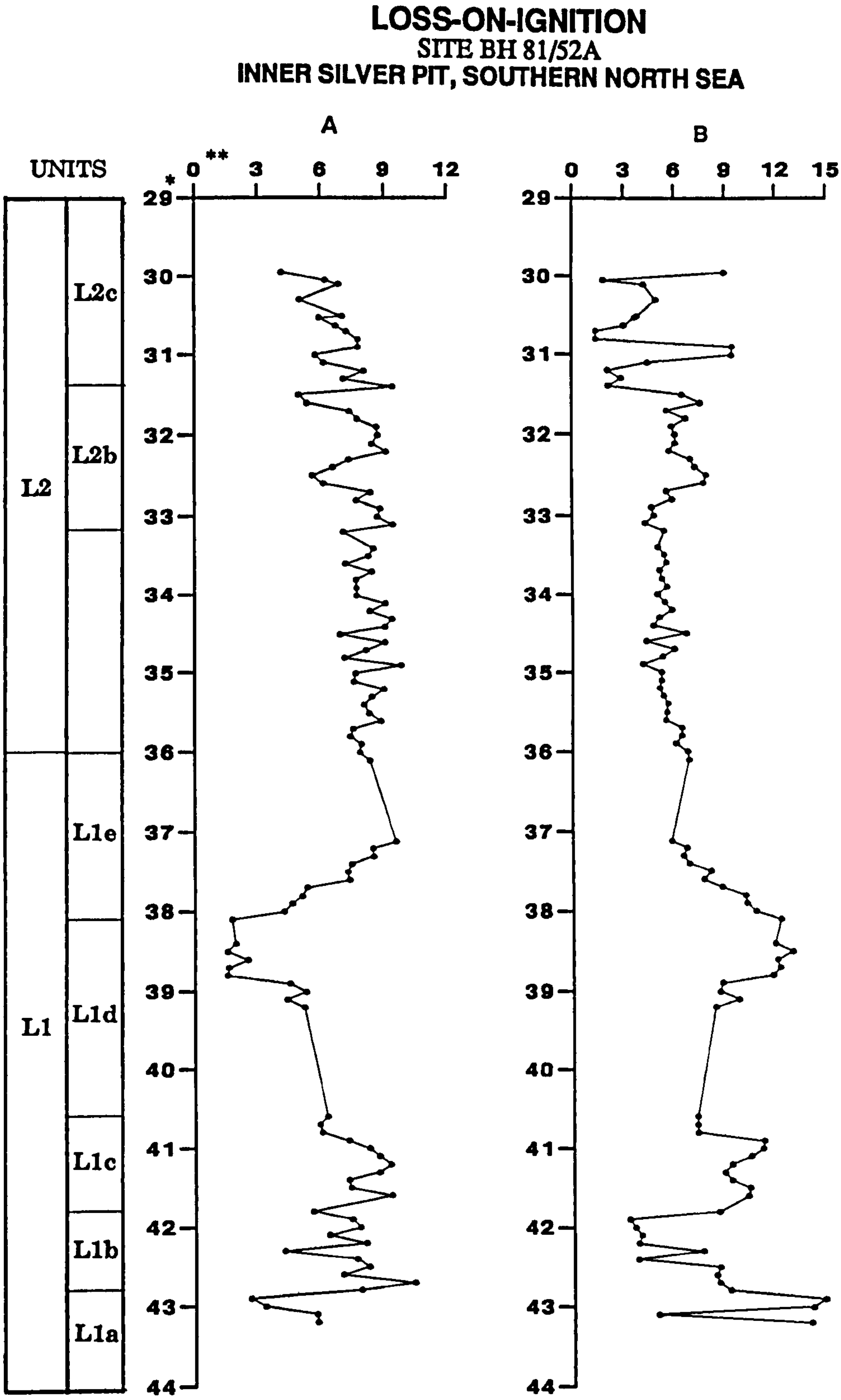


Fig. III.14. Results of the loss-on-ignition from the Sand Hole Formation, Inner Silver Pit, southern North Sea. A, Organic content. B, Carbonate content. *, Depth below seabed (M). **, Percent of dried sample weight.

matter and carbonate content between 40.60 m and 38.10 m.

5. In subunit L1e the sequence between 38.10 m and 37.12 m shows a gradual and consistent change. Values for organic matter vary between 1.7 - 9.6 %, and the carbonate content decreases from 12.3 % to 5.8 % upwards.

The sequence between 36.10 m and 29.67 m shows comparatively few changes. It can nevertheless be divided into 3 subunits as follows:

1. Sub-unit L2a shows quite stable curves for both organic matter and carbonate content.

2. The sequence between 33.10 m and 41.40 m represented by sub-unit L2b indicates increased values for both organic matter and carbonate. Apart from two fluctuations the curves represent quite stable values.

3. Sub-unit L2c, the sequence between 31.40 m and 29.67 m, shows great changes in both organic matter and carbonate content.

a) Interpretation of data

The sequence analysed for loss-on-ignition covers both glacigenic and interglacial sediments.

The data from loss-on-ignition enable the subdivision of the glacigenic sequence into three sub-units (L1a, L1b and L1c). It is interesting to note that this division is exactly same as suggested by the textural analysis data. It therefore seems reasonable to suppose that the distribution of organic matter and carbonate content is related to the distribution of particle size. If this is the case then :

i) The unstable curve for both organic matter and carbonate content in sub-unit L1a represents high energy pre-glacial-marine environment of deposition represented by T1a.

ii) Sub-unit L1b represents glacial-marine deposition. The stable curve for carbonate in this subzone can be correlated with the stable curve for sand in T1b (standard deviation in Appendix VI - L1b).

iii) Sub-unit L1c, which represents textural sub-unit T1c, shows higher values for both organic matter and carbonate content. Correlation between organic matter and carbonate content shows a +ve value for this unit (Appendix VI). It is interesting to note that this subzone is the only part of the whole sequence between 43.20 m and 29.67 m which shows such a +ve correlation (Appendix VI).

Sub-unit L2b constitutes the optimum phase of the interglacial stage by comparison with the curve of *Abies*. Sub-unit L2c represents the post-temperate substage of the interglacial stage. Unstable curves for both organic matter and carbonate content possibly result from regression of sea-level.

III.16. Discussion

a) Anglian cold stage

It is believed that the onset of fully glacial conditions in the southern North Sea during the Elsterian stage led to the erosion and infilling of a system of subglacial valleys. In the southern North Sea these valleys increase in frequency eastwards into the Dutch sector, where the uppermost component of the fill commonly comprises sparsely shelly Holsteinian marine sands (Egmond Ground Formation; Laban *et al.*, 1984).

Balson and Cameron (1985) observed that all the palaeovalleys have a basal infill which is structureless with a chaotic reflector configuration on seismic profiles, interpreted as gravelly, coarse sand or perhaps till or slump deposits. They also state that many of the palaeovalleys also contain an overlying well-bedded seismic facies, which is draped over topographic irregularities, suggesting lower energy deposition in a glaciolacustrine environment. Moreover, an upper unit with cut-and-fill structures and oblique reflectors is incised into the underlying beds. They interpret this unit to be the result of a shallow glacial marine phase of deposition.

Sediment description and analyses of core recovered from borehole 81/52A shows that the sequence between 29.67 m and 43.20 m represents glacigenic sediments of Anglian age overlain by estuarine-marine silty-clay of Hoxnian age. Detailed investigation suggests that the glacigenic sediments are represented by three phases of deposition (Fig. III.15), all of which can be correlated with the Lowstoft Till (on the basis of geotechnical properties of the glacigenic sediments, cf. Balson and Cameron, 1985; discussions in section VII.2).

The depositional environments of these glacigenic sediments are described and discussed in detail in chapter VI. A brief description of the three types of glacigenic facies are given as follows:

i) Glacigenic sequence

Unit I (43.20 - 42.50 m)

This unit is characterised by relatively lighter colour than unit II, and the lower part is very similar to the Lowestoft Till (cf. Balson and Cameron, 1985). A striking feature is the clast free zone between 42.57 m and 42.76 m. This unit is largely unfossiliferous and probably represents

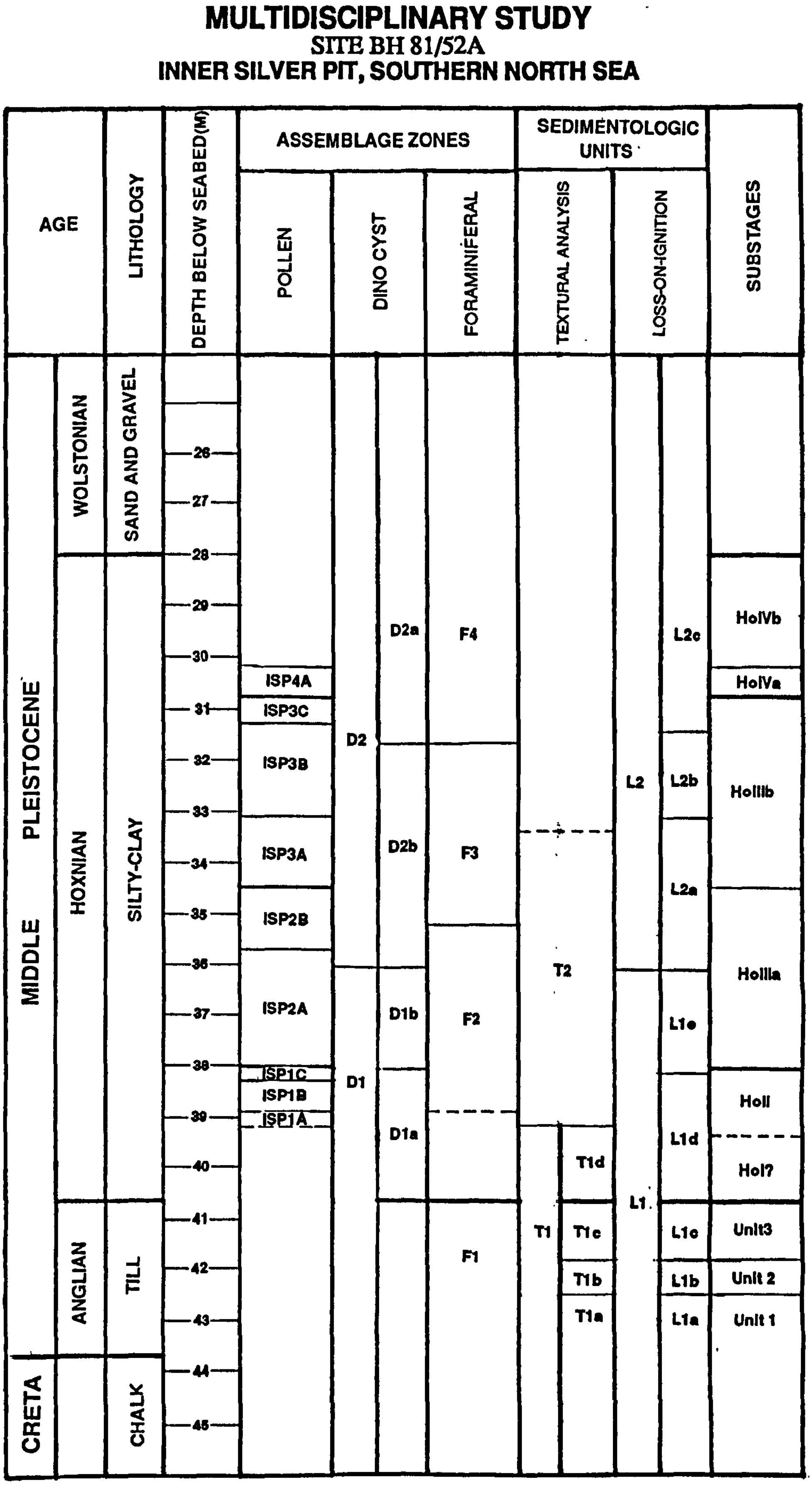


Fig. III.15. Multidisciplinary study of the Middle Pleistocene sediments recovered in BH 81/52A.

deposition immediately after the formation or reshaping of the valleys, deeps or basins (origin discussed in section VII.2,a). Such units are represented by chaotic reflectors on the seismic record.

Unit II(42.58 - 41.80 m)

This unit is darker in colour and suggests an even closer similarity with the Lowestoft Till. The grain size distribution for the Lowestoft Till is remarkably uniform (Perrin *et al.*, 1979; also see Ehlers *et al.*, 1991c). Evidence from textural analysis (Fig. III.13) for this unit shows a remarkably uniform sand content, though the silt and clay values are more variable. This unit is characterised by cold water forams and is probably of glacial-marine origin.

Unit III (41.80 - 40.67 m)

Fine laminations at the base of this unit suggest low energy glacial marine depositional conditions. This unit is highly fossiliferous and the glacial marine interpretation is supported by the high proportion of *Nonion orbicularae*.

b) Hoxnian temperate stage

HoI (40.67 - ?39.20 m)

Pre-temperate substage

Evidence from pollen analysis suggests that the sequence above 39.20 m represents deposits certainly younger than the pre-temperate substage of Hoxnian (HoI).

Unfortunately sediment between 39.20 m and 40.67 m, which may have probably represented the pre-temperate substage, was only poorly recovered. The recovery consists of 9 cm long section of greenish brown silty-clay containing a large quantity of chalk granules. The size of the chalk granules is relatively large, which may be the result of extensive erosion of coastal areas at a time of rising sea-level. This interpretation is supported by the dino cyst data from 40.67 m and 38.90 m (Fig. III.11).

A rapid increase in the total numbers of dino cysts is indicative of the onset of marine conditions. It seems possible that as sea-level continued to rise, extensive erosion caused an increase in sediment supply. These conditions would explain the low concentration of palynomorphs but with a high percentage of reworked and bisaccate types.

HoII (?39.20 - 38.00 m)

Early-temperate substage

The sequence between 39.20 m and 38.10 m represents the early-temperate substage of the Hoxnian temperate stage. Though this stage is represented by thermophilous trees such as *Quercus, Alnus, Taxus* and *Corylus,* poor pollen concentrations hamper interpretation.

Evidence from textural analysis suggests the onset of fairly stable marine conditions with the deposition of a higher proportion of fine sediment. However, it is probable that sea-level was continuing to rise and supplying high amounts of reworked pollen. The foraminiferal and dino cyst data for this phase are also unclear.

HoIII (38.00 - 30.75 m)

Late-temperate substage

The late-temperate substage is represented by the longest sequence of marine silty-clay between 38.00 m and 30.75 m. The vegetation of this substage is represented by established temperate forest of *Picea* and *Abies*. The evidence from the dino cysts and textural analysis suggests stable marine conditions to 31.53 m. Above this climate began to deteriorate as indicated by the pollen, foraminifera and dino cysts.

It is interesting to note that the frequency curve for *Abies* is reflected in the curves for the dino cysts *O. centrocarpum*, *Achomospaera andalousiensis* and *Protoperidinium* spp., and the forams *Bulimina marginata*, *Cassidulina laevigata* and *Nonion barleenum*. On the other hand, *Spiniferites* spp., *Cassidulina reniforme* and *Epistominella vitrea* appear to continue unaffected to the end of the amelioration. The peak of *A. andalousiensis* can be used to indicate the optimum phase of the amelioration.

HoIV (30.70 - 29.67 m)

Post-temperate substage

The silty-clay sequence between 29.67 m and 30.70 m constitutes the post-temperate substage of the interglacial cycle. That this substage is complete at this site is suggested by the curves for *Empetrum*, Gramineae, *Betula* and *Pinus*. The vegetation of this substage is dominated by herbaceous plants, particularly by *Empetrum* heath. The end of the temperate stage is marked by the curves for *Empetrum*, Gramineae and *Betula*, and perhaps most importantly, by *Artemisia*. This interpretation of the pollen data is quite well supported by the foraminiferal and dino cyst data.

III.17. Deposits of sand and gravel

The silty-clay sequence of the Hoxnian Sand Hole Formation is overlain by sand and gravel (Fig. III.3 & III.16). Tappin (1991), on the basis of seismic interpretation, has correlated these sand and gravel deposits with the Holsteinian (Hoxnian) interglacial of *Laban et al.* (1984) in the Dutch sector of the southern North Sea. Detailed pollen analyses of underlying Hoxnian silty-clay clearly indicate that Hoxnian (Holsteinian) interglacial ends at the top of the silty-clay of the Sand Hole Formation. This means that the pollen results conflict with Tappin's interpretation, and suggest that the Hoxnian interglacial stage is represented by only the Sand Hole Formation, and that his Egmond Ground Formation (Fig. III.1) cannot be correlated with the Egmond Ground Formation of Laban *et al.* (1984) in the Dutch sector.

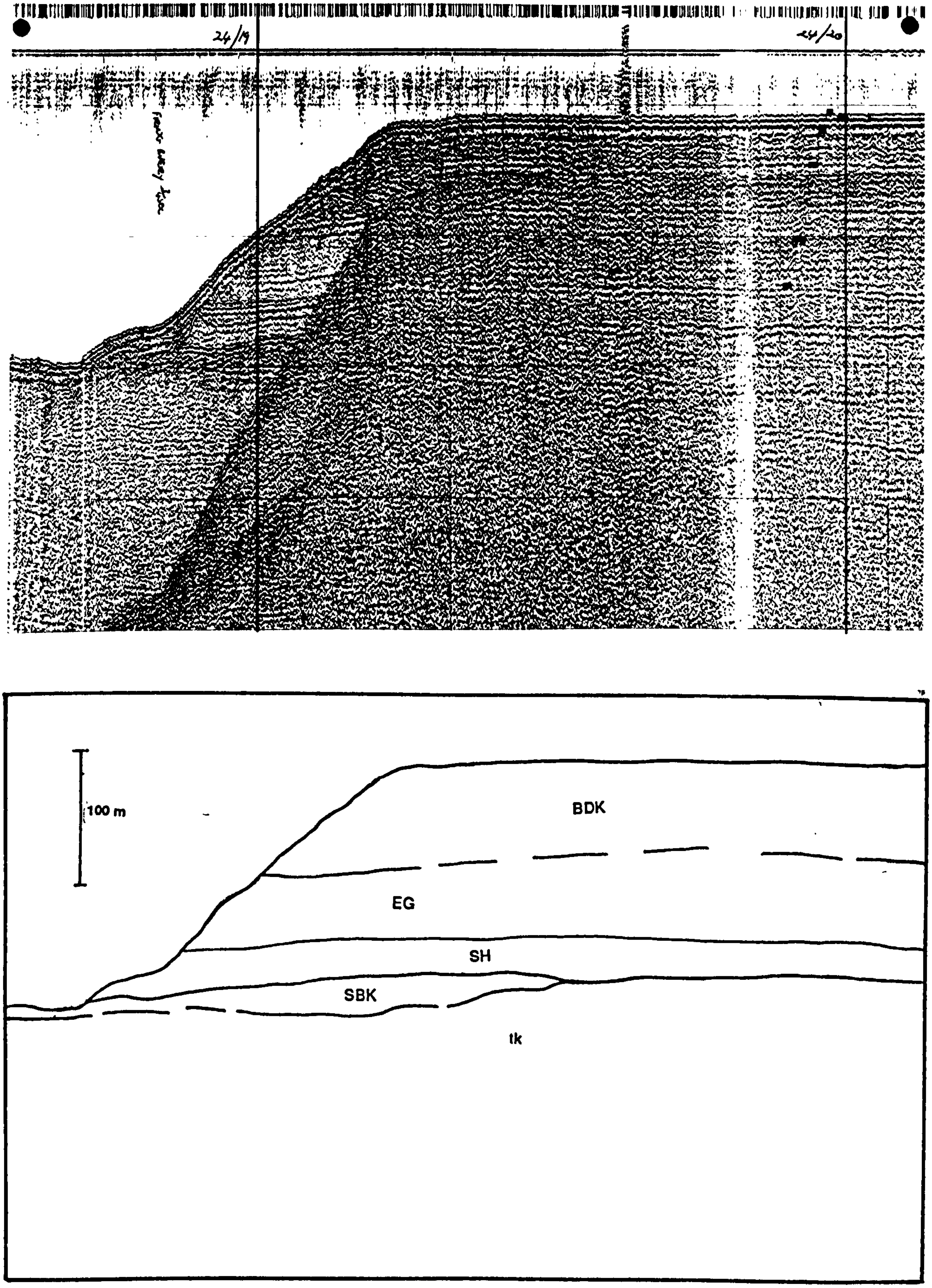


Fig. III.16. Seismic results showing the general relations of the sedimentary formations. A, Photograph of seismic record from sparker line BGS 81/02/24. B, Interpretation by Dr D.R. Tappin.

a) Note on the name of sand and gravel 'Egmond Ground Formation'

On the basis of seismic interpretation Tappin (1991) has correlated this sand and gravel with the Egmond Ground Formation of Laban *et al.* (1984) in the Dutch sector. He has assigned them the same name, the 'Egmond Ground Formation'. Tappin (1991) has correlated both the Sand Hole Formation and Egmond Ground Formation from the Inner Silver Pit with the Egmond Ground Formation of the Dutch sector (Fig. III.1.).

III.18. Conclusions

Borehole 81/52A in the vicinity of the Inner Silver Pit has been investigated in detail. A sequence between 29.67 m and 43.20 m which comprises 11 m of silty-clay and 2.53 m diamicton has been subjected to detailed palynological and textural analyses combined with organic matter and carbonate content determinations. Complementary data from dino cyst and foraminiferal analyses and seismic surveys have been kindly provided by the British Geological Survey (BGS).

Evidence from the above investigations enable the following conclusions:

1. During the Anglian glaciation the British ice sheet advanced from the northwest, covering the Spurn area of the southern North Sea.

2. This glacial event caused the formation of a shallow basin in the Inner Silver Pit area.

3. Till of Lowestoft facies was deposited in this basin, probably in the later half of the Anglian cold stage, followed by a phase of glacial marine sedimentation.

4. Overlying marine silty-clays contain a fairly complete depositional sequence representing the Hoxnian temperate stage. Substage HoI is absent (not recognisable due to low pollen concentrations or practically barren) and substage HoII is represented by only poorly-polleniferous sediments. However, substage HoIII and HoIV are represented by a richly polleniferous sequence which covers most of the silty-clay recovered.

5. The end of the temperate stage is recorded at the top of this silty-clay sequence.

6. The age of the overlying sands and gravels (Egmond Ground Formation of Tappin, 1991) remains unclear but nevertheless is demonstrateably post-Hoxnian.

CHAPTER IV

Vibrocores from the Inner Silver Pit
UK sector, southern North Sea

IV.1. Introduction

In order to establish the geologic and stratigraphic history of the Quaternary in the North Sea, seismic surveys have assumed a central role and constitute a basis for all subsequent work. The age and correlation of the identified seismic-stratigraphic units is based on micropalaeontological, palynological and amino-stratigraphic analyses (Cameron *et al.*, 1987). Samples for such investigations are generally taken from undisturbed cores recovered in boreholes.

However, drilling is very expensive, so many samples are taken from shallow cores, including gravity cores and vibrocores. These provide useful samples even though the depth of penetration is quite shallow and, carefully situated in relation to the outcrop pattern of the seismic-stratigraphic units, can provide critical data. These data also provide a basis for describing the lateral distribution of sedimentary units. Amongst many hundred vibrocores, the British Geological Survey has taken several vibrocores from the flanks of the Inner Silver Pit deep (Fig. III.2).

Nine vibrocores (Table IV.1) taken from the flanks of

Table IV.1. Detail about vibrocores examined from Inner Silver Pit.

CORE NUMBER	LATITUDE	LONGITUDE	A[1]	B[2]	C[3]	RESULT[4]
VE 53/00/961	53° 28.12′	00° 40.98′	43 m	0.54 m	0.15 m	-
VE 53/00/962	53° 28.34′	00° 40.77′	68 m	1.51 m	0.34 m	+
VE 53/00/963	53° 28.14′	00° 40.50′	84 m	1.27 m	0.31 m	-
VE 53/00/1101	53° 28.37′	00° 40.91′	78 m	4.90 m	0.07 m	-
VE 53/00/1102	53° 28.49′	00° 40.94′	82 m	5.81 m	0.16 m	-
VE 53/00/1103	53° 28.62′	00° 41.02′	68 m	3.11 m	0.17 m	+
VE 53/00/1104	53° 28.28′	00° 41.02′	54 m	2.60 m	0.16 m	+
VE 53/00/1105	53° 29.05′	00° 41.41′	34 m	SHOE	0.00	-
VE 53/00/1106	53° 28.94′	00° 41.49′	36 m	SHOE	0.00	-

[1] Water depth

[2] Silty-clay sediments

[3] Recent sediments

[4] - means non polleniferous sediments
+ Holsteinian (Hoxnian) age

the Inner Silver Pit were examined in the hope of establishing the lateral distribution of the interglacial deposits identified in borehole 81/52A. Well-spaced samples from these nine vibrocores were prepared for pollen analysis. The results showed that three of the nine vibrocores contained interglacial deposits similar to those found in the borehole (results in Table IV.1); these are vibrocores VE 53/00/962, VE 53/00/1103 and VE 53/00/1104. The locations of these vibrocores are shown on Fig. III.2 and longitudinal and latitudinal data are presented in Table IV.1.

IV.2. Methods

a) Pollen analysis

Pollen results of well-spaced samples from these three vibrocores showed few changes within each vibrocore. On the basis of these preliminary samples it was decided that a 20 cm sampling interval would provide enough stratigraphic detail.

b) Dinoflagellate cyst analysis

Although pollen data are very useful, they are largely representative of terrestrial conditions. In order to obtain information about changes in the marine environment dinoflagellate cysts were analysed. No separate sample preparation was undertaken for the dinoflagellate cyst analyses, and slides which were used for pollen counting were also used for dinoflagellate cyst counting. The dino cyst data proved to contain many more changes than the pollen data indicating fluctuations in marine conditions. In constructing the dino cyst diagrams only those levels which contained all five dinoflagellate species or groups defined by Harland (1988, Appendix II) have been included .

c) Loss-on-ignition

Samples for loss-on-ignition were taken every 10 cm. All the samples were combusted at 550 C° and 950 C° to provide data on the distribution of organic matter and carbonate content respectively (Dean, 1974).

d) Zonation of vibrocores

Results from the pollen analyses show that the silty-clay sequence penetrated in these three vibrocores represents different parts of the sequence recovered in borehole 81/52A. As they do not show many changes these pollen diagrams have not been divided into zones. However, the changes in the dino cyst assemblages have enabled these diagrams to be zoned. The data from the organic matter and carbonate content analyses are from a closer sampling interval and provide detailed information which enables the subdivision of the sequence.

IV.3. Results

a) Vibrocore 53/00/1103

i) Sediment description

0.0 - 0.17 m

Sands and gravel. Shells and flint cobbles at base.

0.18 - 3.28 m

Light olive-grey (5Y-6/2) silty-clay. Calcareous with sparse shell debris. Apparently structureless. There are no changes and the whole sequence of the vibrocore consists of similar sediments.

ii) Results from pollen analysis

Twelve samples from the sequence between 0.2 m and 3.0 m were prepared for pollen analysis. These samples produced rich and diverse pollen spectra dominated by tree pollen. The pollen assemblages do not show many changes and the relative frequencies (Figs. IV.1 & IV.2) remain almost unchanged throughout the sequence.

The pollen spectra are dominated by *Pinus* and *Abies* which show unchanged frequencies throughout the sequence. *Pinus* is well represented and varies between 63.86 % and 54.56 %; with a maximum of 67.73 % at 2.0 m. *Abies* is the subdominant tree taxon and ranges between 29.47 % and 21.24 %; but drops to a minimum of 17.73 % at 2.0 m. *Picea* is represented by insignificantly low values throughout the sequence. Other tree taxa include *Betula, Alnus, Taxus and Populus* but these are all represented by very low frequencies. *Corylus* is the only shrub and is represented by

PERCENTAGE POLLEN DIAGRAM
SITE VE 53/00/1103
INNER SILVER PIT, SOUTHERN NORTH SEA

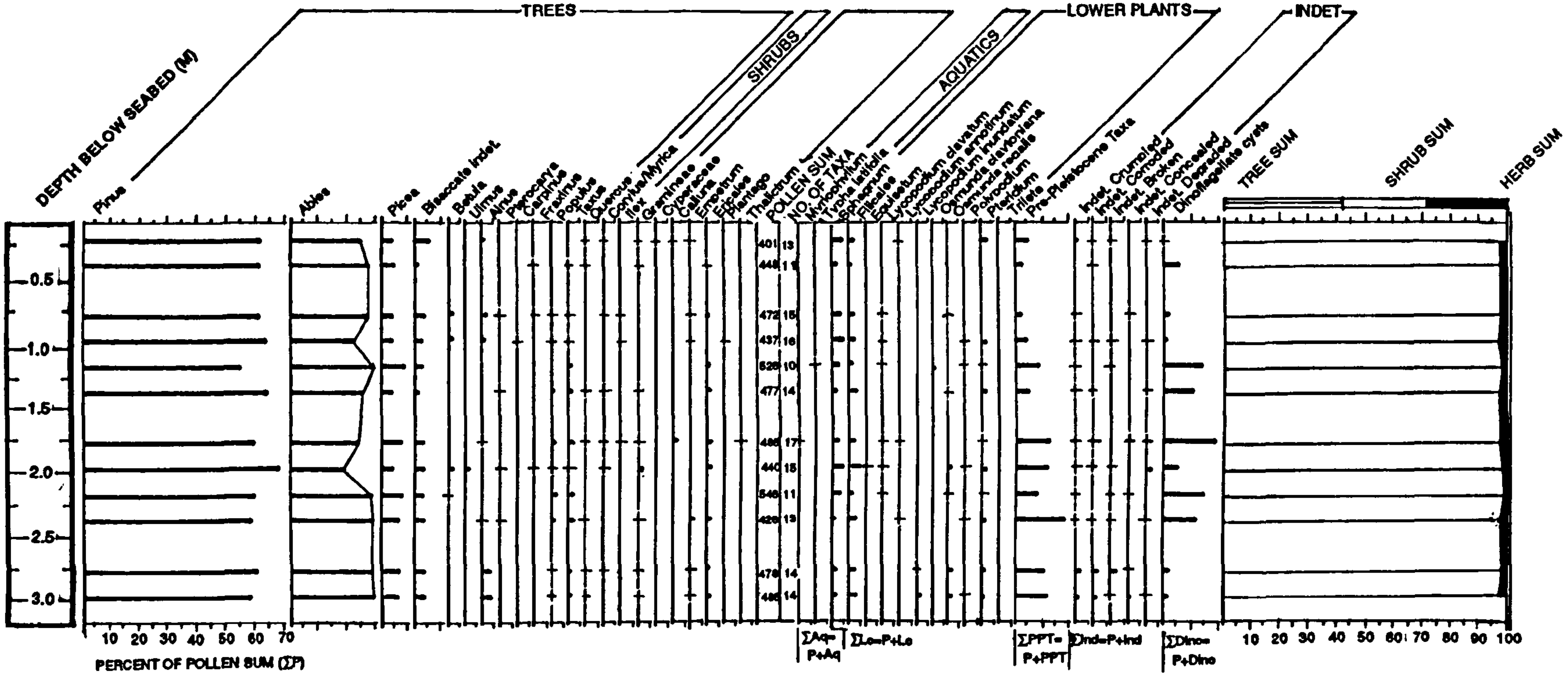


Fig. IV.1. Results of the palynological analysis from the VE 53/00/1103, Inner Silver Pit, southern North Sea. Analysed by M.H. Ansari, 1990.

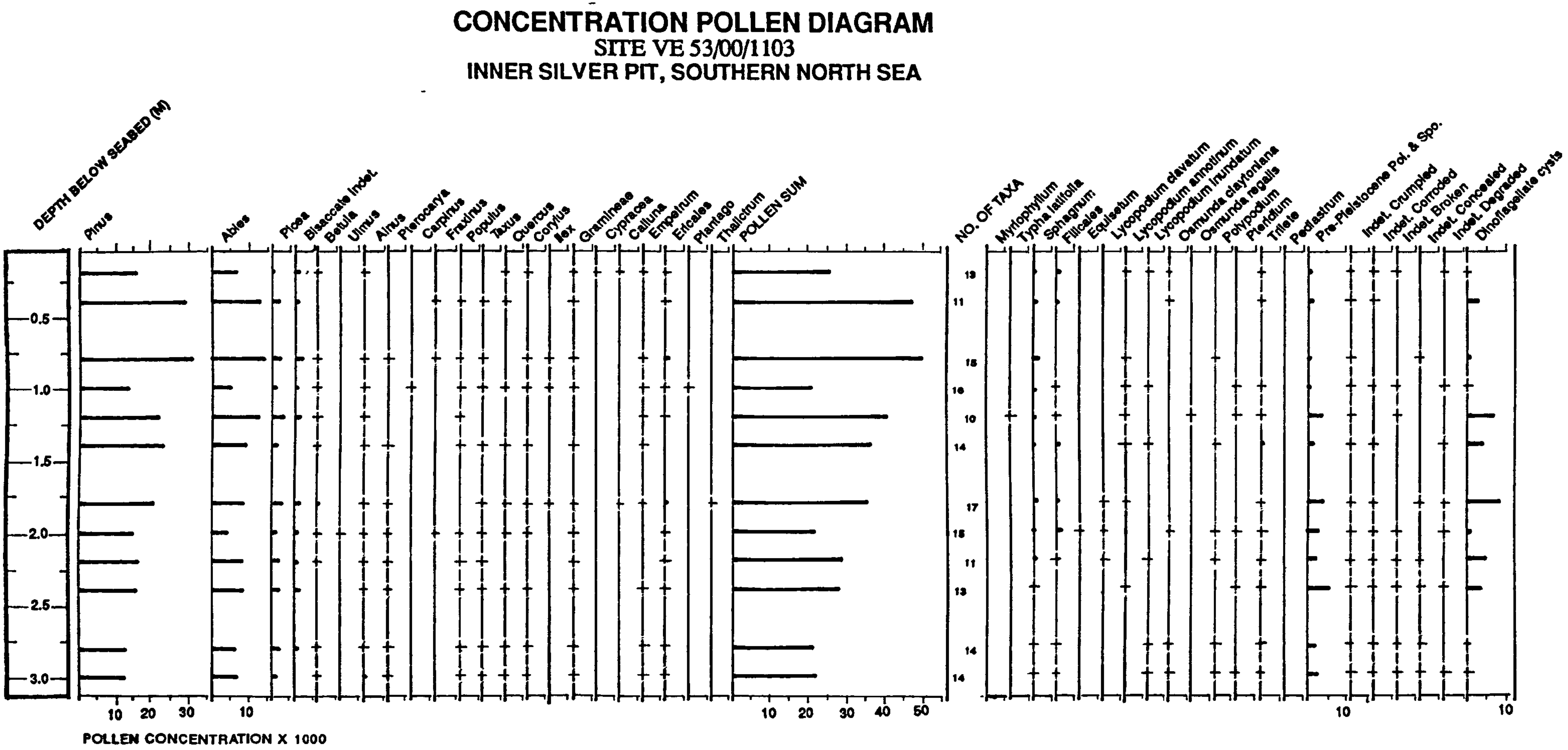


Fig. IV.2. Concentration pollen diagram of the palynological analysis from VE 53/00/1103, Inner Silver Pit, southern North Sea.

very low values throughout the sequence.

A varied assemblage of herbaceous taxa is present dominated by Ericales, *Calluna, Empetrum, Ranunculus, Thalictrum,* Cyperaceae and Gramineae. All these taxa are very low in frequency and not significant.

Though aquatic representatives are almost absent, a varied assemblage of spores is present, dominated by *Sphagnum* and Filicales. Other important spores include *Osmunda, Polypodium,* and *Equisetum* and various species of *Lycopodium.* The trilete group represents a category which includes all indeterminable spores.

A) Interpretation of pollen diagram

The pollen diagram reveals a vegetation dominated by *Pinus* and *Abies.* Very high percentages of *Pinus* are often characteristic of boreal climates. However, the presence of *Abies* indicates that the diagram represents a period of temperate climate. The high percentages for *Pinus* can be explained as follows:

1. Boreal climate vegetation dominated by *Pinus* usually also includes *Betula* and various taxa of non-tree species in which the most important is Gramineae.

2. The pollen diagram of borehole 81/52A (Fig. III.7), which includes high frequencies for *Abies,* indicates that this sequences is representative of

a temperate rather than boreal climate.

3. This pollen diagram is derived from marine sediments containing pollen originating from adjacent land areas. A major transportation mechanism is therefore water in which bisaccate pollen are over-represented. The pollen of *Pinus* is often found to be over-represented in such situations (see taphonomy in section III.8,b,i, above).

On the basis of comparison of this pollen diagram with the pollen diagrams of borehole 81/52A and from Marks Tey (Turner, 1970; Fig. I.11) it is possible to assign this sequence to the late-temperate substage of the Hoxnian temperate stage, and to interpret the high percentages of *Pinus* as the result of transportation over-representation.

iii) Dinoflagellate cyst analysis

Seven of the twelve levels used for pollen counting were found to contain sufficient dino cysts for analysis. Results from these seven samples (Fig.IV.3) enable the sequence to be divided into three parts, in which the upper and lower parts are characterised by lower dino cyst concentrations. Generally the samples contained a rich and diverse dino cyst flora dominated by various species of *Spiniferites*. Species of *Spiniferites* show high and fairly

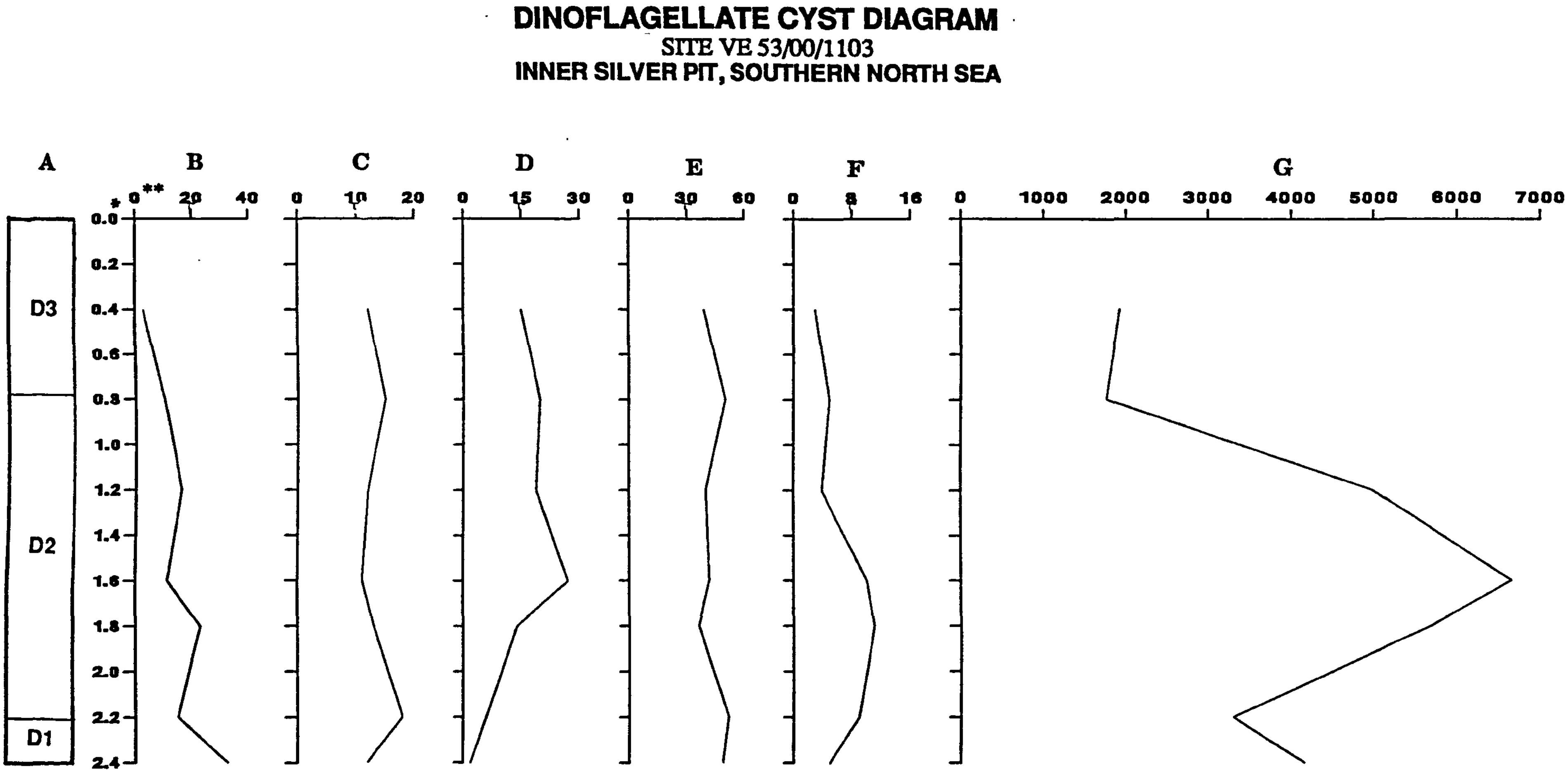


Fig. IV.3. Dinoflagellate cyst biostratigraphy from the VE 53/00/1103, Inner Silver Pit, southern North Sea. A, Dino cyst zones. B, *Operculina centrocarpum* (Deflandre and Cookson) Wall. C, *Bitectatodinium tepikiense* Wilson. D, *Achomosphaera andalousiensis* Jan du Chene. E, *Spiniferites* cysts. F, *Protoperidinium* cysts. G, Cysts/Slide. *, Depth below seabed (M). **, Percent of total cysts.

constant frequencies ranging between 36 % and 52 %. The frequency curve for *Bitectatodinium tepikiense* shows a similar pattern. Although the frequency changes for *Operculina centrocarpum* are also small, the abundance of these species decreases towards the bottom of the sequence. *Achomosphaera andalousiensis* shows quite low values at the base and increases upwards. At 1.6 m its value increases quite sharply and remains high despite a slight decrease towards the top. Changes in the curve of the total cyst enable the possible division of the sequence into three parts.

A) Palaeoecological note on dinoflagellate cysts

As in borehole 81/52A these vibrocores provide rich and diverse dino cysts assemblages which indicate temperate marine conditions. Dino cyst spectra dominated by a high proportion of *Spiniferites* spp. and *O. centrocarpum* indicate amelioration. As in the borehole this vibrocore also shows considerable proportion of *Bitectatodinium tepikiense* which is representative of cool conditions or deterioration. The presence of *B. tepikiense* here, however is not indicative of cool conditions but rather lowered salinities (cf. Austin, 1991b; also see chapter III).

iv) Zones of VE 53/00/1103

Zonation of this vibrocore has been summarised in Fig.IV.4. On the basis of pollen analysis the sequence can be correlated with the pollen diagrams from Marks Tey (Fig.

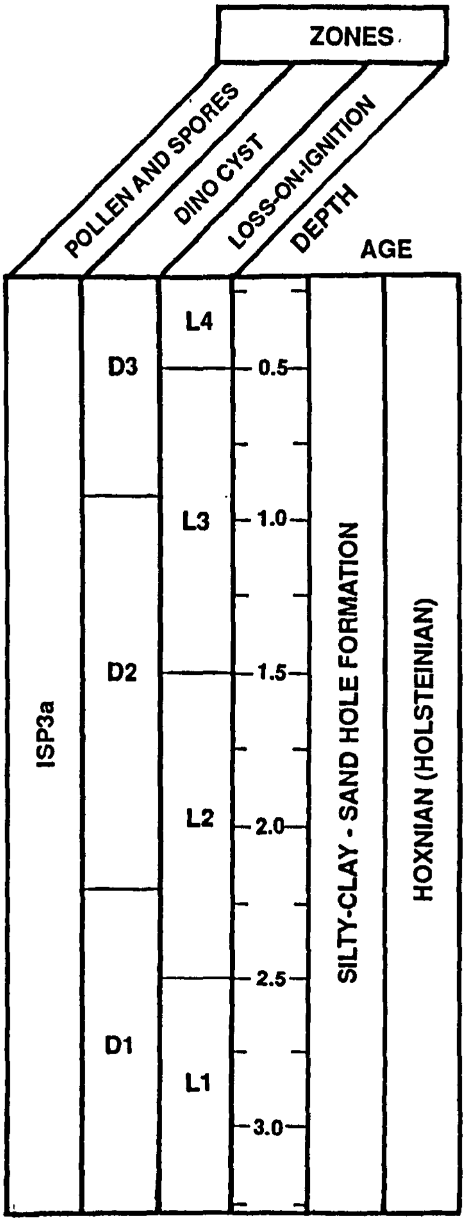


Fig. IV.4. Summary of results from the VE 53/00/1103, Inner Silver Pit, southern North Sea.

I.11) and borehole 81/52A (Fig. III.7). Pollen data suggest that this sequence provides a longer and better quality record of subzone ISP3a than BH 81/52A (see section IV.3,a,i, below for detail). Although the pollen assemblages fall within a single zone, the dino cyst data enables the division of this sequence into three zones, D1, D2 and D3. The organic matter and carbonate content distribution (Fig.IV.5) provides data enabling a division into four rather that three zones.

b) Vibrocore 53/00/962

i) Sediment description

0.0 - 0.34 m

Light brownish gravelly-sand. Rich in shells and plant debris particularly towards sea-bed. Several complete *Mytilus* shells present.

0.35 - 1.85 m

Dark greenish-grey (5G 4/1) silt-clay. Very stiff and calcareous with faint traces of lamination.

ii) Results from pollen analysis

Seven samples taken from the sequence between 0.6 m and 1.8 m were prepared for pollen analysis, and yielded rich pollen assemblages dominated by *Abies* and *Pinus* (Figs. IV.6 & IV.7). *Abies* is very high, ranging between 54.6 % and 37.6 % at 0.6 m and 1.6 m respectively. *Pinus* is well

LOSS-ON-IGNITION
SITE VE 53/00/1103
INNER SILVER PIT, SOUTHERN NORTH SEA

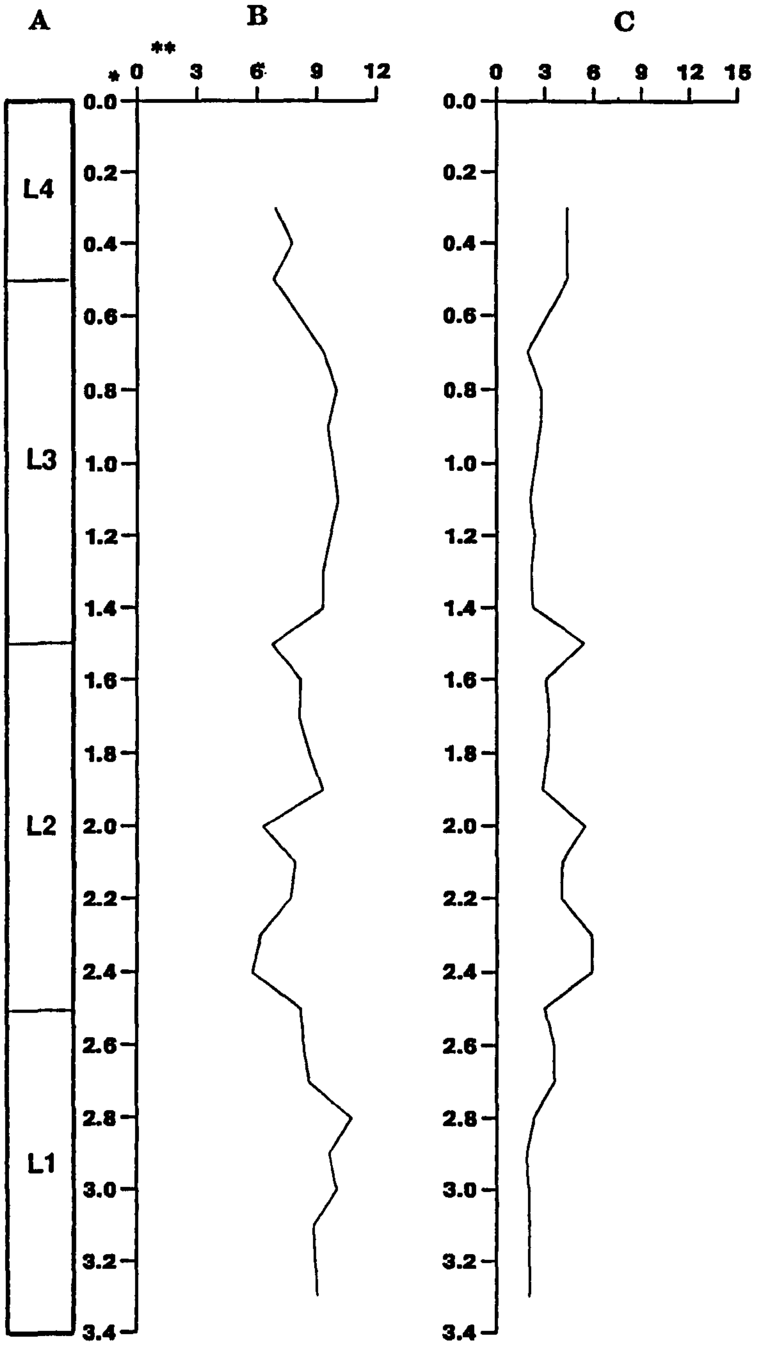


Fig. IV.5. Results of the loss-on-ignition from the VE 53/00/1103, Inner Silver Pit, southern North Sea. A, Zones. B, Organic content. C, Carbonate content. *, Depth below seabed (M). **, Percent of dri sample weight.

represented. Its curve can be divided into two parts, the upper one range between 37.93 % and 42.35 % and the lower one which ranges between 47.95 % and 51.20 %. *Picea, Alnus* and *Quercus* are also present in very low quantities. Other minor tree taxa include *Betula, Populus* and *Taxus*. *Corylus* is present at low values throughout the sequence.

A varied herbaceous assemblage is present including Gramineae, *Empetrum*, Ericales, Compositae, Chenopodiacea, *Plantago* and *Umbelliferae*. Frequencies for all these taxa are very low.

A) Interpretation of pollen diagram

The vegetational composition revealed by the pollen diagram, VE 53/00/962, suggests forest domination by *Abies* and *Pinus*. This pollen diagram presents a pollen assemblage quite similar to that found in vibrocore 53/00/1103. The main difference is the dominance of *Abies* over *Pinus*. Comparison of this pollen assemblage with the pollen diagrams from Marks Tey (Fig. I.11) and borehole 81/52A (Fig. III.7) suggests that this pollen diagram represents the late-temperate substage of the Hoxnian interglacial. This vibrocore therefore represents a younger sequence than that found in vibrocore VE 53/00/1103.

iii) Dinoflagellate cyst analysis

This vibrocore proved to contain the richest dino cyst record of the three vibrocores. Six out of the seven samples were found to be useful for dino cysts analysis. The samples

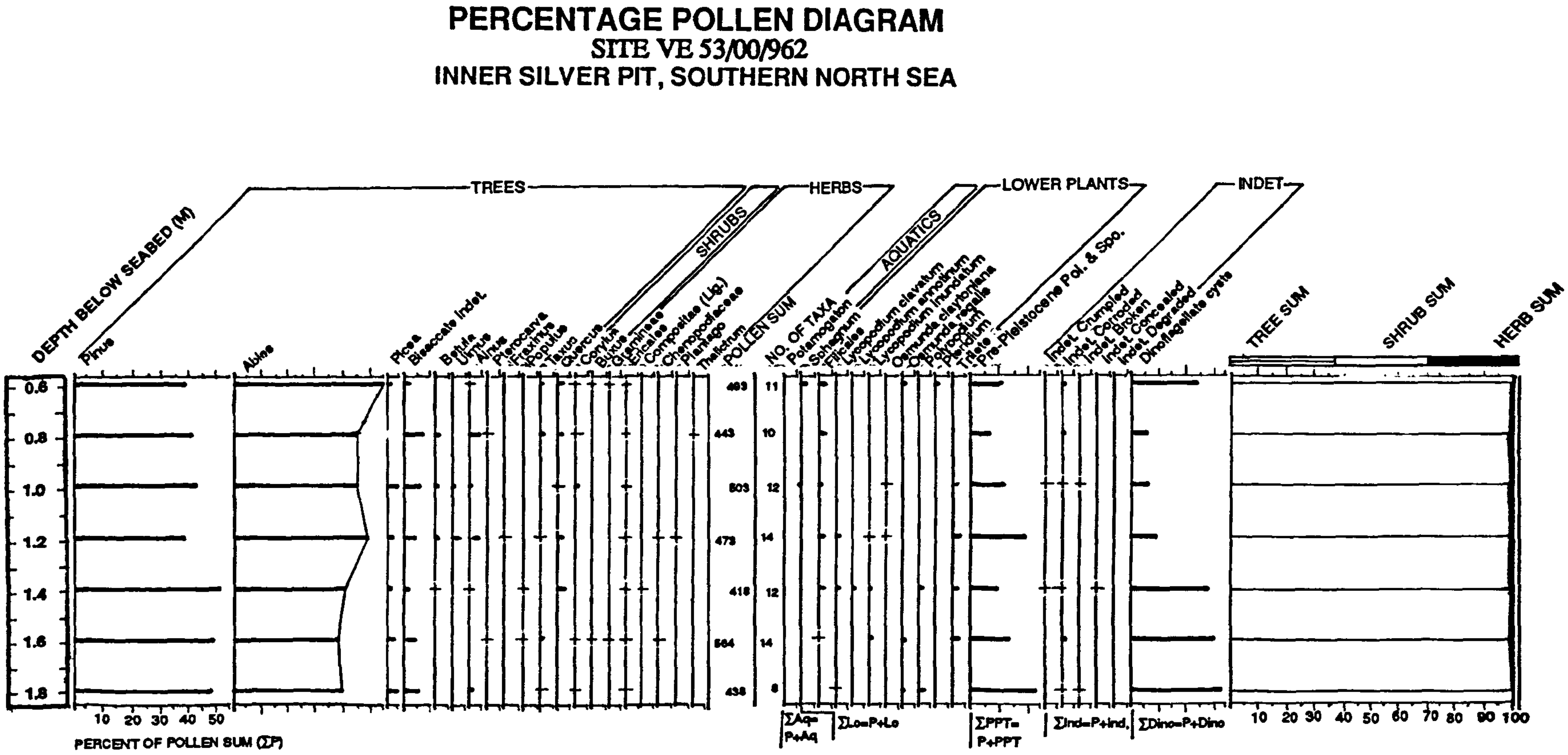
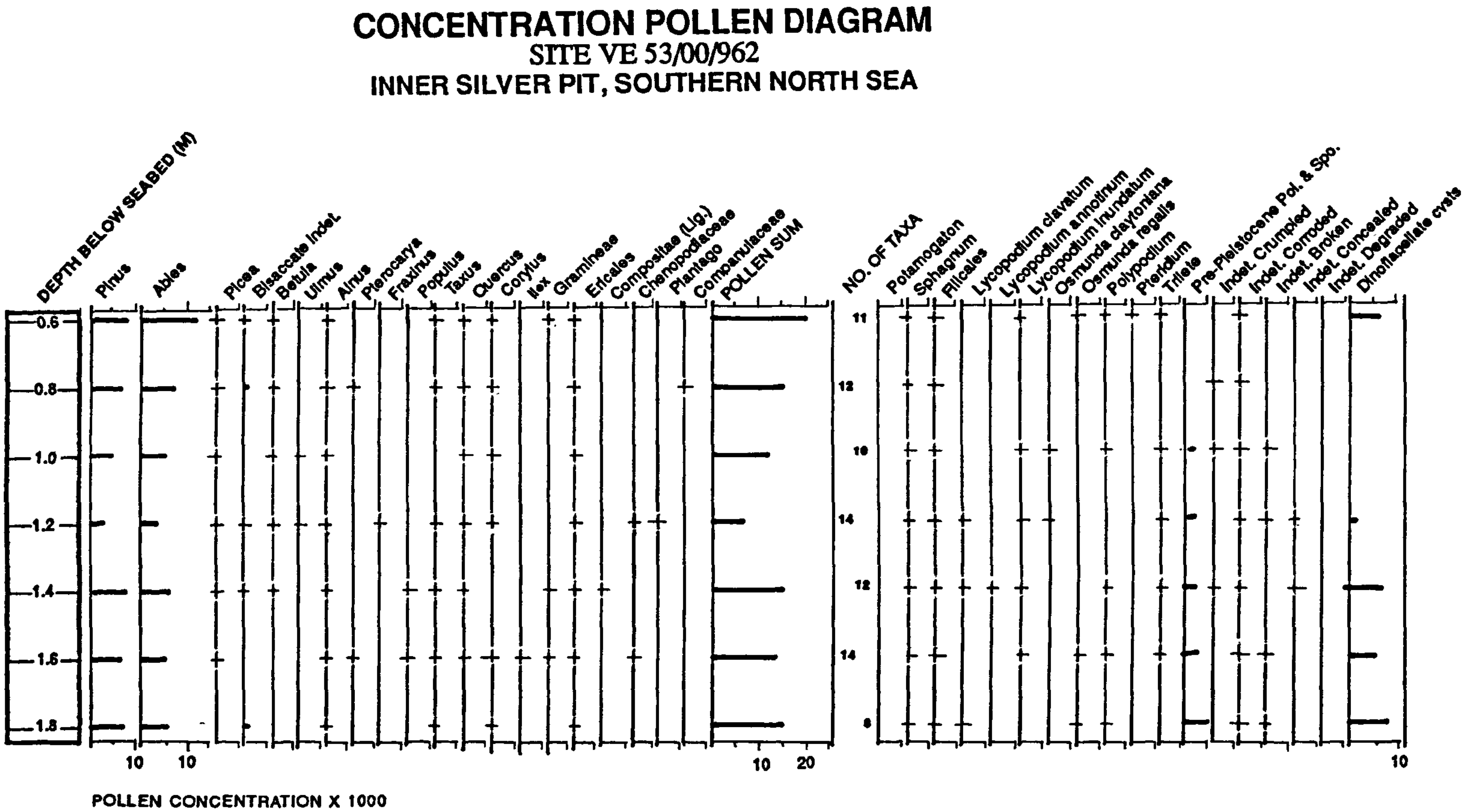


Fig. IV.6. Results of the palynological analysis from the VE 53/00/962, Inner Silver Pit, southern North Sea. Analysed by M.H. Ansari, 1990.



CONCENTRATION POLLEN DIAGRAM
SITE VE 53/00/962
INNER SILVER PIT, SOUTHERN NORTH SEA

Fig. IV.7. Concentration pollen diagram of the palynological analysis from VE 53/00/962, Inner Silver Pit, southern North Sea.

from 0.6 m, 1.6 m and 1.8 m show concentrations of over 5000 cysts per gram (Fig.IV.8). The curve for total dino cysts indicates a fluctuation in environmental conditions between 0.8 m and 1.2 m. The dino cyst assemblage is dominated by a high proportion of *Spiniferites*, and their curve follows the trend for total dino cysts.

iv) Zones of VE 53/00/962

Correlation of this vibrocore with the pollen diagrams from Marks Tey (Fig. I.11) and borehole 81/52A (Fig. III.7) is fairly straightforward. Like VE 53/00/1103, the pollen data fall into a single zone. Results from the dino cyst assemblage, however, enable the division of the sequence into three zones (Fig. IV.9). Organic matter and carbonate content determinations (Fig. IV.10) have enabled division of the sequence into four zones, L1, L2, L3 and L4 in ascending order. Zonation of this vibrocore is presented in Fig. IV.9.

c) Vibrocore 53/00/1104

i) Sediment description

0.0 - 0.16 m

Sands, gravel and cobbles.

0.17 - 2.76 m

Silty-clay, greenish-brown (5Y 4.5/1). Very stiff, slightly calcareous with scattered shell debris, chalk and

DINOFLAGELLATE CYST DIAGRAM
SITE VE 53/00/962
INNER SILVER PIT, SOUTHERN NORTH SEA

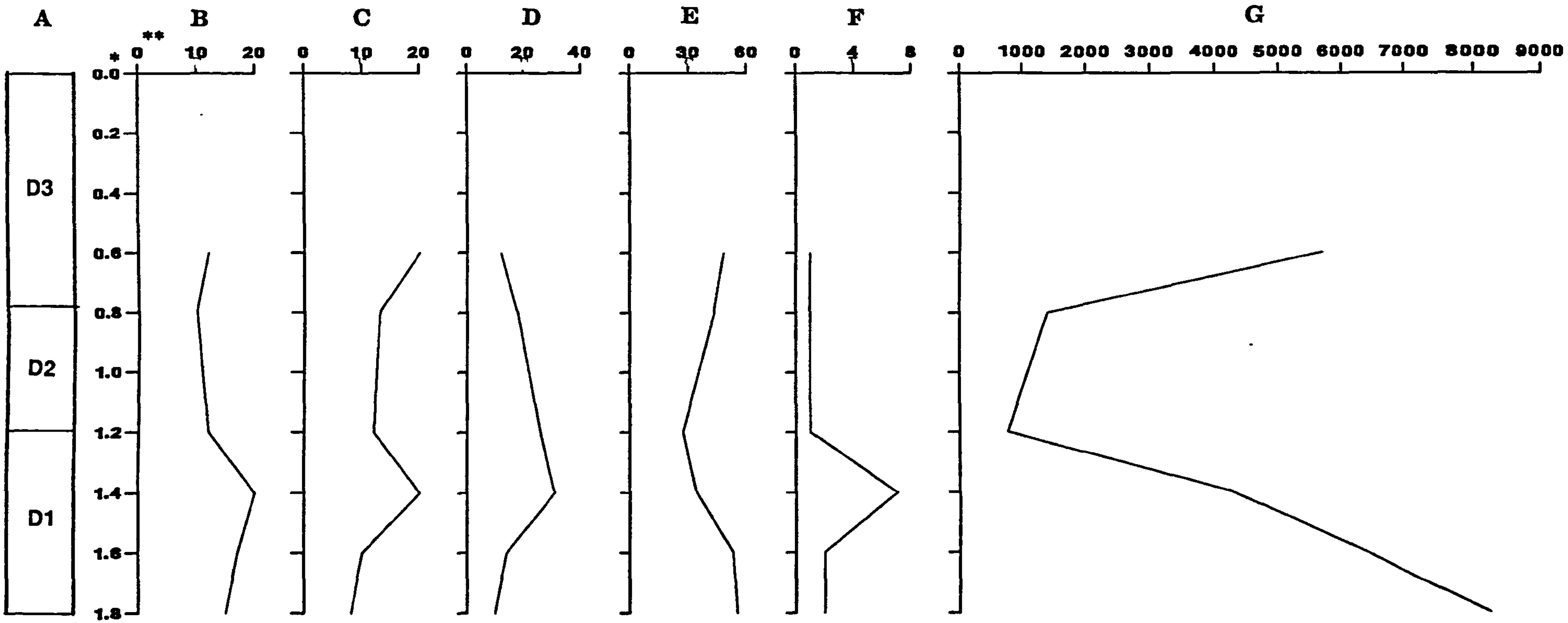


Fig. IV.8. Dinoflagellate cyst biostratigraphy from the VE 53/00/962, Inner Silver Pit, southern North Sea. A, Dino cyst zones. B, *Operculina centrocarpum* (Deflandre and Cookson) Wall. C, *Bitectatodinium tepikiense* Wilson. D, *Achomosphaera andalousiensis* Jan du Chene. E, *Spiniferites* cysts. F, *Protoperidinium* cysts. G, Cysts/Slide. *, Depth below seabed (M). **, Percent of total cysts.

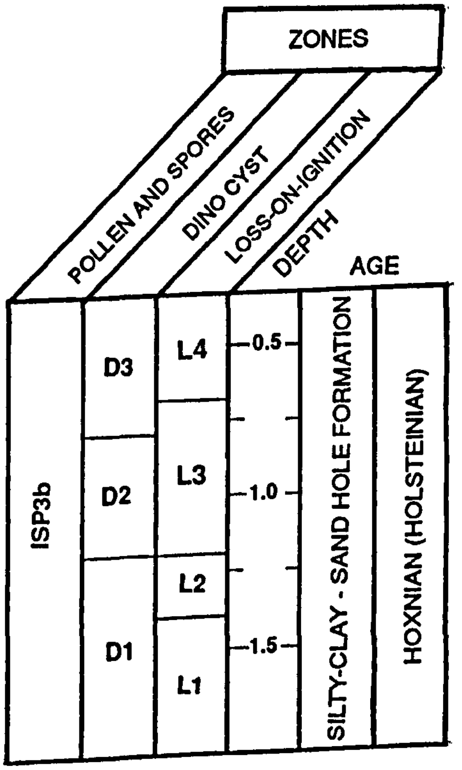


Fig. IV.9. Summary of results from the VE 53/00/962, Inner Silver Pit, southern North Sea.

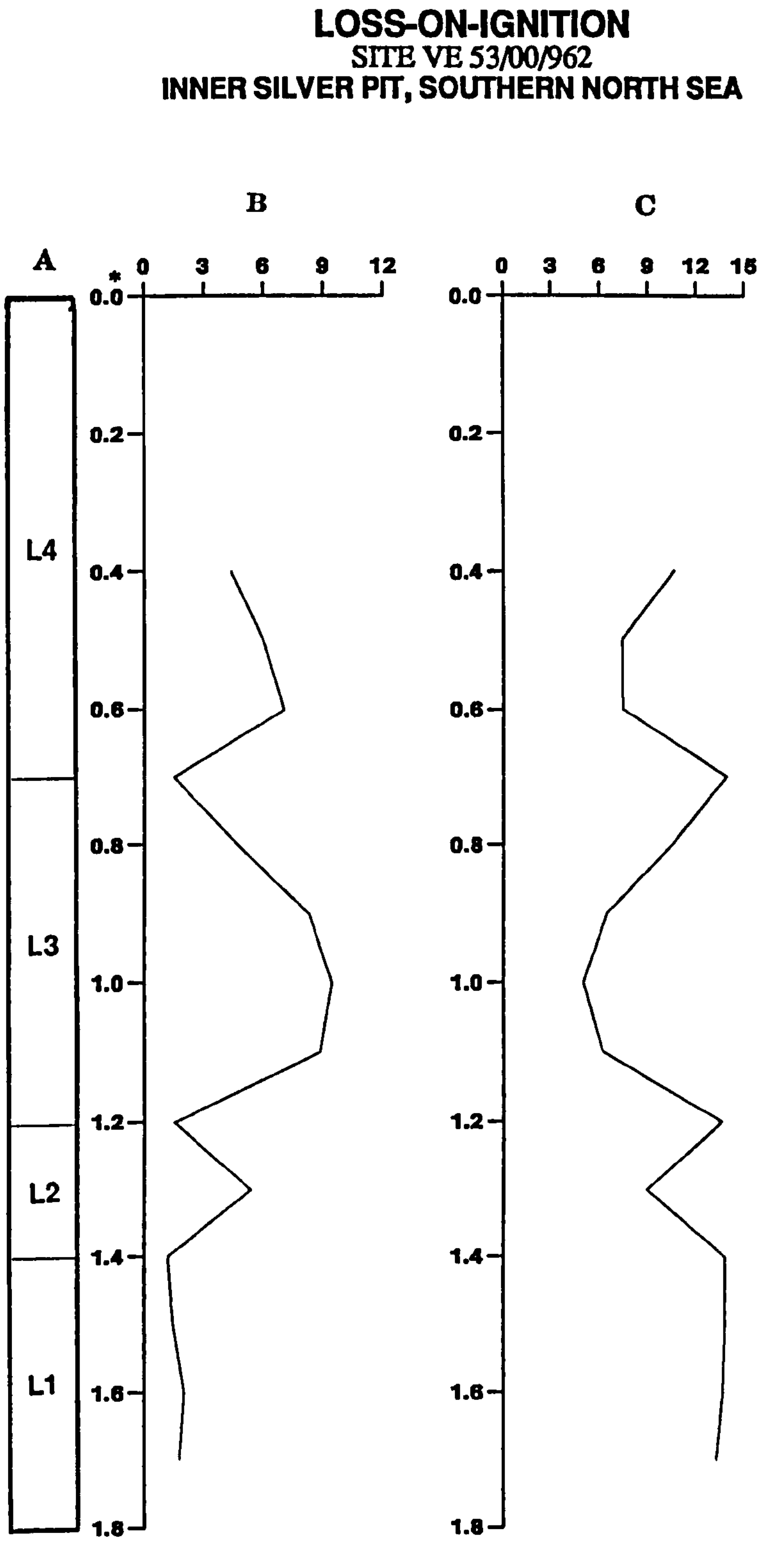

LOSS-ON-IGNITION
SITE VE 53/00/962
INNER SILVER PIT, SOUTHERN NORTH SEA

Fig. IV.10. Results of the loss-on-ignition from the VE 53/00/962, Inner Silver Pit, southern North Sea. A, Zones. B, Organic content. C, Carbonate content. *, Depth below seabed (M). **, Percent of dried sample weight.

ferruginous granules. No visible structures except bioturbation.

ii) Results from pollen analysis

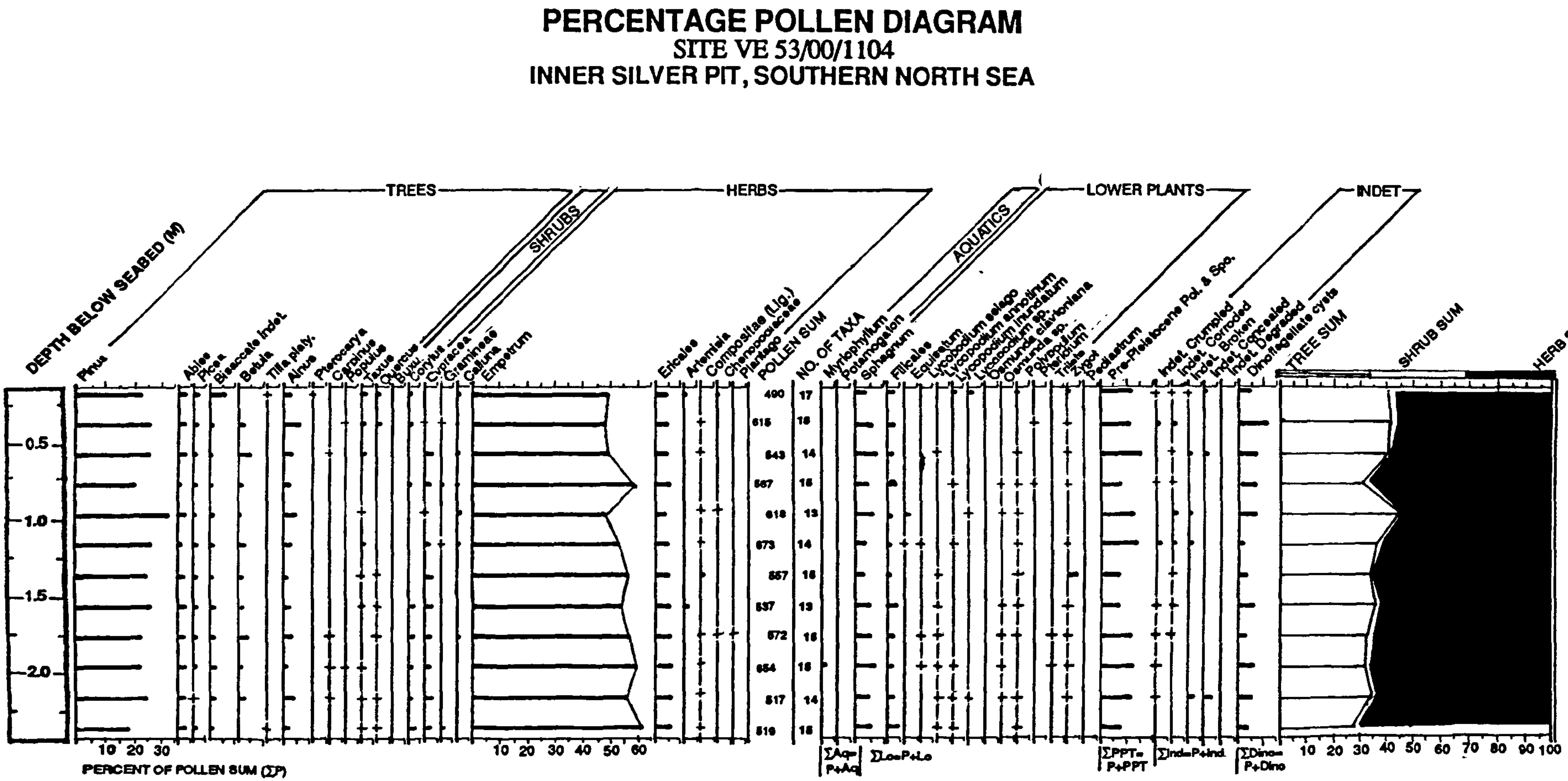
Twelve samples from the sequence between 0.2 m and 2.4 m were prepared for pollen analysis. These have yielded pollen spectra dominated by *Empetrum* and *Pinus* (Fig.IV.11 & 12), quite unlike the other two vibrocores. Other important taxa, though not dominant, include Gramineae, *Betula, Alnus, Abies* and *Picea*.

The pollen diagram is dominated by non-tree pollen such as *Empetrum* which is represented by very high frequencies ranging between 61.9 % at 2.4 m and 48.1 % at 1.0 m. The subdominant herb taxon is Gramineae which shows very low frequencies. Other herbaceous taxa include *Artemisia*, Compositae, Chenopodiaceae and *Plantago*, all represented by very low values.

Corylus is the only shrub representative and aquatic plants are represented by *Myriophyllum*. A varied assemblage of spores is present amongst which *Sphagnum* and Filicales dominate whilst *Osmunda (*O. regalis*), Polypodium* and various species of *Lycopodium* are represented by very low values. Trilete spores constitute a category which includes all indeterminable spores.

A) Interpretation of the pollen diagram

The pollen diagram of this vibrocore represents vegetation very different from the previous two vibrocores.



PERCENTAGE POLLEN DIAGRAM
SITE VE 53/00/1104
INNER SILVER PIT, SOUTHERN NORTH SEA

Fig. IV.11. Results of the palynological analysis from the VE 53/00/1104, Inner Silver Pit, southern North Sea. Analysed by M.H. Ansari, 1990.

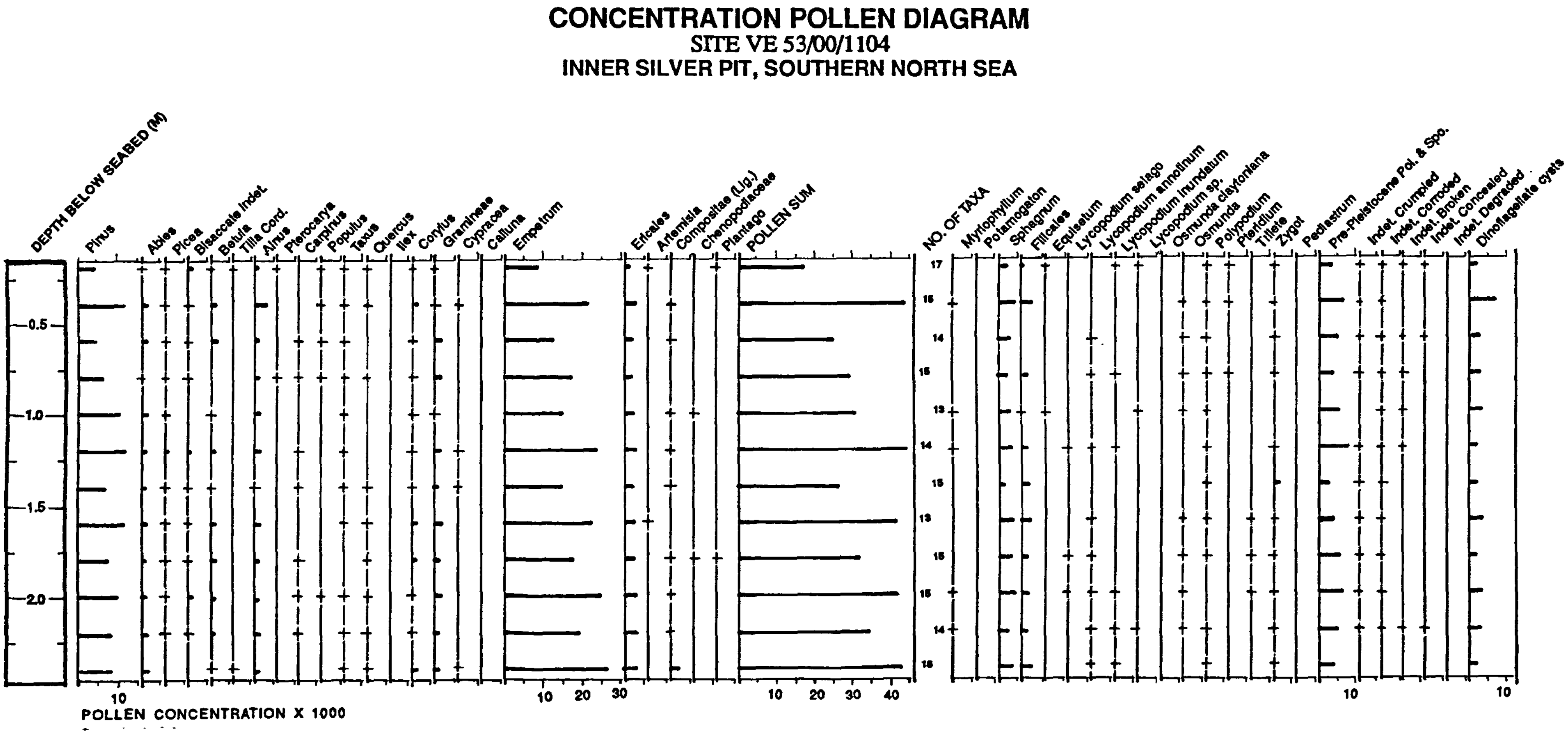


Fig. IV.12. Concentration pollen diagram of the palynological analysis from VE 53/00/1104, Inner Silver Pit, southern North Sea.

The vegetation indicated by this pollen diagram is exclusively dominated by non-tree herbaceous communities rather than forest. This suggests that the diagram is representative of the post-temperate substage of the Hoxnian interglacial, on the basis of the following points:

1. The vegetation of herbaceous communities is representative of either the pre- or post-temperate substages of the interglacial.

2. The diagram shows the dominance of *Empetrum* heath. This distinguishes the post-temperate vegetation from the pre-temperate vegetation of the Hoxnian stage.

Comparison of this pollen diagram (VE 53/00/1104) with the pollen diagrams from borehole 81/52A (Fig. III.7) and Marks Tey (Fig. I.11) suggests that this pollen assemblage represents the post-temperate substage of the Hoxnian.

It is interesting to note that Gramineae does not show any increase in frequencies, and towards at the top *Alnus* slightly increases. This suggests that the pollen diagram represents the central part of the post-temperate substage and that it does not extend to the end of the substage.

iii) Results from dino cyst analysis

This vibrocore has not provided a good dino cyst record

(Fig.IV.13). Only five of the samples from the twelve used for pollen counting contained a rich dino cyst flora. Furthermore only one of the samples contained over 4,000 cysts per gram and the other four contain less than 4,000 cysts per gram. As in the other vibrocores the dino cyst assemblage of this vibrocore is dominated by a high proportion of *Spiniferites* spp.

The substage represented by this vibrocore constitutes the regressive phase of the sea-level cycle associated with a deterioration in climate. In the borehole this situation is clearly indicated by lower number of dino cysts. The curve for total dino cysts is not followed by any particular species even including *Spiniferites* spp.. The total dino cyst curve shows climatic deterioration above 2.2 m.

iv) Zones of VE 53/00/1104

As in VE 53/00/1003 and VE 53/00/962 the pollen assemblage of this vibrocore is representative of a single zone. However, the dino cyst data enable the sequence to be divided into three zones. The organic matter and carbonate content data also suggest division into three zones but with different boundary levels (Fig. IV.15). The zones based on these parameters are summarised in Fig. IV.14.

IV.4. Discussion

a) Correlation with borehole BH 81/52A

Comparison of the pollen diagram from borehole 81/52A

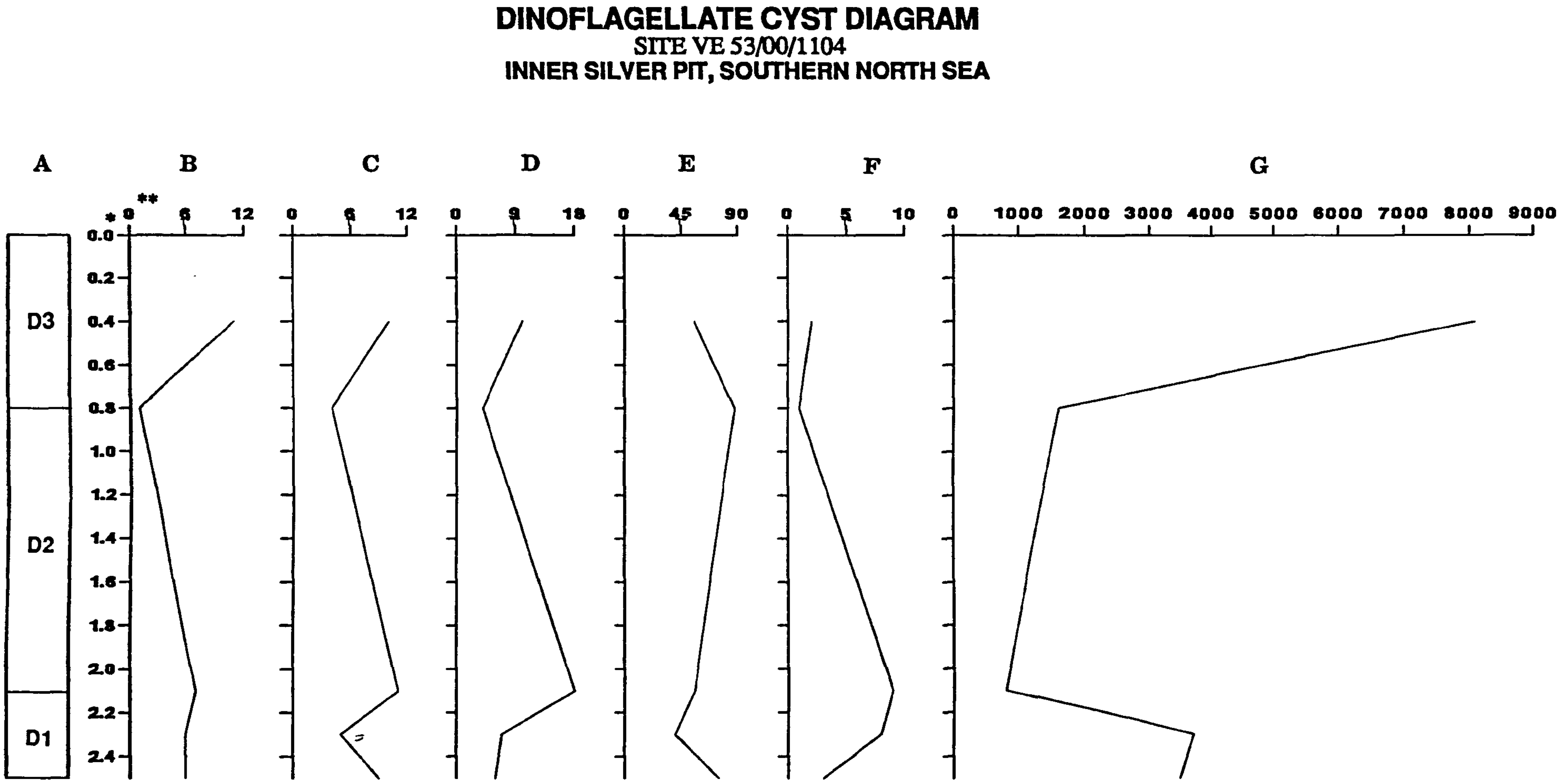


Fig. IV.13. Dinoflagellate cyst biostratigraphy from the VE 53/00/1104, Inner Silver Pit, southern North Sea. A, Dino cyst zones. B, *Operculina centrocarpum* (Deflandre and Cookson) Wall. C, *Bitectatodinium tepikiense* Wilson. D, *Achomosphaera andalousiensis* Jan du Chene. E, *Spiniferites* cysts. F, *Protoperidinium* cysts. G, Cysts/Slide. *, Depth below seabed (M). **, Percent of total cysts.

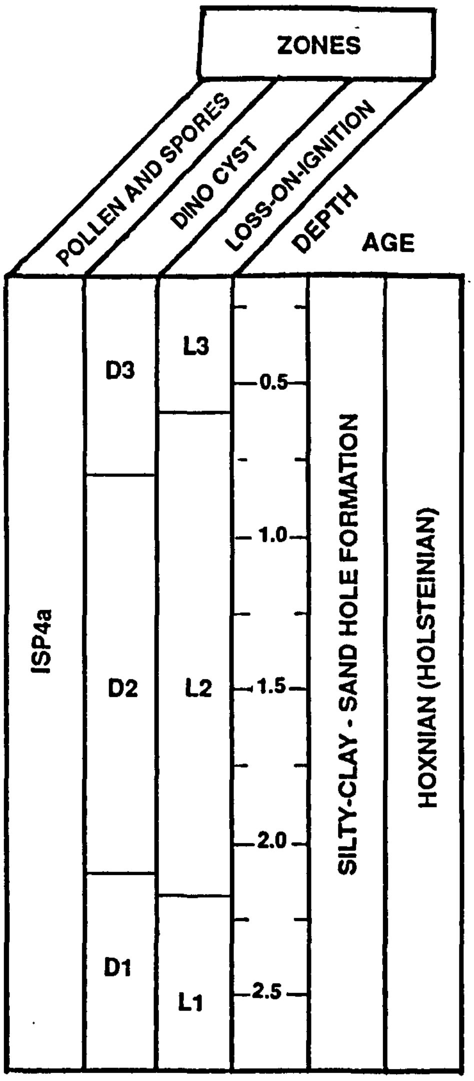


Fig. IV.14. Summary of results from the VE 53/00/1104, Inner Silver Pit, southern North Sea.

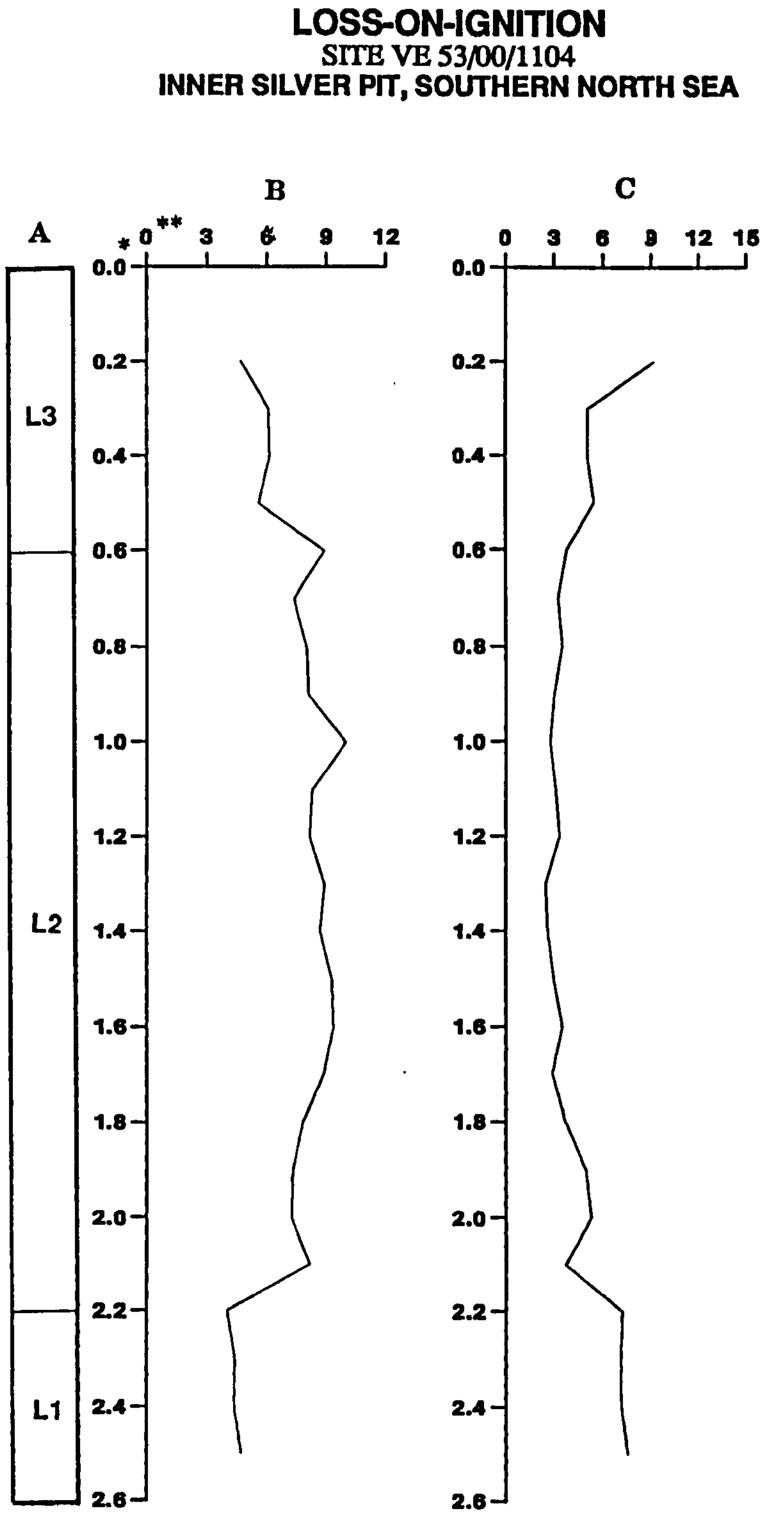


Fig. IV.15 Results of the loss-on-ignition from the VE 53/00/1104, Inner Silver Pit, southern North Sea. A, Zones. B, Organic content. C, Carbonate content. *, Depth below seabed (M). **, Percent of dried sample weight.

and these three vibrocores suggests that these vibrocores represent the same temperate stage. Correlation is particularly good between 81/52A and vibrocores VE 53/00962 and VE 53/001104.

Correlation between the pollen diagrams from Marks Tey (Fig. I.11), borehole 81/52A (Fig. III.7) and these vibrocores (Fig. IV.1, 6 & 11) is also very convincing (discussed below). The pollen diagrams of these vibrocores are images of particular parts of the pollen diagram of the borehole (Fig. IV.16). This correlation suggests that vibrocore VE 53/00/1103 can be chronologically assigned as the oldest and VE 53/00/1104 as the youngest among the three vibrocores. According to water depth they follow a trend from deep to shallow water.

i) VE 53/00/1103 and BH 81/52A

The pollen diagram of VE 53/00/1103 very clearly represents the late-temperate substage of an interglacial cycle. In 81/52A this substage has been divided into two pollen assemblage zones, ISP2 and ISP3. Zone ISP3 has been subdivided into three subzones a, b and c (ISP3a, ISP3b and ISP3c) in ascending order. Subzone ISP3b is quite distinct and is represented by very high values for *Abies*, higher than *Pinus*, whereas ISP3a and ISP3c are also represented by high percentages for *Abies* but which are lower than the frequencies of *Pinus*. These two subzones are therefore based on the increasing and decreasing values for *Abies*. Though

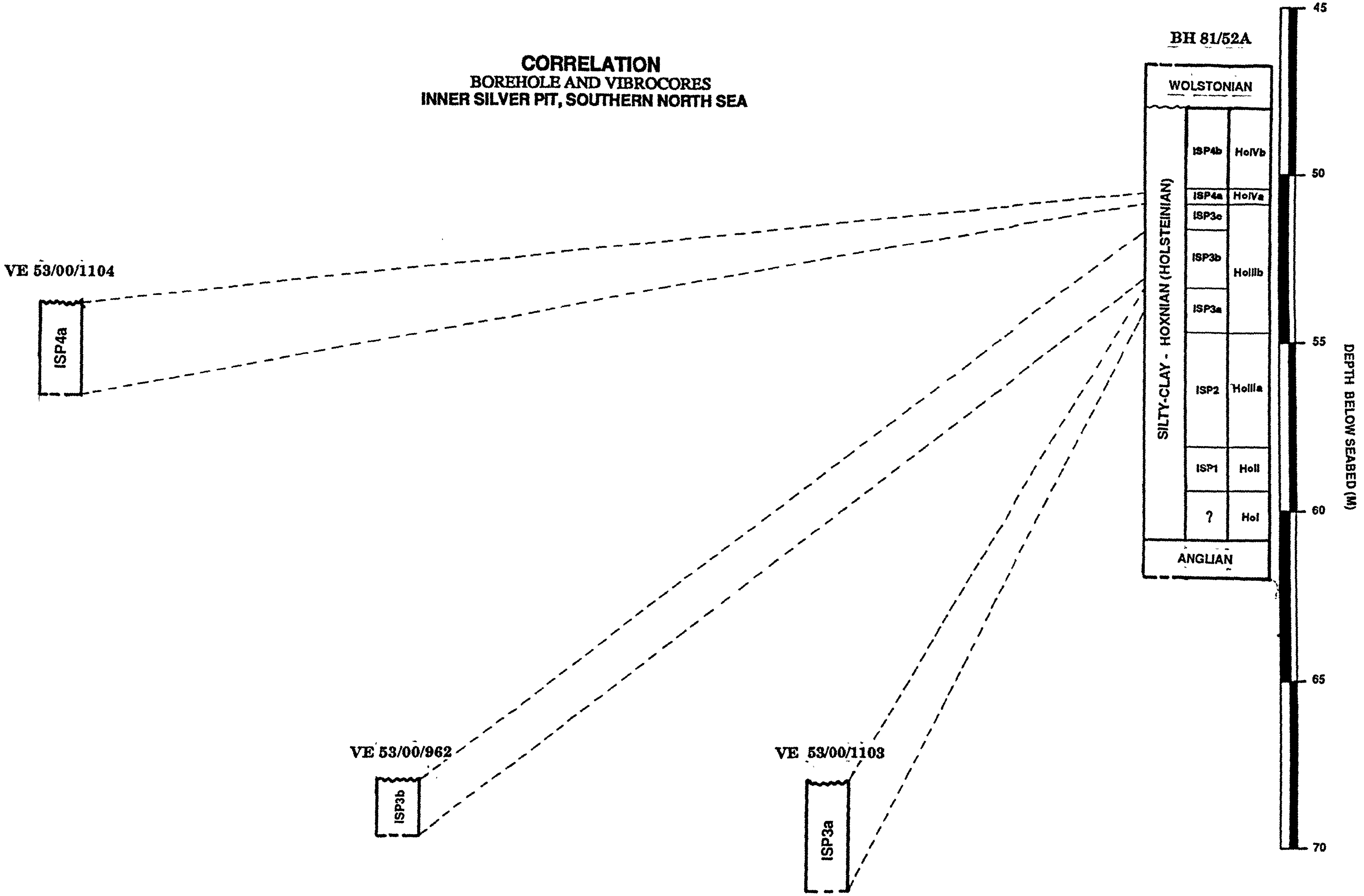

CORRELATION
BOREHOLE AND VIBROCORES
INNER SILVER PIT, SOUTHERN NORTH SEA

Fig. IV.16. Correlation of borehole and vibrocores sequences, based on their pollen and dino cyst assemblages. The substages follow Turner and West (1968) and subdivision of the Hoxnian (Holsteinian) substages (*sensu stricto*) follow Turner (1970).

such a trend does not occur in the percentage pollen diagram of this vibrocore, it is present in the concentration pollen diagram (Fig.IV.2). The increasing values for *Abies* in this concentration diagram enable correlation with ISP3a rather than ISP3c which shows a decreasing trend in values for both *Abies* concentrations and frequencies.

A) Differences

1. The pollen diagram from this vibrocore does not show as large increases in the frequencies of *Abies* as in the pollen diagram from the borehole. In addition the concentration of pollen is higher in this vibrocore.

2. ISP3a in BH 81/52A represents a sequence 1.20 m thick in which the lower half shows quite high values for *Picea*. Excluding this part, only 50 or 60 cm of the BH 81/52A sequence can be correlated with this pollen diagram.

These differences may be explained if i) the location of the site, ii) comparison between the percentage and concentration pollen diagrams and iii) evidence from other parameters such as dino cyst and organic matter and carbonate content, are all taken into consideration.

This vibrocore is situated on the flank (inside) of the Inner Silver Pit enclosed deep (Fig. III.2), whereas the borehole is located outside the deep (see also Fig. IV.16). The geometry of the interglacial sequence (Fig. III.6) shows that the sediments were deposited in a shallow basin, and that the deposits are thicker towards the centre of this basin. The water depth where the borehole is situated is 20.20 m, plus the subsample depth of ISP3a (33.20 m), making a total depth of 52.40 m, whereas the equivalent depth of the vibrocore is 68.17 m. Thicker deposition in the centre of the basin means that any core from the flanks of the bathymetric deep will provide a lower resolution record. Higher pollen concentrations in the vibrocores also indicates that in addition to quicker sedimentation in the central part of the basin, the deposition of pollen and spores itself was more rapid. This is analogous to lake sedimentation where focusing (Davis and Ford, 1982) causes thicker sequences to accumulate in the centre of the basin.

Apart from differences in sedimentation rate and microfossil concentrations, correlation on the basis of the dino cyst data is not difficult (Fig. IV.16). The frequencies of dino cysts suggest that the vibrocore perhaps represents the sequence in the borehole between 33.10 m (53.30 m) and 33.90 m (54.10 m).

ii) VE 53/00/962 and BH 81/52A

The pollen diagram of VE 53/00/962 clearly shows that it represents the late-temperate substage of an interglacial. This diagram is exclusively dominated by *Abies* which is a characteristic feature of the middle part of the upper half (HoIIIb) of the late-temperate (HoIII) substage of the Hoxnian interglacial. This is represented in the pollen diagram of BH 81/52A by the ISP3b pollen assemblage subzone. Correlation of this vibrocore with BH 81/52A (Fig. IV.16) is straightforward and any differences in terms of thickness of the sequence and pollen concentrations can be explained as above for vibrocore VE 53/00/1103.

iii) VE 53/00/1104 and BH 81/52A

The pollen diagram from this vibrocore is characterised by the abundance of *Empetrum* which strongly suggests correlation with the post-temperate substage of the Hoxnian interglacial. This substage in the pollen diagram from borehole BH 81/52A (Fig. IV.16) is represented by ISP4 which is exclusively dominated by *Empetrum* pollen. Pollen assemblage zone ISP4 is divided into two subzones ISP4a and b. In subzone ISP4a the frequencies of Gramineae and *Betula* are not significant whereas ISP4b is characterised by decreasing values for *Empetrum* and increasing values for Gramineae and *Betula*. The pollen assemblage of this vibrocore is similar to ISP4a and strongly suggests correlation with this subzone of the pollen diagram from BH 81/52A; this represents the earlier part of the post-temperate substage.

Comparison of both the percentage and concentration pollen diagrams from the borehole and vibrocores suggests that the vibrocore provides a longer record of the post-temperate substage than is represented by the relatively thin sequence in the borehole. Frequencies of *Empetrum* demonstrate that 0.45 m of the borehole (the five levels between 30.25 m and 30.70 m) is represented by a 1.64 m thick sequence in the vibrocore.

A 33 cm section of the sequence in the borehole between 29.67 m and 30.00 m was not recovered in good condition in the form of Hammer samples. Although this long vibrocore sequence provides additional data it does not cover this missing part, represented by ISP4b in the BH 81/52A. This interpretation is supported by the moderately high values for Gramineae in the borehole. Similarly, the silty-clay sequence between 29.67 m and 28.00 m not recovered in the borehole is also absent from this vibrocore.

b) Evidence from dinoflagellate cysts

The pollen data provide convincing correlation with various parts of borehole 81/52A. These data also indicates the thicker sequence of interglacial sediments towards the centre of the basin, and the siting of the borehole through the margins of the interglacial sequence.

Prior to comparison of the dino cyst data from the borehole with these vibrocores, it is important to take the following points into consideration:

1. In this diagram the sum of dino cysts has been presented as total cyst per gram of sediment rather

than total cyst per slide (Fig. III.11).

2. The borehole data represents a 50 cm sampling interval whereas the slides for these vibrocores have been counted with a 20 cm sampling interval.

Results of the dino cyst counts suggest that VE 53/00/1103 is equivalent to the 80 cm sequence between 33.10 m and 33.90 m (Fig. IV.16) in borehole 81/52A. Although the samples have been taken from different stratigraphic levels this correlation appears reasonable. The dino cyst data suggest that the sequence can be divided into three distinct sections. The central part of the sequence indicates a favourable marine environment for the dino cyst flora. This period probably correlates with the peak at 33.16 m in the borehole.

Like vibrocore 53/00/1103, the sequence from 53/00/962 can be divided into three zones using the dino cyst evidence. Generally the sequence represents a period of favourable marine environment which fluctuated and declined between 0.8 m and 1.2 m depth. On the basis of this fluctuation this sequence can be correlated with the peak at 32.12 m in the borehole.

Though the sequence recovered in vibrocore 53/00/1104, does not contain good dino cyst records the available data suggests, that this sequence can be correlated with the increasing total values recorded between 30.25 m and 30.70 m in borehole 81/52A. Individual species curves suggest that level 30.56 m in the borehole can be correlated with level 0.8 m in the vibrocore. The moderately good concentration in the lower zone seems to be the result of improved marine conditions.

c) Palaeoenvironmental interpretation

The combined pollen and dino cyst data indicate undoubted interglacial conditions; this is indicated by the cyst genus *Spiniferites* and confirmed by the pollen evidence. Dino cyst concentrations reach up to 6,000 cyst per gram in vibrocore 53/00/1103 and 8,000 in /962 and /1104. The curve of total dino cysts reflects a series of alternating improvements and declines in marine conditions.

Results from pollen analysis of the borehole and all three vibrocores suggest that pollen concentrations vary between the different sites, but that within sites the concentrations and frequencies are stable. This leads to the conclusion that the terrestrial environment was quite stable, but that oceanographic parameters, such as salinity and currents, were variable causing variations in dino cyst productivity.

The curve for *Spiniferites* in the dino cyst spectra of vibrocore 53/00/1103 supports the interpretation of marine conditions throughout the sequence. The curve of total cysts suggests fluctuating conditions but with improvements between 0.8 m and 2.2 m. During this period of amelioration the high frequencies of *Operculina centrocarpum* are interesting. This species is indicative of the North Atlantic current.

The curves of *B. tepikiense* indicate that higher frequencies may be the result of depressed salinity rather than cooler climate. This situation has also been found with the foraminiferal assemblages in the borehole.

On the basis of the pollen evidence it is clear that vibrocores /1103 and /962 represent the late-temperate substage of the Hoxnian interglacial cycle whereas /1104 represents the post-temperate substage. All three vibrocores are therefore within the cycle of temperate climate. Deteriorating marine climate is indicated by the dino cyst data from vibrocore /1104.

IV.5. Conclusions

Detailed investigation of vibrocores 53/00/1103, /962 and /1104 from the Inner Silver Pit offshore area of the UK sector of the southern North Sea clearly indicate that these three vibrocores are representative of the silty-clay sequence of the Sand Hole Formation of Tappin (1991). These vibrocores reveal very similar pollen assemblages found in the silty-clay sequence of BH 81/52A. The pollen diagrams from these three vibrocores can be clearly correlated with various parts of the pollen diagram of BH 81/52A.

The other six of the nine vibrocores showed very poor pollen concentrations. Moreover, they contained large quantities of reworked and pre-Quaternary pollen and spores.

Chapter V

Borehole 81/34, Devil's Hole
British sector, Central North Sea

V.1. Aims

Cores from boreholes drilled in the North Sea suggest that in the central North Sea the stratigraphy is more complete than in the southern North Sea. The encouraging results from BH 81/52A stimulated a comparison of this nearshore interglacial site close to an esturine sediment source with a site away from any such source in the central North Sea. Borehole 81/34 was chosen because it has provided the longest Quaternary recovery from the central North Sea. An additional aim was to use pollen analysis to attempt to explain the conflict between the dino cyst data and the foraminiferal evidence from this borehole.

V.2. Stratigraphy - evidence from the central North Sea

Initial geological surveys of the central North Sea were carried out by the British Geological Survey (BGS) between 1969 and 1975, and a preliminary Quaternary stratigraphy presented (Holmes, 1977; Thomson and Eden, 1977). In 1980/81, as part of their regional offshore mapping programme of the UK continental shelf, the BGS collected geophysical and geological data which facilitated improvements to this stratigraphy. Using both the old and new data Stoker *et al.* (1985b) presented a revised stratigraphy.

Stoker *et al.* (1985b) have constructed a three dimensional diagram (Fig. I.8) to demonstrate the Quaternary sequence in the UK sector of the North Sea. The Quaternary forms an easterly thickening wedge of sediments which ranges in thickness from less than 25 m in the west to over 200 m in the east. Seismic records show that in the west the base of the succession rests with an angular unconformity on rocks of Palaeozoic, Mesozoic and Cenozoic age, but to the east, as the sequence thickens, the base becomes obscure. Caston* (1977, 1979) suggests that the Quaternary sequence may be up to 600 m thick in the extreme southeast of the area. Interformational boundaries vary from planar to highly irregular, and represent surfaces of erosion or non-deposition.

Stoker *et al.* (1985a & b) have taken the Lower/Middle Pleistocene boundary at the Brunhes/Matuyama palaeomagnetic boundary (Butzer and Isaac, 1975) which is dated to 730,000 yrs BP by Mankinen and Dalrymple (1979), and 790,000 yrs BP by Johnson (1982). In the Quaternary sequence of the central North Sea Stoker *et al.* (1983) have identified this palaeomagnetic boundary within the Aberdeen Ground

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* Caston (1977, 1979) has used commercial well data. The reliability of commercial data is questionable because many companies do not distinguish the Pleistocene from the Pliocene (Stoker *et al.*, 1985a).

Formation.

According to Stoker *et al.* (1985b) the Middle Pleistocene sequence includes the uppermost part of the Aberdeen Ground Formation, the Ling Bank Formation, the Fisher Formation and the basal part of the Coal Pit Formation. The thickness of the sequence is variable due to erosion. The most complete succession is in the eastern half of the UK sector of the central North Sea (Fig. I.8), where up to 180 m of sediments may be locally preserved. The sequence mostly comprises glacigenic sediments predominantly of a distal glacimarine nature. The base of the Upper Pleistocene is taken as the beginning of the Eemian (Butzer and Isaac, 1975) which began at ca. 128,000 yr B.P. (Bowen, 1978).

i) Aberdeen Ground Formation

The Aberdeen Ground Formation of Stoker *et al.* (1985b) replaces the Aberdeen Ground Beds of Holmes (1977) (Table I.4). The type sequence for this Formation is taken from BH 81/34 (Stoker *et al.*, 1985b) where the sequence extends from 140 m to 230 m but without representing the base of the Formation. Borehole 81/36 is suggested as a reference section for lateral variations of this Formation where it is represented by the section from 16 m to 31.4 m. The thickness of the formation varies due to post depositional erosion, and forms a wedge-shaped unit which reaches a maximum thickness of at least 130 metres in the central part of the Devil's Hole area, thinning markedly towards the west. Sediments of this Formation comprise "very dark grey to brown, very stiff to hard silty mud locally interbanded with thin (<5m) yellowish, firm, variably sorted shelly and pebbly sands and coarsely interlaminated muds and sands" (Stoker et al., 1985b).

Stoker *et al.* (1983) undertook palaeomagnetic studies and identified the boundary between the Brunhes normal and Matuyama reversed palaeomagnetic zones and also the Jaramillo event within the Aberdeen Ground Formation. This suggests Waalian to Cromerian (Complex) age (late-Early to early-Middle Pleistocene) for this part of the sequence.

Lithofacies interpretations suggest that the bulk of the Aberdeen Ground Formation, which is dominated by bioturbated argillaceous sediments, was deposited in an inner to middle shelf environment.

ii) Ling Bank Formation

The Ling Bank Formation of Stoker *et al.* (1985b) replaces the Lower Channel Deposits of Holmes (1977) (Table I.4). The type sequence for the Ling Bank Formation is taken from borehole 81/34 (Stoker et al., 1985b) where the sequence extends from 55 m to 142 m below sea bed.

Seismostratigraphically the Ling Bank Formation is extensive. It varies in thickness across the area from less than 20 m to around 100 m. The maximum thickness is found where the Formation infills deep erosive features. According to Stoker *et al.* (1985b), in the Devil's Hole area the seismic texture is locally masked by acoustic blanking believed to be caused by gas.

Sediments of this Formation, in general, comprise dense silt and silty sand with interbedded sand and clay, especially towards the top of the sequence.

Evidence from the palaeomagnetic analysis of borehole 81/34 (Appendix in Stoker *et al.*, 1985b) shows that the Ling Bank Formation, apart from several minor isolated reversed horizons, is dominantly normally magnetised. This normally magnetised zone has been considered part of the Brunhes normal epoch. The age of this Formation is uncertain, but on the basis of general stratigraphic position of the unit Stoker *et al.* (1985b) have tentatively suggested an age range from Holsteinian to early Saalian.

On the basis of preliminary micropalaeontological data (Stoker *et al.*, 1985b; Harland, 1988) the lower part of the Formation in BH 81/34 appears to have been deposited under marine interglacial conditions. However, the upper part of the sequence represents a falling sea level associated with deteriorating climate.

iii) Fisher Formation

In the new nomenclature of Stoker *et al.* (1985b) the Fisher Formation replaces the Fisher Beds and Lower Swatchway Beds of Holmes (1977). The type section is taken from BH 81/34 (Stoker *et al.*, 1985b) from the Devil's Hole where its thickness extends from 153 m to 55 m below sea bed. According to Stoker *et al.* (1985b) the seismostratigraphic base of the unit occurs as a distinct planar erosion surface which cuts across both the Ling Bank and Aberdeen Ground Formations. The top of the unit is generally characterised by an irregular surface associated with the erosional features infilled by the Coal Pit and Forth Formation where these Formations are present, though elsewhere the Formation occurs at sea bed.

Stoker *et al.* (1985b) state that the sediments of the Formation consist of "interbedded, very stiff to hard over-consolidated clays and silty-sands with occasional shell fragments and pebbles of various lithologies, including chalk, flint and metamorphic rocks". In borehole 81/34, the base of the Formation is defined where the dominantly sandy basal sediments rest on interbedded silts and clays of the underlying Ling Bank Formation. The top of the unit is marked by an abrupt lithological change from the interlaminated sands and stiff clays to pebbly sands which form the base of the unconformably overlying Forth Formation.

Palaeomagnetic analysis of BH 81/34 (Stoker *et al.*, 1983) reveals that the Fisher Formation is dominantly normally magnetised. Micropalaeontological and lithological evidence suggest that the sediments were deposited in a dominantly glacimarine environment.

iv) Coal Pit Formation

The Coal Pit Formation replaces the Lower Series of the Upper Channel Deposits and the Upper Swatchway Channel Deposits of the previous nomenclature (Holmes, 1977). The type section for this Formation is taken from borehole 81/37 (to the north of BH 81/34) between 32 m and 107.5 m below sea bed.

On the basis of the seismostratigraphic evidence, Stoker *et al.* (1985b) suggest that the Coal Pit Formation occurs mainly in the central and eastern part of the study area. Its thickness varies considerably from less than 10 m in the Marr Bank and Peterhead areas to in excess of 120 m in the Devil's Hole and Forties areas. Seismic records show that the base of the formation is usually irregular and erosional. The top of the Formation is normally represented by an irregular erosion surface underlying the Forth Formation of late Weichselian age.

According to *Stoker et al.* (1985b) sediments of this Formation vary from "firm, dark grey to brownish grey, variably sorted, muddy, pebbly sands and hard, dark grey, silty matrix-supported pebbly muds to very stiff, grey to very dark grey, occasionally pebbly interbedded muds, silty muds, sandy silts and very fine to fine sands".

Palaeomagnetic evidence from boreholes 75/33, 77/3, 81/27 and 81/35 (Stoker *et al.*, 1983) indicate that the Coal Pit Formation occurs within the Brunhes normal epoch.

V.3. Present chronostratigraphic status of the Middle Pleistocene in the central North Sea

The UK sector of the central North Sea has been glaciated at various stages by separate ice sheets. The Quaternary sequences recovered in boreholes from the central North Sea have been investigated by Holmes (1977), Stoker *et al.* (1983), Stoker *et al.* (1985a & b), Harland (1988), Sejrup *et al.* (1987), Jensen and Knudsen (1988), Knudsen and Asbjörnsdòttir (1991), Knudsen (in prep.). On the basis of these investigations, it has become clear that these boreholes contain a more complete Quaternary sequence than can be found in the neighbouring onshore areas (Hall and Connell, 1982, 1991). Dinoflagellate cyst analyses by Harland (1988) have provided detailed marine floral evidence which strengthens this interpretation. However, foraminiferal analyses by Knudsen (in prep.) do not agree with the conclusions made on the basis of the dino cyst analyses.

Borehole 81/34 from the Devil's Hole area represents the longest recovery of the Quaternary sequence of the central North Sea. The borehole represents the type section for all Formations (except the Coal Pit Formation) of the Middle Pleistocene (Stoker *et al.*, 1985b). Harland (1988) has investigated the dinoflagellate cyst assemblages of this borehole, and these support the stratigraphic division of the borehole presented by Stoker *et al.* (1985b). He interprets the entire sequence between 82 m and 142 m as a single interglacial stage. This conflicts with recent work undertaken on the foraminiferal assemblages of this borehole (Knudsen, in prep.). She suggests that the sequence between 82 and 142 m represents two temperate stages separated by a cold stage rather than a single temperate stage.

Apart from this conflict it is quite clear that BH 81/34 contains sediments of interglacial status. In order to clarify the stratigraphy the borehole was selected for pollen analysis.

Only the sequence representing the Ling Bank Formation was selected for pollen analysis.

V.4. Location

Borehole 81/34 is situated 257 Km off Fife Ness at 56° 7.68′ N latitude and 1° 35.21′ E longitude in the Devil's Hole offshore area, one of considerable topographic relief Fig.V.1. The Devil's Hole area consists of a series of buried valleys (origin discussed in section VII.2,a) near East Bank. These valleys have cross sections of the same order of size as the Inner Silver Pit enclosed deep. The average water depth over most of the Devil's Hole Sheet area is between 80 m and 90 m although this increases to over 200 m in enclosed bathymetric deeps. On the bathymetric maps these are striking features, and on the seismic record they appear as apparently steep-sided channel-like forms (Fyfe, 1985).

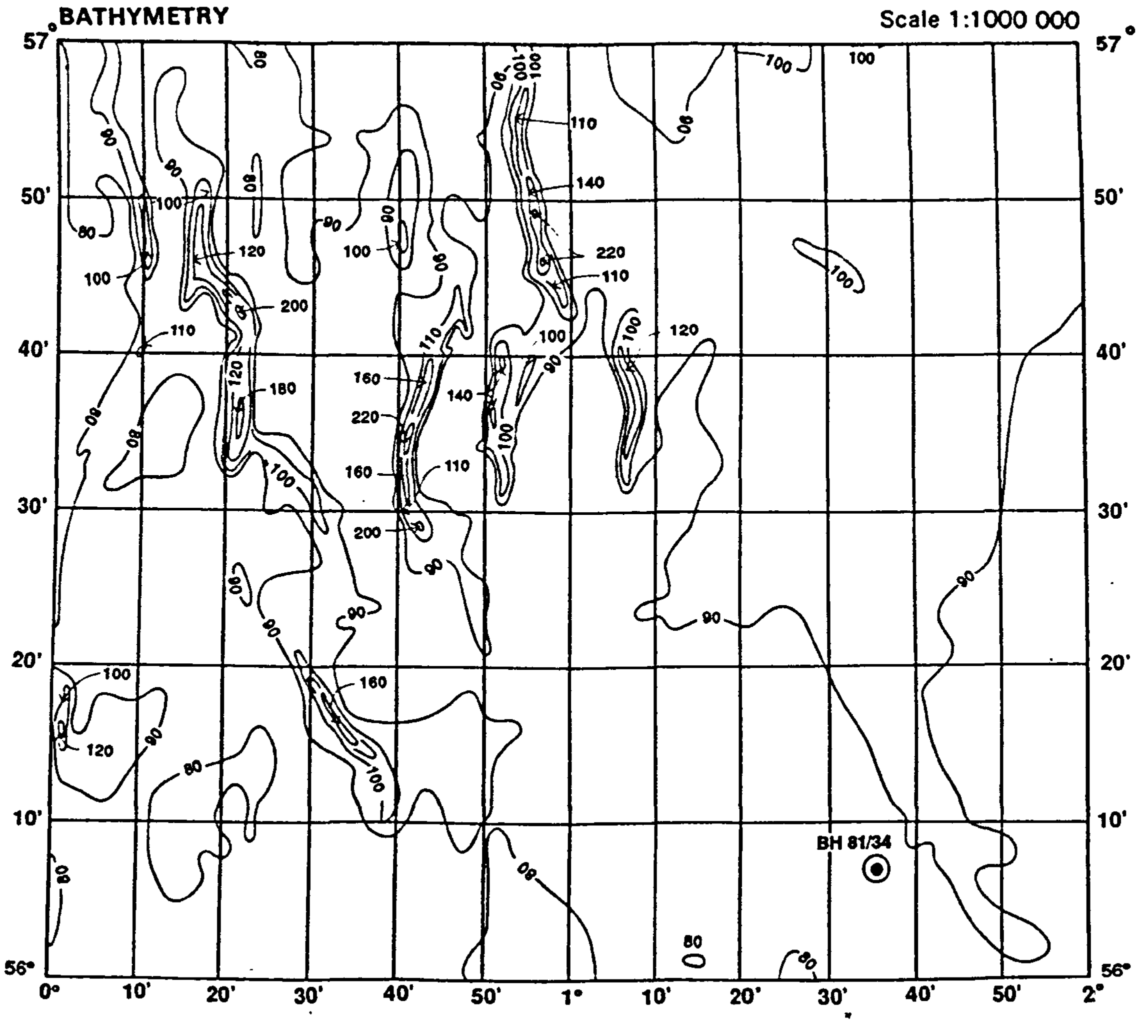


Fig. V.1. Bathymetric map, Devil's Hole, central North Sea (from Fyfe, 1985).

V.5. Bathymetry

The bathymetry of the study area is summarised in Fig.V.1. based on BGS data, supplemented by Hydrographic Office soundings north of 56° 30′N and west of 1° E (Fyfe, 1985). Within the enclosed deeps the contour interval below 120 m has been changed from 10 m to 20 m because of the high density of contour lines. These contours give only a general impression of the bathymetry of the deeps because of the relatively wide survey line spacing.

The sea bed slopes from 80 m in the south and west to over 90 m in the north-east (Graham, 1985). However, this relatively smooth topography is incised by several north-south trending deeps which extend to 220 m below sea level. These deeps are very similar in shape, trend and size to the 'buried channels' in the underlying Quaternary deposits mapped from seismic records. These records show that some of the deeps are partially filled channel features. Graham (1985) suggests that the channels were probably formed during the Devensian (Weichselian) glaciation by subglacial or proglacial meltwater erosion, and possibly modified by tidal scouring (also see section VI.2,a). He also suggests that the sedimentary infill commenced in the Late Devensian and continued into the early Holocene when sea-level was much lower than at present. The modern deeps may therefore be partially infilled and unfilled channels remaining after the change in the sedimentary environment caused by the continuing rise in the sea-level.

V.6. Geometry of the Ling Bank Formation deposits

The distribution of the deposits of the Ling Bank Formation is shown in Fig. I.8, presents a three dimensional view of the deposits of this Formation in the central North Sea. On the basis of seismostratigraphic evidence Stoker *et al.* (1985b) suggest that the Ling Bank Formation occurs extensively at subcrops mainly in the eastern part of the study area. It varies in thickness across the area from less than 20 m to around 100 m, with maximum thickness developed where the unit infills deep erosive features. In the south of the area the base of the formation is a relatively planar erosion surface, in the north the base is characterised by a highly irregular erosion surface which has cut into the underlying Aberdeen Ground Formation. The top of the unit is generally marked a distinct planar erosion surface which marks the base of the overlying Fisher Formation. On sparker records, the internal reflection pattern varies from chaotic (Fyfe, 1985) to oblique asymmetric or onlapping in character. In the Devil's Hole area the seismic texture is locally masked by acoustic blanking believed to be caused by gas.

V.7 Results

a) Sediment description

The sediment description of the Ling Bank Formation is contained in Fig.V.2. and the description of sediments of

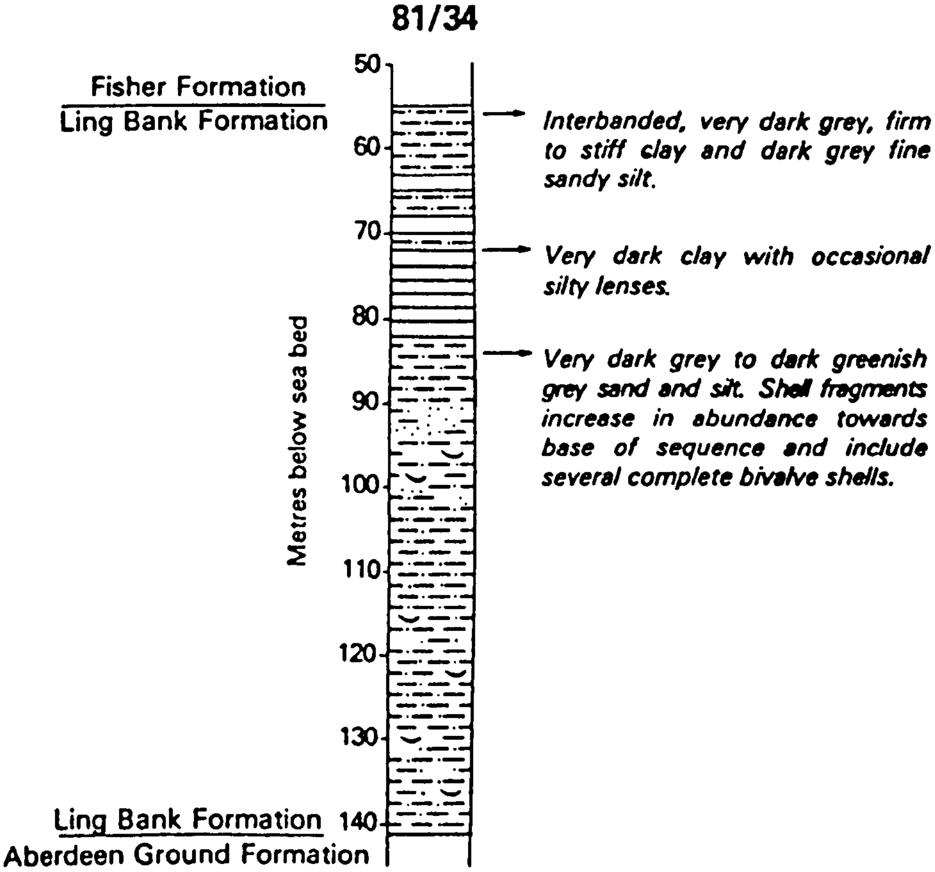


Fig. V.2. Sediments of the Ling Bank Formation in BH 81/34, Devil's Hole, central North Sea.

other Formations is given in Stoker *et al.* (1985b)

b) Pollen analysis

Pollen diagrams from the sequence between 55 m and 142 m are presented in Fig. V.3 & 4. On the basis of the foraminiferal biostratigraphic evidence (Knudsen and Asbjörnsdòttir, 1991) it was decided to select the two temperate periods from the 89 m long sequence for detailed investigation. The sampling interval was 30 cm for the identified warm stages and 5 m for the cold stage interval between 84 m and 137 m. The sequence from the cold stage deposits contained pollen below the "concentration threshold" (Scourse, 1991; section II.3,e above).

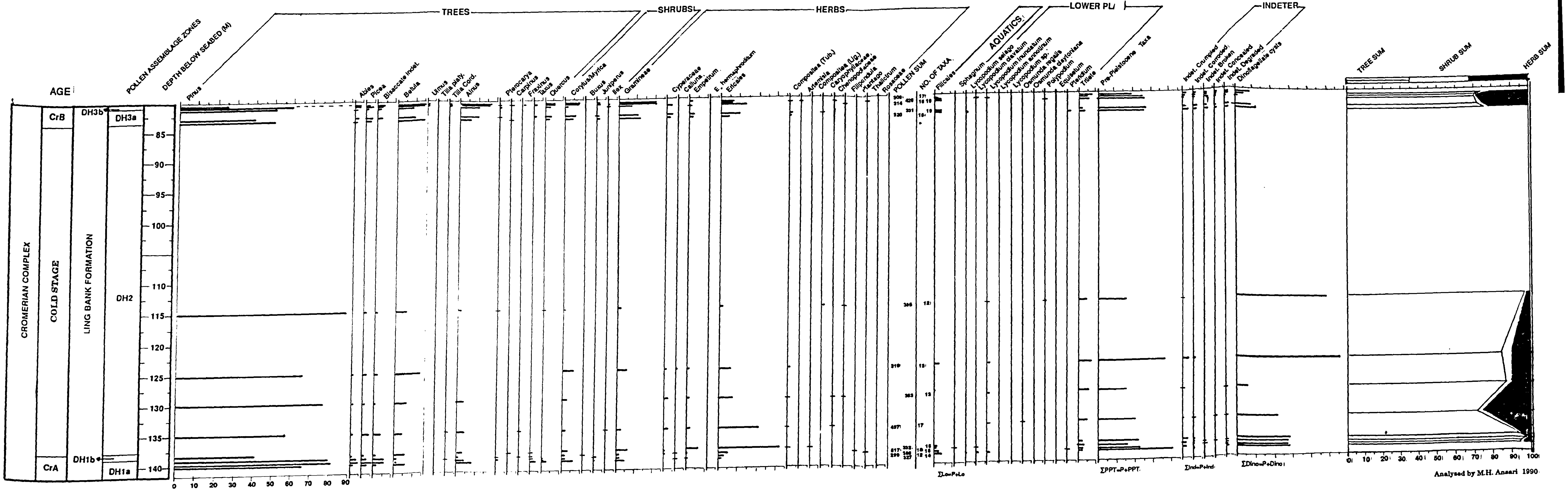
In the upper sequence only the samples between 80.95 m - 81.50 m and 83.0 m - 83.50 m contained a concentration greater than 4,000 grains per gram. The sequence between 82 and 83 m fell below the concentration threshold.

Fortunately the lower temperate sequence between 138 - 140 m contained concentrations greater than 4,000 grains per gram. The one metre thick sequence below 140 m was also included to provide some context, but this proved to be barren or almost barren.

i) Zonation of pollen diagram

As the diagram shows few changes it has not been zoned using numerical techniques (Gordon and Birks, 1972). However, on visual impression the sequence from 82 m to 140

PERCENTAGE POLLEN DIAGRAM
SITE BH 81/34
DEVIL'S HOLE, CENTRAL NORTH SEA



Analysed by M.H. Ansari 1990

Fig. V.3. Results of the palynological analysis from the Ling Bank Formation in BH 81/34, Devil's Hole, central North Sea. CrA and CrB, two Cromerian interglacial stages of the Cromerian Complex.

m can be divided into three zones which are DHP*1, DHP2 and DHP3 in ascending stratigraphic order.

Zone DHP1

This pollen assemblage zone is dominated by pollen grains of *Pinus*, though *Betula, Abies, Picea, Alnus, Corylus* and Gramineae are also present in significant quantities. On the basis of changes in the frequencies of these subdominant taxa this assemblage zone can be subdivided into two subzones.

DH p.a. subzone 1a (140.00 - 139.10 m)

Pinus-Betula-Alnus p.a. subzone

This subzone is dominated by *Pinus* throughout. Other important tree taxa include *Abies, Picea, Alnus, Taxus* and *Quercus*, and *Pterocarya* which becomes significant in the upper part of the subzone.

Pinus frequencies range from 65.8 % to 80.9 %. *Abies* and *Picea* are also present throughout the zone. Although they show slightly higher frequencies in the central part, they are generally present in lower percentages which range from 0.9 % to 3.9 % and from 2.1 % to 4.4 % respectively. *Alnus* is variable but higher towards the base. *Betula* and *Alnus* show a similar pattern, increasing at the base to 5.5 % and 7.7 % respectively, ranging from 0.3 % to 5.5 % and from 0.9% to 7.7%.

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* **DHP** stands for Devil's Hole Pollen assemblage zone.

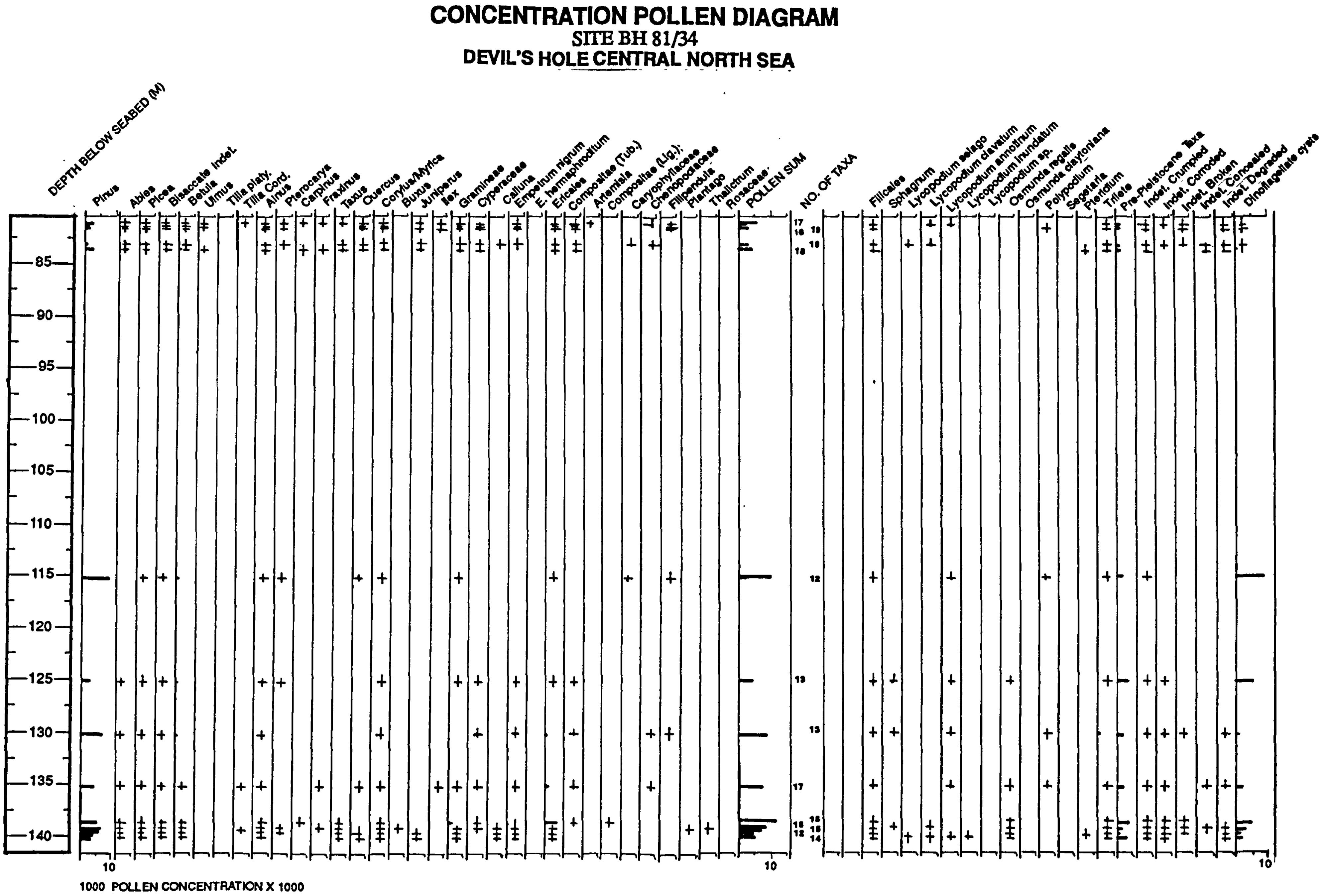


Fig. V.4. Concentration pollen diagram of the palynological analysis from the Ling Bank Formation, Devil's Hole, central North Sea.

Corylus also follows the same trend, reaching 5.8 % at the base and ranging from 0.6 % to 5.8 %. Other shrub taxa include *Juniperus* and *Ilex* but both are represented by very low values.

A varied herbaceous spectra is present, represented by Ericales, *Empetrum, Calluna*, Gramineae and *Thalictrum*. Ericales increase upwards and ranges between 0.7 % at 139.70 m and 32.5 % at 139.10 m. In contrast Gramineae is highest at the base but generally low throughout the rest of the zone. Its frequencies follow a similar trend to *Alnus* and *Betula*.

DH p.a. subzone 1b (139.09 - 138.01 m)

Pinus-Betula-Ericales-Empetrum p.a. subzone

This subzone is of very different composition but is only represented by the single level at 138.5 m. It is dominated by *Pinus*, Ericales, *Betula* and Gramineae.

Pinus dominates with a frequency of 40.4 %, and *Betula* reaches 5.1 %. *Abies* and *Picea,* which were represented by higher frequencies in DHP1a, are almost absent. *Corylus* reaches 2.7 %.

This zone is in particular characterised by high values for Ericales and *Empetrum* which reach 32.4 % and 6.3 % respectively.

Zone DHP2 (138.00 - 84.00 m)

Pinus-Betula-Ericales p.a. subzone

This subzone is dominated by *Pinus* and *Betula* in the upper part and Ericales in the lower part. Ericales, which is significant in DHP1b, remains important but declines to become insignificant upwards; it ranges from 20.4 % at 135 m to 1.3 % at 115 m. Though Gramineae is no higher than in DHP1, it is absent in the lower two levels but is high at 125 m in the middle of the zone. This is the level at which *Betula* is represented by the very high value 13.2 %.

This pollen assemblage zone is dominated by pollen of *Pinus* and *Betula*. *Pinus* ranges from 56.3 % to 87.9 %. Other significant tree taxa include *Abies, Picea, Alnus, Pterocarya* and *Quercus,* all represented by very low values, except *Alnus* which reaches 3.2 % at 81.5 m.

Zone DHP3

This pollen assemblage zone is dominated by *Pinus, Betula, Alnus,* Gramineae, *Quercus, Corylus* and Ericales. On the basis of frequencies of these taxa this assemblage zone can be divided into two subzones.

DH subzone 3a (84.01 - 80.96 m)

Pinus-Betula-Gramineae p.a. subzone

This subzone is dominated by *Pinus, Betula* and Gramineae. *Pinus* ranges from 38.4 m to 58.2 m and *Betula* and Gramineae range from 6.1 % to 14.3 % and 2.8 % to 11.5 % respectively. Pollen grains of thermophilous trees such as

Alnus, Corylus and *Quercus* are well represented, and these three taxa range from 3.8 % to 9.1 %, 1.6 % to 4.8 % and 1.6 % to 3.3 % respectively. These three taxa do not follow any common trends in frequency changes. Other significant tree taxa include *Abies, Picea, Taxus, Carpinus* and *Pterocarya*.

A varied herbaceous assemblage is dominated by Ericales which is represented by high values particularly in the central part of the zone; it ranges between 3.8 % and 12.9 %. *Empetrum* is also represented by low but continuous values.

DHP p.a. subzone 3b (80.96 - 80.90 m)

Pinus-Betula-Alnus-Gramineae p.a. subzone

This subzone is very diverse and is represented by only the single level at 81 m. *Pinus*, which was represented by high values in DHP 3a, declines to 24.3 %. Gramineae is represented by its highest frequency in the pollen diagram, 20.1 %. *Betula* and *Alnus* are also represented by their highest values in the pollen diagram, 14.9 % and 15.9 % respectively. *Quercus, Corylus, Picea* and *Abies* are also well represented, 5.2 %, 7.8 %, 1.6 % and 0.3 % respectively. Other tree taxa include *Ulmus, Carpinus, Fraxinus* and *Taxus*, but these are all represented by very low values. Ericales, dominant in DHP3a, has declined to 5.2 %.

Throughout the pollen diagram a varied spectra of spores are present, dominated by *Sphagnum* and Filicales.

These two groups do not show any significant change throughout the pollen diagram. Other spore taxa include *Osmunda (O. regalis)*, *Polypodium*, *Pteridium* and various species of *Lycopodium*.

ii) Interpretation of pollen diagram

Before interpreting this pollen diagram, it is important to consider taphonomy which is presented above in section III.8,b,i). Moreover, this site is further offshore and distant from zones of fluvial imput so low concentrations and difficulties in vegetational reconstruction are therefore not unexpected. In addition, the site is further north than BH 81/52A and therefore a vegetation of more northerly temperate climatic aspect is more likely.

The pollen diagram suggests that the sequence between 80.95 m and 140.00 m represents two warm episodes separated by a thick depositional sequence of cold character (section V.9 below). Despite the overall thickness of the sequence, it appears that the temperate episodes are represented by only very thin zones overlain and underlain by cold stage deposits. However, it is clear that the pollen spectra do not represent the sequential development of interglacial vegetation as in BH 81/52A. This is highlighted by the parallel trends in the frequency changes of *Betula* and *Corylus*, which in BH 81/52A behave as reciprocal components in the interglacial cycle.

V.8. Discussions

a) Summary of interpretation of dinoflagellate cyst spectra

Harland (1988) has investigated the entire sequence recovered in BH 81/34, finding a very rich and diverse dino cyst flora. His interpretation of this data supports the revised stratigraphic nomenclature presented by Stoker *et al.* (1985b).

He has found a particularly rich and diverse flora in the Ling Bank Formation (Fig. V.5). The dino cyst data for this sequence reveals generally favourable environments which can be divided at about 83 m depth. The older section is dominated by *Operculina centrocarpum* with *Spiniferites* spp. and lower proportions of *Bitectatodinium tepikiense*. This part indicates the marked influence of the North Atlantic Current (Harland, 1983), and without doubt can be attributed to an interglacial stage (Harlan, 1988).

Above 82 m the character of the assemblage changes with a simple reduction in specimen numbers. There is a marked decrease in the proportion of *O. centrocarpum* with a reciprocal increase in the proportion of *B. tepikiense* and *Spiniferites* spp. and especially *Achomosparae andalousiensis*. This part of the sequence can be interpreted as the onset of deteriorating climatic conditions at the end of the interglacial.

b) Summary of interpretation of foraminiferal assemblages

Knudsen (in prep.) have carried out a detailed

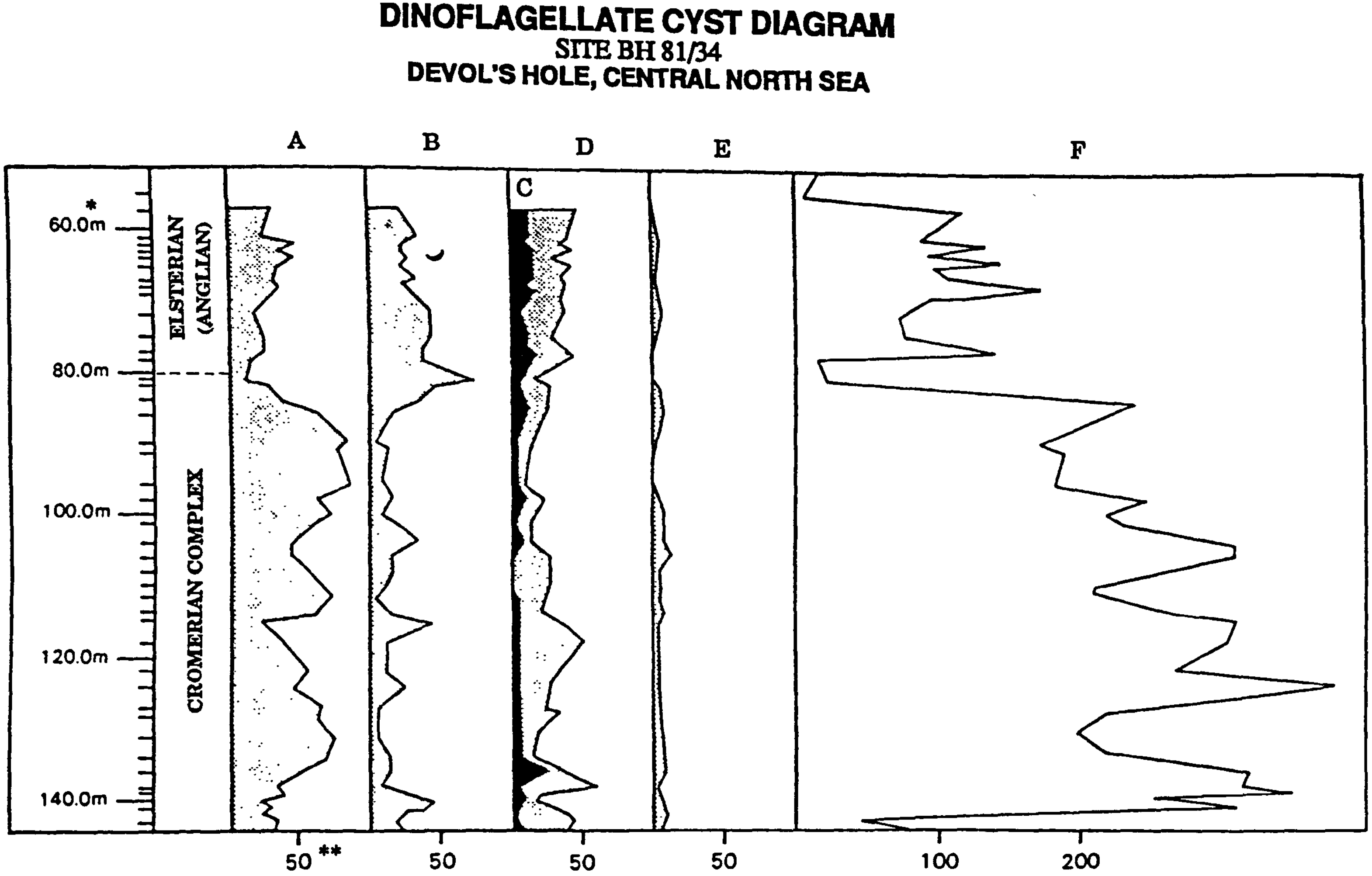


Fig. V.5. Dinoflagellate cyst biostratigraphy of the Ling Bank Formation in BH 81/34, Devil's Hole, central North Sea (data from Harland, 1988). A, *Operculina centrocarpum* (Deflandre and Cookson) Wall. B, *Bitectatodinium tepikiense* Wilson. C, *Achomosphaera andalousiensis* Jan du Chene. D, *Spiniferites* cysts. E, *Protoperidinium* cysts. F, Cysts/Slide. *, Depth below seabed (M). **, Percent of total cysts.

foraminiferal investigation of BH 81/34 (Fig. V.6). Knudsen (in prep.) recognised two interglacial stages within the Ling Bank Formation. Prof. H. P. Sejrup (University of Bergen) has provided preliminary amino acid measurements which suggest that the interglacial deposits at around 140 m depth in BH 81/34 belong either to the Holsteinian or the latter part of the Cromerian Complex.

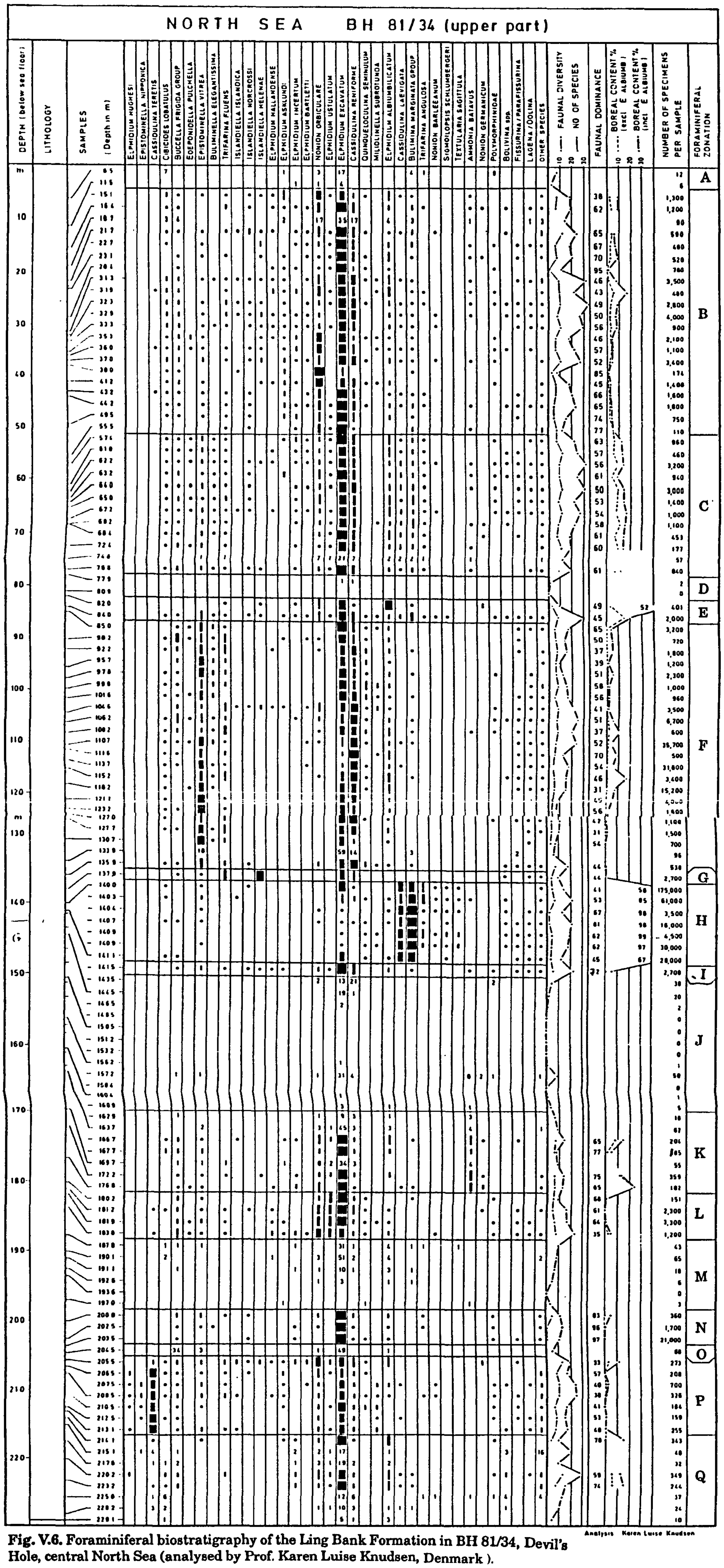
c) Age and correlation of temperate deposits in BH 81/34

A series of samples covering the whole of BH 81/34 is being investigated for amino acid ratios which will enable correlation with other boreholes in the central North Sea. The existing evidence for the age of this sequence is as follows:

1. Stoker et al. (1983) undertook palaeomagnetic measurements which indicates the presence of the Brunhes/Matuyama boundary in the lower Formation (Aberdeen Ground Formation). They suggest that the overlying Ling Bank Formation, in which the two warm stages are recognised, can be correlated with deposits of Holsteinian age (Stoker *et al.* 1985a & b) on the basis of general stratigraphy and, foraminiferal and dinoflagellate evidence (Figs. V.7 & V.8)

2. The amino acid ratio of 0.29 (Fig. V.8) has been obtained from a monospecific sample of *Bulimina*

FORAMINIFERAL DIAGRAM
SITE BH 81/34
DEVIL'S HOLE, CENTRAL NORTH SEA



Analysis Karen Luise Knudsen

Fig. V.6. Foraminiferal biostratigraphy of the Ling Bank Formation in BH 81/34, Devil's Hole, central North Sea (analysed by Prof. Karen Luise Knudsen, Denmark).

marginata (Knudsen and Asbjörndòttir, 1991) from the lower temperate episode. This ratio suggests correlation of this episode with either the Holsteinian or the Cromerian.

d) Palynological evidence

The pollen data support the foraminiferal evidence in clearly indicating the division of the sequence into three parts (Fig. V.3). The central section represents vegetation of cold character, whereas the lower and upper sections are characterised by thermophilous tree taxa. The pollen data also support the foraminiferal data in suggesting that the upper warm stage is not as warm as the lower one. In addition, the records of *Pterocarya* are stratigraphically significant within the Middle Pleistocene.

Pterocarya is particularly well represented in the upper interglacial (warm stage). It is widely accepted that *Pterocarya* occurs in interglacials of Holsteinian age or older (Turner, 1975; West, 1980). This implies that the upper warm period is older than the Eemian interglacial stage. Moreover the pollen data support correlation with the Cromerian as the frequencies of *Picea* are higher than *Abies* whereas the opposite is more usual in the Holsteinian (Figs. V.3 & V.4).

However, the pollen data from the upper warm period is not characteristic of the Holsteinian (Hoxnian) stage. Here the pollen assemblages contain frequencies for *Picea* higher than *Abies*, a characteristic feature of the Cromerian (West,

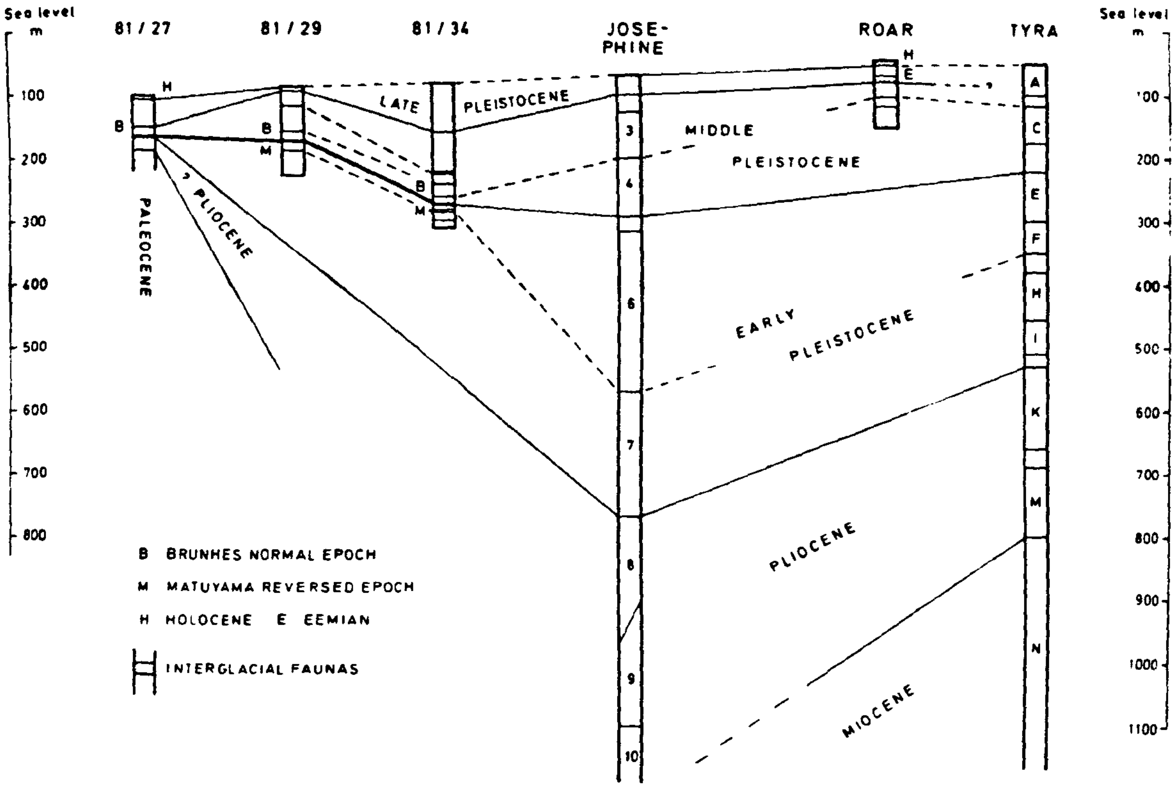


Fig. V.7. Stratigraphic correlation across the central North Sea. The correlation is based mainly on the foraminiferal contents of the seven borehole, but palaeomagnetic results (from BGS) also considered from borehole 81/27, 81/29 and 81/34 (from Knudsen and Asbjornsdottir, (1991).

1980). On the basis of the pollen evidence the upper warm period also seems to represents the Cromerian. The Brunhes/Matuyama palaeomagnetic boundary occurs in the Aberdeen Ground Formation beneath the lower warm period so it is possible that these two warm stages fall within the Cromerian Complex of the Netherlands (Gibbard, 1991). Correlation of these stages with the Cromerian complex is supported by seismic records in which these units are well below the sequence which should represent the Holsteinian (Dr D.H. Jeffery, *pers. comm.*).

Comparison of the interpretation of the dino cyst data with the pollen records from the same sequences in BH 81/52A and BH 81/34 suggest that the role of oceanographic processes is more important than has previously been considered.

The results of the dinoflagellate cyst analysis from BH 81/34 (Fig. V.5) suggest that the thick sequence between 82.00 m and 142.00 m represents a complete interglacial cycle (Harland, 1988). On the other hand, dino cyst results from BH 81/52A (Fig. III.11) are not thought to represent a complete interglacial cycle (Dr R. Harland, *pers. comm.*). This conflicts, however, with the pollen data which suggest that the sequence in BH 81/52A represents a complete interglacial cycle whereas the sequence in BH 81/34 represents two interglacial periods separated by a cold period. Perhaps further ecological studies on the dinoflagellate group are required to explain this apparent conflict.

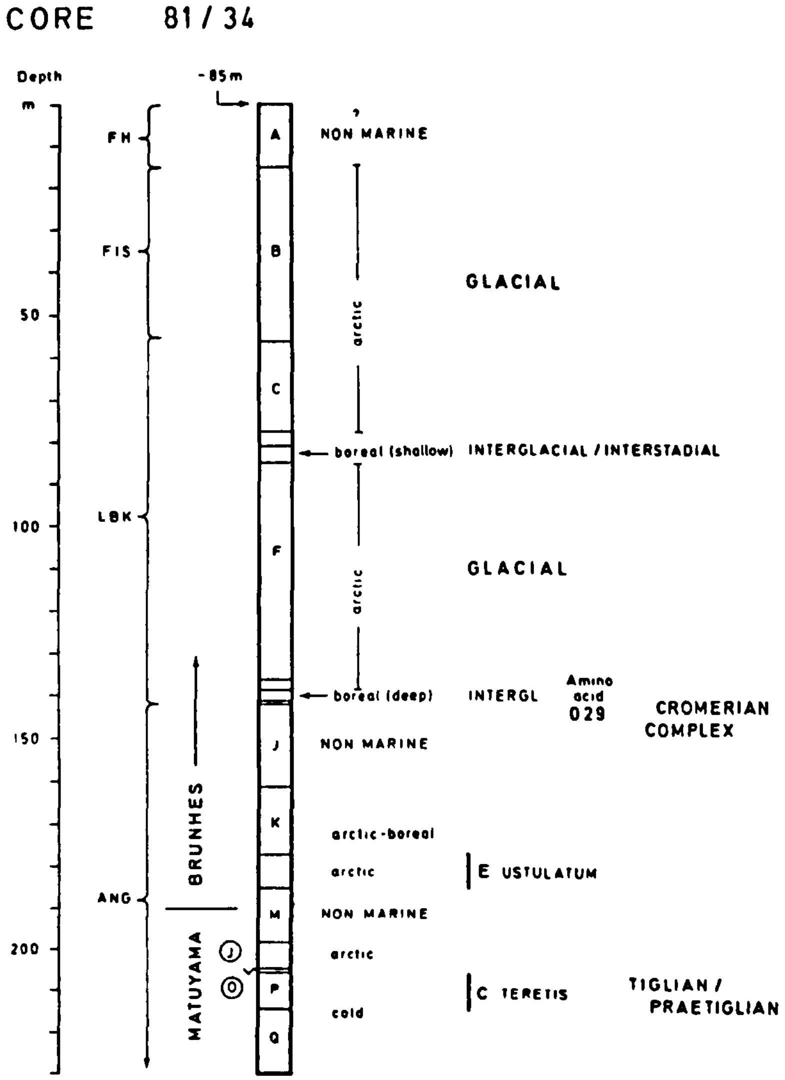


Fig. V.8. Summary of the palaeoenvironmental and chronostratigraphical interpretation at borehole 81/34. The regional seismostratigraphical framework (Stoker *et al.*, 1985b) is shown to the left (FH=Forth Formation, FIS=Fisher Formation, LBK=Ling Bank Formation, ANG=Aberdeen Ground Formation). J=Jarmillo palaeomagnetic event, O=Olduvai event. The letters in the column indicate foraminiferal zones in the core. See Fig. V.3 for pollen zones.

The peak of *Achomosphaera andalouseinsis* appears to indicate optimum conditions in the middle of interglacial stage from both sites (BH 81/52A and BH 81/34) (Figs. III.11 & V.5). Comparison between the pollen and dino cyst data from BH 81/52A indicates that the peak of *A. andalouseinsis* can be correlated with the beginning of the established peak of *Abies*. The *Abies* curve continues until the late stage of optimum sea-level while the peak of *A. andalouseinsis* declines more quickly. Sequence stratigraphy (Chapter VI) reveals that the depth of the peak of *A. andalouseinsis* in BH 81/52A represents the beginning of the optimum phase of sea-level.

V.9. Vegetational history

Pollen assemblage zone DHP1 is dominated by *Pinus*. The marine context of this core suggests that this dominance is a result of over-representation through flotation effects. This indicates that any vegetational changes are better illustrated by other tree taxa. Characteristics of the vegetation represented by the pollen spectra can be summarised as below:

1. In this zone the lowest and uppermost samples show high values for *Betula*. By contrast, the middle section shows very low values. In high values *Betula* is characteristic of boreal forest which represents the beginning and end of the temperate

cycle.

2. Gramineae are an important constituent of the vegetation dominated by *Betula*. Within this zone the values for Gramineae parallel the frequencies for *Betula*.

3. The presence of *Abies* and *Picea*, particularly their higher values in the central section, appears to be significant. It may also be significant that throughout the diagram *Picea* is higher than *Abies*.

4. Although *Alnus* is well represented, the representation of the thermophilous trees such as *Quercus* and *Corylus* is poor. *Corylus* follows the trends of *Betula* and Gramineae rather than the more usual reciprocal relationship.

5. Perhaps the most important feature is the sharp increase in the abundance of Ericales. Ericaceous heath often signifies the end of the interglacial cycle. The abundance of Ericales enables this zone to be separated from the upper sequence.

Poor concentrations, particularly the lack of thermophilous tree taxa, make interpretation of this pollen diagram difficult.

The presence of *Picea* and *Abies* suggests that this part of the diagram represents vegetation of temperate climate, and the abundance of *Betula* and *Gramineae* in the lower and upper part may represent the beginning and end of the temperate cycle respectively. If this is the case then the abundance of Ericaceous heath in the upper part supports this interpretation.

If DHP1 represents a temperate cycle then it seems reasonable to assume that the rest of the sequence represents a different climatic stage.

The pollen stratigraphy between 81 m and 135 m suggests that this sequence should also be divided into two parts: one (DHP2) between 84 m and 135 m which is characterised by boreal forest of *Pinus* and *Betula*, the other (DHP3), between 81 m and 83.5 m, which is represented by a mixture of boreal and thermophilous elements.

The interpretation of boreal forest between 84 m and 135 m (DHP2) is supported by the absence of thermophilous trees such as *Quercus*, *Abies* and *Picea;* the absence of *Alnus* is the strongest support for this interpretation.

The vegetation of DHP3 is also dominated by *Pinus* and *Betula*, but with the presence of thermophilous taxa such as *Abies*, *Picea*, *Alnus*, *Corylus* and *Quercus*.

The frequencies of thermophilous trees are even higher in DHP3 than in zone DHP1, clearly suggesting a temperate period. In particular the high values for *Alnus* clearly suggests the possible supply of contemporaneous pollen grains. This view is supported by the absence of pollen of thermophilous trees in DHP2. It therefore seems unlikely that the thermophilous elements are reworked and also reasonable to suggest that DHP3 represents temperate conditions but not as warm as DHP1.

The sequence between 80.95 m and 140.00 m is therefore interpreted as representing two warm periods of temperate climate separated by a cold period possibly of boreal climate.

V.10. Conclusions

This chapter aimed to compare a nearshore interglacial site close to an estuarine sediment source with a site away from such sources. Major differences are apparent between BH 81/52A and 81/34. Compared to the site in the Inner Silver Pit area, this site in the Devil' Hole area in the central North Sea does not contain pollen concentrations of sufficient magnitude to provide reliable data and the pollen assemblages are mixed with thermophilous and boreal elements occurring at the same level. In this open shelf context sediment supply is poor and the sedimentation rate very low. It is therefore concluded that though pollen analysis is remarkably useful for sites close to an estuarine sediment source area, it is of limited usefulness for sites away from the coast and in deeper offshore areas.

Pollen analysis of samples from the sequence between 81 m and 141 m in BH 81/34 supports the interpretation of the foraminiferal data suggesting that the Ling Bank Formation represents two warm periods separated by a cold period. The pollen assemblages suggest that these two warm periods fall within the later part of the Cromerian Complex of the Netherlands. Evidence from seismic records and palaeomagnetic investigations support this view.

Chapter VI

The North Sea and sequence stratigraphy

VI.1. Introduction

Pleistocene alterations of ocean volumes expressed as relative changes in sea-level are regarded as being largely the consequence of the accumulation and melting of continental ice sheets (Shackleton and Opdyke, 1973; 1976). This results in a lowstand of sea-level during glacial periods and a highstand during interglacial periods (Vail *et al.*, 1977). A lowstand-highstand couplet constitutes a eustatic cycle. These cycles are identified by multiple criteria, including palaeontologic, sedimentologic and seismic evidence (Haq *et al.*, 1988).

Seismic stratigraphy (Vail *et al.*, 1977) is that branch of stratigraphy which facilitates regional and inter-regional correlation by subdividing the rock record into a succession of depositional sequences composed of genetically related strata. Seismic stratigraphy uses eustatic cycle components to identify seismic (depositional) sequences (Vail *et al.*, 1977). Such seismic-sequence analysis is based on identification of discrete stratigraphic units with relatively conformable sequences of strata by using reflection patterns on the seismogram. For example, glacial periods may exhibit chaotic bedding surfaces on the seismogram, whereas interglacial periods may display parallel bedding surfaces (Tappin, 1991). Seismic sequence analyses therefore provide a sound basis for applying the global system of geochronology to seismic data for the improvement of the stratigraphic and environmental interpretation.

Sequence stratigraphy (Posamentier and Vail, 1988) is a recent concept within stratigraphy originating from seismic stratigraphy (Vail *et al.*, 1977). Sequence (Appendix VII & VIII) stratigraphy (Fig.VI.1) does not exclusively depend on seismic data, and it is equally applicable to subsurface (seismic and well-log) as well as to outcrop data (Fig. VI.12). The growth of sequence stratigraphy concept was a reaction to criticism on limitations* of seismic stratigraphy and the need to reduce reliance on proprietary seismic and well log data. This facilitated the development of alternative criteria for the identification of sea-level changes in easily accessible sections. These also provide better biochronostratigraphic information than subsurface sites.

This chapter aims to utilise detailed information available from the Nar Valley (Ventris, 1985) and the Inner Silver Pit (this thesis) within the concept of sequence

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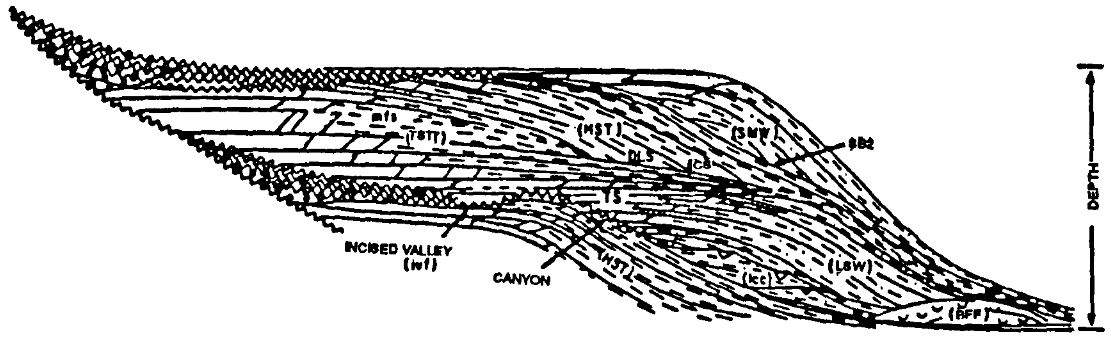
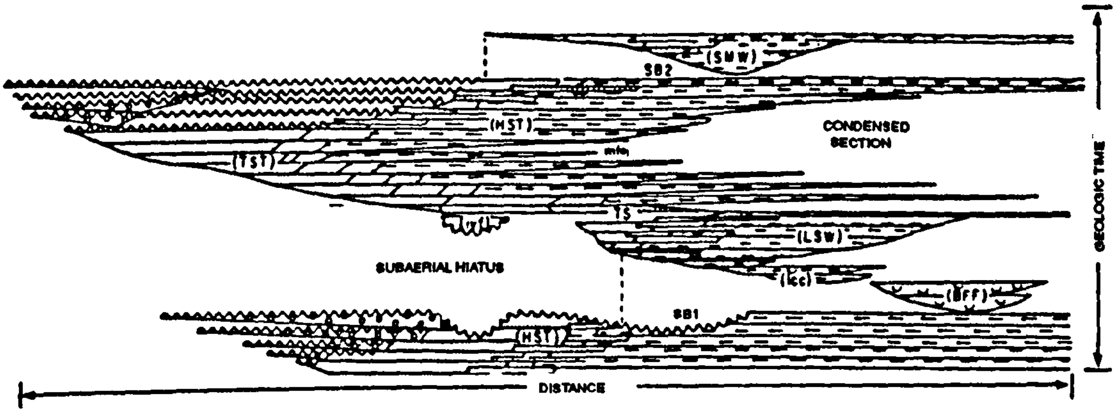
* The resolution of events on seismic stratigraphically based sea-level curves was, however, limited by the resolution of the seismic data. On seismic profiles only features that are several tens of metres and larger in thickness are resolvable.

SEQUENCE STRATIGRAPHY
(Posamentier and Vail, 1988)



A) IN DEPTH



B) IN GEOLOGIC TIME

LEGEND

ALLUVIAL
COASTAL PLAIN
ESTUARINE/FLUVIAL
SHOREFACE/DELATIC SAND
MARINE SILTY, MUDSTONE
MARINE SHAL
DEEP WATER SANDS

SB1 = SEQUENCE BOUNDARY TYPE 1
SB2 = SEQUENCE BOUNDARY TYPE 2
(BFF) = BASIN FLOOR FAN
(LSW) = LOWSTAND WEDGE SYSTEM TRACT
IVf = INCISED VALLEY FILL
lcc = LEVEED CHANNEL COMPLEX

TS = TRANSGRESSIVE SURFACE
(TST) = TRANSGRESSIVE SYSTEM TRACT
mfs = MAXIMUM FLOODING SURFACE
(cs) = CONDENSED SECTION
DLS = DOWNLAP SURFACE
(HST) = HIGHSTAND SYSTEM TRACT
(SMW) = SHELF MARGIN WEDGE SYSTEM TRACT

Fig. VI.1. A schematic diagram of sequence-stratigraphic depositional model, showing depositional system tracts (in depth and geologic time), their boundary surfaces, and contained silisiclastic facies. System tract in a type 1 sequence (those overlying type 1 sequence boundary) include, basin-floor fan (or slope fan), lowstand wedge, transgressive and highstand systems tracts. Those associated with a type 2 sequence (overlying a type 2 sequence boundary) include, shelf-margin wedge, transgressive, and highstand system tracts, (from Haq, 1990).

stratigraphy. Investigations in the Nar Valley provide detailed information about the marine transgression during the Hoxnian (Holsteinian) interglacial stage. These data are gathered from several sites from the Nar Valley; however, none of them has provided a record of the post-temperate substage of the interglacial cycle (Fig.VI.2). This missing substage is probably a result of regression and subsequent erosion (Ventris, 1985). From the extensive amount of research on sequence stratigraphy it is apparent that marine sediments of the post-temperate substage of the interglacial cycle should not be expected on land (Posamentier and Vail, 1988; Haq, 1990; Vail *et al.*, 1991). In the context of sequence stratigraphy, the absence of the post-temperate substage in the Nar Valley area and its presence in the Inner Silver Pit area would appear to be the result of change of sea-level or the basinward migration of the shoreline (detail below). Pollen and micropalaeontological data from the Inner Silver Pit and the Nar Valley suggest that the environmental history of this stage was characterised by eustatically rising sea-level, suggesting that the concepts available from sequence stratigraphy might be useful in explaining the pattern of sedimentation.

In applying the concepts of sequence stratigraphy, the available evidence on sea-level changes are first summarised (section 2a below). These are then used to explain the depositional history of the sequence recovered in BH 81/52A in the light of the model discussed by Posamentier and Vail (1988), Haq (1990), Vail *et al.* (1991) and section 3 below.

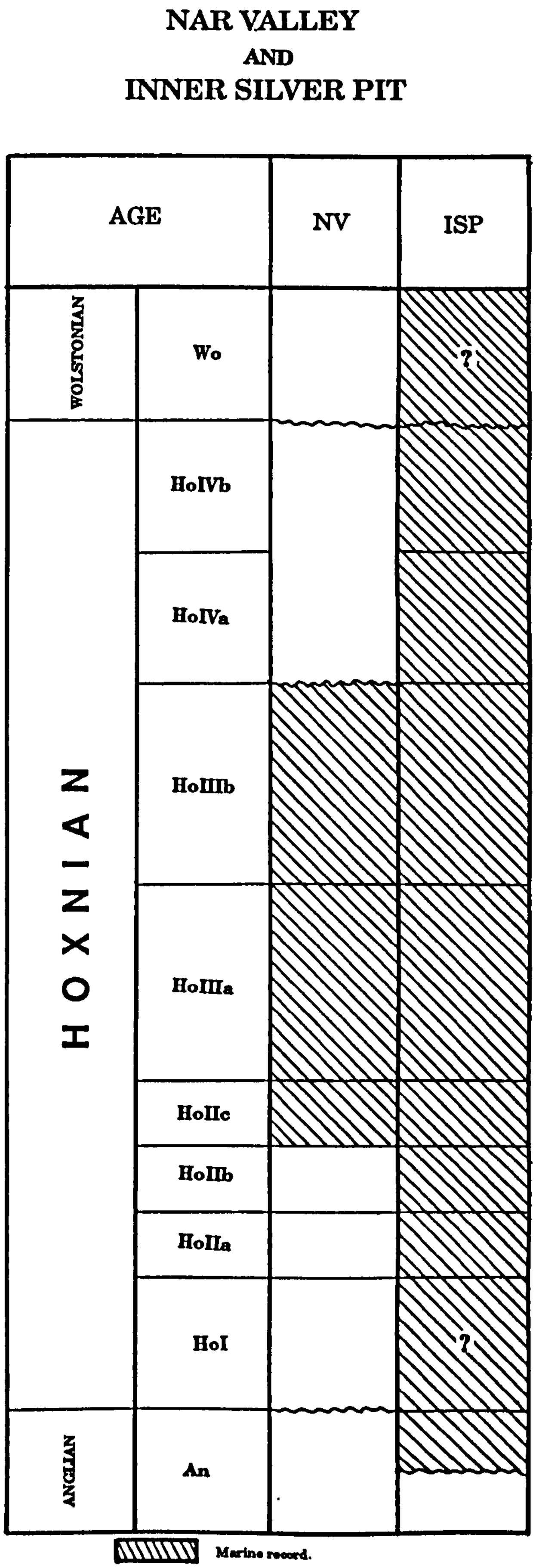


Fig. VI.2. Comparison between marine depositional history in the Nar Valley (Ventris, 1985) and Inner Silver Pit (this thesis) areas.

At the end of this Chapter the evidence available from biostratigraphic and other sources are used to construct sea-level curve for the eustatic cycle (section V.5).

Terms and definitions used below are taken from Mitchum (1977), Mitchum *et al.* (1977) Brown and Fisher (1977), Haq *et al.* (1987, 88a), van Wagoner *et al.* (1988), Jervey (1988), Loutit *et al.* (1988), Posamenteir *et al.* (1988), Sarg (1988) and Vail *et al.* (1991).

VI.2. Data presentation - Results

a) Evidence from the Inner Silver Pit (this study)

1. Borehole 81/52A
2. Vibrocore 53/00/1103
3. Vibrocore 53/00/962
4. Vibrocore 53/00/1104

1. Borehole 81/52A

This borehole presents the complete depositional history of the Hoxnian (Holsteinian) interglacial cycle. Palynological evidence shows that the sequence representing the lower half of the interglacial is sandy and poorly polleniferous. However, the upper half of the sequence contains substages HoII, HoIII and HoIV of the interglacial. The deposit lies in a shallow basin created (or modified) during the Anglian (Elsterian) glaciation. The depth of the base and top of the deposit is variable, but on the eastern margin of the basin (Fig. III.6) the deposits feather out and the overlying Egmond Ground Formation directly overlies the Swarte Bank Formation. The seismic evidence indicates that this depth was the general bathymetric surface at the beginning of Holsteinian (Hoxnian) in this area. This depth may therefore be used as the reference palaeobathymetry of the Holsteinian in the Inner Silver Pit area. The sequence in the borehole suggests that the contact between the Sand Hole Formation and the Egmond Ground Formation is unconformable, but that the contact between the Swarte Bank Formation and the Sand Hole Formation is conformable. In the borehole the Sand Hole Formation rests conformably on the Swarte Bank Formation, this level representing the beginning of the interglacial phase (Table VI.1) This suggests the base of the interglacial deposit represents the base of the palaeobasin. The drilled depth in the borehole for the various substages are:

HoIV	29.67m - 30.70m	very high pollen concentrations
HoIII	30.71m - 38.00m	high pollen concentrations
HoII	38.01m - 39.20m	poor pollen concentrations
HoI	39.21m - 40.67m	not (very poorly) recovered

Anglian glacigenic sediments = 40.68m - 43.20m

2) Vibrocore 53/00/1103

The location of the vibrocores are marked in Fig. III.2 and correlation with borehole 81/51A is presented in Fig.

Table VI.1. Depth below seabed for various units and substages for the Anglian cold stage and Hoxnian temperate stage recognised in BH 81/52A (this thesis).

Age	**Units or Substages**	**Depth below seabed**
Hoxnian temperate stage	HoIV	30.70 - 29.67 m
	HoIII	38.00 - 30.75 m
	HoII	?39.20- 38.00 m
	HoI	40.67 - ?39.20m
Anglian cold stage	Unit III	41.80 - 40.67 m
	Unit II	42.50 - 41.80 m
	Unit I	43.20 - 42.50 m

Water depth at the site is 20.20 m (not included).

IV.16. The water depth at this site was 68 m (also see Table IV.1). This vibrocore comprises 3.11 m of interglacial silty clay with an unconformable upper contact underlying 0.17 m of recent and sub-recent sediments. Palynological investigations suggests that this vibrocore represents the lower part of zone 'a' of Hoxnian substage HoIII (Fig IV.16).

3) Vibrocore 53/00/962

This vibrocore penetrated 1.51 m of silty clay. The top of the sequence is marked by an unconformable contact underlying 0.34 m of recent or sub-recent sediments. Pollen analysis of this vibrocore clearly suggests correlation with the central part of zone 'b' of Hoxnian substage HoIII.

4) Vibrocore 53/00/1104

The interglacial silty-clay sequence recovered in this vibrocore is 2.6 m thick. Water depth at the site was 54 m. The upper unconformable contact underlies 0.16 m of recent or sub-recent sediments. Palynological results from this vibrocore suggest it can be correlated with zone 'a' of substage HoIV.

b) Evidence from the Nar Valley (Ventris, 1985)

Using data from previous work (Ventris, 1985; Stevens, 1960), five sites in the Nar Valley have been chosen as being the most important for the interpretation of Hoxnian (Holsteinian) sea-levels. Evidence from these sites is presented in Fig.VI.3 from west to east and briefly described below.

1. Setch borehole (159/62) (Ventris, 1985).
2. Tottenhill (Ventris, 1985)
3. Horse Fen (Stevens, 1960)
4. East Winch (Ventris, 1985)
5. Summer End (Stevens, 1960)

The heights above O.D. and ages for each of these sites are shown in Fig. VI.3.

1. Setch borehole (159/62) (Ventris, 1985)

The log for this borehole records 'Nar Valley Marine Clay' between -2 m O.D. and 1.7 m O.D. The contact with the underlying Nar Valley Freshwater Member in this borehole is conformable. The age of the Nar Valley Clay at this site has not been established in detail (Ventris, 1985).

2. Tottenhill (Ventris, 1985)

At this site the Nar Valley Clay rests conformably upon the Nar Valley Freshwater Member. The contact is at 2.5 m O.D. and extends up to 3.7 m O.D. to form the ground surface within the pit. Palynological analysis of the Nar Valley Clay at Tottenhill showed that it can be correlated with substage HoIIc of the Hoxnian interglacial.

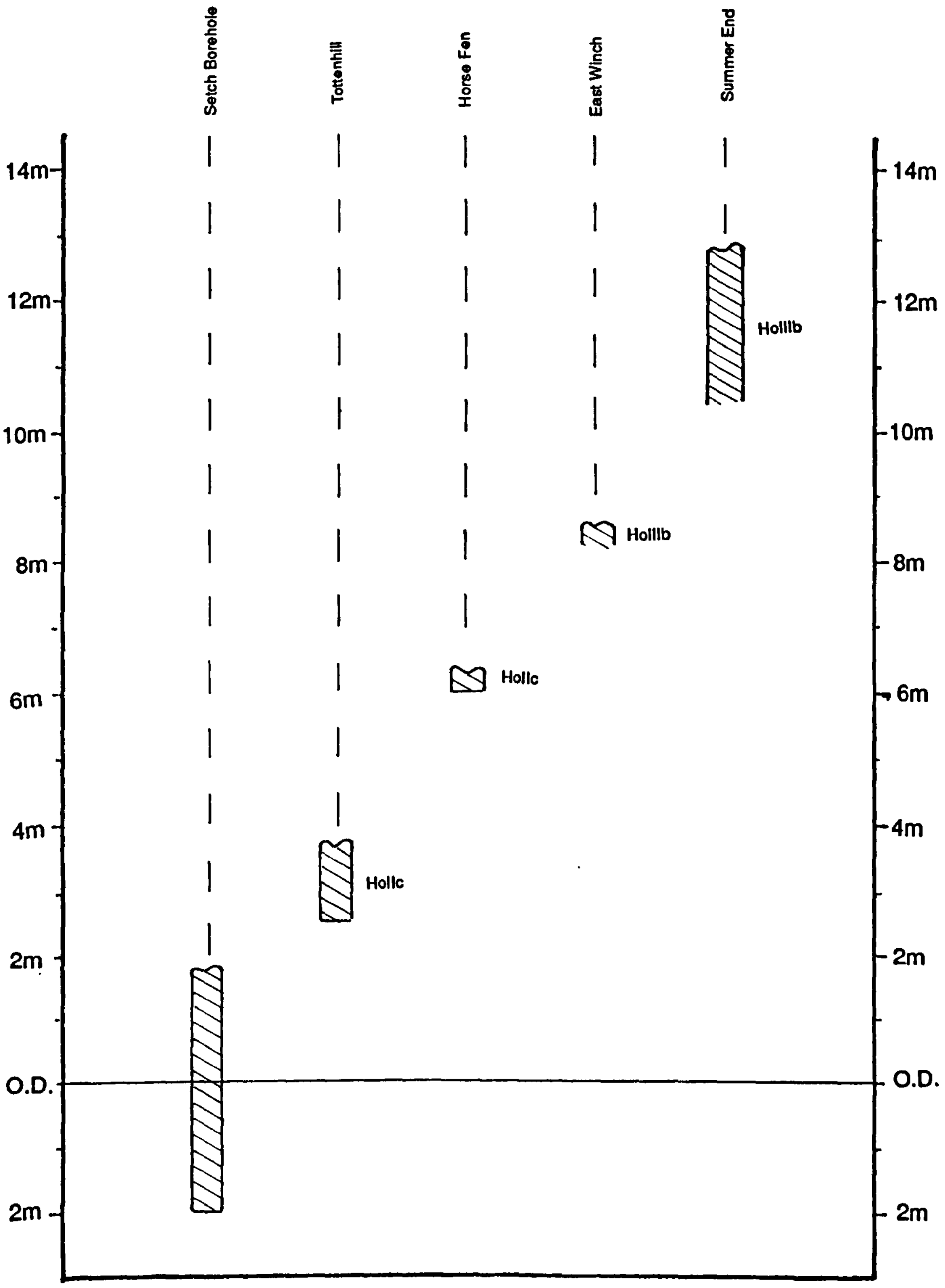


Fig. VI.3. Sites in the Nar Valley recording evidence for high sea-level during the Hoxnian stage (showing age and height between O.D. of the sediments (from Ventris, 1985).

3. Horse Fen (Stevens, 1960)

The Nar Valley Clay described from this site extends from 6.0 m O.D. to the ground surface at 6.25 m O.D., and rests conformably on the Nar Valley Freshwater Member. The pollen, characterised by a peak for *Ulmus* and an increase in *Corylus* pollen frequencies accompanied by an absence of *Carpinus* pollen, led Stevens to correlate this unit with substage HoIIc. An increase in the frequencies of *Pinus* pollen and decreases in the values for other taxa are considered the result of taphonomic factors (described in section III.8,b,i).

4. East Winch

At this site the Nar Valley Clay was exposed at a height of 8.5 m O.D. This exposure was a temporary ditch section and the base of the unit could not be observed. Palynological results indicate correlation with Hoxnian substage HoIIIb.

5. Summer End (Stevens, 1960)

The borehole at this site penetrated through the Nar Valley Clay from 12.8 m O.D. to 10.5 m O.D. but did not reach the base of this unit. Palynological results showed high frequencies of *Abies* and suggested correlation with HoIIIb.

c) Evidence from continental Europe

Evidence of sea-level changes from continental NW Europe for the Holsteinian (Hoxnian) stage are available from:

1. Cléon in France (Lautridon, 1982).
2. Herzele in Belgium (Paepe *et al.*, 1981)
3. Lauenberg Clay in Germany (Ehlers *et al.*, 1984)

In France, the St. Aubin-les-Elbeuf Member of the Cleon Formation contains marine Holsteinian deposits at 11-12 m above sea level, whereas in Belgium the Herzelee Formation is believed to represent marine Holsteinian. Deposits of the Herzele Formation in Belgium reach an altitude of 10-15m O.D.(Paepe *et al.*, 1981). In Germany, near Hamburg, marine deposits of the Holsteinian are found infilling glacial 'tunnel valleys' similar to the Nar Valley sequence (Ehlers *et al.*, 1984). The glacial deposits are overlain by freshwater Holsteinian deposits and then the marine Holsteinian. The top of the marine deposits is 15-20 m below sea level. "These differences in heights of the marine Holsteinian deposits may well reflect downwarping within the North Sea Basin" (Ventris, 1985, *op. cit.*).

VI.3. The Hoxnian (Holsteinian) and sequence stratigraphy

Posamentier *et al.* (1988) have discussed the sea-level control of clastic deposition on continental shelves in considerable detail. Haq (1990) has reviewed the dynamics of clastic deposition along with some variations to models by changing the parameters that control the sedimentary patterns. Vail *et al.* (1991) have presented an overview on sequence stratigraphic signatures. Their model is used as a basis in this study in the context of the Inner Silver Pit and the Nar Valley. This results in a clearer understanding of the context of sea-level in the depositional history during the Hoxnian (Holsteinian) stage.

A complete cycle of sea-level change is considered to start with a sea-level fall from a relative highstand position followed by a rise and a subsequent drop. Once the sea level falls from inflection point F (Fig.VI.4 and Appendix VII) deposition of the lowstand system tract begins and continues until inflection point R which marks the beginning of the transgressive tract. Transgressive tract continues to be deposited until the cycle reaches inflection point F which completes the cycle.

a) Sea-level fall and lowstand system tract

The lower boundary of a sequence is marked by a relative fall of sea level. The lowstand system tract (Fig.VI.5) begins to be deposited once the sea level passes below the inflection point on the sea-level curve (Posamentier *et al.*, 1988). When the sea level drops beyond the depositional shore-line break, and the rate of eustatic

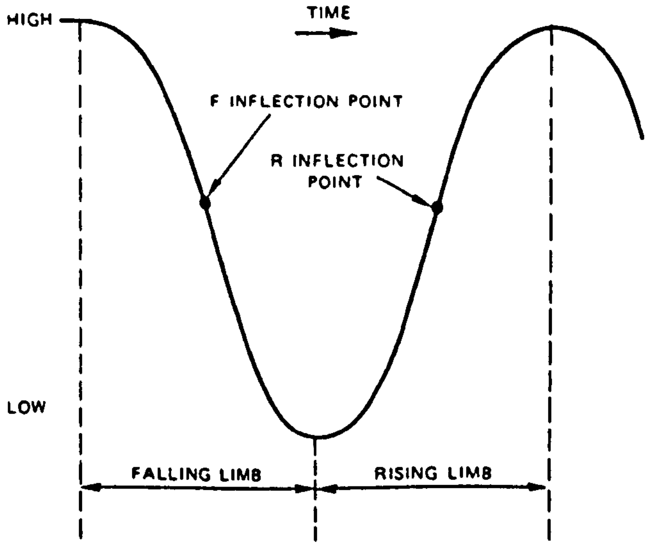


Fig. VI.4. Elements of Eustatic change (from Posamentier *et al.*, 1988)

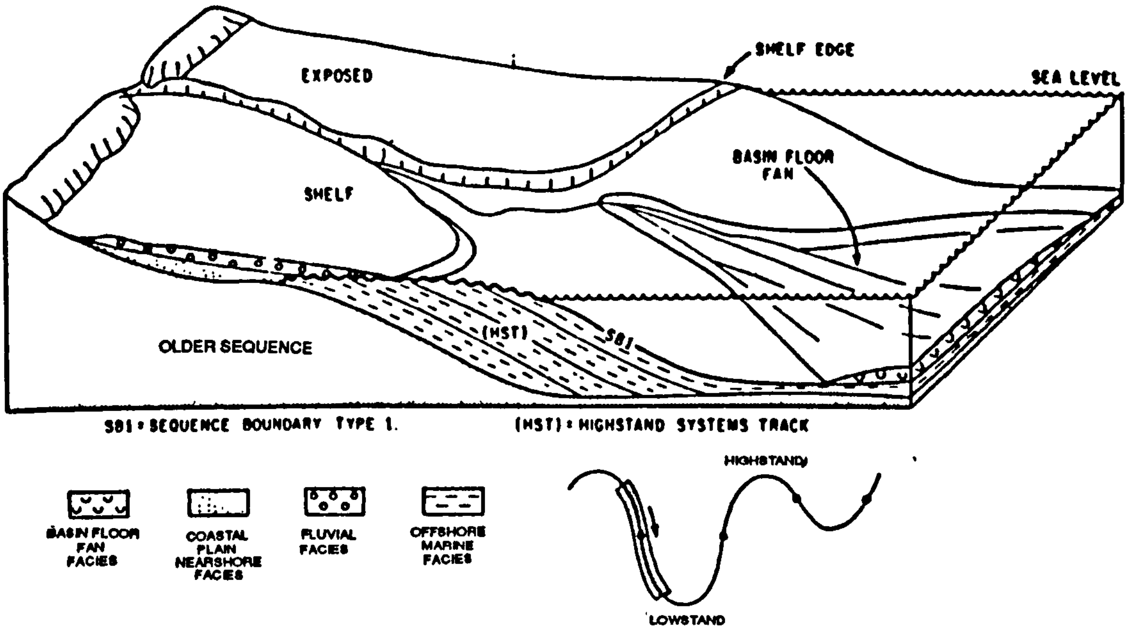


Fig. VI.5. Siliciclastic system. Schematic block diagram showing a major sea-level fall and formation of type 1 sequence boundary, overlain by a basin-floor fan during the early phase of lowstand time (from Haq, 1990).

fall is greater than the rate of subsidence, much of the upper shelf may be exposed. If the sea-level drop is extensive and falls below the shelf break, the entire shelf may be exposed. The resulting sequence boundary may be recognised by an abrupt basinward shift of coastal onlap (Vail *et al.*, 1991).

Erosion is initiated with subaerial exposure of the shelf (Fig. VI.6). Incision of the shelf occurs as stream equilibrium profiles are lowered (Posamentier and Vail, 1988). A prominent unconformity is developed by the transformation of the shelf from an area of deposition to an area of erosion. Directly above the unconformity the basal lithology may display lag gravel, rip-up clasts of underlying lithologies and fossil shell debris (Boum and Vail, 1988; Boulton, 1990).

Lowstand system tracts composed of siliciclastic sediments have been studied in three settings of basin. One is associated with a deep-water shelf-margin setting, another with a growth-fault setting and the third with ramp* setting (Vail *et al.*, 1991).

It is important to note that the area of the Inner Silver Pit has not been subaerially exposed during the period under consideration (section III.16). The depositional system would therefore have been different from

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* "Ramp setting, if there is no physiographic shelf-slope break and the depositional margin is ramp-like as is often the case in basin in the continental interior (epeiric) seas, the lowstand system tract is relatively thin" (Haq, 1990 *op. cit.)*.

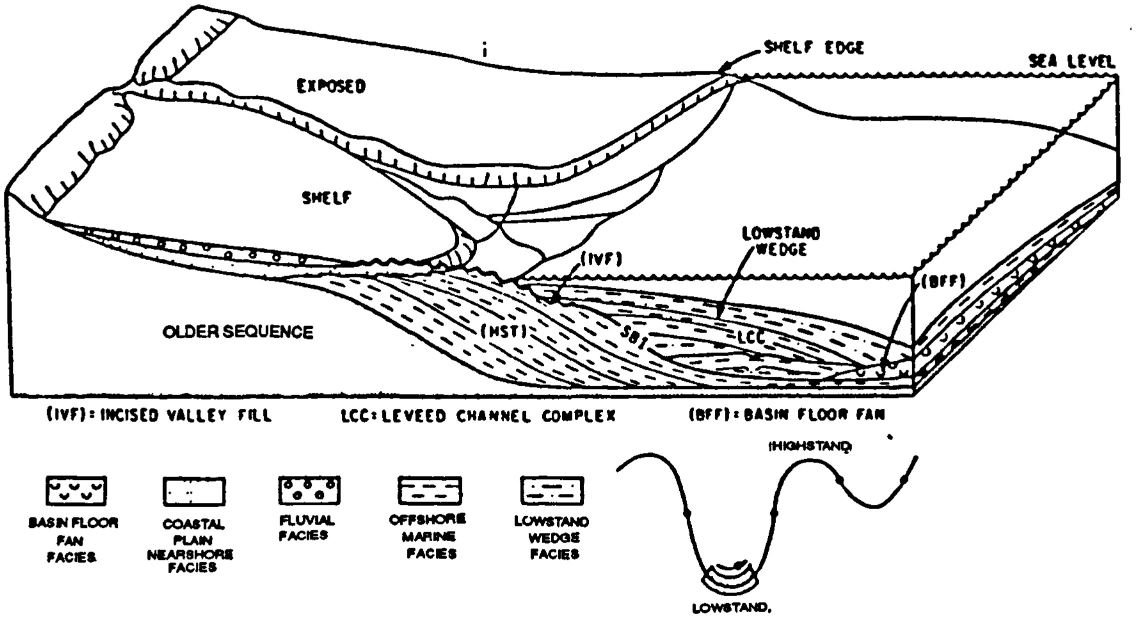


Fig. VI.6. Silisiclastic system. Later phase of the lowstand and the formation of incised valley system, leveed channel complex, and the lowstand wedge system tract, (from Haq, 1990) an area which was subaerially exposed. Instead, the area was covered by ice sheet (Elsterian/Anglian); it is therefore necessary to use a model which can accommodate glacial environments in conjunction with sequence stratigraphy. This can be achieved using the Boulton (1990) model (Fig. VI.7) which accommodates various stages of glaciation and also the nature and type of the corresponding deposits (see discussion below).

i) Lowstand and Anglian (Elsterian) deposits

The site where borehole 81/52A was drilled has a current water depth of 20.20 m. However the boundary between Anglian and Hoxnian is represented at 40.67 m below seabed and the total depth of 60.87 m therefore represents the present-day palaeodepth (Figs. VI.3, III.6).

The Model (Fig. VI.7) shows that the until late-optimum glaciation of the Anglian (Elsterian) there was little sedimentation while the ice sheet kept moving forward and eroding previously deposited sediments. Rapid deposition did not begin until the ice sheet disintegrated. The third stage in the Boulton model demonstrates erosion by moving ice.

The model also demonstrates that on the inner shelf processes are more complicated than on the outer shelf. On the outer shelf, if the basin is fairly deep, stratified glacial marine sediments can be deposited during the advance of the ice sheet. As the ice sheet reaches the outer shelf it deposits till. In the later half of the maximum phase the

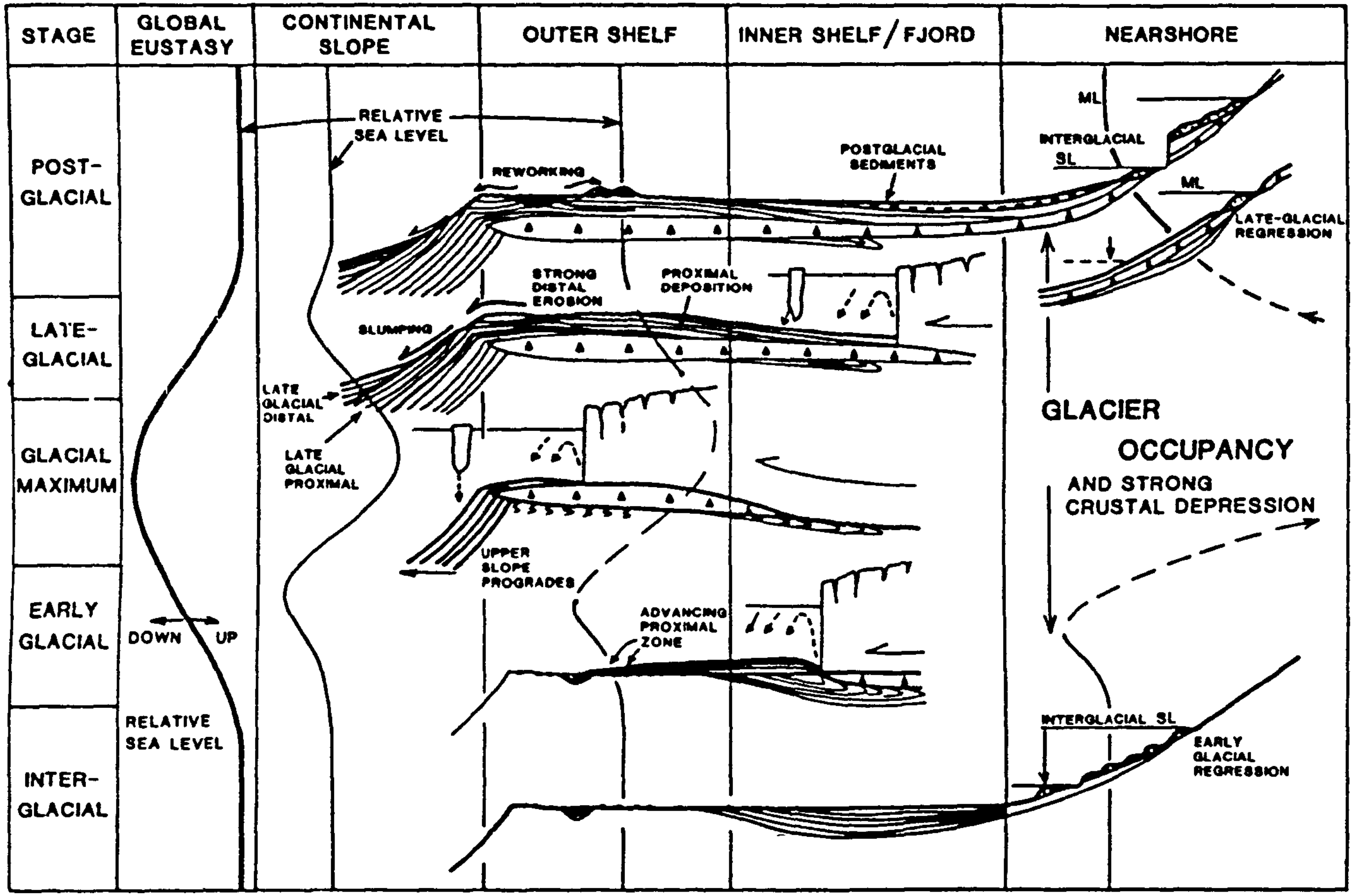


Fig. VI.7. A model of glacimarine architecture in space and time showing the binding blocks of glacimarine facies architecture in different continental margin localities which accumulate through a whole glacial cycle. The relative sea-level changes appropriate to each zone are shown, (from Boulton, 1990).

ice sheet stops and begins to disintegrate and retreats, and sedimentation increases. Tills deposited during this phase are characterised by chaotic reflectors on seismic records.

As the ice sheet continues to melt and disintegrate the area becomes glaciolacustrine and receives increasing amounts of sediment. Sediments deposited during this stage overlies the basal till, and are characterised by parallel to subparallel reflectors draped over the underlying irregularities. These sediments represent quiet water conditions (cf. Balson and Cameron, 1985; Tappin, 1991). As ice continues melting and sea-level rises well-stratified glacial marine sediments are deposited. In the borehole 81/52A all these three types of glacial sediments are recovered (section III.16,a).

b) Transgressive system tract

Transgression of the sea, the eustatic sea-level rise, and the first major flooding event on the shelf is marked by the transgressive surface (Fig.VI.8). This surface is erosional due to the vigorous action of the transgressive sea. This surface separates the deposits of the lowstand and transgressive system tracts. Transgressive facies of this system tract are characterised by reterogradational parasequences. As the transgression continues terrigenous sediments are increasingly deposited in more landward positions. Hemiplegic sediments begin to cover the shelf basinward. Parasequences in the transgressive system tract onlap landward onto the sequence boundary. Basinward they

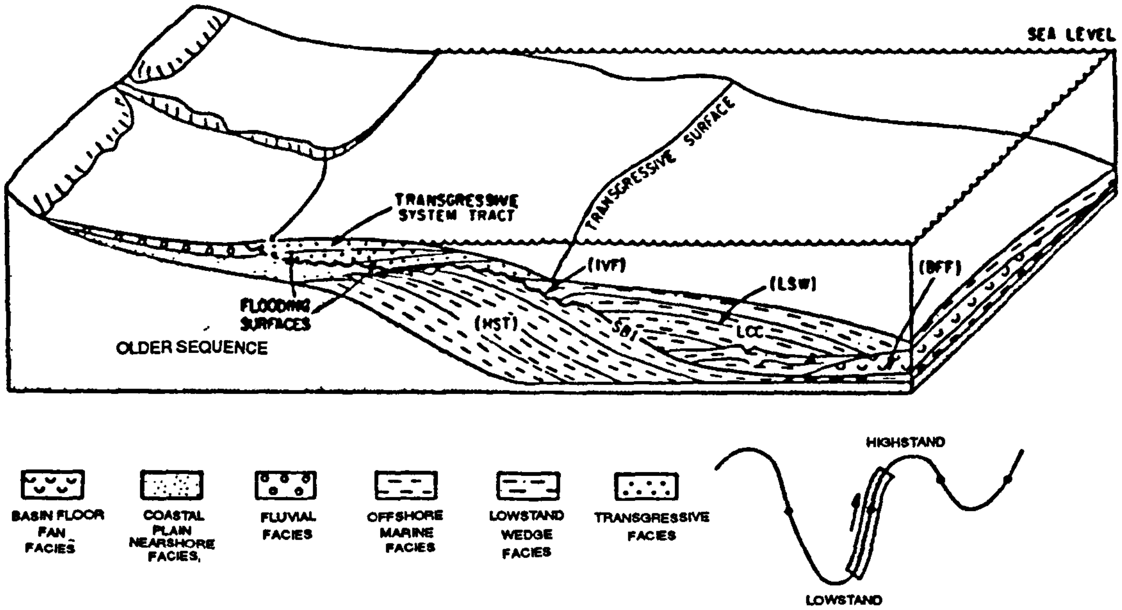


Fig. VI.8. Silisiclastic system. Sea-level rise and transgression of the shelf at the transgressive surface, and the formation of landward back-stepping, transgressive system tract on the shelf, punctuated by numerous flooding events, marked by flooding surface, from Haq, 1990).

downlap onto the transgressive surface (van Wagner *et al.*, 1988). Deposition of the transgressive facies continues progressively landward until the time of maximum flooding (Fig. VI.1). The point of maximum flooding is itself represented as a downlap surface on seismic profiles and is not included in the transgressive system tract sequence. It is included in the following deposits of the highstand system tract.

The top of the transgressive system tract is marked by a condensed section at the maximum flooding surface which is produced by sediment starvation (Fig. VI.9).

The deposits recovered in BH 81/52A were deposited in a shallow basin on the inner shelf. This shallow basin became submerged before the transgressive stage or within the lowstand system tract deposits. Sediments in the later stage of lowstand deposition (Anglian stage) were deposited in a glacial marine environment. Transgression of the sea, which is usually marked by an erosional surface on the top of the lowstand deposits, is thus represented as a conformable contact. This contact, which cannot be recognised on the seismic records (D. Tappin, *pers.comm.*), has been recognised on the basis of biostratigraphy and sedimentology (Chapter III).

i) Transgressive system tract and Hoxnian (Holsteinian) deposits

The transgressive surface, or first flooding event, is

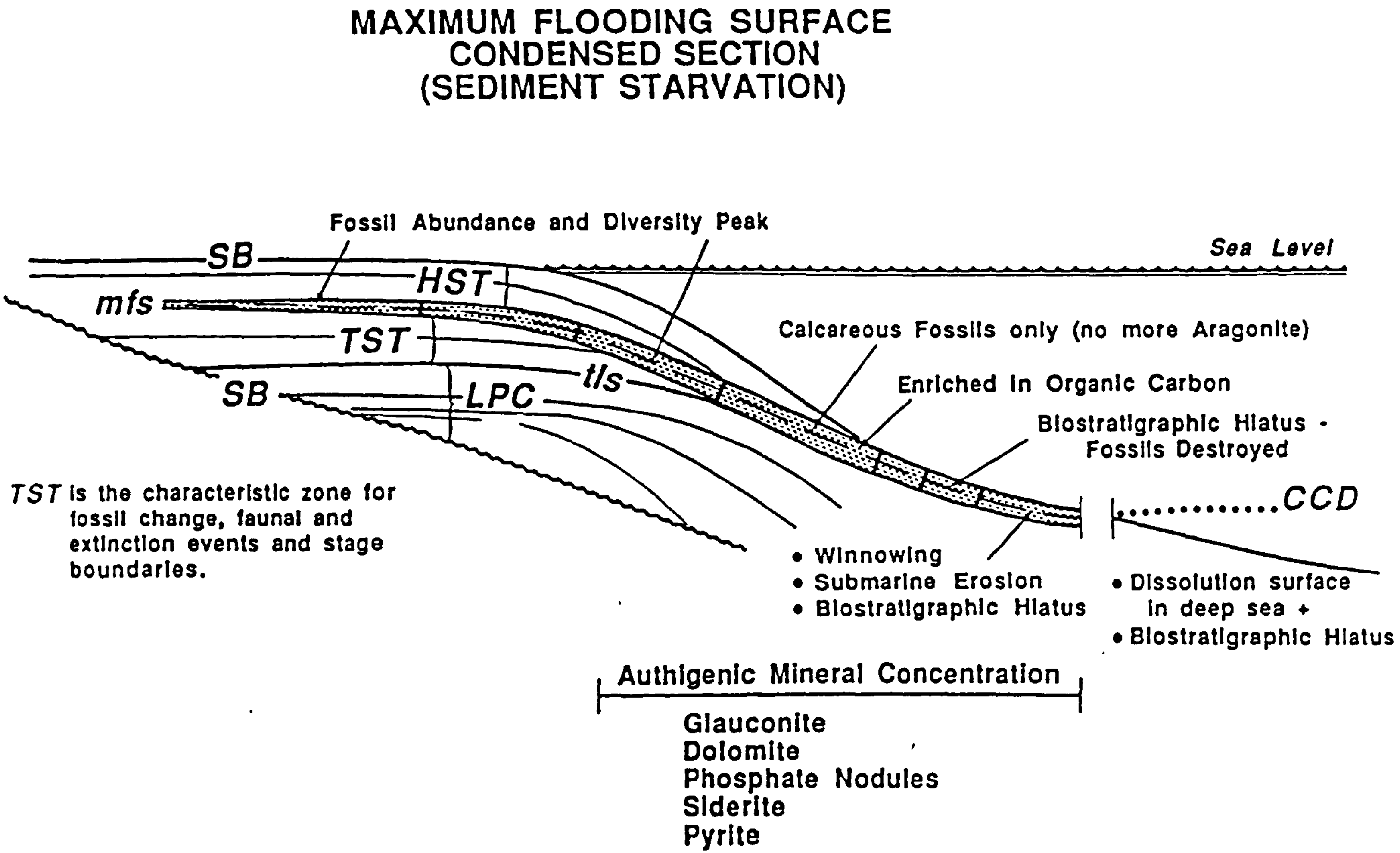


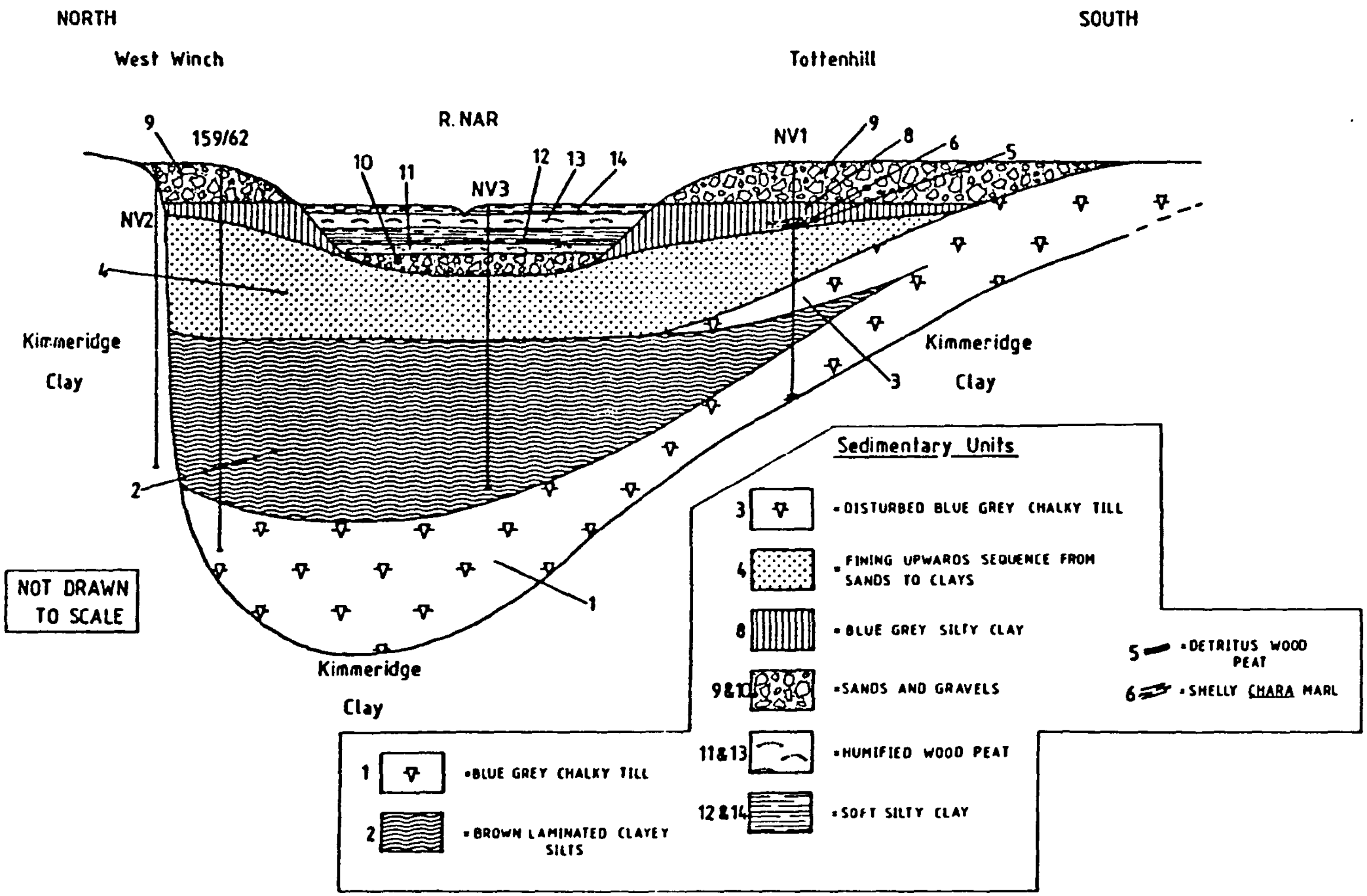
Fig. VI.9. Character of maximum flooding surface from shallow to deep settings, (from Vail *et al.*, 1991).

recorded in the Nar Valley where evidence of a gradual transgression has been found (for detail see Ventris, 1985).

The sequence represented by sediments that onlap and fill incised valleys consist of a complex system of fluvial, estuarine and marine sediments (Ventris, 1985; Fig. VI.10). The incised valley fill sediments tend to have a strong aggradational component with no indication of landward movement of shoreline (Clifton 1982; Mossop and Flach, 1983).

The top of the incised valley-fill deposits is marked by a transgressive surface that separates the incised valley-fill deposits from overlying deposits of the same sequence. The transgressive surface is characterised by erosional features. This means that it is uncommon to find a continuous sequence representing lowstand and transgressive deposits, even in valleys where the top of the lowstand deposits is not directly exposed to shoreline erosion. In the Nar Valley a sequence of freshwater deposits through lacustrine to marine sediments is found (Ventris, 1985). However, "the Freshwater Member is conformably overlain by the Nar Valley Clay but these clays do not always rest on the Freshwater Member deposits. Apart from the isolated occurrences within the Nar Valley, the extent of the unit remain largely unknown" (Ventris, 1985, *op. cit.*). This situation may be a result of the encroachment or landward migration of the shoreline which caused erosion and also removal of the Freshwater Member. This clearly suggests that a complete sequence can be found only in those valleys or

Fig. VI.10. Cross section of the lower Nar Valley, Norfolk, from Ventris, 1985).



basins which would have become submerged within the lowstand system period. The deposits of the Inner Silver Pit are situated in such a setting and represent glacial-marine deposition during the lowstand system tract.

In the Inner Silver Pit deposits of this transgressive system tract are very well represented. Since this is an offshore site, transgressive records are not isolated or fragmentary. The continuous sequence here represents the complete interglacial cycle. The various stages can be correlated with the pollen zones as below:

i) The cycle begins with estuarine erosion on coastal areas supplying a high amount of reworked material and resulting in the very poor concentrations of pollen in substage HoI. The sedimentation rate was very high during this stage (detail in discussions below).

ii) Sea-level continued rising and supplied a large amount of reworked material. However, though poor, pollen concentrations improve in HoII and the sedimentation rate was relatively low.

iii) As sea-level continued rising in HoIIIa higher pollen concentrations and lower amount of reworked material are found. In this zone the sand proportion is lower whilst silt and particularly clay dominate.

iv) HoIIIb represents the peak of the transgression characterised by low sand and high clay percentages during the later phase of the late-temperate substage represented by the peak of *Abies*. Transgressive facies continued to be deposited until the time of maximum flooding. The surface of maximum flooding can be identified at 31.4 m which shows the maximum starvation of sediments. This depth represents the time when the 'highstand sea' become established and the 'highstand facies' began to accumulate.

ii) Condensed section

During the time of maximum flooding a physically condensed section is created on the outer shelf and slope (the Inner Silver Pit lies within the inner shelf as discussed below). Land-derived sediments are increasingly deposited nearshore, Loutil *et al.* (1988) and the shelf is starved of sediments. Loutil *et al.* have discussed, in detail, the significance of such condensed sections. During this time pelagic or hemiplegic sediments may be deposited over broad areas of the shelf (Fig. VI.9).

In a depositional sequence the condensed section occurs within the highstand system tract. The condensed section is represented by thin marine stratigraphic units consisting of pelagic to hemiplagic sediments characterised by very slow sedimentation rates (Loutil *et al.*, 1988). Since marine condensed sections are created by sediment starvation, they are often characterised by thin zones, apparent hiatus and bioturbated somewhat lithified beds or hardgrounds (Baum and Vail, 1988; Loutit *et al.*, 1988). Sediment starvation usually causes concentration of authigenic minerals (phosphorite, glauconite), pelagic fossils (diverse planktonic and benthonic assemblages), organic matter and trace elements. Strong positive anomalies on gamma-ray well log readings, produced by the concentration of radiogenic matter (U, Th) in the condensed sections may be used to identify such sections (Baum and Vail, 1988; Loutit *et al.*, 1988).

In borehole 81/52A the level at 31.40 m seems to represent the point of maximum flooding or the base of the condensed section, represented by high values for organic matter and the highest value for *Abies*.

c) Highstand system tract

This system tract is bounded at its base by the condensed section and the downlap surface, and its top is the sequence boundary, representing a sea-level fall and the beginning of a new cycle of sedimentation (Fig.VI.11). After maximum flooding, the deposits of the highstand system tract are marked by aggradationally stacked parasequences (van Wagnor *et al.*, 1988).

The deposits of the highstand system tract are commonly

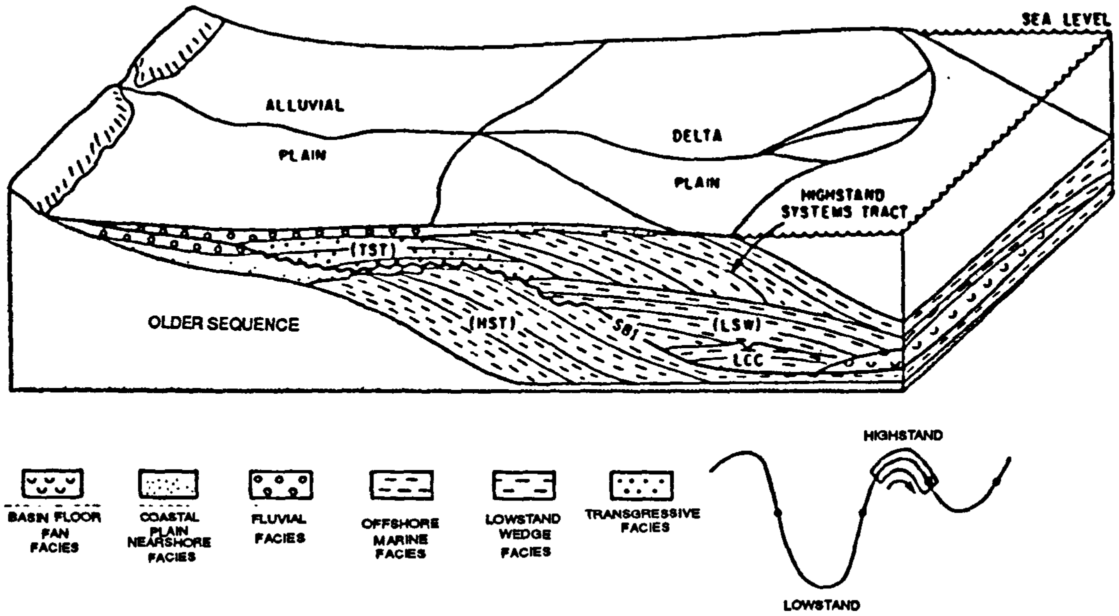


Fig. VI.11. Silisiclastic system. Highstand time and formation of initially aggradational and later increasingly progradational parasequences of the highstand system tract, (Haq, 1990).

the most widespread genetically-related sediment packages on the shelf, often prograding out over the slope. However, major sea level falls and the erosion of the shelf often remove at least part of the complete record of the previous sedimentary cycle(s). On the other hand, the record of sea-level rise may be preserved intact, or may at least be represented by the maximum landward marine incursion. These intact records represent the available evidence of sea level change. This is why the sedimentary record gives the impression that sea-level rises are gradual and sea-level falls are abrupt. During the highstand of sea level, as the accommodation potential for the sediment accumulation on the shelf decreases progressively or the space between sea level and seafloor is filled, the shoreline starts to regress and the sediments prograde further out into the basin. The regression of the shoreline basinward is caused by sediment accumulation characteristically associated with the latter phase of the relative sea level highstand. This means that the top of the highstand system tract will be associated with widespread fluvial deposition above the shoreline (Posamentier and Vail, 1988). During the highstand, however, associated with basinward migration of shoreline, landward migration of longshore currents may cause erosion and extensive hiatus. If the currents are strong enough and encroach the shelf, they can cause extended erosion of the shelf. This may be another reason why the interglacial marine sedimentary record is so fragmentary and explain why such sediments are only found in deeps.

Sea level continues to fall and once the inflection point F is reached the depositional cycle is completed. The top of the highstand deposits (sequence) is bounded by a sequence boundary. When the fall of relative sea-level is extensive and extends beyond the shelf break a type 1 sequence boundary terminates the cycle (Appendix VIII and Fig.VI.1). However, if the fall is not extensive and the shelf only partially exposed, the shelf margin wedge system tract progrades directly over the shelf break.

i) Highstand system tract and Hoxnian (Holsteinian) deposits

In borehole 81/52A the sediments of the highstand system tract are represented by the sequence between 29.67 and 30.70 m. These highstand deposits are represented by quite high pollen concentrations.

No sediments younger than pollen zone HoIIIb have so far been recorded from the Nar Valley. This is interpreted as the result of erosion and nondeposition during regression of the shoreline as a result of the fall of sea-level. None of the Nar Valley sites show the later phase of the *Abies* decline. In the light of sequence stratigraphy concepts it seems reasonable not to expect the decreasing part of the *Abies* curve on land. The youngest record found on land will be older than the period of maximum flooding which correlates with the highest percentage of *Abies*. Only offshore sites, such as BH 81/52A will contain the post-temperate substage.

Sea-level dropped so low after the Holsteinian that the site was exposed and glaciofluvial deposits of the Egmond Ground Formation of Saalian (Wolstonian) age were deposited.

VI.4. Egmond Ground Formation

Sands and gravels of this Formation in borehole 81/52A are represented by the sequence overlying the Sand Hole Formation of Holsteinian (Hoxnian) age (Fig. III.3). On the basis of seismic interpretation Tappin (1991) has correlated these sands and gravels with the Holsteinian stage. He interprets both the Sand Hole Formation and the overlying sands and gravels of the Egmond Ground Formation as being of Holsteinian age (Fig. III.1).

The Egmond Ground Formation was first described from the Dutch sector of the southern North Sea where it consists of largely sandy lithofacies. On the basis of seismic interpretation Tappin (1991) has identified similar sands and gravels over most of the Spurn sheet. Seismically this Formation is characterised by low-amplitude parallel and even reflectors (also see section III.1,b,iv). In BH 81/52A this unit is represented by a 16 m thick sequence overlying the Sand Hole Formation. Similarities in seismic reflectors and especially their lateral extent to the east led Tappin (1991) to correlate their sequence with the Holsteinian Egmond Ground Formation of the Dutch sector.

The palynology of the underlying Sand Hole Formation very clearly suggests, however, that the interglacial cycle ends with the silty-clay sequence of Sand Hole Formation.

This conclusion is supported by the foraminiferal and dinoflagellate data (detail in Chapter III).

This interpretation clearly conflicts with Tappin's interpretation of the overlying sands and gravels as being of Hoxnian age.

Unfortunately the sands and gravels of the Egmond Ground Formation overlying the silty-clay of the Sand Hole Formation were only poorly recovered. The contact itself and the sequence immediately above are missing. In any case the lithology is unsuitable for pollen analysis.

It seems significant that: i) over much of East Anglia sands and gravels of Wolstonian age overlie Hoxnian (Holsteinian) deposits; ii) periglacial sediment of Saalian (Wolstonian) age are present in the Dutch sector and are thought to continue into the UK sector (detailed discussion in Chapter VII); iii) palynological investigation of the silty-clay of the Sand Hole Formation indicates that the upper surface of the Hoxnian (Holsteinian) is non-erosional; iv) Fig. III.6 demonstrates that the contact between the two deposits is non-erosional and very remarkably smooth. If the contact is non-erosional then it seems likely that these sands and gravel represent the Wolstonian (Saalian); if so, they may correlate with the widespread sand and gravel spreads of Wolstonian age over East Anglia.

VI.5. Sea-level curve

The depositional model needs to be modified for each location (Fig. VI.12), taking into consideration the regional rate of subsidence (or emergence), rate of sediment supply and topography of the basin floor (typical shelf-slope setting vs. ramp setting and isolated platforms). Observations along continental margins in sections with typical shelf/slope profiles suggest that the response also differs when the system is siliciclastic-dominated in comparison with a system with mixed clastic/carbonate deposition (Haq, 1990; Vail *et al.*, 1991).

According to Vail et al. (1977) it is believed that a complete analysis of sea-level change in many areas is impractical or impossible because of problems such as distribution and quality of data, erosion of coastal onlap, or structural displacement of stratigraphic units. "However, no matter how much complete the onlap data may be, a practical analysis should be made using whatever information is available. Where onlap data is missing, other indirect or only supporting data, occurrence of abrupt marine transgressions, abrupt changes from prograding shelf pattern to deep marine fans, units showing persistent marine onlap or downlap, thickness of leached zones in carbonate rocks, and general fans can be supplementary aids in building a chart of relative changes of sea level."

VI.6. Anglian-Hoxnian stratigraphy and sea-level

Data relating to relative sea-level change during the Hoxnian in this area are strengthened by pollen biostratigraphic controls (Stevens, 1958, 1960; Ventris,

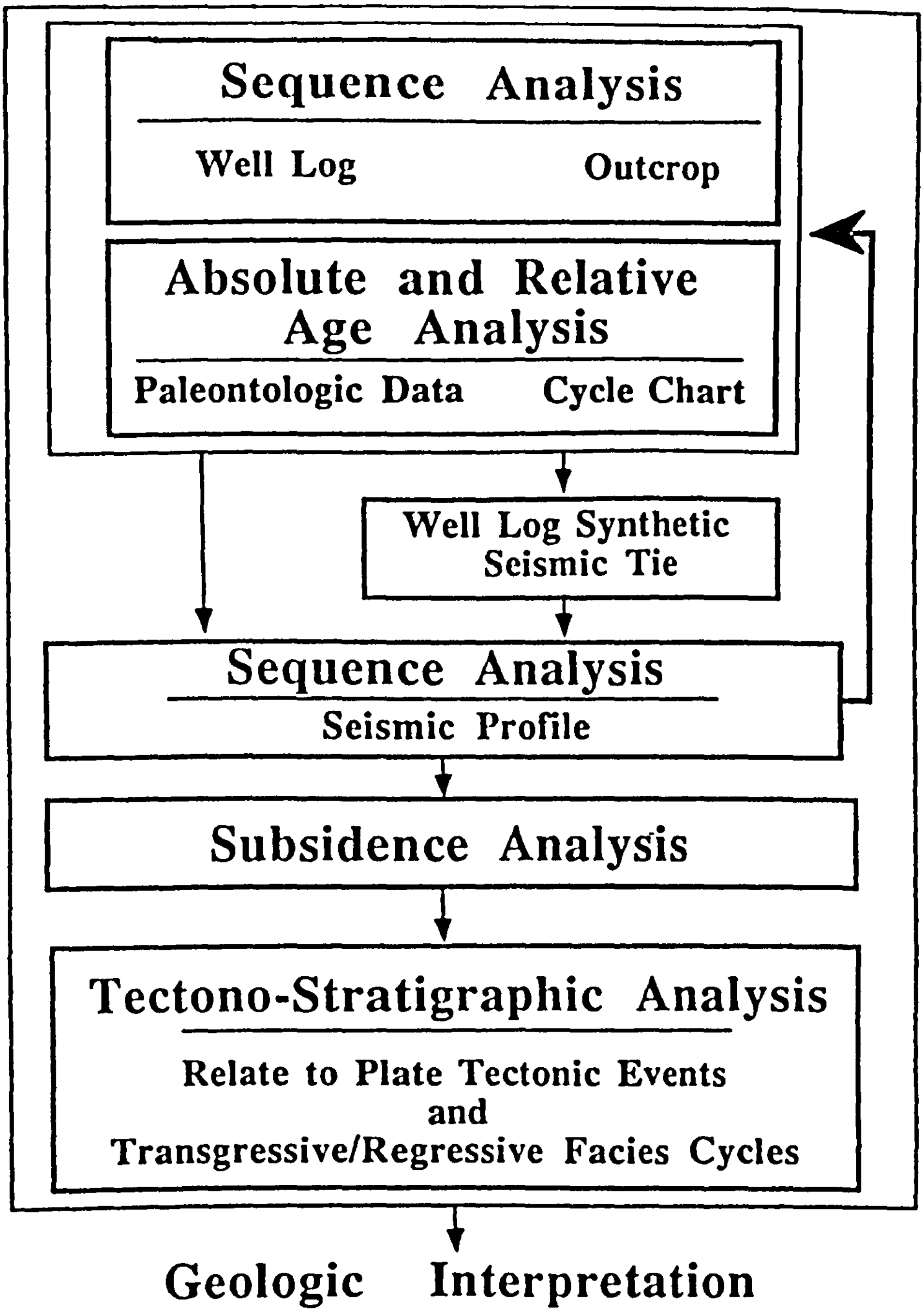


Fig. VI.12. Sequences stratigraphic interpretation procedure (from Vail et al., 1991).

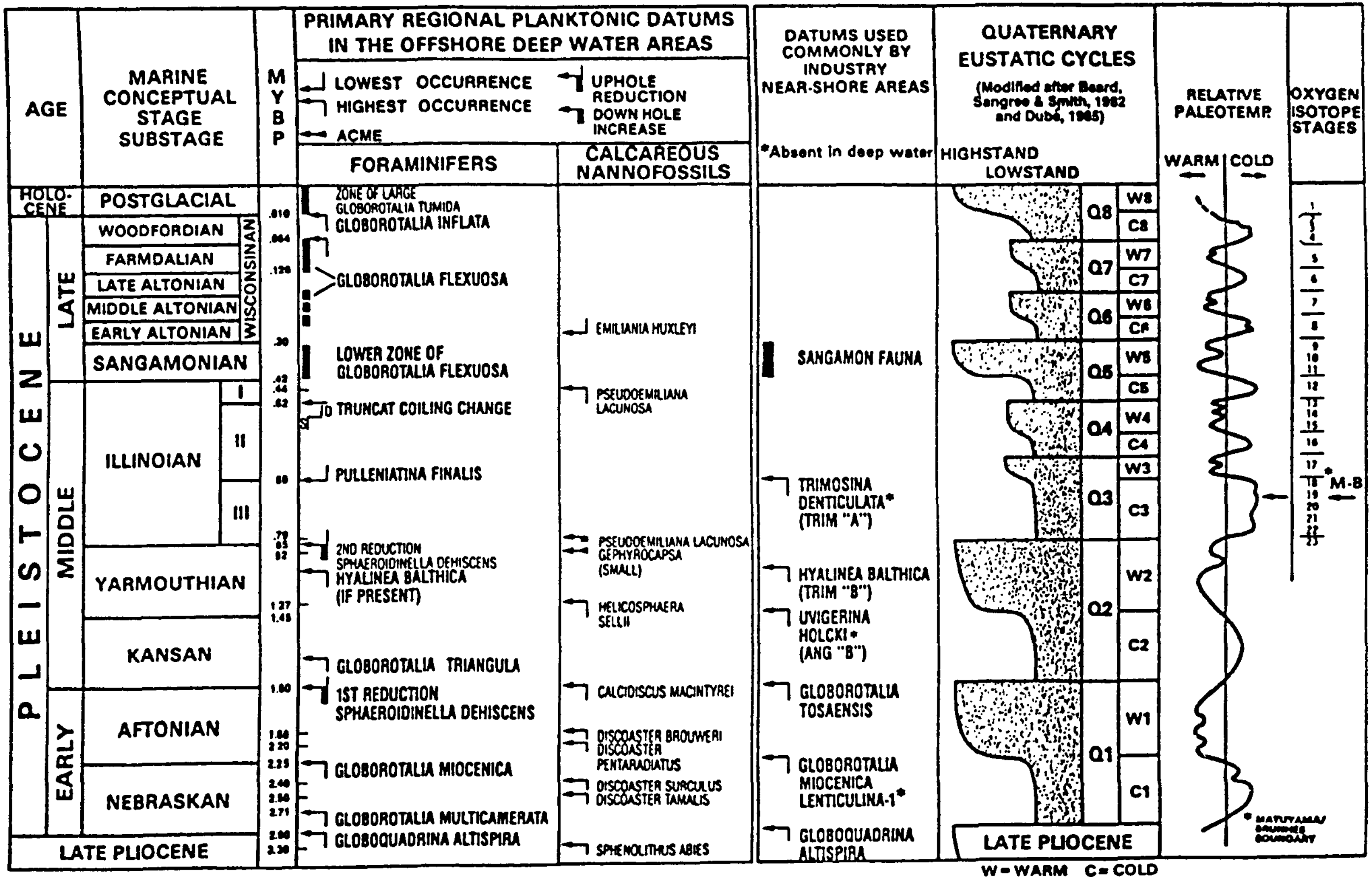


Fig. VI.13. Model for Quaternary multiple-event stratigraphy, Gulf of Mexico, from Lamb *et al.* (1987).

1985). Palaeobathymetry is available from seismic records which can be compared with the foraminiferal palaeoecology. Marine deposits above modern sea level indicate a former higher depositional sea-level, or subsequent uplift or a combination of both factors. Figs. VI.14 and 15 present curves for eustatic sea-level, relative sea-level curve and coastal onlap curves; "Tectonic movement during the Pleistocene in Britain is generally regarded as being unimportant, but the evidence from the south coast may indicate that in certain areas these processes are underestimated" (Ventris, 1985, *op. cit.*).

In order to construct sea-level curves (Fig.VI.16) for NW Europe, particularly for the central and southern North Sea and its adjoining present-day land area, the main data source is provided by biostratigraphic datums. Planktonic foraminifera, which generally provide regional and worldwide data (Fig. VI.13), cannot be used because of the shallow shelf sea setting. Instead, pollen assemblage zone biostratigraphy enables correlation with Pleistocene climatic stages.

VI.7. Conclusions

The various concepts of sequence stratigraphy enable the depositional history of this area to be more clearly understood. The important conclusions drawn from this sequence stratigraphic analysis are: i) marine record of the

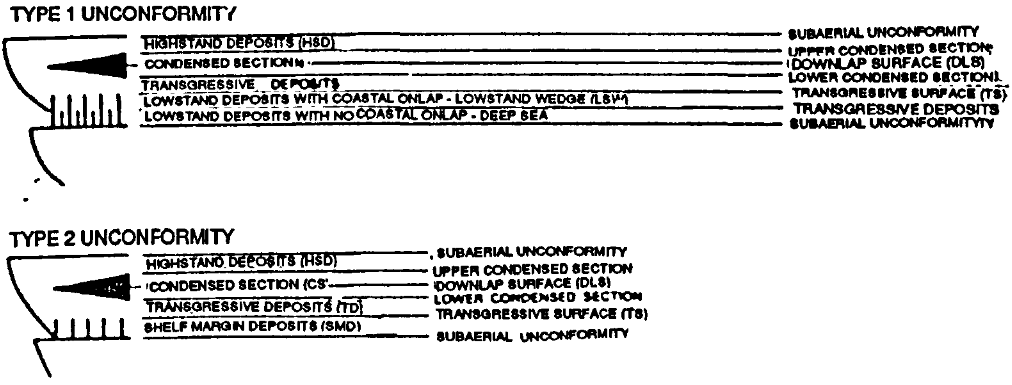


Fig. VI.14. Showing nature of onlap at various stages described in sequence stratigraphy from Baum and Vail (1988).

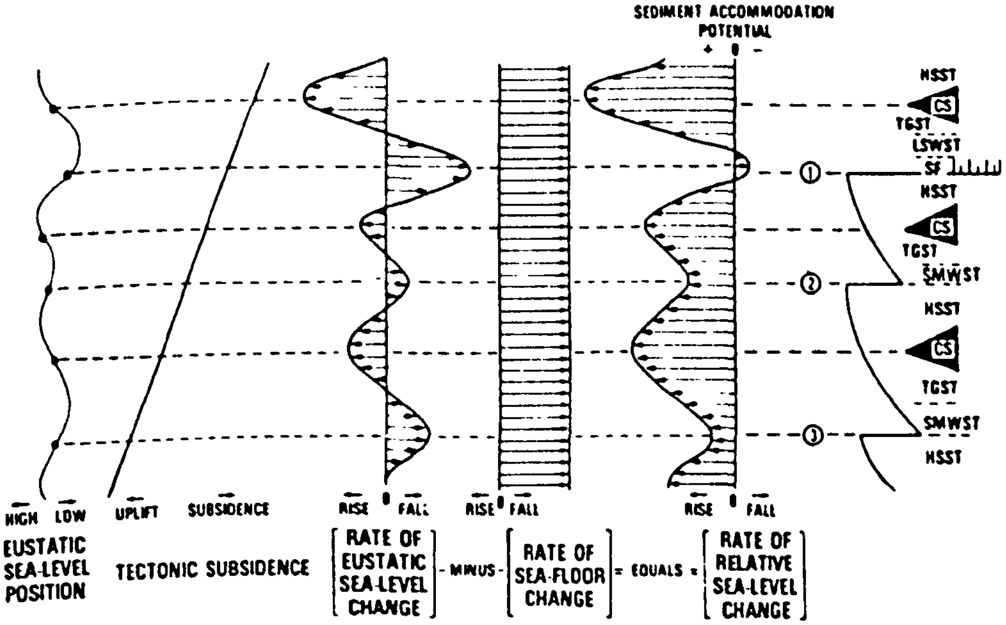


Fig. VI.15. One-dimensional model depicting global sea level, subsidence, rate of eustatic change, subsidence rate, rate of change of accommodation and estimated coastal onlap chart. Negative accommodation potential at sequence-boundary 1 represent a period when sediment is transported into the basin, thus forming a submarine fan. During the formation of sequence boundaries 2 and 3, sediment accommodation potential remains positive and space is available for sedimentation. Condensed sections form at peaks in accommodation potential associated with the period of maximum rates of eustatic rise.

post-temperate substage of the Hoxnian (Holsteinian), which has not been found on land in this area, is probably absent; ii) marine record of the post-temperate substages of other interglacial cycles will not be found in similar estuarine settings; iii) In such settings the youngest marine record of any interglacial cycle found on land will be older than the period of maximum flooding when the shoreline starts moving basinward. This change not only stops marine deposition on the shore, but it also causes extensive erosion on the upper surface of the transgressive system tract.

Sequence stratigraphy therefore indicates that only offshore sites will contain a marine record of the post-temperate substage of the Hoxnian interglacial and probably other interglacial stages. It is also clear from the data that in those areas transgressed during the interglacial cycle, the boundary between the glacial and interglacial sequence is unconformable. Conformable sequences can only be found in offshore sites where glacial-marine sediments form the upper part of the glacial sequence.

Boulton's model suggests that on the inner shelf (area covered by grounded ice during glacial stage) deposition of glacigenic sediment will not begin until the later half of the optimum phase of glaciation.

ELSTERIAN - HOLSTEINIAN EUSTATIC CYCLE
(MULTIPLE-EVENT STRATIGRAPHY, NW EUROPE)

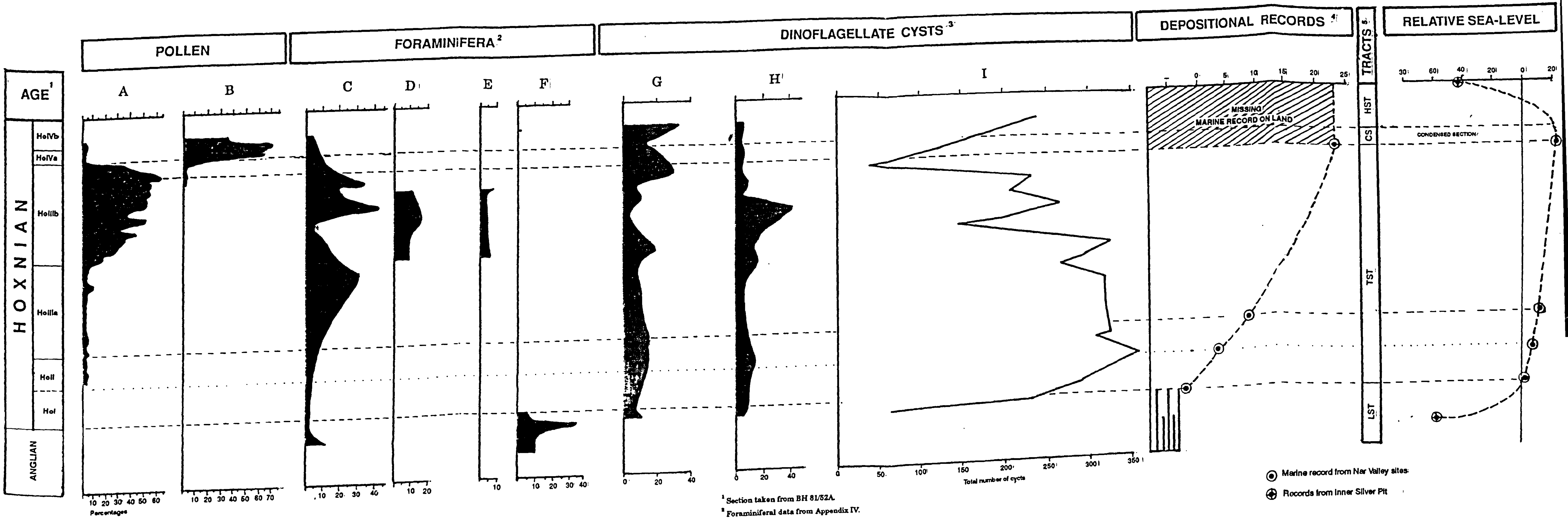


Fig. VI.16. Anglian-Hoxnian multiple-event stratigraphy, NW Europe. A:*Abies*; B:*Empetrum*; C:*Bulimina marginata*; D:*Cassidulina laevigata*; E:*Nonion barleeanum*; F:Nonion orbicularae; G:*Operculina centrocarpum*; H:*Achomosphaera andalouseinse*; I:Total Dinoflagellate cysts;

[1] Section taken from BH 81/52A.

[2] Foraminiferal data from Appendix IV.

[3] Dinoflagellate cyst data from Appendix II.

[4] Sea-level data from Ventris (1985).

[5] TRACT=Genetically related sedimentary packages (also see Appendix VII & VIII).

LST=Lowstand System Tract, TST=Transgressive System Tract,
CS=Condensed Section, HST=Highstand System Tract,

Chapter VII

Environmental history of the Middle Pleistocene in the southern and central North Sea and correlation with deposits on adjacent land areas

Investigations of the Middle Pleistocene succession of the southern and central North Sea over the past few decades has resulted in the acquisition of both physical and biological data of stratigraphical significance. Although a considerable proportion of this work has been undertaken by commercial companies, the main effort has been made by the BGS in collaboration with the geological surveys of the other countries surrounding the North Sea.

In the UK and Dutch sectors the initial results of systematic surveys have been presented in geological maps. Each map includes a table correlating the sequence of seismic formations with the Quaternary climatostratigraphy of Britain and the Netherlands (Fig. III.1). These tables have been compiled by combining the available palaeontological and palaeomagnetic data with seismic stratigraphy. Cameron *et al.* (1987) have summarised this correlation in their Fig.3. One of the aims of this Chapter is to update this correlation by incorporating evidence from this thesis. The modified table is presented in Fig. VII.1 and discussed below.

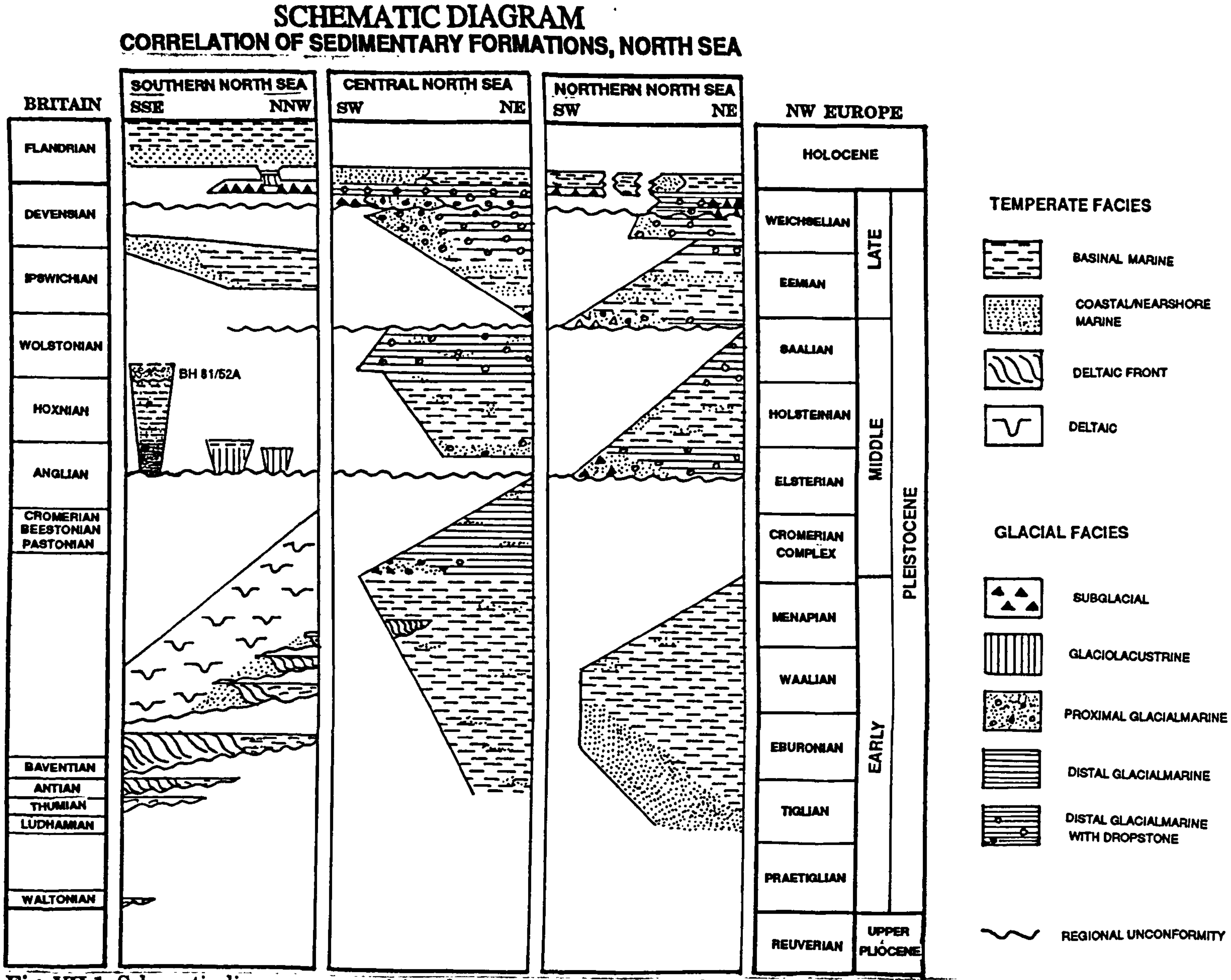


Fig. VII.1. Schematic diagram summarising the stratigraphic range of the Pleistocene facies units in the southern, central and northern North Sea (modified from Long *et al.*, 1988 by adding data from BH 81/52A for the Middle Pleistocene). It should be noted that the Early Pleistocene correlation does not conform to the most recent stratigraphic synthesis (Gibbard *et al.*, 1991b).

Using the data concerning depositional environments from the investigations of the sedimentary units encountered in borehole 81/52A and vibrocores 53/00/962, /1103 and /1104 from the southern North Sea, and borehole 81/34 from the central North Sea, together with information from previous work in the region, the sedimentation history of the area can be revised. This chapter is mainly concerned with glacial and interglacial deposition during the Middle Pleistocene as encountered in the investigated cores.

The base of the Middle Pleistocene has been placed at the base of the Cromerian (Zagwijn, 1985) or at the Bruhnes/Matuyama palaeomagnetic boundary (Butzer and Isaac, 1975). Various ages have been proposed for this boundary. According to Mankinen and Dalrymple (1979) it is placed at 730,000 yr B.P. whereas Johnson (1982) placed it at 790,000 yr B.P. In the central North Sea this palaeomagnetic boundary has been recognised in several boreholes, including BH 81/34 (Stoker *et al.*, 1983) which has been investigated in this project (Chapter V). The sedimentary formation in which this boundary has been identified correlates with the Aberdeen Ground Formation. In the Dutch sector this boundary has been recognised within the Cromerian Complex (Zagwijn, 1979; Gibbard *et al.*, 1991). This led Stoker *et al.* (1985b) to correlate the Aberdeen Ground Formation with the Cromerian Complex. In the southern North Sea the Elsterian glaciation eroded most of the older deposits and in practice the base of the Elsterian is regarded as the boundary between the Early and Middle Pleistocene. It should therefore be remembered that the age of the Early/Middle Pleistocene boundary is older than the base of the Anglian deposits.

VII.1. Cromerian Complex

The status of the Cromerian Complex has long been a matter of debate. Apart from the deposits on the coast of N Norfolk, the deposits of the Cromerian are not characterised by a cyclic single stage (Zagwijn, 1979; Gibbard and Peglar, 1990; Gibbard *et al.*, 1991a). Pollen analysis of these deposits indicates the presence of more than one stage explaining the definition as a complex rather than a single stage.

On land the best record for the Cromerian is found in the Netherlands and, unlike the Holsteinian, at present four interglacials have been defined during the Cromerian Complex, known as CrI to Cr IV (Zagwijn, 1991). The CrI interglacial is also known as the Waardenberg and is characterised by the presence of *Eucommia* and significant frequencies of *Carpinus* pollen. The vegetational succession of CrII (Westerhoven) is known from only the first-half of the interglacial cycle and it is not clear whether or not *Abies* is present in the later part. CrIII (Rosmalen) is quite well known and *Abies* is present in this interglacial and also in the later part of the less complete CrIV (Noordbergum).

In Britain all the sites of Cromerian (s.s.) age are restricted to the coastline of NE Norfolk and N Suffolk in East Anglia. The stratotype at West Runton contains a typical temperate cycle of vegetation. The pre-temperate substage (CrI) includes significant frequencies of *Picea* and *Alnus* (Fig. I.10). By the early-temperate substage (CrII) deciduous forest is fully established with *Quercus, Alnus* and later *Tilia* and *Corylus* all represented by high frequencies. In the late-temperate substage (CrIII) there is a marked change shown by the rise to dominance of *Carpinus* and *Abies* accompanied by a apparent decline of mixed oak forest taxa. In the post-temperate substage (CrIV) boreal forest returns to be ultimately replaced by heath vegetation. The pollen spectra at this site very clearly represent a complete cycle in a single stage as in the Hoxnian and Ipswichian. A correlation between this site and the Cromerian Interglacial IV of the Netherlands has been suggested but is now regarded as unlikely (Gibbard and West, 1991). Recent research at the sites of Broomfield and Ardleigh, Essex (Bridgland, 1988); Nettlebed, Oxfordshire (Turner, 1983) and Scole, Norfolk (c.f. Gibbard and Peglar, 1990) indicates that at least two or possibly more temperate stages occur between the Cromerian and Pastonian. It seems likely, that unlike the Hoxnian and Ipswichian, the Cromerian in Britain should also be regarded as a complex rather than a single stage (Gibbard and Peglar, 1990). It is thought likely that there is a considerable period of time apparently unrepresented by fossiliferous sediments in

Britain.

The Cromerian in the southern North Sea is represented by the Yarmouth Roads Formation (Fig. III.1b & VII.1). This Formation does not only comprise the Cromerian Complex (interglacial stages), but also includes sediments of Waalian and Menapian age. Deposits of this Formation have not yet been positively identified within the UK sector.

In the central North Sea the deposits include a large proportion of prodelta and fully marine sediments, and are believed to represent a more complete stratigraphic sequence than is found in the southern North Sea. Stoker and Bent (1985) suggest that major deltas of the north European Plain eventually coalesced at this time with the much smaller local deltas of eastern Britain.

In the central North Sea the thick Pleistocene deposits are dominated by glacigenic sequences. In borehole 81/34, the 230 m thick sequence mostly represents sediments younger than the Early Pleistocene (Stoker *et al.*, 1985b). In the central North Sea the stratigraphy is less clear than in the southern North Sea. Here the main classification is based on Holmes (1977) revised by Stoker *et al.* (1985b).

Possible sediments of Cromerian complex age have been identified in borehole 81/34 from the central North Sea (Chapter V). Here probably two out of the four interglacial stages of the Complex have been identified. As result of foraminiferal analyses Knudsen (in Prep., Fig. V.6) found two warm periods, which on the basis of amino acid ratios, are of Middle Pleistocene age. The amino acid ratio of 0.29

from a monospecific sample of *Bulimina marginata* suggests the lower warm phase can be correlated with either the Cromerian or the Holsteinian. However, on the basis of pollen analysis (Fig. V.3), the two warm periods found within the Ling Bank Formation can probably be correlated with the Cromerian Complex. This interpretation is supported by the seismic records in which the sequences representing both warm periods occur well below the expected stratigraphic context of the Holsteinian (Dr D.H. Jeffrey, *pers. comm.*).

The presence of Abies suggests that these two warm stages may correlate with Cromerian interglacials III and IV of the Dutch sequence. Concerning the central and northern North Sea it is important to note that :

1. Deposits representing interglacial phases will take the form of thin condensed sequence by analogy with Holocene sedimentation in this area.

2. Pollen analysis ideally requires samples with a very close sampling interval, but this is impractical in this context because of: i) low pollen concentrations and ii) the "mixed" nature of the pollen assemblages. Temporal variations may not be as clear as on land or in shallower sites closer to the shore (coast).

It is clear that the two warm stages found within the Ling Bank Formation do not represent the Eemian or Holsteinian. On the basis of pollen, foraminiferal, dino cyst, aminostratigraphic and palaeomagnetic data they have been correlated with the Cromerian Complex.

VII.2. Anglian (Elsterian) cold stage

The Anglian glaciation (Fig. VII.2) had very widespread effects and the area overridden by the ice was subject to complete landscape remodelling . Existing deposits were destroyed or buried, and entirely new surfaces were formed beneath the ice by glacial and glaciofluvial erosion and deposition (Balson and Cameron, 1985; Cameron et al., 1987; Stoker *et al.*, 1985a & b; Gibbard, 1988) Balson and Jeffrey, 1991; Gibbard *et al.*, 1991b). Most of the pre-existing Quaternary and Tertiary deposits were destroyed, and over most of the area deposits of Anglian age directly overlie Cretaceous Chalk (Fig. III.6, III.3). The boundary between the Early and Middle Pleistocene, which is placed within the Cromerian Complex, has so far been not found in the UK sector of the southern North Sea. The base of the Elsterian is therefore used as practical working boundary between the Early and Middle Pleistocene. This usage reflects the extensiveness of the Elsterian glacial deposits.

In eastern Britain (from Lincolnshire and East Anglia) stratigraphic evidence indicates that the region was affected by the glacial advance during the Anglian. This

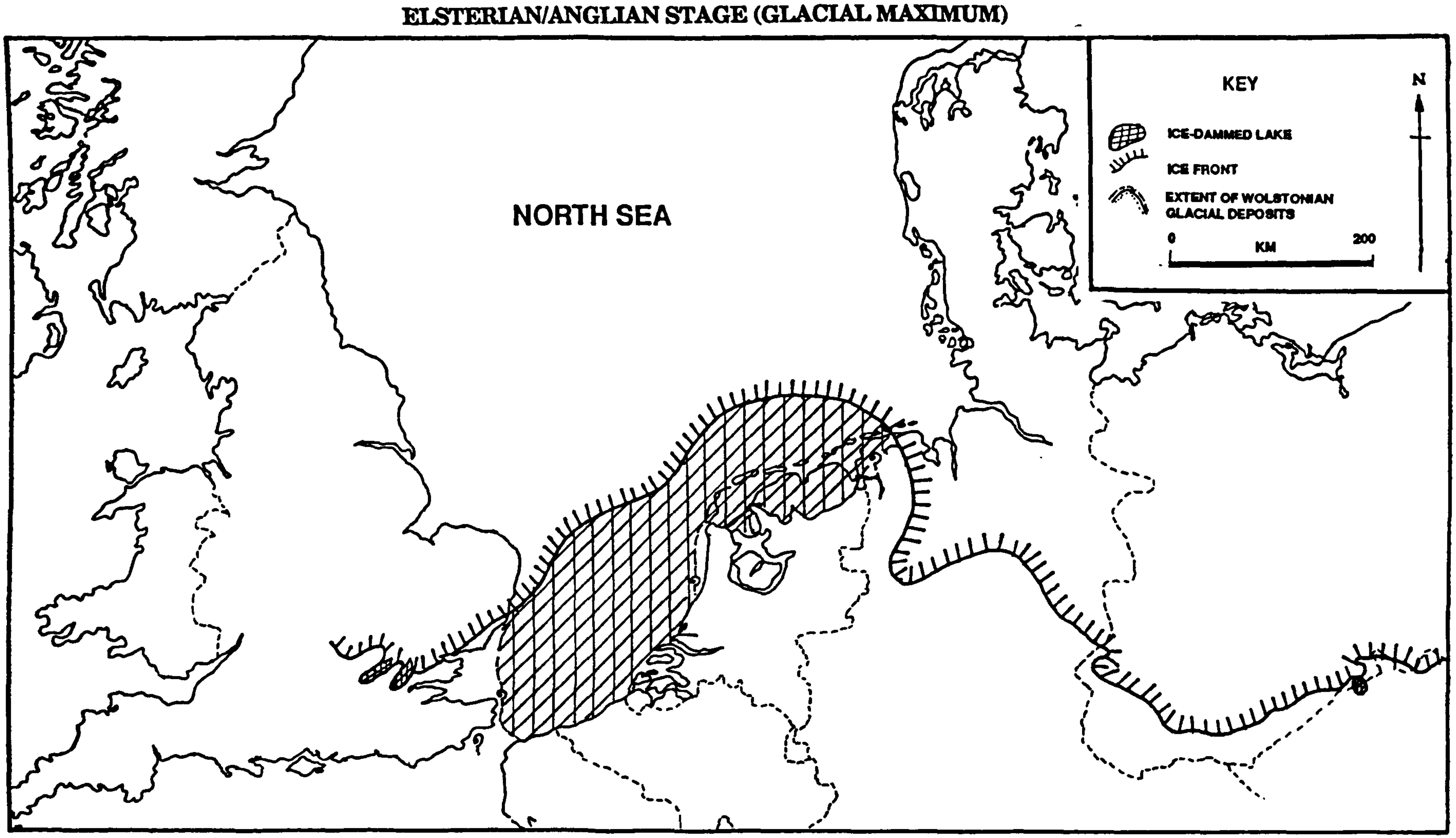


Fig. VII.2. Schematic palaeogeographical reconstruction of the Elsterian - Anglian stage at the glacial maximum (from Gibbard, 1988).

was caused by the advance of ice sheets from two different directions (NE and NW). This pattern is clearly demonstratable on land, particularly in East Anglia (Ehlers, *et al.*, 1991c; Hart and Boulton, 1991; Straw, 1991; Chapter III). These various phases within the Anglian resulted in the deposition of three till units, known as the Cromer Till, Lowestoft Till and Marly Drift in East Anglia (Ehlers, 1991c; section III.1,a). On the basis of evidence from the glacigenic sequence in BH 81/52A it seems likely that information related to deposition of these till types may not be found from offshore area of UK because:

1. The Cromer Till was deposited by an ice sheet from the continent (Table III.1) and would have been eroded by advance of the British (Lowestoft) ice sheet.

2. The Lowestoft Till was deposited by the Lowestoft ice sheet which arrived later from northwest Britain.

3. The Marly Drift was also deposited by the Lowestoft ice sheet and represents a later stage of deposition.

It is widely accepted (section III.1,a) that in East Anglia the Lowestoft ice sheet replaced the continental ice sheet. It is assumed that the same situation occurred in the Inner Silver Pit offshore area (Hart and Boulton, 1991) which is not far from East Anglia (Fig. III.2). Evidence from BH 81/52A indicates a continuous sequence from glacial to glacial-marine and finally marine during the Holsteinian. This clearly indicates that any replacement of the ice sheet would have been taken place prior to the deposition of this sequence. Boulton's model (Fig. VI.7) suggests that deposition should begin after the mid-optimum phase of the glaciation at inflection point F (Fig. VI.4, Appendix VI.1A)

It therefore seems likely that the earlier continental ice sheet would have covered the Inner Silver Pit area. However, the area was later covered by the Lowestoft ice sheet which eroded any deposits related to the earlier continental ice sheet. No glacial sediments correlative of the Cromer Till are therefore found in BH 81/52A. The Till in BH 81/52A below the silty-clay of the Sand Hole Formation correlates with the later Lowestoft Till.

Valley systems and their infills record the extension of a grounded ice sheet into both the southern North Sea and its hinterland. Together with ice-pushed deposits, they demonstrate that there was a continuous cover of ice from eastern England across the southern Bight into the Netherlands and Germany during Elsterian times.

The earliest evidence of glaciation is represented by local ice-pushed deformed ridges in the Lower to early Middle Pleistocene deposits in the Brown Bank area and along the eastern margin of the Flemish Bight (Laban *et al.*, 1984;

Cameron *et al.*, 1987). These features demonstrate that the margin of the Elsterian ice sheet extended southwards to at least 52° 20′ N. The Anglian tills which cover much of East Anglia extend as far south as Ipswich (52° N).

a) Origin of incisions

Glacial processes during the Elsterian led to the erosion and filling of a system of subglacial valleys. As in East Anglia, northern Germany and the Netherlands, in the southern North Sea a complex system of anastomosing subglacial valleys was eroded and infilled during the Elsterian glaciation (Woodland, 1970; Ehlers *et al.*, 1984; Balson and Jeffrey, 1991) mainly to the north of 53° N.

The origin of the incisions has long been a matter of discussion (Hamilton and Smith, 1972; Holmes, 1977; Ehlers, 1981; Ehlers et al., 1984; Long and Smith, 1986a), Ehlers and Link (in press; Boulton and Hindmarsh, 1987; Boyd et al., 1988; Moorse, 1985; Wingfield, 1990b; Ehlers and Link, 1989; Jeffery, 1991; Wingfield, 1991).

There are three schools of thought on the origin of these features. One emphasises the significance of substrate such as fault lines and the soft nature of strata or subsurface processes such as faulting, salt withdrawal and karstic collapse. The second group concentrates on the importance of the local overdeepening of preexisting features, for example delta channels or river valleys. The third school of thought emphasizes a compound process of origin in which the nature of the substrate, overdeepening of preexisting features and involvement of more than one glacial stages are significant.

It has been assumed by Cameron *et al.* (1987) that the features were most likely to have been eroded subglacially under very high hydrostatic pressure by outburst of meltwater beneath a continuous cover of melting ice, with slumping of moraine and the deposition of glaciofluvial sediments. After the ice had retreated from the area, a thick accumulation of glacio-lacustrine sediments, locally overlain by fluvial or glacial marine deposits, infilled most of the Elsterian valleys. Similar sedimentary sequences are well known from the onshore area of Britain (Ventris, 1985), The Netherlands and Germany (Kuster and Meyer, 1979; Ehlers et al., 1984). More recently Wingfield (1990b) presented an alternative model and proposed that each incision was created separately at a lowland or tidewater ice sheet margin as a jökulhlaup plunge pool which cut back and unroofed into the ice sheet margin. Wingfield (1990b) has attempted to explain processes outside, inside and at the margin of the ice sheet. This model has been criticised by Jeffery (1991) who comments that according to Wingfield's model incision infills should contain the products of waning high-volume/high-velocity fluvial changes and be topped in places by terrestrial periglacial sediments. Jeffery (1991) himself has proposed a model which produces major incisions during stagnation of the ice sheet by subglacial erosion by summer meltwater under the whole ice sheet. Wingfield (1991) has criticised this model citing evidence from Boulton and Hindmarsh (1987) and Hart *et al.* (1990) who comment that erosional activities are only likely on the margin of the ice sheet.

From Jeffrey's model it follows that the process of incision is spatially and temporally continuous throughout the ice sheet. The other models emphasize the late stage of the glaciation when ice sheet meltwater was supplied in large amounts.

It is significant that the basal infill of Elsterain/Anglian sediments directly overlie the base of the palaeovalleys or basins (Balson and Jeffery, 1991; Tappin 1991; this thesis). This suggests that the basal infill was deposited immediately after the formation of the incisions (Balson and Cameron, 1985; Cameron et al., 1987; Balson and Jeffery, 1991; Tappin, 1991; this thesis). Seismic records have clearly illustrated that there are three units of glacigenic sediment in the UK sector of the southern North Sea. In the southern North Sea the Elsterian infill of these tunnel valleys, the Swarte Bank Formation, comprises a complex sequence of sediments. The basal unit, which is structureless or has a chaotic reflector configuration, contains zones of reduced acoustic penetration and consists of gravelly coarse sandy till deposited penecontemporaneously with valley incision (Tappin, 1991; section III.16a). Later, a second well-bedded unit contains rare sub-parallel, light-amplitude reflectors at similar intervals. This large unit is a glacio-lacustrine clay with beds of silty-clay and fine gained sands. The third unit of infill is characterised by gently inclined low- or moderate amplitude reflectors on seismic profiles. This unit represents a delta-related influx of fine grained sands and clays into a glacial-marine environment. This indicates that there are three units of glacigenic sediments conformably in contact with each other.

Chapter III has shown that the contact between the Anglian diamictons (Till) and the Hoxnian silty-clay is conformable. In descending stratigraphic order the silty-clay sequence is followed by glacial-marine sediments followed by the basal infill overlying the base of the valley. Boultons model suggest that these glacigenic sediments were deposited in the later half (after inflection point F, Fig. III.4, Appendix VI.A) of the glaciation. This view is strongly supported by the conformable contact between the glacigenic units and between the Hoxnian silty-clay and the overlying sequence. This suggests that the valley was formed at the time of inflection point 'F', the mid-optimum phase of the glaciation. This suggests that there is no hiatus between the formation of the valley and deposition of the basal infill.

This suggest that just after inflection point 'F' the ice sheet was characterised by meltwater under very high hydrostatic pressure which formed the palaeovalleys. The basal infill was deposited at the late stage of this process.

Some workers (e.g. Wingfield, 1990) believe that there is a close relationship between the existence of the palaeovalleys and the limit of the ice sheet of the corresponding glacial stage. They cite the following evidence:

1. The valleys follow a NNW - SSE trend in the centre of the southern North Sea (Balson and Cameron, 1985). They range from long anastomosing valley systems to short isolated oval channels.

2. The palaeovalleys are of similar dimension and morphology, and are the direct continuation of the Elsterian subglacial valley system of East Anglia and the continental part of northwest Europe (Balson and Cameron, 1987).

3. The valleys have not been identified south of 52° 50′ N in the UK sector and are most extensively developed between 53° and 54° N and east of 2° E (Balson and Jeffrey, 1991).

4. All these valleys have been completely filled with Anglian and younger age sediments (Tappin, 1991).

The similarities in the geometry, the size and the lithological infills of the palaeovalleys suggest that they were created by common processes.

It can be proposed that :

a) Palaeovalleys were formed during the later period of the optimum phase of the glaciation.

b) These valleys were formed under very strong hydrostatic pressure of meltwater.

c) They were formed at or in the margin of ice sheet.

Apart from these deep channels there are some shallow channels, perhaps basins (eg. Fig. III.6), filled with morainic material (Grube, 1979). From this infill Grube deduced that the shallow channels were formed by direct glacial erosion ('Glaziellen' in the sense of Gripp, 1975), whereas those over 100 m deep were formed mainly by meltwater action.

In the central North Sea the basal Elsterian unconformity changes in character from a sub-glacial planar erosion surface in the SW to an irregular surface with a local relief up to 80 m in the NE (Stoker *et al.*, 1985b). In their stratigraphic framework Stoker *et al.* (1985b) placed the Brunhes - Matuyama palaeomagnetic boundary in the Aberdeen Ground Formation. The age of this Formation is late

Waalian to Cromerian Complex. The upper age limit of this Formation has been recognised as Elsterian in the area where the Aberdeen Ground Formation is unconformably overlain by the Ling Bank Formation. According to Stoker *et al.* (1985b) the overlying Ling Bank Formation (Chapter V) is of Holsteinian to Saalian age. The recognition of stages of the Cromerian Complex within the Ling Bank Formation will require a change to this scheme. The current status of the stratigraphy is:

1. The Bruhnes-Matuyama palaeomagnetic boundary is present in the Aberdeen Ground Formation.

2. Dinoflagellate cyst analysis suggests that the Ling Bank Formation overlying the Aberdeen Ground Formation represents a single complete interglacial stage (Holsteinian).

3. Foraminiferal evidence conflicts with this dino cyst data and suggests that the Ling Bank Formation includes two marine temperate stages separated by a cold stage.

4. Though the pollen data is not very clear they seem to agree with the foraminiferal evidence. In addition, the pollen assemblages indicate that the two warm stages might well be older than the

Holsteinian and represent two interglacial stages of the Cromerian Complex.

These data suggest that Elsterian deposits might be expected in and above the upper part of the Ling Bank Formation. On the basis of the foraminiferal and pollen data, and analogous sedimentation during the Holocene, it seems that deposits of interglacial status in the central North Sea will always be thinner than deposits of glacial stages. The thick sequence suggested by the dino cyst data is very difficult to explain.

The Quaternary stratigraphy of the central North Sea is not very clear based on the preliminary dinoflagellate cyst and foraminiferal data. Unfortunately pollen analysis is unable to play a conclusive role as compared to sites close to fluvial sources.

VII.3. Hoxnian (Holsteinian) temperate stage

The interglacial period between the Anglian and Wolstonian cold stages is known as the Hoxnian in Britain, and its correlative between the Elsterian and Saalian in the continental part of NW Europe is known as the Holsteinian. The type site of the Hoxnian is at Hoxne (West, 1956) in Suffolk, England; the Holsteinian has its type site, defined by Woldstedt (1953), in the neighbourhood of Lauenburg where marine deposits of the Holsteinian sea occur. The significant Hoxnian sites on land in England are at Hoxne (West, 1956) in Suffolk, Marks Tey and Clacton (Turner, 1970) in Essex (Pike and Godwin, 1953), the Nar Valley (Ventris, 1985) in west Norfolk, Dunston Common (Phillips, 1976) in central Norfolk, Nechells (Kelly, 1964) near Birmingham, Hatfield (Sparks *et al.*, 1969) in Hertfordshire and (Coxon, 1985) at Athelington in Suffolk.

a) Marine deposits

A number of the investigated sites have been found to contain evidence of the major marine transgression of the Holsteinian interglacial. These sites occur in the countries surrounding the North Sea in eastern England, northern Germany, Denmark and France. In Ireland, the site at Cork Harbour presents a marine depositional record for the correlative Gortian interglacial stage (Scourse *et al.*, 1992).

On the margin of the southern North Sea, Holsteinian marine deposits occur in marine terraces 23 m above sea level in East Anglia (Ventris, 1985), at an elevation of 10 - 12 m near Sangatte on the French coast (Somme', 1979) and in Belgium (Paepe and Baeteman, 1979). In the Netherlands, the surface of marine Holsteinian deposits occur at -25 to -40 m (van Staalduinen, 1977) and in northern Germany they fill a *'Forde'*-like system to an elevation of *ca.* -20 to -30 m (Ehlers et al., 1984; Linke *et al.*, 1985). The difference in elevation can perhaps be attributed to post-Holsteinian isostatic and tectonic processes (cf. Ventris, 1985).

In East Anglia, the northwestern part of the European mainland and in the North Sea, Holsteinian deposits are found as the uppermost component of the valley fill deposits overlying Elsterian glacio-lacustrine or glacial-marine muds (Ventris, 1985; Laban *et al.*, 1984; Balson and Jeffrey, 1991; this thesis). Most of the Elsterian valleys are totally filled by Elsterian (Anglian) glacial, glacio-lacustrine and glacial-marine sediments. The depressions which were not completely filled received younger (Holsteinian) sediments. The valleys/depressions on land which were in the reach of the transgression received lacustrine and marine sediments, as in the Nar Valley (Ventris, 1985) and at Woodston (Horton *et al.*, 1991).

In the southern North Sea this study has demonstrated the existence of sediments of Holsteinian age in the Inner Silver Pit. The pollen spectra obtained from BH 81/52A that indicate an Hoxnian age include the presence of *Pterocarya* in association with the frequency curves for *Picea, Abies* and *Empetrum* . The presence of *Pterocarya* makes correlation with the Ipswichian (Eemian) very unlikely, since *Pterocarya* has so far only been found in Holsteinian or older interglacial stages. The higher percentages of *Picea* in the diagram may suggest a Cromerian (s.s) affinity. However, in the Cromerian (s.s.) the frequencies of *Picea* are high throughout the interglacial, even in substage CrIII in which *Abies* is also represented by high percentages. This pattern is not found in BH 81/52A. Instead, this pollen diagram is characterised by the dominance of *Abies* and *Empetrum*, which in Britain are typical features of the Hoxnian (see Fig. I.11, Pollen diagram from Marks Tey). Unfortunately, detailed chronological investigation has not yet been performed, and the only sample which has been analysed for amino acids ratios yielded a value 0.29, anomalously high (older) for correlation of this sequence with the Hoxnian. However this value is too low to correlate with the Cromerian (Austin, 1991b). The underlying glacigenic sediments (till) which have been correlated with the Lowestoft Till, support correlation with the Hoxnian rather than the Cromerian.

Since the work of Fisher *et al.* (1969) the presence of Holsteinian (Hoxnian) deposits has been known in the British sector of the southern North Sea. This investigation has confirmed the presence of such Holsteinian deposits. The sediments in the area (Chapter III & VI; see also Balson and Cameron, 1985; Cameron et al., 1987; Balson and Jeffrey, 1991) suggest that this borehole presents a conformable sequence from 43.2 m to 29.67 m. Detailed investigation shows that this part of the borehole presents a record from the later part of the Elsterian (Anglian) into the Saalian (Wolstonian) cold stage (Chapter VI). As such it contains a complete history of the Holsteinian interglacial stage.

Apart from the poorly recovered and polleniferous nature of the sequence representative of the pre-temperate (HoI) and early-temperate substages (HoII), the interglacial cycle is complete. There is no unconformity between the

Elsterian and Holsteinian sediments, but the contact between the Holsteinian and Saalian is unconformable.

Three vibrocores from the Inner Silver Pit provide additional detailed evidence on this interglacial cycle (Fig. IV.16).

Evidence from the Inner Silver Pit area (offshore) and from the Nar Valley (onshore) sequence suggests that during the transgression of the sea the shoreline moved landwards, depositing marine sediments (section VI.3). During the pre-temperate substage low-lying areas of the Nar Valley became marshy with fen vegetation communities, but in better drained sites boreal forest of *Pinus* and *Betula* developed (Ventris, 1985). Evidence from the Nar Valley shows that by HoIIc sea-level had reached +2.5 m O.D. in the Tottenhill area with much of the Nar Valley becoming estuarine. Deposits at Summer End indicate that by HoIIIb sea-level had reached +12 m O.D. Palaeoecological studies of the molluscan fauna indicate that sea-level reached up to +23 m O.D. at some places in the Nar Valley (Ventris, 1985). Similar evidence on the extent of the sea-level rise has been found in northern German (Ehlers et al., 1984).

Pollen evidence from the Nar Valley demonstrates that no Hoxnian sediments younger than substage HoIIIb occur onshore (Ventris, 1985, section VI.3,c). This suggests that after HoIIIb sea-level began to fall and deposition of marine sediments ceased.

During eustatic sea-level rise the coast line continued to move landward until the time of maximum flooding.

Biostratigraphic and sedimentological evidence from BH 81/52A indicates that the top of the peak of the Abies curve represents the time of maximum flooding and also represents the base of the condensed section. At this level there are a significant changes in the content of organic matter and carbonate. The main condensed section occurs between the top of the peak of the Abies curve and the base of the peak of the *Empetrum* curve.

After the phase of maximum flooding the shoreline moved basinward and the deposition of marine sediments ceased on land (section VI.3,c). This regression of the shoreline also caused erosion which may have removed previously deposited sediments. This explains why marine sediments are only found offshore. It has also become clear that marine deposits of the post-temperate substage HoIV are unlikely to be found in fluvial/estuarine contexts (section VI.3,c).

Pollen evidence combined with microfauna from the sediments recovered in borehole 81/52A indicate that the arctic climate of the late Elsterian gave way to boreal conditions and eventually to a temperate climate. This is supported by evidence from molluscs and microfauna of the Holsteinian sediments in the Danish North Sea sector and in the German onshore area (Grahle, 1936; Woszidlow, 1962; Lang, 1962; Knudsen, 1980) as well as from palynological studies (Menke, 1970; Müller, 1974b).

In the central North Sea, prior to this study, the Ling Bank Formation of Stoker *et al.* (1985a & b) has been placed within the Holsteinian interglacial cycle. This Formation includes two thin horizons representing two warm stages (Knudsen, in prep.). An amino acid ratio (0.29; monospecific sample of *Bulimina marginata*) obtained from the lower warm stage indicates that it represents either the Holsteinian or Cromerian interglacial stage, suggesting the upper warm stage to be either Holsteinian or Eemian. However, pollen analysis (this thesis, Chapter V) suggests that neither of these two warm stages represents the Holsteinian interglacial stage. Instead both interglacial stages are probably representative of two different stages within the Cromerian Complex. These conclusions support the stratigraphic interpretation in which the Ling Bank Formation in BH 81/34 occurs well below the seismic-stratigraphic level which should represent the Holsteinian (D.H. Jeffrey, pers. comm.). This means that deposits of Holsteinian age have yet to be found in the central North Sea.

b) Age and duration of the Hoxnian (Holsteinian)

The age of the Hoxnian interglacial has long been a matter of discussion. There is no conclusive date for the Holsteinian interglacial, although new efforts in U/Th (uranium series), ESR (Electron Spin Resonance) and TL (Thermoluminescence) dating are in progress. Nevertheless it is probable that the age of this temperate stage is more than 350,000 years.

Linke *et al.* (1985) produced a U/Th dates for the

Holsteinian interglacial using twenty-seven molluscs collected from the Holsteinian site in the vicinity of Hamburg and the Lower Elbe (Hallik, 1960; MÜller, 1974b). The age ranges between 195,000 +2500 and 218,000 +2500 years.

Sarnthein *et al.* (1986) have produced ESR dates (Electron Spin Resonance) for shells from Holstein beds. These cluster into two groups: one between 51,000 - 17,000 yrs B.P., and other between about 300,000 to more than 370,000 yrs B.P. This large difference has been found to be related with the quality of the shells; small, thin shells with high potential of contamination show young U/Th ages. The ESR ages estimations for these shells range consistently between 300,000 and 370,000 yrs B.P.

Sarnthein, *et al.*, (1986) reported U-series dates on shells from the Herzeele Formation (Holsteinian) in northern France that cluster around 330,000 years.

Schwartz and GrÜn *et al.* (1988) compared and contrasted the age (greater than 350,000 yrs) suggested by Sarnthein *et al.* (1986) with those (an age between 195,000 and 223,000 yrs) of Linke *et al.* (1985). Barabas et al (1988) replied to the comment made by Schwartz *et al.* (1988) and discussed the age discrepancy for the Holsteinian. Barabas et al. (1988), on the basis of their new empirical evidence, advised that the method of age derivation used by Linke *et al.* is incorrect and favoured the age (more than 350,000 yrs or more than 370,000 yrs) suggested by Sarnthein et al. (1986).

Laminated sediments or rythmites have been extensively used as a basis for a chronology, especially in Scandinavia. The sediment may be principally inorganic in origin, as in varved clays in which each sediment pair (varve) results from annual deposition. However, the best laminated sediments have been recorded from deep lakes, beneath the thermocline in oxygen poor environments, where sediments are not disturbed because of an absence of bottom fauna. The nature of the lamination and the methods by which annual cycles of deposition can be demonstrated has been discussed by Turner (1975) and West (1980). Using evidence of this kind, durations for interglacial stages have been suggested by MÜller (1974b) and Turner (1970); they have suggested a duration of 28,000 - 36, 000 years for the pre-Elsterian interglacial of Bilshausen and 17,000 - 25,000 for the Holstein interglacial.

The duration for the Holsteinian suggested by Turner (1970) is from the site of Marks Tey in England. Sediments from substage HoI and the early part of substage HoII were too finely laminated for analysis and Turner could only make a broad estimation of the number of lamination pairs present. He found approximately 5,000 - 10,000 pairs estimated to cover substage HoI and zones HoIIa & HoIIb. For zone HoIIc, he found 2,500 lamination pairs and 2,025 pairs for zone HoIIIa. Sediments in the upper part of substage HoIII were clearly laminated but too slumped and bracciated to give any possibility of an accurate count.

Turner (1975) has presented a summary of MÜller's results (Table VII.1). The duration suggested by MÜller (1974b) is 3,300 years for substage HoI, 38,00 years for substage HoII and 7,750 years for substage HoIII. On the basis of this estimate, the duration of the Holsteinian interglacial from substage I to substage HoIIIa has been estimated at 14,850 years. Comparing the lamination pair counts and sedimentation rates, a total duration of between 20,000 and 25,000years for the whole interglacial period has been suggested by Turner (1970).

VII.4. Wolstonian (Saalian) cold stage

The cold stage which separates the Hoxnian from the Ipswichian is the Wolstonian* in Britain and on the continent the Saalian. Prior to this study (Fig. VII.3) Saalian deposits had not been identified in the UK sector of the southern North Sea although periglacial deposits in Dutch sector were believed to extend into parts of the UK sector. Correlation of sands and gravels in BH 81/52A with the Wolstonian (section VI.4) is based on pollen evidence from the underlying Hoxnian silty-clay (Fig. III.7) which includes the end of the interglacial cycle within the Sand Hole Formation.

There has been much controversy over the extent of the

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* In Britain the term Wolstonian replaced an earlier informal term Gippingian, the latter based on till which was later found to represent the upper weathered zone of the stratigraphically older Anglian, Lowestoft Till.

SAALIAN/WOLSTONIAN COLD STAGE

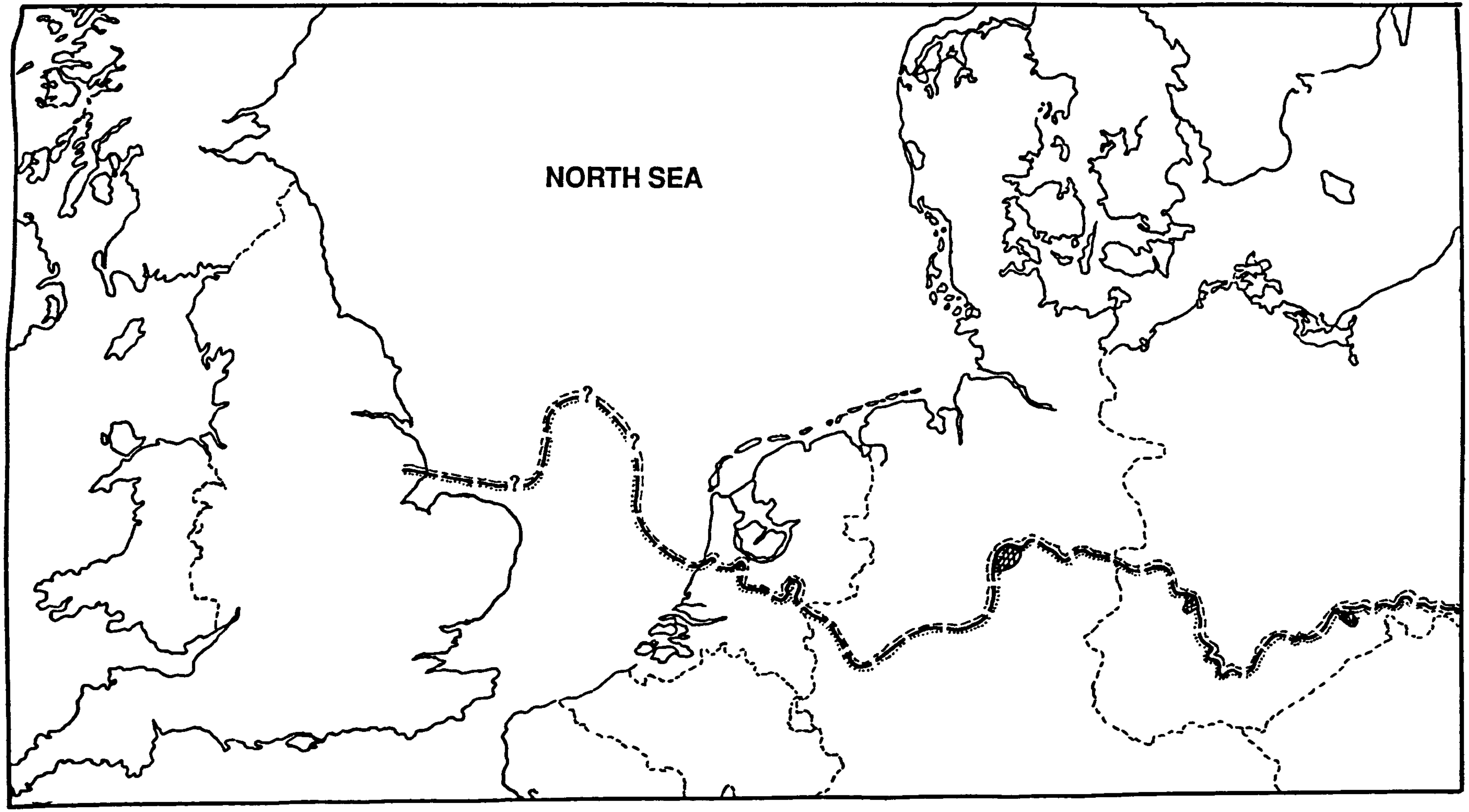

Fig. VII.3. Schematic palaeogeographic reconstruction of the extent of the Saalian/Wolstonian glacial deposits (from Gibbard, 1988). For key to symbols, see figure VII.2.

Wolstonian glaciation in England. This appears to be due to the fact that over much of England this glaciation was less extensive than the succeeding Devensian glaciation and the evidence has been widely destroyed or obscured. There is no till of Wolstonian/Saalian age in East Anglia (Whiteman, 1991).

There are currently two schools of thought: one suggests that the Wolstonian ice sheet only reached as far south as the area of Welton in Lincolnshire. This view is based on the Welton Till of east Lincolnshire (Alabaster and Straw, 1976; Madgett and Catt, 1978), the Basement Till of east Yorkshire (Catt and Penny, 1966) and the Warren House Till of coastal Durham (Francis, 1970). The other school believes that the Wolstonian ice sheet reached as far south as Norfolk (Gibbard, 1991; Lewis and Rose, 1991; Straw, 1991). Gibbard interprets the Tottenhill Sand and Gravel in the Nar Valley as Wolstonian cold climate deltaic sedimentation close to the ice margin. He suggests that lake deposition could only have been possible if there was a temporary barrier in the form of a Wolstonian (Saalian) ice sheet in this vicinity.

This debate continues and will hopefully eventually provide a clearer picture about the extent of ice during the Wolstonian cold stage. At present the placing of the Tottenhill Sand and Gravel within the Wolstonian cold stage is not questioned, whether it records the extent of the ice sheet or not. In addition to the Tottenhill Sand and Gravel there are two additional members of sand and gravel within the Nar Valley of Wolstonian age.

The Saalian (Wolstonian) is very well represented in NW Europe Ehlers *et al.*, 1984). In the Netherlands the Saalian was even more extensive than the Elsterian. In the Dutch sector of the southern North Sea the Saalian ice sheet extended as far west as 4° E and periglacial deposits of this stage are believed to be preset in the UK sector (Long *et al.*, 1988; Balson and Jeffery, 1991).

In BH 81/52A the silty-clay Holsteinian sequence is overlain by sand and gravel of the Egmond Ground Formation. The age of this unit is unknown beyond being post-Holsteinian and the recovery of the unit is very poor. These sands and gravels are probably either glacio-fluvial or periglacial deposits of Wolstonian or Devensian age.

A Wolstonian age for this sequence is supported by the presence of Saalian periglacial sediments in the Dutch sector extending towards the UK sector. This view is also supported by the presence of Wolstonian sands and gravels overlying Hoxnian sediments in East Anglia, as in the Nar Valley.

A Devensian age is supported by the presence of Devensian till above these sediments in BH 81/52A. However, this interpretation implies a considerable hiatus between the Hoxnian and the Devensian, with the erosion or non-deposition of Wolstonian and Ipswichian age sediments.

Ehlers *et al.* (1984) have discussed the extent of the Saalian glaciation in detail. Their discussion indicates that during the maximum extent of the Saalian glaciation an extensive ice-sheet covered the entire lowland area of Lower Saxony, Germany (Meyer, 1983) and parts of the adjacent mountainous regions to the south. In Germany the ice-thrusted ridges of Hterbeck-Uelsen, and Krefeld-Kleve in the Lower Rhine, represent the southern limit of the ice sheet. The ice advance formed the ice-pushed ridges of Nijmegen, Arnhem and Rhenen, and formed deep glacial basins in the Amsterdam-Haarlem area of the Netherlands. Laban *et al.* (1984) have described till up to 40 km off the coast on the Terschelling Bank sheet, and an ice-marginal valley and ice-pushed structures have been detected in the northwestern Flemish Bight sheet. These data suggest that Saalian ice extended from the continent to west of 4° E on the Indefatigable and Silver Well sheets. Glacigenic sediments of Saalian age have not been sampled in the UK sector of the southern North Sea, nor in the western half of the Dutch sector. However, the offshore evidence in the Dutch sector indicates that periglacial conditions prevailed over most of the southern North Sea during this period (Long *et al.*, 1988). It therefore seems likely that the sands and gravels of the Egmond Ground Formation overlying the Sand Hole Formation are Saalian/Wolstonian in age.

As far as the nature of the basal contact of this sandy and gravelly unit is concerned, the critical 1.67 m part of the silty-clay sequence of the Sand Hole Formation and the base of sand and gravel sequence, which could have provided evidence of the nature of the contact between these two units, was unfortunately not recovered in the borehole. However, it seems probable that the contact between the Holsteinian and the Saalian is unconformable, though whether this results from non-deposition or erosion is less clear.

The water depth in the area investigated in the Inner Silver Pit is only 20.20 m. It seems probable that during the Wolstonian sea-level fell and exposed the continental shelf causing a non-depositional unconformity.

The lower boundary between the Hoxnian and Wolstonian is recorded in lacustrine sequences where herb-dominated vegetation replaces the pre-existing interglacial forest. The most complete record is found at Marks Tey (Turner, 1970) where post-temperate boreal woodland dominated by Pinus and Betula (HoIV) is replaced by grassland rich in Artemisia accompanied by a variety of herb taxa (EWo - Early Wolstonian).

Pollen analysis of BH 81/52A indicates that 29.67 m represents the end of the Holsteinian temperate stage. The evidence is provided by the curves of *Betula* and more specifically Gramineae and *Artemisia*.

It is however probable that the sand and gravel overlying the Hoxnian deposits are periglacial fluvial or glacial gravels (Gibbard *et al.*, 1991a) of the Wolstonian cold stage, and can be correlated with the sand and gravel of the Tottenhill area of the Nar Valley and with Saalian periglacial sediments in the Dutch sector of the southern North Sea.

Chapter VIII

Conclusions

This study has dealt with various aspects of the Middle Pleistocene stratigraphy of the southern and central North Sea. The data generated has enabled a fairly detailed stratigraphy and environmental history of sediment deposition in the UK sector of the central-southern North Sea. This stratigraphy incorporates all the evidence found within the area investigated and it is hoped that further detail can be incorporated into the model to provide still further resolution.

In Chapter I three stratigraphic problems of particular relevance to this present study were outlined. These problems were :

a) The age of the silty-clay sequence (Sand Hole Formation of Tappin, 1991) recovered in borehole 81/52A from the Inner Silver Pit area of the southern North Sea.

b) The status of the sand and gravel (Egmond Ground Formation of Tappin, 1991) overlying the Sand Hole Formation in BH 81/52A.

c) The status of the Ling Bank Formation.

a) Age of the Sand Hole Formation

To address the first problem widely-spaced samples of the silty-clay sequence were analysed. Initial results showed similarity with the pollen assemblage found by Fisher *et al.* (1969; section III.8,a,i). Temporal variation in pollen assemblages reflected a trend which indicated the presence of an interglacial cycle. Detailed analyses of closely-spaced samples were then undertaken which provided a record of a temperate vegetational cycle preserved in the offshore area. The nature of the pollen spectra showed a close similarity with the widely cited pollen diagram from Marks Tey and lead to the correlation of the silty-clay sequence with the Hoxnian (Holsteinian) interglacial stage (section III.8,b,ii). The biggest problem in correlating this pollen spectra with the Hoxnian was the high frequencies of *Picea* in the lower half of the pollen diagram. High frequencies of *Picea* are a characteristic feature of the Cromerian interglacial stage (*s.s.*) at West Runton (West, 1980). Neither the site at Marks Tey, which has provided the standard pollen diagram for the Hoxnian, nor the site at Hoxne, which is the type site, show high frequencies for *Picea*. However, high frequencies of *Picea* have been found by Kelly (1964) at Nechells in Birmingham. The frequencies of *Picea* in this pollen diagram have been interpreted as a flotation effect of the marine context of deposition (section III.8,b,i). It is interesting to note that in HoIIIb, when *Abies* become dominant, *Picea* does not show high values and similarly in HoIV *Picea* does not seem important. These characters support correlation with the Hoxnian rather than the Cromerian in which *Picea* shows high frequencies throughout the cycle. In the future any site of Hoxnian age in the UK sector of the southern North Sea should show pollen spectra characterised by:

1. Dominance of Abies in HoIII showing a trend similar to the *Abies* curve at Marks Tey.

2. Dominance of *Empetrum* in HoIV.

3. Frequent presence of *Pterocarya* in upper half of the interglacial cycle.

4. Abundance of *Picea* in HoII, particularly in HoIIIa.

The lower part of the sequence did not provide any reliable pollen evidence. For this part of the sequence textural analysis (III.14) and loss-on-ignition (III.15) provided useful evidence and helped to explain why the lower part of the sequence did not provide any reliable pollen evidence. It seems reasonable to conclude that :

i) Offshore sites, even those which provide good pollen results, may not present an adequate vegetational record for the lower part of the interglacial cycle.

ii) Textural and geochemical analyses will be required.

iii) High percentages of coarser material and lower percentages of organic matter will be found in the lower part.

Besides pollen analysis, dinoflagellate cyst (III.12) and foraminiferal data (III.13), kindly provided by BGS, have also been used. The dino cyst data indicates an incomplete interglacial cycle within the silty-clay sequence (Dr R. Harland, *pers. comm.*). In the light of this situation it seems that either: i) the dino cyst spectra include a large number of reworked cysts, or ii) that the palaeoecology of dinoflagellate cysts requires more research.

On the basis of comparison of various species of dino cyst with the pollen biostratigraphy it can be concluded that the peak of *Achomosphaera andalouseinsis* represents the base of the peak of the Abies curve (III.12,b). This situation is found in both boreholes (BH 81/52A and BH 81/34) and suggests that in the recognition of interglacial deposits the abundant presence of *Achomosphaera andalouseinsis* can be associated with the optimum phase of the transgression.

The foraminiferal data generally support the pollen data, though they often do not indicate a climate as warm as that indicated by the pollen data. In the foraminiferal diagram *Bulimina marginata*, in particular, and *Nonion barleeanum, Cassidulina reniforme* and *Epistominella vitrea* represent the optimum phase of the transgression. In borehole 81/52A foraminifera provide the longest history of deposition, from the Anglian glacial marine environment to the Holsteinian interglacial environment.

It can be concluded that the silty-clay sequence of the Sand Hole Formation of Tappin (1991) represents a complete interglacial cycle, and that on the basis of pollen evidence it can be satisfactorily correlated with the Hoxnian.

From comparisons between the pollen, dino cyst and foraminiferal data it appears that foraminifera are the most generally useful group. They are equally useful for interglacial and glacial stages. For instance, *Bulimina marginata* clearly represents the optimum phase of interglacial climate and *Nonion orbicularae* glacial marine conditions. Dinoflagellate cysts record detailed changes in marine conditions. When pollen assemblages are present in significant concentrations they play a decisive biostratigraphic role, in particular in the recognition of interglacial stages. In addition they are able to provide the basis for the subdivision of various stages and the boundaries between substages of interglacial cycles.

In the central North Sea pollen assemblages have been found to be less useful. The technique is of limited use for sites which are in deep water far from fluvial influence. However, even in this case, in terms of the relative dating of interglacial stages, pollen can still play an important biostratigraphic role.

BH 81/52A contains Anglian glacial and Hoxnian interglacial sediments which are thought to represent a complete eustatic cycle. This depositional history has been discussed in the light of 'sequence stratigraphy' (Chapter VI), a stratigraphic concept originating from seismic stratigraphy. In this depositional environments are defined in terms of genetically related sedimentary packages deposited during various stages of eustatic sea-level cycles. The application of this concept does not depend exclusively on seismic data, and data available from outcrops can also be employed.

In the sequence stratigraphic framework glacial deposition is defined as lowstand deposition whereas interglacial deposition represents highstand deposition which itself includes a transgressive system tract, maximum flooding event and highstand system tract (regressive phase of the interglacial cycle).

For glaciated shelves, Boulton (1990) has presented a model which incorporates the position of the ice sheet and the nature of depositional processes on the shelf.

In this project the use of Boulton's model in conjunction with sequence stratigraphy has employed all biostratigraphic, sedimentologic and eustatic evidence available from the Nar Valley (Ventris, 1985) and the Inner Silver Pit (this thesis). Collectively the events elucidated by these data and models can be summarised as follows :

1. Deposition during the Anglian did not begin until the later half of the optimum phase of the glaciation. Once deposition began it continued into the Holsteinian interglacial stage. This implies that the advance of the continental ice sheet and its replacement by the Lowestoft ice sheet occurred before deposition began.

2. The contact between the Anglian and Hoxnian is conformable.

Detailed evidence from the Nar Valley indicates that no sediments younger than HoIIIb have been found. The sequence stratigraphic model explains this absence in that after maximum flooding the shoreline begins to move basinward, which not only halts deposition of marine sediments but also causes erosion of previously deposited sediments. It indicates that the maximum flooding surface will take the form of an erosional surface. The events indicated after the maximum flooding recognised in BH 81/52A suggest that :

i) the maximum flooding surface coincides with the peak of the *Abies* curve.

ii) The condensed section may be found between the maximum flooding surface and the base of the peak of *Empetrum* (or Ericaceous heath) curve.

iii) The highstand system tract, represented by deposits of the post-temperate substage, can only be found in offshore sites such as BH 81/52A, and not on land in fluvial-estuarine sequences.

Pollen evidence indicates that the silty-clay sequence represents the complete interglacial cycle.

b) Status of the Egmond Ground Formation

Tappin (1991) has interpreted both the Sand Hole Formation and Egmond Ground Formation as being of Holsteinian age. Tappin's interpretation is based on seismic evidence and preliminary micropalaeontological data.

Detailed pollen analysis of the Sand Hole Formation indicates that the Hoxnian interglacial cycle ends within the Formation and therefore the overlying sand and gravel of the Egmond Ground Formation cannot be correlated with the Egmond Ground Formation of the Dutch sector which represents the Holsteinian (Hoxnian) interglacial stage.

These sands and gravels represent fluvial or glacio-fluvial sediments of Wolstonian or Devensian age. The most likely correlation has been discussed in section VI.4 and it has been concluded that they are probably of Wolstonian age. In this situation these sands and gravels could be correlated with the Wolstonian sands and gravels of the Nar

Valley (Tottenhill). The contact between the Sand Hole Formation and the Egmond Ground Formation is probably unconformable but nonerosional (section VII.4).

This detailed palynological and sedimentological evidence, in conjunction with the seismic record, indicate that the sands and gravels overlying the silty-clay of the Sand Hole Formation should not be called the Egmond Ground Formation as they cannot be correlated with the Egmond Ground Formation of the Dutch sector of the southern North Sea.

c) Status of the Ling Bank Formation

Pollen evidence has failed to indicate decisively whether the Ling Bank Formation represents a single interglacial stage, as suggested by the dino cyst data, or whether it represents two warm periods separated by a cold period as suggested by the foraminiferal evidence. The pollen evidence, though poor, does support the hypothesis of two warm periods in the Ling Bank Formation (section V.8). The sequence between these two warm periods is certainly colder, and cannot be interpreted as the central part of an interglacial cycle. This implies that the pollen data support the foraminiferal data. Neither of the warm periods can be correlated with the Eemian or the Holsteinian on pollen grounds. These data support a correlation with the Cromerian Complex.

The main conclusions of the study are therefore :

1. The glacial deposits recovered in BH 81/52A represents the Anglian glacial stage.

2. The contact between the Anglian diamictons and Holsteinian silty-clay is conformable.

3. The age of the silty-clay sequence of the Sand Hole Formation of Tappin (1991) is Hoxnian (Holsteinian). The sequence represents the complete interglacial cycle.

4. The contact between the Hoxnian silty-clay and overlying sand and gravel is unconformable but not erosional.

5. The age of the sands and gravels of the Egmond Ground Formation is uncertain. However, they probably correlate with the sands and gravels at Tottenhill overlying the Hoxnian Nar Valley marine clay and as such are probably of Wolstonian age.

6. In the central North Sea the Ling Bank Formation does not represent a single interglacial stage, but rather two warm periods separated by a cold period. These two warm periods probably represent two interglacial stages within the Cromerian Complex.

7. Pollen analysis can be regarded as a very useful biostratigraphic tool for neritic or inner shelf deposits. However, for sites in deep water far from fluvial influence it is limited.

8. A combination of the interglacial subdivision and zonation scheme (Turner and West, 1968), sequences stratigraphy (Posamentier and Vail, 1988) and Boulton's model (Boulton, 1990) have been found useful in clarifying the depositional history of the complete eustatic cycle (Anglian glacial stage to Holsteinian interglacial stage).

Recommendations and suggestions for future work

1. The silty-clay sequence of the Sand Hole Formation contains a complete history of the Hoxnian interglacial cycle. Apart from the pre-temperate substage (HoI) pollen analysis has provided a detailed biostratigraphy for the complete interglacial cycle. These results, combined with the marine Hoxnian sites of The Nar Valley have enabled a detailed depositional history to be established. A detailed geo-chronological investigation is now required which would assist correlation of this site with other interglacial sites in NW Europe.

2. In the central North Sea :

i) Pollen concentrations have been found to be too low to provide a detailed geological history.

ii) Foraminiferal analysis of the whole sequence recovered in BH 81/34 has provided the longest record for this borehole. However, a closer sampling interval of sampling is suggested which could provide a continuous curve rather than the existing block diagram.

Detailed amino acid analysis of the sequence recovered in BH 81/34 is currently being undertaken which will enhance the justification for generating a more detailed foraminiferal record from this borehole. In addition a calcareous nannofossil investigation might prove useful.

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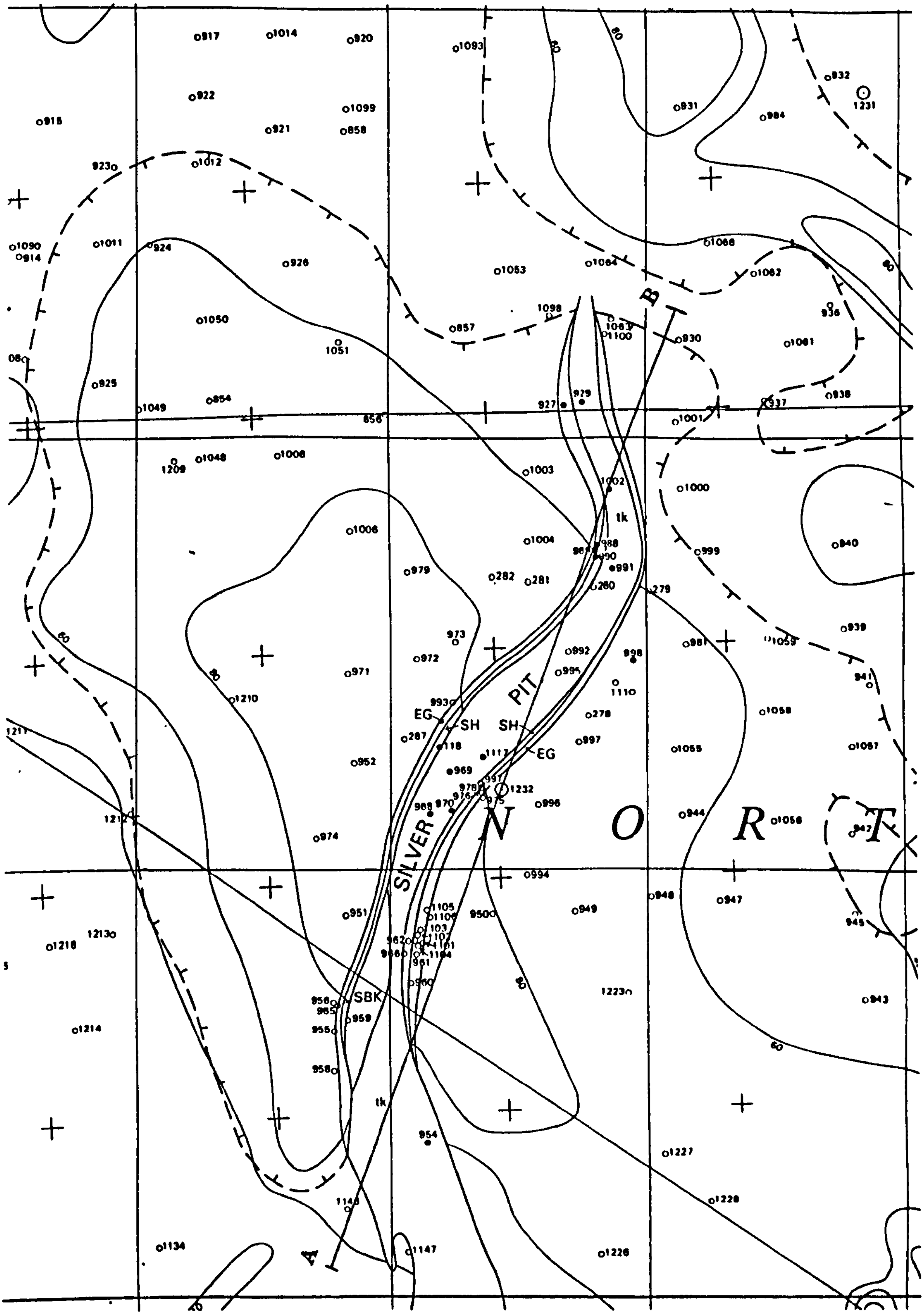

APPENDIX I. Quaternary geology - lateral distribution of the Sand Hole Formation (SH) and Egmond Ground Formation (EG) along the section A-B.

7 P 142

FDL 84/80

APPENDIX II.

To : D A Ardus
Copy 1 of 4 : T D J Cameron
Copy 2 of 4 : Pal Group Manager
Copy 3 of 4 : Pal Group Files
Copy 4 of 4 : R Harland

DINOFLAGELLATE CYST ANALYSIS OF BOREHOLE 81/52A, SPURN SHEET (53/+60), SOUTHERN NORTH SEA

Submitted by : Marine Geology Unit
Prepared by : Mr S Marsh
Examined by : R Harland

Purpose

To assist in the dating and palaeoenvironmental analysis of Quaternary sediments recovered in Borehole 81/52A, Spurn Sheet (53/+60), southern North Sea.

Summary Conclusions

Samples encompassing 30.0 to 41.0m drilled depth proved an excellent interglacial marine sequence characterised by the cyst genus *Spiniferites*. The age of this sequence is not known but the character of the dinoflagellate assemblages show similarities to that climatic ameliotatation seen in Borehole 75/33 between 132.0 and 143.0m drilled depth within the Aberdeen Ground Formation.

Introduction

A suite of twenty-six samples was submitted from Borehole 81/52A drilled on the Spurn Sheet (53/+60), southern North Sea at Latitude : 53° 31.355' N, Longitude : 0° 44.291' E in 20.2m of water. Sample details are as follows:-

CSB N^{O}	Depth	Result
6494	19.09	+
6495	29.90	+
6496	30.56	+
6497	31.03	+
6498	31.67	+
6499	32.12	+
6500	32.67	+
6501	31.78	+
6502	32.07	+
6503	32.61	+

CSB N^{o}	Depth	Results
6504	33.16	+
6505	33.21	+
6506	33.76	+
6507	34.64	+
6508	35.16	+
6509	35.51	+
6510	36.03	+
6511	38.08	+
6512	38.30	+
6513	38.90	+
6514	40.67	+
6515	40.97	+
6516	41.20	+
6517	41.55	-
6518	41.58	+
6519	42.20	-

Results

Only samples CSB 6517 and 6519 proved to be entirely barren of dinoflagellate cysts but samples CSB 6494, 6516 and 6518 contained such poor floras to preclude further discussion. Indeed, all these samples indicate unfavourable environmental conditions for the dinoflagellate cysts.

The remaining samples from CSB 6495 at 29.9m to CSB 6515 at 40.97m drilled depth contained rich and diverse dinoflagellate floras, indicative of a strongly ameliorative episode of interglacial proportions. The dinoflagellate cyst assemblages are characterised by high proportions (c. 60.0%) of Spiniferites spp. including Achomosphaera andalousiense Jan du Chene. A full list of species found within this interval is given below:-

Gonyaulacacean cysts

Achomosphaera andalousiense	Jan du Chene
Bitectatadinium tepikiense	Wilson
Operculodinium centrocarpum	(Deflandre and Cookson) Wall
Planinosphaeridium choanum	(Reid) Wall et al.
Spiniferites belerius	Reid
Spiniferites elongatus	Reid
Spiniferites mirabilis	(Rossignol) Sarjeant

Spiniferites ramosus	(Ehrenberg) Sarjeant
Spiniferites spp. indet	
Peridiniacean cysts	
Protoperidinium conicum	(Gran) Balech
Protoperidinium divaricatum	(Meunier) Balech
Protoperidinium pentagonum	(Gran) Balech
Protoperidinium subinerme	(Paulsen) Balech
Protoperidinium (*P*. sect *Quinquecupis*) sp. indet	
Protoperidinium spp. indet (round brown cysts)	

This cyst assemblage points to a good temperate climate possibly in a rather more inner neritic environment without the presence of too much North Atlantic water. There is little variation in the dinoflagellate spectrum (Figure 1) except for a possible increased influence of *Bitectatadinium tepikiense* in the lower part of the sequence indicating some possible cooling.

Unfortunately, an age cannot be assigned to this amelioration and indeed most other ameliorative episodes as seen in the North Sea are characterised by high proportions of *Operculodinium centrocarpum*. Some assemblages seen in Borehole 75/33 between 132.0 and 143m and between 149.0 and 182.0m are also characterised by *Spiniferites* spp. Perhaps a correlation is suggested or perhaps these *Spiniferites* spp dominated assemblages are in rather more inshore expression of the more open water *Operculdinium centrocarpum* dominated ameliorative episodes. Further work is necessary to explore these possibilities.

R. Harland

R HARLAND

17 April 1984

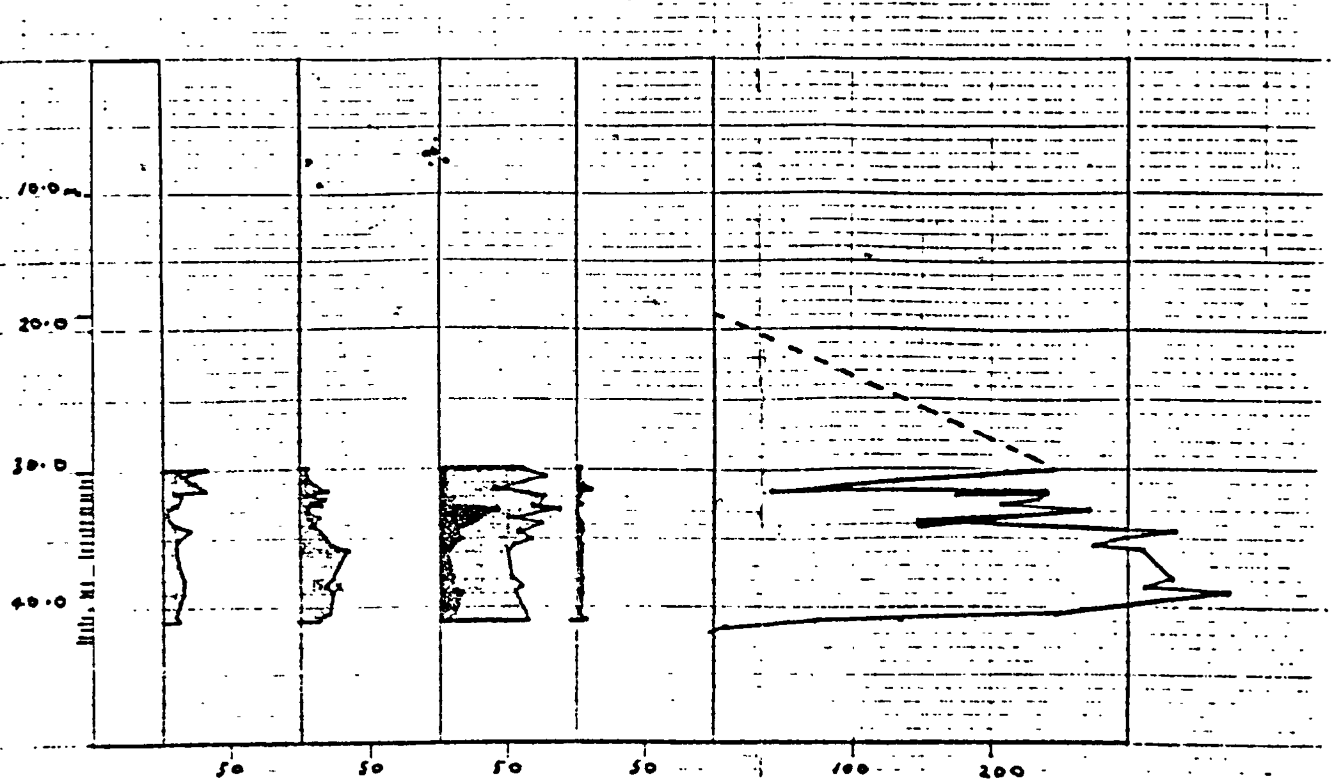
Borehole 81/52 A
10.0m
20.0
30.0
40.0
50
50
50
50
100
200
O. centroc'
B. tepik'
Spiniferites
Protoperid'

Figure 7

APPENDIX III

Statistical results from the dino cyst data.

Table D1=Depth 40.67 - 36.03 m

	MEAN	MEDIAN	STDEV
A	13.00	12.00	2.71
B	22.14	23.00	7.60
C	9.57	10.00	2.88
D	53.14	53.00	5.55
E	6.29	7.00	1.38
F	317.10	325.00	41.10

Table, Correlation among species

	A	B	C	D	E
B	0.210				
C	0.492	-0.438			
D	-0.233	-0.929	0.463		
E	0.803	0.583	0.246	-0.550	
F	0.778	0.668	0.284	-0.611	0.913

Table D2=Depth 35.51 - 29.95 m

	MEAN	MEDIAN	STDEV
A	14.50	11.00	9.32
B	12.25	12.00	6.47
C	14.08	11.50	11.79
D	60.92	62.50	16.13
E	5.25	5.00	2.22
F	212.50	222.50	81.70

Table, Correlation among species.

	A	B	C	D	E
B	0.017				
C	-0.619	-0.108			
D	-0.282	-0.825	0.235		
E	0.652	0.483	-0.487	-0.560	
F	-0.379	0.039	0.324	0.029	-0.515

Reference PDL 84/7

APPENDIX IV

D Cameron
D Ardus
Chief Palaeontologist

Quaternary calcareous micropalaeontology

Bh/81/52A

Latitude :	53° 31.855'N
Longitude:	0° 44.291'E
Water Depth:	20.2 m
Sheet :	53.5N 00E (Spurn)

Submitted by:	D Cameron
Prepared by:	Susan Prince
Examined by:	Diane Gregory

Registration Details - see attached chart.

Comment.

Three units can be defined.

Unit 1 CSB 6509 (35.51 m) - CSB6519 (42.20 m).

A shallow, cold water foraminiferal fauna was recovered. The dominant species is Elphidium clavatum. Below 41.55 m faunas are sparse indicating inhospitable conditions.

Unit 2 CSB 6498 (31.67 m) - CSB 6509 (35.16 m)

Strong unflux of southern species including Bulimina marginata, Buccella vicksburgensis, Cassidulina laevigata and Nonion barleeanum, indicates a considerable level of amelioration, probably to interglacial conditions. Significant deepening (to circa 50 m) is also suggested by these assemblages. It is interesting that at 32.61 m there is a horizon with relatively few southern species, where cold water conditions are again postulated. A similar situation was recorded in Bh 78/9 (Skinner and Gregory 1983 Boreas 12 pp 145-52 in a probable Eemian Interglacial.

Unit 3 CSB 6494 (19.09 m) - CSB 6597 (31.03).

A return to colder shallower conditions is indicated by the recovered microfaunas although a few southern species remain to suggest a slight ameliorative influence up to 29.90 m. In the top sample at 19.09 m many specimens are abraded and heavily stained possibly separating this material into a fourth mainly reworked unit.

Diane Gregory

DIANE GREGORY

11 January 1984

CODE 18-77

41/52 A

CSB	6494	6495	6496	6497	6498	6501	6502	6499	6503	6500	6504	6505	6506	6507	6508	6509	6510	6511	6512	6513	6514	6515	6516	6517	6518	6519
Depth (m).	19.09	20.40	30.56	31.03	31.67	31.78	32.07	32.12	32.61	32.67	33.16	33.21	33.76	34.44	35.16	35.51	36.03	36.06	36.30	36.40	40.67	40.97	41.20	41.55	41.58	42.20
Ammonia batavus				5	5		1	2		1												3				
Bolivina sp.							1						1	2	2			1		1						
Buccella frigida	2	4	3																	1				1		
B. vicksburgensis		2		3	12	33			9	24	7	3	4	4	3	3	1					1				
Bulimina gibba	1																									
B. marginata		2		5	105	54	57	134	21	129	24	15	30	63	93	1					3	1			1	
Cassidulina carinata						3																				
C. laevigata							30				42	54	33	30	2		2									
C. ?teretis								1																		
C. teniforme	4	4	36	1	2		1	12		21				9	24	4		10	2	1		1	4			
Cibicides grossa	1																									
C. lobatulus	18	1																								
Elphidium asklundi																					1	15				
E. bartletti	2																				1					
E. clavatum	40	32	261	20	174	180	186	159	264	126	222	213	210	177	174	291	297	265	297	297	276	243	136	17	7	10
E. subarcticum																					1	9				
Fissurina lucida	1																									
F. marginata																										
Lagena clavata													1		1			2								
L. distoma				1	2		1	1		2																
L. semilineata				3																						
Lenticulina sp.																1			1							
Miliolinella subrotunda	1																									
Nonion barleeanum						2	21	11			5	15	21	15												
N. depressulum	2																									
Oolina squamosa															1											
O. sp	1																									
Polymorphinids.																							2			
Protelphidium orbiculare	18	1																			18	24	156	2		1
Quinqueloculina seminulum	22																									
Q. stalkeri							1											2								
Trifarina angulosa.	1																									
Total species	14	7	3	7	6	5	9	7	3	6	5	5	7	7	6	5	3	5	3	4	6	6	4	3	2	2
Total specimens.	114	46	300	36	300	272	296	300	294	303	300	300	300	301	300	301	300	300	300	300	300	297	300	20	6	11
	St																									

St- stained.

81/52A

CSB	6494	6495	6496	6497	6498	6501	6502	6499	6503	6500	6504	6505	6501	6507	6508	6509	6510	6511	6512	6513	6514	6515	6516	6517	6518	6519
Depth (m).	19.09	20.40	30.56	31.03	31.67	31.78	32.07	32.12	32.61	32.67	33.16	33.21	33.76	34.44	35.16	35.51	36.03	36.06	36.30	36.40	40.67	40.97	41.20	41.55	41.58	42.20
Ammonia batavus				5	5		1	2		1												3				
Bolivina sp.							1						1	2	2			1		1						
Buccella frigida	2	4	3																	1				1		
B. vicksburgensis		2		3	12	33			9	24	7	3	4	4	3	3	1					1				
Bulimina gibba	1																									
B. marginata		2		5	105	54	57	34	21	129	24	15	30	63	93	1					3	1			1	
Cassidulina carinata						3																				
C. laevigata							30				42	54	33	30	2		2									
C. ?teretis								1																		
C. tenuiforme.	4	4	36	1	2		1	12		21				9	24	4		10	2	1		1	4			
Cibicides glossa	1																									
C. lobatulus	18	1																								
Elphidium asklundi																					1	15				
E. bartletti	2																				1					
E. clavatum	40	32	261	201	74	100	166	157	264	126	222	213	210	177	174	211	287	265	297	297	62	43	136	17	7	10
E. subarcticum																					1	9				
Fissurina lucida	1																									
F. marginata																										
Lagena clavata													1		1			2								
L. distoma				1	2		1	1		2																
L. semilineata				3																						
Lenticulina sp.																1			1							
Miliolinella subrotunda	1																									
Nonion barleeanum						2	21	11			5	15	21	15												
N. depressulum	2																									
Oolina squamosa															1											
O. sp	1																									
Polymorphinids.																							2			
Protelphidium orbiculare	18	1																			16	24	156	2		1
Quinqueloculina seminulum	22																									
Q. stalkeri							1											2								
Trifarina angulosa.	1																									
Total species	14	7	3	7	6	5	9	7	3	6	5	5	7	7	6	5	3	5	3	4	6	6	4	3	2	2
Total specimens.	114	46	300	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	6	11

St- stained.

St

APPENDIX V

Statistical results from the textural data.

Table T1a= 43.20 - 42.60 m

	MEAN	MEDIAN	STDEV
Sand	9.44	13.80	7.43
Silt	21.74	28.10	14.06
Clay	68.82	56.20	21.06

Table, Correlation.

	Sand	Clay
Silt	0.914	
Clay	-0.963	-0.990

Table T1b=Depth 42.50 - 41.90 m

	MEAN	MEDIAN	STDEV
Sand	12.83	12.90	2.07
Silt	31.07	30.95	15.54
Clay	56.07	56.10	16.15

Table, Correlation. x.

	Sand	Silt
Silt	0.237	
Clay	-0.356	-0.992

Table T1c=Depth 41.80 - 40.70 m

	MEAN	MEDIAN	STDEV
Sand	9.45	6.20	9.20
Silt	29.05	28.50	5.66
Clay	61.83	66.80	14.00

Table, Correlation.

	Sand	Silt
Silt	0.744	
Clay	-0.965	-0.889

Table T1d=Depth. 40.60 - 39.20 m

	MEAN	MEDIAN	STDEV
Sand	7.50	7.50	0.14
Silt	49.25	49.25	2.90
Clay	43.25	43.25	3.04

Table, Correlation.

	Sand	Silt
Silt	1.000	
Clay	-1.000	-1.000

Table T2=DEPTH 39.10 - 33.40 m

	MEAN	MEDIAN	STDEV
Sand	1.91	1.90	0.62
Silt	38.09	37.80	5.69
Clay	60.00	60.00	5.67

Table, Correlation.

	Sand	Silt
Silt	-0.080	
Clay	-0.027	-0.994

APPENDIX VI

Statistical results from the loss-on-ignition data.

Table L1=Depth 43.20 - 37.20 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	6.030	6.301	2.370	-0.533
Carbonate content	8.995	8.792	2.850	

Table L1a=Depth 43.20 - 42.50 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	6.382	6.413	2.579	-0.631
Carbonate content	10.35	8.92	3.54	

Table L1b=Depth 42.40 - 41.80 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	6.755	7.439	1.421	-0.851
Carbonate content	4.933	3.805	2.176	

Table L1c=Depth 41.60 - 40.70 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	7.832	7.837	1.249	0.560
Carbonate content	9.554	9.789	1.416	

Table L1d=Depth 40.60 - 38.40 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	3.478	3.440	1.838	-0.978
Carbonate content	10.364	10.760	2.002	

Table L1e=Depth 38.10 - 37.20 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	5.994	6.277	2.151	-0.976
Carbonate content	8.822	8.469	1.962	

Table L2=Depth 37.12 - 29.67 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	7.659	7.742	1.230	-0.265
Carbonate content	5.408	5.480	1.678	

Table L2a=Depth 37.12 - 33.20 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	8.169	8.176	0.774	-0.463
Carbonate content	5.557	5.441	0.656	

Table L2b=Depth 33.10 - 31.50 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Carbonate	7.571	7.722	1.396	-0.804
Carbonate content	6.169	6.055	1.057	

Table 12c=Depth 31.40 - 29.67 m

	MEAN	MEDIAN	STDEV	Correlation between OM & CC
Organic matter	6.740	6.849	1.287	-0.487
Carbonate content	4.247	3.680	2.812	

APPENDIX VII

Posamentier *et al.* (1988)

DEFINITION OF KEY TERMS

Sequence Stratigraphy:
The study of rock relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related stratal units (sequences and systems tracts).

Depositional System:
A three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments (delta, river, barrier island, and so on) (Brown and Fisher, 1977).

Systems Tract:
A linkage of contemporaneous depositional systems (Brown and Fisher, 1977). Each is defined objectively by stratal geometries at bounding surfaces, position within the sequence, and internal parasequence stacking patterns. Each is interpreted to be associated with a specific segment of the eustatic curve (i.e., eustatic lowstand—lowstand wedge; eustatic rise—transgressive; rapid eustatic fall—lowstand fan, and so on), although not defined on the basis of this association.

Sequence:
A relatively conformable succession of genetically related strata bounded at its top and base by unconformities and their correlative conformities (Vail and others, 1977). It is composed of a succession of systems tracts and is interpreted to be deposited between eustatic-fall inflection points.

Parasequence:
A relatively comformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces (Van Wagoner, 1985).

Unconformity:
A surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated.

Condensed Section:
A thin marine stratigraphic interval characterized by very slow depositional rates <1-10 mm/1000 yr) (Vail and others, 1984). It consists of hemipelagic and pelagic sediments, starved of terrigenous materals, deposited on the middle to outer shelf, slope, and basin floor during a period of maximum relative sea-level rise and maximum transgression of the shoreline (Loutit, and others, this volume).

Accommodation:
The space made available for potential sediment accumulation (Jervey, this volume).

Equilibrium Point:
The point along a depositional profile where the rate of eustatic change equals the rate of subsidence/uplift. It separates zones of rising and falling relative sea level.

Equilibrium Profile:
The longitudinal profile of a graded stream or of one whose smooth gradient at every point is just sufficient to enable the stream to transport the load of sediment made available to it. It is generally regarded as a smooth, parabolic curve, gently concave to the sky, practically flat at the mouth and steepening toward the source (Gary and others, 1974).

Appendix VIII

(Haq, 1988)

The type of sequence is determined by the rate of relative fall of sea level. When the rate of fall of sea level exceeds the rate of regional subsidence at the depositional-shoreline break on the shelf (landward of which the depositional surface is at or near sea level and seaward of which the surface is below sea level) the exposed and incised shelf will result in a type 1 sequence boundary (system overlying this boundary will be type 1 sequence). When the base of the sea-level fall is less than the rate of subsidence the shelf seaward of the depositional-shoreline break will not be exposed and a type 2 sequence boundary will result (sequence overlying type 2 boundary is a type two sequence.

A type 1 sequence is typically composed of lowstand, transgression and highstand tracts. In type 2 sequence the 'lowstand system tract' is replaced by the marginal system tract. The distinction between lowstand and shelf margin systems tracts will become clear after the explanation of the depositional events during a complete cycle of sea-level change given in the following section.