DOCTOR OF PHILOSOPHY

Ostracod palaeoecology and biogeochemistry of marine and estuarine interglacial deposits in North West Europe.

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OSTRACOD PALAEOECOLOGY AND BIOGEOCHEMISTRY OF MARINE AND ESTUARINE INTERGLACIAL DEPOSITS IN NORTH WEST EUROPE.

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CAROLINE S. INGRAM

I would like to dedicate this thesis to my parents for their unstinting faith in my abilities and their constant love and encouragement throughout my education.

ABSTRACT

Ostracods were obtained from two cores in the southern North Sea area: the Sand Hole and Swarte Bank Formations of Tappin (1991) in BGS borehole 81/52A, cored from the Inner Silver Pit, southern North Sea; and a core from Shoeburyness in Essex, borehole S1. The faunal assemblages in BH81/52A were dominated by *Sarsicytheridea punctillata*, *Elofsonella concinna* and *Acanthocythereis dunelmensis*. The assemblages recovered reflect a transition from glacio-marine conditions in the Swarte Bank Formation up into a cold-temperate marine environment in the Sand Hole Formation with deteriorating temperatures indicated at the top of the interval studied. In BHS1 a freshwater to brackish transition occurred in the core, the freshwater section being dominated by *Darwinula stevensoni* and *Ilyocypris* spp., and the brackish section by *Cyprideis torosa* and *Cytheromorpha fuscata*. The palaeoecology of the ostracod assemblages recovered is compared to other palaeoecological data from the same sections in each core and to ostracod data from other Hoxnian/Holsteinian sites in north western Europe. These data are also discussed in the light of evidence indicating that there was a barrier across the southern North Sea when the sediments examined were deposited.

Sarsicytheridea spp. and *Cyprideis torosa* were used for trace element (Mg:Ca, Sr:Ca) and stable isotope ($\delta^{18}O$, $\delta^{13}C$) analyses. A calibration equation for the calculation of temperature from Mg:Ca ratio was successfully established from analysis of modern *Sarsicytheridea*. Modern Sr:Ca data could not be used to establish a calibration for salinity since there was too much scatter in the data. *Cyprideis torosa* has been used for trace element and stable isotope work by other authors who have published relationships between *Cyprideis* and the water chemistry. Ostracods were also analysed down core to examine the changing ratios of Mg and Sr as a proxy for temperature and salinity changes in the Hoxnian of the southern North Sea.

In BH81/52A, Mg:Ca data indicated a deterioration in temperature from 36.20 m to the top of the section studied of 9°C. Oxygen stable isotopic analyses from the same species, measured through the same core intervals, did not exhibit a trend, but their values were indicative of normal marine salinities. Carbon stable isotope analyses, performed at the same time as the oxygen analyses, indicate that there may have been high productivity in the region of deposition of the Sand Hole Formation, implying deposition in a region of freshwater influence. However, C/N analyses indicated that the sediments in the Inner Silver Pit were deposited under fully marine conditions.

In BHS1, both the Mg:Ca and Sr:Ca data suggested that salinity had increased upcore. However, there was a lot of scatter in the data, indicating that the estuarine environment, under which the palaeoecology suggests the sediments were deposited, was a highly fluctuating one. These data compare favourably with previously published records. Published partition coefficients were used to compare the trace element data obtained to mean river and seawater values.

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Chapter 1

Introduction, Aims and Objectives

This study concentrates on two Pleistocene interglacial sites within the North Sea basin, one fully marine site from the Inner Silver Pit, and the other, containing a transgressive overlap, from Shoeburyness on the Essex coast.

1.1 Introduction

Ostracods are small crustaceans which occur in practically every aquatic environment and are particularly sensitive to changes in water temperature (Chivas *et al.*, 1986a). Temperature and salinity exhibit predictable shifts with changing water depth, circulation, water mass and geographical area and these are paralleled by changes in ostracod assemblages. The geographical distribution of discrete assemblages thereby provides a guide to different environments.

The speed of response of marine and freshwater ostracods to even subtle alterations to their environment makes them one of the most sensitive organisms that fossilise in abundance. Their microscopic size means that a great number of specimens can be easily examined, allowing for a measure of quantification in such studies. The complexity of ostracods and their relatively long life span (for a microscopic animal) lends information on seasonality not possible from more simple protozoans such as foraminifera (Delorme 1969).

The Inner Silver Pit is an incision in the North Sea bed (Fig 1.1). As Fig 1.2 (Ch 2.1) shows, it is surrounded by Quaternary sediments which are infilling a shallow saucer-like depression in the sea-bed. The borehole log (Fig 1.3) indicates the formations present, where sediment samples have been taken, and the 'classical' stratigraphy of the area. Pollen

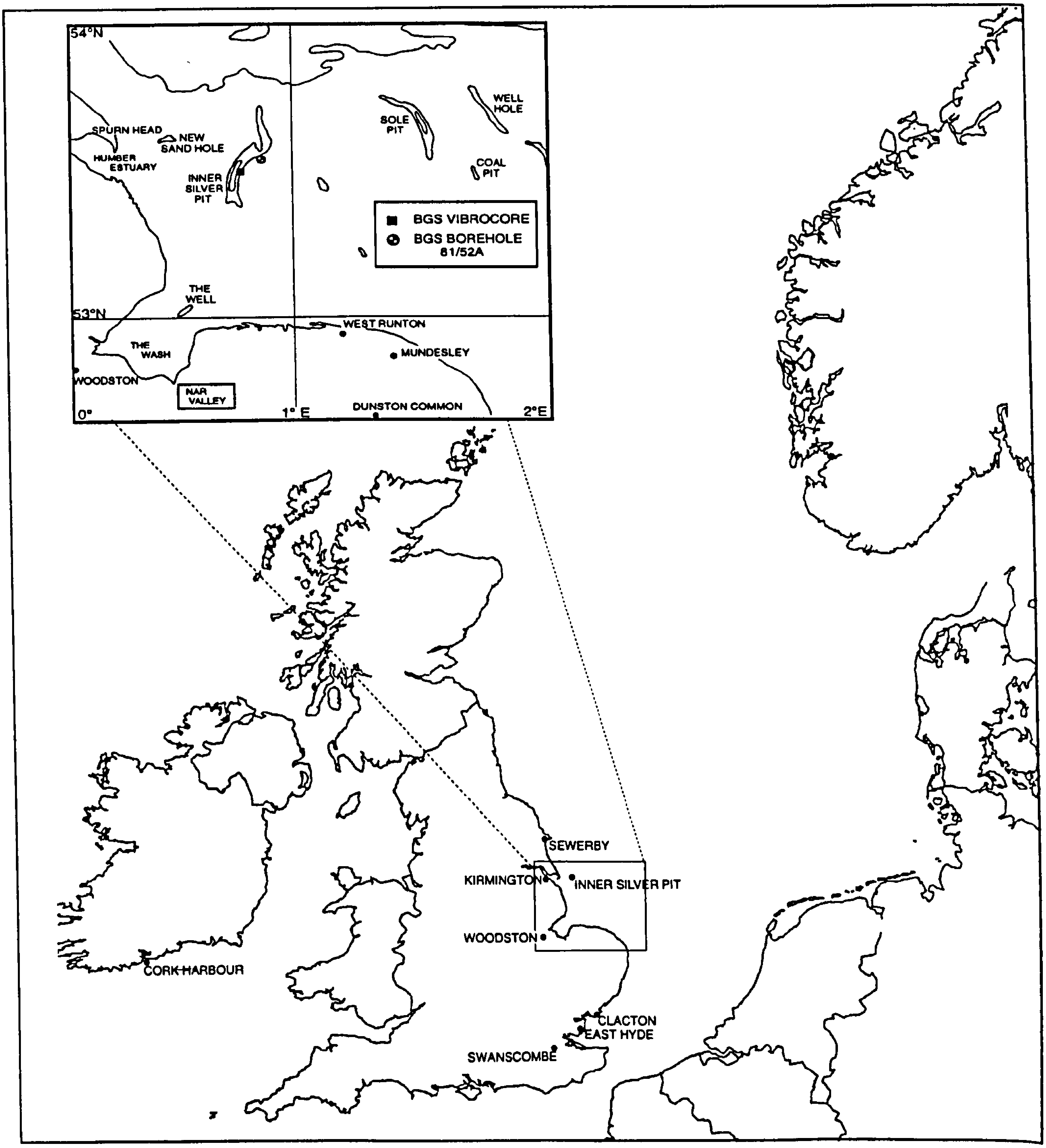


Fig 1.1 Map of Britain and north west Europe with inset detail of Inner Silver Pit area.

Fig 1.2 **Relationships between the sedimentary formations of the Inner Silver Pit, southern North Sea**

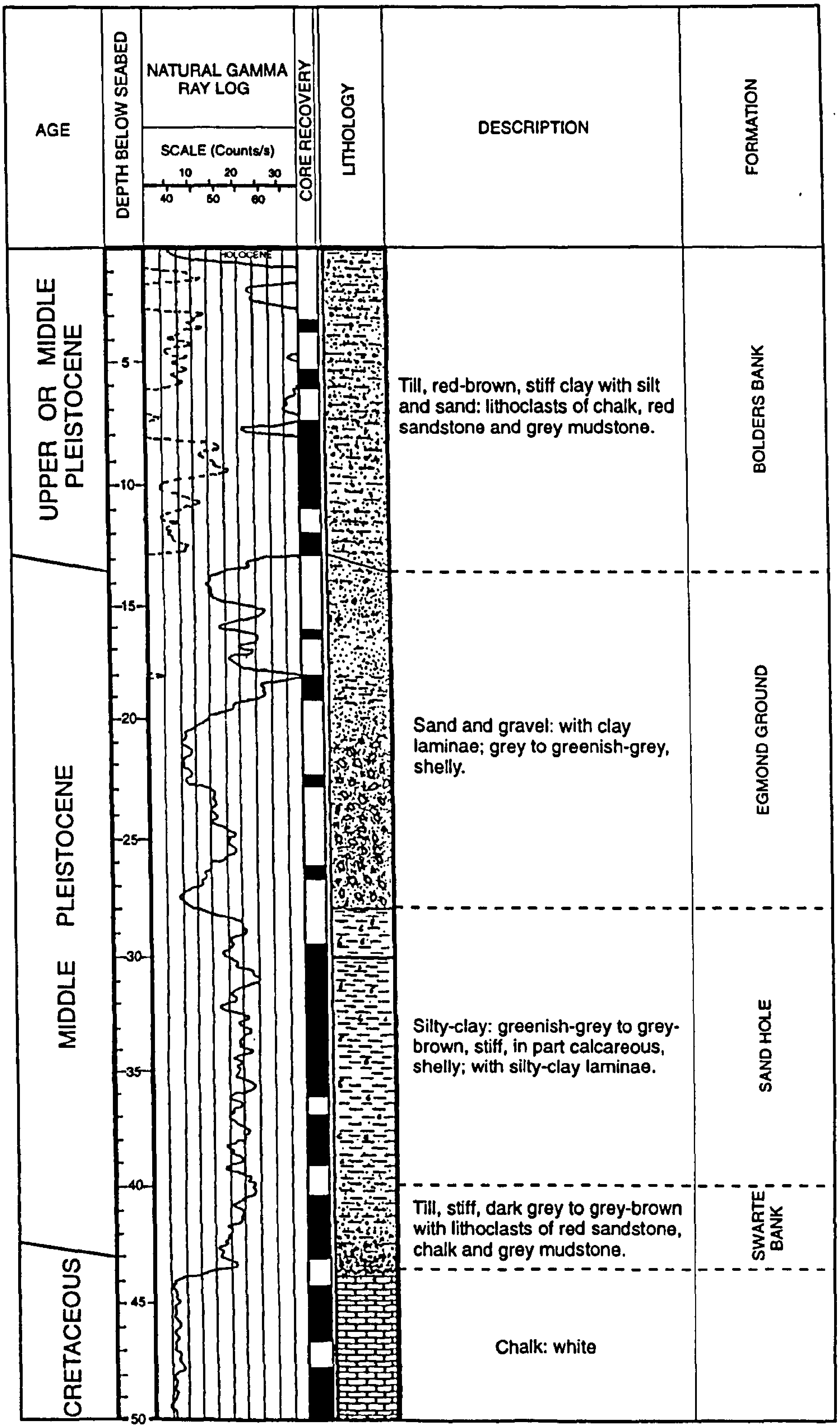


Fig 1.3 Borehole log, BH81/52A, Inner Silver Pit.

assemblages studied by Ansari (1992) showed a series of floristic changes which indicated an interglacial sequence from an estuarine or subtidal environment. It was clear from initial foraminiferal analyses (Fisher *et al.*, 1969; Ansari, *ibid.*) that the main formation from the Inner Silver Pit was of marine origin. On pollen grounds the sequence suggests a Hoxnian signature similar to that of Marks Tey, Essex (Turner, 1970; Fig 1.4 herein). Amino-acid stratigraphy (Sejrup, pers com) suggests an older age than this, which might indicate that the sediments were lain down in a similar interglacial with the same pollen signature.

The site at Shoeburyness consists of a buried channel, in a series of similar channels (Fig 1.5) that were probably fluviatile in origin. This fluvial incision is thought to postdate the period when the Thames first entered southern Essex during the Anglian Stage of the Middle Pleistocene (Bridgland, 1988) and to have occured in a periglacial climate, since no evidence of glacial deposits has been found in the area. The channel has been infilled with *c.* 10-20m of fine grained Middle Pleistocene sediment. This channel deposit was found to be fossiliferous (Lake *et al.*, 1977). Roe (1994) extensively examined this and other deposits from Essex for pollen, and also performed a preliminary palaeosalinity study using ostracods to identify a freshwater to brackish transition at around 10 m below present surface. The pollen spectra from Shoeburyness show two phases of vegetational development, and again compare closely to the Marks Tey succession (Turner, 1970). This would indicate that the cores at Shoeburyness and the Inner Silver Pit are related by a similar pollen signature and, therefore, may be of similar Hoxnian age.

Use of ostracods should help to develop a firmer palaeoenvironmental signature (in terms of temperature and salinity) of the southern North Sea during the interglacial in which these sediments were lain down.

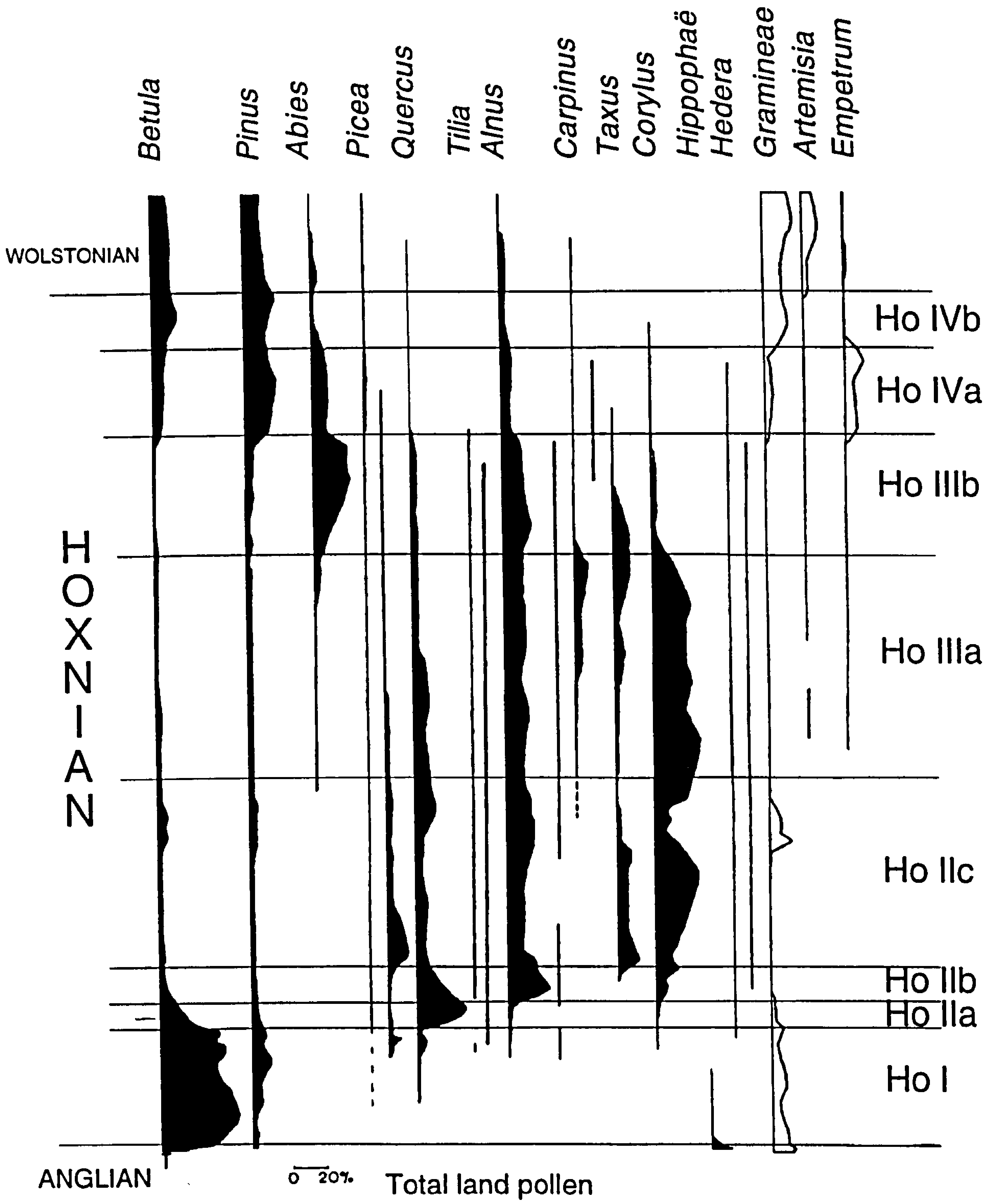
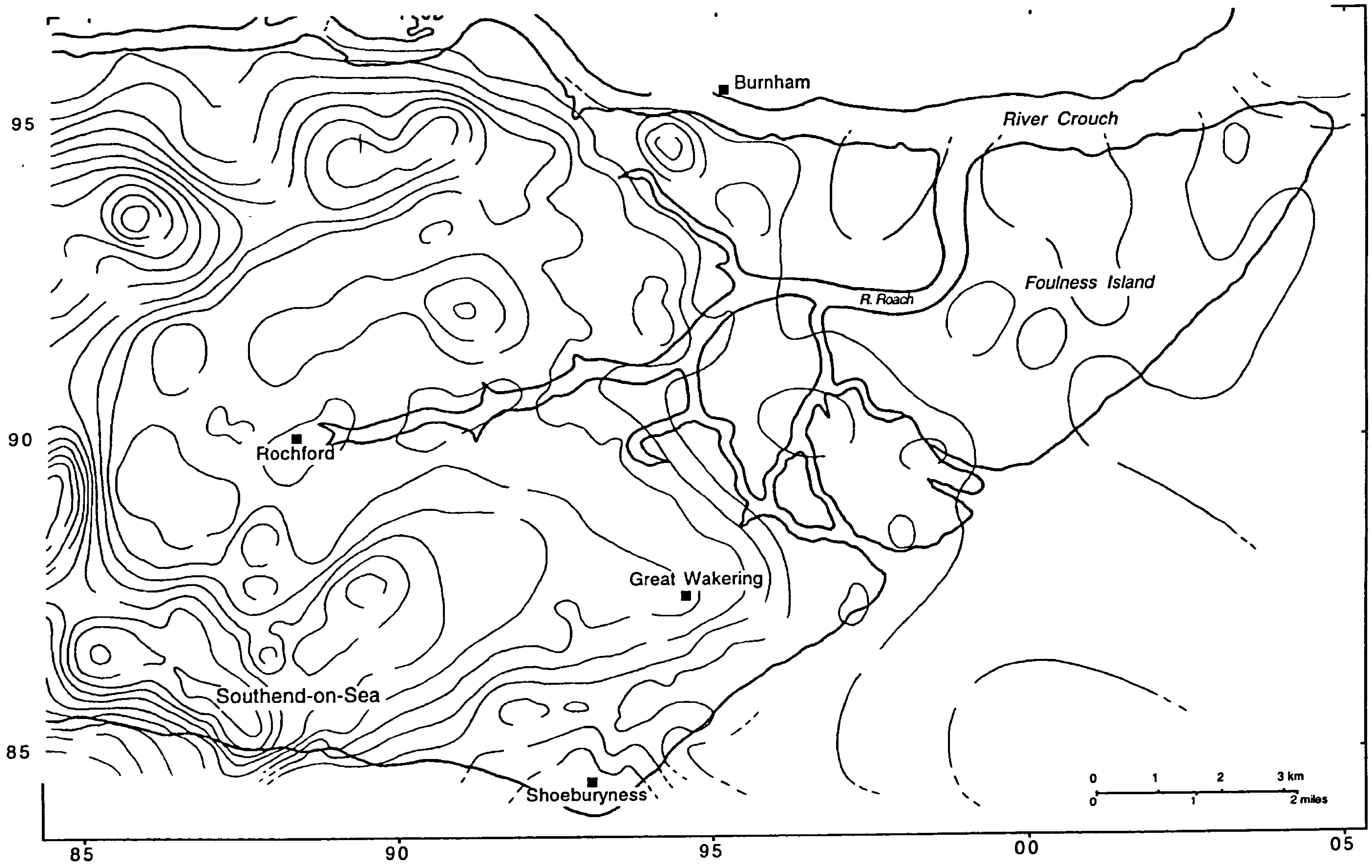


Fig 1.4 Summary pollen diagram from Marks Tey, Essex (Turner, 1970).



Contours on the bedrock surface at 5 m intervals relative to O.D.

Fig 1.5 Computer generated contour map of the London Clay surface showing channels on the *Southend Peninsula* (Roe, 1994).

1.2 Aims and Objectives.

The main aim of the project was to enhance the palaeoenvironmental interpretations of the two interglacial sites using ostracod palaeoecology and assessing the potential for biogeochemical techniques.

To recognise this potential the objectives of the project can be defined as follows:

1. To use ostracod palaeoecology to elucidate the local environmental histories of the two sites.

2. To establish the relative ages of the sites by comparison of the faunal assemblages found to other studies in the southern and central North Sea area, and to place the sites within the broader context of changes observed elsewhere in the North Sea.

3. To set up a modern calibration equation for the use of *Sarsicytheridea* in trace element studies.

4. To assess the use of biogeochemical techniques (trace-element composition, stable isotopes) on fossil ostracod shells to provide data on palaeo-temperature and salinity.

5. To use the data obtained from the biogeochemical analyses to discover water mass provenance in the southern North Sea in a previous interglacial and, for the Inner Silver Pit, to use further geochemical techniques to assess the contribution of marine and terrestrial sediment input into the North Sea at the time of deposition of the Sand Hole Formation.

To achieve these aims the following steps were taken:

1. In order to obtain the fossil ostracod fauna from each of the boreholes it was necessary to sample at a range of depths downcore, wash the sediment and pick out the ostracods present. The ecology of the fossil ostracod faunas and of any other faunal remains (echinoderm spines, plant macrofossils, molluscan fragments, foraminifera) was considered. Their stratigraphical significance was also determined.

2. A modern collection of *Sarsicytheridea* was obtained from B.G.S. core tops from the North Sea, University of Aarhus collections from the North Sea and the Skagerak, sites in the Canadian Arctic and also the North West Atlantic (Cronin, pers. comm.). Each ostracod analysed could be related to a certain water temperature and, thereby, a calibration between bottom water temperature and Mg:Ca ratio in the ostracod shells was set up. Calibration equations for *Cyprideis torosa* already exist in the literature.

3. Both trace element and stable isotope analyses were carried out on single genera fossil ostracod shells from the faunas picked (*Sarsicytheridea* in the Inner Silver Pit; and a single species, *Cyprideis torosa*, at Shoeburyness) in order that there were two independent signals indicating any water column changes that may have occurred. The ostracod valves were examined for stable isotopes, since this should lead to greater understanding of the palaeoenvironmental significance of the sites. This type of data can also have the potential to lead to inferences about the chronostratigraphy of the area.

The thesis is structured as follows:

Chapter 2 explains the geological context of the areas studied, and presents a summary the previous research carried out at each site. The use of Ostracoda in palaeoenvironmental studies is also considered, with particular attention being drawn to the taphonomic history recorded by ostracod shells.

Chapter 3 outlines the methodology employed in obtaining and collating the data for each of the techniques used.

Chapters 4 and 5 present the palaeoecological and biogeochemical results; Chapter 4 those for the Inner Silver Pit; and Chapter 5 those for the Shoeburyness site.

Chapter 6 integrates the results with previous and current research in the area to suggest a history of changes in the circulation pattern in the southern North Sea.

Chapter 7 presents the main conclusions of the study, and puts forward suggestions for further work.

Chapter 2

Background information

This chapter looks at the rationale behind the project and discusses the relevant literature in the areas considered. The chapter also addresses the use of ostracods in Quaternary research.

2.1 Geological context of the study

2.1.1 The Quaternary

The Quaternary is characterised by a series of climatic fluctuations which have served as the basis for the stratigraphical division of the period. Historically, terrestrial records have proved most important in the recognition of glacial-interglacial fluctuations (references in West, 1980), however, more recently, deep marine records have become increasingly important with the development of stable isotope techniques (Shackleton, 1974) to recognise environmental oscillations. In spite of this progress, relatively little is known about the continental shelves, which offer the potential to link oceanic and terrestrial evidence.

In terrestrial records, for instance in north west Europe, it has proved possible to erect a series of stages characterised by the development of temperate forest, which are separated from one another by stages showing evidence of cold conditions - cold stages. Temperate stage history is recorded palaeontologically by a number of fossil groups in freshwater and marine sediments. Cold stage history is recorded in glacigenic deposits, marine and fluvial sediments and the occurrence of periglacial episodes.

INTERVAL CONDITIONS	BRITAIN	IRELAND	NORTH WESTERN EUROPE	OXYGEN ISOTOPE STAGES
Temperate	Flandrian	Littletonian	Holocene	
Cold	Devensian	Midlandian	Weichselian	2
Temperate	Ipswichian	Last interglacial	Eemian	5e
	Ilfordian		Brørup/Odderade	
Cold	Wolstonian	Munsterian	Saalian	8 or 6
			Interstadial	
			Schöniggen/Maasrichtian (?)	7 (?)
			Dömnitzian/ Wacken Reindorf/ Hoogeveen	
Temperate	Hoxnian	Gortian	Holsteinian	11 or 9
Cold	Anglian	Pre-Gortian	Elsterian	12 or 10
Temperate	Cromerian			

Table 1 Major divisions and some postulated extra stages of the Middle and Late Pleistocene for Britain, Ireland and North-western Europe (sources: Turner and West (1968); Mitchell *et al.* (1973); Zagwijn (1975); Bowen (1978); Stuart (1982); Preece (1995); and Gibbard, pers. comm.).

As can be seen from Table 1 it is uncertain how many glacial-interglacial cycles occurred between the Anglian/Elsterian and the Devensian/Weichselian cold stages. Pre-Elsterian evidence is extremely fragmentary and will not be discussed here. The current British stratigraphical scheme (Mitchell *et al.*, 1973) envisages that only interstadial environments occurred between the Hoxnian/Holsteinian and Ipswichian/Eemian interglacial stages. However, over the last two decades a considerable amount of evidence has been put forward to support the existence of at least one additional temperate episode of interglacial ranking, which was preceded and followed by colder conditions in this interval. This evidence has come from two sources; first a re-evaluation of deposits traditionally placed in either the Hoxnian/Holsteinian or the Ipswichian/Eemian (Sutcliffe, 1975, 1976; Bowen, 1978; Sutcliffe *et al.*, 1987; Shotton, 1986; Wymer, 1988); and, second, from new sites whose geomorphology, lithostratigraphy and biostratigraphy have not conformed to the established succession (Turner, 1975; Green *et al.*, 1984; Briggs *et al.*, 1985). Many indications have also come from improvements to geochronometric data (e.g. Wintle and Huntley, 1982; Sejrup and Knudsen, 1993; Bowen *et al.*, 1989) such as amino acid and thermoluminescence dating techniques, the results of which are highly diverse, and are a matter for active debate due to this variation.

2.1.2 The Hoxnian

This interglacial stage (termed Hoxnian in the British succession, correlated with the Gortian in Ireland and correlative to the Holsteinian in continental Europe) is classically recorded as following the Anglian cold stage (Mitchell *et al.*, 1973) and has a number of recognisable palynological features. The importance of *Abies* in the late-temperate substage HoIII forest in all areas is notable and, furthermore, the significant role of *Picea* in eastern Europe and *Pinus* in Ireland in the early-temperate substage HoII forests whilst Britain contained a mixture of deciduous trees is also likely to have been significant in terms of climate (Turner, 1975). Recently there has been much discussion as to whether there was only one post Anglian Hoxnian-type stage (Bridgland, 1994; Scourse *et al.*, in press). Oxygen isotope evidence has been provided to suggest that there were five temperate stages after the Anglian, currently thought to be represented by Oxygen Isotope Stage 12 (Bowen *et al.*, 1986), the last being the Holocene. This implies that the Hoxnian and Ipswichian type vegetational sequences recorded have been repeated during that time, and that not all sites assigned to the Hoxnian or Ipswichian were necessarily lain down contemporaneously (cf. Bowen *et al.*, 1989; Bridgland, 1994; Ashton *et al.*, 1995, West and Gibbard, 1995; Scourse *et al.*, in press). However, although the classical stages defined by Mitchell *et al.* (1973) and pollen signatures (Turner, 1975; West, 1980) may not be unique, the stratigraphical succession of the stages is still assumed to be the same (Scourse *et al.*, in press).

Faunal data are sparse and come from scattered sites, however, similarities exist between vertebrate remains of this age in Germany (Adam, 1954, 1975) and assemblages from Hoxnian deposits at Swanscombe and Clacton in Essex (Singer *et al.*, 1973; Sutcliffe, 1964; Stuart, 1982). Similarities between shallow marine fossil ostracod assemblages from sites assigned Holsteinian age in Denmark (Knudsen and Penny, 1987) and Germany (Lord *et al.*, 1993) and Hoxnian sites on mainland Britain (Lord and Robinson, 1978; Mitlehner, 1992; Horton *et al.*, 1992) and offshore in the Inner Silver Pit (Ingram, in press; this study) have also been observed.

Estimates of the age of the Hoxnian have reflected the available methods, dates and correlations at particular times. Szabo and Collins (1975) obtained dates around 245 ka BP, and in excess of 272 ka BP as a result of Uranium-series determinations on bones of Hoxnian 'age' from Clacton and Swanscombe respectively. Shackleton (1975) has suggested that the Hoxnian temperate stage could be accommodated by Oxygen Isotope Stage 11, which lasted from *circa* 428 to 352 ka BP, whereas Bowen *et al.* (1986) elected to correlate the Hoxnian with Oxygen Isotope Stage 9, from about 338 to 302 ka BP, a view which was based on the equivalence of the Ipswichian/Eemian temperate stage with Oxygen Isotope Stage 5, and the existence of another temperate episode between this and the Hoxnian. Grün *et al.* (1988) established a date of 319 +/- 38 ka BP using the Electron-Spin-Resonance (ESR) technique on teeth collected from Hoxne. Bowen *et al.* (1989) have employed this date as a geochronometric control on the amino acid ratio data in non-marine Mollusca from other sites representative of Pleistocene events, such as Swanscombe, Kent and Stanton Harcourt, Oxfordshire. On these criteria the Hoxnian has been assigned to Oxygen Isotope Stage 9.

On continental Europe, Zagwign (1975, 1989) considered that the Holsteinian occurred in the Netherlands around 220 ka BP, while Bowen (1978) suggested an age range from circa 500 to 400 ka BP in Northern Europe. Sarnthein *et al.* (1986) used Th/U and ESR techniques on marine molluscan shells from paratype and other localities of the Holsteinian temperate stage to obtain dates of more than 350 to 370 ka BP. Shells from the Herzeele marine unit III, believed to be an equivalent of the Hoxnian/Holsteinian or the Wacken (Domnitz) warm stage in northern France, revealed ages of between 300 and 350 ka BP, indicating correlation of these two warm stages to Oxygen Isotope Stages 11 and 9 respectively.

The duration of the Hoxnian temperate stage is more easily resolved. Turner (1975) calculated a duration of 20 to 25 ka, based on the analysis of laminated sediments at Marks Tey. This interval is comparable to that obtained by Müller (1974) from the Holsteinian in Germany of 16 to 17 ka, using the same method.

2.1.3 Marine Hoxnian deposits and sea level changes

A number of the sites investigated around the edge of the North Sea contain evidence of a single major marine transgression of the Hoxnian/Holsteinian interglacial. In the Nar Valley in Norfolk marine terraces from Ho IIIb have been found at 23 m O.D. (Ordnance Datum) (Stevens, 1960; Ventris, 1985, 1986; Mitlehner, 1992), although the earliest incursion appears to have been in Hoxnian substage Ho IIc (Ventris, 1986; West 1987).

At Clacton channel deposits have recorded the onset of estuarine sedimentation quite late in the interglacial, in substage Ho IIIb (Pike and Godwin, 1953; Turner and Kerney, 1971), however, sea-level continued to rise, allowing progradation of marine influenced sediments up to 9 m O.D. At Swanscombe, upstream from Clacton, the record of marine sedimentation extends to *circa* 25 m O.D. (Kerney, 1971), providing an approximate upper limit for the extent of the transgression.

At Woodston, near Peterborough, marine molluscs and ostracods clearly show the presence of well established marine influence in Ho IIc at between 11 and 14 m OD (Horton *et al.*, 1992). However, this site has complicated the conventional picture of Hoxnian sea-level change, since the earliest marine influence seems to have been prior to Ho IIc (Horton *et al.*, *ibid*), which is difficult to reconcile to the neighbouring Nar Valley, which is closer to the sea. There are implications of this incongruity; either the pattern of Hoxnian sea-level change may have been more complicated than previously documented, or regional tectonism between the two areas may have distorted the sea-level signal. It is also possible that the Woodston beds may be a different age to those in the Nar Valley. Reconstructions of sea-level changes in Britain have mainly been based on these sites in East Anglia, where the estuarine and marine deposits have all been assigned to the latter part of the interglacial (Ho IIc to Ho IIIb).

In continental Europe, Somme (1979) discussed marine deposits near Sangette on the French Coast at an elevation of 10 to 12 m NGF (French mean sea-level), and at Herzeele (Somme *et al.*, 1978) where the base of the deposits lies between 7 and 11 m NGF. Paepe and Baeteman (1979) found similar marine and brackish sediments at the same heights in Belgium. In the Netherlands and Germany the surfaces of marine Holsteinian deposits occur at a wide range of heights from -25 to -40 m (van Staalduinen, 1977; Linke, 1986). However, most Holsteinian deposits in Europe will have been affected by post-depositional movements (Long *et al.*, 1988), for example, in the Netherlands and Germany

many sites were overridden by Saalian ice, so it is not possible to attach much significance to their modern altitude.

One site which does justify further attention is Herzeele in France, where fine grained intertidal sediments are thought to have been deposited in a shallow marine embayment. The sediments are distributed in three sequences. The lower one, Series I has a sparse pollen flora, and has been assigned to an early marine Holsteinian phase (Vanhoorne and Denys, 1987) or to an older high sea-level event (Somme *et al.*, 1978). On pollen grounds the upper two units, Series II and III, of the sequence are correlated to the early and late temperate substages of the Holsteinian (Somme *et al.*, 1978), between the expansion of *Quercetum mixtum* and the arrival and expansion of *Abies*. This sequence shares many similarities with those in Eastern Essex (Roe, 1994) since the onset of the marine incursion occurs prior to or during the early-temperate substage of the Hoxnian, and the transgressive maximum occurs during the late-temperate substage of the interglacial in sediments lying at 8 to 11 m NGF (Somme *et al.*, 1978). These marine and brackish water deposits do not appear to extend into the Netherlands however and, due to a lack of southern, warmer water Lusitanean species in these areas (Meijer and Preece, 1995; this study), it has been implied that there may have been a physical barrier across the Strait of Dover. This would denote that there were two marine embayments in the southern North Sea, one open to the south, via the Strait of Dover, and one with access to the north. Evidence for the intervening landbridge exists in the form of a 'Rhenish' fauna (Roe, 1994), a fluvial molluscan group found at sites in Eastern Essex and also in the southern Netherlands.

The deposits at Herzeele have been dated with a number of geochronological techniques, but the results remain equivocal. Amino-acid determinations on shells have revealed dates equivalent to Oxygen Isotope Stage 9 (Bowen and Sykes, 1988), and Stage 7 (Miller and Mangerud, 1985). Balescu and Lamothe (1993) obtained thermoluminescence (TL) dates of 266 +/- 21 ka from sands in Series III, whereas Uranium series dates (Sarnthein *et al.*,

1986) from shells in that unit gave dates of between 300 and 350 ka BP, and so assigned this upper unit to Stage 9. Sarnthein *et al.* (1986) believe that an unconformity exists between the top of Series II and Series III, implying that the middle unit represents an older interglacial, perhaps Stage 11.

There have been few attempts to assess the importance of additional high sea-level events in the context of the southern North Sea region (cf Long *et al.*, 1988). From existing biostratigraphical data it is impossible to establish whether any extra events occurred. However, some support has been given by amino acid dating of molluscs. For example, the Woodston Beds appear to be younger than the interglacial beds at Clacton and Swanscombe (Horton *et al.*, 1992), which compares favourably with Bowen *et al.* (1989) who used aminostratigraphical data to assert that there were two temperate events in the British record showing affinities to the Hoxnian (Fig 1 in Bowen *et al.*, 1989); an older event at Swanscombe (Oxygen Isotope Stage 11) and a younger event at Hoxne (Stage 9) to which the Woodston Beds are also correlated.

2.1.4 The Inner Silver Pit

The Inner Silver Pit is the longest of several trench-like enclosed basins in the North Sea floor, east of the Humber. The Inner Silver Pit is over 50 km long, 4 km wide and up to 70 m deeper than the adjacent sea floor. It is incised into a thickness of Quaternary sediments that fill a broad shallow basin in the southern North Sea (Fig 1.2). This basin is infilled with the Swarte Bank Formation (SBK), the Sand Hole Formation (SH), the Egmond Ground Formation (EH) and the Bolders Bank Formation (BDK) described by Tappin (1991) (Fig 1.3).

Origin of the valley in the area of Inner Silver Pit

Sedimentation in the North Sea basin has been dominated by glacial erosion and deposition since the Middle Pleistocene. The Anglian glaciation was extremely extensive and had widespread effects, overriding most of the North Sea (Fig 2.1), destroying or burying existing deposits in most areas, and forming new surfaces beneath the ice by glacial and glaciofluvial erosion (Cameron *et al.*, 1987; Stoker *et al.*, 1985). The most characteristic glacial feature left on the seafloor were conspicuous shallow subglacially eroded shallow 'valleys' or incisions, which have since been partially or entirely infilled (Stoker *et al.*, 1985). Discussion on the origin of the valleys has dominated the literature and there are three schools of thought; the first emphasising the significance of substrate, such as fault lines and the soft nature of strata or subsurface processes and tidal scour (Hamblin, 1990); the second concentrating on the importance of the local over-deepening of pre-existing features, for example delta channels or river networks (Smith, 1985, 1989); and a third concerning a compound process of origin in which the nature of the substrate, over-deepening of pre-existing features and involvement of more than one glacial stage are significant (Ansari 1992). Cameron *et al.* (1987) stated 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 moraines and the deposition of glaciofluvial sediments in tunnel valleys. 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 channels. This is the most likely explanation for the origin of the valleys. Similar sedimentary sequences to those found in the southern North Sea are well known from the onshore area of Britain (Ventris, 1985), the Netherlands and Germany (Ehlers *et al.*, 1984). However, when the broad shallow basin was formed is more uncertain, although it was probably cut into the Cretaceous Chalk in an earlier phase of erosion (Scourse *et al.*, in press).

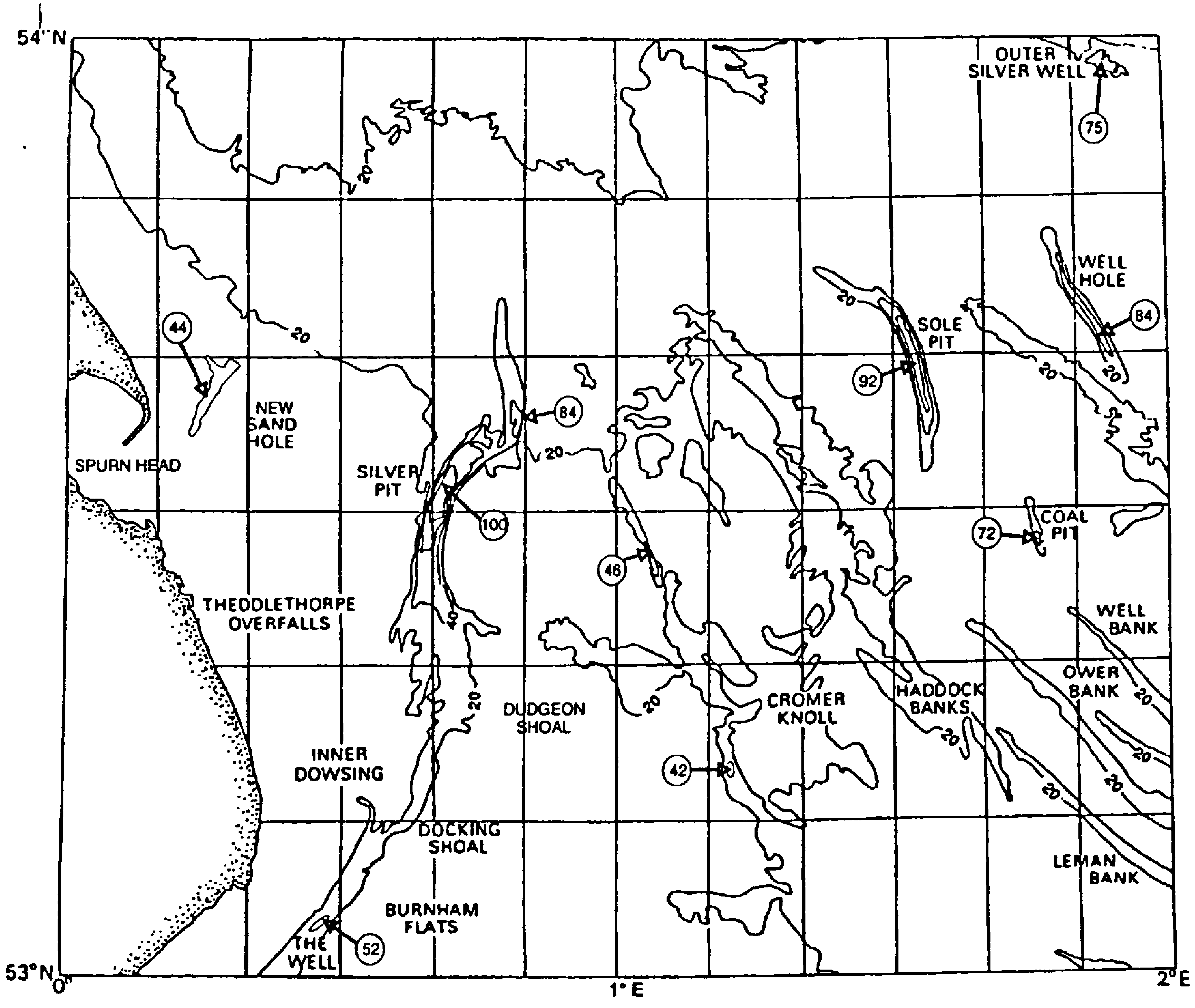


Fig 2.1 Contour map of the southern North Sea around the Inner Silver Pit showing greatest depths (⑥) of incision into the sea bed.

Recently Wingfield (1990) controversially presented an alternative 'finger lakes' model and proposed that each incision was created separately at a lowland or tidewater ice sheet margin as a plunge pool which cut back and unroofed into the ice margin. Wingfield (1990) has attempted to explain processes outside, inside and at the margin of the ice sheet and states that there is a close relationship between the existence of the palaeovalleys and the limit of the ice sheet of the corresponding glacial stage. He cited 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 north west Europe (Ehlers *et al.*, 1984; Balson and Cameron 1985).
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 west of 2°E (Balson and Jeffrey, 1991).
4. All of the valleys have been completely filled with Anglian and younger sediments (Tappin, 1991).

The similarities in the geometry, the size and the lithological infill of the palaeovalleys suggest that they were created by common processes. Therefore, it was proposed that the palaeovalleys were formed during the later period of the optimum phase of a cold stage, under very strong hydrostatic pressure of melt water, and at or in the margin of an ice sheet (Wingfield, 1990; Balson and Jeffrey, 1991). Donovan (1973) suggested that tidal scour may have played a major role in modifying the form of pre-existing subglacial valleys during the Flandrian marine transgression.

Glacigenic deposits of Anglian age directly overlie Cretaceous Chalk in the broad basin that surrounds the Inner Silver Pit. In the British sector of the southern North Sea these glacigenic deposits infilling the channels are usually of one or more of three units of the Swarte Bank Formation (SBK), defined in terms of their geophysical signal and by composition of the sediment (Cameron *et al.*, 1987). A series of Pleistocene sediments overlie the SBK around the Inner Silver Pit. These terminate in the BDK, which is when the Inner Silver Pit must have been incised. The age of the BDK is contentious, since thermoluminescence dating (Bateman and Catt, 1996) appears to contradict the traditional view that it was incised in the Late Devensian/Weichselian (Cameron *et al.*, 1987). The implication that the BDK is of Saalian/Wolstonian age or later indicates that the Inner Silver Pit must therefore have been incised in the Saalian/Wolstonian or later (Scourse *et al.*, in press). The area is overridden by strong currents and active tidal scour (Lee, 1980) at the present day, which would account for the lack of Holocene sediments in the region. Scourse *et al.* (*ibid*) also suggested that it was possible that the Inner Silver Pit has been enhanced by tidal scour since it was first initiated. No sedimentary evidence exists to lend support to this theory, however, and it is possible that any material has been removed by strong Holocene scour.

2.1.5 Borehole 81/52A and vibrocores (53/00/962, /1103, /1104): borehole logs and palaeobotanical information

This investigation is concerned with the Inner Silver Pit area whose location is detailed on the 'Spurn sheet' of the British Geological Survey offshore series (Tappin, 1991). Borehole 81/52A was located on the eastern flank of the Inner Silver Pit, close to its margin at 53°31.855'N and 0°44.291'E in a water depth of 20.20 m, and penetrated up to 50m below the sea bed (Fig 2.2). The recovered sequence included deposits of Cretaceous chalk and Pleistocene till, silty-clay, sand and gravel.

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

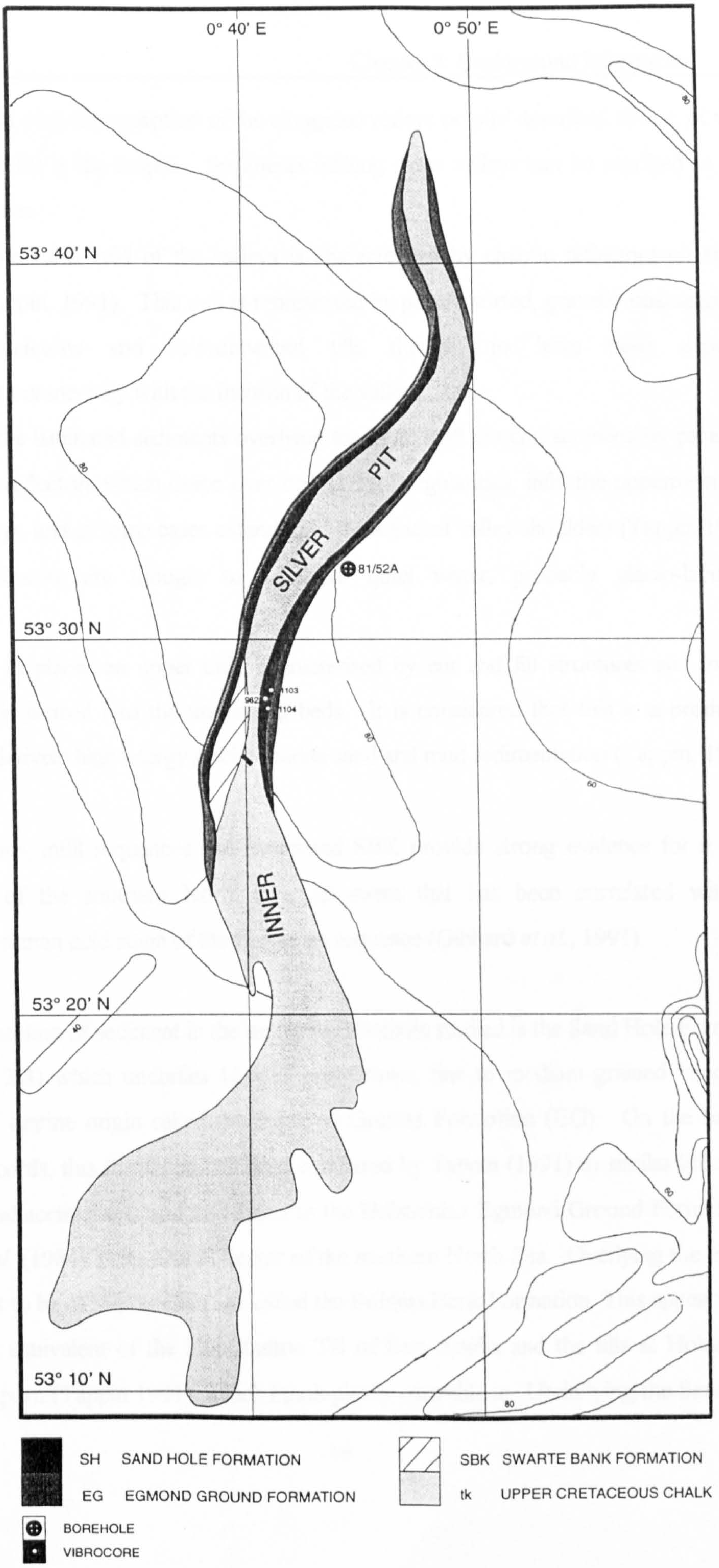


Fig 2.2 Extent of sedimentary formations around the Inner Silver Pit and position of borehole and vibrocores.

relatively flat with the exception of the elongated valleys or 'pits' described above, of which Inner Silver Pit is the largest. Sediments infilling these valleys can be ascribed to three different facies:

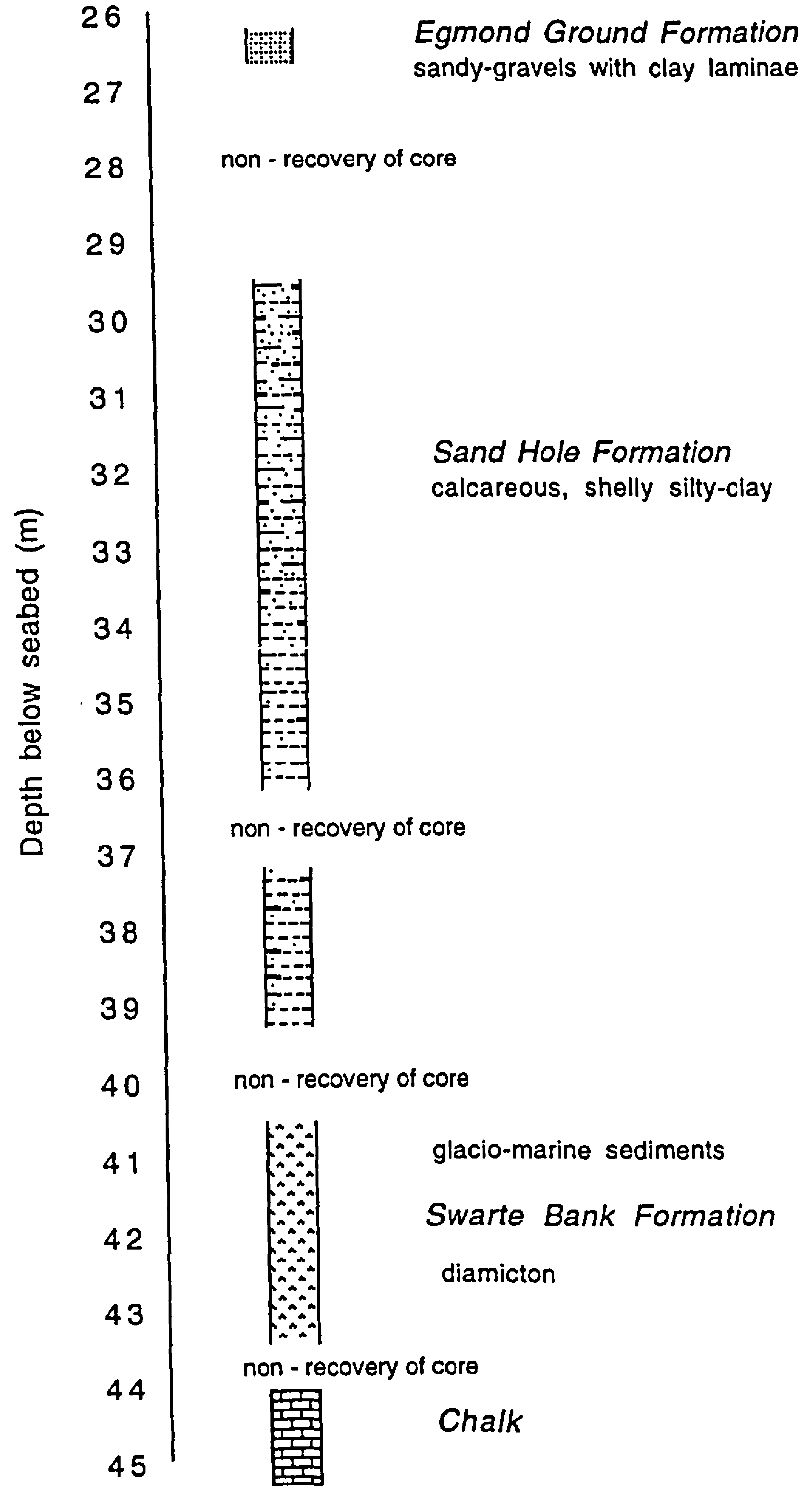
i) the basal infill of the valleys is characterised by chaotic reflectors on seismic profiles (Tappin, 1991). This unit is represented by poorly sorted, gravelly coarse grained sands, diamictons and re-sedimented tills thought to have been deposited penecontemporaneously with the incision of the valleys.

ii) the laminated sediments overlying the basal infill are characterised by parallel to subparallel reflectors which drape over underlying irregularities, infill the uppermost parts of the valleys, and in some cases extend onto the adjacent valley shoulders (Tappin 1991). These sediments are thought to 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).

The incisions, infill sequences and associated SBK provide strong evidence for a major glaciation of the southern North Sea, an event that has been correlated with the Anglian/Elsterian cold stage of the European sequence (Gibbard *et al.*, 1991).

The main section of sediment in the section of borehole studied is the Sand Hole Formation (SH) (Fig 2.3) which underlies 16m of grey-brown, fine to medium grained 'sands and gravels' of marine origin called the Egmond Ground Formation (EG). On the basis of seismic records, this formation has been compared by Tappin (1991) to similar lithologies found on adjacent sheets and correlated to the Holsteinian Egmond Ground Formation of Laban *et al.* (1984) in the Dutch Sector of the southern North Sea. Overlying the EG is a till thought to be of Weichselian age called the Bolders Bank Formation. This appears to be the lateral equivalent of the Huntstanton Till of East Anglia and the tills at Holderness, north of Spurn (Tappin 1991), which lithologically resemble it. Underlying the Sand Hole



Formation names from Tappin, 1991

Fig 2.3 Summary borehole log of BH81/52A showing the main sedimentary formations mentioned in the text (Tappin, 1991).

Formation is another till, the Swarte Bank Formation (SBK), which infills the subglacial valleys cut during the Elsterian glaciation (Cameron *et al.*, 1987) and rests directly on Upper Cretaceous chalk. In borehole 81/52A, the SBK is made up of a stiff grey-brown diamicton.

Hoxnian sediments are absent from most of the British sector of the southern North Sea, with the exception of the Inner Silver Pit, which contains marine muds assigned to the Hoxnian by Fisher *et al.* (1969) on the basis of pollen analysis. All samples analysed by Fisher *et al.* (*ibid*) also contained abundant foraminifera, together with ostracods, cirripede valves and fragments of bryozoans, echinoids and molluscs. The dominance of *Elphidium clavatum* suggested relatively shallow water (<20 m) at the time of deposition, although a lack of *Cibicides lobatulus* and other species of *Elphidium* seemed to indicate the presence of a sublittoral environment. Climatically all the samples indicated full interglacial conditions, based on the abundance of the temperate *Ammonia becarii* (Fisher *et al.*, *ibid*).

It was clear that the sediments of the Sand Hole Formation were of marine origin from the foraminiferal evidence (Fisher *et al.*, 1969; Ansari 1992) and preliminary ostracod studies of this project. Before fossil pollen zones and vegetational history from a marine sequence can be reviewed, the taphonomy of the pollen must be considered, since in marine environments water movement and turbulence are important in the distribution of pollen and there is a tendency for winged conifer pollen to be over-represented through flotation (Stanley 1969) and to be aerially transported for long distances out to sea (Nichols *et al.*, 1978). The sequence analysed palynologically from BH81/52A was thought to be estuarine/subtidal (Fisher *et al.*, 1969; Ansari, 1992; Scourse *et al.*, in press), and therefore would have been subject to fluvial influences. This means that the pollen assemblages may have a large regional source area, and since pollen is affected by the different dispersal rates of taxa (West, 1980) the assemblages may be biased. This site was also found to contrast with sites away from fluvial influence in the central North Sea such as those in BH 81/34

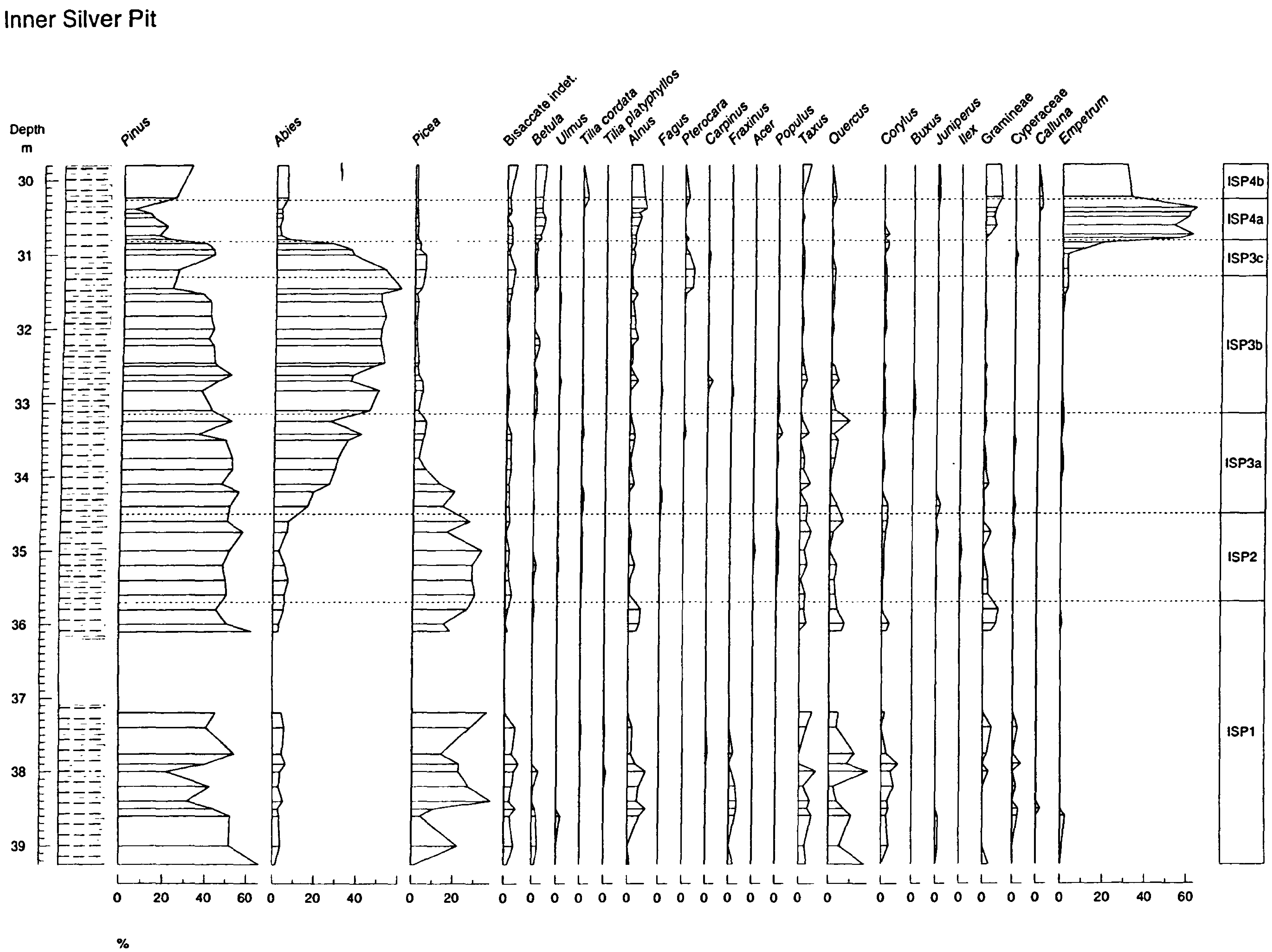
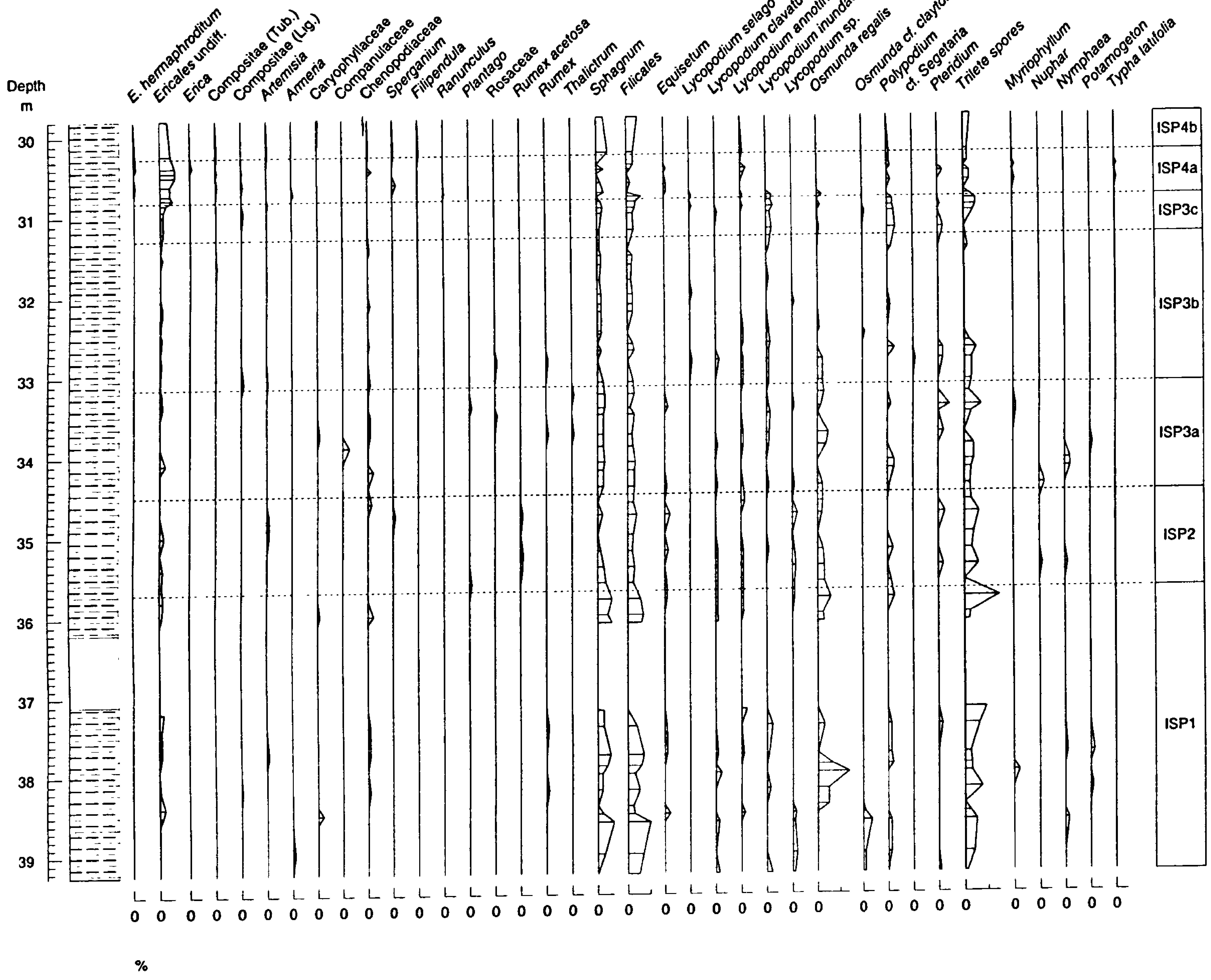
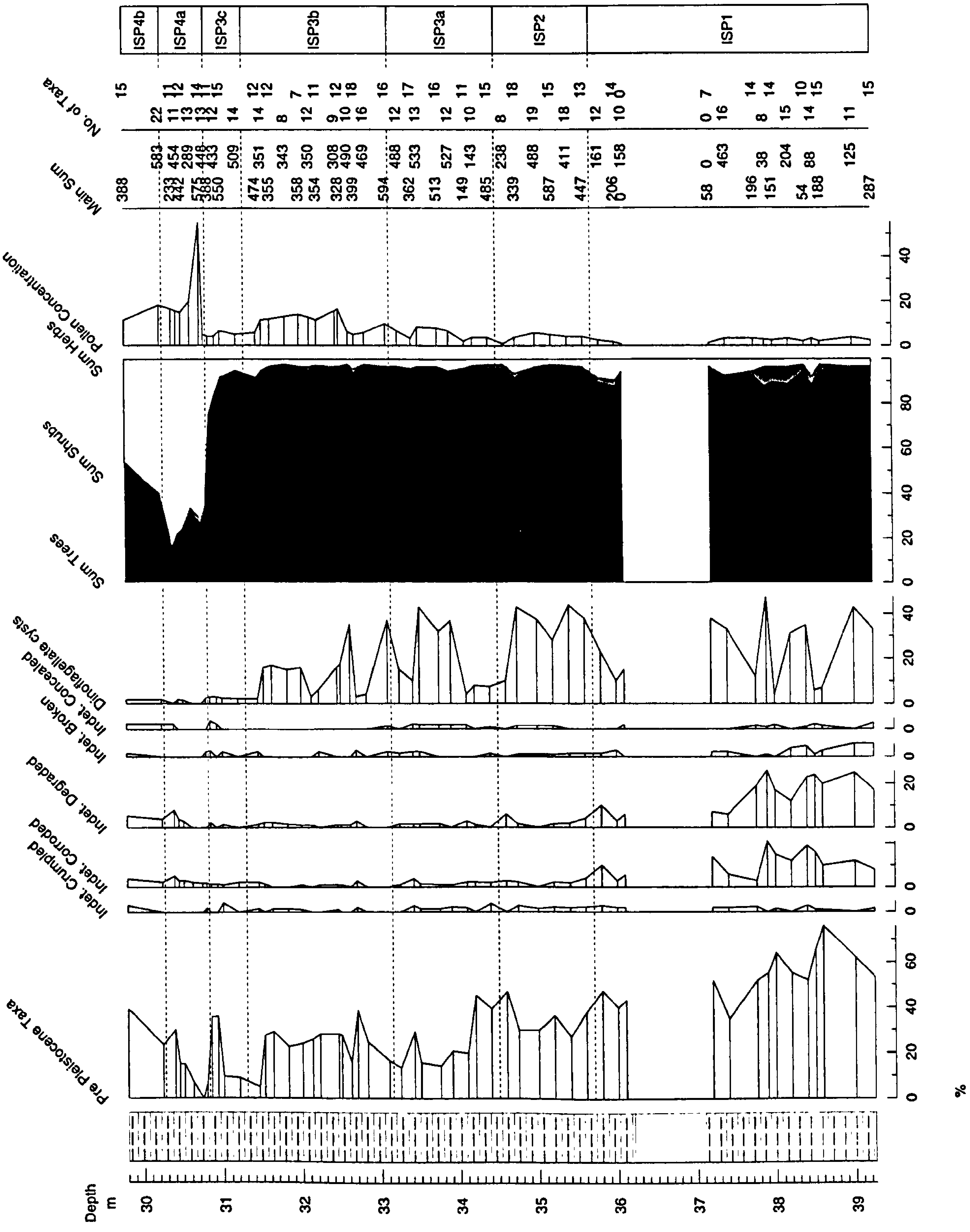


Fig 2.4 Inner Silver Pit pollen diagram (Ansari, 1992).

Inner Silver Pit



Inner Silver Pit



and 81/29 (Ansari 1992; Ekman, 1994, in press) and also the record of a cold stage in BH81/26 from the northern North Sea (Ekman and Scourse, 1993).

The pollen assemblages studied by Ansari (1992) showed a series of floristic changes which enabled the pollen diagram produced to be divided into four major pollen zones and five further subzones (Fig 2.4). These show that there is a gradual shallowing of sea level towards the top of the part of the core studied from the Sand Hole Formation. High frequencies of *Picea*, *Abies* and *Empetrum*, and the presence of *Pterocarya* made correlation of this pollen with the Ipswichian/Eemian interglacial stage unlikely (Turner, 1970; Ansari 1992). It appeared that correlation with the Hoxnian/Holsteinian stage was more likely. The BH81/52A sequence of pollen did not show a vegetational record of a complete temperate cycle, but it did record the presence of two out of the four interglacial substages. Above 35.7 m the pollen assemblages were better preserved and were indicative of fully temperate conditions. This was partly based on the high frequencies of tree taxa, and also on the presence of thermophilous angiosperms, such as *Alnus*, *Pterocarya* and *Quercus*, albeit at lower frequencies. At the top of the section studied there is a distinctive decrease in the frequencies of arboreal taxa, and concurrant increase in the ericaceous taxa such as *Empetrum* (Fig 2.4). Turner and West (1968) state that this indicates an opening of the vegetation usually associated with deterioration of climate or soil degradation in an area characteristic of the post-temperate substage in an interglacial cycle. This pollen evidence suggests that the Sand Hole Formation records the end of an interglacial and is supported by the foraminiferal (Kristensen *et al.*, in press) and ostracod (Ingram, in press; this study) results.

Detailed palynological investigation (Ansari 1992) of three vibrocores from the Inner Silver Pit area indicated that the sediments were representative of the silty-clay sequence of the Sand Hole Formation (SH) of Tappin (1991) which has only been identified in the area of the Inner Silver Pit. The vibrocores revealed a very similar pollen assemblage to that found

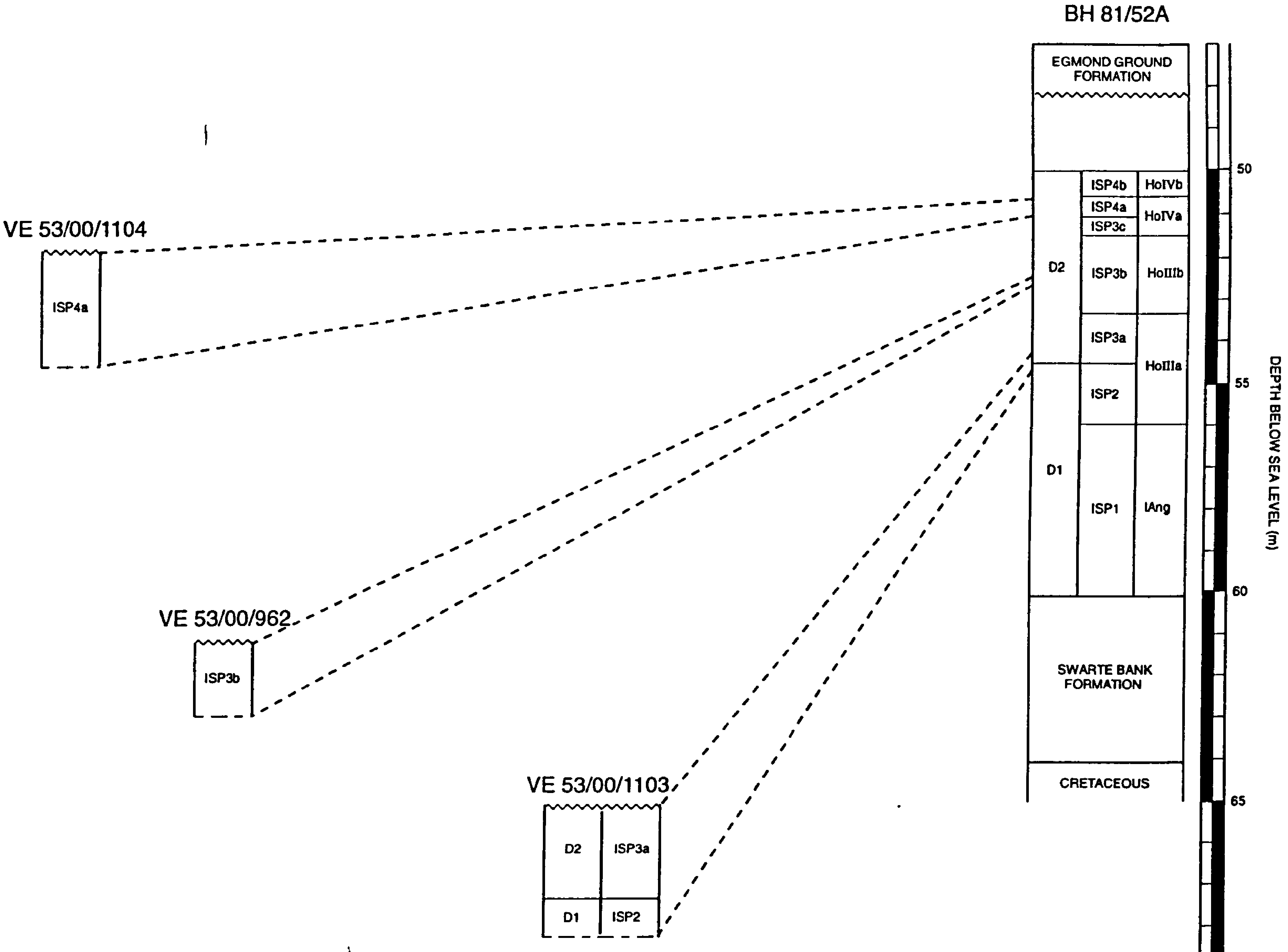


Fig 2.5 Correlation between borehole and vibrocores on pollen evidence, Inner Silver Pit.

in the silty-clay sequence of the borehole. The pollen diagrams from the vibrocores could clearly be correlated with various parts of the pollen diagram of BH 81/52A (Fig 2.5).

2.1.6 Essex

The area around the second site investigated in this study consists of a broad tract of land running parallel to the coastline of eastern Essex, extending from the Thames Estuary in the south to the Blackwater Estuary in the north (Fig 2.6). The bedrock topography of the Southend Peninsula is dominated by the broad arcuate ridge which curves between Southend and Canewdon. The ridge is flanked by two steeply incised, channel-like depressions. The first trends eastwards past Shoeburyness and onto the coast where it widens and deepens achieving a maximum depth of *c.* -15 m O.D. The second is a larger feature which forms an arc around Rochford (Roe, 1994). Only the former depression and its associated deposits will be considered in this study. Most of the region around Shoeburyness is lowland, the highest ground in the area occuring on the west of the Southend Peninsula at 40 m O.D. It declines gradually to the east to *c.* 15 m O.D.

History of Pleistocene research in eastern Essex

Most of the early work in eastern Essex focussed on the origins of the terrace gravels. The first major study was that of Wood (1866a), who described a "broad sheet of gravel" stretching between Kent and the Blackwater Estuary. He considered that this 'East Essex gravel' "intimately resembled the Thames gravels of the London area, both in constituent material and thickness" (Wood, 1866b). Later these ideas were dismissed by Whittaker (1889) who argued that the Essex gravels were fluviatile. This link between the coastal gravels in Essex and the deposits in the Thames Valley remained a central theme of research into the early part of this century. Gregory (1922) made the first attempt to assess the composition and provenance of the gravels in Essex. He noted that they contained

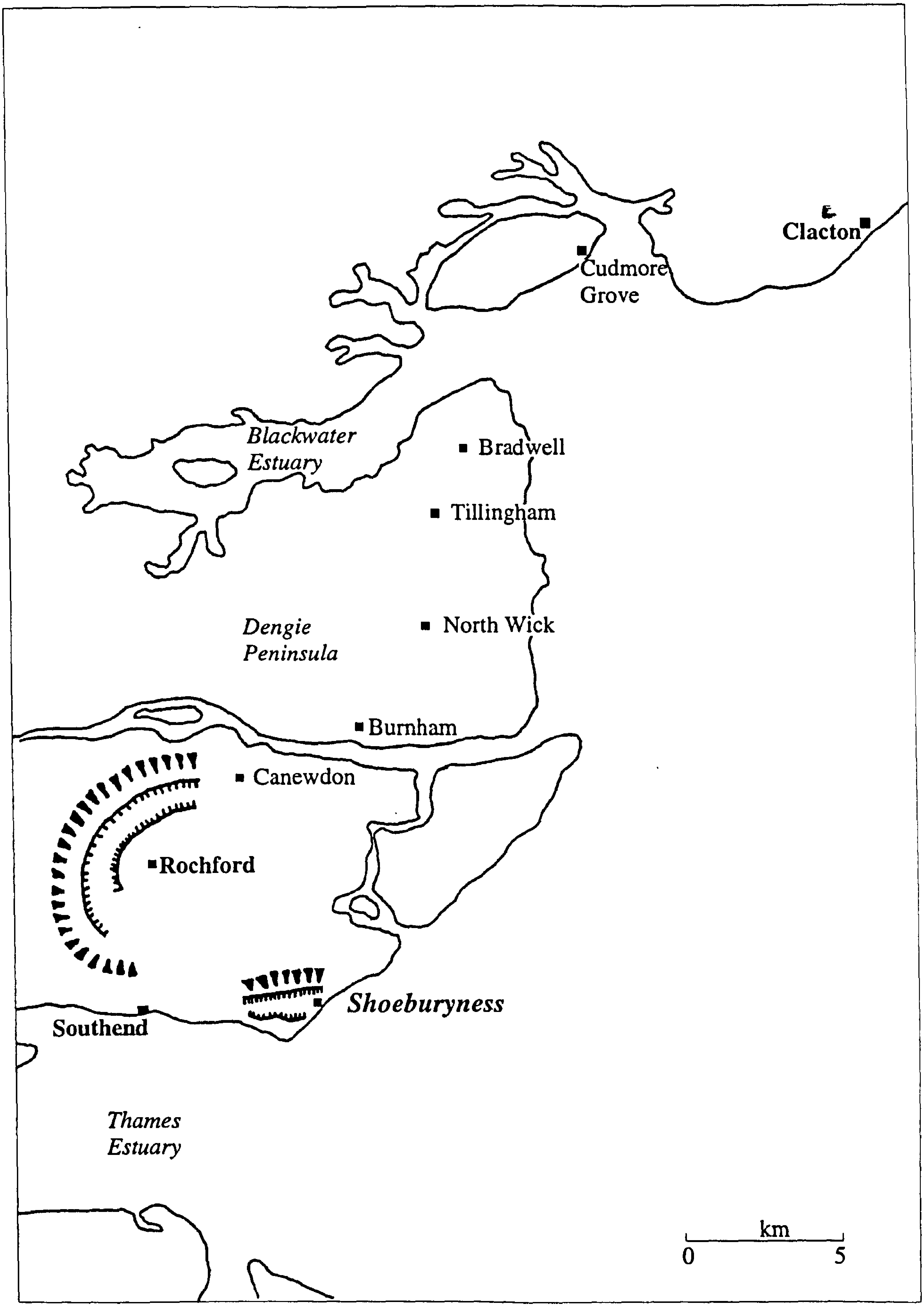


Fig 2.6 Map of Essex showing sites mentioned in the text

high levels of Lower Greensand chert, a rock originating in the Weald. This led him to believe that the deposits were probably related to the "Pliocene denudation of the Weald".

During this period, substantial attention was paid to the 'Thames' deposits in central and northern Essex. Sherlock and Noble (1912), for example, studied the gravels in Hertfordshire and proposed that before glaciation the Thames had taken a more northerly route. They attributed its later diversion into its modern valley across London to an advance of ice in the area. However, of all the workers, Warren (1942, 1955) probably made the most noteworthy contribution to Pleistocene research in Essex when he established, for the first time, that the Thames had flowed across the county before and after the advance of ice into the area. He suggested that the early Thames had flowed eastwards across northern Essex, however, "after its diversion into its present channel", he believed that it had "swung north....from the area of the south Essex coastline...into the previously established course of the Medway" bringing it into the Clacton area (Warren, 1955). This interpretation had pivotal influence on later work, and was supported by faunal and archaeological finds from the 'Clacton Channel', a sequence which had close affinities to a channel fill sequence at Swanscombe, near London (Warren, 1955).

The emphasis on terrace identification continued into the 1970's, the most important work being that of Gruhn *et al.* (1974) who carried out the first regional study of deposits in south eastern Essex. They examined the structure and composition of the eastern Essex gravels, focusing on terrace agradations. They confirmed the earlier findings of Gregory (1922) when they demonstrated that the gravels contained material of Wealden derivation, from which they concluded that an 'ancient river' had flowed into the area from the south, before continuing to Clacton. However, they did not elaborate on its exact course, only commenting that "throughout most of the Pleistocene the Medway and the Thames were joined in one great system which flowed across southeast Essex".

In the mid- 1970's the British Geological Survey carried out comprehensive mapping of eastern Essex, compiling 'Sand and Gravel Resource sheets' for the Southend and Dengie peninsulas (Hollyer, 1978; Hollyer and Simmons, 1978; Simmons, 1978; Lake *et al.*, 1986). They recognised, from boreholes, a series of buried channels beneath some of the gravel terraces (Lake *et al.*, 1986), which had gone undocumented before due to their similarity to the ubiquitous superficial deposits in the area. The buried channels at Shoeburyness will be discussed further below.

The wider relevance of the channel deposits mapped by the B.G.S. remained unclear until the early 1980's when Bridgland (1980, 1983) carried out a thorough investigation of the fluvial sediments of eastern Essex and Kent. This work, based on the use of clast lithological analysis (Bridgland, 1986), led to the adoption of a new terrace stratigraphical framework for eastern Essex, and the adjacent Lower and Middle Thames regions. Bridgland (1983) reconstructed the sequence of events which had taken place in Essex prior to and during the Thames diversion. In his later work Bridgland (1988, 1994) continued to revise the detail of the correlations. This, with the work of Gibbard (1994) in the Lower Thames Valley, currently forms the basis of Pleistocene research in the area.

2.1.7 Shoeburyness, and borehole S1

Shoeburyness is a coastal town at the southernmost tip of the Southend Peninsula, 10 km east of Southend. Most of the town lies above a depression in the bedrock surface of the London Clay, which is filled with a thick sequence of Pleistocene deposits. These mostly consist of sands and clays, and are capped by sand and gravel of the Barling Gravel Sequence (Bridgland, 1983, 1988).

Previous research

Since 1889, when Whittaker recorded "a thick accumulation of river drift infilling a channel in the London Clay", the presence of Pleistocene sediments at Shoeburyness has been recognised. However, the Pleistocene channel deposits remained largely uninvestigated until the late 1970's when the British Geological Survey reviewed the whole area (Lake *et al.*, 1977; Hollyer, 1978). These studies confirmed that there was a steep-walled, bedrock depression filled mainly with fine grained sediment. This was found to be well developed at Elm Road, near the centre of town, where the Pleistocene infill exceeded 20 m (Lake *et al.*, 1977).

Roe (1994) undertook a study of Pleistocene channel fillings in Essex, and obtained a deep borehole from an area of open ground at the western end of Elm Road. This was one of the only locally accessible sites. Borehole S1 (Fig 2.7) was excavated with a 10 cm internal percussion corer and penetrated 16.90 m of sediment. It terminated in gravel at -9.76 m O.D.

Information from BH S1 was integrated with data from other deep boreholes (Fig 2.8) in the immediate vicinity to establish the site stratigraphy (Roe, 1994), which was summarised as follows:

(e) Brown silts ('brickearth')
(d) Upper Sands and Gravels (Barling Gravel)
(c) Grey silty clays
    1. Sandy clays
    2. Silty clays
    3. Sandy silts
(b) Basal sands and gravels
(a) London Clay

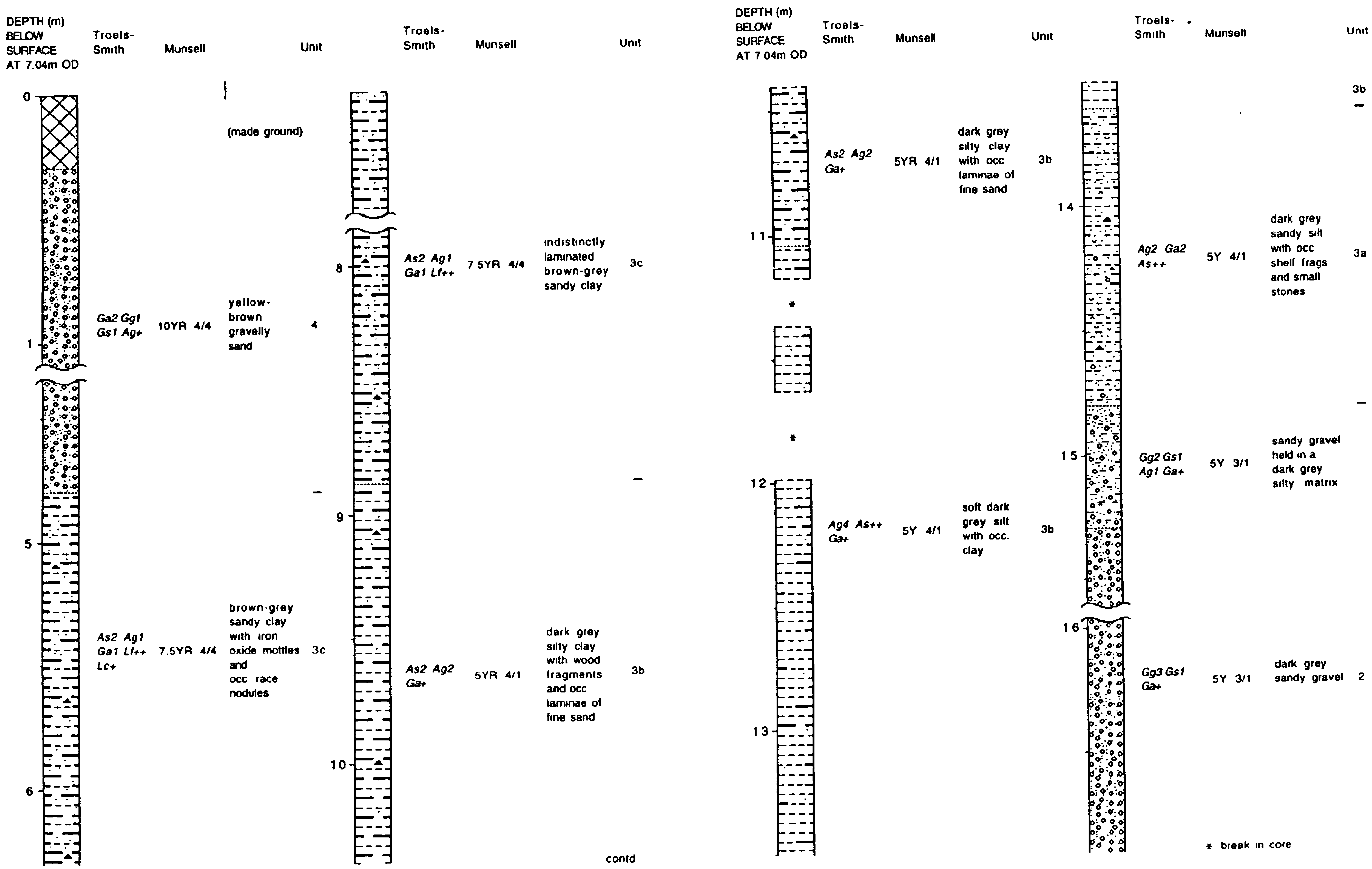


Fig 2.7 Borehole log, BHS1, Elm Road, Shoeburyness, Essex.

(a) London Clay : not penetrated at Elm Road, but proved previously in adjacent well excavations.

(b) Basal sands and gravels: 2-4 m thick forming the basal member of the Pleistocene sequence at Elm Road. Flint was the dominant (92.5 %) pebble lithology, and with the other proportions of exotic and southern material, the deposit was consistent with those recorded in the low level East-Essex Gravel (Bridgland, 1988) and suggest a Thames-Medway origin (Roe, 1994, Table 1.2)

(c) Grey silty Clays : in a thick, 9 - 12 m sequence which represent most of the infill at Elm Road. Small compositional and structural fluctuations allowed the sequence to be divided into three sub-units:

1. Sandy silts: dark grey silts with a high proportion of fine to medium grained sand occupy the lower 1 m. These contain the occasional fleck of detrital wood and scattered shell fragments. Forms a gradational contact at *c.* -8 m O.D. with the underlying basal sands and gravels.
2. Silty clays : Sandy silts grade into a 4-5 m series of silty clays with occasional wood fragments. The silty clays have distinct laminae, alternating 0.5 mm bands of light and dark grey silty clay.
3. Sandy clays : The silty clays in turn grade up into a 4 m sequence of brown-grey sandy clays, forming the uppermost unit of the Grey silty clays. The transition is marked by the replacement of silt with sand at *c.* 2 m O.D. The sandy clays are also distinctly laminated, and in the upper 2 m there are scattered calcium carbonate concretions.

(d) Barling gravel : *c.* 5 m of sands cap the grey silty clays and are assigned by Bridgland (1983, 1988) to the Barling Gravel. The contact between the upper part of the sandy clays and the gravels at 2.20 m O.D. was abrupt.

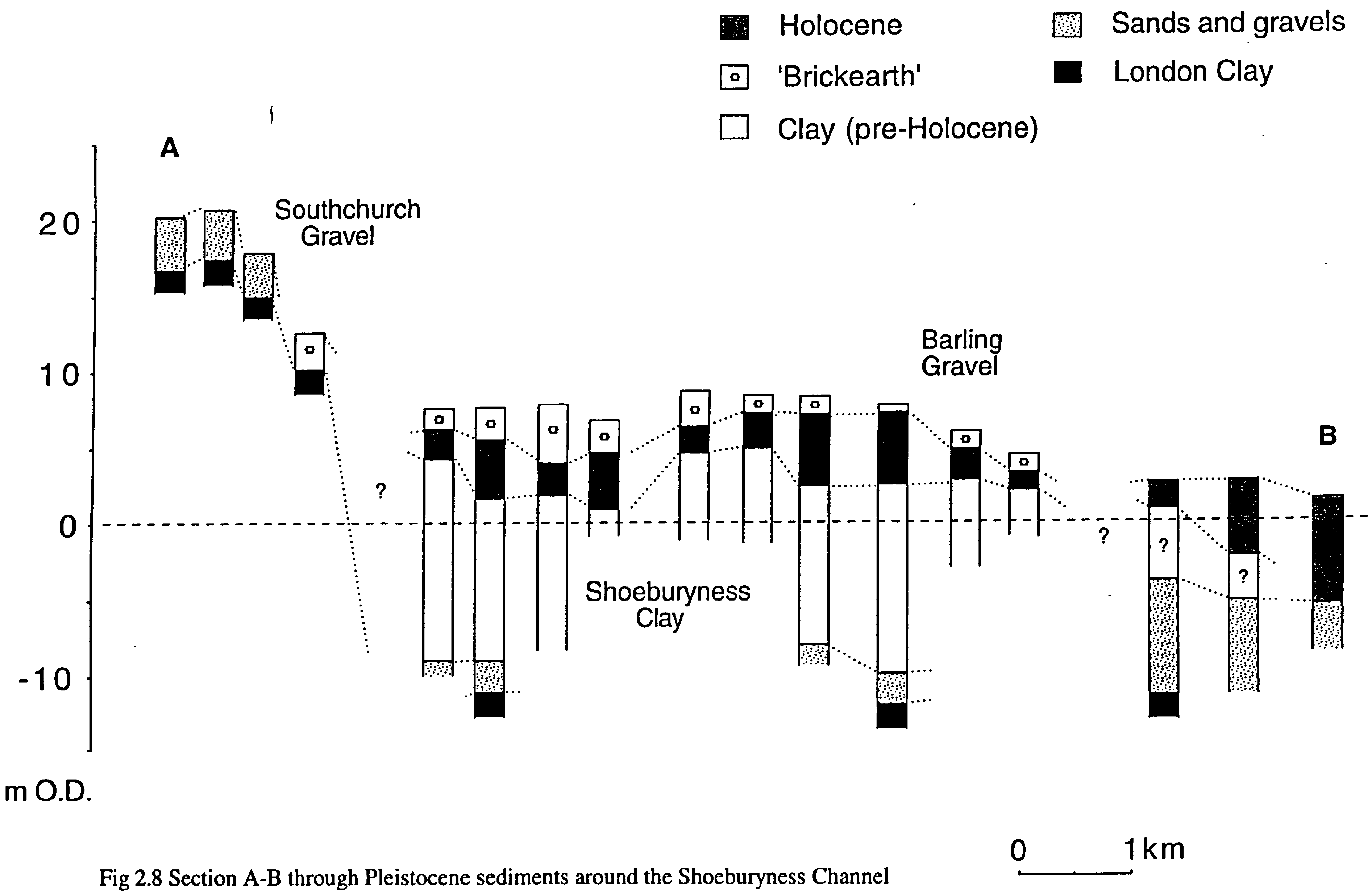


Fig 2.8 Section A-B through Pleistocene sediments around the Shoeburyness Channel (adapted from Roe, 1994).

(e) Brown silts : A 1 m thick layer of heavily oxidised brown silt was proved in two early boreholes at Elm Road, which has since been classified as 'brickearth' (Roe, 1994, Table 2.1) This deposit, which has subsequently been removed, lay at *c.* 6 m O.D.

Terminology

The term 'Shoeburyness Buried Channel deposits' was previously used to collectively describe the coarse and fine grained sediments infilling the bedrock depression at Shoeburyness (Lake *et al.*, 1977; Bridgland, 1983, 1988). Roe (1994) demonstrated that, in fact, the deposits could be separated into two units; the basal sands and gravels and the silty clays. Both occurred in the channel like depression and did not appear to extend beyond the immediate area of Shoeburyness. Roe (1994) therefore proposed that the terms 'Shoeburyness Channel Gravel' and Shoeburyness Clay' be adopted to describe the units, and that the stratotype proposed is borehole TQ 98 NW 73 at Elm Road [TQ 9380 8561]. The 'Shoeburyness Channel Gravel' was defined by Roe (1994) as the unit of sands and gravels immediately overlying the London Clay bedrock in the borehole at -12 m O.D. This deposit was overlain by the silty clays which are defined as the 'Shoeburyness Clay', the base of which occurs at -10 m O.D.

Sedimentary history inferred by the stratigraphy at Shoeburyness

With the exception of the Barling Gravel and the upper superficial deposits, all the Shoeburyness sequence was deposited in a depression in the surface of the London Clay. The scale and form of the depression suggest that it probably represents a segment of a former river channel, with a slightly irregular, U-shaped cross-sectional profile and a steeply sloping long profile. Roe (1994) states that steep slopes cannot remain stable in the London Clay under temperate conditions, so this depression was probably cut in a periglacial regime. The channel may have been excavated further by the river that deposited the Shoeburyness Channel Gravel. These basal sands and gravels are of

Thames-Medway origin, and appear to have been laid down when the river flowed in an easterly direction (Lake *et al.*, 1977; Roe, 1994).

After this depositional energies fell considerably and fine sediments began to accumulate. The observed lithofacies are indicative of a large fluviatile channel environment, possibly associated with a freshwater river or the subtidal and intertidal zones of an estuary. All three environments promote the development of thick silt and clay sequences, even though depositional processes may vary considerably in each of those environments.

Later, after an indeterminate period, depositional energies in the channel increased again (Roe, 1994), and the Barling Gravel would have been lain down marking the onset of fluviatile conditions (Bridgland, 1983). The Thames-Medway would no longer have been confined to the Shoeburyness channel, but may have been guided by it in part, since the soft sediments would have offered a path of least resistance. The river may have eroded away large areas of the argillaceous beds and promoted the general denudation (large scale oxidation) observed in the upper parts of the sequence.

The Shoeburyness area experienced at least one further period of periglacial climate after the aggradation of the Barling Gravel (Roe, 1994), which promoted the deformation of the Barling Gravel at Barling Hall (Bridgland, 1994).

Pollen Stratigraphy from Borehole S1

Roe (1994) made a detailed examination of the pollen-bearing sediment in BHS1, which came from 5.1 - 14.75 m below the ground surface. She was able to divide the pollen diagram into three pollen assemblage zones of local significance (Fig 2.9) on the basis of the frequencies of pollen in the sediment. The environmental information gleaned form the pollen assemblages can be summarised as follows:

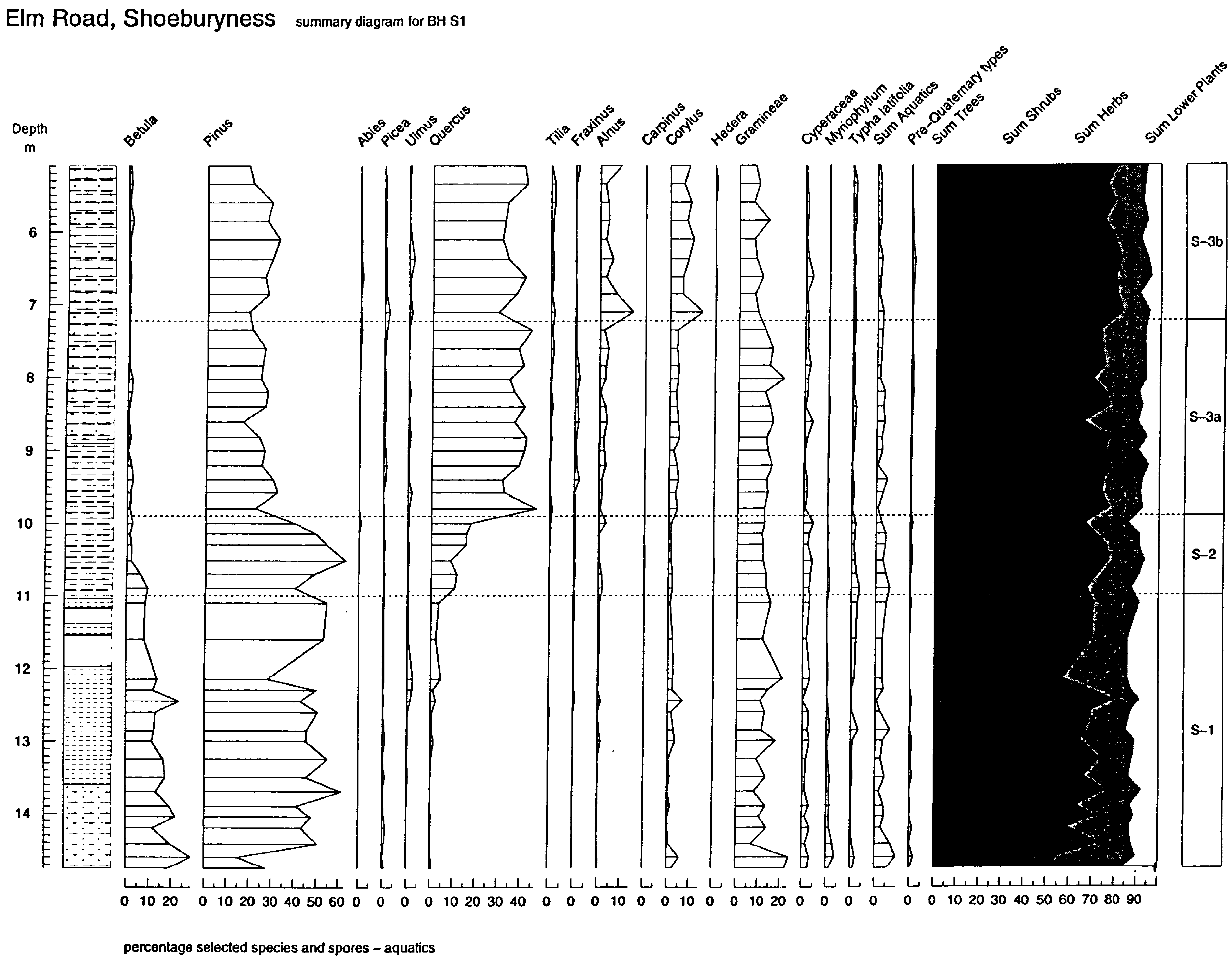


Fig 2.9 Summary pollen diagram , BHS1, Shoeburyness, Essex (summarised from Roe. 1994).

S-1 (14.75 - 11.00 m): this was a phase of silt deposition in a stagnant or slow flowing river, indicated by the high frequencies of freshwater ostracods (Roe, 1994). The area was surrounded by boreal woodland, dominated by birch and pine. The woodland also contained some thermophilous tree taxa, such as *Quercus*, *Ulmus*, *Corylus* and *Tilia*. The channel itself also supported an aquatic flora suggestive of still, eutrophic conditions and including *Myriophyllum*, *Chara* and a free floating water fern *Azolla filiculoides*. The pollen spectra suggest that conditions were mild throughout this zone, with winters of limited severity indicated by the occasional appearance of *Hedera* (Iverson, 1944).

S-2 (11.00 - 9.00 m): at the base of this zone *Quercus* expands in the area, replacing *Betula* in the surrounding woodland (Fig 2.9). All other communities remained fairly similar to zone S-1, although the appearance of the aquatic plant, *Najas minor* indicated that an "interglacial climate with warmer conditions than present " (Godwin, 1975) prevailed.

S-3 (9.00 - 5.35 m): the beginning of this zone coincided with an influx of brackish water into the area, again indicated in the ostracod fauna by a marked decrease in the number of freshwater taxa (Roe, 1994), and the introduction of marine foraminifera (this study) which could have been washed into a tidally influenced area. This would have affected the taphonomy of the pollen assemblages, with a significant increase in the number of water-borne palynomorphs (section 2.1.5). Leaving taphonomic affects aside, however, Roe (1994) concluded that the mixed oak woodland persisted in this zone. The progressive rise in Chenopodiaceae pollen in the latter part of the zone indicated that the brackish water was being invaded by saltmarsh vegetation. There was also a decline in the concentration of pollen throughout this zone which is consistent with the rapid deposition of sediment in estuarine areas (Nichols and Briggs, 1985).

Pollen was absent from the upper part of the sequence at Shoeburyness which may indicate the degradation and removal of pollen by the oxidation of the upper layers of the core, or that the depositional environment was unfavourable for pollen sedimentation.

2.2 *Ostracods for use in palaeoecological studies*

Low-Mg calcium carbonate carapaces of ostracods, preserved in fluvial, lacustrine and marine sediments, provide palaeo-environmental information in two ways. First, the presence of fossil shells contributes information on the depositional environment through knowledge of species environmental tolerances and by the structure of the fossil assemblage. Environmental factors that most affect ostracods physiologically are salinity, temperature and ionic composition of the water (Forester 1983; Anadon *et al.*, 1994; Holmes, 1996). Differences in salinity and temperature requirements and tolerances can be used to examine distributions and permit palaeo-environmental reconstructions. Second, the trace element concentrations in the calcium carbonate shells vary with genera and ontogenetically, and with water temperature and salinity (Sohn, 1958; Cadot and Kaesler, 1977; Chivas *et al.*, 1986a, b; De Deckker *et al.*, 1988).

2.2.1 *Survival strategies*

Many physical and chemical factors influence ostracods in their natural environments, of which salinity, temperature, substrate, pH, oxygen concentration and food supply are considered to be the most significant. Salinity has a major influence on ostracod distribution, and recently instead of classifying ostracods as freshwater, brackish or marine, ostracodologists have tended to use non-marine, to cover a range of saline and freshwater habitats, and marine. Brackish water ostracods are either those marine types that can tolerate lowered salinities (*e.g.*, *Hirschmannia viridis*) and true stenohaline brackish water species that are only found in waters of less than normal marine (33 - 36‰ in north west

European waters) salinity (*e.g.*, *Loxoconcha elliptica* or *Elofsonia baltica*). Some species are also freshwater, but can tolerate higher than normal salinities (*e.g.*, *Cyprideis torosa*).

Temperature is the main factor causing periodicity in the life-cycles of podocopid ostracods (Horne, 1983). This is clearly evident in the restriction of reproduction and development to spring, summer and early autumn in many species, and in experimental work which has demonstrated that the development of eggs and instars is slower at lower temperatures (Majoran, pers. comm.). Temperature is also probably the main control on geographical distributions. Around the British Isles at the present day many species are living close to their northern limits, for example *Carinocythereis* and *Aurila* spp. are more common in the Mediterranean; whereas *Acanthocythereis dunelmensis*, *Robertsonites tuberculatus*, *Elofsonella concinna* and *Palmenella limicola* are at the southern limits of their distribution around northern Scotland, and are more frequently found in Arctic waters.

Depth in itself is unimportant, especially in shallow north west European seas where pressure cannot be taken into account. pH and dissolved oxygen concentrations are also of little significance, since shelf waters are fairly uniform in these aspects.

Ostracods are found living on a variety of substrates, both sedimentary and phytal. They can also be either epifaunal or infaunal. Due to the assortment of niches in which ostracods live, a number of different shell architectures have developed, which aid movement on or through the sediment and also contribute to the reduction of frictional drag in the water column. Ostracods have also developed a number of different types of shell ornament, which may have developed in response to the environmental pressures exerted on the ostracods. Within the sediment ostracods are confined to the oxidised surface layer or to the oxidised halos around the burrows of larger organisms (Murray, 1997). Therefore they are restricted to a few centimetres depth, although they do influence the sediment even at these depths by forming burrows and disturbing sediment grains since they are the same size as the detrital particles.

Some ostracods appear to have particular substrate preferences; for example all of the marine ostracods found in the Sand Hole formation exhibit a preference for sand or mud sediments. Some sediment-dwelling ostracods are very particular about where they live, which can be helpful in speciation, e.g. *Leptocythere psammophila*, as its name suggests, is usually found associated with sand, whereas *L. porcellana* is more commonly associated with mud (Athersuch *et al.*, 1989). However, ostracods can also stray from their natural habitat preference, and sediment-dwelling ostracods can often be found associated with algal holdfasts (Horne, 1983).

Competition appears to be a major factor controlling ostracod life-cycles. The pressure of competition for food and space may have caused species to evolve life-cycles which enable them to reach their reproductive maxima at times of year when competition from other species within the same habitat is at a minimum. This would seem to be particularly true of *Hirschmannia viridis* (O.F.Müller, 1785); the slow development of the last two juvenile stages, which has been shown experimentally to be unaffected by temperature, allows this species to reach its maximum reproductive potential earlier in the spring than most other species (Athersuch *et al.*, 1989)

Most ostracod species probably deposit their eggs singly or in groups on algae, sand grains, or other firm substrates (Neale, 1965), although there are few observations of marine ostracods to confirm this. Some, such as *Cyprideis torosa* (Jones, 1850) and species of *Xestoleberis* Sars, 1866, retain their eggs, and early instars may be found within the brood space of the female carapace. At least one brackish water species, *Elofsonia baltica* (Hirschmann, 1909), is known to produce resting eggs, but this is probably not as common an occurrence in marine ostracods as it is in freshwater species.

The majority of marine and brackish ostracods have seasonal life-cycles, with reproduction restricted to relatively brief periods in spring, summer or autumn (Horne, 1983). Many north-west European ostracods produce one generation annually, with most of the development taking place in spring and summer, and pass the winter months variously as eggs, juvenile instars or adults. Some individuals hatched early in the year will mature by the autumn; others will remain as a juvenile instar for the winter, and then mature the following spring. A few species show little or no seasonality in their population dynamics and are apparently capable of reproducing throughout the year. One such species is *Paradoxostoma variabilae* (Baird, 1835), populations of which were studied by Horne (1980) in the Severn Estuary and Bristol Channel. At one site it lived and reproduced throughout the year on the intertidal calcareous alga *Corallina*, except for a few weeks in the summer when it apparently migrated to different algae, probably to avoid competition with other, seasonal species which were reaching their reproductive maxima around that time.

Therefore due to their ecological affinities ostracod biofacies can be used in order to reconstruct palaeo-environments from changes in the depositional environments.

2.2.2 *Ostracod palaeoecology*

Ostracods are closely attuned to their ambient physicochemical environment, particularly with regard to water temperature, salinity, and dissolved oxygen (Valentine, 1976). These parameters show predictable shifts with changing water depths that are parallelled by changes in the ostracod fauna. The geographic distribution of discrete ostracod assemblages thereby provides a map of the different environments on the ocean bottom. Knowledge of modern biofacies can be used to help recognise fossil environments of deposition and to reconstruct Pleistocene palaeoceanographical conditions (Brouwers 1988).

The rapidity of response of ostracods to even subtle changes in the bottom environment makes them one of the most sensitive organisms that readily fossilise. Their small size means that large numbers of specimens can be easily analysed, allowing for a measure of statistical validity. The metazoan complexity of an ostracod and its relatively long life span affords information on seasonality not possible with the more simple protozoans such as Radiolaria, diatoms or foraminifers (Delorme, 1969).

Studies of Quaternary sea-level changes along continental margins are important for climatic models, because the local sea-level record of stable regions is controlled primarily by glacio-eustatic processes. Marginal marine ostracod species restricted to brackish water lagoonal, estuarine and salt marsh habitats can be used for identifying palaeoshorelines and coastal environments (Cronin, 1987). In Quaternary deposits, ostracod assemblages reflect not only living populations but also sedimentary processes that transport and mix ostracod valves. It is imperative to palaeo-environmental studies to consider the taphonomy of an assemblage - that is to determine the degree to which a fossil assemblage reflects a life assemblage (Chapter 3.1.6).

Delorme (1969) was the first to recognise that ecology and biogeography of non-marine ostracods were so habitat-specific that they could be used to make quantitative palaeo-environmental interpretations. He established a modern quantitative data base for Canadian ostracods and has used this information to interpret past hydro-environments and climate (e.g. Delorme 1987). He has also shown that ostracod hydrochemical sensitivity is great enough to describe particular environments in terms of salinity and solute composition.

Information on energy levels associated with particular environments can be obtained from the study of adult to juvenile ratio of ostracod valves recovered in samples (Brouwers, 1988; Whatley 1988; Chapter 3.1.7). By studying all the sizes of ostracod valves belonging to an individual species, thus inferring recovery of an entire or incomplete life assemblage, it is possible to indicate whether or not a sample has undergone some sorting or reworking. Shoreline environments are characterised by high energy and disturbance.

Thus ostracod shells will often become sorted, broken, abraded and finally mixed with a variety of other organic debris, other fossil remains and terrigenous material.

2.2.3 *Carbonate geochemistry*

The multiple moult stages of ostracods produce discarded instars (valves and carapaces). There is no uptake of calcium once the shell has been fully calcified (Turpen and Angell, 1971). Ostracod moult processes are short, so a single ostracod valve represents the environmental conditions of the ambient water mass at the time of calcification only (usually a few hours). Where further information about species habitat and seasonal growth patterns is known, the use of a particular species allows close constraints to be placed on the timing and environmental setting of shell construction (De Deckker *et al.*, 1988; Holmes, 1996).

a) *Trace elements*

Trace element geochemistry of marine ostracods provides palaeo-environmental data which often complements data from other techniques, such as oxygen isotopes (Durazzi, 1977; Von Grafenstein *et al.*, 1992; Chivas *et al.*, 1993; Anadon *et al.*, 1994). Many trace elements are found in carbonate shells (Sohn, 1958), the most common of which are magnesium, strontium, barium and potassium. Through a combination of analyses of magnesium and strontium on single ostracod valves for any sample representing a life assemblage, or for a series of samples which occur above one another stratigraphically, it is possible to detect changes in salinity and temperature. Magnesium and strontium are conservative elements in the ocean, so the Mg:Ca and Sr:Ca ratio is constant with depth in the present day ocean (Broecker and Peng, 1982). Based on numerous measurements, partition coefficients (K_D) have been developed for Mg^{2+} and Sr^{2+} for several species of ostracod (Chivas *et al.*, 1986b):

$$K_D\,(Me) = (Me{:}Ca)_v \,/\, (Me{:}Ca)_w$$

where Me is for either Mg^{2+} or Sr^{2+}, v is valve ratio, and w the water ratio. In this way it was found that phylogenetically closely-related genera or species within the same genus have similar partition coefficients for Mg^{2+} and Sr^{2+}.

Chave (1954) recognised a covariance of Mg content in the calcite of marine organisms with latitude and suggested that a relationship exists between the substitution of Ca by Mg and water temperature. A positive correlation between temperature and Mg:Ca ratios in ostracod shells was demonstrated by Cadot and Kaesler (1977) and has since been confirmed in studies of non-marine taxa (Chivas *et al.*, 1986a, b; DeDeckker *et al.*, 1988; Anadon *et al.*, 1994; Holmes *et al.*, 1995). The uptake of strontium is apparently directly related only to the concentration of strontium and the Sr:Ca molar ratio of the host water (Chivas *et al.*, 1985). Chivas *et al.* (1985) determined that there was a positive correlation between salinity and trace metal composition of the planktonic Australian ostracod *Mytilocypris henricae*. Conversely, Teeter and Quick (1990) found a negative correlation between salinity and the magnesium concentration in *Cyprideis americana* from the Bahamas. The inverse relationship between Mg:Ca and Sr:Ca ratios shown by the non-marine ostracods *Limnocythere ceriotuberosa* and *Candona caudata* suggest that culturing studies should be performed on certain species (Holmes, personal communication) before using ostracod shell chemistry as a firm basis for palaeohydrochemical investigation. Much of the previous work on the application of shell chemistry has been dominated by work on non-marine species. However, in the past decade, palaeotemperature and palaeosalinity reconstruction using trace element techniques has been applied to deep sea benthic ostracods (Correge, 1993; Dwyer *et al.*, 1995; Cronin *et al.*, 1996) demonstrating that these marine taxa also have excellent potential to provide palaeo-environmental information.

b) Stable isotopes

Stable isotope analyses of ostracod shells provide yet another source of palaeo-environmental information.

Oxygen isotope analyses

The application of oxygen isotopes in biogenic carbonates to studies of palaeosalinity and temperature was first suggested by Urey (1947). Shortly after this Epstein *et al.* (1951, 1953) developed a palaeotemperature scale for biogenic carbonate that was later modified by Craig (1965),

$$t = 16.9 - 4.2\,(\delta^{18}O_C - \delta^{18}O_w) + 0.13\,(\delta^{18}O_C - \delta^{18}O_w)^2$$

where t is the temperature in °C, $\delta^{18}O_C$ is corrected $\delta^{18}O$ obtained from the carbonate, and $\delta^{18}O_w$ is the corrected $\delta^{18}O$ of CO_2. Emiliani (1954) applied this equation to foraminifera in deep sea cores and estimated changes in ocean temperature. Like foraminifera, ostracods are another source of biogenic carbonate containing geochemical tracers of past environmental conditions.

The relationship between $\delta^{18}O$ and the salinity of the water in the North Atlantic is well established (Craig and Gordon, 1965) according to empirical data. For every 1‰ change in salinity there should be a corresponding 0.6‰ change in $\delta^{18}O$. The relationship between $\delta^{18}O$ and temperature has been similarly defined (Shackleton, 1974) in that for a 4°C change in temperature there is a 1‰ change in $\delta^{18}O$. The variation in the isotopic composition of ocean waters over time is revealed by the changing ratios of $^{18}O/^{16}O$ in carbonate shells. Calcium carbonate is formed in sea water from the abstraction of oxygen (Lowe and Walker, 1984). If calcium carbonate is crystallised in water, as it is in the formation of ostracod shells, ^{18}O is slightly concentrated in the calcium carbonate relative to that in the water. The process is temperature dependent, with the concentrating effect diminishing as temperature increases. Knowing that $\delta^{18}O$ values increase with an increase in water salinity, and that $\delta^{18}O$ values decrease with a temperature rise, it becomes possible to detect temperature and salinity changes from the analysis of ostracod shells (De Deckker and Forester, 1988; Anadon *et al.*, 1994; Holmes, 1996).

There is a stratigraphic significance to these records as well as a palaeo-environmental one. In shallow water sequences this palaeo-environmental analysis is of greater significance, since it can delineate the temperature and salinity changes on the shelf. The oxygen isotopic composition of a sample is generally expressed as a departure of the $^{18}O/^{16}O$ ratio from an arbitrary standard, S:

$$S = \frac{(^{18}O/^{16}O)\text{sample} - (^{18}O/^{16}O)\text{standard}}{(^{18}O/^{16}O)\text{standard}} \times 10^3$$

The values are expressed in ‰ units relative to the standard; negative values represent lower ratios in the sample (i.e. less ^{18}O than ^{16}O and therefore isotopically "lighter") and positive values represent higher ratios in the sample (more ^{18}O than ^{16}O and therefore isotopically "heavier"). The difference between the $\delta^{18}O$ value of the water and the standard can be expressed as δw.

There is a considerable body of evidence to suggest that the ratios of ^{18}O to ^{16}O in the oceans varied in a quasi-cyclic fashion with succeeding glacial and interglacial periods (Lowe and Walker, 1984). During glacial periods the removal of isotopically light water from the oceans to form continental ice sheets led to an increase in the $^{18}O/^{16}O$ ratio of the oceans as a whole. Thus the expected increase of the ratio in the carbonate of ostracod shells due to decreasing temperatures is complicated by the increase in δw at these times.

During the evaporation of seawater, a natural fractionation of oxygen isotopes occurs. In other words, there is a preferential evaporation of the lighter $H_2{}^{16}O$ molecules so that atmospheric water vapour becomes relatively enriched in ^{16}O. Fractionation is particularly marked at higher latitudes where colder air masses are increasingly less able to support the heavier isotope ^{18}O. During the cold phases of the Quaternary, with marked expansion of ice sheets in both the northern and southern hemispheres, large quantities of ^{16}O were trapped leaving the oceans relatively enriched in ^{18}O and thus isotopically more positive. Conversely, the melting of the ice masses in interglacials liberated large volumes of water enriched with ^{16}O back into the oceans. An oxygen isotope trace through cores of sediment can therefore reveal a record of glacial/interglacial changes over the whole of the Quaternary (Shackleton, 1974). Sharp transitions from a cold state to a warmer one are known as terminations, and these delimit the oxygen isotope stages, which are global time boundaries. This deep sea oxygen isotope stratigraphy underpins understanding of the Quaternary cyclicity, although many problems remain in correlating this ocean-based history with the terrestrial record.

Another complication in calculating water temperatures from the isotopic composition of biogenic carbonate is the problem of variations in the depth habitat of the microfossil in question. Even if the ice effect and vital effects are known, there is still some uncertainty as to whether Ostracoda lived at the same depth from glacial to interglacial times. Water temperatures in the upper few hundred metres of the ocean change rapidly with depth, particularly outside the Tropics, so small variations in depth habitat can be equivalent to a change in temperature of several degrees.

The oxygen isotope composition of ostracods is now used as a palaeoclimate proxy; however, the isotopic fractionation between ostracods and water has not been studied extensively. One recent experimental study into fractionation in ostracod shells (Xia *et al.*, 1997a) showed that for *Candona rawsoni*, a freshwater ostracod, the adult shells did not form in isotopic equilibrium with the water, but had a constant offset from equilibrium based on the oxygen isotope fractionation of inorganic carbonates. The observed fractionations were expressed by regression equations:

at 25°C: $\delta^{18}O_{shell} = -0.47 + 0.97\,\delta^{18}O_{water}$

at 15°C: $\delta^{18}O_{shell} = 1.12 + 1.07\,\delta^{18}O_{water}$

The oxygen isotope composition of the ostracod shells from the 15°C cultures were higher by about 2 ‰ compared to that from the 25°C cultures, a difference similar to that expected for inorganic calcite (Xia *et al.*, 1997a). Non-equilibrium fractionation of this sort can be induced by biological factors (vital effects) or by variability in shell composition caused by physiological conditions within a population of ostracods (McConnaughey, 1989). Xia *et al.* (*ibid.*) also found that ostracods in the 15°C experiment grew more slowly (i.e. were under stress) and that the slower growth rate led to a closer approach to equilibrium fractionation. Their experiment pointed at two possible factors affecting oxygen isotope fractionation: (1) a temperature dependent rate of calcification, with faster calcification at higher temperatures leading to more incorporation of ^{18}O relative to inorganic calcite; and (2) environmental stress during calcification leading to incomplete calcification and more incorporation of ^{16}O.

Carbon isotope analyses

$\delta^{13}C$ can be used as a measure of the productivity present in the water column. The $^{13}C/^{12}C$ ratio of carbonates is little affected by temperature variations, but is a response to changes in the isotopic ratio of the total dissolved inorganic carbon (TDIC) from which carbonates precipitate. The $^{13}C/^{12}C$ ratio of the TDIC is, in turn, controlled by the rate of exchange of CO_2 with the atmosphere, the rate of photosynthesis and organic decay, the occurance of bacterial processes (e.g. sulphate reduction) and inputs from the dissolution of carbonates (McKenzie, 1985; Conway *et al.*, 1994). Durazzi (1977) established that ostracod shell calcite is precipitated in near isotopic equilibrium with the host water and

TDIC. This early result has more recently been confirmed by Xia *et al.* (1993) and Heaton *et al.* (1995).

However, because ostracod shell secretion is completed over a very short time, the $^{13}C/^{12}C$ ratios provide a highly localised and temporally restricted reflection of the isotopic composition of the host water and TDIC. $\delta^{13}C$ values can also be used to indicate microhabitat effects and vital offsets in ostracod valves (von Grafenstein, pers. comm.), and can record salinity in that fresh water is usually characterised by very negative values of $\delta^{13}C$ due to dominance of respiratory processes. More detailed discussion relevant to each site will be found in Chapters 4 and 5.

2.2.4 Carbon/nitrogen (C/N) analyses

The origin of organic carbon in continental margin sediments has often been debated (Gearing *et al.*, 1977), since a certain amount would arise from the local marine biomass, and a certain portion from terrestrial detritus. The terrestrial contribution may be dominant even some distance from the shore (Gearing *et al.*, 1977). The major influence of terrestrial runoff on the make up of nearshore sedimentary organic matter lies in the associated nutrients carried by rivers (Bordovskiy, 1965), which allows high rates of productivity in the nearshore water column. Land plants are depleted in ^{13}C by several ppm compared to organic carbon produced by marine phytoplankton (Craig, 1953). So carbon tracers can be used to determine the downcore distribution patterns of terrigenous mud and marine organic matter.

However, terrestrially derived organic matter plays only a small part in setting the $\delta^{13}C$ of total organic carbon in continental shelf marine sediments (Müller *et al.*, 1994). In areas offshore of heavy runoff and sediment input (i.e. estuaries) locally produced marine organic matter dilutes out the contribution from land plants in an approximately logarithmic fashion with distance from the shore (Gearing *et al.*, 1977; Müller *et al.*, 1994). Therefore, $^{13}C/^{12}C$

ratios reflect a definite terrestrial input only close to the land where a significant proportion of the total inorganic carbon consists of the remains of land plants. Hence the C/N ratio can be used as an indicator of freshwater, fluvial influence in an area such as that potentially occupied by the Inner Silver Pit.

In the next chapter the techniques used in order to obtain data on the applications of ostracods in palaeoecological analysis discussed above are outlined.

Chapter 3

Techniques

3.1 Palaeoecological methods

Detailed micropalaeontological analyses was used to identify local environments in two areas in the southern North Sea during previous interglacial stages of the Quaternary. Information on the ecological affinities of ostracod species can be used to generate hypotheses concerning the circulation history of the North Sea, and the environment that prevailed at the time of deposition of the sediment examined.

3.1.1 Ostracod analysis

Ostracoda are small laterally compressed Crustacea, enclosed within a protective calcareous carapace. This shell is made up of two valves hinged in the dorsal region of the body. Hinge structure is an important taxonomic character (van Morkhoven, 1962). Appendages are protruded from between the two valves for feeding, locomotion and reproduction, but they can be completely withdrawn and the valves closed by the means of adductor muscles attached to the inside of each valve. The muscle scars formed on the inside of the carapace at the attachment points of these muscles are of great significance at higher taxonomic levels for the identification of species. Species of ostracod with strongly calcified carapaces are readily fossilised and these ostracods are often abundantly represented in marine, brackish and fresh water sediments. The chitinous appendages and soft parts are rarely preserved, although phosphatised specimens have occasionally been found preserved in their entirety (Athersuch *et al.*, 1989; R. Smith, pers. comm.).

3.1.2 Sampling and preparation of samples

For the study of fossil assemblages 50 - 100 g of sediment was taken every 10 -20 cm downcore for both the Inner Silver Pit borehole (81/52A) and the Shoeburyness core (S1). Each sample was dried in an oven and weighed. The samples were decanted into clean 63 µm sieves and washed in water to remove the finest sediment fraction. The residue was washed onto filter paper and dried at 80°C.

3.1.3 Assemblage counting

Either the entire 500 - 125 µm fraction, or a known proportion of the sample, was transferred onto a gridded picking tray. All the ostracods were picked out using a fine sable brush (000), and the individuals were placed onto a gridded adhesive slide for subsequent sorting and identification. The ostracods were picked out using an Olympus (model CO11) low power binocular microscope at x40 magnification. Since the entire ostracod fauna was picked percentage frequencies were calculated prior to analysis.

3.1.4 Classification and identification

The Ostracoda form a distinct class within the Phylum Crustacea, due to their laterally compressed body, the undifferentiated head, the seven-or-less head and thoracic limbs, the pair of furcae (cleaning limbs) and the bivalved perforate carapace lacking in growth lines. Fossil ostracods are diagnosed taxonomically entirely on carapace features. Since all of the ostracod carapaces are constructed in the same way, the 1000 genera and around 10 000 species are classified according to:

- the outline and contour of the valves and the features of the ventral edge
- the structure of the hinge
- the characteristics of the marginal zone

- the pore and the ornamentation on the valve.

Phylum **CRUSTACEA** Pennant, 1777

Class **OSTRACODA** Latreille, 1806: The class contains five orders, in most classification systems, three of which are extinct (Order ARCHAECOPIDA, Order LEPERDITICOPIDA, Order PALAEOCOPIDA) and are not considered to be ostracods by current workers (Siveter, pers. comm.):

Order MYODOCOPIDA Sars 1866 : This order includes most of the pelagic ostracods. Their soft parts are distinct from those of other living groups in having a biramous antenna, modified for swimming. They secrete thin, amorphously calcified or chitinous carapaces and so are rarely found fossilised.

Order PODOCOPIDA G.W. Müller, 1894 : The Podocopida comprise the bulk of the Mesozoic and Cainozoic fossil ostracods, although they have a longer history (L.Ord.-Rec.). Living forms are generally diagnosed from their soft parts, but fossil taxa have been erected on carapace morphology. The majority of Podocopida have adapted to crawling and burrowing niches in marine sediments or on seaweeds. However, this order also includes the terrestrial and freshwater Cyprididae and fresh- and brackish water genera of the Cytheridae. Some fresh water genera are nektonic, but the majority of the Podocopida are benthonic.

Individuals in this study were identified to the highest taxonomic level using the keys of Athersuch *et al.* (1989) and Henderson (1990), as well as various references therein. The classification was based on that adopted by Athersuch *et al.* (1989) of Maddocks (1982) since there is no up-to-date definitive classification scheme at present.

The Ostracoda are divided into suborders as described above. All ostracods found in this study belong in the Order Podocopida. Following Maddocks (1982) the Podocopida may be divided into five superfamilies: Sigillacea, Darwinulacea, Bairdiacea, Cypridacea and Cytheracea (the traditional palaeontological endings '-acea' are used in contravention to the modern zoological practise dictating the ending '-oidea'). The Sigillacea and Bairdiacea are not considered in this study since the former has only one living representative, and is not known in European waters, and the latter are only known from deep water. The Darwinulacea are confined to fresh water, and some representatives from this family were found. However, most of the species were Cypridaceans or Cytheraceans, found in marine, brackish and fresh water environments.

3.1.5 Scanning electron microscopy

In order to facilitate the recognition of small or problem taxa, and to check the identification of the fauna, a number of scanning electron microscope (SEM) pictures were taken on a Cambridge Instruments Stereoscan 120 SEM. The ostracods to be photographed were mounted on aluminium stubs previously coated with photographic film. The film is sticky enough that the ostracods stay in place whilst each stub is sputter-coated with a Gold - Palladium alloy. Each specimen was photographed using Ilford FP4 black and white 35 mm film. Once photographed the specimens were detached from the stub using a fine sable brush and water, and returned to their respective faunal slides. Only whole valves were chosen, and the plates (Appendix 1) show the main elements of the fossil assemblages from the Inner Silver Pit and Shoeburyness respectively. Instar valves of a couple of species were also photographed to illustrate changing carapace morphology and size during development.

3.1.6 Taphonomic considerations.

Extant ostracod life histories are not well known; however, it is thought that for many species reproduction can occur at anytime of year. Some ostracod eggs are resistant to desiccation and cold, hence this first developmental stage can aid survival through harsh conditions, and also facilitate dispersal on the feet of aquatic birds. Other species exhibit brood care in which the young instars are retained in the carapace of the adult throughout the first three to four developmental stages. Young ostracods grow in discontinuous stages called instars, or moult stages, which are designated A (=adult), A-1, A-2 through to A-7, in descending order of size.

In the Podocopida there are usually eight moults in between the egg and the adult; the first instar (A-8) or nauplius which hatches from the egg is usually relatively short lived, lacks thoracic appendages, has a poorly calcified shell, and is so small that it is unlikely to be seen except in laboratory cultures. A properly calcified shell appears at the A-7 stage. When the body of an instar has grown too large for its exoskeleton, the rigid chitinous and calcareous layers are shed. Rapid growth and development follow. Each moulting of the shell introduces an animal differing not only in size but also in form. The old appendages may change their form and function, and entire new appendages are added quickly before the hardening of the new carapace occurs (van Morkhoven, 1962). A new carapace will harden within hours of being secreted and after that there is no incremental growth of the carapace (Turpen and Angell, 1971).

The valves of ostracod instars increase progressively in size and become thicker and more heavily calcified. These changes are accompanied by modifications in shape and sculpture, and in Podocopida by the increasing complexity of hinge, duplicature (the margins of the thin calcified inner lamella) and marginal pore canals. Muscle scars are not usually seen before instar 6 (A-2), genital impressions before instar 7 (A-1), and sexual dimorphism is absent prior to the adult stage.

3.1.7 Recognition of the life and death assemblages in fossil ostracod populations

The accuracy of palaeontological reconstructions of past environments depend on the certainty that the fossils used actually lived in that environment, especially when using geochemical methods of analysis on calcareous organisms. Small microfossils are at the mercy of *post mortem* transport, and so no such certainty exists. The recognition of the relative contributions of autochthonous and allochthonous components to a fossil assemblage must be considered before meaningful conclusions can be drawn from the assemblage present.

Many microfossil assemblages are obviously size-graded and this, while possibly the product of a catastrophic event killing off all of the specimens in a certain area, is more likely to be the consequence of *post mortem* aggregation (Whatley, 1988). Other non-size sorted microfossil assemblages may equally be of mixed origin.

For most groups of microfossils there are no known means of separating autochthonous from allochthonous components in such mixed assemblages unless the latter components are abraded. However, the Ostracoda provide a near infallible means of effecting this separation by virtue of their ontogeny. In common with all other crustaceans, ostracods grow discontinuously, old carapaces being shed in ecdysis. Valves from most of the juvenile stages (which often become disarticulated) are preserved as fossils. The potential fossil history, therefore, of any ostracod species comprises a record of a series of valves of different sizes, shapes, weights and hydrodynamic properties (Whatley, 1983a). Any species within a population which has all or most of its ontogeny represented in reasonably equivalent proportions must be considered as autochthonous to the environment in which it is found. Conversely, species in the same population represented by only a part of their complete ontogeny are likely to be allochthonous (Whatley, 1983b). General application of the population age structure technique to the recognition of palaeo-energy levels and the autochthonous components of mixed faunas is described by Whatley (1983a, 1983b).

However, through time the total autochthonous population ultimately converts to a fossil assemblage which is modified by a series of taphonomic processes. The total assemblage is in a state of permanent dynamic flux and represents a composite of the processes active at the time of formation as the shells are moved into or out of the area of deposition or are destroyed by dissolution. The faunal composition may be further altered during diagenesis which effectively reduces species diversity and the number of specimens. The composition of the fossil assemblage may be further modified by the introduction of valves from living infaunal species. Awareness of these factors is of great importance when considering a fossil assemblage.

Ostracod taphonomy is complex and can significantly influence the composition of fossil assemblages. However, with the use of population age structure techniques and a uniformitarian approach, using modern analogues to reconstruct palaeo-environments can be extremely successful.

3.1.8 Analysis and presentation of data

Diagrams were constructed using a number of computer based packages. The percentage distribution diagrams were constructed using version 2.6 of Psimpoll, a plotting program designed and developed in 'C' by Dr. K.D. Bennett (University of Cambridge). Psimpoll allows the sediment description to be appended to the percentage diagrams. Species percentages were calculated from the total number of individuals counted, taking the weight of the sediment sample at the particular level into account. All horizontal scales are comparable and are plotted with x 10 exaggeration to emphasise species of lower abundance. The diagrams were zoned at levels where there was a clearly defined change in the composition of the fossil ostracod assemblage.

Instar diagrams were drawn up using Aldus Superpaint for MAC. Percent fauna was calculated from the number of individuals counted and instars were divided into paired groups. These plots were produced in order to illustrate the population age structure techniques.

Most of the analysis on the trace element and isotope data was performed in Quattro Pro v.6. This is a spreadsheet package allowing simple mathematical procedures, such as regression analysis to be performed on whole data sets, and also facilitates plotting of the data. Some analyses used MATLAB, since a more complicated manipulation of the data was required.

3.2 Geochemical techniques

A number of geochemical techniques were employed to elucidate the water column history in the two areas examined. Pollen and sedimentary evidence (Ansari, 1992; Scourse *et al.*, in press) appear to indicate that the Sand Hole Formation was deposited in the latter half of an interglacial cycle. If this is the case, then a temperature decline and falling sea-level, together with increasing fresh water influence should be documented in the ostracod shell chemistry. The Essex sites have a well documented sea-level history (references in Bridgland, 1994 and Gibbard, 1994) and trace element information was taken from this sample set in order to compare it to other brackish sites as a mechanism to check the accuracy of the technique in different areas of the world.

Trace element geochemistry is a fast growing technique that has excellent potential for providing palaeo-environmental information from the shell composition of fossils, It has been used successfully in non-marine and brackish settings (Chivas *et al.*, 1983, 1985, 1986a, b; DeDeckker *et al.*, 1988; Andadon *et al.*, 1994; Holmes *et al.*, 1995) and more recently with marine taxa in the deep sea (Corrège, 1993; Dwyer *et al.*, 1995; Cronin *et al.*, 1996).

The aim of conducting the analyses was to elucidate the temperature and salinity histories of the Inner Silver Pit and in Essex from trace element data, developing the technique, and extending the body of results into a shallow marine setting, for comparison with the palaeo-environmental information arising out of the micropalaeontological study of the ostracod faunal assemblages present. It was also hoped that the trace element chemistry of the fossil assemblage would have recorded information on temperature and salinity decline in the Inner Silver Pit, and the transition from fresh to brackish water at Shoeburyness.

Oxygen and carbon stable isotope analyses were performed at the same levels as the trace element analyses in both cores in order to correlate the trace element data from an independent source and to supply an independent salinity signal.

3.2.1 Trace element methods.

After picking out a monogeneric fauna from the assemblage available in each sample (*Sarsicytheridea* from the Sand Hole Formation; *Cyprideis torosa* from Shoeburyness), and placing individuals into carefully labelled single hole slides, the following procedure was carried out for the cleaning and preparation of ostracods for trace element analyses.

Equipment required:

1 x 4 x 6 plastic culture tray (2ml) with lid
1 x polyester bristle brush (not hair)
1 x sable hair brush
commercial Clorox bleach (5% by volume of sodium hypochlorite)
2 x 2ml pipette
1 x ultrasonic bath
2 x cut away Nalgene 8 ml bottle
2 x wash bottle (one for de-ionised water, one for Clorox)
acid cleaned 8 ml bottles (enough for all ostracod shells to be prepared)

Procedure:

1. **Acid Bath for Nalgene bottles**

8 ml Nalgene bottles were placed in 10% (1M sol^n) HNO_3 in a large jug with a lid and left for 4-6 hours. They were then removed, washed in deionised water and left to drain on a rack, before being placed in 10% (1M sol^n) HCl for 4-6 hours. The washing procedure was then repeated and the bottles placed back into the jugs for a final acid bath in 10% HNO_3. The bottles were then taken out of the acid, washed once more in deionised water and put to dry on trays in an oven at 50°C.

2. **Clorox**: Each ostracod was then cleaned in 5% sodium hypochlorite over night. The ostracods from each level can be placed, using a polyester picking brush, into a compartment of a plastic cleaning tray. Approximately 3 drops of Clorox solution were carefully added to each compartment. The tray was then left for between 4 and 12 hours, usually overnight. All ostracods were poked with a clean picking brush to ensure that they were completely covered by the Clorox. The Clorox was then pipetted out of each compartment, and the ostracods twice bathed in de-ionised water using a second pipette,

before being replaced on a slide. Care was taken not to leave the ostracods in the deionised water for more than a few minutes, to ensure that no dissolution of the shell occurred. Once on the microslide, any remaining sediment was poked out of the vestibule or pores using a microscope, brush and deionised water.

3. **Preservation:** Based on microscopic examination individual ostracods can be assigned a value on a visual preservation index (VPI):

(1) Transparent
(2) Transparent / Translucent
(3) Translucent / Transparent
(4) Translucent
(5) Translucent / Opaque
(6) Opaque/ Translucent
(7) Opaque

Opaque shells are those that have undergone post-mortem alteration by dissolution or diagenetic processes; transparent valves are those that are perfectly preserved.

4. **Ultrasonic Bath**: An ultrasonic bath was filled to a depth of about 1 cm with de-ionised water. Using a cut away, acid-clean, high density polyethylene bottle, a little deionised water was placed in the bottom, then one ostracod valve was placed into the water in the base of the first bottle. The ostracod was poked with a clean brush to ensure that it had sunk into the water. If left floating, the ultrasonic vibrations may crush the valves.

Each ostracod valve was left in the ultrasonic bath for approx 20 seconds, then removed carefully, and placed into the second cut away bottle, which also contained a little deionised water. At this time, whilst the ostracod was in its second bath, the picking brush and the first Nalgene bottle were rinsed with deionised water using a squirt bottle. A little more clean de-ionised water was placed into the base of the first bottle and the next ostracod valve added. Whilst this ostracod had its first 20 second bath, the first ostracod was taken out of the deionised water and placed into an acid washed polyethylene bottle, labelled appropriately with the sample number.

For each valve the method was continued in this way, making sure that each piece of equipment was washed with deionised water in between use with each ostracod shell.

5. **Placing of ostracods into sample bottles**: Each ostracod was placed into a separate acid cleaned 8 ml Nalgene bottle, with care being taken not to introduce any contamination into the bottle as this was done. Each ostracod was picked up with a clean picking brush, and whilst holding the bottle and bottle top in one hand, the ostracod was placed into the bottle, and the cap screwed back on. Each time the brush was then rinsed before handling the next ostracod.

6. **Weigh the bottles**: Once the ostracods have been placed into the bottles they can then be weighed. (Optional step as there is very little variation in the bottle weight). The mean weight for each species was calculated from a large sample of ostracod valves weighed on a fine balance.

7. **Add acid**: To each bottle 3 to 4 ml of 0.05M Nitric acid was added whilst using the DCP method at Duke University, and 3 ml 0.05M Aristar HCl was added for the ICP-AES technique at Kingston University. The ostracods were then left to dissolve overnight.

8. **Run DCP analyses**: DCP or ICP-AES were set up according to laboratory protocols (Appendix 2), and once calibrations of elements were checked the machines were ready to receive samples and standards according to a run sheet. Standards were as follows:

Duke University

lo : just nitric acid, no elemental component
st1: 1ppm Ca, 0.001ppm Mg, Na, Sr etc.
st2: 2ppm Ca, 0.002ppm Mg, Na, Sr etc.
hi : 3ppm Ca, 0.003ppm Mg, Na, Sr etc.

Kingston University

mon : just hydrochloric acid, no elemental component
st1 : 100 ppm Ca, 1 ppm Sr, Mg
st2 : 50 ppm Ca, 0.5 ppm Sr, Mg

All standards were made up to the same specifications from the same base acid for each run to minimise the effects of interference from different solutions made up with different pieces of equipment, and to enable calibration of the machine against its natural drift. Only three separate runs were made in order to analyse all the individual ostracods for Mg and Sr.

It is also common to run a standard of known concentration of the elements. In these cases a standard known as pe3 (Pleistocene 'Baker' Limestone) was used at Duke University, and a molluscan aragonite of known elemental concentration at Kingston University. The standards are used to check the drift of the machine for measuring each element. Repeated analyses of these in-house limestones showed that analytical precision on the DCP spectrometer was of the order ± 0.00004 mmol/mol, and for the ICP-AES spectrometer it was ±0.000015 mmol/mol. The data obtained from the spectrometry in both laboratories was automatically corrected for any drift, and it was found that both machines gave very similar results for both Mg and Sr concentrations in ostracods from the same levels down-core.

3.2.2 Stable isotope analyses

A monospecific sample of ostracods was selected from 25 levels from BH81/52A, and at 21 levels in BHS1, on which trace element analyses had already been performed. Four to five well preserved adult valves (*Sarsicytheridea punctillata* from the Sand Hole Formation, and *Cyprideis torosa* from Shoeburyness) were taken from the assemblage for each sample, and sent to the University of Bergen, Norway, for cleaning and analysis.

The stable isotope measurements were made at the University of Bergen on a Finnigan MAT 251 mass spectrometer after reaction with orthophosphoric acid at 50°C. The preparation line was an automatic on-line system with ten separate reaction chambers, following the design described by Shackleton and Boersma (1984) for a single-chambered manual version. Analytical precision of the system as defined by replicate measurements of carbonate standards is ± 0.07‰ for $\delta^{18}O$ and ± 0.06‰ for $\delta^{13}C$.

3.2.3 Carbon/nitrogen (C/N) analyses.

The carbon/nitrogen ratio is commonly used to establish the terrestrial versus marine contributions to marine sediments (Jasper and Gagosian, 1990; Müller *et al.*, 1994). These tracers can be used to determine the down-core distribution patterns of terrigenous and marine organic matter. Terrestrial organic matter is relatively nitrogen poor in comparison to marine organic matter. Strong inverse relationships between $\delta^{13}C$ and C/N ratios have been clearly demonstrated to reflect mixing between marine and terrestrial organic matter in regions close to major riverine sources. The aim in performing C/N ratio analyses on sediments from the Inner Silver Pit was to use the working hypothesis that, at the time of deposition, the Sand Hole Formation may have been in a region of freshwater influence.

Fourteen samples were taken from BH81/52A at 50 cm intervals down-core from 29.70 - 38.90 m. Each sample was weighed and then ground with a pestle and mortar. The samples were then split into two parts and ground to a fine powder using a grinder. Each half sample was placed into a marble pot with 3-4 marble balls, a lid was fitted to the pot and it was placed into the grinder for 5 minutes. Five replicate samples of 30 mg of powder were then measured into pre-combusted aluminium foil crucibles, and each one weighed again.

The aliquots of sediment were then de-calcified by drop-wise addition of 1 M HCl until effervescence ceased and then dried in an oven at 40°C. A quartz combustion furnace was then filled with chromium oxide, silver wool, nickel sheet, copper oxide and silica (quartz wool). The furnace was placed into a Europa Scientific CN-Analyser and heated to 1020°C. Data was output directly to a spreadsheet on a computer. The precision of the machine is measured at 2% (relative standard deviation) (Kennedy, pers. comm.).

A combustion furnace is used to combust samples containing carbon and nitrogen so that these are converted to the gaseous form and can be analysed. The combustion furnace is plumbed into a helium line which is periodically flushed with oxygen during the period of analysis.

All the trace element and C/N analyses were performed personally. The stable isotope analyses were carried out by staff in the Geology Dept., Bergen University.

Chapter 4

Results: Inner Silver Pit

Both the palaeoecological and the geochemical aspects of the study for the Inner Silver Pit are discussed in this chapter. The focus for the study were the ostracod assemblages identified; however, other groups (such as pollen and foraminifera) will be mentioned in the light of the ostracod evidence.

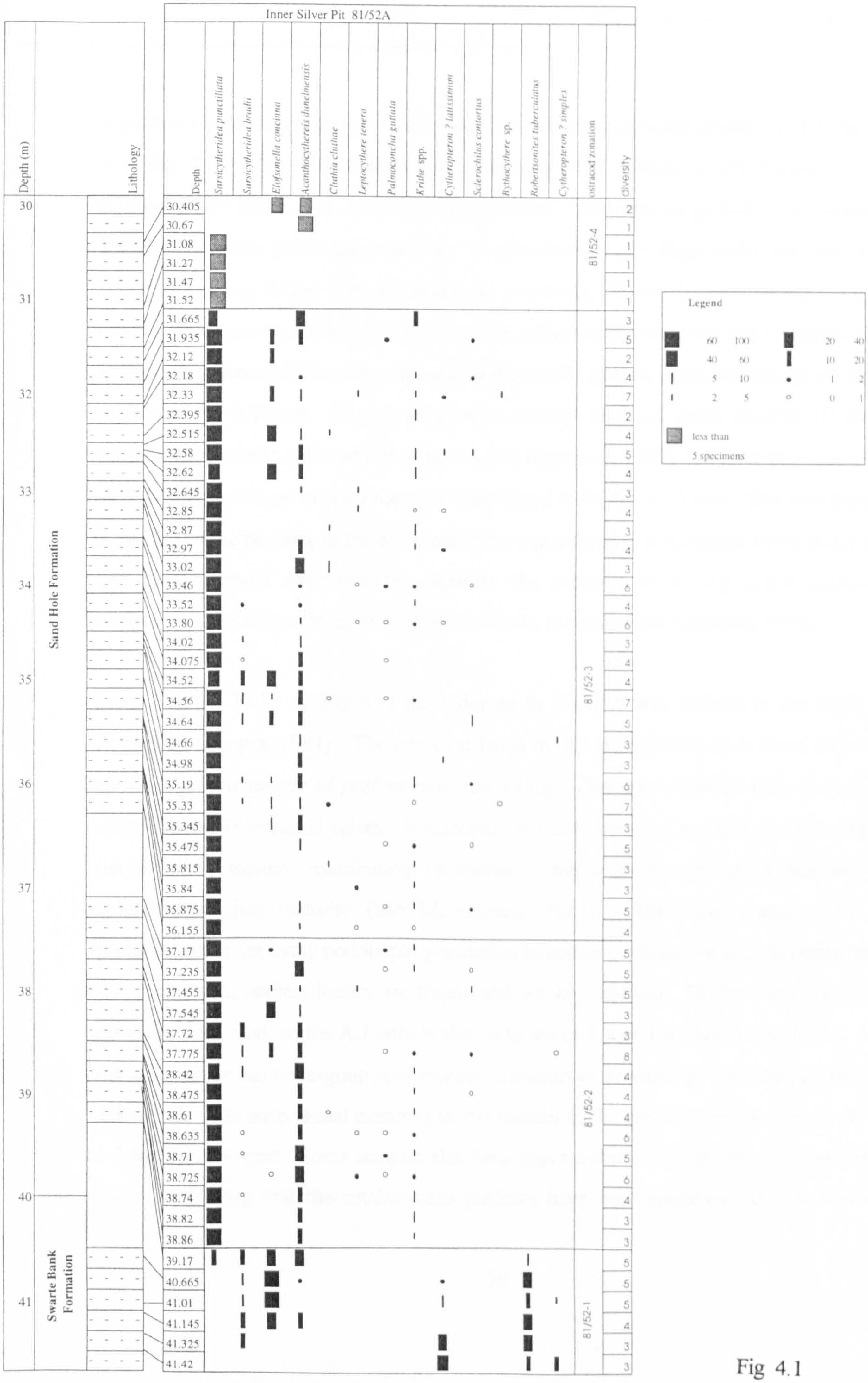
4.1 Palaeoecology

The Sand Hole Formation yielded a low diversity assemblage, in which four dominant species occurred in high frequencies (62 - 89% of the fauna) . The percentage data (Fig 4.1) represent the total counts of ostracods from all depths studied downcore (see Raw Data on disc appended to thesis). The assemblage of the main faunal elements (Table 2), *Sarsicytheridea punctillata*, *S. bradii*, *Acanthocythereis dunelmensis*, *Elofsonella concinna* and, at the base of the core, *Robersonites tuberculatus*, were considered representative of live ostracod communities since both adults and many juvenile valves were present (Whatley, 1983 a,b).

The basal sediment examined was diamicton from the Swarte Bank Formation and, at the top of the section from 41.43 - 39.15 m, this graded into silty clay at the base of the Sand Hole Formation (Fig 4.1). This zone (81/52-1) contained a cold Arctic, glacio-marine fauna with adult:juvenile (A:J) ratios of 1:5. These ratios would only be expected in an assemblage that had been deposited *in situ* (Whatley, 1983a, b; Brouwers, 1988). The main faunal elements were *E. concinna*, *R. tuberculatus* and in two samples, *A. dunelmensis* and *S. bradii*. Apart from *A. dunelmensis* these are all infaunal species,

SPECIES	DISTRIBUTION	ENVIRONMENT	DEPTH (M)	STRAT.
Sarsicytheridea punctillata (Brady, 1865)	Scandinavia, North Atlantic, Canadian Arctic, Northern Britain	sublittoral, silty substrate, boreal	10 - 100	PHM
Sarsicytheridea bradii (Norman, 1865)	Circum-Arctic, Scandinavia, Northern Britain	sublittoral, silty, boreal-arctic	10 - 100	PHM
Acanthocythereis dunelmensis (Norman, 1865)	North Britain, Norway, Greenland	sublittoral, silty, boreal	50 - 100	PHM
Elofsonella concinna (Jones, 1857)	North Britain, Norway, Iceland, N.W. Atlantic, North East America	sublittoral, silty, boreal	2 - 250	PHM
Robertsonites tuberculatus (Sars, 1866)	Arctic, Scandinavia	sublittoral, silty, arctic, boreal	<75	PHM
Cytheropteron latissimum (Norman, 1865)	50° - 70°N, North West Europe	sublittoral, silty, arctic, boreal	5 - 80	PHM
Cytheropteron simplex Whatley and Masson, 1979	(northern North Sea)	sublittoral, cold (arctic?)	<100	P
Cluthia cluthae (Brady, Crosskey and Robertson, 1874)	North Atlantic, Arctic	littoral, silty, boreal - arctic	50 - 190	PM
Palmoconcha guttata (Norman, 1865)	North Britain, Scandinavia, N.W. Atlantic	littoral, silty, occasionally on algae	0 - 90	PHM
Sclerochilus contortus (Norman, 1861)	Britain	sublittoral, silty, temperate	10 - 100	PHM

Table 2. Environmental preferences of the main faunal elements (Elofson (1941); Neale and Howe (1975); Rosenfeld (1977); Whatley and Masson (1979); Athersuch *et al.* (1989)) P: Pleistocene; H: Holocene; M: Modern.


Inner Silver Pit 81/52A
Depth (m)
Lithology
Depth
Sarsicytheridea punctillata
Sarsicytheridea bradii
Elofsonella concinna
Acanthocythereis dunelmensis
Cluthia cluthae
Leptocythere tenera
Palmoconcha guttata
Krithe spp.
Cytheropteron ? latissimum
Sclerochilus contortus
Bythocythere sp.
Robertsonites tuberculatus
Cytheropteron ? simplex
ostracod zonation
diversity
30
31
32
33
34
35
36
37
38
39
40
41
Sand Hole Formation
Swarte Bank Formation
30.405
30.67
31.08
31.27
31.47
31.52
31.665
31.935
32.12
32.18
32.33
32.395
32.515
32.58
32.62
32.645
32.85
32.87
32.97
33.02
33.46
33.52
33.80
34.02
34.075
34.52
34.56
34.64
34.66
34.98
35.19
35.33
35.345
35.475
35.815
35.84
35.875
36.155
37.17
37.235
37.455
37.545
37.72
37.775
38.42
38.475
38.61
38.635
38.71
38.725
38.74
38.82
38.86
39.17
40.665
41.01
41.145
41.325
41.42
81/52-4
81/52-3
81/52-2
81/52-1
2
1
1
1
1
1
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5
6
4
3
3
5
5
5
4
3
3
Legend
60 100
40 60
5 10
2 5
20 40
10 20
1 2
0 1
less than 5 specimens

Fig 4.1

characteristic of fine sandy mud substrates, and occurring at water depths from 40 to 130 m (Table 2; Penney, 1993; Majoran and Agrenius, 1995). Majoran and Agrenius (1995) cultured a live fauna of *S. bradii*, *R. tuberculatus*, *Palmoconcha guttata*, *Cytheropteron latissimum*, *Krithe praetexta praetexta*, *A. dunelmensis* and *Elofsonella concinna* in an aquarium. They found that *K. praetexta praetexta*, *Sarsicytheridea bradii* and *R. tuberculatus* were commonly found below the surface of the sediment and to depths of up to 20 mm, whereas *A. dunelmensis* and *Palmoconcha guttata* predominantly lived on the surface of the sediment. Oxygen penetration through sediment rarely exceeds 10 mm in sandy shallow water sediments (Rasmussen and Jörgensen, 1992); however representatives of *S. bradii* and *K. praetexta praetexta* were found at depths > 10 mm. This was thought to be due to the porosity of the sediment in the aquarium (i.e. it contained more water than that in the natural environment) and/or to the presence of a very active burrowing macrofauna, mainly made up of polychaete worms (Majoran and Agrenius, 1995).

From 38.88 - 37.15 m (Fig 4.1) the sediment in the core was defined as the Sand Hole Formation (Tappin, 1991). The ostracod fauna in this zone (81/52-2) is more diverse but shows a greater degree of *post mortem* reworking. This was identified from the ratios of adult to juvenile ostracod valves. Podocopid ostracods moult up to eight times during their development, thereby contributing 18 valves to the sediment through a lifetime if the individual reaches maturity (van Morkhoven, 1962). Therefore, complete or ideal preservation of the living podocopid population structure produces an adult:juvenile ratio of 1:8. However, earliest instars are fragile and weakly calcified. Under natural conditions these are destroyed, so the A:J ratio is altered to about 1:5 or 1:6 (Brouwers, 1988). When the assemblage has undergone *post mortem* transport or reworking, then the A:J ratios are 1:3 or 1:2. The main faunal elements in this section of the core are represented in the ratio 1:2 for the most part. Some samples also have high numbers of adult valves and no juvenile valves, indicating that the smaller-sized particles have been winnowed out or destroyed.

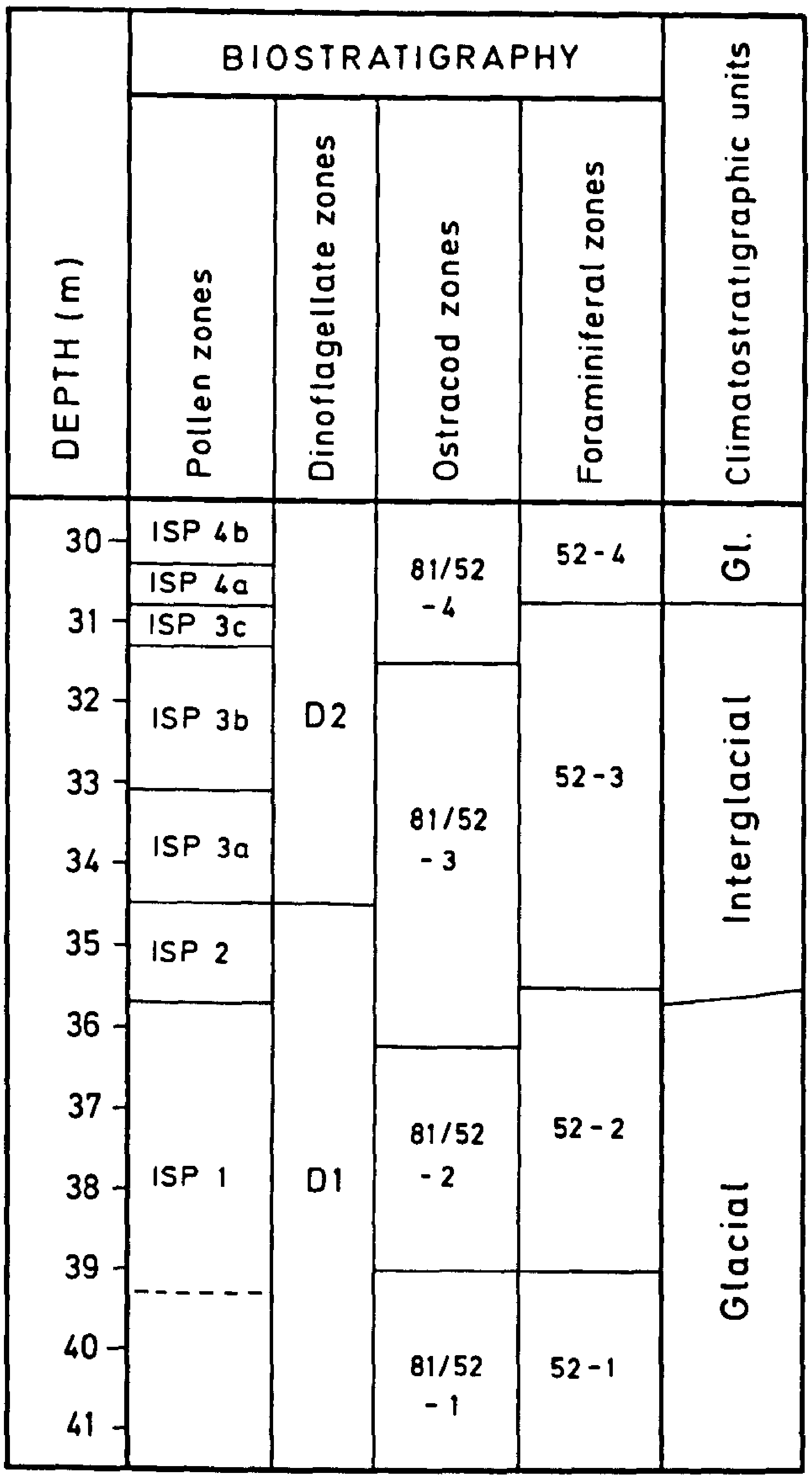


Fig 4.2 Zonation summary diagram (Knudsen, pers. comm.) (Summary of Ansari (1992) Harland in Scourse *et al.* (in press), Kristensen *et al.* (in press) and Ingram (in press)).

Kristensen *et al.* (in press) found that the foraminiferal fauna indicated redeposition, since both temperate and arctic species were present at the same levels. Between 37.15 and 36.20 m the core was not recovered.

In the interval 36.20 - 31.50 m the ostracod fauna was at its most diverse (Fig 4.1), all species found indicating a cool, marine, sublittoral (10 - 75 m) environment. The samples in zone 81/52-3 appeared to have undergone little or no *post mortem* reworking since all the ostracod valves and assemblages were well preserved. All species identified are extant around the coasts of northern Britain and Scandinavia. At the present day these species normally inhabit silty substrates, similar to the sediment making up the Sand Hole Formation. The fauna is dominated by *A. dunelmensis, S. punctillata* and *E. concinna*, but the presence of *Krithe* spp., *Cluthia cluthae* and *Cytheropteron* spp., indicate deeper, stenohaline conditions. The cumulative evidence of the individual species (Table 2) builds a clear picture of conditions that must have prevailed at the time of deposition. All ostracod genera recorded in the pollen- and foram-based interglacial section of the Sand Hole Formation have a preference for water of normal marine salinity of between 10 and 75 m depth, but of Arctic or cold-temperate affinity; temperate and warm temperate species are absent. The assemblage represents a boreal fauna, with none of the warmer water elements commonly found in similar sites around the southern North Sea, such as Hamburg (Lord *et al.*, 1993) and in the Nar Valley (Lord and Robinson, 1978; Mitlehner, 1992), which is unusual for an interglacial sequence in the southern North Sea area (Meijer and Preece, 1995).

Between 31.49 and 29.75 m, the fauna was at its lowest abundance and diversity. *S. bradii* and *A. dunelmensis* dominate the assemblage, with occasional valves of *E. concinna* in this zone (81/52-4) (Fig 4.1). The reduction in diversity upcore could either be attributed to a change in water depth (perhaps a negative sea level tendency (Fig 4.12)), altering the temperature and salinity characteristics of the water column, the latter two perhaps affecting ostracod food sources; to *post mortem* destruction of the ostracods; or to non-preservation of ostracods in the sediment at that time due to increased current activity. The few valves of species found in this interval (Fig 4.1) have cooler preferences (Table 2), although at similar water depths, to the more diverse fauna found in zone 81/52-3.

As can be seen from the zonation summary diagram (Fig 4.2) the ostracod biostratigraphy closely resembles that of the foraminifera (Kristensen *et al.*, in press), although there appears to be a lag time between the reaction of the ostracods to changing water mass properties and that of the foraminifera.

4.2 Trace element analyses

The palaeoecological information obtained from the faunal analysis only gives an indication of the possible ambient environment at the time of deposition of the Sand Hole Formation. In testing the second hypothesis in this study a number of trace element analyses on the ostracod valves were undertaken in order to determine independently the temperature and salinity characteristics of the water column at the time of deposition.

4.2.1 Taxonomy

Species identifications were based on examination of valve morphology, with reference to the literature. Summary information regarding the systematics, identifying characters and general ecology of the three species used for trace element and stable isotope analyses are detailed below.

Sarsicytheridea punctillata (Brady, 1865)

Plate 1, figs 1-8

1865 *Cytheridea punctillata* sp. nov. Brady, 189, pl.9, figs 9-11 (= juvenile)

1866 *Cyprideis proxima* sp. nov. Sars, 54

·1961 *Eucytheridea punctillata* (Brady); van den Bold, 294, pl.9, figs 1-9; text figs,14-20

1982 *Sarsicytheridea punctillata* (Brady); Athersuch, 241, pl. 6, figs 7-11; pl. 7, figs 1, 3, 5; fig 8f

Characters: elongate carapace, pitted with samll, shallow fossae, particularly incentral area. Greatest height front of mid length.

Average length: male: 850μm ; female: 800μm

Remarks: genus was erected by Athersuch (1982) and has the same taxonomic content as *Cytheridea sensu* Sars (*non* Bosquet) and *Eucytheridea auct.*; the reasons for the nomenclatural change are explained in Athersuch (1982).

Ecology: marine, sublittoral, depths 10-100 m on sand and silt substrates around the northern coasts of Britain, Scandinavia, including the Baltic, and at those depths around the North Atlantic.

Sarsicytheridea bradii (Norman, 1865)

Plate 1, fig 14

1865a *Cythere bradii* sp. nov. Norman, 192.

1865b *Cythere debilis* (Jones); Norman, 15, pl.5, figs 5-8 (*non Cytheridea debilis* Jones, 1857).

1866 *Cyprideis bairdii* sp. nov. Sars, 52.

1866 *Cytheridea papillosa* Bosquet; Brady, 370, pl.58, figs 8a-g.

1925 *Cytheridea papillosa* Bosquet; Sars, 159, pl.73; pl.74, fig 1.
1960 *Eucytheridea bairdii* (Sars); Kollman, 130, pl.2, figs 4a-c.
1961 *Eucytheridea bradii* (Norman); van den Bold, 288, pl.8 figs 1-15.
1982 *Sarsicytheridea bradii* (Norman); Athersuch, 241, pl.7, figs 2, 4; pl.8, figs 1-14; figs 7a, 8c-e.

Characters: elongate, smooth carapace except for normal pores. Dorsal and ventral margins almost parallel.

Average length: male: 975 µm; female: 900 µm

Remarks: (as *Sarsicytheridea punctillata*)

Ecology: (as *Sarsicytheridea punctillata*), also found around Spitsbergen, Greenland and Iceland.

Cyprideis torosa (Jones, 1850)

Plate 2, figs 1-4

1850 *Candona torosa* sp. nov. Jones, 27, pl.3, figs 6a-e.
1857 *Cyprideis torosa* (Jones); Jones, 21, pl.2, figs 1a-i, woodcut fig 2.
1868 *Cytheridea littoralis* nom. nov. (*sic*) Brady, 125.
1870 *Cytheridea torosa* (Jones) var. *teres* var. nov, Brady and Robertson, 22.
1909 *Cytheridea pedaschenkoi* sp. nov. von Daday, 24, pl.1, fig 7-21, text fig 8a-f,9
1974 *Cyprideis torosa* (Jones); Kilenyi and Whittaker, 21-32.

Characters: female subovate, inflated posteriorly. Male carapace elongate and not inflated. Valves pitted or smooth, sometimes nodose with up to seven sites of tubercular development on each valve. Weak dorso-median sulcus. Posteroventral spine on right valve.

Average length: male: 900 μm ; female: 825 μm

Remarks: A comprehensive review is given by Sandberg (1964). Noding in *Cyprideis torosa* is discussed further in Chapter 5.

Ecology: found in a wide range of salinities from almost freshwater to over 60‰ in inland ponds, lakes, lagoons, estuaries, fjords, deltas and other marginal marine environments. Found to a depth of around 30 m, seems to prefer mud or sandy-mud substrate, sometimes found on algae. Widespread throughout Europe, West and Central Asia, Mediterranean, and as far north as Iceland, also in lakes in Central Africa.

4.2.2 Shell preservation

Modern *Sarsicytheridea* from bottom sediment samples and core tops from Arctic, Atlantic and European shelf seas (Fig 4.3) display a wide range of 'Visual Preservation Index' (VPI) preservation states. However, no apparent correlation exists between Mg:Ca ratios and the VPI (Fig 4.4). The down-core *Sarsicytheridea* (Fig 4.5) also show similar random variation of Mg:Ca ratio to VPI.

4.2.3 Modern Mg:Ca ratios

Fig 4.6 shows Mg:Ca molar ratios for all modern specimens plotted against water depth, bottom water temperature and salinity. There does not appear to be any correlation between the Mg:Ca ratio and salinity or water depth. Mg:Ca ratios of the shells show a wide range of variability, but with a general trend towards increasing Mg:Ca ratio with increasing bottom water temperature. This establishes a direct relationship between the Mg-content of the individual ostracod valves and the temperature of the water in which the *Sarsicytheridea* lived. A calibration equation (1) can be derived from a regression line (Fig

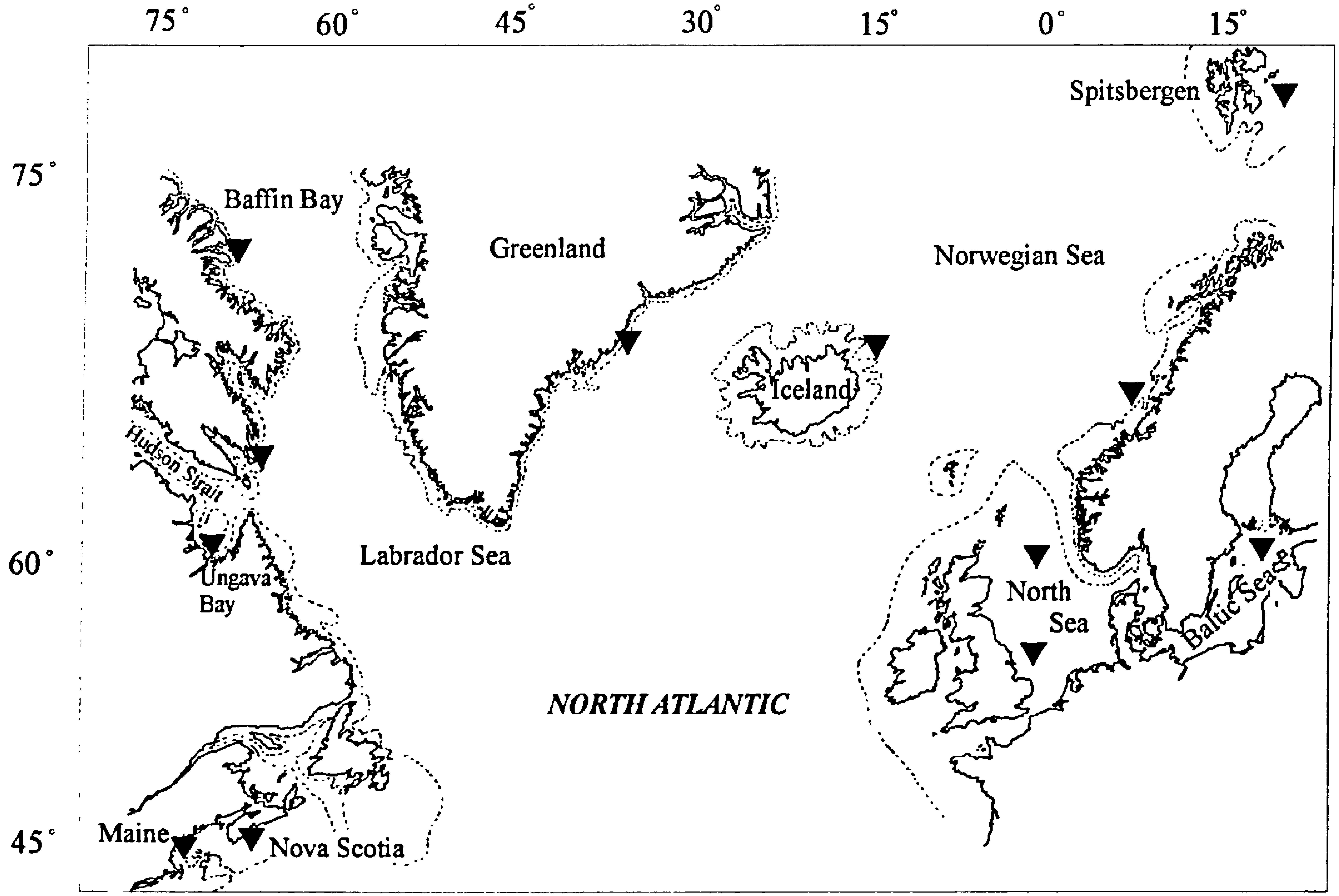
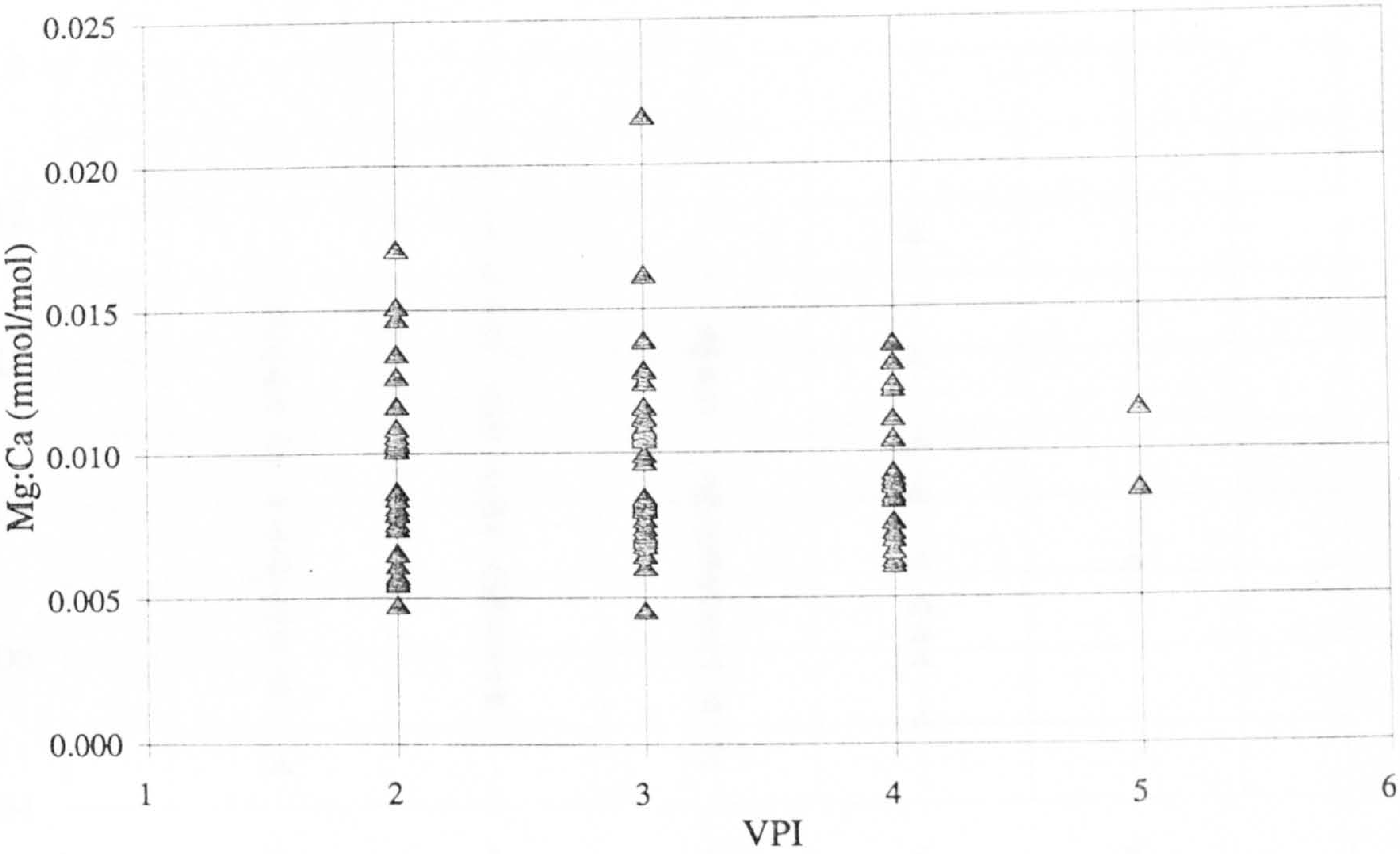


Fig 4.3 Sites from which modern *Sarsicytheridea* were obtained around the North Atlantic.



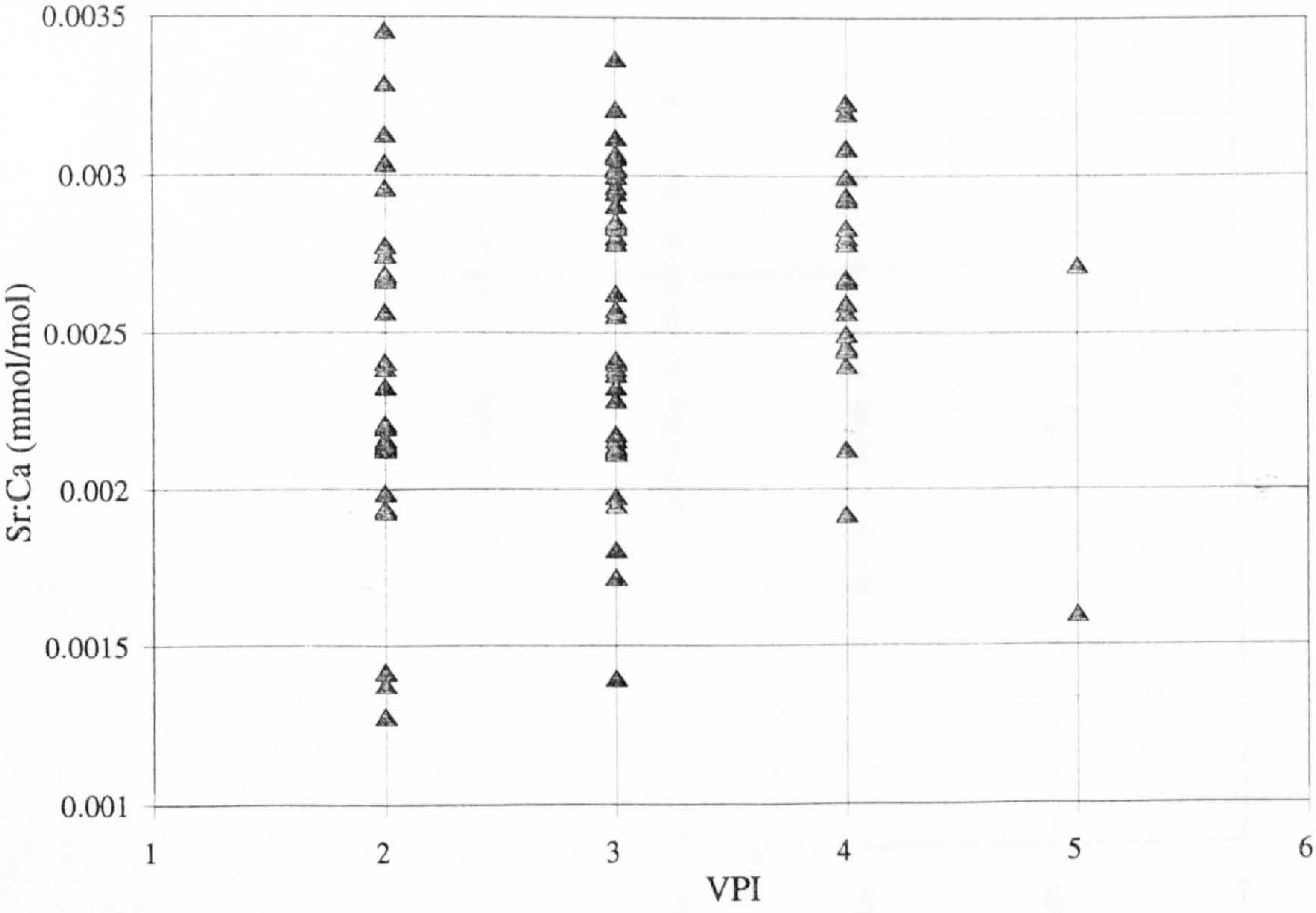
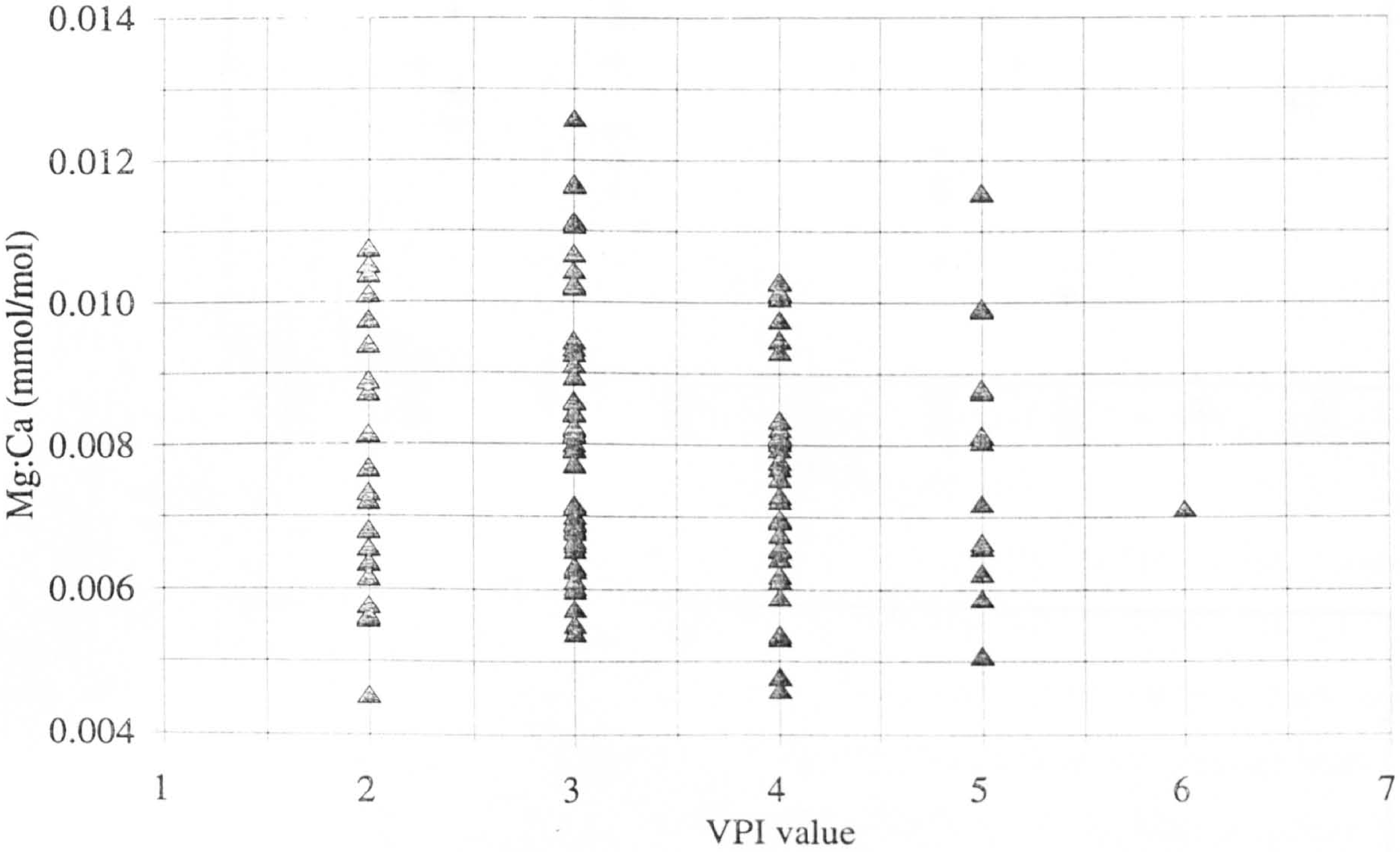


Fig 4.4 a. Plot of visual preservation index against Mg:Ca ratios for modern *Sarsicytheridea* shells; b. Plot of visual preservation index against Sr:Ca ratios for modern *Sarsicytheridea* shells.



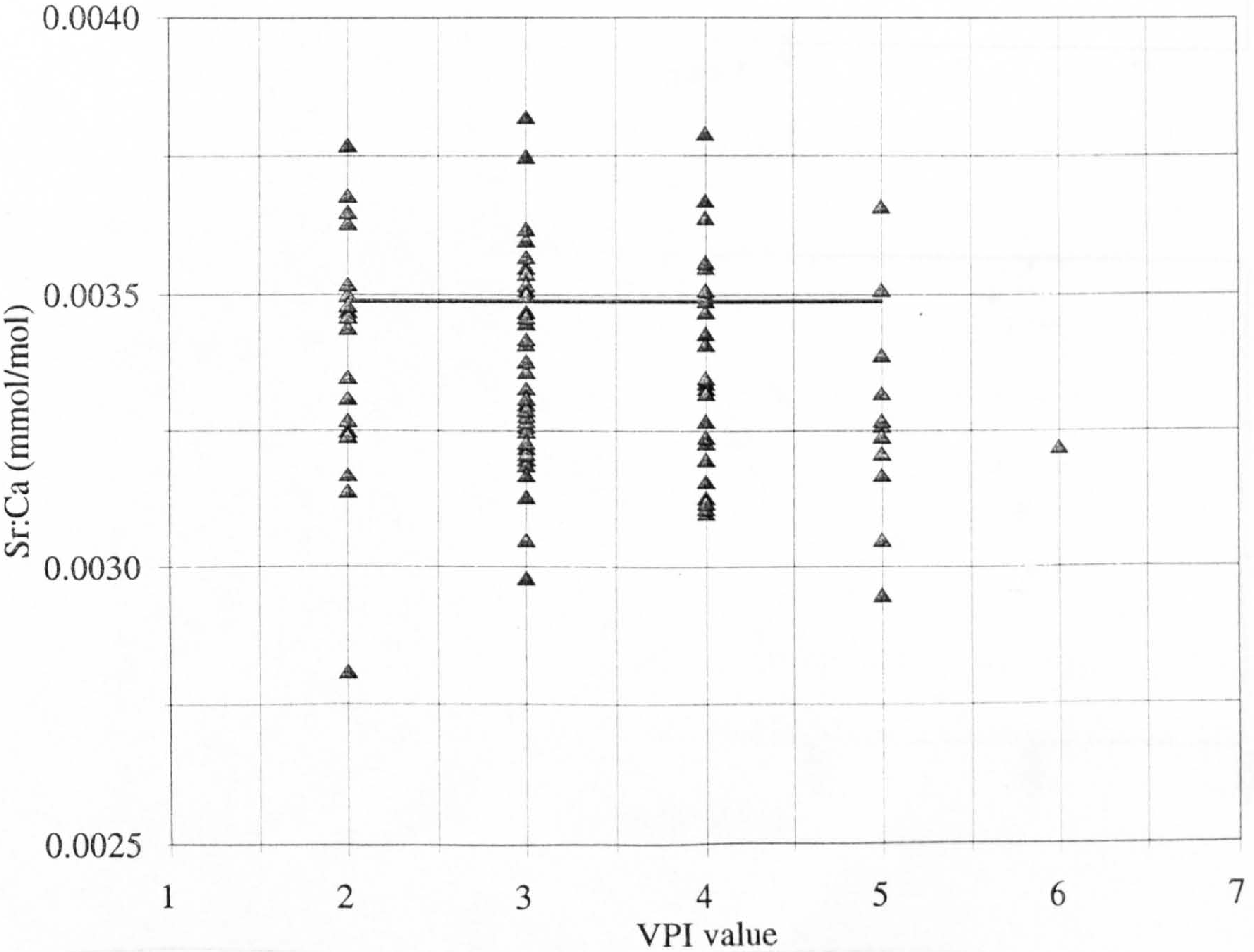


Fig 4.5 a. Plot of visual preservation index against Mg:Ca for down-core *Sarsicytheridea* from BH81/52A; b. Plot of visual preservation index against Sr:Ca for down-core *Sarsicytheridea* from BH81/52A.

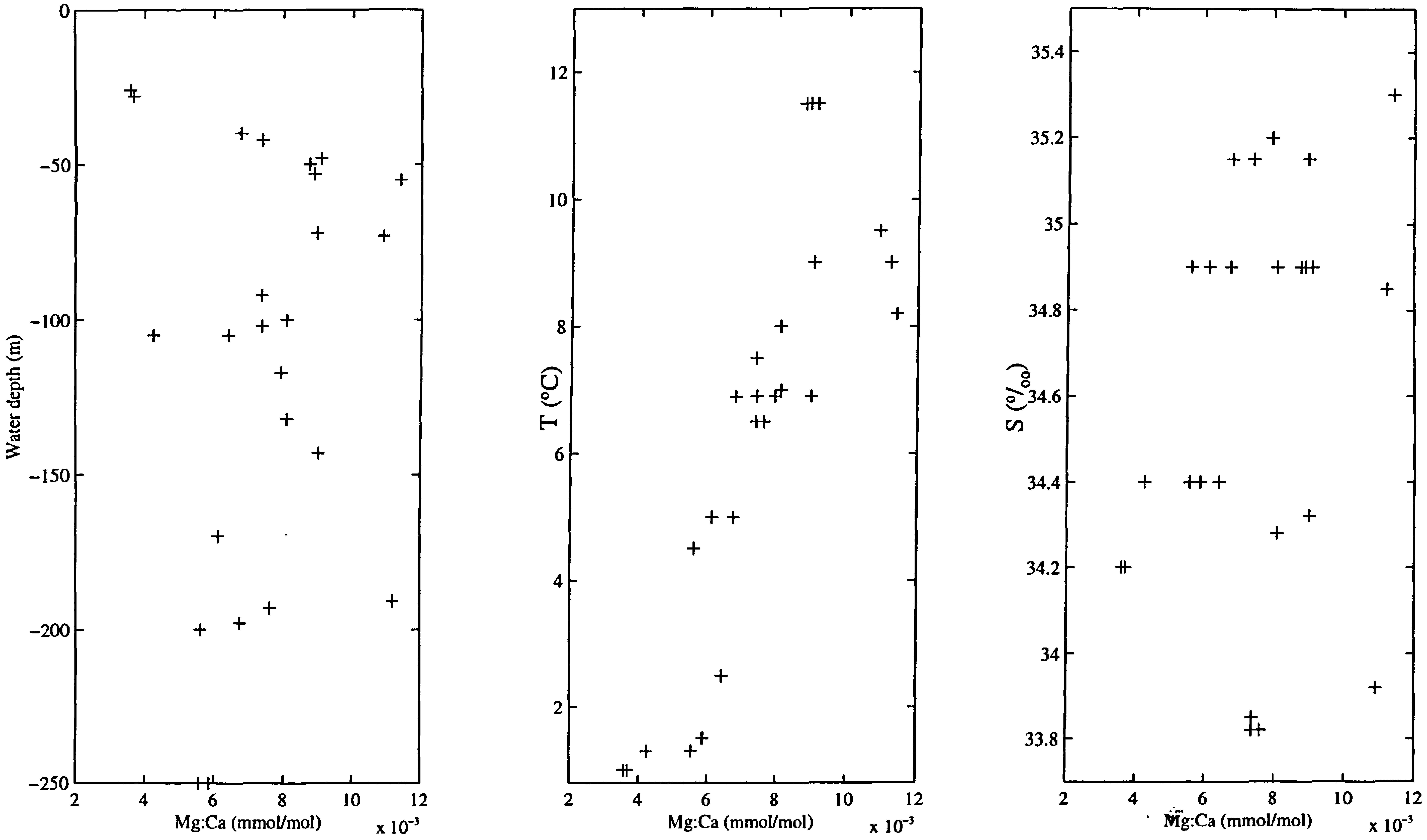


Fig 4.6 Plots of Mg:Ca ratios in modern *Sarsicytheridea* against water depth, temperature and salinity (temperature and salinity information from unpublished cruise data).

4.7) based on analysis of the whole data set of mean values for each sample (three to eight valves analysed from each sample).

(1) $$T = 1325\,(Mg{:}Ca) - 3.6$$

The regression line (Fig 4.7) showed a positive correlation ($r^2 = 0.704$) between bottom water temperature and Mg:Ca over the temperature range 1°- 11.5°C. There are several possible explanations for the scatter. The simplest explanation is that bottom water temperature varies seasonally, and that sampled valves did not secrete their adult shells at the same time of year as the bottom water temperature measurements were taken. No valves used in these analyses had preserved soft parts, and the temperature estimates were obtained not only from on-board ship during collection, but also from published literature. These data therefore constitute only a preliminary calibration and would benefit by supplementation with further analyses of modern *Sarsicytheridea*. Varying chemical parameters at the sediment-water interface may also account for some of the variability (Holmes, 1996). Ideally the values should be supported by laboratory culture experiments, nonetheless the data for these specimens are the first for the genus *Sarsicytheridea* and fall within the range of values quoted for other genera (Chivas *et al.*, 1986a; Engstrom and Nelson, 1991; Holmes *et al.*, 1995; Cronin, pers. comm.).

In order to refine the temperature signal obtained from the Mg data, a double regression using a function of the effect of temperature and salinity on the Mg-content of the form:

(2) $$Mg = \alpha T^{\beta} S^{\gamma}$$

can be performed (Fig 4.8). This type of regression uses both Mg and Sr data and elucidates their respective inputs to the shell chemistry signal of bottom water temperature.

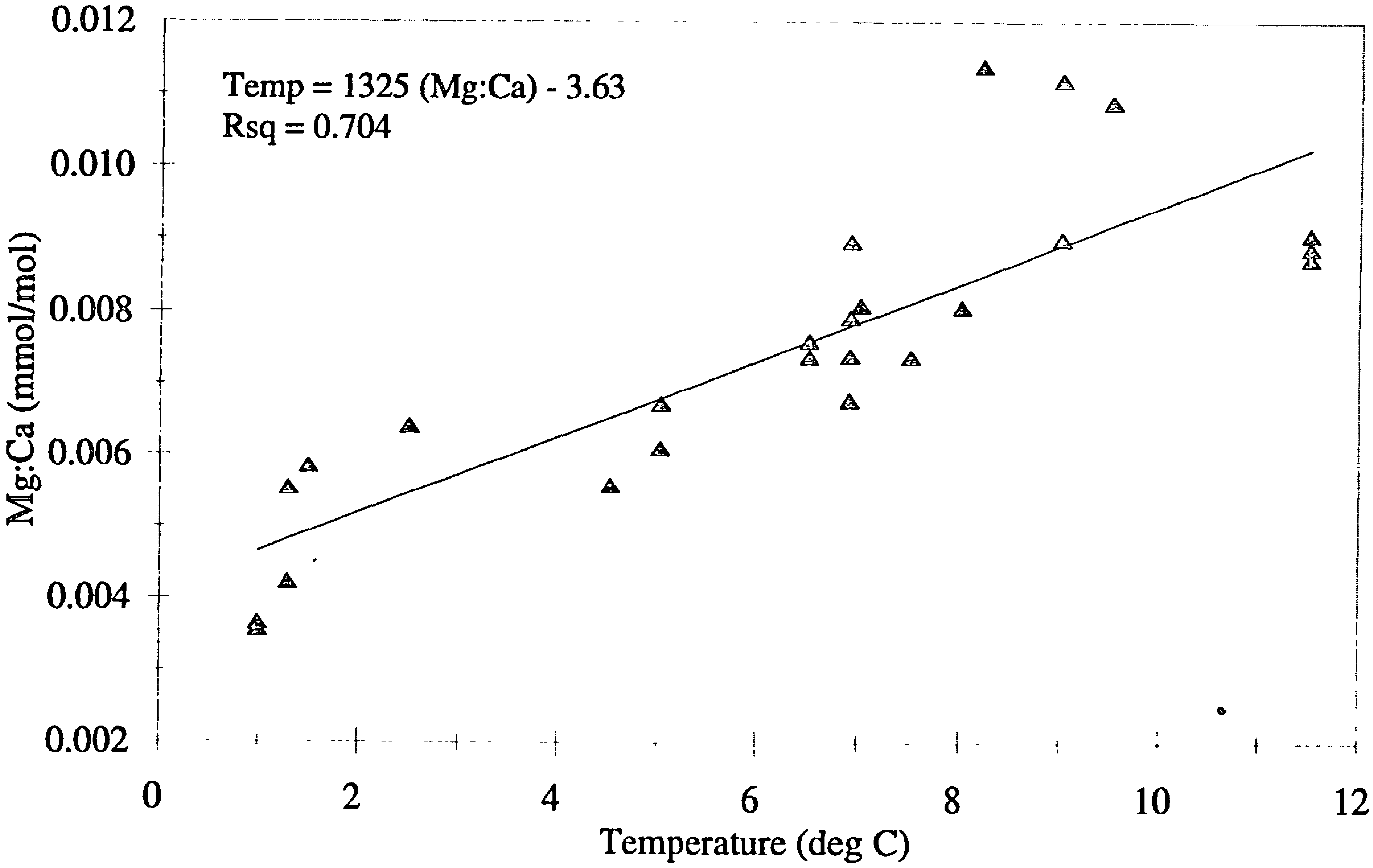


Fig 4.7 Plot of Mg:Ca ratio in modern *Sarsicytheridea* against bottom water temperature.

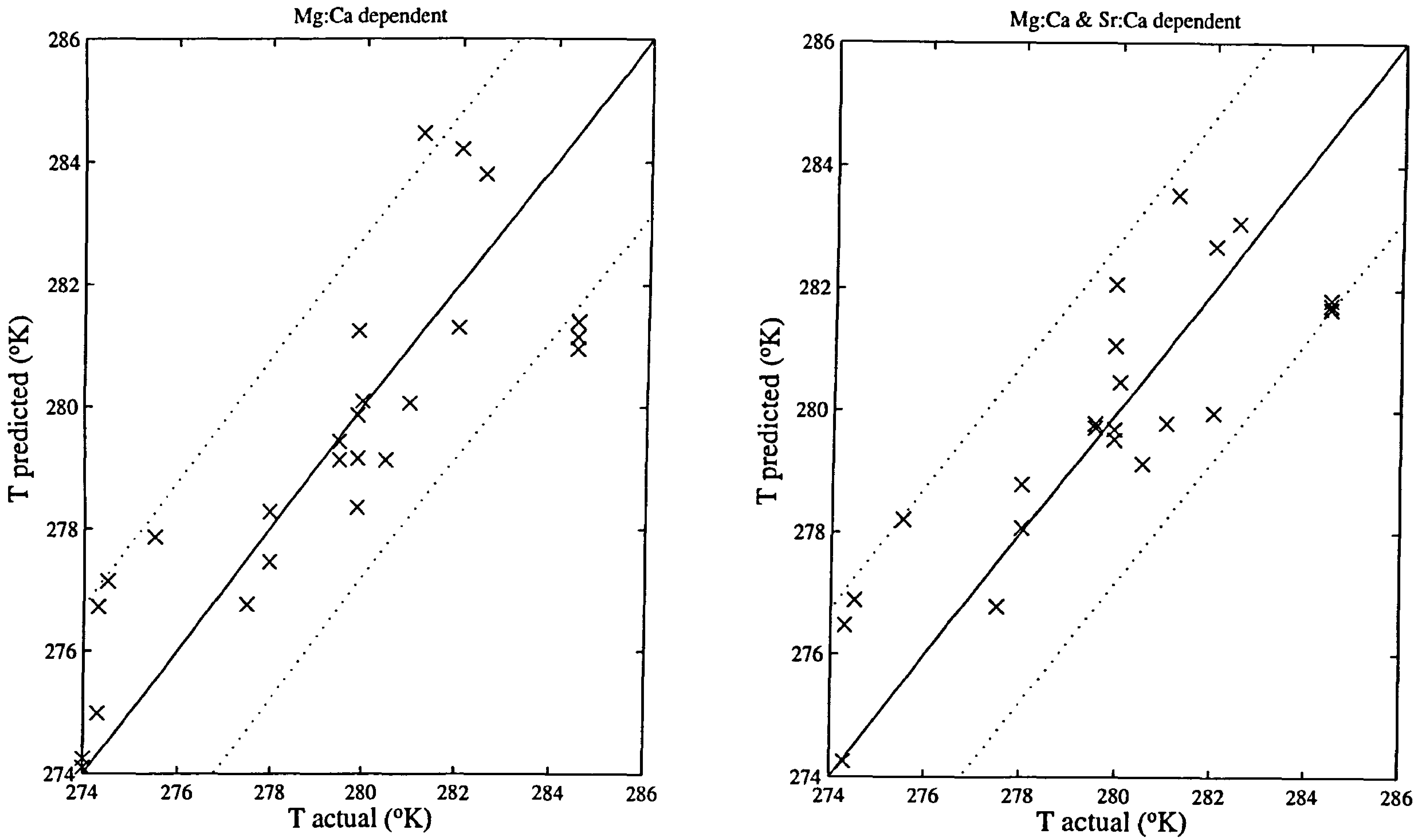


Fig 4.8 a. Plot of the regression line using just the effect of concentration of Mg on the Mg:Ca ratio; b. Plot of the result of a double regression using Equation (2) for the dependence of the Mg:Ca ratio on both Mg and Sr concentration in the water.

The results of this regression on the function above are:

$\beta = 0.345$

$\gamma = 0.0374$

illustrating an order of magnitude difference between the effects of temperature and salinity of the Mg:Ca ratio of *Sarsicytheridea* shells.

However, in spite of the scatter, these data do support the hypothesis, developed in the Pacific (Corrège, 1993) and Atlantic (Dwyer *et al.*, 1995; Cronin *et al.*, 1996) deep sea, that water temperature is the major factor in determining the concentration of Mg in the calcite of marine ostracod shells.

4.2.4 Modern Sr:Ca ratios

The ratio of strontium to calcium in the shells of ostracods has been related to the Sr:Ca content of the water, or salinity (Chivas *et al.*, 1983). Fig 4.9 plots Sr:Ca ratio values from modern *Sarsicytheridea* from the same valves as those used for the Mg:Ca data, against water depth, bottom water temperature and salinity. There is no obvious relationship between Sr:Ca and either temperature or salinity, which is supported (Fig 4.10) when Mg:Ca and Sr:Ca dependancy are assessed in another double regression on the data of the form:

$$\text{(3)} \qquad \mathrm{Sr} = \alpha \mathrm{T}^{\beta}\, \mathrm{S}^{\gamma}$$

where:

$\beta = 1.27$

$\gamma = 1.78;$

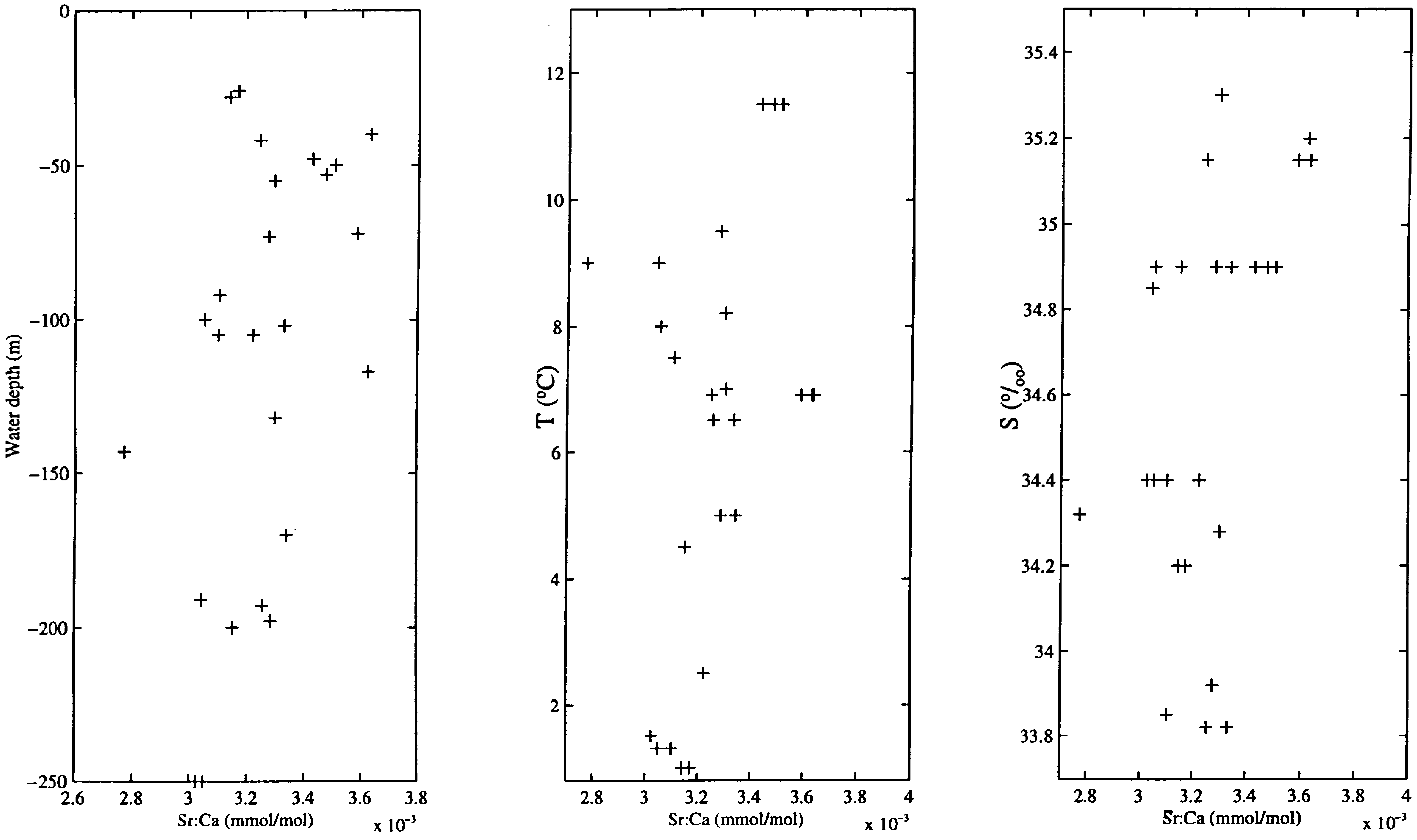


Fig 4.9 Plots of Sr:Ca ratios in modern *Sarsicytheridea* against water depth, temperature and salinity (temperature and salinity information from unpublished cruise data (as Fig 4.5)).

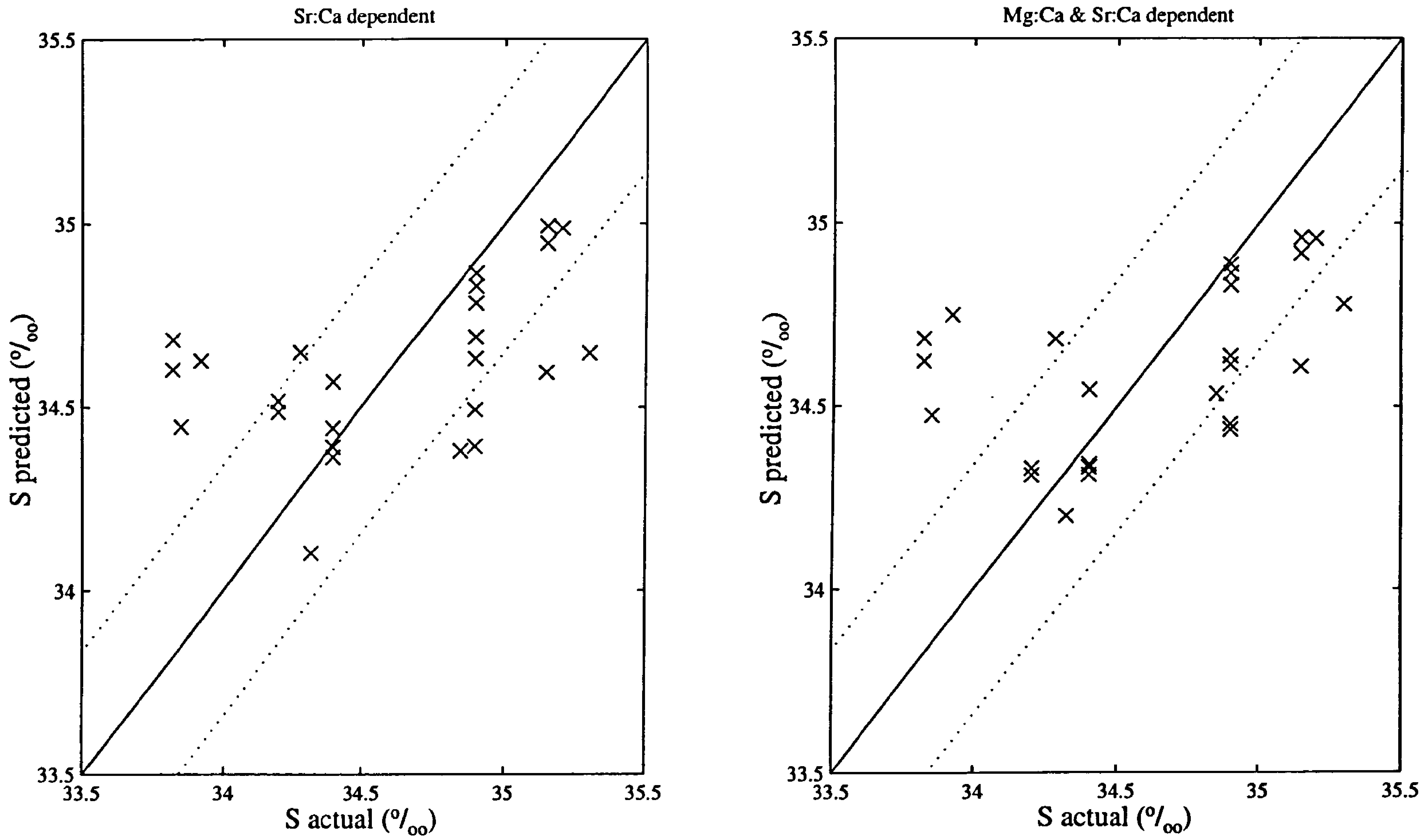


Fig 4.10 a. Plot of the regression line using just the effect of concentration of Sr on the Sr:Ca ratio; b. Plot of the result of a double regression using Equation (2) for the dependence of the Sr:Ca ratio on both Mg and Sr concentration in the water.

indicating that the Sr content of the ostracod valve is dependant on temperature and salinity, but in this case salinity is only marginally more important than temperature.

If salinity and temperature act on the Sr content of the modern *Sarsicytheridea* shells to a similar extent when considering a salinity signal, prediction of salinity from this data alone would be extremely difficult due to the effects of temperature. Strontium uptake into calcite is a poorly understood process (Engstrom *et al.*, 1993). It is therefore difficult to interpret these data further in the absence of supporting modern stable isotopic data.

4.2.5 Downcore Mg:Ca ratios

Fig 4.11 is a plot of Mg:Ca ratios downcore in BH81/52A. Each point in the plot represents the mean value of the analysis of two, three or four valves from each sample downcore. Some valves gave seemingly anomalous results (very high or low within the range of values for that sample) and were excluded from the statistical analysis of the data since these valves had been well preserved but broken at the outset of the analysis. These valves were included in the down-core analyses since in the modern material the Mg:Ca ratio was not altered for the damaged valves, indicating that breakage was due to mechanical means. They are plotted with closed circles (Fig 4.11). The trends observed in the data are discussed on the basis that these points are excluded.

The data show a wide range of variation which could result from a number of factors. The ostracods analysed showed a wide range of VPI values, but no consistent correlation between VPI and Mg:Ca ratios. Therefore, dissolution or diagenesis of the carbonate is unlikely to have caused the observed variation in Mg:Ca values. It is not known whether *Sarsicytheridea* moults and grows all year, or only at particular times of the year. In the shallow parts (<30 m) of the North Sea at the present day, bottom temperatures can vary

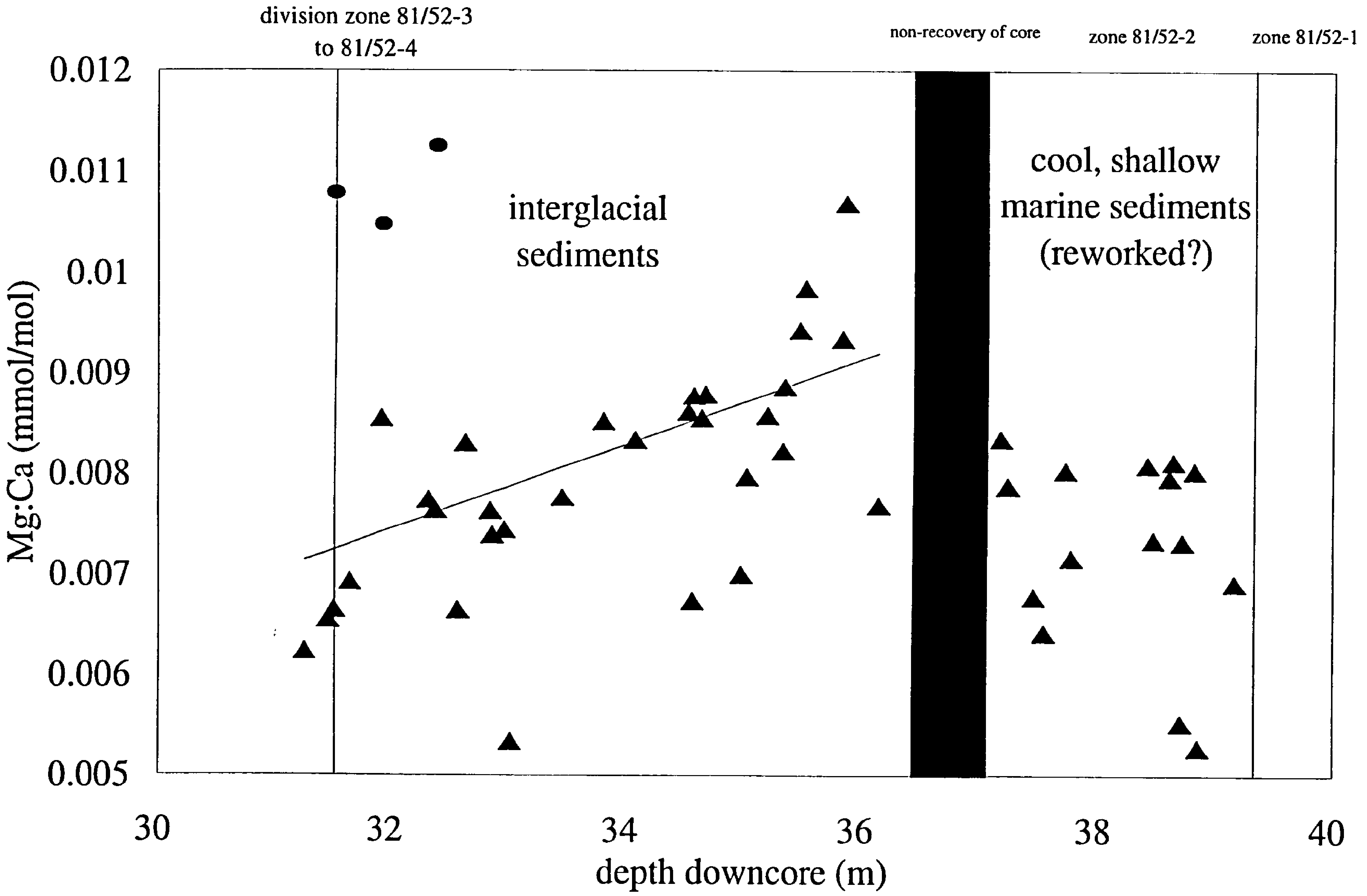


Fig 4.11 Plot of Mg:Ca ratio for down-core samples.(●, data points excluded from analysis; ▲, main body of data).

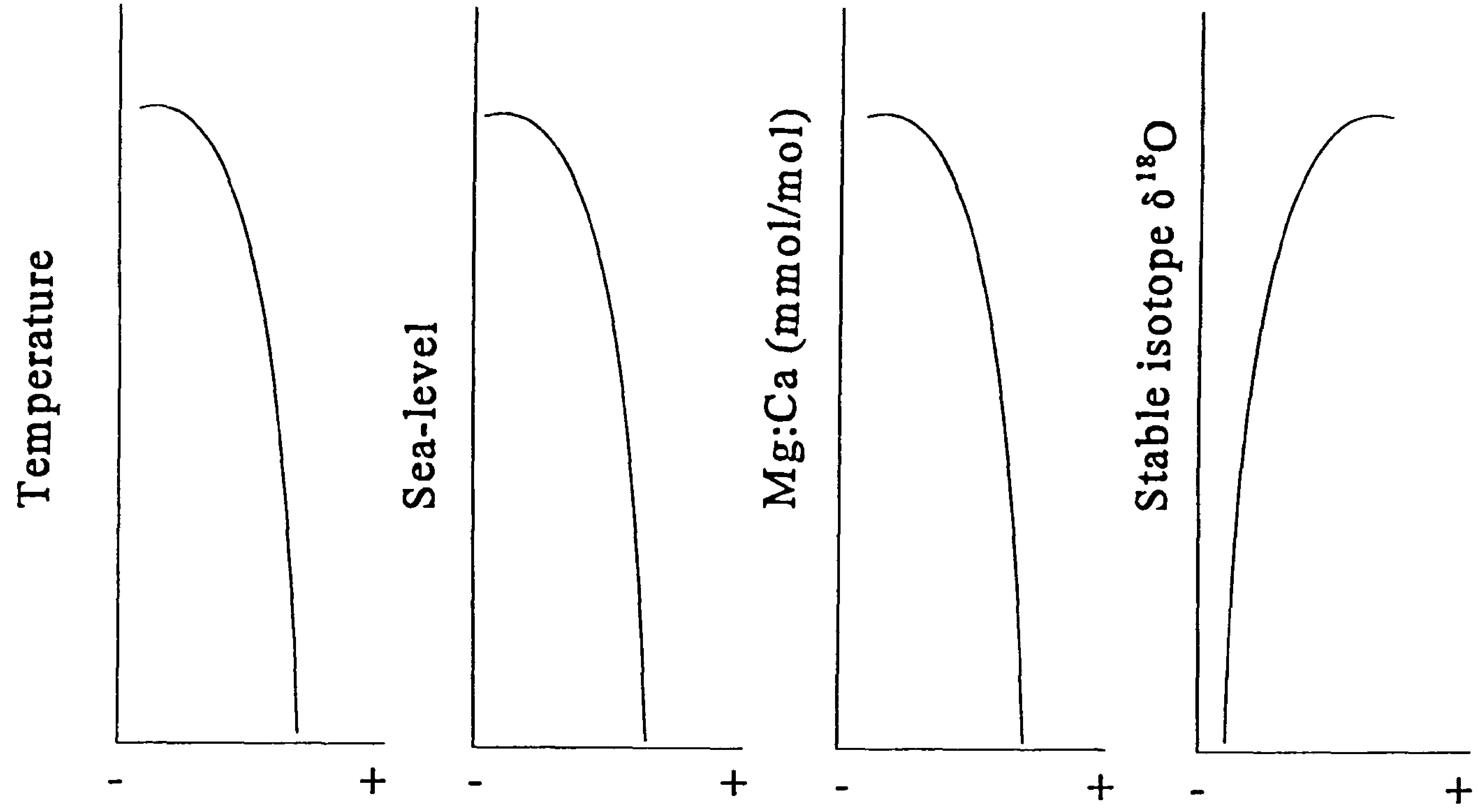
between 6 and 11°C seasonally, which would account for variation in the data, since the species can tolerate bottom water temperatures of between 1 and 12°C. The spread of temperatures within the 'interglacial' section (z.81/52-3) is between 4.5 and ~ 11°C. These data are similar to current ranges in bottom water temperatures. The spread of data in z.81/52-2 indicates temperatures ranging between 3 and 7°C, significantly lower than the zone above, but with no significant trend over the section. Another likely factor that could affect the data, creating a spread of values, may be that the sample resolution (10 - 20 cm) downcore was too low, so ostracods living in different temperature regimes may have been analysed in the same sample.

From the palaeoecological information disussed above (Ch. 4.1) and following a model hypothesis (Fig 4.12: relating temperature, sea-level, Mg:Ca and $\delta^{18}O$), an initial jump would be expected in Mg:Ca ratios from 41.43 m to 36.20 m, followed by a decrease in values of Mg:Ca towards the top of the core. It can be seen in Fig 4.11 that, first, the ostracods sampled from below the section of non - recovery of the core show a very confused signal, perhaps a further indication that these valves were reworked; and, second, that in the 'interglacial' sediment (36.20 - 31.50 m), the values of Mg:Ca steadily decrease towards the top of the core, indicating a decrease in temperature. This decrease is of the order of 7°C (from ~ 11.5°C to 4.5°C). In the section above 31.50 m only a few valves were analysed, and these were all present day boreal - Arctic species, which would be expected to show ratios around 0.006 mmol/mol (or 2-3°C, using the calibration Equation (1)).

4.3 Stable Isotopes

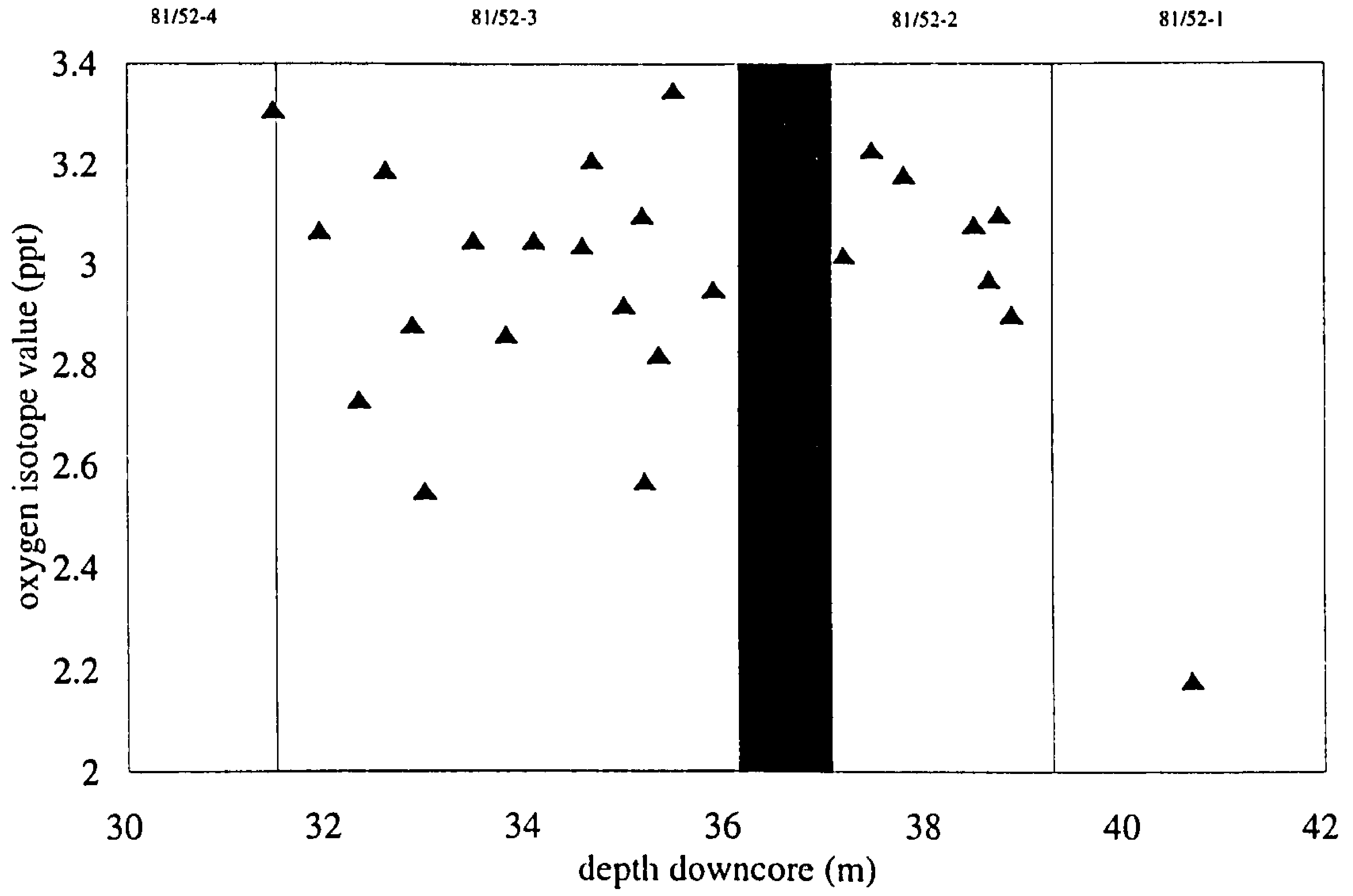
Stable isotope ($\delta^{18}O$, $\delta^{13}C$) data was obtained for twenty levels down-core concurrent with the trace element analyses.

Fig 4.12 Model diagram to show predicted changes in temperature (°C), sea-level, Mg:Ca (mmol/mol) and $\delta^{18}O$.



4.3.1 Oxygen isotope data

The oxygen isotope results (Fig 4.13 a) exhibit a range of values between +2.18‰ and +3.35‰ indicating that the Inner Silver Pit was fully marine during the entire time of deposition of the Sand Hole Formation, since, in general, more positive $\delta^{18}O$ values correlate with seawater phases (Anadon *et al.*, 1994), as well as generally indicating colder, deeper waters (Brasier, 1995). Using the relationship developed by Craig (1965) (description in Ch. 2.2.3) temperature estimates can be calculated: for the section from 31.47 - 35.875m the temperatures are in the range 3 - 6.5°C, equivalent to an average actual change of only 1‰ (with no correction for δw at time of formation of shell). A variation of 1‰ in stable isotope content of the water has the same effect on the $\delta^{18}O$ content of solid carbonate analysed as a variation in temperature of 4.2°C (see also Ch. 2.2.3). These estimates are lower than those calculated from the Mg:Ca data in the same section. This could be due to a number of factors including temperature or salinity differences in the water mass when the individual ostracods formed their valves. The ostracod valves used for the trace element analyses were not the same as those taken for the stable isotope analyses, although from the same levels down-core, since the technology to couple the analyses was not available. Heaton *et al.* (1995) found variability in both the carbon and oxygen isotope ratios in modern ostracods was quite small ($\delta^{18}O$ and $\delta^{13}C$ generally < 1‰). Within a single centimetre core sample, however, much greater variability was found in $\delta^{18}O$ and $\delta^{13}C$ of single valves (4‰ and 7‰ respectively). Heaton *et al.* (1995) suggested that this may reflect greater seasonality or, more likely, inter-annual variability in the temperature and isotopic composition of the water during the period over which the section of core was deposited (which could potentially be 100 or more years). Also since no modern stable isotope analyses were available it was impossible to take account of complicating factors caused by uncertainties in the isotopic composition of ancient seas and glacial-interglacial changes in shallow continental seas, which would affect the ratio of $^{18}O/^{16}O$ in the preserved



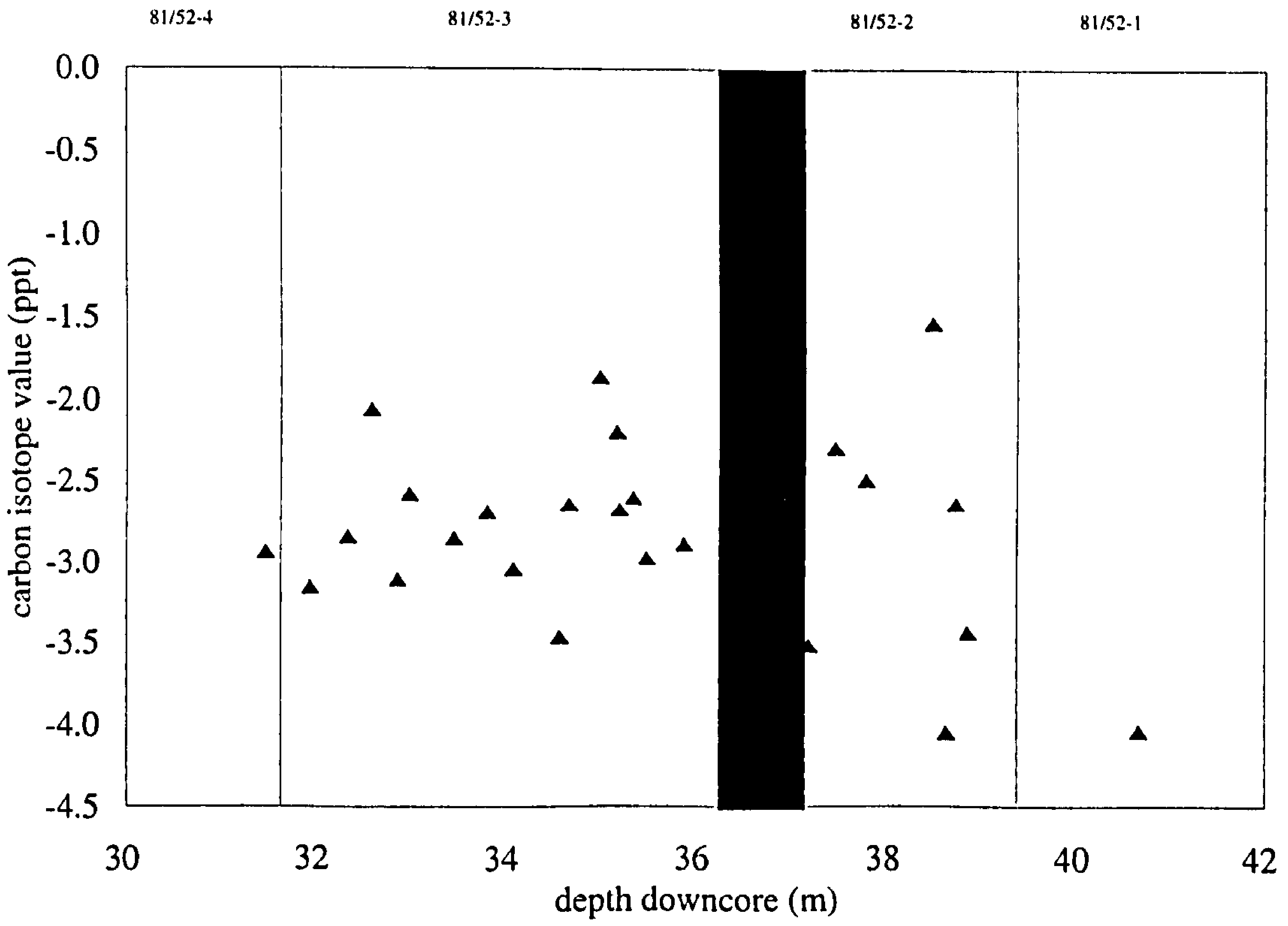


Fig 4.13a Oxygen isotopes for the Sand Hole Formation ($\delta^{18}O$, ‰); b Carbon isotopes for the Sand Hole Formation ($\delta^{13}C$, ‰).

carbonate. It is also clear from studies of modern shells (especially foraminifera and molluscs, Hudson, 1977; Lee and Anderson, 1991; Murray, 1991) that 'vital effects' can overprint the environmental signal, producing values that are much lighter than ambient seawater. These effects are little understood, but appear to involve the utilisation of metabolic carbon during secretion of the calcium carbonate shell.

The direction of response in Mg:Ca and $\delta^{18}O$ is different, since an increase in temperature increases Mg:Ca but decreases $\delta^{18}O$; an increase in salinity increases Mg:Ca, Sr:Ca and $\delta^{18}O$. There is a decrease in Mg:Ca over z. 81/52-3, but in the same section $\delta^{18}O$ stays relatively stable with no significant trend in the data. In a shallow shelf sea, during an interglacial, $\delta^{18}O$ levels are likely to be fairly constant (Shackleton, 1974; more recent review: Corfield, 1995), but significant temperature changes would be expected in shallow (< 30m) water depth. Due to warming of the surface layer the sea would become well stratified, with temperatures below the thermocline close to the annual mean (5-7°C). Highest values would be reached in the autumn when thermal stratification becomes less stable due to seasonal surface cooling (Lee, 1980). Minimum temperatures would be reached in late winter and early spring. $\delta^{18}O$ of single adult ostracod shells should provide a sample of the seasonal temperature cycle and will scatter according to the temperature extremes. In sediment samples, which would cover years, mean $\delta^{18}O_{carbonate}$ from multiple measurements of several shells should relate to an average of the annual water temperature, similar to results from a single mollusc, which accumulates shell carbonate throughout the year (von Grafenstein *et al.*, 1992).

The sample from the Swarte Bank Formation (40.665 m) indicates that the water was considerably less saline, although if calculation of temperature is made from this single data point then it indicates a temperature of around 8°C, a considerably higher temperature than that indicated by the faunal assemblage picked out of z.81/52-1. The change in conditions could be due to a number of factors, including a higher pore water than bottom water temperature (since the species analysed is infaunal in habit). However, differing values in the different zones agrees with the hypothesis that water mass characteristics changed over the time of deposition of the core (see also Harland in Scourse *et al.*, in press). There is no firm evidence for increased freshwater influence at the top of the core from the oxygen isotope data, which does not support the hypothesis of a regressive sea level tendency and reduced salinities at the time of deposition of the Sand Hole Formation.

4.3.2 Carbon isotope data

$\delta^{13}C$ is regarded as an indicator of productivity in the water column since organic matter preferentially accumulates ^{12}C. Fluctuations in $\delta^{13}C$ can therefore be used as a proxy measure for productivity changes. Values range (Fig 4.13b) from -4.05‰ to -1.52‰, which are quite negative in comparison to similar marine records (Austin and Scourse, 1997), indicating enhanced respiratory processes in the bacterial degradation of phytoplankton in the area of deposition of the Sand Hole Formation, perhaps due to the infaunal habitat of the ostracods sampled. Hence a pore-water rather than bottom-water signature may have been recorded. Stable isotope content of total dissolved inorganic carbon (TDIC) may be partially controlled by the type of chemical and isotopic system: open systems in which the whole chain of reactions and equilibria are controlled by the gaseous CO_2; closed systems in which the TDIC partially results from the dissolution of pre-existing carbonate (Fontes *et al.*, 1985), as may well be the case of pore water solutions from bottom mud, similar to those in which infaunal ostracods would exist.

No trend is observed between the oxygen isotope data and the carbon isotope data (Fig 4.14), indicating that the sediments were not lain down in a closed system, such as a lake (cf. Talbot, 1990). These results are compared to those from the Shoeburyness site in Ch.5.

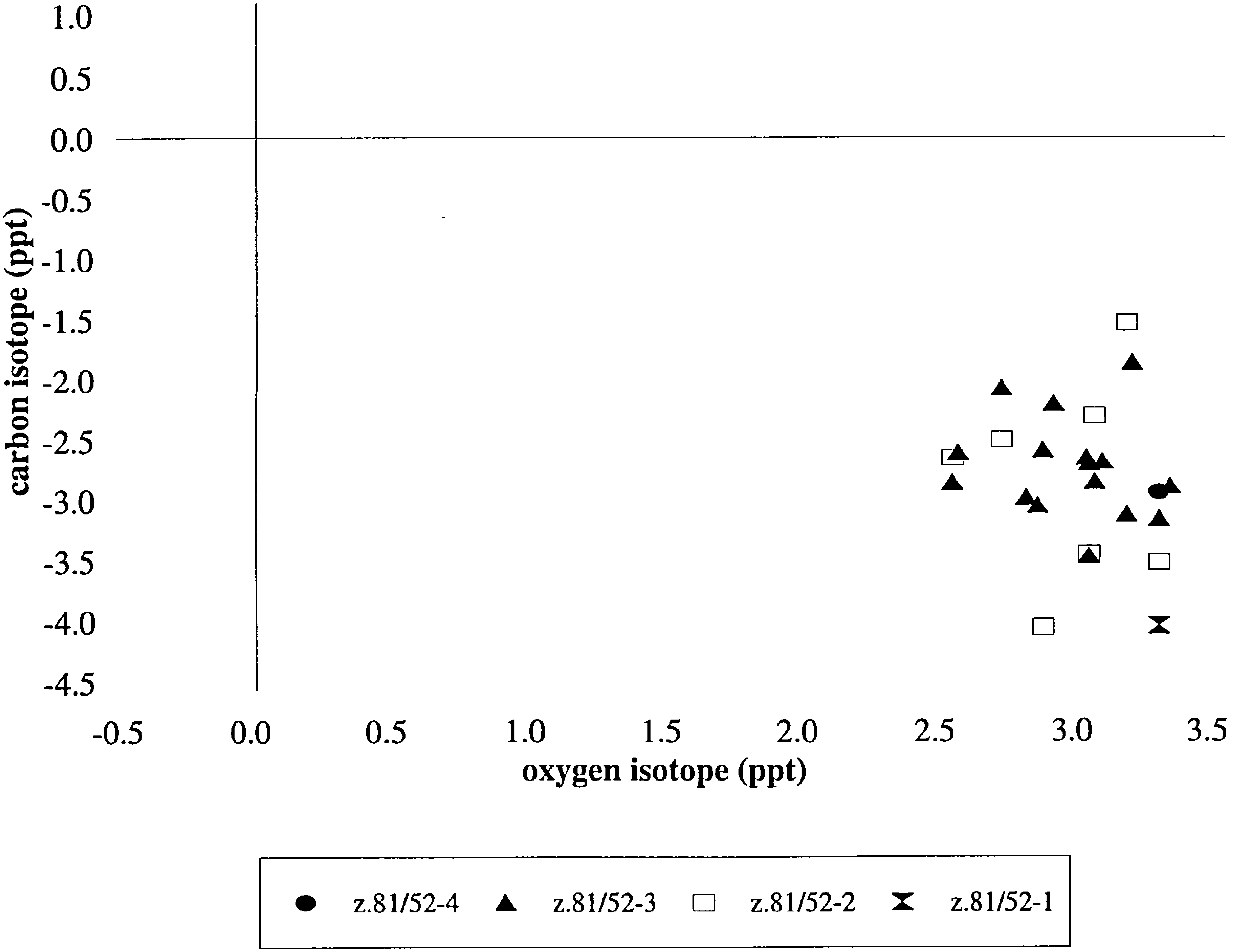


Fig 4.14 $\delta^{13}C$ (‰) and $\delta^{18}O$ (‰) vales plotted for BH 81/52A (axes through 0,0 for reference).

4.4 Carbon/nitrogen (C/N) ratios

The C/N ratio results on 18 downcore samples from the Sand Hole Formation indicate that the whole core section was made up of sediment deposited in a fully marine environment, away from any major riverine sources of freshwater. All the C/N ratios fell in the range 10.14 - 12.30. Terrestrial organic matter is usually nitrogen poor, yielding ratios of C/N > 15, whereas marine organic matter is nitrogen rich, usually giving C/N ratios of between 7 and 9 (Jasper and Gagosian, 1990; Müller *et al.*, 1994). As sediment ages some nitrogen is degraded, making the samples seem deficient in nitrogen, which in modern samples would indicate the influence of freshwater in the area. This is demonstrated by these samples since the ratios are slightly higher than would be expected in a modern fully marine situation.

4.5 Summary

The faunal assemblage found in the Sand Hole Formation conforms to a warm stage. However, the fauna shows close similarities to boreal - Arctic faunas at the present day, perhaps indicating that the southern North Sea was much cooler when the Sand Hole Formation was deposited than at present. The fauna at the base of the core shows signs of being reworked (A:J < 1:5), whereas the fauna in the bulk of sediment from the Sand Hole Formation appears to be a well preserved, *in situ* assemblage.

The trace element geochemistry demonstrated that there was a *circa* 7°C decline in temperature occurring over the length of the Sand Hole Formation, perhaps indicating that climate was in decline at the time of deposition of the sediment.

Stable isotope analyses did not help to resolve the environmental signals. Carbon/ nitrogen (C/N) ratio analyses on samples spaced every 50 cm between 39.00 and 29.50 m upcore indicated that the whole core is made up of marine sediment with no freshwater influence (C/N = *c.* 10). The ratios were slightly higher than those expected for marine sediments (C/N = 7 - 9), since as marine sediments age some nitrogen degrades, yielding ratios which are slightly higher than those obtained for modern sediments.

Chapter 5

Results: Shoeburyness, Essex

This chapter addresses both the palaeoecological and the geochemical results from the study of the core taken from a site at Shoeburyness in Essex. The focus for the study were the ostracod assemblages identified; however, other groups (such as diatoms, molluscs and foraminifera) are mentioned since they contribute further, previously unreported, evidence on the site. Previously reported evidence (Roe, 1994) was discussed in Ch. 2.1.7.

5.1 Palaeoecology

The basal section of the Shoeburyness clay from 14.60 to 10.18 m yielded a moderately high diversity, low abundance (< 300 individuals per 25 g sediment) freshwater assemblage (Table 3; Fig 5.1). The dominant species (45 - 70 %) was the infaunal burrower, *Darwinula stevensoni*, which was also well represented in all stages of instar development, suggesting that it had been deposited *in situ*. Above this the samples consisted of a low diversity, high abundance (>1000 individuals per 25 g sediment) assemblage, strongly dominated by the brackish/marine species *Cyprideis torosa*. Foraminifera, molluscs and diatom frustules were also found above 10 m in the core. None of the assemblages found indicated fully marine conditions, although the presence of marine ostracods and foraminifera suggest that there was a certain amount of tidal influence in the area.

5.1.1 Ostracods

Zone S1-1 (Fig 5.2), from 14.60 to 12.23 m, of the Shoeburyness core yielded a fairly high diversity freshwater assemblage. The dominant elements were *Darwinula stevensoni*, *Ilyocypris* sp. and *Candona* sp. Apart from one sample, at 13.145 m, there were negligible numbers of brackish water species such as *Cyprideis torosa*, which occurred in

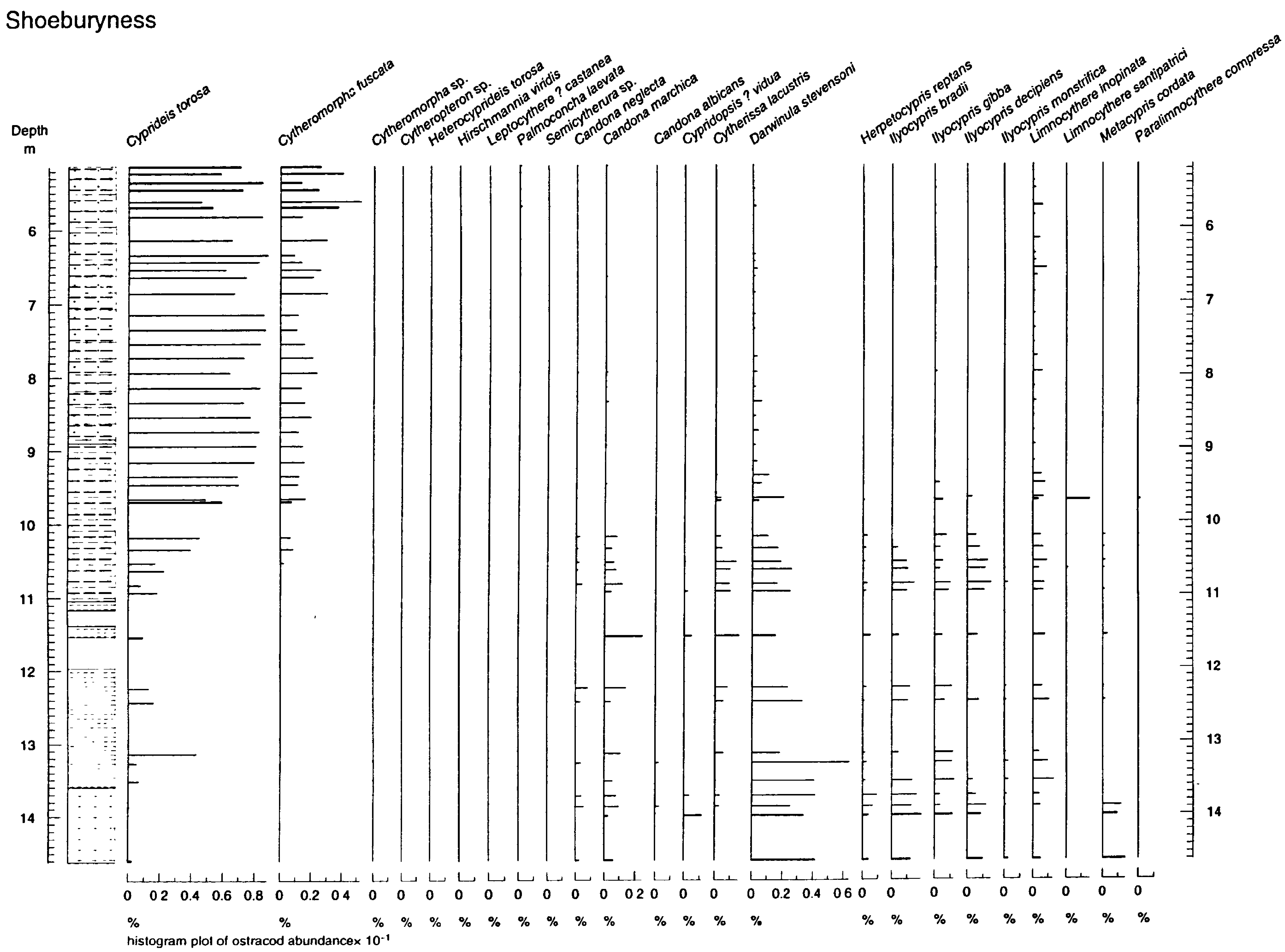


Fig 5.1 Ostracod abundance against sample depth and lithology.

SPECIES OF OSTRACOD	ENVIRONMENT	TEMPERATURE AND SALINITY	SUBSTRATE	STRAT
BRACKISH/MARINE				
Cyprideis torosa (Jones, 1850)	prolific in marginal marine environments (estuaries, brackish lagoons, creeks) and lakes.	Wide range of salinities from 2 - over 60 ‰	<30 m, sandy-mud, or algae	PHM
Cytheromorpha fuscata (Brady, 1869)	estuaries and lagoons	Temperate conditions, less common at present day		PHM
Cytheropteron sp.1	marine species, only juveniles found, probably washed in		sandy, muddy	PHM
Elofsonia baltica (Hirschmann, 1909)	shallow, brackish waters, estuaries, Europe	Temperate, brackish	saltmarsh, muddy	PHM
Hirschmannia viridis (O.F.Müller, 1875)	phytal species, very common, mainly occurs in weed rich littoral fringes in marine and brackish water	2- 33‰, Arctic - NW Europe (boreal, temperate, lusitanean)	muddy, algae rich	
Leptocythere castanea (Sars, 1866)	exclusively brackish water, estuarine and salt marsh	NW Europe, Greenland; 4-30‰	mud, algae	PHM
Palmoconcha laevata (Norman, 1865)	common, marine, sublittoral - littoral	Approx 35‰; boreal	sediment substrate	PHM
Semicytherura sp.1	marine species, only juveniles found, probably washed in, commonly associated with littoral algae	Temperate	phytal, littoral	PHM
FRESHWATER				
Candona neglecta (Sars, 1887)	freshwater ponds, lakes, marshes, ditches and oligohaline (0.15‰) creeks	5-8°C, fresh, can be found in saline lakes (DeDeckker, 1979)	soft, muddy, marshy vegetation	PHM
Peudocandona albicans (Brady, 1864)	Streams, lakes, ponds and ditches. Common in periodically drying pools	Europe and N. America	muddy	PHM
Pseudocandona marchica (Hartwig, 1899)	ditches, pools, small ponds in fields - settings which periodically dry out (Keen *et al.*, 1984)	cold temperature indicator, maximum occurrence in late glacial horizons (Absolon, 1973)	muddy	PH
Cypridopsis vidua (Muller, 1776)	small and large water bodies rich in aquatic vegetation, *active swimmers*	warm waters (DeDeckker 1979)		PHM

SPECIES OF OSTRACOD	ENVIRONMENT	TEMPERATURE AND SALINITY	SUBSTRATE	STRAT
Cytherissa lacustris (Sars, 1863)	deep, oligotrophic lakes (Geiger, 1993); calcareous sediments, little plant matter	cool, deep water (Günther, 1986)	muddy	PHM
Darwinula stevensoni (Brady and Robertson, 1870)	lakes with organic rich debris, crawls, does not swim	Freshwater, salinity up to 0.75‰		PHM
Herpetocypris reptans (Baird, 1835)	quiet water rich in plant debris (Klie, 1938); clambers on weed or burrows, close to margins of lakes and ponds (Shotton *et al.*, 1993)	Freshwater, common in Europe and Africa - warmer water	soft mud, algae	PHM
Ilyocypris bradyi Sars, 1890	springs and shallow ponds (Klie, 1938), clambers of vegetation, can swim in still or slow moving water	Boreal/cool water, withstands only small temp changes; tolerates brackish water		PHM
Ilyocypris decipiens Masi, 1905	generally in cold water (i.e. springs, away from springs in the north of its range (Shotton *et al.*, 1993); may contrast with other climatic indicators since found in cold water	cold water		PM
Ilyocypris gibba (Rahmdor, 1808)	freshwater ponds, lakes, streams and brackish water	4-19.5°C (Alm, 1916); freshwater only	muddy	PHM
Ilyocypris monstrifica (Norman, 1862)	lakes, canals, rivers, large still or slow moving water	Freshwater only, widely distributed in Europe (warmer waters)		PM
Limnocythere inopinata (Baird, 1843)	wide range of aquatic habitats, streams, rivers, ponds and swamps. Also upper reaches of estuaries	Brackish to 0.75‰, Northern Europe and North America, cool-temperate	muddy	PHM
Limnocythere santipatricii Brady and Norman, 1869	common in calcareous waters at low latitudes and in Alpine areas	cold indicator (known in Iceland and Greenland - Poulson, 1939; Röen, 1962)		PHM
Metacypris cordata Brady and Robertson, 1870	peaty, humic water bodies, intolerant of aquatic hypoxia (Danielopol *et al.*, 1993); usually in lakes, limited dispersal potential, late stage in lake ontogeny	cool temperate, sub-Arctic water (Henderson, 1990)	muddy, humic, choked with plants	PHM
Paralimnocythere compressa (Brady and Norman, 1889)	shallow, non-permanent waters, potential for dispersal, scarce at present due to warmth? (Griffiths and Evans, 1995)	Cold		PH M(rare)

Table 3. Species affinities and distributions from BH S1 (Henderson, 1990; Athersuch *et al.*, 1989). P: Pleistocene; H: Holocene; M: Modern.

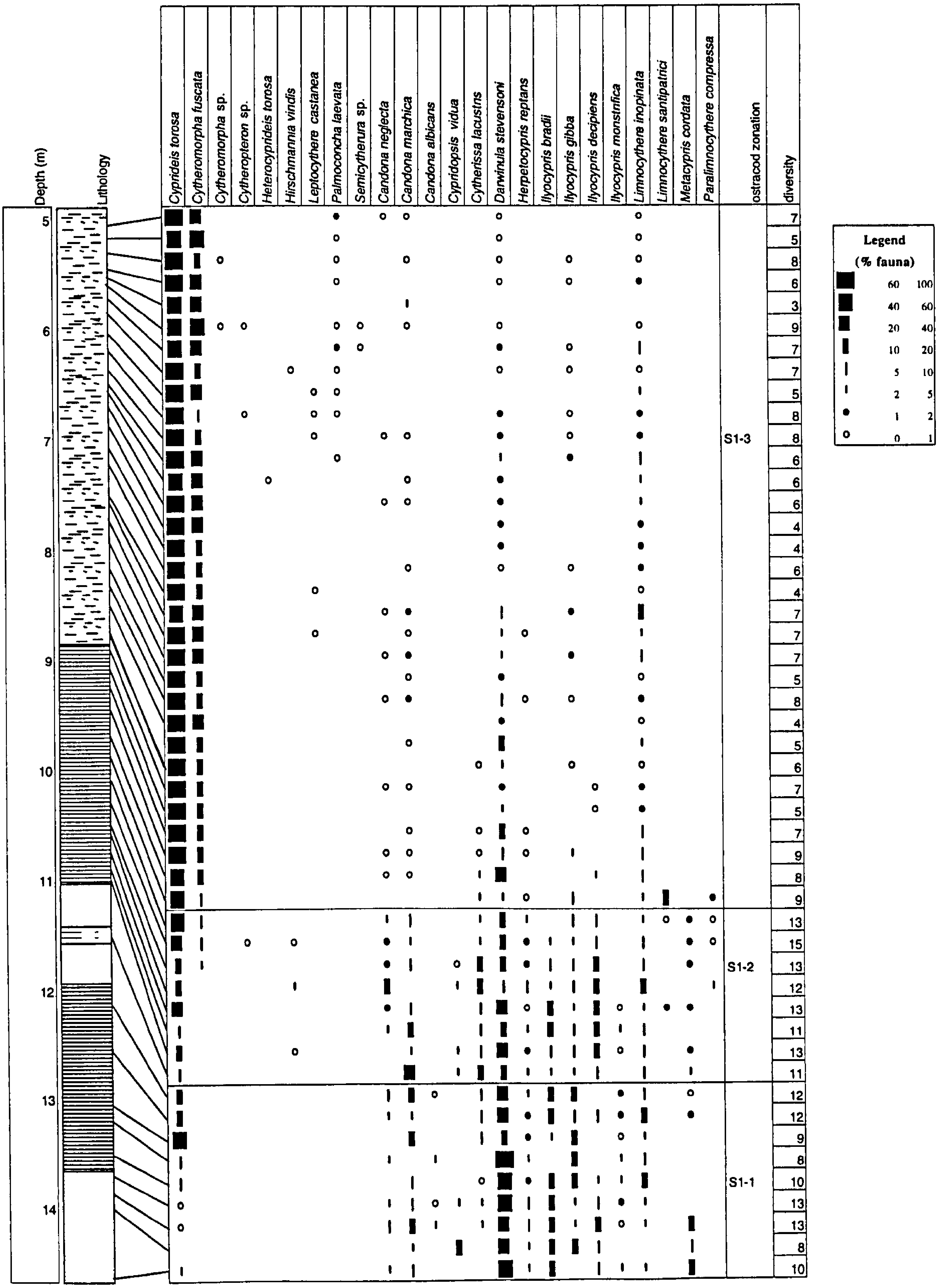


Fig 5.2 Concentrations of all ostracod species found in samples between 14.60 and 5.25 m depth (average depths for each 2-3 cm sample) below the sea floor in BHS1, Shoeburyness. Core recovery and lithology are shown on the left, ostracod zones and explanation of symbols on the right of the diagram.

this section only as noded juveniles. The freshwater assemblage exhibits a diverse range of habitats in the area at the time of deposition. The burrowing species, *D. stevensoni*, *Candona neglecta*, *C marchica* and *C. albicans* occur with phytal associated species, such as *Limnocythere inopinata*, and smaller numbers of free-swimming ostracods, *Cypridopsis vidua*. Most of the freshwater assemblage has been recorded inhabiting shallow lakes, ponds and streams (Henderson, 1990; Shotton *et al.*, 1993; Table 3). Several complete valves of the thin shelled ostracod *Herpetocypris reptans* were found between 13.72 and 14.00 m, indicating that depositional energies must have been low. All the ostracods in this sediment section were recorded with a range of juvenile instars, a further indication that water movements were small enough to promote preservation of the indigenous population. The most common ostracods found were eurythermal, existing over a wide temperature range (4-19°C). However, *Ilyocypris bradii*, a colder water species incapable of withstanding more than a slight change in water temperature (DeDeckker, 1979), reaches its highest proportions in this interval (*c.* 10% of the fauna).

Between 12.23 and 10.18 m (zone S1-2) (Fig 5.2) the numbers and diversity of brackish water species increase, with a concurrent decrease in the number, but not diversity, of freshwater species. Abundances of *D. stevensoni* decrease, which could be due to an increase in water depth, since numbers of *Cytherissa lacustris*, a deeper water lake species, increase in this section. However, aquatic vegetation must still have been common in the area, indicated by the continued presence of *Metacypris cordata*, and the introduction of the phytal associated species *Limnocythere santipatricii* and *Paralimnocythere compressa*. Colder water indicators, such as *Ilyocypris decipiens* and *P. compressa* are found at their maximum concentrations in this interval, and *Metacypris cordata*, a cool temperate or sub-Arctic indicator, is still present in significant numbers. The brackish species diversity increases in this interval indicating an influx of more saline water, to the extent that a couple of juvenile valves of the fully marine genus *Cytheropteron* were found at 10.34 m. High concentrations of *Candona marchica* in this zone may indicate a certain amount of seasonality in the amount of water present in the area, since it is a species which can cope with a wide range of ecological niches, but is most commonly found in ditches, pools or small ponds, liable to periodical drying out (Keen *et al.*, 1984).

In contrast to the lower part of the sequence, the upper part of the Shoeburyness Clay, zone S1-3, between 10.00 and 5.00 m (Fig 5.2), was dominated by brackish water species, especially *Cyprideis torosa*, which made up between 50 and 90 % of the entire assemblage throughout this zone. Ostracods can be divided into marine, brackish or freshwater types, which can be coupled with attributes of either wide tolerance of varying salinity (euryhaline) or intolerance and, therefore, restriction to environments where a limited variation in salinity occurs (stenohaline). In brackish environments the diversity of species is minimal and the abundance of individuals tends to reach a maximum (Fig 5.3) (Murray, 1973; Neale, 1988), due to the physiological stresses inherent in highly variable environments. *Cyprideis torosa* is an ostracod which can occur in noded or un-noded forms. The causes of this supposed phenotypic variation are not known, and current theories are discussed below.

High concentrations of another common brackish (salinity < 30‰) species, *Cytheromorpha fuscata*, were also observed. This is a rare species, recorded in Britain only from the Suffolk Stour Estuary and localities in the Norfolk Broads (Robinson in Horton *et al.*, 1992). It always occurs marginal to the tidal influx and this habitat preference has been used in palaeoecological interpretations in the Netherlands, north Germany and the Baltic (Klie, 1938; Elofson, 1941; Wagner, 1957). Since the species is now rare in Britain it may have stratigraphic association with the Middle and Late Pleistocene in East Anglia (Robinson in Horton *et al.*, 1992). It also occurs in abundance in the Balanus Bed of the March gravels at Somersham (Robinson, unpub. data) and at Eye (Keen *et al.*, 1990), both in Cambridgeshire and of probable Ipswichian age.

Frequencies of both brackish species increase towards the top of the section, implying enhanced marine influence. All stages of instar development were found for both

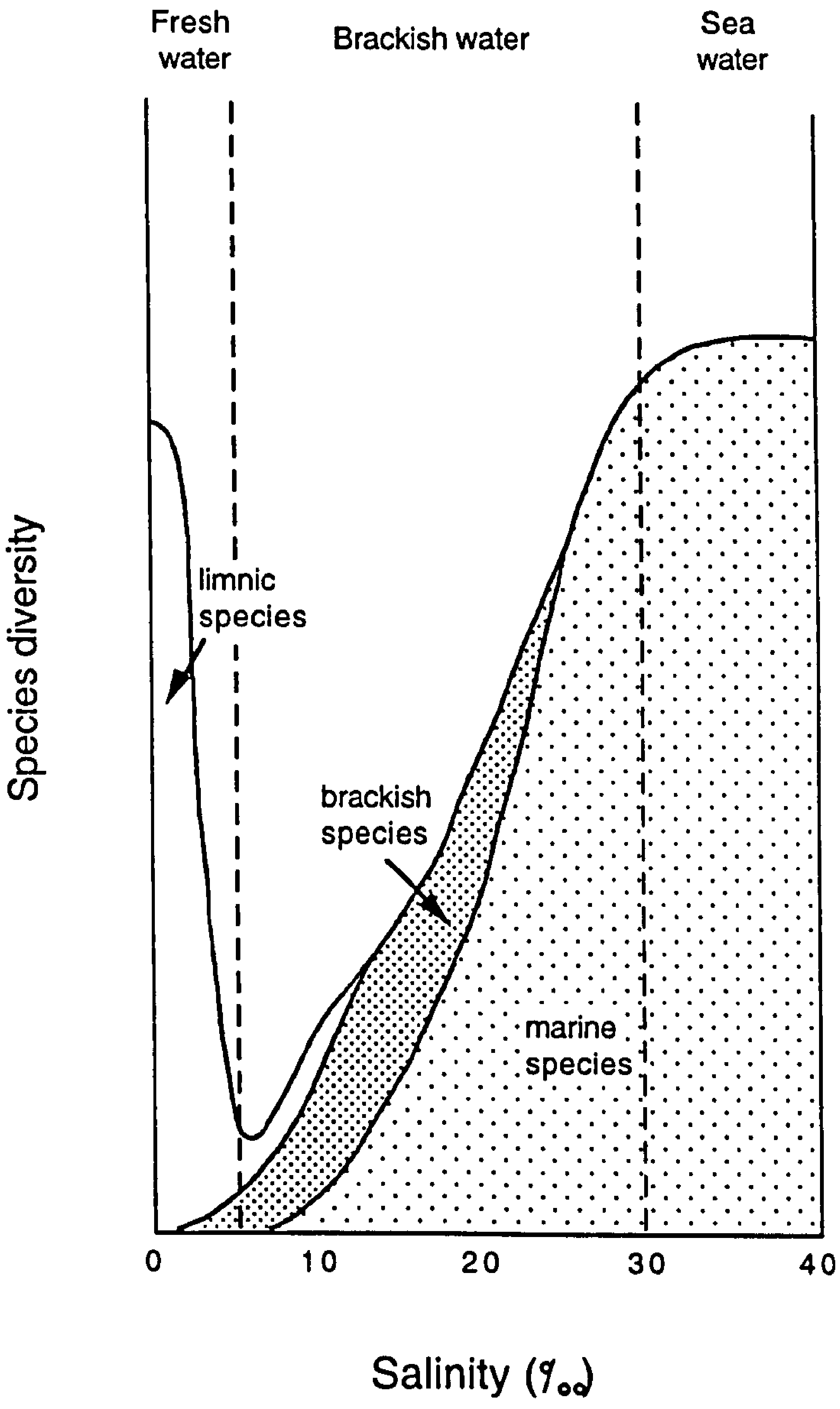


Fig 5.3 Schematic diagram showing the relationship between the diversity of ostracod populations and salinity (after Remane, 1934 and Carbonel, 1988).

Cyprideis torosa and *Cytheromorpha fuscata*, indicating that they were living and breeding in a region of little current activity, which might otherwise have caused *post-mortem* transport. Small concentrations of freshwater species were also found in this interval; however, most of these appear to have been transported into the area as they were only represented by adult or juvenile specimens. One freshwater species, *Limnocythere inopinata*, is known to be tolerant of slightly brackish conditions (euryhaline) and was represented by both adults and juveniles. Towards the top of this zone brackish tolerant marine species, such as *Palmoconcha laevata* and *Leptocythere castanea*, appear to have been carried into the area. This section appears to document an *in situ* brackish fauna, typical of an estuarine channel, in which the mixing of imported freshwater and fully marine species prevailed.

Although the ostracod assemblages detailed above are clearly interglacial, there is little in the fauna to support a precise age estimation. One possible exception is provided by the presence of *Paralimnocythere compressa*, a species common in the Middle Pleistocene, but rare in the Late Pleistocene (Diebel and Pietrzeniuk, 1969).

5.1.2 Noding in Cyprideis

Cyprideis torosa is a ubiquitous species in temperate brackish environments. It often contributes 70 to 90 % of the ostracod population in these environments (Kileyni, 1972). It is the type species of the genus and has been more thoroughly investigated morphologically and ecologically than any other brackish species.

Euryhaline marine and brackish species may react to lowered salinities by developing hollow tubercles (torosities) on the valve surfaces. As salinities become lower, these tubercles become more evident, appearing first on juvenile instars, and then developing in adults at salinities between 5 and 8 ‰ (Vesper, 1975; Carbonel, 1988; Neale, 1988). These tubercles are usually referred to as phenotypic characters since they develop with environmental changes, and the character does not appear to be transferred to offspring. Even though the factors that bring out the nodes appear to be environmental (Sandberg, 1964), the location and number of nodes can differ markedly among species. A number of general statements can be used to describe the position of the nodes by instar, sex and valve:

a) nodes are more common and stronger on the right valve;
b) nodes are more common on juvenile valves, particularly A-I and A-II;
c) among adults, females are more commonly and strongly noded, although less frequently than juveniles (Sandberg, 1964).

In *C. torosa* a total of seven different possible node positions have been observed (Sandberg, 1964: fig.13). *C. torosa* usually lives in brackish water with a connection to the open sea (i.e. estuaries, lagoons), but it is also known to occur in NaCl dominant water, so that it can commonly be found in inland saline lakes with NaCl chemistry (Neale, 1988; Whatley, pers. comm.).

The relationship between noding and salinity cannot be a simple one, since noded forms can occur with smooth ones (Vesper, 1975; Neale, 1988), as in this case, where throughout most of the core both noded and un-noded types were counted. However, noded forms dominate where lower salinities are indicated by an increase in the abundance of freshwater species (Fig 5.4).

The reason for the occurrence of noded and smooth forms together is not amenable to an easy solution, and a number of explanations have been put forward. Different reaction of individuals to physiological stress (Sandberg, 1964), adaptation to a gradual reduction in salinity (Hartmann, 1964), and the idea that lower salinities favoured noded forms leading to a balanced polymorphism (Kilenyi, 1972) have all had their proponents. Opposed to this last assumption is the proportion of un-noded and noded individuals found together in the populations of this study, both apparently *in situ*, and previously by Vesper (1972, 1975).

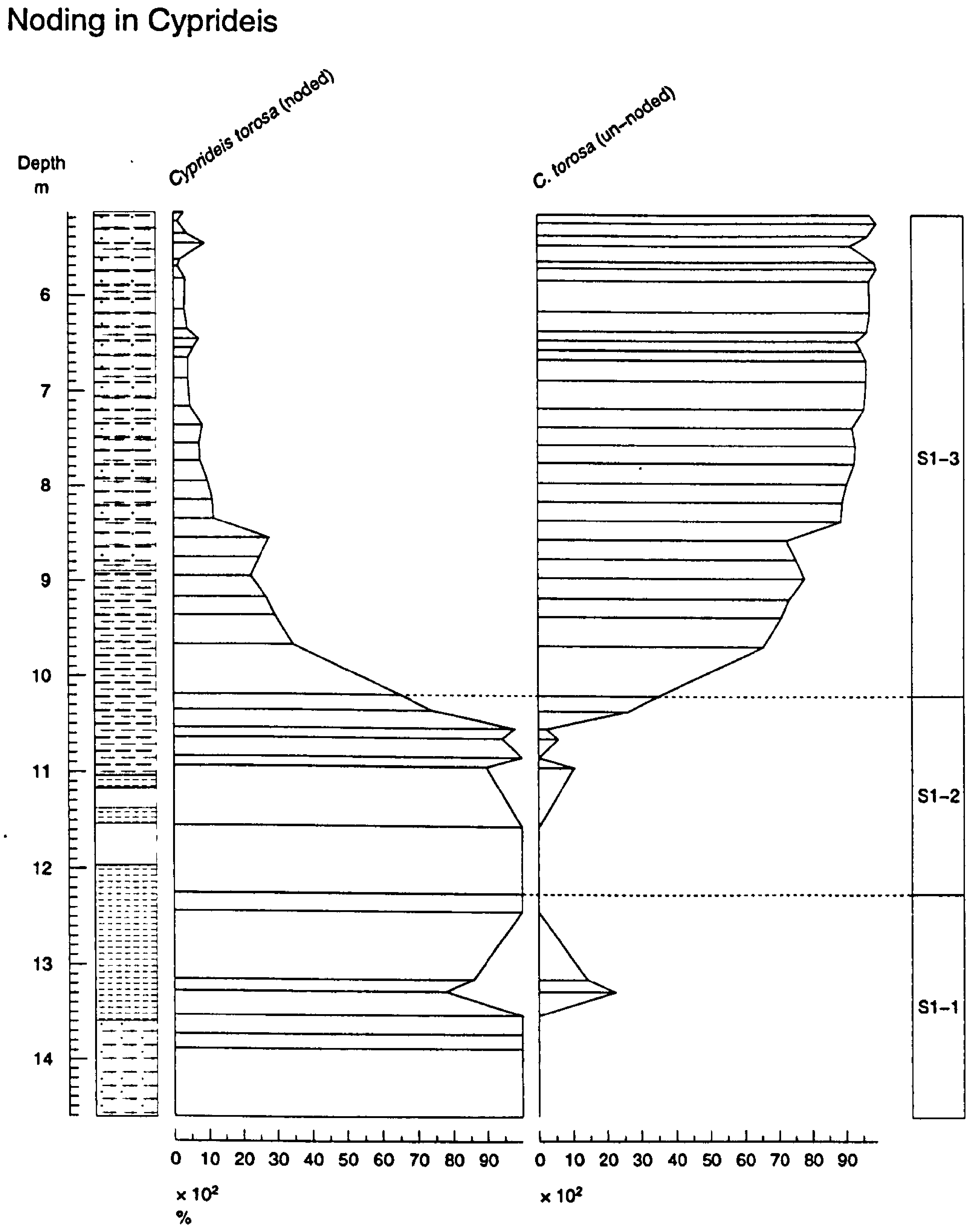


Fig 5.4 Relationship between noding in *Cyprideis torosa* and core depth, zonation at same depths as Fig 5.2.

The advantages of nodes have never been explained, although both a buoyancy function or some physiological or biochemical factor increasing fitness have been suggested (Triebel, 1941; Sandberg, 1964; Neale, 1988). Whatever the explanation, the incidence of noding in *Cyprideis torosa* appears to give a useful general indication of the ambient salinity at the time of deposition of the sediment in which the noded population occurs.

Apart from the development of hollow tubercles, a significant increase in the size of *C. torosa* has also been observed in salinities lower than 5‰ (van Harten, 1975). However, as van Harten stated, "the correlation between carapace size and environmental salinity does not necessarily draw the conclusion that size depends on salinity in a causal way". Instead he interpreted the results to indicate that, rather than salinity itself, salinity variation might control size.

5.1.3 Foraminifera, Molluscs and Diatoms

Most of the samples in zone S1-3 also contained an assemblage of foraminifera, dominated by *Ammonia becarii* (50 - 60%), a common brackish, estuarine species. It occurred in two different forms, *A. becarii* var. *limnetes* Todd and Brönnimann 1957 and *A. becarii* var. *tepida* Cushman 1926, both common in brackish estuarine settings, tolerant of salinity between 0 and 35‰. Also present were *Asterigerinata mamilla* Williamson 1858, *Elphidium earlandi* (Cushman, 1936) *Elphidium oceanensis* d'Orbigny 1826, *E. williamsoni* Haynes 1973, *E. magellanicum* (Heron-Allen and Earland, 1911), *E. albiumbilicatum* (Weiss, 1954), *E. voorthyseni* (Haake, 1962), *Nonion depressulus* (Walker and Jacob 1798), *Rosalina williamsoni* (Chapman and Parr 1932), other *Rosalina* spp. and *Haynesina germanica* (Ehrenberg 1840). These are all shallow, euryhaline species, and the dominance of *A. becarii* and *E. williamsoni* indicates stringent environmental conditions. Boomer and Godwin (1993) found that this assemblage was diagnostic of a saltmarsh environment, and also that in their study *Cyprideis torosa* reached its greatest abundance in the same zone as this foraminiferal fauna. *N. depressulus* and *A. mamilla* are likely to have been introduced from the shelf (Murray, 1991). Odd degraded tests of *Lagena* sp. were also picked at different levels down-core. These are marine forms which live on muddy substrates, but *post-mortem* transport during storms sometimes leads to their deposition in estuarine muds (Murray, 1979).

All the foraminifera identified were extremely small (< 180 µm diameter). This could have been due to size sorting during transportation into the area, so that only smaller individuals were preserved in the core. Murray (1979) states that small species and juveniles of large species (mean size ~140 µm) may be transported from the shelf during tidal action. He found that this process commonly operated around estuaries which have a well mixed lateral salinity gradient and a high tidal range (such as the Severn Estuary at present). Alternatively, size could be related to environmental stresses in the local habitat. All of the species found are also common in inner-shelf marine settings. Perhaps more brackish environments, suggested both by the foraminifera and the ostracod assemblages, do not represent the optimum living conditions and fail to stimulate growth.

None of these foraminifera appeared to be reworked, they were well preserved and the faunal assemblage is a common one. At other levels in the core (especially between 10.35 and 12.65 m) a number of Cretaceous forms were found, which are likely to have been eroded from the London Clay bed rock.

A number of opercula plates were found in the lower section of the core (zones S1-1 and S1-2). These were identified (Preece, pers. comm.) as coming from the freshwater mollusc *Bithynia tentaculata* (Linné). A few *Valvata piscinalis* (Müller), *Pisidium moitessierianum* (Paladilhe) and *Pisidium henslowanum* (Sheppard) were also found in the freshwater section of the core. This assemblage indicates deposition by a substantial well-vegetated stream (Holyoak and Preece, 1985), which is consistent with the slow flowing, vegetation rich water body inferred from the freshwater ostracod fauna in zone S1-1 (Fig 5.2).

Towards the top of the core the mollusc, *Paladihlia radigueli* was found. Small hydrobiid gastropods are common in quiet estuarine environments which are sheltered from the influence of strong tidal activity. Such conditions favour thriving hydrobiid communities which cannot tolerate currents (Ellis, 1969). This now extinct species was last recorded at Shoeburyness by Kennard and Woodward (1922), although the precise location of their sample is uncertain. The species has been found in a sequence from Barling, to the north of Shoeburyness (Roe, 1994) and has also been found in other Middle and Late Pleistocene interglacial sites in the Thames area (Kennard and Woodward, 1922; Preece, pers. comm.). These sitings make *Paladilhia radigueli* a stratigraphic marker for the Pleistocene.

5.2 Trace element analyses

The weight of the evidence from the initial study on the Shoeburyness core (Roe, 1994) indicated that the channel infill was deposited in a continuous sequence during one interglacial cycle (the Hoxnian). The ecological evidence also suggested that the clay in the channel accumulated under transgressive conditions, with freshwater species at the base of the core, and brackish species towards the top. This would suggest a shallow estuarine environment, in which temperatures could be expected to fluctuate widely, and salinities slowly change up-core as the transgression occurred. This is a very different scenario to that in the Inner Silver Pit, and these geochemical analyses were carried out in order to ascertain whether palaeosalinity changes were documented by ostracod shell chemistry in such an environment. Most studies on *Cyprideis torosa* prior to this were carried out under laboratory conditions, or on individuals from lacustrine environments (Chapter 2.2).

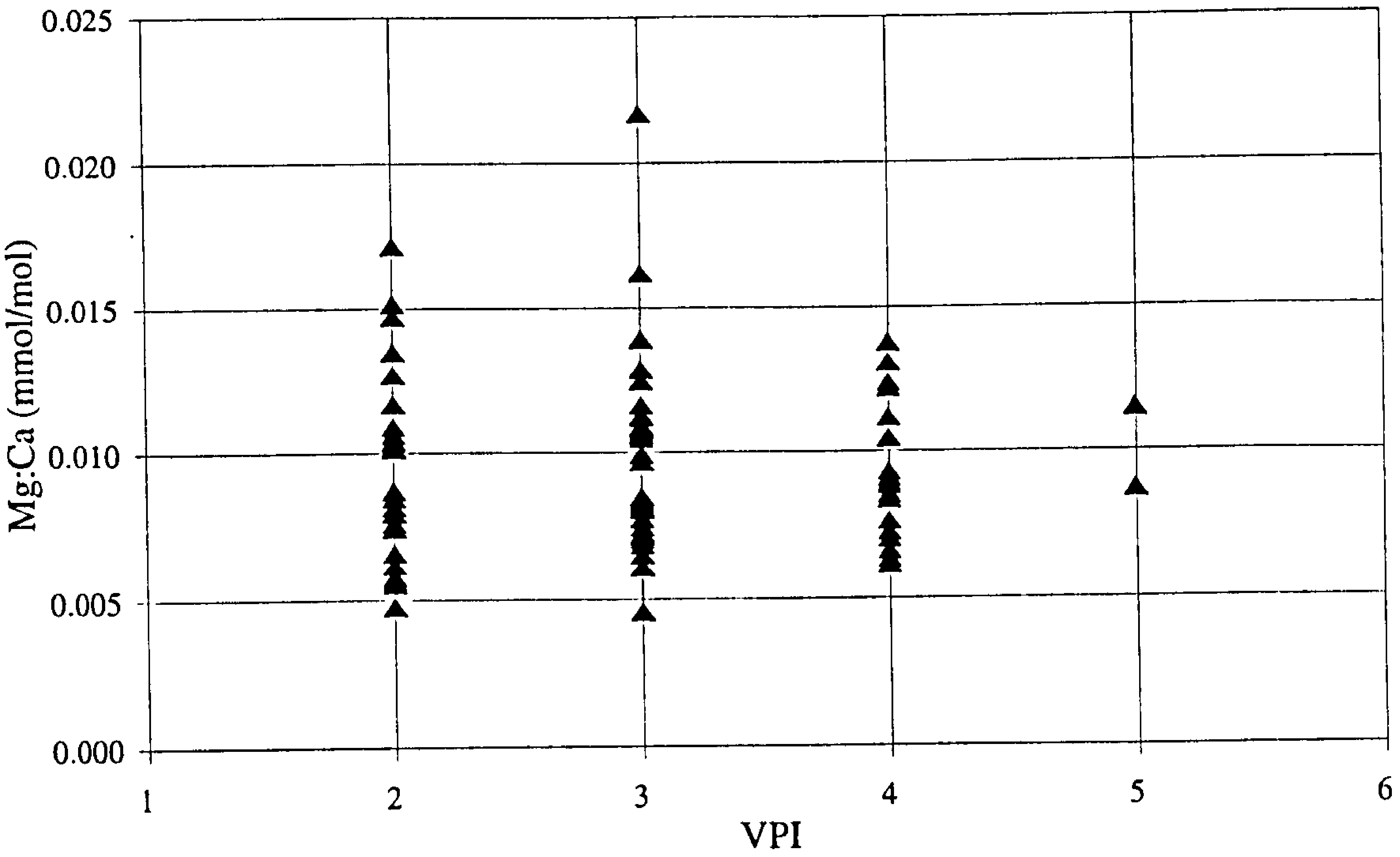
Cyprideis torosa is extremely well suited to ecological investigations. Numerous studies have shown that species of *Cyprideis*, together with a commonly associated microfauna, characterise brackish water environments. *Cyprideis torosa* is a very euryhaline species, whose development is entirely in brackish water (2 - 17‰), an environment in which there is often a low diversity but high numbers of successful individuals and where *Cyprideis* individuals often comprise the majority of the ostracod fauna. Apart from the numbers of *Cyprideis* present in the samples, it is also a thick shelled well calcified genus, making it amenable to single valve shell chemistry analysis. In these samples *Cyprideis* was also represented by large numbers of adults, an important consideration when selecting ostracods for geochemical work, since poorly calcified and juvenile valves give anomalous results (Chivas *et al.*, 1983, 1986a, b; Anadon and Julià, 1990; Anadon *et al.*, 1994).

5.2.1 Shell preservation

Each valve to be analysed for its trace element content was assigned a value on a visual preservation index (VPI). These values were compared to the Mg:Ca and Sr:Ca results for each ostracod in order that any influence of preservational factors could be assessed (Fig 5.5). It was observed that there was no correlation between the VPI value and the result of the trace element analysis.

5.2.2 Modern Mg:Ca and Sr:Ca ratios

Cyprideis torosa is a well studied non-marine ostracod which is often abundant in Pleistocene and modern sequences. The relationship between the geochemical properties of its aquatic habitat and the morphological response of its carapace has been discussed above, but the incorporation of trace elements into its shell has also been the subject of several studies (Bodergat and Andreani, 1981; Chivas *et al.*, 1986b; Anadon and Julià, 1990; Anadon *et al.*, 1994). The work by Chivas *et al.* (1986b) permitted the calculation of the partition coefficients of Mg and Sr in *Cyprideis*. The authors showed that the Sr distribution coefficient in non-marine ostracods (including *Cyprideis*) is independent of temperature and that for individual species the valves contain Sr in proportion to the Sr in



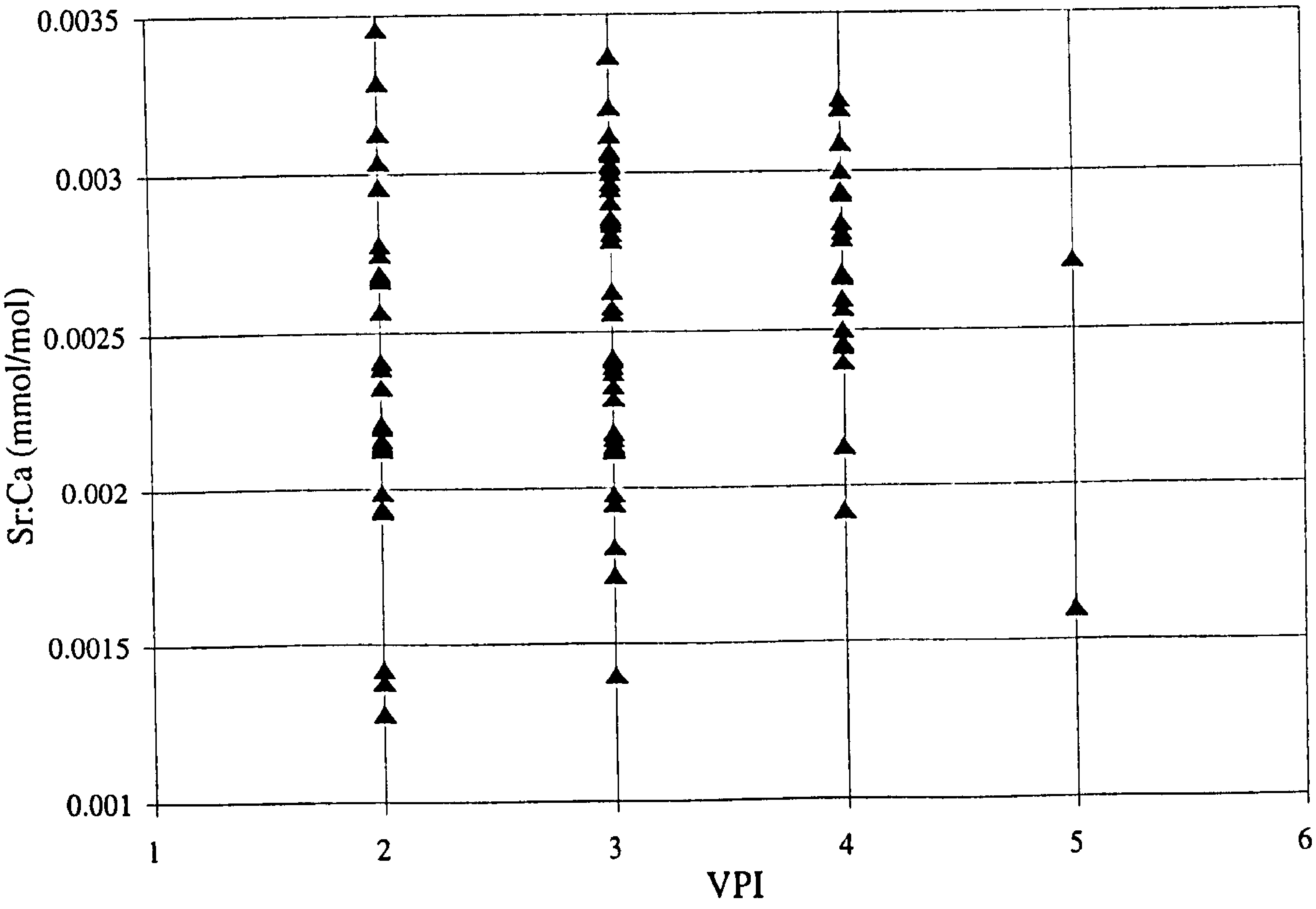


Fig 5.5 a. Plot of visual preservation index against Mg:Ca for down-core *Cyprideis* from BHS1; b. Plot of visual preservation index against Sr:Ca for down-core *Cyprideis* from BHS1.

their habitat. This raised the possibility that the Sr content of some non-marine ostracod species (such as *Cyprideis*) could be used to determine the former Sr content of the water and, hence, the palaeosalinity in the area. As discussed above (Chapter 2.2.3), incorporation of magnesium into ostracod shells is dependent on both temperature and the Mg:Ca ratio of the water. Thus a combination of Mg:Ca and $\delta^{18}O$ measurements on non-marine ostracods should enable a joint resolution of palaeotemperature and palaeosalinity variations.

The existence of these published results meant that a new modern calibration for *Cyprideis* was not thought necessary. Instead the distribution coefficients listed below were used for comparison of the *Cyprideis* Mg:Ca and Sr:Ca data to palaeotemperatures and salinities.

K_D [Sr] = 0.474± 0.061 for the field collection;
K_D [Sr] = 0.475± 0.057 for the laboratory culture;
and,
K_D [Mg] = 0.0046± 0.001 for a laboratory culture.

Analyses of the Mg:Ca and Sr:Ca contents in individual *Cyprideis* valves were coupled with these experimentally determined distribution coefficient values calculated by Chivas *et al.* (1986b), in the hope that this would enable determination of the Mg:Ca and Sr:Ca of the water in which the ostracods lived.

5.2.3 Down-core Mg:Ca and Sr:Ca ratios

The Sr:Ca plot (Fig 5.6) is made up of average points representing the analysis of three to five individual *Cyprideis* valves from each level downcore. The data exhibits a lot of scatter and, although the ratio appears to increase from the base to the top of the core, suggesting a relative increase in the Sr content of the host water in which the ostracods were living, the actual difference between the mean Sr:Ca in the brackish zone and that in

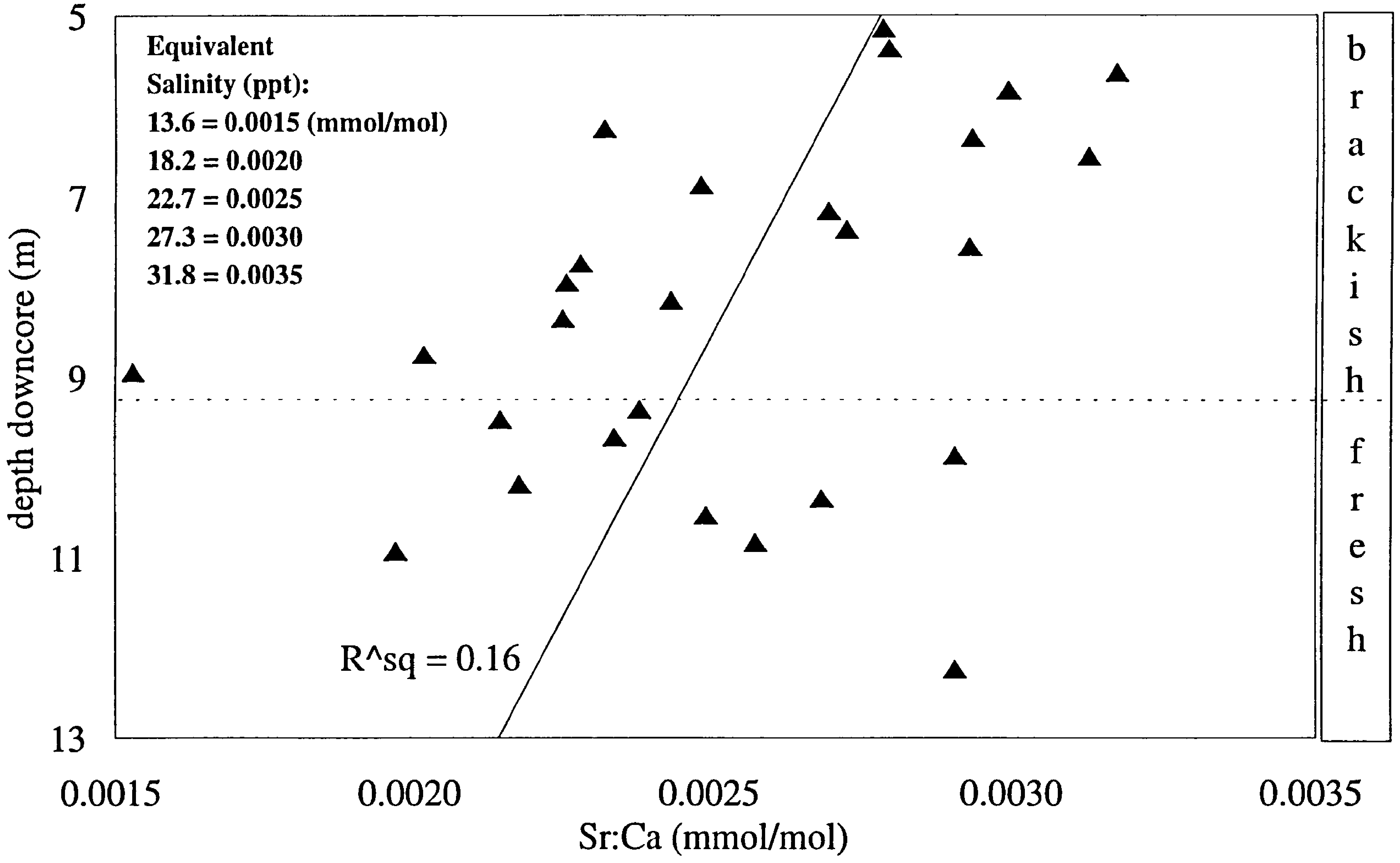


Fig 5.6 Plot of Sr:Ca ratio for down-core samples, transition from fresh to brackish water marked.

the freshwater zone is only 0.000174 mmol/mol, which is equivalent to a change in salinity of only 1.6‰ (calculated from Chivas *et al.*, 1986b). However, since the sediment in the core was deposited in a continuous sequence (Roe, 1994), this can be interpreted in terms of an increase in the salinity of the ambient water mass over time, but with many extraneous factors contributing to the spread of the data, which is equivalent to fluctuations over an 18‰ range in salinity over the length of the core analysed. This interpretation is supported by the increasing dominance of brackish indicator species, and also, at the top of the core, by the presence of brackish foraminifera (such as *Ammonia becarii*), molluscs (*Paladilhia radigueli*) and diatoms. The variation shown in the graph (Fig 5.6) indicates that salinity was probably fluctuating widely over short timescales, as would most commonly occur in an estuary in between tidal cycles.

The Mg:Ca deviations (Fig 5.7) are more difficult to interpret due to the strong thermodependence of the distribution coefficient of Mg in calcitic ostracod shells (Chivas *et al.*, 1986a, b). Low Sr:Ca and high Mg:Ca values usually correspond to higher salinity water, whereas high Sr and low Mg values correspond to water with lower salinity (Anadon and Julià, 1990). The ratio of Mg:Ca increases in the same way as the Sr:Ca ratio; however, there is a clearer difference in values between the freshwater section of the core and the brackish sediment (average fw value = 0.007785 mmol/mol; average brackish value = 0.10447 mmol/mol). There is stronger evidence for a change in water mass conditions since the difference between the mean Mg:Ca values in the two zones is 0.102485 mmol/mol. This is likely to be related to the change in salinity indicated by the faunal ecology (Ch. 5.1) rather than a temperature change of the order of 3.5°C (calculated from Chivas *et al.*, 1986b), although most of the ostracod fauna collected would have been capable of withstanding temperatures ranging between 6 and 10°C. The fluctuations in the Mg:Ca (demonstrated by the low R^2 value and the large amount of variation around the line, Fig 5.7) of *Cyprideis* from individual layers in the core suggest a shallow water body where recurrent changes in water temperature and salinity (perhaps over a tidal cycle) and in the Mg:Ca in the water occurred.

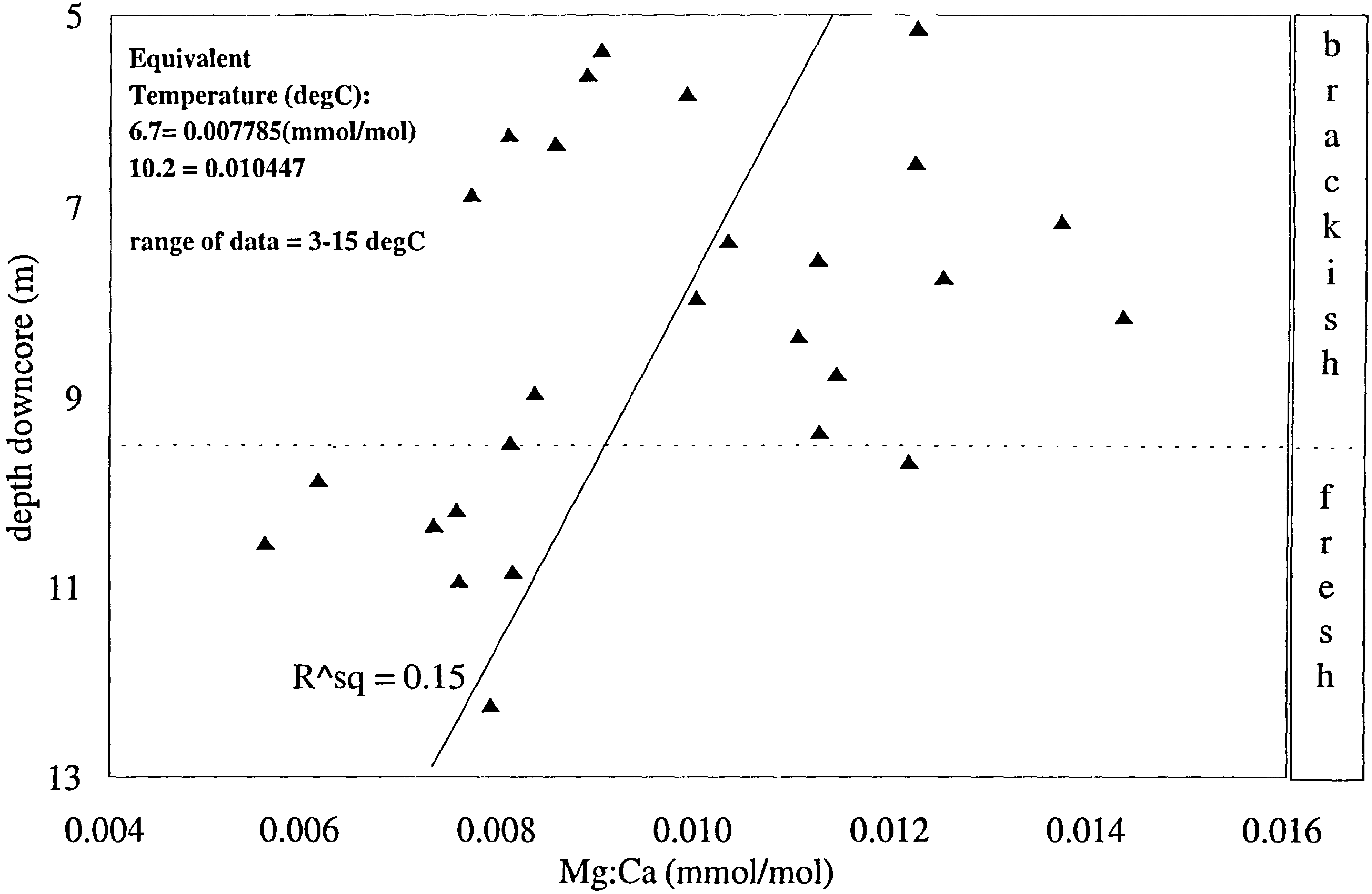


Fig 5.7 Plot of Mg:Ca ratio for down-core samples, transition from fresh to brackish water marked.

The Mg:Ca vs. Sr:Ca diagram (Fig 5.8) shows that the samples analysed in this study display a section grouping similar to that found by Anadon and Julià (1990). Their samples came from three shallow areas (Yeseras, Barranco Leon and Venta Micene) of a highly saline lake in the Baza Basin, S.E. Spain during the Pleistocene. They also plotted data which showed much greater variation in the Mg:Ca ratio (Fig 5.8). This was thought to represent wide fluctuations in the water body temperature and Mg:Ca ratio, and perhaps that the ostracods used, which were generally smaller, may have been poorly calcified. Chivas *et al.* (1983, 1986a) demonstrated that newly formed and/or poorly calcified shells often have disproportionately high Mg values. Only after reaching the adult size was the Mg content a good indication of geochemical conditions that prevailed in the water when the shell was formed.

The application of the Sr and Mg distribution coefficient relationships (detailed above) to the Sr:Ca and Mg:Ca ratios obtained from the analyses allows calculation of the Sr:Ca and Mg:Ca ratios in the host waters. The Sr:Ca versus Mg:Ca diagram (Fig 5.9) for the deduced geochemistry of the host waters shows that the molar ratio distributions are removed from the typical values for marine water and also differ markedly from the mean values for continental freshwater (mean values from Renard, 1985). All the samples indicate Mg:Ca values for host waters ranging between one and three. These values, common for non-marine waters (Anadon and Julia, 1990), are differentiated from sea water values, implying that the ostracods formed their shells in a complex set of hydrological conditions, in which fluctuations in the composition of the water prevailed.

5.3 Stable Isotopes

In isolation both trace element and stable isotope techniques produce results that are a function of several variables. In this case it was hoped that the analysis of a combination of stable isotopes and trace elements would enhance the precision of their interpretation.

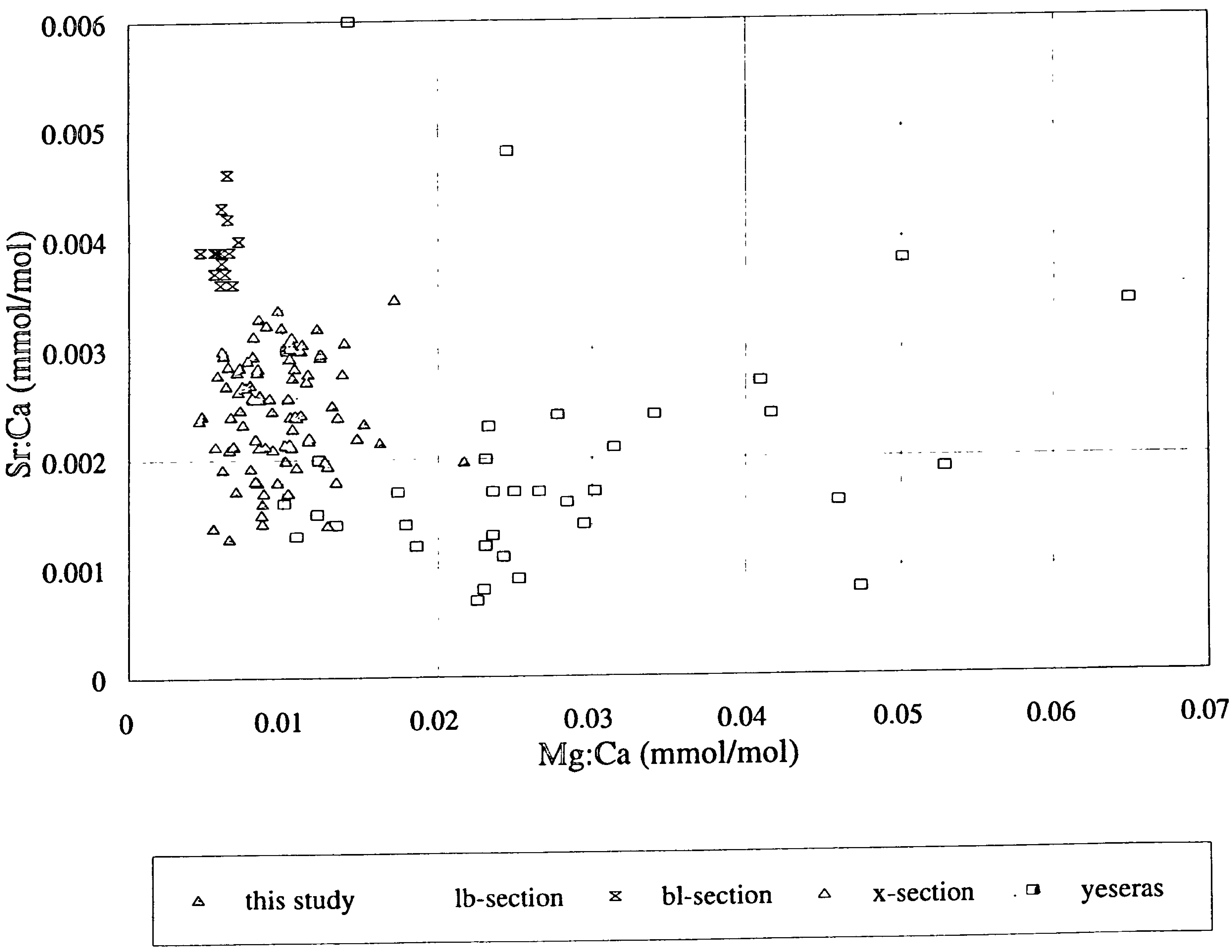
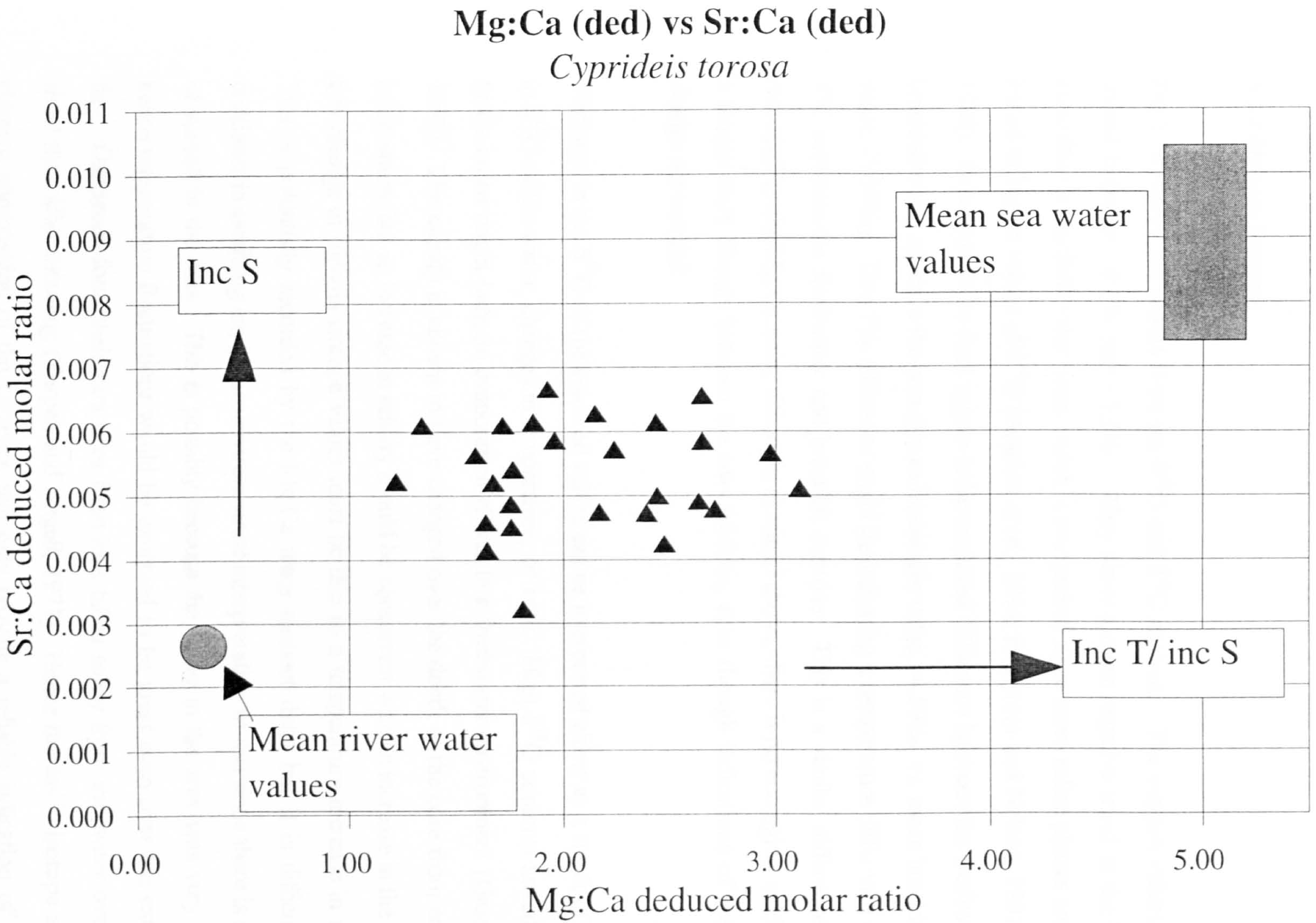


Fig 5.8 Comparison of trace element data from this study to the published results of Anadon and Julia (1991).



Kd (Sr) = 0.475 +/- 0.057
Kd (Mg) = 0.0046 +/- 0.0007

Fig 5.9 Comparison of data deduced from the results of this study, using partition coefficients established by Chivas et al. (1986b), to mean sea and river water values of trace elements (Broecker and Peng, 1982).

5.3.1 Oxygen isotopes

Fig 5.10 shows the results from the $\delta^{18}O$ and $\delta^{13}C$ analyses. The oxygen values show a spread between - 6.5‰ and - 3.5‰. They show a more negative trend in the brackish zone than in the freshwater zone, which is unexpected since more saline phases are usually linked to higher values of $\delta^{18}O$ (Anadon *et al.*, 1994; Engstrom and Nelson, 1991; Lister, 1988). However, there does appear to be a marked difference between the freshwater and brackish water zones in the core (mean freshwater value, -4.59‰ vs. mean brackish water value, -5.59‰). This 1‰ difference could be indicating a temperature difference of about 4°C between the freshwater and brackish sections. This is a similar difference to that recorded by the Mg:Ca ratio, although, as stated above, there is no ecological evidence for a temperature change between the two sections, even though indications of the salinity change are marked.

Variation in the $\delta^{18}O$ of the ostracod valves can be interpreted either as a result of changes in $\delta^{18}O$ of the water, changes in temperature, or both. High $\delta^{18}O$ contents linked to high Sr:Ca ratios might indicate evaporation effects in a freshwater environment (Gasse *et al.*, 1987). The salinity is known to have changed over the depth of the core from ecological information, but an increase in salinity should be concurrent with an increase in the $\delta^{18}O$, so this change in oxygen isotope values must be due to a temperature increase in the area. This is potentially recorded by the Mg:Ca trace element data, but it is difficult to be confident in ascribing any palaeoenvironmental interpretation to this since there is still a lot of spread in the data. This is possibly because the water in the area was very shallow, hence temperature fluctuations would be expected to be great even over the extent of a day. Ostracods form their carapaces from ions taken solely from the water over a very short time after moulting (Turpen and Angell, 1971). Hence the stable isotope and trace element composition of the carapace will only provide a reliable indication of the host water composition at the time and place of formation for the particular ostracod. The $\delta^{18}O$

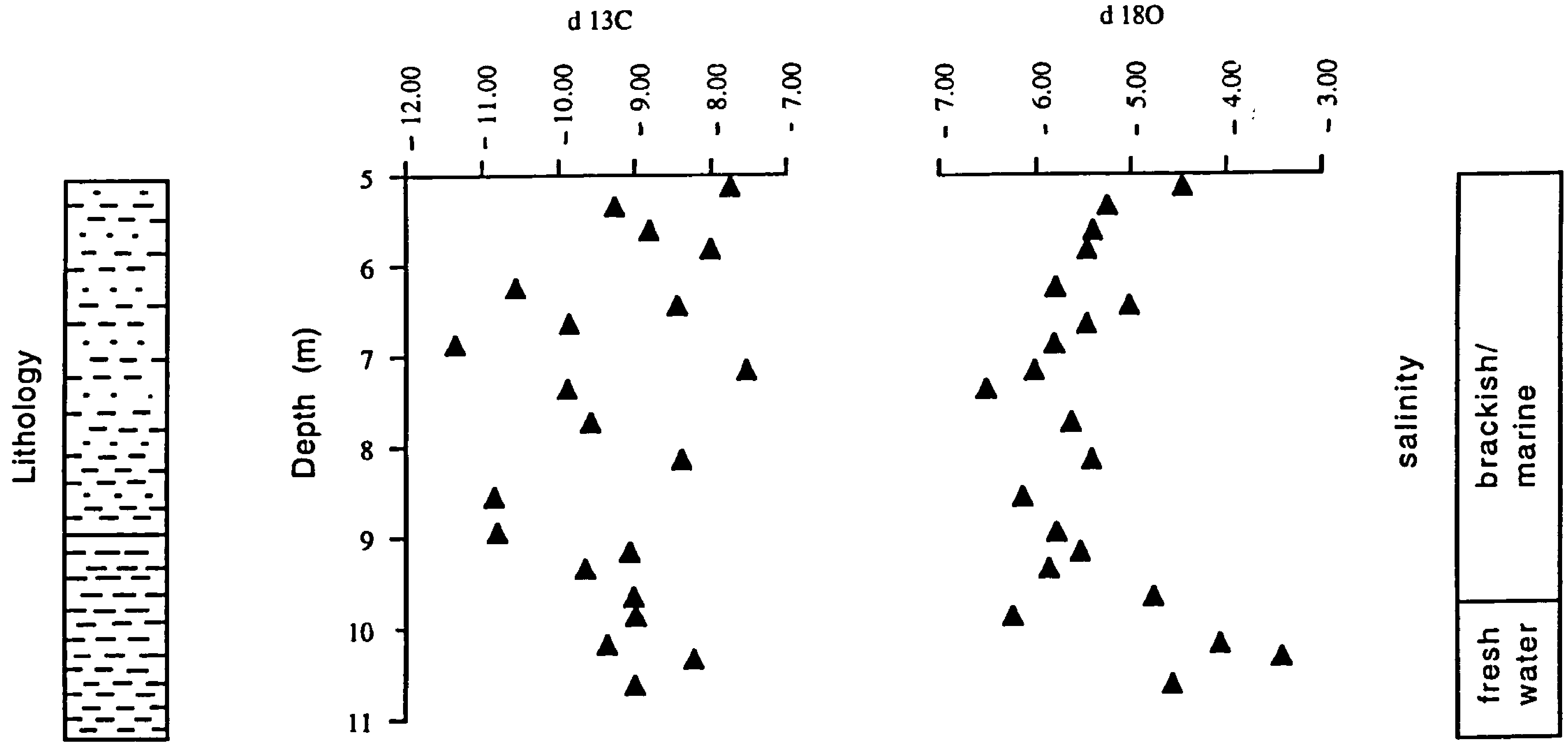


Fig 5.10 Oxygen and carbon isotope trends for BHS1 ($\delta^{18}O$, $\delta^{13}C$, ‰).

would be expected to vary with conditions of freshwater input and evaporation, which would vary often (even daily) in a shallow water body or an estuary.

5.3.2 Carbon isotopes

Fig 5.10 also plots the $\delta^{13}C$ from core S1. The spread of values of $\delta^{13}C$ is between - 11.5‰ and - 7.5‰. Low values of $\delta^{13}C$ are usually indicative of the decay of large amounts of organic matter (Holmes, 1996), which can indicate a freshwater riverine influence in the area. Certain species found down-core live on or around decaying matter, so even though there is no particular trend in the $\delta^{13}C$ data, it still suggests an environmental signal. Large fluctuations in $\delta^{13}C$ are usually due to varying conditions of organic photosynthesis or decay and also exchange with atmospheric CO_2, since the decay of high levels of organic matter will release ^{13}C depleted carbon into the water. Some freshwater species (Table 3) live in association with macrophytes in shallower water, where the photosynthetic uptake of ^{13}C depleted inorganic carbon may produce micro-environments where the total dissolved inorganic carbon (TDIC) of the water is correspondingly enriched.

In comparison with the Inner Silver Pit (Fig 4.13b) values, these data are much more negative. The ostracods analysed from the Shoeburyness core would also have had an infaunal habit, indicating that an even larger amount of decay, and therefore depleted ^{13}C in the pore waters, as would commonly be expected in a riverine/estuarine environment as compared to marine sediments, since productivity and decay tend to be greater in shallower freshwater situations.

No trend is observed between the $\delta^{13}C$ and $\delta^{18}O$ (Fig 5.11), as for the Inner Silver Pit (Fig 4.14), indicating that this was not a closed lake system (cf. Talbot 1990), even in its freshwater phase.

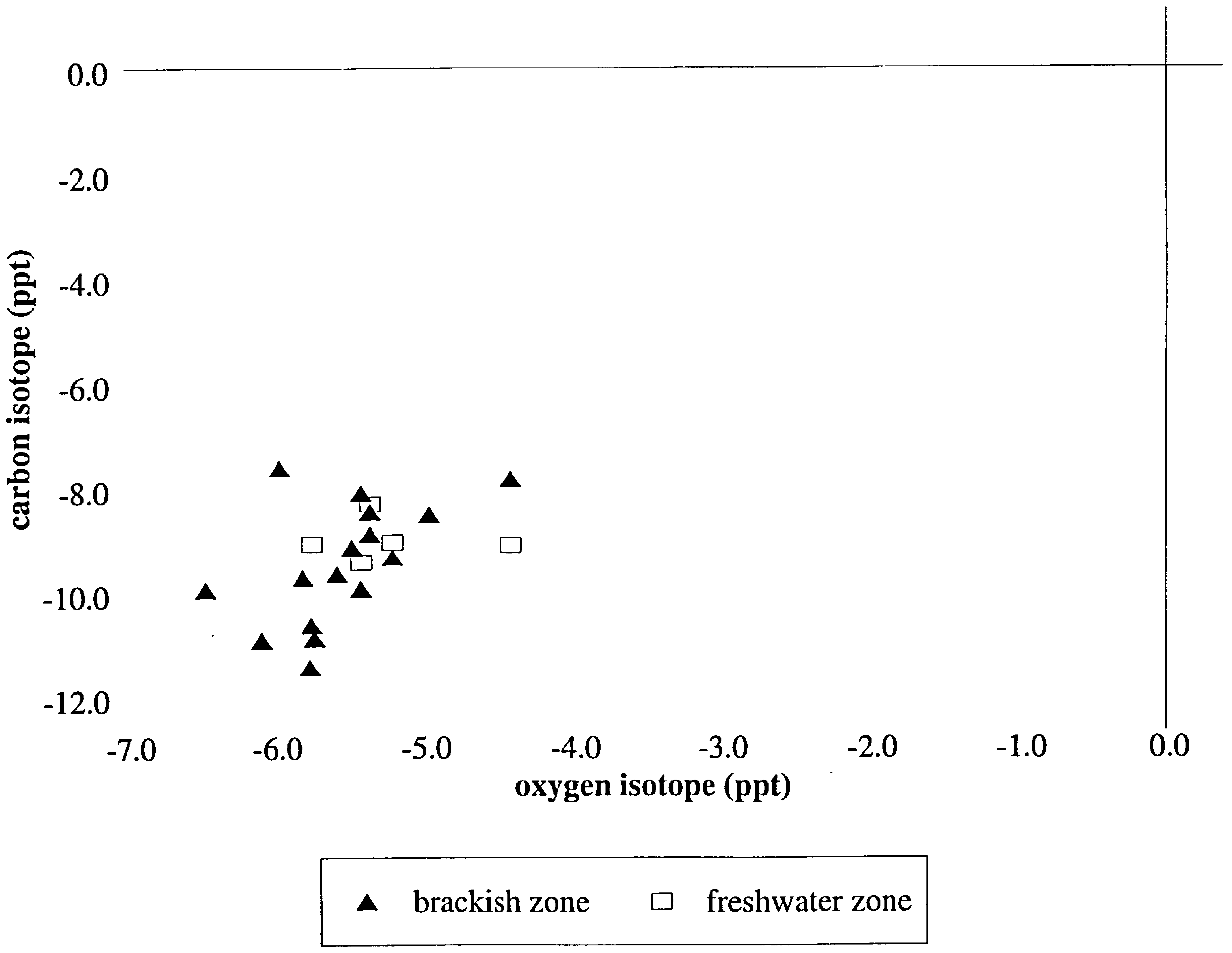


Fig 5.11 $\delta^{13}C$ (‰) and $\delta^{18}O$ (‰) values plotted for BHS1 (axes through 0,0 for reference).

5.4 Summary

The faunal assemblages identified from this site in Shoeburyness conform to a warm stage. The fauna is clearly freshwater and estuarine in character, and is made up of a diverse range of ostracods, foraminifera, molluscs and diatoms. The assemblages record a change from freshwater to more saline conditions at about 10 m down-core. The entire fauna is similar to that found in estuaries on the east coast of Britain at the present day, except for the extinct species of mollusc, *Paladilhia radigueli*, which indicates that the core from Shoeburyness is Middle Pleistocene in age. None of the other species found show a distinct stratigraphic character. The core appeared to have been deposited *in situ*, and showed no sign of reworking.

The trace element geochemistry showed that there was a distinct salinity difference over the core, which correlated well with the observed ecological changes. The isotope data did not tie in with the trace element results.

Chapter 6

Discussion

In this section the palaeontological and geochemical data from the preceding chapters are discussed, and these data are drawn together in a synthesis of the research. In the first part the Inner Silver Pit findings are discussed in the light of other evidence for the area and regionally in the North Sea. The second section addresses the results from Essex in the same way. Finally the linking themes between the two sites are considered.

6.1 Inner Silver Pit

6.1.1 Palaeoenvironmental interpretations

The study of shallow marine Ostracoda from this sediment sequence beneath the North Sea illustrates how palaeoenvironments can be determined by a combined study of palaeoecological and geochemical data. In this case the ostracod assemblage found in the interglacial section of the core was of boreal - Arctic character, found at normal marine salinities, and tolerant of a range of bottom water temperatures (<0 - 15°C). The use of the trace element analyses has contributed further information on the temperature changes that prevailed during deposition of the Sand Hole Formation than would have been apparent from faunal analyses alone. Seasonal effects obviously must be taken into consideration in the shallow marine environment, and these probably account for a significant proportion of the scatter in the data. Shallow seas, such as the North Sea, can typically experience bottom water temperature fluctuations of the order of 10°C from February to August. Little is known about the biology and moulting or developmental behaviour in *Sarsicytheridea*, so it is difficult to determine whether a temperature change of this kind would be reflected in their shell chemistry. Differences in shell chemistry could indicate that individuals are reaching maturity at different times of the year. However, their growth could be restricted to certain temperatures, and therefore, seasons. In a related genus, *Cyprideis torosa*, adults and juveniles overwinter so there is no development in the winter months (Horne, 1983; Athersuch *et al.*, 1989). However, the effect on the population is that some juveniles from the same generation will mature in the autumn, and others do not mature until the following spring, seemingly splitting each generation into two. If *Sarsicytheridea* behaves in the same way, then the trace element analyses will reflect changes in summer bottom water temperatures over the interglacial.

Shallow marine Hoxnian/Holsteinian records are unusual in indicating relatively cool water in the North Sea area in comparison to the Eemian and Holocene. However, pollen evidence from the main part of the Sand Hole Formation (Ansari, 1992; Scourse *et al.*, in press) is clearly indicative of temperate conditions onshore from the Inner Silver Pit. This apparent contrast in climatic conditions could be due to changes in circulation patterns in the North Sea since the Hoxnian/ Holsteinian.

The North Sea plays an important modifying role on the climatic conditions of north west Europe because of the influence of Atlantic water. During periods of glaciations and low sea level stands, the influx of Atlantic water will be minimised because of the breakdown of the thermohaline circulation (Bond, 1995) and, as a result, the continental aspect of the climate in the bordering countries will increase. The Quaternary sediments of the North Sea are thus potentially important for understanding the palaeoceanographic evolution and glacial history of the whole region.

Present day circulation in the North Sea is dominated by a strong influx of waters entering the basin between Scotland and the Shetland Islands, and north of the Shetland islands. These water masses contribute 90% of the water budget of the North Sea (Otto, 1976). Other sources of inflow include the English Channel (*c.* 9%) and the Baltic Sea and river runoff. The outflow from the North Sea is northward along the Norwegian coast to the Norwegian Sea. The bottom temperatures and salinities show almost no seasonal variations in the northern part of the North Sea, with values close to that of the Atlantic water in the Norwegian Sea. The shallow south part is characterised by a large seasonal amplitude in temperature and relatively low salinity (Lee and Ramster, 1981).

Current speculation about the structure of the southern North Sea during the Hoxnian includes the theory that the barrier in the Straits of Dover was breached into the English Channel. This happened, perhaps catastrophically, during the preceding Elsterian/Anglian glacial Stage (Funnell, 1995; Gibbard, 1995 and references therein).

An absence of warm water molluscs in southern North Sea assemblages during the Hoxnian has been observed (Meijer and Preece, 1995) and related to an absence of the warm water input through the Dover Straits during the Hoxnian/Holsteinian, which led to a low diversity (<20 species), cold temperate molluscan assemblage. In southern North Sea sequences, a high proportion of cold temperate boreal species have been found, conforming mostly to the cooler 'Celtic' provinces of Hall (1964). Warm temperate elements were scarce and those that did occur were small and prone to passive dispersal by birds (Meijer and Preece, 1995). Further support for a terrestrial link between Britain and continental mainland Europe during the Hoxnian/ Holsteinian is provided by presence of the so-called 'Rhenish' freshwater mollusc fauna in sediment of that age in Essex and Kent (Roe, 1994; Meijer and Preece, 1995). This fauna has been found at sites in southern Essex, in the Thames, and also in the River Scheldt valley in Belgium. It has been postulated that the land between Britain and continental Europe split the drainage basin of these two rivers from that of the Rhine, since the fauna is not found in the Rhine or in sediment sequences of the river.

The weight of the available evidence indicates that there was no free flow of water from the English Channel into the Southern Bight of the North Sea in the Hoxnian/Holsteinian. However, the presence of a barrier and the evolution of the Dover Strait in the Hoxnian/Holsteinian are unclear (Gibbard, 1995). There are marine deposits at Herzeele in France which suggest that a sea passage may have existed during the maximum interglacial sea level, but it was probably a very narrow opening. If it existed then Lusitanian species would have had the opportunity to migrate northwards into the Southern Bight, and from there into the southern North Sea in the region of the Inner Silver Pit. Since no Lusitanian species have been found (Meijer and Preece, 1995; this study) north of Herzeele, it has been postulated (Roe, 1994; Gibbard, pers. com.) that a physical barrier existed further north, between the Netherlands and Essex.

The ostracod data from this study appear to support the theory that the Dover Strait was not open, or that the Inner Silver Pit region of the southern North Sea had no contact with warmer water from the south, supporting the hypothesis of a land barrier across the southernmost North Sea, between Essex and the Netherlands, at the time of deposition of the Sand Hole Formation. The faunal assemblage found in the interglacial sequence within the Sand Hole Formation is a cold-temperate to boreal one, not found further south than Scandinavia at present. For the latter part of the Hoxnian interglacial represented by the Sand Hole Formation there is no evidence at this site for the migration of a Lusitanian, warm-temperate ostracod or foraminiferal fauna from the English Channel into the central North Sea.

6.1.2 Comparison with other sites

In continental Europe (Fig 6.1), Knudsen and Penney (1987) described Ostracoda and foraminifera from several marine Holsteinian deposits in Denmark. The faunas were similar in the sites throughout Jutland, largely of boreal aspect, and contained a few warm

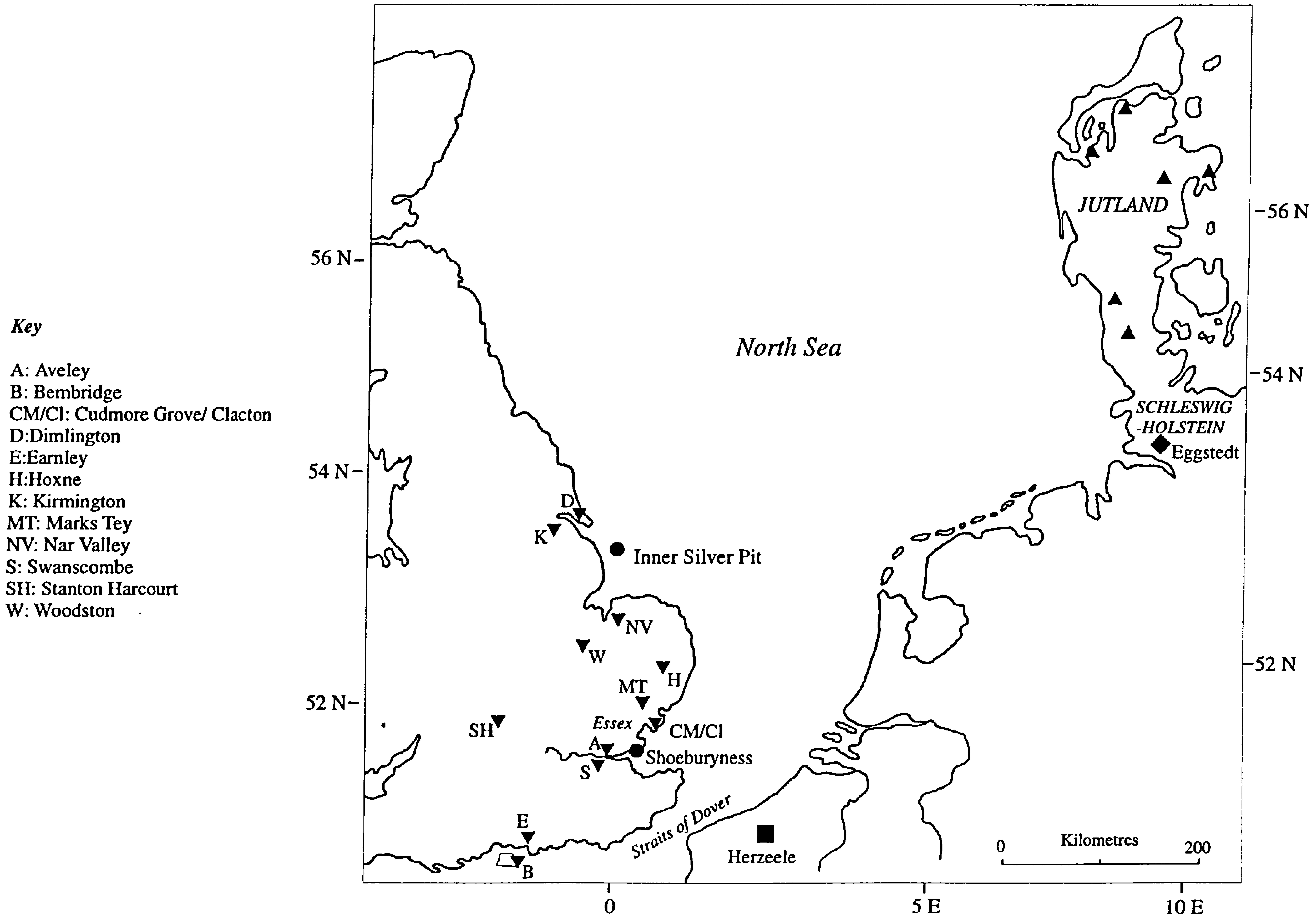
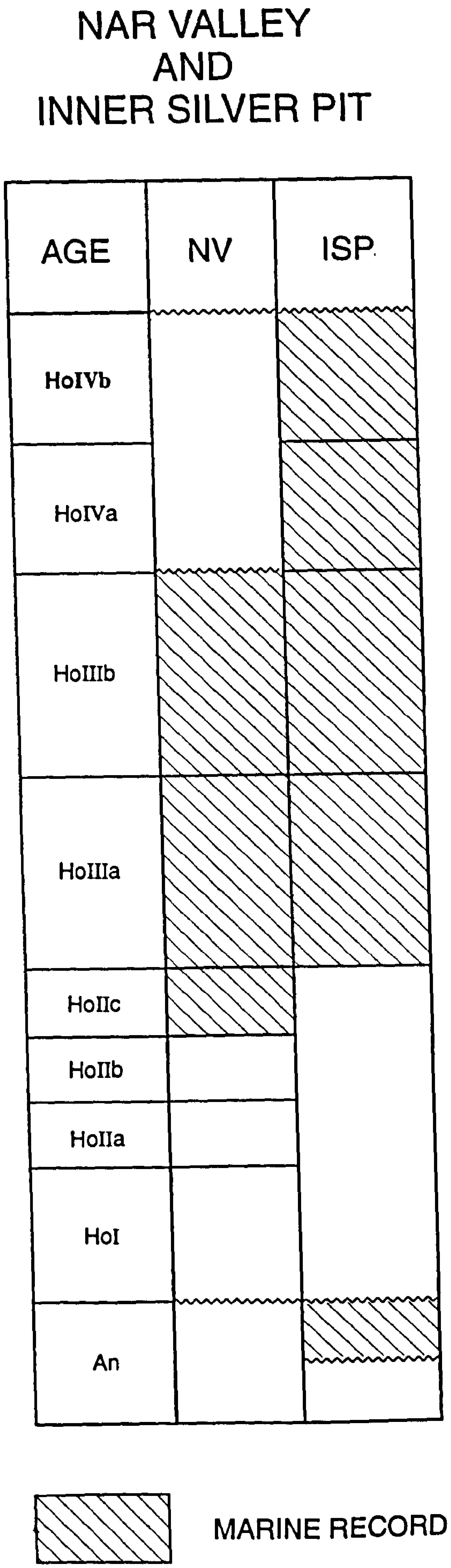

Key
A: Aveley
B: Bembridge
CM/Cl: Cudmore Grove/ Clacton
D:Dimlington
E:Earnley
H:Hoxne
K: Kirmington
MT: Marks Tey
NV: Nar Valley
S: Swanscombe
SH: Stanton Harcourt
W: Woodston
56 N
54 N
52 N
North Sea
JUTLAND
SCHLESWIG
-HOLSTEIN
Eggstedt
Inner Silver Pit
D
K
NV
W
H
MT
Essex
CM/Cl
A
Shoeburyness
S
SH
E
B
Straits of Dover
Herzeele
0
Kilometres
200
0
5 E
10 E

Fig 6.

temperate species. All species were extant, but some are not found in Danish waters at the present day. The cold temperate parts of the Holsteinian faunas found in Denmark are entirely analogous to those found at present. The ostracod assemblage composition of German stratotype Schleswig-Holstein and Eggstedt sites in Northern Germany (Woszidlo, 1962; Lord *et al.*, 1993) is also similar. Important members of the assemblages in Germany and the five sites in Denmark studied by Penney (Knudsen and Penney, 1987) included: *Acanthocythereis dunelmensis*, *Cytheropteron latissimum*, *Elofsonella concinna*, *Palmoconcha guttata*, *Robertsonites tuberculatus*, *Sarsicytheridea punctillata* and *Sarsicytheridea bradii*. However at the Danish sites, in the later part of the interglacial, certain warm-temperate species were observed, including *Carinocythereis whitei*, *Pterygocythereis coronata*, and *Callistocythere* sp.

Of particular interest is the close similarity between the rarer species elements of the ostracod assemblages in Denmark and the Inner Silver Pit. There is a common overlap in the distribution of *Cluthia cluthae* (an Arctic species at present) and its temperate equivalent *Leptocythere*. Moreover the cold temperate species *Cytheropteron latissimum* occurs below the Elsterian- Holsteinian transition in Denmark, and occurs in large concentrations in the glacio-marine sediments of the Swarte Bank Formation (Fig 4.2).

In Britain, both Lord and Robinson (1978) and Mitlehner (1992) have described ostracod assemblages from the Nar Valley in Norfolk. These interglacial deposits have also been correlated with the Hoxnian Stage (Stevens, 1960). Lord and Robinson (1978) found cold temperate species such as *Elofsonella concinna* and *Robertsonites tuberculatus* together with a warm temperate assemblage, dominated mainly by *Carinocythereis whitei* which has been recorded in the Middle Pleistocene deposits at Earnley (Robinson, in West *et al.*, 1984) but has not been found in Ipswichian/Eemian interglacial sediments (Whatley, in Kidson *et al.*, 1978). The assemblages found indicate that at least part of the Nar Valley sequence was deposited in fully marine, cool water (Fig 6.2). Mitlehner (1992) interpreted



NAR VALLEY
AND
INNER SILVER PIT

AGE	NV	ISP
HoIVb		▨
HoIVa		▨
HoIIIb	▨	▨
HoIIIa	▨	▨
HoIIc	▨	
HoIIb		
HoIIa		
HoI		
An		▨

▨ MARINE RECORD

Fig 6.2 Comparison between the marine record in the Nar Valley and the Inner Silve Pit (for extended description see Scourse *et al.*, 199x) the presence of cold temperate species in an otherwise warm assemblage as reflecting a cooling climate towards the close of the Hoxnian Stage. The pollen stratigraphy (Ansari 1992; Scourse *et al.*, in press) from the Inner Silver Pit is correlated with the last two substages of the interglacial; however, only at the top of the final substage (HoIV (Turner, 1970)) would any marked cooling be expected.

The Bridlington Crag at Dimlington, North East England is also conventionally correlated with the Hoxnian/Holsteinian. The ostracod faunas from this site were described by Neale and Howe (1975) who found 22 species, 13 in common with Holsteinian sites in Denmark and Germany, and 8 in common with the present study. The fauna was identified as being native to waters colder than those found off the coast of Britain at the present day. The assemblage found by Neale and Howe (1975) has little in common with that in the Nar Valley Clay (Lord and Robinson, 1978; Mitlehner, 1992), but 73% of the fauna found is equivalent to that found in the Sand Hole Formation.

All the data discussed above are from shallow sub-littoral sites. Very few ostracod studies have been undertaken on such shallow marine interglacial deposits in North West Europe, making correlation between sites very difficult. It appears that the Sand Hole Formation in the Inner Silver Pit contains a fauna which closely matches the Hoxnian/Holsteinian faunas found in Denmark and Germany, and those at onshore sites in eastern Britain. Any evidence of warm elements in the faunal assemblage is lacking and this could either be due to the palaeo-geographical reasons postulated above, or to the fact that the earlier substages of the temperate cycle have not been preserved in the Inner Silver Pit.

6.1.3 Calculation of past temperatures and salinities

The Mg:Ca data suggest that there was a change in the bottom water environment occurring towards the top of the core. This was characterised by a decrease in the Mg:Ca content of the ostracod shells of 0.05 mmol/mol. This can, by the use of the calibration equation, be used as a proxy measure of a concurrent decrease in the bottom water temperature by about 9°C. No change in depth was indicated by the faunal assemblage found in this study, so from the ostracod data it appears that there was a deterioration in climate and no fluctuation in sea level and/or fluvial input. However, foraminiferal evidence (Kristensen *et al.*, 199x) records a marked decrease in water depth towards the top of the interglacial, the boundary of the foraminiferal zone also occurring at 31.50 m, the same depth at which the transition in the ostracod assemblage occurs. If this reduction in water depth occurred, then the decrease in the Mg:Ca values would indicate that the climate had cooled considerably through the interglacial, since shallow water usually warms considerably when the atmospheric temperature is high. At the top of the Sand Hole Formation, the bottom water temperature indicated by the trace element analyses is around 2°C, at present the bottom water temperature at similar depths (*c.* 50 m) in the northern North Sea is *c.* 7°C (Lee, 1980). This appears to denote that there was a concurrent deterioration in climate, with regressive tendency, towards the top of the Sand Hole Formation. At the top of the section of core studied, a transition of the fauna into a boreal-Arctic assemblage may reflect a return to glaciomarine conditions, though significant reworking is apparent. Thus records of Mg content of shallow marine fossil ostracod shells may provide a record of past temperatures. The corollary is that changes due to seasonality, creating changes of magnesium concentrations in solution may also be recorded by the ostracods, creating a small, but significant, salinity effect on the data. However, this variability in the shell composition could be used to advantage if the life cycle and habit preferences were known for the ostracod studied, since it appears that the ostracod shell is recording seasonal effects.

If salinity ranges for the ostracods studied are well known then they may be used to assess whether observed changes in the Mg content of ostracods reflect changes in temperature and/or salinity. *Sarsicytheridea punctillata* and *S. bradii* are restricted to normal marine

(34.5-35.5 ‰) salinity within their extensive latitudinal range, spanning from northern Britain to the Arctic (Table 2). This means that salinity variation is a much less significant factor than temperature in controlling the Mg:Ca ratio in the carapaces of this genus (Fig 4.9).

A potential solution to the uncertainty in the interpretation of the trace element contents of ostracods in general involves the introduction of an independent parameter. The oxygen isotope composition ($\delta^{16}O/\delta^{18}O$) of biogenic calcite varies as a function of the water temperature and salinity (Epstein and Mayeda, 1953). The variation in the latter is essentially due to changing bulk $\delta^{18}O$ content within evaporation and precipitation cycles (Chappell and Shackleton, 1986). Importantly, $\delta^{18}O$ responses are different to those in Mg:Ca partitioning, since an increase in temperature or salinity produces a concurrent increase in the Mg content of the ostracod shell, whereas an increase in temperature produces a decrease in $\delta^{18}O$ of the valve and an increase in salinity leads to an increase in $\delta^{18}O$ (Fig 4.13). The relative contributions of temperature and salinity induced changes to the Mg content of the modern ostracods have been deduced. However, combining $\delta^{18}O$ data with down-core Mg:Ca measurements has the potential to resolve which factor is responsible for changing Mg:Ca ratios and past water mass/ climate could therefore be more confidently elucidated. In this case the oxygen isotope data (Fig 4.14) show that the whole of the section of core studied was deposited under normal marine conditions, so fluctuations in the $\delta^{18}O$ data would therefore be due to seasonal effects on the salinity of the water column or to vital effects at the sediment-water interface.

In contrast to the oxygen isotope ratio in carbonates, the carbon isotope ratio ($^{13}C/^{12}C$) is little affected by temperature variations, but is a response to changes in the ratio of total dissolved inorganic carbon from which the shell forms. This ratio is in turn controlled mainly by primary productivity in the water column, but also by rate of CO_2 exchange with the atmosphere, occurrence of bacterial processes and inputs from the dissolution of carbonates in the water column (McKenzie, 1985). Ostracod shells are formed over a very short amount of time, and therefore produce a temporally restricted record of isotopic composition. Moreover, it has been found (Durazzi, 1977; Xia *et al.*, 1993) that ostracod shells form in near-isotopic equilibrium with the host water, making them an accurate recorder of isotopic composition.

The samples analysed for stable isotopes (Fig 4.14) from the Swarte Bank Formation and the Sand Hole Formation appear to indicate that the majority of the studied section was deposited under normal marine salinities. However, only a single sample was analysed from zone 81/52-4 (Fig 4.2), which from the foraminiferal (Kristensen *et al.*, in press) and ostracod data appeared to mark the transition from temperate conditions into glacio-marine. This was due to lack of material in the samples analysed from that zone, as indicated on Fig 4.2. Contrary to the hypothesis put forward (Fig 4.13) the isotopic composition of the ostracod shells does not record firm evidence of a regressive tendency in sea-level, perhaps due to lack of data above the zone boundary. This is a similar result to those from sedimentary and dinoflagellate analyses (Scourse *et al.*, in press).

6.2 Essex

6.2.1 Palaeoenvironmental information

The ecological information obtained from the study of the ostracod assemblages shows that the sediments in the Shoeburyness channel were first deposited under slowly flowing water or in small ponds, which later developed into a dynamic estuarine setting in which mixing of fresh and brackish water was commonplace. The sequence records an increasing marine influence through time, so that at the top of the core some fully marine species were observed, which must have been washed into the estuary. The pronounced transition between the freshwater fauna and the more brackish assemblage is marked by the replacement of oligohaline and mesohaline species with almost monospecific *Cyprideis* dominated groups. These more saline biofacies are comparable to those found in the seaward reaches of the Thames (Kileyni, 1969). In regions such as these flocculation of clay and silt particles is common, increasing rates of sedimentation, which would help to preserve an ostracod fauna such as the one identified *in situ*.

The palaeobotanical findings for Shoeburyness (Roe, 1994) add further weight to the inferred salinity changes, and also show that the sequence was deposited under fully temperate, forested conditions. At Shoeburyness the vegetational succession (Fig 2.9) is typical of that in the pre-temperate and early-temperate substages of an interglacial. The pollen spectra clearly record the initial invasion of oak and other thermophilous trees into the pine-birch forest present in the area, and the subsequent expansion and dominance of a mixed oak woodland. These periods are not diagnostic of any one interglacial stage (Phillips, 1976); however, certain taxa common to the Middle Pleistocene interglacials, and rare or unheard of in the Late Pleistocene point to a pre-Ipswichian age (Roe, 1994). Roe (1994) concluded that the Shoeburyness sequence compared closely to the Hoxnian parastratotype succession from a lake sequence at Marks Tey (Turner, 1970). The only noticeable difference between the two sequences was the higher proportion of *Pinus* pollen at Shoeburyness; this can be explained in terms of taphonomic variability between lacustrine and fluviatile environments.

The occurrence of *Paralimnocythere compressa* lends evidence that the site is Middle Pleistocene in age, as does the presence of *Paladilhia radigueli* at certain levels downcore. However, apart from this there is little to indicate the precise age of the sediments. The ostracod fauna shows strong similarities with an assemblage recovered from a channel fill at Barling (Roe, unpublished data), 5km north of Shoeburyness. This assemblage comprised a lower freshwater fauna containing *Candona* sp., *Ilyocypris gibba* and *Darwinula stevensoni*, and an upper fauna dominated by *Cyprideis torosa*. However, on palynological grounds this site has provisionally been correlated with the early half of the Ipswichian stage (Roe, pers. comm.).

On the basis of the wide variety of evidence collected for the site at Shoeburyness, there is close agreement as to the environment in which the sediment was deposited. The channel in which the section studied was lain down was inundated as sea-level rose, giving it an estuarine environment. Present day distributions of ostracods in estuaries depend on several major factors; the composite effect of these affects the species habitats. Some are prohibitive factors, such as pollutants and the nature of the sediment (Kileyni, 1969), whilst others influence the composition of the ostracod fauna, like temperature and salinity (for review see Neale, 1965).

6.2.2 Comparisons with other sites

Roe (1994) studied the lithological and palaeontological data from five sites in Essex (Shoeburyness, the Rochford area, North Wick near Southminster, East Hyde near Tillingham and Cudmore Grove, East Mersea). She described seven channel-like depressions which fell into two broad groups; (i) 'high-level' channels, which are filled only with sands and gravels; and (ii) 'low-level' channels, a series of low-lying channels filled with a basal unit of sands and gravels and an overlying sequence of clays. Shoeburyness, Rochford, Burnham, Tillingham and Cudmore Grove channels are assigned to the latter group (Fig 6.3). These low-lying channels appeared to have been formed by rapid fluvial incision, although the depth and orientation of incision varied with the sites (Roe, 1994). After each incision the channels were initially filled with sand and gravels, which then gave way to an accumulation of clays. The lithology of the sediments was similar to those found at the present day in large fluviatile channels or in subtidal and intertidal zones in estuaries.

Each of the sequences (Canewdon, North Wick, East Hyde, Shoeburyness and Cudmore Grove) studied by Roe (1994) showed similar faunal and floral successions, indicating a similar history. A mixed fauna was found at Canewdon and North Wick, suggestive of a transitional environment characterised by fluctuating salinities. The ostracod assemblages from East Hyde (near Tillingham) contained a similar succession to that documented at Shoeburyness, but with high proportions of the phytal associated species *Scottia browniana* in the freshwater section. *Scottia browniana* is believed to have become extinct after the Hoxnian (Kempf, 1971; Robinson, 1979), so a pre-Hoxnian or Hoxnian age can be confidently assigned to the East Hyde sequence. Fig 6.3 shows a summary of the transgressional history, height of the deposits, and comparison to Hoxnian pollen zones (Turner, 1970) in the east Essex area (Roe, 1994; Roe, in press).

The pollen sequences from Canewdon, North Wick and Shoeburyness were not particularly diagnostic of any interglacial stage, although their similarities to other Hoxnian sequences led to their zonation as Hoxnian; however at Cudmore Grove and East Hyde the pollen spectra showed strong similarities to established Hoxnian sequences (Turner, 1970). At Cudmore Grove the sequence was found to document a return to less saline conditions during the latter stages of deposition (Roe, 1994), indicated by a fall in the numbers of *Cyprideis torosa* towards the top of the core and a rise in freshwater species frequencies. The latter were dominated by *Candona neglecta*, with the free-swimming species *Cypridopsis aculeata*. Roe (1994) observed that *Cyprideis* valve frequencies increased again near the uppermost part of the core.

Roe (1994) suggested three alternative palaeogeographical models to explain her litho- and biostratigraphical findings. The first, 'Hypothesis 1', involved channel infilling through one interglacial event, the Hoxnian Stage (Mitchell *et al.*, 1973). The second and third were more complex and involved channel incision and infilling during two glacial-interglacial cycles. The weight of the evidence favoured the first model.

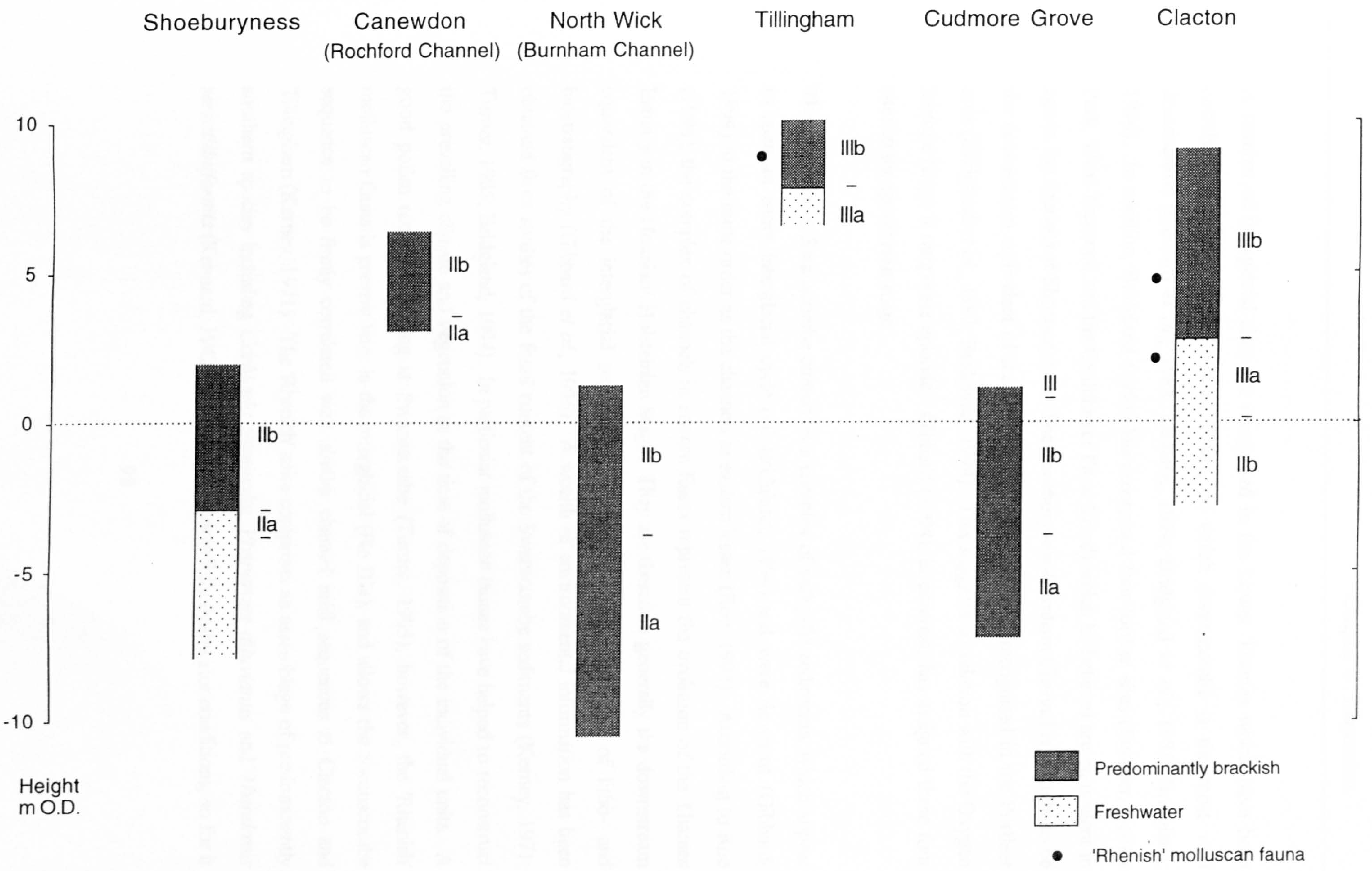


Fig 6.3 Sections indicating the salinity characteristics of the east Essex channels through interglacial time (cf Turner and West, 1968; adapted from Roe, in press).

A number of interglacial sites are recognised in the Lower Thames which have been correlated with the channel-fills of Essex, of which Swanscombe is the most well documented (Gibbard *et al.*, 1988; Gibbard, 1994; Bridgland *et al.*, 1985; Bridgland, 1994). In addition, Bridgland (1994) has recognised four further sites (Purfleet, Belhus Park, West Thurrock and the Cauliflower Pit at Ilford) which he believes are equivalent in age to the deposits at Shoeburyness. The Shoeburyness-Burnham Channel is thought to be the downstream equivalent of the interglacial Thames channel recognised in the Purfleet area (Bridgland *et al.*, 1993; Bridgland, 1994). This suggests correlation with the Oxygen Isotope Stage 9 temperate episode. Gibbard (1994), in contrast, has assigned these four sites to the Ipswichian stage.

The sequence at Swanscombe comprises a complex of valley-fill sediments, which appear to span an entire interglacial cycle (cf. Bridgland, 1994) and were downcut (Gibbard, 1994) to the same order as the channels in eastern Essex (Roe, 1994). According to Roe (1994), the complex of channels in eastern Essex represent the evolution of the Thames Estuary in the Hoxnian/ Holsteinian Stage. They are therefore generally the downstream equivalent of the interglacial sediments at Swanscombe, on the basis of litho- and biostratigraphy (Gibbard *et al.*, 1996). A wealth of environmental information has been obtained from studies of the fossil content of the Swanscombe sediments (Kerney, 1971; Turner, 1985; Bridgland, 1994). In particular molluscan faunas have helped to reconstruct the prevailing climate and vegetation at the time of deposition of the individual units. A good pollen record is lacking at Swanscombe (Turner, 1985); however, the 'Rhenish' molluscan fauna is present later in the interglacial (Ho IIIa), and allows the Swanscombe sequence to be firmly correlated with similar channel infill sequences at Clacton and Tillingham (Kerney, 1971). The 'Rhenish' suite comprises an assemblage of predominantly southern species including *Corbicula fluminalis*, *Viviparous diluvianus* and *Theodoxus serratiliniformis* (Kennard, 1942). This fauna requires fully freshwater conditions, so for it to migrate across the North Sea basin there must have been a fluvial connection. However, it is not recorded in Essex or Swanscombe until well after the initial flooding of the North Sea and isolation of Britain (in stage Ho IIb) (Meijer and Preece, 1995). One explanation is that conditions in channels in Essex were unsuitable for the molluscs survival, since sediments are dominated by fine sediment, the fauna may only have survived in more sandy areas. An alternative explanation (papers in Preece, 1995) is that, later in the interglacial, progradation of the Thames became so great that the estuary became linked with the Scheldt Estuary in Belgium, allowing the 'Rhenish' fauna to migrate.

The most convincing evidence for the age of the Swanscombe sediments has been derived from comparison of its molluscan fauna with that in sediments from Clacton (Kerney, 1971). The channel fill preserved at Clacton is traditionally attributed to the Thames-Medway (full review in Bridgland, 1994) and contains faunal and floral remains indicative of temperate climatic conditions (Ho IIb and III) (Pike and Godwin, 1953; West, 1956; Turner and Kerney, 1971). The Clacton series also yielded the remains of terrestrial, fluvial and marine floras and faunas. These illustrated the environmental history of the river in the early part of the temperate interval (thought to be Hoxnian) and, higher in the sequence, an influx of marine species marked a change to estuarine conditions.

At Clacton, ostracods from a Hoxnian age fluvial-estuarine sedimentary sequence represent a mix of faunal elements (Holmes, 1997) very similar to those identified from Shoeburyness. Holmes (*ibid.*) applied both faunal analyses of ostracod assemblages and trace-element determinations of ostracod shells to sediments from the sequence with the aim of determining the nature and extent of salinity change during the marine transgression previously identified using other palaeoenvironmental indicators (for summaries see Bridgland, 1988, 1994; Gibbard, 1994). It was found that, for the most part, the Clacton sequence was dominated by freshwater forms (such as *Ilyocypris* sp. and *Candona* sp.), although many of these are also tolerant of elevated salinities. In an estuarine environment such as this mixing of faunal elements is common, and Holmes (*ibid.*) concludes that "precise palaeosalinity reconstruction (is) difficult".

Further afield at Woodston, near Peterborough, interglacial sediments deposited under fully temperate conditions in zone II of the Hoxnian interglacial have been described (Horton *et al.*, 1992). These also show evidence of a marine transgression, the ostracod fauna changing rapidly from a *Cypridopsis vidua* and *Herpetocypris reptans* dominated freshwater assemblage to a *Cyprideis* and *Cytheromorpha* brackish fauna. The molluscan fauna consisted of *Hydrobia*, *Mytilus* and *Ostrea* in the upper part of the Woodston Beds, marking the onset of brackish and more saline conditions associated with the marine transgression (Kennard and Woodward, 1922; Horton *et al.*, 1992). The timing of the marine incursion is similar to that in the Nar Valley, however the height of the two deposits is quite different. This can be attributed to (i) a height difference in the Hoxnian; (ii) higher spring tide levels in the valley around Woodston, since the Nar Valley was closer to the sea; (iii) differential post-depositional uplift or tectonic warping between the two sites. Horton *et al.* (1992) summarise that without better dating of sites a more complete picture of Hoxnian sea-level changes could not be obtained, due to the many problems hindering correlation of sites.

At Kirmington, near to the Lincolnshire Wolds, peat associated with estuarine sediments, which overlie glacial deposits, has been referred to as Hoxnian on palynological criteria (Watts, 1959). Molluscs have also been noted in the peat deposit (Stather, 1905; Penny *et al.*, 1972; Catt, 1977), of which the freshwater shells were mostly *Valvata piscinalis* and *Bithynia tentaculata*, indicating the presence of slow moving water and a brackish influence. The estuarine sediments also yielded faunas, including *Cerastoderma edule*, *Mytilus edulis*, *Scrobicularia plana* and *Hydrobia ulvae*, which are comparable with those in the Humber and Essex estuaries at the present day.

Another Pleistocene site which contains an ostracod fauna indicating euryhaline conditions is the Steyne Wood Clay at Bembridge on the Isle of Wight (Preece *et al.*, 1990). The ostracod assemblages here were dominated by leptocytherids, particularly *Leptocythere castanea*, also found in this study; *L. lacertosa*, a euryhaline intertidal species; *L. psammophila*, which is usually found on sandy sediments; and *L. steynewoodensis*, a new species which appeared to be restricted to the Steyne Wood Clay. Also found were many marine and outer estuarine taxa, represented almost exclusively by juvenile valves, which were thought to have undergone *post mortem* transportation (Penney in Preece *et al.*, 1990). The foraminiferal assemblages were also similar to those found at Shoeburyness, being dominated by *Elphidium williamsoni* and *Haynesina germanica.*

At Bembridge, the lusitanean foraminifera species *Aubignyna perlucida* Heron-Allen and Earland (1911) was also a dominant element of the fauna. This species has usually been found in Hoxnian/Holsteinian deposits in the southern North Sea. Assemblages composed entirely of *A. perlucida* are found at Kirmington, Yorkshire (Knudsen, 1980) and it is also common in the Nar Valley Clay in Norfolk (Knudsen, 1980); they were also found in Middle Pleistocene estuarine deposits in Cork Harbour, Ireland (Scourse, pers. comm.) On the continent *Aubignyna perlucida* has been found in the Holsteinian deposits of north west Germany, East Germany and south west Denmark (Knudsen, 1980, 1988). At Cuxhaven and Wacken (in the Schleswig-Holstein, NW Germany) very similar foraminiferal faunas to that in Shoeburyness were found (Knudsen, 1988, 1989). At those sites the presence of *Elphidium albiumbilicatum* was taken to provide indication of slightly ameliorated conditions or the presence of lowered salinities in the area (Lutze, 1965; Knudsen, 1982), both of which would be relevant to its presence at Shoeburyness.

6.3 Synthesis

There is good justification for combining studies of ostracod shell chemistry with detailed palaeoecological work. It is important to understand the ecological range of the species used in trace element work, since environmental conditions in a sediment sequence can change markedly, and certain species may be incapable of tolerating salinities and temperatures outside their preferred range. Engstrom and Nelson (1991) found mixed results for a comparison of reconstructed and measured salinity for Devils Lake, North Dakota (USA). At low salinity (≤10‰) there was good agreement between reconstructed and measured salinity, but the ostracod used, *Candona rawsoni*, seemed unable to record water conditions accurately at higher salinity values. Engstrom and Nelson (1991) suggested that the periods of highest salinity were unfavourable for *C. rawsoni*, which only appeared during brief periods of freshwater input during otherwise quite saline phases.

For this study the ostracods chosen for trace element and stable isotope study were the most abundant in the samples studied from each core. This is not in itself a rational criterion, however, since both *Sarsicytheridea punctillata* and *S. bradii* are quite eurythermal (tolerant of temperatures between about -1 and 19°C), their shells therefore have the potential to record changes in the ambient bottom water temperature. *Cyprideis torosa* is euryhaline (tolerating salinities between 0 and 60‰) so its shell potentially has the capacity to record wide fluctuations in salinity. These criteria allow further justification for the use of these species in this type of study. Large differences in ambient geochemical environment were implied by the ecology of the fossil faunas picked out at each site. However, both cores appeared to record an interesting salinity or temperature history, which was encouraging for the use of geochemical analyses.

In most studies the ultimate aim of using ostracod shell chemistry is to reconstruct the palaeosalinity and palaeotemperature that prevailed at the time the ostracod shells were formed. However, recent research (Holmes, 1996; Xia *et al.*, 1997a, b) has shown that these aims are fraught with difficulty, and the results gained during this study cannot resolve the constraints on the method.

A commonly encountered problem is the non-systematic variation of Mg:Ca and Sr:Ca with salinity. This may arise for several reasons. At Devils Lake, Engstrom and Nelson (1991) and Xia *et al.* (1997b) detected a weak relationship between Sr:Ca and salinity. This resulted from the highly non-conservative behaviour of Sr during salinity changes owing to the precipitation of aragonite, which removes Sr and Ca from the water, and calcite (Engstrom and Nelson, 1991). In contrast a strong relationship was found between Mg:Ca and salinity, making the Mg:Ca in fossil ostracods from Devils Lake a potentially valid indicator of palaeosalinity. However, in other environments (Holmes, 1996) Mg:Ca has been found to be a poor proxy for palaeosalinity, and other studies (Anadon *et al.*, 1994; Chivas *et al.*, 1993) have concluded that the trace element contents are not direct indicators of temperature or salinity, but depend on a complex set of factors, including: salinity, temperature, Mg, Ca and Sr concentrations, carbonate precipitation, anomalous trace element inputs and non-equilibrium uptake of Mg and Sr when the shells are formed.

Due to the problems outlined above, $\delta^{18}O$ may sometimes provide a better indication of salinity (Holmes, 1996) than trace element chemistry. A number of studies (Gasse *et al.*, 1987; Chivas *et al.*, 1993; Curtis and Hodell, 1993; Anadon *et al.*, 1994; Xia *et al.*, 1997a, b) have now addressed both factors in coupled analyses of trace elements and stable isotopes. These also elucidated various results, which must have been due to the environmental setting of the sites selected for analysis, but, overall, each study concluded that a multidisciplinary approach gave the best data, from which more confident assumptions could be made about palaeoenvironmental change. This approach was adopted for both sites studied herein with variable results. In the Inner Silver Pit temperature change over the length of the core sampled was inferred by the fossil ecology (this study; Ingram, in press; Kristensen *et al.*, in press), so the temperature proxy signal from Mg:Ca was closely examined, with stable isotope results potentially acting as a secondary measure of any temperature change; whereas in Essex the site chosen exhibited an obvious freshwater to brackish transition up-core, leading the study towards the salinity proxy previously observed in Sr:Ca ratios, and an independent salinty signal from $\delta^{18}O$ since no temperature changes were inferred by the fossil ecology. The attempt to link trace element to stable isotope data was made in order that the methods could be assessed both in conjunction with the ecological data, and as a tool independent of it, in unstable estuarine and shelf sea environments.

DeDeckker (1997) has stated that the water chemistry is a much more important factor than biogeography in determining the composition of the ostracod calcite and controlling ostracod distribution. The ostracod shell is made of low Mg-calcite, a mineral in which a certain amount of Mg replaces calcium in the lattice. However, ostracods appear to form their shells out of equilibrium with the water chemistry, and are also affected by the temperature of the water. DeDeckker and colleagues (1997) have found that a temperature increase of around 3°C has a larger effect on the uptake of Mg in the shell than a similar change in water chemistry. DeDeckker (pers. comm.) has advised that in order to verify the analyses of ostracod shell chemistry aragonite and calcite within a system (eg, from the same level in a core) could be analysed:

ostracod calcite	-	Sr	-	Sr:Ca
	-	Mg	-	Mg:Ca
			-	T°C
aragonite	-	Sr	-	T°C
(e.g. mollusc, *Psidium*)			-	Sr:Ca
	-	Mg	-	Mg:Ca

As this summary shows, the information gained from such analyses would allow more accurate calculation of temperature dependent on knowledge of the partition coefficient for the particular species being examined. If these investigations were carried out at the same time as stable isotope analyses then this should give a good temperature signal. At the sites investigated in this study sizeable and consistent molluscan faunas were not found. In BH81/52A fragments of molluscs, probably *Nuculana pernula,* were only found above 31.00m (Peacock, pers. comm.). Macrofaunal work was abandoned on the core due to the paucity of shell material, although the occurrence of *Nuculana pernula,* a cool temperate to Arctic species no longer found in the southern North Sea, did lend some ecological information about the core above 31.00m. In the Shoeburyness core mollusc shells were in low abundance at various levels in the core, but concentrated in the shorter freshwater section (Ch.5), and were mostly the very small *Paladhilia.* There was no other source of aragonite in either core.

This study has shown that trace element results can successfully be used to elucidate the previous climate history in an area. In the case of the Inner Silver Pit the temperature signal proved strongest, as was hypothesised, and the Mg:Ca ratio in the ostracod shells appeared to indicate a similar temperature change over time to that which had been observed in the palaeobotanical and palaeoecological data. In Essex the environmental setting was considerably different, with the ecology indicating a freshwater to brackish transition over the core as happens in the development of an estuary. In this case the Sr:Ca and Mg:Ca signals were both weak (Ch.5) but with a positive change up-core so, as in other studies (DeDeckker *et al.*, 1988; Chivas *et al.*, 1986a, 1993; Holmes, 1996), this was thought to represent salinity change over time, equivalent to that indicated by the ecology.

However, throughout most of the record in these two cases, the isotope data did not correlate well with the environmental and trace element trends and interpretations. Xia *et al.* (1997a) discuss the impact of 'vital effects' or biological factors causing non-equilibrium fractionation of stable isotopes in ostracod shells. Variability in shell composition can also be caused by physiological conditions within a population. Xia *et al.* (1997a) cultured a single species of ostracod, *Candona rawsoni*, under controlled laboratory conditions in order to determine its isotopic fractionation behaviour. They found that there was a clear and consistent temperature dependence of oxygen isotope fractionation during biological calcification by *C. rawsoni* (Xia *et al.*, 1997a, Fig. 3). The regression lines through the data show that the culture at 15°C is nearly parallel to that at 25°C but is shifted upward by about 2‰. This type of disequilibrium fractionation in biogenic carbonates has also been discussed by many other workers, mainly with reference to planktonic foraminifera (e.g. Shackleton *et al.*, 1973; Duplessey *et al.*, 1981; Erez and Luz, 1983), but also more recently with benthic species (McCorkle *et al.*, 1990). Erez and Luz (1983) suggested several explanations for the observed disequilibria: (a) authors have made incorrect assumptions regarding water temperature and isotopic composition, (b) many isotopic analyses on foraminifera include large amounts of organic matter that is hard to remove, and (c) non-equilibrium values often occur in the early stages of growth when metabolic activity is more intense (Berger *et al.*, 1978). Metabolic growth rates are known to be faster at higher temperatures, within reasonable limits, which could contribute to disequilibrium. For ostracods Chivas *et al.* (1983, 1986b) found shell weight to be a good proxy for the degree of calcification, and advised avoidance of the use of juvenile valves in trace element and stable isotope studies, which was followed in this research. No juvenile valves were selected, and damaged valves were generally avoided.

It is likely that the unexpected decrease in oxygen isotope values observed in the Essex data was due to some type of 'vital effect' (biological process such as use of isotopically light carbon-oxygen compounds derived from the metabolic CO_2 pool within the organism (Grossman, 1984, 1987)) or to a microhabitat effect (due to the variations in the habitat of different individuals, i.e. including infaunal habits) rather than an increase in temperature upcore. If vital effects are the cause of the variation then it would be expected that the

$\delta^{18}O$ and $\delta^{13}C$ isotopic compositions of the shell would become more negative (Grossman, 1987; McCorkle *et al.*, 1990; Corfield, 1995). However, since only well calcified, adult valves were used for the analyses, and ostracod valves do not have a lot of adhering organic material, it remains difficult to explain. The values obtained are similar to those that would be expected at British latitudes at the present day (Gat, 1980), and the pollen evidence points to ameliorating and not deteriorating climate changes (Roe, 1994).

In moderate climate zones von Grafenstein *et al.* (1997) have used high resolution records of the oxygen isotope composition of benthic ostracods to reconstruct the oxygen isotope composition of lake water ($\delta^{18}O_L$). However, they found that for *Candona* spp. and *Cytherissa lacustris*, the isotopic signature of ostracod valves, in addition to the $\delta^{18}O_L$, is influenced by vital offsets and by physical conditions during valve formation. Von Grafenstein *et al.* (1997) made an extensive collection of living material over the period of a year from two lakes in southern Germany. They analysed valves of individual adults and of several individuals of each instar (amount dependent on size). The isotopic compositions were compared to that of theoretical calcite ($\delta^{18}O_{EQ}$) formed in equilibrium with $\delta^{18}O_L$ and the water temperature. It was found that the effect of evaporation from the lake created an effective richness in $\delta^{18}O$ in the calcite. Differing temperatures were found to create differences of 5-6‰ in $\delta^{18}O$. The offsets reported were in perfect agreement with reported intra-specific differences (Xia *et al.*, 1997a). Their study also provided new information on seasonality of valve formation in these species. Von Grafenstein (pers. comm.) has also found that stressed situations (such as differing temperatures or salinities) can create strange $\delta^{13}C$ and $\delta^{18}O$ records with decreasing values by up to 4‰, similar to the data obtained from analyses on *Cyprideis* from Shoeburyness.

Another explanation for the atypical data from Essex could be the possible seasonal temperature effects on $\delta^{18}O$. *Cyprideis torosa* is well studied and is known to have one generation per year, with no development during the winter months (Horne, 1983). Over-wintering populations of adults and juveniles give rise to a large adult populations in spring; then the over-wintering adults and newly maturing juveniles produce new generations which overlap in time, and can lead to some individuals reaching maturity in the autumn, while others hatching later in the spring do not mature until the following year. In a fossil population it is impossible to tell what time of year the adult shells formed, leaving open the possibility that in a shallow water environment, such as that postulated for Essex, the valves analysed may have matured under quite different temperature regimes.

This study has attempted to use a multidisciplinary approach to elucidate the climate history of two cores thought to be of similar age from the southern North Sea area. The proposal that geochemical techniques carried out on the calcite shells of ostracods could be used to elicit information on temperature and salinity changes has been addressed. However, as discussed above, there are many ways in which the data could have been altered and, therefore, there are many other ways in which the results could be interpreted other than those presented in this thesis.

Chapter 7

Conclusions and further research

7.1 Conclusions

This study has examined two sites in the southern North Sea area, one fully marine, and the other demonstrating a freshwater to brackish transition upcore. The following findings have emerged:

(a) Inner Silver Pit:

1. The ostracod fauna from the interglacial section of the Sand Hole Formation indicates a cold-temperate, boreal climate, with bottom water temperatures of between 0 and 10°C, and of normal marine salinity. The fauna consisted of *Sarsicytheridea punctillata*, *S. bradii*, *Acanthocythereis dunelmensis*, *Cluthia cluthae* and *Elofsonella concinna* during the interglacial, with significant frequencies of *Robertsonites tuberculatus* and *Cytheropteron latissimum* toward the base of the section studied. This is an unusually 'cold' fauna for interglacial conditions in the southern North Sea, indicating that climatic conditions were considerably different from those encountered today. This might be attributable to a change in the circulation pattern of the North Sea, controlled by the presence of land bridge between Essex and the Netherlands.

2. The faunal assemblage closely matches those from Holsteinian sites in Denmark and in northern Germany, and also Hoxnian sites in eastern Britain. This affirms the hypothesis that the upper part of the Sand Hole Formation is an interglacial deposit of Hoxnian/Holsteinian age.

3. The shallow marine ostracod genus *Sarsicytheridea* shows some promise for trace element analyses, yielding a positive correlation between Mg:Ca and temperature, previously observed in non-marine and deep sea ostracod species. The potential for the use of ostracod shells as a proxy for bottom water temperature would be greatly enhanced by knowledge of the life histories and seasonal development of modern ostracod genera.

4. Trace element trends in the Sand Hole Formation appear to show a deterioration in climate from 36.50 m to the top of the Sand Hole Formation, equivalent to a decrease in bottom water temperature of 9°C.

5. The stable isotope data ($\delta^{13}C$ and $\delta^{18}O$) indicate that the Sand Hole Formation was deposited under normal marine conditions. No regressive tendency is marked by the ostracod isotope data at the top of the core.

(b) Essex:

1. The ostracod assemblages obtained from the channel fill sediment at Shoeburyness exhibit a freshwater to brackish transition, indicative of transgressive tidal conditions, which occurs at about 10 m downcore. The dominant species in the freshwater section were the bottom crawling *Darwinula stevensoni*, various species of *Ilyocypris* and *Limnocythere inopinata*. This changed to a *Cyprideis torosa* dominated, low diversity fauna with significant percentages of the brackish species *Cytheromorpha fuscata*. This type of assemblage transition is common as estuaries develop.

2. The ostracod assemblages did not contain any stratigraphic markers, however, the extinct hydrobiid mollusc *Paladilhia radigueli* was found at a couple of levels in the brackish section of the core. This is a Middle Pleistocene indicator species (Preece, pers.

comm.). Other fossil remains included a number of brackish foraminifera, *Ammonia becarii* and *Elphidium* sp., and some large diatomaceous discs.

3. Trace element analyses on specimens of *Cyprideis torosa* elucidated variable results. From the ecological information it was obvious that the freshwater to brackish transition should be recorded by the ostracod shells. A strong trend in the Sr:Ca data was observed. This was correlated to the salinity change suggested by the faunal assemblages. The Mg:Ca data did not show any trends, probably due to the temperature dependence of Mg^{2+} uptake in ostracod shells and the very shallow estuarine setting.

4. The stable isotope data were difficult to interpret, and did not add to the palaeoecological and trace element explanations of the site.

7.2 Further research

There are several possibilities for development of this type of research:

1. Detailed ecological data are required for more species and geographical localities and over extended periods of time at single locations. These data would include information on the habitat preferences of ostracod species as well as life histories (life cycles, seasonality). For most regions of the world little is known of the ecological controls on the ostracod distribution which could be transferred into interpreting fossil assemblages.

2. Standardisation of experimental methods among ostracod specialists could contribute to the development of method and a more rigorous understanding of what partition coefficients (K_D) and trace element ratios imply.

3. Additional chemical analyses of numerous ostracod species from a range of environments are required to determine the temperature dependence of Mg^{2+} uptake, and the salinity dependence of Sr^{2+}. This in turn will be useful to reconstruct palaeoenvironment curves from sediment records.

4. In-situ studies on aquarium-reared ostracod species would contribute to information on the differential uptake of trace elements and stable isotopes into the carapace. This would also provide a method for parameterisation of 'vital effects'

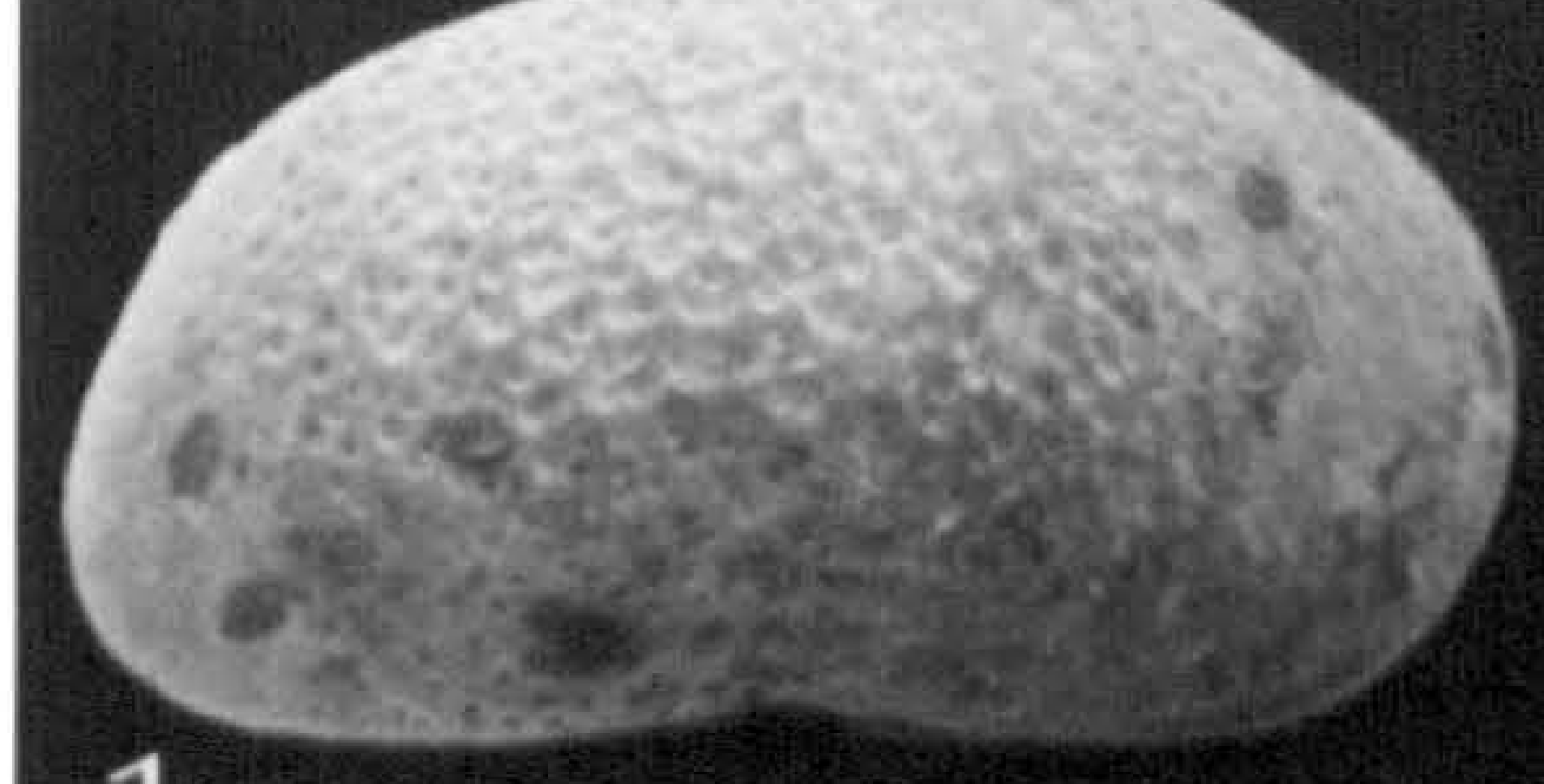
5. The most fruitful approach with fossil ostracod studies can be achieved through the simultaneous analysis of multiple proxies (faunal, trace elements, stable isotopes). Using all possible approaches together should provide the best chance of quantitatively inferring climate change from fossil ostracods.

Appendix 1

Plates

Plate 1. The most common species found in the Inner Silver Pit interglacial sequence

1. *Sarsicytheridea punctillata*(Brady), ♂ RV, ext; x121
2. *S. punctillata* (Brady), ♀ LV, ext; x121
3. *S. punctillata* (Brady), A-1 LV, ext; x121
4. *S. punctillata* (Brady), A-2 RV, ext; x121
5. *S. punctillata* (Brady), A-3 LV, ext; x121
6. *S. punctillata* (Brady), A-4 RV, ext; x121
7. *S. punctillata* (Brady), A-5 LV, ext; x121
8. *S. punctillata* (Brady), A-6 LV, ext; x121
9. *Acanthocythereis dunelmensis* (Norman), ♀ LV, ext; x99.4
10. *A. dunelmensis* (Norman), A-1 RV, ext; x99.4
11. *A. dunelmensis* (Norman), A-3 RV, ext; x99.4
12. *A. dunelmensis* (Norman), A-5 RV, ext; x99.4
13. *Cluthia cluthae* (Brady, Crosskey and Robertson), A RV, ext; x123
14. *Sarsicytheridea bradii* (Norman), ♀ LV, ext; x99
15. *Elofsonella concinna* (Jones), ♂ LV, ext; x99
16. *Sclerochilus contortus* (Norman), A RV, ext; x123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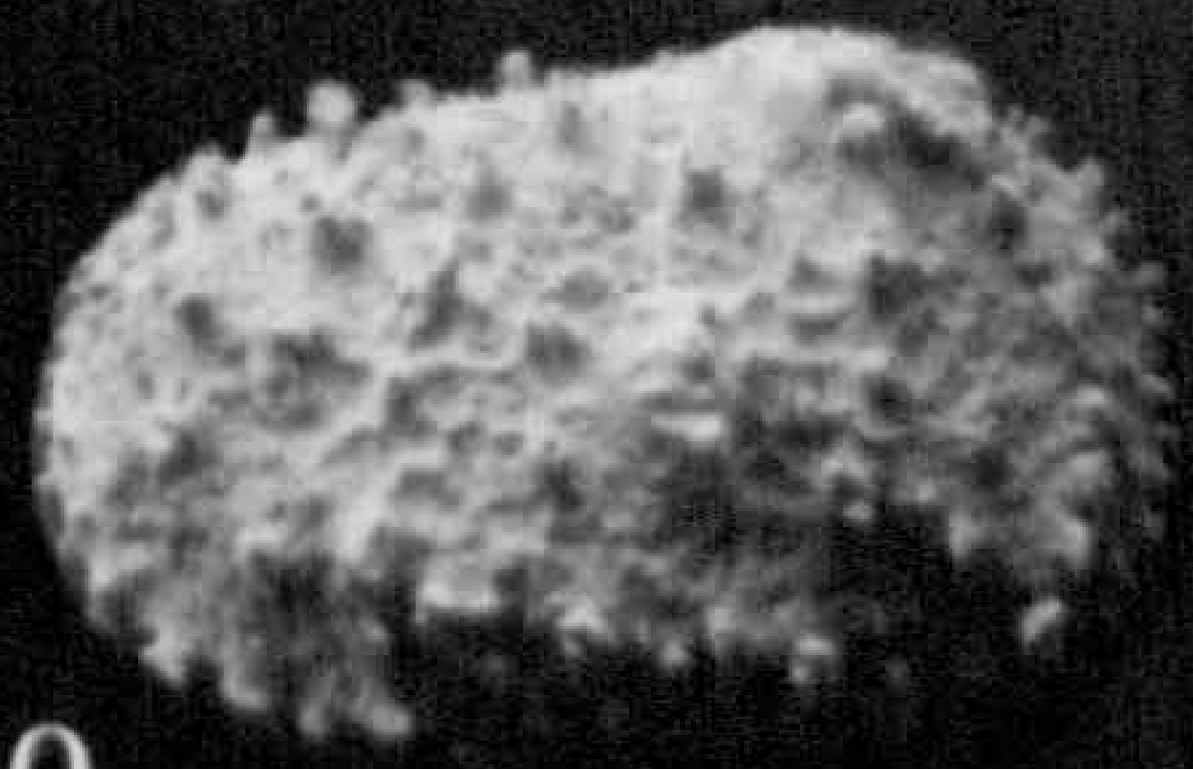
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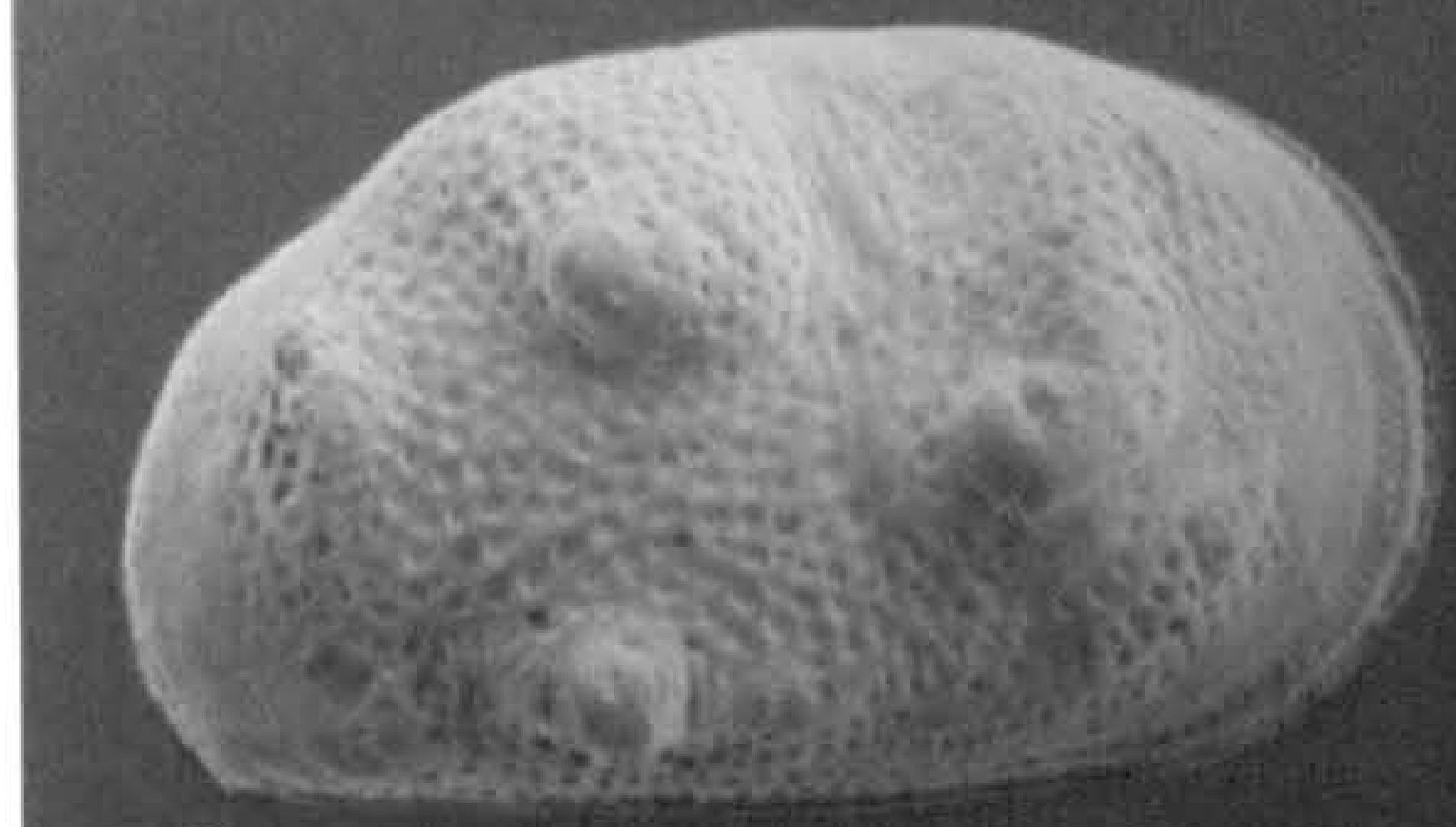
Plate 2. Most common species found in Shoeburyness, Essex interglacial sequence (all views external)

1. *Cyprideis torosa* (Jones), ♀ RV; x95 (noded)
2. *C. torosa* (Jones), ♂ RV; x90 (smooth)
3. *C. torosa* (Jones), A-1 LV; x100 (smooth)
4. *Cyprideis torosa* (Jones), LV; x300 (posterior spine)
5. *Cytheromorpha fuscata* (Brady), ♂ RV; x124
6. *C. fuscata* (Brady), ♀ LV; x124
7. *C. fuscata* (Brady), juv. (?A-5) RV; x124
8. *Limnocythere inopinata* (Baird), ♂ RV; x124
9. *Limnocythere inopinata* (Baird), ♀ LV; x124
10. *Cytherissa lacustris* (Sars), A RV; x124
11. *Ilyocypris gibba* (Rahmdor), A LV; x124
12. *Ammonia becarii var. limnetes.*
13. Diatom disc, convex side (real size ≈ 200 μm)
14. Diatom disc, concave side
15. *Elphidium earlandi.*



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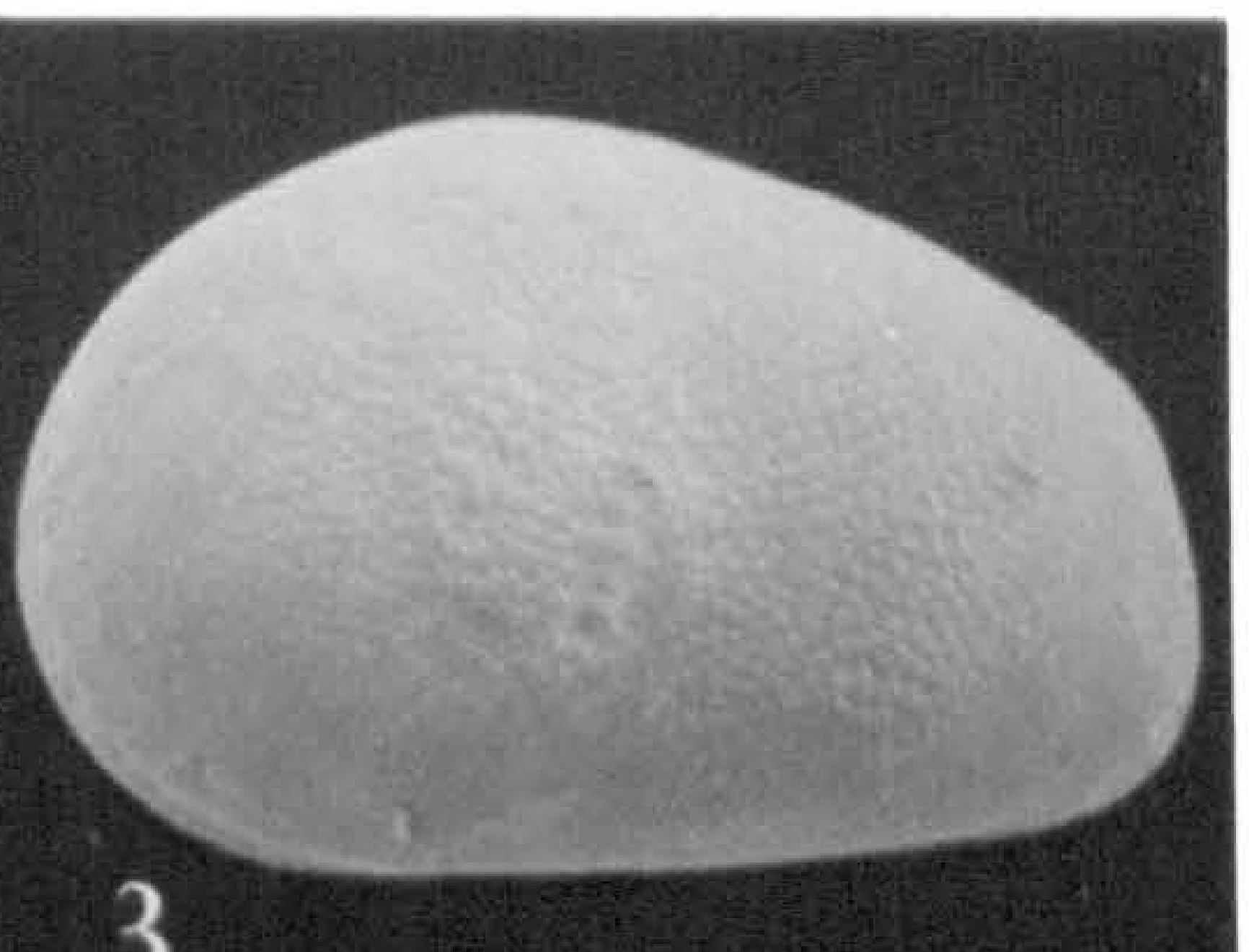

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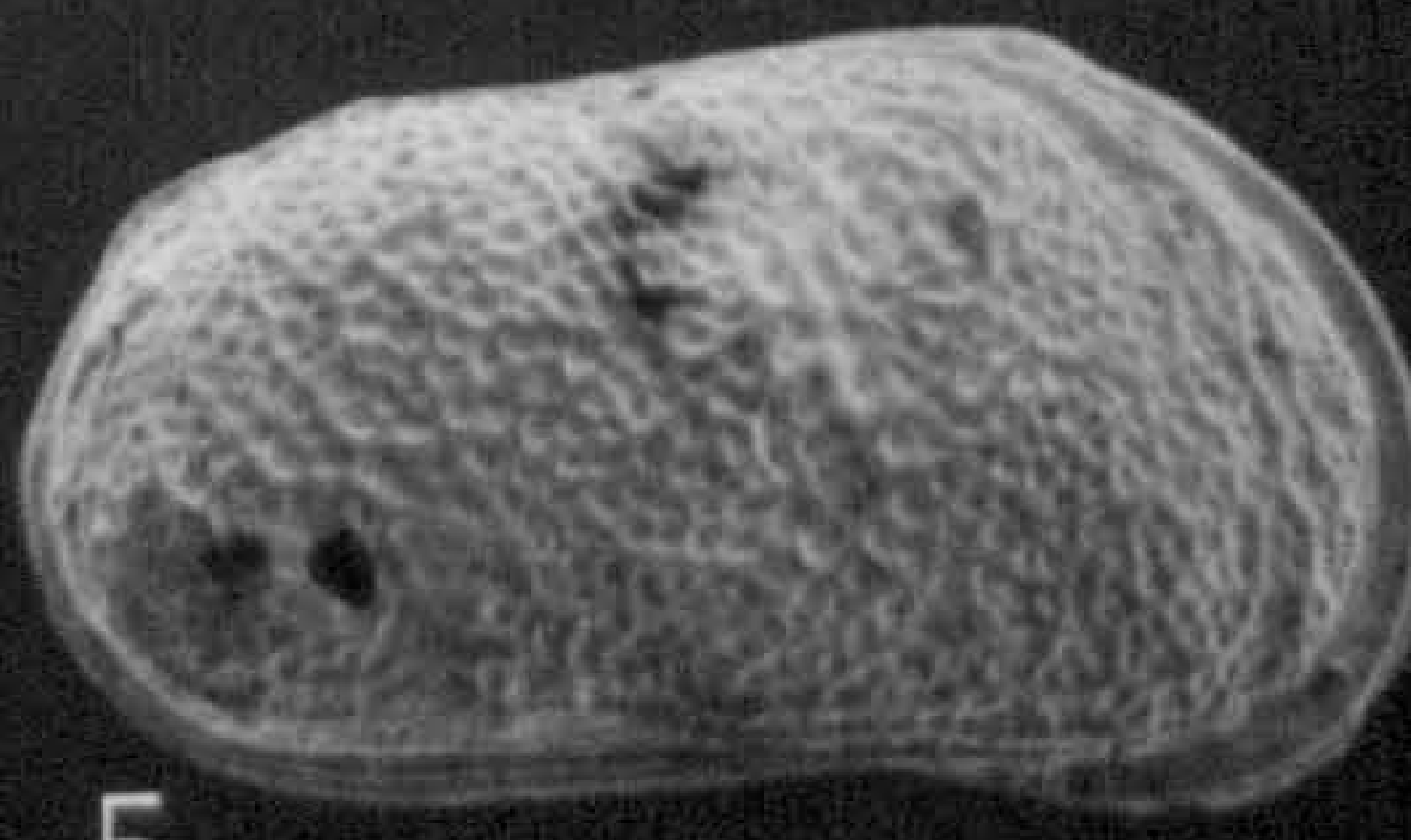

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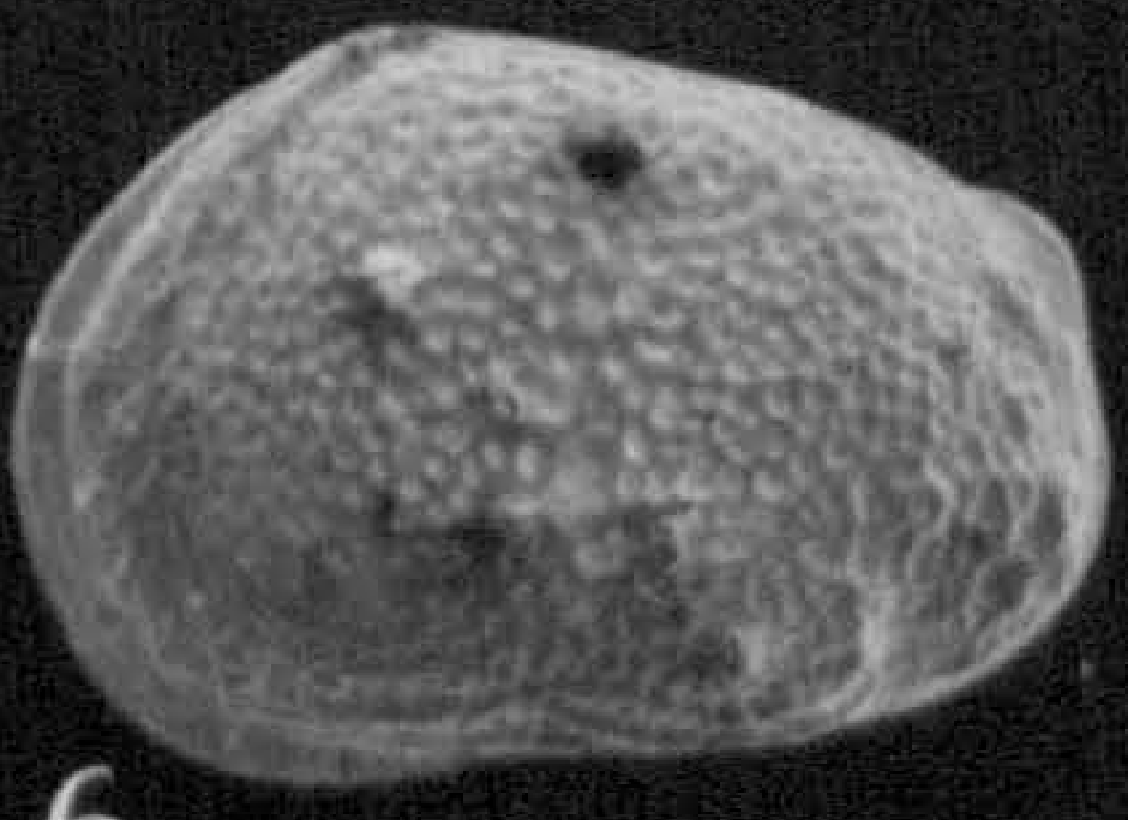

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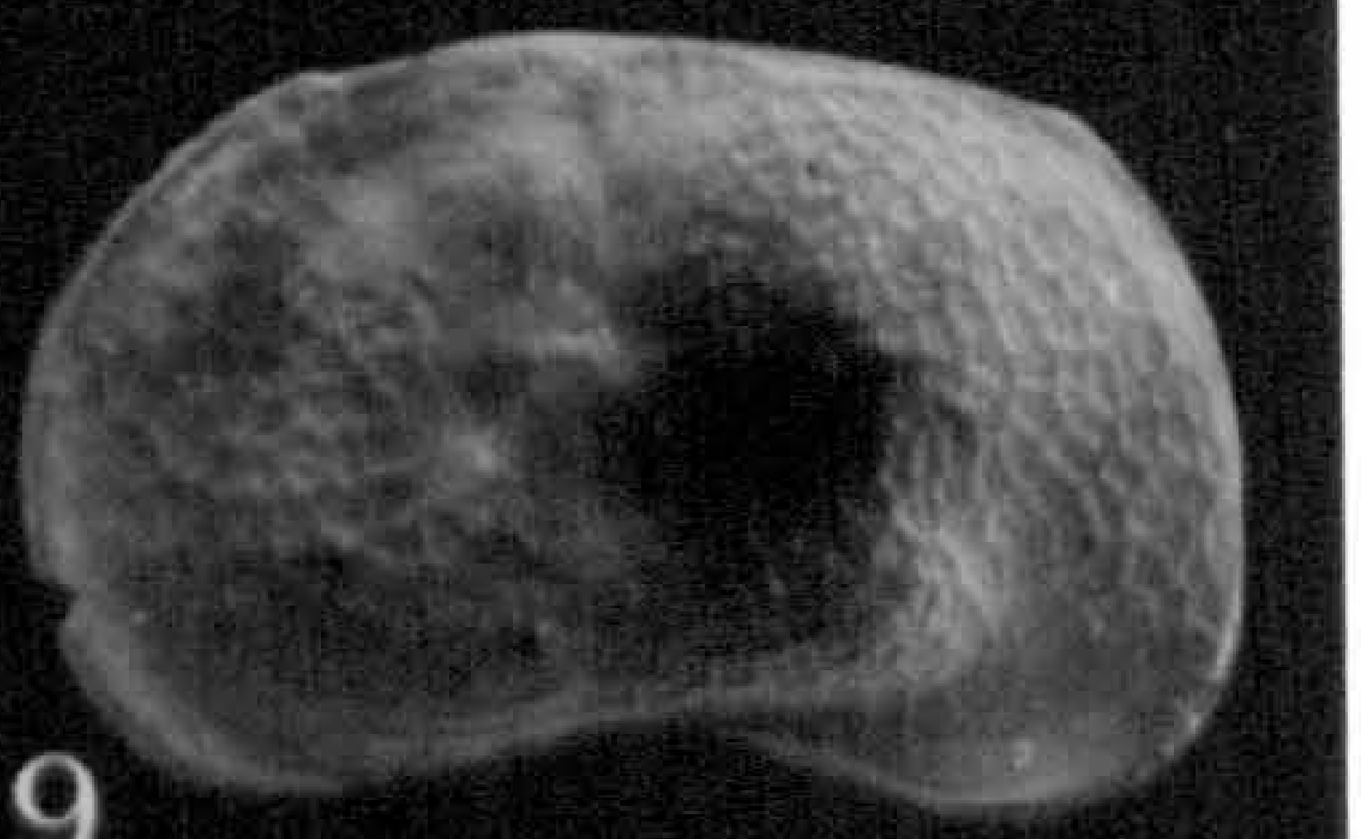

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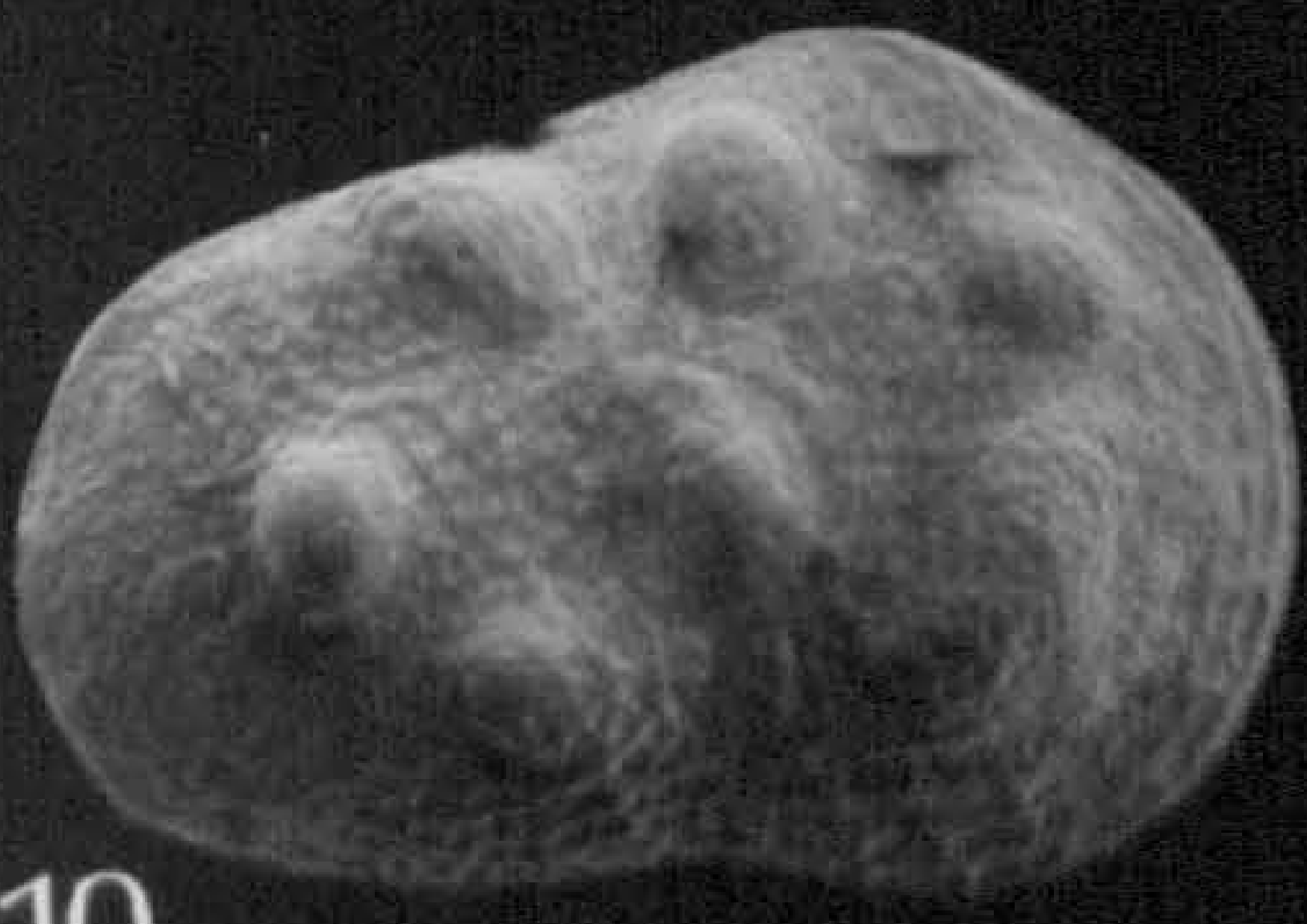

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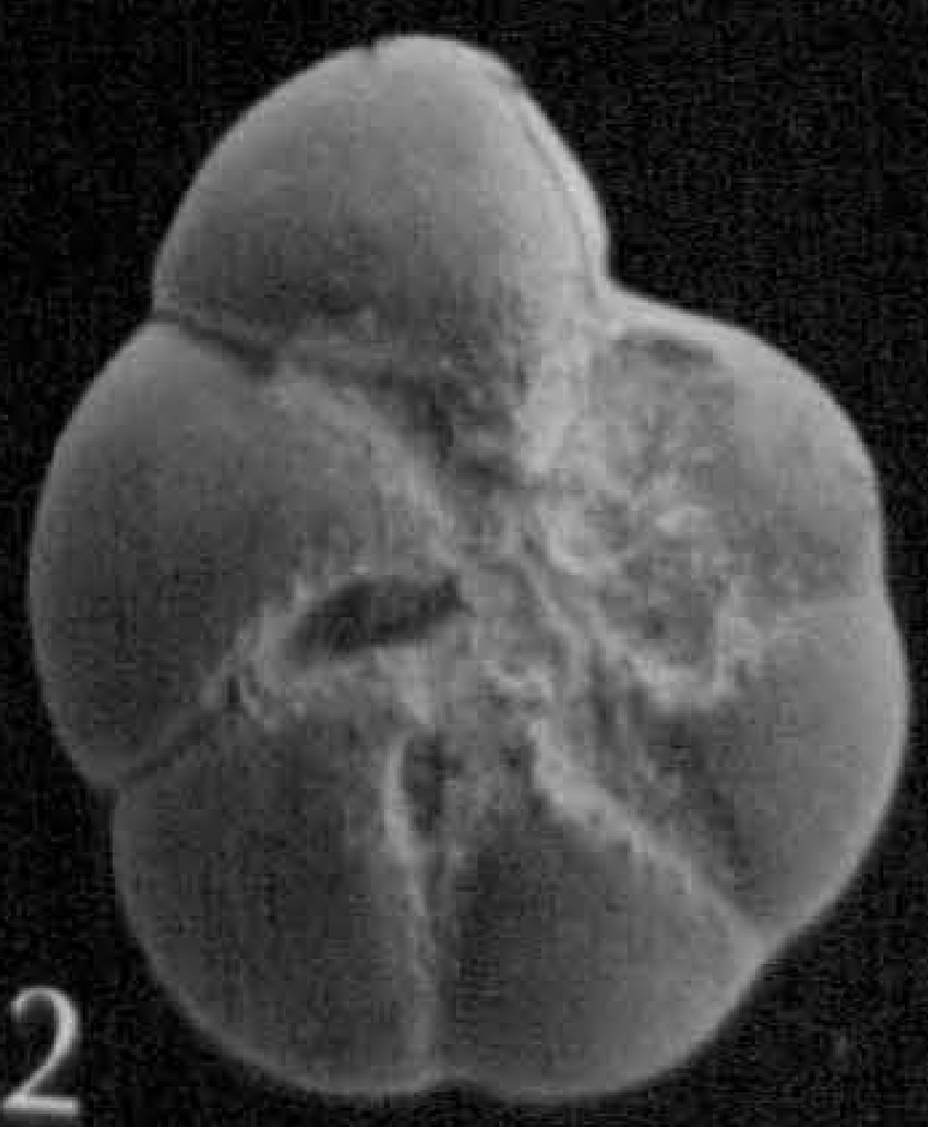

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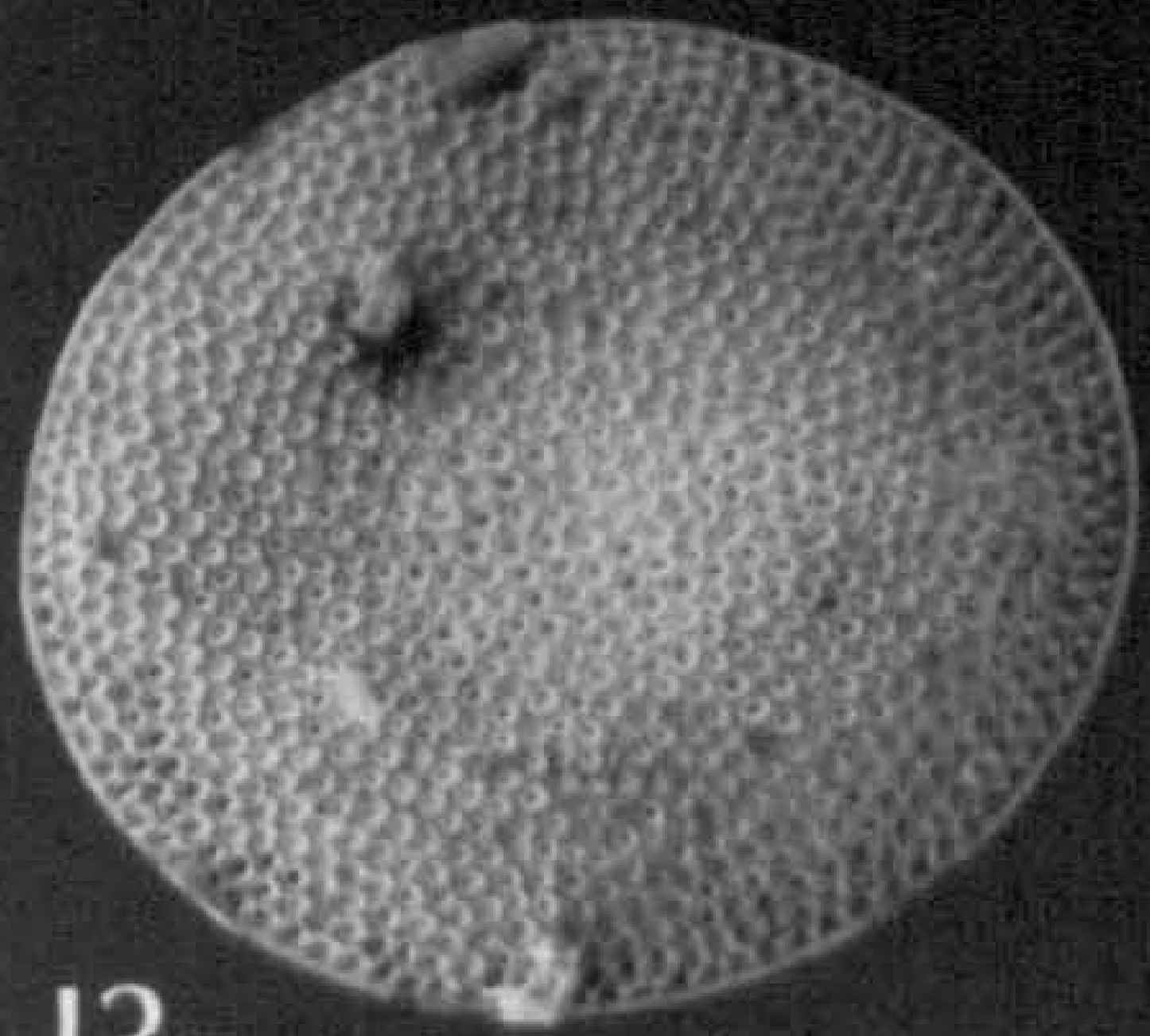

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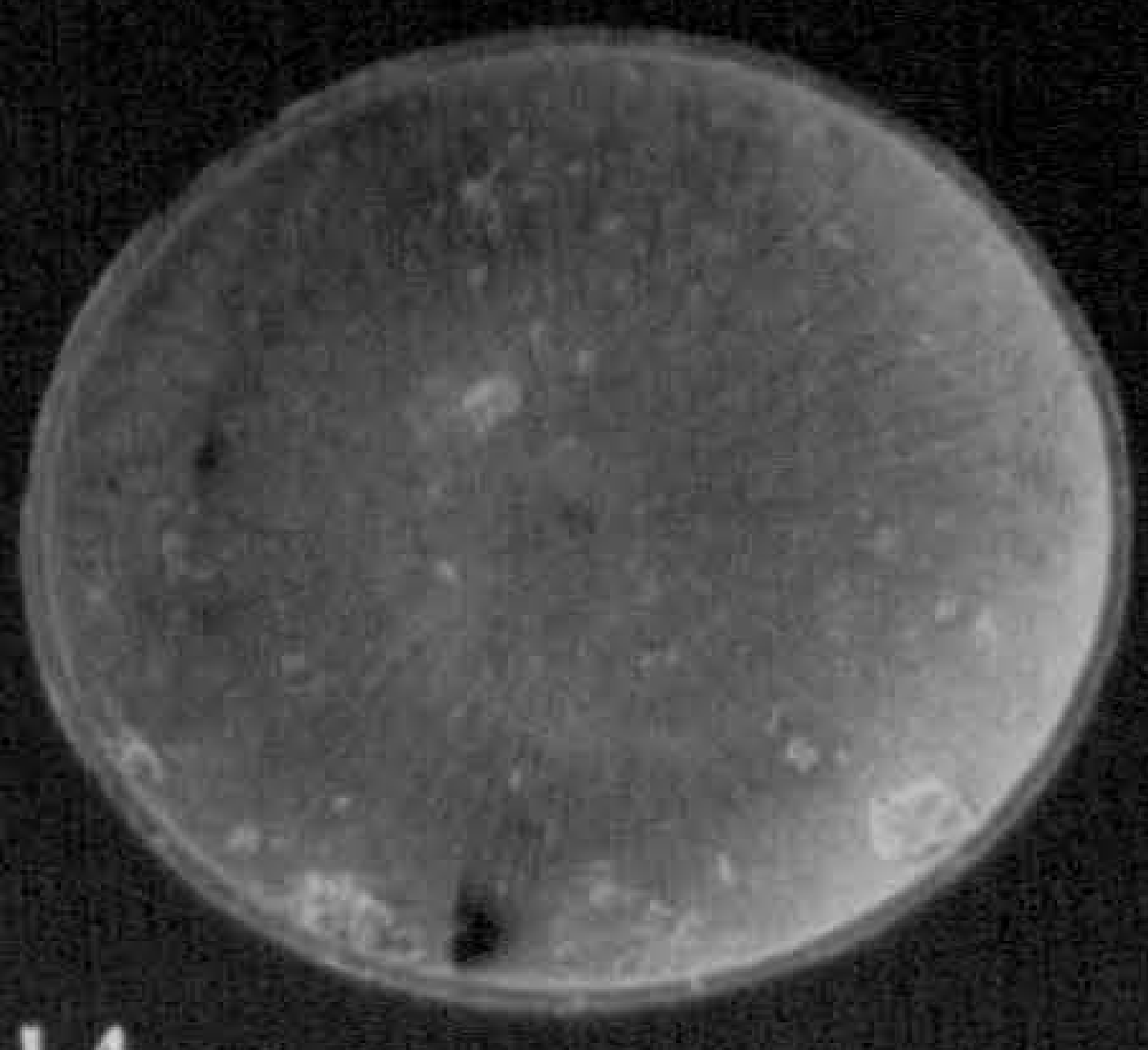

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Appendix 2

Laboratory Protocols

Laboratory protocols for running of ICP-AES (Kingston University, U.K.) and DCP (Duke University, North Carolina, U.S.A.)

1. Kingston University.

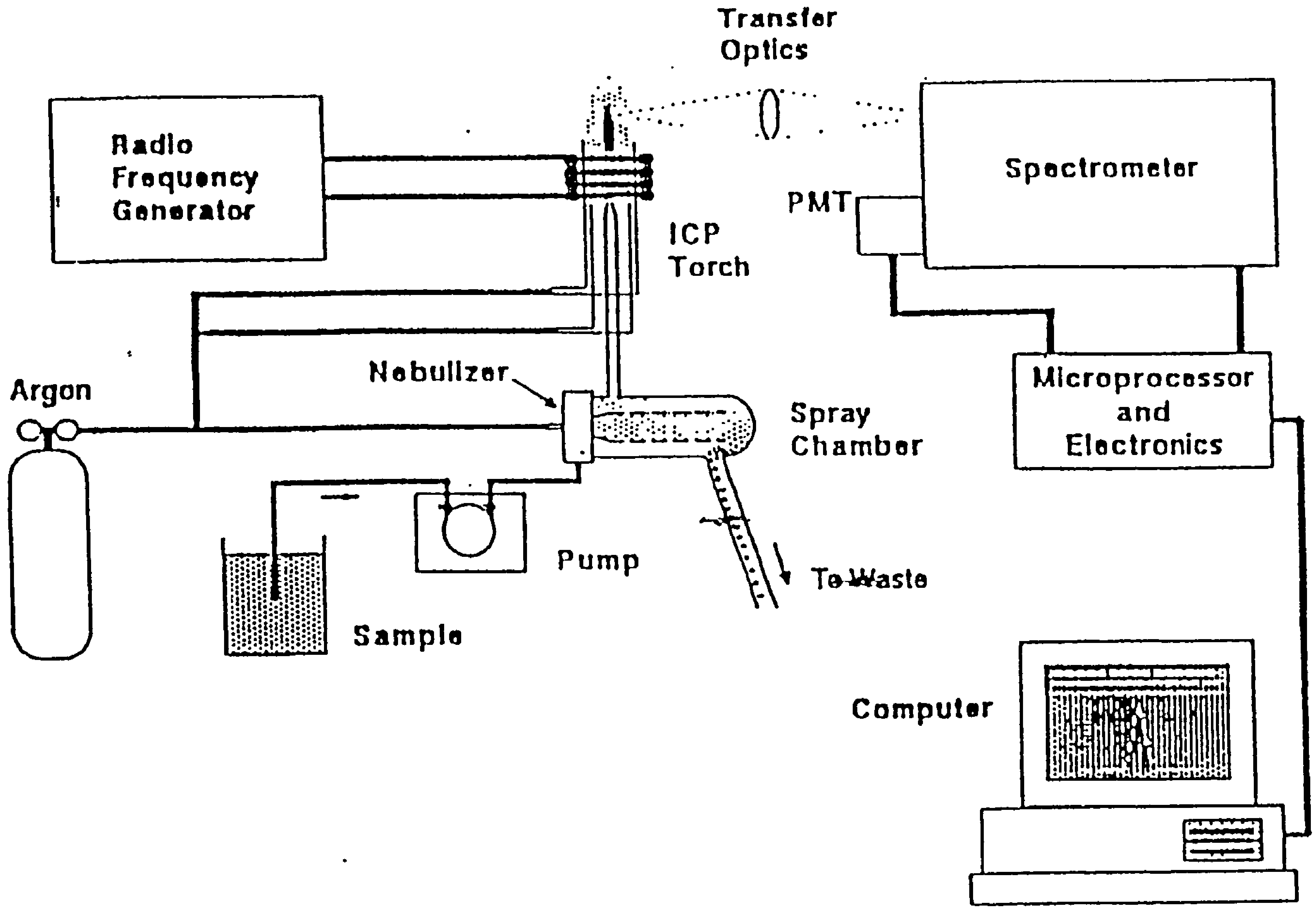
Solutions were analysed using a Jobin Yvon 70 Plus® (Instruments S.A., Longjumeau, France) inductively coupled plasma atomic emission spectrometer (ICP-AES) at Kingston University. The instrument was calibrated using multi-element standards prepared by dilution of BDH Spectrosol® 1000 *mg* ml^{-1} monoelement standard solutions for ICP. Corrections were made for blank concentrations of the elements in the solvent acid (BDH *Aristar*®, Merck Ltd., Lutterworth, Leicestershire, U.K.) and for instrumental drift using an external drift monitor. The Ca (wavelength 317.93 nm), Sr (407.77 nm) and Mg (279.55 nm) contents of the solutions were detemined and expressed as the weight, in *mg*, of the metal present. The concentration, in *mg* g^{-1}, of the trace element in $CaCO_3$ was also calculated, together with the nominal shell weight. The latter value, following Chivas *et al.* (1986a), was calculated from the Ca content of each dissolution, under the assumption that an ostracod shell is commonly composed of ~90% $CaCO_3$; the remaining ~10% consisting of trace elements, chitin and proteins (Sohn, 1958). Finally, the results were expressed as molar M:Ca ratios for plotting purposes. Analytical precision was ±3% for Mg, ±1.4% for Ca and ±0.9% for Sr (n=20).

All analyses were carried out under the supervision of Dr. J. A. Holmes, School of Geography, Kingston University, Penrhyn Road, Kingston-upon-Thames, Surrey, KT1 2EE.

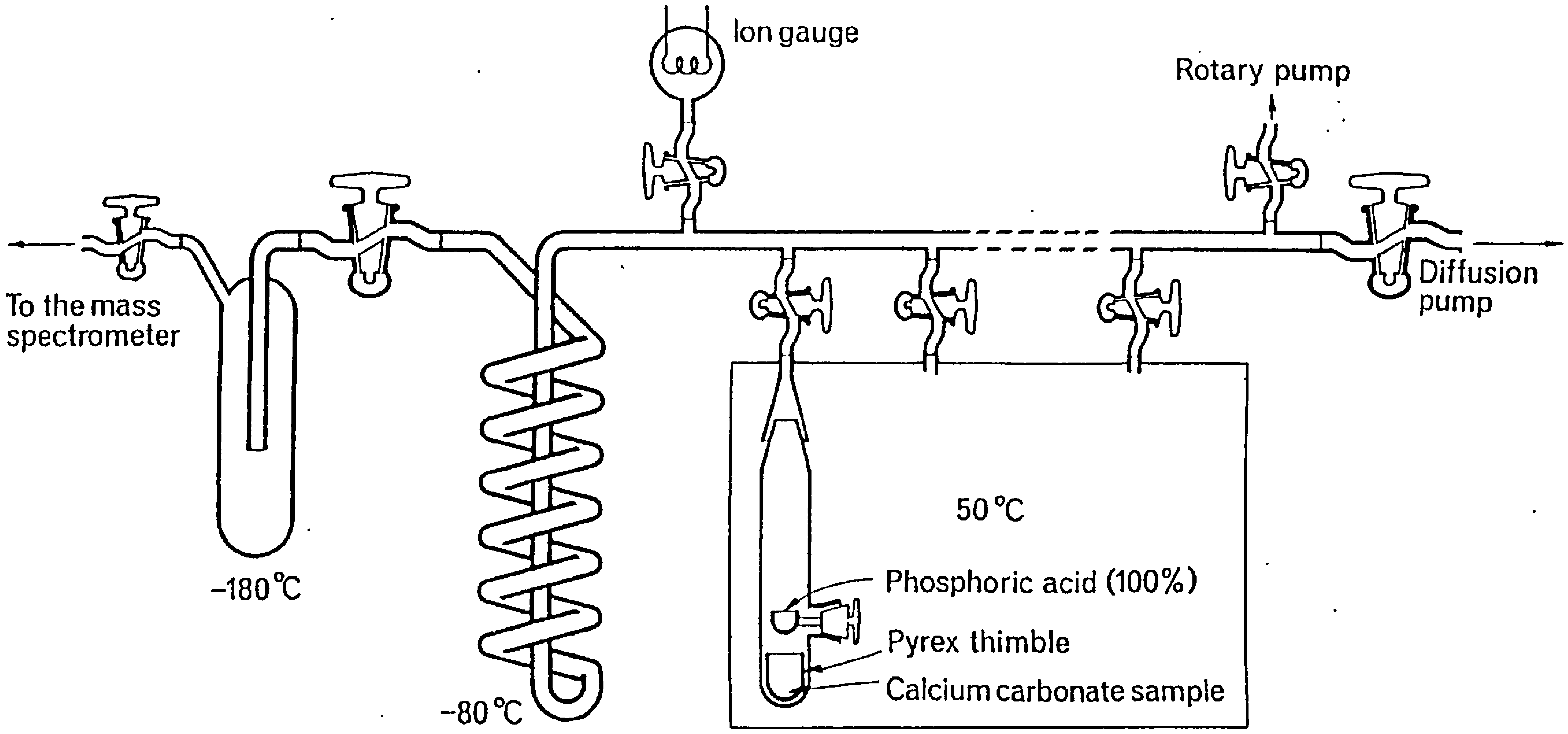
2. *Duke University.*

Following treatment with Clorox (Chapter 3) and sonication, each valve was dissolved in ~4 ml of 0.05 M nitric acid. Ca, Mg and Sr were determined simultaneously on the SpectraSpan® 7 DCP spectrometer. Matrix-matched instrument calibration standards were mixed from pure plasma-grade standard solutions. Analytical precision based on replicate analyses was ±3% (n=15). The results were expressed in the same way as above.

All analyses were carried out under the supervision of Gary S. Dwyer, Department of Geology, Duke University, Durham, NC 27708, U.S.A.



Schematic layout of an ICP-AES spectrometer.



Equipment for analysing stable isotopes from carbonates
(after Gribbin, 1978)

Appendix 3

Attached documents

The files on the attached disc consist of the following:

a:\counts\rawisp.xls - raw data counts of numbers of adult and juvenile ostracod valves for each species picked from BH 81/52A, Inner Silver Pit, southern North Sea.

a:\counts\rawessex.xls - raw data counts of numbers of adult and juvenile ostracod valves for each species picked from BHS1, Shoeburyness, Essex.

a:\geochem\isotopes.xls - mean values of stable isotope data for both cores (BH 81/52A and BHS1).

a:\geochem\mgsrisp.xls - mean values of Mg:Ca and Sr:Ca from analyses on ostracod valves for BH 81/52A.

a:\geochem\mgsrshoe.xls - mean values of Mg:Ca and Sr:Ca from analyses on ostracod valves for BHS1.

All files were made using ***Microsoft EXCEL version 5.0***

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