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Contemporary ecology and stable isotope geochemistry of benthic foraminiferids in the Celtic Sea.

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Contemporary ecology and stable isotope geochemistry of benthic foraminifera in the Celtic Sea

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R.V. Prince Madog docked at Menai Bridge Pier

Abstract

The primary aim of this thesis was to assess the value of foraminifera in downcore studies of shelf-sea stratification using both assemblage and geochemical characteristics. An examination of the modern distribution of foraminifera in the context of stratification in the Celtic Sea and comparison of these distributions with measured environmental variables was undertaken to this end. In addition, several species were examined for their stable oxygen and carbon isotopic composition with reference to the ambient bottom and porewaters.

Cruises were run to the Celtic Sea in July, 1995 and July-August, 1996, during which hydrographic data, water and surface sediment samples were collected from 138 stations. Fifty-three samples were subsequently analysed for grainsize, geochemical and foraminiferal properties, while the water samples were analysed for oxygen isotopic composition. A total of six multicores were extracted and sectioned. Each section was analysed for porewater carbon isotopic composition and foraminiferal content. Selected foraminifera from both the surface and subsurface samples were analysed for the oxygen and carbon isotopic composition of their test calcite.

Statistical analyses of the foraminiferal data indentifed four distinct assemblages which have potential for palaeostratification studies. The mixed-type assemblage included *Cibicides lobatulus*, *Ammonia beccarii*, *Quinqueloculina seminulum*, *Textularia bockii* and *Spiroplectammina wrightii*. The stratified-type assemblages included *Bulimina marginata*, *Hyalinea balthica*, *Nonionella turgida* and *Adercotryma glomeratum* while *Stainforthis fusiformis* was diagnostic of the front. *Bulimina gibba*, *Elphidium excavatum* forma *selseyensis* and *Eggerelloides scabrus* defined an eastern asseblage. It is believed that the true controls on these assemblages are oxygen and food supply.

Ammonia beccarii precipitated its test in oxygen isotopic equilibrium while *Q. seminulum* was consistently, negatively offset by approximately 0.5 $^{0}/_{00}$. This demonstrates the potential of these species in palaeo-temperature and particularily, palaeo-stratifcation studies. The 'microhabitat effect' was examined for several species of foraminifera but was not observed.

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Chapter 1 Introduction

The north-eastern Celtic Sea area is characterised by a tidal front which marks the transition between waters which become seasonally stratified and those which remain mixed throughout the year. Shelf sea fronts have long been recognised as zones of high productivity (*e.g.* Le Fèvre & Grall, 1970; Pingree *et al.*, 1974) and their implications for organisms higher up the food-chain can be profound. This study examines the relationship of benthic foraminifera to this feature and, in keeping with the principle aim of benthic foraminiferal studies of shelf seas, to define the range, numbers and distribution of living and dead species in order to provide an analogue for interpretation of the fossil record.

1.1 Study Area

The study area comprises only that part of the northern Celtic Sea which is contained between 51 and 52.25 degrees of latitude and the western part of the Bristol Channel delimited by - 4 degrees of longitude. However, because of the exposed nature of the area, the approaches to sampling localities are influential and are therefore, also discussed (see figure 1.1).

1.1.1 Structure and bathymetry

The Celtic Sea extends from the 200 m bathymetric contour in the south and west of the continental shelf bordering the Atlantic, to South Ireland and the entrances to the Irish, Bristol and English Channels (Pugh & Thompson, 1986).

The continental margin of the outer shelf area is characterised by a steep slope cut by many canyons, excepting the central margin region, the Goban Spur. The steepness is attributed to faulting (Day, 1959). In addition there is some subsidence of the outer shelf resulting in a relatively deep shelf edge of between 185 - 205 m. World-wide average shelf edge depths are about 140 m suggesting a local subsidence of around 55 m for the shelf edge between Brittany and Ireland (Pantin and Evans, 1984).

That part of the shelf extending oceanward from the 110 m (Pantin & Evans, 1984) or the 120 m (Evans, 1990) isobath is defined as the outer shelf. In the Celtic Sea this area is covered by exceptionally large tidal sand ridges which are thought to be moribund (Bouysse *et al.*, 1976).

The central shelf area, which includes the Western English Channel, is wide and relatively featureless. The gentle slope (1:1500) has almost no relief excepting outcrops of igneous rocks which make up the Isles of Scilly and several shoals including Haig Fras (Evans, 1990). To the north-east lie the inner shelf platforms which have gentle gradients of 1:100 to 1:2000 and reach up to 200 km width in the Bristol Channel. Depths on the platforms are generally between 10 - 60 m but slope down to -110 m

on the Haig Fras Platform (Tappin *et al.*, 1994).

The St. Georges Channel Trough in the southern Irish Sea runs in a NW - SE direction into the extensive and broad (60 km wide) Celtic Deep in the northern part of the Celtic Sea. The Deep, with a maximum depth of 160 m but, more commonly, 110 m, is not immediately distinguishable from the, nonetheless, relatively shallow Nymphe Bank and Lundy platforms which flank it because of the subdued slopes (< 1:50). To the south lies the Haig Fras Platform (Tappin *et al.*, 1994).

1.1.2 Recent sediments and Holocene history

The thickest Pleistocene deposits in the S. Irish Sea and N. Celtic Sea are concentrated in the St. Georges Channel and Celtic Deep Troughs, and tend to follow the bathymetric contours (Tappin *et al.*, 1994). Deposits reach up to 375 m in thickness in the Celtic Deep compared to just 50 m on the surrounding platforms. On the Nymphe Bank platform, however, the enclosed depression with dimensions of 20 km length and less than 5 km width may contain thicknesses of up to 175 m of Pleistocene sediment.

The British Geological Survey (BGS) have carried out extensive mapping of the Quaternary sediments in the area and the deposits have been divided into six formations. From oldest to youngest these are the Bardsey Loom, Caernarfon Bay, St. Georges Channel, Cardigan Bay, Western Irish Sea and Surface Sands formations (Tappin *et al.*, 1994). The Western Irish Sea and Surface Sands formations, which includes the late Devensian and Holocene, are the most pertinent to benthic studies since these form the majority of the surface sediments.

The upper till of the preceding Late Devensian Cardigan Bay Formation also reaches the sea bed. It is interpreted as a sub-glacial lodgement till and makes up most of the seabed of St. Georges Channel and Cardigan Bay. South of 50^0 N it begins to thin until about 51^0 20' N it wedges out. South of this only patches are preserved but it appears in coastal sections in the northern Scilly Isles, as the Melville or Scilly Till, which based on ^{14}C determinations of underlying organic material, post-dates 21,500 $^{+890}/_{-800}$ BP (Scourse, 1991).

The Western Irish Sea (WIS) formation lies over a marked unconformity and comprises incision infill deposits and thinner, more extensive tabular stratified deposits. Facies changes representative of proximal to distal sediment source changes are both lateral and vertical. The oldest facies is chaotic, found only in the base of infilled incisions and is interpreted as ice- proximal, glacimarine or glacilacustrine. The majority of incision infills are prograded facies, interpreted as prodeltaic and glacimarine sands which became increasingly distal from the Late Devensian ice sheet. This facies passes up into a mud facies which becomes increasingly temperate-marine upwards (Tappin *et al.*, 1994).

The Surface Sands formation is often very thin or even absent. It is divided, by morphology, into three members by the BGS (Tappin *et al.*, 1994): The Sea Bed Depression (SBD), Sea-level 1 (SL1) and Sea-level 2 (SL2). SBD usually forms as an infill of hollows in the WIS formation and comprises a sandy silt with shell debris and a rich temperate fauna. The fauna of SL2 is also temperate but indicates shallower than present water conditions. This deposit comprises basal lag gravels and reworked shallow marine and, occasionally, beach deposits lain on erosion surfaces formed in the post-Devensian marine transgression. SL1 is a mobile deposit lying above unconformable surfaces and forms active sand bodies such as tidal ridges, sand sheets and sand ribbons. All sediments are rich in bioclastic debris and carbonate content is roughly positively correlated with grain size (Evans, 1990).

From a study of the SE Celtic Sea, Bouysse *et al.* (1976) reconstructed its Quaternary history starting with an early Pleistocene levelling of the shelf and gullying into the surface due to a eustatic sea-level low of around - 240 m, and following the subsequent transgressions a Devensian fall in sea-level to - 110 m to - 120 m. Sea-level reached its present level during the Holocene. Pantin & Evans (1984) have instead suggested a sea-level low of - 135 m in the Late Devensian.

Bouysse *et al.* (1976) reported the Celtic Sea sand banks and observed their orientation parallel to the NE- SW trend of the Western Approaches to the English Channel. Dimensions were given as averaging 50 km in length, 6 km in width and 40 m in height. These are believed to have formed during the Holocene transgression. The sand banks appeared to be relict tidal sand ridges, slightly truncated by erosion. Pantin & Evans (1984) proposed that, as the tidal regime in the area of the ridges is not now vigorous enough to form and maintain the ridges when compared to their modern analogues, that past tidal currents were twice as strong as today. Present day mean tidal springs currents reach a peak of only 50 cms^{-1} in this area while a peak of 90 cms^{-1} is required for the maintenance of tidal sand ridges. The ridges are also found in water which far exceeds depths in which active ridges are maintained. This implies that the increased currents coincided with lower eustatic sea-level.

Numerical tidal modelling for a sea-level lowered by 100 m in the Celtic confirms the plausibility of such a hypothesis (Belderson *et al.*, 1986). The model also indicated a clockwise rotation of the major axes of the tidal ellipses which would offset the tidal ridges relative to the palaeocurrent rather than the parallelism they presently display. This too is in keeping with modern tidal sand ridges.

Holocene tidal modelling is also useful for the estimation of the effects of eustatic sea-level variation on tidal amplitudes, tide-generated fronts and sand transport paths. The model of R.M. Austin (1991) showed that changes in the position of the tidal amphidrome with time would have caused strong, spatial gradients in the rate of change of tidal amplitude in the Irish Sea and English Channel. This

must complicate constructions of sea-level curves for those areas such as the Bristol Channel.

Some of the first seismic surveys and offshore drilling and coring projects off the coast of Wales by Garrard & Dobson (1974) place the southern limit of Devensian ice at the southern entrance to St. George's channel, this being, according to their work, the southern limit of Irish Sea till deposits. The Irish Sea ice moved southwards from the Scottish highlands as a major ice stream. On the Welsh coast it was confluent with the local ice there producing the complex coastal sections seen today. However, Scourse (1991) and Scourse *et al.* (1990) have mapped a till comparable to the Irish Sea till in coastal sections in the northern Scilly Isles and offshore as far south as 49^0 N.

The offshore glacigenic sediments are discontinuous and have been divided by Scourse *et al.* (1990) into two facies. Facies A, defined lithostratigraphically as the Melville Till and belonging to the Melville Formation of Pantin & Evans (1984), is overconsolidated, fine gravel in a poorly sorted matrix and contains a sparse reworked fauna. Facies B also belongs to the Melville formation and is termed Melville Laminated clay; it is a silty clay, sometimes containing laminae, which fine upwards, sand pods and occasional gravel. The contained ostracod fauna indicate deposition in cold quiescent conditions.

Facies A may be interpreted as either a basal lodgement till or as a deposit in a proximal glacimarine environment. Scourse *et al.* (1990) believe that a thin ice lobe, extending from the Irish Sea glacier, advanced southwards into the Celtic Sea as a result of surging over deformable marine substrates. This occurred in the Late Devensian. Since the grounding line is calculated at around - 135 m OD at this time (19,000 years BP) ice thickness in the Isles of Scilly region could not have exceeded 100 m or all of the archipelago would have been covered.

This calculated sea-level is in direct conflict with those calculated by Eyles & Eyles (1984) for this time. In their 1984 paper, Eyles & Eyles presented an interpretation of the Devensian stratigraphy of the northern Isle of Man. They identified the Bride Moraine as a large push moraine which divides the different sediment types of the north and south. To the south lies a marine sequence which coarsens upwards and comprises dropstones, sands and gravels. This, it is argued, has a sub-aqueous origin. The northern succession is formed by offlapping stratified and massive diamict overlying glacitectonised marine sediments. Comparisons are drawn with facies deposited on sub-aqueous aprons close to grounded ice-margins. The conclusion of Eyles & Eyles is that in the Devensian relative sea-levels were actually higher than at present in contrast to the eustatic low experienced in other parts of the world at that time. This is attributed to glacio-isostatic depression of the crust in the region by the Irish Sea glacier. Eyles and McCabe (1989) support this interpretation based on studies from around the Irish Sea basin. They date the flooding of the Irish Sea basin to the Late Devensian and marine limits at this time are placed at 140 m OD. The Irish Sea glacier is pictured as a rapidly retreating tidewater ice-margin eventually collapsing because of the rapidity of evacuation of ice.

Rebound was also rapid - recovery of 100 m in just three thousand years.

Thomas & Dackombie (1985) have criticised these findings because of the 'depositional systems approach' used by Eyles and Eyles (1984) and Eyles and McCabe (1989). In contrast to what has been termed the 'layer-cake', traditional, approach to Quaternary stratigraphy which uses type sections and correlation of mappable units away from such sections, the depositional systems approach is three dimensional, providing recognition that correlated units are time transgressive and emphasising the importance of spatial change in facies accretion. This dynamic stratigraphy lumps facies rather than splits them as the traditional approach does. Inherent in this depositional systems approach is the recognition of the depositional controls by use of subcodes, which categorise the mode of deposition, and this has been criticised by Thomas & Dackombie (1985) as a fundamental defect, the subcodes having 'specific genetic connotations' which thereby bias the interpretation.

Many other workers dispute the high glacial sea-level theory on the basis of core and fossil evidence: An investigation of the contained foraminifera of glacigenic deposits at Aberdaron, N. Wales adjacent to the Irish Sea basin could lend no support to the Eyles & McCabe hypothesis (W.E.N. Austin & McCarroll, 1992). Assemblages were uniform throughout the samples taken from the diamicts in Aberdaron which is in keeping with a terrestrial model of glaciation. In a depositional environment as pictured by Eyles & McCabe a faunal change would be expected in response to increasingly distal sedimentation. The dominance of *Elphidium excavatum* forma *clavata* traditionally associated with glacimarine environments is not considered indicative as it may equally represent the cold reduced salinity conditions experienced at many points in the Irish Sea basin during Quaternary times. Also in the western Lleyn, an investigation of glacigenic deposits by McCarroll & Harris (1992) concluded that deposits were in keeping with the stagnation and decay of a terrestrial Irish Sea glacier. Similarly, glacial deposits at Wylfa Head, Anglesey, are not considered to have been deposited in a marine environment (Harris, 1991). The foraminiferal and molluscan stratigraphy of BGS vibrocore 51/-07/199 recovered from the central Celtic Sea, in addition to consideration of sediment type and radiocarbon dating, led Scourse & W.E.N. Austin (1994) to reject the notion of high relative sea-levels in the Irish Sea basin during the Late Devensian. The fauna indicates a rise in sea-level from around - 93 m OD to - 63 m OD during the late Glacial to mid-Holocene period which is consistent with sea-level curves modelled by Lambeck (1995; 1996) for the Ireland and the British Isles, but far below the level proposed by Eyles & McCabe (1989).

Sea-level rise in the last 20 K years in NW Europe is a consequence of the deglaciation of the Laurentide ice-sheet with minimal contributions from the Scandinavian and British ice-sheets and the concomitant eustatic sea-level rise as ocean basins, world-wide, filled with meltwater. Sea- level data from around the British Isles for this time helps to constrain glacio-hydro-isostatic rebound model parameters such as ice thickness and mantle viscosity, while the models in turn allow prediction of palaeoshorelines and water depths (Lambeck, 1995). Modelling work of Lambeck (1996) does not

support the theory that sea-levels around the Irish Sea were higher than present in Late-glacial times but it does suggest that a landbridge may have existed across the Celtic sea, between Britain and Ireland 18,000 - 14,000 years BP.

Sea-level data comes from local studies by many different workers in many different areas. Shennan (1989) compiled over 400 sea-level index points from around Britain, from the 904 cases compiled and stored in the IGCP Project 200 databank. These were used to investigate glacial rebound in Great Britain since 8,800 BP. The general pattern is one of uplift in highland Scotland where an ice cap was centred during the last glaciation and subsidence in Southern England. Sea-level determinations in the Bristol and English channels are complicated by their tidal ranges which are the largest in the British Isles. A compilation of curves drawn by various workers is this area is presented by Pirrazzoli (1991). Shennan (1989) concludes that the data sets used to draw the curves of SE England and the Bristol Channel are poorly resolved because they come from a wide range of sites characterised by different palaeoenvironments. Heyworth & Kidson (1982) list ten reasons why correlations in this area are problematic including variations in tidal ranges which was almost certainly the case in the Bristol Channel during the last 8500 years. The SE England data is considered satisfactory but more work is suggested for a complete picture of changes in the British Channel.

The sea-level change along the Irish coast is surmised by Lambeck (1996) as being a response, primarily, to the deglaciation of the former ice-sheet over Britain but the currently available observational data is insufficient to better constrain the model chronologically.

1.1.3 Physical Oceanography: Subtidal (non-tidal) and tidal movements

The hydraulic regime of the Celtic Sea today is largely controlled by the bathymetry, climate and tidal regimes and is believed to be in partial equilibrium with the bedforms and sediment transport paths. As with the rest of the north-west European shelf, the Celtic Sea is both tide and storm influenced with tides the dominant control (Johnson & Baldwin, 1991). Meteorological factors are also important, however, because of the exposure of the Celtic Sea to prevailing winds and oceanic waves.

The climate is windy, cloudy, damp and cool temperate, with mild winters. Weather conditions are highly variable. The Celtic Sea receives frequent storms with prevailing westerly and south- westerly wind. These winds blow for at least 25 % of the time and result in a long fetch ensuring a high degree of wave action. Gales occur throughout the year but are ten times more frequent midwinter than midsummer (Cooper, 1967). The highest waves likely in the area reach over 20 m height in the north-eastern part of the sea, but only occur with a frequency of 50 years. However, Hamilton *et al.* (1980) calculate that for force 10 winds, the orbital wave velocity could entrain particles the size of medium sand (0.3 mm diameter), down to a depth of 200 m. However, these and other subtidal movements in the Celtic Sea are irregular. Many move at periods longer than a day and, in addition to wind stress,

are driven by oceanic forcing, atmospheric pressure and spatially variable density fields (Pugh & Thompson, 1986). Local wind forcing is only responsible for less than half of the current variance and it has been suggested by Thompson & Pugh (1986) that the remaining variance may be related to wind activity in the adjacent Irish Sea and North Sea via the English Channel. Though the largest boundary of the Celtic Sea is the connection with the Atlantic Ocean, oceanic forcing at subtidal frequencies is not in evidence (Thompson & Pugh, 1986).

All subtidal movements must be set against the background of strong oscillatory tidal currents. The M_2 semi-diurnal tidal constituent is the most important tidal wave constituent in the Celtic Sea area, with the Atlantic tidal wave approaching from the south-west, normal to the greatest slope of the shelf edge. On spring tides the tidal ranges along the coast of Britain reach a maximum of 14 m at Avonmouth in the Severn Estuary while at neaps the amplitude is about half that of the springs (Evans, 1990). In the Celtic Sea the tidal stream is generally rotary clockwise (Evans, 1990). During springs speeds of 25 cms^{-1} are experienced at the shelf edge, increasing to more than 100 cms^{-1} at the entrance to the Bristol and St. Georges Channels (Thompson & Pugh, 1986). In 100 m water depth, 1 m from the bottom experiences tidal streams half that of the surface (Evans, 1990).

1.1.4 Physical Oceanography: Tidal Fronts

Tidal fronts occur on continental shelves at the juxtaposition of deeper stratified waters with shallower unstratified waters. In a stratified sea, the warmer surface and cooler bottom waters are prevented from mixing by the sharp density gradient between them, which is known as the pycnocline. The pyncocline generally coincides with the thermocline, defined as the sharp temperature gradient between the surface and bottom waters. The shallow-mixed region has a uniform temperature and density throughout, intermediate between the surface and bottom characteristics of the stratified side (see figure 1.2). Such fronts can be recognised by temperature and salinity measurements across the boundary area and may sometimes be detected by infrared satellite imagery (see figure 1.3) which detect the sharp, horizontal, surface temperature gradients (Simpson & Bowers, 1979). The main tidal front in the study area is entitled 'The Celtic Sea front' and runs from around 51^0 N between Britain and Ireland and curves round to run southwards along by the British coast (see figure 1.3).

Tidal fronts are seasonal phenomena common to high and mid-latitude continental shelves. During winter the entire water column is mixed with relatively uniform temperature, density and salinity characteristics throughout. Water acts as a heat store returning heat gained during the previous summer to the atmosphere throughout the winter. As a result, the water is coldest just prior to spring when solar insolation increases and the heat begins to flux from the atmosphere to the ocean. Heating from atmosphere to sea continues until the following autumn, reaching a maximum in midsummer. However, once a thermocline is formed, heat flux to the bottom layers is restricted. Temperatures in the surface layers continue to rise at an increasing rate while those in the bottom layer rise more

slowly but relatively constantly regardless of the flux to the surface, suggesting that tidal mixing is only able to transmit heat downwards through the thermocline at a fixed rate (Pingree, 1975). The surface layer reaches a temperature maximum in late summer but the temperature in the lower layer continues to rise until autumn even when the heat flux is from the ocean to atmosphere. The surface layer is thus losing heat both upwards and downwards. Eventually the two layers become equal in temperature, the thermocline disappears and the whole water column becomes mixed by convective overturning. Temperature stratification may be accompanied by salinity stratification in some areas. One reason for this is the addition of fresh water to the surface layer by precipitation and/or river input. This causes a reduction in density in the surface layer and results in a downward heat flux. Evaporation acts in the opposite sense, increasing the density of the surface layer and cooling it through the abstraction of latent heat.

Heating induces buoyancy and stability but the turbulence generated by the action of bottom friction on tidal currents acts against this and may provide a sufficient level of kinetic energy to maintain vertical mixing throughout the depth of the water column. Variations in tidal mixing and water depth result in some areas of the shelf becoming stratified while adjacent waters are mixed and the transition between the two is marked by a strong horizontal gradient known as a front. Since stratification is a function of the energy balance between surface heat flux and bottom tidal mixing, Simpson & Hunter (1974) derived a simple criteria for the formation of a thermocline based on this: h/U_s^3, where h = depth of water and U_s is the amplitude of the tidal stream. Hence the Simpson-Hunter parameter is simply found by the dividing the mass of the water column by the mean energy dissipation rate. Where this parameter reaches a critical value the water becomes stratified. Using 1.5 as the critical contour value of the Simpson-Hunter parameter in seas around the British Isles, Pingree & Griffiths (1978) compared their results with those observed on infra- red satellite and with sea-surface temperature measurements, finding good agreement between prediction and reality in most cases. The Simpson-Hunter parameter gradients are quite large for the Celtic Sea Front and it is thus considered quite stable. Simpson (1976) confirms the applicability of this parameter in the Celtic Sea. He also found that, as might be expected, stratification breaks down at the entrance to the Irish Sea and Bristol Channel were tidal energy is more vigorous.

Models are helpful in predicting the position of fronts and understanding the mechanisms controlling their formation and affecting their movements. James (1977) modelled the annual cycle of the Celtic Sea front using a 1-D model set to run from mid-March, estimated as the approximate beginning of heating, and run for 5 different stations across the frontal region. Model results were consistent with observational data which are essential for the validation and testing of models. Mapping of the temperature distribution on the shelf can indicate where and when waters actually become stratified and the advance and retreat of fronts can be followed through the seasons (Elliott *et al.*, 1991). A database of monthly surface and bottom temperature averages has been compiled by Li & Elliott (1990) for the NW European continental shelf. All data is averaged within a 20 x 20 nautical mile grid

and over a month long period. This archive data shows that in January and February the Celtic Sea is mixed. Temperatures range from 8-10 ^{0}C over this time but are consistent throughout the water column. Heating commences in March and continues through the spring. By May, a distinct thermocline has formed in the southern Celtic Sea with a difference between surface and bottom temperatures of 1 - 2 ^{0}C, the difference increasing towards the south-west. Through June the gradient sharpens as surface temperatures rise rapidly until the gradient reaches a maximum of 5-7 ^{0}C in July and August. Surface cooling begins in September and by October gradients have weakened to 1-2 ^{0}C though they remain sharper to the south-west. By December the water column has overturned and is completely mixed. Using this observational data Elliott & Li (1991) calculated thermocline depths for particular areas of the shelf since thickness of the surface mixed-layer plays an important role in many biological and physical shelf processes. They selected a site in the Celtic Sea at lat. 50^{0}30', long. 7^{0}45', for examination and found that it showed significant vertical stratification with a thermocline depth of approximately 40 m for most of the summer.

The typical structure of a tidal front can be seen in figure 1.2. The isotherms run horizontally and group together along the thermocline but where they enter the mixed waters they diverge towards the surface and bottom. The bottom front tends to step-out under the surface front. The isopycnals also generally follow this pattern. However, fronts at the surface may differ in position and strength to those at the bottom. The horizontal density gradients found at the front create a density-driven current which, in the absence of friction, is in approximate geostrophic balance and flows parallel to the isopycnals, that is, along the front. The closer the isopycnals the faster the jet-like flow. For typical shelf sea density gradients an along front flow of 15 cms^{-1} is predicted (Hill *et al.*, 1993). Radio tracked parachute drogues combined with knowledge of cross-frontal temperature and salinity gradients in the Celtic Sea implied along-front velocities of up to 30 cms^{-1} to Simpson (1976) while Simpson *et al.* (1978) found strong velocities of 110 cms^{-1} in this region when the tidal component was removed. However, the flow regime could not be demonstrated to be in geostrophic balance. Simpson (1981) states that the available evidence does not support the idea of an along front jet though a jet-like flow of 15 cms^{-1} has been observed in the North Sea by van Aken *et al.* (1987) and Hill *et al.* (1993). The generation of eddies due to the instability of the flow complicates the model and this is discussed below. In addition to this, friction cannot be ignored in shallow waters and with its inclusion, a component of flow perpendicular to the isopycnals, from lower to higher density in the upper layer and in the opposite direction in the lower layer, is expected. As water is incompressible, these horizontal flows are compensated for by vertical flows creating a slight horizontal convergence to the stratified side of the geostrophic flow and a slight divergence to the mixed side (see figure 1.2). Two-dimensional hydrodynamic models (Garrett and Loder, 1981; James, 1978) of frontal systems predict weak (less than 3cms^{-1}) cross-frontal circulations which have implications for the transport and distribution of biota and nutrients.

It is apparent from the very high levels of productivity associated with fronts that mechanisms exist

which deliver nutrients to the frontal region. Pingree *et al.* (1975) suggested that the movement of fronts with tides as a candidate mechanism: since current speeds vary over the tidal cycle, the level of energy available for mixing and thus, turbulence varies. As current speeds increase the depth of water for which it is possible for the turbulence to break down stratification increases so that the position of the front shifts towards deeper waters. As current speeds decrease, the depth over which turbulence is effective at destroying stratification decreases and the stratified area reforms, retaining the nutrient level of the mixed water it once was. The effectiveness of this process is clearly related to the length of the tidal excursion. Simpson & Bowers (1981) attempted to predict the tidal excursion for the fronts lying west of the British Isles, including the Celtic Sea front, for the summer season. The movement predicted by their model produced an excursion four times the actual excursion of 4 km which was calculated by removing the effects of the semi-diurnal tidal movement from satellite imagery. The mean frontal position does not actually alter significantly with the spring-neap cycle despite the fact that this cycle produces a strong semi-monthly variation in tidal-stirring in this area. They believe that this may indicate that a feedback process of vertical mixing is in operation. Eliminating the effects of tidal advection on frontal positions using infrared satellite imagery, their observational data confirm the results from the James' (1978) model; that fronts show a consistency of position. The feedback process must come into operation after the establishment of stratification and reduce mixing efficiency ensuring the survival of stratification even with increased stirring. They conclude that over the spring-neap cycle there is a non-linear movement of the mean frontal position with a sharpening of the horizontal density gradient at springs.

Modelling by Wang *et al.* (1990) concurs with the non-response to spring-neap cycles of the Celtic Sea surface front, but finds that the main control is atmospheric forcing. A north-westerly wind drives a southward Ekman transport in the upper layer and northward return flow in the bottom. This drives the surface front southwards. However, a southerly wind driving a northward surface current does not move the front because a southward flow of surface water resulting from a northerly wind brings in cooler mixed waters reducing vertical stability and enhancing vertical mixing, while a reverse flow of water merely advects a warmer water-body to a mixed one and becomes entrained itself. Wind may also cause frontal movement by increasing the energy available for vertical mixing (Simpson & Bowers, 1981).

Another possible mechanism for cross-frontal mixing is vertical diffusivity. Tett (1981) suggests that the frontal region experiences a vertical diffusivity intermediate with the high vertical diffusivity of the mixed side created by tidally induced turbulence and the low vertical diffusivity of the stratified side where the thermocline acts as a barrier to exchanges. These intermediate levels of diffusivity are high enough to allow a greater flux of nutrients than on the stratified side but are low enough to keep the phytoplankton cells in the euphotic layer long enough for them to multiply. Vertical diffusion may also be important in near bottom waters (Le Fèvre, 1986). This again relates to mixing and migration of the fronts by tidal currents, but it is expected that this process should be more significant at the bottom

front, where it would occur during each tidal cycle but may increase with the increased currents of the spring tides.

The transverse or cross-frontal circulation caused by the action of friction on the along front flow is quite weak and is estimated at less than 5 cms^{-1} (Hill *et al.*, 1993). The implied convergences at the surface and divergences in the subsurface (see figure 1.2) can be observed at fronts which are often demarcated by narrow bands of seaweed and other floating materials which converge here before sinking beneath the front (Loder & Platt, 1985; Le Fèvre, 1986) and are additionally confirmed by current measurements in frontal regions (Pingree *et al.*, 1974), observed surface temperature minima on the mixed side (Simpson *et al.*, 1978) and the deformation of bottom front isolines (van Aken *et al.*, 1987). Modelling by James (1978) using a density distribution corresponding to that of the Celtic Sea Front at the end of August calculated that flow along the front reached a maximum of 12cms^{-1} and that the maximum velocity normal to the front and towards the stratified region in the surface layer was about 4 cms^{-1}. Garrett & Loder (1981) also modelled these flows and predicted that the frontal jet and the associated vertical movements are enhanced during springs They estimate the vertical flows at approximately 1 $mmday^{-1}$ or about 1 litre per day up through each square metre. Linden & Simpson (1988), however, performed laboratory experiments which suggest that the reverse is the case; flows are strongest at neaps. Most insights into frontal circulation are provided by one and two dimensional models but are difficult to verify as current, particularly slow current data are difficult to collect. However, improved instrumentation has revived efforts to measure frontal circulation patterns (Hill *et al.*, 1993).

Three dimensional modelling suggests that fronts may be baroclinically unstable causing them to meander and shed eddies (James, 1990). Instabilities in the front allow small departures from geostrophic balance to grow at the expense of potential and/or kinetic energy in the front (see figures 1.2 and 1.3). Eddies occur on the surface front only and are evidenced by the irregular shape of the line of debris marking the front and often twist warm and colder waters together which is visible on infrared satellite images (Pingree, 1978). During this process the warmer water overrides the cooler water which sinks, becoming elongated in the process and produces the 'hook like' feature of the colder water which is visible on satellite images. Most eddies are cyclonic though adjacent eddies occasionally wind in an anti-cyclonic direction (Pingree, 1978). The model of James (1990) was forced using data from the North Sea near Flamborough Head and predicts that friction and bathymetry tend to suppress eddy growth. The hydrographic survey of van Aken *et al.* (1987) in the same area revealed both small and large scale meanders. Pingree (1979) documents pronounced eddy activity along the Celtic Sea Front with average wavelengths of 30 km and suggests that dissipation time for the eddies is of the order of a few days. Garrett & Loder (1981); Loder & Platt (1985); Pingree (1978; 1979) and Pingree & Griffiths (1978) suggest that they may cause water and thus, nutrients, to be exchanged across the front.

While it is understood that shelf seas store up heat in summer and release it in winter, thereby modifying the climate of maritime regions, the influence of stratification on terrestrial climate is not clear. The overall effect of stratification is to reduce the amount of heat stored in the water column as shown by Pingree (1975) in a comparison of the mixed English Channel with the stratified Celtic Sea. Stratified water has a higher surface temperature than mixed water and so gains heat more slowly during summer heating. Once stratification breaks down the cold bottom waters mix with the surface making them colder than water that is mixed year-round. Since the loss of heat from water to atmosphere by evaporation is a function of the temperature of the surface water, the rate of heat loss in sea areas which are annually stratified is slower than in mixed areas. Simpson & Bowers, (1984) modelled this process and compared their results to observational data. Though there were some discrepancies, the importance of tidal stirring in controlling heat storage on shelf seas was demonstrated, implying that climate on land in maritime areas may be influenced by local levels of tidal stirring, with regions inshore of deep mixed seas experiencing a relatively small range in seasonal temperatures.

The effects of anomalous seasons on heat storage has been modelled by Elliott & Clarke (1991). Using anomalous climate data from meteorological records they modelled the effects of such seasons and compared their results to observational data, finding agreement to within a $1^{o}C$ temperature range. Results suggest that during a hot summer the resulting strengthening and shallowing of the seasonal thermocline reduces the ability of the water column to store heat. A cold summer results in a higher heat content in stratified waters than a warm one. Similarly, after an anomalously cold winter, there is a greater influx of heat because of the increased temperature gradient between atmosphere and water. The implication is that there is a feedback mechanism which operates to restore heat content and structure to the sea following an anomalous heating season, but that the memory of these perturbations does not persist beyond one year. The terrestrial consequences of this are uncertain but it is known that the temperature of the shelf seas plays an important role in determining the climate of the British Isles; a warm sea in the Bay of Biscay in July favours a warm British August, while a cold sea in autumn favours a cold, dry winter in England and Wales (Radcliffe, 1973). However, ocean temperatures have more of an effect in winter than in summer, which is not surprising given that the heat exchange between ocean and atmosphere is greater in winter.

1.1.5 Biological oceanography: Tidal fronts

The 'classical' phytoplankton cycle for temperate seas is characterised by a spring bloom, when planktonic organisms become sufficiently abundant to visibly discolour the sea, followed by a later, lesser, autumnal bloom. The controls are light and nutrient availability. Le Fèvre (1986) summarises this cycle in his overview of frontal biology: the spring bloom is explained by 'Critical Depth Theory' (Sverdrup, 1953) a formalisation of the ideas of Gran & Braarud (1935). The theory states that as light attenuation decreases down through the water column, a depth is reached where phytoplankton

growth cannot take place. Since phytoplankton are generally moved vertically by wind-mixing, the shallower this wind-mixed layer the more illumination they receive. This layer is deep in winter and incident light is low so the integrated amount of light received by an organism over time is correspondingly low. The winter situation is that there are few phytoplankton living but there is a high availability of nutrients. In spring, light input increases and the wind-mixed layer shallows until it no longer exceeds the critical depth, the phytoplankton experience high levels of illumination and the bloom is triggered.

Herbivorous zooplankton blooms lag the phytoplankton blooms and it is this grazing pressure, and the exhaustion of nutrients in the illuminated layers (separated from the nutrient-rich lower layers by the pynocline) which causes low summer phytoplankton standing stock. The autumn bloom is attributed to a decrease in zooplankton numbers as a consequence of predation and the increased availability of nutrients due to wind-driven mixing. Once this vertical mixing depresses the wind-mixed layer significantly, winter conditions prevail and the water column eventually overturns. However, this simple cycle consists of several successions. Diatoms, which have a fast growth rate and, thus, a high nutrient requirement, comprise the majority of the spring bloom, while the summer population is most often dominated by dinoflagellates which are slower growing and require lower nutrient availability. Phytoplankton and autotrophic zooplankton depend on molecular diffusion for the transfer of nutrients and waste products. Motionless, they would soon use up the nutrients in the water surrounding them so they generate movement relative to water by either sinking or swimming. Only larger organisms, such as diatoms, sink at a fast enough rate for it to be beneficial so smaller organisms, such as dinoflagellates, swim. The mobility of dinoflagellates, allowing selection of optimal levels in the water column, explains their suitability to the summertime situation. In addition to this a bacterial bloom lags the phytoplankton bloom; when phytoplankton become senescent non-living particulate material derived from the phytoplankton (phytodetritus) becomes available for bacteria.

It is clear that the described 'classical cycle' is applicable to the stratified areas of the shelf only. A different situation occurs in those areas characterised by year-round tidal mixing and a very particular biology is associated with fronts. Holligan (1981) observed that fronts mark the landward limit of the spring bloom, which only occurs in stratified waters, while the tidally mixed waters are dominated by diatoms. These thrive here because they are dependent on movement for enhanced diffusion of nutrients. The distribution of phytoplankton varies, not only throughout the year, but across the front. In fully stratified conditions it typically appears as a surface maximum in the frontal region and a discontinuous subsurface maximum (10 - 40 m) along the thermocline in the stratified region (*e.g.* Pingree *et al.*, 1975). The phytoplankton in the frontal region consist of a low diversity dinoflagellate population which have a single summer peak, rather than a biannual bloom, as do the subsurface maximum nearest the front. The longevity of the bloom in these areas is attributed to low levels of grazing (Holligan *et al.* 1984a). The subsurface maxima further offshore tend to be dominated by small, naked flagellates (Holligan *et al.*, 1984b). Blooms of coccolithophores also occur in the nutrient-

deficient well-illuminated waters above the thermocline (Houghton, 1988).

Fronts have long been recognised as zones of high productivity (*e.g.* Le Fèvre & Grall, 1970; Pingree *et al.*, 1974). Many workers have attempted to measure the productivity associated with frontal regions by examining phytoplankton biomass. Photosynthesis, which drives primary productivity, depends on photosynthetic pigments, usually contained in algal chloroplasts. The dominant pigment is chlorophyll-a and this can be measured in a sample using a fluorometer or spectrophotometer which measures extinction of different wavelengths in a beam of light shining through a sample. From this phytoplankton biomass is estimated. Tett (1987) believes that it is legitimate to use chlorophyll-a as a measure of bloom intensity and notes that discolourations become noticeable at concentrations > 10 mgm^{-3}. The transfer of energy during photosynthesis occurs in a series of reactions in which the ADP (adenosine diphosphate) is changed to ATP (adenosine triphosphate). The measurement of cellular ATP in a water sample is thought to yield information on physiological activity (Sakshaug, 1980) and is not always correlated with chlorophyll-a (Fogg, 1985). Best of all, however, is a measure of the rate at which plant material is produced or actual primary productivity. The most commonly used method is known as the ^{14}C method (Grall, 1966), where radioactive bicarbonate is added to two samples. One is kept in the dark, the other in light to allow photosynthesis to take place. The amount of radioactive carbon taken up per unit time is measured and compared with the dark sample. This measure is sometimes known as the assimilation index. The measurement of oxygen, which is produced during photosynthesis, is also used as a productivity proxy though values appear to be integrated over several days so it is not quite as useful as the assimilation index (Pingree *et al.*, 1976).

In their study of the Irish Sea Front, Simpson & Hunter (1974) reported that in August the nitrate-nitrogen content (a measure of nutrient availability) of the tidally-mixed water was about 2 μgl^{-1}. The bottom stratified waters registered a content of 7 μgl^{-1} while the surface stratified water had a content of <1 μgl^{-1}. This suggests that a process which enables waters from either the deep stratified or tidally-mixed areas to enter the surface stratified area would enhance productivity there. However, Pingree *et al.* (1974) observed along-front slicks indicating that fronts are also zones of convergence and sinking and raising the possibility that the high biomass was a result of convergence rather than stimulated growth. This presents two possible mechanisms to explain the enhanced productivity associated with fronts: advection and accumulation of organisms or *in situ* growth. The possible mechanisms for cross-frontal mixing and promotion of *in situ* growth have been described in section 1.1.4 and include frontal movement over the spring-neap cycle, baroclinic eddies, residual currents and vertical transport.

In their 1975 cruise to the Ushant Front in the Western English Channel, Pingree *et al.* observed the classic distribution of chlorophyll-a found across frontal regions. This, they suggested, might be explained by mixing over the tidal cycle. Simpson & Pingree (1978) found a similar distribution but attributed the subsurface maximum to cross-pycnocline transfer of nutrients by internal wave activity

which was detected during the cruise. Internal waves are caused by tidal currents and movements of 8 m have been detected in the Celtic Sea (LeFèvre, 1986). Calculations by Loder & Platt (1985) suggest the rate of transfer of nitrate to the frontal zone over the tidal cycle at around 0.12 $mgm^{-1}s^{-1}$. They also tried to calculate the rate of transfer that might be attributed to baroclinic eddies but used two different methods. The first, a semi-empirical formula, following Pingree (1979), arriving at a value of 0.08 $mgm^{-1}s^{-1}$. The second is given by the number of eddies multiplied by the eddy volume and nutrient gradient over time. To arrive at the same answer the number of days between eddies would have to be 60. According to satellite imagery this is far too long and so it may be that rate of transfer has been underestimated. This value is still very large when compared with the estimate of transfer attributable to residual currents which is only 0.01 $mgm^{-1}s^{-1}$. This was again calculated by Loder & Platt (1985) based on calculations provided by Garrett & Loder (1981). For transfer by vertical transport Loder & Platt (1985) arrive at a figure of 0.2 $mgm^{-1}s^{-1}$ based on the work of Pingree & Pennycuick (1975). Holligan *et al.* (1984b) also calculated the rate of vertical transport and arrived at a flux value ten times that of Loder & Platt (1985) but their semi-empirical calculations may involve measurements which are not typical and assumptions which are not valid (Mann & Lazier, 1991). The combination of the four mechanisms gives an estimated carbon flux of 0.28 g C $m^{-2}dday^{-1}$ in a 10 km wide frontal zone (Loder & Platt, 1985). However, the one dimensional model of Tett (1981) shows that it is possible to explain the high productivity observed at fronts by the mechanism of vertical transfer alone.

Pingree *et al.* (1975) measured various parameters of primary production along the Ushant Front including chlorophyll-a, the light extinction coefficient, the assimilation index and integrated water column productivity expressed relative to a value of unity for the vertically mixed waters. They found a typical structure: in stratified waters away from the front primary productivity was very low but within the thermocline it was very high and accounted for at least 50 % of the carbon fixed. The frontal region had 40 times the phytoplankton biomass of the mixed but only 6.5 times the productivity and a very low rate of carbon fixation. Tett (1981) constructed his model based on these results, setting the upper stratified layer as nutrient limited and the lower stratified layer as light limited. The frontal region is depicted as a region in which organisms experience minimal turbulence combined with moderate illumination and nutrient supply by diffusion. The model reached a steady state after 40 days and showed a distribution of chlorophyll and nutrients comparable to the natural situation showing that the distribution was explicable in terms of vertical diffusion alone.

Enhanced productivity is not the only possible explanation for the distribution of phytoplankton at fronts. The accumulation of organisms due to convergent circulation also provides an alternative hypothesis (Pingree *et al.*, 1975). Richardson *et al.* (1985) report that the frontal region only appears richer when the surface values are examined, but if these are integrated down to 30 m then they are comparable to values in mixed waters. A passive accumulation explanation can also be invoked for the subsurface chlorophyll maxima. Yamamoto (1983; 1984) showed, using Stokes Law, that the decelerating effects of the density gradient found at the pycnocline, could explain the accumulation of

sinking phytoplankton along the pycnocline. This is supported by Lorenzen (1967) who reports that the production maximum is found higher in the water column than the chlorophyll maximum in Californian waters. Le Fèvre *et al.* (1983) also found that the oxygen maximum lay consistently higher in the water column than the chlorophyll maximum in the region of the Ushant Front. This suggests that maximal growth occurs in the upper mixed layer and that maximal biomass results from settling on the pycnocline. The subsurface maximum closest to the front has a similar composition to the front, that is, completely different from the other subsurface regions.

1.2 Foraminifera - an overview

1.2.1 Foraminifera as palaeoecological tools

Foraminifera are one of the most popular fossil groups in palaeoenvironmental reconstructions. In addition to the information derived by the comparison of fossil with modern assemblages, calcareous species can be radiocarbon dated, providing a time framework for cores and analysed for stable isotope ratios, and act as proxies for various environmental variables including temperature, salinity and productivity. Stable isotope techniques applied to foraminifera are discussed in more detail in section 1.2.3. Within the Quaternary and particularly for the late Glacial and early Holocene periods, foraminiferal techniques are employed to examine changes in ocean circulation, hydrographic conditions, sea-level and more recently, anthropogenic effects (*e.g.* Barmawidjaja *et al.*, 1992; W.E.N. Austin & Kroon, 1996; Knudsen *et al.*, 1996).

An assumption of uniformitarianism is inherent in the interpretation of fossil assemblages by comparison with modern analogues. However, this assumption may not be entirely correct; fossil sets may have no modern equivalent giving a 'no-analogue' situation. This might be because the ecological tolerances of taxa have changed or that the outcome of anthropogenic effects on niche availability and assemblage composition is that assemblages which occurred in the past, no longer exist (Murray, 1991). Even where this assumption is valid, it is generally inadvisable to directly apply modern results to fossil assemblages since those individuals which manage to become buried in the sediment and which survive burial are not always representative. Discrepancies occur as a result of inter-species variability in production, *post-mortem* transport and destruction before burial as will be discussed in section 2.3.1. These problems are mitigated by the comparison of either the total (Scott & Medioli, 1980) or dead (Murray, 1982) data with the fossil data. However, some test destruction takes place after burial, particularly of agglutinated forms (Smith, 1987) which will be represented in the modern analogue assemblage but not the fossil.

1.2.2 Modern studies of foraminiferal ecology

An ecological community comprises a group of species living in sufficient proximity to each other to

maintain the potential for interaction. Interactions may include commensalism, mutualism, parasitism, predation or competition. Communities with few interactions arise largely from mutually independent autecological processes rather than synecological ones. In this situation abiotic variables are likely to be the main controlling force on the population. The complexity of the effects of biotic or abiotic variables, or the synergistic effect of several variables on a species and its position within a community are difficult to resolve.

Dayton (1984) examined the processes structuring benthic marine communities and observed that they tended to form as distinct patches. In considering individual populations within the community, such as the foraminiferal population, Dayton declares that there is little evidence of interspecific competition for limited resources. On the otherhand, a study by Lee (1974), while not providing a firm conclusion on interspecific competition, suggested that it might be important. Intraspecific competition was investigated using tracer feeding studies and crowding of a population was found to affect feeding and reproduction rates, so constituting a kind of feedback mechanism. Grouping of individuals of a particular species increases the energy expense of looking for food but reduces the energy required to attract mates.

Interspecific competition is largely ignored by modern foraminiferal workers since it is generally regarded as being of little significance (Murray, 1991). Most modern studies try to relate assemblage structure to measured environmental variables since their principle aim is to assist the interpretation of fossil assemblages (*e.g.* W.E.N. Austin & Sejrup, 1994; Hald *et al.*, 1994). The majority of these studies are observational field studies. Experimental field studies are difficult because of the small size of foraminifera but laboratory studies are increasingly popular because geochemical techniques require a greater understanding of foraminiferal physiology and habitat.

1.2.3 Stable isotopes in palaeoecology

The use of the naturally occurring stable isotopes of, particularly, oxygen and carbon are now indispensable tools in palaeoceanography (Berger, 1981). Ratios of the relevant isotopes of oxygen (^{18}O and ^{16}O) and carbon (^{13}C and ^{12}C) vary in the calcium carbonate, which forms the tests of many foraminifera, as a result of chemical and physical fractionation processes. The measured ratios of a foraminiferal sample therefore act as a proxy to these processes. Changes in the oxygen ratios of inorganic carbonate, precipitated in equilibrium with the surrounding seawater, vary as a function of temperature, salinity and water oxygen isotope composition (Epstein *et al.*, 1953), while those of carbon are believed to correlate to the isotopic ratio of the surrounding dissolved bicarbonate (Grossman, 1987). Since bicarbonate ratios are very variable carbon isotopes are very complicated proxies. ^{13}C is discriminated against during photosynthesis causing a relative depletion in organisms of ^{13}C compared to ambient CO_2. This occurs in surface waters which then become enriched in ^{13}C. Organic matter, depleted in ^{13}C, sinks to the deep ocean thereby enriching deeper waters in ^{12}C.

The isotopic ratio of a sample is expressed as the deviation relative to a standard in parts per thousand (McKinney *et al.*, 1950). Thus, the conventional notation is $\delta\ ^{0}/_{00}$. The original standard used by Urey *et al.* (1951) for both oxygen and carbon ratios measured on carbonate was a sample of Belemnite Guard from the Pee Dee formation (PDB). Since the exhaustion of PDB, standards produced by the National Bureau of Standards, USA, are used but results are still expressed relative to PDB. By convention, isotope ratios measured on water are expressed relative to Standard Mean Ocean Water (SMOW) after Craig (1961), which is offset from the PDB standard by -0.2 parts per thousand. In addition to reference to a standard, all oxygen and carbon isotope ratios are automatically Craig corrected for the errors caused by the fact that several different isotope species in CO_2 have the same mass (Craig, 1965).

Isotopic palaeoceanography began with the theoretical calculations of Urey (1947) and were developed experimentally by McCrea (1950) who derived an empirical palaeotemperature equation from inorganic precipitate studies. Epstein *et al.* (1951; 1953) derived a similar equation from organically precipitated carbonates within the temperature range of 7 ^{0}C - 21.5 ^{0}C. After modifications by Craig (1965), this form is the most widely used in stable isotope work. The equation of O'Neil *et al.* (1969) is essentially the same as that of Epstein *et al.* (1953) but covers a wider range of temperatures. Shackleton (1974) produced an equation based on that of O'Neil *et al.* (1969) but which gave a better fit with measurements on deep-sea benthic foraminifera than that of Epstein *et al.* (1953).

Emiliani (1955) pioneered the use of oxygen isotope measurements on foraminifera contained in deep sea cores. The earliest phase of isotopic palaeoceanography focused on temperature reconstruction using the palaeotemperature equation with allowance for the 'background' ice volume effect. This is the reduction in lighter isotopes in the oceans during glaciations because of their preferential uptake by growing glaciers. Later the 'background' ice volume effect was realised to be of greater significance (Shackleton & Opdyke, 1973). Oxygen isotope records from measurements on foraminifera have yielded information on ice-sheet volume, sea-level and deep ocean temperature changes and are a routine tool for stratigraphic correlation of deep-sea sediments (Shackleton & Opdyke, 1973). The use of carbon isotope measurements on foraminifera was initiated by Shackleton (1977). Measurements on deep-sea material can be used as a proxy for surface productivity, ocean ventilation and chemistry and to examine atmospheric CO_2 variations and variations in the partitioning of carbon between the various carbon reservoirs, though it is very difficult to distinguish between these effects (Kroopnick, 1980, Duplessy *et al.*, 1984; Shackleton *et al.*, 1984). Carbon isotope stratigraphy can also be used as a dating tool (Jansen, 1989).

Knowing the isotopic composition, temperature and salinity of the ambient water, the isotopic ratio of

calcite precipitated in equilibrium with the water can be predicted . Any difference between the predicted values and those actually measured shows disequilibrium or fractionation on the part of the organism. Fractionation is calculated by subtracting the equilibrium from the measured value and expressing it as $\Delta\delta^{18}O$ or $\Delta\delta^{13}C$ (Graham *et al.*, 1981). Studies of $\delta^{13}C$ and $\delta^{18}O$ in benthic and planktonic species of foraminifera have found that disequilibrium precipitation of these isotopes into tests is a common occurrence (Duplessey *et al.*, 1970; Vinot-Bertouille & Duplessy, 1973; Erez, 1978; Wefer & Berger, 1980; Grossman, 1987), though some of the species do precipitate in $\delta^{18}O$ equilibrium (Smith and Emiliani, 1968). Factors causing disequilibrium precipitation of oxygen isotopes include the mineral phase secreted and vital effects. Carbon isotopes ratios are altered as a result of vital but also microhabitat effects.

The palaeotemperature equation was developed for calcite and is unsuitable for measurements made on aragonite, another form of carbonate, which has a different temperature coefficient (Grossman & Ku, 1986). Grossman (1987) states that the palaeotemperature curve for aragonite follows closely that established for calcite but is offset positively by 0.7 parts per thousand.

Vital effects in foraminifera were first reported by Duplessey *et al.* (1970) and include the effects of uptake of metabolic CO_2 during calcification, growth or calcification rate, physiological changes with ontogeny, kinetic isotope effects in the transport of carbonate ions to the site of calcification and photosynthetic activity of symbionts.

Growth or calcification rate effects on isotope values have been measured on large tropical benthic species of foraminifera by Wefer & Berger (1980). A tendency towards incorporation of lighter, ^{12}C isotopes with increasing age was observed in several species of the Miliolina suborder although this was not found in two species from the Rotaliina suborder. This ^{13}C depletion towards the end of the life cycle was considered to reflect increased metabolic activity associated with reproduction.

Studies have indicated that kinetic effects may also operate (McConnaughey, 1989). These are so called because they result from kinetic isotope effects during CO_2 hydration and hydroxylation. The relative importance of this remains uncertain but it produces a simultaneous depletion of ^{18}O and ^{13}C, though this depletion is larger for carbon.

Erez (1978) established a correlation between photosynthesis and the enrichment of the skeletons of corals and foraminifera in the lighter ^{16}O and ^{12}C isotopes for those species with symbiotic algae. This enrichment shows a mid-water maxima in depth profiles and is thought to reflect a combination of the natural decrease of photosynthesis away from the surface and the inhibition of photosynthesis by over-illumination in surface waters. Metabolic CO_2 enriched in ^{16}O and ^{12}C may come from other sources such as food and respiration so, although active symbiotic algae increase overall metabolic activity and CO_2 levels in the host organism, asymbiotic species of foraminifera are not immune from vital

effects.

All vital effects lead to depletion of isotopes but not necessarily an equal depletion in oxygen relative to carbon isotopes. The vital effect appears to have a greater effect on ^{13}C than ^{18}O. Grossman (1987) found that of the taxa studied, most were depleted in ^{13}C relative to the equilibria represented by the DIC, but acknowledged that this may in part result from a poor understanding of carbon isotopic equilibrium particularly at low temperatures. It has also been suggested that some foraminifera may incorporate porewater DIC into their tests (Woodruff *et al.*, 1980 and Belanger *et al.*, 1981), producing what is termed 'the microhabitat effect'. As porewater DIC is depleted in ^{13}C relative to bottom waters, depletion in certain infaunal taxa may be, at least partially, the result of the microhabitat effect rather than disequilibrium precipitation. The microhabitat effect is discussed in more detail in section 1.2.5.

Vital effects vary for different species and within the same species but certain trends can be inferred for different families of foraminifera (Grossman, 1987). Those tests which do actually appear to be in isotopic equilibrium with their surroundings tend to occupy low oxygen environments suggesting that whatever it is that allows them to live in such inhospitable sites also enhances the ability of their tests to equilibrate with the surrounding water. Such species have an ability to exchange gases rapidly with the ambient waters because their respiratory organs are located just below their test wall pores. This implies that there may be a relationship between test morphology and the isotopic behaviour of certain superfamilies (Grossman, 1987). Adaptation for low oxygen conditions such as those found in some asymbiotic species include higher surface to volume ratios, thinner test walls and less ornamentation. Adaptations in subsurface dwellers include rounded or cylindrical shapes or triserially arranged chambers with globular and ovate morphology with pores evenly distributed over the test. The equilibrium isotopic behaviour found in buliminaceans and cassidulinaceans can tentatively be related to their adaptations for rapid gas exchange permitting survival in low oxygen conditions (Grossman, 1987). Discorbaceans on the other hand have morphologies in keeping with epifaunal species (low trochospiral chamber arrangements, plano-convex or biconvex) and species in this superfamily tend to show predominantly disequilibrium taxa.

1.2.4 Modern isotopic studies of shelf foraminifera

Vinot-Bertouille & Duplessy (1973) found that individuals of the same species of benthic foraminifera display oxygen and carbon isotopic disequilibrium frequently larger than 2 $^{0}/_{00}$, and this increased to 3 $^{0}/_{00}$ when mixed populations of species were considered. It was concluded that in order to obtain a characteristic value for each species a large number of individuals needed to be analysed and that all isotopic palaeoecological measurements should made on monospecific samples. Much calibration work has been carried out since then, particularly on the deep-sea species used to produce oxygen isotope records (*e.g.* Shackleton, 1974 and Woodruff *et al.*, 1980).

Considerably less attention has been directed towards shelf species though Vinot-Bertouille & Duplessy (1973) performed their studies on north-west African foraminifera sampled from depths shallower than 40 m. Buchardt & Hansen (1977) examined two genera *Planorbulinella* and *Bolivina* from the Gulf of Elat and found both to have $\delta^{18}O$ values close to equilibrium but were enriched with respect to $\delta^{13}C$.

Poole *et al.* (unpublished) examined some of the more common shelf foraminifera from the Barents and Kara seas for equilibrium precipitation. These included *Elphidium excavatum* f. *clavatum*, *Uvigerina peregrina*, *Cassidulina laevigata*, *C. terretis*, *Nonion labradoricum*, *N. barleeanum*, *Cibicides lobatulus*, *Trifarina angulosa* and *Textularia fluens*. Of these, *C. lobatulus*, *N. barleeanum* and *T. angulosa* were found to approximate equilibrium values most closely, and so these species were recommended for future isotopic work. The carbon isotope values appeared to be related to the mode of life of the species concerned since eight of the species which were infaunal were depleted relative to *C. lobatulus* which was the sole epifaunal species. Also significant was the fact that species belonging to the same genus did not show similar isotopic behaviour as suggested by Grossman (1987) However, no living individuals of *C. lobatulus* were measured and the *Cassidulina* spp. used in the study were a mixture of both living and dead individuals.

1.2.5 The 'microhabitat effect'

Microhabitat variations affect only the $\delta^{13}C$ and not the $\delta^{18}O$ values. Lowered $\delta^{13}C$ values in porewater DIC results from oxidation of organic carbon within the sediment. Given that the microhabitat effect influences the test composition of many infaunal taxa, it follows that the measurement of the $\delta^{13}C$ content in the DIC of porewater rather than bottom waters for comparison with these species is more meaningful. An infaunal study by McCorkle *et al.* (1990) examined the microhabitat effect on foraminiferal test composition. Performing a series of measurements on deep-water species from over 15 localities in the Atlantic and Pacific oceans they found that the $\delta^{13}C$ values of infaunal taxa were consistently lower than those of the epifaunal, even where the organism precipitates oxygen in equilibrium. Though they suggest that this isotopic difference could be correlated with the chemistry of the pore waters, some of the difference may be due to vital effects.

Jorissen *et al.* (1995) explain the microhabitat preferences of foraminifera as a function of food availability and oxygen concentration. This, they believe, explains why in some regions there is a positive relationship between organic carbon flux and microhabitat depth and in others the relationship is negative. Microhabitats are food-controlled in oligotrophic conditions, while under eutrophic conditions depth of habitat is controlled by a critical oxygen level. The depth of habitat shallows from oligotrophic to eutrophic, increasing the size of the infaunal niche and supporting the proposed relationship between organic flux and percentage of infauna (Corliss & Chen, 1988 and Altenbach &

Sarnthein, 1989). According to this study, the shelf environment, being largely eutrophic, and thus, with oxygen as the limiting factor, contains foraminifera with relatively superficial habitats. However, the complications introduced by sediment porosity and bioturbation are acknowledged. In an experimental mesocosm Alve & Bernhard (1995) also found that shallow water species appeared to track a critical oxygen level a conclusion which concurs with the findings of Barmawidjaja *et al.* (1992). However, interspecies differences in vertical distribution have been observed (Alve & Bernhard, 1995) and this may be attributed to variable feeding with some species preferring fresh easily-metabolised material and others tolerating more refractory organic matter (Caralp, 1989 and Gooday, 1993).

A relationship between test morphology and microhabitat has been suggested by several workers (Corliss, 1985; Corliss & Chen, 1988; Jorissen, 1988) with long and tapering forms assigned as infaunal and rounded, flatter forms as epifaunal. Such a relationship would be convenient to the palaeontologist, not only helping distinguish contemporaneous specimens from different levels in a core, but perhaps, with much calibration work, producing a simple offset for correction of measured $\delta^{13}C$ values. However, in their study of microhabitat selection in the Northern Adriatic Sea, Barmawidjaja *et al.* (1992) could not find evidence to support this. However, they found that the majority of infaunal specimens were restricted to a size fraction smaller than 150 μm.

1.3 Relevant studies in the Celtic Sea

1.3.1 Other foraminiferal studies in and around the Celtic Sea

Murray (1979a) carried out the first study of recent foraminifera of the northern Celtic sea (the Irish sector), examining the >140 μm fraction only. Sampling took place over four years; October the first two years, July-August and March in the third and fourth. The living assemblages were recorded as being fairly diverse and the dead assemblages more so. Most of the living assemblages were primarily composed of the Rotaliina and Textulariina suborders with less than 10% Miliolina, though the percentage of Miliolina increased to 22% in the July to August period. Similar proportions were found in the dead assemblages. The higher values of Textulariina were correlated with coarser sediments and, where they formed >50% of the dead assemblage, they were usually found between 75 - 110 m depth, narrowing to between 80 - 100 m for the living assemblage. There was also a strong correlation between standing crop and sediment size with the highest values found in the finest fraction. At each station one or more of the following species formed more than 10% of the living assemblage : *Nonionella turgida, Fursenkoina fusiformis, Cancris auricula, Textularia sagittula* group. *N. turgida* and *F. fusiformis* were correlated with muddy sediments and hence depth, while the latter prefer muddy sand.

On the basis of measurements of individuals, Murray surmised that winnowing of forms smaller than 200 μm occurs in the higher energy bank areas. Significant differences between the living and dead

assemblages were also attributed to *post-mortem* transport processes and exposure of relict sediments which is common in the Celtic Sea. This, combined with a slow sedimentation rate, produces a mixed dead assemblage. Murray estimates sedimentation rates in this area of the Celtic Sea at 5 mm per 1000 years, which, allowing for bioturbation to a depth of 10 cm, suggests that the dead assemblage has been integrated over thousands of years. Dominant species in the dead assemblage include: *T. sagittula* group, *C. lobatulus*, *F. fusiformis*, *Gavelinopsis praegeri*, *Epistominella vitrea* and *Cassidulina obtusa*.

Murray (1970) examined foraminifera from several sites in six areas on the western approaches to the English Channel, including sites in the Celtic Sea and the entrance to the Bristol Channel. The other study areas were the shelf edge directly west of Brittany, the entrance to the English Channel south of Lands End, the south coast off Cornwall and a traverse from Eddystone Rocks northwards and landwards to Plymouth Sound. Samples were stained using the rose Bengal technique and sieved at 200 µm.

The study revealed a strong contrast between the foraminiferal populations of the Celtic Sea and the entrance to the Bristol Channel. While the living assemblage in the Celtic Sea was dominated by *N. turgida*, *Hyalinea balthica* and *Bulimina marginata* with localised peaks of *Cassidulina carinata* and *C. crassa*, the Bristol Channel was dominated by *B. marginata* and *F. fusiformis*. *Quinqueloculina seminulum*, *C. auricula* and *Eggerella scabra* were found to be locally dominant. The Celtic Sea dead assemblages included significant proportions of *B. marginata*, *C. carinata*, *C. crassa*, *F. fusiformis*, *H. balthica*, *N. turgida* and *T. sagittula* group, but also many small and immature planktonic forms, while the Bristol Channel was dominated by *Bulimina gibba/elongata*, *Quinqueloculina seminulum*, *Textularia sagittula* group and *C. lobatulus*. The Celtic Sea samples, set in an area of net deposition, showed reasonable similarity between the living and dead assemblages, both in species composition and species proportions. However, surprisingly, diversity was greater for the living assemblage suggesting that some sort of destruction or removal is taking place. The dissimilarities between living and dead assemblages of the Bristol Channel, where the vigorous tidal currents of the area are more effective, were distinct.

A high degree of similarity between the living and dead was also found at the shelf edge. Here *C. crassa*, *C. carinata* and *Brizalina spathulata* dominated both assemblages. *Brizalina pseudopunctata* was significant in the living but not the dead, and *T. angulosa*, *C. lobatulus*, *Bulimina cf. B. alazanensis* and *T. sagittula* group were present in significant proportions in the dead but not the living. Planktonic forms were abundant here.

The English Channel living assemblages included *G. praergeri*, *Haplophragmoides jeffreysii*, *Spirillina vivipara*, *Trochammina globigerinoides* var. *pygmaea*, *C. lobatulus*, *Patellina corrugata* and *T. sagittula* group. The dead included *Gaudryina rudis*, *Textularia sagittula* group, *C. lobatulus* and *Q. seminulum*.

The two assemblages were almost entirely dissimilar. The Cornish coast and the Eddystone-Plymouth transects produced similar results; *Ammonia beccarii*, *B. gibba/elongata*, *E. scabra* and *F. fusiformis* dominated the living and *A. beccarii*, *C. lobatulus*, *Q. seminulum*, *G. praergeri* and *Textularia sagittula* group dominated the dead. Again the living and dead were dissimilar.

Murray (1970) in discussing his results, examines the differences between the living and dead assemblages in the context of whether the area is one of sedimentation or not. The less significant differences between the living and dead of the Celtic Sea and shelf edge are attributed to seasonal and production differences and the more substantial differences of the remaining areas to *post-mortem* transport, though Murray deems it unlikely that larger foraminifera such as *Q. seminulum* could be transported without abrasion. However, there is a coincidence of sites of greatest dissimilarity between living and dead with those areas of non-deposition.

Rosset-Moulinier (1981) undertook a study of the modern distribution of foraminifera in the adjacent English Channel, but does not report the mesh size used for sieving. No distinction was made between living and dead specimens. The Channel has a more rigorous tidal current ranging from 30 - 34 cms^{-1} at 100 cm from the bed and this tends to remove much of the finer sediment. Thus, grain size tends to be coarser in the English Channel than in the Celtic Sea. The Channel is generally shallower than the Celtic Sea and does not develop a thermocline over most of its area except in the far west. While the range of annual bottom temperatures in the Celtic Sea is about 4 - 5 ^{0}C, temperatures at the Channel bed may vary by up to 10 ^{0}C, the variability increasing eastwards. Relative to the Celtic Sea, standing crop values were found to be low, though they increased to the west towards the Celtic Sea.

Rosset-Moulinier identified three categories of foraminifera which included 'gravel-dwellers', 'sand-gravel' dwellers and 'sand and gravel' dwellers; 'sand-gravel' dwellers being biased towards sandy sediments, while 'sand and gravel' dwellers are more evenly distributed between the two size fractions. Sand and gravel dwellers, which include the species *A. beccarii, B. elongata, Cribrononion gerthii, E. scabra, Elphidium excavatum, Nonion depressulum* and *Stainforthia fusiformis* were further analysed for other ecological controls.

Cribrononion gerthii and *E. excavatum* were found to have a western limit and *S. fusiformis* an eastern one, while *B. elongata* was only found in certain bays. Those species with a western limit were first considered by Rosset-Moulinier (1981) to be contained by depth. However, since they were not depth-limited in the bays temperature is proposed as the true control. *Eggerelloides scabra* is not found in colder mid-channel waters and *A. beccarii* is not found in stratified areas. It is reasoned that, as a southern species, the cold waters found beneath a thermocline make an unsuitable habitat. *Cribrononion gerthii* also appears to prefer higher temperatures and so is absent from the mid-channel. *Elphidium excavatum*, however, stays close to the coast where temperature ranges are

largest. *Stainforthia fusiformis* and *B. elongata* occur where tidal currents speeds are less than 2.5 knots.

Rosset-Moulinier (1987) also identified substrate type and temperature effects as the major controls on foraminiferal distribution in the Channel. Four assemblages were identified within the Channel; the *C. lobatulus* - *Textularia truncata* assemblage which generally coincided with sandy-gravel substrates, the *Deuterammina ochracea* - *Remaneica plicata* assemblage, found in coarse sediments controlled by strong currents, the *E. scabra* assemblage found in the finer sands and silts of the coastal zones and the *N. depressulum* assemblage which was found inshore of the *E. scabra* assemblage.

The foraminiferal populations of both the Celtic Sea and Channel are largely controlled by substrate and so indirectly with depth and current strength. Sturrock and Murray (1981) made a comparison of the microfauna of the two sea areas and examined the differences between the high energy, coarser grained Channel assemblages and the relatively low energy, finer grained Celtic Sea assemblages, which are, nonetheless, sufficiently similar in depth, temperature, salinity and latitude to warrant reasonable comparison.

They identified three high energy areas; the shell pavement of the English Channel , the mobile sands of the English Channel and Celtic Seas and the headland lag deposits of the English Channel. The deep-water, well-sorted medium sands of the English Channel exist in a moderate energy regime, while the deep muddy sands and the shallow muddy seas of the English Channel and Celtic Sea are relatively low energy environments. The living assemblages of the shell lag of the Channel and the lag deposits of the headlands were found to be similar in that they contained a large proportion of attached, immobile species related to the high currents in these areas. Dominant in both areas were *Rosalina anomala* and *C. lobatulus*. The foraminiferal composition of the mobile sands of the English Channel differed from the deep water sediments in the area which had a large free moving component. However, the Celtic Sea mobile sand group comprised living species of both. Both low energy environments compared well in respect of having a dominance of free moving forms, but differed in species which may relate to other ecological differences between the coast and shelf.

Sturrock & Murray (1981) concluded that loss of tests occurs commonly after death in the shell pavement mobile sands and lag deposits of the English Channel. Sediment mobility is considered responsible for most of the *post-mortem* changes in the high and medium energy areas, while bioturbation is of greater significance in the low energy regions.

1.3.2 Palaeostratification studies and palaeotidal modelling

R.M. Austin (1991) and Scourse & R.M. Austin (1995) attempted to model Holocene tidal parameters for the north west European shelf for six different sea-levels from - 30 m OD to - 50 m OD, in 5 m

intervals. These depths are believed to approximate sea-level conditions between 9,000 and 5,000 years BP. Using the modelled tide data and setting the Simpson-Hunter parameter to 1.5 to demarcate stratified from mixed waters, approximate positions of fronts around Britain were calculated for each time slice. For each, the stratified area in the Celtic Sea is hindcast as being less extensive. The modelling suggests that the Celtic Sea front would still have appeared south of Ireland and at the entrance to St. Georges Channel, but would have extended seawards in a NE - SW direction and would have been found only in the extreme west and south-west of the Western Approaches to the English Channel. As sealevel increases the front moves seaward. R.M. Austin (1991) acknowledges that 'The hypothetical tides generated in these numerical experiments require careful testing against observational evidence before their worth can be evaluated'. Palaeo-records of sediments with characteristics indicative of stratification or mixing, including fossils, are suggested.

Preece *et al.* (1990) examined fossil evidence from uplifted marine interglacial sequences of the English Channel which indicate that, in the past, stratified conditions may have existed there. The fossil data was calibrated against the results of Houghton (1988) who made a comparative study of the diversity and abundance of coccolith assemblages from recent sediments in the Celtic Sea and English Channel. He found that in the seasonally stratified Celtic Sea coccolith numbers make up over 10 % of the fine fraction of the sediment while accounting for less than 0.1 % of the fine sediments in the tidally mixed English Channel. Diversity dropped significantly from maximum values in the Celtic Sea to lows of three or less in parts of the eastern Channel. Assemblages were dominated by the species *Emiliania huxleyi* especially in the Celtic Sea where it frequently accounted for over 90% of the total abundance. The significant differences between the Celtic Sea and English Channel populations were attributed to the presence or absence of a thermocline. Since stratified and mixed waters have a contrasting diversity and abundance of organisms and as these organisms sink, on death, to the sea bed, the state of the overlying water column is recorded in the fossil assemblage.

W.E.N. Austin & Scourse (1997) used foraminiferal evidence to reconstruct the appearance of stratified waters above the site of BGS vibro-core 51/-07/199, extracted from a seasonally stratified site in the Celtic Deep. In addition to foraminifera, the core was examined for molluscs and grain size among others. The foraminifera were analysed for stable isotope ratios and the molluscs were used for radiocarbon dating. Dating established that the sequence covered the last 12,000 years BP, while an examination of the fossil evidence identified four separate foraminiferal zones within this timespan. Three lithozones were also identified. The lowermost, L1, comprising very fine-grained sediment, coincided exactly with the lowermost fossil zone (B), which was barren. L2, defined by coarser sediments, covered foraminiferal zones F1, defined by a dominance of *C. lobatulus,* and over half of F2, which was dominated by *Q. seminulum.* The remainder of F2 and all of F3, which was dominated by *B. marginata*, comprised sediments which fined upwards towards the silty sediments of the present day. Both the garnishee and foraminiferal changes are consistent with a progressive deepening of the watercolumn over time from under 30 m in F1 to greater than 60m in F3 (Scourse & W.E.N. Austin,

1994). Given the dramatic rise in global sealevels seen at the end of the last glaciation, this is not unexpected.

Isotopic measurements were made on specimens of *Q. seminulum* and *A. batavus,* which, although not the dominant species, were the most consistent throughout the core. The general trend in $\delta^{18}O$ values up-core was one of gradual enrichment, and in $\delta^{13}C$ of depletion. The total increase in $\delta^{18}O$ from bottom to top was approximately 1.2 $^{0}/_{00}$ which corresponds to a cooling in bottom waters of around 5 ^{0}C, while the $\delta^{13}C$ suggest a gradual increase in surface water productivity.

Based on this and the faunal evidence W.E.N. Austin & Scourse (1997) have reconstructed the gradual encroachment of stratified waters over the area as sea level rose meeting the depth criteria for the formation of a thermocline (Simpson & Hunter, 1974). With a summer thermocline comes the separation of bottom waters from surface heating so that conditions here are cool relative to those beneath mixed waters. In addition, the increased productivity found in the region of fronts can be invoked to explain the depletion in $\delta^{13}C$ over time as the increasing flux of organic matter to the seafloor results in the continued depletion of the bottom waters. and thus, the foraminiferal calcite with respect to ^{13}C. This interpretation also supports the modelling work of R.M. Austin.

1.4 Aims & Objectives

The overall aim of this work is to assess the value of foraminifera in downcore studies of shelf- sea stratification using both assemblage composition and geochemical characteristics as environmental indicators. Specifically the objectives are :

1. To map the modern distribution of benthic foraminifera in the Celtic Sea and to analyse the environmental controls on their distribution patterns with particular reference to seasonal thermocline development.

2. To investigate changes in the stable oxygen isotope content of living formaniferal tests across the Celtic Sea front and to test the reliability of this as a tool for downcore palaeotemperature, and hence, stratification assessment.

3. To compare the stable carbon isotope content of sediment porewaters with that of infaunal foraminifera to calibrate for the 'microhabitat effect'.

Chapter 2 Methodology

2.1 Ship work

2.1.1 Cruise plans

Data for this study was collected over two cruises on the R.V. Prince Madog to the north-eastern part of the Celtic Sea during June - July 1995 and June 1996 (see figure 2.1).

The aims of the 1995 cruise were as follows:

1. To take grab samples at selected stations on three transects in the northern Celtic Sea area for foraminiferal, grain size and sediment geochemical analysis (see figure 2.1). A total of 72 stations were sampled in this way.

2. To drop a conductivity, temperature and depth probe (CTD) at each station to collect hydrographic data for the entire water column and to identify the position of the Celtic Sea front.

3. To collect bottom water samples at each station for oxygen isotope analysis.

4. To make multicore deployments at stations with suitable sediments (very fine-grained) for foraminiferal stable carbon isotope and porewater dissolved inorganic carbon (DIC) analysis (see figure 2.2). Cores from 4 sites were extracted during this cruise.

However, data collected during the 1995 cruise were found lacking in several ways; information was needed from over a larger area to provide a reasonable ecological study of this part of the Celtic Sea. In particular, mixed waters had been sampled extensively and there was no information for the Irish side of the front, or that part of the front traversing the Bristol Channel. An attempt was made during the 1996 cruise to measure the dissolved oxygen concentration of bottom water samples on board ship. Additional multicores were also required. The aims of the 1996 cruise were to fill these gaps, sampling in the way described for 1995. Samples were again taken at stations along three transects. (see figure 2.1). A total of 56 stations and cores from two sites were sampled.

2.1.2 Hydrographic data collection

Vertical profiles through the water column of pressure, conductivity and temperature were obtained at each station using a Neil Brown Mk IIIb profiling CTD, which was mounted in a rosette system fitted with water bottles and a reversing thermometer (see figure 2.3). The pressure was measured using a high performance strain gauge bridge transducer. This gives pressure to an accuracy of +/- 1.0 dbars

with a resolution of 0.01 dbars (Neil Brown, 1989a). Temperature was measured using a platinum resistance sensor in conjunction with a flat response thermistor, which improved the response time of the instrument. The sensor has an accuracy of +/- 0.0005 ^{0}C, a resolution of 0.0005 mmhocm^{-1} and has a cell flushing rate of 0.003 seconds. The data were collected on an IBM compatible PC using an EG + G software package (Neil Brown, 1989b).

In 1995, as the data collected was also needed for a complementary physical oceanographic study, the resolution of the CTD was set to 1 m intervals. In 1996, this resolution was reduced to 5 m intervals, which did not impair the quality of the bottom water data or impede detection of the frontal position.

2.1.3 Surface sampling

A Shipek grab was deployed for the collection of seabed surface sediments (see figure 2.4). The sediment collected in this way was subsampled for foraminiferal, grain size and geochemical analysis. Care was taken to ensure that only the surface of each sample was subsampled. Samples to be examined for foraminifera were stored in collection jars with the same volume of ethanol and 10 - 20 ml of rose Bengal stain (see section 2.2.1). All sediment samples were stored in collection jars and those for geochemical analysis were frozen immediately.

It has been reported that, as the Shipek has imperfect closure, some sediment may be lost as the grab surfaces through the water column (Murray, 1991). Those with better closure include the small gravity corer and the box corer but these samplers were not available. Murray (1991) states that corers are generally suited to soft (fine-grained), cohesive sediments only. In addition, these corers are preceded by a down-wash/bow wave resulting in the displacement of surface sediments and their contained fauna (Murray, 1991; Bett *et al.*, 1994). As a result, both gravity and box corers have been shown to underestimate meiofaunal abundance (Bett *et al.*, 1994).

A multicolour was also used in this study (see figure 2.5). This corer has complete closure preventing washing of the sample as it is raised and is thus more successful than other methods at taking representative samples (Holme & McIntyre, 1984; Bett *et al.*, 1994). However, this technique proved untenable in all but the finest sediments and was not used for surface sampling.

2.1.4 Subsurface sampling.

The multicolour used for subsurface sampling was the Midicorer Mark 1 - 400 (see figure 2.5). It is designed to take undisturbed cores which preserve the sediment/water interface. It comprises a bell-shaped, stainless steel solid bar frame, 1.5 m high and 1.2 m in diameter at the base and topped by the frame top plate. The hydraulic damper tube sits in the centre of the frame. Bolted to the lower part

of the damper is the head which carries the mounting pins. The damper controls the rate of penetration of the core tubes (approx. 50 mm per sec). Weights can be mounted on the head if required. When assembled the corer weighs 1850 Newtons but an additional 3000 Newtons of lead weights can be added. Prior to deployment the damper and head are raised by attachment to a winch whilst the frame remains on deck. When fully extended the corer stands 2.28 m high. Four tube carriers are then attached to the head. Each tube carrier comprises an open fronted box with a sealing lid or top closer for the cores which can slide along the two bars providing the frame for the carrier. At the lower end of this frame is the core catcher or bottom closer. The tube carriers accommodate transparent core tubes fixed in place by retaining rings. In readiness for deployment the top and bottom closers are opened and a holding pin is inserted in the top plate. This holds a latch in place until after the hydraulic damper, and thus the cores, have entered the sediment. The purpose of the latch is to hold the corer head in position after it has taken cores, preventing attempts at multiple sampling if the corer is replaced on the bed. The corer is then ready for lowering over the side of the ship. On recovery, the closers are triggered, and the damper and head are again contained within the frame (Bowers & Connelly, 1991).

The multicore returned four cores in transparent tubes and the sediments within were inspected for burrows and signs of disturbance. The longest and least disturbed core was selected for sampling. The core tube was placed in a specially built frame designed to allow very careful extrusion of the core (see figure 2.6). In this way it was possible to sample the core at intervals of millimetres.

The overlying water was first siphoned off. In the 1996 cores only, the sediment-water interface was sampled and treated on board in preparation for dissolved inorganic carbon (DIC) isotope analysis (see below). Cores from both years were sampled for the 0 - 0.5 cm interval and subsequently at 1 cm intervals for a further 4 cm. Each level sampled was subsampled for foraminiferal analysis and for porewater DIC analysis. Certain cores were further sampled at 1 cm intervals down to 9.5 cm (see Appendix V) for foraminiferal analysis only. Samples for foraminiferal analysis were preserved and stained in the way described in section 2.2.1.

Pore waters were extracted using the method developed by McCorkle (1987). Samples were placed and balanced in centrifuge tubes and spun for 20 minutes. Those samples awaiting the centrifuge were stored in ice. After centrifuging the supernatant fluid was extracted from the tube by syringe, taking care not to draw up any sediment. Filters were then attached to the syringes and the syringes were capped and stored in ice until the transfer of their contents to labelled ampoules which were also spiked with poison. The ampoules were placed in a retort clamp and prepared for the water by flushing with nitrogen. Nitrogen was delivered through two tubes, both inserted into the ampoule and one of which had a needle attached. Flow of nitrogen was equal through both; this was checked by putting both ends in a beaker of water and using the bubbles to gauge and adjust the flow. Once flushed, the needle source was removed from the ampoule and the water transferred by placing a needle on the

end of the syringe, inserting it into the ampoule and delivering the contents to the ampoule. The ampoule was then taken and sealed using a torch. Once sealed the ampoule required no special storage conditions.

2.1.5 Bottom water collection

The water collection facility on the CTD was triggered to collect a water sample close (~ 10 m) to the seabed. A ration of the collected water was used to calibrate the CTD whilst the remainder was transferred to a glass, rubber sealed, screw top bottle with a capacity of 250 ml for subsequent analysis for oxygen isotopes. A nalgene tube was used to transfer the water as it facilitated control of the water flow. The bottle was filled from the bottom and at least three times the capacity of the bottle was allowed to overflow to eliminate all air bubbles before removing the tube and capping the bottle.

In 1996 the remainder of the collected bottom water was transferred in the same way to a 250 ml borosilicate glass bottle for dissolved oxygen measurement. The nalgene tube was swirled in the bottle to assist the elimination of air, three times the volume of the bottle was allowed to flow through and the tube was slowly removed as the water still flowed. The sample was then ready for on board measurement. Calibration samples were also collected at 13 sites. These samples were collected as described above, then the oxygen contained within the water was 'fixed' by the addition of 1 ml of manganous sulphate, followed by 1 ml of alkaline iodide delivered by pipette to just beneath the water surface. The bottle was briskly capped by a lid designed to displace an amount of water on insertion, thereby ensuring no air was trapped and the bottle was shaken vigorously. An explanation of this method can be found in section 2.7.

2.2 Preparation of foraminifera for analysis

2.2.1 Preservation and staining

Samples for foraminiferal analysis were stored in ethanol for preservation (Murray, 1991) and rose Bengal for staining. The rose Bengal technique, first described by Walton (1952), is not vital but stains protoplasm so distinguishing dead from living or recently dead. Walker *et al.* (1974) found that this technique stained 70.3% of specimens tested but the technique is criticised because it may stain dead or broken tests (Boltovsky, 1964). As dead individuals may retain protoplasm (and thus, the possibility of staining) longer in a low oxygen environment this technique may result in site dependent bias. Corliss (1985) advises against selecting those individuals with spots of red, an all over pink stain or red strips as these may be the result of other organic matter or organisms, particularly worms.

2.2.2 Separation and sieving

Preparation of foraminifera for examination under a light microscope involves the separation of the tests from the sediment by washing and sieving. There is no single, standard aperture size which should be used during sieving. The aim is to remove as much of the inorganic portion as possible without losing significant quantities of smaller specimens. Schröder *et al.* (1987) carried out a study of the fauna contained within different size fractions and concluded that use of large apertures (such as > 125 μm) resulted in significant loss of specimens including environmental index species and suggested that use of these sieve sizes may produce apparently "barren" zones. However, very small apertures retain too much inorganic matter and unidentifiable juvenile tests significantly increasing the labour involved in processing a sample. Jennings & Helgadottir (1994) also found that samples from Greenland, analysed for the 63 μm - 125 μm size fraction, had up to 23 times the foraminiferal abundance of the > 125 μm fraction and comprised different faunas. The conclusions of Schröder *et al.* (1987) and Jennings & Helgadottir (1994) were that a 63 μm aperture is ideal because, whilst removing most of the clay and silt, it retains most of the smaller adult foraminifera. Thus, this was the aperture size chosen for this study.

Foraminifera may be separated from the remaining sediment using a flotation technique. However, flotation in heavy liquids may cause loss of infilled species and some agglutinated forms. Haynes (1981) suggests that this technique is only useful when a quantitative study is not necessary. W.E.N. Austin (1991) inspected and counted foraminifera from both the light and heavy fractions of a sediment separated by liquid fractionation and found both to be similar but broken and abraded specimens were often absent from and therefore under-represented in the light. This did not cause problems in the context of his work but might in other situations. However, flotation considerably reduces processing time which was a problem in this study.

Flotation was carried out according to the methods described in Meldgaard & Knudsen (1991) using carbon tetrachloride (CCl_4) which, with a specific gravity of 1.66 $gcm^{-1}s^{-1}$, is deemed suitable for recent/Holocene sediments.

Despite separation by heavy liquids many samples remained unmanageably large and so further sample reduction was carried out by splitting, or successively splitting the sample into equal halves so that the sample size was reduced by a factor of two each time. Results were later multiplied up appropriately. Care was taken to ensure that there was no bias in the size of foraminifera.

For the subsurface samples each level was floated and picked clean of stained foraminifera excepting core mc296 which had too many specimens in the shallowest level and so was split before microscope analysis.

2.3 Microscopy

Foraminifera were picked and identified using light microscopes. For initial picking and identification of larger individuals an Olympus SZ30 was used but for smaller and problematic individuals the more powerful Olympus VM4 was necessary.

Picking and identification involved a combination of the methods described by Meldgaard & Knudsen (1991) and Murray (1979b); the former for efficiency where larger and common species were found and the latter for more careful identification of smaller and rarer species. A total of 52 samples from 1995 and 1996 were examined for living and dead foraminifera.

2.3.1 Assemblage counts

Each surface sample was picked for 300 living and 300 dead individuals as the relative proportions of the component species are reasonably constant for this number (Murray, 1991). The 'live' assemblage is believed to represent the actual population living in the area but it has been suggested that assemblage composition may vary seasonally (Murray, 1991). Since the dead assemblage integrates data over time, it can differ significantly from the living assemblage. This may be the result of post-mortem transport of tests into or out of the sampling site. Production is also significant as it can enhance or diminish the contribution of an individual species to the dead assemblage (Loubere *et al.*, 1993). Similarly, preferential preservation over-represents the more robust species. Boltovsky (1991) and Boltovsky & Totah (1992) report that different species display varied resistances in laboratory tests and propose the development of a preservation index. Agglutinated tests tend to disaggregate easily (Smith, 1987) and are thus under-represented in dead assemblages but calcareous tests can also be removed by dissolution in waters under-saturated with respect to $CaCO_3$ (Murray, 1989).

However, since the study of modern foraminiferal assemblages is largely driven by the need to interpret fossil assemblages, Scott & Medioli (1980) suggest that the total assemblage, which includes both the living and the dead data, is the most useful for comparison. Murray (1982) disputes this since 'live' component may be subject to post-mortem removal.

2.3.2 Additional measures applied to faunal data

(i) Diversity indices

There are a wide range of diversity indices available to the ecologist, each of which seeks to characterise the diversity of a sample or community by a single number. Diversity measures take into account richness (the number of species) and/or eveness (how equally abundant the species are). The relative weighting given to eveness and richness distinguishes the different indices.

Species diversity measures can be divided into three main categories. The simplest of these are the species richness indices which are a measure of the number of species in a defined sampling unit. Species abundance models describe the distribution of species abundances while the last group, indices based on the proportional abundances of species, attempt to combine richness and eveness into a single figure.

Species richness indices

Numerical species richness is defined as the number of species per specified number of individuals or biomass (Kempton, 1979). The advantage of species richness indices is their ease of calculation. However, they provide no information on the relative abundances of species. A simple species richness index, Margalef's diversity index where

$D_{Mg} = (S - 1) / \ln N$

has been applied to the data in this study where S = number of species and N = Total number of individuals.

Species abundance models

Fisher *et al.*, (1943) was one of the first to report that species abundances occurred in characteristic patterns; never all equally common in a particular community, rather, only a few very abundant species, while others are less abundant. This observation has led to the development of species abundance models and although there are many types of distribution diversity is usually examined in relation to four main models. These are the geometric series, the logarithmic series, the log normal series and the broken stick model. There is a continuum from the geometric series where a few species are dominant with the remainder fairly uncommon, through the log series and log normal distribution where species of intermediate abundance become more common and ending in the conditions represented by the broken stick model in which species are as equally abundant as is ever observed in the real world (Magurran, 1988). The log series distribution is characterised by a small number of abundant species and a large proportion of rare species. It is most applicable in situations where one or a few factors dominate the ecology of a community and so was applied to the data in this study. This model is the basis for the logarithmic series index a (Fisher *et al.*, 1943) which takes the form:

$\alpha\chi, \alpha\chi^2/2, \alpha\chi^3/3 \ldots \alpha\chi^n/n$

$\alpha\chi$ being the number of species predicted to have one individual, $\alpha\chi^2/2$ those with two and so on.

Adding all the terms in the series gives the total number of species, S, also written as:

$S = \alpha\chi\text{-}\ln (1-\chi)]$

χ may be estimated from the iterative solution of

$S/N = (1-\chi)/\chi\ [-\ln (1-\chi)]$

where N = the total number of individuals. The diversity can then be calculated from:

$N\ (1-\chi)/\chi$

A series of studies (Taylor, 1978; Kempton & Taylor, 1974; 1976) investigating the properties of this index and have come out strongly in favour of its use, even when the abundance data is not best described by a log series distribution.

Indices based on the proportional abundances of species

While species abundance models provide the fullest description of diversity data they are dependent on some arduous model fitting and calculations. Indices based on the proportional abundances of species provide an alternative. Southwood (1978) refers to them as non-parametric indices because no assumptions are made about the shape of the underlying species abundance distribution , while Peet (1974) terms them heterogeneity indices because they take both eveness and species richness into account. One group of heterogeneity indices are referred to as dominance measures since they are weighted towards the abundances of the commonest species rather than providing a measure of species richness. The dominance measure applied in this study was the Simpson's index (D).

Simpson (1949) gave the probability of any two individuals drawn at random from an infinitely large community belonging to different species as:

$D = \sum\theta i^2$

Where θi equals the proportion of individuals in the i*th* species. In order to calculate the index the form appropriate to a finite community is used:

$D = [n_i(n_i - 1) / N(N - 1)]$

Where n_i equals the number of individuals in the n_ith species and N equals the total number of

individuals. The reciprocal of Simpson's index is usually used for comparative purposes.

(ii) Index of affinity

The index of affinity was first used by Sanders (1968) in work on soft-bottom benthic communities and is used to compare assemblages. An evaluation of this index was carried out by Rogers (1976) and it was compared to the chi-squared test and factor analysis and the results of all three methods were found to concur. The index of affinity is calculated in the following way:

Species	Sample j	Sample k	% in common I.A.	% difference C.B.
A	20	15	15	5
B	8	17	8	9
C	43	19	19	24
D	24	31	24	7
E	5	18	5	13
Total	100	100	71	58

$$I.A. = (100 - 1/2C.B.) = (100 - 0.5 \times 58) = 71$$

In this study the index of affinity is used to compare living and dead assemblages from the same sites.

2.4 CTD data processing

Post-processing of the CTD data was performed using EG + G software (Neil Brown 1989a and 1989b). The data was checked for rogue values which were removed and then averaged into 1 m vertical intervals for 1995 and 5 m intervals for 1996.

Salinity and density were derived using the International standard procedure for sea water (Unesco, 1981). The CTD temperature sensor was calibrated against an independent temperature measurement. This was the SIS RTM4002 reversing thermometer with an accuracy of +/- 0.001 ^{0}C. The temperature was adjusted using the formula :

$$\text{Temperature} = \text{CTD temperature} + dT\ (^0C)$$

where dT is the mean difference between the CTD and the reversing thermometer.

Salinity is a function of conductivity, temperature and pressure. The salinity was calibrated by comparison of the water sample salinity measured using an Autosal Laboratory Salinometer with the appropriate salinity measured using the CTD. The salinometer works by employing a continuous flow system, where the sample is drawn under low pressure from the original sample bottle. A high stability temperature control bath and heat exchanger maintain the sample at a precisely defined temperature during analysis, avoiding the need for temperature compensation (Guildline, 1985). This gave an

accuracy of better than 0.002 PSU and a resolution of better than 0.0002 PSU. The salinity calibration was calculated as a ratio. These values were adjusted in a similar manner to the temperatures :

$$\text{Salinity} = \text{CTD salinity} + dS$$

where dS is the mean difference in salinity. All salinities were quoted using the practical salinity scale (PSS78) and have no units.

The text files of data from EG + G software were converted, using in-house software, into a standard form suitable for plotting which incorporated a header containing station number and position and station depth, as obtained from the ships depth-sounder, followed by the temperature, salinity and pressure for each depth.

CTD data was processed by G. Fulton and K. Horsburgh, at Bangor, for the 1995 and 1996 data respectively.

2.5 Geochemical analysis of sediments

In the laboratory, sediments for analysis were thawed, subsampled and homogenised to ensure that the sediment was evenly mixed throughout. Samples were then dried in an oven at 60 ^{0}C until completely dry. Once dried, the samples were again homogenised, by both manual and mechanical grinding, to allow a good combustion in the analyser. In preparation for the Europa Scientific Roboprep, which measures organic carbon, total carbon and nitrogen content, samples were placed in silver boats and weighed. In addition to this, the samples for organic analysis were each reacted with 100 µl of HCl and dried to remove all $CaCO_3$. The boats were then scrunched in a ball using a pair of tweezers. These balls were placed into a sample tray and the position of each noted. The samples, encapsulated in sample containers, were introduced into a combustion column reactor by means of an autosampler and combusted at 1020 ^{0}C. The Europa ensures complete oxidation by passing the combusted products through a bed of chromium trioxide using a helium carrier gas. The oxidation was completed and sulphur removed by a layer of copper oxide and a layer of silver wool. The products were then passed into a second furnace containing copper at 600 ^{0}C, where excess oxygen was absorbed and nitrogen oxides reduced to elemental nitrogen. Water was removed by anhydrous magnesium perchlorate and carbon dioxide by a trap containing 'Carbosob'. The quantities of carbon and nitrogen were given by a printout. Samples were run in batches of up to 50 which were interspersed with empty cups and the recommended standard for organic carbon/nitrogen microchemical analysis, Acetanilide, a National Bureau of Standards certified standard reference material. The data from the analyser was regressed linearily by the least squares method, setting total carbon and nitrogen against area counts. The organic carbon and nitrogen contents were calculated using the algorithm given in Verardo *et al.* (1990). Inorganic carbon was found by subtracting organic

carbon from total carbon. The geochemical analyses were performed on 59 samples from the 1995 cruise by I. McMyn at Bangor.

2.6 Grain size analysis of sediments

Samples were sieved into gravel, sand and mud fractions based on the Wentworth scale (Wentworth, 1922) by initially wet sieving on a 63 μm (4.00 phi) sieve then drying the retained sample at 105 ^{0}C overnight in preparation for dry sieving on a 2 mm (-1.00 phi) mesh. Each fraction was weighed and then the sand sized sediment was resieved at 0.5 phi class intervals using a mechanical sieve shaker (Pascall Inclyno) for 15 minutes. Each sample was weighed to an accuracy of 0.01 g.

The Micromeritics Sedigraph 5000ET, a particle size analyser for fine grade sediments, was used to measure grains of less than 100 μm in diameter. The sedigraph works by passing an X-ray beam through a 3 - 5$^{0}/_{0}$ solution of a sample which detects relative particle concentration because the magnitude of X-rays absorbed by a particle is proportional to its mass. The suspended sediment concentration and, thus, sedimentation rate of a sample suspended in a sample cell is measured in this way and then converted into equivalent spherical diameter using Stoke's Law, which states that the force exerted on a sphere falling at low velocity is directly proportional to the product of the fluid viscosity, particle velocity and particle diameter.

In preparation for the sedigraph samples were centrifuged with distilled water, treated with 10$^{0}/_{0}$ hydrogen peroxide to remove organic matter and then centrifuged again with distilled water. Calgon was used to deflocculate the sample which was then dispersed in an ultrasonic bath for 15 minutes (Stein, 1985) followed by the use of a magnetic stirrer. The suspended solution was loaded into the sample cell and the X-ray intensity set to 700 as recommended in the micromeritics 5000ET instruction manual. Samples were analysed for sizes between 3 -100 μm. Samples were maintained at 32 ^{0}C since this is the temperature for which the selected program converts the values. The cumulative percentage data was stored in the attached computer and a cumulative frequency plot was obtained.

Grain size parameters for each sample were calculated using a Fortran grain size analysis package (Jones, 1990). These include modal and mean grain size, sorting, skewness and kurtosis for both 'moments' and 'Folks'. 'Moments' statistics is so called because the computations involve multiplying a weight, frequency, in percent, by a distance which is analogous to computing moments of inertia for grains in each size grade in the distribution. A definition of the moment statistics applied to grain size analysis can be found in Carver (1971). 'Folks' statistics is based on a graphical computational technique, the first step being the construction of a cumulative percentage curve on probability paper. From this, various percentiles are read off for insertion in the formulae for calculating graphical parameters. A review of the available formulae can be found in Folk (1966). Those used in this study

were those proposed by Folk & Ward (1957). The advantage of the method of 'moments' over 'Folks' is that the entire distribution is used in computing the statistics rather than just part of the distribution while graphical techniques avoid the lengthy calculations required by moments statistics.

Modal grain size is defined as the most frequently occurring grain diameter (Folk, 1966). On a plot of grain size against weight percentage frequency, the mode is the grain size at the peak of the curve. Frequently there is more than one peak and the sample is said to be bimodal or polymodal which means that it is composed of more than one grain size population. Thus, the recognition of modal size is particularly useful when the sediment has been derived from multiple sources. Mean grain size refers to the average grain diameter of a sample and gives a simple indication of the magnitude of energy applied by the transporting mechanism. A steady change in mean grain size over an area indicates the direction of transport. A measure of the degree of sorting is given by the standard deviation which is derived from the spread of data about the average grain size. Sorting increases along the transport path. Skewness measures the bias of sizes towards the fine or coarse. It is a positive or negative dimensionless number ranging between -1 to +1 with positive values indicating fines and negative coarse. Duane (1964) suggests that negative skewness is the result of winnowing of fines (erosion in a high energy environment), while positive skewness is due to the accumulation of fine grains (deposition in a low energy) environment. Areas where neither positive nor negative skewness dominate are characterised by fluctuating energy levels. Kurtosis measures the peakedness of a frequency curve. This is also a dimensionless parameter and is a test of the normality of the curve.

Grain size measurements were carried out at Bangor by E. Roberts on 43 surface and all the multicore samples from 1995 and by J. McDonagh on 50 surface samples from 1996.

2.7 Dissolved oxygen measurements

On board measurement of dissolved oxygen content in bottom water samples was attempted using a portable waterproof dissolved oxygen meter. The meter has an attached probe which was swirled in the sample for several minutes as water movement of at least 0.3 ms^{-1} is required to ensure that the oxygen depleted membrane surface is constantly replenished and because it is necessary to allow time for the thermal equilibrium to occur between the probe and the sample. The probe membrane covers the polarographic sensors and an integral thermistor for temperature measurements and compensation, isolating them from the testing solution but allowing oxygen to enter. When a voltage is applied across the sensor, oxygen that has passed through the membrane reacts causing the current to flow, allowing determination of its concentration. The dissolved oxygen concentration, automatically compensated for temperature, is displayed on the unit in ppm or mgl^{-1}. The meter used (HI9142, Hanna Instruments) had a range of 0.0 to 19.9 mgl^{-1}, a resolution of 0.1 mgl^{-1} and an accuracy of +/- 1.5% (Hanna, 1990).

The calibration samples were measured for dissolved oxygen concentration using a chemical technique (Strickland & Parsons, 1972). Manganous sulphate and alkaline iodide solution were added to the seawater sample on collection which was stoppered and shaken. A manganous hydroxide precipitate resulted. The oxygen in the seawater oxidised some of the hydroxide to a tetravalent manganese compound, which was later quantified in the laboratory at Bangor, by the acidification of the solution. This causes the compound to oxidise iodide ions (present in the added alkali) to iodine. The quantity of iodine produced is determined by titration with sodium thiosulphate thus allowing back calculation of the dissolved oxygen concentration. A description and explanation of the method is provided by Strickland and Parsons (1972). These measurements were carried out by Hillary Wilson at Bangor.

2.8 Stable isotope analysis

2.8.1 Analysis of water/porewaters for ^{18}O and ^{13}C

The oxygen isotope ratios of H_2O were determined by the placement of each water sample in a sealed, spherical reaction vessel where the gases were evacuated by freezing. An aliquot of CO_2 was added and the sample was left for a set period of time to allow the exchange of oxygen between the water and CO_2 to reach equilibrium. The CO_2 gas was then extracted from the sample by freezing and collected for subsequent measurement on the mass spectrometer, a VG ISOGAS, SIRA II, at the School of Oceans Sciences, University of Wales, (Bangor). Samples were run in batches of eight against a standard, Norwich Tap Water, and final values are expressed relative to SMOW after Craig (1961). Five samples from the 1995 cruise and six from the 1996 cruise were run by R. Owen, Bangor.

The dissolved inorganic carbon (DIC) content of the samples was determined by the acidification of the water samples which displaced the equilibrium between the different species of CO_2 found in seawater so that all of the CO_2 existed as $CO_{2(aqueous)}$. The released CO_2 was collected by cryogenic distillation in an N_2 gas flow. This was directly analysed by mass spectrometry. An internal reference standard was used during analysis (Middleton, 1997). Extraction efficiency was approximately 99 %, indicating that the isotopic composition of the extract should closely resemble that of the sample, and the precision of the method was ±0.07 %. Values were expressed, following convention, relative to Pee Dee Belemnite (PDB) after Craig (1961). A detailed description of the technique employed can be found in Middleton (1997). The porewater samples were run by G. Middleton at Bangor. Twenty of these were derived from 1995 multicore sediments and twelve from 1996.

2.8.2 Analysis of foraminifera for $\delta^{18}O$ and $\delta^{13}C$

Measurement of the stable isotopic ratios of oxygen and carbon in the $CaCO_3$ of calcareous foraminifera involved the gentle crushing of the samples and transfer to a sealed automatic preparation system where the $CaCO_3$ was reacted with 100 % orthophosphoric acid at 90 ^0C. The resulting CO_2 was analysed on a mass-spectrometer; the VG isotech PRISM at the University of Edinburgh University or the VG isotech PRISM series 2 at the University of Cambridge. The more numerous 'dead' specimens were analysed at Edinburgh by S. Tudhope in samples of approximately 10 - 15 individuals, while the less abundant 'live' were analysed at Cambridge by M. Hall in samples composed of approximately 5 individuals, because the system at Cambridge requires very little $CaCO_3$. Results were calibrated by the repeated analysis of a carbonate standard and expressed relative to (PDB). Results were also were Craig corrected (Craig, 1957) for different isotopic species in CO_2 which have the same molecular mass. Analytical accuracy was greater than 0.08 $^0/_{00}$ for $\delta^{18}O$ and 0.03 $^0/_{00}$ for $\delta^{13}C$ at Edinburgh and 0.08 $^0/_{00}$ for $\delta^{18}O$ and 0.06 $^0/_{00}$ for $\delta^{13}C$ at Cambridge.

2.9 Statistical techniques

2.9.1 Mapping of variables

Mapping of both environmental and faunal data was performed using the Advanced Visualisation Systems (AVS) / UNIRAS mapping package Gsharp. This package produces a continuous surface from discrete data using various interpolation functions. These functions estimate Z-values (variables) by looking at each values neighbour with the assumption that dependency on the neighbouring data points diminishes with increasing distance. The interpolation function chosen was bilinear interpolation. This creates a smooth 2-D data set from bilinear and quadratic functions on X, Y and Z data sets (longitude, latitude and the variable to be mapped). The method approximates existing data points onto a grid, interpolates by linear interpolation and then improves the estimate by computing gradients at the points using quadratic interpolation. It then refines the values using distance weighting methods. The new surface smooths the original data points, it will not necessarily pass through them (AVS/UNIRAS, 1997). As a result the class intervals produced for each map are not necessarily linear.

This package also allows the definition of regions, the boundaries beyond which values are not interpolated. This helps prevent production of contours for areas for which there are no data. Two regions were defined, the first enclosing all the transects for those variables measured for both 1995 and 1996, and the second enclosing transects 1, 2 and 3 for those variables measured in 1995 only.

2.9.2 Factor analysis

Ordination is the term for a group of statistical techniques, widely used in the analysis of large data sets, which arrange sites along axes on the basis of species compositions. The results of an ordination, such as factor analysis, in two-dimensions can be graphically summarised or plotted on two axes such that the points which are closest together correspond to sites that are most similar in species composition.

In ecological studies, where the influence of abiotic factors on the biota is of interest, sampling is carried out by at a number of sites and the species composition recorded for these sites. This data set, which is often very large, is then summarised by ordination. This information is subsequently interpreted in the context of the environment; formally, if environmental data is available and informally if it is not. This two-step approach is termed 'indirect gradient analysis'. By contrast 'direct gradient analysis' (*e.g.* regression) is impossible without environmental data and these variables are of interest from the outset.

Between ordination and regression lie the canonical ordination techniques, including canonical correspondence analysis (CCA), the main aim of which is to elucidate the main pattern in relations between the species and the observed environment. This type of analysis is described in section 2.9.3 below.

(i) Preparation of data

In multivariate data sets a set of samples (n) are described by a series of variables (m). Often where these data sets are large some kind of summary is needed in order to understand how sample sets respond to groups of variables simultaneously. Application of simultaneous R- and Q-mode factor analysis can help to do this because factor analysis makes the assumption that a small set of common factors can be used to describe the data. Any remaining variance in the data is then considered to be the result of 'error'. Both R- and Q-mode factor analysis are based on eigenvector methods. R-mode analysis is similar to principle components analysis and Q-mode to cluster analysis (Birks, 1995; Kovach, 1995). The actual steps involved in the analyses are described in Walden & Smith (1995).

R-mode analysis transforms the raw data matrix (n X m) into a m X m matrix with each element representing the similarity between variable pairs in terms of the way they respond to the samples. The original variables are then transformed into factors, groups of variables which account for more of the variation within the data set than any individual variable does. The extraction of factors is constrained by the condition that all are mutually uncorrelated, that is, they occupy mutually orthogonal axes in 'multidimensional factor space' (Walden & Smith, 1995). The eigenvalues or factor-loadings also produced using this technique can be used to determine the amount of variance explained by

each factor as will be demonstrated in part (iii) of this section.

Q-mode analysis also begins with the (n X m) data set and produces a n X n matrix which represents the similarity of pairs of samples in terms of the variables response to them. Again factors are produced which summarise the data.

(ii) Preparation of data

Data was prepared for analysis in the way prescribed by Imbrie & Kipp (1971). The first step involves the elimination of rare species from the data set. The cut-off point is set at some percentage of the species data, that is, any species which do not comprise that percentage of the data in at least one of the samples is removed from the data set. This reduces the influence of rare species on the analysis but is also necessary because the number of variables must be considerably less than the number of samples they describe for factor analysis to be performed.

The data is then transformed by the division of each element (% occurrence of a species) by the range over which that species occurs (maximum occurrence less minimum occurrence). This transformation has the advantage that it extracts the maximum ecological information since there is no reason to assume that the ecological importance of a species is correlated with its average dimensions' (Imbrie & Kipp, 1971). The disadvantage of this transformation is that it magnifies counting error. However, it is hoped that the selection of a high cut-off point should minimise this problem.

The final step involves the row-normalisation of the data matrix. The data set is entered in the form of species by column and sites by row. The rows are then normalised by the multiplication of each by a constant which then produces a row, the elements of which when squared, sum to 1. The constant (k) is calculated as

$$k = \sqrt{\frac{1}{(a2+b2+c2...)}}$$

where a, b, c *etc.* represent each element of the row (the % species data for each site). Row-normalisation is not strictly necessary before analysis but helps to simplify the interpretation of the output.

(iii) Interpretation of output

R-mode output is in the form of a data matrix with factor columns and species rows. This data is row-normalised in the way described above to facilitate the comparability of the species scores. The number of factors produced is the same as the number of species but only some will be of ecological significance. The first factor is most significant and the subsequent factors successively less so. The

eigenvalues or factor loadings produced by R-mode analysis can be used to calculate the % variance of the data explained by that factor. This is calculated by summing the eigenvalues and then using this as the 100 % mark for comparison with the eigenvalue for each factor.

Species scores may be positive or negative, but the higher the absolute value of a score the greater that species contribution to that factor. If a species scores close to zero then it has no influence on that assemblage. If a species scores negatively in a factor then it is negatively related to that factor and vice-versa. These scores allow the identification of the assemblages of species contributing to a particular factor and the relative importance of each.

Q-mode output comprises a matrix of factor columns and sample rows. The scores for each factor can then be mapped using each samples co-ordinates, thus, producing a map of that factors/assemblages distribution over the study area (Conradsen, 1993; Conradsen *et al.*; 1994, Imbrie & Kipp, 1971; Steinsund *et al.* unpub.). Conradsen (1993) also used the Q-mode scores as dependent variables for regression against controlling environmental variables, exploring the relationship of a particular assemblage with these parameters. To determine how much of the data at a site is explained by the factors accepted as being ecologically significant, the communality, the square of the scores for each included factor, should be summed for that site.

2.9.3 Canonical correspondence analysis

While ordination summarises data in a convenient way, most techniques (excluding factor analysis) do so by assuming that there is an underlying structure in the data; that the species distribution is controlled by a few environmental variables according to a simple response model. CCA and a related technique, correspondance analysis (CA), assume a unimodal species response model to an environmental gradient and Whittaker (1967) among others observed that species do commonly show bell-shaped response curves. Different species tend to occupy different intervals along an environmental gradient. To compare the explanatory power of different environmental variables each must be standardised. In the case of CCA environmental variables are automatically standardised to mean 0 and variance 1. This is done by finding the centroid of the site scores subtracting this from each value and then dividing each by the square root of the dispersion.

To provide a measure of how well an environmental variable measures the data an indication, known as a species score, is needed of where a particular species occurs along an environmental gradient. This is estimated by taking the average of the environmental values of the sites at which the species is present. If a species has a unimodal response then the average is also the optimum or the preferred value of the environmental variable. The method for calculating these values is expanded on below. The spread of the species scores along the environmental gradient is then a measure of how well that variable explains the species data. The larger the dispersion the better that variable is at explaining

the distribution of species.

Correspondance analysis maximises the distribution of the scores along a hypothetical environmental gradient. CCA, however, maximises this spread using linear combinations of environmental variables *e.g.* (2 x var A) + (3 x var B). All possible combinations of environmental variables, including each variable alone, are considered (ter Braak, 1987). Canonical Correspondance Analysis, thus, chooses the best weights for the environmental variables. Since the site scores used are restricted to being linear combinations of environmental variables and this method is sometimes termed 'restricted correspondence analysis'.

Since correspondence analysis, like factor analysis, uses matrices it is a form of eigenanalysis. The outputted ordination axes are eigenvectors and each eigenvector has a corresponding eigenvalue . This indicates the importance of the ordination axis because it is a measure of dispersion. Thus, for the first axis, λ_1 has the largest dispersion and for the second, λ_2, has the second largest and so on.

Another measure of the association between species and environment, though not an ideal one, is the species-environment correlation (R). This is the multiple correlation of the final regression in CCA analysis and is the correlation between the site scores that are weighted averages of the species scores and the site scores that are linear combinations of the environmental variables.

An important phenomenon in CA is the 'arch effect'. Even when the data can be perfectly explained by the first axis, CA will uncover a second axis which shows a quadratic relation to the first. This is termed the 'arched effect' because it produces an arch shape when plotted. It is a mathematical artefact corresponding to no real structure in the data and can be eliminated by 'detrending' (Hill & Gauch, 1980). The analysis is then known as 'detrended correspondance analysis' or DCA. This effect may also crop up in CCA (Gauch, 1982) because though CCA is restricted CA, the more environmental variables included in the analysis the less restrictions there are. The arch effect can be removed from a CCA analysis by detrending or by dropping superfluous environmental variables.

Chapter 3 Results of environmental analyses

The actual data for the environmental variables measured are given in Appendix I.

3.1 Echo-soundings

The depths, for both the 1995 and 1996 cruises were recorded by the onboard echo-sounder. These data have been manipulated using the mapping program GSHARP to produce bathymetric maps. The results are presented in 2 D and 3 D colour in figure 3.1 (a and b). From these figures it can be seen that part of the Celtic deep covered by the two cruises is composed of two, possibly three discrete basins orientated in a NNE - SSW direction. The sides of this trench-like feature appear to rise sharply to the relatively shallower (-75 m) Nymphe Bank and Lundy Platforms on either side but these slopes are actually less than 1:50 (Tappin *et al.*, 1994) and therefore exaggerated in these figures. The single transect running into the Bristol Channel climbs in a steady arch out of the most southerly basin to a depth shallower than - 65 m.

3.2 Water analyses

3.2.1 1995 CTD profiles

The 1995 temperature, salinity and density data were plotted for each transect (see figures 2.1 and 2.2 for the transect and frontal positions and figures 3.2 - 3.10 for the results of the CTD measurements). The length of each section is given by the distance along each transect and has been arranged so that the most northerly end of each transect lies to the left. The dotted lines indicate where measurements were taken. The sections show that this area of the Celtic Sea was strongly stratified at the time of the cruise. The vertically well-mixed water has just been captured on all three transects. The entire frontal region and around 40 km of stratified waters have also been sampled.

In stratified waters the wind-mixed homogenous surface layer is approximately 10 m thick and is underlain by a 25 - 30 m thick thermocline. This is shallow enough for light penetration and thus phytoplankton growth (Tett *et al.*, 1986).

In all three transects the surface and bottom fronts are in approximately the same position. The surface to bottom temperature contrast in stratified waters ranges between 5.5 - 7 ^{0}C. The bottom stratified area is marked by the 9.5 - 10 ^{0}C isotherms or the 27.2 - 27.3 density contours. This cold pool of water is insulated by the strong stratification.

The surface and bottom isotherms diverge between 12 and 12.5 ^{0}C for transect 1 (see figure 3.2) while transects 2 and 3 diverge between 11.5 and 12 ^{0}C (figure 3.5 and 3.8). All three transects show a surface pooling of less dense and less saline waters to the south of the front but this is not observed in the temperature profiles.

Salinity seems to contribute little to stratification in the Celtic Sea but does approximately mirror the isotherms for transect 1 (compare figures 3.2 and 3.3). The salinity profiles for transects 2 and 3 are much more complicated (figure 3.6 and 3.9). For transect 2 the upward thrust of the 35.3 and 35.2 isohalines in the frontal region are also reflected in the density profile, suggesting that upwelling may be taking place in this area. A less pronounced upward curve of the isohalines can also be seen in transect 3.

3.2.2 1996 CTD profiles

The 1996 profiles have been plotted so that the most northerly ends for transects 6 and 7 and the most westerly for transect 8 lie to the left (see figures 2.1 and 2.2 for the transect and frontal positions and figures 3.11 - 3.19 for the results of the CTD measurements). These show that the Celtic Sea area was also strongly stratified in 1996. The mixed area has only been significantly captured on transect 6 though the frontal region and some of the stratified area has been captured on all three. The depth of the thermocline is similar to that of 1995 but it is about 5 m thicker in 1996. However, this may be the result of the lower resolution of the 1996 data which were resolved into 5 m rather than 1 m bins as in 1995.

Upwelling in the frontal region of transect 6 is strongly suggested by the rising 11.5 ^{0}C isotherm (figure 3.11). The surface to bottom temperature change here is approximately 5 ^{0}C for transect 7 and 4.5 ^{0}C for transect 8 (see figures 3.14 and 3.17). The salinity profiles do not exactly match those of temperature and density, indicating that salinity is not very significant in controlling the frontal position (figures 3.12, 3.15 and 3.18). However, resolution is much lower in the 1996 data and this may have resulted in the erratic profiles. The salinity profile of transect 8 appears to reflect the relatively fresher to fully saline gradient to be expected along the Bristol Channel.

3.2.3 Bottom water oxygen concentrations

Oxygen concentrations were measured by swirling a probe in a water sample collected in the rosette sampler attached to the CTD. To calibrate, water samples from some of the stations were also analysed using the Winkler titration method. The results from both techniques are presented

in table 3.2.3.1 at the end of the chapter. It is clear from these results that the probe data is invalid and this data is not explored further. However, the titration results suggest that the mixed sites (*e.g.* T6S02, T7S16) are more oxygenated than those which are stratified (*e.g.* T7S01, T6S16).

3.2.4 Distribution of bottom water characteristics

The temperature and salinity gradients most pertinent to the study of benthic foraminifera are those of the bottom waters. Mapping the bottom water values recorded for temperature produced the colour contours shown in figure 3.20 (a). This clearly shows the pooling of the coldest waters to the south-west with a gradual increase in temperatures to the north and into the Bristol Channel. A lobe of cold water pushes up towards the north-east giving the contours a looping shape. By comparison with the bathymetric contours (see figure 3.1) it can be seen that this incursion coincides with the deep basin found in this area suggesting that the cold sub-thermocline waters are fixed here by depth. However, the temperature contours do not follow those of depth completely. The south-west connection to more open ocean waters clearly influences where the coldest bottom waters occur.

The salinity contours (see figure 3.20, b) show a similar lobe of more saline water pushing towards the north along the isobaths. The least saline waters are found to the North in mixed water and into the Bristol Channel. The most saline are found to the south rather than the south-west as in the case of temperature. There are also several pools of water isolated by either more or less saline waters which may simply be the result of the combining of two different years data though the salinity profiles for each transect also show some discontinuous salinity features (see figures 3.12, 3.15 and 3.18).

Since no single variable provides a measure of the degree of stratification at a particular site an estimate is given made using a comparison of surface and bottom temperatures. This has been termed the 'Sindex' and is simply calculated by the subtraction of the bottom temperature from that of the surface. The results have been mapped (see figure 3.20, c). Mixed sites are those with a Sindex value of below 2 though the more conservative value of 1.3 is more accurate for the Bristol Channel where fully mixed waters were never recorded. Those sites with an Sindex greater than 6 are deemed fully stratified and those which lie between the two thresholds are frontal.

From figure 3.20 (c) it can be seen that very little mixed area was ever captured but that most of the frontal region and some of the stratified area was captured along each transect. This concurs with the results of the profiling. The frontal area is pushed northwards along the bathymetric deep as might be expected. The area of greatest stratification lies to the south-west, inbetween the

coldest and most saline waters.

3.3 Grain size analyses

The various grain size fractions, % gravel, % sand, % silt and % clay were mapped over the area and are presented in figure 3.21, a,b,c and d. To summarise the grain size distribution the % of sediment larger than 63 lm and modal grain size were also mapped (see figure 3.22, a). The relative contribution of gravel is highest in the mixed areas in the north but decreases markedly through the frontal region to zero (3.21, a). No gravel was recorded for any station along the entrance to the Bristol Channel. There is an increase in % gravel to the south-west in the stratified region.

Sand content (see figure 3.21, b) by contrast, is relatively low in the mixed area to the north but increases southward to peak in the mid-frontal region. Content is highest in the west where sand comprises almost 100% of the sediment. Overall values are very high; sand generally composes at least 50 % of the sediment. The % sand is relatively low in the southerly area shaded blue on figure 3.21 (b), but increases again to the south-west of here and into the Bristol Channel as far as the frontal region when values again decline. A band of sandy sediments marks the back-frontal area and this band is wider to the west and along the Bristol Channel where tidal currents are greatest.

Silt is abundant in areas of low sand and gravel content (see figure 3.21, c). Values for % silt tend to be very low, particularly in the west along transect 6 and at that point on the Bristol Channel transect where sand comprises a large percent of the sediment. However, sediments in the bathymetric low to the south-east are composed of almost a quarter silt.

The silt and clay figures are very similar (see figure 3.21, c and d). The highest percentages of clay are found in the south and at the end of transect 8. There is virtually no clay to the north and west along transect 6 and none to the extreme south-west.

Figure 3.22 (a) shows that the coarsest sediments lie to the north and north-west and midway along transect 8 while the finest are concentrated to the South of the study area and towards the end of transect 8.

Modal grain size, the most frequently occurring grain size diameter (Folk, 1966) has been mapped for the study area (see figure 3.22, b). This is measured in units of v after Wentworth (1922) so that the lower the value the coarser the grain. These data support figure 3.22 (a) where the

coarsest sediments are in the north and the finest in the south. The mapping of mean grain size (see figures 3.23, a and b) as calculated using moments and Folks respectively confirm the modal grain size distribution in that all three parameters are very highly correlated.

The variation in sorting across the area is shown in figures 3.24 (a and b). Again both the moments and Folks parameters produce very similar results with highest sorting found in the south but also the end of transect 8 and the extreme north-east. Poor sorting is found in the mid-frontal region and midway along transect 8.

The mapping of Folks and moments skewness presented in figures 3.25 (a and b) describes several bands across the study area; very positive skewness in the frontal-stratified region and at the end of transect 8, very negative skewness in the mid-frontal area and close to zero skewness in the extreme north, in the fully stratified area and separating the very negative areas from the very positive.

The change in kurtosis over the area is shown for both Folks and moments in figure 3.26 (a and b). The kurtosis measured using moments maps in a very similar way to the bathymetry with the lowest values found in the deepest areas, though the end of transect 8 also shows low kurtosis values despite being very shallow. That measured by folks describes quite a different pattern. Lowest values are found in a band across the north of the area, isolating high values found at the northern end of transect 6. Low values also occur in the south east and midway along transect 8, while highest values are found along the remainder of the transect and across the frontal-stratified area.

3.4 Geochemical analyses

Geochemical data were only analysed for the 1995 transects and so have been mapped for this area only. Calcium carbonate ($CaCO_3$) is a measure of inorganic carbon in the sediments and is usually derived from shelly material and chalky/limestone clasts. The highest proportions of $CaCO_3$ are found in the north and east of the study area and the lowest in the west (see figure 3.27 a). The high percentage of calcium carbonate in the south-east of the study area is easily explained as the result of funnelling of carbonate rich sediments to this area which is well sorted and skewed towards fine (south-east section 3.3), thus suggesting that it is an area of net deposition. The highs to the north of the area cannot be the direct result of enhanced production of calcareous organisms in association with the front since this area is within the mixed zone. It is more likely that the calcareous tests are being transported from elsewhere and deposited here. There is a broad similarity between the distribution of $CaCO_3$ and sorting (see figure 3.24 a and

b). Sorting can indicate distance along a sediment transport path and whether an area is one of deposition (Larcombe, 1991). However, the sediments in this northern area are not skewed towards fines (see figure 3.25 a and b) which might argue against it being a sediment sink. If, however, the source material is coarse, as is the case with many of the sediments in the Irish Sea, sediment deposited distally along a transport path could be both coarse and well sorted. It is possible that the $CaCO_3$ in these sediments is derived from fairly coarse shelly material originating further north in the Irish Sea.

The maps of organic nitrogen and organic carbon are very similar to each other (see figure 3.27, b and c). Both are highest in the basins to the east and lowest to the west. This also suggests that sediment is being focused into the basins which run from the north-east to the south-west through the study area and supports the hypothesis that the area to the north is one of deposition, for certain size fractions at least, rather than one of erosion. Since the greatest productivity should be concentrated around the front, deposited material is clearly being removed from the frontal region, particularly on the western side, and possibly being deposited in the bathymetric lows to the south-east or elsewhere. It is difficult to assess whether this removal is ongoing throughout the year even during summer stratification or whether it takes place during winter when currents are more vigorous.

A comparison of carbon with nitrogen (CN ratios) gives an indication of terrestrial/marine influence. The higher the ratio the greater the terrestrial influence (MacDonald & Pedersen, 1991) as marine sediments generally have low CN ratios (Stevenson & Cheng, 1971). Mapping of this ratio over the area suggest that the northern end of the 1995 transects are the most terrestrially influenced, particularly on the east side, while the south-west and south-east are more open marine (see figure 3.4.1 d).

3.5 Covariance among the environmental variables

It is clear from the mapping of the environmental data that many of these variables covary and are thus superfluous. It is an important part of preparation for canonical correspondence analysis that these superfluous variables are removed. It is also useful for the interpretation of environmental gradients to compare them with each other.

The links between the different water characteristics have been elucidated in the matrix plot presented in figure 3.28. Depth is negatively correlated with temperature and positively with salinity and Sindex. The relationship with Sindex shows the greatest scatter. Temperature and salinity are negatively correlated in a linear sense but a quadratic relation is also suggested.

Unsurprisingly, as it is a function of temperature, Sindex shows a very strong negative correlation. Salinity and Sindex are positively correlated but the relationship may be quadratic. From these comparisons it is clear that depth, though weakly correlated with temperature, salinity and Sindex, cannot be represented by them. Temperature and Sindex are probably interchangeable and this is acceptable given that the stratification in the Celtic Sea is maintained, for the most part, by temperature. There is a definite relation between salinity and temperature and thus, Sindex, but this relation is possibly non-linear which explains the difference in the maps produced for temperature and salinity.

Since the Folks and moments parameters are designed to produce a measure for the same sedimentary characteristics, a matrix plot to compare each has been produced (see figure 3.29). The Folks and moments mean parameters correlate almost perfectly, as do the sorting parameters. The relationship between the two skewness parameters has a more quadratic appearance while that between the two measures of kurtosis shows no definite relation. Other possible relationships can be seen for kurtosis (derived from moments) and skewness (derived from moments) which have a quadratic relation. From these comparisons it is certain that mean derived from moments and mean derived from Folks are interchangeable as are either of the sorting parameters. There are possible relationships between skewness derived from moments and skewness derived from Folks and kurtosis derived from moments.

A further set of matrix plots examining the interrelationship between the different grain size classes and of these classes with depth is shown in figure 3.30. This clearly demonstrates that depth is not the main control on the grain size characteristics in this area. A degree of relationship is expected for the % classes of grain size since these are interdependent. For approximately half the sites sand is proportional to gravel but for the remainder irrelevant. This is true of sand and silt or clay. Gravel and silt or clay have no relationship. Silt and clay are positively correlated and are probably interchangeable for statistical purposes.

Plotting the grain size classes against the grain size parameters (figure 3.31) demonstrates that modal grain size is not influenced by any one size class. However, it does have a broadly linear relationship with mean grain size. Mean grain size appears to be weakly, positively correlated with % silt (and thus, % clay) but has a more quadratic relation with % sand and a threshold type relation with % gravel. Sorting shows some relation with the % size classes for some of the sites but not others. There is no clear relation for any of the size classes and skewness or kurtosis.

A matrix plot of the geochemical, depth and modal grain size is shown in figure 3.32. Organic carbon and organic nitrogen show a clear relationship with each other but all other variables

appear relatively independent. Comparing the geochemical characteristics with the % size classes suggests a possible relationship between the organic carbon and the silt (and thus, clay) fraction (see figure 3.33). Calcium carbonate also shows a relationship with silt and clay for some sites but not others. Comparison of the grain size with the geochemical characteristics, also shown in figure 3.33, demonstrates no significant relationships.

Station	Sampling depth	Oxygen probe (ml/l)	Oxygen titration (ml/l)
T6S01	63	88.3	
T6S02	70	85.9	6.29
T6S03	70.9	92.5	6.44
T6S04	71.6	91.5	
T6S05	71.8	89	
T6S06	76	89.8	
T6S07	70.1	92.3	
T6S08	66.9	89.5	
T6S09	68	87.8	
T6S10	67.1	84	
T6S11	75.4	84.6	
T6S12	77.8	84	
T6S13	80.8	86	
T6S14	88.5	73.6	
T6S15	81.7	85	5.82
T6S16	88.1	75.1	5.34
T7S01	100.6	*	5.31
T7S02	98.5	75	
T7S03	103.2	80.3	
T7S04	103.2	74.1	5.31
T7S05	112.5	80.9	
T7S06	110.9	80.6	
T7S07	111.7	70.9	
T7S08	100	80.9	
T7S09	107.7	79.9	
T7S10	106	73.1	
T7S11	106.9	72.5	
T7S12	108.9	69	
T7S13	111.4	72.4	
T7S14	109	68.9	
T7S15	121.4	70	
T7S16	102.2	70.8	7:1
T7S17	103	72.4	
T8S01	101.3	78.1	6.61
T8S02	99.6	78.5	
T8S03	91	83.1	
T8S04	84.8	81	
T8S05	84.3	82	
T8S06	77.7	76:1	
T8S07	72.4	80.4	
T8S08	70.1	80.1	
T8S09	68.4	84.1	
T8S10	66.7	85	
T8S11	76.5	76.5	
T8S12	79.9	79.9	
T8S13	81.9	81.9	
T8S14	82.5	82.5	
T8S15	84.2	84.2	
T8S16	81.5	81.5	
T8S17	84	84	
T8S18	86.8	86.8	
T8S19	88.5	88.5	
T8S20	88.2	88.2	
T8S21	87.8	87.8	
T8S22	96.1	96.1	6.6
T8S23	107.9	107.9	

Table 3.2.3.1 Oxygen concentrations measured using a probe and the Winkler titration method

Chapter 4 Results of faunal analyses

4.1 Surface assemblages

The numbers of living and dead foraminifera are given in Appendices II and III.

4.1.1 Diversity and density

Diversity

Three different diversity indices were applied to both the living and dead species data; the Margalef index, the logarithmic series or the Fisher-alpha index and the Simpson index. These indices, each of which emphasises a different aspect of the data, are described in Chapter 2, section 2.3.2. To reiterate, the Margalef index is a simple measure of species richness, that is, the number of species per specified number of individuals, and takes no account of relative proportions. In contrast, the Simpson index tends to emphasise dominant species at the expense of richness. The Fisher-alpha index provides a measure somewhere between these two extremes.

Contour maps of the three measures of diversity of the living assemblages are shown in figure 4.1 (a, b and c). The inverse of the Simpson index is used here, as is conventional, so that the larger the value given the greater the diversity. Comparing the three maps shows good consensus between the different measures; a band of high diversity across the north of the study area in the approximate position of the front, a decrease south-westwards to a diversity low in that area to the stratified side of the front and an increase again to the south-west. Samples from the entrance to the Bristol Channel show some of the lowest diversities.

The greatest difference between the three measures is seen for the western part of the study area, along transect 6. Here an area of very low diversity is indicated by the blue contours. In terms of richness, as measured by the Margalef and Fisher-alpha indices this area is relatively small, but becomes much more extensive when measured by the Simpson index. This suggests that samples from these sites are dominated by a single species and this is confirmed on examination of the actual data (Appendices II and III) which reveals the species as *Stainforthia fusiformis*. The same species is responsible for the area of low diversity but high dominance on transect 8, picked out in blue in the Simpson index contour map (Figure 4.1, c).

As for the living, each of the diversity measures of the dead assemblages produce similar contour maps (see figure 4.2, a, b and c). Areas of high diversity are concentrated in a band to the north-east

of the study area and to the south-east at the start of transect 8 but also at the end. The lowest diversity is found midway along transect 8 and in the frontal region , particularly to the west.

There are several differences between the diversity of the living and dead assemblages in parts of the study area, most notably in the basin to the south-east where diversity is high for the dead but low for the living. The opposite is true for the frontal region where there is low diversity among the dead but high among the living.

Density

The density of foraminifera per litre of sediment has been calculated for both the living and dead and the results have been mapped in the way described in section 2.9.1. The results are presented in figures 4.3 a and b. The density of dead foraminifera is over 200 times that of the living in places as might be expected given that the dead assemblage integrates foraminiferal tests from over many years. The greatest density of living foraminifera occurs in a band which stretches across that area where frontal and mixed waters meet. A second area of high density is found to the south around the bathymetric low and in stratified waters lying just beyond the frontal region. The entrance to the Bristol Channel, mixed water stations and those stations lying in the centre of the frontal region have relatively fewer living individuals, containing as little as one-seventh of the density of those sites directly underlying the front.

The density distribution of the dead assemblage is very different. The greatest densities are found in the bathymetric low to the south-east and diversity lowers with increasing distance from here. An exception is the small, enclosed area of relatively higher density located mid-front. Samples from transect 8 and the frontal region have particularly low densities relative to the south-east basin high, being as much as forty times lower.

4.1.2 Individual species

The distributions of the most abundant living and dead species and, thus, the most characteristic species of the study area, were also mapped. These species and their ranking in order of absolute abundance for both the living and dead assemblages are given in table 4.1.2 below. The absolute abundance was calculated for each species by summing that species abundance (percentage*density) for all the sites examined. The rank order means that the species assigned the value 1 is the most abundant, the value 2, the second most abundant, and so on. Only the most significant species have been included in table 4.1.2 below.

Species	Dead	Living
Ammonia beccarii	1	15
Adercotryma glomeratum	35	7
Bulimina gibba	5	4
Bulimina marginata	2	13
Cibicides lobatulus	3	9
Cancris auricula	38	5
Elphidium excavatum forma *selseyensis*	12	3
Epistominella naerensis	10	12
Eggerelloides scabrus	24	18
Gavelinopsis praegeri	7	10
Hyalinea balthica	11	24
Nonionella turgida	23	2
Quinqueloculina seminulum	8	11
Stainforthia fusiformis	4	1
Spiroplectammina wrightii	13	33
Textularia bockiii	6	8

Table 4.1.2 Ranking held by the most abundant species in the living and dead assemblages

Discrepancies between the ranking held by any species in the dead assemblage and the living may be the result of preferential preservation of the more robust tests (Boltovsky, 1991; Boltovsky & Totah, 1992) or the post-mortem destruction of the more fragile, particularly agglutinated forms (Smith, 1987). Alternatively, discrepancies may result from post-mortem transport of tests into or out of the study area or inter-species differences in production (Loubere *et al.*, 1993). Seasonality in production can also cause discrepancies if a particular species is in bloom during the collection period (Murray, 1970).

Comparisons between the living and dead rankings of the above species reveal that many comprise much larger proportions of the dead than the living assemblages, most notably *A. beccarii*, *B. marginata*, *C. lobatulus*, *G. praegeri*, *H. balthica*, *S. wrightii* and *T. bockii*. Those which are underrepresented in the dead relative to the living include *A. glomeratum*, *C. auricula*, *E. excavatum* forma *selseyensis*, *E. scabrus*, *N. turgida* and *S. fusiformis*.

To measure the differences between the living and dead assemblages an index of affinity (Rodgers, 1976) was applied to the living and dead data from each site. This measure is the percentage of species which the two assemblages have in common. The results are given in Appendix IV. Affinity was as high as 57 % or as low as 5 % but averaged at around 27 % implying that, overall, there is a significant difference between the living and dead foraminifera. The results were mapped and are presented in figure 4.4 below. The greatest affinity is found for those samples along the entrance to the Bristol Channel, the south-west, the north-east and in a zone around the north-west corner of the study area. The lowest affinity is found for the central and eastern part of the main study area. There is no obvious connection between degree of affinity and stratification.

Planktonic forms

The distribution of unidentified, dead, planktonic foraminifera were mapped over the study area (figure 4.5). Maximum numbers of planktonic tests occur in the basin to the south-east and in an isolated patch to the central northern part of the study area. Virtually no planktonic tests occur in samples from the north-east, the central part of transect 8, in parts of the frontal region towards stratified waters and to the extreme south-west. Planktonic foraminifera were not included in any of the analyses performed during the course of this study, nor were their numbers included with the benthic forms in percentage of assemblage calculations. However, the data used to produce figure 4.5 were the percentage contribution of planktonic foraminifera relative to benthic forms. This information can be useful in determining the open ocean influence to a particular area.

The distribution of the most significant benthic species, living and dead, are described below:

Ammonia beccarii

Figure 4.6 (a) living and (b) dead

Ammonia beccarii rarely comprises more than 3 % of the living assemblages or 5 % of the dead. It is found in mixed, frontal and stratified regions. This species is found in the greatest living proportions along the central part of the study area and to the north. It is particularly concentrated in the stratified area to the south-west but is completely absent from parts of transect 6 and most of transect 8. The pattern is broadly one of banding in a NW-SE direction. For the dead this banding runs in a NE-SW direction. *Ammonia beccarii* is most significant in the northern and southern parts of the study area, excepting the first samples along transect 6. In between *A. beccarii* contributes very little to the assemblages. It is also found along transect 8. This is the most significant difference between the living and dead distributions and may indicate post-mortem transport of this species to the area. The same may be true for the north-east of the study area.

It is worth noting here that colour differences between the living and dead maps for a particular part of the study area can be deceptive. An example of this can be seen for the central southern area which is red (high) for the living but blue (low) for the dead but where the percentage contribution of this species does not in fact vary. The colour change is the result of the larger range found among the dead than the living but both of which are represented by the same range of colours.

Adercotryma glomeratum

Figure 4.7, (a) living (b) dead

The distribution of the living *A. glomeratum* is broadly similar to that of the dead with lowest proportions found to the north and along transect 8 and the highest in the main and southern part of the study area. Like *A. beccarii,* when living, *A. glomeratum* tends to occupy a band along the central part of the area but is particularly abundant to the south-west. It appears to especially favour stratified waters. There is, as has already been observed, a very large difference between the contribution made by this species to the living assemblages, which can be as much as 10 % and the contribution made to the dead which rarely exceeds 1 %. This may be because this species was blooming at the time of collection or it may be the result of post-mortem destruction or removal of the dead tests.

Bulimina gibba

Figures 4.8, (a) living (b) dead

In complete contrast to *A. beccarii* and *A. glomeratum*, living *B. gibba* is found in the lowest proportions in that NE-SW band through the centre of the main study area. It is more significant to the west of this band along transect 6, and to the east along part of transect 1 but most notably along transect 8 where it contributes up to 20 % of the assemblage. It is almost completely absent from the basin to the south-east and north-east. The distribution of dead *B. gibba* is almost identical to that of the living implying that there is little transport or destruction of this species.

Bulimina marginata

Figures 4.9, (a) living (b) dead

The distribution of living *B. marginata* is also concentrated along the central part of the study area. Greatest numbers of foraminifera are found to the south-west and tend to decrease in a north-easterly direction, excepting that area to the north where the relatively higher proportions of *B. marginata* are indicated in red. This species is rarely found living to the extreme north and north-west or along the entrance to the Bristol Channel. *Bulimina marginata* never comprises more than around 9 % of the living assemblage at any site but is disproportionally represented in the dead assemblages where it may account for over a quarter of the individuals found at some sites. Despite this the distribution of dead *B. marginata* is very similar to that of the living.

Cibicides lobatulus

Figures 4.10, (a) living (b) dead

The distribution of *C. lobatulus* is very different from that of the species so far presented but is almost inverse to that of *B. marginata* with greatest contributions made to living assemblages in the north. The contribution is least for sites along transect 8 and the southern half of the main study area which is indicated by blue and blue colour combinations. For the living there is a slight increase in abundance to the south-west. *Cibicides lobatulus* never contributes more than around 10 % of the living assemblage but may account for more than 20 % of the dead at many sites, most of which are located to the north-east. High values shift westward in the dead relative to the living while dead values do not rise to the south as they did in the living. Dead tests of this species are found in high numbers along transect 8, at sites for which no living individuals have been found, and are particularly important towards the end of this transect.

Cancris auricula

Figures 4.11, (a) living (b) dead

This species makes significant contributions to the living assemblages in many places but shows a very patchy distribution. These areas include the central northern, the south-western and some central areas within the study grid. Sites from which living individuals of *C. auricula* are completely absent include the main part of transect 6 and the end of transect 8. This species is very poorly represented in the dead assemblages, rarely contributing more than 1 %. The distribution of the dead is also patchy and since some contours are based on the picking and identification of just a single individual any interpretation is speculative.

Elphidium excavatum forma *selseyensis*

Figures 4.12, (a) living (b) dead

For both the living and the dead this species makes the greatest contributions to those sites found along transect 8 and to the east of the main study area and, less significantly, to the north. This species tends to comprise less of the living assemblages (up to 4 %) than the dead (up to 6 %) but this discrepancy is relatively small when compared with the living/dead discrepancies of other species. Living individuals of this species are absent form many sites to the south of the study area but for the dead this zone of absence expands northward along the western part of the study area and contracts in the south-east relative to the living.

Epistominella naerensis

Figures 4.13, (a) living (b) dead

Although this species never contributes more than 4 % of a living assemblage, it has a very distinctive distribution. It is found, for the most part, in the frontal region and in stratified waters away from the front while the intervening area and the mixed waters to the north are practically devoid of a single individual. This species is not very significant along transect 8 but its numbers do rise towards the end of the transect as frontal waters are approached. *Epistominella naerensis* constitutes a similar proportion of the dead assemblage as it does in the living but the distribution patterns are considerably different. The greatest contribution to the dead assemblage is made along the central part of the study area and in a stratified band of water which stretches westward from the bathymetric low to the south-west. This species is present in low numbers or absent from the central part of transect 8 and from the eastern and western sides of the mixed and frontal waters.

Eggerelloides scabrus

Figures 4.14, (a) living (b) dead

From the above figures it is obvious that occurrences of living *E. scabrus* are restricted to the south and west of the study area in stratified and frontal waters. Occurrences are particularly high along transect 8. The same is true for the dead though there is a westward shift in the red contours which indicate those areas where this species is most significant. This species is not as well represented in the dead assemblages, the contribution being about half that of the living.

Gavelinopsis praegeri

Figures 4.15, (a) living (b) dead

This species is marginally better represented in the dead than the living but immediately apparent on comparison of the two figures are the very different living and dead distributions. While this species makes its most significant living contribution in mixed and frontal sites to the north and to the extreme south-west, the distribution of the dead is almost the inverse of this. The dead tests are most significant in the stratified waters just beyond the frontal region and become less so to the north and south of this area. There are virtually no living occurrences of this species along transect 8 but dead tests are found at sites along most of this transect bar those towards the centre and indicated in blue. Contributions to the dead assemblage are also found to rise to the extreme north-east.

Hyalinea balthica

Figures 4.16, (a) living (b) dead

Living specimens of *H. balthica* never account for more than 4.5 % of the living assemblages. This species is absent from the entrance to the Bristol Channel and the north of the study area, particularly the north-eastern part, but increases in abundance to the south and west. This species is well represented in the dead where it may constitute as much as 17 % of an assemblage, four times as much as in the living. Dead tests are absent or rare in the Bristol Channel and to the north-east and north-west. The contribution to the dead assemblage increases evenly in a south-west direction from about 51.6 ^{0}N. There is an isolated area of increased contribution in the central north where this species may comprise as much as 3 % of the dead assemblages.

Nonionella turgida

Figures 4.17, (a) living (b) dead

Nonionella turgida makes significant contributions to living assemblages (up to 14 %) but contributes very little to the dead (< 2%). However, the distribution for both follow similar patterns. Broadly, this species is most significant in the south and least in the north. *Nonionella turgida* is rare or absent in the entrance to the Bristol Channel but, like *H. balthica*, becomes significant in an isolated spot in the central north.

Quinqueloculina seminulum

Figures 4.18, (a) living (b) dead

Quinqueloculina seminulum makes important contributions to both the living and dead assemblages of the Celtic Sea but constitutes twice the proportion of the dead assemblage than it does for the living. The greatest % of *Q. seminulum* occur in the living assemblages to the west of the study area, including the eastern part of transect 8 but excluding a small area to the extreme south-east. Areas from which living individuals are rare or absent include the end of transect 8, the far north-west and much of the west extending eastward to more than - 6.5 ^{0}W. For the dead the distribution is far more complicated. Numbers are still high for the north-east but not the south-east. Many tests occur along transect 8 even in that part of the transect from which living examples of this species were rare or absent. Areas for which this species is relatively more significant occur in an almost circular band around an area for which it is relatively less significant in the centre of the north. This circle is broken to the far north-west where, as for the living, this species makes little contribution. Numbers are also relatively low for most of the south though the colour contours are slightly deceptive in that the same % are represented by different colours for the living and dead. For example, at the base of transect 8,

though the percentage occurrence is very similar for the living and the dead the living values come in at the top end of the scale and the dead towards the bottom of their respective contours.

Stainforthia fusiformis

Figures 4.19, (a) living (b) dead

Stainforthia fusiformis is the most abundant living species in this part of the Celtic Sea appearing in almost every sample examined and constituting up to 66 % of some samples at some sites. It is particularly abundant in that area where frontal waters become stratified but also in the northern end of transect 6, encircled by an area of relatively lower *S. fusiformis* abundance and along the bathymetric deep to the north-east. Lower percentages are found in the northern part of transect 1 and in the south-west. The contribution made by *S. fusiformis* tends to decrease along transect 8 though this species still accounts for a fifth of all the individuals examined from here. This species does not contribute as much to the dead assemblages (generally < 10%) but is, nonetheless, a very significant component. The area for which it is most significant is still that where mixed and frontal waters meet but the contours also push into the central northern part. Either side of this incursion, this species contribution decreases, though there is a small increase in the north-east corner. Transect 8 has a lower relative abundance than the main study area but numbers do increase into the Bristol Channel.

It was noted when picking and counting that, when living, this species was occasionally to be found coated with a thin veneer of very fine grains and/or hosting green cells, possibly chloroplasts.

Spiroplectammina wrightii

Figures 4.20, (a) living (b) dead

Very few living individuals of this species were identified for this area. This may have resulted from the difficulty in identifying a stained test of this species which is a densely built agglutinate. The low numbers make any discussion of this species distribution rather speculative though a distinctive pattern has emerged from the data: greater abundance to the north and lesser in the stratified area to the south and along transect 8. Numbers rise particularly for the east and west of the northern half of the study area but also in the far south. The contribution made by this species to the dead assemblage is far greater, comprising up to 12 % in places. These areas tend to be in the frontal region and in the south-west. Relatively lower numbers are found to the east and along transect 8.

Textularia bockii

Figures 4.21, (a) living (b) dead

Both the living and dead distributions of this species are very similar to that of *S. wrightii*, though this species is much more significant for the living where it may constitute over 10 % of the assemblage. It is also more significant among the dead where it may make up over 17 % of the assemblage. Like *S. wrightii*, the highest numbers are found in north and the lowest in the south, stratified area, with some increase to the far south. Samples from transect 8 contain the lowest numbers of this species though numbers do increase slightly among the dead for the central part of this transect. The area to the far south of relatively higher abundance among the living extends northwards along the western side for the dead.

4.2 Subsurface analyses

In total six multicores were extracted to examine for the microhabitat preferences of benthic foraminifera. The location of each core is indicated in figure 4.22 and given in table 4.2.1 below.

Core	Latitude N	Longitude W	Water depth (m)	Year
mc195	51^0 17.05'	06^0 04.01'	99	1995
mc295	51^0 21.78'	06^0 14.13'	111	1995
mc395	51^0 34.95'	06^0 05.81'	115	1995
mc495	51^0 17.04'	06^0 04.03'	98	1995
mc196	51^0 13.34'	05^0 58.49'	91	1996
mc296	51^0 29.18'	04^0 40.90'	47	1996

Table 4.2.1 Location and water depth from which the multicores were extracted

The cores span a range of depths and were taken in the months of July/August in 1995 or 1996. The hydrological and sedimentary conditions, extrapolated from measurements at or near each core site (Appendix I) are summarised in the table below:

Core	Temperature ^oC	Salinity $^o/_{oo}$	State
mc195	9.93	35.36	stratified
mc295	10.03	35.37	stratified
mc395	9.67	35.28	stratified
mc196	9.93	35.3	stratified
mc296	10.34	34.6	mixed

Table 4.2.2 Environmental conditions at each coring locality

The range of environments sampled was not very diverse, excluding mc296, because of the limitations imposed by the multicorer which had difficulty sampling in coarser substrates. In addition, the similarity of the sites provided an opportunity to study the same set of species at different localities. The most environmentally distinct site, mc296, was also notable as a habitat for a large number of spider crabs

(Macropodia tenuirostris). A grab sample returned very fine dark, sulphurous mud and several crab specimens suggesting that the sediment at the site was anoxic and possibly disturbed.

Only stained foraminifera from each core were picked and counted. Two levels from mc195 were found to be missing and so this core was not analysed for foraminifera. The actual count data for each level of each core can be found in Appendix V. The density of stained foraminifera found at each level is shown below and depicted graphically in figure 4.23.

Level	mc295	mc395	mc495	mc196	mc296
0.25 cm	12211	13147	14342	55185	758462
1 cm	10549	6573	12939	14524	24553
2 cm	3871	5508	3923	8886	3741
3 cm	1663	1507	1065	6651	1039
4 cm	1247	2962	2936	11640	9743
5 cm			4235	17408	11796
6 cm			182	15953	4729
7 cm			3352	12861	
8 cm			4989	4573	
9 cm			9431	2832	

Table 4.2.3 The number of stained foraminifera at each multicore level per litre of sediment

The overall pattern is one of decreasing density with depth and this is consistent between cores though there are some significant differences. All five cores show the greatest densities in the top 0.5 cm. The three cores taken in 1995 have comparable numbers of foraminifera at the sediment surface while mc196 has over four times and mc296 over fifty times that amount. All cores show a decrease in numbers to 3 cm depth. This decrease is sharp in the case of the 1996 cores which have the greatest surface densities and more gradual in the less populated 1995 cores. For those cores sampled below 4 cm there are distinct subsurface increases in density. Such an increase is even suggested by the 4 cm level sample in mc395 which shows a moderate rise in numbers relative to the 3 cm level. This subsurface increase is most substantial in mc196 where the foraminiferal densities at 5 and 6 cm are greater even than those found at 1 cm depth. Core mc495 appears to have two subsurface maxima peaking at 5 and 9 cm respectively. In none of the cores did the final level sampled comprise foraminiferal densities lower than 1000 foraminifera per litre of sediment indicating that foraminifera are likely to be living even deeper in the sediment than sampled.

In almost all the cores the foraminiferal diversity is highest at the surface (see figure 4.24) with the exception of mc296 where the very low diversity and high dominance suggests an 'extreme' environment (Murray, 1971) *i.e.* an environment for which most foraminifera are not adapted because of the unusual physico-chemical conditions found there. The 1995 cores comprise similar numbers of surficial foraminiferal species while mc196 is more diverse in addition to having greater densities of foraminifera (see figure 4.23). The subsurface increases in diversity do not seem to be directly related to density changes. The abundance and depth of the dominant species in the cores are depicted in

table 4.2.4 and in figure 4.25 (a-l).

Core/ level	*A. beccarii*	*A. glomeratum*	*B. gibba*	*B. marginata*	*C. auricula*	*E. excavatum*	*E. scabrus*	*H. balthica*	*N. auricula*	*N. turgida*	*Q. seminulum*	*R. scopiurus*	*S. fusiformis*
mc195/1	260	1403	260	727	779	0	1403	1039	520	1923	6080	0	2079
mc195/3	0	338	78	182	52	0	130	234	104	0	468	26	1143
mc195/4	0	0	0	26	52	0	52	0	26	104	104	78	364
mc295/1	52	520	104	624	312	0	0	52	1871	4001	156	0	4001
mc295/2	26	208	0	312	598	0	26	130	416	3611	130	0	4599
mc295/3	26	0	0	130	130	0	0	0	52	1039	0	52	2390
mc295/4	0	26	0	156	0	0	0	0	26	338	0	0	1065
mc295/5	130	0	0	52	104	0	0	0	0	26	0	26	857
mc395/1	572	935	260	52	208	0	208	0	0	1351	624	104	5248
mc395/2	0	78	78	0	208	0	0	0	0	1117	130	78	4651
mc395/3	26	338	26	26	364	0	26	0	0	364	26	130	3897
mc395/4	0	130	0	0	130	0	0	0	0	0	0	0	1169
mc395/5	0	0	0	0	78	0	0	0	0	0	0	0	2780
mc495/1	0	572	260	208	208	0	364	208	208	2494	1663	104	6495
mc495/2	26	78	26	208	0	0	416	104	0	1767	234	234	9561
mc495/3	26	52	0	156	0	0	260	26	26	104	156	78	2884
mc495/4	130	0	0	52	52	0	104	0	0	0	0	26	676
mc495/5	0	52	26	208	156	0	104	52	0	78	182	52	1897
mc495/6	26	0	0	52	52	0	78	0	0	208	130	26	3456
mc495/7	0	0	52	0	0	0	0	0	26	0	0	0	0
mc495/8	0	78	0	156	208	0	0	78	0	104	52	26	2442
mc495/9	0	0	26	208	78	0	52	52	26	0	52	104	4235
mc495/10	0	0	0	104	26	0	0	0	26	0	0	0	9276
mc196/2	1091	24215	0	312	2598	0	1975	312	520	9977	987	1039	2858
mc196/3	416	3066	26	182	1143	0	598	78	130	4365	182	104	3014
mc196/4	156	2208	26	234	961	0	546	390	78	442	78	0	2806
mc196/5	78	1065	0	546	676	0	416	312	26	312	156	130	1689
mc196/6	364	1377	26	598	624	0	442	338	52	624	26	104	6106
mc196/7	130	3066	0	572	364	0	416	234	0	1559	26	182	9587
mc196/8	104	2079	0	805	520	0	364	753	0	1689	26	286	8418
mc196/9	78	1715	0	572	598	0	260	364	0	598	104	520	7872
mc196/10	26	234	0	338	78	0	182	0	0	104	0	312	3196
mc196/11	0	78	0	234	130	0	52	26	0	156	0	78	1975
mc296/2	0	0	0	0	0	754512	0	0	0	0	0	0	831
mc296/3	0	0	0	0	0	24261	0	0	0	0	0	0	292
mc296/4	0	0	26	0	0	2105	0	0	26	0	0	0	1455
mc296/5	0	0	0	0	0	805	0	0	0	0	0	0	234
mc296/6	0	0	26	0	0	3378	0	0	0	26	0	0	6288
mc296/7	52	0	78	0	26	6937	0	0	0	26	0	0	4599
mc296/8	26	0	234	0	0	3793	0	0	0	26	0	0	650

Table 4.2.4 The abundance (no. per litre) of the dominant species of stained foraminifera in each multicore level

The shallowest core, mc296, is also the most faunally distinct having a very low diversity even at the surface and an exceptional dominance of *Elphidium excavatum* forma *selseyensis* (see table 4.2.4).

The faunal composition at this site is not comparable to any of the other adjacent surface samples (see Appendices II and III). This site however was specifically chosen as the only site not fully stratified and with the very fine-grained sediment needed for the successful operation of the multicorer. Also present at mc296, but in conspicuously low numbers at the surface is *Bulimina gibba* which is very significant at proximal surface sampling stations. Numbers do however increase significantly downcore. Subdominant at this site are *Stainforthia fusiformis* and *Elphidium megallanicum*, which, while contributing little in relative proportions to the overall composition are as abundant here as at the other core sites. *Elphidium megallanicum*, in particular, does not seem to suffer from the presence of very large numbers of *E. excavatum* forma *selseyensis* at the surface suggesting that they are not in direct competition. However, as already stated, the very low faunal diversity found here suggests an extreme environment and this high dominance of *E. excavatum* forma *selseyensis* may be a result of this species tolerance of the, possibly, anoxic conditions. This may also be true of *E. megallanicum*. *Stainforthia fusiformis* is relatively depleted in the upper few centimeters of sediment but increases deeper down. This may be in direct response to a decrease in *E. excavatum* forma *selseyensis* since this species is less abundant within the sediment though both species increase deeper in the core. It is *E. excavatum* forma *selseyensis* which drives the overall density profile for the core with a maxima at the surface and a smaller peak between 5 - 6 cm. *Elphidium megallanicum* also achieves maximal values at the surface but all other species tend to peak deeper in the sediment.

In the other cores several species are consistently found in high numbers (see figure 4.25). Of these *Nonionella turgida* and *Stainforthia fusiformis* are dominant. The downcore distribution of *N. turgida* almost mirrors the overall density profile (see figure 4.25, i) including the substantial subsurface increase found in mc196. Surface values are very high for mc196 but less so for the 1995 cores. Counts of *N. turgida* fall dramatically away from the surface in mc196, more gradually in the others. *Stainforthia fusiformis* on the other hand shows a much more erratic profile (see figure 4.25, l). Core mc395 excepted, the maxima do not occur at the surface as with most other species but at depth. This may be relatively shallowly as in mc295 (~ 1 cm) or at mid-depths (~ 5 cm) as in mc196 and mc296. It is the very high numbers of *S. fusiformis* found between 3 - 8 cm in mc196 which drives the overall density profile of this core. The same is true of mc495 where there are maxima at 1 cm, 5 cm and 9 cm though, curiously, a complete absence of *S. fusiformis* at 6 cm.

Other species which achieve subsurface maxima in a characteristic way are *Bulimina marginata* and *Hyalinea balthica* (see figure 4.25, d and g respectively). While these species contribute far less to the total numbers of foraminifera in mc495 and mc196 their profiles bear a strong resemblance to that of *S. fusiformis*. Like *S. fusiformis* they exhibit the large subsurface increase between 2 - 8 cm in mc196 and the two subsurface increases in mc495. However, closer examination of the mc495 profiles reveals some important differences. Both *B. marginata* and *H. balthica* achieve their first peak below 1 cm at 4 cm rather than 5 cm and their second at 9 and 8 cm respectively rather than 10 cm. Neither do they peak at 1 cm as *S. fusiformis* does. Both are found in very low numbers or are absent in

mc395 while in mc295 *H. balthica* is found to 1 cm depth only. Here *B. marginata* is found in high numbers at the surface but decreases significantly downcore with the exception of a small inversion at 3 cm.

The profiles of *Reophax scorpiurus* and *C. auricula* are also variations on that of overall density (see figure 4.25, k and e). In mc495 *R. scorpiurus* shows increases at 1, 4 and 8 cm and between 5 - 8 cm in mc196. *Cancris auricula* peaks at the surface and at 4 and 7 cm in mc495 and between 4 - 7 cm in mc196 though this species achieves its true maximum at the surface. In mc295 and mc395 the maximum is found at 1 and 2 cm respectively.

A significant contribution to the total stained assemblages in some cores is also made by *A. glomeratum* (figure 4.25, b). Although seeming to prefer the sediment surface where the highest numbers are found it is abundant subsurficially between 4 - 7 cm in mc196. Elsewhere its occurrence clearly decreases with depth. Similarly a surface or shallow infaunal habitat preference can be inferred for *N. auricula* (figure 4.25, h) on the basis of its downcore distribution. It is plentiful in the surface sediment of mc295 but occurs dramatically less frequently deeper into the sediment. The same pattern can be observed in mc495 and mc196. *Quinqueloculina seminulum* (figure 4.25, j) also shows some preference for a shallow habitat since the greatest proportion tend to occur in the first few centimetres of sediment with numbers tending towards zero below this. Exceptions are found at 4 and 8 cm in mc495 and at 7 cm in mc196.

The profile of *E. scabrus* (figure 4.25, f) is singular because, although it appears in the lower core levels in mc495 and mc196, it does not follow the distinct profile of the other infaunal species. In mc196 it prospers at the surface and decreases gradually downcore without a large inversion. In mc495, *E. scabrus* is relatively abundant in the first centimetre then decreases beneath this. It is not found below 5 cm until it reappears, albeit in very low numbers, at 8 cm.

The microhabitat preferences of *A. beccarii* and *B. gibba* are the most difficult to elucidate (see figure 4.25, a and c). The optimal occurrences of *A. beccarii* are variable between cores; at the surface in mc395 and mc196 but also between 3 and 5 cm in these cores and in mc295, mc495 and mc296. However, on the whole, it would seem that *A. beccarii* does not living as deep infaunally as other species. *B. gibba* is found mostly at the surface in the 1995 cores and in very low numbers only in mc196. It is the subsurface maximum at 7 cm in mc296 which is the most curious feature of the *B. gibba* profiles.

By examining the data in another way - calculating the relative proportions of each species at each level, information on the species microhabitat preferences can be extracted (see table 4.2.5 below).

Core	*A. beccarii*	*A. glomeratum*	*B. gibba*	*B. marginata*	*C. auricula*	*E. excavatum*	*E. scabrus*	*E. naerensis*	*H. balthica*	*N. auricula*	*N. turgida*	*Q. seminulum*	*R. scorpiurus*	*S. fusiformis*
mc295/1		4	0	5	3	*	0	1		15	33	1	0	33
mc295/2		2	0	3	6	*			1	4	34	1	0	44
mc295/3	0	0	0	3	3	*	0	0	0	1	27	0	1	62
mc295/4	0	2	0	9	0	*	0	0	0	2	20	0	0	64
mc295/5	10	0	0	4	8	*	0	0	0	0	2	0	2	69
mc395/1	4	7	2		2	*	2	13	*	*	10	5	0	40
mc395/2	0	1	1	0	3	*	0	2	*	*	17	2	1	71
mc395/3		6			7	*		0	*	*	7		2	71
mc395/4	0	9	0	0	9	*	0	0	*	*	0	0	0	77
mc395/5	0	0	0	0	3	*	0	0	*	*	0	0	0	94
mc495/1	0	4	2	1	1	*	3		1	1	17	12	0	45
mc495/2		0		2	0	*	3		0	0	14	2	2	74
mc495/3	0	1	0	4	0	*	7	0	0	0	3	4	2	74
mc495/4	12	0	0	5	5	*	10	2	0	0	0	0	2	63
mc495/5	0	2	0	7	5	*	4	0	2	0	3	6	2	65
mc495/6	0	0	0	1	1	*	2	1	0	0	5	3	0	82
mc495/7	0	0	29	0	0	*	0	29	0	14	0	0	0	0
mc495/8	0	2	0	5	6	*	0	0	2	0	3	2	0	73
mc495/9	0	0	0	4	2	*	1	1	1	0	0	1	2	85
mc495/10	0	0	0	1		*	0	0	0		0	0	0	98
mc196/2	2	44	0	0	5		4	0	0	0	18	2	2	5
mc196/3	3	21		1	8		4	1	0	0	30	1	0	21
mc196/4	2	25		3	11		6		4	0	5	0	0	32
mc196/5	1	16	0	8	10		6	0	5		5	2	2	26
mc196/6	3	12		5	5		4	1	3		5		0	54
mc196/7	0	18	0	3	2		2	2	1	0	9		1	56
mc196/8	0	13	0	5	3		2		5	0	11		2	53
mc196/9	0	13	0	4	5		2		3	0	5	0	4	61
mc196/10	0	5	0	7	2		4	0	0	0	2	0	7	70
mc196/11	0	3	0	8	5		2	0	0	0	6	0	3	70
mc296/2	0	*	0	*	*	99	*	*	*	*	*	*	*	
mc296/3	0	*	0	*	*	99	*	*	*	*	*	*	*	1
mc296/4	0	*	0	*	*	57	*	*	*	*	*	*	*	39
mc296/5	0	*	0	*	*	77	*	*	*	*	*	*	*	22
mc296/6	0	*		*	*	35	*	*	*	*	*	*	*	65
mc296/7		*	0	*	*	59	*	*	*	*	*	*	*	39
mc296/8	0	*	5	*	*	81	*	*	*	*	*	*	*	14

Table 4.2.5 Relative proportions of the most significant species in each level of each core

Some depth preferences now become apparent for different species. *Ammonia beccarii*, though generally found throughout some cores is relatively most abundant at depth and so could be termed 'infaunal' or 'shallow infaunal' at least. *Adercotryma glomeratum* on the other hand is relatively most abundant at the surface, as is *E. excavatum* (data presented in tables 4.2.4 and 4.2.5 but not

graphically). However, there is only data from one core to support this and it is clear from this study that the depths at which different species living is very variable. *Quinqueloculina seminulum* is also relatively highest at the surface while *N. turgida* is most abundant just below the surface. Both *B. gibba*, *B. marginata*, *C. auricula* and *E. scabrus* have infaunal maximum relative abundances but it is *S. fusiformis* which has the deepest relative abundance of all. Species such as *R. scorpiurus*, *H. balthica* and *N. auricula* seem to be spread throughout the core while *E. naerensis* is difficult to place. It is also difficult to decide which of absolute or relative abundances are the most important in determining whether a species is epifaunal or infaunal; if physico-chemical parameters are the sole control on distribution then it is the absolute values which should be used, if competition is also a factor, as proposed by Ernst *et al.* (1998), then the relative abundances must also be considered.

From individual species data alone, as found by Barmawidjaja *et al.* (1992), the relationship between test morphology and microhabitat is not at all clear; forms such as *S. fusiformis,* conventionally designated as 'infaunal', occur at the sediment-water interface while 'epifaunal' miliolids such as *Q. seminulum* are found deep in the sediment. However, when the foraminifera are grouped according the morphotypes of Corliss (1985) and Corliss & Chen (1988) and then graphed as a percentage of each sediment level, more general trends can be observed. Table 4.2.6 below shows the various morphotypes to which each species was assigned.

Morphotype	Habitat	Species
Milioline	epifaunal	*Q. seminulum, M. circularis* var *elongata, O. balkwilli, P. depressa, P. williamsoni*
Biconvex trochospiral	epifaunal	*E. naerensis*
Planoconvex trochospiral	epifaunal	*H. balthica, C. fletcheri, C. lobatulus, G. praegeri, L. haliotidea, R. williamsoni, T. ochracea*
Flattened ovoid	infaunal	*C. obtusa, F. lagenoides, F. lucida, F. marginata*
Rounded planispiral	infaunal	*N. auricula, N. turgida, C. auricula, E. advent, E. girth, E. megallanicum, E. oceansis, M. barleeanus, N. depressulus, N. pauperatum, E. excavatum* forma *selseyensis, A. runiana, A. pseudpspiralis, Trochammina* sp., *S. excavata, S. vivipara*
Flattened tapered	infaunal	*B. psuedopunctata, B. variablis, T. bockii*
Tapered & cylindrical	infaunal	*E. scabrus, B. gibba, B. marginata, A. scalaris, D. frobisherensis, D. subarcuata, R. artica, R. fusiformis, S. loeblichi, R. scorpiurus, S. fusiformis*
Spherical	infaunal	*A. glomeratum, A. orbicularis, L. clavata, L. interrupta, L. striata, L. perlucida, T. globigerinata* var *pygmaea*
Rounded trochospiral	infaunal	*A. beccarii*

Table 4.2.6 Groupings of the multicore species based on the morphotypes of Corliss & Chen (1985) and Corliss (1991)

In figure 4.26 it can be seen that the cores contain, on the whole, infaunal forms. At any one level epifaunal forms comprise no more than 20 % but more usually less than 10 % of the assemblages. The 'epifaunal' forms are not restricted to the surface layers, except in mc295, but show, albeit weakly, a decrease with depth though there is a large relative increase in the 'epifaunal', biconvex trochospiral form at 7 cm in mc495. The dominance of infaunal forms suggests a high organic carbon sediment content at the core sites (Corliss & Chen, 1988).

All five cores show a dominance of rounded planispiral and tapered and cylindrical forms, with significant proportions of spherical forms in mc196 (see figure 4.26). Excepting mc296, which is regarded as ecologically distinct from the other sites, the trend is for the rounded planispiral forms to decrease downcore and for tapered and cylindrical forms to increase. This trend is most apparent in mc196 where the spherical forms also show a marked decline with depth. Corliss (1991) further distinguishes between shallow, intermediate and deep infaunal types; cylindrical tests are deep infaunal and rounded planispiral forms intermediate. This may explain the trends seen in these cores.

4.3 Comparison of species and environmental data

Only those aspects of the species-environment relationship which are not explored using the statistical methods described in the following chapters will be examined here. This includes the density of and the affinity between the living and dead assemblages. Since percentage data is to be used in the more sophisticated statistical analyses, thus losing the density information, and living and dead data are to be separately analysed, these characteristics need to be examined independently of the main data.

By producing a series of plots of density and affinity against the measured environmental variables (excluding those which were found to covary in chapter 3, section 3.5) simple relationships could be identified (see figures 4.27 - 4.31). Figure 4.39 includes 1995 data only since the environmental variables used were not measured for 1996.

Although the affinity of a dead assemblage to the living at the same site is probably a function of reworking, affinity does not show any relation to the measured sedimentary variables, even those, such as skewness, which are a function of transport (see figure 4.27 and 4.28). There is no clear relation either between density of living foraminifera and any of the measured variables. For the density of dead foraminifera, however, two variables show a very strong correlation; % silt and mean grain size (see figure 4.27). By fitting lines to these data, linear in the case of % silt (figure 4.30) and quadratic for mean grain size (figure 4.31), the strength of these correlations are well demonstrated. The best fit is for % silt (R^2 = 92. 9%) but that for mean grain size (R^2 = 85.8 %) is also very high.

Chapter 5 Results of isotopic analyses

5.1 Oxygen isotope ratios of bottom waters

Bottom water samples were collected from the study area during July 1995 and July-August 1996 from the stations shown in figure 5.1 Those samples clustered towards the north of the study area were collected in 1995 while those covering the entrance and into the Bristol Channel were collected in 1996.

Samples were selected for analysis so as to cover the widest range of salinities observed. Since the sharpest gradient occurred towards the end of transect 8 (see figure 3.18) the majority of the 1996 samples are taken from here. The values returned are given in Table 5.1.1. below.

Sample	Latitude	Longitude	Temp ^{0}C	Salinity $^0/_{00}$	^{18}O ($^0/_{00}$) v SMOW
T2S22	51.9715	-5.874	11.582	34.894	0.263
T2S21	51.9305	-5.9042	10.649	35.117	0.306
T2S14	51.6267	-6.097	9.73	35.21	0.331
T2S18	51.7978	-5.984	9.591	35.303	0.353
T2S17	51.7562	-6.0147	9.674	35.348	0.352

(a)

Sample	Latitude	Longitude	Temp ^{0}C	Salinity $^0/_{00}$	^{18}O ($^0/_{00}$) v SMOW
T8S01	51.1717	-6.1667	9.8159	35.354	0.518
T8S19	51.493	-4.839	11.9412	34.93	0.366
T8S20	51.5127	-4.7515	12.2684	34.67	0.304
T8S21	51.5368	-4.6648	12.3524	34.6	0.34
T8S22	51.53	-4.575	13.2758	33.884	0.112
T8S23	51.568	-4.485	13.6595	33.696	0.137

(b)

Table 5.1.1 δ ^{18}O values of bottom water samples relative to SMOW for (a) 1995 and (b) 1996. Samples were run against Norwich Tap Water. The error of the method is given as 1 σ = 0.05 $^0/_{00}$.

By performing a linear regression of δ ^{18}O v. SMOW against salinity for both 1995 and 1996, two different mixing line equations were produced (see figures 5.2 and 5.3). For both years the fitted lines give excellent fits for the data ($R^2$1995 = 0.988 and $R^2$1996 = 0.955). These lines were then compared with the mixing line equation for Liverpool Bay and the Irish Sea of Owen (1998) produced from 35 data points and water sampled from throughout an entire year (see figure 5.4).

The relationship between the isotopic ratio of the water and the salinity derived from the 1995 data is very similar to that of Owen (1998) but begins to diverge at lower salinities. However, there are no measurements on Celtic Sea samples with salinities below 34.85 $^{0}/_{00}$. The difference between the samples analysed and the equation of Owen (1998) is less than the error of the method (0.05 $^{0}/_{00}$).

The relationship derived from the 1996 data is offset from the equation of Owen (1998) and the 1995 data by around 1- 1.2 $^{0}/_{00}$. Data from this year covers a much wider range of salinities because of the significant salinity gradient found along the Bristol Channel. Where the same salinities are measured for different years very different isotope values are returned. Station T1S08 which lies closest to the 1995 sites has an isotope value which is very different from the 1995 data. This suggests that the region between both sets of data, for which there are no measurements, requires a mixing line intermediate between the two.

Since most of the foraminiferal samples analysed for stable carbon and oxygen isotopes are derived from the area covered by the 1995 data, and since this data converges with the mixing line equation produced for Liverpool Bay and the Irish Sea, for which there are more data points collected over a longer time, it is the equation of Owen (1998), in conjunction with that of O'Neil *et al.* (1969), which is used to generate the results presented in the following sections (see equations i and iii in section 5.2 below). This is also the case for those samples deriving from sites which fall in the area sampled in 1996 since there are too few points to develop a new mixing line equation for this area. As a result the temperatures calculated using isotopic measurements on foraminifera from these sites may be as much as 5 ^{0}C too high.

5.2 Isotopic measurements on foraminifera from surface samples

A range of living and dead foraminifera were selected from the surface samples from which they were most abundant for isotopic analysis. These included *Ammonia beccarii*, *Quinqueloculina seminulum*, *Cibicides lobatulus*, *Bulimina gibba* and *Bulimina marginata*. The values returned for each sample are shown in Table 5.2.1 and 5.2.2 at the end of the chapter

All of the living samples, excepting T2S20 (*Q. seminulum*), T1S02 (*C. lobatulus*) and T2S07 (*B. marginata*), were analysed using a VG Isotech PRISM series 2 mass spectrometer by Mike Hall at Cambridge University and calibrated to VPDB by the repeated analysis of a carbonate standard. Analytical accuracy for these samples is better than 0.08 $^{0}/_{00}$ for oxygen and 0.06 $^{0}/_{00}$ for carbon. All the remaining samples were analysed on a VG Isogas Prism mass spectrometer, which required a larger amount of carbonate, at Edinburgh University by Colin Chilcott, and are also quoted relative to PDB. The oxygen values have an analytical accuracy of 0.08 $^{0}/_{00}$ and the carbon 0.03 $^{0}/_{00}$.

Data also presented in Tables 5.2.1 and 5.2.2 are the temperature and salinity values for each site in addition to the maximum and minimum temperatures at these sites over the annual cycle (Li & Elliott, 1990). The $\delta^{18}O$ value for water given for each site has been calculated from salinity using the equation of Owen (1998):

Equation (i) $$\delta^{18}O_{SMOW} = -7.419 + 0.220S$$

where S = salinity in $^{0}/_{00}$ and $\delta^{18}O_{SMOW}$ is the isotopic composition of water relative to SMOW. For the purpose of comparison with calcite this is then converted to relative to PDB using the following equation:

Equation (ii) $$\delta^{18}O_{PDB} = (\delta^{18}O_{SMOW} * 0.99978) - 0.22$$

It is this value which is then used as the value $\delta^{18}O_{water}$ in the palaeotemperature equation of O'Neil *et al.* (1969):

Equation (iii) $$T = 16.9 - 4.38(\delta^{18}O_{foram} - \delta^{18}O_{water}) + 0.1(\delta^{18}O_{foram} - \delta^{18}O_{water})^2$$

where T = temperature in ^{0}C and $\delta^{18}O_{foram}$ = the isotopic value of a foraminiferal sample relative to PDB.

To produce the equilibrium value for calcite at each site this equation was rearranged so that the $\delta^{18}O_{foram}$ could be calculated from the temperature.

As there were many more dead individuals of a species than living (stained) at most sites, living measurements were not always possible for every species at each site studied. In addition to this the living specimens in some species were sometimes smaller. This was particularly true for *C. lobatulus* where the size difference was often very large but also *Q. seminulum*.

Where both living and dead specimens were analysed, a comparison is made by plotting the isotopic values for one against the other (see figure 5.5 and 5.6). The line y = x in these figures represents the situation where the dead assemblage is exactly representative of the living. A relationship other than this, assuming equilibrium precipitation implies that either most of the dead assemblage is reworked or that the greatest contribution to the dead assemblage at that site is made at a different time of year, when these variables are different to those recorded at the time of collection. This contribution may increase at the time of greatest growth, reproduction or both.

It is immediately apparent on examination of figure 5.5 that the majority of the samples, while showing a good overall relationship, fall below the line x = y. This implies that the areas or time of year from which these samples are derived are probably warmer or more saline. The fact that the mixing line equation may not be ideal for some of the sites should have no influence since the same equation has been used for both the living and the dead specimens from these sites.

For only one of the *A. beccarii* samples are the dead representative of the living. The remaining samples record more negative values in the dead than the living suggesting that the dead assemblages were produced in warmer or more saline conditions. With *Q. seminulum* the dead from the mixed sites are more representative of the living than from those from frontal or stratified areas which lie below the line x = y. Like *A. beccarii* there is a clear relationship between the living and dead.

Cibicides lobatulus is relatively complicated. Those samples from the frontal area show reasonable agreement between living and dead as does one mixed site sample (T2S22) while those from the other mixed sites, T1S01 and T1S02, show no relationship at all. This may indicate reworking in these areas particularly as this species is known as a surface dweller (Murray, 1991).

Two of the samples containing *B. marginata* show close agreement between living and dead, though the dead record slightly warmer temperatures. A third site, T8S01, records much warmer temperatures. All three are derived from stratified waters. A fourth frontal sample, T3S07, exhibits a poor relationship, lying well above the 1:1 line. This may be due to reworking, or, alternatively it may indicate that in this area *B. marginata* precipitates or reproduces most vigorously when temperatures are cooler.

Bulimina gibba is the species for which the dead is least representative of the living. Since the samples produce widely different relationships regardless of their oceanographic context or geographical proximity it is hard to explain the differences observed on the basis of either reworking or greater contribution at a different time of year.

Similar inferences can be made by examination of the carbon isotope values (see figure 5.6). Again the assumption is made that the foraminifera are in equilibrium with their surrounding waters and that relationships are not random. Where values fall below the 1:1 line the implication is that that species is generally produced at a time or place of greater primary productivity or lower oxygenation of the bottom waters than recorded during the cruise (Berger & Vincent, 1986; McCorkle & Emerson, 1988). Alternatively, the foraminifera may live deeper in the sediment column (Grossman, 1984). If the values fall above this line then derivation from a time or area of lower productivity or greater oxygenation can be inferred. Since the living samples were collected from the first few centimetres of the sediment surface the higher values are unlikely to be the result of a shallower microhabitat.

Overall, samples are dispersed either side of the 1:1 line (figure 5.6). *Ammonia beccarii* shows a consistent positive offset, from the line dead = living even at T6S16, where the dead appear to record the oxygen values of the collection period. This suggests that this species precipitates when the bottom water is more oxygenated or productivity is lower. Reworking is unlikely given that the offset from a 1:1 relationship is consistent for all the samples despite their location.

Quinqueloculina seminulum is also consistently offset from this line but in the opposite direction suggesting production, growth or derivation from a time of year or area of greater productivity, lower oxygenation or, perhaps, that this species occupies a more infaunal habitat. The single exception is sample T2S23. This site shows no great disparity between living and dead oxygen measurements. If reworking is invoked to explain the carbon discrepancy this sample would have to be largely derived from an area of much lower productivity or oxygenation but similar temperatures.

There is a good correlation between the living and dead *C. lobatulus* from two of the sites, T2S20 and T2S22 which is curious as the live-dead oxygen comparisons from the same sites are different. However, it may be that while the temperature conditions have changed, productivity has not and this would not be surprisingly in mixed waters. *Bulimina gibba* plots below the line x = y suggesting that it is produced or derived from a time or area of lower productivity and higher oxygenation. *Bulimina marginata* values are spread with the mixed sites showing the greatest living-dead consistency as was seen with the $\delta^{18}O$ (see figure 5.5).

The $\delta^{18}O$ disequilibrium value for each sample (the actual measurement less the equilibrium calcite value for that site) in addition to the corresponding, uncorrected, foraminiferal $\delta^{13}C$ values, are presented in figure 5.7 and plotted against each other in figures 5.8 and 5.9. Since the bottom water Dissolved Inorganic Carbon (DIC) $\delta^{13}C$ was not measured, the carbon values can only indicate in what region and over what range the various species shown precipitate rather than how they compare to equilibrium. It is also possible, as previously mentioned, that the calculated oxygen isotopic values for the water at some sites may be 1 - 1.2 $^{0}/_{00}$ too low thus making the calculated temperature up to 5 ^{o}C too low and producing a disequilibrium value 1 $^{0}/_{00}$ too large.

The living *A. beccarii*, of all the species examined, returns values closest to equilibrium (figure 5.7). The dead specimens of this species, on the other hand, are more negative than the living and cover a wider range of disequilibria but are reasonably closely spaced nonetheless. This negative offset between the living and dead is seen for almost all the species, as also shown by the comparison of the living and dead assemblages (figure 5.9). *Quinqueloculina seminulum* shows a negative disequilibria but a narrow range for the living. This range is nearly doubled for the dead. For the living, a single site, T8S05, belongs to that group of sites for which the mixing line equation used to calculate the equilibrium calcite value may not be appropriate. The living sample from this site is the closest to

equilibrium of all the samples but if compensation were to be made for its provenance it would lie at around - 0.92 $^{0}/_{00}$; much closer to the other samples and with a comparable offset. The same is true for the dead sample from this site.

Cibicides lobatulus shows no tendency to equilibrium and, curiously, the living span a greater range than the dead. Both are very negative relative to equilibrium. The living *B. marginata* lie close together just to the positive side of the equilibrium line, excluding one sample (T3S07). The dead are more negative, but not as negative as T3S07 (living) so that the dead appear to be more clustered than the living.

Bulimina gibba shows a range in disequilibria in the living samples but some possibility of representative precipitation. However, three of these sites lie in the Bristol Channel and thus may be too positive. Were this to be corrected for the spread between samples would be even greater. The scatter among the dead is greater still, though this is reduced very slightly if allowance is made for provenance.

As mentioned above, the carbon values are only qualitative since no comparison has been made with the bottom water DIC $\delta^{13}C$ values. The patterns found here confirm the comparisons made earlier between the living and dead of each site (see figure 5.6). The dead *Q. seminulum* assemblage covers a wider range of values but are generally more negative than the living, excepting two of the samples which are more positive (T1S02 and T2S23). Relative to the other species both living and dead *Q. seminulum* have more positive values suggesting an epifaunal habitat.

The opposite is true for *A. beccarii*, again confirming the results shown in figure 5.6, in that the dead are more negative than the living. *Ammonia beccarii* also exhibits the narrowest range in values (both living and dead) of all the species. This may mean that it is the most selective of the species examined with regard to microhabitat or that the growth or reproduction period is triggered by very particular conditions.

As with the oxygen values of *C. lobatulus*, the living samples occupy a wider range than the dead which would seem to argue against equilibrium precipitation except that both living and dead samples are shifted in the positive direction relative to the other species which is what would be expected for a species with an epifaunal habitat.

Bulimina gibba and *B. marginata* are both more widely dispersed in the dead than the living, but with *B. gibba* the dead are more negative than the living and with *B. marginata* the opposite is true. They both produce the widest range of values.

Examining figures 5.8 and 5.9 it is clear that most of the species tend to cluster together in different

portions of the graph. *Ammonia beccarii* clusters close to equilibrium oxygen values and slightly negative carbon values while *C. lobatulus* has widely dispersed values, both positive and negative. *Bulimina marginata* and *B. gibba* cover a wide range of both positive and negative carbon values but lie to the negative side of oxygen equilibrium with a few exceptions. *Bulimina gibba* is more widely dispersed in terms of oxygen values than *B. marginata*. Though *Q. seminulum* measurements are generally shifted negative of equilibrium, some are positive.

To examine what the oxygen disequilibria mean in terms of palaeotemperature calculations the oxygen measurements on the living of each species at the various sites has been used to calculate temperature using equation iii (O'Neil *et al.*, 1969) and the results have been plotted against the actual temperatures measured (see figure 5.10). Equilibrium precipitation is represented by the line x = y. From this plot it is obvious that, of all the species, *A. beccarii* is the primary candidate for equilibrium precipitation. This means that temperatures derived from measurements on fossil *A. beccarii* are the most likely to be accurate for the temperatures at which that species grows or precipitates. This might also be true for *B. marginata* except for the single outlying sample. From this data it seems possible that measurements on *Q. seminulum* overestimate temperatures by around 2^0C and that temperatures would also be greatly exaggerated by measurements on *C. lobatulus*, though this exaggeration might not be consistent. *B. gibba* is also very variable, though were the two outlying samples to be ignored, and there is no valid argument for doing so, then *B. gibba* would seem to overestimate temperatures by around 1^0C. The general pattern is for overestimation of temperature.

In figure 5.11 the temperature calculated using the equation of O'Neil *et al.* (1969) and the measurements on the dead of each species are plotted against the actual temperatures for each site. The same axes are then reused to plot the red and blue lines which represent the warmest and coldest conditions experienced annually at these sites (Li & Elliott, 1990) so that the temperatures on the x axis become sites and the y axis becomes measured temperature. As might be expected the mixed sites show the greatest annual range in temperatures. At all the sites the highest temperatures are achieved in September and the lowest in February.

To the right-hand side of the *Q. seminulum* plot lie three mixed sites and to the left two stratified. The remaining sites are frontal. The living data suggests that *Q. seminulum* may record temperatures 2^0 C higher than in reality and this may explain why many of the samples lie above even the maximum temperatures experienced at a site during an annual cycle. Even allowing for this, the sample from T2S16 is too high by several degrees. There is no clear pattern to the data, even allowing for different triggers to growth and/or reproduction between mixed, frontal and stratified regions, other than that this species may precipitate in late summer (*i.e.* in September).

The temperatures derived from the plots of dead *C. lobatulus* seem to tell a more promising story than might have been expected on the basis of the living data; by allowing that many sites overestimate

temperatures the majority of points would fall into the mid-summer band of temperatures suggesting that this is when this species grows or reproduces.

Ammonia beccarii presents an interesting story. While the individuals living at the stratified sites appear to produce most calcite during the warmest time of year, those living in mixed areas seem to precipitate in spring or early summer when temperatures are cooler. This suggests that whatever triggers growth and/or reproduction in this species occurs in spring on the mixed side and in autumn on the stratified.

Bulimina gibba also seems to record late summer temperatures (if 1 ^{0}C overestimation is allowed for), excluding two samples which, as in the living, are recording temperatures far higher than those experienced at any time of year at the site. There is no valid argument for excluding these sites. If allowance were made for those sites from the Bristol Channel the plot would be even more erratic.

Most *B. marginata* samples record the late summer temperatures - T8S01 is somewhat anomalous and this is exacerbated if allowance is made for the possibility that temperature may be underestimated by this sample.

5.3 Carbon isotope ratios of porewaters

The results of the measurements of the $\delta^{13}C$ of the porewater DIC in the multicores are presented in table 5.3.1 below. These values have an error margin of +/- 0.07 $^{0}/_{00}$ (Middleton, 1997).

Depth (cm)	mc195	mc295	mc395	mc196	mc296
0	*	*	*	-3.57	-2.14
0.25	-6.4	-2.28	-2.52	-3.46	-9.51
1	-3.86	-2.65	-1.65	-5.1	-11.03
2	-5.35	-2.9	-2.17	-5.81	-11.81
3	-6.16	-3.14	-3.13	-7.06	-12.15
4	-5.72	-2.95	-4.58	-7.46	-11.68

Table 5.3.1 $\delta^{13}C$ porewater DIC for 1995 and 1996 multicores

A comparison between the porewater DIC and stable carbon isotopic measurements on various species of foraminifera extracted from corresponding levels in the multicores is presented in figure 5.12. The species measured were: *Quinqueloculina seminulum*, *Ammonia beccarii*, *Bulimina marginata*, and *Nonionella turgida*.

The $\delta^{13}C$ porewater DIC profiles vary between the cores but generally show a decline from the surface through the first 4 cm. However, there is a large inversions at 1 cm in mc195 and smaller inversions at

4 cm in mc295, 2 cm in mc395 and 4 cm in mc196. The most classical gradient is seen for mc296. The profile of mc295 is almost linear while those of mc195 and mc395 are more irregular. The negativity of the porewaters varies between cores. Cores mc295, mc395 and mc196 have a surface $\delta^{13}C$ porewater DIC content of between -2 and -3.5 $^{0}/_{00}$. These values fall away for all three cores but most dramatically for mc196.

Bottom water isotopic values were measured for mc196 and mc296 only. The values for the bottom water are comparable to that of the surface porewaters for mc196 but decreases significantly from - 2 $^{0}/_{00}$ to - 9.5 $^{0}/_{00}$ for mc296. These exceptionally negative values continue through the core though the subsequent declines are not as marked. Core mc195 is notable because the surface value is - 6.5 $^{0}/_{00}$ while the lowest sample measured is only - 5.5 $^{0}/_{00}$.

5.4 Isotopic measurements on living foraminifera from the multicores

In comparison to the porewater profiles, the foraminiferal values through the core are remarkably consistent (see figure 5.12). The foraminiferal $\delta^{13}C$ data used to produce these profiles, and the foraminiferal $\delta^{18}O$ values, are shown in table 5.4.1 below. The location of and environmental data for each of the multicore sites examined is presented in Chapter 4, tables 4.2.1 and 4.2.2. The equilibrium calcite value has been calculated from the temperature and salinity values for the sites using the equation of Owen (1998). The oxygen disequilibria for each specimen is also shown.

Although the $\delta^{13}C$ of the foraminiferal calcite does not vary with depth there are consistent offsets between different species measured in a single core (see figure 5.12). All the species examined appear in mc196 while both *Bulimina marginata* and *Nonionella turgida* are found in mc295. *Quinqueloculina seminulum* is found in mc195, *Bulimina marginata* in mc395 and a single value was returned for *Nonionella turgida* in mc395. The offsets are also consistent for the same species in different cores despite the fact that the values have not been corrected for the bottom water DIC $\delta^{13}C$. All the measurements for each species, regardless of its core or level, have been presented in figure 5.13. It is clear from this figure that *Quinqueloculina seminulum* exhibits the most positive $\delta^{13}C$ ratios. Measurements from cores mc395 and mc196 both plot within a less than 0.5 $^{0}/_{00}$ range. (0 to - 0.5 $^{0}/_{00}$).

Most specimens of *B. marginata* measured fall into the - 0.2 to - 0.75 $^{0}/_{00}$ range and this includes specimens from down to 8 cm depth and from three different cores. The single exception is found at 2 cm depth in mc295 (- 2 $^{0}/_{00}$). Fewer individuals of *Ammonia beccarii* were analysed, but those measured fall into an extremely narrow range (less than - 1 to -1.25 $^{0}/_{00}$). However, the narrowness of this species range relative to the others may be because all the specimens are from the same core. The species which is most negative is *Nonionella turgida* which falls between -1.3 to -1.8 $^{0}/_{00}$.

Core	Measure	Depth (cm)	0	0.25	1	2	3	4	5	6	7	8
		Specimen										
Mc195	$\delta^{18}O$	Equilibrium calcite		1.79	1.79	1.79	1.79					
		Q. seminulum		1.75	1.71	1.67	1.59					
	$\Delta\delta^{18}O$	*Q. seminulum*		-0.04	-0.08	-0.12	-0.2					
	$\delta^{13}C$	*Q. seminulum*		-0.23	-0.33	-0.15	-0.36					
mc295	$\delta^{18}O$	Equilibrium calcite		1.77	1.77	1.77	1.77					
		N. turgida		2.06	2.44	2.3						
		B. marginata		0.29	0.67	0.53						
	$\Delta\delta^{18}O$	*N. turgida*		2.14	2.19	2.68	2.36					
		B. marginata		0.37	0.42	0.91	0.59					
	$\delta^{13}C$	*N. turgida*		-1.71	-1.45	-1.62						
		B. marginata		-0.51	-0.45	-2	-0.37					
mc395	$\delta^{18}O$	Equilibrium calcite			1.84							
		N. turgida			2.14							
	$\Delta\delta^{18}O$	*N. turgida*			-1.24							
	$\delta^{13}C$	*N. turgida*			-1.24							
mc495	$\delta^{18}O$	Equilibrium calcite	1.79		1.79	1.79					1.79	1.79
		B. marginata	2.12		1.93	2.01					2.04	1.69
	$\Delta\delta^{18}O$	*B. marginata*	0.33		0.14	0.22					0.25	-0.1
	$\delta^{13}C$	*B. marginata*	-0.61		-0.62	-0.47					-0.51	-0.74
mc196	$\delta^{18}O$	Equilibrium calcite	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	
		Q. seminulum	1.52	1.41	1.37							
		A. beccarii	1.72	1.68	1.53		1.66	1.56				
		N. turgida	1.55	1.29				1.59				
		B. marginata	1.82	1.32	1.59	2.02	2.13	2.18	1.96	2.09	1.96	
	$\Delta\delta^{18}O$	*Q. seminulum*	-0.16	-0.27	-0.31							
		A. beccarii	0.04	0	-0.15		-0.01	-0.12				
		N. turgida	-0.13	-0.39				-0.08				
		B. marginata	1.82	1.32	1.59	2.02	2.13	2.18	1.96	2.09	1.96	
	$\delta^{13}C$	*Q. seminulum*	-0.03	-0.11	-0.38							
		A. beccarii	-1.18	-1.07	-1.13		-1.08	-1.21				
		N. turgida	-1.63	-1.87				-1.57				
		B. marginata	-0.19	-0.44	-0.4	-0.51	-0.36	-0.34	-0.61	-0.28	-0.45	

Table 5.4.1 A summary of the isotopic data from measurements on specimens extracted from the multicores

Measurements were also made for $\delta^{18}O$. From these the corresponding equilibrium calcite value has been subtracted to examine oxygen disequilibrium. This data supplements that of the surface samples for *Quinqueloculina seminulum*, *Bulimina marginata* and *Ammonia beccarii*. *Quinqueloculina seminulum* and *Ammonia beccarii* are in agreement with the disequilibria found in the surface specimens; *Ammonia beccarii* is very close to equilibrium while *Quinqueloculina seminulum* is a little negative. Many more measurements have been made on living specimens of *Bulimina marginata* from the multicores than from the surface samples and these show that this species shows a range in disequilibria, centred at around 0.4 $^{0}/_{00}$. *Nonionella turgida* also shows a wide range of both positive and negative disequilibria ranging from ~ - 0.4 to 0.6 $^{0}/_{00}$.

Plotting both the carbon and oxygen disequilibria data for each species in figure 5.14 identifies distinct clusters. All the species measured lie in the negative carbon area of the graph; from *Quinqueloculina seminulum* which is the least negative to *Bulimina marginata* then *Ammonia beccarii* and to *Nonionella turgida* the most negative. *Bulimina marginata* tends towards positive oxygen disequilibria, *Quinqueloculina seminulum* towards the negative, *Ammonia beccarii* towards equilibrium while *Nonionella turgida* shows a large spread in disequilibria.

To more clearly illustrate what is already apparent from figure 5.12, the $\delta^{13}C$ of foraminiferal calcite has been plotted against the $\delta^{13}C$ of the porewater DIC in figure 5.15. None of the species exhibit any change in the $\delta^{13}C$ of calcite despite changes in the $\delta^{13}C$ of porewater DIC and this would suggest that there is no relationship between the two.

Species	Station	Temp °C	Salinity °/₀₀	Min temp at that site	Max temp at that site	$\delta^{18}O$ (°/₀₀)	$\delta^{13}C$ (°/₀₀)	$\delta^{18}O$ of water relative to SMOW (°/₀₀)	$\delta^{18}O$ of water relative to PDB (°/₀₀)	Temperature calculated from O'Neil *et al.* (1969)	Discrepancy between calculated and actual temperature	Equilibrium value (°/₀₀)	Discrepancy between measured and equilibrium value (°/₀₀)
Q. seminulum	t1s01	12.27	34.9	7.9	15.3	0.88	-0.1	0.26	0.03	13.28	1.02	1.12	0.24
Q. seminulum	t2s23	11.61	34.91	8.1	14.6	0.98	0.07	0.26	0.04	12.87	1.27	1.28	0.3
Q. seminulum	t8s05	10.36	35.29	8.5	14	1.75	-0.07	0.34	0.12	10.04	-0.32	1.67	-0.07
Q. seminulum	t2s20	9.84	35.23	8.2	14.3	1.32	0.72	0.33	0.11	11.75	1.91	2.67	0.47
Q. seminulum	t2s16	9.53	35.32	8.3	13.3	1.16	-0.1	0.35	0.13	12.5	2.97	1.88	0.72
C. lobatulus	t1s01	12.27	34.9	7.9	15.3	0.74	0.83	0.26	0.03	13.87	1.61	1.12	0.38
C. lobatulus	t1s02	11.95	34.97	8.3	14.2	-0.56	-0.27	0.28	0.05	19.64	7.69	1.22	1.78
C. lobatulus	t2s22	11.58	34.89	8.2	14.3	0.72	1.27	0.26	0.03	13.96	2.38	1.29	0.57
C. lobatulus	t3s03	10.23	35.16	8.2	14.3	0.69	0.73	0.32	0.09	14.34	4.11	1.68	0.99
C. lobatulus	t2s20	9.84	35.23	8.2	14.3	0.83	0.81	0.33	0.11	13.8	3.96	1.79	0.96
A. beccarii	t2s21	10.65	35.12	8.2	14.3	1.57	-0.44	0.31	0.08	10.62	-0.02	1.56	0
A. beccarii	t2s20	9.84	35.23	8.2	14.3	1.42	-0.62	0.33	0.11	11.34	1.5	1.79	0.37
A. beccarii	t3s19	9.38	35.27	8.9	12.5	2.03	-0.96	0.34	0.12	8.9	-0.48	1.91	-0.12
A. beccarii	t6s16	8.89	35.23	8.9	12.5	2.04	-0.75	0.33	0.11	8.82	-0.06	2.02	-0.01
B. gibba	t8s20	12.27	34.67	7.7	15.8	0.96	-0.11	0.21	-0.01	12.74	0.47	1.07	0.11
B. gibba	t8s15	11.26	35.12	8	15.1	1.24	0.01	0.31	0.08	11.98	0.72	1.41	0.17
B. gibba	t8s10	10.75	35.24	8.2	15	0.73	-0.38	0.33	0.11	14.24	3.48	1.56	0.84
B. gibba	t1s07	10.1	35.38	8.3	14.1	1.6	0.61	0.36	0.14	10.73	0.63	1.76	0.16
B. gibba	t6s10	10.28	35.05	8.3	13.2	1.94	0.17	0.29	0.07	9.07	-1.22	1.64	-0.3
B. gibba	t1s09	9.9	35.36	8.3	14.1	1.51	0.18	0.36	0.14	11.09	1.19	1.8	0.29
B. marginata	t8s01	9.82	35.35	8.7	12.5	2.04	-0.63	0.36	0.14	8.93	-0.88	1.82	-0.22
B marginata	t3s07	9.69	35.27	8.3	13.2	0.65	-1.3	0.34	0.12	14.59	4.9	1.83	1.18
B. marginata	t1s19	9.56	35.37	8.7	12.8	1.92	-0.11	0.36	0.14	9.43	-0.13	1.89	-0.03
B. marginata	t2s07	9.33	35.35	8.7	12.8	1.97	-0.81	0.36	0.14	9.21	-0.12	1.94	-0.03

Table 5.2.1 Isotopic composition of mono-specific samples of living (stained) foraminifera

Species	Station	Temp ^{0}C	Salinity $^0/_{00}$	Min temp at that site	ax temp at that site	$\delta^{18}O$ ($^0/_{00}$)	$\delta^{13}C$ ($^0/_{00}$)	$\delta^{18}O$ of water relative to SMOW ($^0/_{00}$)	$\delta^{18}O$ of water relative to PDB ($^0/_{00}$)	Temperature calculated from O'Neil *et al.* (1969)	Discrepancy between calculated and actual temperature	Equilibrium value ($^0/_{00}$)	Discrepancy between measured and equilibrium value ($^0/_{00}$)
Q. seminulum	t1s01	12.27	34.9	7.9	15.3	0.26	-0.01	0.26	0.03	15.94	3.68	1.12	0.87
Q. seminulum	t1s02	11.95	34.97	8.3	14.2	0.23	0.86	0.28	0.05	16.12	4.17	1.22	0.98
Q. seminulum	t2s23	11.61	34.91	8.1	14.6	0.56	0.89	0.26	0.04	14.67	3.07	1.28	0.73
Q. seminulum	t2s21	10.65	35.12	8.2	14.3	1.02	0.45	0.31	0.08	12.89	2.24	1.56	0.54
Q. seminulum	t8s05	10.36	35.29	8.5	14	1.17	-0.49	0.34	0.12	12.42	2.06	1.67	0.5
Q. seminulum	t2s20	9.84	35.23	8.2	14.3	0.5	0.3	0.33	0.11	15.2	5.36	1.79	1.28
Q. seminulum	t2s16	9.53	35.32	8.3	13.3	-0.02	-0.58	0.35	0.13	17.59	8.06	1.88	1.91
Q. seminulum	t2s01	9.41	35.34	8.9	13	1.13	-0.39	0.36	0.14	12.67	3.26	1.92	0.79
C. lobatulus	t1s01	12.27	34.9	7.9	15.3	-0.56	0.14	0.26	0.03	19.56	7.29	1.12	1.68
C. lobatulus	t1s02	11.95	34.97	8.3	14.2	0.47	0.09	0.28	0.05	15.09	3.14	1.22	0.74
C. lobatulus	t3s01	11.6	34.89	8.1	14.6	0.31	0.72	0.26	0.37	15.72	4.12	1.62	1.31
C. lobatulus	t2s22	11.58	34.89	8.2	14.3	0.88	1.26	0.26	0.38	13.26	1.68	1.63	0.74
C. lobatulus	t3s03	10.23	35.16	8.2	14.3	0.48	1.3	0.32	0.09	15.23	5	1.68	1.2
C. lobatulus	t1s06	10.17	35.38	8.3	14.1	0.45	1.06	0.36	0.14	15.56	5.39	1.74	1.29
C. lobatulus	t2s20	9.84	35.23	8.2	14.3	0.38	0.79	0.33	0.11	15.74	5.89	1.79	1.41
C. lobatulus	t1s19	9.56	35.37	8.7	12.8	0.88	0.36	0.36	0.14	13.74	4.18	1.89	1.01
A. beccarii	t2s23	11.61	34.91	8.1	14.6	0.63	-0.27	0.26	0.04	14.35	2.75	1.28	0.65
A. beccarii	t2s21	10.65	35.12	8.2	14.3	0.82	-0.02	0.31	0.08	13.72	3.07	1.56	0.74
A. beccarii	t2s20	9.84	35.23	8.2	14.3	1.06	-0.05	0.33	0.11	12.84	3	1.79	0.73
A. beccarii	t2s16	9.53	35.32	8.3	13.3	0.79	-0.19	0.35	0.13	14.06	4.53	1.88	1.09
A. beccarii	t2s01	9.41	35.34	8.9	13	1.49	-0.25	0.36	0.14	11.15	1.74	1.92	0.43
A. beccarii	t3s19	9.38	35.27	8.9	12.5	1.61	-0.21	0.34	0.12	10.59	1.22	1.91	0.3
A. beccarii	t6s16	8.89	35.23	8.9	12.5	1.88	-0.39	0.33	0.11	9.46	0.58	2.02	0.14
B. gibba	t8s15	11.26	35.12	8	15.1	0.49	-0.34	0.31	0.08	15.14	3.87	1.41	0.92
B. gibba	t8s10	10.75	35.24	8.2	15	1.1	0.49	0.33	0.11	12.67	1.92	1.56	0.46
B. gibba	t1s07	10.28	35.38	8.3	14.1	1.1	0.49	0.36	0.14	13.91	3.63	1.71	0.61
B. gibba	t6s10	10.17	35.05	8.3	13.2	0.76	-0.05	0.29	0.07	17.97	7.8	1.67	0.9
B. gibba	t1s06	10.1	35.38	8.3	14.1	-0.09	-0.3	0.36	0.14	12.82	2.72	1.76	1.85
B. gibba	t1s09	9.9	35.36	8.3	14.1	-0.99	-1.42	0.36	0.14	21.98	12.08	1.8	2.79
B. gibba	t3s15	9.3	35.32	8.5	12.8	0.94	0.07	0.35	0.13	13.43	4.13	1.94	1
B. marginata	t8s01	9.82	35.35	8.7	12.5	1.1	-1.22	0.36	0.14	12.78	2.96	1.82	0.72
B. marginata	t3s07	9.69	35.27	8.3	13.2	1.46	-0.14	0.34	0.12	11.22	1.52	1.83	0.37
B. marginata	t1s19	9.56	35.37	8.7	12.8	1.49	-0.03	0.36	0.14	11.18	1.62	1.89	0.4
B. marginata	t2s07	9.33	35.35	8.7	12.8	1.62	-0.53	0.36	0.14	10.64	1.32	1.94	0.33
B. marginata	t3s15	9.3	35.32	8.5	12.8	1.48	0.42	0.35	0.13	11.18	1.88	1.94	0.46
B. marginata	t6s14	8.88	35.22	9	11.6	1.14	0.16	0.33	0.11	12.48	3.6	2.02	0.88

Table 5.2.2 Isotopic composition of mono-specific samples of dead foraminifera

Chapter 6 Results of statistical analyses

6.1 Factor analysis

In preparation for the factor analysis all species which did not constitute 8 % or more of at least one sample were excluded. Several species of the same genus were, in some cases, grouped together under single headings, either because of doubts expressed by various authors over their taxonomic separation or because they are not regarded as ecologically distinct. These included all the *Bolivina* and *Brizalina* species under the heading '*Bolivina* spp.' and all the *Reophax* species under '*Reophax* spp.'. In addition, *Textularia bockii* and *Spiroplectammina wrightii* were grouped under the heading *Textilina* spp. because of their very similar distributions (see figures 4.20 and 4.21) and because Murray (1979a) believes that they need not be separated.

6.1.1 Living assemblages

The 22 species remaining, after the elimination of 'rares' were prepared for analysis in the way described in chapter 2, section 2.9.2. R-mode analysis produced results for 22 factors and the complete, row normalised, output data set is given in Appendix VI. However, of these, only the first four were judged to be ecologically significant (see table 6.1.1.1 below).

Species	factor 1	factor 2	factor 3	factor 4
A. glomeratum	-0.46	0.28	-0.61	-0.32
B. gibba	-0.46	-0.02	0.42	-0.21
B. marginata	-0.49	0.2	-0.71	-0.26
Trochammina sp.	-0.26	0.52	-0.03	0.04
C. lobatulus	-0.35	0.62	0.24	0.32
C. auricula	-0.47	0.5	0.04	0.13
E. excavatum forma selseyensis	-0.31	-0.05	0.34	-0.25
E. gerthi	-0.23	-0.03	0.22	-0.07
E. magellanicum	-0.28	0.4	0.24	0.19
E. scabrus	-0.35	0.03	0.06	-0.39
E. naerensis	-0.48	0.2	-0.27	-0.03
H. fragile	-0.29	0.43	-0.23	-0.27
L. haliotidea	-0.28	0.3	0.25	0.07
N. auricula	-0.44	0.17	-0.34	0.12
N. turgida	-0.61	-0.02	-0.49	-0.12
Q. seminulum	-0.46	0.34	0.08	-0.12
Reophax spp.	-0.07	-0.07	0.18	-0.14
G. praegeri	-0.49	0.74	0.1	0.09
R. williamsoni	-0.32	0.57	0.13	0.26
S. fusiformis	-0.86	-0.31	-0.19	0.34
Textilina spp.	0.98	-0.07	0.16	-0.11
Trochammina globeriginiformis var. pygmaea	-0.45	0.67	-0.17	0.06

Table 6.1.1.1 Result of R-mode factor analysis on the living assemblage data

These four factors account for over 80 % of the variance in the input data set (see table 6.1.1.2). The first factor alone explains 57.5 % of the data analysed.

Factor	Eigenvalues	% variance explained	Cumulative % variance explained
1	30.48	57.5	57.5
2	5.86	11.05	68.55
3	4.09	7.72	76.27
4	2.37	4.48	80.75
5	1.77	3.33	84.08
6	1.23	2.32	86.4
7	1.14	2.15	88.54
8	1.04	1.96	90.5
9	0.84	1.58	92.08
10	0.68	1.29	93.37
11	0.67	1.27	94.64
12	0.57	1.07	95.71
13	0.44	0.83	96.54
14	0.4	0.76	97.29
15	0.36	0.67	97.97
16	0.32	0.61	98.57
17	0.21	0.39	98.96
18	0.17	0.33	99.29
19	0.14	0.27	99.56
20	0.13	0.24	99.8
21	0.1	0.2	100
22	0	0	100
total	53		

Table 6.1.1.2 Calculation from the eigenvalues of the % variance accounted for by each factor

The species which contribute most significantly to these assemblages are those with the largest scores and can be determined from the R-mode species scores shown in table 6.1.1.1. The Q-mode site scores, given in table 6.1.1.3, indicate the importance of these factors at each site. A positive Q-mode score indicates the presence of the positive components of the factor at that site and the absence of the negative. The reverse is also true. This can be illustrated by examining the first factor where characteristic species, *Reophax* spp. and *S. fusiformis* have negative R-mode scores. As a result, this factor is most significant at those sites which have negative Q-mode scores and therefore, when these scores are mapped, as in figure 6.1 (a), it is the blue areas in which this assemblage dominates. Also shown in table 6.1.1.3 is the communality for each site. This is the sum of the squares for the first four factors and is a measure of how much of the data at each site is explained by these factors. For the live data, this is almost always above 0.7 or 70 %.

	Communality	Factor 1	Factor 2	Factor 3	Factor 4
T1S01	0.66	-0.42	0.58	0.26	0.28
T1S02	0.55	-0.56	0.36	-0.11	0.32
T1S03	0.83	-0.78	0.33	0.04	0.33
T1S06	0.35	-0.35	0.32	0.35	0.07
T1S07	0.35	-0.46	0.28	0	-0.24
T1S09	0.89	-0.74	-0.23	-0.22	0.48
T1S14	0.91	-0.71	-0.32	-0.38	0.4
T1S17	0.61	-0.6	0.07	-0.49	-0.07
T1S19	0.81	-0.5	0.52	-0.51	-0.2
T2S01	0.55	-0.49	0.45	-0.25	-0.21
T2S03	0.72	-0.44	0.21	-0.5	-0.47
T2S07	0.81	-0.67	-0.06	-0.58	-0.09
T2S11	0.77	-0.79	-0.13	-0.33	0.1
T2S14	0.49	-0.48	0.44	-0.22	-0.11
T2S16	0.84	-0.66	0.59	-0.17	-0.16
T2S19	0.51	-0.65	0.2	0.08	0.21
T2S20	0.76	-0.47	0.72	0.1	0.1
T2S21	0.55	-0.5	0.49	0.16	0.15
T2S22	0.78	-0.56	0.62	0.18	0.21
T2S23	0.81	-0.46	0.72	0.19	0.17
T3S01	0.92	-0.64	0.66	0.27	0.08
T3S03	0.73	-0.65	0.55	0.11	0.06
T3S05	0.64	-0.72	0.34	0.09	0.02
T3S07	0.91	-0.84	-0.16	-0.42	-0.05
T3S10	0.96	-0.85	-0.34	-0.09	0.35
T3S11	0.99	-0.88	-0.35	-0.07	0.3
T3S13	0.95	-0.92	-0.2	-0.08	0.24
T3S15	0.9	-0.74	0.23	-0.41	-0.37
T3S16	0.98	-0.92	-0.2	-0.23	0.21
T3S17	0.86	-0.85	-0.15	-0.3	0.18
T3S19	0.71	-0.67	0.04	-0.5	-0.13
T3S23	0.86	-0.76	0.23	-0.44	-0.2
T6S02	0.91	-0.91	-0.16	0.25	0.08
T6S06	0.53	-0.59	0.27	0.32	-0.05
T6S08	0.96	-0.95	-0.16	0.16	0.07
T6S10	0.96	-0.94	-0.21	0.18	0.04
T6S12	0.96	-0.96	-0.21	0.04	-0.01
T6S14	0.99	-0.96	-0.22	-0.05	-0.04
T6S16	0.99	-0.96	-0.25	0.02	0.01
T7S02	0.91	-0.92	-0.2	0.17	0
T7S06	0.93	-0.95	-0.14	0.09	-0.03
T7S10	0.97	-0.95	-0.24	0.11	-0.04
T7S16	0.98	-0.94	-0.29	0.01	0.02
T8S01	0.85	-0.88	-0.21	-0.04	-0.15
T8S02	0.97	-0.94	-0.26	0.11	-0.01
T8S05	0.76	-0.81	-0.09	0.21	-0.23
T8S08	0.93	-0.85	-0.21	0.32	-0.24
T8S09	0.97	-0.91	-0.21	0.28	-0.14
T8S10	0.86	-0.8	-0.17	0.36	-0.24
T8S13	0.93	-0.8	-0.14	0.38	-0.34
T8S16	0.83	-0.76	-0.16	0.36	-0.32
T8S20	0.94	-0.84	0.01	0.41	-0.24
T8S21	0.74	-0.77	-0.19	0.3	-0.17

Table 6.1.1.3 Results of the Q-mode factor analysis on the living assemblage data

Living factor 1 - *Stainforthia fusiformis* and *Reophax* spp.

This factor explains 57.5 % of the living variance, excluding those species which did not made up 8 % of at least one sites assemblage. The main area of dominance for this factor is in stratified waters with a notable zone of low occurrence across the mixed-frontal transitional area (figure 6.1, a).

Living factor 2 - *Gavelinopsis praegeri* , *Cibicides lobatulus* and *Trochammina globigeriniformis* var. *pygmaea*

This factor explains 11 % of the variance and is defined by the above species. In the case of this assemblage the typical species are positively related to the distribution so the most positive areas (indicated in red in figure 6.1, b) are where this assemblage is most significant. There are two main areas for which this is true - in the mixed and mixed-stratified transitional area to the north and in the fully stratified area to the south. The zonation is quite marked for the main study area but is not found at all along the entrance to the Bristol Channel.

Living factor 3 - *Bulimina marginata, Adercotryma glomeratum* and *Nonionella turgida*

The above characterises this assemblage which accounts for 7.7 % of the variance. As with factor one, these species are negatively related to the factor scores and so it is the blue areas in figure 6.21 (c) which indicate where this assemblage is important. The area is largely confined to stratified and stratified-frontal transitional waters, excepting along the entrance to the Bristol Channel.

Living factor 4 - *Eggerelloides scabrus*

This assemblage accounts for only 4.48 % of the total variance and is negatively related to the factor scores. It dominates the eastern part of the study area.

6.1.2 Dead assemblages

After the exclusion of species which did not comprise at least 8 % of the assemblage at any one site, only 13 species remained. These were prepared for analysis in the same way as the living. The results of the row normalised, R-mode analysis, for the first four factors are presented in table 6.1.2.1 below and the scores for all the factors are given in Appendix VI.

Species	factor 1	factor 2	factor 3	factor 4
Ammonia beccarii	-1.2	-0.26	-0.11	0.19
B. gibba	-0.4	-0.16	0.11	0.47
B. marginata	-0.44	0.56	-0.43	0.04
Bolivina spp.	-0.78	0.54	0.27	0
C. lobatulus	-1.12	-0.46	0.14	-0.36
E. excavatum forma selseyensis	-0.32	-0.06	0.25	0.43
E. magellanicum	-0.62	-0.03	0.51	0.2
E. scabrus	-0.42	0.03	-0.11	0.49
G. praegeri	-0.8	0.53	0.2	-0.01
H. balthica	-0.55	0.63	-0.09	0.17
Q. seminulum	-1.66	-0.43	-0.13	0.44
S. fusiformis	-0.67	0.49	0.19	-0.26
Textilina spp.	-1.27	-0.26	-0.46	-0.23

Table 6.1.2.1 Result of R-mode factor analysis on the dead assemblage data

These four factors explain over 84 % of the variance (see table 6.1.2.2 below) but it is the first factor which is by far the most significant, explaining almost 59 % of the variance in the data analysed.

factor	eigenvalues	% variance explained	cumulative % variance explained
1	31.19	58.85	58.85
2	6.89	12.99	71.84
3	3.77	7.11	78.95
4	3.09	5.83	84.78
5	2.26	4.26	89.03
6	1.39	2.62	91.66
7	0.99	1.87	93.52
8	0.88	1.66	95.19
9	0.85	1.59	96.78
10	0.66	1.24	98.02
11	0.45	0.85	98.87
12	0.33	0.62	99.48
13	0.27	0.52	100
total	53		

Table 6.1.2.2 Calculation from the eigenvalues of the % variance accounted for by each factor

The most significant species in each assemblage have been determined from the R-mode analysis (table 6.1.2.1). The distributions of each factor have been mapped using the Q-mode site scores given in table 6.1.2.3 and are shown in figure 6.2. Again, the communality is generally above 0.7 and most often above 0.8.

sample	communality	factor 1	factor 2	factor 3	factor 4
T1S01	0.67	-0.71	0.05	0.4	0.1
T1S02	0.87	-0.88	-0.29	0.05	-0.01
T1S03	0.92	-0.89	-0.36	-0.09	0
T1S06	0.85	-0.81	-0.39	0.01	0.21
T1S07	0.78	-0.77	-0.38	0	0.22
T1S09	0.88	-0.88	0.08	0.22	0.21
T1S14	0.76	-0.63	0.53	0.28	-0.02
T1S17	0.85	-0.69	0.47	-0.34	0.19
T1S19	0.88	-0.79	0	-0.51	0.01
T2S01	0.84	-0.62	0.06	-0.67	0.01
T2S03	0.9	-0.61	0.56	-0.45	0.12
T2S07	0.94	-0.71	0.65	-0.11	0.05
T2S11	0.86	-0.9	-0.03	-0.19	0.13
T2S14	0.92	-0.8	-0.41	-0.22	-0.26
T2S16	0.96	-0.83	-0.36	-0.06	-0.38
T2S19	0.86	-0.82	-0.39	-0.01	-0.16
T2S20	0.92	-0.86	-0.37	-0.16	-0.15
T2S21	0.94	-0.87	0.21	0.36	-0.04
T2S22	0.86	-0.84	0.16	0.35	-0.05
T2S23	0.88	-0.88	-0.32	-0.03	-0.05
T3S01	0.78	-0.83	-0.3	0.05	0
T3S03	0.9	-0.91	-0.27	0.05	-0.08
T3S05	0.98	-0.93	-0.21	0.09	-0.25
T3S07	0.67	-0.46	0.63	-0.27	0.03
T3S10	0.8	-0.82	-0.05	0.17	-0.32
T3S11	0.82	-0.82	0.1	0.26	-0.25
T3S13	0.9	-0.89	-0.15	0.03	-0.27
T3S15	0.84	-0.82	0.39	-0.05	-0.04
T3S16	0.75	-0.68	0.49	0.12	-0.19
T3S17	0.93	-0.71	0.63	0.15	-0.12
T3S19	0.9	-0.7	0.27	-0.58	0
T3S23	0.85	-0.7	0.16	-0.57	-0.07
T6S02	0.72	-0.68	-0.27	0.24	-0.35
T6S06	0.97	-0.85	-0.43	-0.2	-0.13
T6S08	0.94	-0.85	-0.38	-0.03	-0.27
T6S10	0.82	-0.76	-0.49	-0.04	-0.04
T6S12	0.8	-0.82	0.31	0.15	-0.04
T6S14	0.9	-0.73	0.59	0.01	-0.18
T6S16	0.9	-0.73	0.59	0.01	-0.18
T7S02	0.87	-0.9	-0.17	0.15	0
T7S06	0.91	-0.88	-0.3	-0.16	-0.13
T7S10	0.93	-0.95	-0.08	0.05	-0.13
T7S16	0.8	-0.44	0.33	-0.66	0.25
T8S01	0.93	-0.61	0.65	0.36	-0.07
T8S02	0.89	-0.67	0.66	0.11	0.04
T8S05	0.86	-0.78	0.29	0.31	0.24
T8S08	0.77	-0.52	-0.15	0.14	0.67
T8S09	0.84	-0.65	-0.33	-0.07	0.56
T8S10	0.87	-0.66	-0.3	-0.06	0.58
T8S13	0.68	-0.59	-0.14	-0.02	0.55
T8S16	0.71	-0.66	0.04	0.37	0.36
T8S20	0.9	-0.84	-0.09	0.27	0.34
T8S21	0.49	-0.52	-0.04	0.3	0.36

Table 6.1.2.3 Results of the Q-mode factor analysis on the dead assemblage data

The results of the Q-mode analysis are presented in table 6.1.2.3 above for the first four factors only. The total set of scores can be found in Appendix VI. Using the site co-ordinates and these scores as z-variables in a bilinear contour plot produced distribution maps for each of the factors/assemblages.

Dead factor 1 - *Quinqueloculina seminulum*, *Ammonia beccarii*, *Cibicides lobatulus* and *Textilina* spp.

As the characteristic species of this factor are negatively related to the scores, it is the blue areas of figure 6.2 (a) which indicate the areas where this factor is most important. This includes most of the mixed and frontal region bar the west and a very small portion of the east of the study area. Significantly that area in which a lobe of stratified water consistently pushes north is marked by low occurrences of these species. These species are not common along the entrance to the Bristol Channel. This factor explains almost 59 % of the variance.

Dead factor 2 - *Hyalinea balthica*, *Bulimina marginata*, *Gavelinopsis praegeri*, *Bolivina* spp. and *Stainforthia fusiformis*

The distribution of this assemblage, which accounts for almost 13 % of the dead variance, is shown in figure 6.2 (b). In this instance it is the red areas which indicate where the above species are most likely to be found. The distribution of this assemblage is almost the inverse of the *Q. seminulum* assemblage; most significant to the south in stratified areas, unimportant in the frontal and mixed regions. The most striking feature of the distribution, however, is the demarcation of the stratified lobe area. This assemblage is not very significant along the entrance to the Bristol Channel but does show a general increase along the length of transect 8 after a low beyond the stratified area.

Dead factor 3 - *Elphidium magellanicum, Bolivina* spp. and *Elphidium excavatum* forma *selseyensis*

Explaining 7 % of the variance, this assemblage is particularly significant along the entrance to the Bristol Channel (see figure 6.2, c) excepting that area which is also a region of low occurrence for the *H. balthica* assemblage. This assemblage is particularly important across the mixed-frontal transitional area and also, though less so, across the frontal-stratified transitional area.

Dead factor 4 - *Eggerelloides scabrus, Bulimina gibba*, *Elphidium excavatum* forma *selseyensis* and *Quinqueloculina seminulum*

The fourth assemblage explains just under 4 % of the variance but shows a very distinct distribution (see figure 6.2, d). The area in which this assemblage is important is distinctly separated from the rest of the study area along a NW-SE line. This assemblage dominates in that part of transect 8 from which the other assemblages are virtually absent.

6.1.3 Species-environmental correlations

The Q-mode scores for the living assemblages were plotted against the various controlling environmental parameters, demonstrating many direct relationships (see figures 6.3 - 6.7). Conradsen (1993) states that these factor scores are more likely to correlate with the environmental variables than any of the individual species. The most promising of these were explored further using linear and quadratic regression techniques to test for the nature of the relationships and the goodness of the fit.

No distinct relationships were apparent between living factor 1 and any of the environmental variables. However, living factor 2 shows a strong, quadratic correlation with mean grain size (see figure 6.8). The R^2 value is calculated at 44 % which, given that it is unlikely that a single environmental variable will control an assemblage, can be considered significant. As grain size is measured in phi units (Wentworth, 1922) the relationship is actually positive.

Living factor 3 exhibits a positive, quadratic relationship with temperature (see figure 6.9, a). The R^2 value is calculated at 53.2 %. Since the fauna of this assemblage are negatively related to its distribution, this suggests a relationship between these species and cooler temperatures. While the R^2 for the regression of the same assemblage against salinity is only 33.8 % (see figure 6.9, b), the highest correlation is seen for the stratification index (sindex) at R^2 = 67.6 % (figure 6.9, c). Given the high degree of covariance between sindex and temperature (see figure 3.28) this relation is perhaps unsurprising. The implications are that the fauna of this assemblage prefer stratified waters. Also worth noting is the correlation between this assemblage and longitude (figure 6.9, d) which has an R^2 value of 44.7 %. No correlations could be found between living factor 4 and the measured environmental variables.

As for the living, the Q-mode scores of the dead assemblages were plotted against the various controlling environmental parameters (see figures 6.10 - 6.14) and those which showed possible relations were explored further. Dead factor 1 showed no significant correlations with any of the environmental variables. Dead factor 2, however, correlates with several. These are temperature (figure 6.15, a, R^2 = 39.6 %), % clay (figure 6.15, b, R^2 = 48.3 %) and mean grain size (figure 6.15, c, R^2 = 33.1 %). The relationship with temperature is negative, with % clay, positive and with positive in terms of phi units negative in terms of mm.

There are no significant correlations for factor 3 but dead factor 4 shows a correlation with longitude (figure 6.16, R^2 = 32.3 %) which simply confirms that this assemblage is found in the east.

6.2 Canonical correspondence analysis

6.2.1 Ordination of living assemblages and environmental data

In preparation for the analysis those species which did not constitute 5 % or more of at least one sample were removed from the species data set. Those environmental variables found to covary in a significant way in chapter 3, section 3.5 were also excluded from the environmental data set. Percentage values were used for the species data and absolute for the environmental.

The data was analysed using the canoco program (version 3.12, 1991) after ter Braak (1986; 1987; 1988; 1990 & 1991). The summarised results of the analysis are presented in table 6.2.1.1 below.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.31	0.28	0.13	0.07	2.48
Species-environment correlations	0.82	0.85	0.78	0.73	
Cumulative percentage variance of species data :	12.6	23.7	28.9	32	
Cumulative percentage variance of species-environment relation:	32.7	61.4	74.8	82.8	
Sum of all unconstrained eigenvalues (DCA)					2.48
Sum of all canonical eigenvalues (CCA)					0.96

Table 6.2.1.1 Summary of CCA (and DCA) analysis on living assemblage data and the measured environmental variables

The sum of the unconstrained eigenvalues is the sum of the lengths of the maximised spread of species along imaginary environmental gradients (effectively a DCA), while the sum of the canonical or constrained eigenvalues is the sum of a maximised spread along an environmental gradient which is a linear combination of the measured environmental variables. By comparing the two, it is possible to judge whether the measured environmental variables explain the data well or not (ter Braak *et al.*, 1995). Given that the sum of the CCA eigenvalues is only two-fifths of the sum of the DCA eigenvalues, it is very likely that the most important environmental variables were not measured. Only ~ 30 % of the species data is explained by the environmental variables in the first three axes.

The first and second axes are almost equally important, the first explaining 12.6 % of the variance, the second 11.1 %. The third axis explains just 5.2 % and the fourth 3.1 % only. Only the first three axes will be examined further.

To determine the exclusive individual contribution of each environmental variable to the analysis a series of partial CCAs were carried out after Borcard *et al.* (1992). The results of these analyses are shown in table 6.2.1.2 below. By comparison of the eigenvalue of the partial CCA with the sum of the eigenvalues of the main CCA, the % contribution can be calculated. The contribution made by a particular variable

may be greater than that shown because it covaries with the other variables. Over half of the explained variance is determined by the covariance of the variables. The most significant individual contributions are made by latitude, depth and longitude. Since it is unlikely that these variables are, in themselves, controlling species distribution, they are probably acting as proxies for the true controlling parameters.

Environmental variable	Sum of eigenvalues of partial CCA	% of the total explained variance exclusively explained by the environmental variable
depth	0.05	5.85
temperature	0.04	4.91
% gravel	0.04	4.18
% sand	0.04	4.18
mean	0.03	3.44
sorting	0.04	4.38
skew m	0.01	1.98
skew f	0.02	2.51
kurt m	0.02	2.71
kurt f	0.02	2.3
latitude	0.05	6.05
longitude	0.04	5.11
Sum of CCA eigenvalues	0.96	
Covariance		52.4

Table 6.2.1.2 Proportion of the explained variance exclusively determined by the individual environmental variables and by covariances of the variables

The environmental, species and site scores produced by the analysis are given in Appendix VI. To represent the data graphically, the values for the first three axes are used as co-ordinates for biplots. The environmental variables are represented by arrows, the length of which approximate to their relative importance and the orientation to their relationship with the explanatory axes, each other and the sites and species. The optima of a species along an environmental gradient is found by collapsing the species perpendicularly onto the gradient depicted by the arrow.

The species-environmental plots are shown in figure 6.17 (a and b). Since axes 1 and 2 explain similar amounts of the species variance they are comparable in length. However, axis 3 has only half the importance of axis 2 and this was borne in mind when interpreting the biplots. The biplots indicate that the first axis is largely a function of mean grain size, skewness, latitude and % gravel, the second of temperature, depth and longitude and the third of % sand and sorting. Species are spread along the environmental gradients of which mean grain size and % gravel, temperature and depth are the most important. Species such as *Trochammina* sp., *G. praegeri, C. lobatulus* and *C. fletcheri* have their optima at sites which are northerly and contain large proportions of gravel, while species such as *S. fusiformis* are found at much finer grained, southerly sites. *Nonionella turgida, B. marginata, A. glomeratum* and *H. balthica* have maximal occurrences in cold, deep, southerly sites while *Q. seminulum, S. wrightii* and *L. haliotidea* prefer warmer sites. *Bulimina gibba* and *E. scabrus* show the same affinity for high % sand content among the dead assemblages that they do for the living, but *E. gerthi* and *E. excavatum* forma

selseyensis exhibit optima at even higher concentrations of sand. *Epistominella naerensis*, *N. auricula* and *B. pseudopunctata*, on the other hand show, prefer sites with little sand content.

The sites are arranged on the same plot as the environmental variables in figure 6.18. As for the living there are three main arrangements of sites; along the latitude and % gravel gradient where mixed sites are found at high values of these variables, along the temperature gradient where stratified sites tend to group at the low temperatures and along the % sand gradient where sites from transect 8 are found.

6.2.2 Ordination of dead assemblages and environmental data

The dead assemblage and environmental data were prepared for analysis in the same way as the living. The results of this analysis are summarised in table 6.2.2.1 below.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.26	0.18	0.16	0.04	1.54
Species-environment correlations	0.84	0.86	0.82	0.59	
Cumulative percentage variance of species data :	16.7	28.4	38.4	41.4	
Cumulative percentage variance of species-environment relation:	34.1	58	78.6	84.7	
Sum of all unconstrained eigenvalues (DCA)					1.54
Sum of all canonical eigenvalues (CCA)					0.75

Table 6.2.2.1 Summary of CCA (and DCA) analysis on dead assemblage data and the measured environmental variables

As for the living, a large proportion of the species data is unexplained by the measured environmental variables. A comparison of the sum of the canonical with the constrained eigenvalues shows that half of the variance can be explained. This means that the measured environmental variables are better at explaining the distribution of dead tests than the living. Only 41.4 % of the variance is explained by the first four axes. The first and second axes explain similar amounts of the variance (16.7 and 12.3 % respectively) while the third axis explains 10 %. Since the fourth axis explains just 3 %, only the first three are considered further.

A series of partial CCAs were carried out to determine the unique contribution of each in explaining the changes in species occurrences and this is presented table 6.2.2.2 below.

Environmental variable	Sum of eigenvalues of partial CCA	% of the total explained variance exclusively explained by the environmental variable
depth	0.03	4.77
temperature	0.02	2.65
% gravel	0.01	2.39
% sand	0.01	2.52
mean	0.02	3.32
sorting	0.01	1.86
skew m	0.03	5.04
skew f	0.02	2.92
kurt m	0.02	3.58
kurt f	0.02	3.58
latitude	0.07	10.08
longitude	0.04	5.57
Sum of CCA eigenvalues	0.75	
Covariance		51.72

Table 6.2.2.2 Proportion of the explained variance exclusively determined by the individual environmental variables and by covariances of the variables

As for the living, over half of the explained variance is determined by covariance of the variables. Individually the most important variable is latitude but longitude and skewness measured by moments are also important. The importance of latitude and longitude is probably the result of these variables acting as proxies or partial proxies, at least, for the true environmental controls.

The scores produced by the analysis for sites, species and environmental variables are plotted in figures 16.19 and 16.20. From these it can be seen that depth, temperature, longitude and latitude are the most significant explanatory variables. It seems that depth and longitude influence the first axis while % gravel, temperature, latitude and mean grain size influence the second. The third is a function of % sand and sorting.

Examining the position of the various species relative to these gradients suggests some clear patterns. Several species are arranged along the temperature gradient, from *H. balthica* which experiences optima at the coldest temperatures, through *B. marginata, A. glomeratum, G. praegeri, Q. seminulum* to *E. magellanicum*. These species are also arranged along a gradient of increasing depth and decreasing grain size. Latitude, grain size and % gravel all appear to be closely related and species such as *G. rudis* and *E. repandus* show maxima in the most northerly, coarsest conditions, while *C lobatulus, C. fletcheri* and *A. beccarii* are found on the downward side of these gradients. *Bulimina gibba* and *E. scabrus* have an optima at very high percentages of sand while the *Bolivina* spp. prefer much finer substrates. Species arranged along the depth gradient include *S. fusiformis* in the deepest conditions through *S. wrightii, T. bockii, Q. seminulum, M. subrotunda* to *E. excavatum*.

An examination of the orientation of the sites and environmental variables (figure 6.20, a and b) reveals three main arrangements of sites. The first is along the temperature gradient from the cooler sites in the stratified area to the more mixed sites. The second is along the % gravel and latitude gradients with the

more mixed sites to the north and with a higher proportion of gravel. The third arrangement of sites is along the % sand and other grain size parameter gradients. Sites from the Bristol Channel and the east of the study area are found at the most positive end of these gradients.

The first axes of both the living and dead analyses were subject to Monte Carlo permutations, available as an option in the canoco package to test for significances and both produced P-values of 0.01, demonstrating that these axes were significant.

Chapter 7 Discussion

7.1 Environmental data

7.1.1 CTD data

For over half the year, from mid-March to late-September, a sharp, horizontal, transition from the tidally mixed waters to the north and east and the stratified waters to the south and west is found in the Celtic Sea study area (Li & Elliott, 1990). This prominent oceanographic feature marks the separation of cold and warm waters, high energy and low energy tidal currents and is associated with high levels of productivity. The area is unusually deep for an inner-shelf region (see figure 3.1) and it is this bathymetry which maintains the stability of the front (Simpson, 1976). This explains why the stratification index, an invented variable calculated from the surface and bottom water temperatures, correlates so well with depth (see figure 3.28). Given the relative shallowness of waters on the eastern side of the study area, the front at the entrance to the Bristol Channel area might be expected to show different characteristics.

Temperature, salinity and density measurements taken across the front in July-August 1995 and 1996 (figures 3.2 - 3.19) illustrate the very strong stratification found in the area. This is largely driven by temperature rather than salinity as found by Allen (1979), though temperature and salinity do correlate quite well (figure 3.28). The bottom front is found in approximately the same position as the surface for the north of the region but along the entrance to the Bristol Channel the bottom front juts from under the surface front for many kilometres eastwards. Very little of the fully mixed region was captured for any of the transects but the divisions between mixed, frontal and stratified water bodies have been fully recorded.

The thermocline depths, averaging at around -30 m, are much shallower than those given for the Celtic Sea area during July by Li & Elliott (1990) though the mixed-layer thickness, of around 10 m, tallies with that given by Elliott & Li (1991). This is shallow enough to support sub-surface phytoplankton growth along the thermocline away from the front and Raine & McMahon (unpublished) report high concentrations of dinoflagellates in the stratified waters of the Celtic Sea, south of Ireland, as measured during the summers of 1992 through to 1995.

The main phytoplankton growth should, according to the literature (*e.g.* Le Fèvre & Grall, 1970; Pingree *et al.*, 1974) occur around the front. Several mechanisms are proposed to explain the enhanced productivities found in frontal regions (see section 1.1.5) including the cross-frontal transfer of nutrients by cyclonic eddies. The instability of the Celtic Sea front has been observed by Allen (1979) and described as 'patchy and sinuous'. Pingree (1979) discusses the 'pronounced eddy activity' of the Celtic Sea and this is confirmed in the satellite imagery of Simpson & Bowers (1979). From this

it would appear that a cyclonic eddy in the central part of the northern Celtic Sea front is a habitual feature. An eddy was active during the 1995 cruise and was captured by satellite imagery (see figure 1.3). This feature occurs despite the nature of the bathymetry which should suppress eddy growth (James, 1989).

Some upwelling is also in evidence for the northern part of the front, particularly along transects 2 and 6 (figures 3.5, 3.6, 3.7 and 3.11). Though the rates of upwelling and downwelling resulting from along-front flows are difficult to measure (Hill *et al.*, 1993), they are believed to profoundly influence productivity *e.g.* James (1978) and Savidge & Foster (1978). The weak circulation cells depicted in figure 1.2 suggest that the seabed in the frontal region does not receive equal rates of debris and carbon flux from above (Horsbrugh, pers. comm.). It is likely, though unproven, that while the area directly beneath the convergence slick receives flux from above, some of the particulate matter becomes entrained by the flow between the circulation cells and is delivered instead to the stratified area beyond the front. The area of seabed separating these two zones of deposition is, in contrast, deprived of detritus which is drawn away by the same flows.

7.1.2 Geochemical data

Before considering how productivity at the surface influences the sediments beneath, it is important to consider the nature of carbon flux on the continental shelf and particularly around shelf sea fronts. It is well established that rates of production on shelves far exceed those of the deep ocean and though shelves account for just 10 % of the ocean floor area, they may represent up to 20 % or more of the primary productivity (Berger *et al.*, 1989). Net primary productivity on continental shelves has been estimated at around 6×10^9 tonsyr $^{-1}$ (Walsh *et al.*, 1981; Wollast, 1991).

More important than productivity, however, the shelf area is of significance to carbon budgets because a large proportion of organic carbon produced there is not recycled by organisms in the water column. Shelf waters, especially in frontal regions, tend to be dominated by phytoplankton. Holligan *et al.* (1984, b) found that during summer at the English Channel front, carbon was partitioned between phytoplankton in the following way: dinoflagellates living in the front, 26.5 gCm^{-2}, naked dinoflagellates living sub-surficially in the thermocline, 0.42 gCm^{-2} and diatoms living in mixed waters, 7.91 gCm^{-2}. This was in contrast with the planktonic heterotrophs (mostly zooplankton) which comprised just 2.3 - 3.2 gCm^{-2} and 10 - 30 % of which were bacteria. The heterotrophs graze on the phytoplankton, then the faecal pellets produced and the ungrazed phytoplankton sink to become food for benthic organisms. These benthic organisms and planktonic heterotrophs are themselves consumed by larger organisms. However, Wollast (1998) states that only 30 % of this, mostly very refractory, falling material is consumed by predators or bacteria, leaving 70 % for burial or export. This contrasts with the open ocean where only a small fraction of the phytoplankton and faecal pellets reach the sea floor. There, balance is maintained between producers and consumers in the water column. The productivity difference between shelves, which are rich in nutrients from river run-off, and the open ocean, which is

nutrient limited, is about a factor of 2 but this is amplified to a factor of 10 in terms of carbon export (Wollast, 1998). However, production associated with fronts is seasonal and it is also reported that the ratio between autotrophs and heterotrophs is variable through the year (Mullin & Brooks, 1970) changing from 0.3 in April/May to 2.1 in May/June to 1 to 2 in July and August in coastal waters off California. This is certain to influence flux rates.

The proportion of the carbon flux from shelf waters which becomes buried or is transported off the shelf must be around 2200 x 10^6 Cyr^{-1} (including 67 % of the primary productivity) to satisfy mass balance equations (Wollast, 1998). Of the remaining 33 % of primary productivity which is deposited on the sea floor, 30 % is rapidly oxidised after burial leaving just 3 % to for preservation in the sediment. However, these figures are averages only; burial differences between shelves and between different areas on the same shelf can be very large. For example Kemp *et al.* (1994) estimate that only 4 % of primary productivity on the mid-Atlantic Bight is exported while Walsh & McRoy (1989) state that the outer shelf is an area of limited deposition and the middle shelf one of intensive deposition. The rate of utilisation of organic matter is also a function of its refractoriness, oxygenation of the water and the overall rate of sedimentation, all of which mean that flux and burial of carbon on the shelf is highly variable both spatially and temporally. This is compounded by the nature of currents on shelves, where sediments are, in most places, continually resuspended.

The distribution maps for organic carbon and nitrogen in the Celtic Sea (figures 3.27, b and c) suggest that there is a strong degree of decoupling between the surface waters and the seabed. Though it might be expected that, since productivity concentrates around the frontal region, this would be reflected in the sediments, there is instead an east-west gradient. This is probably the result of the redistribution of organic material to the more quiescent areas. That the north-west and south-west are areas of deposition would seem to be confirmed by the high degree of sorting found here (figures 3.24, a and b) and the correlation, though weak, between organic carbon and mean grain size (figure 3.33). However, while the south-west basin area is a repository for fine grained sediments, the north-east is largely composed of sand and gravel and has no clay and few silt-sized particles (figure 3.21). Since the organic matter produced in association with the front is very fine, and given the very strong correlation between organic carbon content and % silt (figure 3.33), this either suggests that matter found here is not derived from the productivity found at the front or, as is most likely, that almost all of the fine matter in the sediment is organic.

There is no support in the organic carbon data for the depositional zones suggested in section 7.1.1, but neither is there a clear record in the sediments of the position of the overlying front. The % $CaCO_3$ shows a similarly disappointing pattern but with greater concentrations in the north than south (figure 3.27, a). This is probably a function of the coarser grain sizes deposited in this area. However, the contention of Evans (1990) that carbonate content is roughly positively correlated with grain size is not borne out by the data (figure 3.22, a). The calcareous material is unlikely to consist of much

foraminifera since the numbers of tests are quite low in this area (figure 4.3). The geochemical data suggests that the high levels of productivity are being recorded, not in the sediments directly beneath, but in the deeper basin to the south-west and the area of deposition to the north-east.

The C/N ratios are rather high in the south of the study area (figure 3.27, d). This indicates that the sediment here is likely to be terrigenous in origin (MacDonald & Pedersen, 1991). Low C/N ratios are expected in sediments of marine origin (Stevenson & Cheng, 1971) and these are found to the north. This suggests that the river Severn, which discharges to the Bristol Channel is delivering terrigenous matter to the south of the study area and this riverine influence is supported by the isotopic difference between water samples from the Celtic Sea and those from the Bristol Channel (see figure 5.4) .

7.1.3 Grain size data

The distribution of grains between the four size fractions (figure 3.27) confirms the grain size distribution maps produced by BGS (Evans, 1990). In agreement with the BGS findings, the 1995 and 1996 data show that the finest grain sizes are found in the deepest areas and are surrounded by a large area of sand. The finer sediments are a combination of silts and clays and this is reflected in the strong correlation between these size classes (figure 3.30). Sandy sediments dominate along transect 6, midway along transect 8 and in the mid-frontal region. To the north there are gravel-rich sediments which form part of extensive gravel deposits found in the Irish Sea and through St. Georges Channel. These sediments correspond to the southern limit of Irish Sea till deposits according to Garrard & Dobson (1974) but disputed by Scourse (1991) and Scourse *et al.* (1990).

The coarsest grain sizes are found to the north and the finest to the south (figure 3.22 a) and, given that the frontal position is reported by some to mark a sharp transition from coarse grained sediments on the mixed side to fine grained on the stratified side (Cruetzberg, 1984), this distribution is broadly as might have been expected. However, stratification does not seem to influence grain sizes on the western side of the study area where tidal currents are stronger and to the south, so the dampening effect of the stratification must be more influential in the stratified-frontal area than in the main part of seasonally stratified waters which extend to the shelf edge.

There is good agreement between the mean and modal grain size measurements over the area (figures 3.22, b, 3.23, a and b). Differences occur where there are multiple sediment sources, a lack of certain ranges in the source material, trapping of fines among gravels, extreme variations in current speed or a combination of different modes of deposition (Sahu, 1964). As the mean grain size is an indication of the current velocities, the contours of grain size indicate that currents are greatest to the north but decrease to the south, though increasing slightly to the south-west. This also confirms that currents are stronger on the west side of the study area. The steady change in grain size from the north-east/north to south may also indicate focusing of sediments to this area along an approximate

North - South transport path, the size decreasing in the direction of transport due to progressive sorting (Larcombe, 1991).

Transport paths can be examined further using the sorting parameter which is based on standard deviation (see figures 3.24, a and b). Highest sorting is found in the south, but also at the end of transect 8 and the extreme north-east. Since sorting increases along the transport path it would seem that the general transport is in a north - south direction and both into and out of the Bristol Channel. The north and north-east of the area may be receiving sediments from outside of the study area. The areas which have the highest proportions of sandy sediments also show the poorest sorting. This data confirms the known sand transport paths for the area (Stride & Belderson, 1990) which run from the Irish Sea through the Celtic Sea and out of the Bristol Channel, excepting transport round St. David's Head.

Skewness is a measure of the bias of grain sizes towards finer or coarser sizes. Duane (1964) has suggested that negative skewness, which is a bias towards coarser sizes, is the result of the winnowing of fines due to erosion in a high energy environment while positive skewness is the result of the deposition of fines. Given that this is the case, then the mapping of Folks and moments skewness presented in figures (3.25, a and b) could be interpreted to mean that the central study area, the south-east and the end of transect 8 are areas of net deposition while the north and north-west are characterised by net erosion. The areas of net erosion are coincident with frontal regions nearest to the mixed waters while the area of net deposition lies in the stratified waters just beyond the front. The areas where neither positive nor negative skewness dominates are considered to be ones of fluctuating energy levels. This would then include the mid-frontal region and the extreme north of the study area in mixed waters. These may be the areas where the tidal or other currents are effective while the currents in areas of net erosion and deposition are enhanced or dampened respectively by the position of the tidal front.

The final grain size parameter mapped was kurtosis (see figures 3.26 a and b). This is a measure of the normality of the curve and is a difficult parameter to interpret in terms of the environment. The kurtosis, as calculated by moments, is very different from that calculated by Folks.

7.2 Foraminiferal data

7.2.1 Individual species

Ammonia beccarii var. *batavus*

The most abundant dead species, *A. beccarii*, rarely forms more than 5 % of an assemblage but is found in almost all samples. It is much less abundant in living assemblages (see table 4.1.2). It is one

of the defining species of dead factor 1 which dominates the mixed and frontal regions of the study area. Canonical correspondance analysis traces a relationship between the living individuals of this species and % gravel and warmer waters (figure 6.17). For dead individuals CCA suggests that this species is most likely to be found in warmer waters, coarser grain sizes and sites with high % gravel (figure 6.19). Despite this, comparison of living occurrences of *A. beccarii* with dead (figure 4.6) shows that there are large distributional differences between the two, suggesting either that *A. beccarii* is subject to extensive reworking after death, or that the distribution of the living at the time of collection was not typical of the rest of the year. If the living distribution is atypical then this suggests that *A. beccarii* is able to tolerate a wide variety of conditions and can exploit, say, the phytodetritus found in the frontal region though generally preferring other conditions.

Murray (1979, b) reports that *A. beccarii* reaches the northern limit of its distribution around Britain and is found widely distributed across the shelf, though Thiede *et al.* (1981) have found it living in the shallow, warm parts of the Oslofjord. Murray (1970) suggests that it tends to be more coastal and Alve & Murray (1990) find *A. beccarii* common in brackish waters. However, since the specimen they illustrate has no apertural plug, it is probably not the variety *batavus* which is under discussion. Murray (1986) also finds *A. beccarii* dominant in the near shore sandy waters of Lyme Bay. This species is widely reported as tolerant of great variability in temperature, salinity and even oxygen (Lutze, 1965; Risdal, 1964). Moodley & Hess (1992) found that *A. beccarii* specimens increase their pore-sizes in response to poor oxygen conditions which does indicate some degree of tolerance but Sen Gupta & Machain-Castillo (1993) believe that *A. beccarii* is not tolerant of hypoxia events so there is probably a threshold limit.

The vertical distributions of *A. beccarii* in the cores examined (see figure 4.25, a) are not very conclusive. They suggest that this species prefers a shallow infaunal habitat as it is quite infrequent below 5 cm but living individuals were found at 10 cm depth in mc196. The relative abundances presented in table 4.2.5 also show that this species is relatively most abundant at mid-depths (~ 5 cm).

To summarise *A. beccarii* is found all over the study area and, because of its catholic tastes, is probably able to living in most of the area for at least some of the year. The dead assemblage, however, which integrates the tests produced over the full annual cycle, indicate a preference for the coarser, more turbulent and hence oxygenated waters to the north, where it is found in association with species such as *Q. seminulum*, *C. lobatulus*, *S. wrightii* and *T. bockii*. It probably has a shallow infaunal habitat and this is in keeping with its 'rounded trochospiral' form according to Corliss (1991) and Corliss & Chen (1985).

Adercotryma glomeratum

As this species is a fragile agglutinate, it is, unsurprising that it is much more frequent in living assemblages than dead (table 4.1.2) and has maximum abundances of less than 1 % in the dead compared to 10 % in the living. However, the distribution of both the living and dead forms appears to reflect that of stratified and frontal waters (figure 4.7). This species is characteristic of living factor 3 and the correlation of this factor with cooler, stratified waters confirms this association (compare figure 6.1, c with 6.9). Canonical correspondance analysis also suggests that the distribution of *A. glomeratum*, both living and dead, is related to colder waters (figures 6.17 and 6.19). Living occurrences are also related to longitude, while the dead also correlate with skewness. Since longitude is not an ecological control in itself, the importance of this parameter must be related to competition and/or missing environmental variables for which the spatial variable is acting as a proxy (Borcard *et al.*, 1992). What these might be will be discussed below. The increase in dead occurrences along a skewness gradient is probably related to reworking of these tests despite the good agreement between living and dead distributions.

Adercotryma glomeratum is often considered an arctic species and its distribution was thought by Williamson *et al.* (1984) to correlate to temperatures of 1.8 - 3 ^{0}C but to be unaffected by salinity, depth or substrate type. Clearly, this cannot be the case since this species thrives in the Celtic Sea in temperatures of greater than 9 ^{0}C. Alve & Nagy (1986) found both living and dead tests of *A. glomeratum* in Sandebukta, Norway where salinities ranged from 29.5 - 34.7 $^{0}/_{00}$ and temperatures from 3.9 - 6.8 ^{0}C. Schafer & Cole (1982) found this species living in association with normal marine water masses (34 - 35 $^{0}/_{00}$) on the Newfoundland continental slope, while Christiansen (1958) and Leslie (1965) report that it can living on both hard and soft substrates but believe that it is stenohaline. Thiede *et al.* (1981) also believe that it is salinity limited.

The consensus is that temperature and substrate (though perhaps salinity) are not the main controls on the distribution of this species. Alve & Nagy (1986) believe instead that its distribution in the Sandebukta estuary is related to total organic carbon values higher than 0.8 - 2.1 % and Gooday (1993) found that it exploits phytodetritus from the spring bloom on the Porcupine Abyssal Plain. This suggests that this species is opportunistic and its small size is certainly appropriate to such a life strategy.

Austin & Sejrup (1994) collected both living and dead individuals of this species from Syslakv'g in seasonally stratified waters with low levels of oxygen (2 -4 ml^{-1}) which implies that this species not only prefers to living where there is high fluxes of organic carbon, but can tolerate the low oxygen levels often found in such areas. This is confirmed by the work of Bernhard & Alve (1996) who studied ATP survival in nitrogen incubated foraminifera including *A. glomeratum*. This simulates the effects of an anoxic event and it was found that *A. glomeratum* successfully survives such events but sustained

damage to the contained ATP. They conclude that *A. glomeratum* is a facultative anaerobe, able to survive periods of anoxia, possibly doing so (judging by the damage to the ATP) by becoming dormant.

Adercotryma glomeratum is generally found living in the greatest numbers at the sediment surface in the cores studied (see figure 4.25, b) but is found in relatively high numbers throughout the length of mc196. Relative to the other species measured in the Celtic Sea cores it has its highest occurrences at the surface (table 4.2.5). Alve & Bernhard (1995) and de Stigter *et al.* (1998) also found *A. glomeratum* to be predominantly epifaunal.

Both the Celtic Sea data and the published information concerning this species, suggest that its distribution is related to stratified waters in the Celtic Sea both because of its ability to exploit phytodetritus and because of its tolerance to the low oxygen concentrations. As an opportunist, the relatively low numbers of dead tests found might be explained by its seasonal occurrence rather than, or in addition to, the destruction of its agglutinate tests. However, it is quite typical for opportunistic species to appear in high numbers in living assemblages and low in dead because of their fragile nature. This species generally lives at the sediment surface or near-surface, though according to Corliss (1991) and Corliss & Chen (1988) its spherical form is more suited to an infaunal microhabitat.

Bulimina gibba

Living and dead individuals of *B. gibba* show very similar distributions (see figure 4.8). Abundant in both assemblages (see table 4.1.2), *B. gibba* was selected by factor analysis as characteristic of dead factor 4. No relationship could be found for this assemblage with any of the measured environmental variables, but it is distribution is distinctly eastern (figure 6.2, d). However, living and dead individuals of *B. gibba* are also found to the west. These results might suggest that the true environmental controls on this species have not been measured in this study, but the CCA strongly detects a relationship with % sand for both living and dead individuals (figures 6.17 and 6.19).

With respect to microhabitat, *B. gibba* has a subsurface maximum in mc495 and mc296 (see figure 4.25, c) and might be regarded as infaunal were it not for the contrast provided by mc295 and mc395 where it has an epifaunal habitat. However, the relative abundances (table 4.2.5) indicate that this species is probably infaunal.

Though *Bulimina* spp. are widely regarded as oxygen tolerant (Sen Gupta & Machain-Castillo, 1993), *B. gibba* does not dominate in all the areas of the Celtic Sea which are assumed to be oxygen depleted (*e.g.* under stratified waters). However, this species tends to replace *B. marginata* in samples from stratified waters to the west and east where sediments are coarser. It is tentatively suggested that while *B. gibba* may be tolerant of certain levels of organic flux and oxygen depletion, its lower-

threshold levels are higher than for *B. marginata* and so it prefers sandier substrates where oxygen levels tend to be higher. This species is probably an infaunal dweller in keeping with its 'tapered & cylindrical' form (Corliss , 1991; Corliss & Chen 1988).

Bulimina marginata

The second most abundant dead species, *B. marginata*, is not as well represented in the living assemblages (table 4.1.2). Despite this, the living and dead specimens show very similar distribution patterns (figure 4.9). Factor analysis identifies *B. marginata* as characteristic of living factor 3 and dead factor 2, both of which correlate with colder waters. The living factor is also correlated with longitude and the dead with % clay and finer grain sizes. Both factors distributions mirror that of stratified waters, including the area of the persistent eddy (figures 6.1, c and 6.2, b).

The relationship between *B. marginata* and temperature is borne out for both the living and dead data by the CCA (figures 6.17 and 6.19). For the living, *B. marginata* experiences optima at temperatures cooler than those preferred by *H. balthica* but for the dead this is reversed. This may be a function of the reworking of *H. balthica* to deeper colder waters (see figure 4.16).

Gevitz *et al.* (1971) found that *B. marginata* preferred salinities of 33 - 35 $^{o}/_{oo}$ and temperatures of between 10 - 14 ^{o}C. However, it is also clear from the literature that temperature is not the main control on this species. Bandy *et al.* (1965) found this species (forma *denudata*) in abundance in the area around the hyperion sewage outfall, California. They also found that living foraminiferal abundances were 10 - 20 times greater than those found elsewhere on the shelf. This strongly suggests that *B. marginata* prefers high organic fluxes and possibly that it can withstand low levels of oxygen. Other studies support this hypothesis; Risdal (1963) found *B. marginata* living in association with the polluted, poorly oxygenated waters of the Oslofjord with high organic carbon content but found no relationship with silt or clay. However, other studies have drawn attention to the affinity between *B. marginata* and substrates *e.g.* Conradsen (1993), Conradsen *et al.* (1994) and Murray (1986). This relationship is probably the result of the fact that, as organic content increases, grains become finer (Cato, 1977), since *B. marginata* is also reported from sandy sediments (Murray 1983). Further evidence to support the theory that *B. marginata* likes to living in association with high levels of organic carbon can be found in the work of Conradsen (1993), Conradsen *et al.* (1994) and Qvale & van Weering (1985).

Sen Gupta & Machain-Castillo (1993) confirm that *B. marginata* can tolerate low oxygen levels quite well but in their experiments to test the response of various species to anoxia events through nitrogen incubation, Bernhard & Alve (1996) found that *B. marginata* had a poor survival rate. This was not unexpected since the species does not possess the ultrastructural characteristics of other anaerobes. Their conclusion was that *B. marginata* is not well adapted to anoxia though it is able to tolerate poor

ventilation.

With regard to microhabitat, *B. marginata* has similar downcore profiles to *S. fusiformis* and *H. balthica* (see figure 4.25), but an examination of the relative proportions of these species (table 4.2.5) shows that, while *H. balthica* is spread through out the cores and *B. marginata* and *S. fusiformis* both have infaunal maxima, these maxima never occur at the same depths in the same core. Barmawidjaja *et al.* (1992) also found that *B. marginata* increased in relative abundance with depth while Bernhard & Alve (1996) found that, with regard to absolute data, *B. marginata* lives primarily at the sediment surface and thus, describe it as 'near-surface'. This was not the case in the Celtic Sea cores.

The low oxygen tolerance of *B. marginata* and its affinity to organic flux explain why it is distributed beneath the stratified waters (section 1.1.5). It has also been observed to dominate in the tidally stratified area of the north North Sea (Klitgaard-Kristensen & Sejrup, 1996). The intolerance of this species to anoxia may be reflected in its absence from sediments dominated by *S. fusiformis*. *Bulimina marginata* is an infaunal species in keeping with its 'tapered & cylindrical' form (Corliss 1991; Corliss & Chen 1985).

Cibicides lobatulus

This species is much more frequent among the dead than the living (table 4.1.2). Lutze & Thiel (1989) believe that the unde-representation of this species in the living is due to its preference for an elevated habitat in high energy areas and thus its loss during sampling. Nevertheless, it is characteristic of living factor 2. This assemblage is distributed across the mixed region but is also found in the fully stratified area to the south (figure 6.1, b). It has a strong correlation with coarser grain sizes. However, when dead, *C. lobatulus* is not at all common in the fully stratified waters (figure 4.10). *Cibicides lobatulus* is also characteristic of dead factor 1, also found in mixed waters (figure 6.2, a).

These associations are confirmed by CCA; both living and dead individuals are most abundant in the north and both show a relationship with substrates; coarser sediments for the living and % gravel for the dead (figures 6.17 and 6.19). This species, living and dead is most abundant in the mixed areas to the north becoming rare or absent from stratified waters to the south (figure 4.10). The preference of *C. lobatulus* for these conditions is easily explained by this species ecological preferences about which there is almost complete consensus. It consistently occurs in high energy waters and the coarse-grained sediments which are the result of strong currents (Conradsen, 1993; Hald & Steinsund, 1992; Klitgaard-Kristensen & Sejrup, 1996; Mackensen *et al.*, 1985; Steinsund *et al.*, unpublished). Interestingly Conradsen (1993) also finds it in association with *A. beccarii* as in dead factor 1 of this study. Some authors limit its tolerances further suggesting it prefers waters of around 5 ^{0}C (Hald & Steinsund, 1992; Mackensen *et al.*, 1985) though Austin & Sejrup (1994) found *C. lobatulus* at temperatures of 3 ^{0}C in Syslakv'g, Norway.

The case for *C. lobatulus* as a high energy water indicator is well established. In the context of shelf-sea stratification this species is diagnostic of the relatively energetic mixed waters and mixed-frontal transitional waters.

Cancris auricula

Found in reasonable numbers in the living assemblages, this delicate foram rarely preserves in the dead (table 4.1.2). Given the large size this species often attains it is also possible that it has a longer life-cycle and relatively low turnover rate and is thus, under-represented relative to those species with higher rates of production. This species is not confined to stratified or mixed areas (figure 4.11) nor was it selected by factor analysis as typical of any assemblage. It was too rare for to be included in the CCA analysis of the dead but an analysis of the living distribution suggests relationships with % gravel (figure 6.17). Living specimens of *C. auricula* were found attached to large quartz grains perhaps indicating that this species employs an epiphytic life strategy, which explains this correlation.

However, contrary to the proposed epiphytic life strategy, this species was found at depth in several of the multicores (figure 4.25) and while its absolute abundance profile matches that of overall densities in the core (see figure 4.23) the relative abundances (table 4.2.5) suggest an infaunal microhabitat.

This species appears to favour gravely substrates but its true ecology is difficult to determine from this data set. It is, possibly, an infaunal dweller. However, as it is virtually absent from the dead assemblage, this species would not be very useful in a palaeo-stratification context

Elphidium excavatum forma *selseyensis*

This species is found largely in the eastern part of the study area, in mixed and frontal waters and especially along transect 8 (figure 4.12). Although it rarely forms a very large proportion of the foraminifera at any one site (with the exception of mc296) it is characteristic of dead factor 3, the distribution of which is not unlike sorting (compare figures 6.2, c and 3.24). However, no correlation was found. If sorting is a factor then this suggests that the distribution of this assemblage is related, at least in part, to reworking, though the living and dead distributions of *E. excavatum* are very similar (figure 4.12).

Canonical correspondance analysis reveals a strong relationship between living and dead *E. excavatum* and sandy sediments (figure 6.17 and 6.19). CCA also identifies sorting as a control on the dead distribution. A relationship with warmer temperatures, shallower and eastern sites is also apparent. However, this species is reported from a wide variety of environments. Conradsen (1993) and Conradsen *et al.* (1994) found that *E. excavatum* (which was not further divided into forma) is

tolerant of a wide range of salinities, temperatures, oxygen concentrations and currents but did show some preference for sandy-silty substrates. Lutze (1965), Risdal (1964), Qvale & van Weering (1985) and Kuijpers *et al.* (1989) find this species in a wide variety of salinities and temperatures and report that it is insensitive to oxygen depletion. More helpfully, Steinsund *et al.* (unpublished) conclude that this species prefers those areas with very changeable conditions and Alve & Murray (1997) state that this species is able to tolerate less than fully saline conditions and is found in association with estuarine blooms in spring. It often occurs in assemblages of very low diversity and in extreme environments. This species was found living in only one of the multicores examined (mc296), where it dominated with exceptionally high numbers of individuals and with a very low diversity of species (see table 4.2.4).

Rather than discovering what controls this species distribution, its distribution seems to say more about the area of the Celtic Sea from which it is derived. That the entrance to the Bristol Channel is an extreme environment, as the presence of this species seems to suggest, has not been recorded by the environmental data which merely record an instant in time. However, it seems likely that this area is subject to large fluctuations in water flow given the strong tidal currents found here. In addition, the front is much weaker here than to the north and may not be as stable. Tidal streams are also stronger to the west and this may explain the occurrence of this species here. However, *E. excavatum* does not generally occur in samples which have low diversities (excepting mc296) as might be expected of extreme environments and it is circular to describe the environmental conditions at a site on the basis of a fauna whose ecological tolerances have not been firmly established.

This species is possibly epifaunal though the Celtic Sea data is insufficient to confirm this. Its rounded planispiral form, however, is more in keeping with an infaunal microhabitat (Corliss & Chen 1985; Corliss, 1991).

Epistominella naerensis

This species constitutes similar proportions of both the living and dead assemblages and, when living, lives under frontal waters and fully stratified waters but with a zone of low occurrence separating the two. When dead, *E. naerensis* is distributed in a north-south direction through the centre of the main study area but concentrates in the region where frontal waters become stratified (figure 4.13). This species was not subject to factor analysis because of the high cut-off used but according to CCA it shows some relationship with cooler waters when living and longitude when dead (figures 6.17 and 6.19).

The measured environmental variables are clearly insufficient to explain this species distribution and these missing variables probably relate to oxygen concentration and organic flux. Sen Gupta & Machain-Castillo (1993) find that *Epistominella* spp. are commonly found in oxygen minimum zones in

communities which have high dominances and low diversities (typically only 2 - 3 species comprising 80 % of the population) and Gooday (1993) found *Epistominella* spp. associated with the spring bloom on the Porcupine Abyssal Plain. This species is very characteristic of those which thrive in these conditions being small in size, spherical in shape and having a thin-walled test. These adaptations mean that not much energy is required for this species to reproduce, that it doesn't need to grow very large to reproduce and thus, that it is able to respond quickly to bloom events. It is typical for such species to be under-represented in dead assemblages (Sen Gupta & Machain-Castillo, 1993). Given that this is not the case for *E. naerensis* in the Celtic Sea and the differences between the living and the dead distributions (figure 4.13), it is possible that this species was not in production at the time of sampling and that most individuals are produced at another time of year, possibly the spring and autumn bloom events. It is interesting to note that this species occurs living in areas which might be expected to have high levels of organic flux (*e.g.* under frontal and stratified waters) but only where *S. fusiformis* makes up less than half the assemblage. This suggests that they have slightly different tolerances or requirements with regard to oxygen concentration and/or organic flux.

The microhabitat preferences of this species could not be ascertained from the study of the Celtic Sea multicores. Though no references to this species microhabitat could be found in the literature, *E. vitrea* has been studied and declared deep-infaunal by Alve & Bernhard (1995) and potentially infaunal by Barmawidjaja *et al.* (1992). However, the biconvex form of both E. vitrea and E. naerensis suggests an epifaunal habitat according to Corliss & Chen (1985) and Corliss (1991).

Epistominella naerensis is an opportunistic species which prefers high organic fluxes and can tolerate low oxygen levels. Though these conditions are assumed for the frontal and stratified areas of the Celtic Sea, they have not been measured and so it is not possible to confirm these as the controls on this species distribution in the Celtic Sea.

Eggerelloides scabrus

Living or dead, *E. scabrus* is found largely in the south and east of the study area (figure 4.14) and makes up more of the living assemblages than the dead. It is characteristic of living factor 4 and dead factor 4, both of which are found in the east of the study area (figures 6.1, d and 6.2, d), though no correlation with any of the measured environmental variables could be found for this assemblage. A strong relationship with % sand was detected by the CCA for both dead and living specimens (figures 6.17 and 6.19). Skewness was also identified as a control on the dead, suggesting reworking.

Eggerelloides scabrus is described as being widely distributed across the shelf by Murray (1979, a). Though this species distribution in the Celtic Sea coincides with areas which are sandy, Murray (1996) finds it living in muddy sediments in Lyme Bay and Alve & Nagy (1986) have found it in both coarse and fine-grained sediments in the Sandebukta branch of the Oslofjord. It also seems to tolerate a wide

variety of salinities ranging from 24 - 34.2 $^{0}/_{00}$ in Sandebukta and 29 - 31.5 $^{0}/_{00}$ in Syslakv'g, Norway (Austin & Sejrup, 1994). Though Alve (1990) believes that it reaches the lower levels of its salinity tolerance at 31.2 $^{0}/_{00}$, Austin & Sejrup (1994) report it from salinities of 29 $^{0}/_{00}$.

Alve & Nagy (1986) find that *E. scabrus* is tolerant of the high organic input and wood fibre content found in the polluted Sandebukta and suggest that it enjoys the reduced competition here. Conradsen (1993) and Conradsen *et al.* (1994) also find that it correlates positively with the organic content of the sediments in the Kattegat and Skaggerak. In the Drammensfjord, Norway, it is found in waters which are transitional between those which are brackish and those which are oxygen depleted suggesting that it is tolerant of poorly oxygenated conditions but still requires a certain level of oxygen to thrive. This species tolerance for low oxygen conditions is also proposed by de Stigter *et al.* (1998). It is also found in the seasonally stratified waters of Breidangen, Oslofjord (Alve & Nagy, 1990) and close to a front in the Kattegat-Skagerrak (Conradsen *et al.*, 1994). Lutze (1965) find *E. scabrus* in the inflowing waters of the Danish Straits and concluded from this that it was tolerant of variability in temperatures and salinities, but also currents. In addition, de Stigter *et al.* (1998) believe that *E. scabrus* is a non-specific feeder.

It is difficult to ascribe this species to a particular microhabitat because the absolute data suggests that it is largely epifaunal, though found deeper in sediments (see figure 4.25) while the relative data implies that it is infaunal (see table 4.2.5). Barmawidjaja *et al.* (1992) also found it increased in relative abundance with depth in the Adriatic, though this varied throughout the year, and de Stigter *et al.* (1998) also find it living infaunally in the southern Adriatic. Hohenegger *et al.* (1993) describe it as exclusively infaunal which is clearly not the situation in the Celtic Sea. Its 'tapered & cylindrical' form supports an infaunal habitat (Corliss, 1991; Corliss & Chen, 1985).

This species is possibly adapted to 'difficult' environments, rich in organic inputs and which may experience low levels of oxygen. *Eggerelloides scabrus* probably has a poorer tolerance to low oxygen conditions than some opportunists, but which is compensated for by an ability to withstand greater fluctuations in temperatures, salinities, currents and the nature of the food supply and this may explain its abundance along the entrance to the English Channel.

Gavelinopsis praegeri

The distribution of this species, when living, is completely different to when dead (figure 4.15). Living, it inhabits the mixed areas to the north and the fully stratified areas to the south, dead, it is most commonly found in the frontal-stratifed area. Either this species living distribution at other times of the year is entirely different from when sampled, or it is particularly easily redistributed by currents on death. The latter is more probable since there is no significant difference in the living and dead contributions and the low trochospiral shape of the *G. praegeri* test suggests an epifaunal perhaps

clinging habitat and it is easy to conceive of the ease with which a concave form might be entrained. As a consequence of the differences in the living and dead distributions the factor analyses produce completely different relationships for living and dead specimens. Living, *G. praegeri* is characteristic of factor 2 which is found in mixed waters (figure 6.1, b) and dead, in stratified waters (figure 6.2, b). Similarly, CCA of the living data shows that *G. praegeri*, like *C. lobatulus*, prefers gravel-rich sediments and the mixed waters of the north, while the same analysis of the dead data shows a relationship with skewness (figure 6.17 and 6.19). This supports the theory that the distribution of the dead is a function of reworking.

Gavelinopsis praegeri has a similar living distribution to *C. lobatulus* (compare figures 4.10 a and 4.15, a) and may prefer the same ecological conditions; high energy waters and coarser substrates. The reworking of *G. praegeri* after death demonstrates the importance of considering living assemblage data separately from the dead. Why this species should be removed so completely from its true habitat while *C. lobatulus*, also a clinging form and also often concave, remains in mixed waters is not certain but the buoyancy of the more inflated *G. praegeri* test may be responsible

Hyalinea balthica

Hyalinea balthica is under-represented in the living assemblages relative to the dead. Its distribution (figure 4.16) almost exactly coincides with that of stratified and frontal waters but the frontal position and the persistent mid-frontal eddy are better preserved in the dead data than the living. Since the living data is just a 'snapshot' in time it may be that this species was not in full production during the time of collection and this may also explain why it appears to be over-represented in the dead.

Hyalinea balthica is characteristic of dead factor 2 which is found in stratified waters, confirmed by the correlation of this factor with cooler waters and finer grain sizes. Qvale & van Weering (1985) find that *H. balthica* correlates with organic content of sediments, and Sen Gupta & Machain-Castillo (1993) find that this species is common in oxygen minimum zones, both characteristics which are advantageous to a species living in a stratified environment.

With regard to microhabitat, *H. balthica* was found living throughout the cores examined (see table 4.2.5) and its profile generally mirrored that of the density. Alve & Bernhard (1995) describe *H. balthica* as infaunal but while it certainly lives infaunally, it was not possible from the Celtic Sea data to determine its preferred habitat.

Hyalinea balthica lives in association with stratified waters. Though it is very likely from the abundance data of other bloom species, such as *S. fusiformis*, that the flux of organic matter and oxygen concentrations are variable across the frontal region, this species shows a steady increase into stratified waters and records the area of the persistent eddy where cross-frontal transfer of stratified

waters occurs. While it may tolerate low oxygen and prefer high organic flux, exactly what this species distribution tracks is unclear though it is almost certainly related to stratification.

Nonionella turgida

The distribution of *Nonionella turgida*, living and dead mirrors that of stratified and frontal waters and the area of the persistent eddy (figure 4.17). This species is the second most frequent living foram though it does not usually form more than a tenth of the assemblage at any site (see table 4.1.2). The good agreement between the distribution of the living and dead foraminifera suggests that this species is not easily reworked. The discrepancy between its contribution to the living and dead assemblages is either the result of it being in production at the time of collection or that it is very fragile and becomes destroyed after death. As *N. turgida* is so poorly represented in the dead assemblage it was removed from the data set before factor analysis and so does not form a part of the *H. balthica* assemblage (dead factor 2), which is associated with stratified waters, and where it surely belongs. This species is, however, considered characteristic of living factor 3, also found in stratified waters (figure 6.1, c). The abundance of this species in the dead assemblage was too low to include in a CCA but the same analysis of the living data places the optimum occurrence of this species in the relatively colder, deeper more southerly waters *i.e.* in association with stratification.

This data suggests that this species might be tolerant of the high carbon fluxes found under stratified waters yet Bandy *et al.* (1965) found that the pollution from the Hyperion sewage outfall, California, affected a *Nonionella* group unfavourably. These species were named as *N. scapha basispinata* and *N. miocenica stella* but showed a marked similarity to *C. auricula* and *N. turgida* respectively in an illustration. However, in support of the Celtic Sea data, Conradsen (1993) found *N. turgida* living in association with *B. marginata* in fine grained sediments with high organic carbon content.

Of all the species examined for microhabitat preferences *N. turgida*, is the most likely surface or near-surface dweller based on the absolute data (see figure 4.25). When considering relative abundances it consistently has its maximum occurrences just below the sediment surface yet Alve & Bernhard (1995) describe this species as 'infaunal' based on their mescosm experiment. However, Hohenegger *et al.* (1993) found *N. turgida* living in surficial sediments in the Gulf of Trieste and attributed this to the preference of *N. turgida* for diatoms; Barmawidjaja *et al.* (1992) also believe that it is predominantly epifaunal.

This species distribution resembles that of stratified waters, including the position of the Celtic Sea eddy. This may be a function of temperature but, more likely, it is related to organic carbon flux. Though this species is present in very low numbers in the dead assemblage, it is significant because of its strong affinity with stratified waters and because it does not seem to be reworked. This species demonstrates the importance of rarer species in core material, which should not always be thought of

as reworked. *Nonionella turgida* probably lives, for the most part, in near surface sediments though this might not have been predicted based on the habitat-morphotype assignments of Corliss (1991) and Corliss & Chen (1985).

Quinqueloculina seminulum

Concentrated on the east side of the study area when alive, dead *Q. seminulum* tests are found largely in the mixed and frontal regions (figure 4.18). Either this species is readily reworked or the living distribution at the time of collection was not typical of rest of the year. As the cut-off threshold used in factor analysis was so high, *Q. seminulum* was not analysed with the living data but it is characteristic of dead factor 1 which is found in most of the mixed and frontal waters excluding the far west and the entrance to Bristol Channel (figure 6.2, a). It is also characteristic of dead factor 4 which is found to the east. Canonical correspondance analysis relates maximal occurrences of dead *Q. seminulum* to warmer temperatures and shallower sites while the living are also found in shallow sites but with high levels of % sand (figure 6.17 and 6.19). If the dead distribution is related to reworking it is surprising that there is no correlation between the distribution and any of the grain size characteristics or classes. It is possible then, that this species generally enjoys a wider distribution, particularly in the mixed and frontal areas, and that water depth is not the main control.

Buzas (1993) describes *Q. seminulum* as an opportunist because in an *in situ* experiment in a shallow site, *Q. seminulum* was the first species to recolonise a site after disturbance. Murray (1991) describes it a phytodetrital feeder and, as a result, lives epifaunally being a phytodetrital feeder. This is confirmed by both the absolute and the relative abundances of this species in the Celtic Sea multicores (see figure 4.25 and table 4.2.5).

The ecological controls on *Q. seminulum* have not been identified by this study, possibly because the living distribution of this species was not typical at the time of collection. This species is probably predominantly epifaunal in agreement with the morphotype categories of Corliss (1991) and Corliss & Chen (1985).

Stainforthia fusiformis

By far the most abundant species in living assemblages, *S. fusiformis* is not nearly as well represented in the dead though it can form over 20 % of the dead assemblage at some sites. There are some differences between the distribution of living and dead tests (see figure 4.19) but the main features are the same; a heavy concentration of tests in the area of frontal waters and those waters transitional between frontal and stratified and an absence along the Bristol Channel and in the fully stratified waters to the south. *Stainforthia fusiformis* is characteristic of Living factor 1 which is strongly associated with frontal waters (figure 6.1, a). No environmental variable showed any correlation with

this assemblage.

The results of the CCA demonstrate that, when living, this species is found in the greatest abundances in fine grained, skewed sediments with low sand content (figure 6.17). Dead, it has an affinity for well sorted, skewed sediments and depth and has an optima at mid-depths (figure 6.19).
Many workers have reported this species from fine-grained sediments; Collison (1980), Conradsen (1993) and Murray (1983). Murray (1986) also records the observed discrepancy in abundance between living and dead specimens in Lyme Bay. However, *S. fusiformis* is most often observed living in association with high levels of organic matter *e.g.* Alve (1990), Alve (1994), Alve & Murray (1997) and Conradsen (1993). The association of *S. fusiformis* with muddy sediments may be a function of its affinity for organic matter since, as organic content increases, grains become finer (Cato, 1977). This would explain why *S. fusiformis* also occurs in sandy sediments (compare figures, 4.19 and 3.22, b).

Gooday (1993) found that species of Stainforthia (Fursenkoina) were opportunistic, able to exploit the high levels of phytodetritus produced during spring blooms on the Porcupine Abyssal Plain. Typical of such environmentally exceptional sites, the associated assemblages have low diversity and high dominances. This has also been observed of the Celtic Sea assemblages in which *S. fusiformis* dominates (see Appendix III).

A characteristic feature of opportunistic foraminifera is their small size and thin-walled tests, adaptations which mean that not much energy is required for reproduction and growth to reproductive size and allows them to respond quickly to triggering events. In support of this Duijnstee *et al.* (1998) found in a mesocosm experiment that *S. fusiformis* could reproduce at very small sizes when stressed. Alve (1994) also suggests that their small size may enable them to be easily transported from site to site, allowing them to develop pioneer populations. A tolerance of low oxygen conditions and even anoxia is often a feature of bloom responding foraminifera and has been recognised by several workers *e.g.* Alve, (1990) and Sen Gupta & Machain-Castillo (1993). To test this species resistance to anoxic events Bernhard & Alve (1986) incubated living specimens in nitrogen to test their survival and ATP response. This species was found to survive the simulated event well but did show some ATP damage, suggesting that it may survive by becoming dormant.

Like other facultative anaerobes, *S. fusiformis* contains special enzymes which allow it to survive without oxygen but its survival is probably also a function of its maintenance of chloroplasts. These have also been observed in Celtic Sea specimens. Chloroplasts are derived from ingested phytoplankton and Leutnegger (1984) proposes that foraminifera which maintain chloroplasts have evolved thin-walls to allow light penetration as photosynthesis is generally the function of symbionts in foraminifera. This probably not the function of the chloroplasts in S. *fusiformis* which often lives at depths below which light penetrates. Cedhagen (1991) found chloroplasts in individuals of *Nonionella labradoricum* living deep in the Norwegian trench and though McFarland & Loew (1983) have shown

that waves can focus flashes of high intensity light to great depths, Cedhagen believes that the chloroplasts are probably heterotrophic and receive nutrients from their host and in return produce vitamins and lipids. Bernhard & Alve (1996) suggest that the chloroplasts may be a source of food enabling *S. fusiformis* to survive anoxia.

Alve (1994) found mono-specific samples of *S. fusiformis* in Frierfjord, Norway, in waters polluted from paper mill waste which were thus, very organic, and which became stratified in the summer. Like some of the Celtic Sea specimens, many had a veneer of transparent mud-sized particles and Alve suggests that this acts as a barrier against harmful chemical compounds which may form in the anoxic microenvironment. *Stainforthia fusiformis* was also found in Drammensfjord (Alve, 1990) having recolonised sediments which had been anoxic and compounding the theory that this species is opportunistic.

Though it often dominates assemblages, *S. fusiformis*, is also found living in association with *B. marginata* (Conradsen, 1993; Murray, 1983) and *N. turgida* and *E. megallanicum* (Conradsen, 1993). An explanation for the living distribution (figure 4.19, a) can be devised based on the theory of frontal circulation cells since the areas in which this assemblage dominates are also those which, in theory, receive phytodetritus from above. That area, transitional between mixed and frontal waters, receives organic matter directly from the zone of convergence at the surface, while the area transitional between frontal and stratified receives matter from here but which has become entrained in the flows and delivered to the stratified side of the front. This same theory of circulation proposes that the intermediate area is one of divergence, swept free of detritus, and this seems to be reflected in the faunal data which shows a marked decrease in this area, not only for the *S. fusiformis* assemblage but also in the density of living foraminifera (see figure 4.3, a).

Alve (1994) believes that the elongate test of *S. fusiformis* allows it to move easily through the sediment to different microhabitats and this species has been found living deep in the multicores extracted from the Celtic Sea (see figure 3.25). While Alve (1990) found specimens of *S. fusiformis* down to 5 cm depth in unbioturbated sediments in Drammensfjord, demonstrating that it is able to use a transient habitat which is typical of opportunists (Grassle & Grassle, 1974), large numbers of *S. fusiformis* have been found at 9 cm depth in mc495 and probably living even deeper. When the relative abundances are considered this species is found to be a deep infaunal dweller (table 4.2.5). It was also observed that, according to the relative abundances, *S. fusiformis* and *B. marginata* always increase and decrease at different levels in the core. This confirms the findings of Bernhard & Alve (1986) who suggested that the two species tracked different oxygen levels (*B. marginata* a higher level than *S. fusiformis*).

Stainforthia fusiformis is an opportunistic foraminifera whose distribution is related to the high levels of organic matter, and possibly low levels of oxygen, found in the frontal region. The unusual changes in

this species living distribution across the frontal region may be a function of the theoretical circulation cells. These changes are smoothed out in the dead assemblage. Though the preservation potential of this species is quite low it is so abundant that some record does remain in the sediments. In the context of stratification *S. fusiformis* indicates the position of the seasonal front and Alve (1994) has used changing abundances of this species in a core as a bloom indicator. It is also predominantly infaunal in support of the morphotype models of Corliss (1991) and Corliss & Chen (1985).

Spiroplectammina wrightii and *Textularia bockii*

These two species have very similar distributions for both living and dead forms (see figures 4.20 and 4.21) and this together with the assertion of Murray (1979, a) that these species are not worth separating, argues that their ecological tolerances should be considered together. The counts for these species were summed together as '*Textilina*' for factor analysis. This group was characteristic of dead factor 1. Though this assemblage explained 58.85 % of the variance it could not be correlated with the measured environmental variables.

Canonical correspondance analysis of each species separately found associations for both species, when living, with warmer, coarser grained sites (figure 6.17). For the dead, *T. bockii* shows a correlation with sorting and depth and *S. wrightii* with depth and % sand (figure 6.19). The relationship with sorting probably indicates reworking and the differences between the living and dead distributions of both species suggests some measure of reworking, though this may be because their distributions are different at other times of the year. Both species are much better represented in dead assemblages than living but as *T. bockii* is known to be very robust, despite being an agglutinate, this is probably a function post-mortem enhancement.

Murray (1986) observed that *T. bockii* preferred living in shelly sand and Klitgaard-Kristensen & Sejrup (1996) have found it living in coarse-grained sediments and strong currents in the northern North Sea. Conradsen (1993) defined an assemblages of which it was characteristic along with *C. lobatulus* and *G. praegeri* and which correlates with coarser grain sizes - very similar to the composition of dead factor 1. That this species should be found living in coarser substrates is to be expected given its epiphytic life-strategy (Murray, 1991; Vilks & Deonarine, 1987). In contrast Hohenegger *et al.* (1993) believe that it is exclusively infaunal and the morphotype-habitat relations of Corliss (1991) and Corliss & Chen (1985) suggest that both *S. wrightii* and *T. bockii* are infaunal.

These species distributions, when living, are related to coarser sediments though other variables must also be influential since they do not thrive in the coarse substrates of the entrance to the Bristol Channel. Dead, they are not completely redistributed but that they experience some post-mortem transport is plausible given their epifaunal habitat. They are also very well represented in the dead assemblages and so it is important, for core studies that the ecological tolerances of these species are

properly understood.

7.2.2 General foraminiferal trends

In discussing the individual distributions of the most important species in the Celtic Sea, questions are repeatedly raised about whether it is the dead or the living assemblages which are most representative of the species distributions. However, the variables which relate to reworking, such as grain size, sorting and skewness, are available and so it should be possible to identify when reworking effects are important for a particular species, as was demonstrated for *G. praegeri*. Where there is no correlation between the distribution of a particular dead species and any of the reworking proxies, it is reasonable to speculate that that species living distribution is not typical of the rest of the year since the dead assemblage integrates tests produced over the annual cycle and a number of years. It is also very likely, given the large seasonal changes found in a tidally stratified setting, that some species were not in peak production at the time of collection, this being triggered by different environmental conditions.

Other living/dead differences are a function of production and preservation (Boltovsky, 1991; Boltovsky & Totah, 1992; Loubere *et al.*, 1993) and two contrasting examples of this are found in *S. fusiformis* and *T. bockii*. *Stainforthia fusiformis* is under-represented and *T. bockii* over-represented in the dead assemblages relative to the living (see figures 4.19 and 4.21). That *S. fusiformis* preserves at all is surprising, given the very fragile nature of its test, but it is preserved and this is probably the result of the vast number of tests produced by this species, by far the most abundant living in the area. In contrast *T. bockii*, as an agglutinate, probably has a much longer life-cycle (Kuhnt *et al.*, 1998) and thus, lower rate of production, yet is very abundant in the dead assemblage because of its resistance to destruction (Boltovsky & Totah, 1992).

A comparison of living and dead diversities, densities and the affinity between the two (figures 4.1 - 4.4) might initially suggest that the dead assemblages are unrepresentative of the living. In confirmation of this, while the highest living densities are found in the region of the front the dead are the result of the focusing of tests into the bathymetric basin of the south-west (figures 4.7 and 4.8). The highest living densities are often found in the region of the front where it is believed there is poor-oxygenation. This may be the result of low levels of predation by macro-fauna less tolerant of these conditions or the associated, high organic flux (Altenbach & Sarnthein, 1989). Surprisingly, the greatest live-dead affinities are found along the entrance to the Bristol channel and in the mixed areas to the north perhaps because conditions here are consistent throughout the year (figure 4.4). While the poor affinity between the living and dead assemblages of the south-west basin are probably related to the transport of tests from other areas, that found in the frontal region is probably the result of the destruction of the delicate tests that dominate the living assemblages in this area. However, an

examination of individual species distribution establishes that, for the majority of the most significant species, the ecological conditions of the area, particularly those for that half of year when stratification is in place, are faithfully recorded. This concurs with the findings of Sturrock & Murray (1981) who found the Celtic Sea sediments to consist of less reworked material than the western approaches to the English Channel. Considering the distributions individually also demonstrates that species, such as *S. fusiformis* and *N. turgida*, while constituting only a fraction of the dead assemblages, are in fact very significant indicators of frontal and stratified conditions respectively.

Competition is not generally considered important by many in the foram community (Murray, 1991). Increasingly, however, both predation and competition are considered when explaining foraminiferal distributions, particularly between microhabitats (*e.g.* Bernhard, 1992; de Stigter *et al.*, 1998) and in a mesocosm experiment Ernst *et al.* (1998) demonstrated that competitive forces do influence the distributions of some species.

The results of the factor analysis and the CCA provide different perspectives on the same data. Factor analysis, which is performed without consideration of the environmental variables, clusters those species which tend to occur together and then measures the variability in this assemblage's occurrence across the study area. Conceptually, this is very appealing because in foraminiferal palaeontology, ecological interpretations are made on the basis of assemblage composition rather than individual species occurrence. Though factor analysis performs what is intuitive, the identification of species groups, it does so in a quantitative way making the subsequent comparison with environmental variables more meaningful. In addition, a factor is much more likely to be correlated with an environmental gradient than any of the constituent species alone (Conradsen, 1993). The fault of Q-mode factor analysis is the same as that of other cluster techniques; it is designed to search for associations and so finds them whether they are real or not. Also the synergistic effects of environmental factors are not considered. The importance of a factor is, ultimately, a human judgement based on a general understanding of the species involved.

Canonical correspondance analysis, by comparing each species distribution over each environmental gradient and possible (linear) combination of gradients, examines the species-environment relationships in much greater detail. Again, because a correlation is identified by CCA does not mean it is real; the particular environmental variable may be acting as a proxy or partial proxy for the true controls and this is probably true in this study since so much of the species variance is unaccounted for. This kind of analysis is a useful compliment to factor analysis because it examines each species individually and can help explain non-interactive inter-species associations (CCA does not consider inter-species interactions).

Factor analysis identifies a number of assemblages which could, potentially, be used in the

reconstruction of palaeostratification. The results of this analysis have been honed using the species living and dead distributions, the results of the CCA and information from the literature, as discussed earlier in this chapter. For example, dead *G. praegeri* is placed in that assemblage which is found in stratified waters (dead factor 2). However, all other information indicates that this species actually lives in mixed waters and so it would be unsafe to use this species in a palaeostratification context. The identified assemblages are outlined below.

MIXED WATER ASSEMBLAGE

The mixed and mixed-frontal sites are typically dominated by dead tests of *C. lobatulus*, *Textilina* group, *A. beccarii* and *Q. seminulum*. Of these only *C. lobatulus* is typical of a living mixed assemblage which correlates with coarser sediments. This suggests that the remaining species, despite their known preference for mixed-type conditions, are largely the result of reworking.

STRATIFIED WATER ASSEMBLAGE

Stratified and stratified-frontal waters are characterised by *B. marginata*, *H. balthica*, *Bolivina* group, *A. glomeratum* and *N. turgida*. *Gavelinopsis praegeri*, factor analysis suggests, should also be included in this group. However, as mentioned above, its living distribution shows that this species actually lives in mixed waters (Fig. 7, k and l) so its inclusion in this group is probably a function of reworking. *Nonionella turgida* and *A. glomeratum* are also characteristic, despite their uncommoness in the dead, because they are so firmly related to stratification. The area beneath which a habitual eddy is formed (Fig. 9, b) is also dominated by this assemblage so the regular incursion of stratified waters into the predominantly mixed area is being faithfully recorded by the foraminifera. The correlation of the living assemblage with temperature, salinity, Sindex and longitude show very clearly that this assemblage is directly related to stratification, while the relationship of the dead to temperature, % clay (or silt) and mean grain size suggest that some reworking is taking place but not so much that the relationship with stratification is lost.

FRONTAL ASSEMBLAGE

Stainforthia fusiformis and *Reophax* group, it is inferred from the factor analysis, living in direct association with the front. However, this assemblage was not identified by factor analysis on the dead data since both *Reophax group* and *S. fusiformis* do not preserve well, the former being very rare in the dead assemblage and the latter under-represented. *Stainforthia fusiformis* is, nonetheless, present in reasonable numbers and does have potential as a palaeo-frontal indicator since Alve (1994) uses the changing abundance of this species as a bloom proxy in cores taken from Frierfjord, Norway. However, direct explanations for these species association with the front were not identified by this

study though it is very clear from the poor correlations of several of the assemblages derived from factor analysis with the measured environmental variables and from the comparison of the variability explain by unconstrained relative to constrained correspondance analysis that the main environmental controls have not been recorded (ter Braak *et al.*, 1995).

It is probable that oxygen concentration and food supply are in fact the most significant influences on this and, possibly, the other assemblages because, as Nees (1998) acknowledges, most foraminiferal workers now believe that these are the main controls on benthic foraminiferal distribution. Caralp (1989) and Nees (1998) also suggests that the lability and nature of this food supply is significant; Caralp found that while *Bulimina exilis* had an affinity for undegradaded organic matter, *Melonis barleeanum* preferred its food in a more altered form. Nees (1998) identified three main food categories: fluffy aggregate material which is easy to digest and is produced during a bloom, faecal pellets which are a much poorer quality food and marine snow or particulate organic matter (POM) which is rained constantly but in small amounts. It is reasonable to speculate, given the variability in biology across the front, that there is a range of food-types available. The mixed waters are turbulent and well-oxygenated and are likely to consist largely of POM with a strong lateral component. It is probable that the area of the front may be less well ventilated and comprises lots of phytodetritral material since bloom conditions are found here throughout the summer. The fully stratified region will, at least for the latter half of the summer, be poorly oxygenated and have a steady flux of POM. However, where the thermocline is shallow dinoflagellates will thrive and so some stratified areas will also have phytodetrital inputs for at least part of the summer. During the winter months conditions across the area should be as for the mixed waters and during the spring bloom, frontal.

Though oxygen and carbon flux are certainly the most significant controls, measurements of other environmental characteristics can be useful indirect proxies. For example, sandy and gravely areas tend to be well oxygenated and muddy areas poorly so. Organic flux is sometimes recorded in the organic carbon content of the sediments though, like many shelf regions, this is not the case Celtic Sea (see above). Direct measurements are obviously more desirable but oxygen content measurements of the bottom waters were unsuccessful in this study and there are great difficulties in measuring the flux and nature of organic matter in a shelf setting; Puskaric (1991) experimented with sediment traps in the northern Adriatic but found that more sediment was collected in winter than summer, largely due to resuspension.

The nature of the organic matter reaching benthic foraminifera on the sea floor can be surmised from literature concerning phytoplankton and zooplankton in the region of a front but the decoupling of the surface and bottom waters in a stratified setting and the strong lateral transports found on the continental shelf complicate matters. Along-front transport and cross-frontal circulation cells have been invoked (*e.g.* James, 1978) to satisfy the physical laws controlling frontal dynamics but are

difficult to prove. Apparently, however, the effects of the circulation cells have been recorded by the *S. fusiformis-Reophax* group assemblage which dominate in the mixed-frontal and the stratified-frontal transitional regions. These regions are separated by a zone of low occurrence. This is exactly what would have been predicted for organic flux by the cross-frontal circulation model. Perhaps even more significantly, the living density data (Fig. 6, a) shows a very similar pattern though this is largely driven by *S. fusiformis*.

EASTERN ASSEMBLAGE

An assemblage is also defined by factor analysis for the eastern part of the main study area and the Bristol Channel. This comprises *B. gibba, E. excavatum* forma *selseyensis* and *E. scabrus*. The distribution of all three are all related to % sand content by the CCA (see below). *Quinqueloculina seminulum* is also placed in this group and, as previously described, has an affinity for sandier substrates. However, this assemblage does not always occur where there are sandier substrates and it did not correlate with % sand. *Elphidium excavatum* forma *selseyensis* and *E. scabrus*, in particular, are noted for their tolerance of a wide range of environmental conditions. Though measurements made in this study do not confirm it since they were simply taken at a point in time, the Bristol Channel area suffers from great fluctuations in tidal currents and probably other, associated environmental variables. This may be the true influence on this assemblage.

7.2.3 Microhabitats

Bernhard & Alve (1996) believe that infaunal foraminifera track a critical oxygen level but Bernhard (1992), Jorissen *et al.* (1995) and Linke & Lutze (1993) consider that foraminiferal microhabitats are also a function of downward organic flux. Jorissen *et al.* (1995) suggest that under oligotrophic conditions, microhabitat depth is controlled by the availability of metabolizable food particles and that under eutrophic conditions food is no longer the primary control but oxygen. They also propose that when food availability is limited the anaerobic degradation of organic matter around the redox-front in the sediment may supply an additional food source and explain the subsurface maxima observed in the literature (*e.g.* Alve & Bernhard, 1995). In addition to this, Bernhard (1992), Gooday (1986), Mackensen & Douglas (1989) and de Stigter *et al.* (1998) suggest that competition and predation play a role in forcing foraminifera to inhabit subsurface levels.

Like Barmawidjaja *et al.* (1992) no absolute distinction between those species which are epifaunal and those which are infaunal, could be made for the Celtic Sea assemblages. This may, in part, be related to the bioturbation of the sediments and burrows were observed in several of the cores at the time of collection. The downcore variation in $\delta^{13}C$ of the porewater DIC also supports this as will be discussed below. However, some general patterns of vertical distribution were observed. Predominantly epifaunal

taxa include *E. excavatum* forma *selseyensis*, *N. turgida*, *Q. seminulum* and *A. glomeratum*. The most common reason for such a habitat is suspension feeding (Alexander & DeLaca, 1987; Altenbach *et al.*, 1993; Linke, 1992 and Linke & Lutze, 1993) and these species are probably living here because of their food requirements; *N. turgida* prefers diatoms and *Q. seminulum* and *A. glomeratum* are phytodetrital feeders. Ernst *et al.* (1998) also found that *N. turgida* is a good competitor, an advantage in the epifaunal environment which is the most heavily populated of the sediment levels. Predominantly infaunal species include *B. marginata*, *E. scabrus* and the deepest, *S. fusiformis*. All these species have been observed to tolerate low oxygen conditions (anoxia in the case of *S. fusiformis*) and this may explain their relative positions within the sediment. In addition Ernst *et al.* (1998) found that *S. fusiformis* did not like competition and this may explain its adaptation to the deepest environment.

The morphology-habitat types of Corliss (1991) and Corliss & Chen (1988) did not always reflect the microhabitat preferences of many of the species studied *e.g. Elphidium excavatum* forma *selseyensis*. However, the predominance of infaunal forms in the multicores was in keeping with the proposal that stratified waters experience high levels of organic flux. Of all the forms, those which were 'tapered and cylindrical' seemed to dominate, especially deeper in the sediments (figure 4.26). The exception was mc296. The unusually high dominance and low diversity found at this site is usually characteristic of extreme ecological conditions (Murray, 1971) but these were not observed.

7.3 Isotopic analyses

7.3.1 Individual species

Ammonia beccarii

Of all the species analysed this is the most promising as an equilibrium, or near equilibrium, precipitator of oxygen isotopes. Assuming that this is true, then it seems that in stratified areas this species is recording conditions found at the time of collection and a little later (warmer) while in mixed conditions it is earlier, cooler, perhaps spring temperatures which are being recorded. If the carbon isotopes are also in equilibrium or have a consistent offset, then a comparison of the living and dead *A. beccarii* (figure 5.6) suggests that this species thrives in more oxygenated or less productive conditions. These are not conditions associated with the autumn or spring blooms and since it was not possible to demonstrate equilibrium precipitation in this study, *A. beccarii* may not accurately record the carbon isotopes. The considerable consistency in $\delta^{13}C$ values of *A. beccarii* calcite both between sites and in specimens from the same multicore (figures 5.7 and 5.13) suggests vital effects. The relatively negative carbon value of this species compared to *Q. seminulum* and *C. lobatulus* could be interpreted to mean that this species reproduces/grows at depth within the sediment (figure 5.7) and this is in agreement with Murray (1991) and the results of the down-core foraminiferal study. The clear

relationship between living and dead for both oxygen and carbon suggests reworking is not important for this species confirming the findings in the ecological part of this study.

Quinqueloculina seminulum

The dead *Q. seminulum* derived from mixed sites are more representative of the living than those from frontal or stratified areas (figure 5.5). This maybe a function of reworking since, as a robust and epifaunal species, groups of dead *Q. seminulum* might be expected to include some relict species which are not readily distinguishable from the *in situ* population. This species probably records the ambient temperatures since it has a very narrow range of disequilibria for the living when allowance is made for T8S08 which is derived from the Bristol Channel, but with an offset or vital effect of around +2 ^{0}C or -0.5 $^{0}/_{00}$ (figure 5.7). This dispersion is much greater for the dead as might be expected after reworking. *Quinqueloculina seminulum* appears to record the late summer temperatures at all sites with the occasional outlying, possibly reworked, value (figure 5.11). Assuming that this species records carbon ratios in equilibrium, or with a consistent offset, the data implies that it reproduces/precipitates at a time of greater productivity, lower oxygenation or lower in the sediment. However, since this species is regarded as epifaunal (Murray, 1991) and records the least negative carbon values in the multicores (figure 5.14) it is probably not a function of depth in the sediment. Reduced oxygenation and higher carbon flux are also conditions to be expected during the autumn bloom.

Cibicides lobatulus

Some of *Cibicides lobatulus* specimens taken show reasonable agreement between living and dead oxygen ratios while others show no relationship at all (figure 5.5). This may indicate reworking in these areas particularly as this species is known as a surface dweller (Murray, 1991) but may it may be a result of the size difference between living and dead specimens (the living tended to be a lot smaller than dead). Since the spread of oxygen disequilibria of the living specimens is quite narrow, except for one measurement (figure 5.7), it is possible that this species may record ambient temperatures but with large offset. Though the wide range of oxygen values produced by the dead tests suggest reworking, the reconstructed temperatures suggest that this species precipitates/grows in midsummer, though there are large outliers (figure 5.11). The range of carbon isotopic values (living and dead) is very large and suggest that this species does not accurately reflect the isotopic composition of the water with respect to carbon or if it does, that is subject to the large fluxes caused by movement of the fluff layer. However, many of the specimens used in this analysis were very small and it may be that the final samples were actually composed of other species of *Cibicides*.

Bulimina marginata

Bulimina marginata does not show good agreement between the living and dead for oxygen or carbon stable isotopes (figures 5.5 and 5.6) which may indicate reworking. This species also has quite a narrow range in oxygen isotopic disequilibria of living specimens bar a single measurement (figure 5.7) and may record ambient temperatures with a positive offset. The oxygen values are also tightly clustered for the dead suggesting that very particular conditions trigger precipitation/production. From figure 5.11 this would seem to happen in late summer. The carbon isotopic values are much more widely spread possibly because this species is infaunal as reported in the literature *e.g.* Alve & Bernhard, 1995.

Bulimina gibba

It is clear from the large discrepancies between the living and dead assemblages (figures 5.5 and 5.6) and from the very large range of disequilibria and values for oxygen and carbon respectively (figure 5.7) that this species does not precipitate in equilibrium.

Nonionella turgida

It also seems unlikely that *N. turgida* precipitates in oxygen equilibrium given the wide range of disequilibria observed in the multicores (figure 5.13) and though the *carbon* isotopic values fall into a reasonably consistent range, they are very negative for what is believed to be an epifaunal species.

7.3.2 General comments

The isotopic measurements on surface sample foraminifera suggest that almost all the species from each of the sites studied, if equilibrium precipitation is presumed, are recording temperatures from a warmer time of year *i.e.* around the time of the autumn bloom. Given that the spring bloom is regarded as the more significant event, this seems surprising. Possibly, the foraminifera are too depleted after the winter, in terms of general numbers and their own metabolisms, to respond significantly to the spring bloom, but are healthier and ready to respond after a summer of feeding. However, this does not marry well with the idea that many of the Celtic Sea species are opportunists.

Many of the issues raised by the isotopic results can only be resolved through a greater understanding of foraminiferal ecology, growth, reproduction and life-strategy and how these vary throughout the year. Different foraminiferal species may living for different periods of time and reproduce at different rates. Kuhnt (1998) found that agglutinates could living for several years and Hemleben & Kitazato (1995) found that deep-sea calcareous forms could living for up to five years in a laboratory setting.

However, the species observed were from the deep-sea where conditions are relatively consistent throughout the year. It is probable that in the seasonally variable shelf-sea setting, particularly where stratification occurs, the foraminiferal population should consist of more opportunistic species which, given what is known to be generally true of the opportunistic life strategy, are likely to living for shorter periods. For example, Duijnstee *et al.* (1998) found that the reproductive cycle in *S. fusiformis* was just two weeks long in stressed conditions.

The issue, in the context of isotopes, is whether it is productivity or precipitation, or a combination of both, which determines the final isotopic value measured on a particular specimen. If it is production then it must be assumed that the majority of the test is developed in a very short period of time and that the added chambers do not alter the final value too much. If precipitation then the value must combine calcite precipitated at different times of the year, though probably triggered by certain conditions. The final result is most likely to be a combination of both. It is also worth considering that the latest-formed chambers will be the most significant because they tend to be thicker and larger and, thus contain more calcite.

The relative contributions made by new tests versus the growth of old is also important when using foraminiferal calcite to infer the ecological preferences of a species because as Nees (1998) points out, foraminifera require optimum conditions to reproduce but only good conditions to grow. In addition, it is probable that when optimum conditions occur a species is much more likely to invest energy in reproduction than in growth.

Given the erratic pore water $\delta^{13}C$ profiles (figure 5.12) it is likely that burrowing is very influential in these sediments and may explain why the foraminifera are able to living so deeply in what is assumed to be low oxygen conditions. It may also explain why most species, even *Q. seminulum*, which is regarded as epifaunal (Corliss, 1991; Corliss & Chen, 1988 and Murray, 1991) are found living deeper in the sediments, since Meyers *et al.* (1988) suggest that some, otherwise epifaunal or shallow-dwelling organisms, can living deeper in the sediment if it is aerated by burrows. Assuming that the intrusion of these burrows are indicated by the reversals in the pore water profiles, it is surprising that the species numbers do not increase concomitantly (figure 5.12).

There is almost no change in the $\delta^{13}C$ foraminiferal calcite downcore but there is great consistency in offset between the different species (see figure 5.12). This is useful information on individual species effects but can mean just two things in terms of the 'microhabitat effect'; that it is not important for the species measured or that each species reproduced/grew at the same level or in the same oxygen/carbon conditions and then migrated to its position in the sediment column. Some species of foraminifera have been observed to migrate within sediments at up to 10 mm per day (Bornmalm *et al.*, 1997) so movement is a possibility and the within sediment reproduction of otherwise epifaunal

forms has been proposed (Murray, 1991) perhaps to avoid predation. The consistent offsets in $\delta^{13}C$ may mean either that reproduction took place at different depths or that they are a species effect. The proposal that all the specimens examined were produced at the same time is not too far-fetched if the foraminiferal life-cycles of these species are quite short and the reproduction or growth was triggered at the same time.

Chapter 8 Conclusions

8.1 The use of assemblages in palaeo-stratification studies

Many of the faunal changes found in the study area are related to the effects of stratification. Given the very large contrasts in sediment type and water conditions found across a tidal front, this was not altogether unexpected. However, it is probable that oxygen concentration and food supply are the true controls on species distribution rather than the environmental characteristics measured.

Four main assemblages have been identified for the study area. The aspects of those assemblages which have potential for use in a palaeostratification context are outlined below:

Frontal Assemblage This assemblage comprises the most abundant living species in the area, *S. fusiformis*, which, as an opportunistic, facultative, anaerobe is well-suited to the bloom-like conditions which exist in the region of a front. The majority of the *S. fusiformis* tests are subject to post-mortem destruction or removal, but this species is still a significant part of the dead and thus, fossil record. However, it is redistributed after death and much of the interesting detail of the living distribution is lost.

Mixed Assemblage This assemblage is characterized by species which prefer coarser sediments such as *C. lobatulus*, *T. bockii*, *S. wrightii*, *A. beccarii* and *Q. seminulum*. These species are not directly associated with mixed waters but rather the high energy conditions found here. Most prefer an epifaunal habitat and this combined with the strong currents suggests that reworking may be significant. However, that dead assemblage constitutes robust, easily reworked, larger foraminiferal tests is indicative of high energy waters in itself.

Stratified Assemblage The stratified assemblage includes *B. marginata*, *H. balthica*, *A. glomeratum* and *N. turgida*. Of these *B. marginata* and *H. balthica* are over-represented in the dead and *A. glomeratum* and *N. turgida* are underrepresented and this must have a bearing on their appearance in the fossil record. All of these species, excepting, *N. turgida*, are known to tolerate low-oxygen conditions though this species has been reported from sediments with high organic carbon content (Conradsen, 1993).

Eastern Assemblage The faunal contrasts observed for the main study area did not hold true for the entrance to the Bristol channel where an entirely different assemblage of foraminifera were found. This includes species such as *B. gibba*, *E. excavatum* forma *selseyensis* and *E. scabrus* which were all individually correlated to sandier substrates by the CCA. However, the group as a whole showed no such correlation and these species have often been described as tolerant of a wide range of environmental

conditions so this is unlikely to be the true control. As a result of the discrete and instant nature of the environmental measurements made in this study it was not possible to confirm that the Bristol Channel constitutes an area of very variable environmental conditions, though this is very likely given the fluctuating nature of the tidal currents here. This east/west contrast can not be explained in terms of stratification and this confirms that influences beyond those considered in this study, must be at play.

This study also produces some interesting foraminiferal evidence for the mechanisms which deliver nutrients to the frontal region. The cross-frontal transfer of nutrients is supported by the occurrence of stratifed-type foraminifera in both the living and dead assemblages of the seabed underlying the region of the recurring eddy. If these foraminifera are truly associated with stratified waters then this suggests that similar conditions must exist in the area long enough to support these populations.

The second mechanism, that of surface converging circulation cells is also apparently recorded. The lowermost circulation cell (see figure 1.2) causes an area of divergence separating those areas on the bed where detritus is delivered; either by direct rain on the mixed side of this zone, or by entrainment into the circulation cells and delivery to the area on the stratified side of this zone. This exact scenario is captured by the foraminiferal population which is very abundant in the two receptive areas and very spartan in the zone between.

Finally, illustrated by the distributions of *N. turgida* and *S. fusiformis*, is the significance of rarer specimens in the fossil record which may have been destroyed *in situ* rather than have been reworked.

The results of this study support the proposal of Austin & Scourse (1997) that the change from coarse-grained *C. lobatulus* dominated to fine-grained, *B. marginata* dominated assemblages in a core taken from the Celtic Deep records the development of stratification in the area in the early Holocene. Since these species are known to have affinities with the substrate types in which they were found, and as grain size tends to increase with water depth, it is also possible, based on the faunal analyses alone, that the record is simply one of the transition from shallow to deeper waters. The results from this study suggest that if the > 63 μm fraction was examined rather than the > 250 μm, species such as *S. fusiformis* should have been recorded. This species is almost certainly a bloom responder and it has been used as such in other palaeo-studies (Alve, 1990). Its occurrence would demonstrate that there was a concomitant change in oxygen and carbon flux with rising sea levels, almost certainly related to the development of stratification.

8.2 The use of foraminifera and stable oxygen isotope measurements of foraminifera as palaeotemperature/palaeostratification proxies

One of the main objectives of this study was to investigate changes in the stable oxygen isotope content of living formaniferal tests across the Celtic Sea front and to test the reliability of this as a tool for downcore palaeotemperature, and hence, stratification assessment. Of the species examined it is expected that *Q. seminulum* and *A. beccarii* would be the most useful in a palaeotemperature or palaeostratification study of the Celtic Sea because both appear to precipitate oxygen isotopes in equilibrium with the surrounding water, though *Q. seminulum* does so with an offset. It is possible that they reflect something of ambient carbon isotopic composition since shallow, infaunal *A. beccarii* precipitates relatively negative carbon ratios compared to epifaunal *Q. seminulum.* However, no evidence could be found to support the existence of the 'microhabitat effect'. Both these species have the additional advantage of being distributed across both mixed and frontal regions.

Austin & Scourse (1997) made the assumption that while *A. beccarii* recorded the pore water isotopic composition, *Q. seminulum* recorded that of the sediment surface. However, though this study confirms that *A. beccarii* is consistently negatively offset from *Q. seminulum*, an association of these values with pore and bottom waters could not be demonstrated. They also suggested that these species record water temperatures from different times of the year; in the 'mixed-water' part of the core *A. beccarii* records colder temperatures than *Q. seminulum*, but as stratification develops the recorded temperatures begin to converge. This is entirely in keeping with the results of this study since in mixed waters *A. beccarii* records temperatures from a cold time of year, possibly spring, while in stratified areas it records warmer autumn temperatures but *Q. seminulum* records temperatures from the warmest time of year regardless of which area it lives in.

Of the remaining species, only *B. marginata* seems a possible candidate for equilibrium oxygen (but not carbon) stable isotopic precipitation. *Cibicides lobatulus, B. gibba* and *N. turgida* do not precipitate in oxygen or carbon equilibrium.

8.3 Recommendations for future work

The most serious problem encountered in this study was the lack of oxygen and food supply data. Since these variables are almost certainly the main controls on species distribution any future work on species-stratification association should devise methods of measuring them. Unfortunately as Puskaric (1991) demonstrates, it is exceptionally difficult to measure carbon flux in a shelf setting but there are a range of techniques available for the measurement of oxygen content. The measurement of oxygen levels and organic carbon content through the multicores would also have helped resolve the question of species microhabitat Jorissen *et al.* (1995).

The ecological and isotopic stories inferred from this data are complicated by many unknowns; the time of year for which a species precipitates its test and/or reproduces and whether the distributions found at the time of collection were actually typical. The only possible way to resolve these questions is too examine the assemblage composition, foraminiferal size and isotopic changes through an entire seasonal cycle.

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FIGURES AND ILLUSTRATIONS

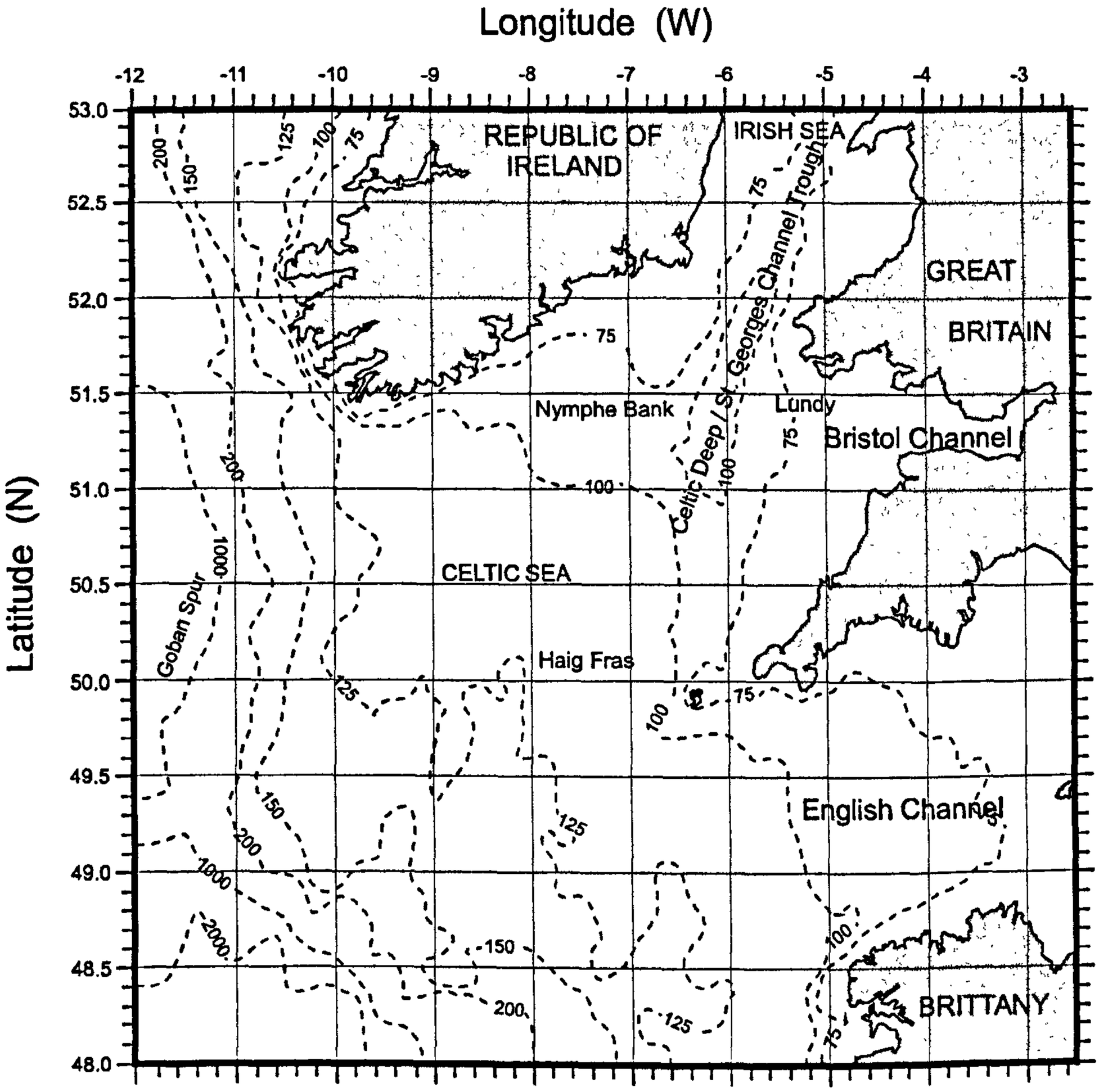


Figure 1.1 Location map of the Celtic Sea study area

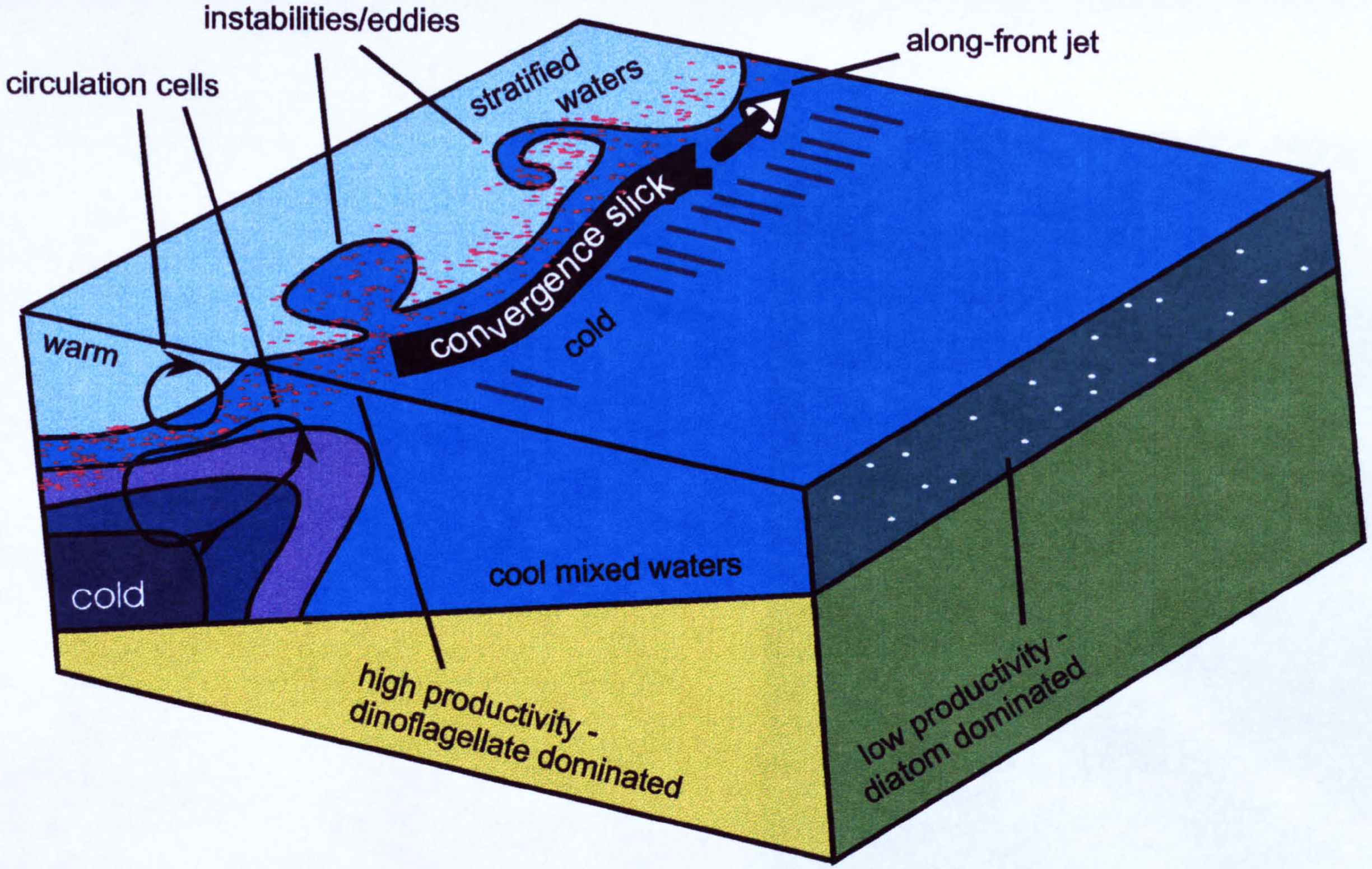


Figure 1.2 Idealised depiction of a tidal front

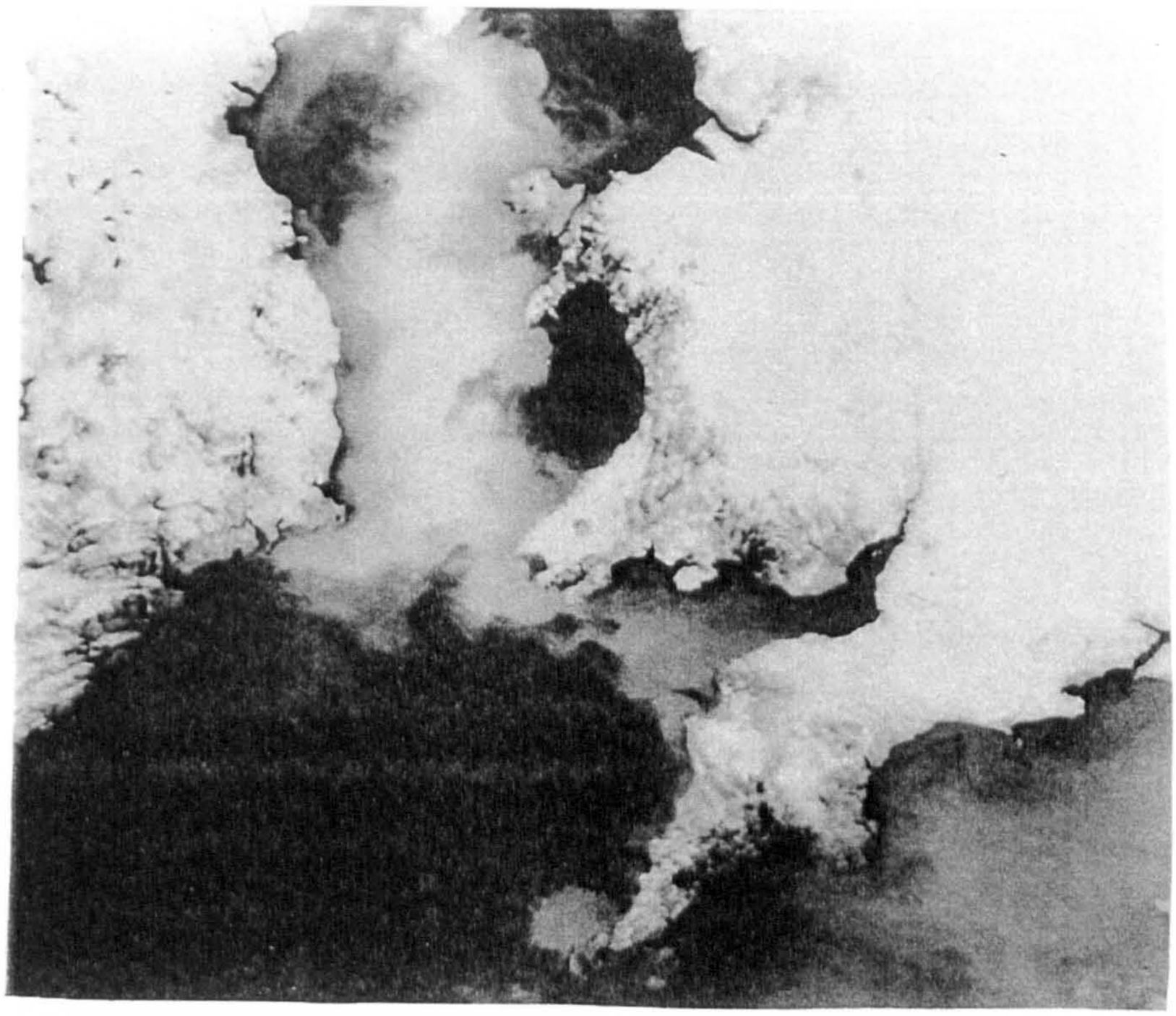


Figure 1.3 AVRHH (NOAA 14) Infra-red satellite image of the Celtic Sea front taken on the 27/6/95. Grey scales represent changes in temperature with the darkest shades being the warmest

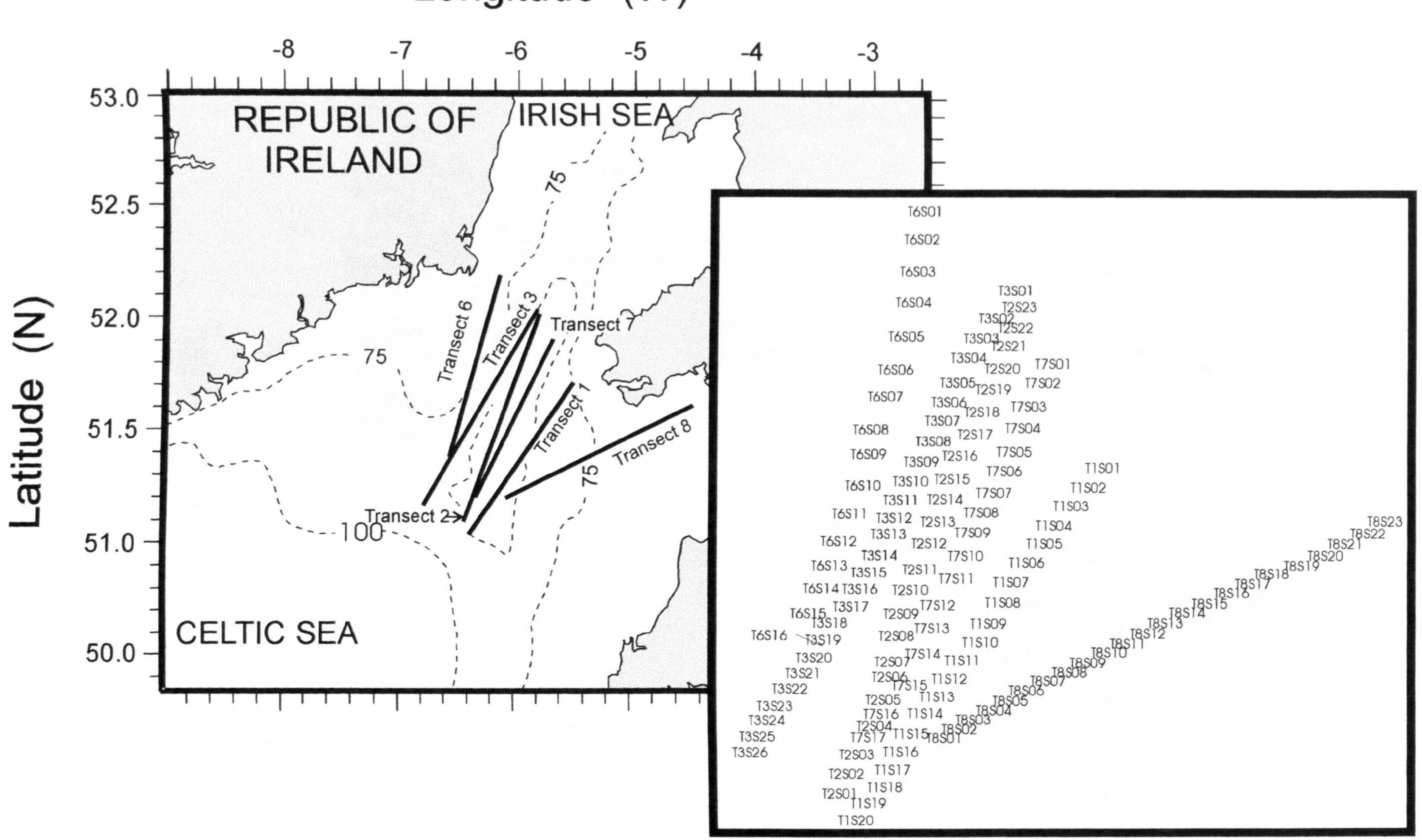


Figure 2.1 Location of the surface and multicore stations

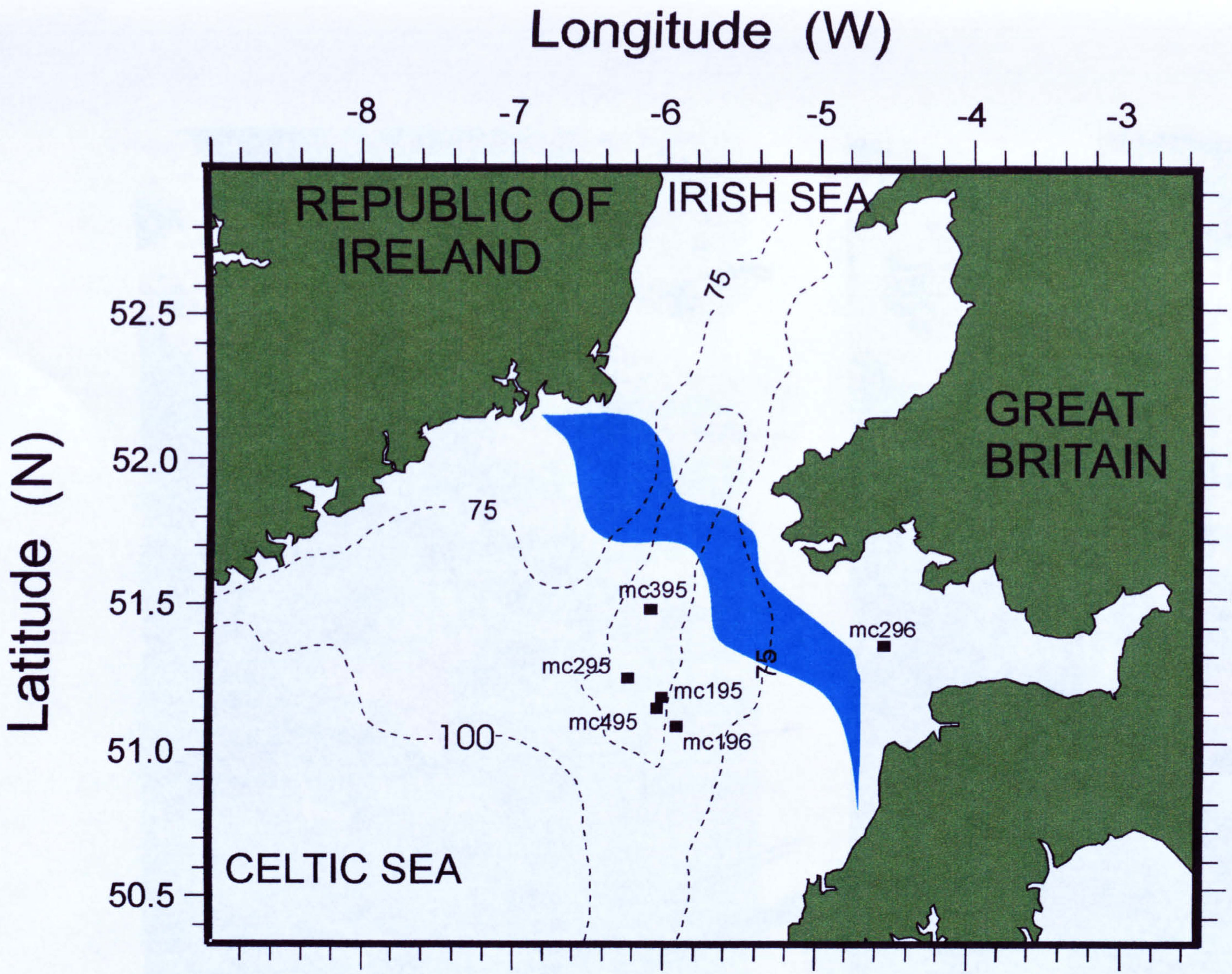
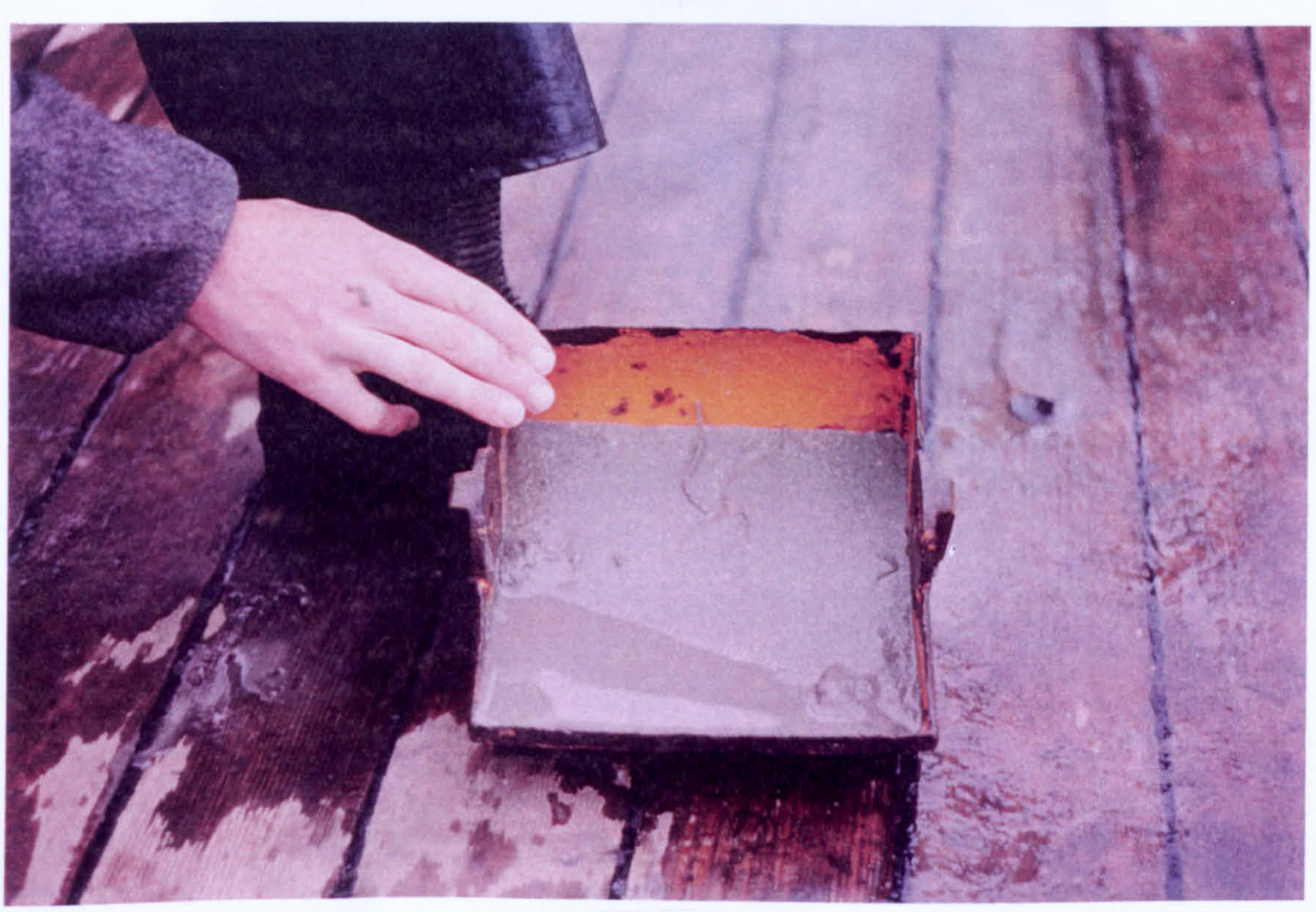


Figure 2.2 Location of the multicore stations and the Celtic Sea front

Figure 2.3 The Neil Brown CTD used to measure conductivity, temperature and depth of the water column

(a)



(b)

Figure 2.4 The shipek grab sampler (a) deployment off the back of the R.V. Prince Madog (b) fine-grained sediment typical of stratified waters

Figure 2.5 The multicorer system (Midicorer Mark 1 - 400) used to collect subsurficial sediments

2.6 Specially built frame designed to hold multicore tubes and extrude sediments

at < cm intervals

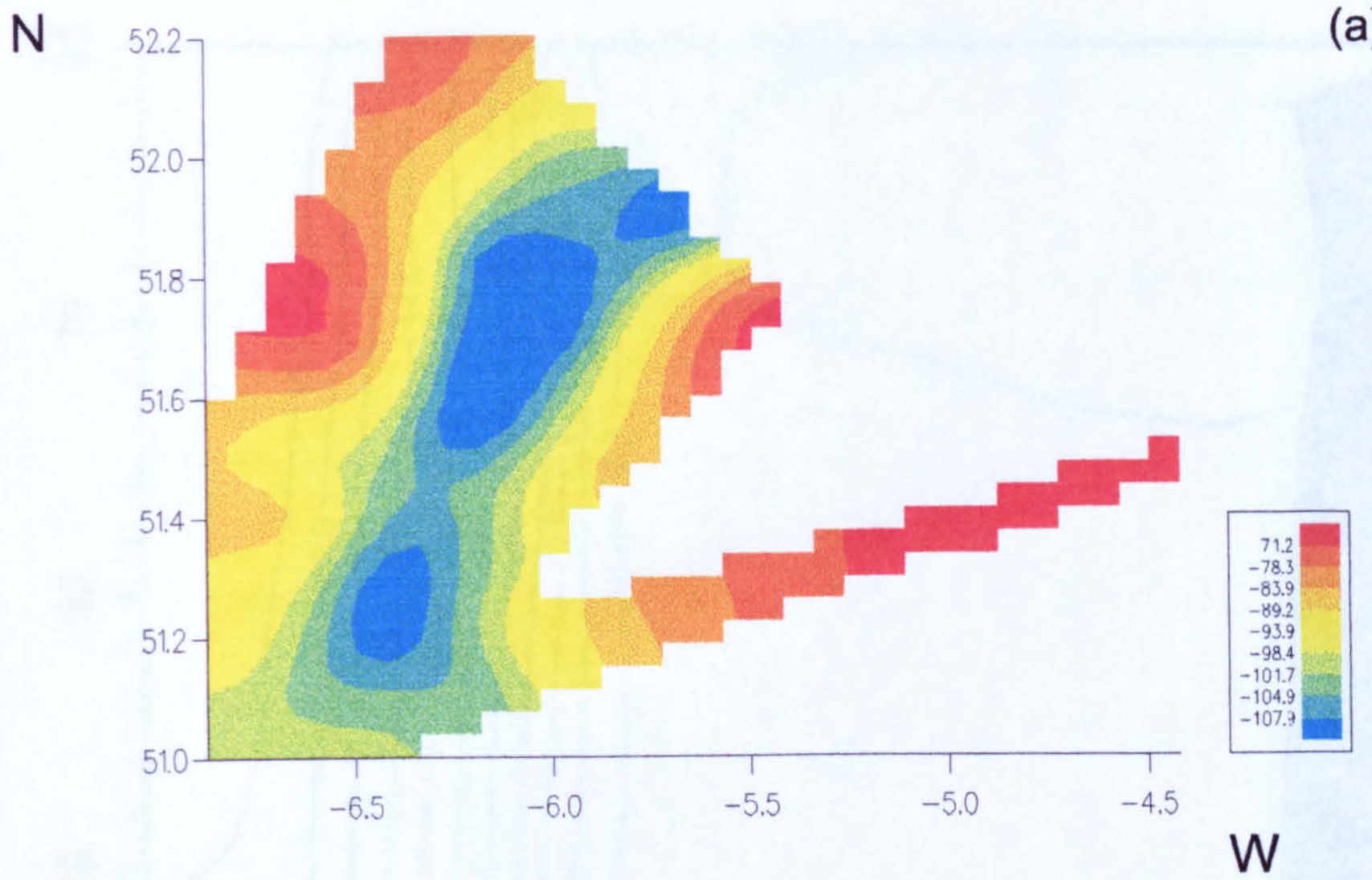


Figure 3.1 The bathymetry of the study area
in metres (a) 2D (b) 3D

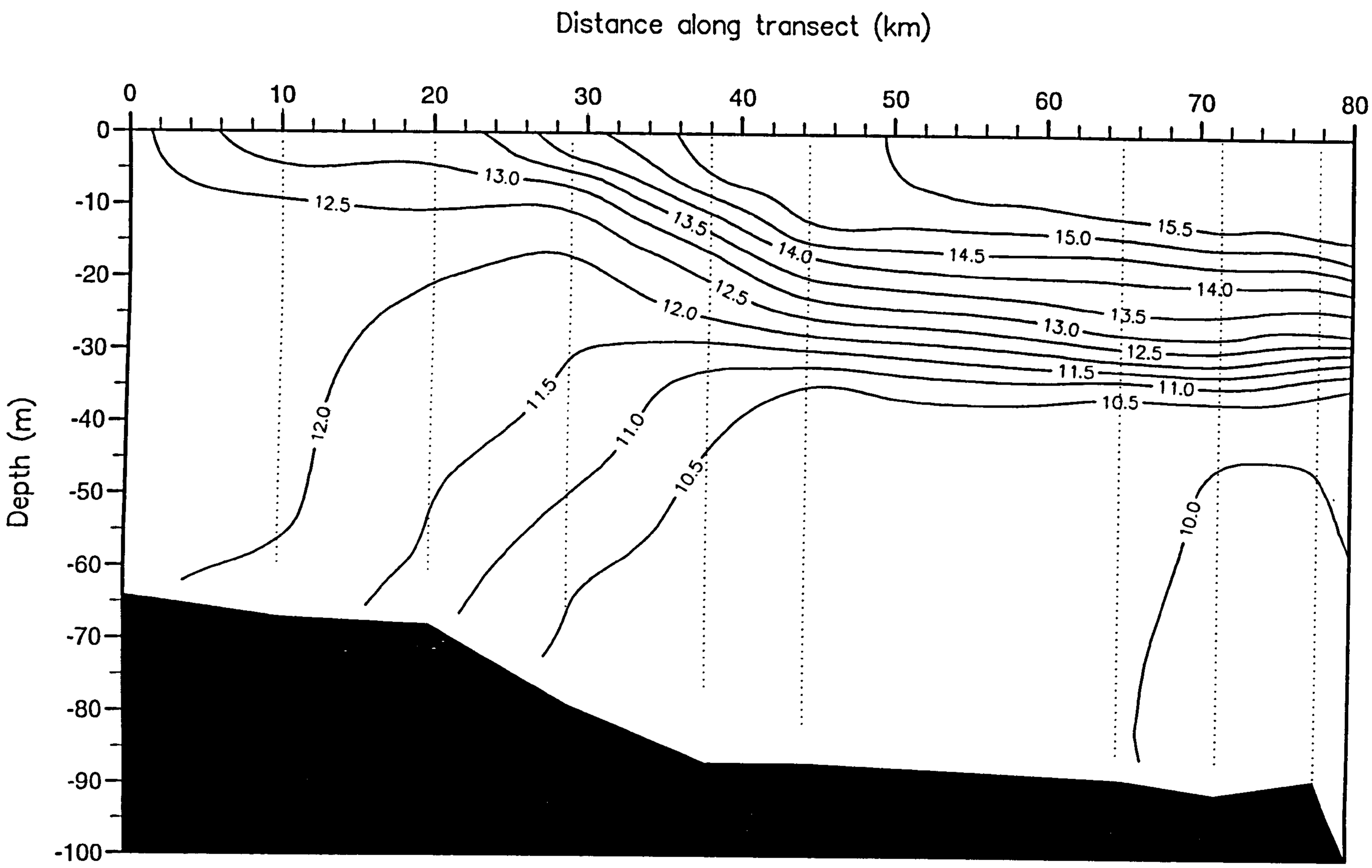


Figure 3.2 Temperature profile for transect 1, 1995

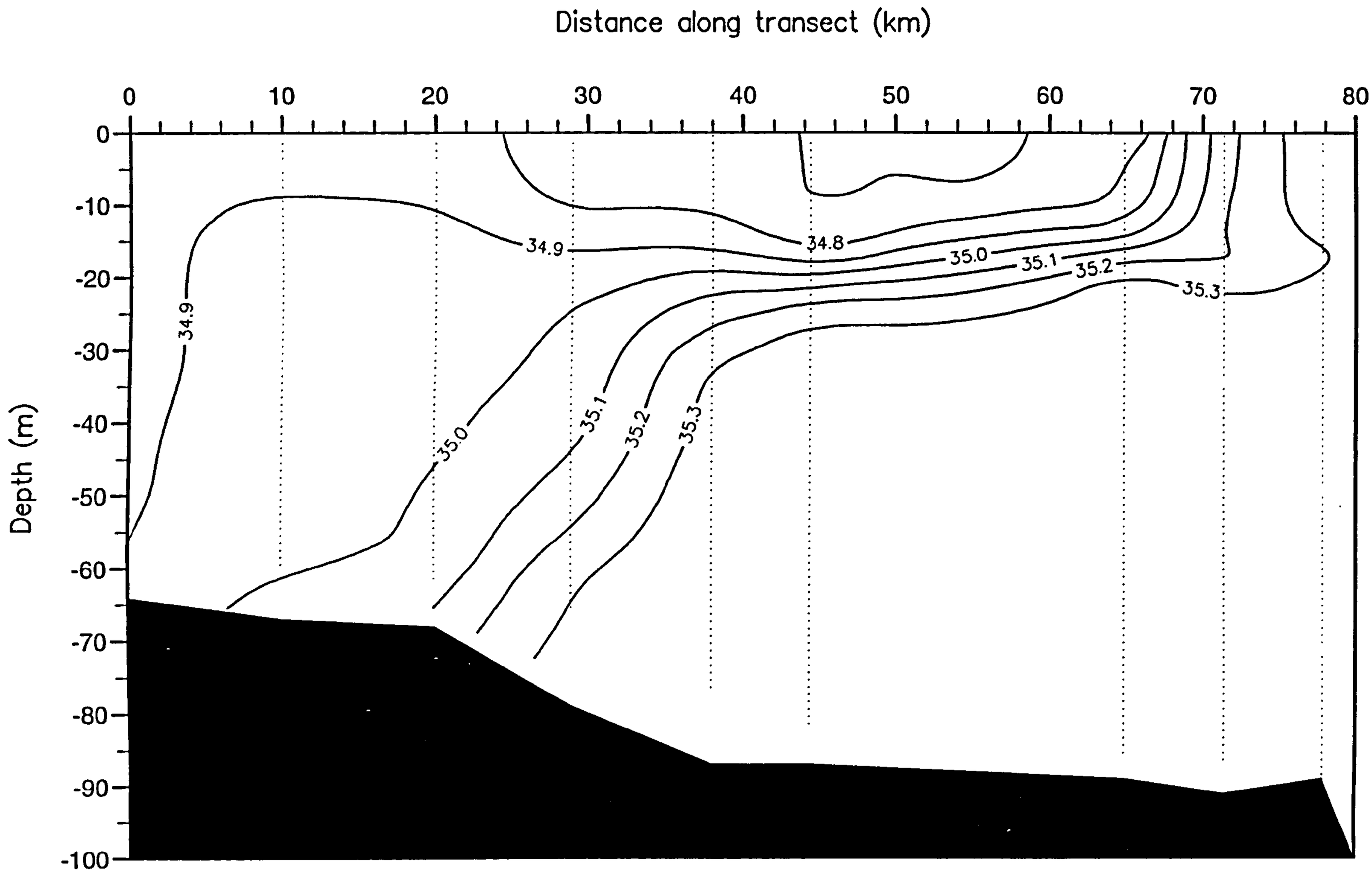


Figure 3.3 Salinity profile for transect 1, 1995

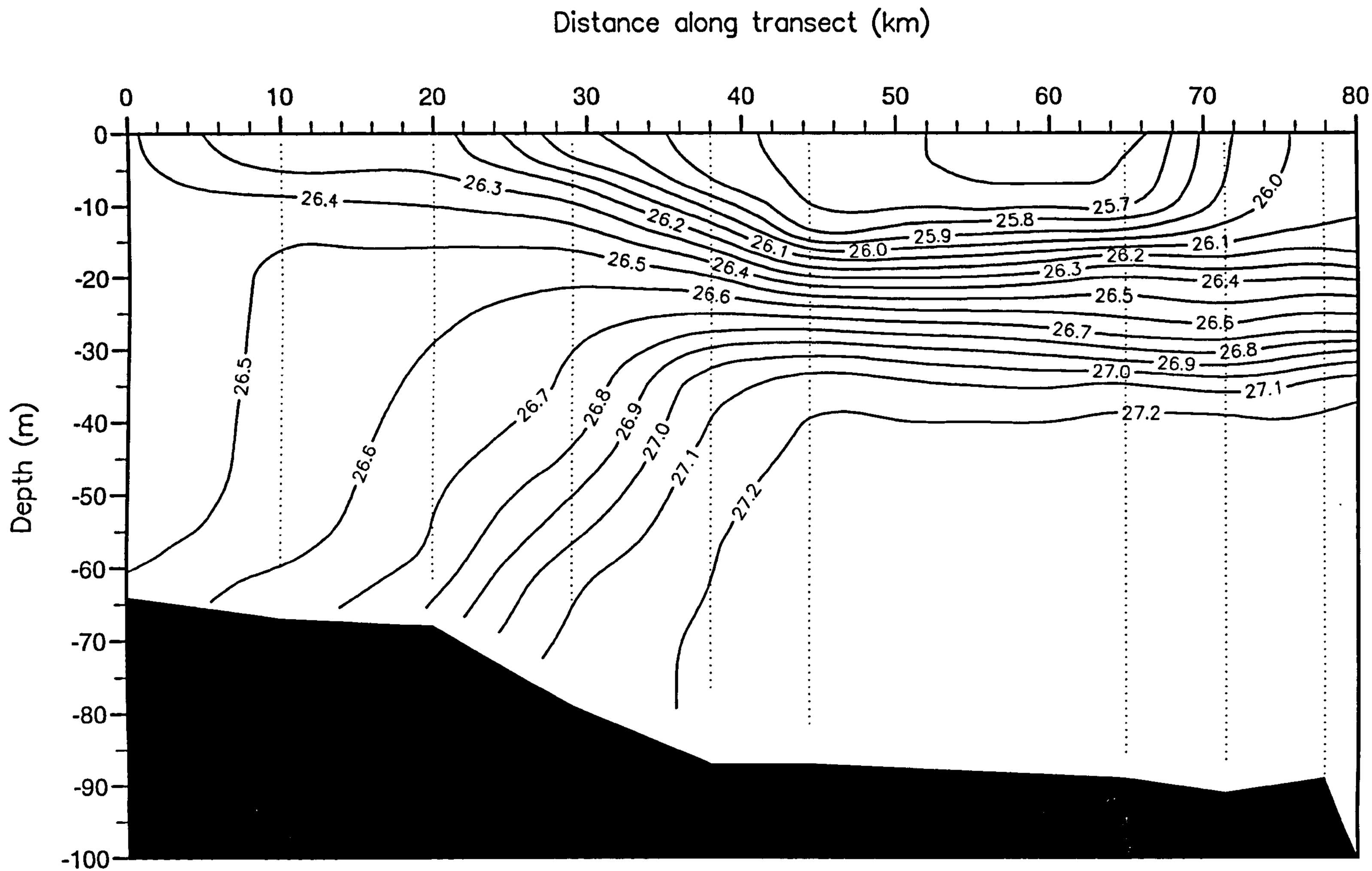


Figure 3.4 Density profile for transect 1, 1995

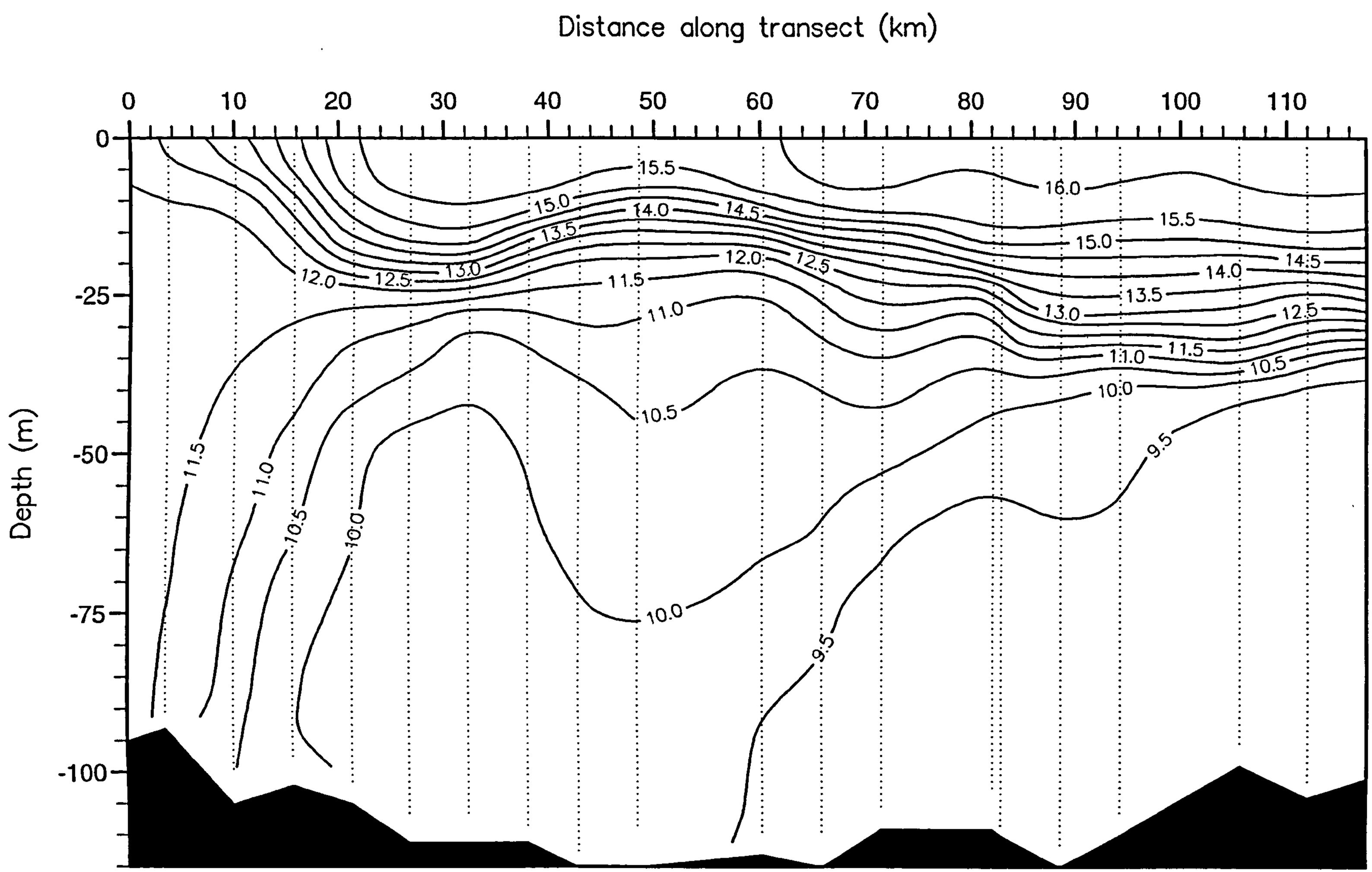


Figure 3.5 Temperature profile for transect 2, 1995

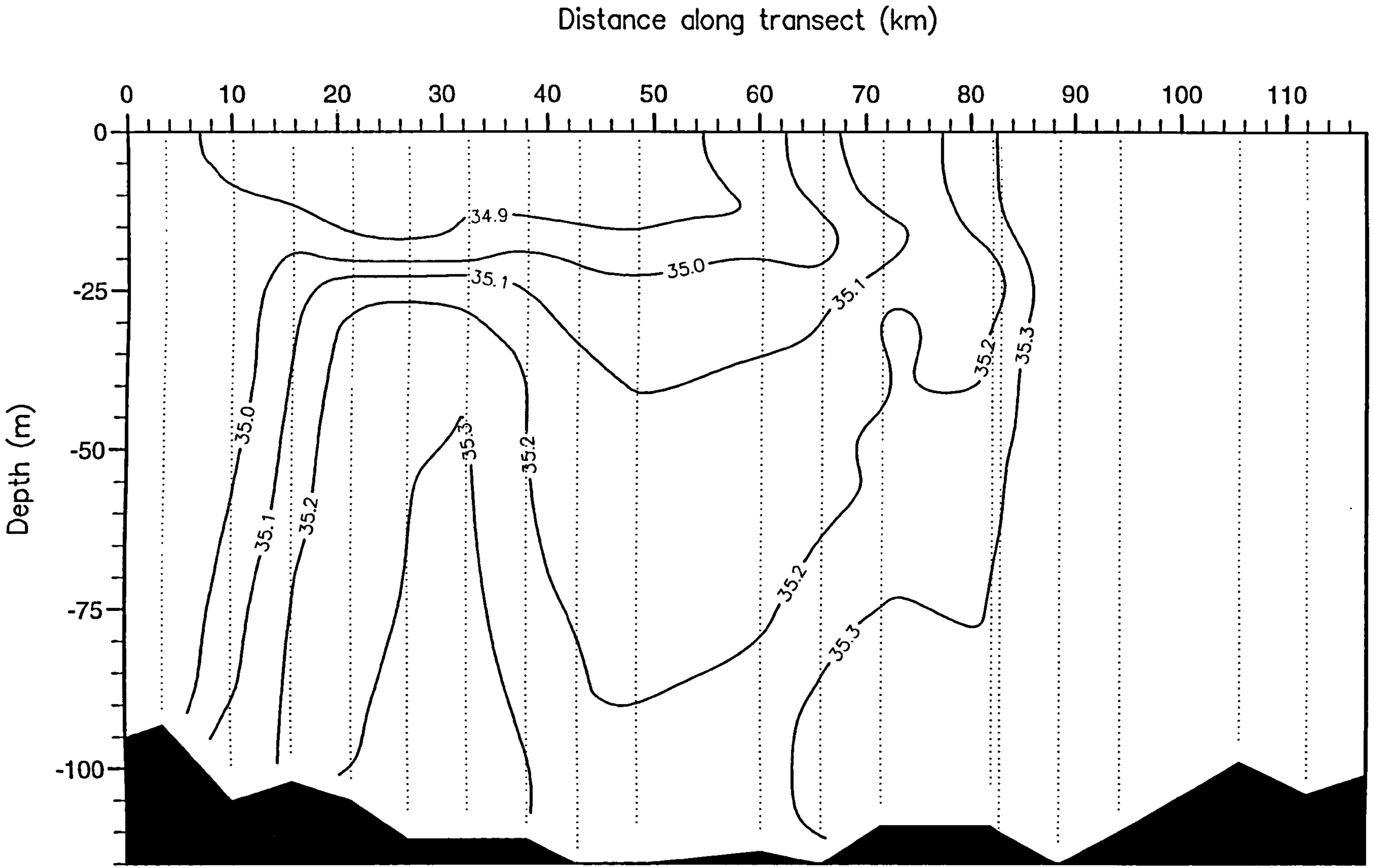
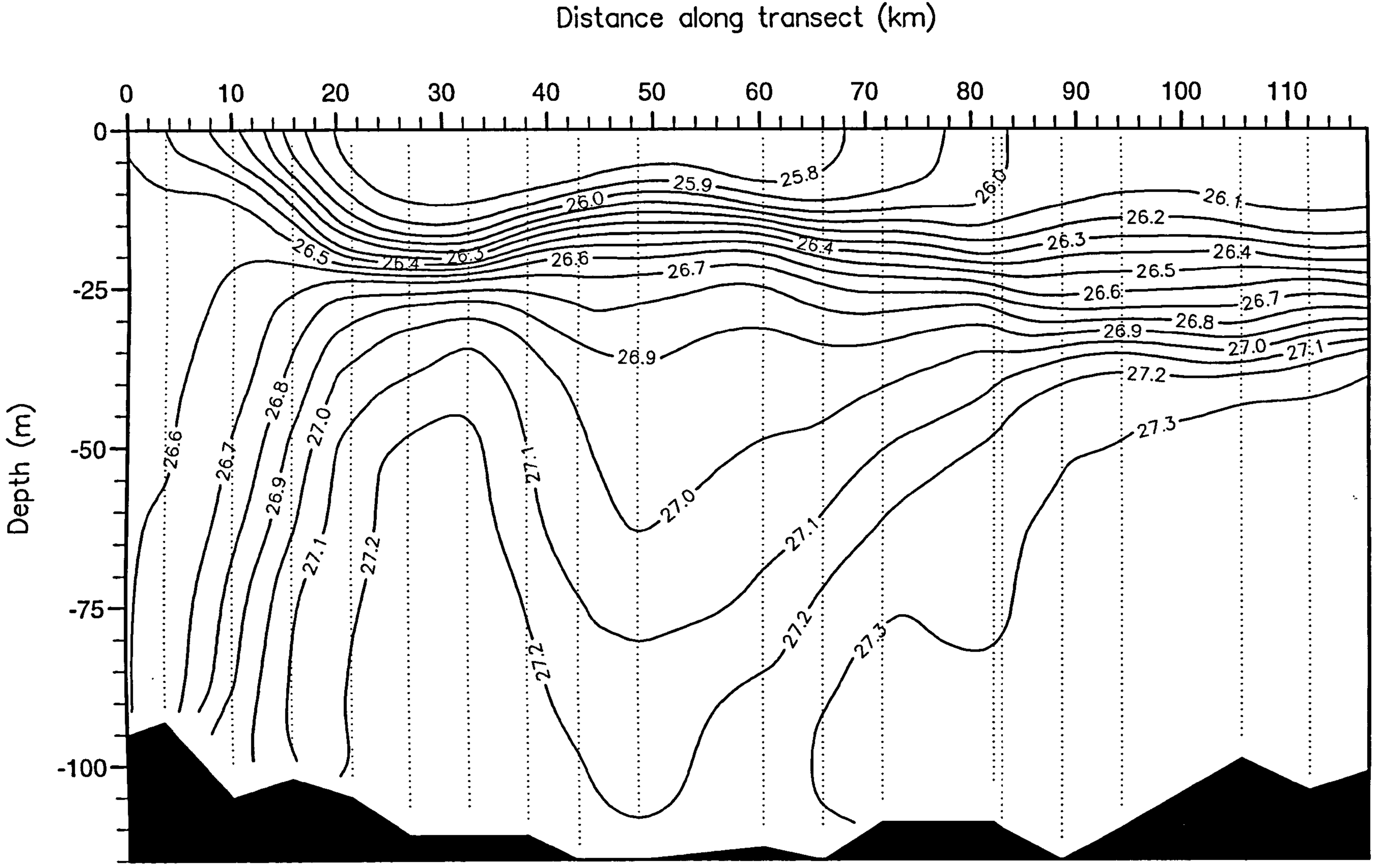


Figure 3.6 Salinity profile for transect 2, 1995



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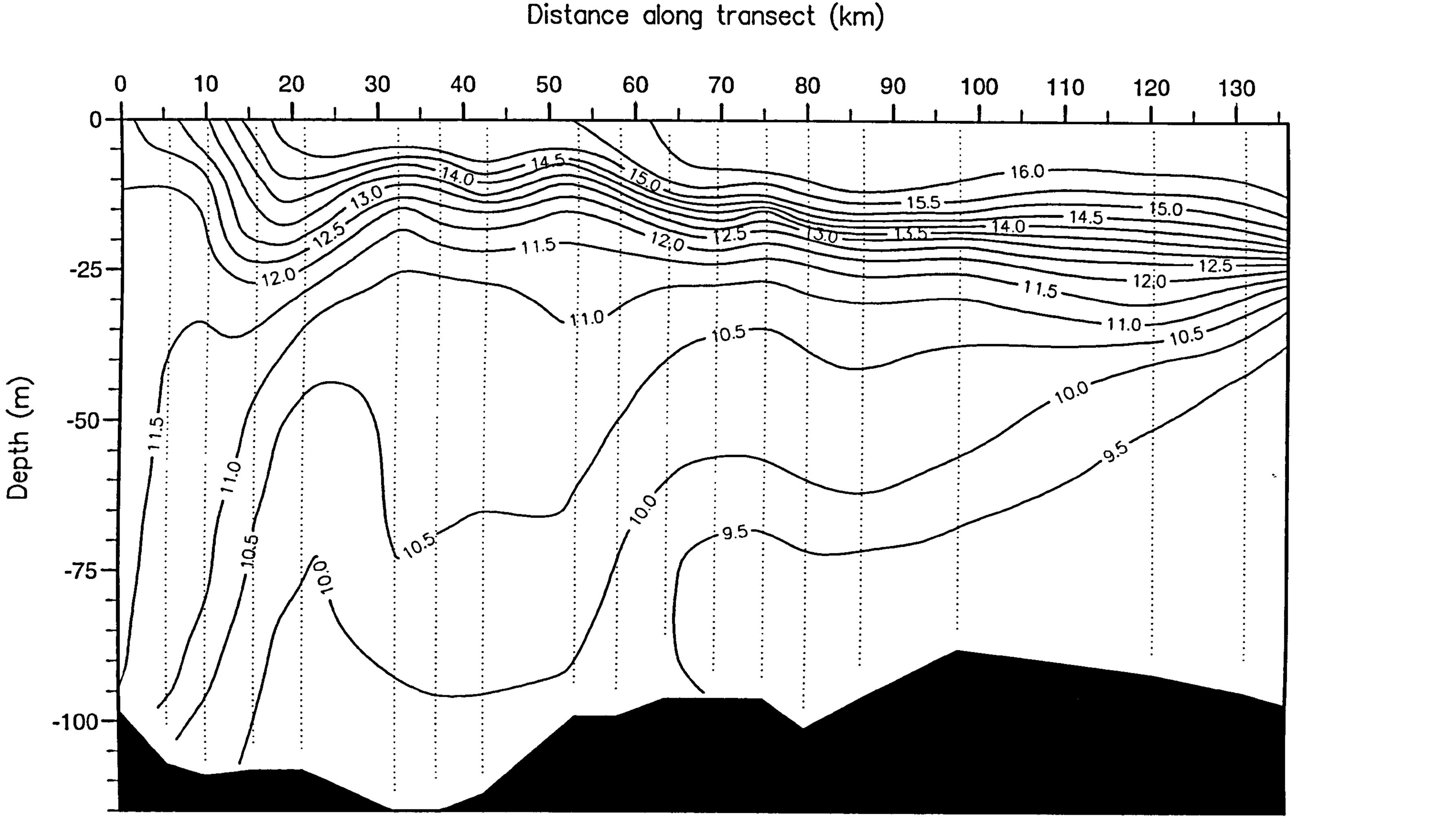


Figure 3.8 Temperature profile for transect 3, 1995

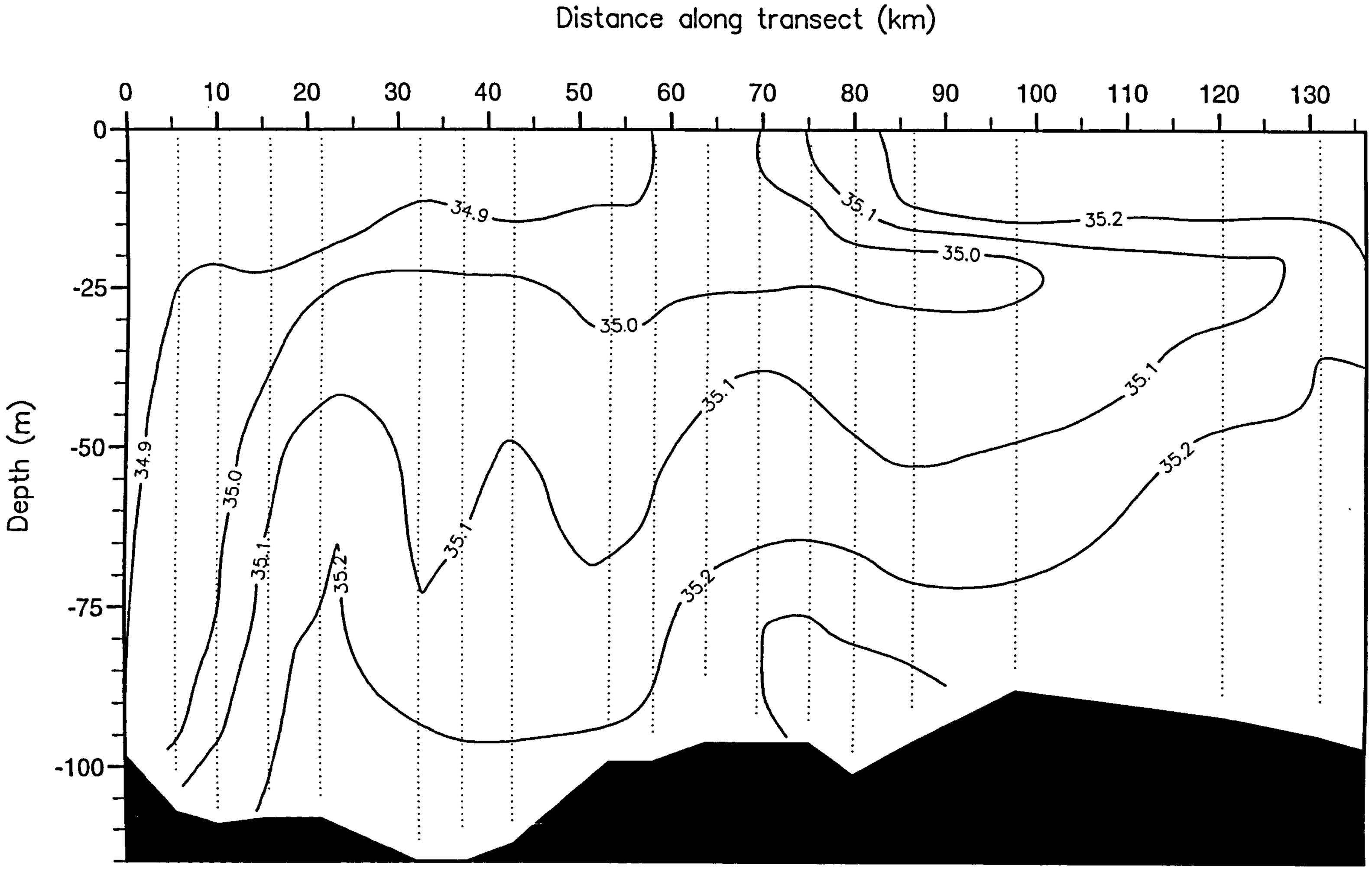


Figure 3.9 Salinity profile for transect 3, 1995

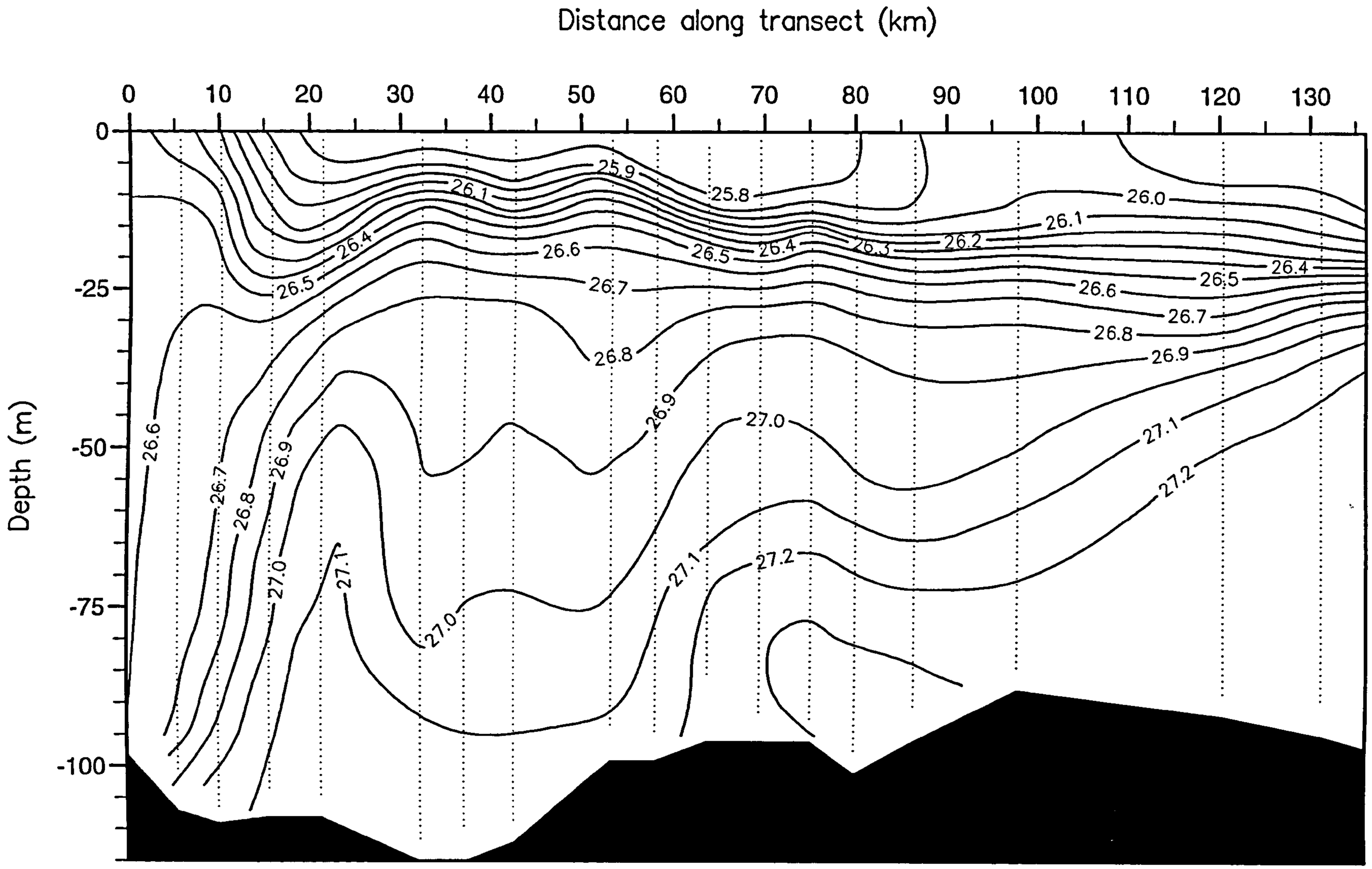


Figure 3.10 Density profile for transect 3, 1995

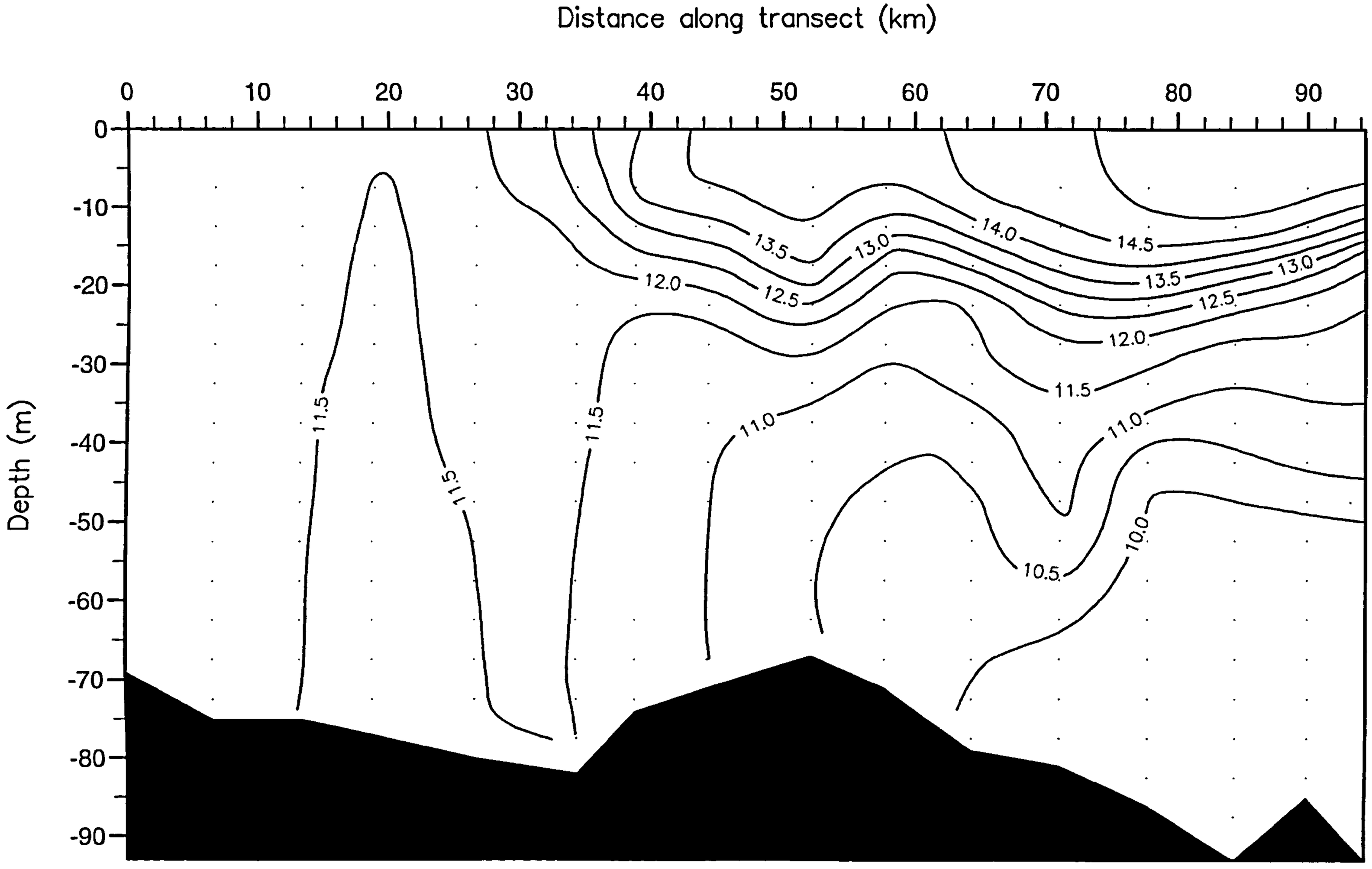


Figure 3.11 Temperature profile for transect 6, 1996

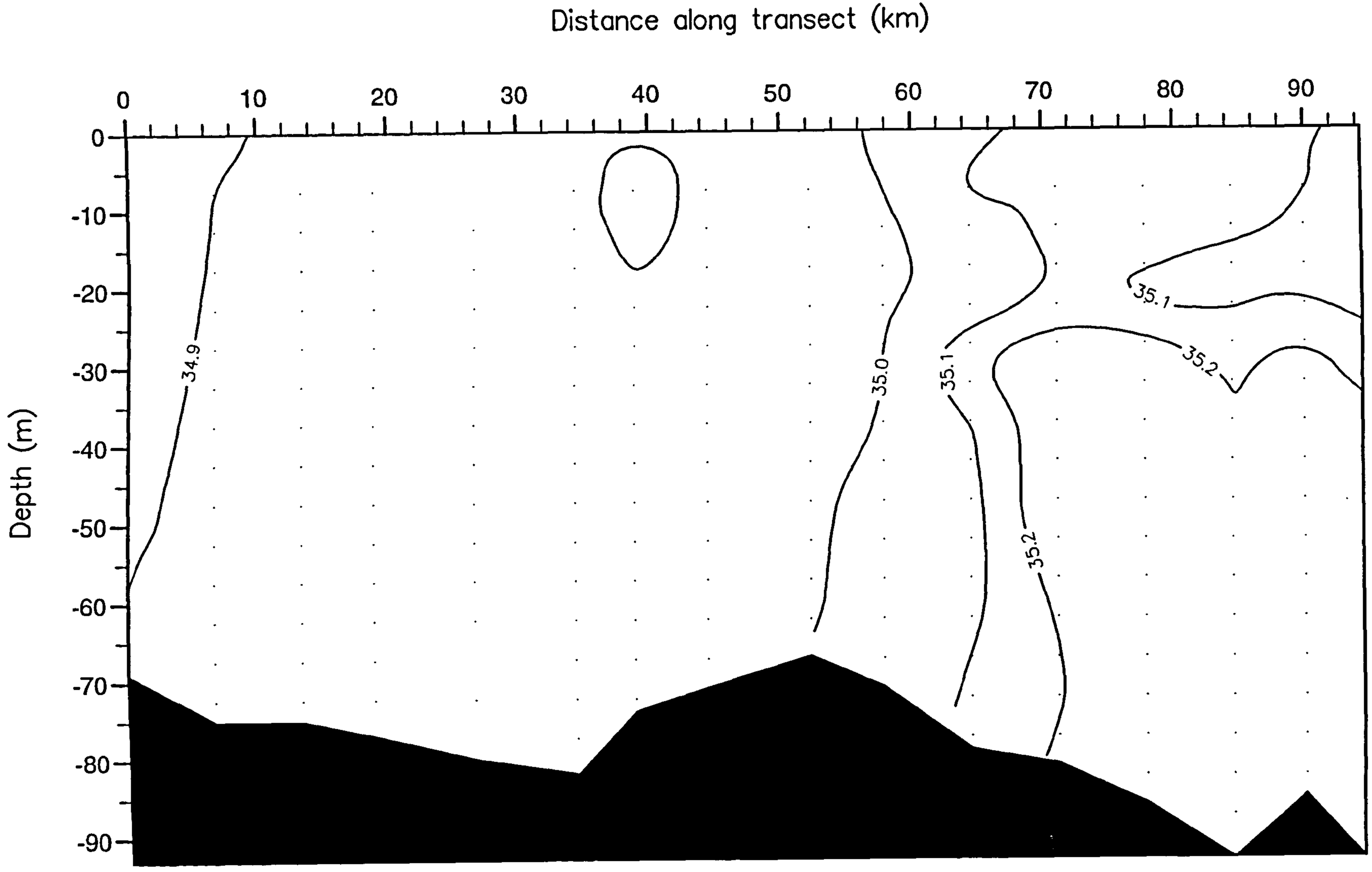


Figure 3.12 Salinity profile for transect 6, 1996

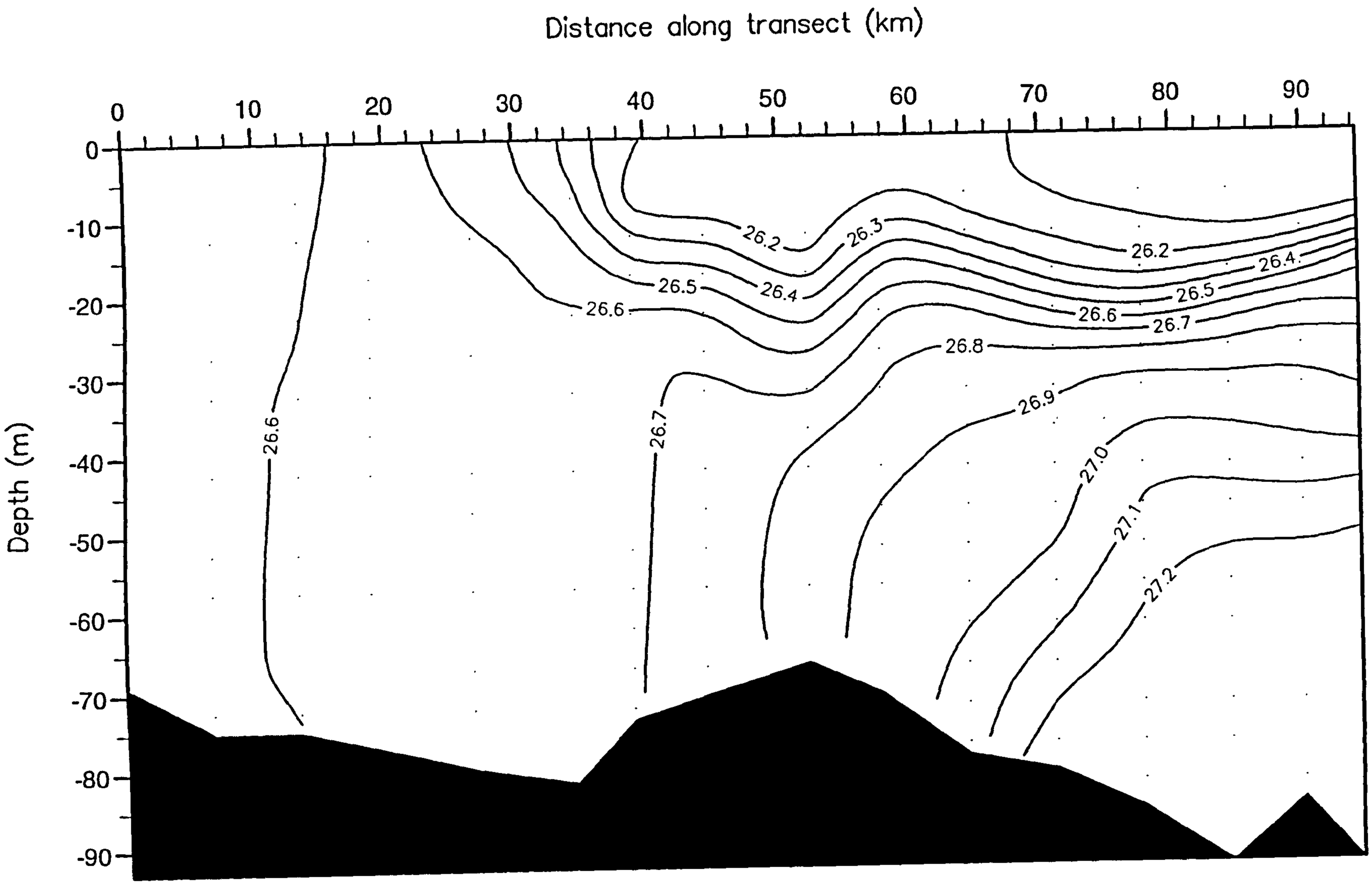


Figure 3.13 Density profile for transect 6, 1996

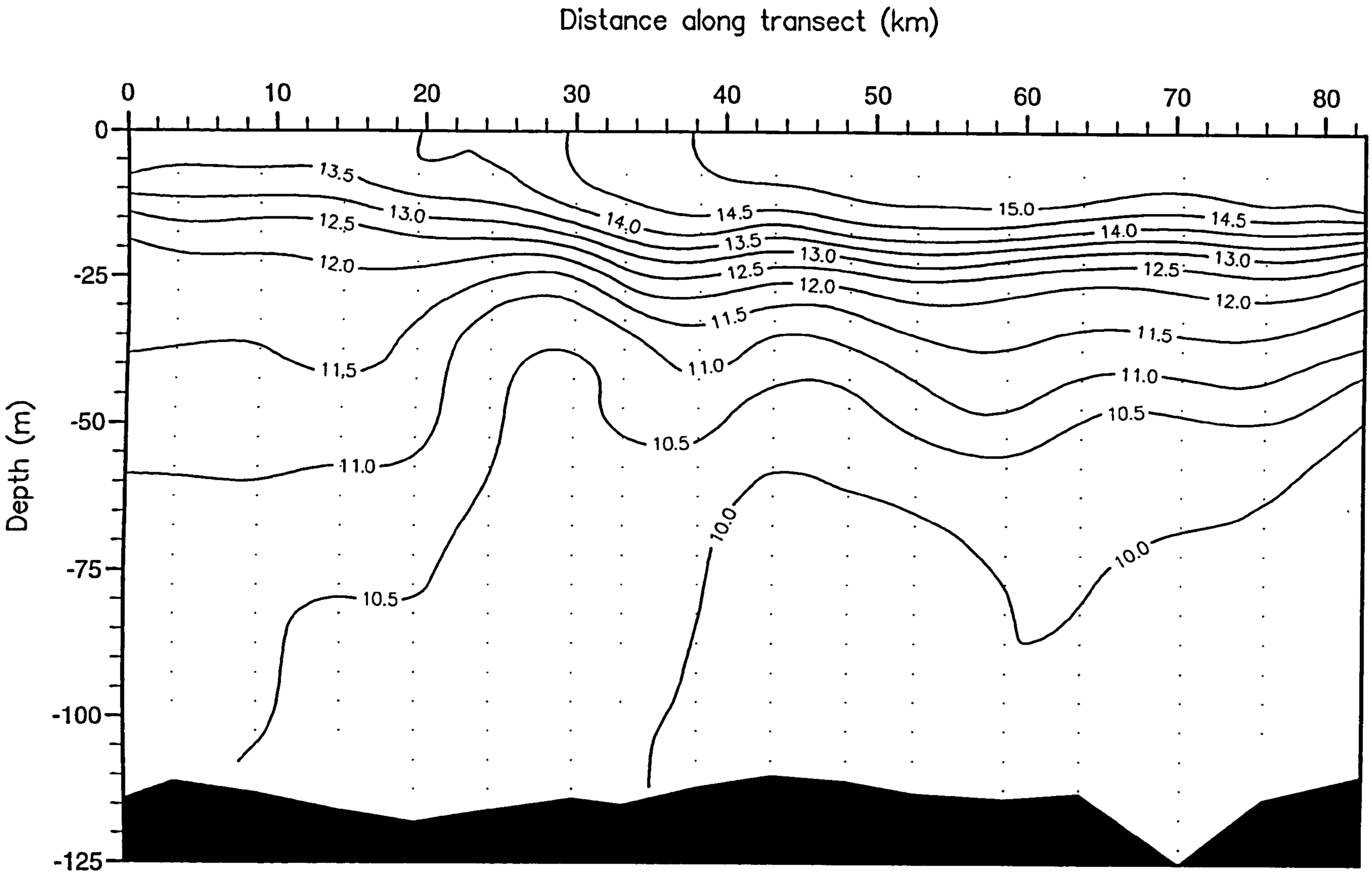


Figure 3.14 Temperature profile for transect 7, 1996

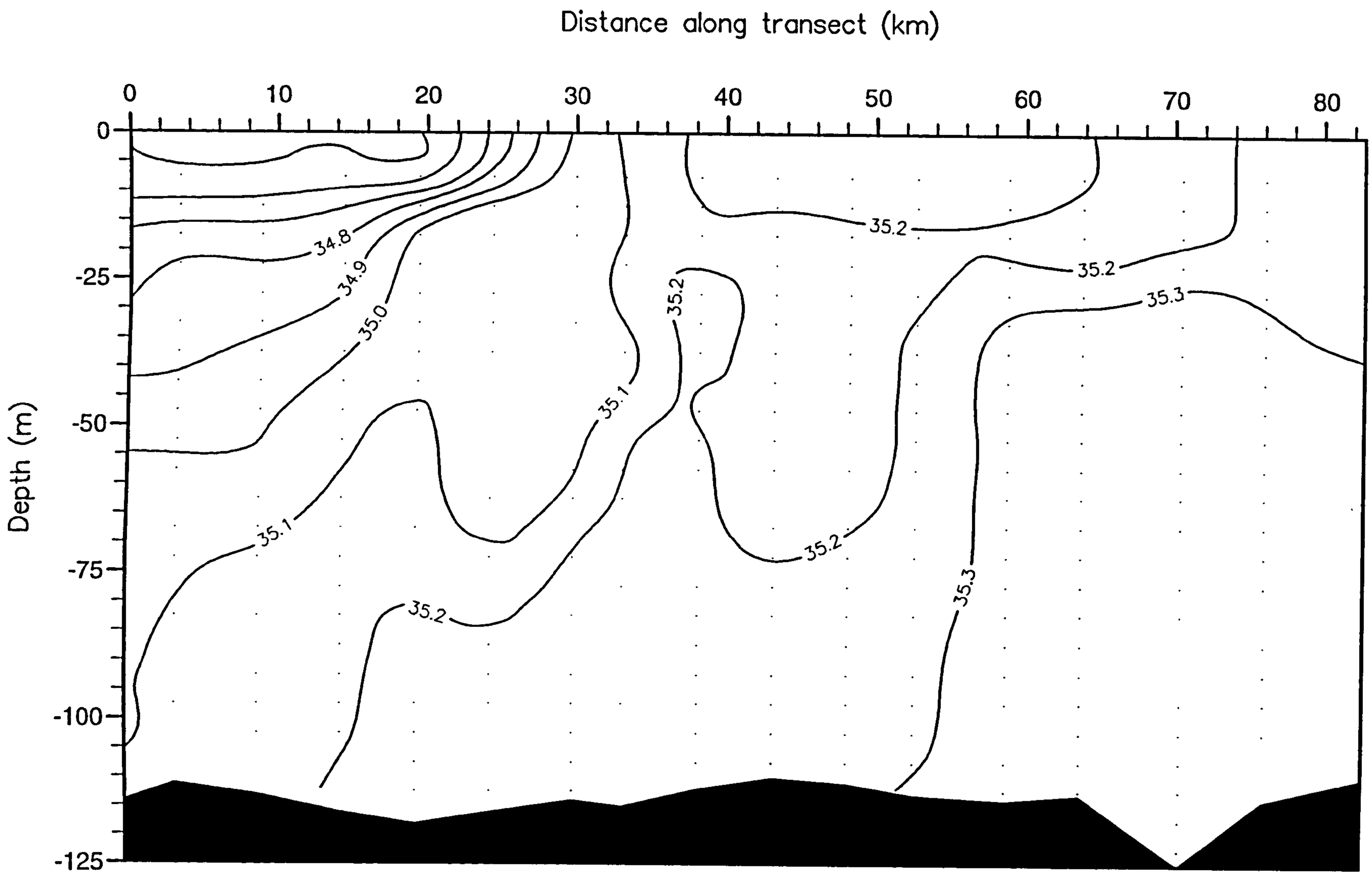


Figure 3.15 Salinity profile for transect 7, 1996

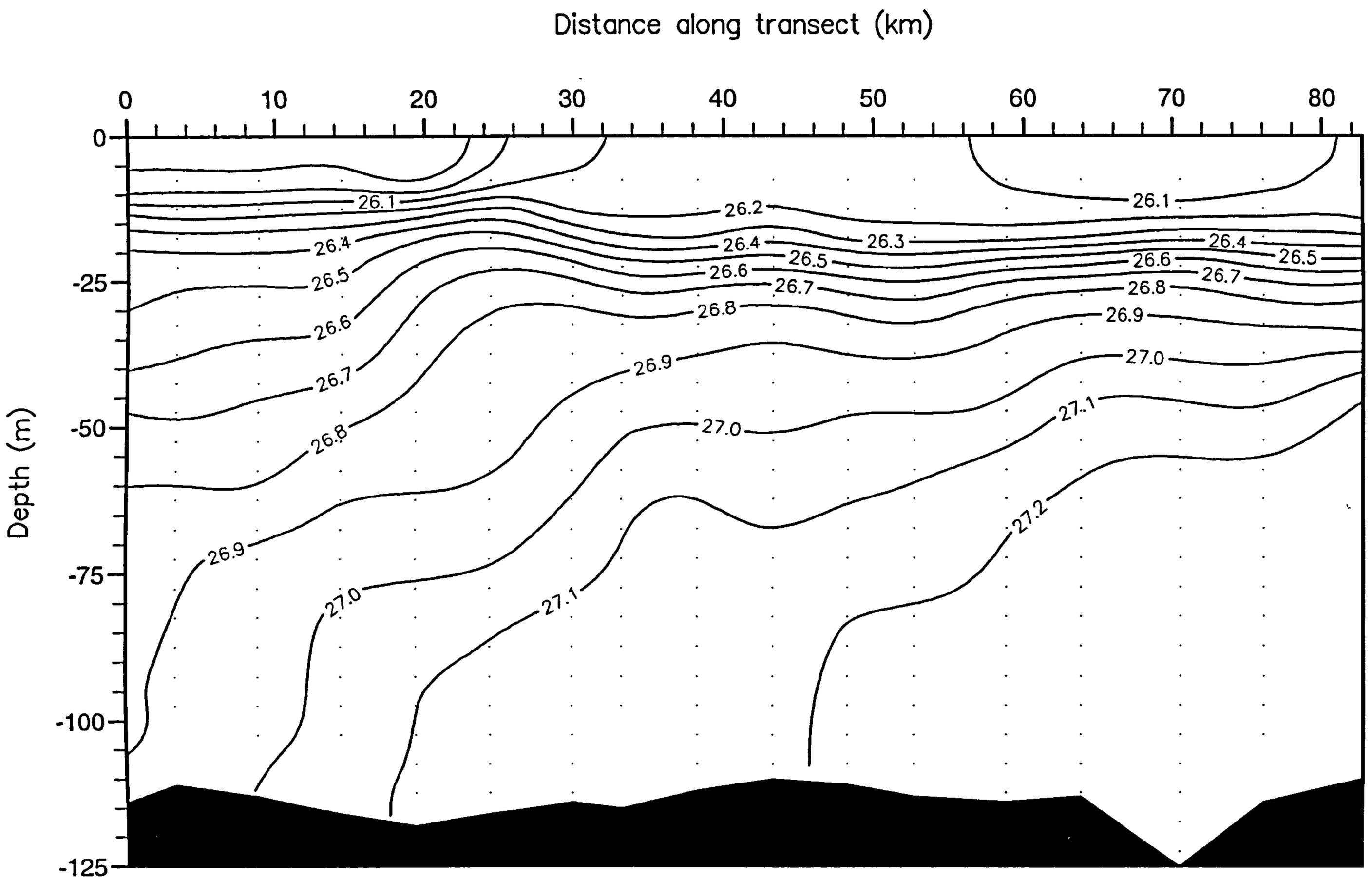


Figure 3.16 Density profile for transect 7, 1996

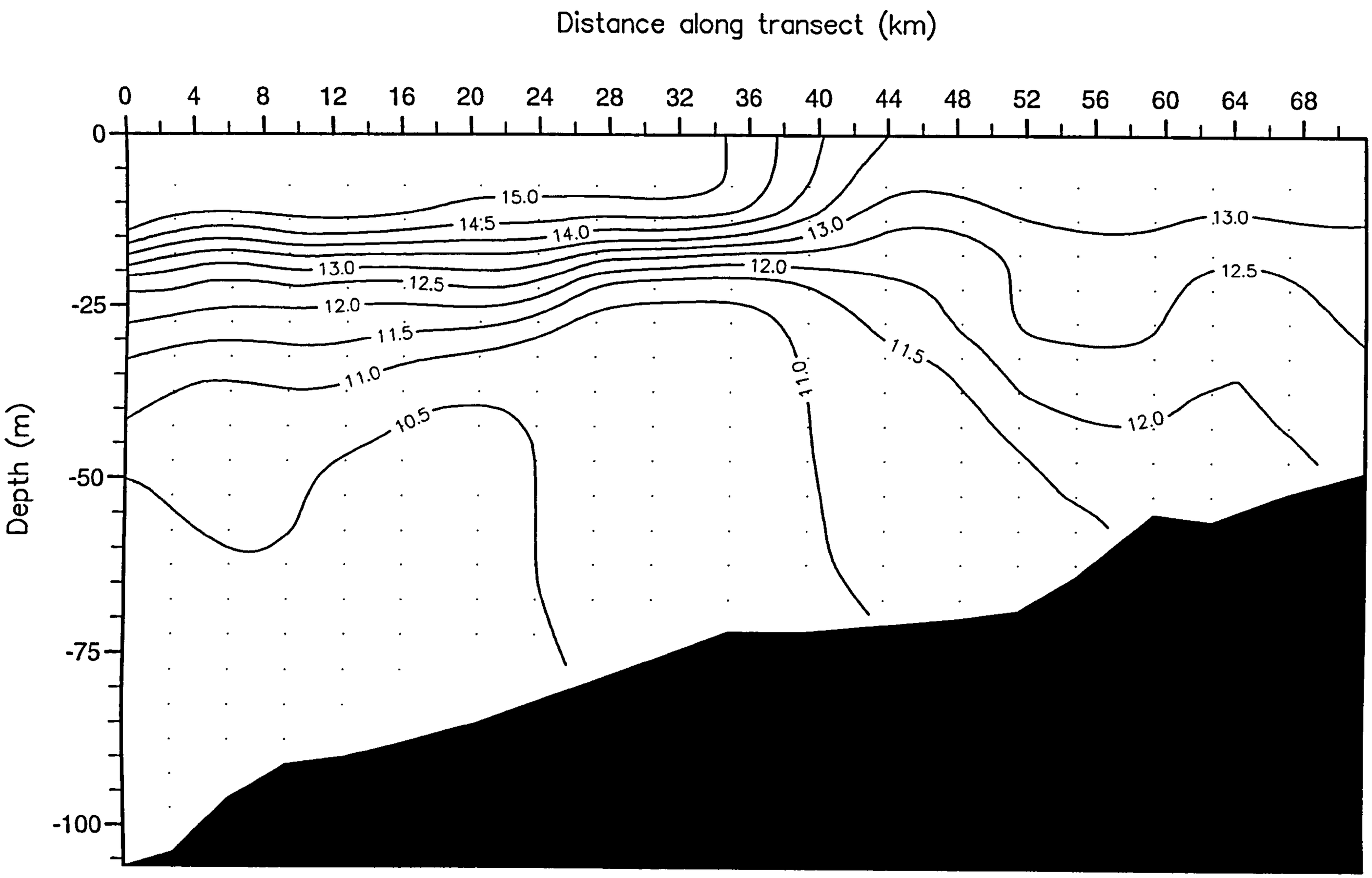


Figure 3.17 Temperature profile for transect 8, 1996

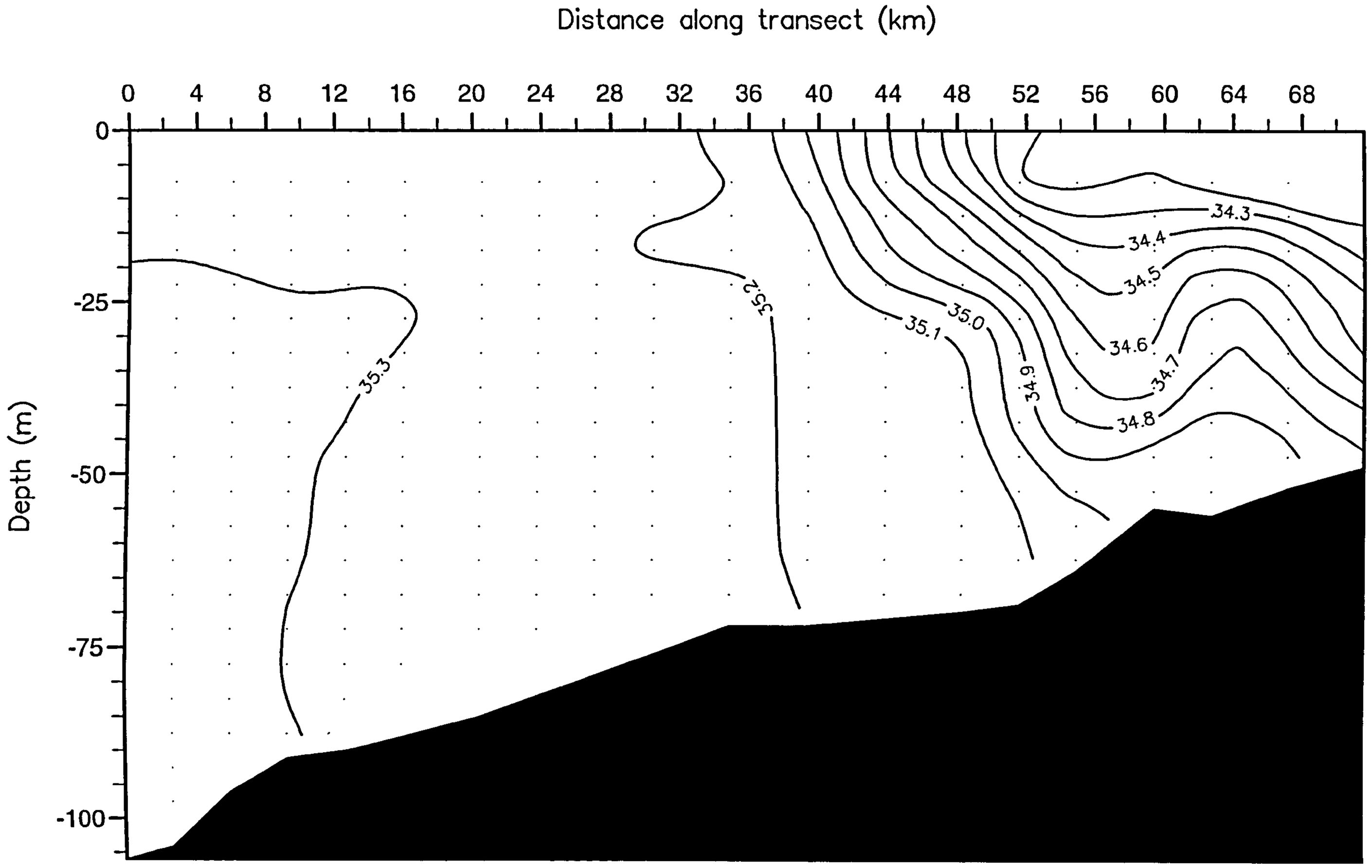


Figure 3.18 Salinity profile for transect 8, 1996

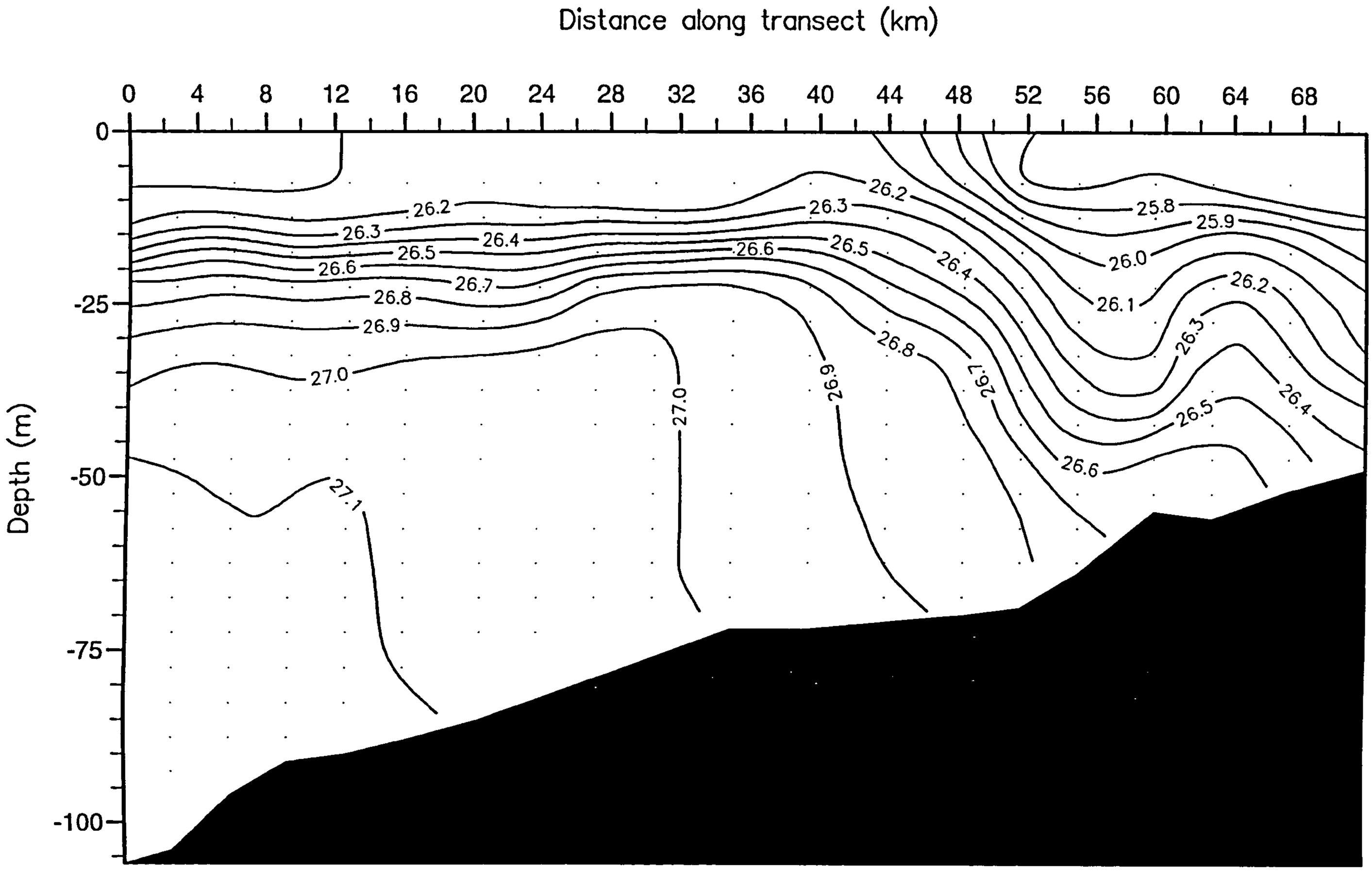


Figure 3.19 Density profile for transect 8, 1996

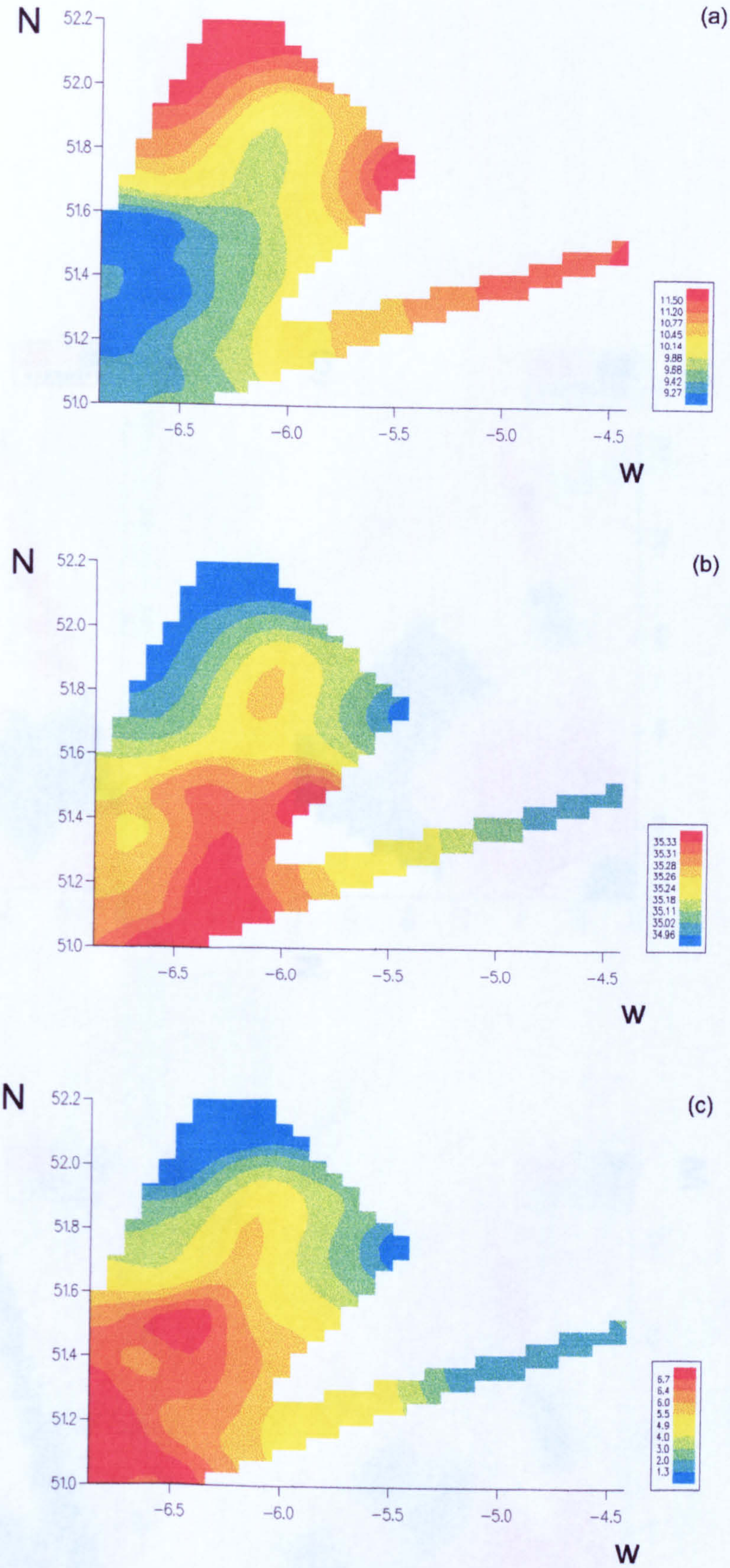


Figure 3.20 Distribution of bottom water characteristics
(a) Temperature ^{0}C (b) Salinity $^{0}/_{00}$ (c) Sindex

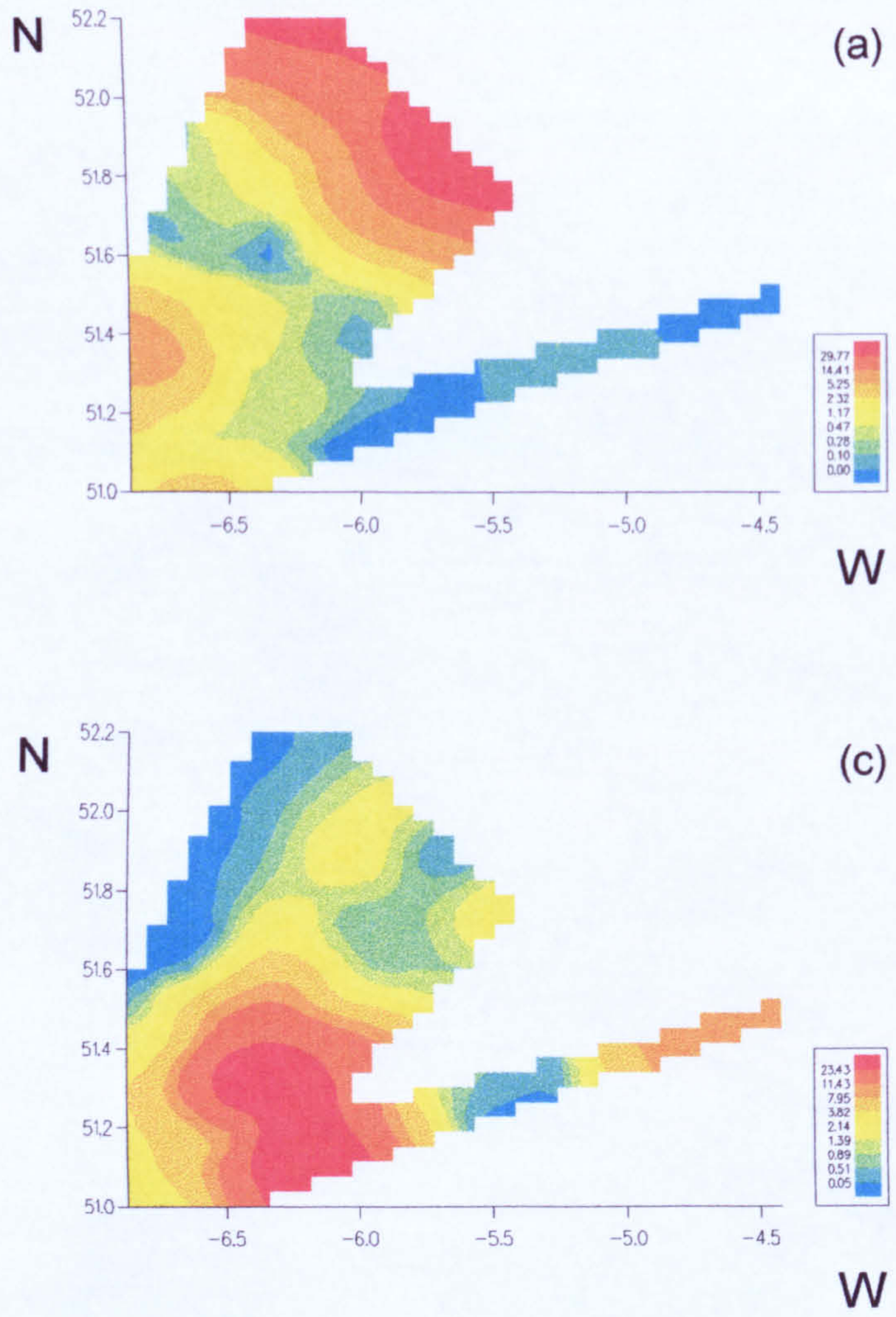
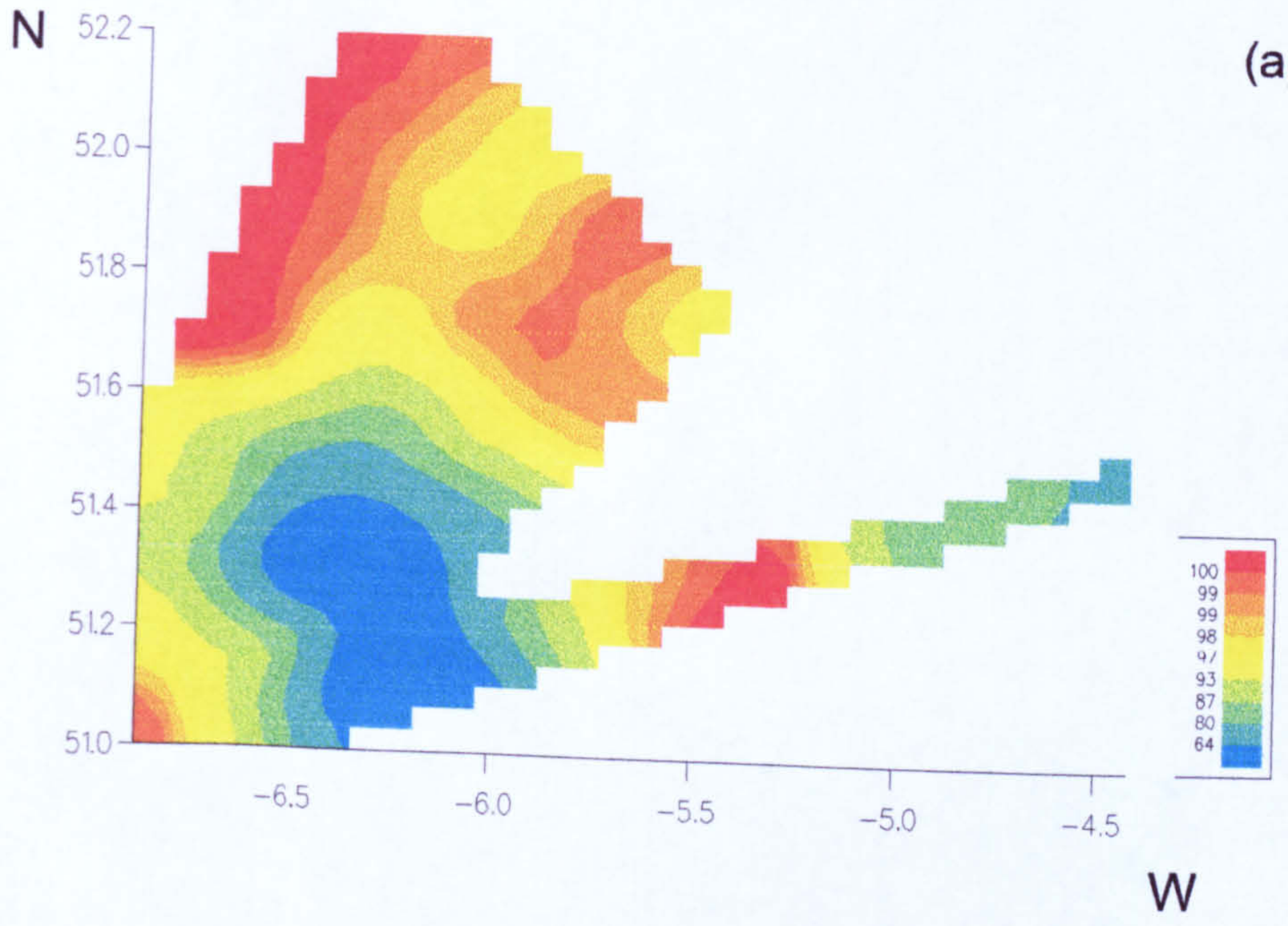


Figure 3.21 Distribution of grain size fractions (a) % gravel (b) % sand (c) % silt (d) % clay



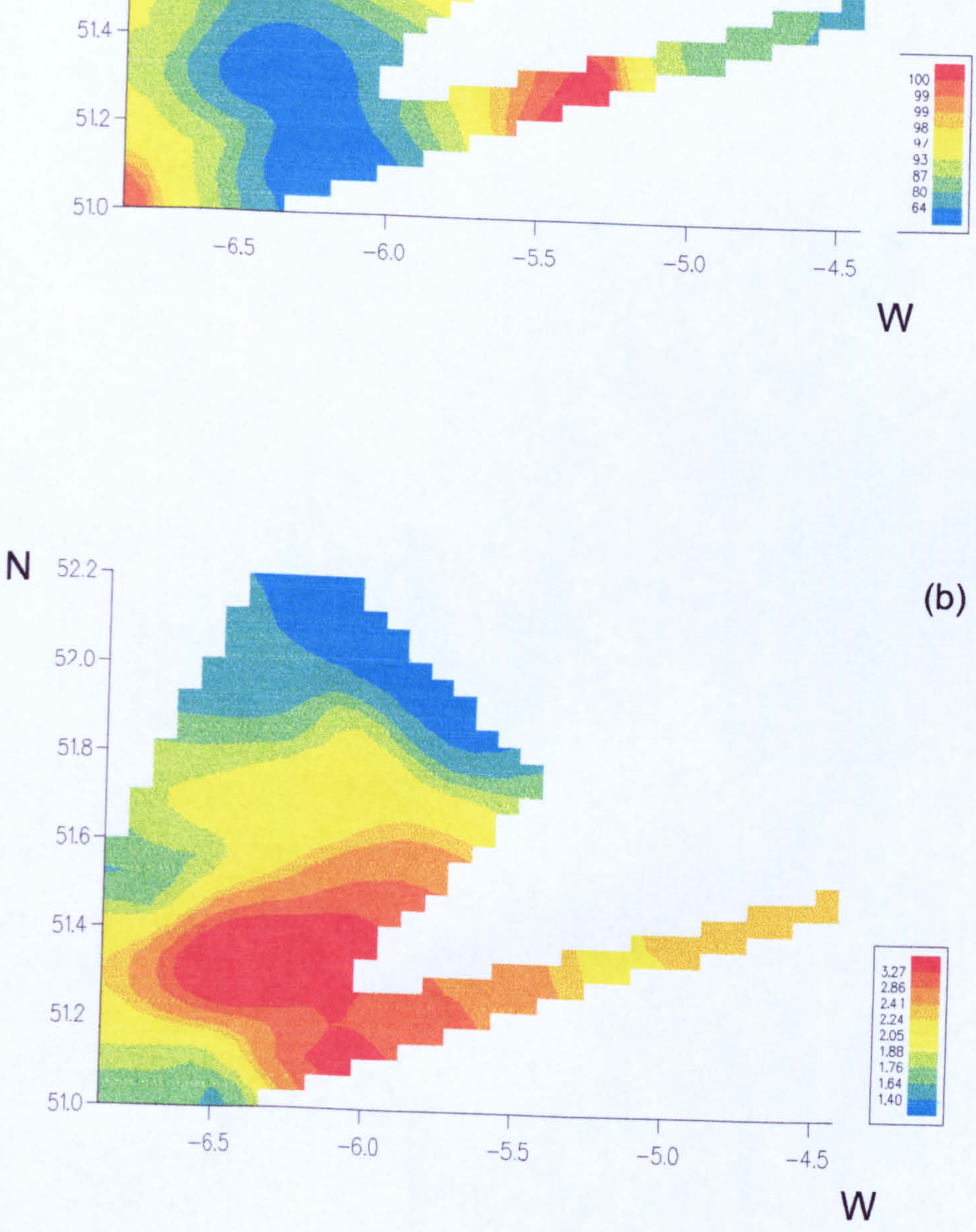


Figure 3.22 Summary of grain size distribution (a) > 63 μm (b) modal in phi units

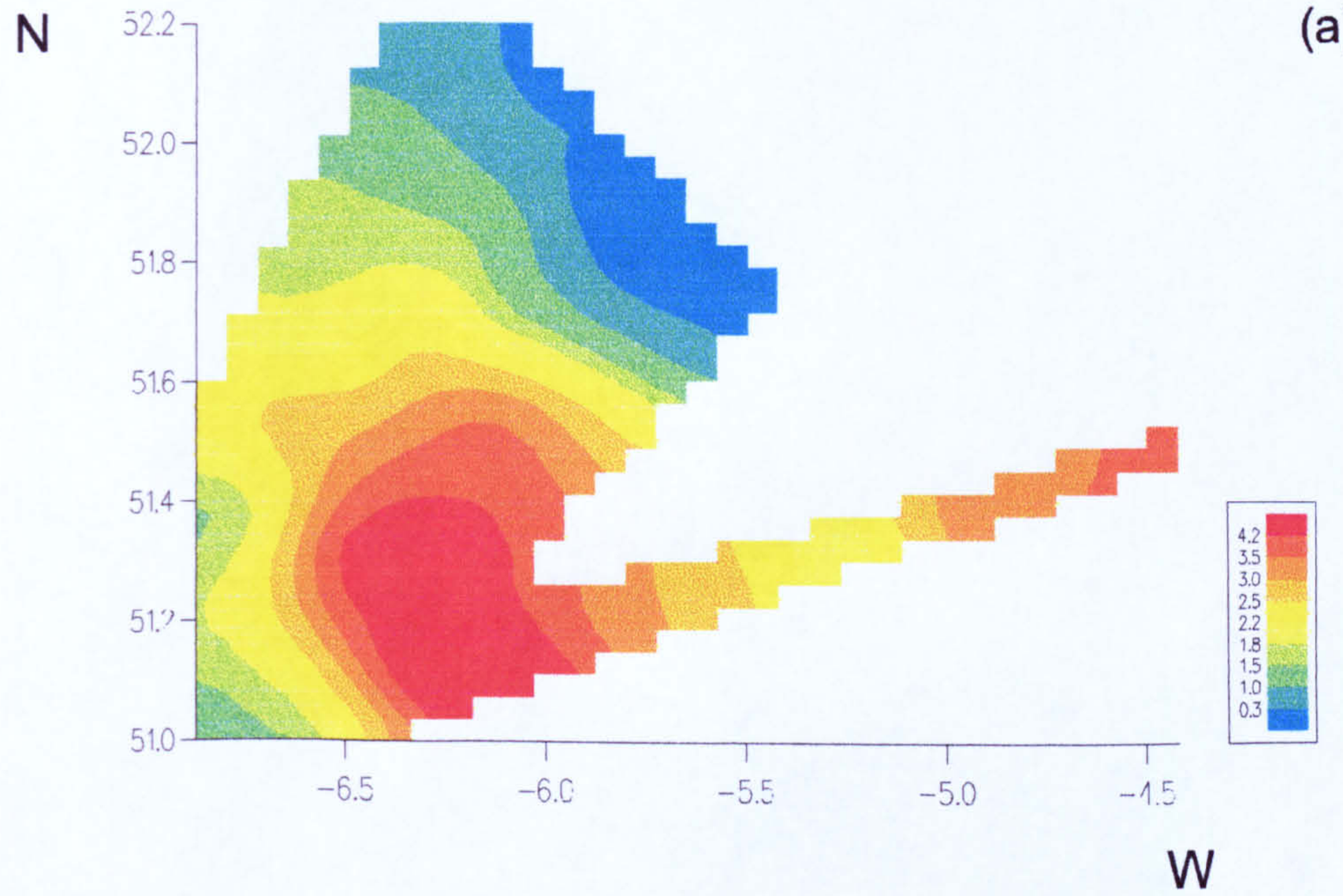


Figure 3.23 Mean grain size measured using (a) moments (b) Folks

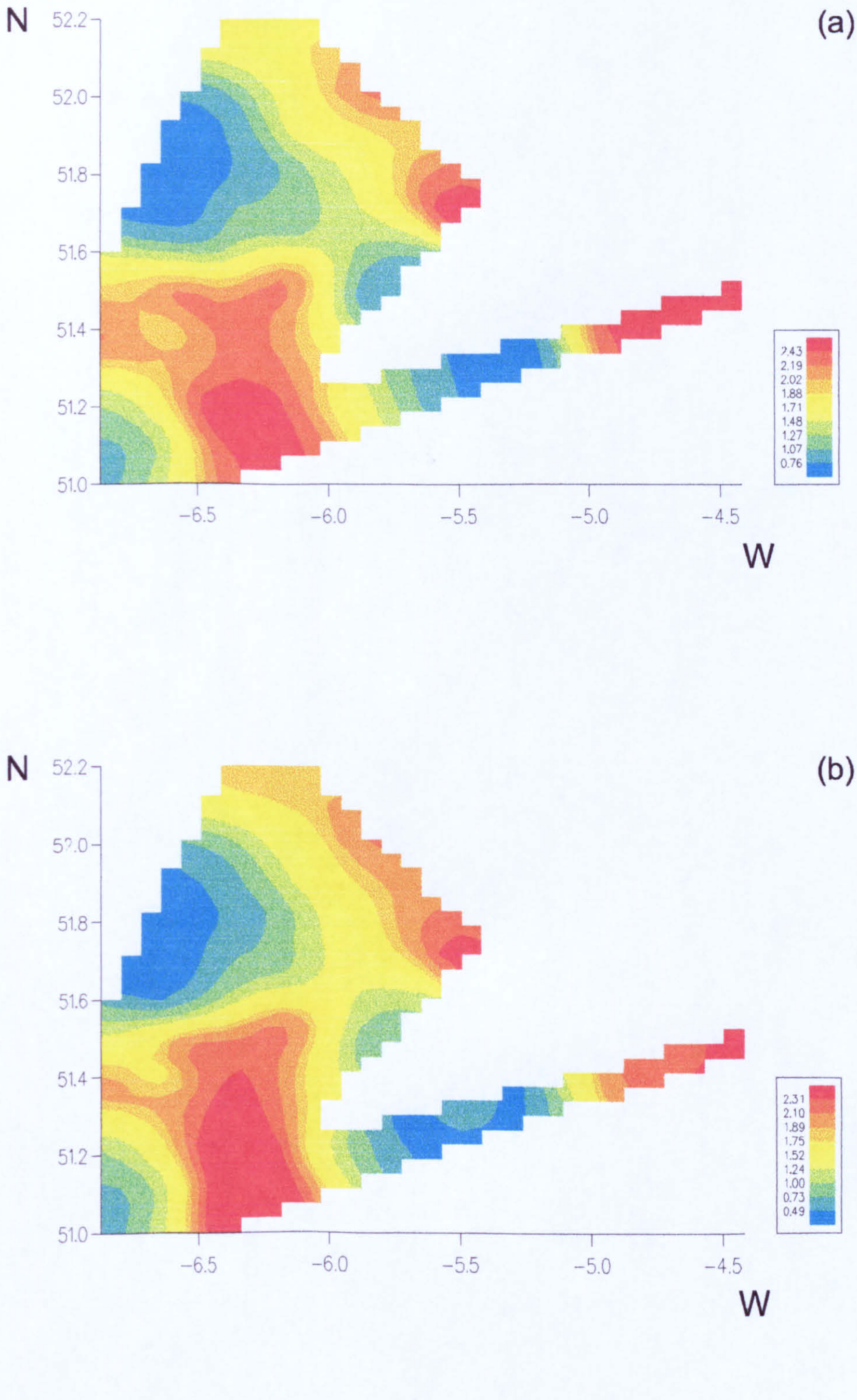
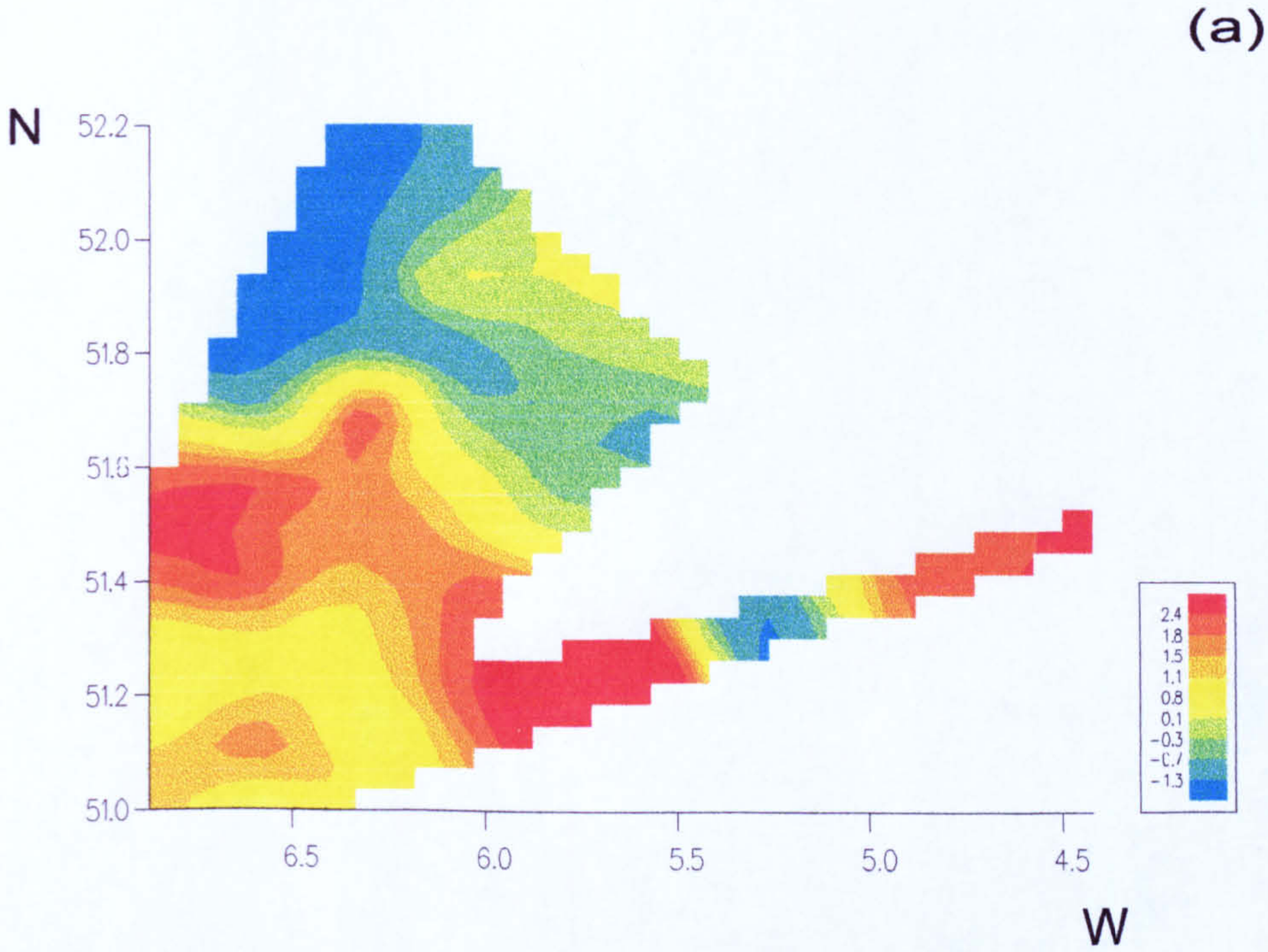


Figure 3.24 Sorting measured using (a) moments (b) Folks



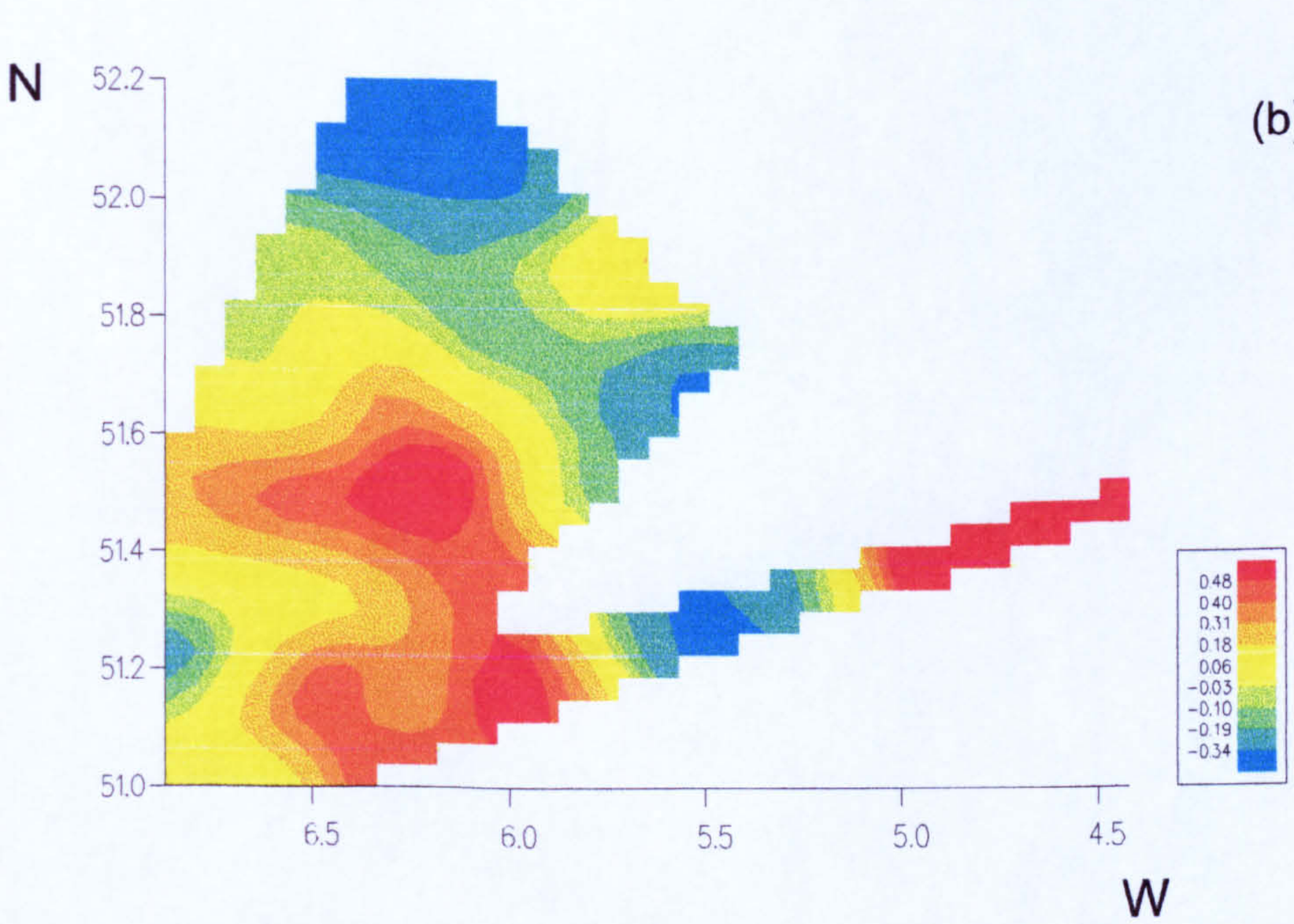
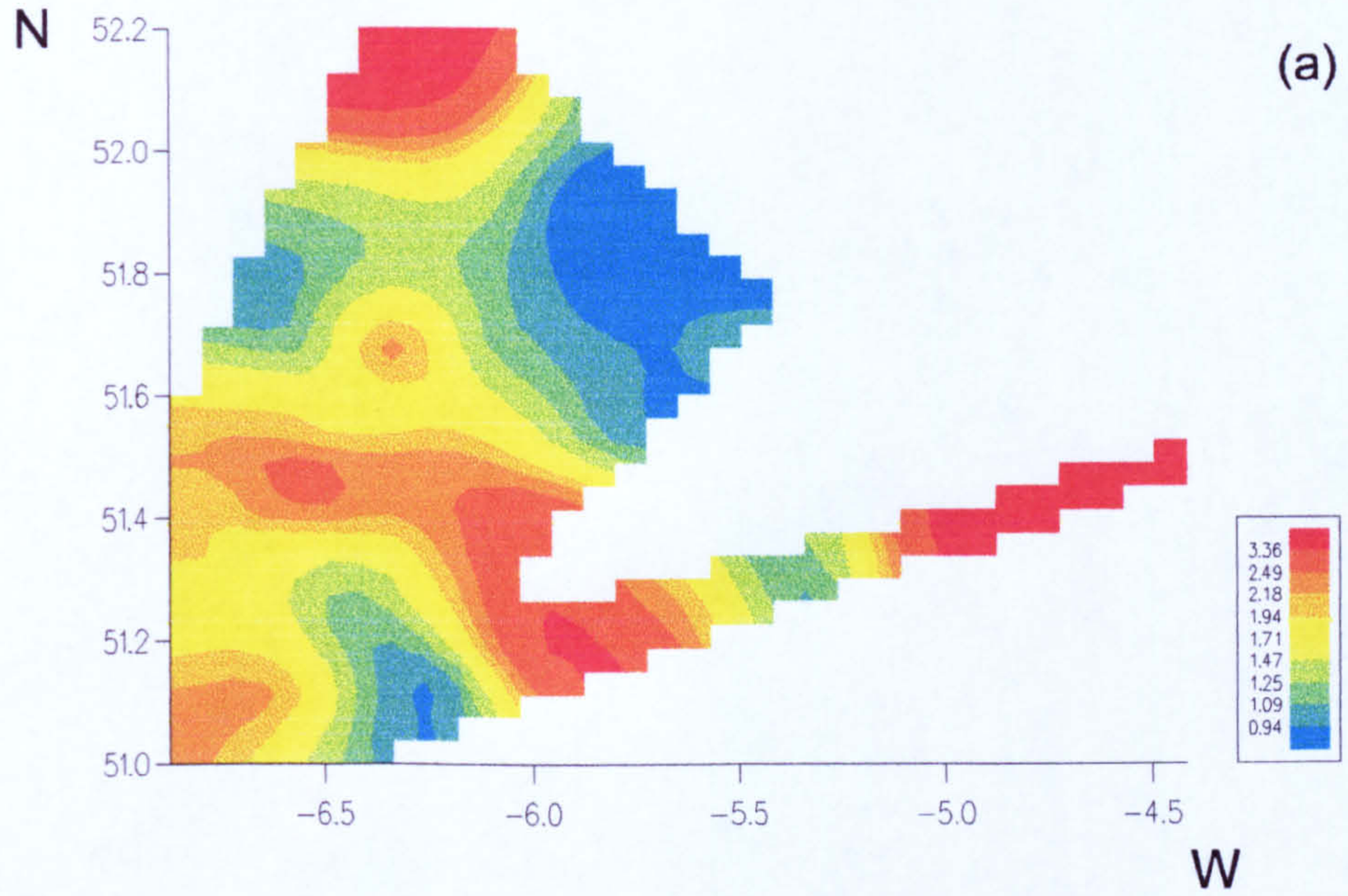


Figure 3.25 Skewness measured using (a) moments (b) Folks



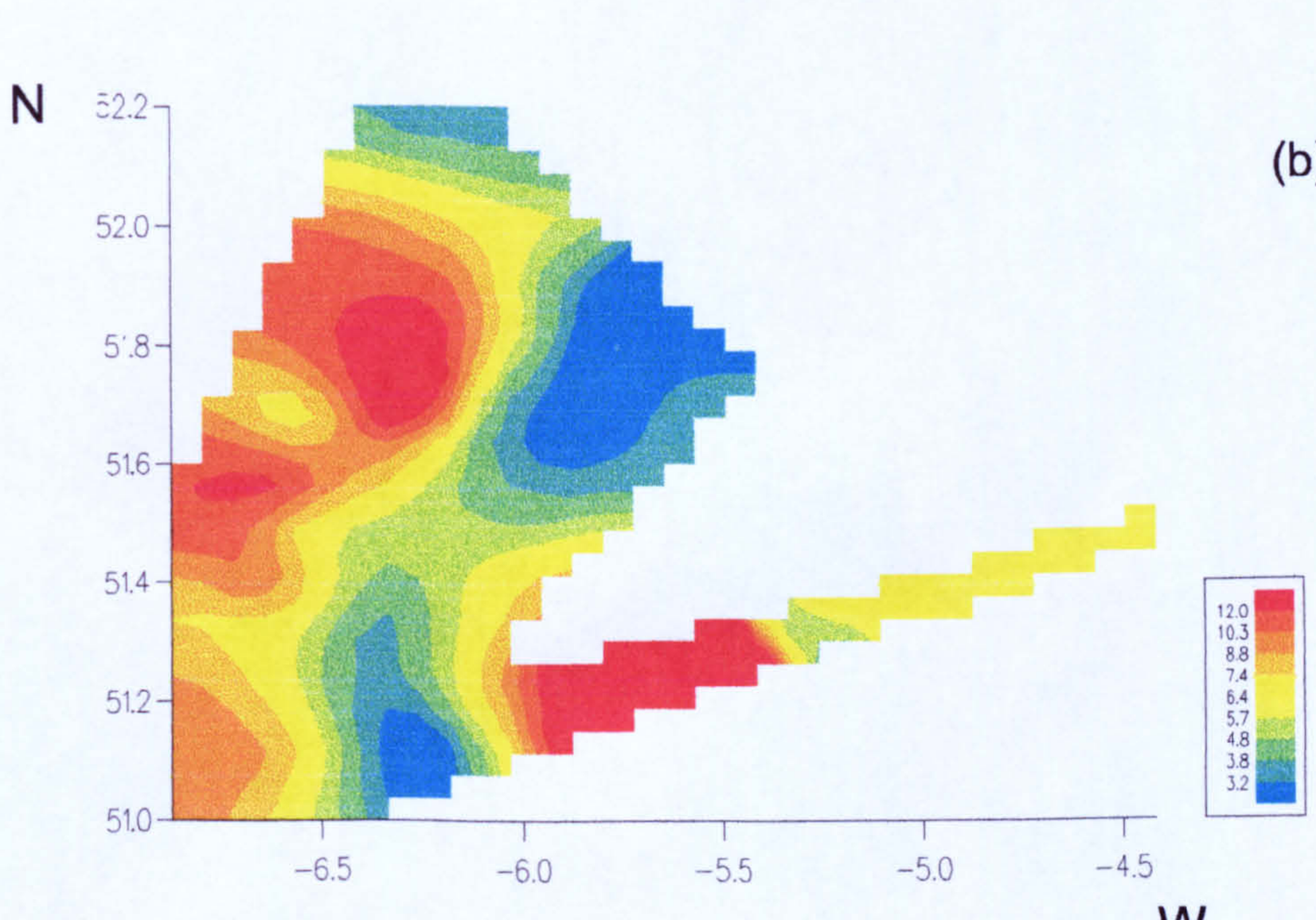


Figure 3.26 Kurtosis measured using (a) moments (b) Folks

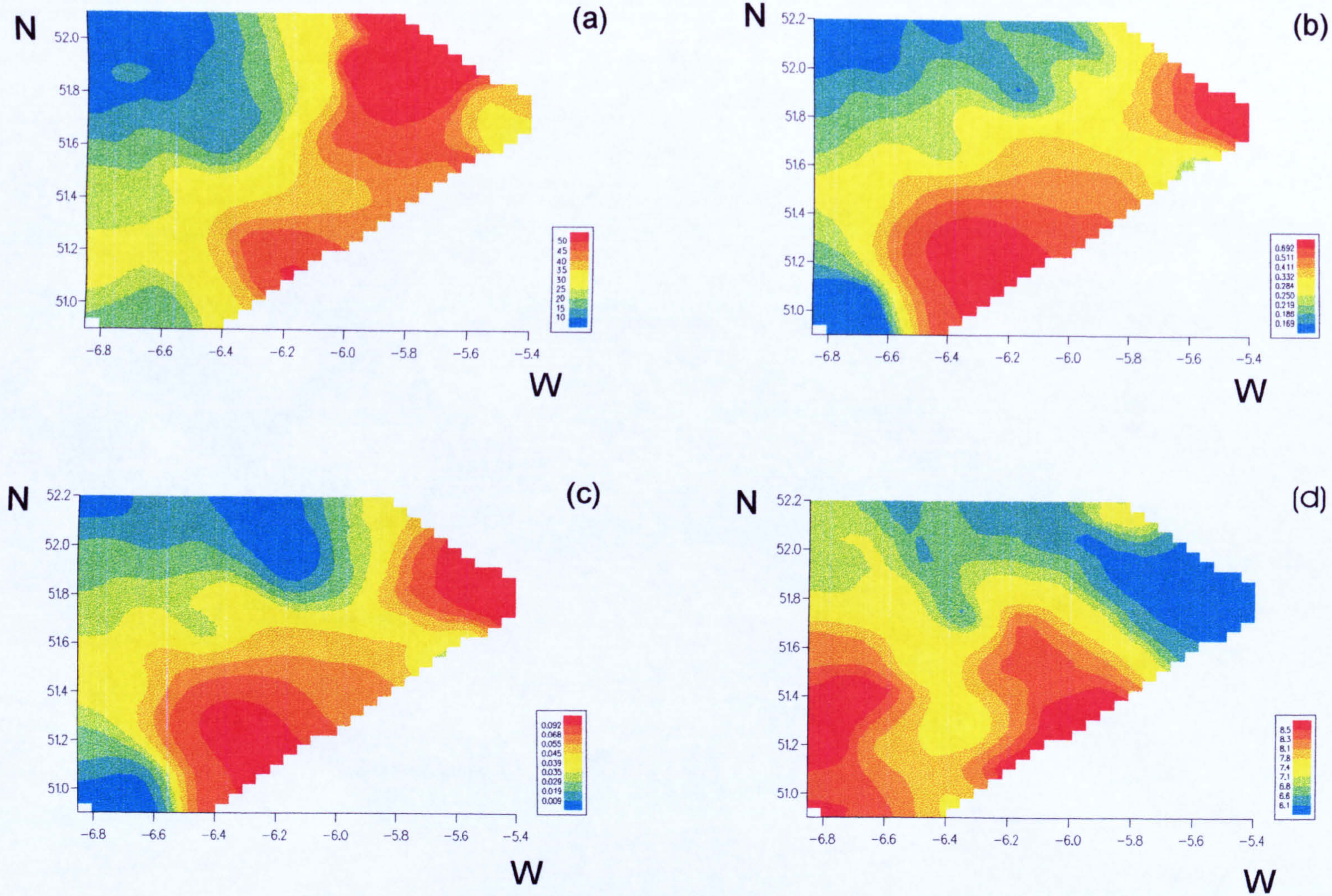


Figure 3.27 Geochemical sedimentary characteristics (a) $CaCO_3$ (b) % Organic carbon (c) % Organic nitrogen (d) Carbon/Nitrogen ratios

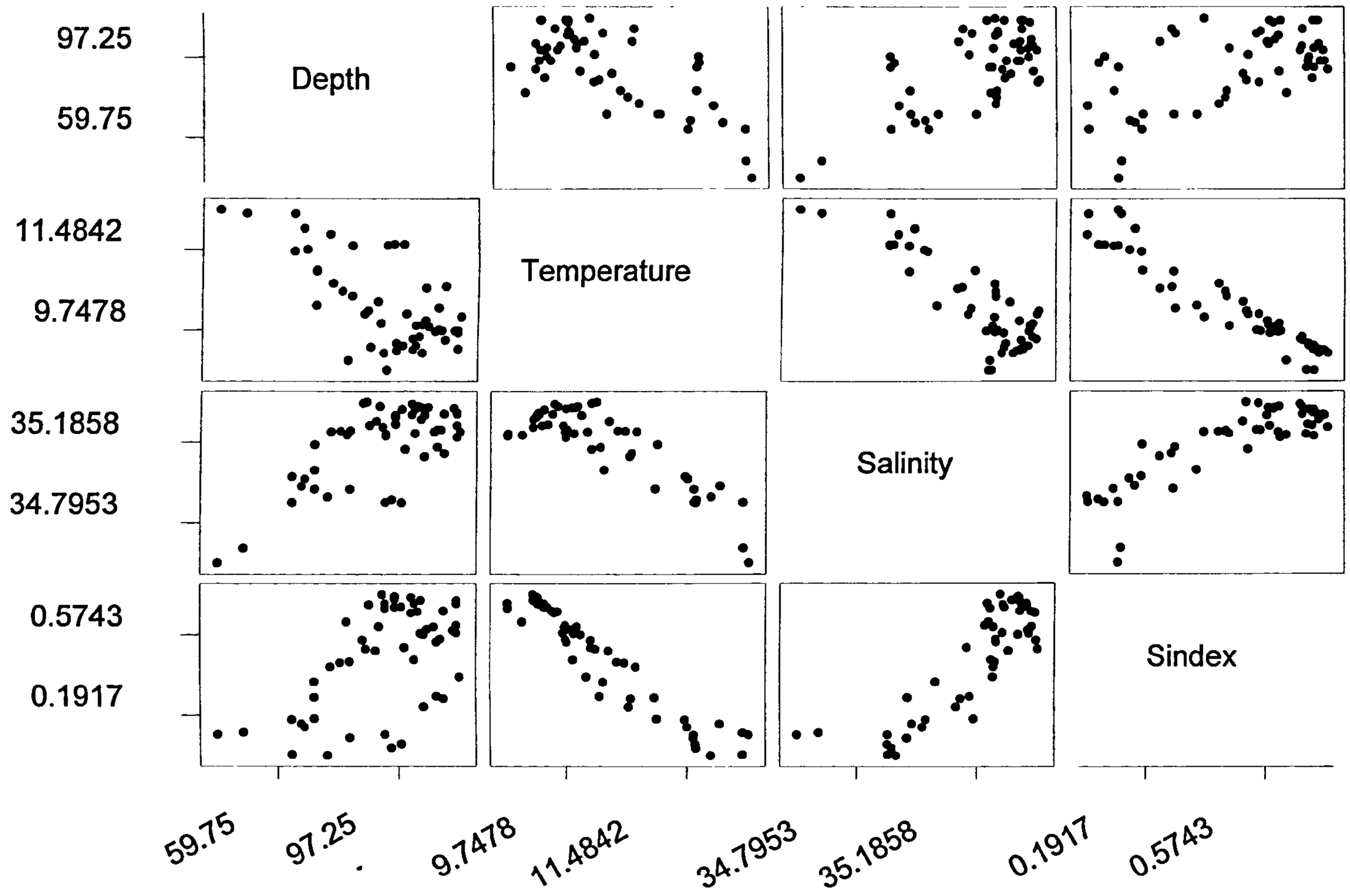


Figure 3.28 Matrix plot of water mass characteristics

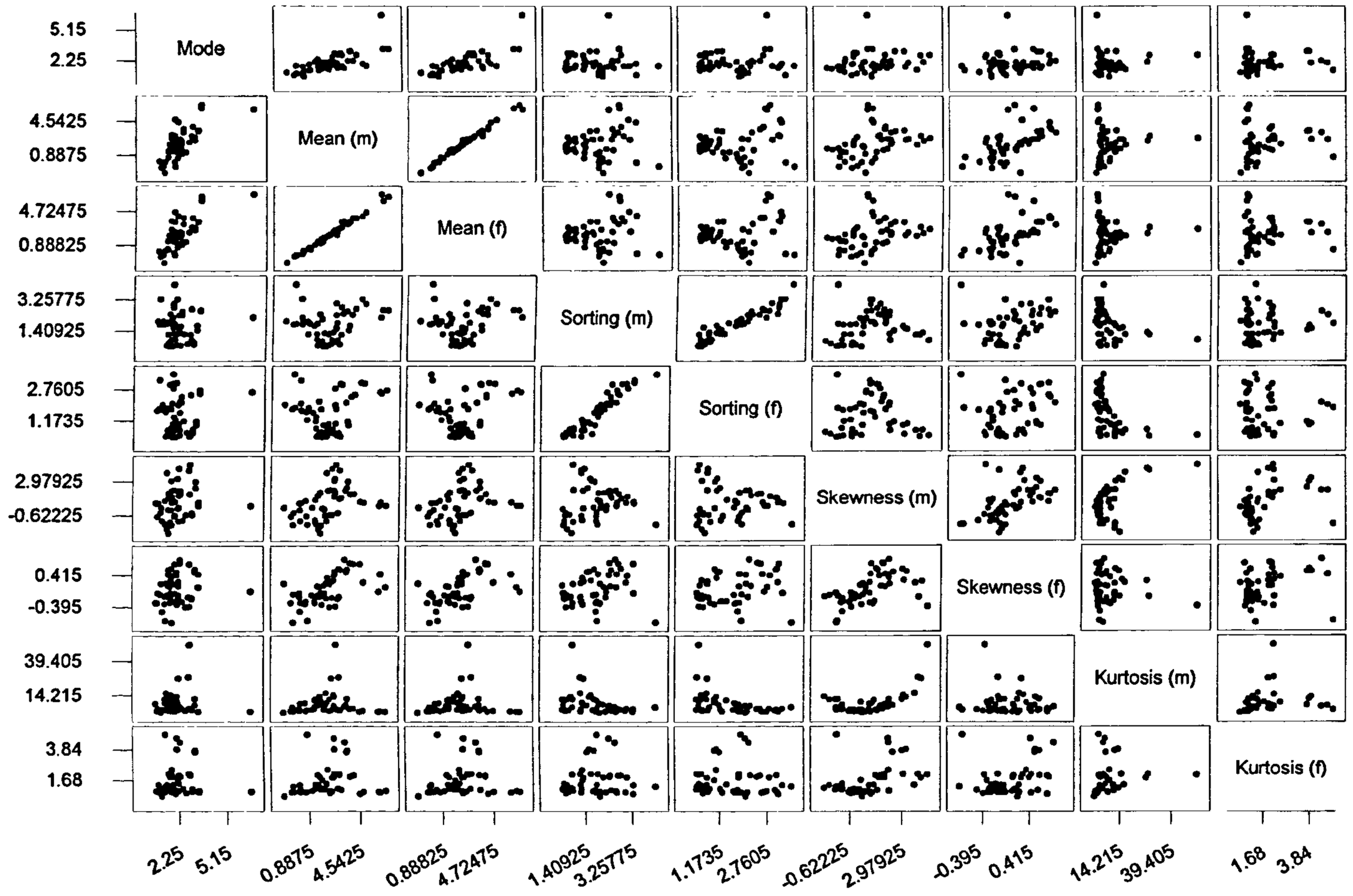


Figure 3.29 Matrix plot of moments (m) and Folks (f) grain size parameters

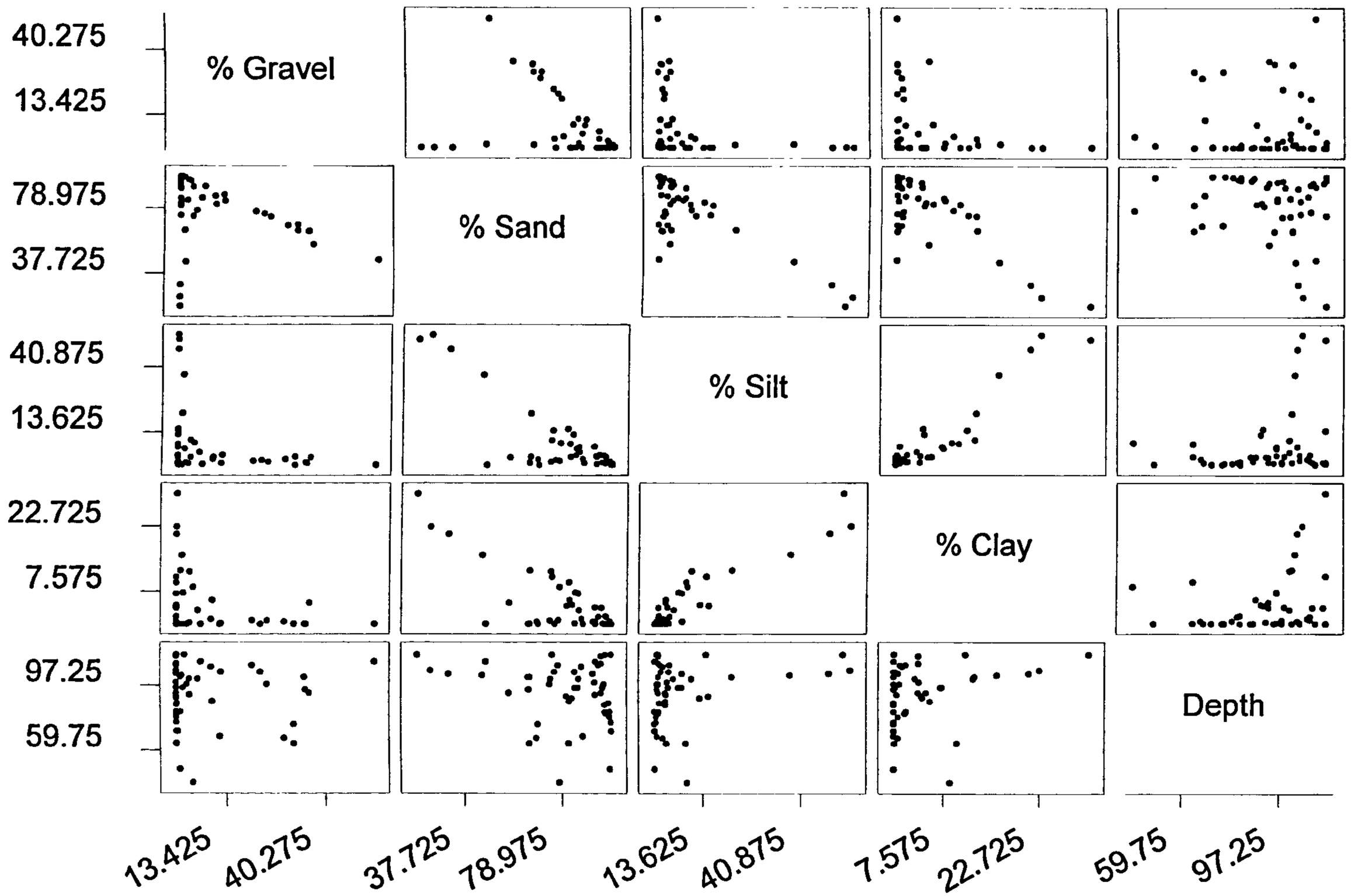


Figure 3.30 Matrix plot of grain size fractions and depth

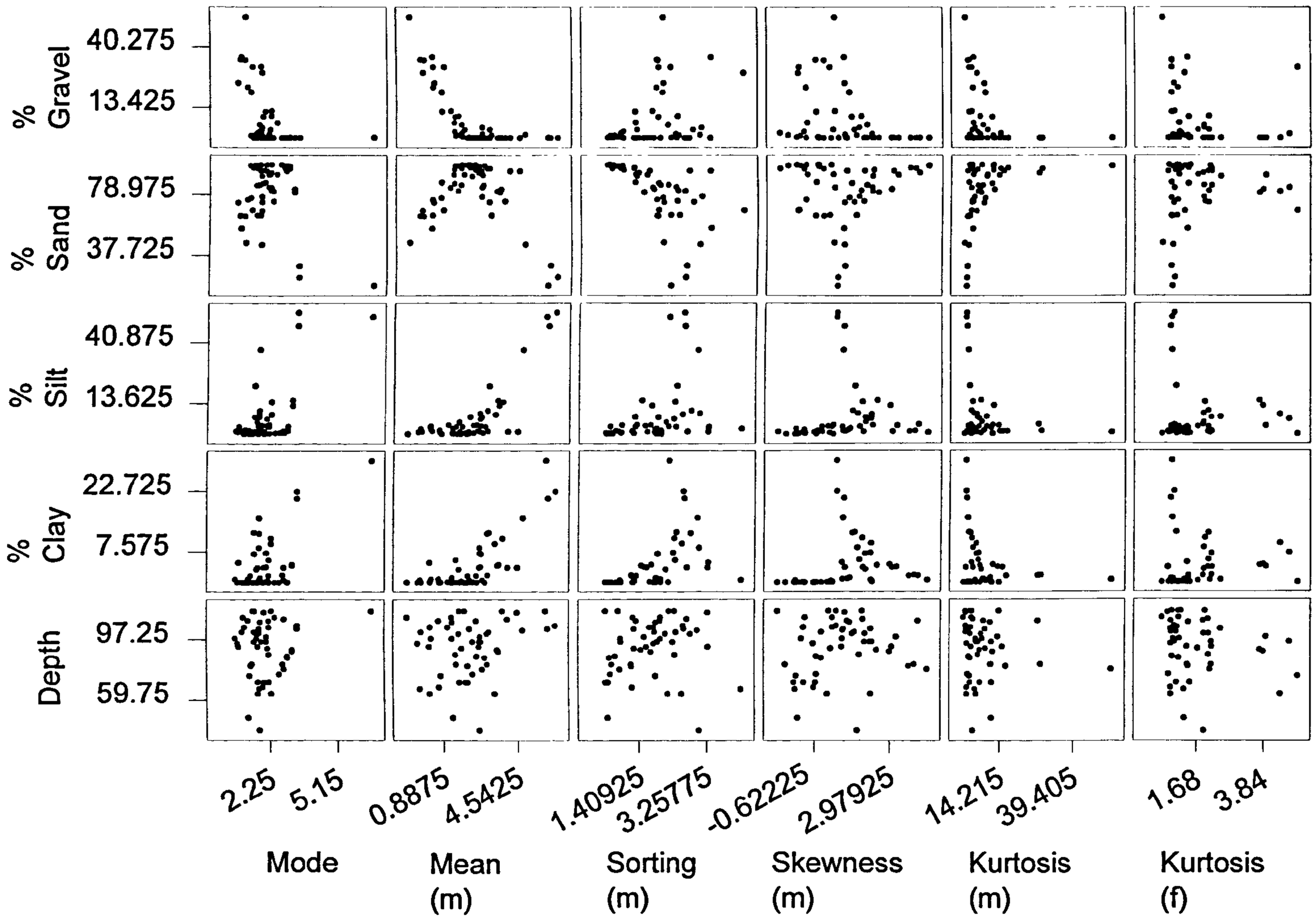


Figure 3.31 Plot of grain size fractions against grain size parameters

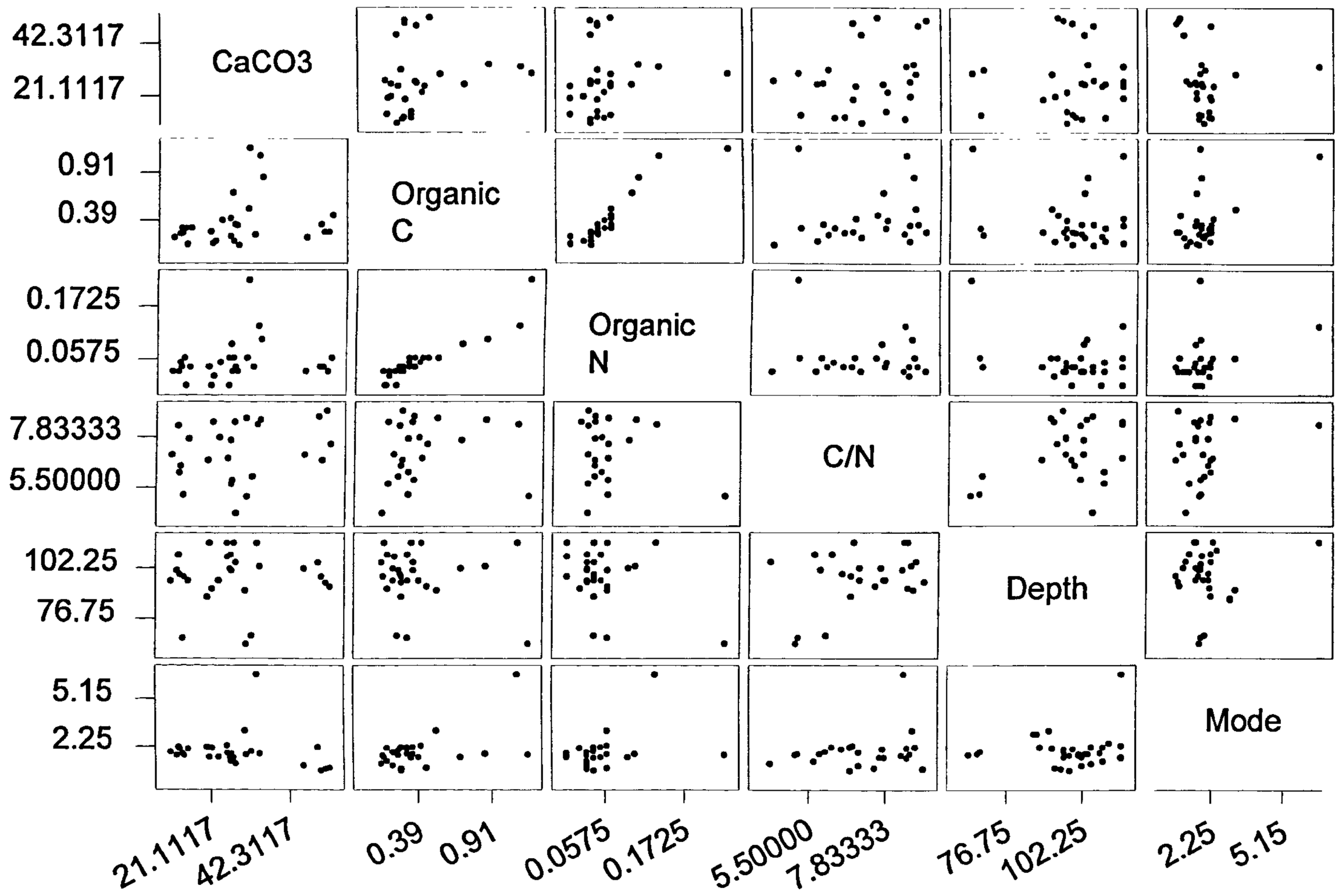


Figure 3.32 Matrix plot of geochemical variables, depth and modal grain size

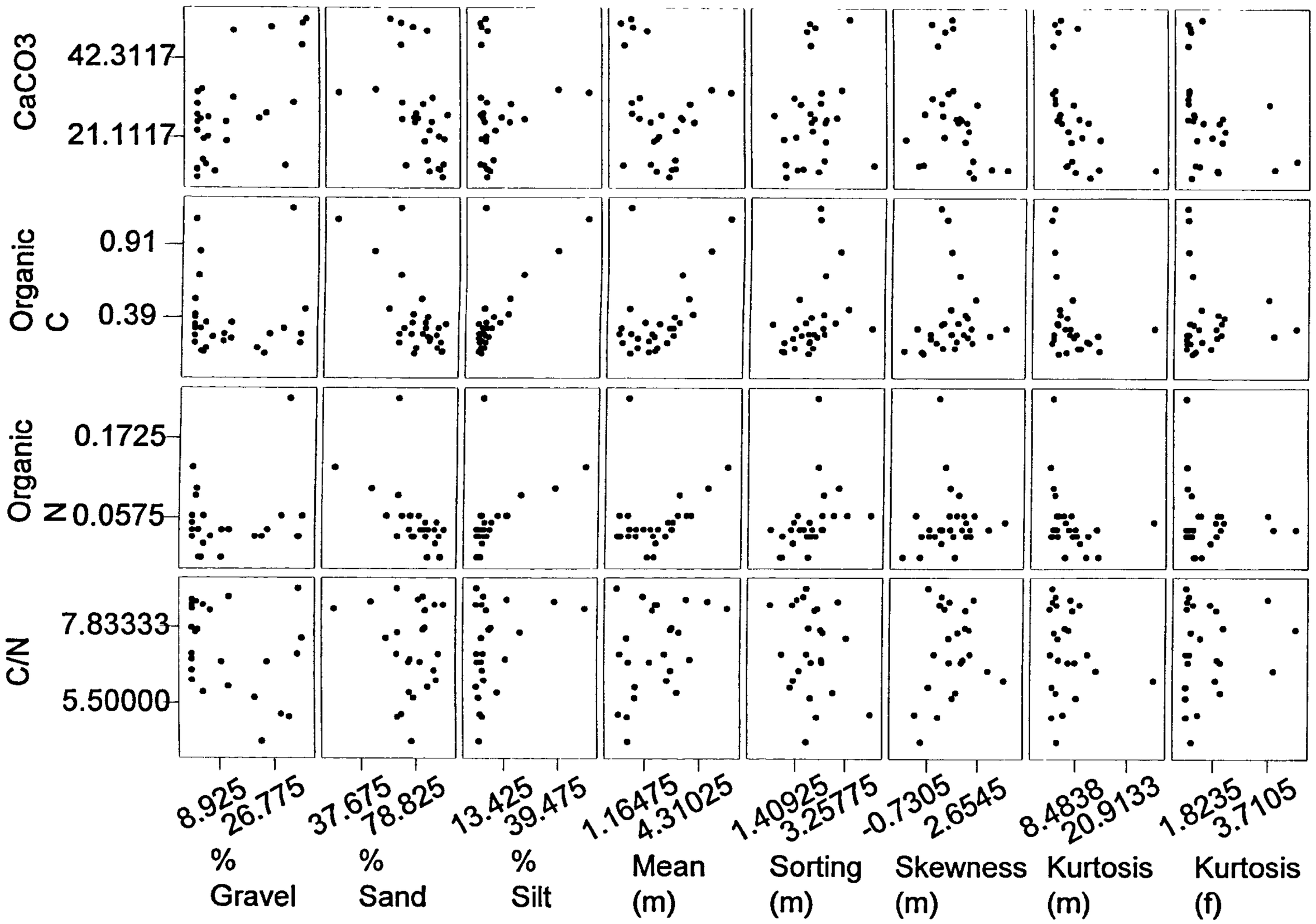


Figure 3.33 Plot of geochemical against grain size characteristics

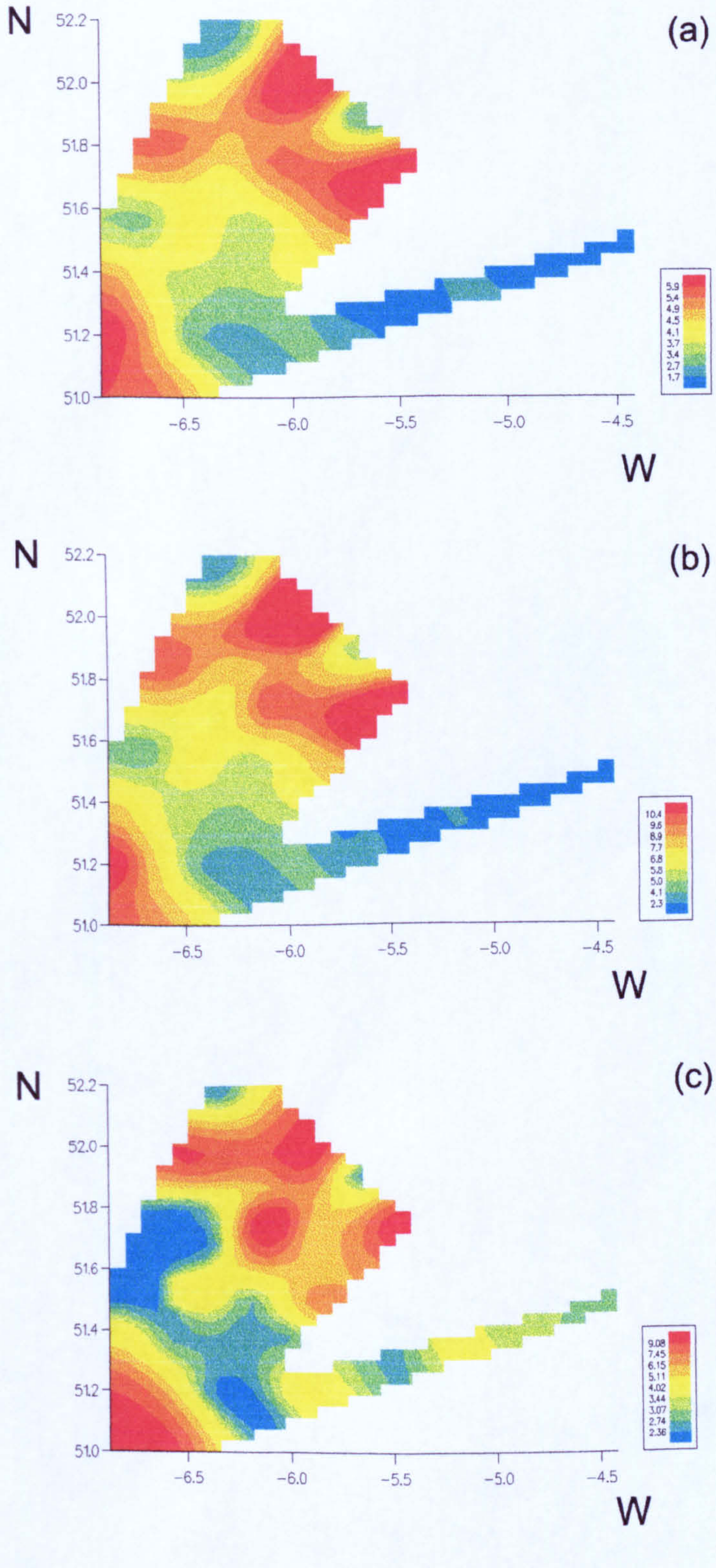


Figure 4.1 Variability in the diversity of the live assemblages across the study area as measured by the (a) Margalef index (b) Fisher-alpha index (c) 1/Simpson index

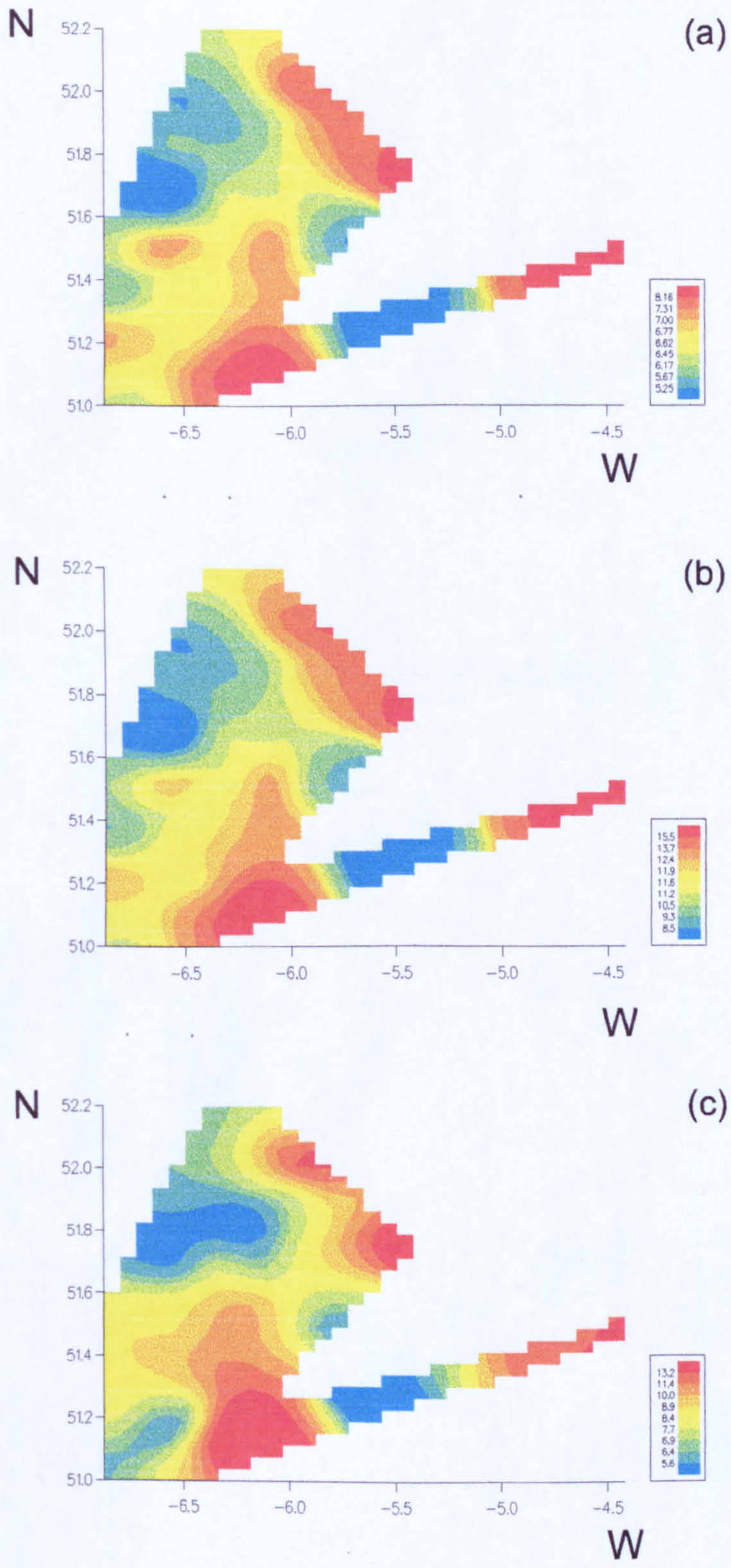


Figure 4.2 Variability in the diversity of the dead assemblages across the study area as measured by the (a) Margalef index (b) Fisher-alpha index (c) 1/Simpson index

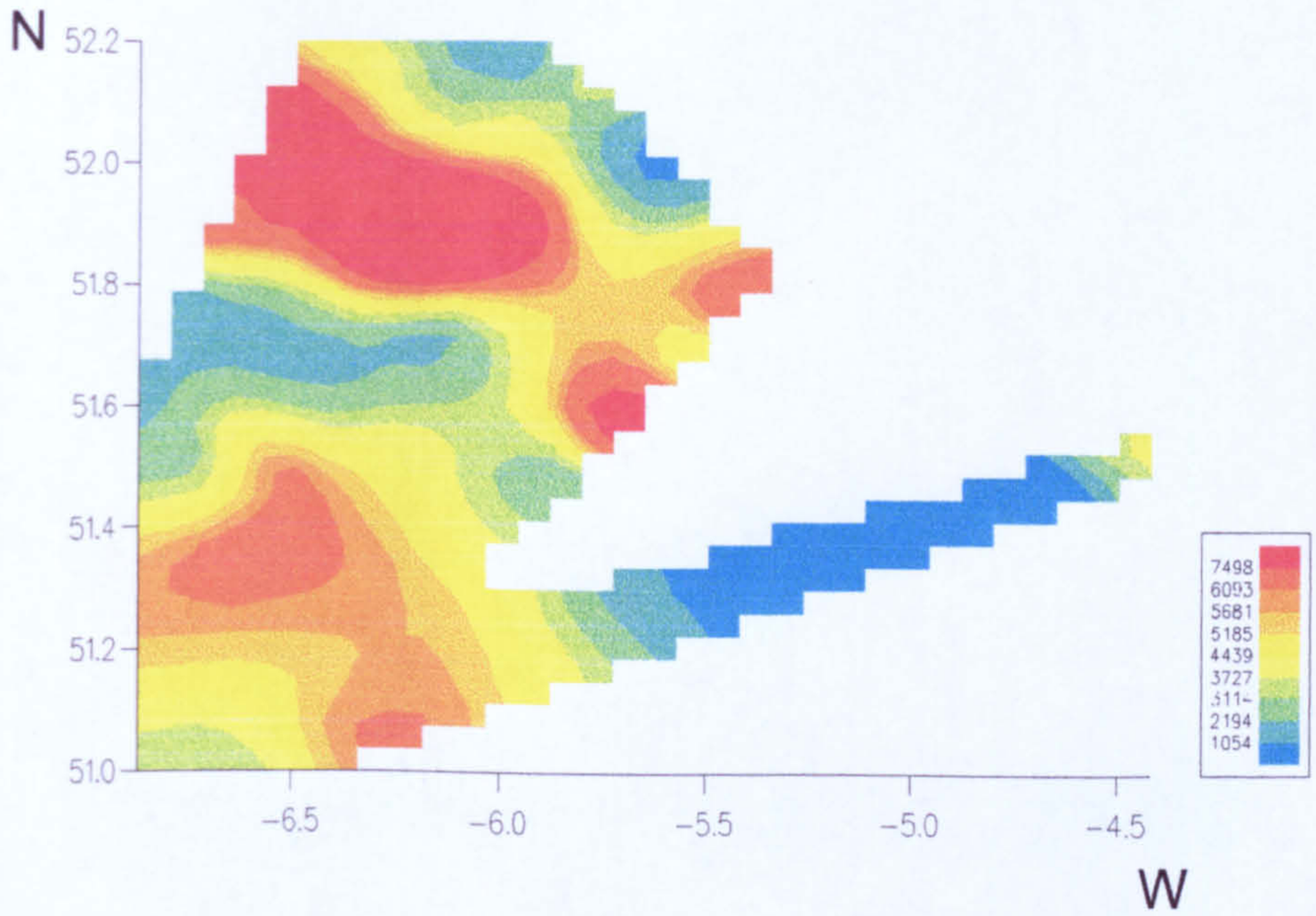


Figure 4.3 Variability in the density of the foraminiferal assemblages across the study area for (a) living assemblages (b) dead assemblages

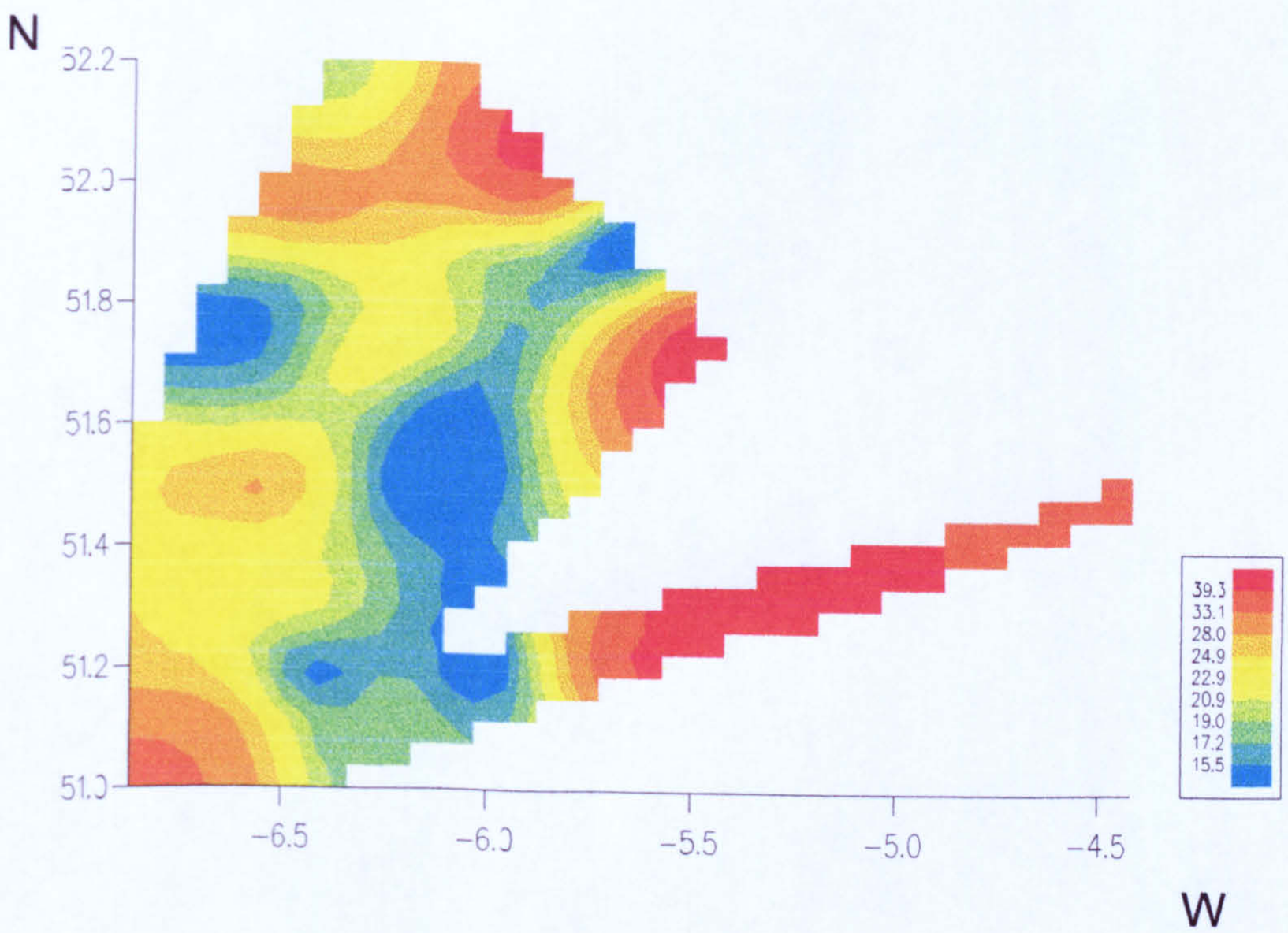


Figure 4.4 Variability in affinity (Rogers, 1976) between the living and dead assemblages of the study area

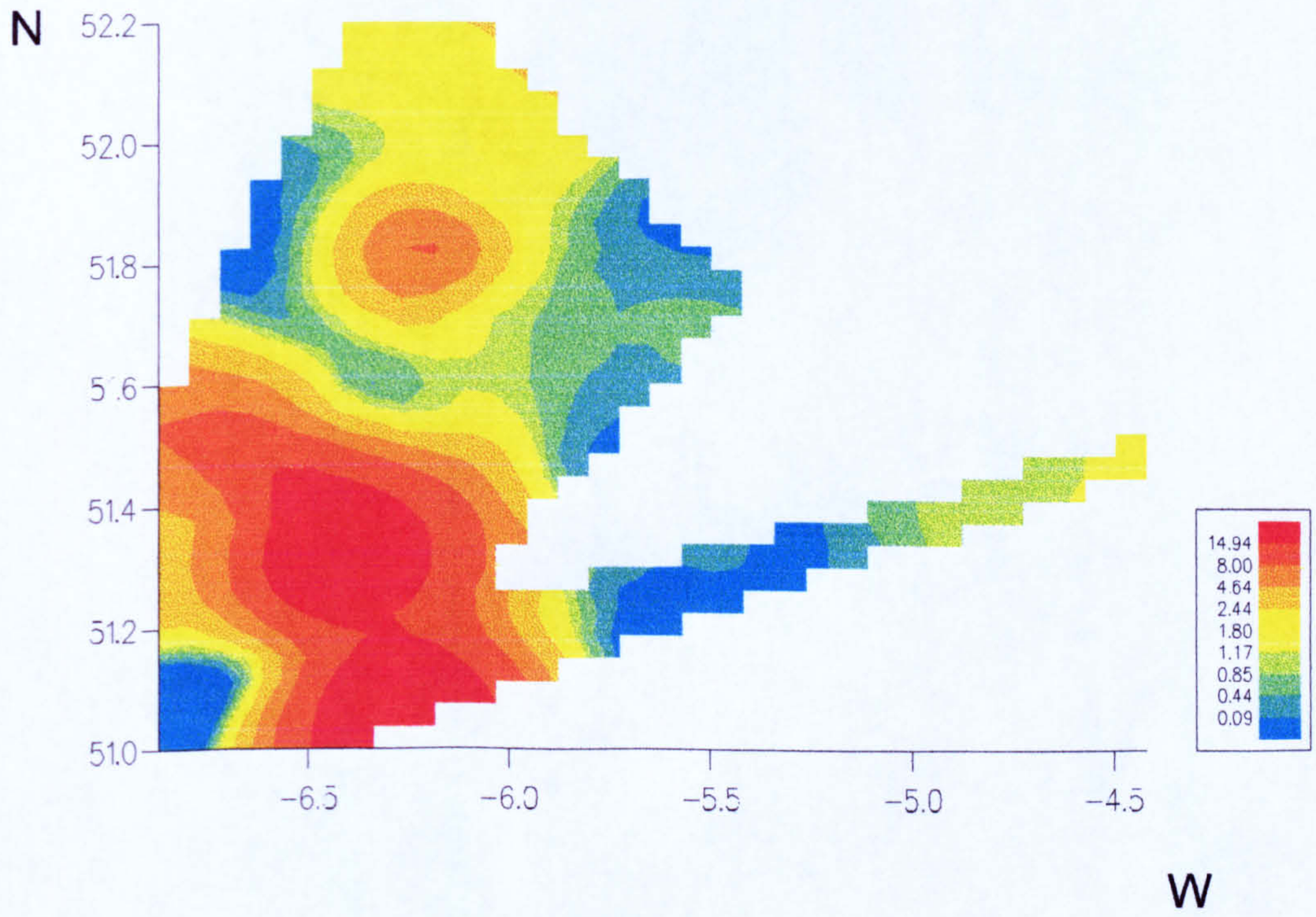
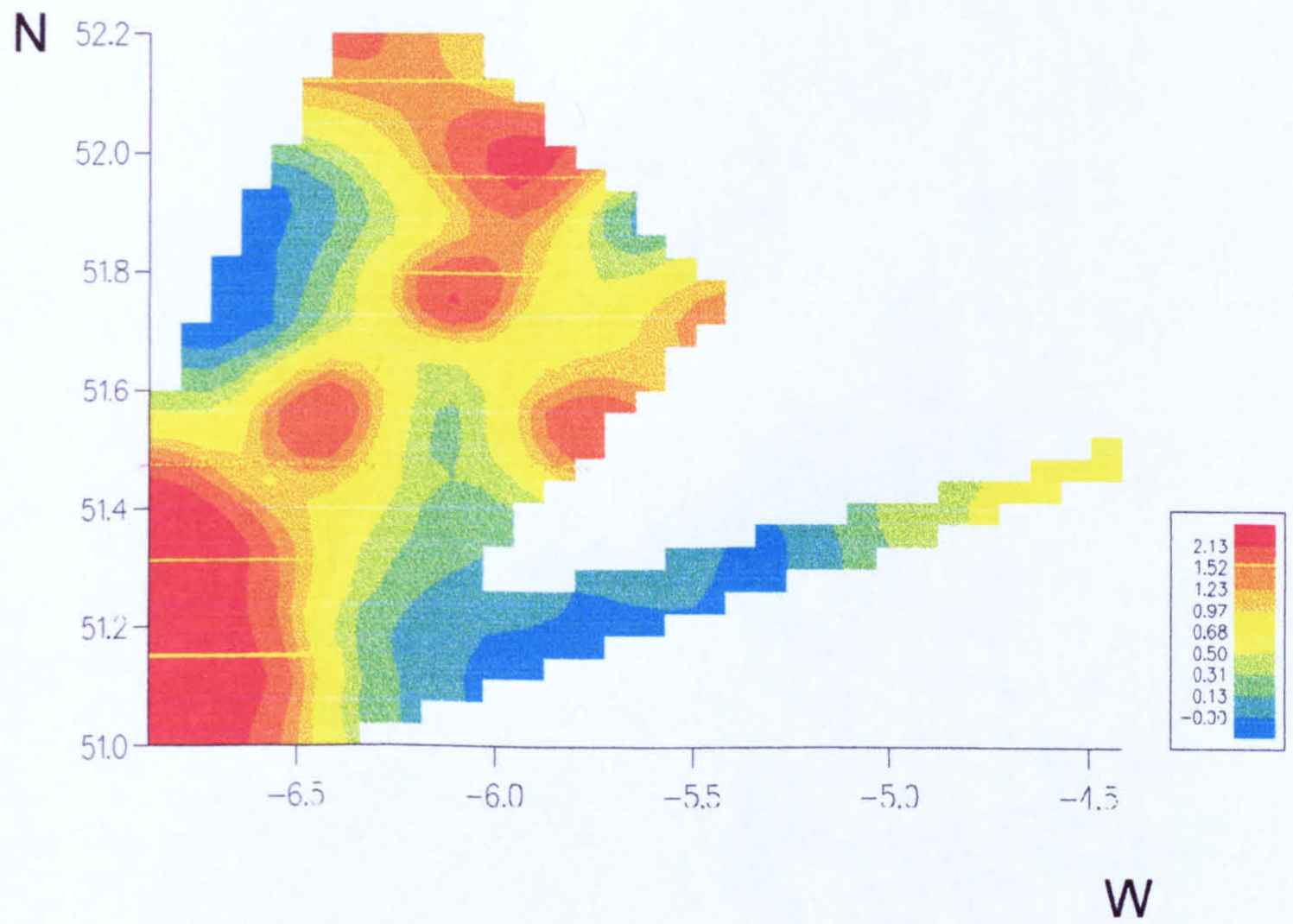


Figure 4.5 Variability in the % contribution of planktonic tests relative to the dead assemblages



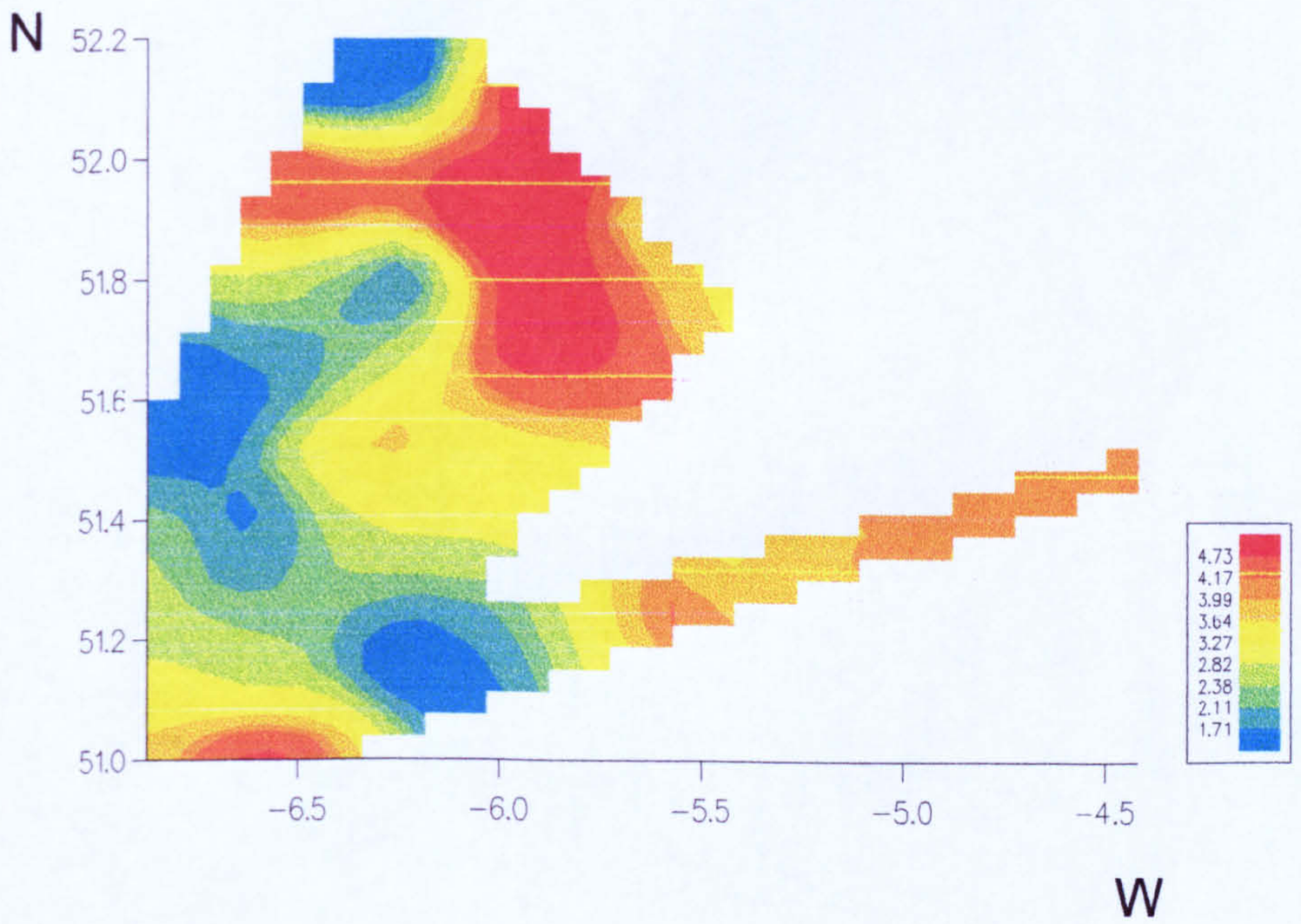
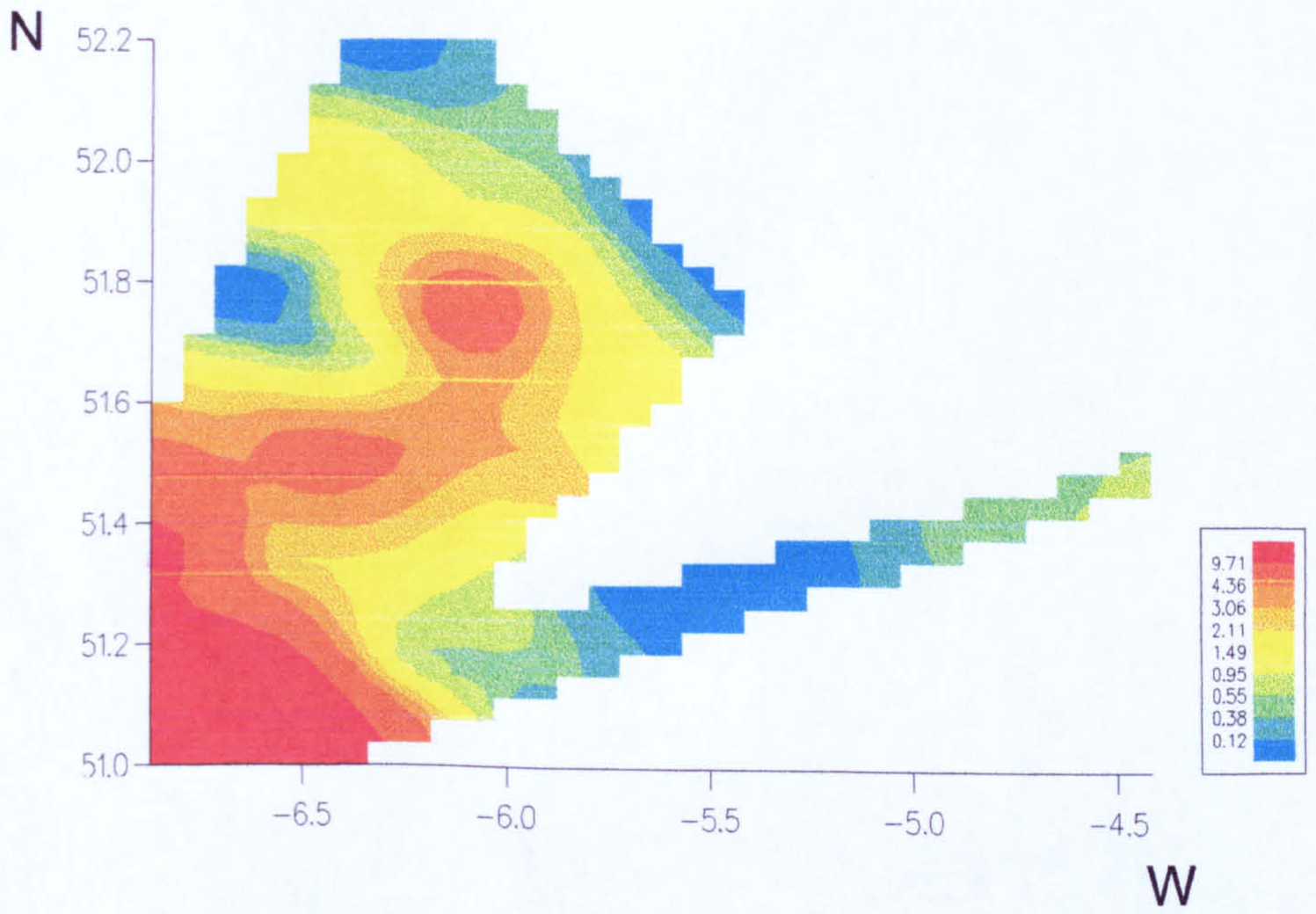


Figure 4.6 % distribution of *Ammonia beccari* (a) living (b) dead



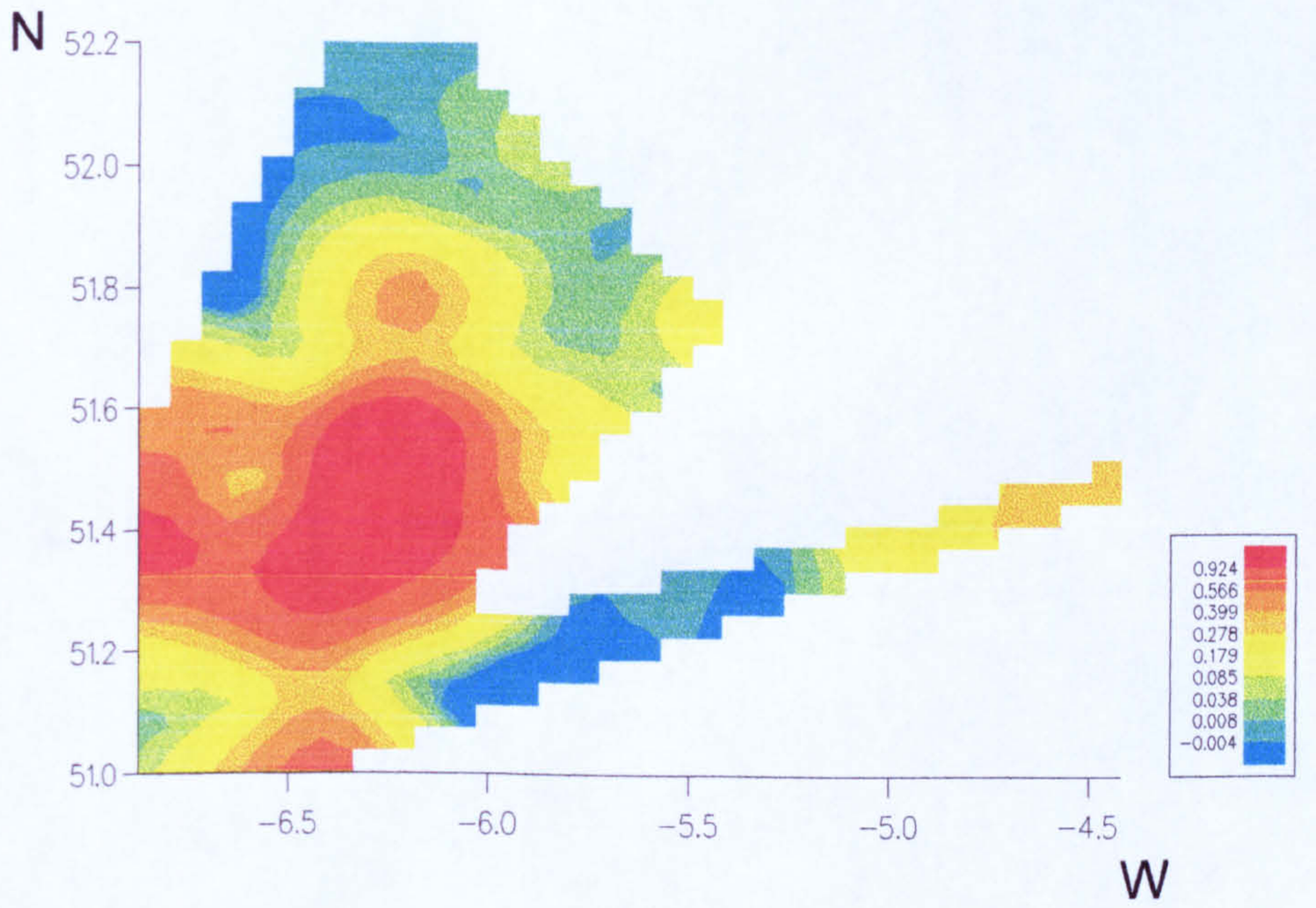
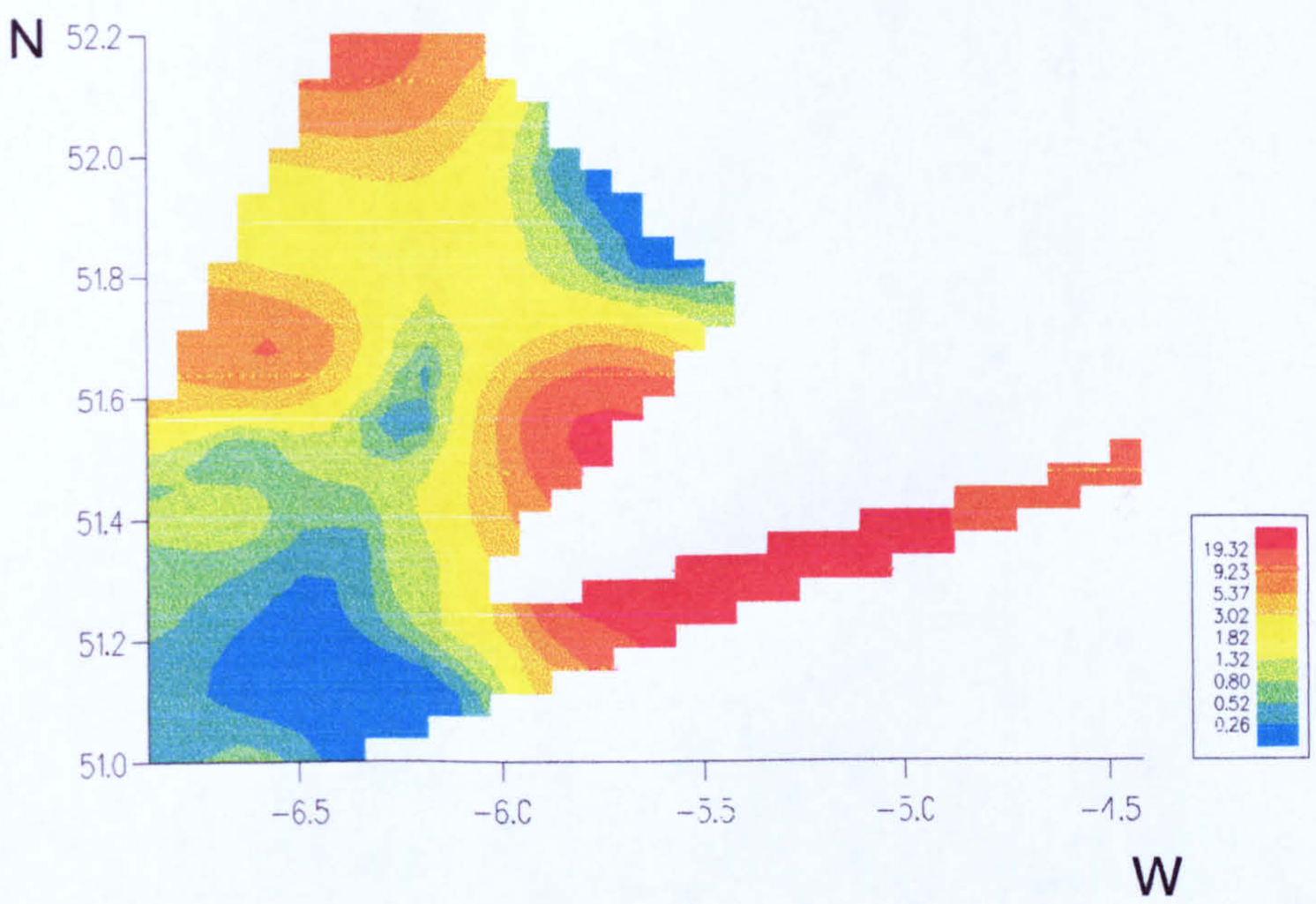


Figure 4.7 % distribution of *Adercotryma glomeratum* (a) living (b) dead



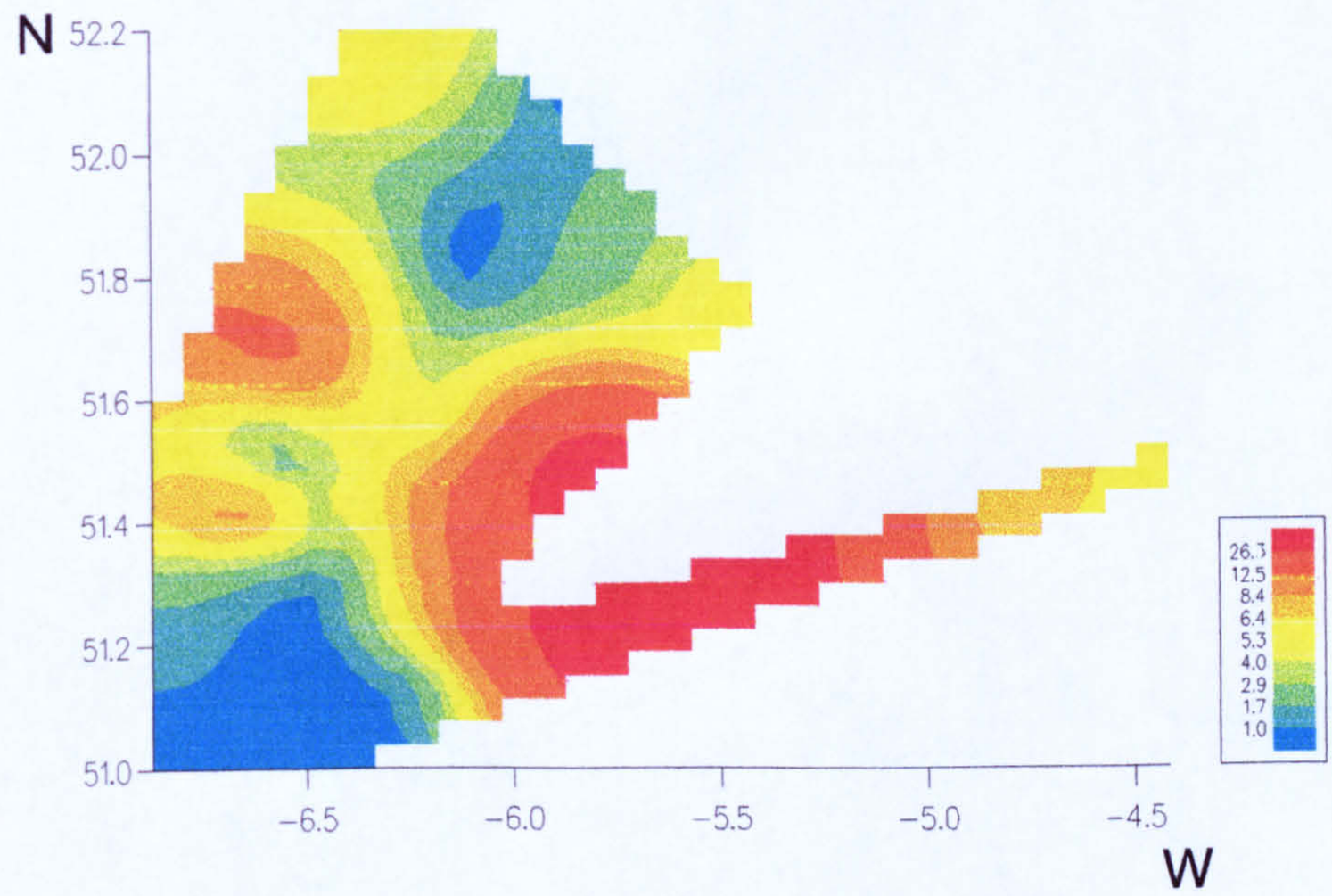


Figure 4.8 % distribution of *Bulimina gibba* (a) living (b) dead

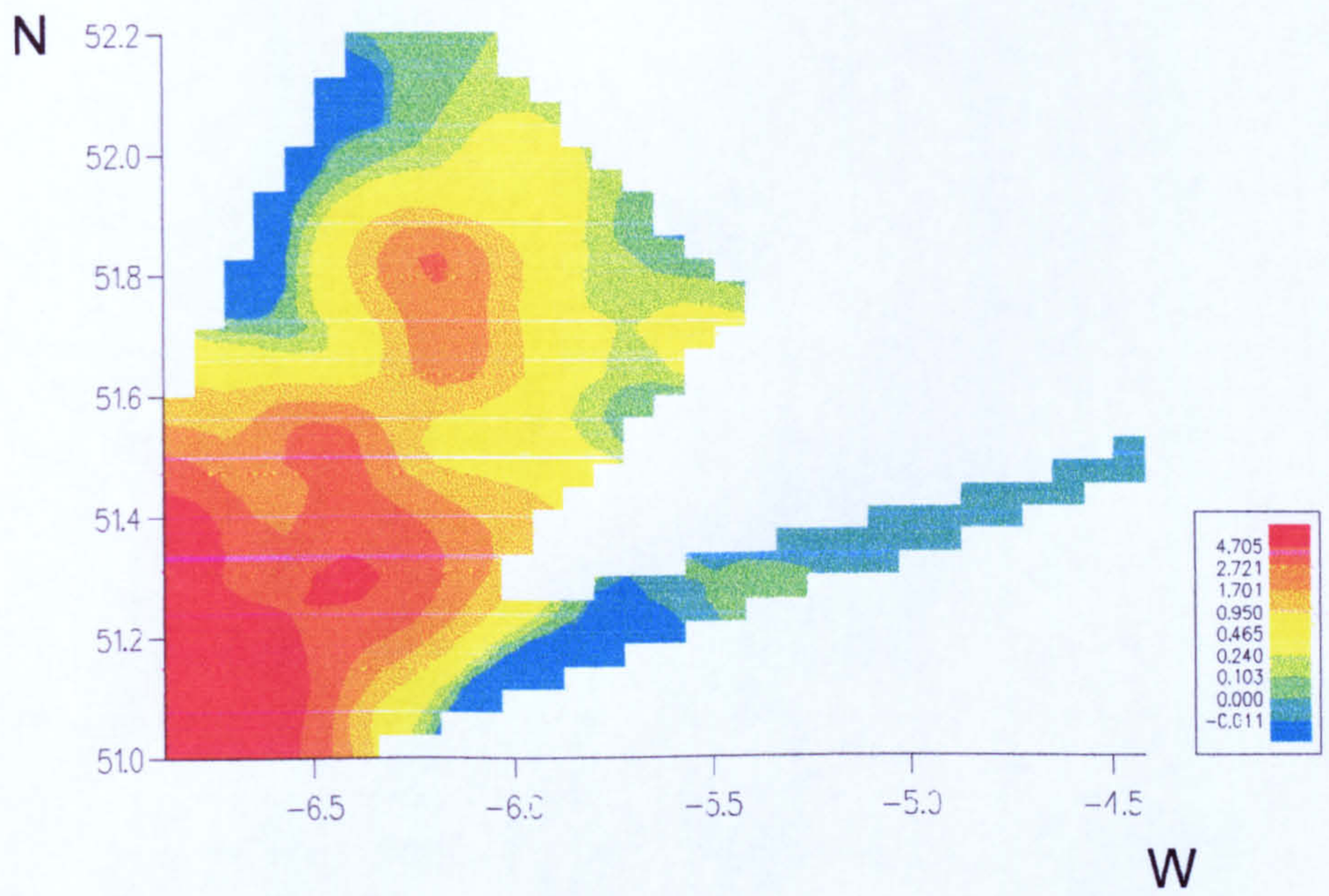


Figure 4.9 % distribution of *Bulimina marginata* (a) living (b) dead

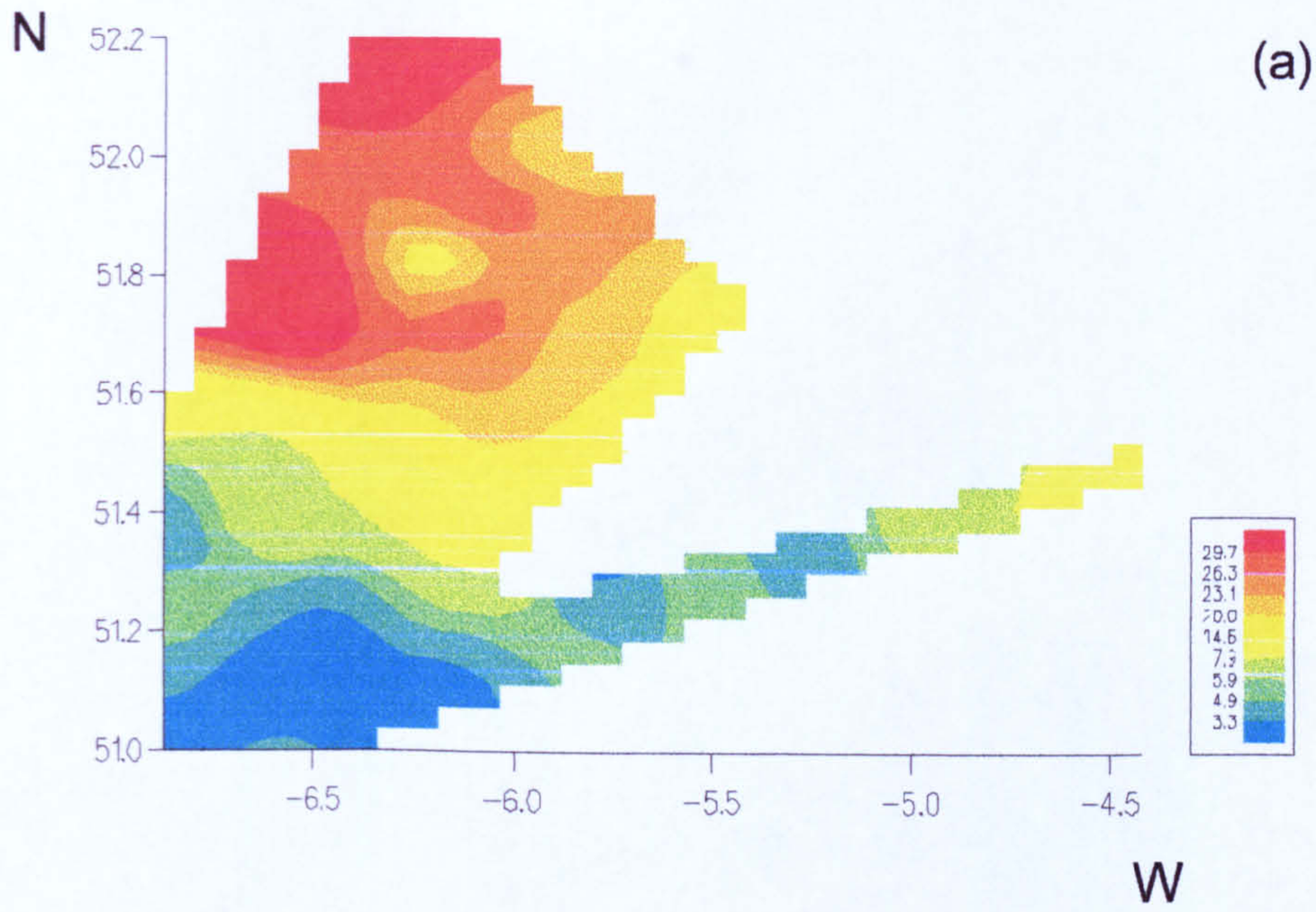
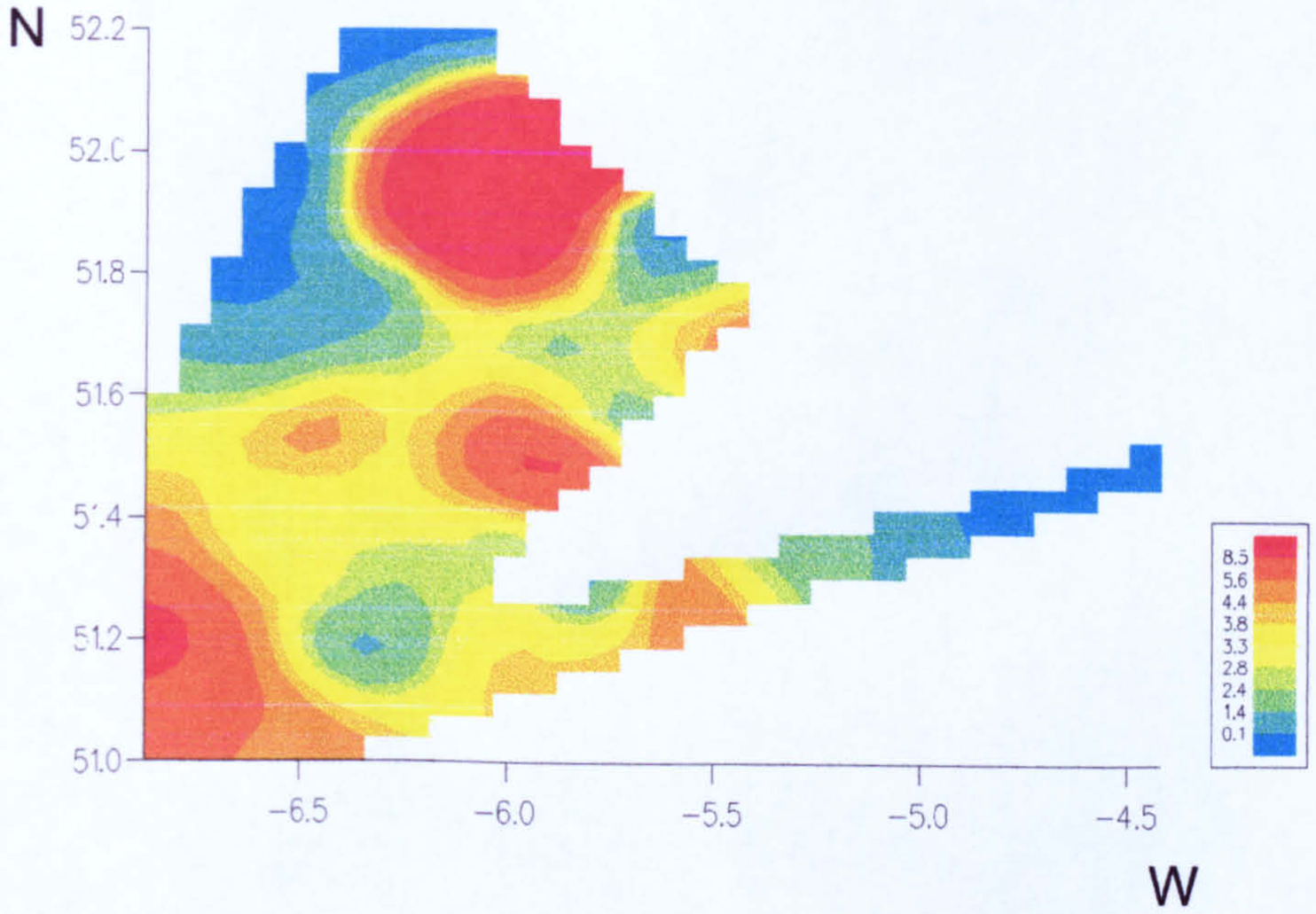


Figure 4.10 % distribution of *Cibicides lobatulus* (a) living (b) dead



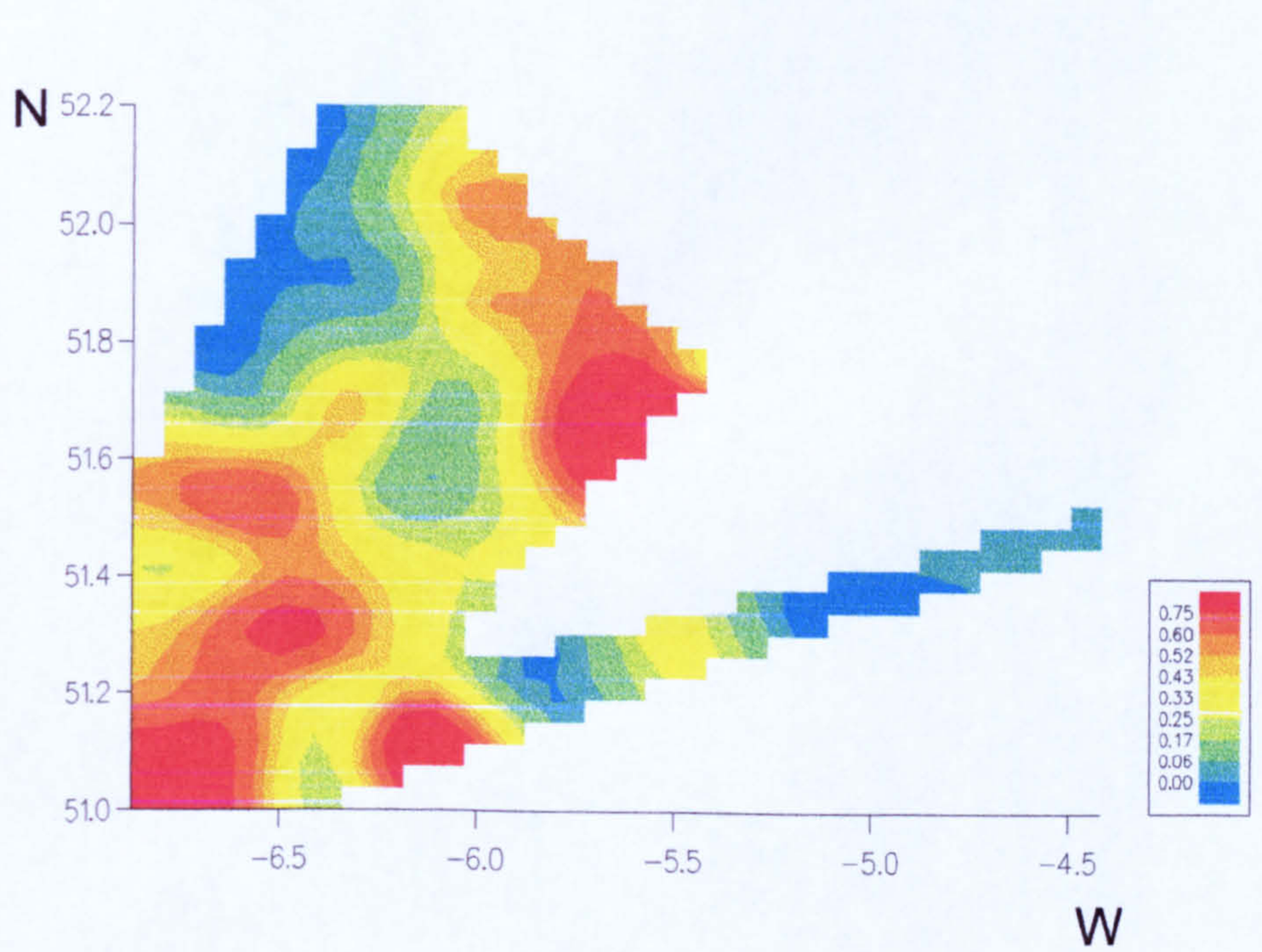
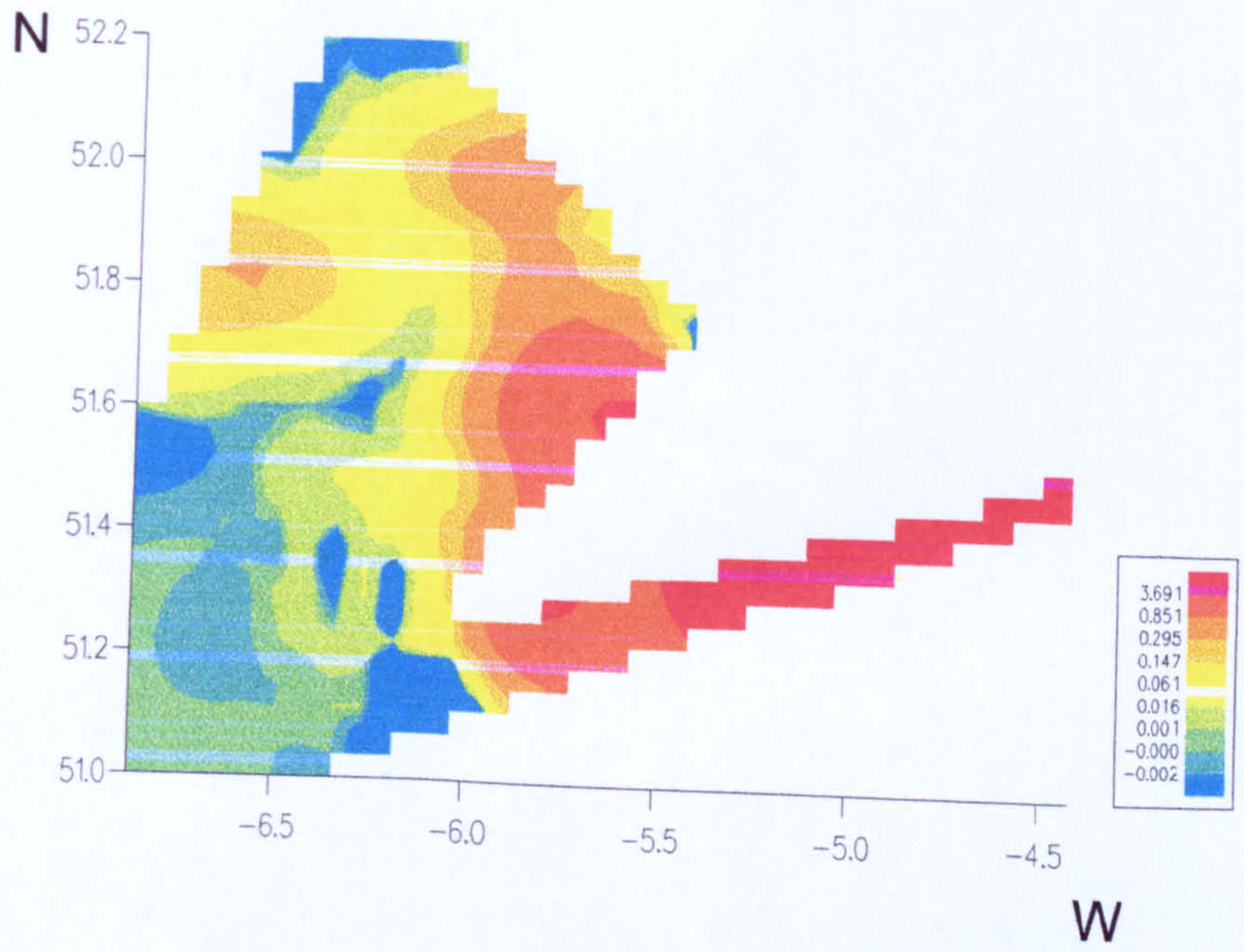


Figure 4.11 % distribution of *Cancris auricula* (a) living (b) dead



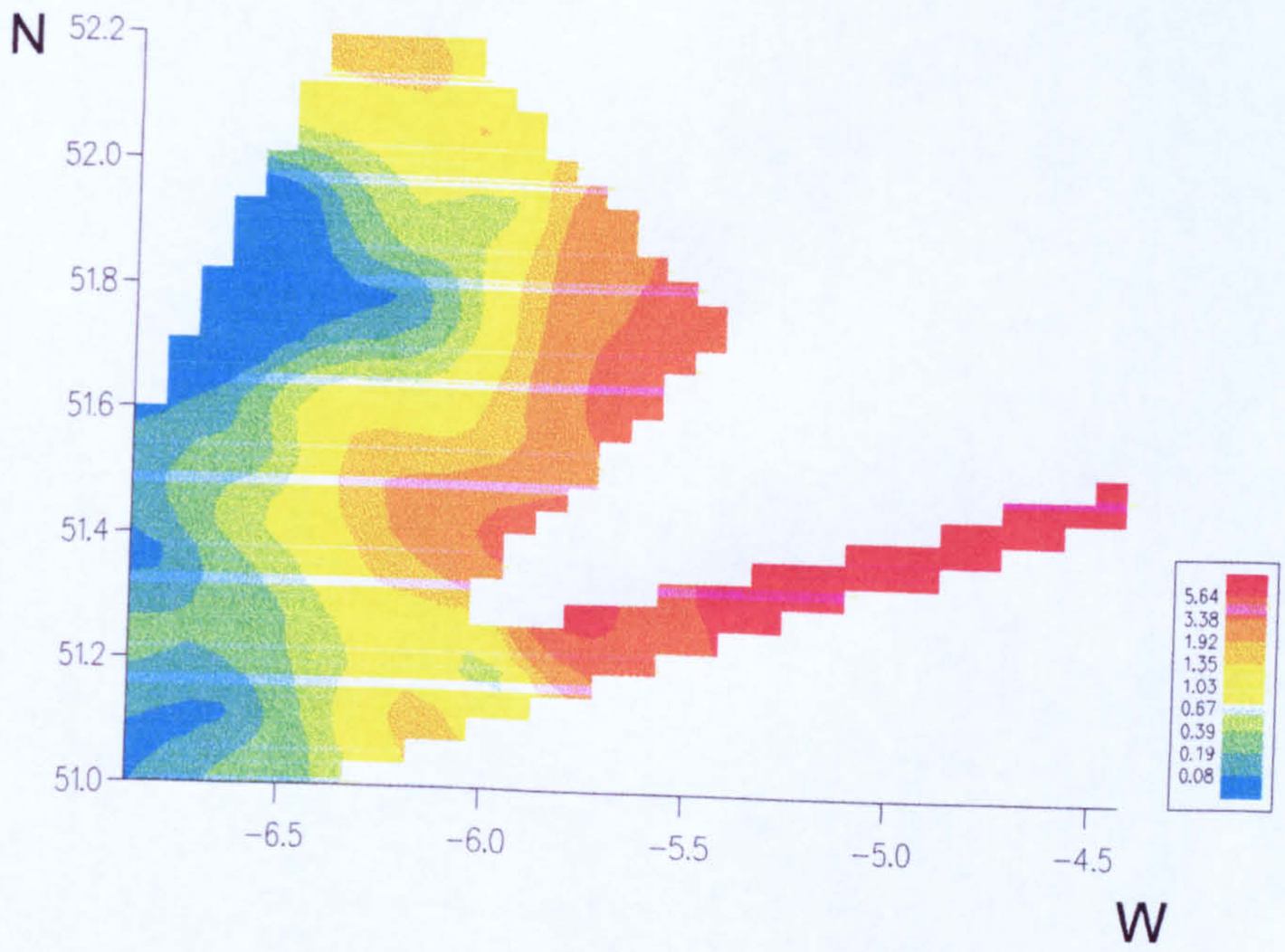
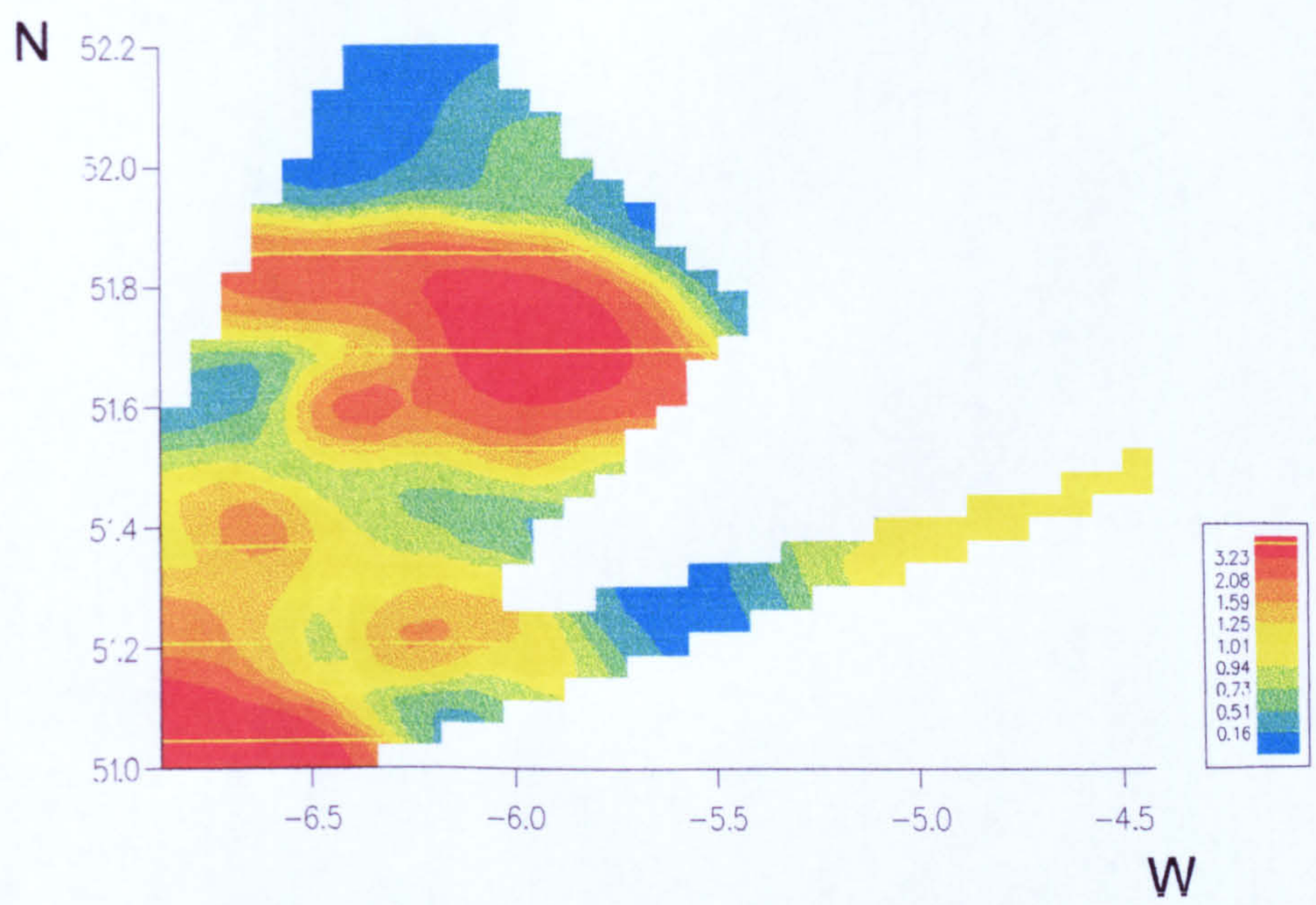


Figure 4.12 % distribution of *Elphidium excavatum* forma *selseyensis* (a) living (b) dead



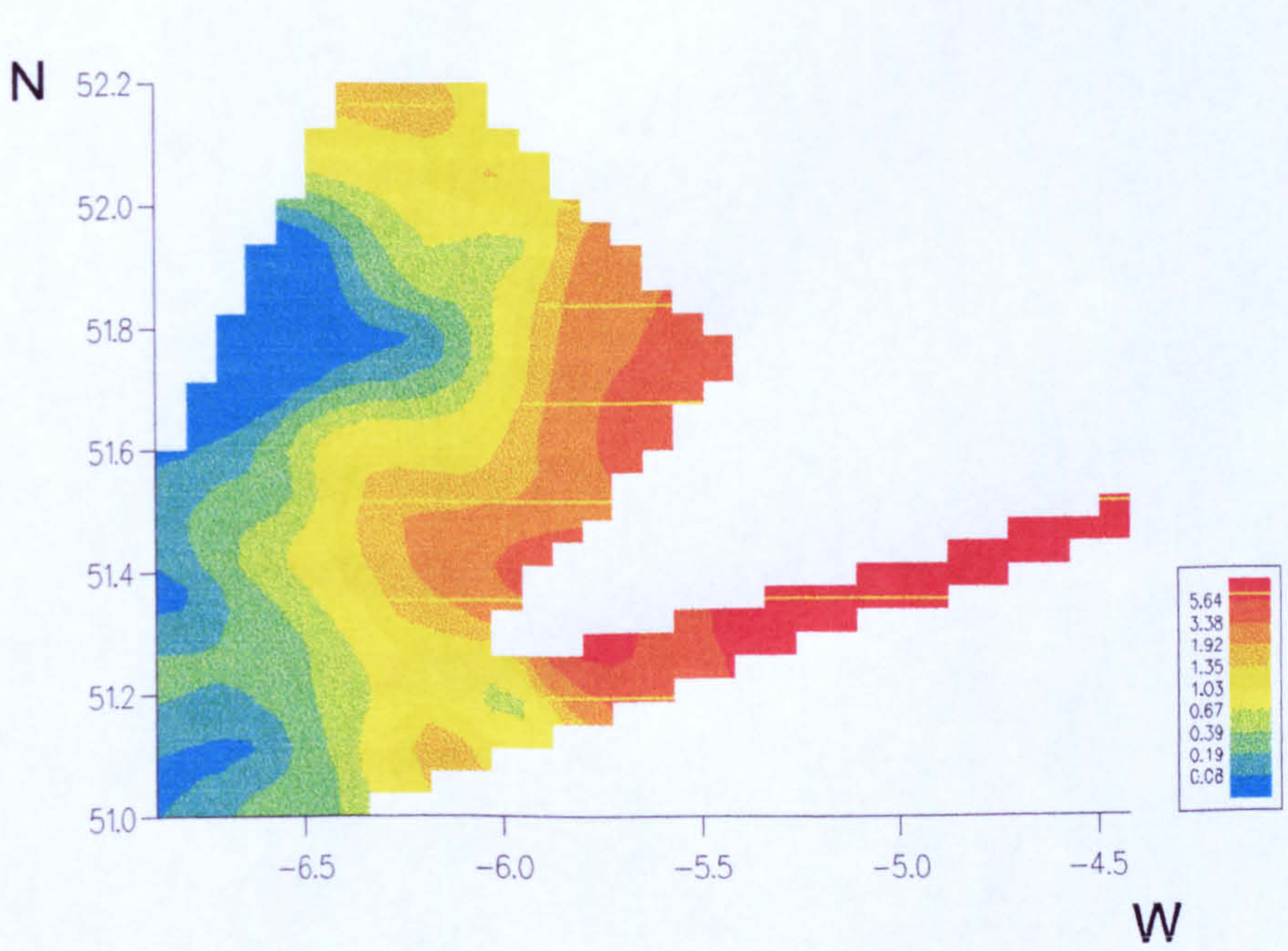
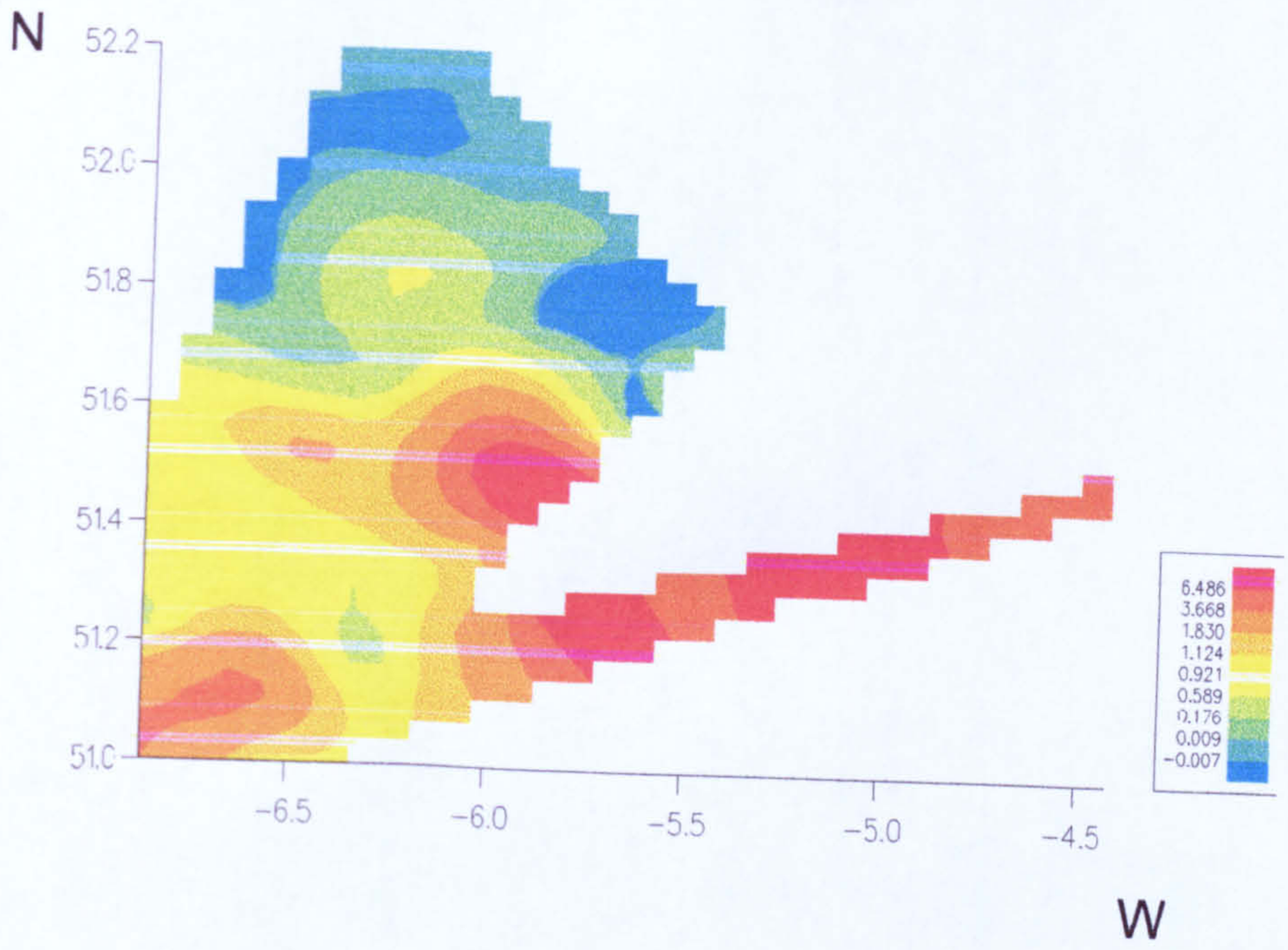


Figure 4.13 % distribution of *Epistominella naerenis* (a) living (b) dead



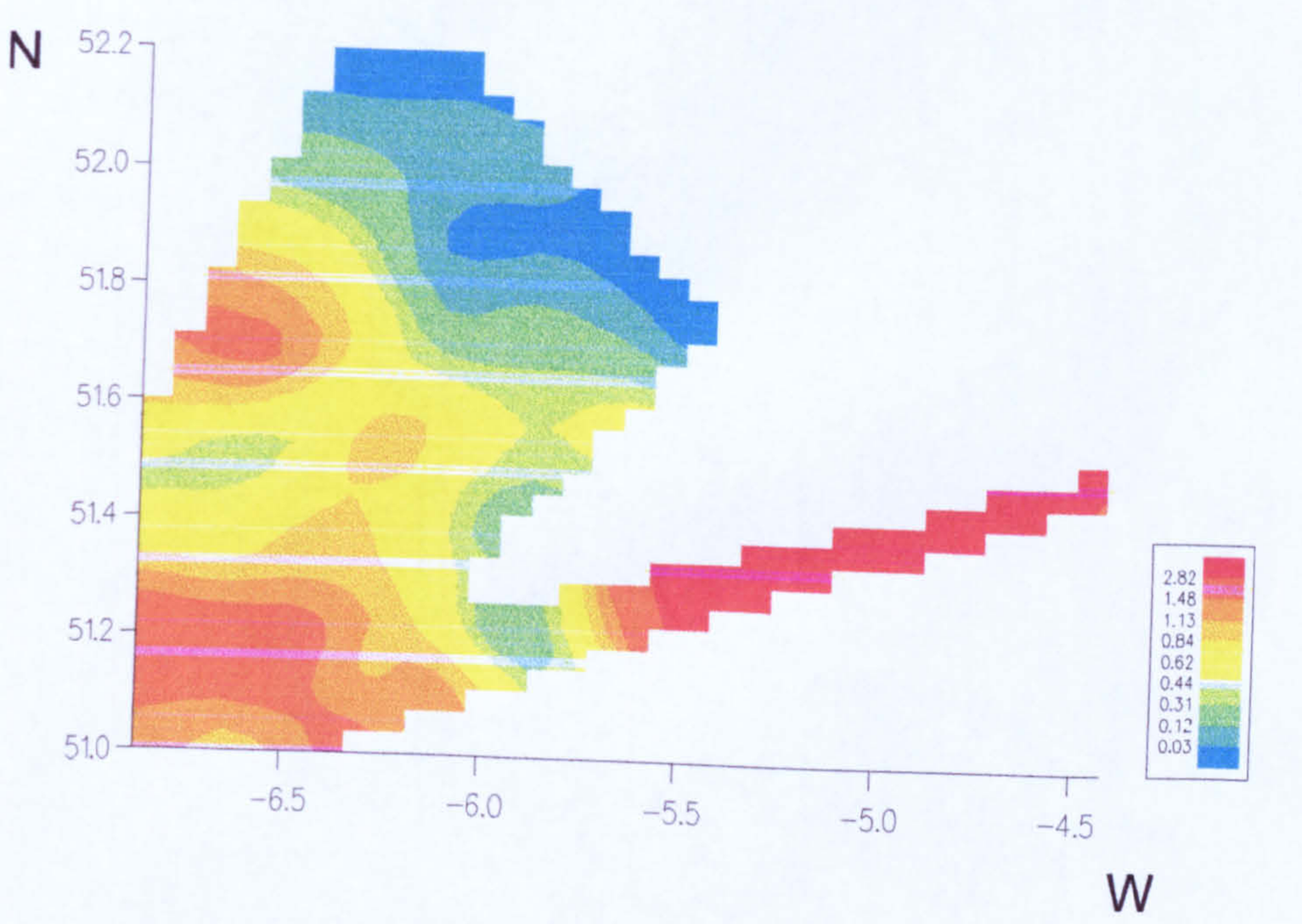
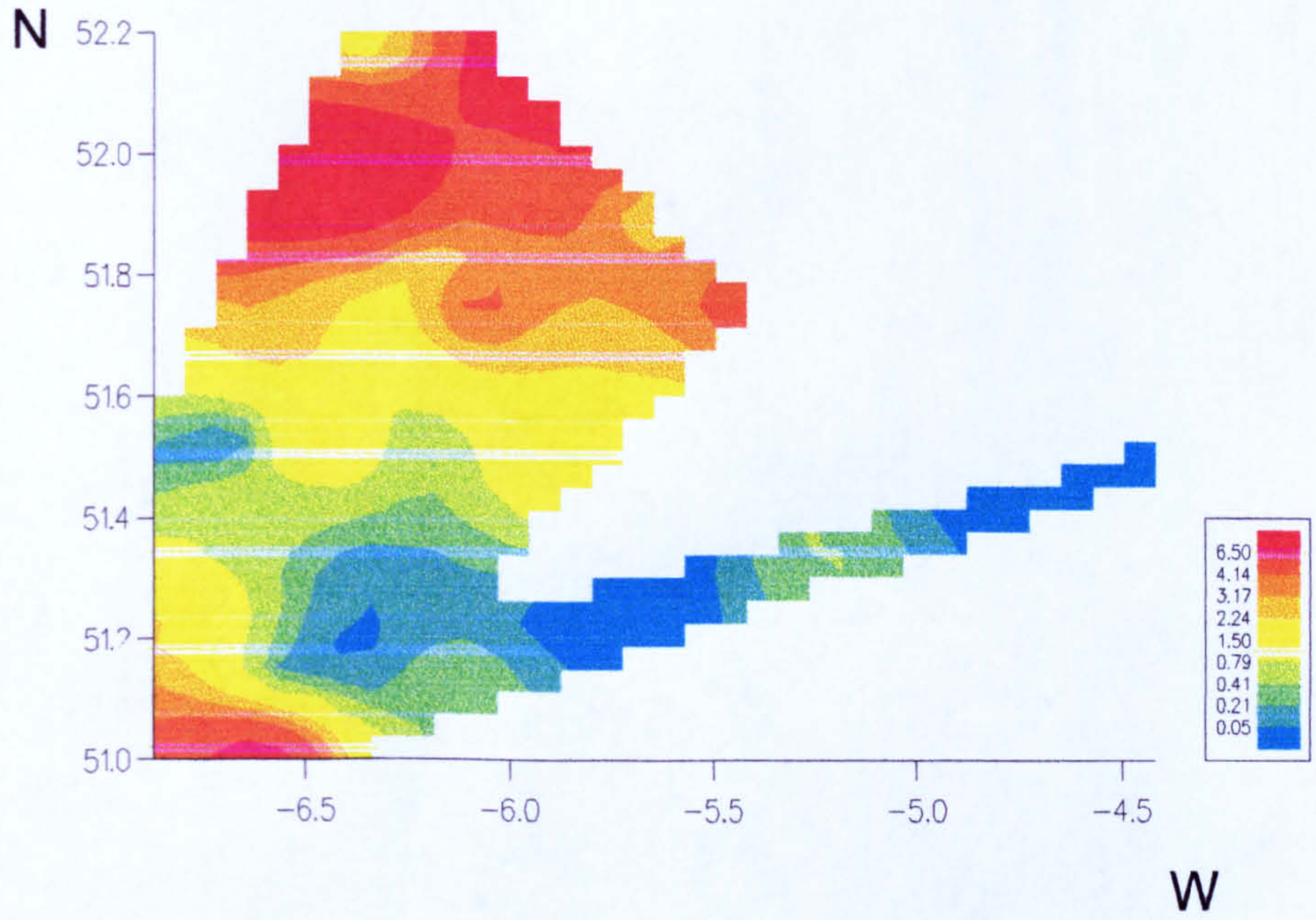


Figure 4.14 % distribution of *Eggerelloides scabrus* (a) living (b) dead



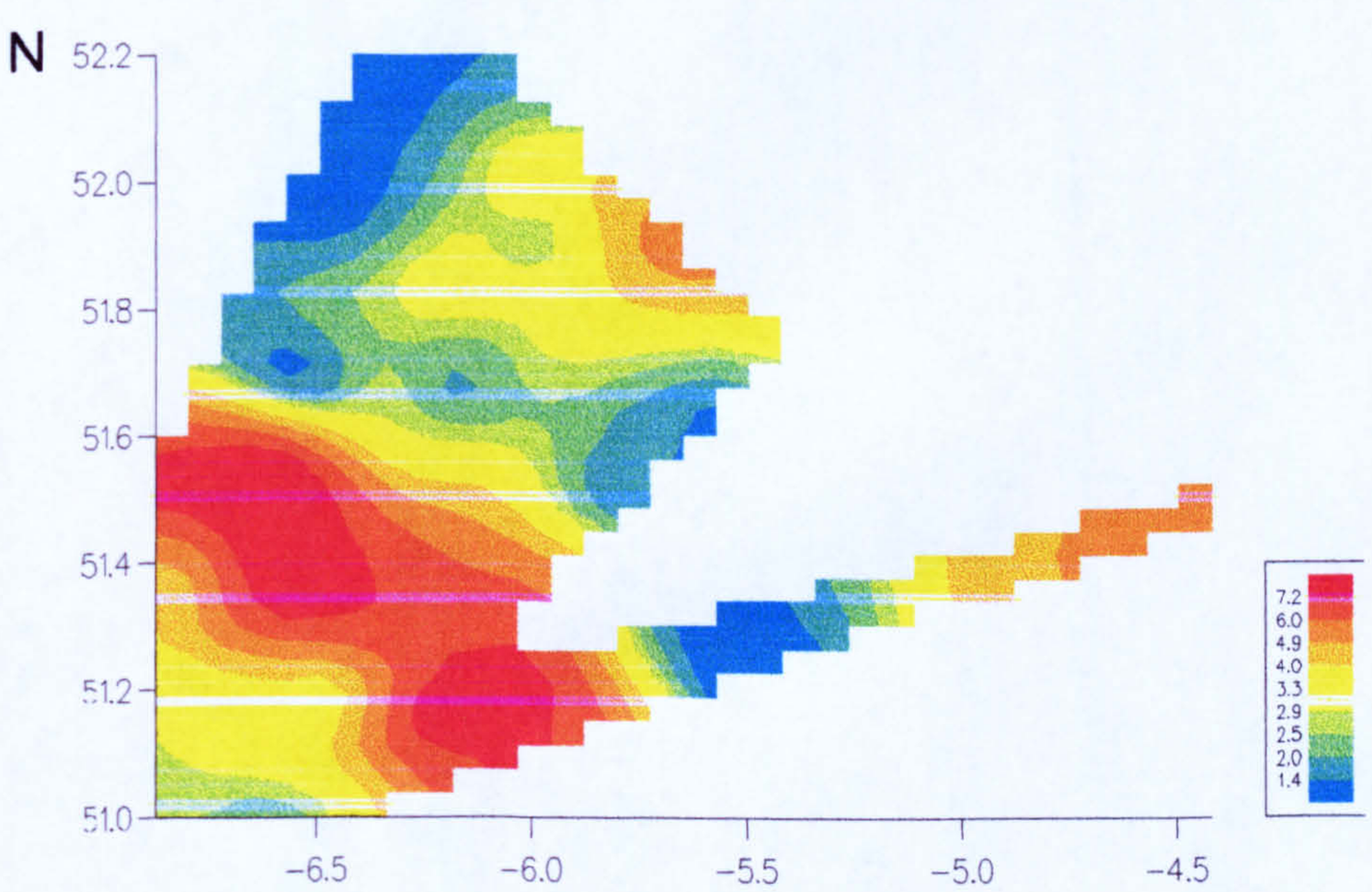
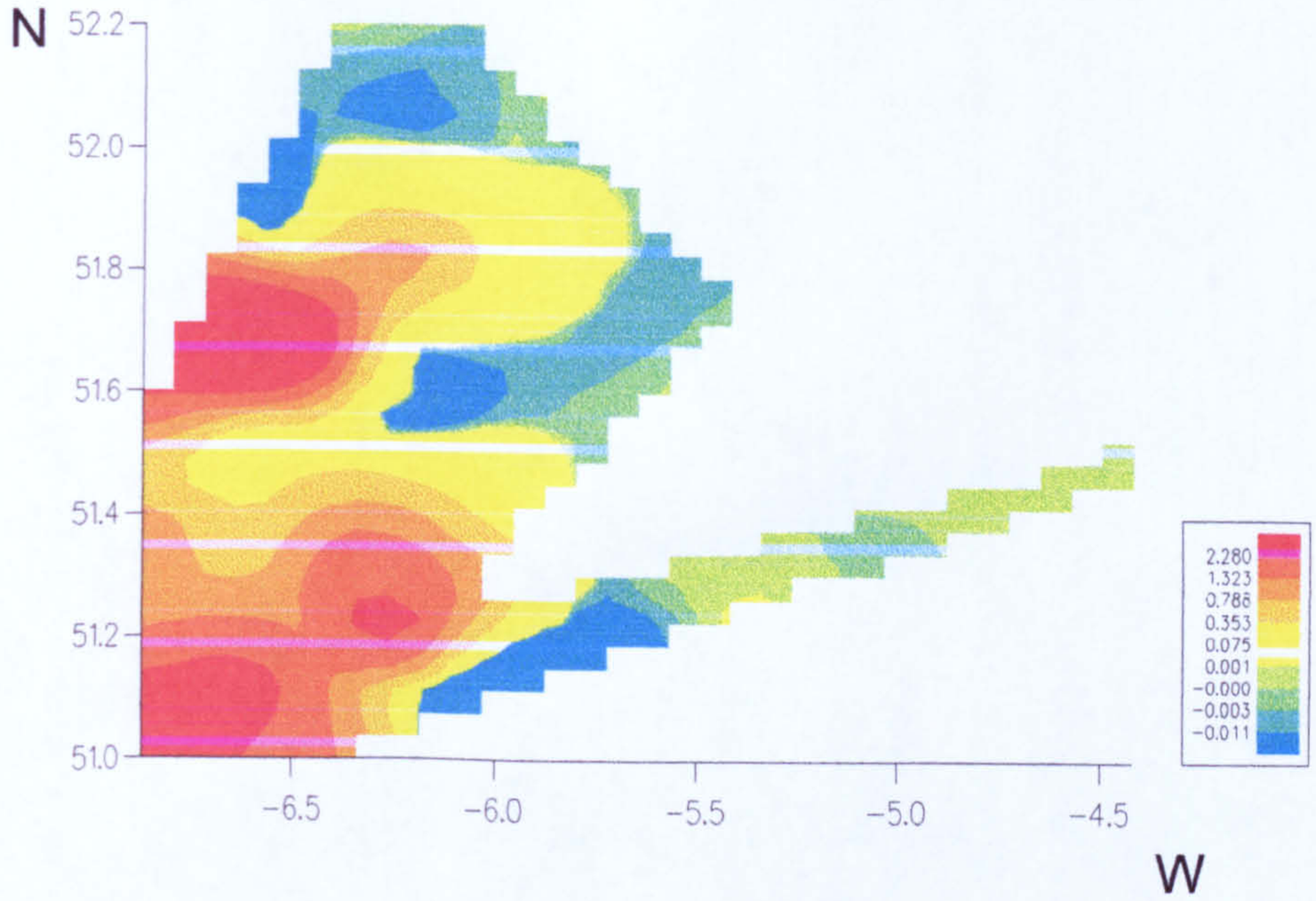


Figure 4.15 % distribution of *Gavelinopsis praegeri* (a) living (b) dead



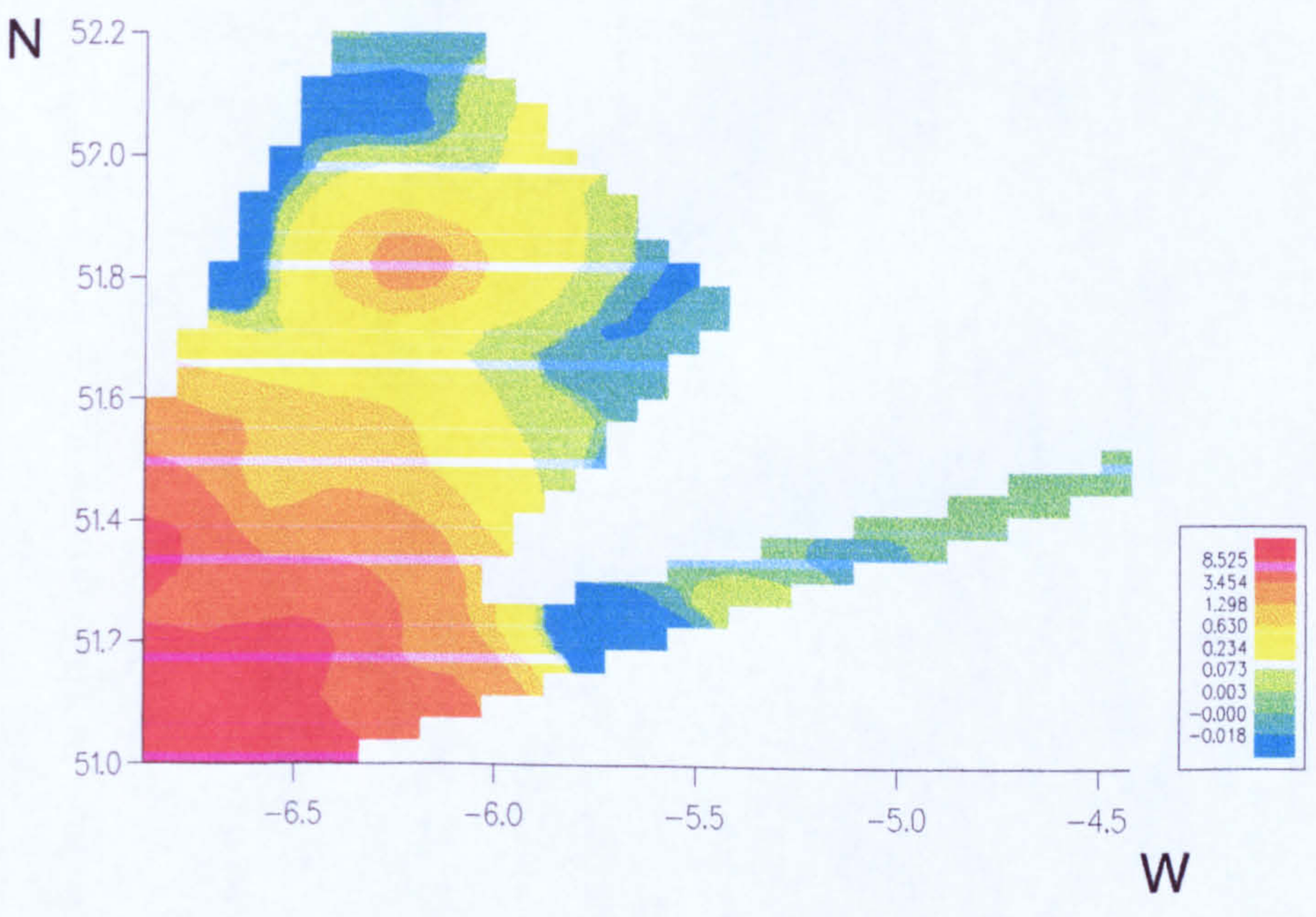
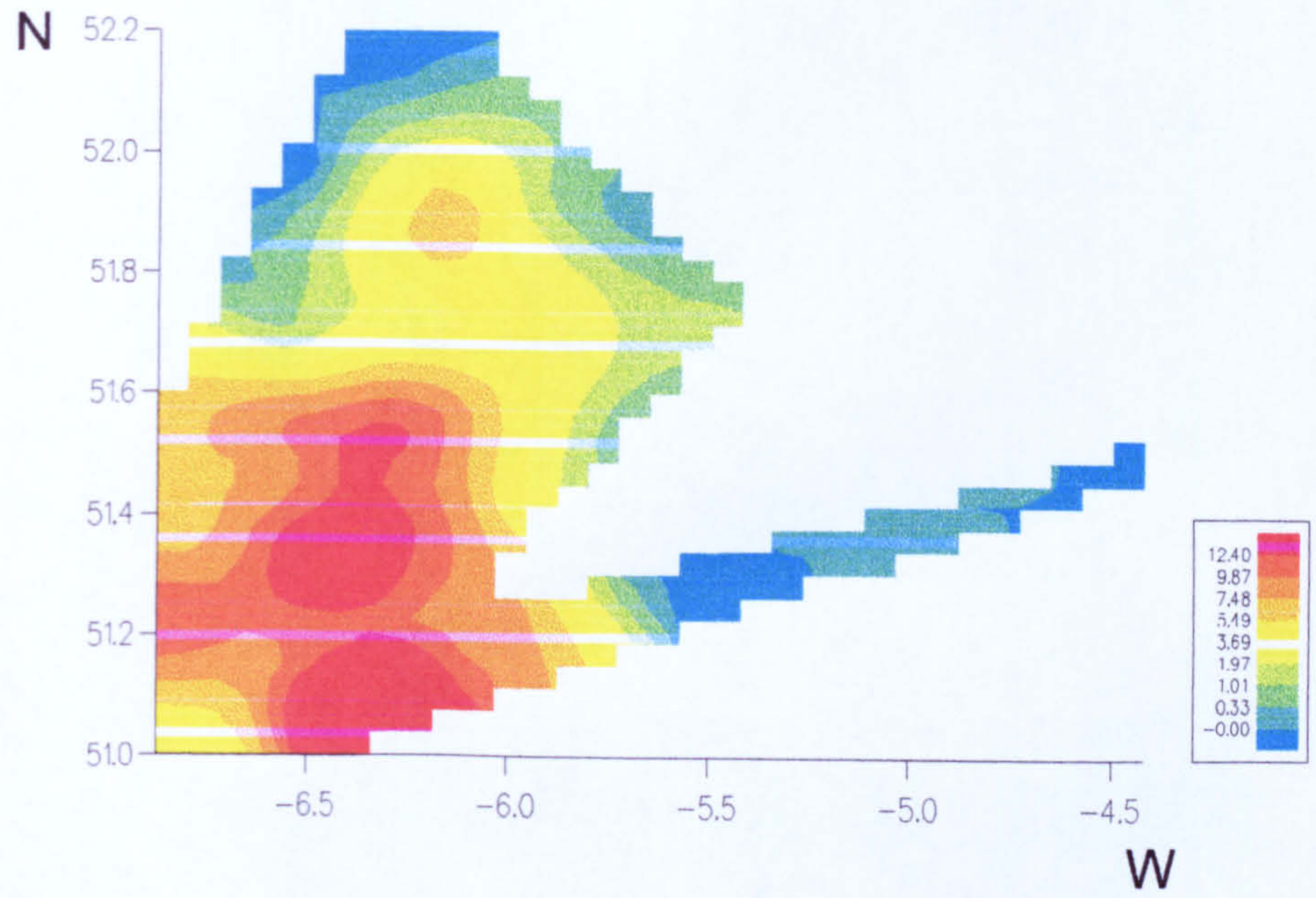


Figure 4.16 % distribution of *Hyalinea balthica* (a) living (b) dead



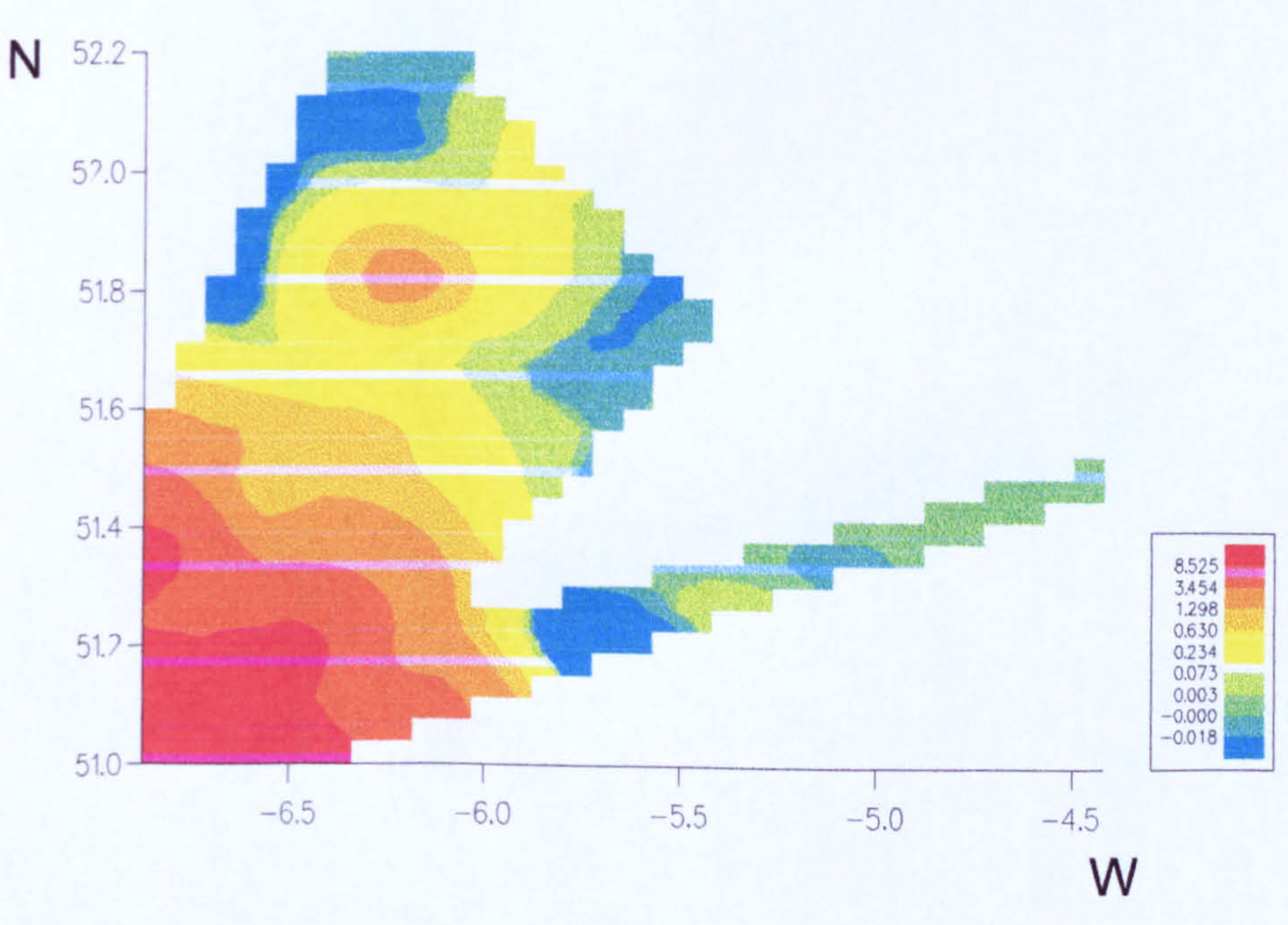
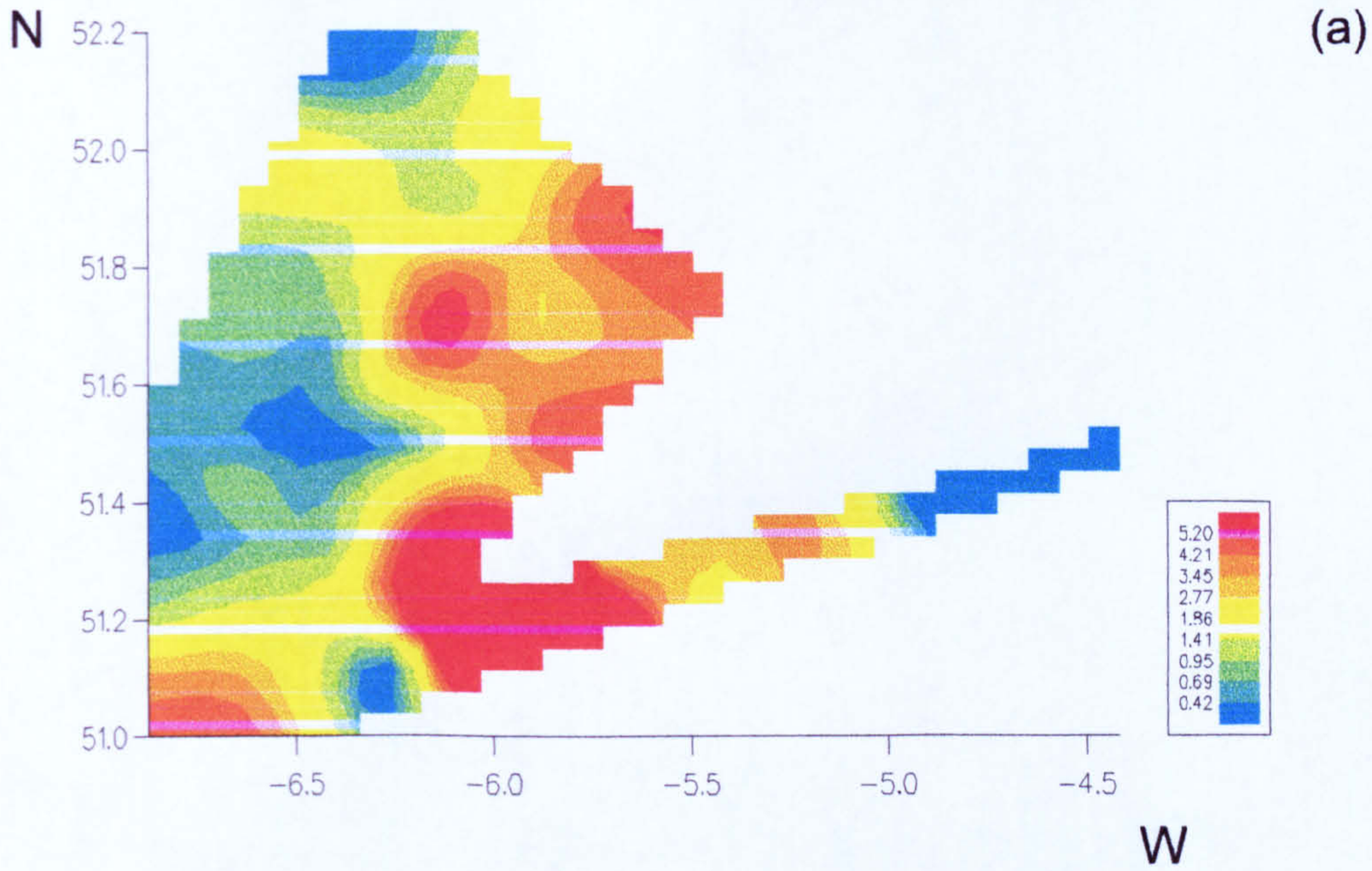


Figure 4.17 % distribution of *Nonionella turgida* (a) living (b) dead



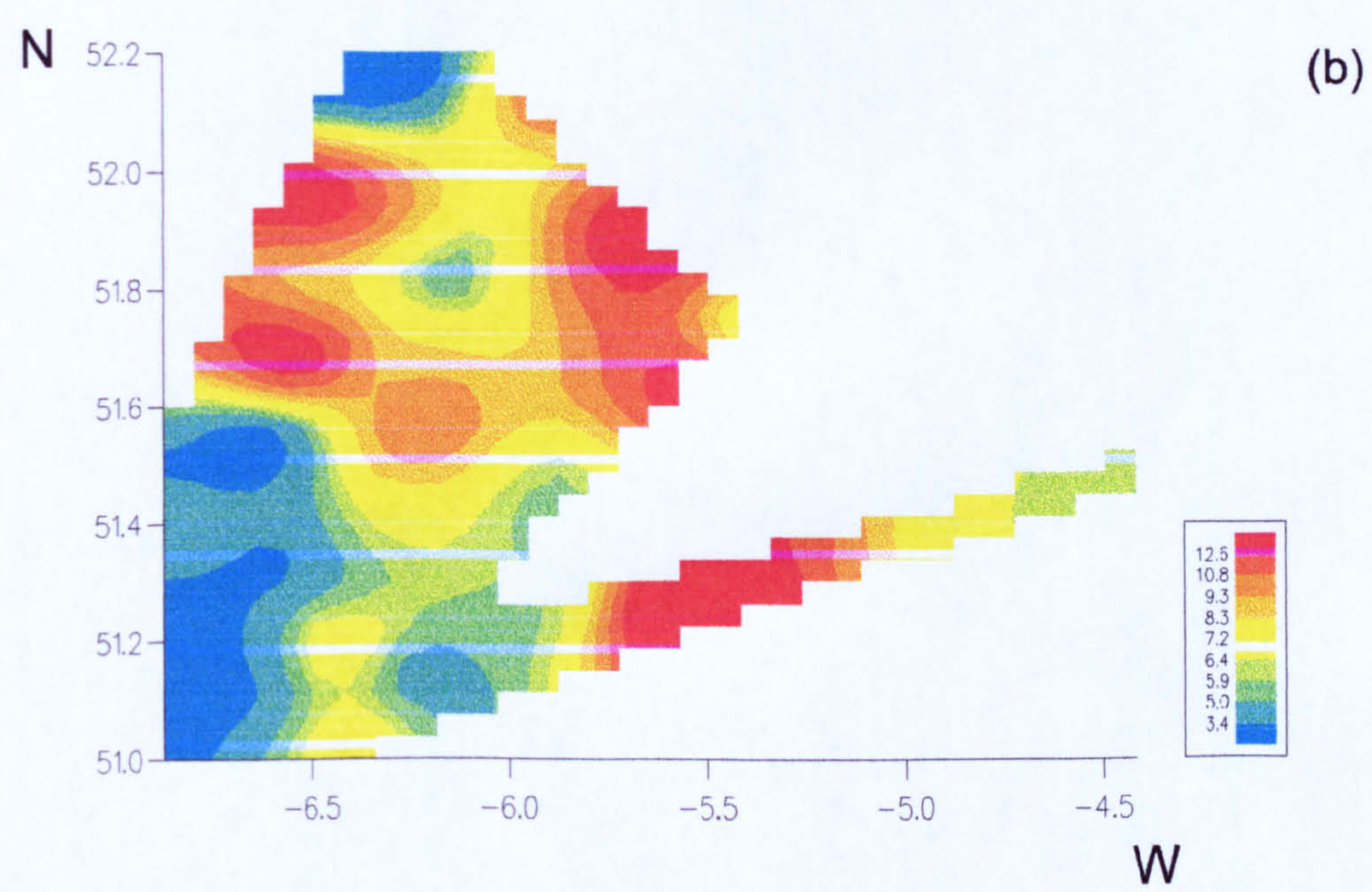
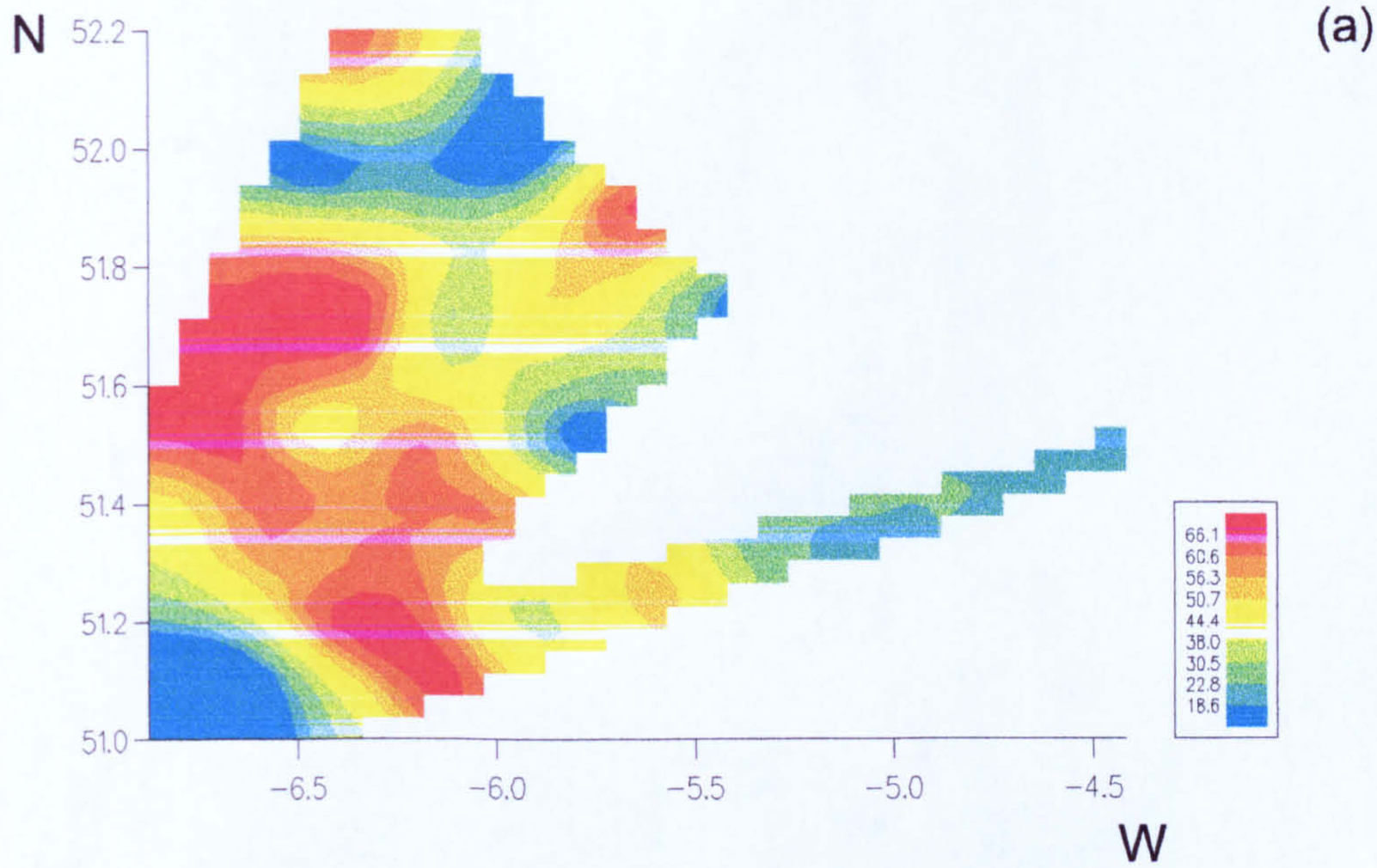


Figure 4.18 % distribution of *Quinqueloculina seminulum* (a) living (b) dead



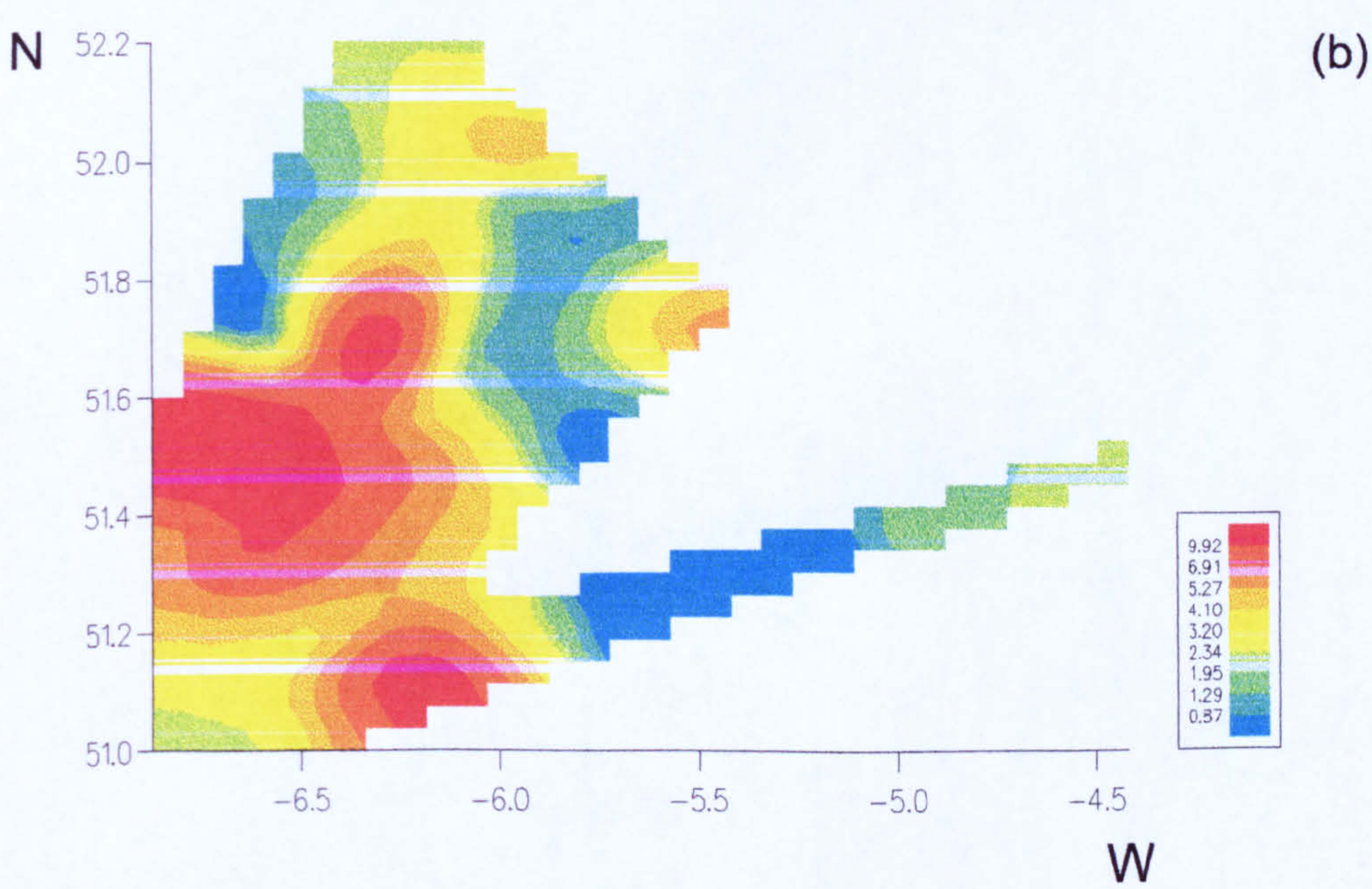
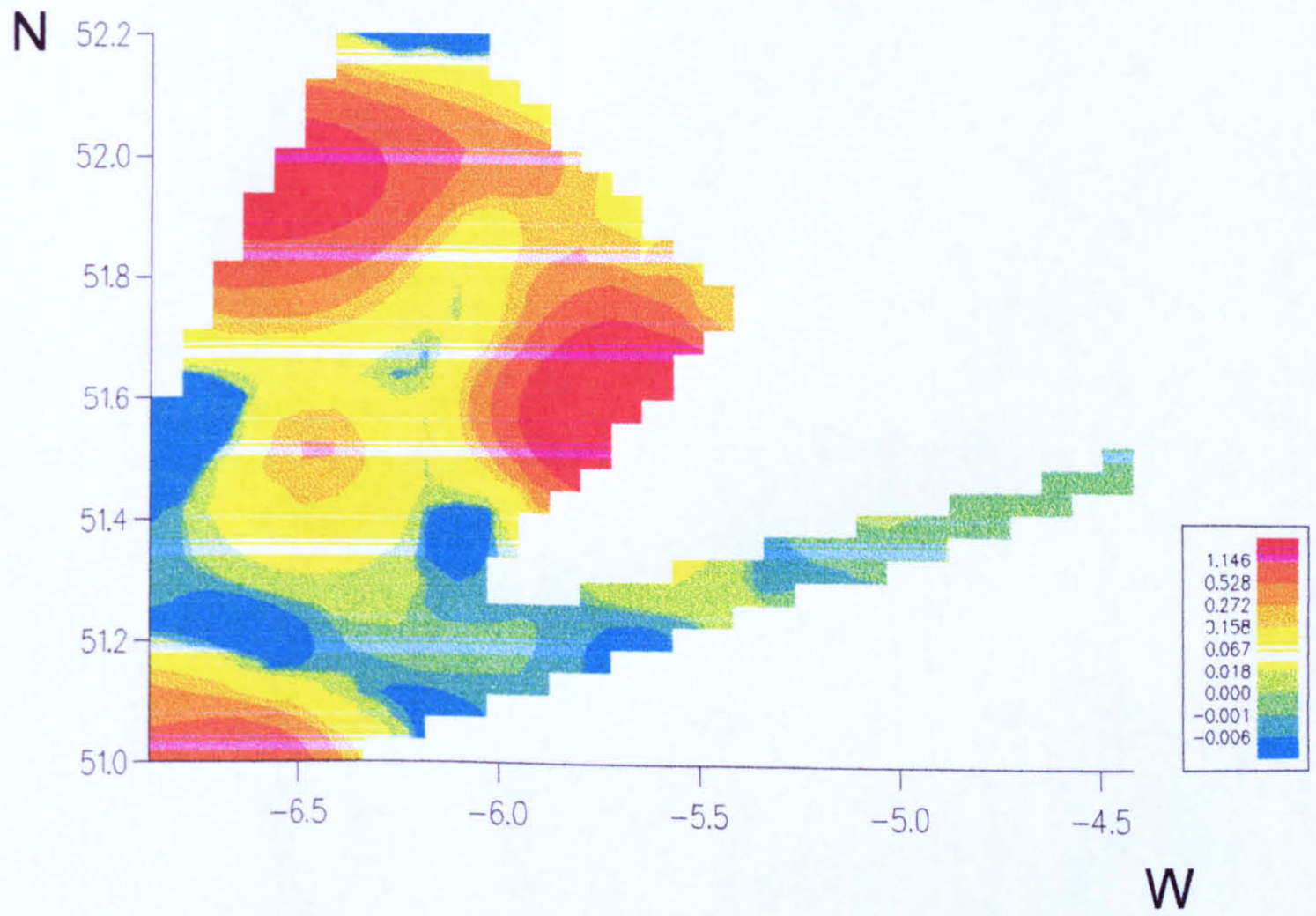


Figure 4.19 % distribution of *Stainforthia fusiformis* (a) living (b) dead



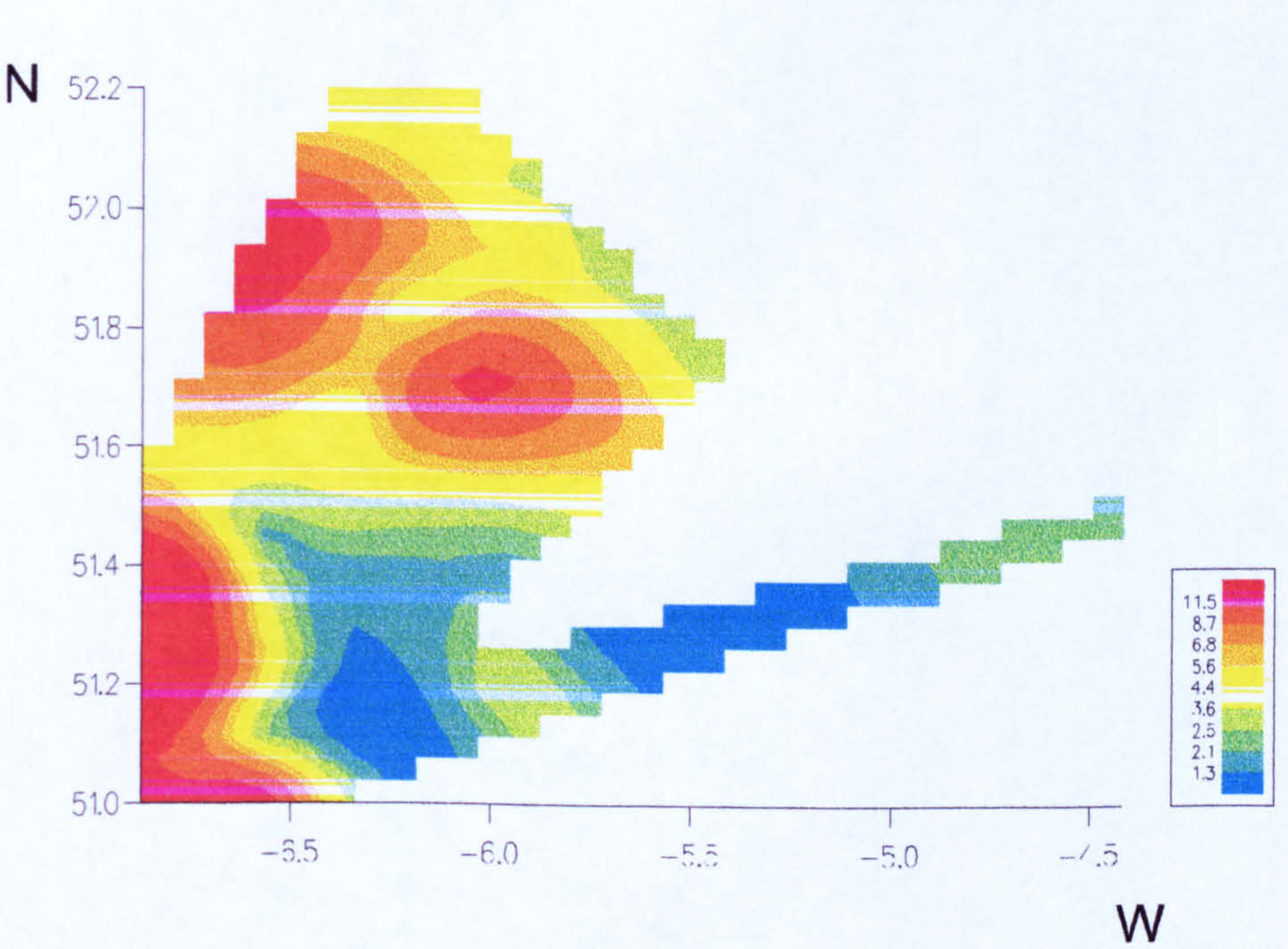
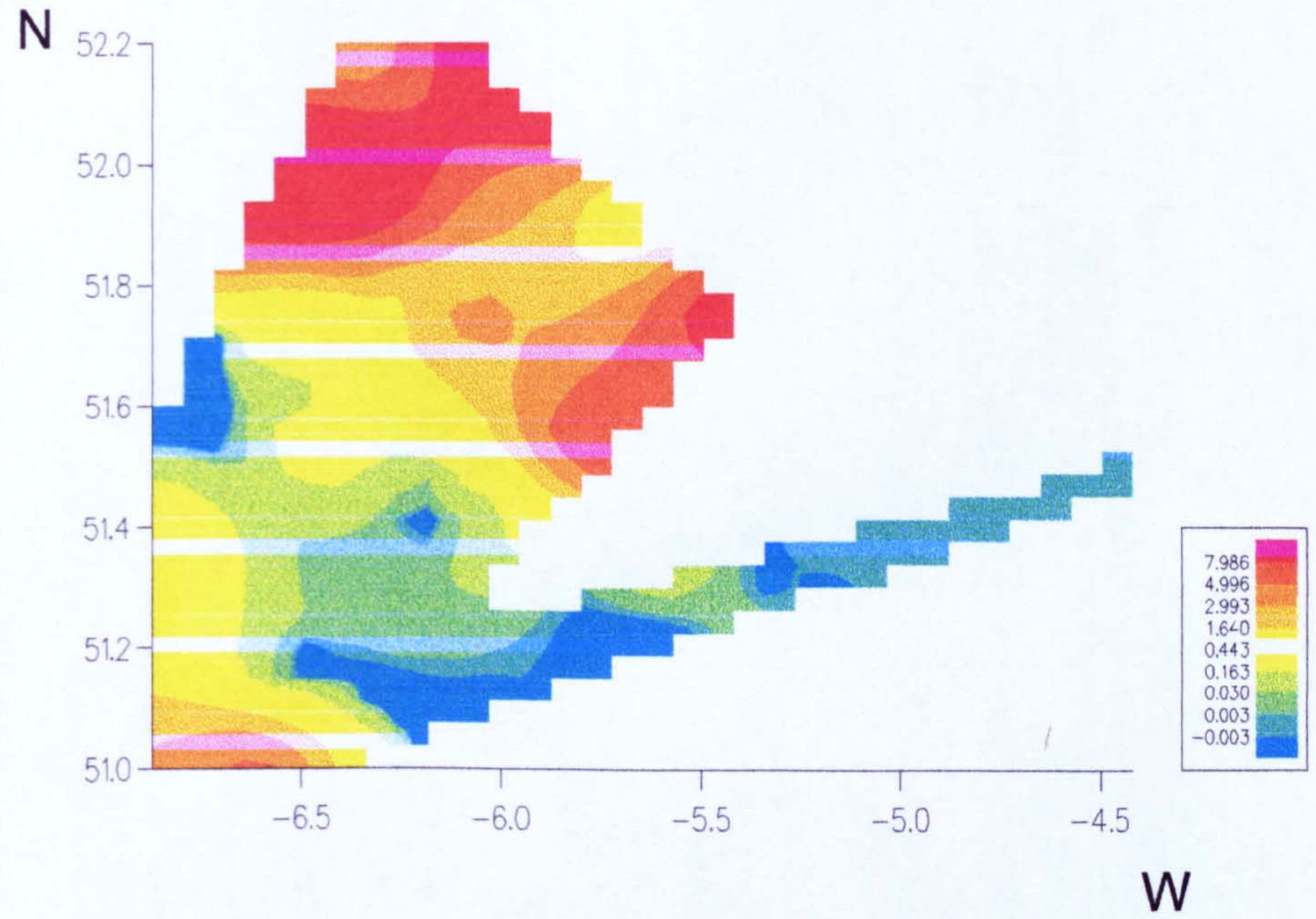


Figure 4.20 distribution of *Spiroplectammina wrightii* (a) living (b) dead



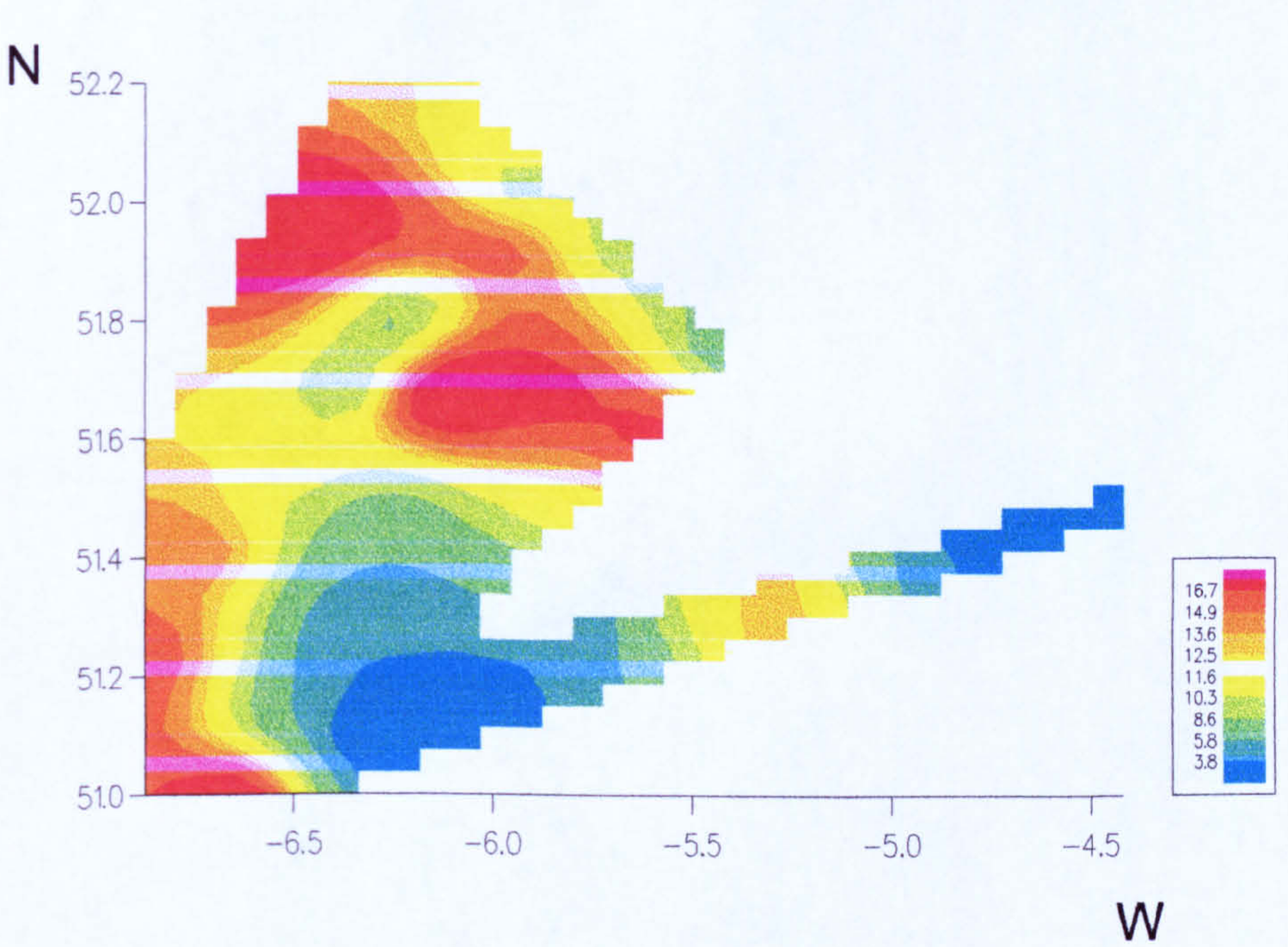


Figure 4.21 % distribution of *Textularia bockii* (a) living (b) dead

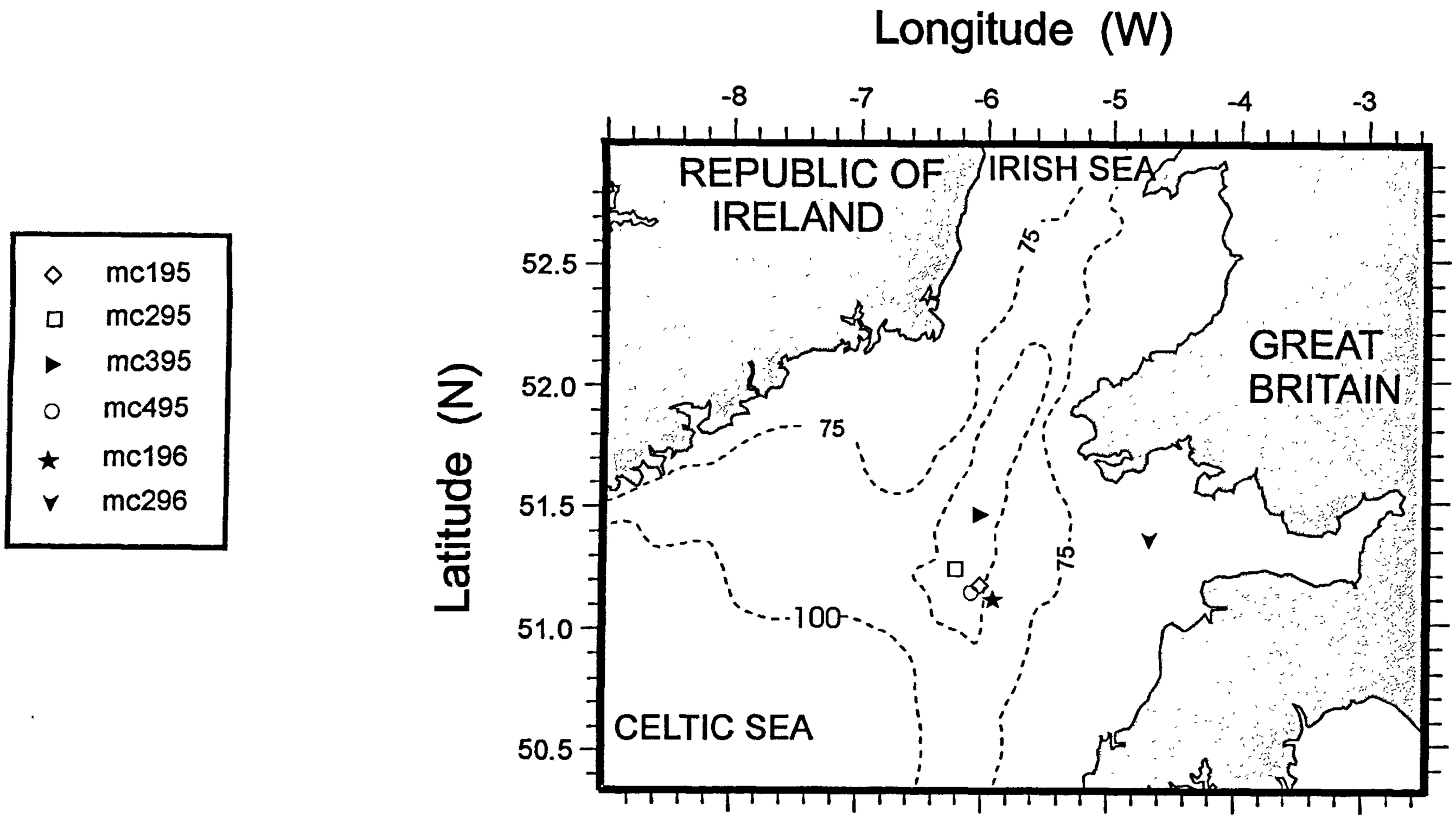


Figure 4.22 Location of the multicore stations

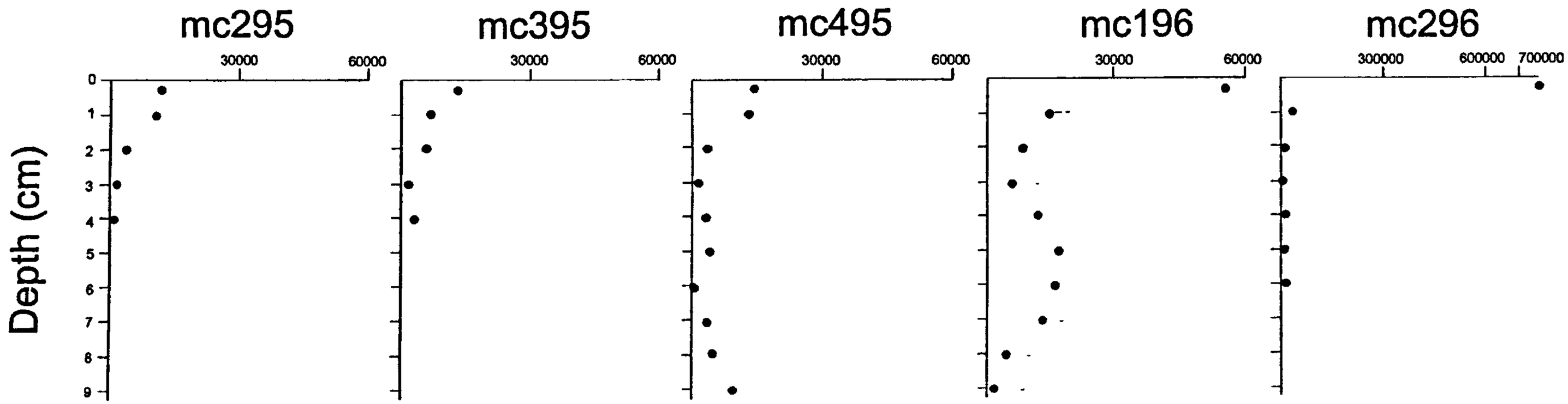


Figure 4.23 The change in foraminiferal densities downcore

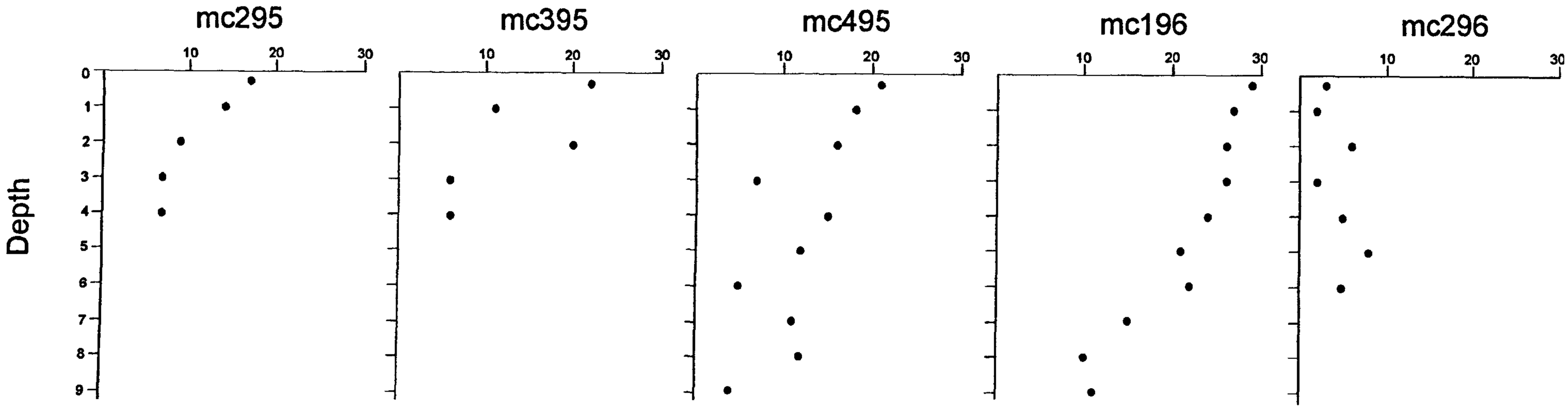


Figure 4.24 The change in the number of foraminiferal species downcore

Figure 4.25 Distribution of foraminiferal species downcore

(a) *A. beccarii*

(b) *A. glomeratum*

(c) *B. gibba*

(d) *B. marginata*

(e) *C. auricula*

(f) *E. scabrus*

(g) *H. balthica*

(h) *N. auricula*

(i) *N. turgida*

(j) *Q. seminulum*

(k) *R.scorpiurus*

(l) *S. fusiformis*

mc295 mc395 mc495 mc196 mc296

Depth downcore (cm)

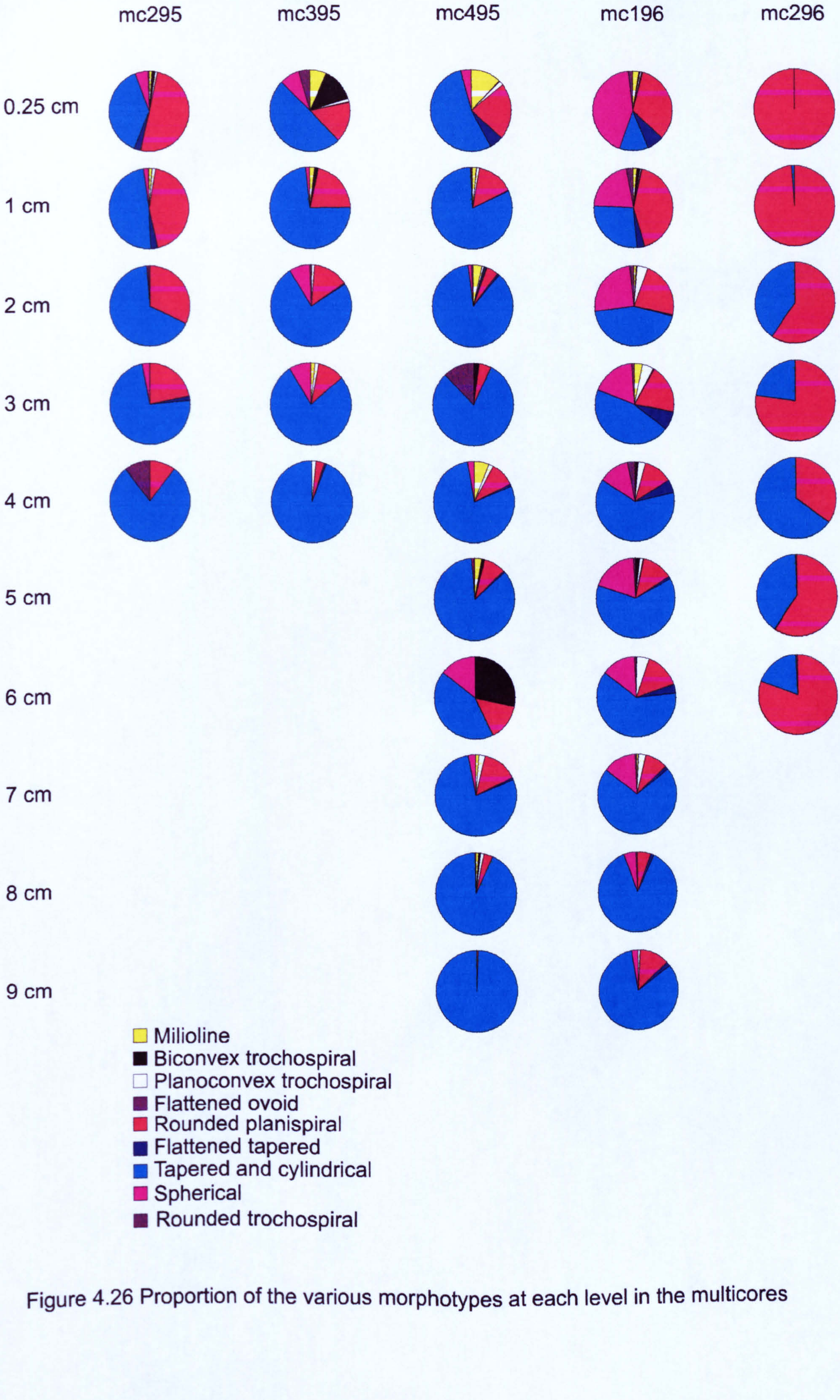


Figure 4.26 Proportion of the various morphotypes at each level in the multicores

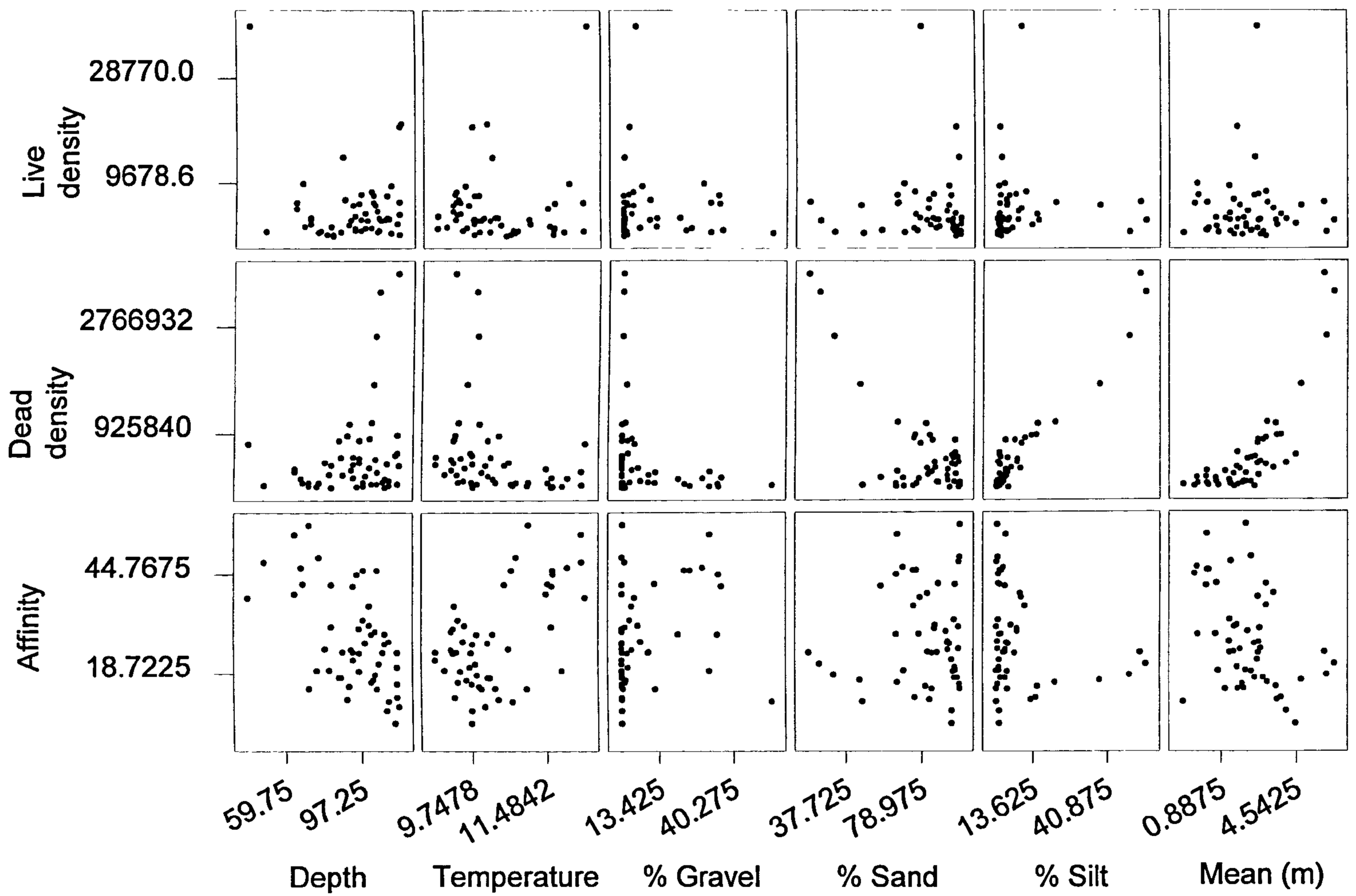


Figure 4.27 Comparison of depth temperature and grain size classes with the foraminiferal assemblage characteristics

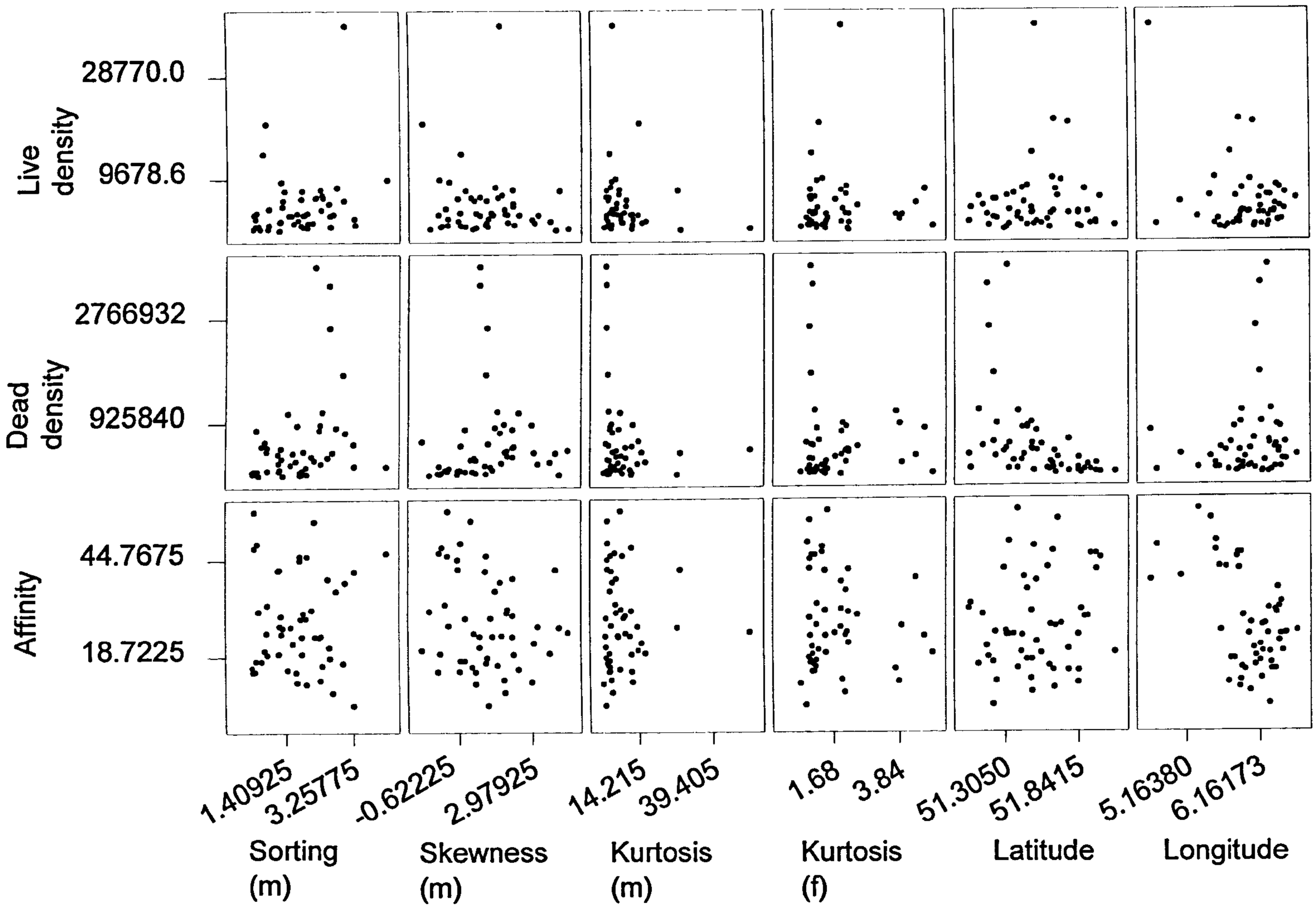


Figure 4.28 Comparison of grain size parameters and geographical co-ordinates with the foraminiferal assemblage characteristics

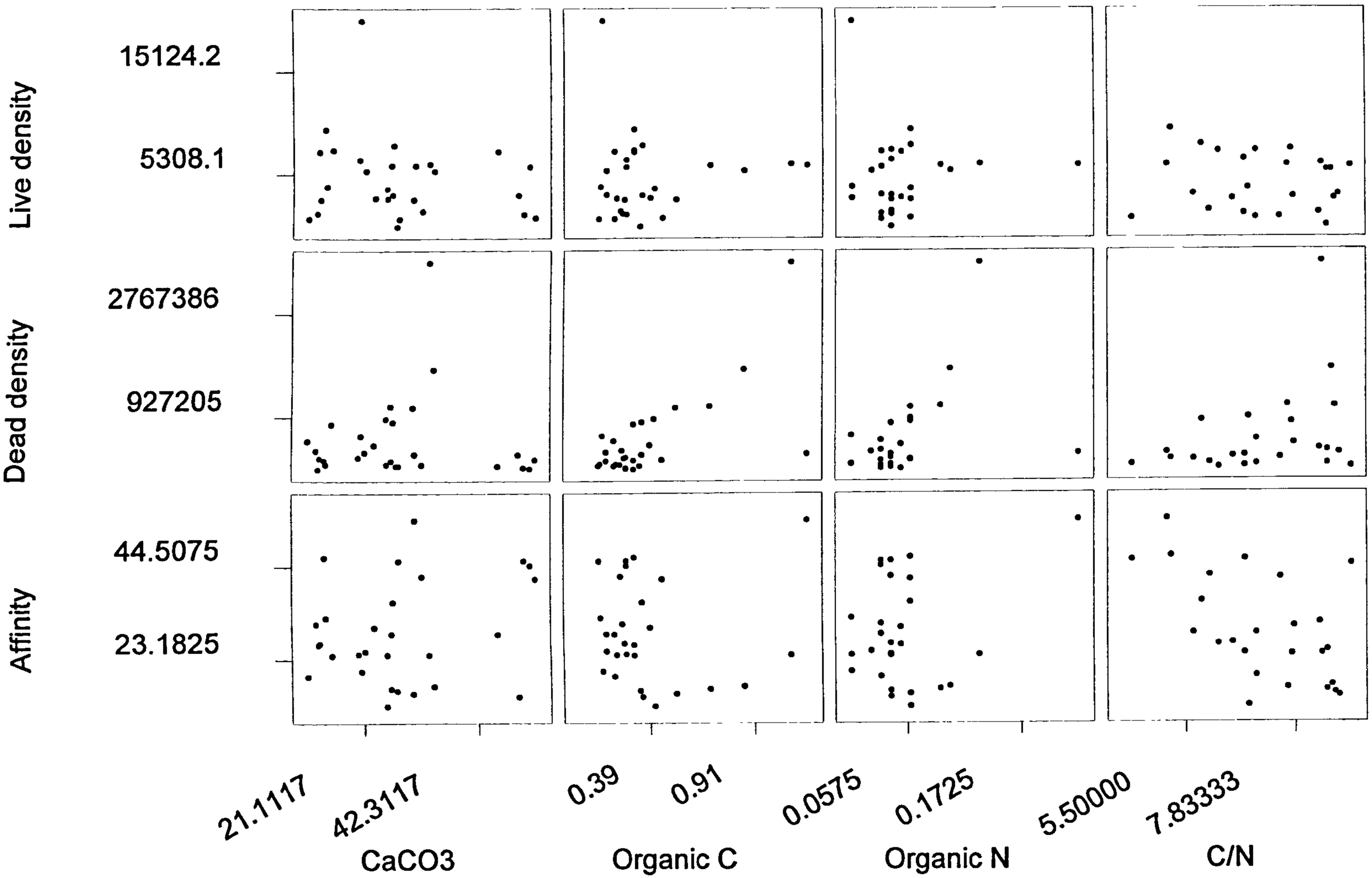


Figure 4.29 Comparison of the geochemical parameters with the foraminiferal assemblage characteristics

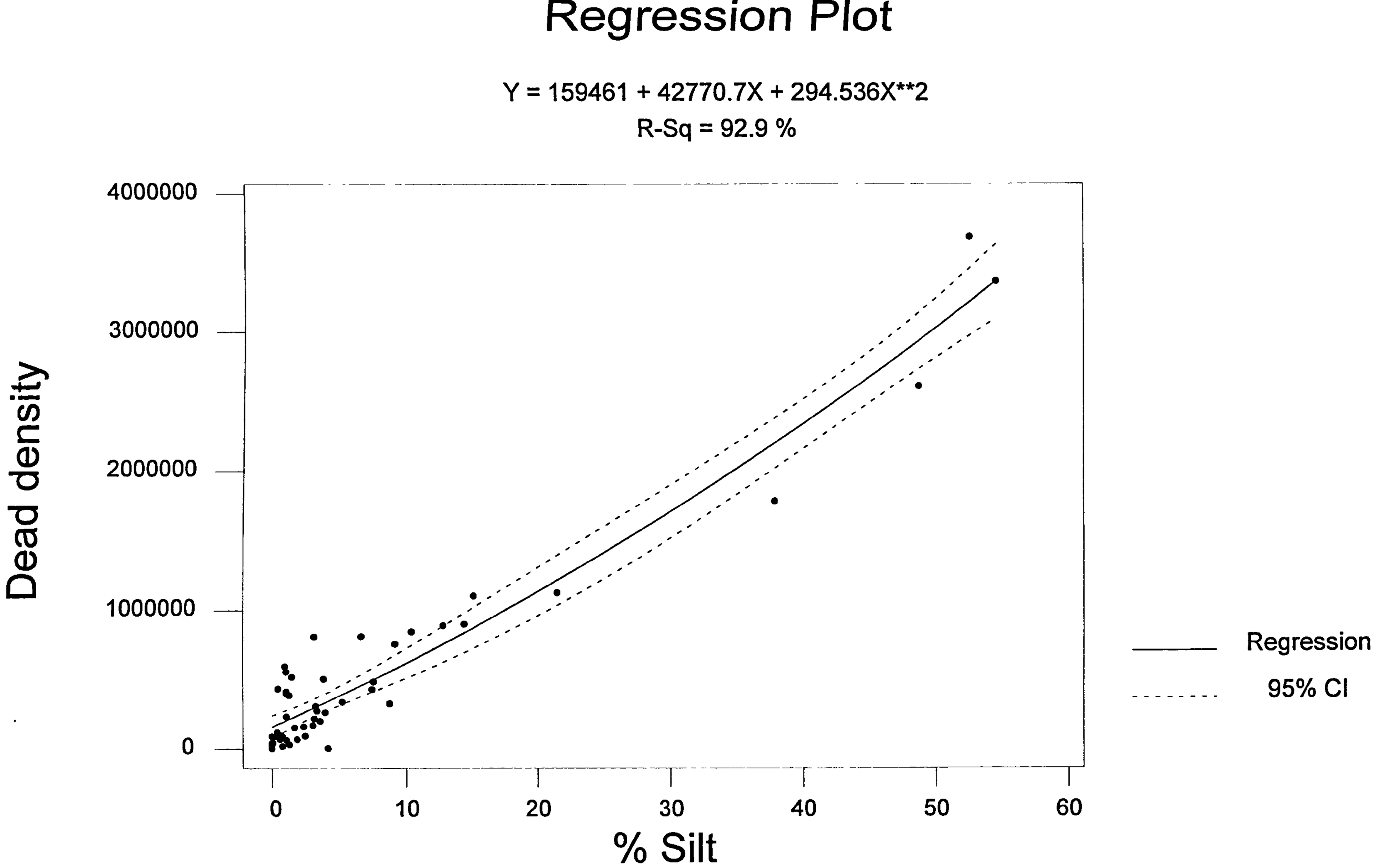


Figure 4.30 Regression of % silt content against the density of dead foraminifera contained within the sediments

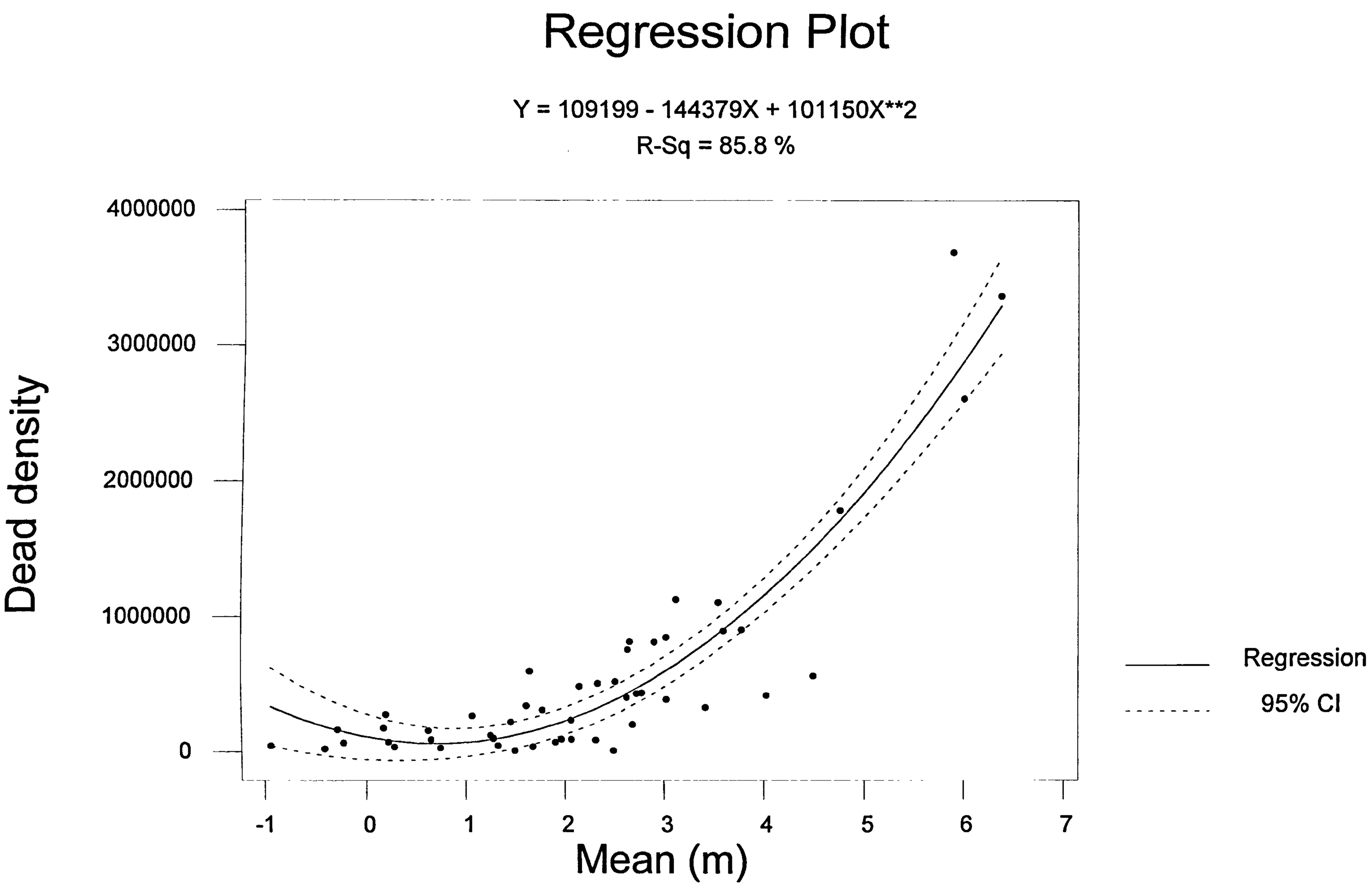


Figure 4.31 Regression of mean grain size against the density of dead foraminifera contained within the sediments

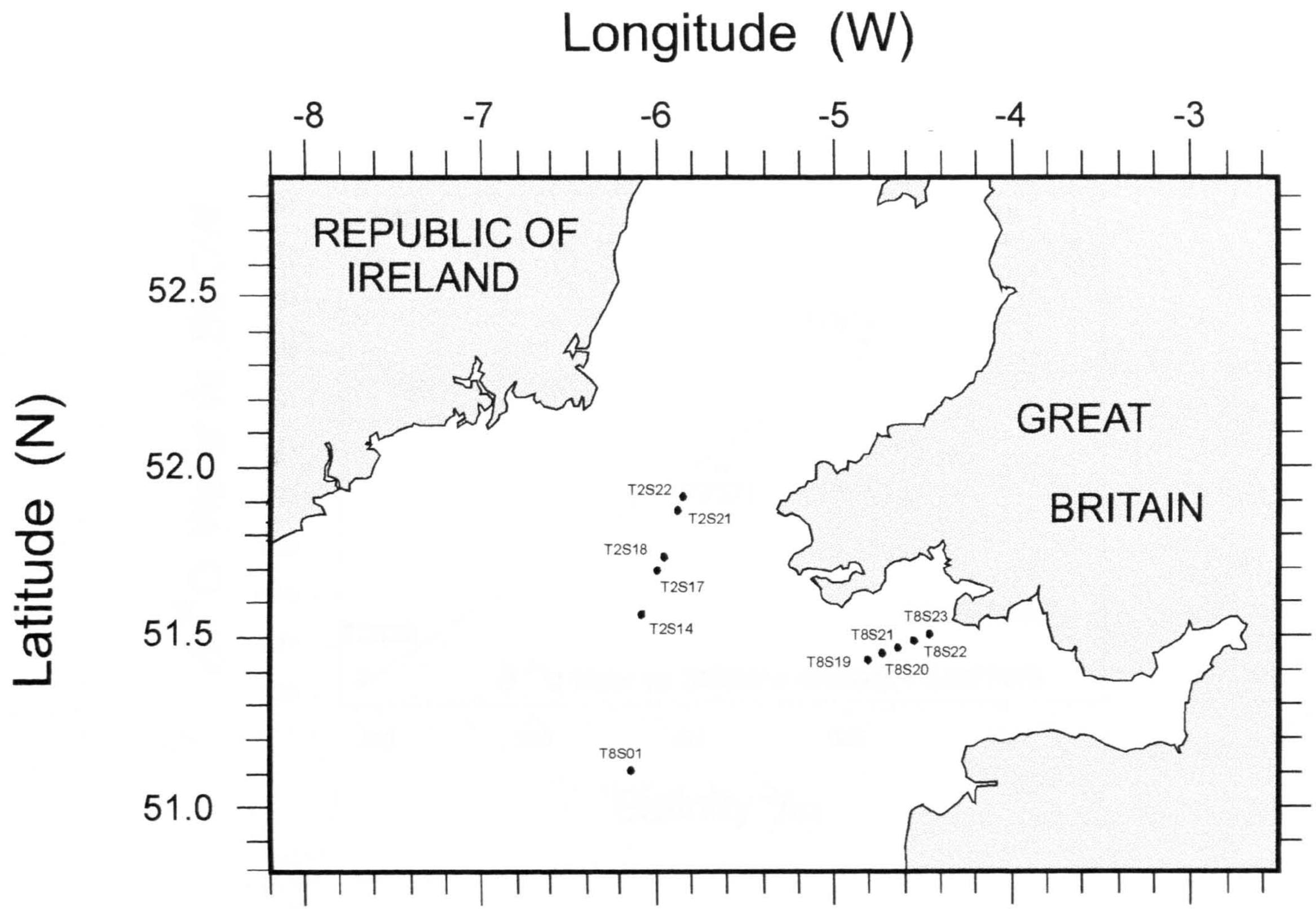


Figure 5.1 Location of water samples measured for isotopic composition

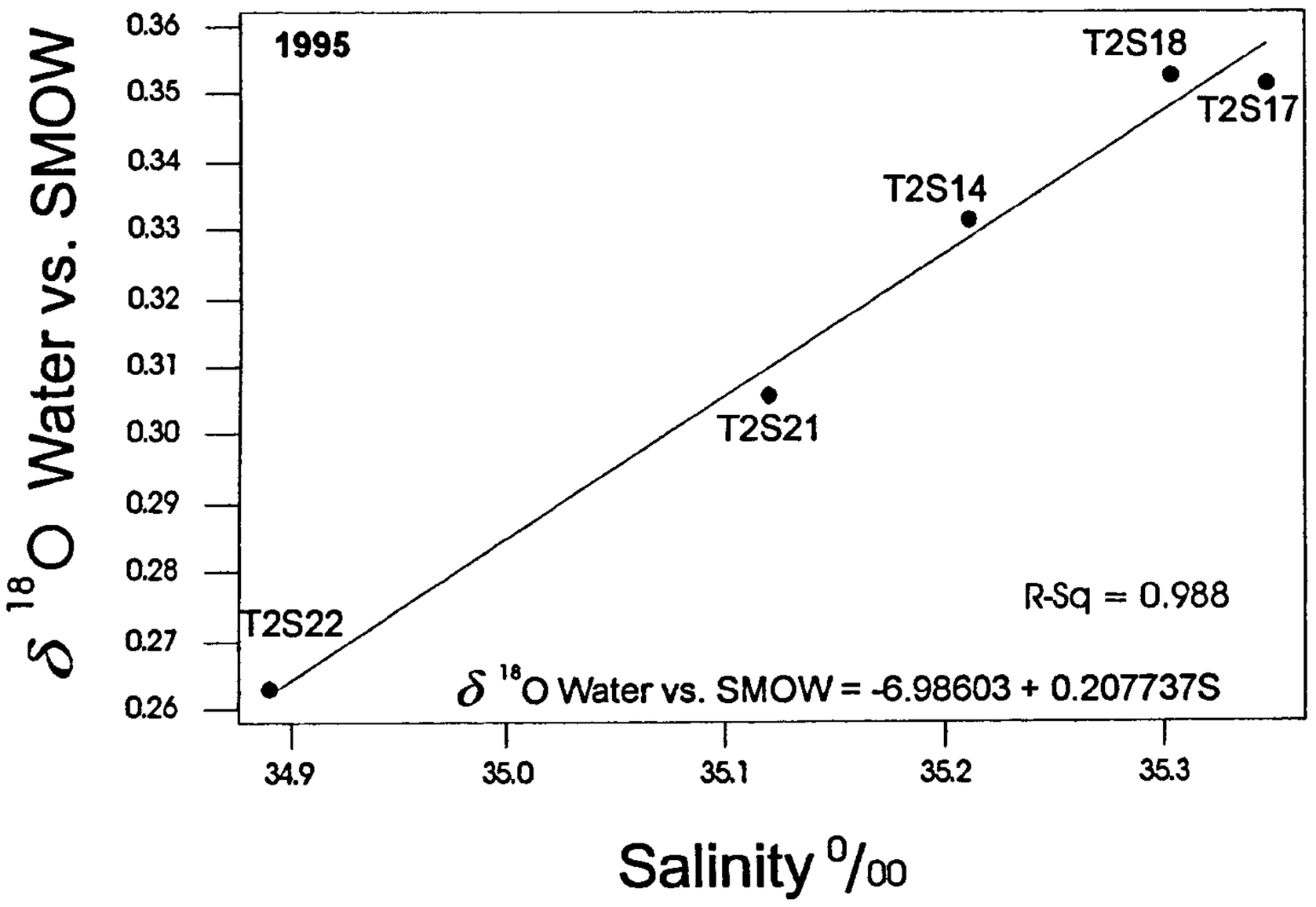


Figure 5.2 Linear regression of δ^{18} O v. SMOW against salinity for 1995

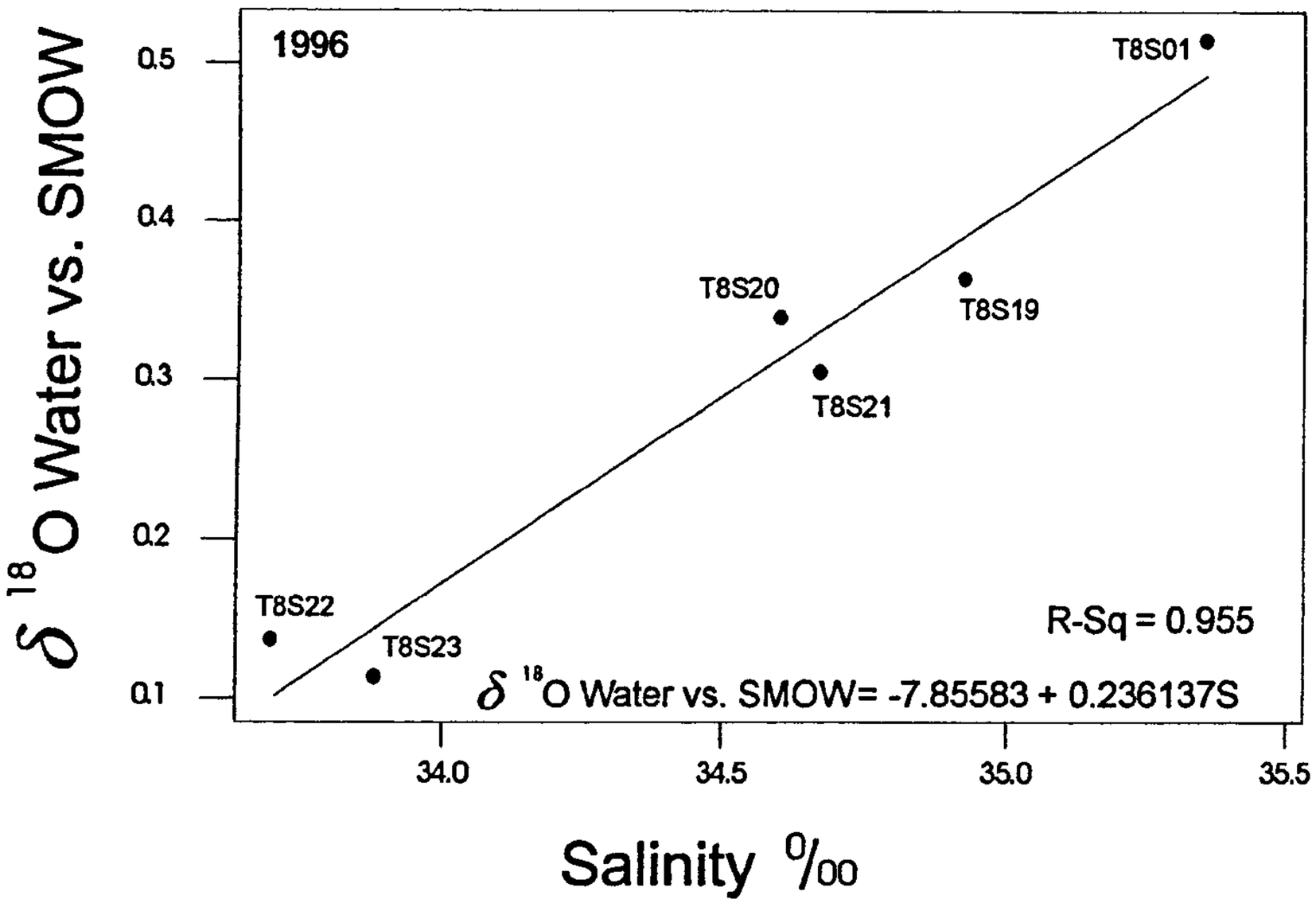


Figure 5.3 Linear regression of $\delta^{18}O$ v. SMOW against salinity for 1996

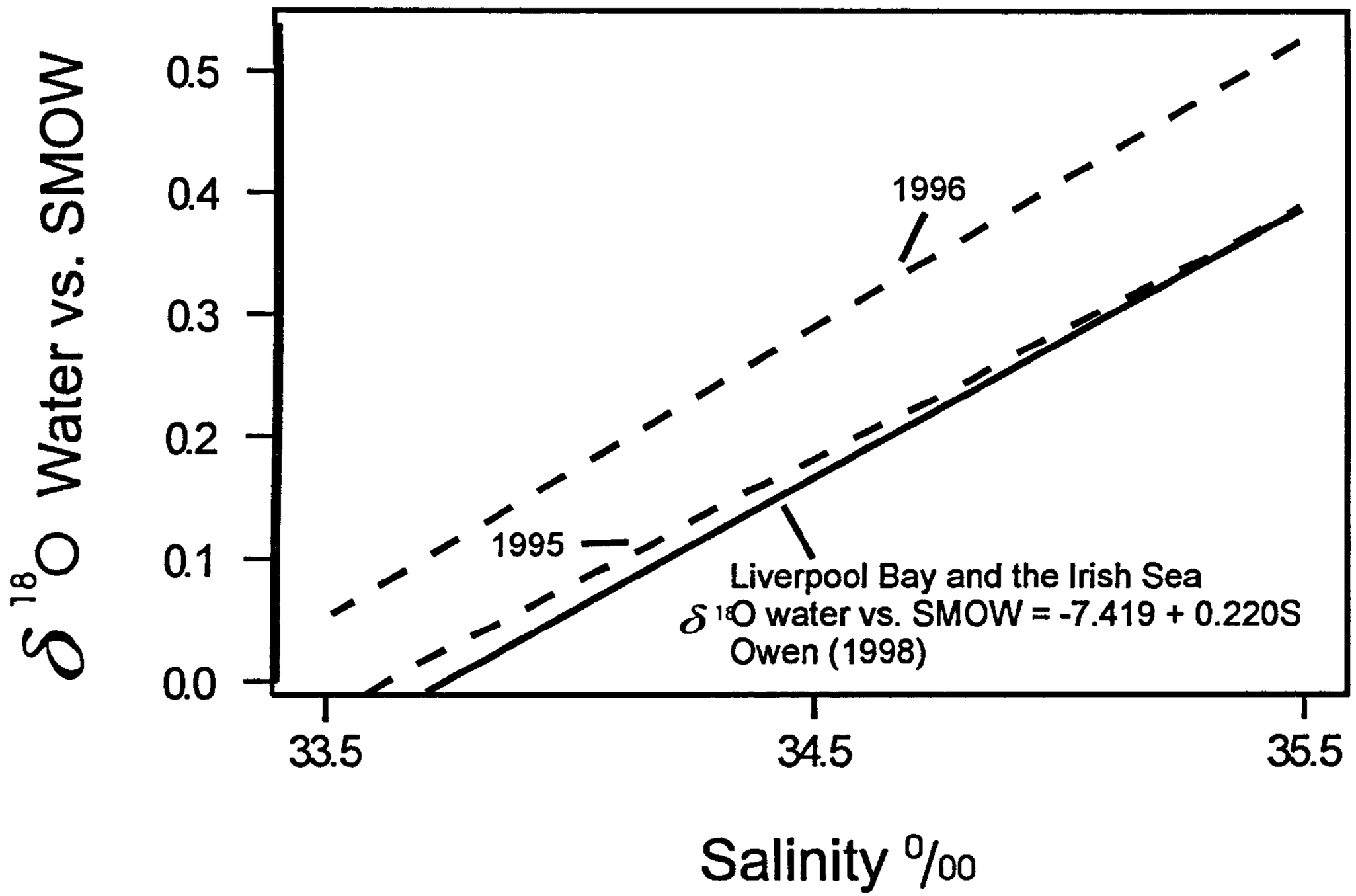


Figure 5.4 Comparison between the lines derived from the 1995 and 1996 data and that of Owen (1998)

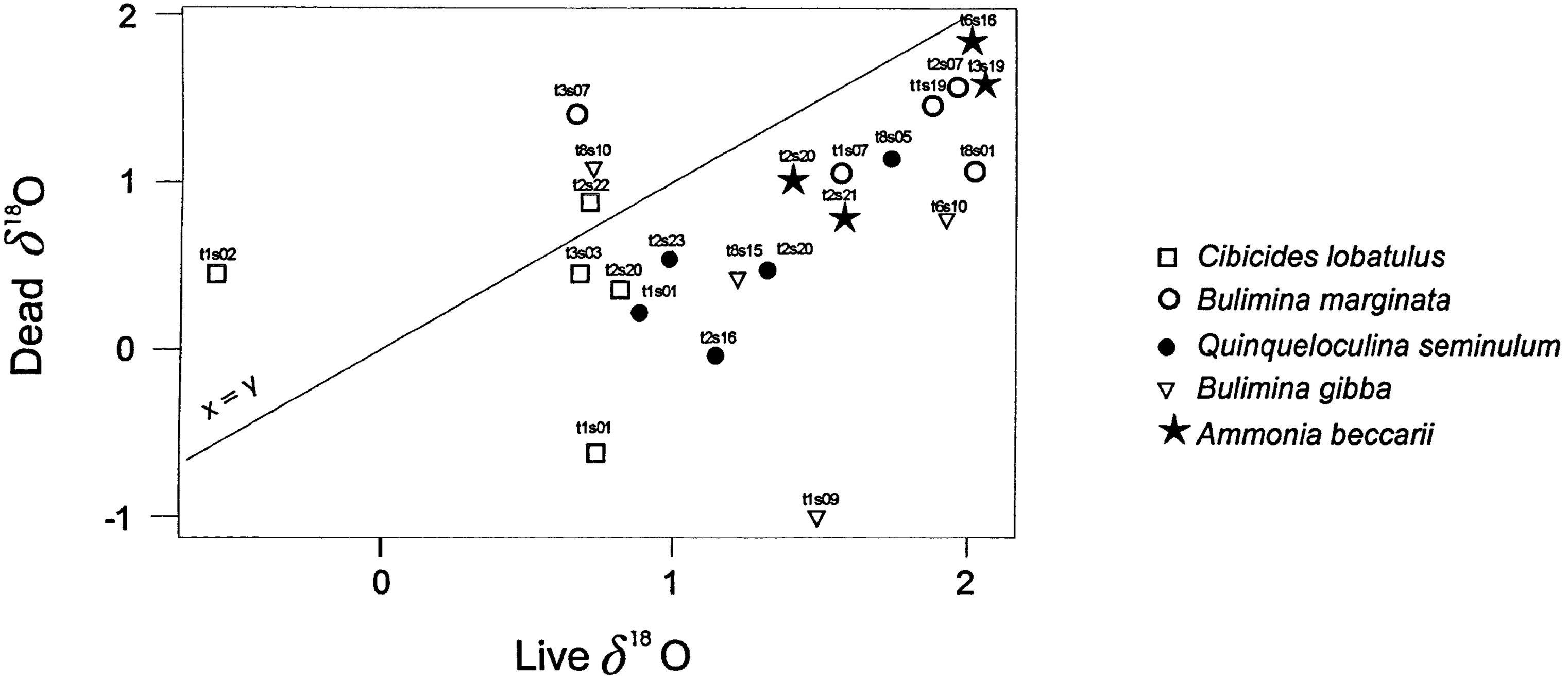


Figure 5.5 Comparison of the living and dead stable oxygen isotopic ratios for each species measured

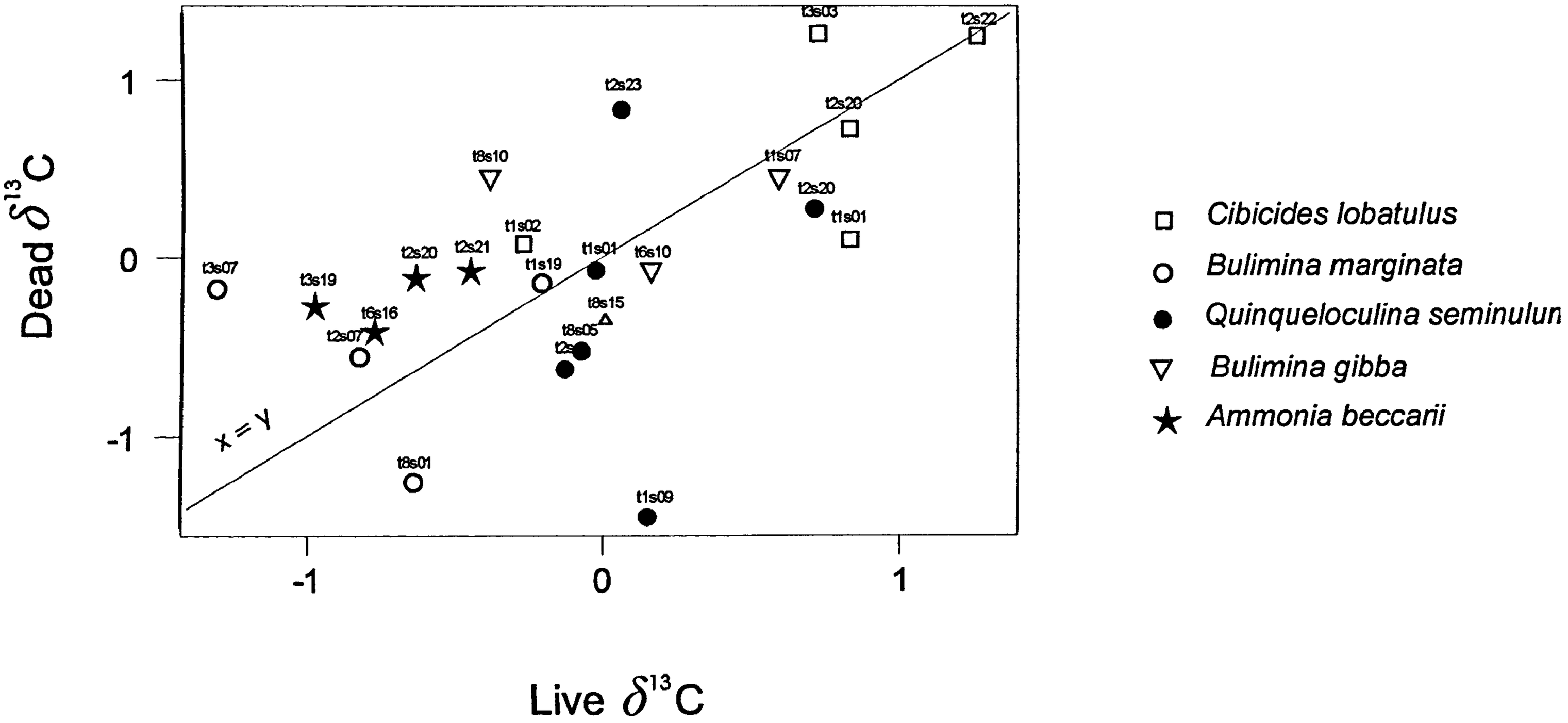


Figure 5.6 Comparison of the living and dead stable carbon isotopic ratios for each species measured

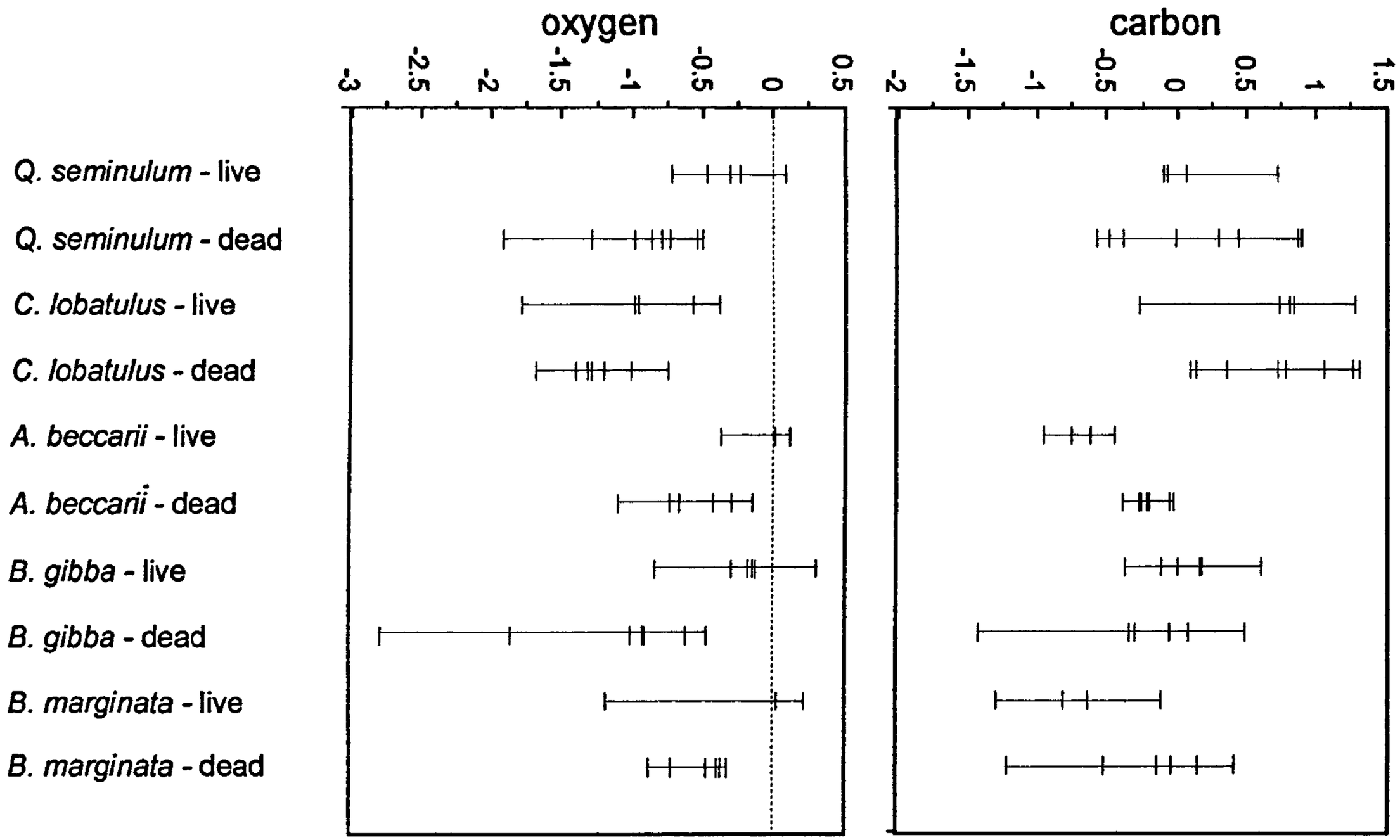


Figure 5.7 Stable isotopic disequilibria and measured stable carbon isotope values of mono-specific samples of living and dead foraminifera

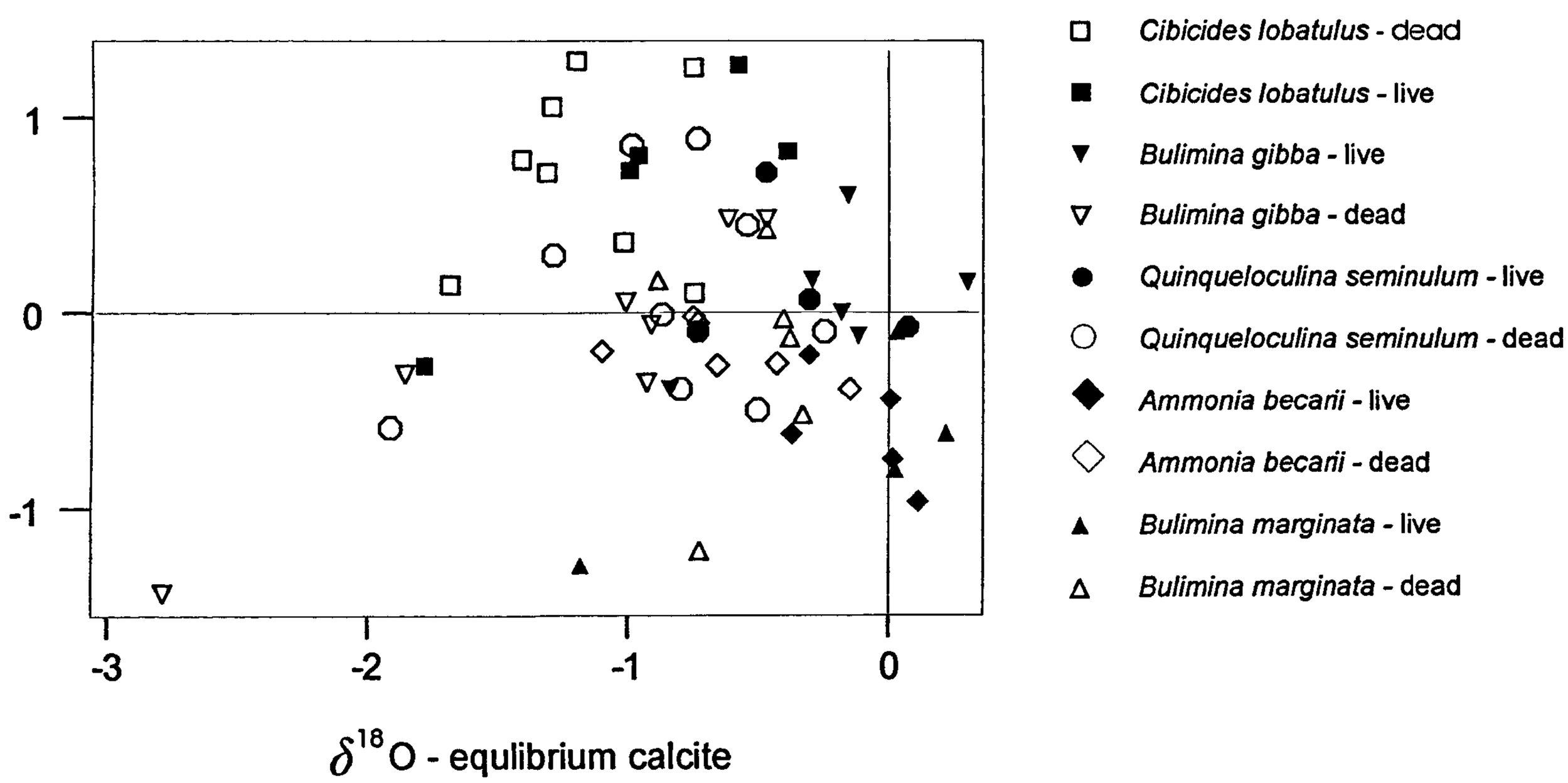
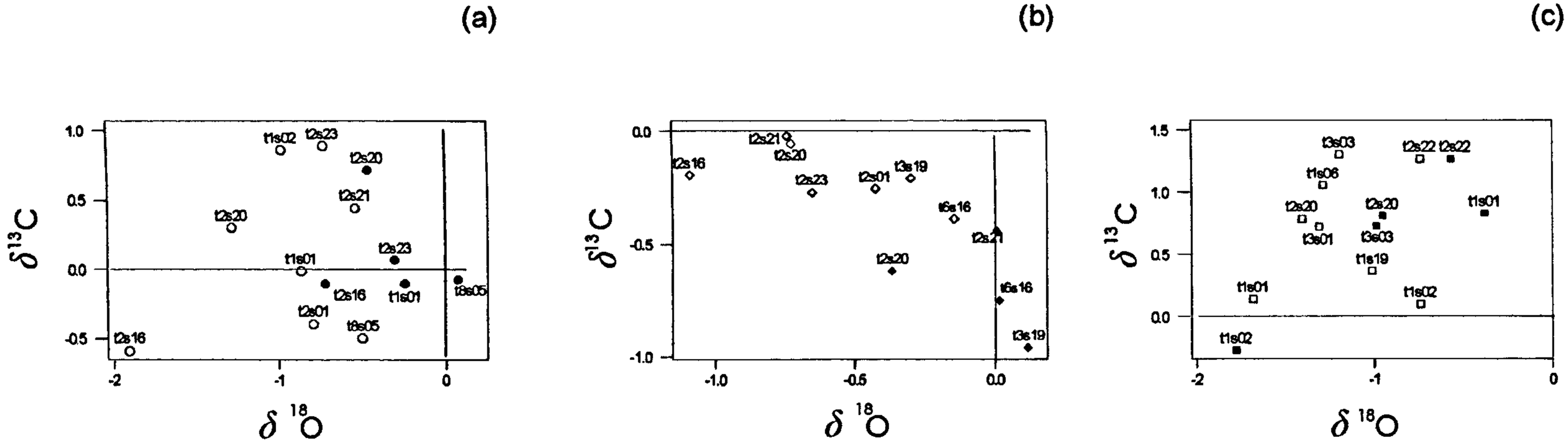
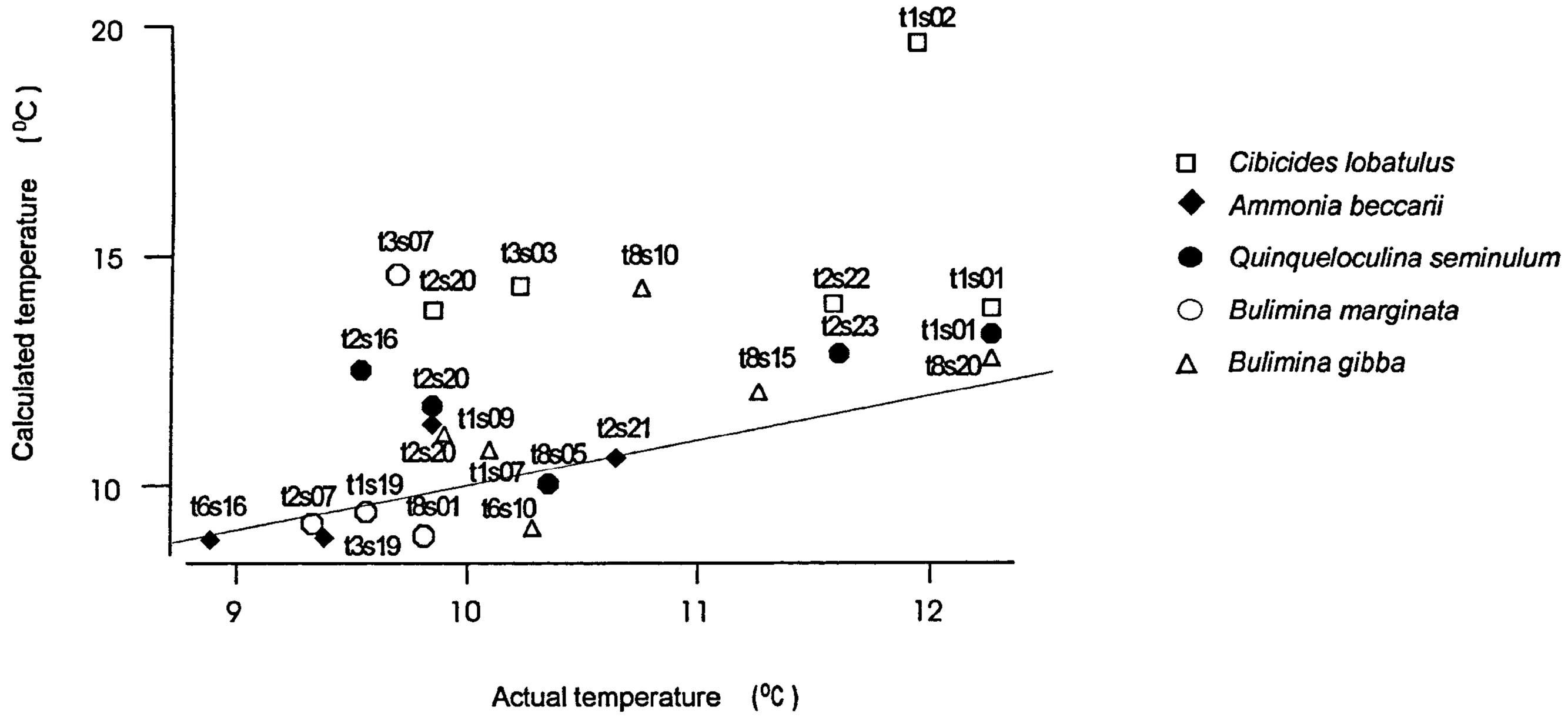


Figure 5.8 Plot of the stable isotopic disequilibria against the corresponding stable carbon isotopic values for each surface sample measured



5.9 Individual species plots of stable oxygen isotopic disequilibria against corresponding stable carbon isotopic values (a) *Quinqueloculina seminulum* (b) *Ammonia beccarii* (c) *Cibicides lobatulus* (d) *Bulimina marginata* (e) *Bulimina gibba*



5.10 Plot of actual temperatures against temperatures derived from oxygen isotopic measurements of foraminiferal calcite

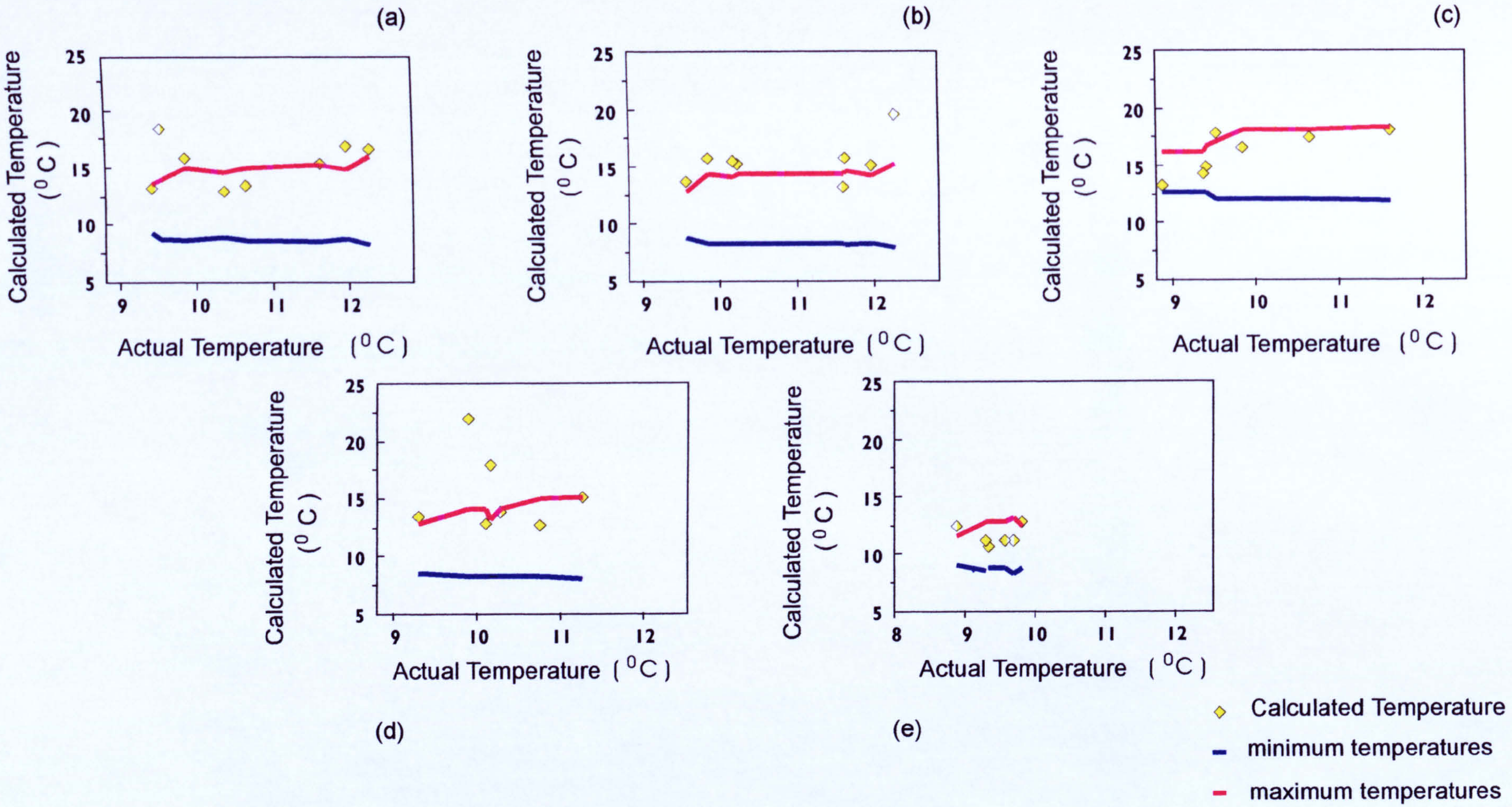


Figure 5.11 Individual species plots of actual temperatures against temperatures derived from calcite and a comparison of the values with the maximum and minimum temperatures experienced at the collection sites (Li & Elliott, 1990) for (a) *Quinqueloculina seminulum* (b) *Cibicides lobatulus* (c) *Ammonia beccarii* (d) *Bulimina gibba* (e) *Bulimina marginata*

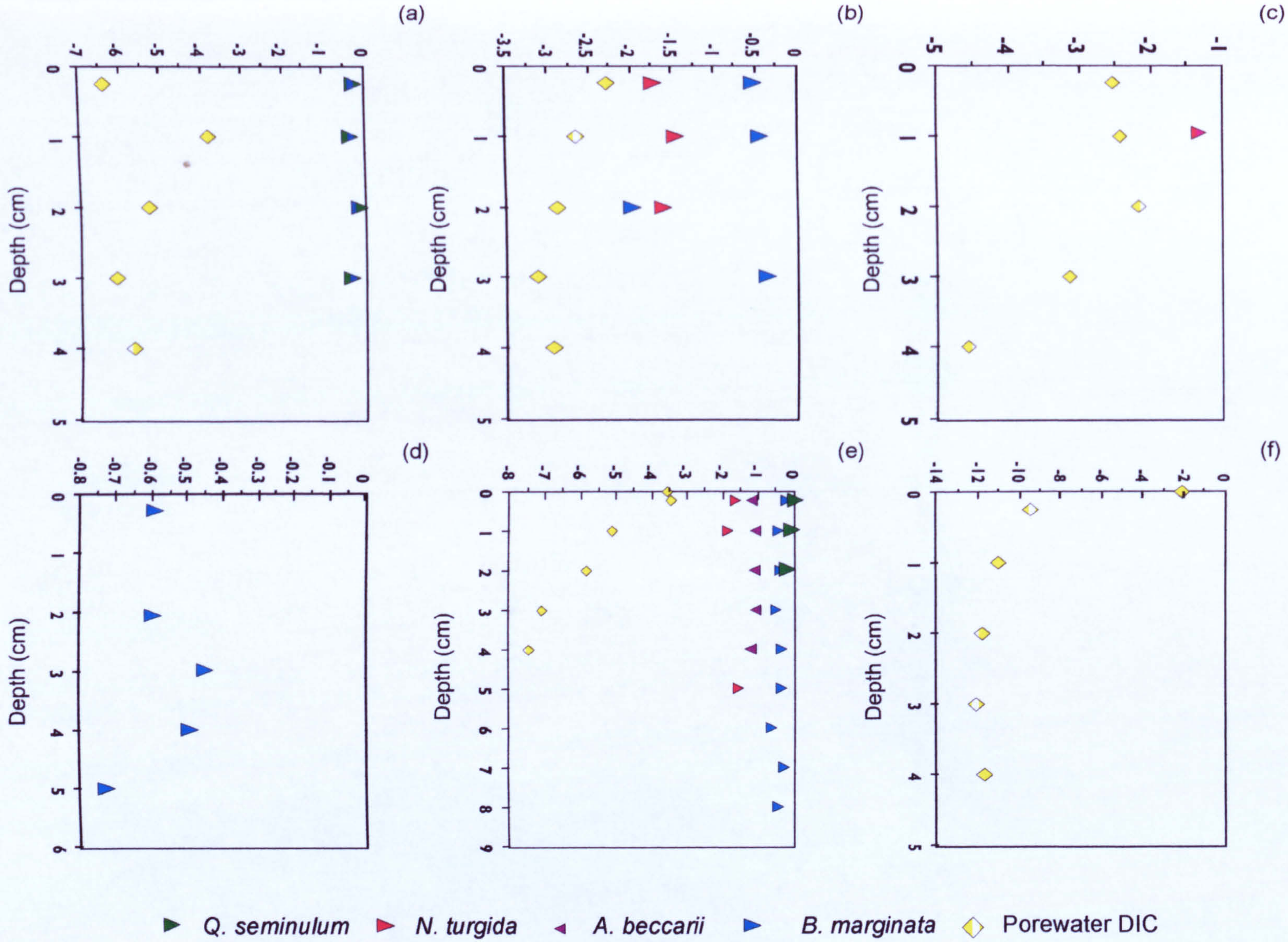


Figure 5.12 Comparison of stable carbon isotopic changes in porewater DIC and foraminiferal calcite through the multicores (a) mc195 (b) mc295 (c) mc395 (d) mc496 (e) mc196 (f) mc296

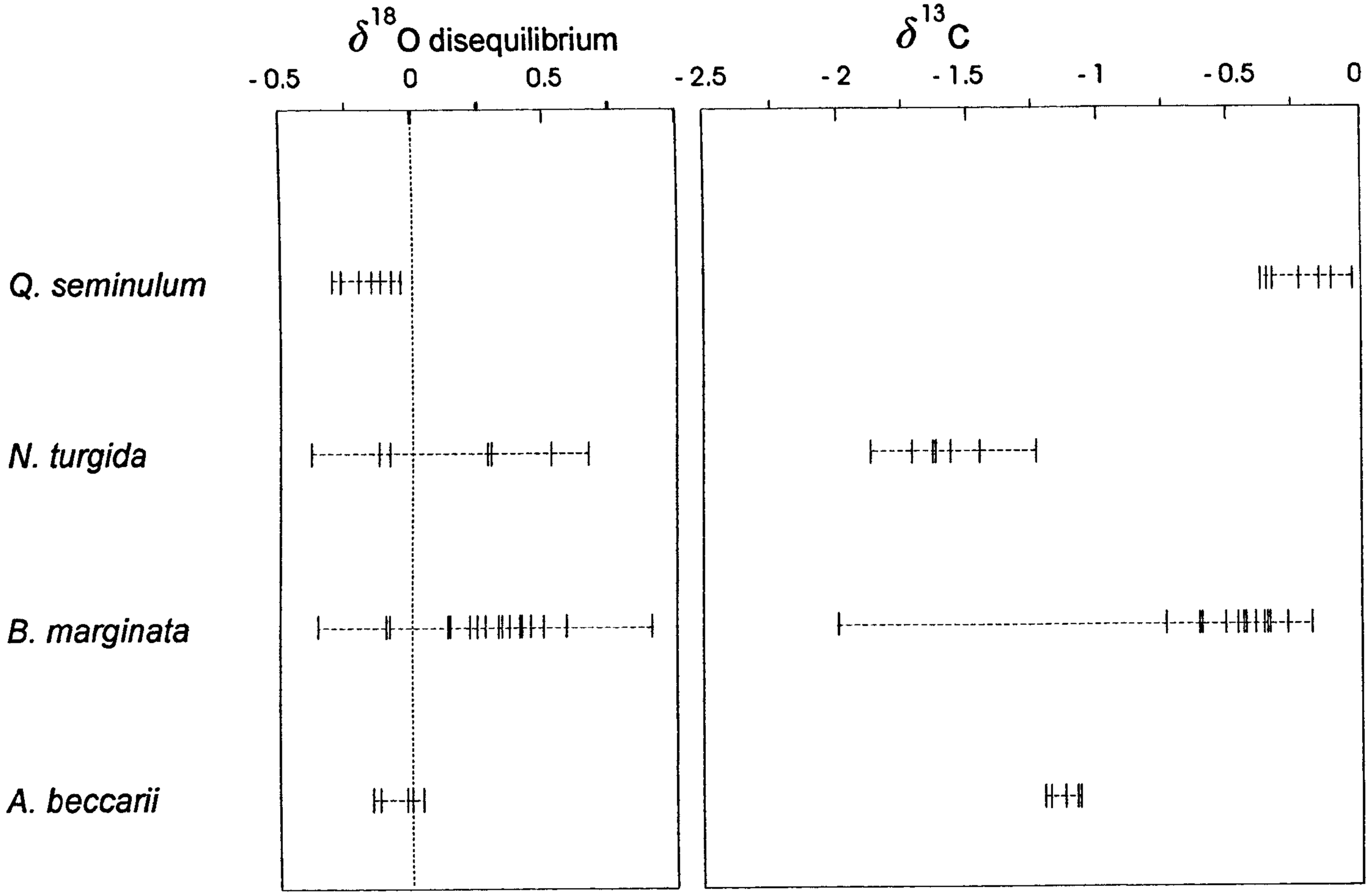


Figure 5.13 Stable oxygen isotopic disequilibria and measured stable carbon isotopic values of mono-specific samples of foraminifera from multicores

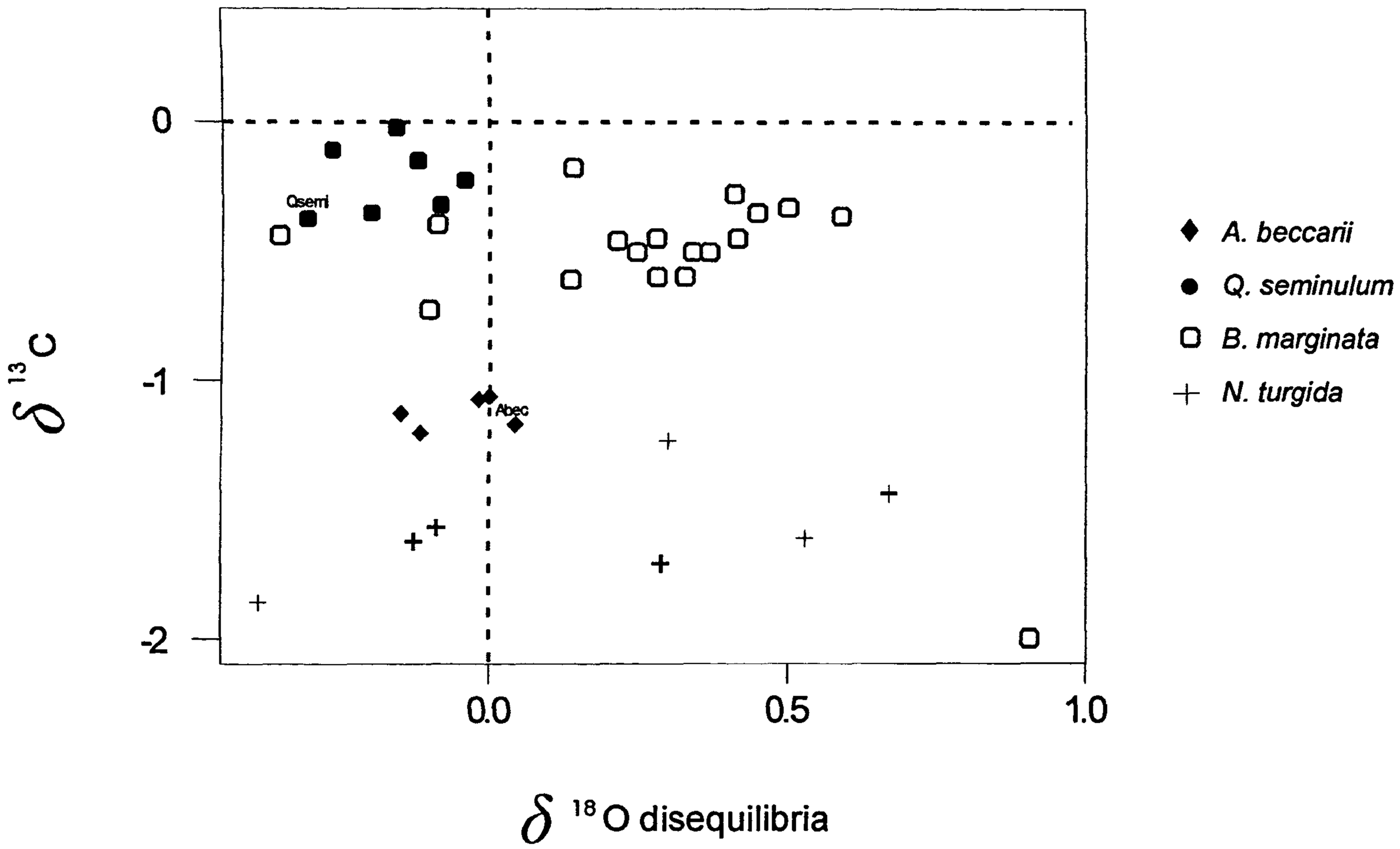


Figure 5.14 Plot of stable oxygen isotopic disequilibria against corresponding stable carbon isotopic values for each multicore sample measured

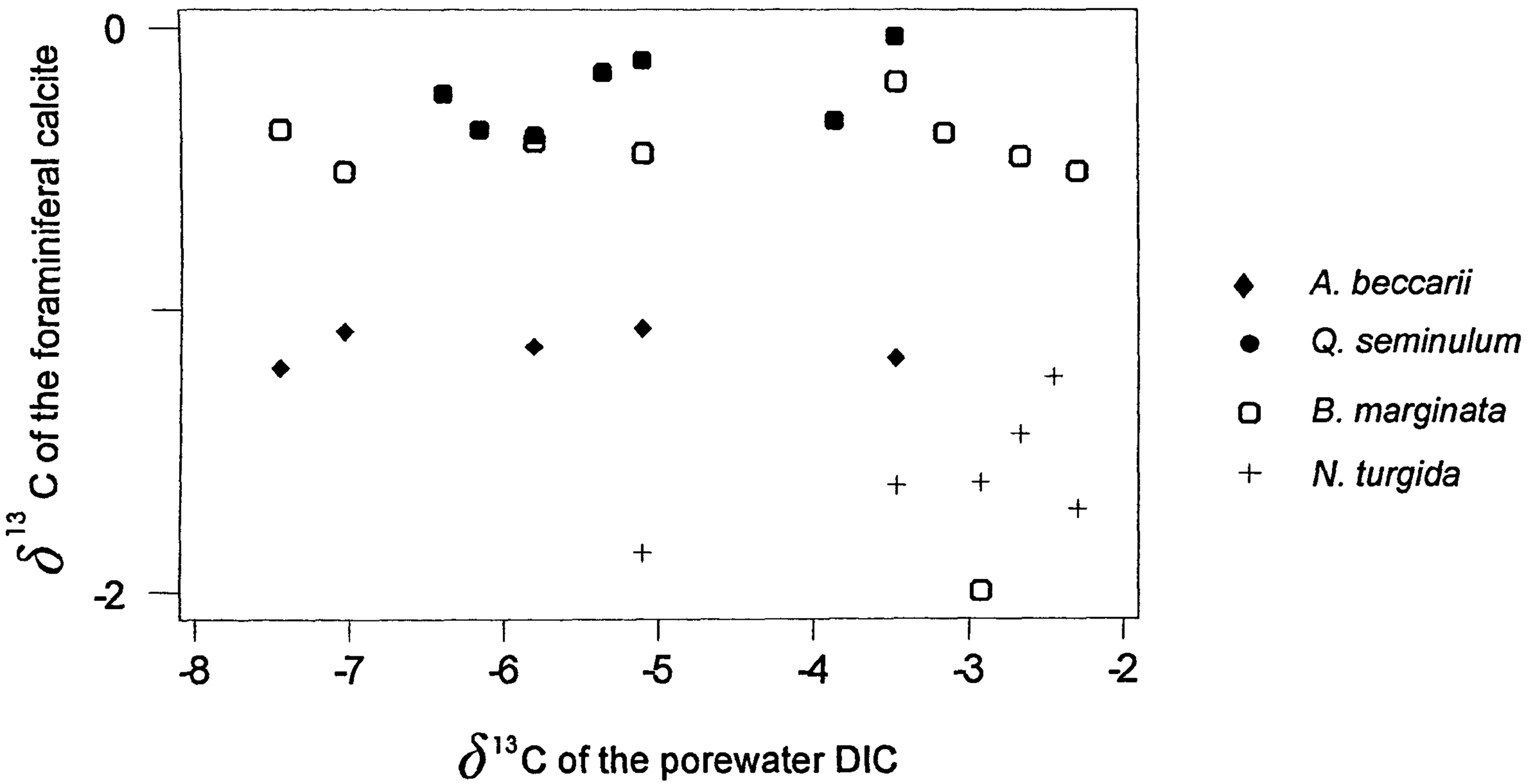


Figure 5.15 Plot of carbon isotopic values of porewater DIC against foraminiferal calcite

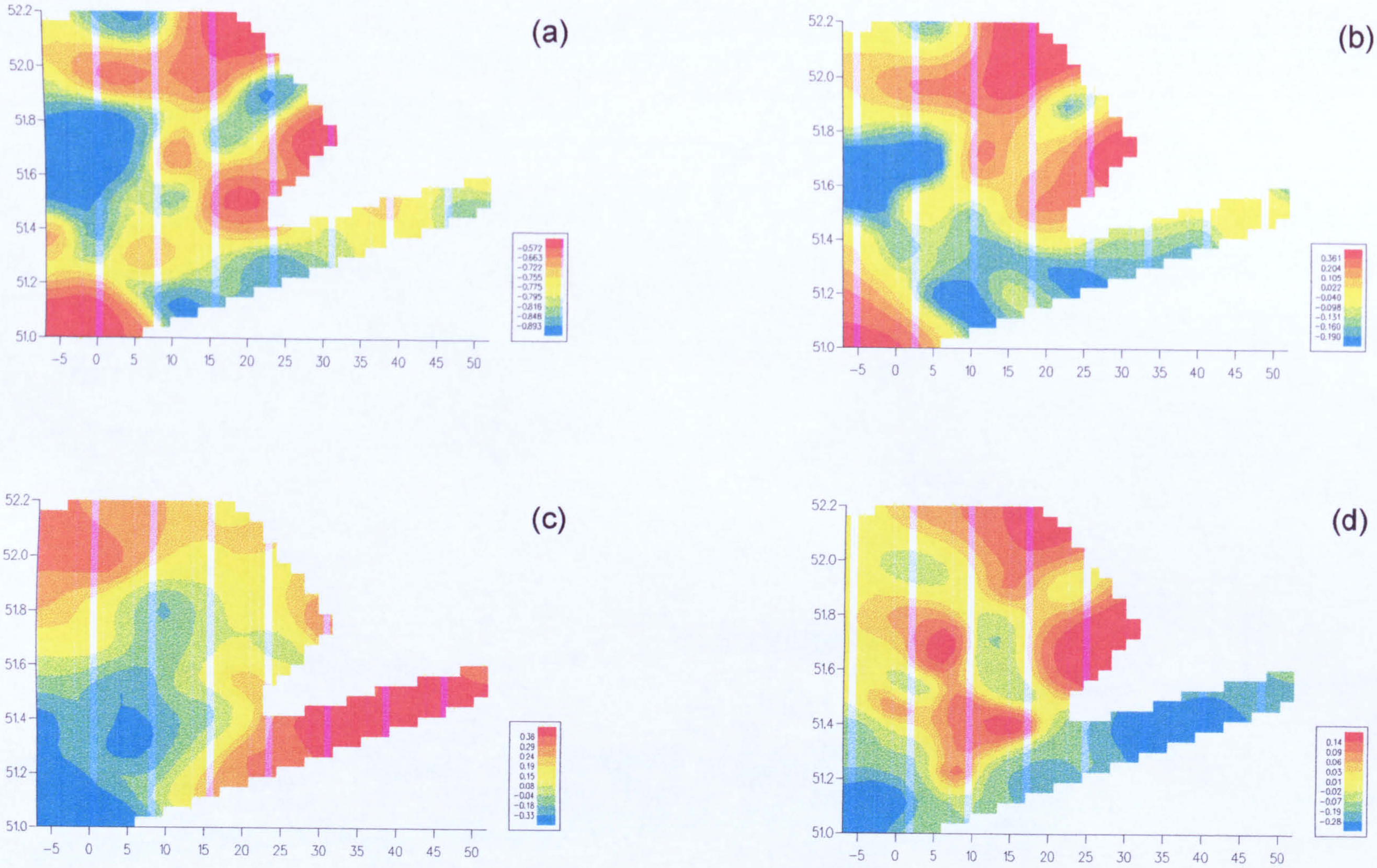


Figure 6.1 Distribution of the factors derived from Q-mode analysis of the living assemblage data
(a) Factor 1 (b) Factor 2 (c) Factor 3 (d) Factor 4

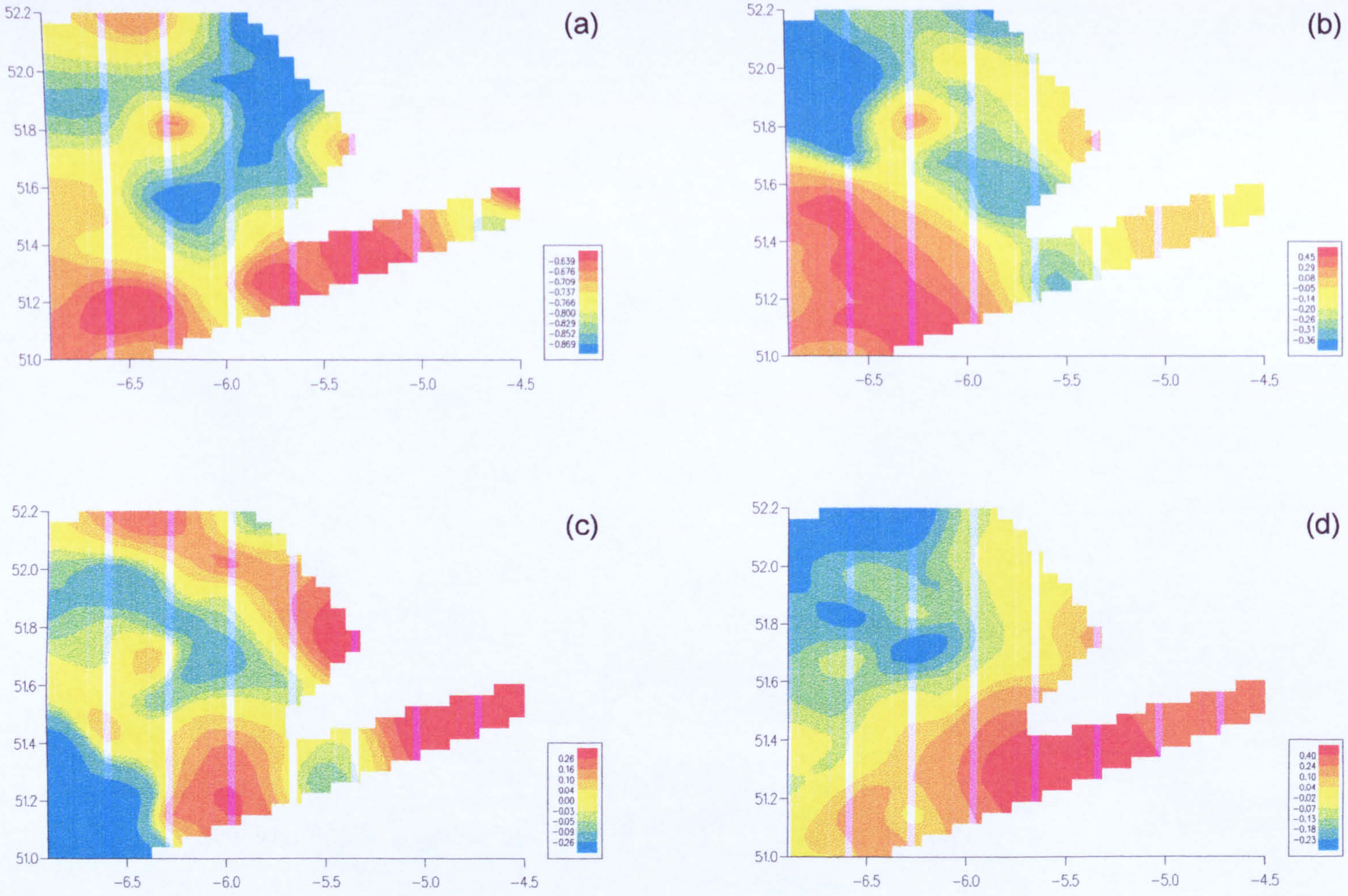


Figure 6.2 Distribution of the factors derived from Q-mode analysis of the dead assemblage data
(a) Factor 1 (b) Factor 2 (c) Factor 3 (d) Factor 4

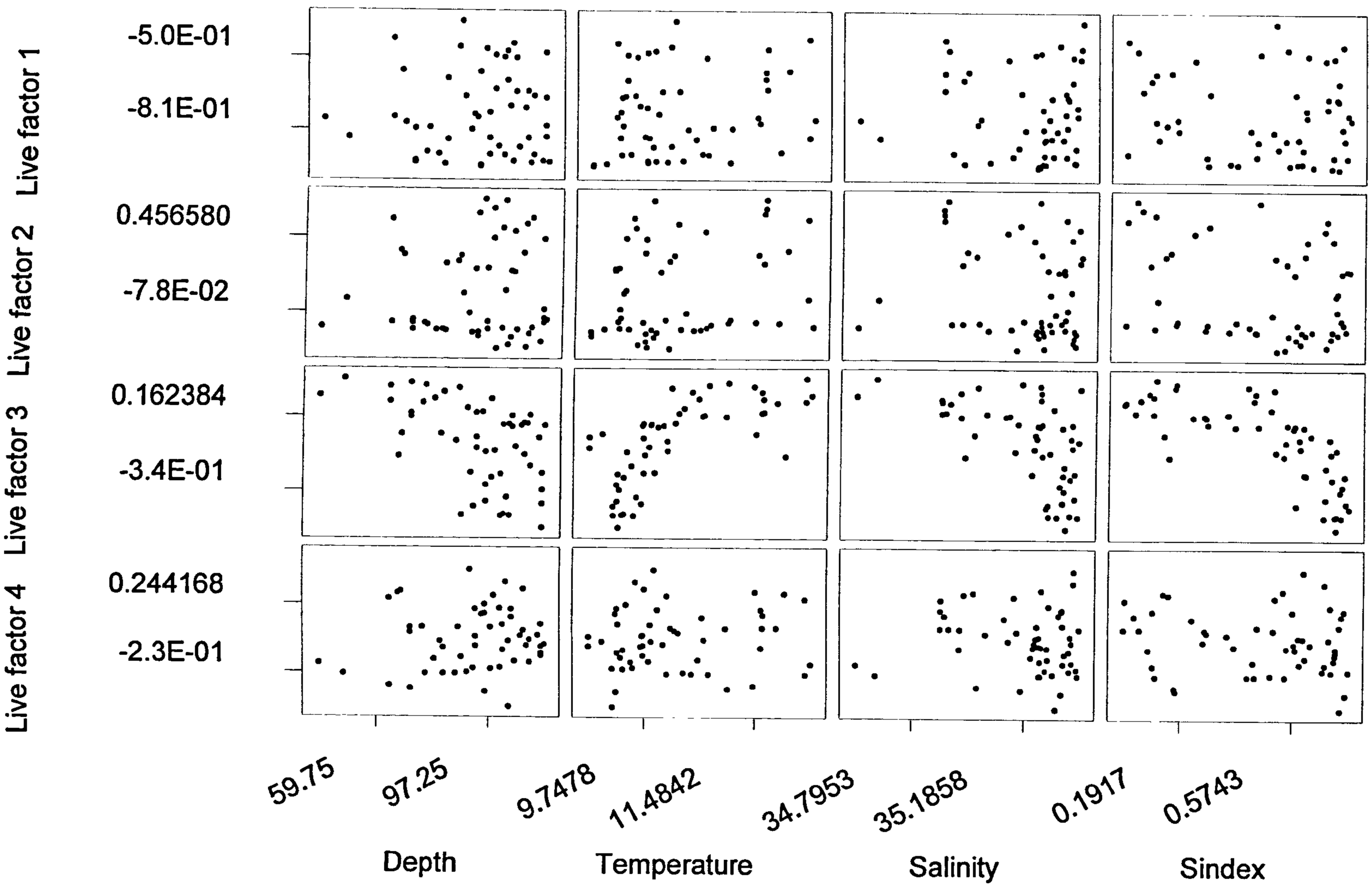


Figure 6.3 Comparison of the first four factors derived from the living assemblage data with depth and water characteristics

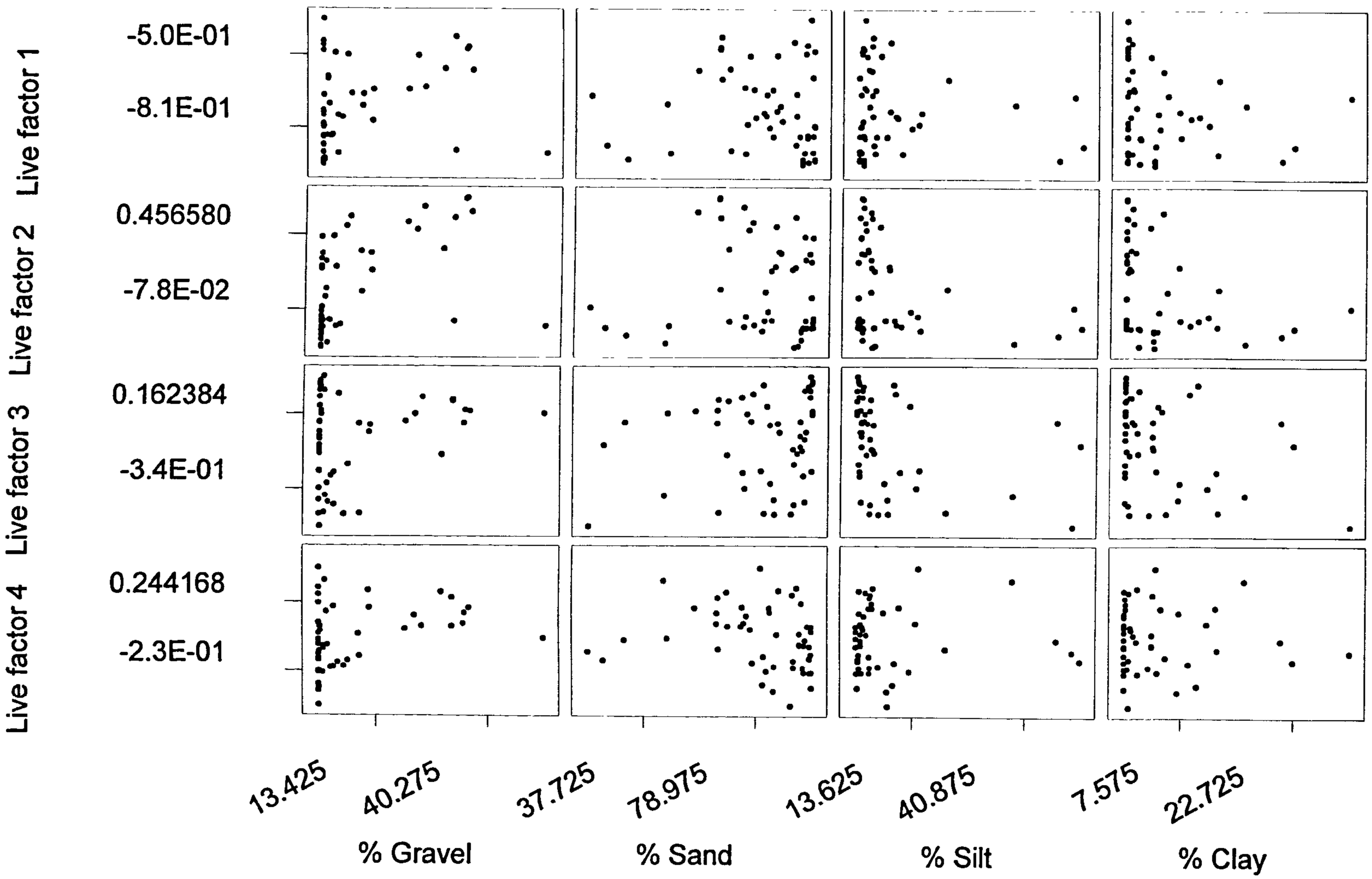


Figure 6.4 Comparison of the first four factors derived from the living assemblage data with grain size classes

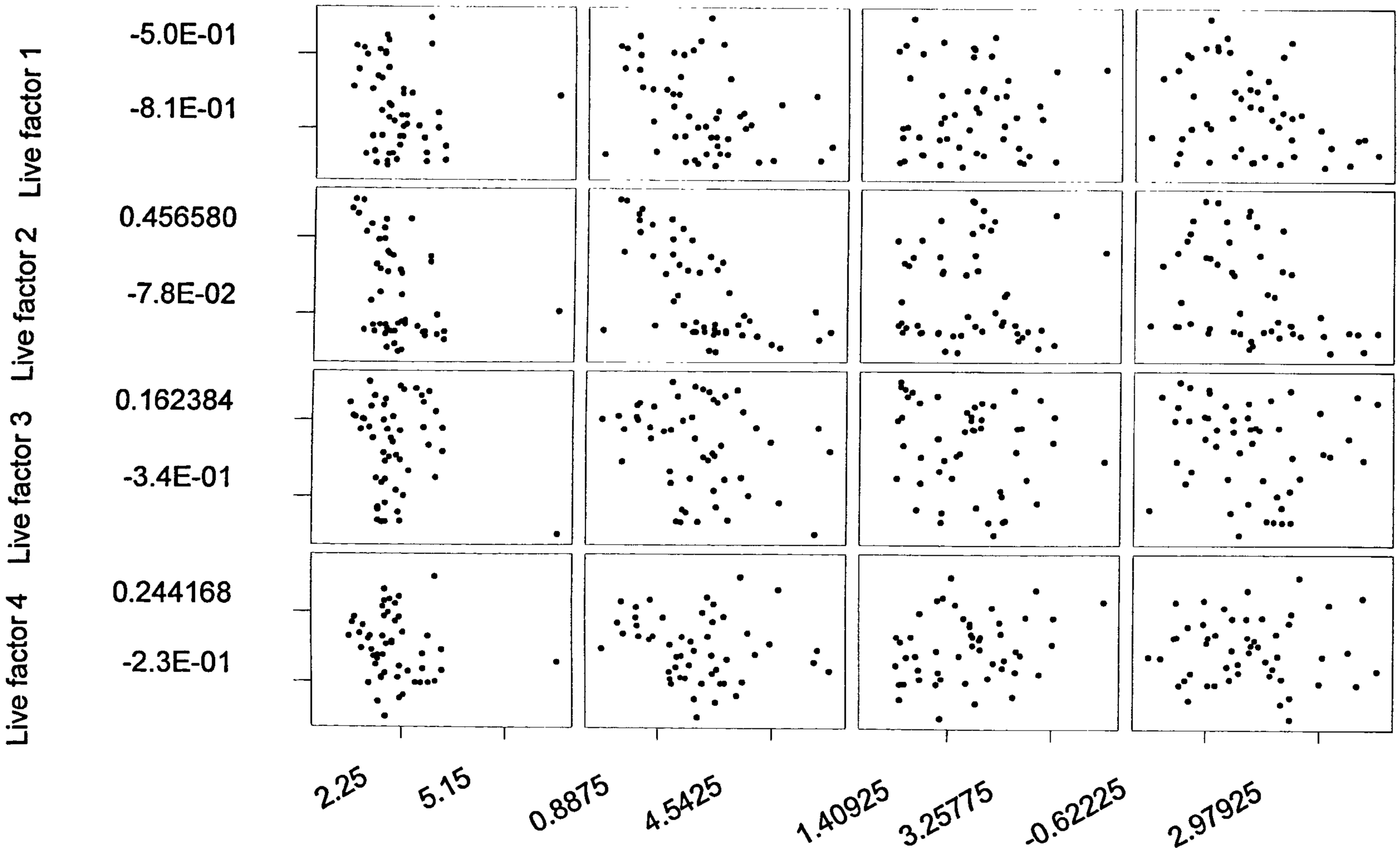


Figure 6.5 Comparison of the first four factors derived from the living assemblage data with grain size parameters

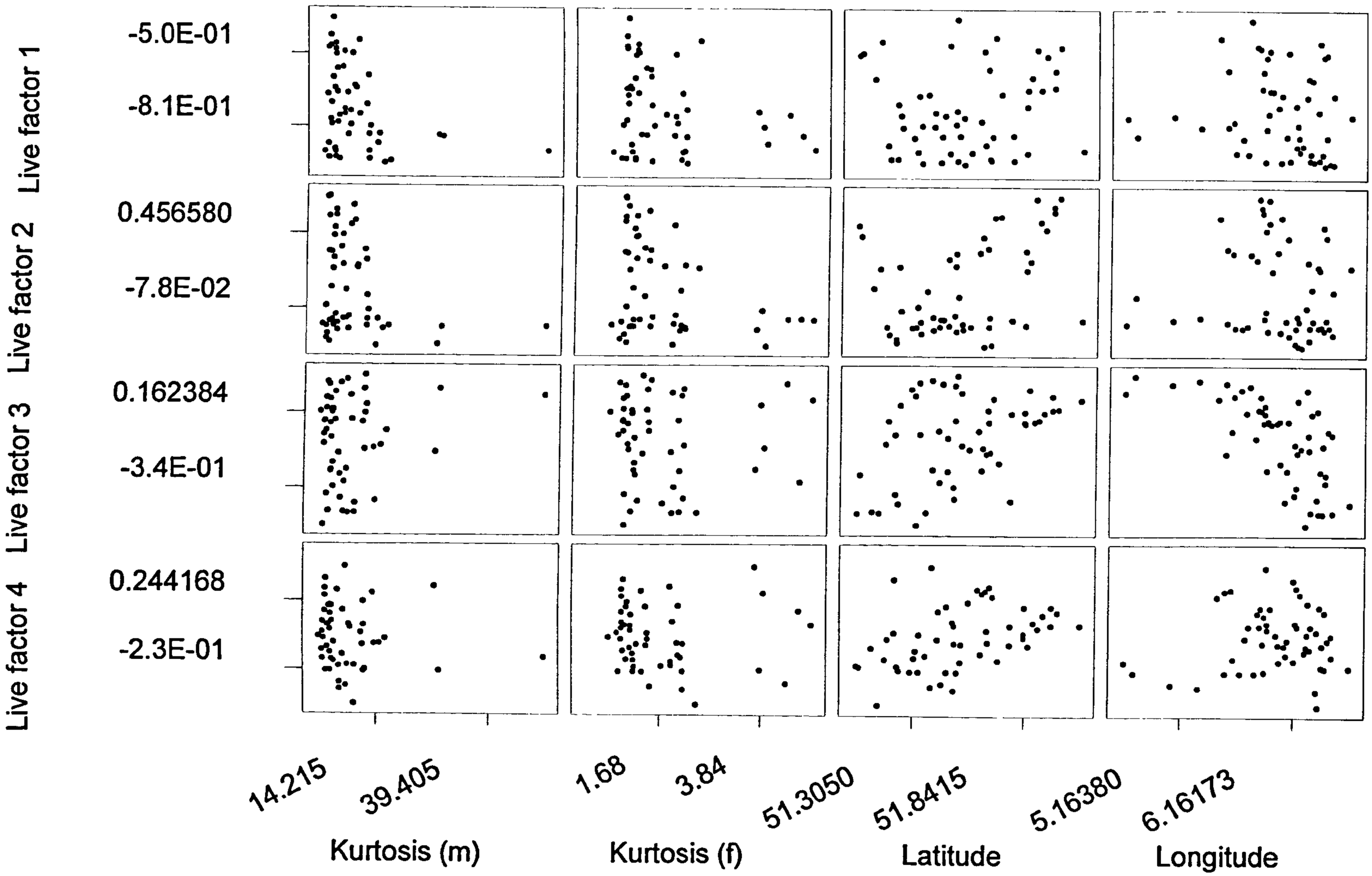


Figure 6.6 Comparison of the first four factors derived from the living assemblage data with kurtosis and co-ordinates

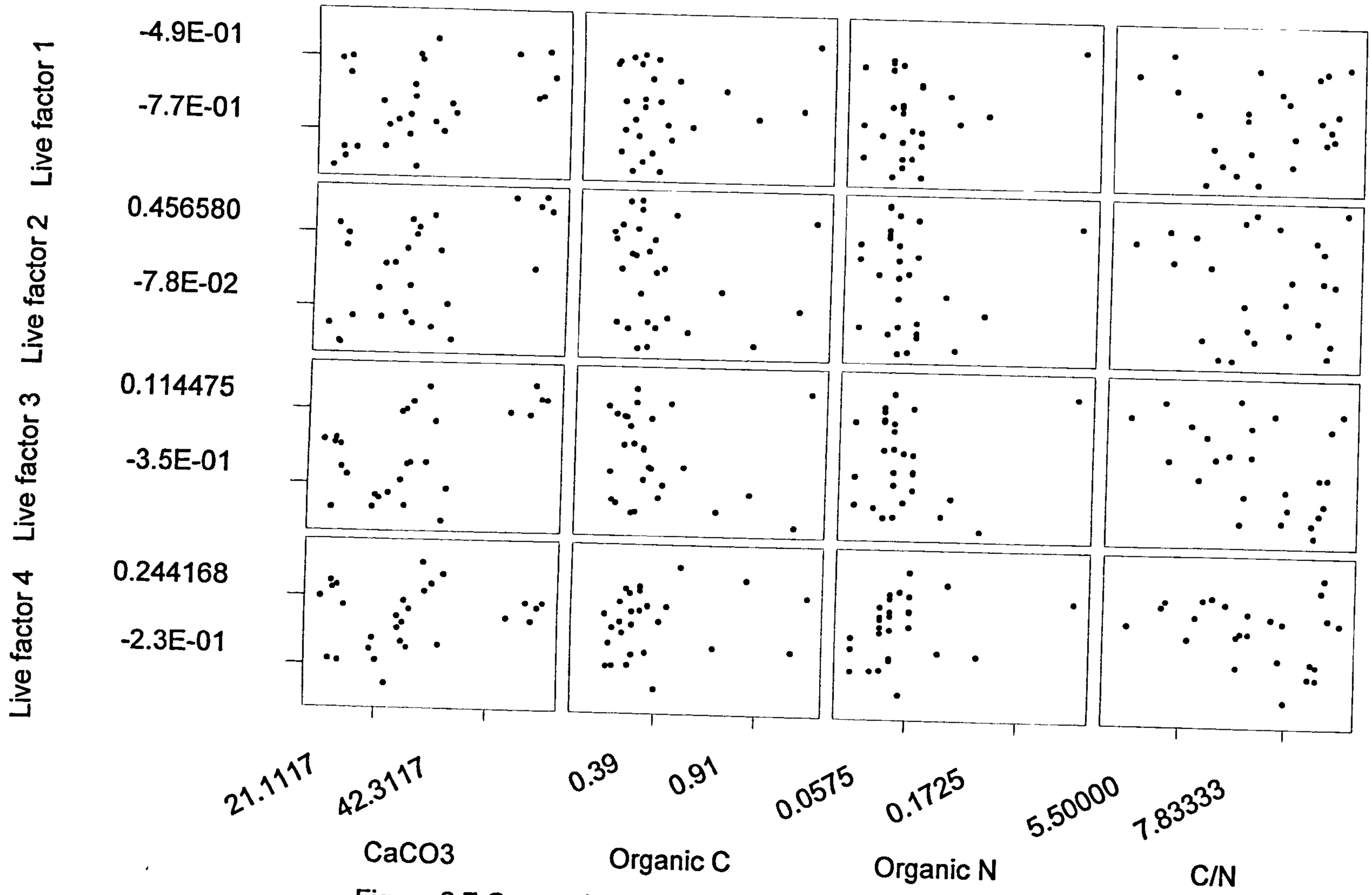


Figure 6.7 Comparison of the first four factors derived from the living assemblage data for 1995 only with geochemical characteristics

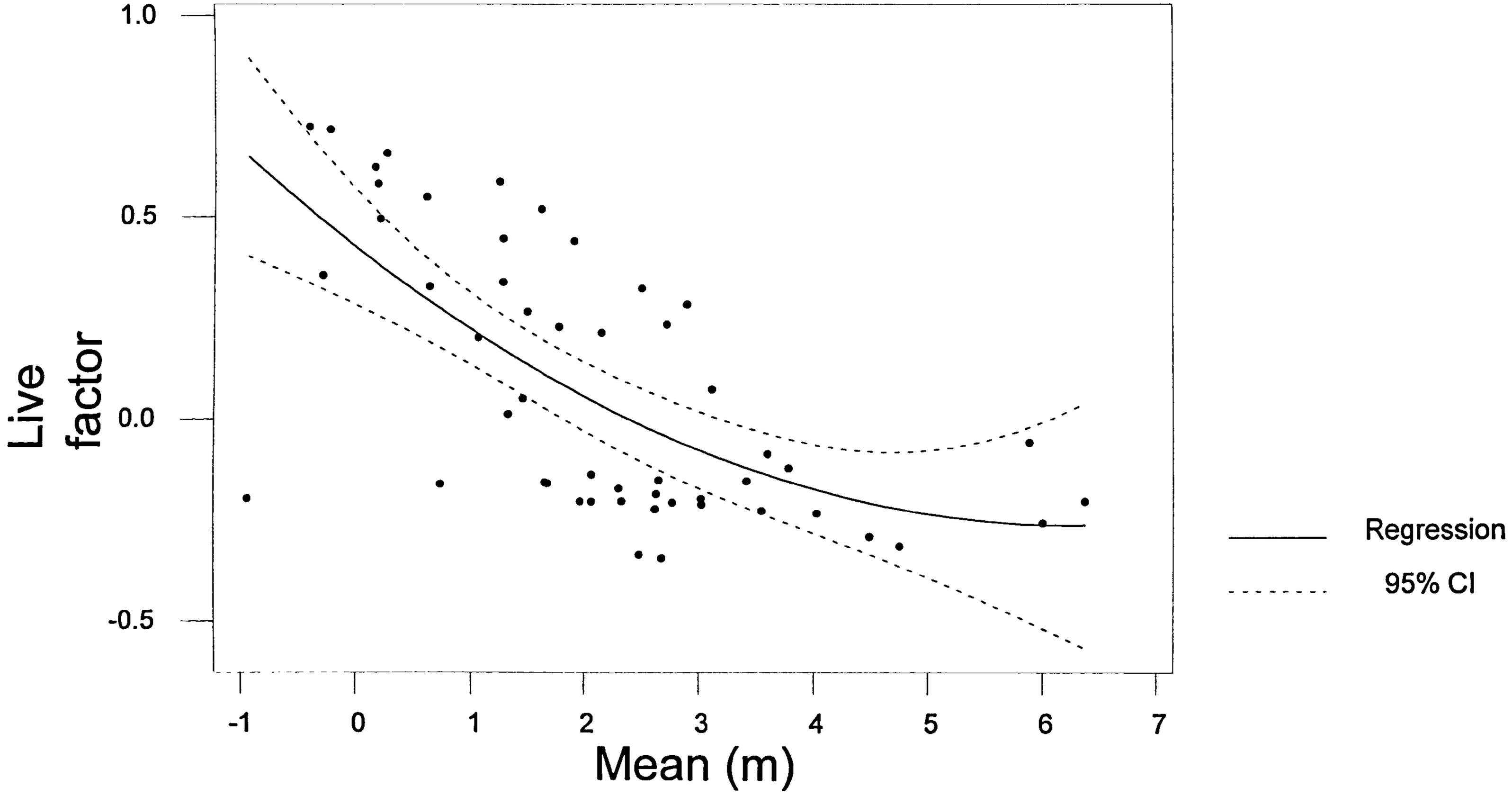
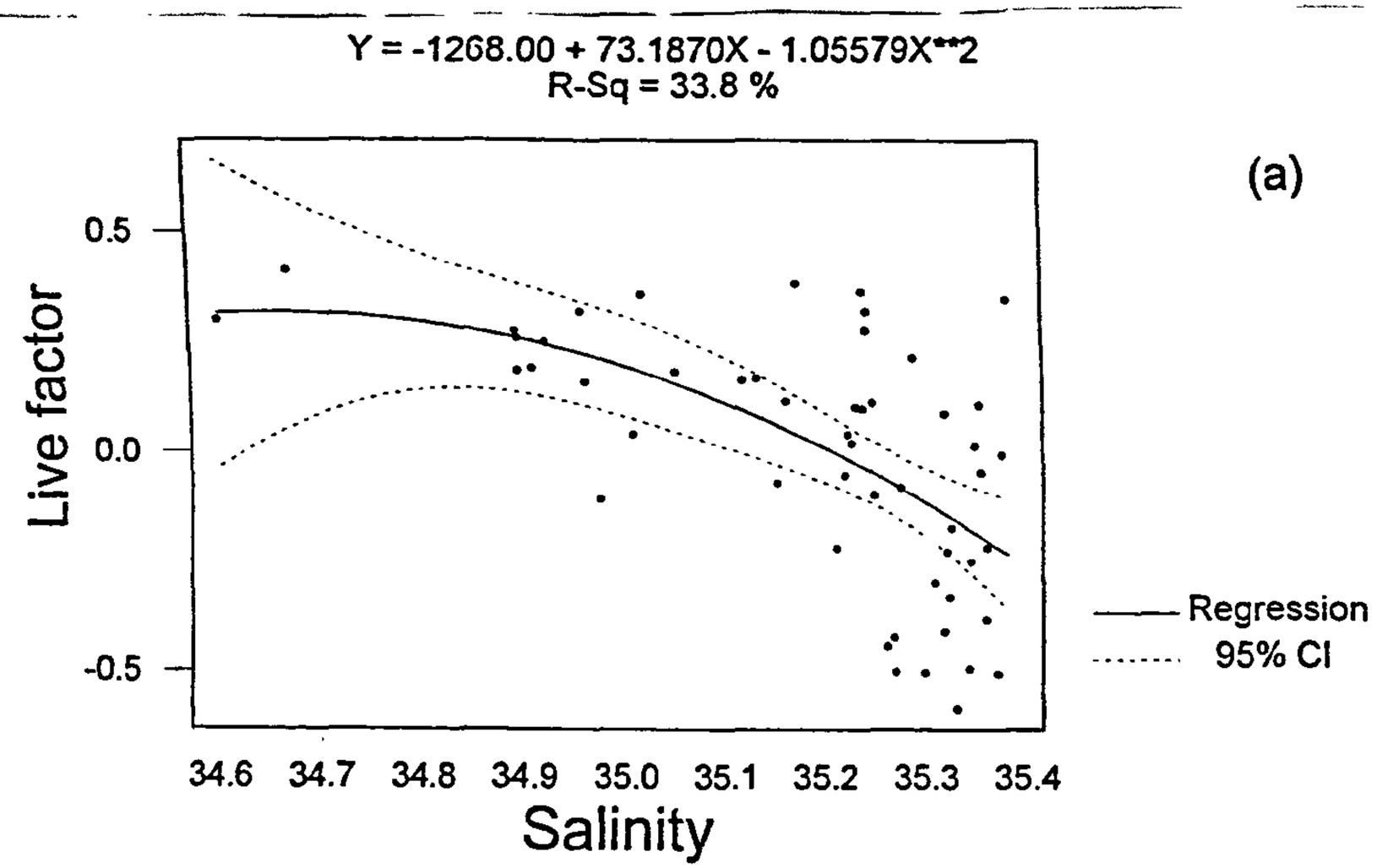
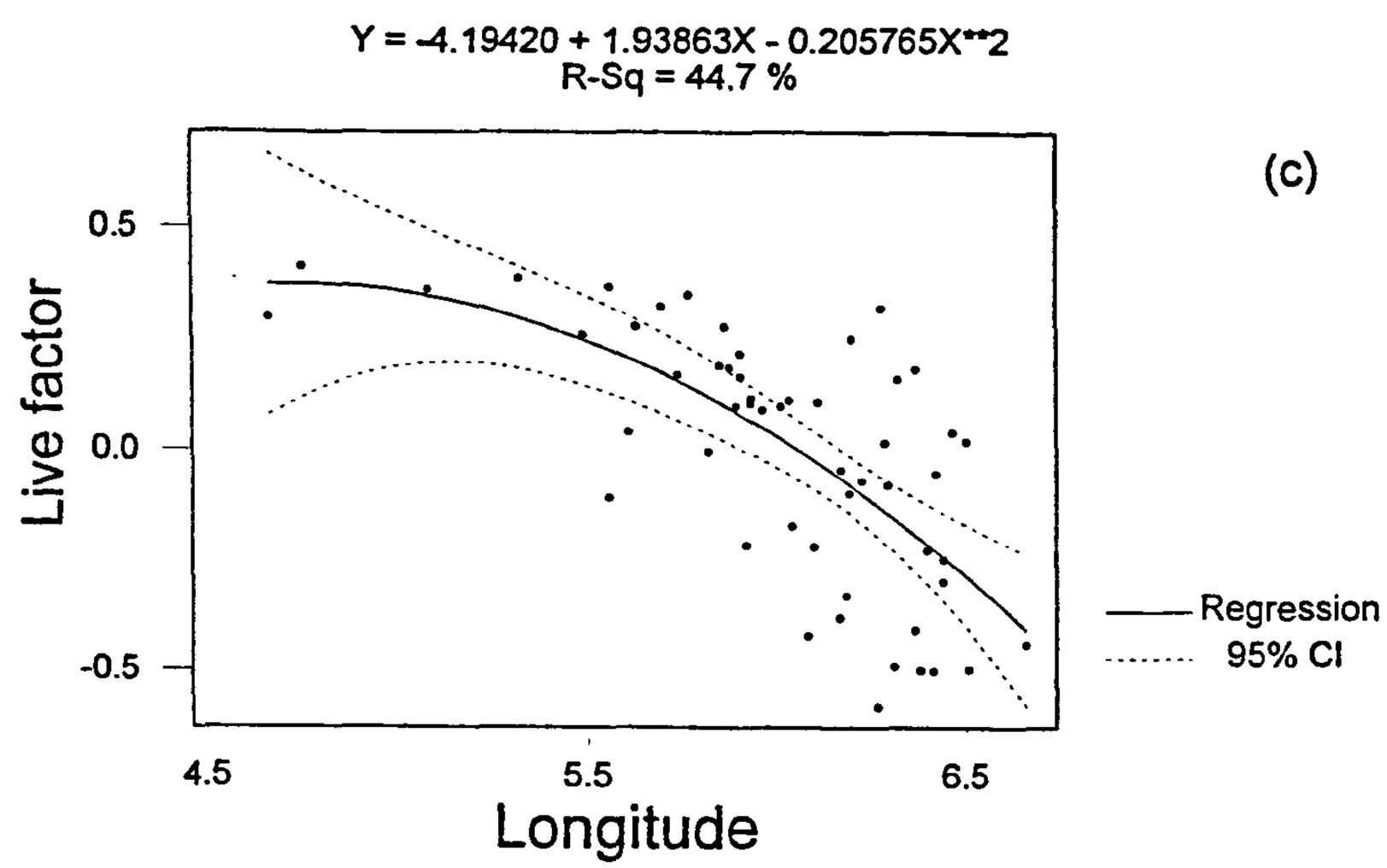
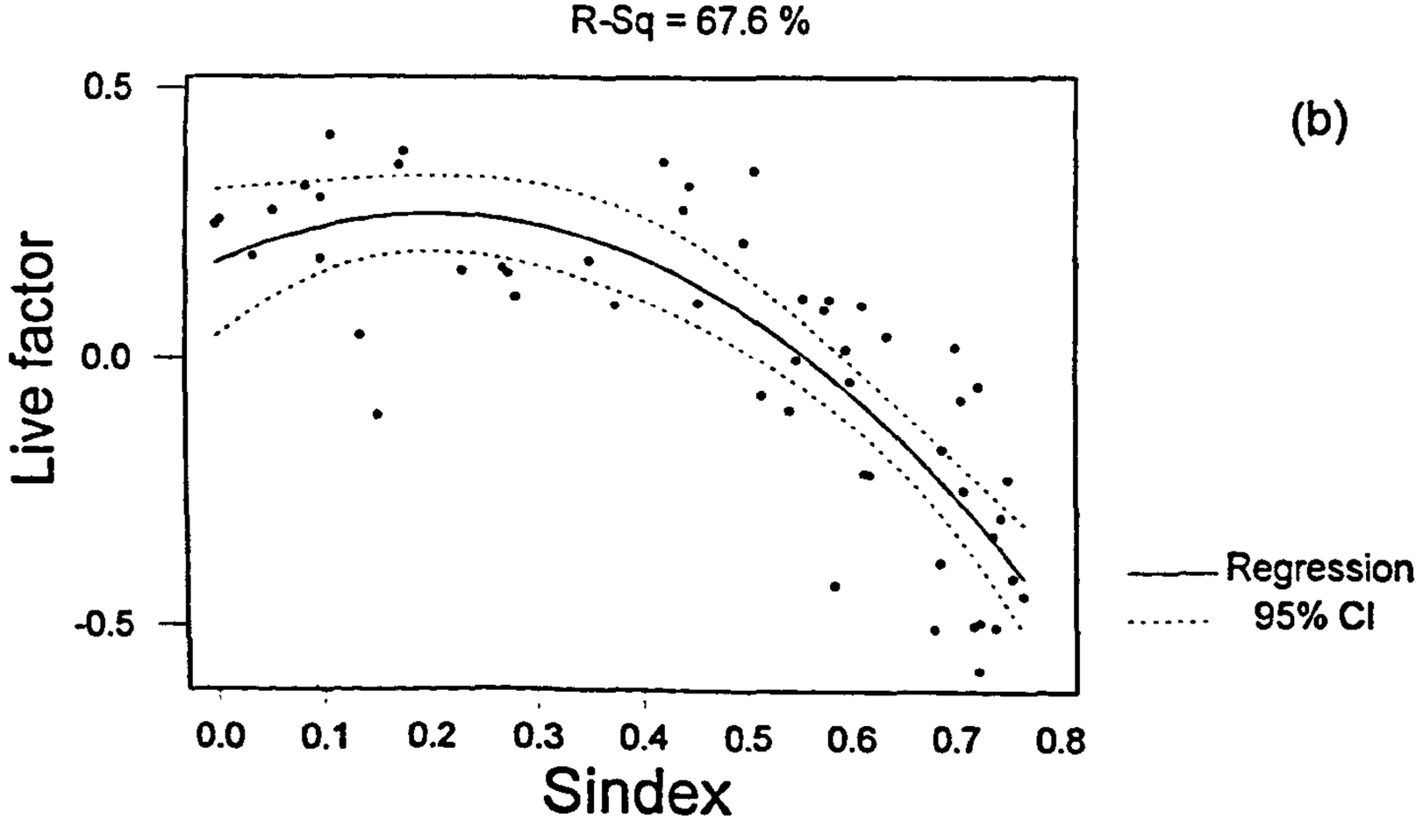


Figure 6.8 Regression of factor 2 (living) against mean grain size measured in phi units







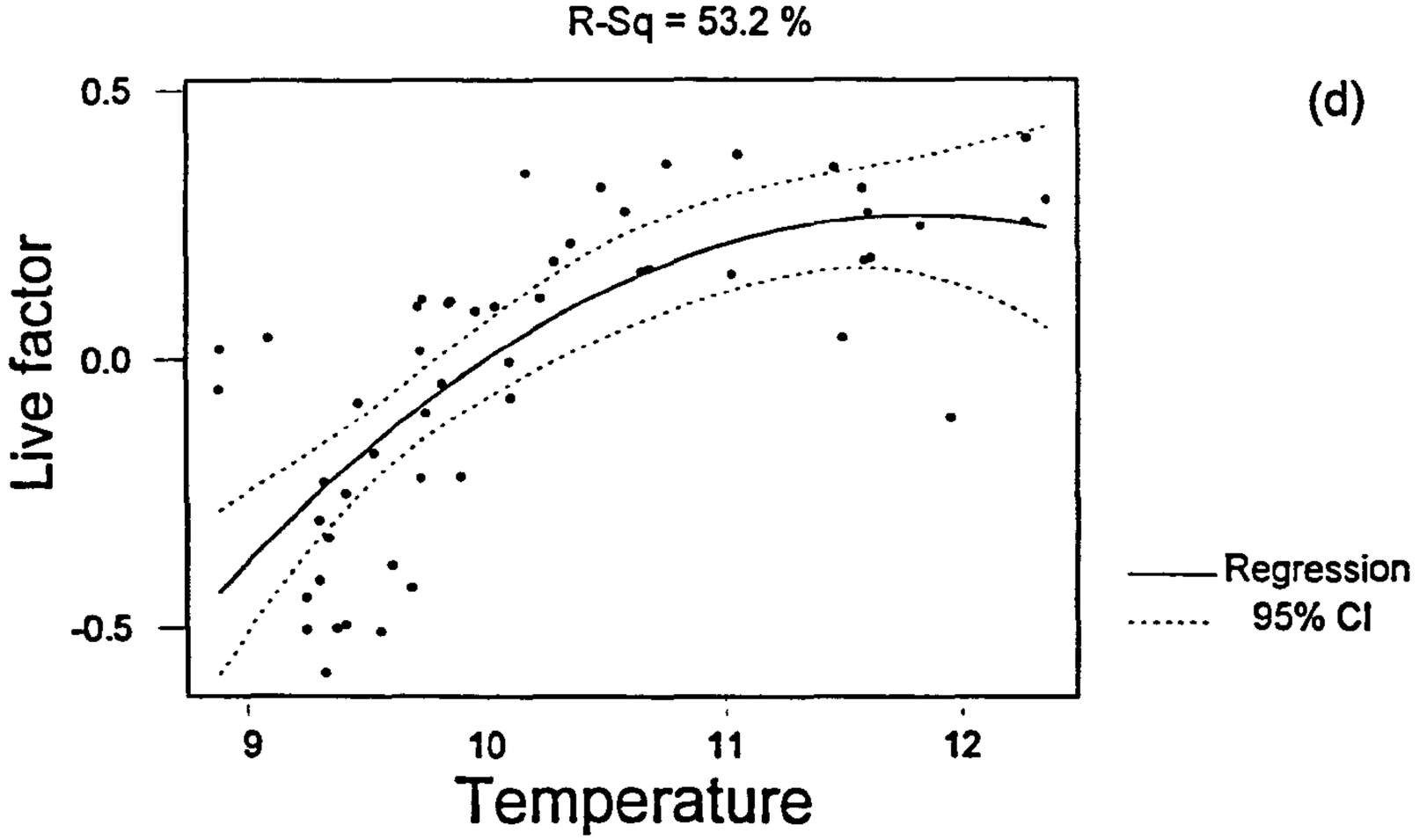


Figure 6.9 Regression of factor 3 (living) against (a) temperature (b) salinity (c) longitude

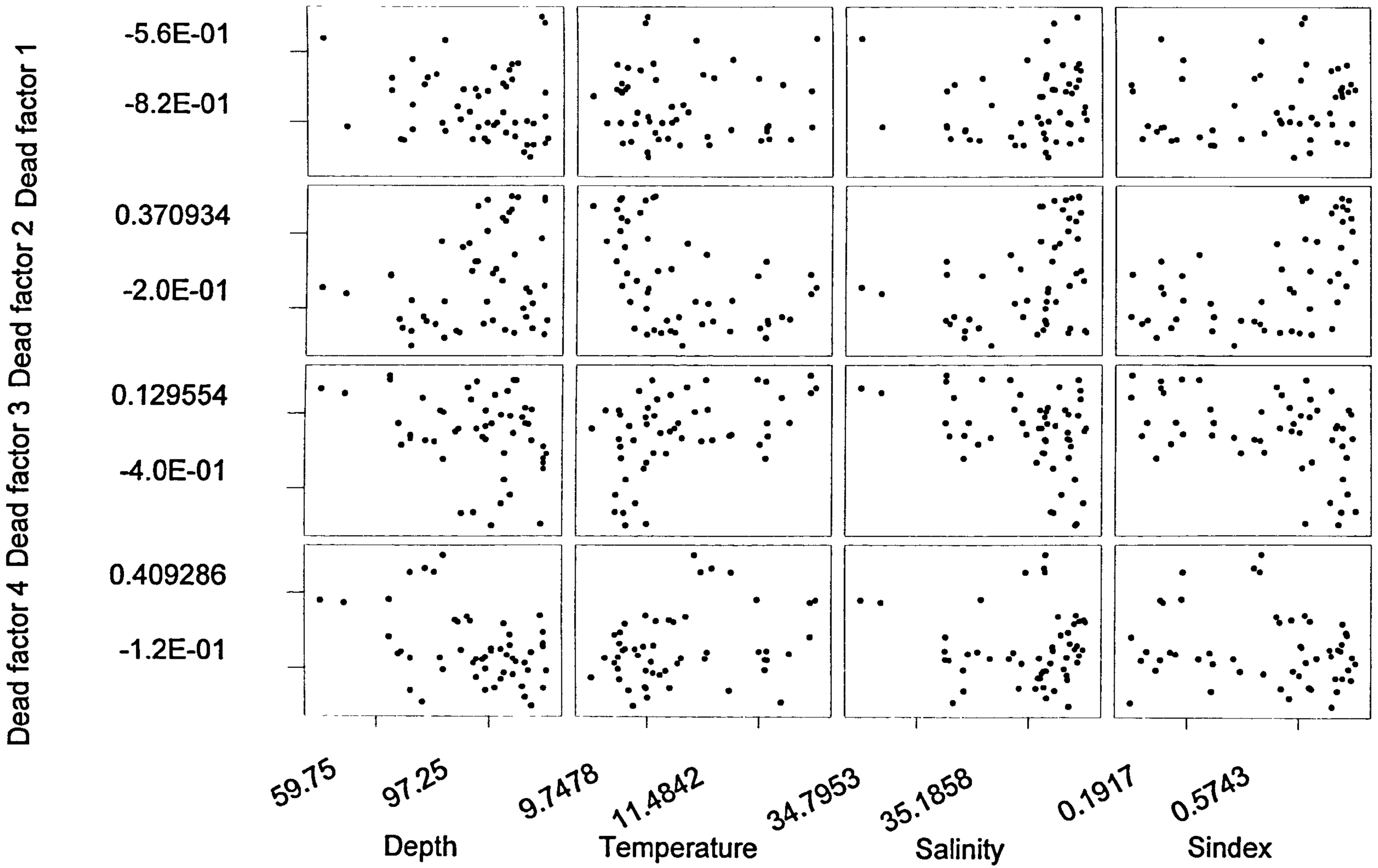


Figure 6.10 Comparison of the first four factors derived from the dead assemblage data with depth and water characteristics

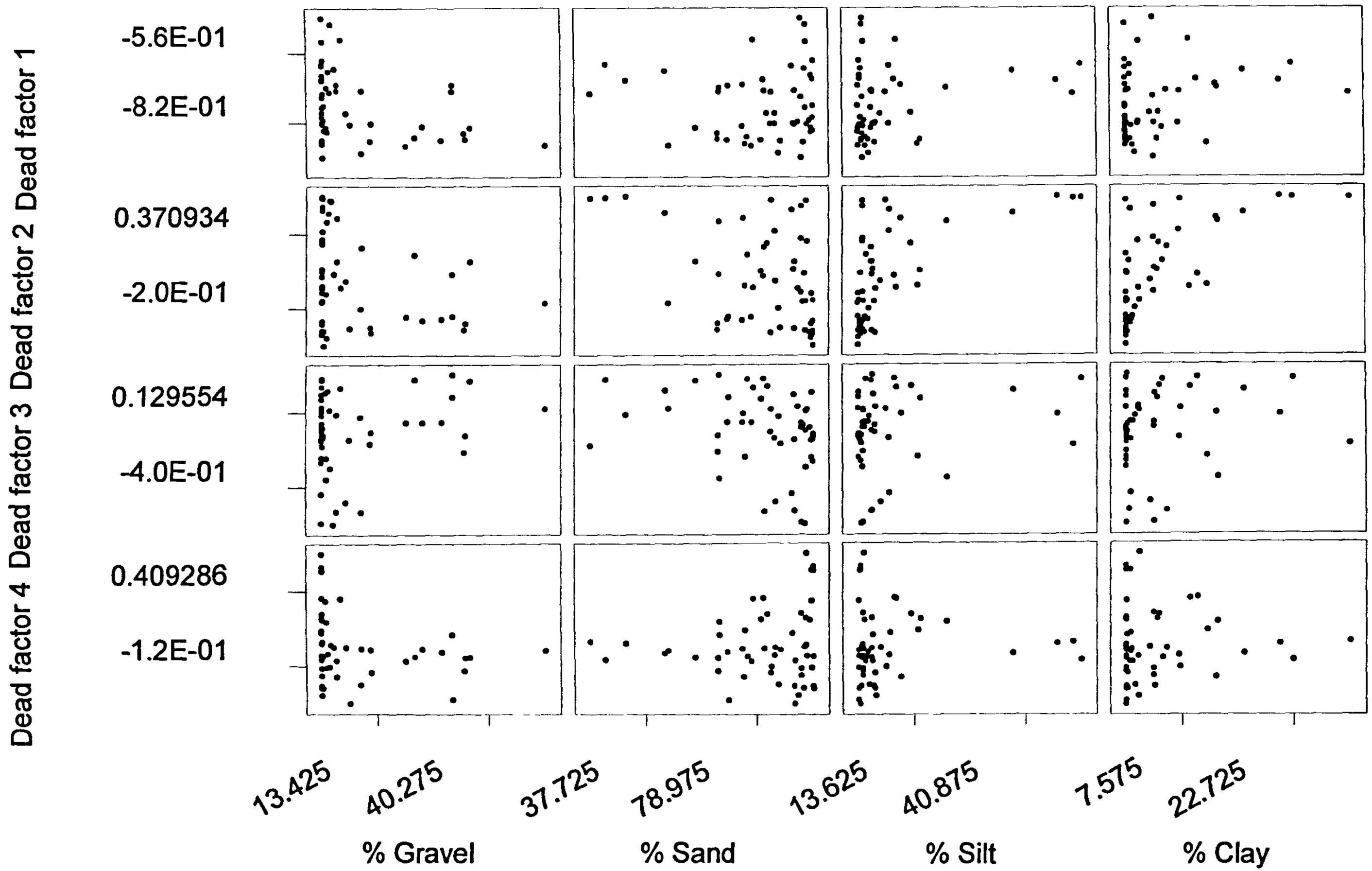


Figure 6.11 Comparison of the first four factors derived from the dead assemblage data with grain size classes

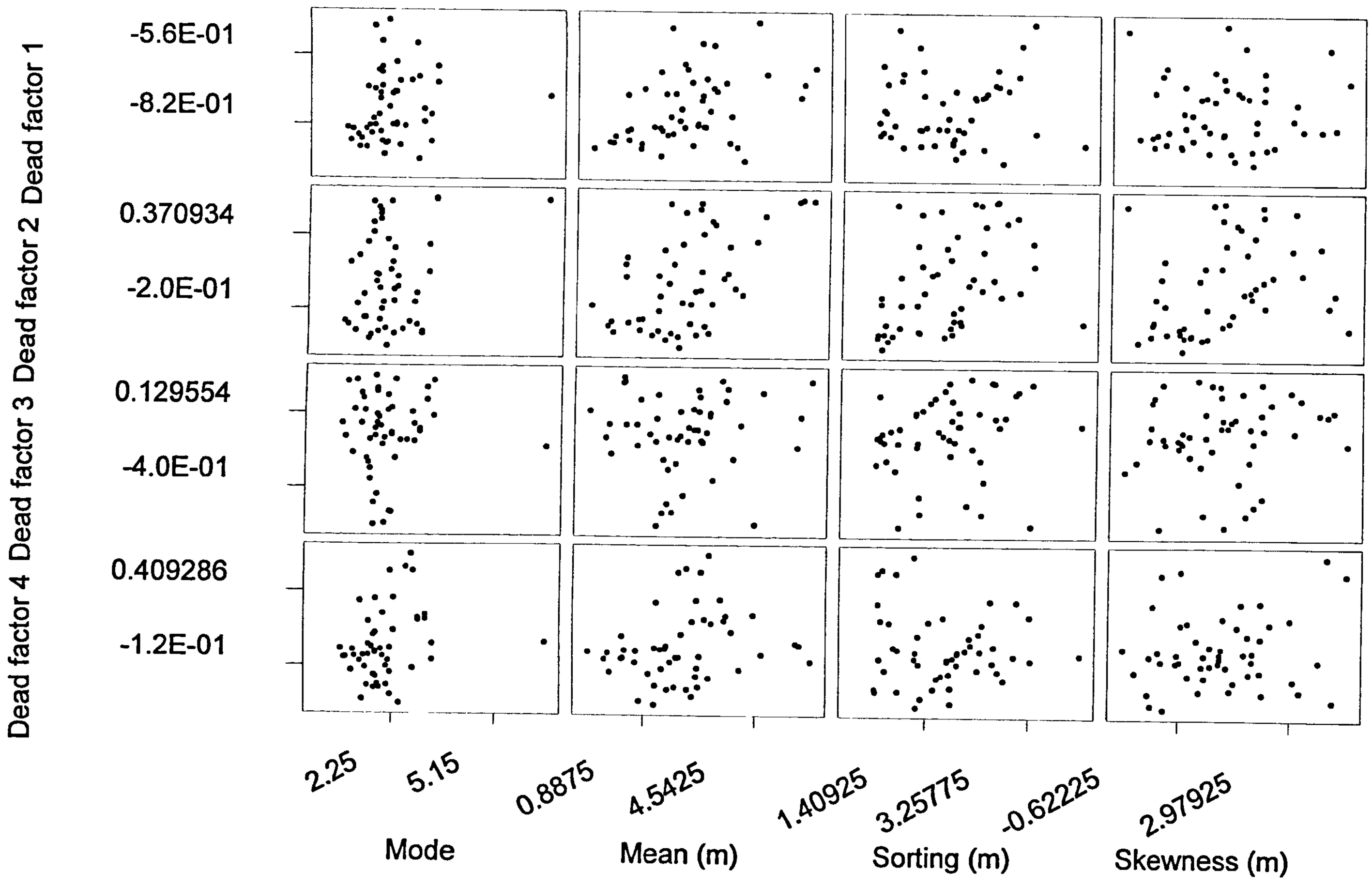


Figure 6.12 Comparison of the first four factors derived from the dead assemblage data with grain size parameters

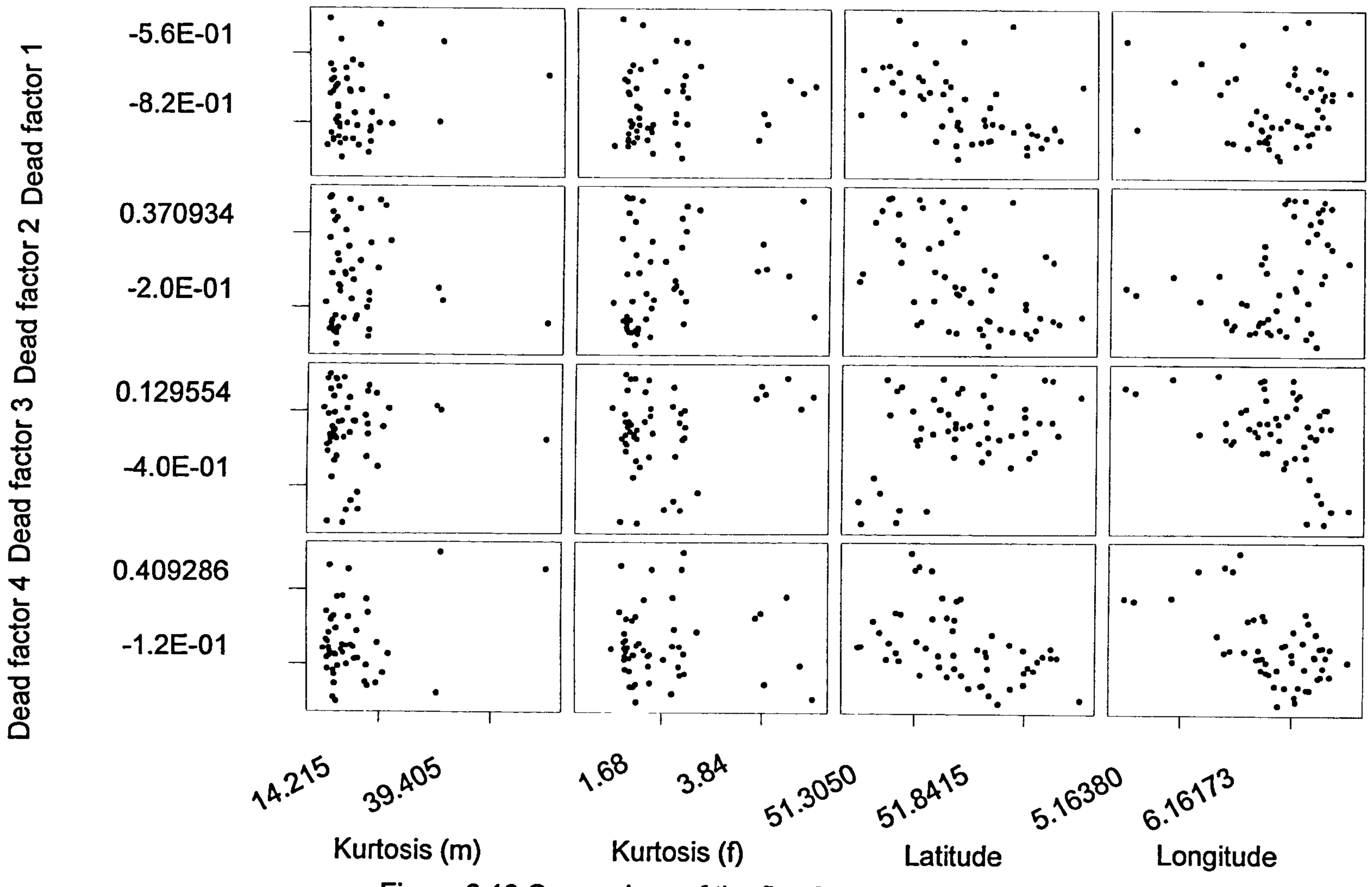


Figure 6.13 Comparison of the first four factors derived from the dead assemblage data with kurtosis and co-ordinates

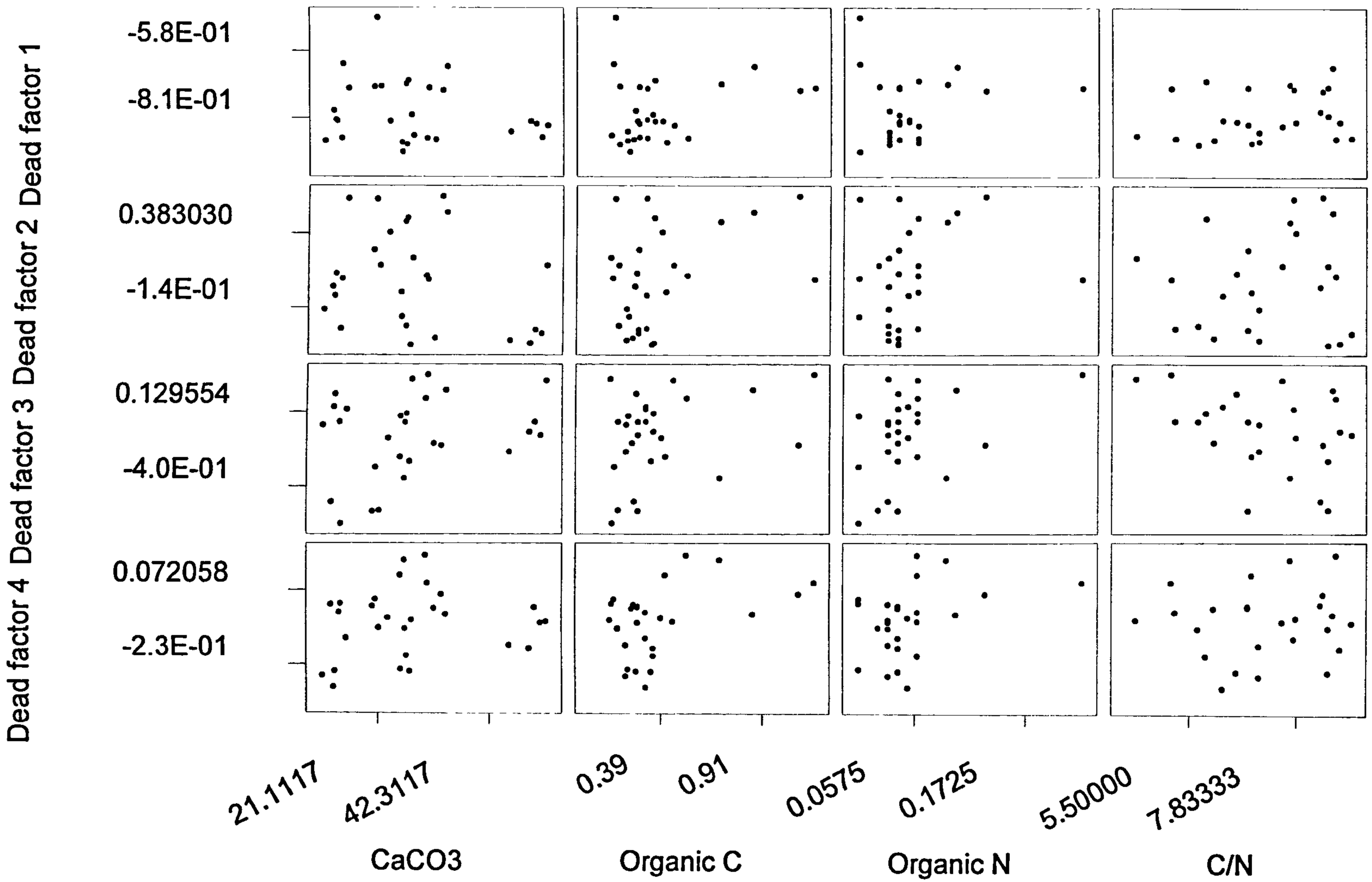


Figure 6.14 Comparison of the first four factors derived from the dead assemblage data for 1995 only with geochemical characteristics

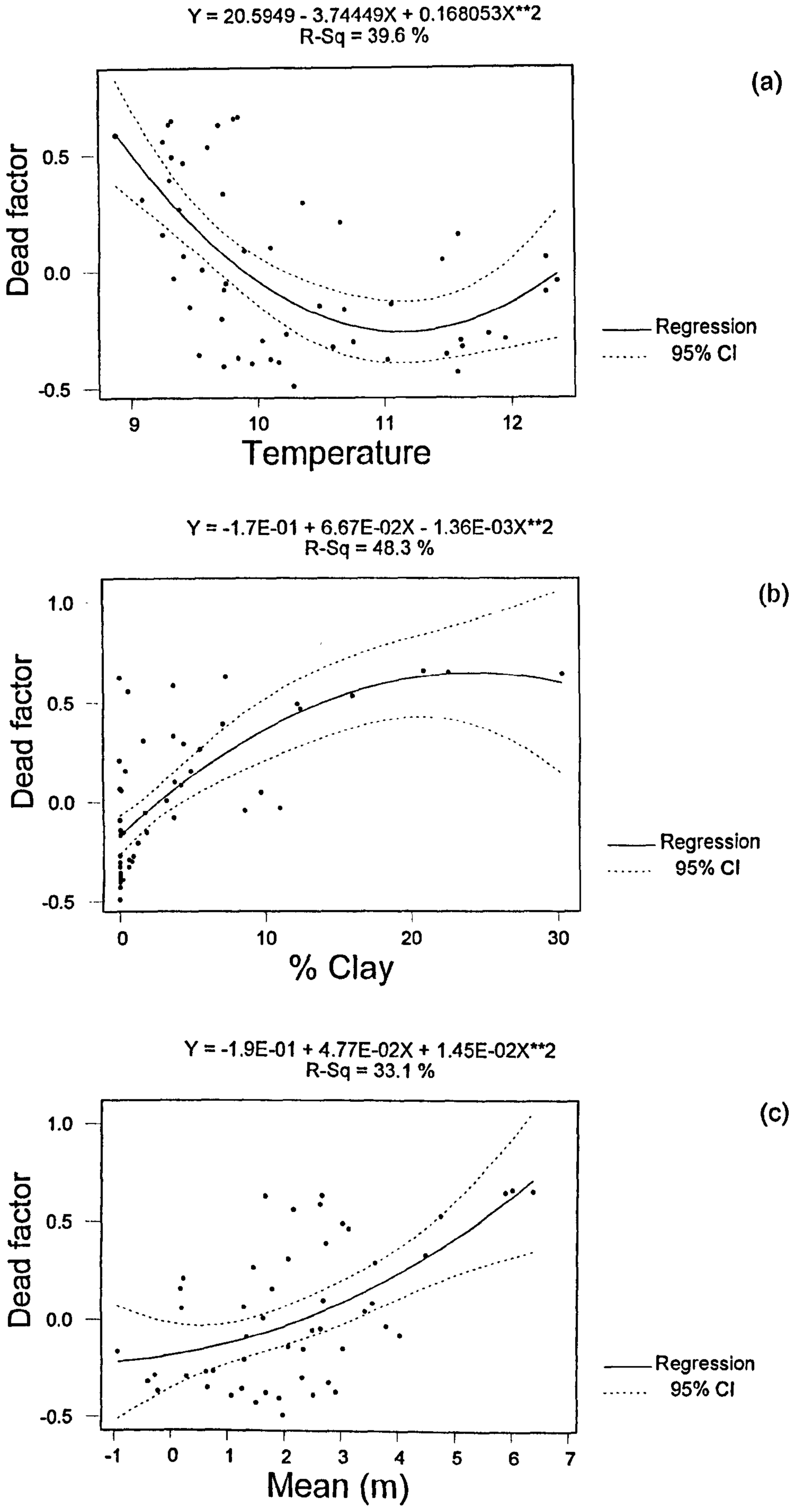


Figure 6.15 Regression of factor 2 (dead) against

(a) temperature (b) % clay (c) mean grain size

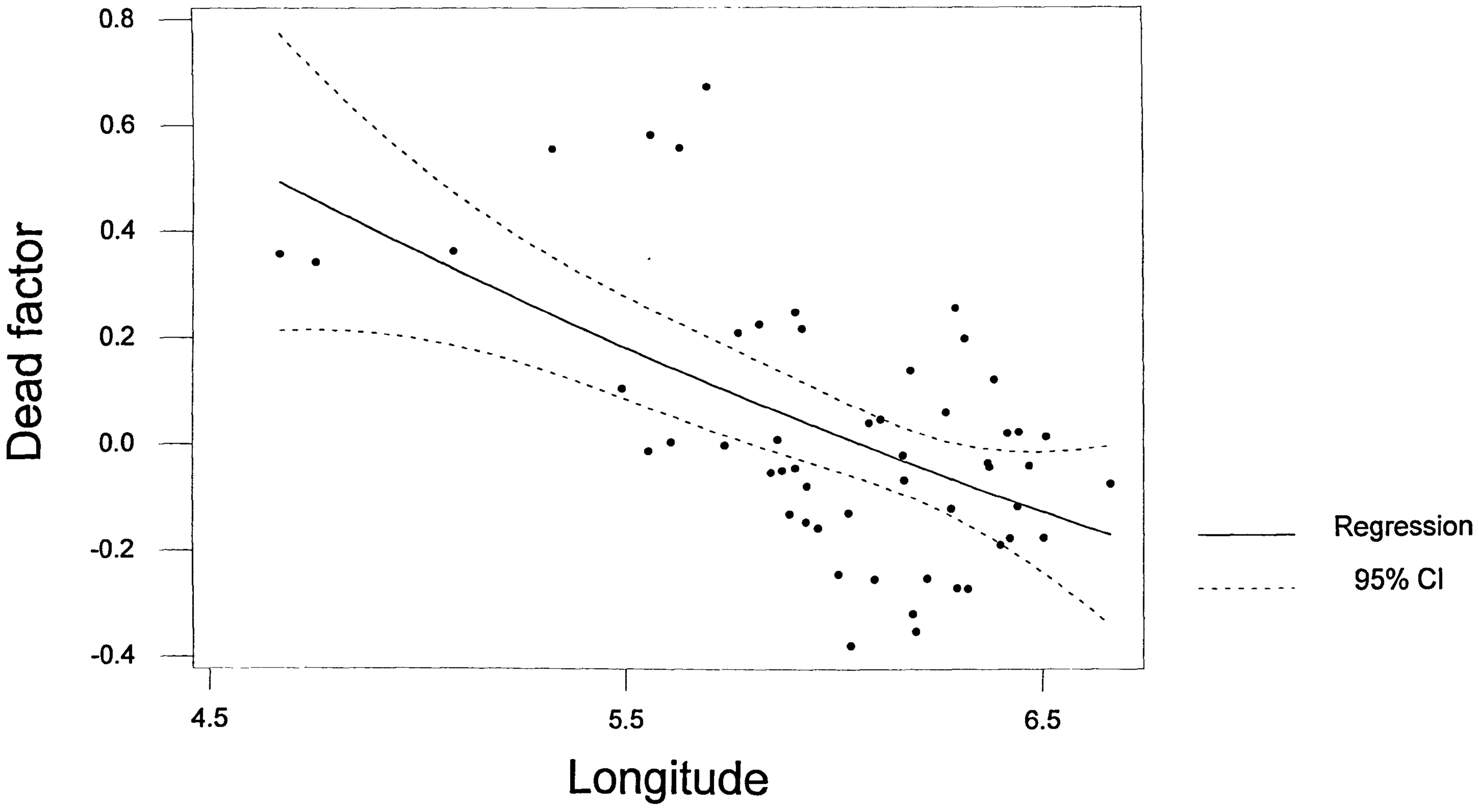


Figure 6.16 Regression of factor 4 (dead) against longitude

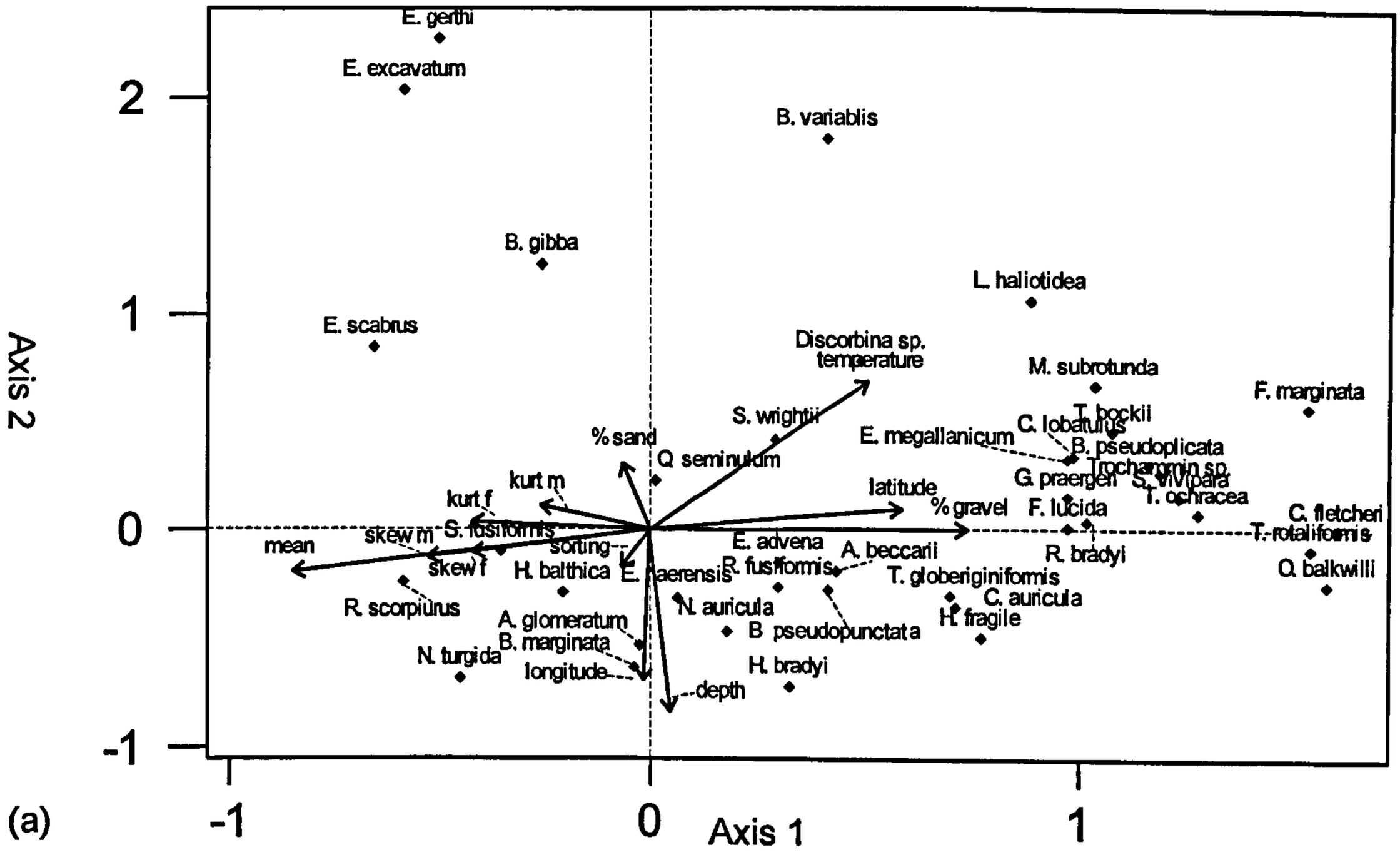


Figure 6.17 Biplot of species and environmental variables from CCA analysis on the living assemblage data (a) for axes 1 and 2 (b) for axes 2 and 3

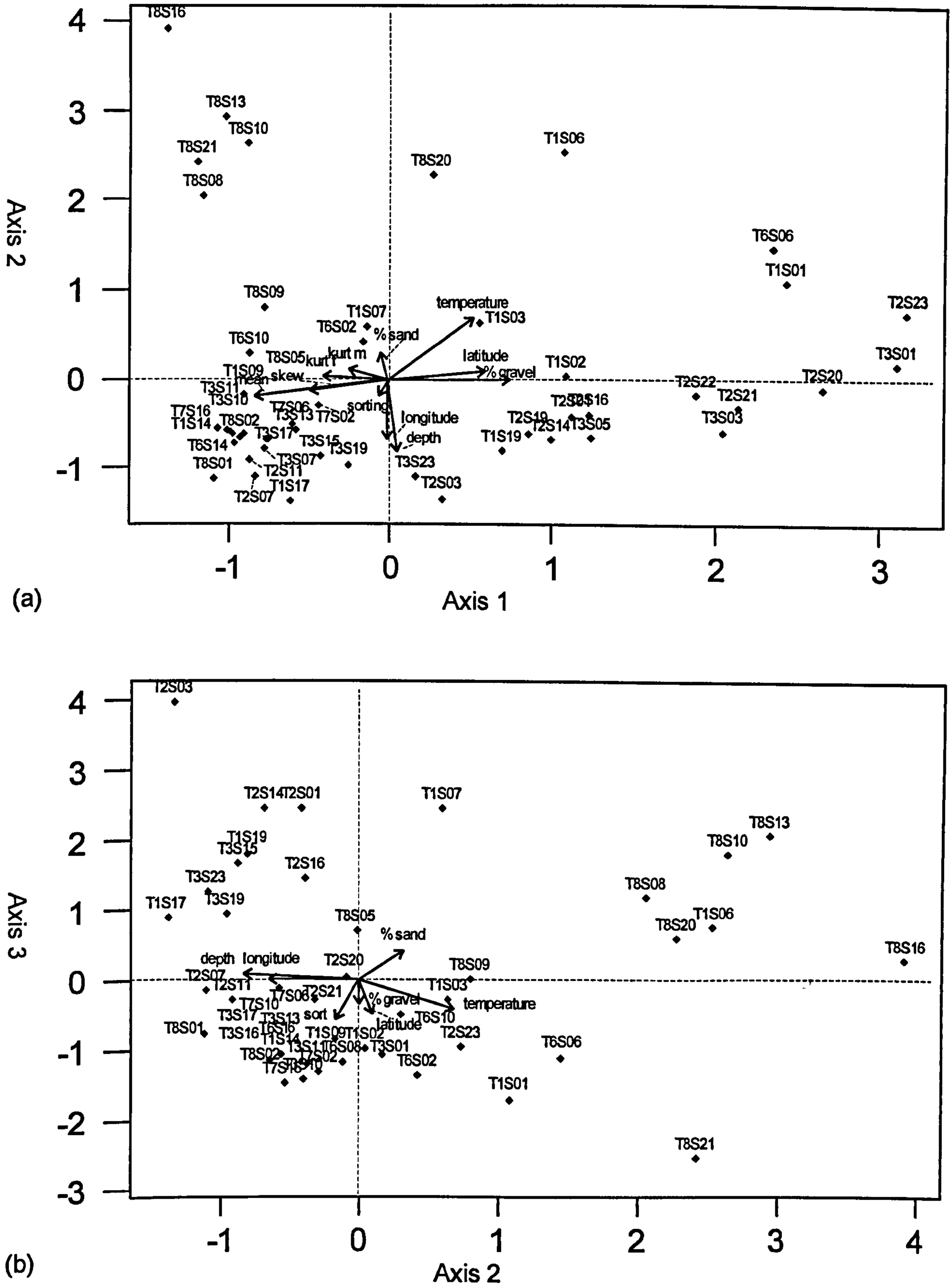


Figure 6.18 Biplot of sites and environmental variables from CCA analyses on the living assemblage data for (a) axes 1 and 2 (b) axes 2 and 3

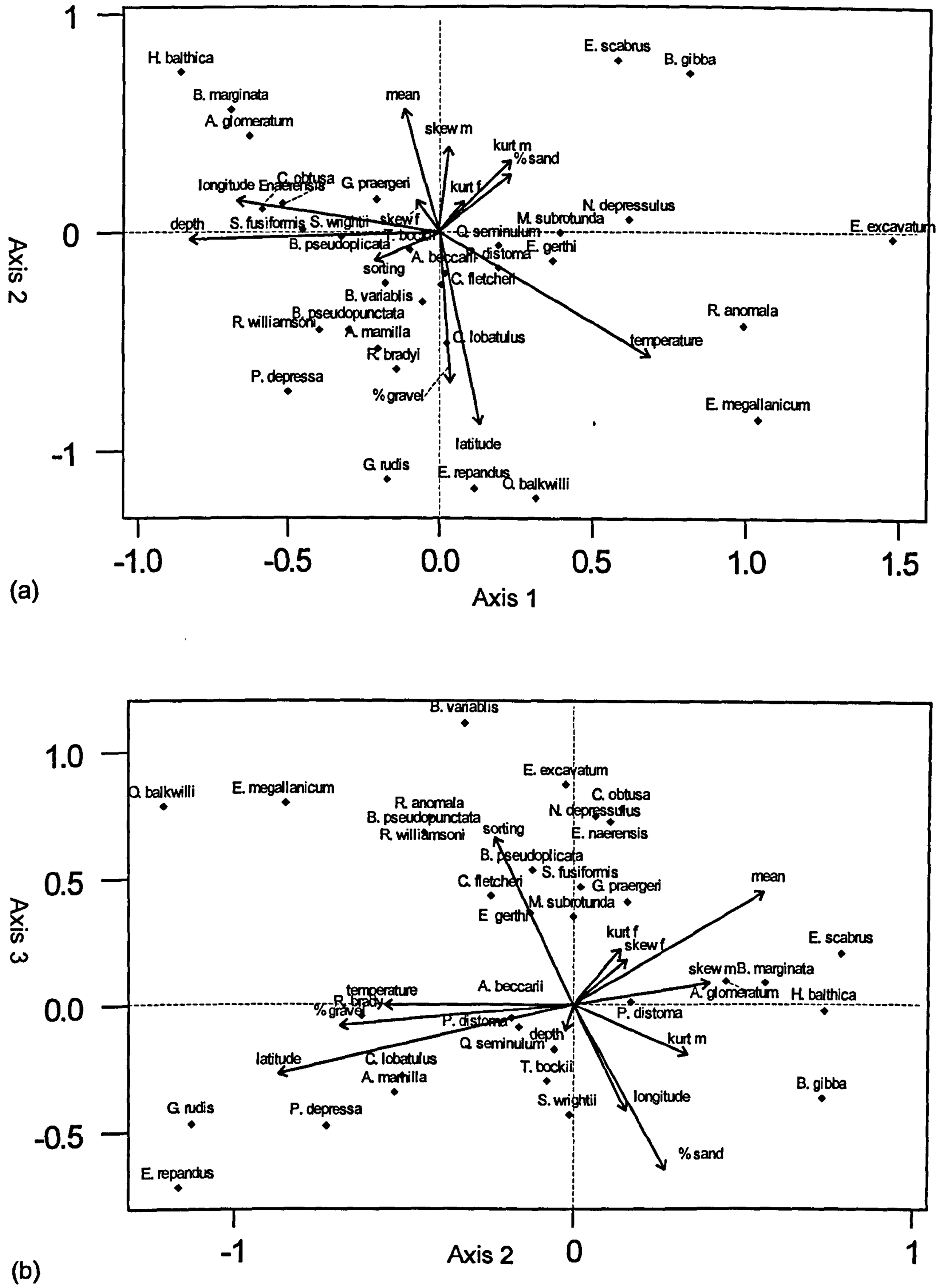


Figure 6.19 Biplot of species and environmental variables from CCA analysis on the dead assemblage data (a) for axes 1 and 2 (b) axes 2 and 3

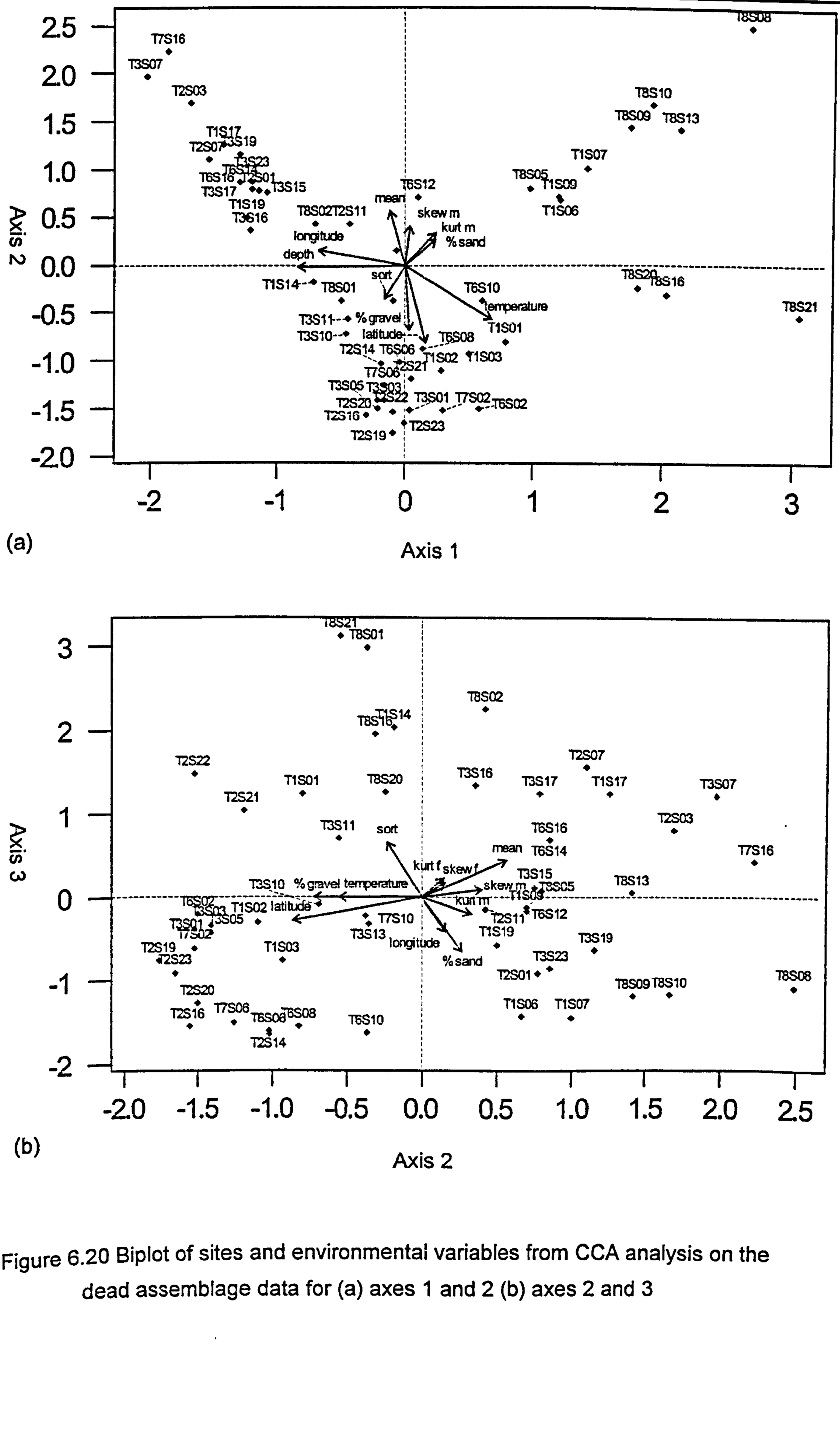


Figure 6.20 Biplot of sites and environmental variables from CCA analysis on the dead assemblage data for (a) axes 1 and 2 (b) axes 2 and 3

PLATES

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PLATE I

PLATE II

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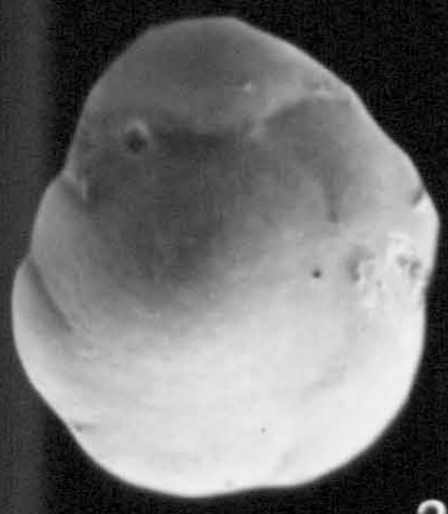

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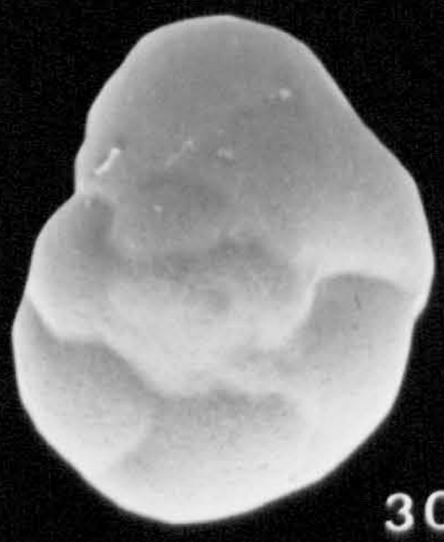

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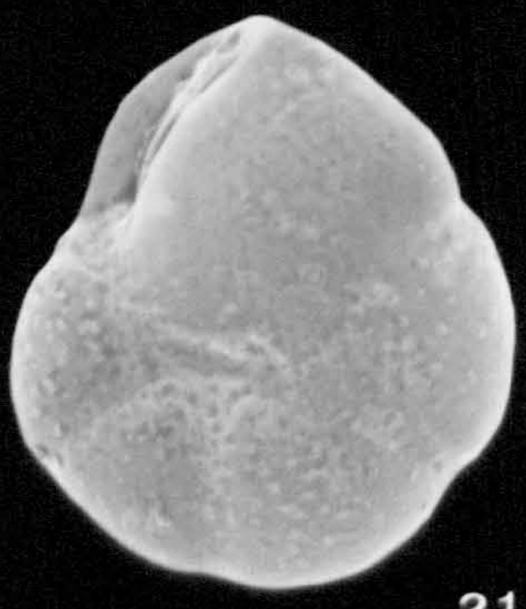

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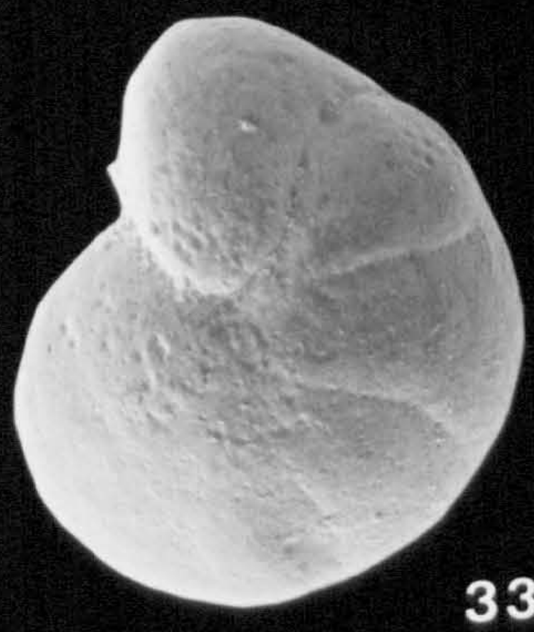

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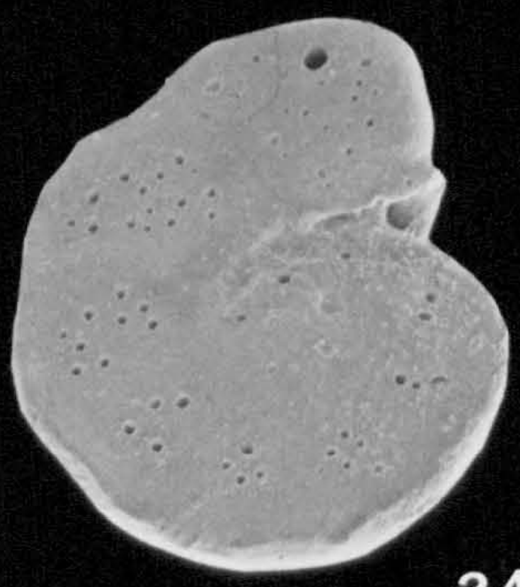

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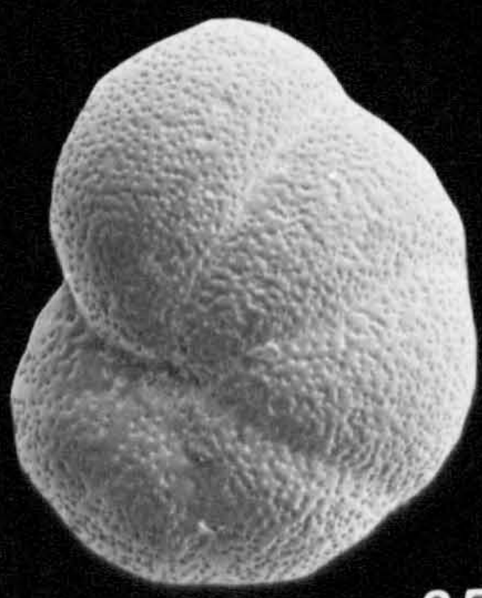

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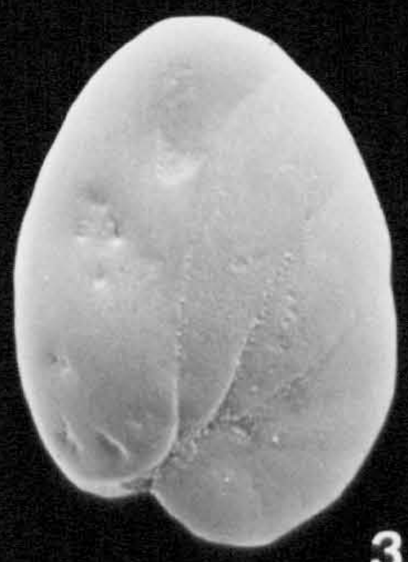

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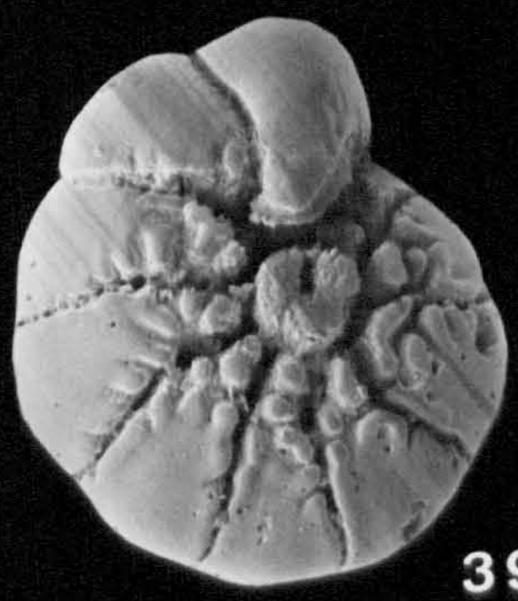

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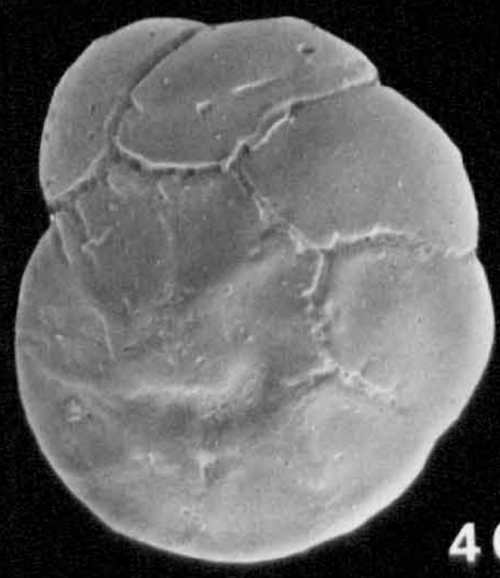

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PLATE II

APPENDICES

APPENDIX I

Sample:	Depth (m)	Temperature (°C)	Salinity ‰	Weight % $CaCO_3$	Weight % organic carbon	Weight % organic nitrogen	C/N ratio	Latitude	Longitude	Sindex
T1S01	64	12.27	34.9	30.48	1.17	0.23	5.09	51.68	5.49	0.0042
T1S02	67	11.95	34.97	13.69	0.31	0.06	5.17	51.65	5.56	0.1520
T1S03	68	11.49	35.01	31.8	0.24	0.04	6	51.61	5.61	0.1357
T1S06	87	10.17	35.38					51.5	5.77	0.5088
T1S07	86	10.1	35.38					51.46	5.82	0.5491
T1S09	91	9.9	35.36	30.12	0.52	0.06	8.67	51.39	5.92	0.6133
T1S14	103	9.61	35.36	34.01	0.86	0.1	8.6	51.22	6.16	0.6853
T1S17	102	9.41	35.34	26.06	0.69	0.09	7.67	51.11	6.31	0.7238
T1S19	101	9.56	35.37	12.1	0.25	0.03	8.33	51.04	6.41	0.6797
T2S01	98	9.41	35.34	13.96	0.14	0		51.05	6.44	0.7083
T2S03	104	9.25	35.3					51.14	6.38	0.7385
T2S07	115	9.33	35.33	33.21	1.09	0.13	8.38	51.32	6.27	0.7220
T2S11	115	9.34	35.32	25.26	0.41	0.06	6.83	51.49	6.18	0.7354
T2S14	115	9.73	35.21	27.12	0.34	0.04	8.5	51.63	6.1	0.6182
T2S16	111	9.53	35.32					51.71	6.04	0.6880
T2S19	105	9.95	35.32	49.73	0.35	0.04	8.75	51.84	5.96	0.5765
T2S20	102	9.84	35.23	45.93	0.21	0.03	7	51.88	5.93	0.4553
T2S21	105	10.65	35.12	27.56	0.13	0.03	4.33	51.93	5.9	0.2322
T2S22	93	11.58	34.89	52.91	0.45	0.06	7.5	51.97	5.87	0.0995
T2S23	95	11.61	34.91	51.85	0.27	0.03	9	52	5.85	0.0360
T3S01	98	11.6	34.89	50.7	0.27	0.04	6.75	51.97	5.86	0.0546
T3S03	109	10.23	35.16	26.23	0.17	0.03	5.67	51.91	5.93	0.2821
T3S05	108	9.71	35.24	25.35	0.22	0		51.84	6.01	0.6114
T3S07	115	9.69	35.27	20.58	0.15	0		51.77	6.08	0.5847
T3S10	109	9.75	35.25	12.54	0.31	0.05	6.2	51.67	6.19	0.5419
T3S11	99	10.1	35.15	12.81	0.26	0.04	6.5	51.63	6.22	0.5153
T3S13	96	9.46	35.27	10.51	0.21	0.03	7	51.57	6.29	0.7059
T3S15	96	9.3	35.32	22.97	0.39	0.05	7.8	51.5	6.37	0.7554
T3S16	101	9.32	35.32	26.5	0.35	0.06	5.83	51.46	6.4	0.7515
T3S17	96	9.3	35.31	15.02	0.31	0.04	7.75	51.43	6.44	0.7432
T3S19	88	9.38	35.27	20.05	0.27	0.04	6.75	51.36	6.51	0.7176
T3S23	92	9.25	35.26	21.29	0.17	0.02	8.5	51.23	6.66	0.7656
T6S02	75	11.82	34.92					52.11	6.2	0.0003
T6S06	82	11.58	34.96					51.86	6.28	0.0842
T6S08	71	11.02	34.96					51.77	6.32	0.2758
T6S10	71	10.28	35.05					51.66	6.37	0.3513
T6S12	81	9.09	35.22					51.42	6.47	0.6356
T6S14	93	8.88	35.22					51.53	6.42	0.7231
T6S16	93	8.89	35.23					51.33	6.5	0.7006
T7S02	111	10.68	35.13					51.84	5.74	0.2707
T7S06	116	10.04	35.24					51.66	5.89	0.3753
T7S10	110	9.73	35.25					51.5	6.03	0.5556
T7S16	114	9.73	35.35					51.22	6.29	0.5962
T8S01	106	9.82	35.35					51.17	6.17	0.6003
T8S02	104	9.85	35.35					51.19	6.11	0.5813
T8S05	90	10.36	35.29					51.24	5.9	0.4991
T8S08	82	10.49	35.24					51.29	5.69	0.4464
T8S09	79	10.59	35.24					51.31	5.63	0.4411
T8S10	76	10.75	35.24					51.33	5.56	0.4216
T8S13	71	11.05	35.17					51.39	5.32	0.1758
T8S16	64	11.46	35.02					51.44	5.08	0.1718
T8S20	49	12.27	34.67					51.51	4.75	0.1087
T8S21	41	12.35	34.6					51.53	4.66	0.0993

APPENDIX I

Sample:	% gravel	% sand	% silt	% clay	mode	mean moments	mean folks	sort moments	sort folks	skew moments	skew folks	kurt moments	kurt folks
T1S01	31.5	65	3.4	0.1	1.75	0.2	0.1	2.19	2.08	-0.03	-0.14	2.95	0.88
T1S02	28.9	68.1	2.4	0.6	1.8	-0.28	-0.16	4.18	3.55	-1.57	-0.8	5.59	1.29
T1S03	11.7	87.6	0.8	0	1.95	0.65	0.68	1.23	1.25	-0.67	-0.25	2.94	0.88
T1S06	0.2	98.3	1.5	0	3	2.51	2.59	0.75	0.77	-0.54	-0.15	3.48	0.93
T1S07	0	96.8	3.2	0	3	2.9	2.91	0.6	0.59	-0.33	-0.18	3.98	1.12
T1S09	0	80.6	15.1	4.2	3.2	3.55	3.56	1.47	1.16	2.34	0.5	7.32	3.71
T1S14	1.4	44.9	37.8	16	1.8	4.75	4.66	2.99	3.08	0.72	0.23	3.02	0.92
T1S17	1.1	65.1	21.5	12.4	1.6	3.12	3.64	2.42	3.02	1.28	0.56	3.39	1.05
T1S19	5.8	85.7	5.3	3.2	1.7	1.62	1.33	2.12	1.8	1.78	0.12	7.76	1.92
T2S01	2.8	96.4	0.7	0	1.7	1.28	1.37	0.9	0.82	-1.28	-0.28	5.89	1.14
T2S03	0	91.8	7.6	0.6	1.8	2.16	2.08	1.27	1.04	2.04	0.35	9.23	2.45
T2S07	0.1	17.1	52.5	30.3	6.6	5.88	6.64	2.22	2.65	0.41	0	2.27	0.91
T2S11	0	74.6	14.4	11	2.3	3.78	4	2.36	2.41	1.63	0.74	4.45	1.96
T2S14	0	99.4	0.6	0	1.55	1.91	1.94	0.48	0.48	0.04	0.15	4.01	1.11
T2S16	6.7	92.9	0.4	0	2.45	1.25	1.34	1.24	1.18	-1.11	-0.25	4.37	1.12
T2S19	11.9	84	4	0.2	2.2	1.07	0.97	1.7	1.63	0.22	-0.09	3.78	0.98
T2S20	34.3	64.5	1.1	0	1.1	-0.23	-0.17	1.83	1.89	-0.31	-0.07	2.51	0.89
T2S21	22.5	75.6	1.9	0	1.2	0.22	0.33	1.81	1.76	-1.18	-0.5	4.13	1.07
T2S22	35.7	56.3	3.1	4.9	0.95	0.17	-0.05	3.29	3.25	0.68	-0.03	4.37	1.38
T2S23	34.6	64.6	0.8	0	0.9	-0.41	-0.33	1.81	1.8	-0.7	-0.29	2.94	0.88
T3S01	24.3	73.6	1.3	0.8	0.8	0.28	0.28	1.99	1.73	0.71	-0.28	8.26	0.95
T3S03	20.3	77	1.7	0.9	1.35	0.62	0.57	1.97	1.66	0.93	-0.31	8.61	0.88
T3S05	9.4	86.9	2.5	1.2	1.85	1.28	1.24	1.86	1.4	1.04	-0.25	10.87	1.42
T3S07	2.1	96.9	1	0	1.6	1.65	1.76	0.83	0.64	-2.42	-0.13	13.8	1.19
T3S10	0	94.1	4.2	1.7	2.2	2.49	2.28	1.33	0.73	4.35	0.26	27.13	1.9
T3S11	0	92.6	3.6	3.8	2.1	2.69	2.36	1.55	1.05	3.28	0.51	13.46	3.9
T3S13	0	95.9	3.9	0.2	1.9	2.34	2.28	0.91	0.73	2.1	0.19	11.41	1
T3S15	0	85.5	7.5	7.1	1.6	2.73	2.67	1.9	1.81	1.77	0.44	6.06	2.16
T3S16	3.5	74	10.4	12.2	1.8	3.03	3.56	2.8	3.06	1.17	0.58	3.94	2.07
T3S17	1.8	84.2	6.7	7.3	2.1	2.66	2.41	2.34	2.01	2.02	0.43	6.86	4.65
T3S19	9.6	81.8	3.2	5.5	2.2	1.46	1.14	2.39	2.19	1.5	0.14	6.72	2.06
T3S23	3.5	92.9	3.3	0.4	2.15	1.78	1.78	1.29	0.97	0.14	-0.32	9.32	1.72
T6S02	31.5	68.5	0	0	1.4	0.74	0.43	1.86	1.87	-1.53	-0.75	3.75	4.92
T6S06	1.1	98.9	0	0	1.5	1.5	1.6	0.67	0.54	-2.05	-0.09	11.22	1.39
T6S08	0.4	99.6	0	0	1.75	1.68	1.7	0.5	0.38	-1.63	-0.03	11.46	1.06
T6S10	0.4	99.6	0	0	2	1.97	1.98	0.57	0.4	-0.59	-0.03	4.01	1.06
T6S12	0	97.3	1.1	1.6	1.45	2.07	1.99	1.21	0.72	3.89	0.22	16.22	1.42
T6S14	0	95.2	1.1	3.7	1.75	2.63	2.09	1.61	0.54	3.08	0.29	14.99	2.17
T6S16													
T7S02	53.7	46.3	0	0	1.15	-0.94	-1.03	1.98	2.02	0.21	0.2	1.62	0.6
T7S06													
T7S10	0	95.2	1.1	3.7	2.85	4.03	4	2.7	2.52	1.67	0.71	4.82	2.05
T7S16	0	95.2	1.1	3.7	2	4.49	4.22	3.27	3.13	0.82	0.71	2.4	0.78
T8S01	0	22.8	54.5	22.6	3.4	6.37	6.39	2.61	2.74	0.41	0.11	2.44	0.98
T8S02	0	30.5	48.6	20.9	3.4	6	5.95	2.63	2.58	0.77	0.44	2.59	0.87
T8S05	0	82.8	12.8	4.4	3.2	3.6	3.53	1.73	0.98	2.97	0.57	11.73	3.82
T8S08	0	96.9	1.3	1.8	2.8	3.03	2.96	1.2	0.41	4.16	-0.14	28.16	2.16
T8S09	0	98.9	0.5	0.6	2.85	2.78	2.74	0.88	0.46	4.78	-0.37	52	2.12
T8S10	0	99.5	0.5	0	2.65	2.31	2.35	0.63	0.6	-0.55	-0.39	3.08	0.81
T8S13	0.1	99.6	0.3	0	2.2	2.07	2.11	0.55	0.47	-1.17	-0.17	7.42	1.47
T8S16	0	81.5	8.8	9.7	2.3	3.42	3.3	2.57	2.14	2.04	0.82	6.06	4.37
T8S20	0.9	99	0.1	0	1.35	1.33	1.37	0.55	0.41	-1.46	-0.12	11.37	1.3
T8S21	4.5	77.7	9.2	8.6	1.8	2.64	2.42	3.04	2.83	1.41	0.4	4.81	1.92

APPENDIX II

LIVE	*A. beccarii*	*A. galloway*	*A. glomeratum*	*A. mamilla*	*A. pseudospiralis*	*A. runiana*	*A. scalaris*	*Astrononion sp.*	*B. elegantissima*	*B. gibba*	*B. marginata*	*B. nodosaria*	*B. pspunctata*	*B. psplicata*	*B. skagerrakensis*	*B. spathulata*	*B. variablis*	*Comuspira sp.*	*C. fletcheri*	*C. involvens*	*C. jeffreysii*	*C. lobatulus*	*C. auricula*	*C. obtusa*	*C. pseudogerianus*
T1S01	5	0	0	0	0	0	0	0	1	3	0	0	7	4	0	0	1	0	7	0	0	41	15	0	0
T1S02	6	4	2	0	0	0	0	0	0	6	4	0	4	6	2	0	1	0	2	0	1	36	22	0	0
T1S03	2	0	4	0	0	0	0	0	0	18	0	0	8	6	0	0	1	0	3	0	0	10	11	0	1
T1S06	10	0	1	2	0	0	0	0	0	102	0	0	0	2	0	0	0	0	0	0	0	54	1	0	0
T1S07	1	0	6	0	0	0	0	0	0	10	1	0	3	0	0	0	0	0	0	0	0	1	22	0	0
T1S09	1	2	2	0	0	0	0	0	0	18	4	1	0	0	0	0	0	0	0	0	0	2	4	0	0
T1S14	0	0	0	0	0	0	0	0	0	1	8	0	1	2	1	0	0	0	0	0	0	0	1	0	0
T1S17	1	0	44	0	0	0	0	0	0	0	2	0	0	2	1	0	0	0	0	0	0	1	14	1	0
T1S19	7	0	48	0	6	0	0	0	0	0	17	0	1	0	1	0	2	0	0	0	0	2	15	1	0
T2S01	4	0	9	0	0	0	0	0	0	5	19	0	1	1	0	0	0	0	1	0	0	4	14	1	0
T2S03	8	0	76	0	1	0	0	0	0	0	24	0	1	9	0	0	0	0	0	0	3	1	18	3	0
T2S07	2	0	5	0	1	3	0	0	0	0	25	0	0	4	0	0	0	0	0	0	0	0	12	0	0
T2S11	1	0	19	0	0	3	0	0	0	0	1	0	0	6	0	0	0	0	0	0	0	0	10	0	0
T2S14	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	1	0	0
T2S16	7	0	19	0	0	0	0	0	1	4	3	0	0	1	0	1	0	0	1	0	0	6	8	1	0
T2S19	4	1	2	1	0	0	0	0	0	6	1	0	0	0	0	0	1	0	0	0	0	8	111	0	0
T2S20	9	1	5	0	0	0	0	0	1	2	1	0	5	6	0	0	0	0	7	0	0	13	33	4	0
T2S21	5	0	1	2	0	0	0	0	0	2	1	0	2	11	0	0	0	0	4	0	0	5	45	4	0
T2S22	6	0	0	0	0	0	0	0	0	1	0	0	2	2	0	0	1	0	4	0	0	11	41	1	0
T2S23	1	0	2	1	0	0	0	0	1	0	1	0	4	2	0	0	0	0	1	1	1	54	2	1	0
T3S01	4	1	1	1	0	0	0	0	0	0	0	0	6	0	0	0	1	0	11	0	0	21	46	0	0
T3S03	7	0	1	2	0	0	0	0	0	1	2	0	1	8	0	0	0	0	6	0	0	15	80	1	0
T3S05	1	0	2	1	0	0	0	0	0	8	0	0	2	2	0	0	0	0	0	0	0	6	106	3	0
T3S07	6	0	26	0	4	0	2	0	0	4	34	0	1	7	3	1	0	0	0	0	0	0	3	0	0
T3S10	1	0	2	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	4	4	0	0
T3S11	2	0	0	0	0	0	0	0	0	9	1	0	0	4	0	0	0	0	0	0	0	2	5	0	0
T3S13	5	0	1	0	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	1	9	0	0
T3S15	9	0	22	1	0	0	0	1	0	5	18	0	0	0	1	0	0	0	0	0	0	3	16	0	0
T3S16	3	0	14	0	0	0	0	0	0	2	5	0	0	2	0	0	0	0	0	0	1	3	17	0	0
T3S17	3	0	17	0	0	0	0	0	0	1	8	0	0	1	0	0	0	0	0	0	0	0	7	0	0
T3S19	14	0	43	0	0	0	0	0	0	3	28	0	1	3	3	0	1	0	0	0	0	0	18	2	0
T3S23	11	0	39	0	0	1	0	0	0	2	20	0	2	2	2	1	0	0	0	0	0	1	35	0	0
T6S02	1	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0
T6S06	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0
T6S08	0	0	0	0	0	0	0	0	0	5	0	0	1	0	1	0	1	0	1	0	0	5	0	4	0
T6S10	0	0	1	1	0	0	0	0	0	55	0	0	0	0	0	0	3	0	1	0	0	0	2	0	0
T6S12	1	0	4	0	0	0	0	0	0	4	0	0	0	2	0	0	0	0	0	0	0	0	6	0	0
T6S14	2	0	10	0	0	0	0	0	0	0	5	0	0	1	0	0	0	0	0	0	0	0	9	0	0
T6S16	8	0	2	0	0	0	0	0	0	2	3	0	0	4	0	0	1	0	0	0	0	0	8	0	0
T7S02	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7S06	1	0	13	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0
T7S10	0	0	8	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	0	0
T7S16	0	0	3	0	0	0	0	0	0	0	5	0	0	2	0	0	0	0	0	0	0	0	0	0	0
T8S01	1	0	2	0	4	0	0	0	0	0	5	0	0	5	0	0	0	0	0	0	0	0	2	0	0
T8S02	0	0	1	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	6	0	0
T8S05	0	0	1	0	1	0	0	0	1	4	0	0	0	1	0	0	0	1	0	0	0	0	6	0	0
T8S08	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S09	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
T8S10	0	0	0	0	0	0	0	0	0	71	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
T8S13	0	0	0	0	0	0	0	0	0	97	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
T8S16	1	0	1	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S20	3	0	0	0	0	0	0	0	0	26	0	0	0	3	0	0	6	0	0	0	0	3	1	0	0
T8S21	5	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX II

LIVE	*D. araçuana*	*D. berthloti*	*D. frobisherensis*	*Discorbinella sp.*	*D. subarcuata*	*D. trondheimensis*	*E. advena*	*E. albiumbilicatum*	*E. earlandi*	*E. excavatum*	*E.gerthi*	*E. laesoensis*	*E. magellanicum*	*E. cf megallanicum*	*E. repandus*	*E. scabrus*	*Elphidium sp.*	*E. naerensis*	*F. laegonoides*	*F. lucida*	*F. marginata*	*F. elliptica*	*G. hamsii*	*G. cf inequalis*	*G. neosolodani*
T1S01	1	0	0	0	0	0	0	0	1	0	10	0	0	42	0	0	0	0	0	1	18	0	0	0	0
T1S02	2	0	0	0	0	0	2	0	2	0	5	0	1	14	0	0	0	5	0	6	1	0	0	1	0
T1S03	0	2	2	0	0	1	2	0	0	16	0	0	1	1	1	1	0	6	0	0	0	0	0	0	0
T1S06	0	0	0	0	0	0	0	0	0	5	0	0	0	2	0	1	0	0	0	0	3	0	0	0	0
T1S07	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0
T1S09	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
T1S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	1	1	0	0	0
T1S17	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	4	0	3	0	0	0	0	0	0	0
T1S19	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	1	0	8	0	0	0	0	0	0	0
T2S01	0	1	0	0	0	0	11	0	0	0	0	0	0	0	0	1	0	66	0	1	0	0	1	0	0
T2S03	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	16	0	5	0	2	0	0	0	0	0
T2S07	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0
T2S11	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	5	0	2	0	0	0	0	0	0	0
T2S14	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
T2S16	0	0	0	0	0	0	8	0	0	0	0	0	6	0	0	0	0	8	0	1	0	0	0	0	0
T2S19	0	0	0	1	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0
T2S20	0	0	0	1	0	0	2	0	1	1	0	0	5	2	0	0	0	2	1	0	0	0	0	0	0
T2S21	0	0	0	1	0	0	0	0	0	0	0	0	2	1	0	0	0	2	0	0	1	0	0	0	1
T2S22	1	0	0	0	0	0	2	0	0	3	0	1	2	0	0	0	0	3	1	1	2	0	0	0	0
T2S23	2	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	0	2	4	0	0	0	0
T3S01	0	0	0	0	0	0	1	0	0	0	0	0	5	3	0	0	0	0	1	1	7	0	0	0	0
T3S03	0	1	0	0	0	0	1	0	0	3	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0
T3S05	1	0	0	0	0	0	2	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0
T3S07	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	8	0	28	0	0	0	0	0	0	0
T3S10	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0
T3S11	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0
T3S13	0	0	0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	9	0	0	0	0	0	0	0
T3S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	1	0	0	1	0	1	0	0
T3S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0
T3S17	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	3	0	0	0	1	0	0	0
T3S19	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	0	3	0	0	0	2	0	0	0
T3S23	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	1	0	7	0	0	0	0	0	0	0
T6S02	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
T6S06	0	0	0	0	0	0	0	0	0	0	1	0	0	9	0	0	0	0	0	0	0	0	0	0	0
T6S08	0	0	0	12	0	0	5	1	0	1	3	2	0	0	0	0	0	8	0	0	1	0	0	0	0
T6S10	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S12	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0	7	0	0	0	0	0	0	0
T6S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	2	0	0	0	0	0	0	0
T6S16	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0	6	0	0	0	0	0	0	0
T7S02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0
T7S06	0	0	0	0	0	0	5	0	0	0	2	0	1	3	0	0	0	33	0	0	0	0	0	0	0
T7S10	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	8	0	3	0	0	0	0	0	0	0
T7S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
T8S01	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0
T8S02	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0
T8S05	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	0	2	0	0	0	0	0	0	0
T8S08	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
T8S09	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	1	0	0	1	0	0	0	0	0
T8S10	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
T8S13	0	0	0	0	0	0	0	0	0	30	1	0	0	0	0	26	0	2	0	0	0	0	0	0	0
T8S16	0	0	0	0	0	0	0	0	0	101	3	0	0	0	0	14	0	2	0	0	0	0	0	0	0
T8S20	4	0	0	0	0	0	2	0	0	18	2	0	0	0	0	5	0	0	0	0	0	0	0	0	0
T8S21	0	0	0	0	0	0	0	0	0	116	11	0	10	0	0	1	0	0	0	0	0	0	0	0	0

APPENDIX II

LIVE	*G. praegeri*	*G. rudis*	*H. balthica*	*H. bradyi*	*H. fragile*	*L. arenulata*	*L. clavata*	*L. gracilis*	*L. haliotid*	*L. hancocki*	*L. interrupta*	*L. lactea*	*L. laevis*	*L. perlucida*	*L. semistriata*	*L. striata*	*L. substriata*	*L. tenuis*	*Marispella sp.*	*M.circularis*	*M. circularis var. elongata*	*M. pompiloides*	*M. subrotunda*	*N. auricula*	*N. depressulus*
T1S01	19	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	1	0	13	1	1
T1S02	10	2	0	0	1	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	8	23	0
T1S03	6	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
T1S06	4	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
T1S07	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S09	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S14	0	0	21	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S17	1	0	4	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S19	20	0	6	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S01	40	0	5	0	19	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S03	0	0	10	0	46	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S07	0	0	6	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S11	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S14	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S16	12	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S19	6	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S20	38	1	0	2	17	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S21	4	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S22	31	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S23	49	3	0	0	9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S01	17	0	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S03	8	0	0	3	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S05	12	0	11	31	4	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S10	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S11	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S13	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S15	11	0	0	3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S16	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S17	1	0	1	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S19	2	0	4	4	2	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S23	9	0	4	8	8	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S02	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S06	7	0	0	0	0	0	1	0	4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S08	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S10	14	0	33	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
T6S12	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S14	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7S02	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7S06	11	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7S10	1	0	1	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7S16	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S01	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S02	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S16	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S20	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX II

LIVE	*Nonion sp. (juv)*	*N. pauperatum*	*N. turgida*	*O. balkwilli*	*O. laevigata*	*O. hexagona*	*O. melo*	*O. williamsoni*	*Parafissurina sp.*	*Peneroplis sp.*	*P. comugata*	*P. depressa*	*P. distoma*	*P. williamsoni*	*Q. bicornis*	*Q. bicornis var. angulata*	*Q. ciarensis*	*Q. oblonga*	*Q. lata*	*Q. rugosa*	*Q. seminulum*	*R. artica*	*R. bradyii*	*R. fusiformis*	*R. anomala*
T1S01	0	2	3	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0	0	17	0	5	2	1
T1S02	0	2	6	12	0	0	0	0	0	0	1	0	5	0	0	0	0	0	0	0	13	0	4	0	1
T1S03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	12	0	1	1	0
T1S06	2	0	0	0	1	0	1	2	0	0	0	4	18	0	0	0	0	2	0	0	18	0	5	1	0
T1S07	0	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	8	0	0	2	0
T1S09	0	0	5	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	3	2	2	8	0
T1S14	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S17	0	0	77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0
T1S19	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
T2S01	0	1	17	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	30	0	0	4	0
T2S03	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	10	0	1	4	0
T2S07	0	0	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0
T2S11	0	0	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
T2S14	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	4	0	0	10	0
T2S16	0	0	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	1	1	4	0
T2S19	0	2	3	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	4	0
T2S20	2	8	3	15	0	0	0	0	1	0	6	0	2	0	0	7	0	0	0	1	10	0	5	0	0
T2S21	0	3	1	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	4	0	6	0	0
T2S22	0	6	5	1	0	0	0	0	0	0	1	0	2	0	0	1	0	0	1	0	3	0	0	2	2
T2S23	0	6	0	7	0	0	0	0	0	1	2	0	5	0	0	0	0	0	2	0	8	0	0	0	8
T3S01	2	5	0	6	0	0	1	0	0	0	1	0	1	0	0	2	0	0	0	0	4	0	8	1	0
T3S03	1	2	3	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	3	1	6	5	0
T3S05	0	0	37	6	0	0	0	0	0	0	3	0	1	0	0	0	0	0	1	0	2	0	5	5	0
T3S07	0	1	41	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	14	0	0	2	0
T3S10	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	0
T3S11	0	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
T3S13	2	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S15	0	3	37	0	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	1	0	0	4	0
T3S16	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0
T3S17	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
T3S19	0	0	20	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	7	0
T3S23	0	0	44	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3	1	2	0	0
T6S02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
T6S06	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
T6S08	0	0	2	0	0	0	0	0	0	0	1	0	4	0	1	0	0	0	0	0	2	0	0	0	2
T6S10	1	1	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0	0	1	0
T6S12	0	0	24	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0	0	0	0
T6S14	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	4	0
T6S16	0	0	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0
T7S02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1
T7S06	0	0	21	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	3	1	0	2	1
T7S10	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
T7S16	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0
T8S01	0	0	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
T8S02	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S05	0	0	13	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	51	0	0	5	0
T8S08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
T8S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
T8S13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1	0	0	0
T8S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	2	0
T8S21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX II

LIVE	*Rosalina sp. (juv)*	*R. scotti*	*R. scorpiurus*	*R. trochamminforme*	*R. williamsoni*	*S. concava*	*S. fusiformis*	*S. excavata*	*S. cf rotuntunda*	*S. squamosa*	*S. vivpara*	*S. wrightii*	*T. agglutinans*	*T.angulos*	*T. bockii*	*Trochammina sp.*	*T. rotaliformis*	*T. bradyi*	*T. globigeriniformis var. pygmaea*	*T. astrificata*	*Juveniles*	*total*
T1S01	0	0	0	0	2	0	25	0	5	0	0	1	0	0	48	6	0	0	4	3	1	331
T1S02	0	0	0	0	0	0	110	0	6	0	0	0	1	0	15	6	2	0	5	3	0	376
T1S03	0	3	0	0	1	0	83	0	0	0	2	14	3	0	16	1	2	0	7	5	1	263
T1S06	0	2	0	0	0	0	0	0	2	0	0	14	0	0	33	0	0	1	0	0	0	299
T1S07	0	10	0	2	0	1	12	0	0	0	0	0	2	0	0	0	0	0	4	0	0	129
T1S09	0	26	0	0	2	0	279	0	0	0	0	0	0	0	1	0	1	1	2	0	0	378
T1S14	0	0	0	0	0	0	266	0	0	0	0	0	0	0	0	0	0	0	0	0	0	327
T1S17	0	5	0	0	0	0	99	0	0	0	0	0	0	0	0	0	0	0	8	0	0	290
T1S19	0	13	0	0	0	0	39	0	0	0	1	4	0	0	16	5	3	0	19	2	0	260
T2S01	0	0	0	0	1	0	8	0	0	0	5	4	0	0	24	0	0	0	3	2	0	314
T2S03	0	5	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	293
T2S07	0	0	1	0	0	3	179	0	0	0	0	0	0	0	0	0	0	0	3	0	0	338
T2S11	0	10	1	0	0	2	180	0	0	0	0	0	0	0	0	0	0	0	8	0	0	320
T2S14	0	0	0	0	0	0	6	0	0	0	0	0	0	0	1	4	0	0	4	0	0	44
T2S16	0	7	0	0	0	0	8	0	0	0	0	0	1	0	9	2	1	0	7	3	0	166
T2S19	0	0	0	0	0	0	100	0	0	0	0	0	0	0	4	0	0	0	0	2	0	273
T2S20	0	0	0	0	8	0	5	0	0	0	16	0	0	0	24	0	3	0	26	21	0	331
T2S21	0	1	0	0	5	0	10	0	0	0	6	1	1	0	9	1	0	1	3	9	4	170
T2S22	0	0	0	0	4	0	37	0	0	0	4	0	0	0	6	3	2	0	3	9	0	215
T2S23	0	0	0	1	4	0	0	1	3	0	13	0	0	0	78	4	3	0	15	17	1	337
T3S01	0	0	0	0	1	0	2	0	0	0	3	0	0	0	28	7	9	0	9	1	1	232
T3S03	1	4	0	0	1	0	20	0	0	0	6	2	0	0	1	1	3	0	15	11	0	239
T3S05	0	3	0	0	2	0	47	0	0	0	4	0	1	0	13	0	2	0	3	6	0	302
T3S07	0	6	0	0	0	0	370	0	0	4	0	0	0	0	0	0	0	0	0	0	0	621
T3S10	1	3	0	0	0	0	341	0	0	0	1	0	0	0	1	0	0	0	1	0	0	379
T3S11	0	12	0	0	0	0	245	0	1	0	0	0	1	0	0	0	0	0	0	0	0	313
T3S13	0	1	0	0	0	0	113	0	0	3	0	0	1	0	0	0	0	0	2	0	0	176
T3S15	0	50	0	0	0	0	39	0	0	0	0	2	0	0	2	0	0	0	5	0	0	256
T3S16	0	3	0	0	1	0	247	0	0	1	0	0	3	0	0	0	0	0	1	0	0	346
T3S17	0	7	0	0	0	0	239	0	0	0	2	1	0	0	0	0	0	0	4	0	0	327
T3S19	0	0	0	0	0	0	164	0	0	0	0	0	0	0	2	0	1	0	2	0	1	372
T3S23	0	2	0	0	3	1	84	0	0	0	1	0	0	0	2	1	1	1	2	0	0	342
T6S02	0	0	0	0	0	0	39	0	0	0	0	0	0	0	2	0	0	0	0	0	0	62
T6S06	0	0	0	0	0	0	5	0	0	0	1	1	0	0	9	0	0	0	0	3	1	48
T6S08	0	0	0	0	0	0	180	0	0	2	0	2	4	0	5	0	1	0	1	2	2	278
T6S10	0	1	0	0	0	0	284	0	0	0	1	0	1	0	1	0	0	0	1	0	0	424
T6S12	0	12	0	0	0	0	131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	212
T6S14	0	16	0	0	0	0	178	0	0	0	0	0	0	0	0	0	0	0	1	0	0	264
T6S16	0	19	0	0	0	0	236	0	0	0	0	0	0	0	0	0	0	0	1	0	1	335
T7S02	0	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37
T7S06	0	8	0	6	0	2	252	0	0	0	0	0	2	0	9	1	3	0	4	1	0	410
T7S10	0	20	0	1	0	0	181	0	0	0	0	0	0	1	0	0	0	0	0	0	0	269
T7S16	0	0	0	0	0	0	231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	264
T8S01	0	2	0	0	0	0	181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	308
T8S02	0	2	0	0	0	0	138	0	0	0	0	0	0	0	0	0	0	0	0	0	0	175
T8S05	0	10	0	0	0	0	49	0	0	0	0	0	0	0	0	0	0	0	1	0	0	153
T8S08	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
T8S09	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42
T8S10	0	0	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	125
T8S13	0	0	0	0	0	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	227
T8S16	0	0	0	0	0	0	48	0	0	0	0	0	1	0	0	0	0	0	0	0	0	211
T8S20	0	0	0	0	1	0	24	0	0	0	5	0	0	0	7	2	0	0	0	3	0	130
T8S21	0	0	0	0	0	0	194	0	0	0	0	0	0	0	0	0	0	0	0	0	0	455

APPENDIX III

DEAD	*A. beccarii*	*A. aberdoveyensis*	*A. galloway*	*A. glomeratum*	*A. inharens*	*A. mamilla*	*A. scalaris*	*A. pseudospiralis*	*A. orbiculatum*	*Astrononion sp.*	*B. elegantissima*	*B. frigida*	*B. gibba*	*B. inflata*	*B. marginata*	*B. minima*	*B. psplicata*	*B. pspunctata*	*B. spathulata*	*B. skagerrakensis*	*B. variablis*	*C. carinata*	*C. lobatulus*	*C. fletcheri*	*C.involven*
T1S01	12	0	0	1	1	0	0	0	0	1	1	0	26	0	13	0	10	5	0	0	8	0	47	9	0
T1S02	19	0	0	0	1	4	0	0	0	0	0	1	21	0	2	0	7	5	1	1	1	0	94	2	0
T1S03	14	0	0	0	1	0	0	0	0	0	0	1	18	0	0	0	5	4	1	0	0	0	69	0	0
T1S06	10	0	0	1	0	2	0	0	0	0	0	0	102	0	0	0	0	2	0	0	0	0	54	0	0
T1S07	11	0	0	0	0	2	0	0	0	0	0	0	124	0	4	0	0	0	0	0	1	0	58	5	0
T1S09	13	0	1	3	5	4	0	0	0	0	0	5	105	0	2	0	6	0	1	6	1	0	44	1	0
T1S14	2	0	1	0	0	0	0	0	0	1	0	6	5	0	9	0	24	10	4	9	1	0	19	6	0
T1S17	11	0	0	2	0	0	0	0	0	0	1	1	2	1	71	0	11	1	1	2	6	0	8	2	0
T1S19	20	0	1	3	0	0	0	3	0	0	0	1	0	0	50	0	5	0	2	1	0	0	17	1	0
T2S01	14	0	0	0	0	0	0	0	0	0	0	0	1	0	36	0	1	4	0	0	0	0	8	2	0
T2S03	9	0	2	0	0	0	0	0	0	0	0	0	2	0	136	0	14	3	1	2	2	0	6	8	0
T2S07	7	0	0	4	0	0	0	0	0	0	0	5	0	0	77	0	9	5	0	2	6	0	12	3	0
T2S11	14	0	0	11	0	3	1	0	0	0	0	2	13	0	55	0	2	0	0	0	0	0	37	0	1
T2S14	10	0	0	0	0	3	0	0	0	0	0	0	9	0	1	0	3	0	1	0	1	0	91	0	0
T2S16	11	0	0	2	4	5	1	0	0	0	0	0	3	0	1	0	2	3	0	0	0	0	153	0	0
T2S19	30	0	0	0	1	9	0	0	0	0	0	0	5	0	0	0	1	0	0	0	0	0	114	15	0
T2S20	32	0	0	0	2	3	0	0	0	0	0	0	2	0	0	0	5	2	0	1	0	0	105	6	0
T2S21	11	0	2	0	0	3	0	0	0	0	1	2	6	0	2	0	15	10	0	2	0	0	50	7	0
T2S22	9	0	0	1	0	0	0	0	0	0	0	2	2	1	2	0	5	5	1	1	12	0	42	24	1
T2S23	24	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	9	1	0	0	1	0	87	1	0
T3S01	31	0	0	0	0	2	0	0	1	0	1	0	4	0	0	0	10	3	1	0	3	0	82	12	0
T3S03	22	0	0	0	0	7	0	0	0	0	0	0	2	0	0	0	5	2	0	0	1	0	81	26	0
T3S05	16	0	0	0	0	1	0	0	0	0	0	0	1	0	3	0	8	2	1	0	1	0	100	10	0
T3S07	1	0	0	2	0	1	0	0	0	0	0	0	0	0	179	0	8	1	0	2	3	0	7	4	0
T3S10	9	0	0	3	1	15	0	0	0	0	1	0	17	0	8	0	13	5	0	0	0	0	124	1	0
T3S11	10	0	1	0	0	8	0	0	0	0	3	0	23	0	3	0	12	1	0	1	2	0	110	11	0
T3S13	9	0	1	1	1	3	0	0	0	0	2	0	35	0	21	0	2	0	1	1	0	0	110	5	0
T3S15	19	0	0	1	0	1	1	0	0	0	0	3	11	0	135	0	2	1	1	0	2	0	42	1	0
T3S16	21	0	0	1	1	0	0	0	0	0	0	2	18	0	110	0	14	5	0	3	0	0	46	17	0
T3S17	5	0	0	0	0	1	0	0	0	0	0	0	4	0	91	0	18	3	0	0	0	0	21	2	0
T3S19	10	0	0	5	0	0	0	0	0	0	0	0	18	0	77	0	1	1	1	0	0	0	13	3	0
T3S23	11	0	0	1	0	0	1	0	0	0	0	1	7	0	62	0	2	1	2	0	1	0	25	1	0
T6S02	0	0	0	0	0	0	0	0	0	0	0	1	17	0	0	0	6	5	0	0	0	1	92	2	0
T6S06	18	0	0	0	0	3	0	0	0	0	0	0	11	0	3	1	1	0	0	0	0	0	93	0	0
T6S08	14	0	0	0	0	7	0	0	0	0	0	0	44	0	3	0	3	1	0	0	0	0	186	1	0
T6S10	6	0	0	0	0	4	0	0	0	0	0	0	51	0	5	0	1	0	0	0	0	0	112	0	0
T6S12	5	0	0	2	1	1	0	0	0	0	0	0	90	0	22	0	9	1	1	0	0	0	52	12	0
T6S14	5	0	0	3	0	0	1	0	0	0	0	0	8	0	94	0	6	0	1	3	1	0	29	3	0
T6S16	5	0	0	3	0	0	1	0	0	0	0	0	8	0	94	0	6	0	1	3	1	0	29	3	0
T7S02	12	0	0	0	1	4	0	0	0	0	0	0	9	0	2	0	1	0	0	0	2	0	78	5	0
T7S06	26	0	0	0	4	13	0	0	0	0	0	3	9	0	1	0	0	0	0	0	1	0	85	1	0
T7S10	14	0	1	6	6	2	1	1	0	0	0	3	21	0	45	0	2	1	2	1	3	0	117	6	0
T7S16	12	0	0	3	0	0	1	1	0	0	0	0	2	0	245	0	5	0	1	1	3	2	4	5	0
T8S01	5	0	0	0	0	0	0	0	0	0	1	6	8	0	20	3	7	9	5	10	37	0	13	36	0
T8S02	4	0	0	0	0	0	0	0	0	0	0	3	6	2	16	1	17	3	1	4	3	0	8	15	0
T8S05	5	0	0	0	0	2	0	0	0	0	0	3	60	0	2	2	7	0	0	1	2	1	14	8	0
T8S08	14	0	0	0	0	1	0	0	0	0	0	1	249	0	2	1	1	0	0	0	0	0	9	7	0
T8S09	18	0	0	0	0	1	0	0	0	0	0	0	167	0	0	0	0	0	0	0	0	0	24	7	0
T8S10	15	0	0	0	0	0	0	0	0	0	0	1	194	0	0	0	0	0	0	0	1	0	25	11	0
T8S13	16	0	0	0	1	1	0	0	0	0	0	2	112	0	3	0	1	1	0	0	1	0	17	3	0
T8S16	15	1	0	1	0	0	0	0	0	0	0	3	30	0	3	0	13	0	2	0	0	0	29	9	1
T8S20	34	0	0	0	1	0	0	0	0	0	0	3	79	0	1	0	10	6	2	0	7	0	77	16	0
T8S21	15	0	0	0	1	1	0	0	0	0	1	3	21	0	0	0	0	1	0	0	6	0	27	15	0

APPENDIX III

DEAD	*C. auricula*	*C. obtusa*	*C. pseudogenianus*	*D. aracuana*	*D. bertlothi*	*D. frobisherensis*	*D. subarcuata*	*Discorbinella sp.*	*D. trondheimensis*	*D. wrightii*	*E. advena*	*E. albiumbilicatum*	*E. asklundi*	*E. earlandi*	*E. excavatum*	*E. gerthi*	*E. incertum*	*E. laesoensis*	*E. macellum*	*E. margaritaceum*	*E. magellanicum*	*E.cf megallanicum*	*E. repandus*	*E. scabrus*	*E. naerensis*
T1S01	0	3	0	2	0	0	0	0	0	0	1	0	0	1	17	8	0	0	0	4	24	7	0	0	5
T1S02	10	2	0	3	0	0	1	0	0	0	1	0	0	1	13	10	0	0	0	0	7	8	1	0	1
T1S03	7	1	0	0	0	0	0	0	0	0	0	0	0	0	24	6	0	0	0	0	1	1	1	1	0
T1S06	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	2	0	1	0
T1S07	1	0	0	0	0	0	0	0	0	0	0	0	0	1	8	5	0	1	2	1	0	0	0	1	0
T1S09	1	3	0	0	0	0	0	0	0	0	0	0	0	1	21	23	0	0	1	1	0	2	0	0	1
T1S14	0	18	0	0	0	0	0	0	0	0	0	0	0	3	2	8	0	0	0	0	1	0	0	3	23
T1S17	0	12	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	2	0	5	18
T1S19	1	6	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	6
T2S01	4	3	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	5	1
T2S03	3	14	0	0	0	1	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	1	0	6	4
T2S07	3	17	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	3	12
T2S11	0	2	0	0	0	0	0		0	0	0	0	0	0	6	4	0	0	0	0	0	0	0	5	0
T2S14	0	3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	1
T2S16	1	1	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	0	0	1	1	0	2
T2S19	4	2	0	0	0	0	0	0	0	0	0	0	0	1	0	6	0	0	0	0	0	6	2	0	3
T2S20	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	2	4	0	2
T2S21	5	1	1	0	0	0	0	0	0	0	2	0	0	0	9	8	0	0	0	0	10	3	1	1	11
T2S22	1	4	0	1	0	0	0	0	0	0	0	0	0	2	3	3	0	3	0	0	6	9	1	0	3
T2S23	2	3	1	0	0	0	0	0	0	0	1	0	0	1	3	8	0	0	0	0	0	0	15	0	1
T3S01	0	2	0	0	0	0	0	0	0	0	1	0	0		2	5	0	0	0	0	4	14	1	0	5
T3S03	1	5	0	0	0	0	0	0	0	0	1	0	0	0	0	3	0	0	0	0	1	6	2	0	5
T3S05	0	2	0	0	0	0	0	0	0	0	0	0	0	0	4	3	0	0	0	0	1	6	0	0	3
T3S07	0	5	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	9
T3S10	3	2	0	0	0	0	0	0	0	0	1	0	0	0	1	3	0	0	0	0	0	2	0	3	12
T3S11	4	22	0	0	0	0	0	0	0	0	2	0	0	0	1	7	0	0	1	0	0	1	0	3	22
T3S13	2	14	2	0	0	0	1	0	0	0	0	0	0	0	7	1	0	0	0	0	1	0	0	0	8
T3S15	4	10	0	0	0	0	0	0	0	0	1	0	0	0	0	5	0	0	0	0	0	0	0	2	4
T3S16	7	18	0	0	0	0	0	3	0	0	0	0	0	3	1	11	0	1	0	0	2	0	0	0	33
T3S17	2	7	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	1	0	0	2	20
T3S19	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3
T3S23	2	3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	8	6
T6S02	0	1	0	0	0	0	0	1	0	0	0	3	0	0	4	2	0	0	0	0	6	5	1	0	3
T6S06	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	2	1	0
T6S08	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	1	4	5	1
T6S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
T6S12	0	8	0	0	2	0	0	0	0	0	0	0	0	1	2	5	0	0	0	0	1	1	0	3	10
T6S14	3	4	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	2	10
T6S16	3	4	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	2	10
T7S02	2	4	0	0	0	0	0	0	0	0	0	0	0	1	10	3	0	1	0	0	3	6	10	0	0
T7S06	0	1	0	0	0	0	0	0	0	0	0	0	0	2	4	1	0	0	0	0	0	0	3	1	0
T7S10	0	3	0	0	0	0	0	0	0	0	0	0	0	1	6	15	0	1	0	0	2	0	0	4	5
T7S16	1	6	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	12	6
T8S01	0	26	0	0	0	0	0	0	0	0	0	0	0	4	4	13	0	2	1	0	6	0	0	0	30
T8S02	5	24	0	0	0	0	0	1	0	0	0	1	0	3	7	6	0	3	0	1	1	1	0	6	14
T8S05	0	0	0	2	0	0	0	0	0	0	1	1	0	1	0	10	0	0	0	1	3	1	0	0	2
T8S08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	6	0	1	0	0	2	2	0	2	1
T8S09	1	0	0	0	0	0	0	0	0	0	0	0	0	0	12	4	0	0	0	0	0	0	0	10	0
T8S10	2	0	0	0	0	0	0	0	0	0	1	0	0	0	22	2	1	3	0	1	0	1	0	17	1
T8S13	0	1	0	0	1	0	0	0	0	0	1	0	0	0	55	7	0	1	0	1	5	0	0	47	0
T8S16	0	5	0	0	0	0	0	0	0	0	1	0	0	0	85	9	2	2	0	2	11	20	0	15	2
T8S20	1	4	0	0	0	0	0	0	0	1	13	0	0	6	97	19	0	2	2	2	2	22	0	10	3
T8S21	0	1	0	0	0	0	0	1	0	0	0	0	0	1	167	14	0	0	0	0	17	2	0	5	0

APPENDIX III

DEAD	*E. voorthusyen*	*Fissurina sp.*	*F. elliptica*	*F. danica*	*F. laegonoides*	*F. lucida*	*F. marginatat*	*F. serrata*	*G. harnisi*	*G.cf inequalis*	*G. myristyformis*	*G. praeger*	*G. rudis*	*H. balthica*	*H. bradyi*	*H. fragile*	*L. clavata*	*L. haliotidea*	*L. interupta*	*L. lactea*	*L. laevis*	*Lenticulina sp.*	*L. gracilis*	*L. hyalscalidia*	*L. perlucida*
T1S01	1	0	0	0	0	3	2	0	0	0	0	13	0	0	1	0	0	1	1	0	0	0	0	0	0
T1S02	0	0	0	0	0	2	1	0	0	0	0	3	5	0	0	0	0	1	0	1	0	0	0	0	1
T1S03	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0
T1S06	0	0	0	0	0	0	3	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S07	0	0	7	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	1	0	0	0	0	1
T1S09	0	0	0	0	0	1	5	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0
T1S14	0	1	0	0	0	2	4	0	0	0	0	25	0	3	0	0	1	2	0	0	0	0	0	0	0
T1S17	0	0	2	0	0	2	7	0	0	0	0	11	0	29	1	0	0	0	0	0	0	0	0	0	0
T1S19	0	0	0	0	0	0	3	0	0	0	0	6	0	18	0	0	0	1	0	0	0	0	0	0	0
T2S01	0	0	3	0	0	0	0	0	1	0	0	5	0	43	0	0	1	0	0	0	0	0	0	0	0
T2S03	0	0	2	0	0	0	2	0	0	0	0	13	0	30	0	0	0	0	0	0	0	0	0	0	0
T2S07	0	0	1	0	0	1	2	0	0	0	0	20	0	15	0	0	0	0	0	0	0	0	0	0	0
T2S11	0	0	0	0	0	1	0	0	0	0	0	9	0	4	0	0	0	0	0	0	0	0	0	0	0
T2S14	0	0	1	0	0	1	0	0	1	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0
T2S16	0	0	1	0	0	0	1	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0
T2S19	0	0	3	0	0	0	0	0	0	0	0	6	7	0	0	1	0	3	0	1	0	0	0	0	0
T2S20	0	0	0	0	0	0	1	0	1	0	0	6	9	1	0	0	1	0	0	3	0	0	0	0	0
T2S21	1	0	0	0	0	1	8	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0
T2S22	0	0	0	0	0	4	6	0	0	0	0	15	0	0	0	1	0	3	0	0	0	0	0	0	0
T2S23	0	0	0	0	0	0	0	0	0	0	0	7	8	0	1	2	1	0	0	0	1	0	0	0	0
T3S01	0	0	0	0	0	0	4	0	1	1	0	4	2	2	0	0	0	1	0	0	0	0	0	0	0
T3S03	0	0	0	0	0	0	4	0	0	1	0	11	1	0	0	0	0	2	0	1	0	1	0	0	0
T3S05	0	0	0	0	0	0	0	0	1	0	0	12	2	0	0	0	0	1	0	0	0	0	0	0	0
T3S07	0	0	1	0	0	0	0	0	0	0	0	13	0	12	0	0	0	4	0	0	0	0	0	0	0
T3S10	0	0	0	0	0	1	8	0	0	0	0	9	0	0	0	0	1	0	0	0	0	0	0	0	0
T3S11	0	0	1	0	0	0	4	0	0	0	0	20	0	1	0	0	0	3	0	1	0	0	0	0	0
T3S13	0	0	1	0	0	0	0	0	0	0	0	10	0	3	0	0	1	1	0	1	0	0	1	0	0
T3S15	0	0	4	0	0	5	0	0	0	0	0	45	0	2	0	0	3	0	1	0	0	0	0	0	1
T3S16	0	0	2	0	1	3	4	0	0	0	0	55	0	7	0	0	1	0	0	0	1	0	0	0	2
T3S17	0	0	5	0	0	1	1	0	0	0	0	40	0	0	1	0	0	0	3	0	0	0	0	0	0
T3S19	0	0	5	0	0	0	1	0	0	0	0	16	0	44	0	0	0	1	0	0	0	0	0	0	0
T3S23	0	0	6		0	1	2	0	0	0	0	12	0	36	0	0	0	0	1	1	0	0	0	2	0
T6S02	0	0	0	0	0	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S06	0	0	1	0	0	0	0	0	0	1	0	3	2	0	0	0	0	1	0	0	0	0	0	0	0
T6S08	0	0	0	0	1	1	1	0	1	0	0	12	1	0	0	0	0	1	0	1	0	0	0	0	0
T6S10	0	0	1	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
T6S12	0	0	3	0	0	1	3	0	0	0	0	40	0	1	0	1	0	2	0	1	0	1	0	0	0
T6S14	0	0	3	0	0	2	4	0	0	0	0	37	0	6	0	0	0	0	0	0	0	0	0	1	0
T6S16	0	0	3	0	0	2	4	0	0	0	0	37	0	6	0	0	0	1	0	0	0	0	0	1	0
T7S02	0	0	0	0	0	0	0	1	0	0	0	18	10	0	0	3	0	1	0	0	0	0	0	0	0
T7S06	0	0	0	0	0	0	0	0	0	0	1	13	2	0	0	0	0	0	0	0	0	0	0	0	0
T7S10	0	0	0	0	0	3	1	0	0	0	0	22	0	1	0	3	0	0	0	0	0	0	0	0	1
T7S16	0	0	0	0	0	2	1	0	0	0	0	4	0	76	0	0	1	2	0	0	0	0	0	0	0
T8S01	0	0	0	1	2	2	11	0	0	0	0	53	0	2	0	0	2	7	0	0	0	0	0	0	0
T8S02	0	0	6	0	1	0	1	0	0	0	0	25	0	19	0	0	0	8	0	0	0	0	0	0	0
T8S05	0	0	1	0	0	2	0	0	0	0	0	18	0	0	0	0	0	0	0	0	1	0	0	0	0
T8S08	0	0	0	0	0	3	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S09	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S10	0	0	0	0	0	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S13	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	1
T8S16	0	0	1	0	0	1	1	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S20	0	0	0	0	0	1	1	0	0	0	0	23	0	1	0	4	1	0	0	1	0	0	0	0	0
T8S21	0	0	0	0	0	0	4	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX III

DEAD	*L. semistriata*	*L. spicata*	*L. striata*	*L. substriata*	*L. sulcata*	*Manispella sp.*	*M. circularis*	*M. circularis var. elongata*	*M. pompiloides*	*M. subrotunda*	*N. auricula*	*N. depressulus*	*Nonion sp. (juv)*	*N. turgida*	*Nodosaria sp.*	*N. pauperatum*	*O. balkwilli*	*O. borealis*	*O. hexagona*	*O. melo*	*O. squamosa*	*O. williamsoni*	*Parafissurina sp.*	*Peneropolis sp.*	*P. corrugata*
T1S01	0	0	0	0	0	0	5	0	6	3	0	0	0	1	0	5	3	0	0	0	0	0	0	0	0
T1S02	0	0	0	1	0	0	0	1	2	4	0	1	0	0	0	1	3	0	0	0	0	1	0	0	1
T1S03	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	0	0
T1S06	0	0	0	0	0	0	0	0	0	5	0	1	2	0	0	0	0	0	1	0	0	2	0	0	0
T1S07	0	0	0	0	0	0	0	1	2	8	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0
T1S09	0	0	0	0	0	0	0	0	3	13	1	2	1	1	0	1	0	0	2	0	0	0	0	0	0
T1S14	0	0	0	0	0	0	0	0	1	1	0	0	0	5	0	7	0	0	0	0	0	0	0	0	0
T1S17	0	0	0	0	0	0	0	3	1	2	0	1	0	5	0	2	0	0	0	0	1	0	0	0	0
T1S19	0	0	0	0	0	0	0	1	6	0	1	0	0	1	1	0	0	0	1	0	0	1	0	0	0
T2S01	0	0	0	0	0	0	0	0	5	3	1	0	0	1	0	0	0	0	1	0	0	2	0	0	0
T2S03	0	0	0	0	0	0	0	0	4	0	0	1	1	4	0	6	0	0	0	0	0	0	0	0	0
T2S07	0	0	0	0	0	0	0	0	2	2	0	2	1	5	0	3	0	0	0	0	0	0	0	0	2
T2S11	0	0	0	0	0	0	0	0	4	5	0	1	1	2	0	2	0	0	0	0	0	0	0		0
T2S14	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	2	0	0	1
T2S16	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	1	0	2	0	0	0	0	0	2	0
T2S19	0	0	0	0	0	0	0	1	1	2	0	2	0	0	0	4	0	3	0	0	0	2	0	0	0
T2S20	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	2	1	0	0	0	0	0	0
T2S21	0	0	0	0	1	0	0	0	0	1	0	1	2	1	0	3	7	2	0	0	0	0	0	0	2
T2S22	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	2	16	0	0	0	0	0	0	0	3
T2S23	0	0	0	0	0	0	0	0	0	1	6	0	0	0	0	8	2	3	0	0	0	1	0	0	0
T3S01	0	0	0	0	0	0	0	1	1	0	0	0	2	0	0	8	1	4	2	0	0	0	0	0	0
T3S03	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	0	0	2	0	0	1
T3S05	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3S07	0	1	0	0	0	0	0	0	2	0	0	2	0	3	0	1	0	0	0	0	0	0	0	0	0
T3S10	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0
T3S11	1	0	0	0	0	0	1	0	0	3	1	1	0	0	0	0	0	0	3	0	0	0	0	0	1
T3S13	0	0	0	0	0	0	0	0	1	2	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
T3S15	1	0	0	0	0	0	0	0	2	2	1	1	0	3	0	1	0	0	0	0	2	2	0	0	0
T3S16	0	0	1	0	0	0	0	0	0	0	5	1	1	4	0	2	0	2	3	1	1	1	0	0	1
T3S17	0	0	0	0	0	0	0	0	1	0	1	1	0	4	0	0	0	0	2	0	0	0	0	0	0
T3S19	0	0	0	0	0	0	0	0	1	0	0	0	1	3	0	1	0	0	0	0	0	0	0	0	0
T3S23	0	0	0	0	0	0	0	0	2	0	1	0	0	4	0	0	0	0	1	0	1	1	0	0	0
T6S02	0	0	0	0	0	0	0	0	0	8	0	1	0	0	0	5	2	0	0	0	0	0	0	0	0
T6S06	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1
T6S08	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	2	1	0	0	0	0	1	0	0	0
T6S10	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6S12	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	5	0	0	1	0	0	0	0	0	0
T6S14	0	0	0	0	0	0	0	0	0	0	0	1	0	8	0	7	0	0	3	0	0	0	0	0	0
T6S16	0	0	0	0	0	0	0	0	4	0	0	1	0	8	0	3	0	0	3	0	0	0	0	0	0
T7S02	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1	0	1	0	0	0	1	0	0	0
T7S06	0	0	0	0	0	0	0	0	0	5	0	4	0	0	0	1	0	1	0	0	1	2	0	1	0
T7S10	2	0	0	0	0	0	0	0	1	11	1	6	0	1	0	2	0	0	0	0	1	0	0	0	1
T7S16	0	0	2	0	0	0	0	0	12	0	0	2	0	2	0	4	0	0	0	0	0	0	0	0	1
T8S01	0	0	0	0	0	0	3	2	5	11	0	7	1	7	0	12	5	0	0	0	0	1	0	0	1
T8S02	1	0	0	0	1	0	0	4	2	8	2	1	0	3	0	6	2	0	0	0	0	0	0	0	1
T8S05	0	0	0	0	0	0	0	0	0	5	0	8	0	0	0	2	0	0	0	0	0	0	1	0	0
T8S08	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	1	0	0	0	0	0	1	0	0	0
T8S09	0	0	0	0	0	0	0	0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
T8S10	0	0	0	0	0	0	0	0	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
T8S13	0	0	0	0	0	0	0	0	0	4	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0
T8S16	0	0	0	0	0	0	0	1	1	2	0	4	0	1	0	1	2	0	0	0	0	2	0	0	0
T8S20	0	0	0	0	0	0	0	0	0	12	1	14	0	0	0	2	2	0	1	1	0	1	0	0	0
T8S21	0	0	0	0	0	0	1	1	0	11	0	6	0	0	0	0	2	0	0	0	0	0	0	0	1

APPENDIX III

DEAD	*P. depressa*	*P. distoma*	*P. fusca*	*P. malcomsoni*	*P. williamsoni*	*Q. aspera*	*Q. bicomis*	*Q. bicomis var. angulata*	*Q. cf cliarensis*	*Q. cliarensis*	*Q. lata*	*Q. oblonga*	*Q. rugosa*	*Q. seminulum*	*R. artica*	*R. bradyi*	*R. fusiformis*	*R. anomala*	*R. irregularis*	*Rosalina sp. (juv)*	*R. neopolitana*	*R. scorpiurus*	*R. scotti*	*R. trochamminiforme*	*R. williamsoni*
T1S01	0	4	0	0	0	0	0	0	0	0	0	2	0	15	0	5	1	6	0	0	0	0	0	0	2
T1S02	0	10	0	0	0	0	4	1	1	0	1	0	0	72	1	19	0	1	0	0	0	0	1	0	3
T1S03	3	0	0	0	1	0	0	4	0	0	0	0	0	53	0	16	0	0	0	0	0	0	0	0	1
T1S06	4	18	0	0	0	0	0	0	0	0	0	2	0	18	0	5	1	0	0	0	0	2	0	0	0
T1S07	0	7	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	1	0	0	0	0	0	0	0
T1S09	0	0	1	0	0	0	0	0	0	0	0	0	0	20	0	3	0	0	0	0	0	0	0	0	5
T1S14	0	1	0	0	0	0	0	2	0	0	0	0	0	15	0	6	0	0	0	0	0	0	0	0	8
T1S17	0	1	0	0	0	0	0	1	0	2	0	1	0	24	0	0	1	0	0		0	0	0	0	3
T1S19	0	0	0	0	0	0	0	1	0	0	0	0	1	18	0	4	1	0	0	0	0	0	0	0	3
T2S01	0	0	0	0	1	0	3	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0
T2S03	0	0	0	0	1	0	1	0	0	0	0	0	0	10	0	2	0	0	0	0	0	0	0	0	1
T2S07	0	0	0	0	0	0	0	0	1	0	0	0	0	13	0	3	0	0	0	0	0	0	0	0	3
T2S11	4	13	0	0	0	0	2	0	0	0	0	0	0	40	0	3	3	0	0	0	0	0	0	0	0
T2S14	2	1	0	0	7	0	0	1	0	0	0	0	0	34	1	6	0	0	0	0	0	0	0	0	0
T2S16	16	1	0	1	1	0	3	2	0	0	5	0	0	28	0	13	0	0	0	0	0	0	0	0	0
T2S19	6	2	0	0	0	0	4	2	0	0	2	0	0	17	0	13	0	0	0	0	0	0	0	0	7
T2S20	3	5	0	0	0	0	6	0	0	0	0	0	0	32	0	18	1	0	0	0	0	0	0	0	3
T2S21	0	4	0	0	0	0	3	1	0	0	0	0	0	25	0	22	0	0	0	1	0	0	0	0	1
T2S22	1	1	0	0	0	0	0	0	0	0	1	0	0	15	0	4	0	1	0	0	0	0	0	0	16
T2S23	4	3	0	0	0	0	3	0	0	0	0	0	0	49	0	6	0	0	0	0	0	0	0	0	2
T3S01	3	1	0	0	0	0	5	1	0	0	0	0	0	29	0	9	0	0	0	0	0	0	0	0	1
T3S03	2	0	0	0	0	0	4	0	0	0	0	0	0	28	1	6	0	0	0	1	0	1	0	0	4
T3S05	4	2	0	0	0	0	1	0	0	0	0	0	0	21	0	11	2	1	0	0	0	0	0	0	3
T3S07	0	0	0	0	2	0	0	0	0	0	0	0	0	9	0	1	1	0	0	0	0	0	0	0	5
T3S10	0	6	0	0	0	0	2	0	0	0	0	0	0	36	0	4	0	0	0	1	0	0	0	0	1
T3S11	0	1	0	0	0	0	2	1	0	2	0	0	0	35	0	7	1	0	0	1	0	0	0	0	0
T3S13	3	15	0	0	0	0	0	0	0	0	0	0	0	30	0	6	0	0	0	5	0	0	0	0	0
T3S15	0	15	0	0	0	0	0	0	0	0	0	0	0	29	0	3	0	0	0	0	0	0	0	0	2
T3S16	1	7	0	0	0	0	0	0	0	0	0	0	0	24	1	6	0	0	0	1	0	0	0	0	8
T3S17	0	23	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	2
T3S19	1	1	0	0	0	0	0	0	0	0	3	0	0	23	0	0	0	0	0	0	0	0	0	0	1
T3S23	0	3	0	0	2	1	1	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0	0	0	0
T6S02	0	3	0	0	0	0	1	0	0	1	0	0	0	0	0	3	0	16	0	0	0	0	0	1	0
T6S06	1	3	0	0	0	0	7	0	0	0	0	0	0	54	0	5	0	2	0	0	0	0	0	0	0
T6S08	2	7	0	0	0	0	2	0	0	0	0	0	0	39	0	1	1	2	0	0	0	0	0	1	0
T6S10	1	8	0	0	0	0	0	0	0	0	0	0	0	58	0	1	1	0	0	0	0	0	0	0	0
T6S12	0	4	0	0	0	0	0	1	0	0	0	0	0	20	2	2	0	1	0	0	0	0	0	0	0
T6S14	0	1	0	0	1	0	0	0	0	0	0	0	0	3	0	2	0	3	0	0	0	0	0	0	0
T6S16	0	1	0	0	1	0	0	0	0	0	0	0	0	3	0	2	0	3	0	0	0	0	0	0	0
T7S02	2	5	0	0	0	0	2	0	0	0	0	0	0	51	0	20	2	1	0	0	0	0	0	0	1
T7S06	14	4	0	0	2	0	1	3	0	0	0	0	0	28	0	12	3	0	0	0	0	2	0	0	0
T7S10	2	15	0	0	0	0	0	0	0	0	0	0	0	50	0	9	1	0	0	0	0	0	0	0	2
T7S16	1	0	0	0	3	0	0	2	0	0	0	0	0	60	0	3	1	1	0	0	0	0	0	0	1
T8S01	0	3	0	0	0	0	0	7	0	1	0	0	0	13	0	6	0	17	0	3	0	0	0	0	10
T8S02	0	5	0	0	0	0	0	0	1	0	1	0	0	16	0	3	2	2	0	0	1	2	0	0	3
T8S05	0	7	0	0	0	0	1	0	0	0	0	0	0	13	0	4	0	3	0	0	0	0	0	0	2
T8S08	0	3	0	0	0	0	0	1	0	0	0	0	0	27	0	1	0	0	0	0	0	0	0	0	0
T8S09	0	5	0	0	0	0	0	0	1	0	0	0	0	93	0	2	0	3	0	0	0	0	0	0	0
T8S10	0	3	0	0	0	0	0	1	1	0	0	0	0	79	2	2	0	0	0	0	0	0	0	0	0
T8S13	0	2	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	1	0	0	0	0	0	0	0
T8S16	0	3	0	0	0	0	0	1	0	0	0	0	0	25	0	2	0	4	1	0	0	0	1	0	1
T8S20	0	11	0	0	0	0	0	5	1	0	0	0	0	53	2	8	0	23	0	0	3	0	0	0	0
T8S21	0	1	0	0	0	0	0	1	0	0	0	0	0	14	0	2	2	6	0	0	0	0	4	0	0

APPENDIX III

DEAD	*S. concava*	*S. excavata*	*S. fusiformis*	*S.cf rotunda*	*S. squamosa*	*S. vivpara*	*S. wrightii*	*T. angulosa*	*T. agglutins*	*T. bradyi*	*T.bockii*	*Trochammina sp.*	*T. globeriginformis var. pygmaea*	*T. astrificata*	*T. rotaliformis*	*T. trihedra*	*U. peregrina*	*Unidentified*	*total*
T1S01	0	0	18	0	0	1	8	3	0	0	19	5	1	1	0	0	0	3	345
T1S02	0	0	39	1	0	1	21	0	3	0	65	3	1	3	0	0	0	0	496
T1S03	0	0	7	0	0	1	19	0	1	0	67	0	0	0	0	0	0	0	341
T1S06	0	0	0	2	0	0	14	0	0	1	33	0	0	0	0	0	0	0	299
T1S07	0	0	1	0	0	0	9	1	0	1	40	0	0	0	0	0	0	0	328
T1S09	0	0	17	0	0	0	6	2	1	1	33	0	0	0	0	0	0	0	392
T1S14	0	0	17	1	0	0	1	0	1	6	14	0	0	0	0	0	0	5	284
T1S17	0	0	18	0	0	0	4	0	0	0	8	1	0	0	0	0	0	0	292
T1S19	0	0	6	3	0	0	57	1	0	1	45	0	2	0	0	0	0	0	303
T2S01	0	0	5	0	0	0	58	0	0	1	94	2	0	1	1	0	0	0	331
T2S03	0	0	12	0	0	0	5	1	0	2	27	0	2	0	1	0	0	0	345
T2S07	1	0	18	0	0	0	3	0	0	2	6	0	0	0	0	0	0	0	274
T2S11	1	0	14	0	0	0	13	0	0	2	19	0	1	0	0	0	0	0	300
T2S14	0	0	4	0	0	0	44	0	0	0	98	0	0	0	0	0	0	1	340
T2S16	0	0	10	2	0	0	59	0	0	0	72	0	0	1	0	0	0	0	434
T2S19	0	0	3	0	0	0	16	0	1	0	48	1	1	1	0	0	0	0	359
T2S20	0	0	3	0	0	0	21	0	0	0	104	2	0	1	0	0	0	0	401
T2S21	1	0	37	5	0	0	4	0	4	0	21	3	1	7	0	0	0	0	352
T2S22	0	0	17	0	0	3	11	0	1	0	20	1	2	3	0	0	0	0	295
T2S23	0	0	7	1	0	0	14	0	0	0	36	3	1	3	0	0	0	0	332
T3S01	0	0	4	0	0	0	10	0	0	0	55	1	1	0	0	0	0	2	340
T3S03	0	0	0	0	0	0	25	0	0	0	25	1	1	2	0	0	0	0	301
T3S05	0	0	16	0	0	0	16	0	0	0	52	2	2	0	0	0	0	0	315
T3S07	0	0	15	0	0	0	1	0	0	2	5	0	0	0	0	0	0	0	308
T3S10	0	0	87	0	0	0	24	1	3	0	27	0	2	0	0	0	0	0	442
T3S11	0	0	88	0	0	0	9	0	0	0	12	0	0	1	0	0	0	1	450
T3S13	0	0	49	0	0	0	10	0	4	0	57	0	0	0	0	0	0	1	431
T3S15	0	0	32	0	0	0	24	4	1	5	56	0	0	0	1	0	0	0	494
T3S16	0	0	228	1	1	0	14	1	2	4	81	0	0	1	0	0	0	2	799
T3S17	0	0	58	0	0	0	3	1	0	0	41	0	0	0	0	0	1	1	384
T3S19	0	0	24	0	0	0	81	0	0	3	56	0	0	1	0	0	0	0	405
T3S23	0	0	18	0	0	0	93	1	0	4	71	0	0	1	0	0	0	0	411
T6S02	0	0	6	0	0	0	11	0	1	1	35	4	8	1	0	0	0	3	267
T6S06	0	0	4	0	0	0	46	0	0	2	76	0	0	0	0	0	1	3	353
T6S08	0	0	7	0	0	0	58	0	0	1	77	0	0	0	0	0	0	1	501
T6S10	0	1	0	0	0	0	20	0	0	0	33	0	0	0	0	0	0	0	316
T6S12	0	0	46	0	0	0	12	0	3	4	80	0	1	0	0	0	0	1	468
T6S14	0	0	56	0	0	0	16	0	1	7	50	0	1	0	0	0	0	2	392
T6S16	0	0	56	0	0	0	16	0	1	7	50	0	1	0	0	0	0	3	394
T7S02	1	0	3	1	0	1	9	1	1	0	30	0	1	1	0	0	0	2	328
T7S06	0	0	1	0	0	0	52	0	0	0	71	0	0	1	0	0	0	1	381
T7S10	0	0	21	0	0	0	16	0	1	0	44	0	0	0	0	0	0	2	489
T7S16	0	0	4	0	0	0	6	0	0	0	18	0	0	0	0	0	0	0	523
T8S01	0	0	80	0	0	0	3	0	0	7	15	0	0	3	0	0	1	11	561
T8S02	0	0	45	1	0	1	3	2	0	2	4	0	0	3	0	0	0	9	353
T8S05	0	0	6	0	0	0	8	3	7	0	9	0	0	0	0	0	0	5	235
T8S08	0	0	1	0	0	0	4	1	0	3	15	1	0	0	0	0	0	2	414
T8S09	0	0	0	0	0	1	4	0	0	1	34	1	0	0	0	0	0	0	399
T8S10	0	0	2	1	0	0	4	0	2	0	55	0	0	0	0	0	0	1	462
T8S13	0	0	1	0	0	0	3	0	2	0	52	0	0	0	0	0	0	1	406
T8S16	0	0	7	0	0	0	8	0	3	1	14	2	0	2	0	1	0	3	375
T8S20	0	0	6	2	0	0	7	0	8	9	22	2	0	0	1	0	0	3	652
T8S21	0	0	9	0	0	0	2	0	3	3	15	1	0	1	0	0	0	0	399

APPENDIX IV

sample	affinity
T1S01	55.17
T1S02	46.62
T1S03	42.25
T1S07	17.69
T1S09	15.39
T1S14	17.06
T1S17	16.48
T1S19	31.44
T2S01	32.79
T2S03	29.80
T2S07	24.26
T2S11	12.52
T2S14	15.99
T2S16	27.20
T2S19	14.71
T2S20	29.06
T2S21	45.82
T2S22	41.65
T2S23	44.79
T3S01	45.85
T3S03	29.15
T3S05	24.29
T3S07	20.53
T3S10	26.54
T3S11	26.89
T3S13	19.34
T3S15	30.62
T3S16	36.40
T3S17	24.13
T3S19	24.48
T3S23	25.08
T6S02	19.56
T6S06	31.05
T6S08	14.84
T6S10	14.86
T6S12	19.66
T6S14	22.41
T6S16	24.36
T7S02	11.46
T7S06	10.17
T7S10	9.09
T7S16	5.70
T8S01	21.33
T8S02	18.44
T8S05	11.98
T8S08	42.02
T8S09	25.31
T8S10	49.26
T8S13	57.79
T8S16	39.70
T8S20	48.08
T8S21	38.73

APPENDIX V

mc295

Depth	0.25	1	2	3	4
Ammonia beccarii	52	26	26	0	130
Adercotryma glomeratum	520	208	0	26	0
Bulimina gibba	104	0	0	0	0
Bulimina marginata	624	312	130	156	52
Brizalina pseudopunctata	104	260	0	0	0
Bolivina spathulata	52	26	0	0	0
Cibicides fletcheri	52	0	0	0	0
Cancris auricula	312	598	130	0	104
Epistominella vitrea	156	26	0	0	0
Hyalinea balthica	52	130	0	0	0
Nonion aunicula	1871	416	52	26	0
Nonionella turgida	4001	3611	1039	338	26
Quinqueloculina seminulum	156	130	0	0	0
Reophax fusiformis	0	0	0	0	52
Reophax scorpiurus	0	0	52	0	26
Stainforthia loeblichi	0	182	0	0	0
Stainforthia fusiformis	4001	4599	2390	1065	857
Trochammina globeriginiformis var. *pygmaea*	52	0	0	0	0
Total number of species	17	14	9	7	7

mc395

Depth	0.25	1	2	3	4
Ammonia beccarii	572	0	26	0	130
Adercotryma glomeratum	935	78	338	130	0
A?. orbiculatum	0	0	52	0	0
Bulimina gibba	260	78	26	0	0
Bulimina marginata	52	0	26	0	0
Cribrostomoides kosterensis	468	52	26	26	0
Cancris auricula	208	208	364	130	78
Eggerella advena	572	52	0	0	0
Elphidium oceanis	52	0	0	0	26
Eggerelloides scabrus	208	0	26	0	0
Epistominella vitrea	1715	104	0	0	0
Fissurina lucida	52	0	0	0	0
Gavelinopsis preaegeri	104	0	26	26	0
Lamarckina haliotidea	52	0	0	26	0
Lagena interrupta	52	0	26	0	0
Lagena perlucida	52	0	0	0	0
Nonionella turgida	1351	1117	364	0	0
Pyrgo williamsoni	260	0	0	26	0
Quinqueloculina seminulum	624	130	26	0	0
Reophax scorpiurus	104	78	130	0	0
Stainforthia fusiformis	5248	4651	3897	1169	2780
juvenilles	156	0	0	0	0
Total number of species	22	11	20	6	6

APPENDIX V

Depth	Ammonia becarri	Ammoscalaria runiana	A.dercotryma glomeratum	Ammoscalaris pseudospiralis	Bulimina gibba	Bulimina marginata	Brizalina pseudopunctata	Bolivina spathulata	Cancris auricula	Eggerella advena	Eggerelloides scabrus	Epistominella vitrea	Hyalinea balthica	Nonion auricula	Nonionella turgida	Pyrgo williamsoni	Quinqueloculina seminulum	Reophax artica	Reophax fusiformis	Reophax scorpiurus	Stainforthia loeblichi	Stainforthia fusiformis	Total number of species
0.25	0	52	572	312	260	208	676	52	208	52	364	52	208	208	2494	104	1663	52	52	104	156	6495	21
1	26	0	78	78	26	208	0	26	0	0	416	26	104	0	1767	0	234	0	52	234	0	9561	18
2	26	26	52	0	0	156	26	0	0	0	260	0	26	26	104	0	156	0	26	78	0	2884	16
3	130	0	0	0	0	52	0	0	52	0	104	26	0	0	0	0	0	0	0	26	0	676	7
4	0	52	52	26	52	208	26	0	156	0	104	0	52	0	78	0	182	0	26	52	0	1897	15
5	26	0	0	104	0	52	26	0	52	0	78	26	0	0	208	0	130	0	0	26	0	3456	12
6	0	0	0	0	52	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0	26	0	5
7	0	0	78	156	0	156	26	0	208	0	0	52	78	0	104	0	52	0	0	26	0	2442	11
8	0	0	0	78	26	208	0	0	78	0	52	26	52	26	0	0	52	0	0	52	0	4235	12
9	0	0	0	0	0	104	0	0	26	0	0	52	0	26	0	0	0	0	0	0	0	9276	4

APPENDIX V

mc196

Depth	Ammonia beccarii	Adercotryma glomeratum	Ammoscalaria runiana	Ammoscalaria pseudospiralis	Bulimina marginata	Brizalina pseudoplicata	Bolivina spathulata	Cribrostomoides kosterensis	Cancris auricula	Dentalina subarcuata	Eggerella advena	Eggerelloides scabrus	Epistominella vitrea	Fissurina lucida	Hyalinea balthica	Lagena clavata	Lagena striata	Lagena perlucida	Melonis barleeanum	Nonion auricula	Nonionella turgida	Pyrgo depressa	Pyrgo williamsoni	Quinqueloculina seminulum	Reophax artica	Reophax fusiformis	Reophax scorpiurus	Stainforthia fusiformis	juveniles	Total number of species	Trochammina globerigiiniformis var. pygmaea
0.25	1091	24215	52	883	312	676	624	4729	2598	104	104	1975	312	260	312	260	0	156	156	520	9977	104	468	987	0	260	1039	2858	0	0	29
1	416	3066	78	104	182	130	104	156	1143	0	0	598	156	26	78	0	0	0	156	130	4365	26	52	182	0	78	104	3014	52	52	27
2	156	2208	78	52	234	0	26	338	961	26	0	546	26	0	390	0	0	0	52	78	442	0	26	78	104	104	0	2806	0	0	26
3	78	1065	0	130	546	208	52	182	676	0	0	416	0	26	312	78	0	78	26	26	312	0	78	156	52	234	130	1689	0	26	26
4	364	1377	0	52	598	104	208	26	624	0	0	442	130	0	338	26	26	0	0	52	624	26	0	26	0	26	104	6106	0	0	24
5	130	3066	0	234	572	52	26	0	364	0	0	416	312	52	234	0	130	0	0	0	1559	0	0	26	0	52	182	9587	78	0	21
6	104	2079	0	78	805	234	52	0	520	0	0	364	78	0	753	52	0	0	0	0	1689	0	0	26	26	26	286	8418	104	260	22
7	78	1715	0	0	572	78	0	0	598	0	0	260	26	0	364	0	26	0	0	0	598	0	0	104	26	0	520	7872	26	0	15
8	26	234	0	78	338	26	0	0	78	0	0	182	0	0	0	0	0	0	0	0	104	0	0	0	0	0	312	3196	0	0	10
9	0	78	0	52	234	26	0	0	130	0	0	52	0	0	26	0	0	0	0	0	156	0	0	0	0	0	78	1975	0	0	11

APPENDIX VI

Dead Q-mode	factor 1	factor 2	factor 3	factor 4	factor 5	factor 6	factor 7	factor 8	factor 9	factor 10	factor 11	factor 12	factor 13
T1S01	-0.71	0.05	0.4	0.1	-0.46	0.09	0.19	0.05	-0.01	0.07	-0.23	0.1	-0.01
T1S02	-0.88	-0.29	0.05	-0.01	-0.14	-0.19	0.02	-0.16	-0.03	0.05	-0.21	-0.02	0.06
T1S03	-0.89	-0.36	-0.09	0	-0.01	-0.09	-0.06	-0.12	-0.05	-0.11	-0.06	-0.14	0.11
T1S06	-0.81	-0.39	0.01	0.21	0.25	0.13	0.15	0.17	-0.04	0.12	0.02	0.01	0.01
T1S07	-0.77	-0.38	0	0.22	0.32	0.16	0.16	0.19	-0.01	0.16	0.08	0	0.04
T1S09	-0.88	0.08	0.22	0.21	0.24	0.16	-0.03	0.11	-0.04	0.07	0.07	-0.08	-0.01
T1S14	-0.63	0.53	0.28	-0.02	0	-0.04	-0.04	0.02	-0.4	-0.18	0.13	-0.04	0.15
T1S17	-0.69	0.47	-0.34	0.19	-0.22	-0.23	0.02	0	-0.15	0.11	0.09	-0.01	-0.06
T1S19	-0.79	0	-0.51	0.01	-0.15	0.2	-0.17	-0.02	-0.04	0.1	-0.03	0	0.09
T2S01	-0.62	0.06	-0.67	0.01	-0.13	0.28	0.06	-0.19	-0.14	0.02	-0.01	-0.03	-0.06
T2S03	-0.61	0.56	-0.45	0.12	-0.18	-0.11	0.11	0.16	-0.01	0.02	0.09	0.04	0.07
T2S07	-0.71	0.65	-0.11	0.05	-0.05	-0.13	-0.04	0.14	-0.06	-0.03	0.11	-0.01	0
T2S11	-0.9	-0.03	-0.19	0.13	0.03	-0.27	-0.19	0	0.16	-0.03	-0.03	0.02	0
T2S14	-0.8	-0.41	-0.22	-0.26	0.06	0.12	0.06	-0.08	-0.05	-0.15	-0.06	-0.03	0.13
T2S16	-0.83	-0.36	-0.06	-0.38	0.06	0.05	0.12	0.03	0	-0.11	0.05	-0.02	0
T2S19	-0.82	-0.39	-0.01	-0.16	-0.17	0.04	-0.16	0.16	0.07	0.16	0.13	0.08	-0.06
T2S20	-0.86	-0.37	-0.16	-0.15	-0.1	0.11	-0.2	0.04	-0.02	0.06	0.05	0.03	0.06
T2S21	-0.87	0.21	0.36	-0.04	-0.18	-0.06	0	-0.07	-0.11	0.04	-0.06	0.02	0
T2S22	-0.84	0.16	0.35	-0.05	-0.31	0.05	0.04	0.02	-0.15	-0.01	-0.12	0.06	0.01
T2S23	-0.88	-0.32	-0.03	-0.05	-0.06	-0.19	-0.25	0.04	-0.05	0.03	0.06	-0.04	0
T3S01	-0.83	-0.3	0.05	0	-0.39	0.03	-0.13	0.08	-0.05	0.16	-0.04	0.11	0.02
T3S03	-0.91	-0.27	0.05	-0.08	-0.18	0	-0.19	0.14	-0.01	0.02	0.03	0.03	-0.07
T3S05	-0.93	-0.21	0.09	-0.25	-0.11	0.02	0	0.06	0	0.01	0.05	0.02	-0.01
T3S07	-0.46	0.63	-0.27	0.03	-0.08	-0.24	0.18	0.34	0.25	-0.05	-0.11	0.01	0.2
T3S10	-0.82	-0.05	0.17	-0.32	0.14	-0.26	0.15	-0.21	0.02	0.19	0.05	0.02	0.05
T3S11	-0.82	0.1	0.26	-0.25	0.19	-0.26	0.05	-0.17	0.04	0.19	0.08	0.01	-0.06
T3S13	-0.89	-0.15	0.03	-0.27	0.18	-0.12	0.16	-0.07	0.1	0.11	0.03	-0.03	-0.01
T3S15	-0.82	0.39	-0.05	-0.04	0.14	0.07	-0.22	0.15	0.22	-0.12	-0.06	0.02	-0.02
T3S16	-0.68	0.49	0.12	-0.19	0.2	-0.01	-0.07	-0.27	0.19	0.29	-0.08	0.05	0.03
T3S17	-0.71	0.63	0.15	-0.12	0.18	0.04	-0.08	0	0.12	-0.07	-0.04	0.01	0.04
T3S19	-0.7	0.27	-0.58	0	-0.01	0.21	0.12	-0.13	-0.03	0.02	-0.09	-0.07	-0.12
T3S23	-0.7	0.16	-0.57	-0.07	-0.03	0.32	0.13	-0.16	-0.04	-0.02	0	0.03	0
T6S02	-0.68	-0.27	0.24	-0.35	-0.15	0.07	0.48	0.13	-0.04	-0.05	0.03	0.04	0
T6S06	-0.85	-0.43	-0.2	-0.13	0.02	-0.02	-0.08	-0.06	-0.02	-0.08	-0.09	-0.03	0.05
T6S08	-0.85	-0.38	-0.03	-0.27	0.12	0.01	0.14	0.06	0	-0.12	0.09	0.01	-0.03
T6S10	-0.76	-0.49	-0.04	-0.04	0.17	-0.3	0.17	0.01	-0.03	-0.16	0	-0.02	-0.03
T6S12	-0.82	0.31	0.15	-0.04	0.36	0.23	0.02	-0.02	0.02	-0.09	-0.05	0	-0.07
T6S14	-0.73	0.59	0.01	-0.18	0.2	0.14	-0.02	0	0.18	-0.04	-0.03	0.02	0
T6S16	-0.73	0.59	0.01	-0.18	0.2	0.14	-0.02	0	0.18	-0.04	-0.03	0.02	0
T7S02	-0.9	-0.17	0.15	0	-0.05	-0.14	-0.08	0.05	0.03	-0.18	-0.12	-0.09	-0.2
T7S06	-0.88	-0.3	-0.16	-0.13	0	0.19	-0.23	0.03	0.03	-0.02	0.04	0.01	0
T7S10	-0.95	-0.08	0.05	-0.13	0.1	-0.17	-0.01	0.08	0.07	-0.13	0.03	-0.02	-0.07
T7S16	-0.44	0.33	-0.66	0.25	-0.19	-0.33	0.18	0.07	0.03	0.02	0.01	-0.04	-0.11
T8S01	-0.61	0.65	0.36	-0.07	0.04	0.02	-0.07	-0.06	-0.23	-0.01	0.03	-0.03	0.08
T8S02	-0.67	0.66	0.11	0.04	0.01	-0.08	0.01	-0.18	-0.2	0.03	0.12	-0.02	-0.11
T8S05	-0.78	0.29	0.31	0.24	0.2	0.18	-0.03	0.16	-0.16	-0.06	-0.07	-0.02	-0.09
T8S08	-0.52	-0.15	0.14	0.67	0.34	0.17	0.13	0.14	0	0.22	-0.01	-0.05	0.03
T8S09	-0.65	-0.33	-0.07	0.56	0.26	-0.23	-0.09	-0.06	-0.07	0	-0.15	-0.02	0
T8S10	-0.66	-0.3	-0.06	0.58	0.3	-0.1	0.02	-0.11	-0.05	-0.04	-0.08	0.05	0.04
T8S13	-0.59	-0.14	-0.02	0.55	0.06	-0.01	0.02	-0.29	0.1	-0.25	0.22	0.34	0.03
T8S16	-0.66	0.04	0.37	0.36	-0.45	0.12	0.11	-0.12	0.16	-0.12	-0.03	0.05	-0.05
T8S20	-0.84	-0.09	0.27	0.34	-0.28	0.01	-0.07	0	0.07	0.01	0.08	-0.05	-0.01
T8S21	-0.52	-0.04	0.3	0.36	-0.42	0.16	0.07	-0.19	0.35	-0.03	0.19	-0.31	0.08

APPENDIX VI

Live J-mode	factor 1	factor 2	factor 3	factor 4	factor 5	factor 6	factor 7	factor 8	factor 9	factor 10	factor 11	factor 12	factor 13	factor 14	factor 15	factor 16	factor 17	factor 18	factor 19	factor 20	factor 21	factor 22
T1S01	-0.42	0.58	0.26	0.28	0.3	0.1	-0.03	-0.27	-0.14	0.16	-0.04	0.22	0	-0.17	-0.09	0.04	-0.01	0.14	0.03	0.02	-0.08	0
T1S02	-0.56	0.36	-0.11	0.32	0.38	0.39	-0.21	-0.02	0.25	0	-0.08	-0.03	-0.13	-0.04	0	0.03	-0.08	-0.05	-0.02	-0.04	0.01	0
T1S03	-0.78	0.33	0.04	0.33	0.09	0.06	0.24	0.12	0.04	-0.12	-0.02	-0.01	-0.02	0.05	-0.2	-0.11	0.05	-0.09	-0.03	0.03	0	0
T1S06	-0.35	0.32	0.35	0.07	0.37	0.51	0.12	-0.13	-0.36	-0.07	0.19	-0.16	0.08	0.02	0	-0.02	0.04	0	-0.02	0	0.07	0
T1S07	-0.46	0.28	0	-0.24	-0.29	0.3	0.33	0.27	-0.11	-0.02	-0.47	0.1	-0.14	-0.12	0.06	0.12	-0.01	0.02	-0.01	-0.01	0.02	0
T1S09	-0.74	-0.23	-0.22	0.48	0	-0.06	0.11	0.18	-0.17	-0.11	0.01	0.11	0.05	-0.02	-0.01	-0.02	0	-0.03	0.07	-0.02	-0.01	0
T1S14	-0.71	-0.32	-0.38	0.4	0.06	-0.07	0.06	0.15	-0.2	0.07	-0.01	0.01	-0.03	0.01	-0.07	-0.02	-0.03	-0.02	-0.01	0	0.02	0
T1S17	-0.6	0.07	-0.49	-0.07	-0.21	0.12	0.18	-0.46	0.07	-0.2	-0.11	0	0.08	0.06	-0.08	-0.04	-0.03	0.01	0.05	0.03	0.03	0
T1S19	-0.5	0.52	-0.51	-0.2	0.06	-0.13	0.24	0.08	0.03	0.07	0.03	0.09	0.06	0.21	0.03	-0.04	0.12	0.07	0.05	0.07	0.03	0
T2S01	-0.49	0.45	-0.25	-0.21	0.18	-0.33	-0.14	0.14	-0.25	0.07	-0.14	-0.36	-0.15	0	-0.15	-0.03	-0.06	0.05	-0.03	-0.02	0	0
T2S03	-0.44	0.21	-0.5	-0.47	0.06	0.04	-0.09	0.11	-0.12	0.02	-0.01	0.02	0.44	-0.15	-0.06	0.07	-0.09	-0.05	-0.06	-0.01	0.01	0
T2S07	-0.67	-0.06	-0.58	-0.09	-0.06	0.02	-0.01	-0.15	-0.25	0.06	0.19	0.08	-0.2	-0.01	0.02	0	0	-0.06	-0.02	-0.08	-0.05	0
T2S11	-0.79	-0.13	-0.33	0.1	-0.21	0.02	0.25	-0.33	0.01	-0.11	-0.05	0.01	0.01	0.02	-0.03	0	-0.04	0	-0.01	-0.03	0	0
T2S14	-0.48	0.44	-0.22	-0.11	0.12	-0.11	0.44	0.13	0.26	0.22	0.3	0.04	-0.09	-0.15	0.03	-0.05	-0.19	-0.03	0.05	0	0.03	0
T2S16	-0.66	0.59	-0.17	-0.16	0.21	-0.05	0.06	-0.05	0.18	0.01	-0.16	-0.12	0.11	0	-0.06	-0.07	0.04	0.02	0.06	0	-0.05	0
T2S19	-0.65	0.2	0.08	0.21	-0.49	0.24	-0.2	0.12	-0.05	0.32	-0.02	-0.07	0.09	0.1	-0.03	-0.01	0	-0.03	0.06	0.01	-0.01	0
T2S20	-0.47	0.72	0.1	0.1	-0.1	-0.3	0.09	0.07	0.06	-0.27	0.04	0.07	0.04	-0.02	0.03	-0.01	0.05	0	-0.1	-0.13	-0.06	0
T2S21	-0.5	0.49	0.16	0.15	-0.4	-0.03	-0.26	0.16	-0.02	-0.26	0.18	0.15	-0.03	-0.2	-0.09	-0.09	0	0.1	-0.03	0.07	0.06	0
T2S22	-0.56	0.62	0.18	0.21	-0.15	-0.26	-0.15	0.03	-0.15	-0.14	-0.04	-0.04	-0.01	0.04	0.08	0.09	-0.06	-0.03	0.18	0.02	-0.02	0
T2S23	-0.46	0.72	0.19	0.17	0.25	-0.09	0.04	-0.08	-0.06	-0.15	0.02	-0.09	0	0.06	0.16	0.2	0.04	-0.05	-0.03	0	0.03	0
T3S01	-0.64	0.66	0.27	0.08	-0.06	0.02	0.06	-0.05	0.07	0.2	0.08	0	0.01	0.01	0.08	0.06	-0.05	0.01	0.01	0.05	0	0
T3S03	-0.65	0.55	0.11	0.06	-0.34	0.15	0.08	0.07	0.16	0.17	0.12	-0.04	0	0.09	0	0	0.11	0.01	-0.15	-0.04	-0.03	0
T3S05	-0.72	0.34	0.09	0.02	-0.52	0.1	-0.2	-0.11	-0.02	0.08	0	-0.08	0	0.04	-0.02	-0.04	-0.06	-0.06	0.01	-0.04	0	0
T3S07	-0.84	-0.16	-0.42	-0.05	0.11	-0.01	-0.06	0.12	-0.16	0.08	0.06	0.02	-0.08	-0.03	-0.03	-0.01	0.04	0.03	-0.02	0.04	0.02	0
T3S10	-0.85	-0.34	-0.09	0.35	0.03	-0.04	0.09	0.11	-0.05	0.05	-0.01	0.03	0.07	-0.01	0.01	0.03	0.02	-0.02	0	0.02	0	0
T3S11	-0.88	-0.35	-0.07	0.3	0	-0.01	0.06	0.01	-0.04	0.01	0	0	0.04	0	0.01	0	-0.02	-0.02	0.01	0	0	0
T3S13	-0.92	-0.2	-0.08	0.24	-0.06	-0.05	0.07	-0.01	0.02	0.02	-0.06	-0.13	-0.03	0.03	-0.08	-0.01	-0.04	0.06	-0.05	0	0.02	0
T3S15	-0.74	0.23	-0.41	-0.37	-0.02	0	-0.02	-0.05	-0.2	0.06	0.06	0.11	-0.09	0.08	0.11	0.05	0.09	0	0	0.01	0	0
T3S16	-0.92	-0.2	-0.23	0.21	-0.02	0.07	-0.06	0	0.04	-0.07	0	0.02	0.03	-0.01	0	0	0	0	0.02	0.01	0	0
T3S17	-0.85	-0.15	-0.3	0.18	0.16	0.11	-0.12	0.16	0.22	-0.06	-0.06	0.02	0	0.04	0.03	0	0.02	0	0	-0.01	-0.01	0
T3S19	-0.67	0.04	-0.5	-0.13	0.22	0.23	-0.32	0.16	0.2	-0.06	0	0.05	-0.05	0.04	0.06	-0.01	0.03	0	0.01	0	-0.01	0
T3S23	-0.76	0.23	-0.44	-0.2	0	0.08	-0.31	0.02	0.05	-0.14	0.06	0.02	0	-0.02	0.01	-0.01	-0.02	0.02	0.03	0.01	0	0
T6S02	-0.91	-0.16	0.25	0.08	0.15	-0.01	-0.02	-0.05	-0.04	0.1	-0.01	0.12	0.07	-0.02	0.02	-0.06	0	0.11	-0.02	0	-0.09	0
T6S06	-0.59	0.27	0.32	-0.05	0.21	-0.26	-0.2	-0.21	-0.04	0.19	-0.29	0.3	0	0.07	0	-0.2	0	-0.13	-0.05	-0.01	0.07	0
T6S08	-0.95	-0.16	0.16	0.07	0.1	-0.11	-0.03	0.02	0.05	0.01	-0.03	-0.08	0	0.04	0.05	0.05	0.02	0.02	0	0.01	0.02	0
T6S10	-0.94	-0.21	0.18	0.04	0.07	-0.07	-0.01	0.05	0.03	-0.01	-0.01	-0.03	0.04	0.06	0.09	-0.03	0.01	0	0.06	-0.03	-0.01	0
T6S12	-0.96	-0.21	0.04	-0.01	-0.01	-0.01	-0.05	-0.11	0.08	-0.04	-0.06	-0.09	-0.04	-0.02	0.02	0	-0.03	0.02	0	0.01	0	0
T6S14	-0.96	-0.22	-0.05	-0.04	-0.03	-0.01	-0.02	-0.05	0.02	0.01	0.02	0.01	0	-0.01	0.04	0.03	0.02	0.01	-0.02	0.03	0.01	0
T6S16	-0.96	-0.25	0.02	0.01	-0.02	-0.04	-0.01	-0.05	0.04	0.01	0.01	-0.03	-0.02	-0.02	0.04	0.02	0	0.01	-0.03	0.01	0	0
T7S02	-0.92	-0.2	0.17	0	0.05	-0.17	0	0.04	0.03	0.05	0	-0.07	0.16	-0.1	0.05	0.05	0	-0.07	-0.02	-0.04	-0.03	0
T7S06	-0.95	-0.14	0.09	-0.03	0.05	-0.13	-0.02	-0.03	0.09	0.01	-0.06	-0.13	-0.01	0.02	-0.02	-0.01	-0.02	0.11	-0.05	0.05	0.03	0
T7S10	-0.95	-0.24	0.11	-0.04	-0.08	-0.03	0	-0.06	0.02	0.02	-0.02	-0.01	0.03	-0.03	0.04	0.05	0	0.03	-0.02	0.05	0.02	0
T7S16	-0.94	-0.29	0.01	0.02	0.01	-0.08	0	0	0	0.05	0.06	0.02	0.02	-0.02	0.05	0.02	0.04	0	-0.02	0.03	0	0
T8S01	-0.88	-0.21	-0.04	-0.15	-0.1	-0.03	-0.02	-0.33	-0.01	-0.03	0.08	-0.04	-0.1	-0.04	0.04	0.02	-0.03	-0.01	-0.03	-0.02	-0.01	0
T8S02	-0.94	-0.26	0.11	-0.01	-0.06	-0.06	0	-0.09	0.03	0.02	0.02	-0.02	0.01	-0.02	0.05	0.04	0	0	-0.03	0.01	0	0
T8S05	-0.81	-0.09	0.21	-0.23	-0.01	-0.01	0.05	-0.07	0.07	0.03	0	-0.16	-0.07	-0.32	-0.05	-0.08	0.23	-0.11	0.1	0.01	-0.01	0
T8S08	-0.85	-0.21	0.32	-0.24	0.02	0.11	0.09	0.13	-0.07	-0.08	-0.05	0.04	-0.01	0.02	0.07	-0.03	-0.06	0.04	0	-0.02	0	0
T8S09	-0.91	-0.21	0.28	-0.14	-0.04	0.05	0.03	0.09	0	0.02	-0.02	0	0	-0.05	0.05	0	0.02	0.03	0.01	-0.02	0.03	0
T8S10	-0.8	-0.17	0.36	-0.24	0.06	0.12	0.03	0.07	-0.07	-0.08	0.12	-0.03	0.05	0.11	0.03	-0.22	-0.04	0.05	0.06	-0.09	-0.02	0
T8S13	-0.8	-0.14	0.38	-0.34	0.02	0.14	0.08	0.13	-0.07	-0.09	-0.02	0.01	-0.04	0.03	0	-0.06	-0.05	0.01	0.02	-0.02	-0.03	0
T8S16	-0.76	-0.16	0.36	-0.32	0.03	0.04	0.03	0.08	0.03	-0.08	0.05	0.07	-0.05	0.14	-0.21	0.12	-0.05	-0.11	-0.03	0.14	-0.15	0
T8S20	-0.84	0.01	0.41	-0.24	0.05	-0.05	-0.05	0.02	0	-0.08	0.06	0.09	-0.04	0.03	0	-0.03	-0.06	-0.09	-0.01	0.06	0.11	0
T8S21	-0.77	-0.19	0.3	-0.17	0.06	-0.05	-0.05	0	0.11	0.04	0.09	0.14	-0.01	0.08	-0.3	0.25	0.06	0.05	0.08	-0.15	0.1	0

APPENDIX VI

Dead R-mode	factor 1	factor 2	factor 3	factor 4	factor 5	factor 6	factor 7	factor 8	factor 9	factor 10	factor 11	factor 12	factor 13
A. beccarii	-1.2	-0.26	-0.11	0.19	-0.22	0.05	-0.31	0.06	0.03	0.19	0.06	0.04	0
B. gibba	-0.4	-0.16	0.11	0.47	0.36	0.11	0.17	0.1	-0.04	0.11	0	0	0.01
B. marginata	-0.44	0.56	-0.43	0.04	-0.04	-0.18	0.09	0.25	0.26	-0.02	-0.05	0.03	0.12
Bolivina spp.	-0.78	0.54	0.27	0	-0.22	-0.09	0.05	0.03	-0.41	0	0.09	-0.01	0.19
C. lobatulus	-1.12	-0.46	0.14	-0.36	0.02	-0.11	0.15	0.1	0.02	-0.01	0.09	0	-0.03
E. excavatum	-0.32	-0.06	0.25	0.43	-0.27	0.13	0.1	-0.21	0.32	-0.08	0.22	-0.28	0.09
E. megallanicum	-0.62	-0.03	0.51	0.2	-0.67	0.12	0.24	0	0.06	0.01	-0.23	0.08	-0.06
E. scabrus	-0.42	0.03	-0.11	0.49	0	-0.11	0.11	-0.33	0.08	-0.3	0.28	0.39	-0.01
G. praergeri	-0.8	0.53	0.2	-0.01	0.12	0.1	-0.08	0.05	0.02	-0.09	0	-0.01	-0.06
H. balthica	-0.55	0.63	-0.99	0.17	-0.3	-0.03	0.29	-0.07	-0.21	0.15	0.11	-0.09	-0.24
Q. seminulum	-1.66	-0.43	-0.13	0.44	0.13	-0.58	-0.14	-0.18	-0.09	-0.19	-0.22	-0.11	-0.02
S. fusiformis	-0.67	0.49	0.19	-0.26	0.19	-0.13	0.05	-0.31	0.12	0.26	-0.04	0.03	0.03
Textularia sp.	-1.27	-0.26	-0.46	-0.23	0.07	0.4	0.04	-0.14	-0.03	-0.1	-0.09	0	0.08

Live R-mode	factor 1	factor 2	factor 3	factor 4	factor 5	factor 6	factor 7	factor 8	factor 9	factor 10	factor 11	factor 12	factor 13	factor 14	factor 15	factor 16	factor 17	factor 18	factor 19	factor 20	factor 21	factor 22
A.glomeratum	-0.46	0.28	-0.61	-0.32	0.03	0.09	0.05	-0.08	0.08	-0.12	-0.16	0.06	0.35	0.06	-0.07	-0.03	0.05	0.05	0.07	0.12	0.06	0.00
B. gibba	-0.46	-0.02	0.42	-0.21	0.19	0.40	0.19	0.16	-0.31	-0.21	0.09	-0.03	0.04	0.18	-0.01	-0.30	-0.09	0.02	0.09	-0.11	-0.01	0.00
B. marginata	-0.49	0.20	-0.71	-0.26	0.15	0.00	-0.12	0.18	-0.18	0.11	0.15	0.09	-0.07	0.00	0.02	0.00	0.03	0.00	-0.01	0.00	0.00	0.00
Trochammina sp.	-0.26	0.52	-0.02	0.04	0.19	-0.04	0.33	0.04	0.29	0.27	0.30	0.09	-0.12	-0.17	0.06	-0.01	-0.38	0.00	0.21	0.12	0.08	0.00
C. lobatulus	-0.35	0.62	0.24	0.32	0.31	0.36	0.04	-0.16	-0.18	0.02	0.11	-0.07	0.04	-0.02	0.00	0.12	0.02	0.00	-0.06	0.04	0.03	0.00
C. auricula	-0.47	0.50	0.03	0.13	-0.61	0.24	-0.17	0.12	0.00	0.19	-0.01	-0.04	0.02	0.03	-0.03	-0.02	0.00	0.00	0.02	0.00	0.00	0.00
E. excavatum	-0.32	-0.04	0.34	-0.25	0.08	0.07	0.09	0.15	0.04	-0.17	0.12	0.17	-0.11	0.30	-0.55	0.23	-0.07	-0.26	0.00	0.17	-0.20	0.00
E. gerthi	-0.23	-0.02	0.22	-0.07	0.14	-0.01	-0.08	-0.06	0.12	0.10	0.05	0.26	-0.05	0.09	-0.52	0.43	0.09	0.15	0.20	-0.39	0.27	0.00
E. megallanicum	-0.28	0.39	0.24	0.19	0.32	0.00	-0.16	-0.31	-0.04	0.28	-0.24	0.44	0.02	-0.14	-0.14	-0.16	-0.04	0.15	-0.02	-0.02	-0.15	0.00
E. scabrus	-0.36	0.02	0.06	-0.39	-0.17	0.31	0.32	0.28	-0.19	-0.12	-0.48	0.17	-0.15	-0.15	0.09	0.18	-0.07	0.00	-0.03	0.00	0.02	0.00
E. naerensis	-0.48	0.20	-0.27	-0.02	0.16	-0.26	0.00	0.16	-0.13	0.05	-0.22	-0.48	-0.20	0.01	-0.33	-0.11	-0.12	0.20	-0.12	0.07	0.06	0.00
H. fragile	-0.30	0.43	-0.23	-0.27	0.10	-0.22	-0.04	0.15	-0.02	0.01	0.01	-0.19	0.51	-0.25	-0.05	0.12	-0.25	-0.14	-0.13	-0.18	-0.07	0.00
L. haliotidea	-0.28	0.30	0.25	0.07	0.05	-0.15	-0.22	-0.12	0.00	0.09	-0.22	0.39	-0.06	0.08	-0.10	-0.38	-0.05	-0.38	-0.23	0.00	0.31	0.00
N. auricula	-0.44	0.17	-0.34	0.12	0.33	0.34	-0.39	0.08	0.44	-0.19	-0.13	-0.06	-0.11	0.00	0.03	-0.01	-0.03	-0.01	0.00	-0.03	-0.02	0.00
N. turgida	-0.61	-0.02	-0.49	-0.12	-0.25	0.05	0.04	-0.51	-0.08	-0.11	0.00	-0.04	-0.10	-0.01	-0.01	0.00	-0.06	-0.02	0.00	-0.03	-0.01	0.00
Q. seminulum	-0.46	0.34	0.08	-0.12	0.19	0.07	0.21	0.03	0.00	0.04	-0.10	-0.25	-0.09	-0.52	-0.19	-0.17	0.27	-0.19	0.18	0.00	-0.02	0.00
Reophax spp.	-0.97	-0.06	0.18	-0.14	0.00	-0.02	-0.02	-0.01	0.03	0.01	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G. praergeri	-0.49	0.74	0.10	0.09	0.11	-0.30	-0.06	-0.02	-0.11	-0.01	-0.17	-0.05	-0.02	0.13	0.09	0.04	0.00	-0.04	0.07	-0.01	-0.01	0.00
R. williamsoni	-0.32	0.57	0.13	0.26	-0.26	-0.21	-0.20	0.14	-0.09	-0.46	0.18	0.16	-0.02	-0.18	-0.04	-0.02	-0.01	0.06	0.00	0.02	0.01	0.00
S. fusiformis	-0.86	-0.31	-0.19	0.34	0.00	-0.01	0.06	0.05	-0.03	0.00	-0.03	0.01	0.02	0.00	0.00	0.00	0.00	-0.01	0.01	0.00	0.00	0.00
Textularia spp.	-0.98	-0.07	0.16	-0.11	0.00	-0.02	-0.02	-0.01	0.02	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T. globigeriniformis	-0.45	0.67	-0.18	0.05	-0.06	-0.06	0.46	0.04	0.25	-0.02	0.06	0.04	-0.03	0.06	0.00	-0.04	0.06	0.02	-0.07	-0.05	-0.02	0.00