The depth distribution of Ostracoda from the Greenland Sea

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ABSTRACT – Sixteen box core samples of Recent sediment collected in three transects across the East Greenland shelf and slope were analysed for Ostracoda. The samples which range in depth from 274 m to 3355 m, yielded a total of 52 species belonging to 25 genera. No less than 26 of the species also occur in the adjacent Scoresby Sund fjord complex. The fauna represents an interesting mixture of high latitude shallow water Arctic species and others known from bathyal and abyssal depths in the North Atlantic, including some pandemic deep sea species. Many species occur in shallower water here than in the North Atlantic due to the colder water. The fauna comprised of three associations (Shelf/Upper Slope; Slope: Lower Slope/Abyss). A marked faunal turnover occurs at the Upper Slope. The study raises questions concerning the constancy and universality of the relationship between certain ostracod species and water masses. *J. Micropalaeontol.* **17**(1): 15–32, April 1998.

INTRODUCTION

The principal aims of this study are to investigate the bathymetrical distribution of benthonic Ostracoda in three transects from the outer shelf to the abyss and spanning depths from 265 m to 3555 m off the East Coast of Greenland. Other samples, from the Scoresby Sund Fjord system, ranging in depth from 270 m to 1280 m are considered elsewhere (Whatley *et al.*, in press).

The samples were collected during September 1990 by the German research vessel R.V. Polarstern on cruise ARK VII3b, as part of the PONAM research project. This project (Late Cainozoic evolution of the **PO**lar **N**orth **A**tlantic **M**argins) seeks to investigate the mechanisms involved in glacial/interglacial exchange with the aim of increasing our understanding of long term climatic change, land/shelf/ocean sediment budgets and ice/ocean mass balance.

Figure 1 shows the general area of the Greenland Sea and the east coast of Greenland, and gives the present day maximum extent of ice cover. Figure 2 gives the position of the sampling stations and also the bathymetry below 500 m offshore.

METHODS

The samples were collected between 31st August and 27th September 1990, by a 0.5×0.5×0.5 m box-corer, recovering an average of 30–40 cm of undisturbed sediment from the surface of the sea bed (Solheim *et al.*, 1991). From each box core, 60 cm^3 of sediment was taken, preserved in buffered formalin and, in the laboratory, washed over a 200 mesh/inch (75 μ) sieve. The dry residue was passed through a nest of sieves, and the 30, 60 and 100 mesh/inch (500, 250, 150 μ) fractions were examined and all the Ostracoda picked out. Location, depth and ecological data for each sample, are given in the Appendix.

OCEANOGRAPHY

The Greenland and Norwegian seas are characterized by a complex exchange and mixing of Polar and Subtropical water masses and by the formation of deep, dense water. The region is controlled by submarine ridges, bounded to the North by the Nansen Ridge and to the South by the relatively shallow (600–800 m) Greenland–Iceland Ridge and Iceland–Shetland Ridge and these ridges are important constraints upon circulation.

Among the important oceanographical studies of the region are those by Aagaard (1968, 1981, 1982); Aagaard & Coachman (1969); Worthington (1970); Peterson & Rooth (1976); Aagaard *et al.* (1981); Aagaard *et al.* (1985) and Bourke *et al.* (1987).

A reduced flow of water passes through the Northern Gateway of the Fram Strait, the Southern Gateway of the Denmark Strait and the region between Iceland and Norway. The exiting water which cascades over the Southern Gateway forms a very large proportion of the North Atlantic Deep Water (NADW). Dingle & Lord (1990) demonstrated the importance of this water mass to the distribution of benthonic Ostracoda in the Atlantic.

The Greenland Basin has depths greater than 4000 m. The Continental Shelf off East Greenland is deep with the slope break occurring at some 500 m; it is widest to the North and decreases in width towards the South.

The Arctic seas are regarded as mediterranean type basins because of their enclosed nature and from the input of light surface waters which balances the southward outflow of deep, dense water. This results in the density of the water of the Greenland Sea being among the densest in the world. Worthington (1970) attributes the high density of the water as being due to its low temperature which is brought about by high latitude and heat loss to the atmosphere. The salinity is generally low, being between 34‰ and 35‰.

There has been much confusion and imperfect understanding of the physical mechanisms at work in the Greenland–Norwegian Sea, which mainly stems from the problem of renewal rates of deep waters and where convective mixing and the amount of 'new' water being added to the deeper layers cannot be easily determined (Peterson & Rooth, 1976). Aagaard (1982) compared the major process of the Greenland/Norwegian Sea to a 'giant snorkel', which draws down the upper layers of water into the abyss and through into the Arctic, forming the deep polar waters.

Details of the circulation and water mass budgets are given by Aagaard *et al.* (1985) who also discuss the water mass structure of the Arctic seas. They divided the water column into four water masses, largely on the basis of increased density with depth, and show that the boundaries between the various water masses occur at different depths throughout the Arctic basins as
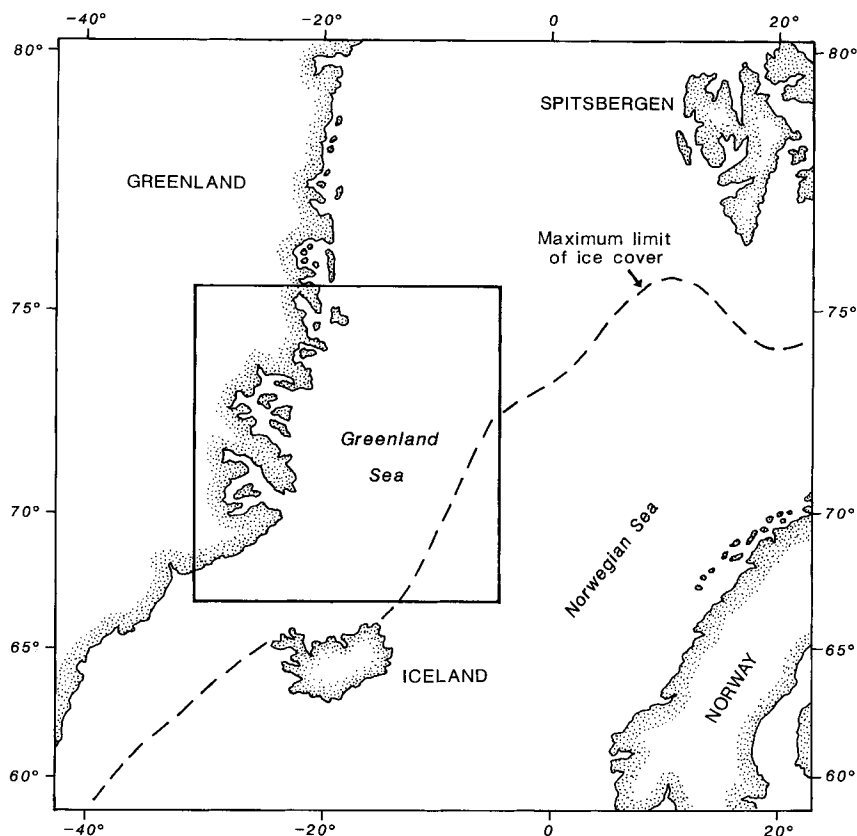
Fig. 1. The study area showing the maximum winter ice cover in the Greenland and Norwegian seas.

a consequence of them being greatly influenced by submarine topographic features:

(1) The North Atlantic Drift (NAD) (surface waters). The surface waters of the Greenland Sea lie above the density level of 27.9. These waters are warmest in the Norwegian Sea (> 1°C) and relatively highly saline (34.5‰). They originate in the Atlantic as part of the NAD and, while much thicker in the Norwegian Sea (< 200m) and Iceland Sea (< 150 m), here the surface water is usually only some 50 m thick and characterized by relatively high salinity (> 35‰) and temperature (> 1°C).

(2) Arctic Intermediate Water (AIW). This originates from the Iceland and Greenland gyres, occurs close to the surface, is well oxygenated and cold. In the Iceland and Norwegian seas, this is the primary water body to flow over the Faeroes Bank; in the latter sea, these intermediate waters are contaminated by deeper waters by upwelling. Peterson and Rooth (1976) interpreted the hydrogen isotope data, indicating that these waters have a short residence time in the Greenland Norwegian Sea Area (GNSA). They concluded that the overflow from the Norwegian Sea into the Atlantic (forming the NADW), through the Southern Gateways originates above the permanent pycnocline and, therefore, these dense overflow waters which cascade over the Greenland–Scotland Ridge are separate from the Norwegian and Greenland sea Deep Waters.

(3) The Greenland Sea Deep Water (GSDW). The NAD enters through the Southern Gateway but in the Norwegian Sea,

the surface waters are too warm to sink, although the salinities are great enough to allow this. It is not until it reaches the Greenland Sea that the cooling of the surface waters by the atmosphere and ice cover, reduces its temperature enough to allow it to sink into the basins. Peterson & Rooth (1976) estimated from the hydrogen isotope decay rate that some 30 years was required for the deep convective mixing of the NAD water in the Greenland Sea. Since some of the basins are 3000 m in depth, this suggests that some 100 m of the surface waters is mixed down annually.

Aagaard *et al.* (1985) divided the water column of the region by the increase in density, in this very dense water. In the Greenland Sea, the boundary between intermediate and deep water, the 32.785 density level, occurs at *c.* 200 m , while in the Iceland Sea it occurs at *c.* 650 m. The GSDW extends down to some 900 m where, below the 37.445 density level, true Arctic deep water occurs. The GSDW is characterized by temperatures of < 1°C and salinities of 34.88 to 34.90‰, with the Norwegian Sea Deep Water (NSDW) being slightly warmer and more saline. The Eurasian Basin Deep Water (EBDW) of the Arctic Ocean is even warmer and saltier, and, with the Lomonosov Ridge restricting the mixing of the EBDW and the Canadian Basin Deep Water (CBDW), this results in the latter water mass being the most saline and the warmest of the Arctic deep waters (Aargaard *et al.*, 1985).

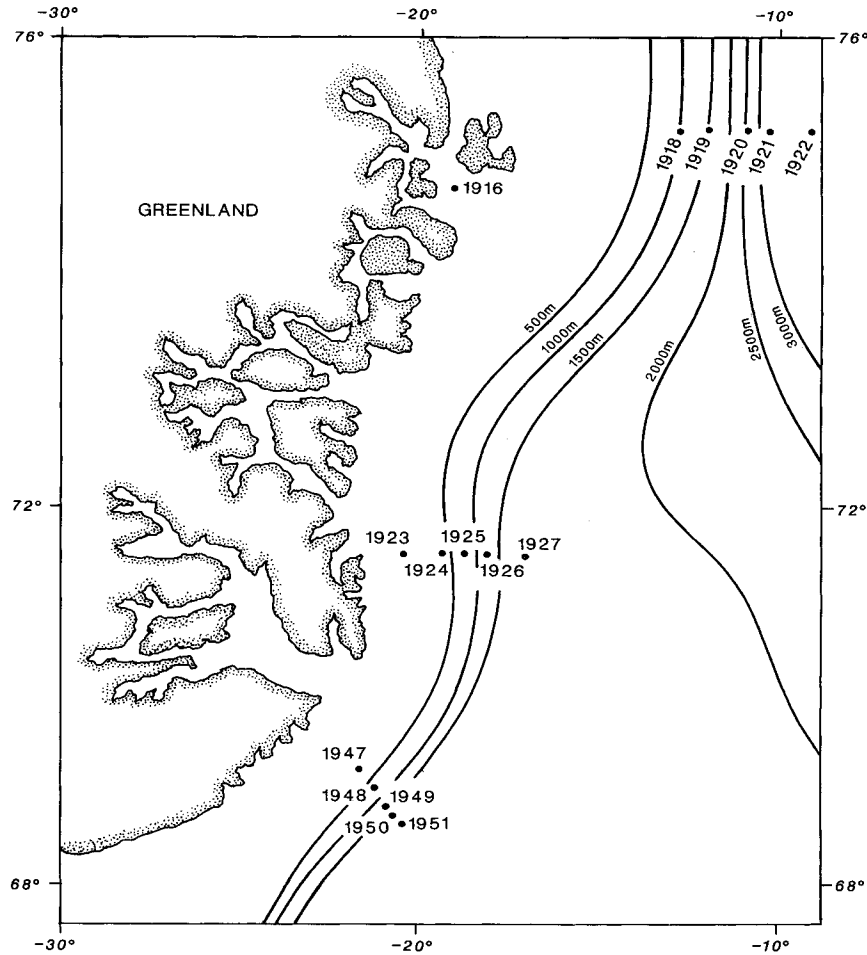(4) The Eurasian Basin Deep Water (EBDW). The input of

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Fig. 2. The location of the sampling stations and the bathymetry of the Greenland Sea.

this water into the Greenland Sea was discovered by Aargaard *et al.* (1985) when they recorded the salinities of the water column in a transect away from the coast of East Greenland This is water from the floor of the Arctic Ocean which spills over the Fram Straits into the Greenland Sea. It has a temperature of 0.95°C and a salinity of 34.93‰, and is characteristically high in silica.

The dissolved oxygen content of the Norwegian and Greenland seas is very high throughout the water column and is among the most highly oxygenated water in the world with values in the Greenland Sea between 7.82 ml l^{-1} and 7.19 l l^{-1}. These high levels are the result of low productivity, relatively low nutrients and the sinking of the NAD in the Greenland Sea. The oxygen minimum zone occurs here between 800 m and 1200 m, with oxygen levels of 7.2 ml l^{-1}; oxygen levels of 7.4 ml l^{-1} obtain below 2000 m.
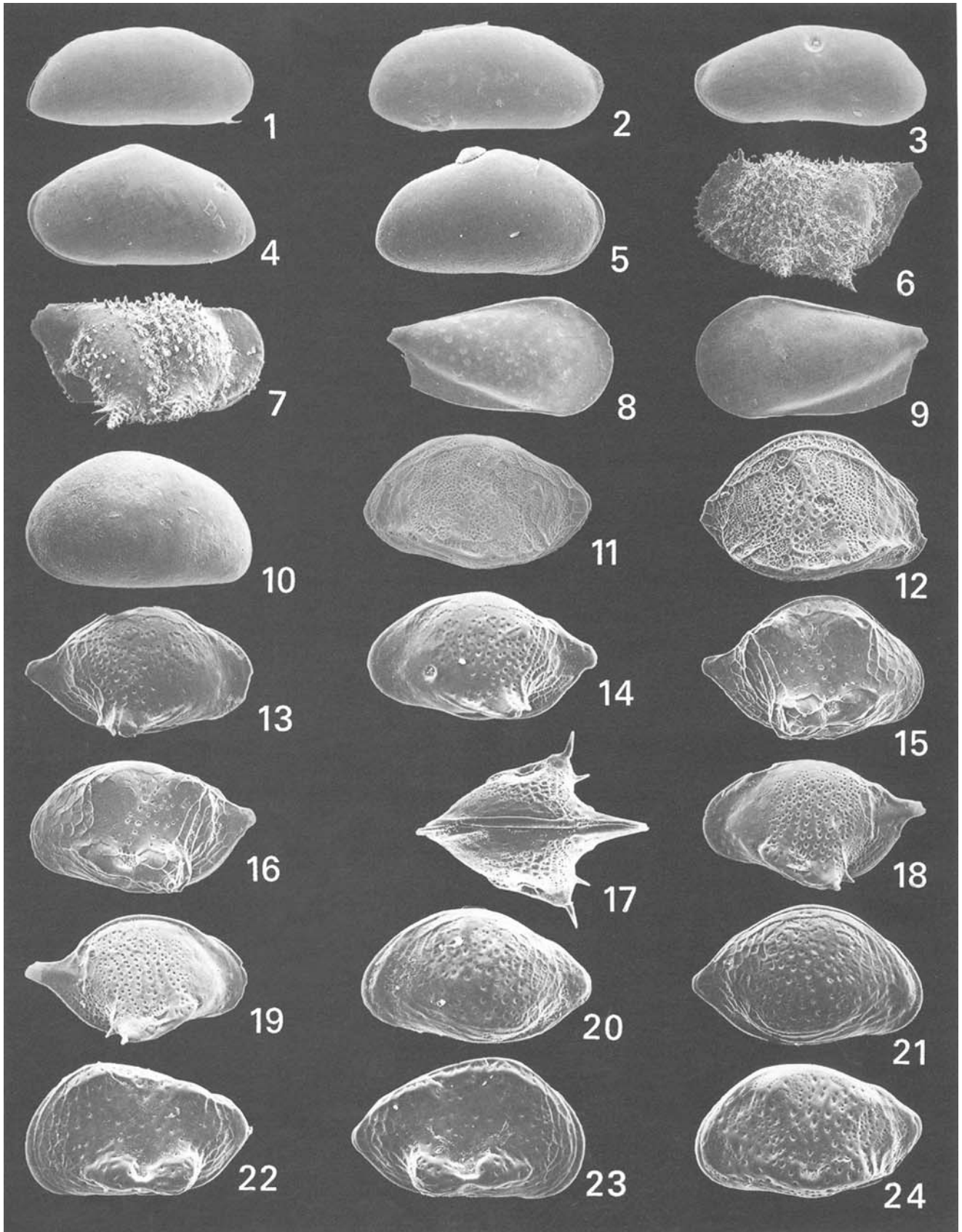
Useful diagrams, showing the water mass structure of the Greenland Sea and the physico-chemistry of its components, are to be found in Aagaard (1981), Aagaard *et al.* (1985) and Belanger & Streeter (1980). Some additional details can be found in Eynon (unpublished MSc Thesis, University of Wales, Aberystwyth).

Nutrients

The Greenland Sea is one of rather low productivity because of the low temperature and ice cover which restrict solar energy input into the system. Nutrient levels, through the water column, are generally characterized by low concentrations in the surface layers (consumed by plants) and higher values at lower depths (concentration due to the death and decay of organisms). In the Greenland Sea, nutrients are fairly constant throughout the water column. Belanger & Streeter (1980), show that, through the column, phosphates are constant, with a slight peak below the Oxygen Minimum Zone (at 1200 m), silicates tend to increase to *c.* 1000 m before becoming relatively constant and nitrates have their maximum between 500 m and 1500 m, before decreasing gradually with greater depth.

Recent Sediments

Sands, clays and muds prevail on the shelf being increasingly contaminated by ice rafted pebbles and boulders towards the coast (Vogt *et al.*, 1981). In some areas substantial gouging by icebergs has taken place.

THE OSTRACODA

Previous studies on benthonic Ostracoda from Greenland and the Arctic

Early taxonomic studies were by Brady (1866) on the fauna from West Greenland and by the same author from the Davis Straits (1868) and the Gulf of St Lawrence (1870). Norman (1877) listed the ostracods collected by H.M.S. *Valorous* from West Greenland in 1875 and Brady (1878) recorded the ostracods to the North of Baffin Bay from samples collected by H.M. Ships *Alert* and *Discovery*. Brady & Norman (1889) documented the podocopid ostracods collected off Northwest Greenland and in the Davis Strait, and combined their recordings with previously published notes on the fauna of the region.

All existing published works on the Ostracoda of East Greenland are based on samples collected from depths of less than 250 m. Sars (1909) recorded the total Crustacea collected by the 2nd Norwegian Arctic Expedition (1898–1902) in the Fram Strait. Stephensen (1913) and Skogsberg (1920) recorded the shallow marine ostracods from between 68°N and 76°N off the East Greenland coast and, in 1939 Stephensen listed the ostracods encountered in Icelandic waters.

Hazel (1967, 1970) studied the ostracods between Cape Stosch, (Latitude 74°04'N; Longitude 21°45'W) from a depth of 7 fm and Clavering Island (Latitude 74°15'N; Longitude 21°00'W) at 50 fm as part of his study of the distribution of ostracods along the North American seaboard. Neale and Howe (1975) recorded the ostracods from Russian Harbour, Novaya Zemlya and also from Shannon Island (Latitude 75°20'N; Longitude 19°00'E) at 11 fm and the H.M.S. *Vidal Station* 46 (Latitude 75°11,2'N; Longitude 22°14'E) at 7 fm.

More recently, Hawley (1980, unpublished MSc Thesis, Aberystwyth) studied the shallow water fauna of Lysefjord in Southwest Greenland, Whatley (1982) listed the littoral and immediate sublittoral ostracods from Sisimiut in Western Greenland, and Penney (1989) reported on the fauna from Ikerssuak, Southwest Greenland. Whatley & Eynon (1996) describe three new species of *Cytheropteron* and one of *Eucytherura* from East Greenland and Whatley et al. (1996) discuss the fauna from the Scoresby Sund Fjord complex, East Greenland. Hartmann (1992, 1993, 1994) has described the Recent and subfossil Ostracoda of the Liefdejords in Spitzbergen.

A number of previous studies on late Cainozoic cold water Ostracoda from Europe, North America and Greenland are relevant to this study. In Europe, Brady et al. (1874) described many species from the British Quaternary which now live in the Arctic. Lord (1980) described an important fauna from the Sandness Clay of Norway and Penney (1990) from the North Sea.

In North America, Benson et al. (1983) demonstrated the distribution and biofacies of Ostracoda from the Newfoundland slope and rise, and Cronin (1979, 1980) described the Pleistocene ostracod faunas from the southeastern Atlantic Coastal Plain and the St Lawrence Lowlands, respectively, and in the Greenland Sea area, Malz (pers. comm.) described the very poor fauna recovered from the Cainozoic of ODP Leg 104 on the Voting Platform off Norway, and Whatley (pers. obs.) recovered very few ostracods from the late Cainozoic of ODP Leg 151 in the region of the Fram Strait. Brouwers et al. (1991) documented the fauna of the Pliocene Kab Kobenhavn Formation, northern Greenland. Cronin (1991) described an essentially warm water Pliocene fauna from Tjornes, Iceland, and Cronin et al. (1994) discussed Quaternary palaeoceanography based on the Ostracoda of the deep Arctic Ocean.

Modern studies on the deep water faunas of the North Atlantic include those by Whatley (1993), Whatley and Coles (1987, 1990), Coles (1990) and Coles et al. (1990).

The Greenland Sea fauna

The species encountered in the present study are listed below. Those marked with an asterisk also occur in the adjacent Scoresby Sund Fjord complex (Whatley et al., 1996). All the species are illustrated in Plates 1–3, and the catalogue numbers refer to the Eynon Collection in the Micropalaeontology Museum at Aberystwyth, where the specimens are housed.

Acetabulastoma hyperborea Schornikov, 1970
*Argilloecia conoidea Sars, 1923
*Argilloecia cylindrica Sars, 1923
Baffinicythere howei Hazel, 1967
Bythocythere scaberrima (Brady, 1886).
*Cluthia cluthae Brady, Crosskey & Robertson, 1874
*Cytherois pusilla Sars, 1928
*Cytheropteron arcticum Neale & Howe, 1973
*Cytheropteron carolinae Whatley & Coles, 1987
*Cytheropteron groenlandicum Whatley & Eynon, 1996
*Cytheropteron hamatum Sars, 1869
*Cytheropteron inflatum Brady, Crosskey & Robertson, 1874
*Cytheropteron neali Cronin, 1981
*Cytheropteron nodosum Brady, 1868
*Cytheropteron porterae Whatley & Coles 1987
*Cytheropteron pseudoinflatum Whatley & Eynon, 1996
*Cytheropteron pyramidale Brady, 1868
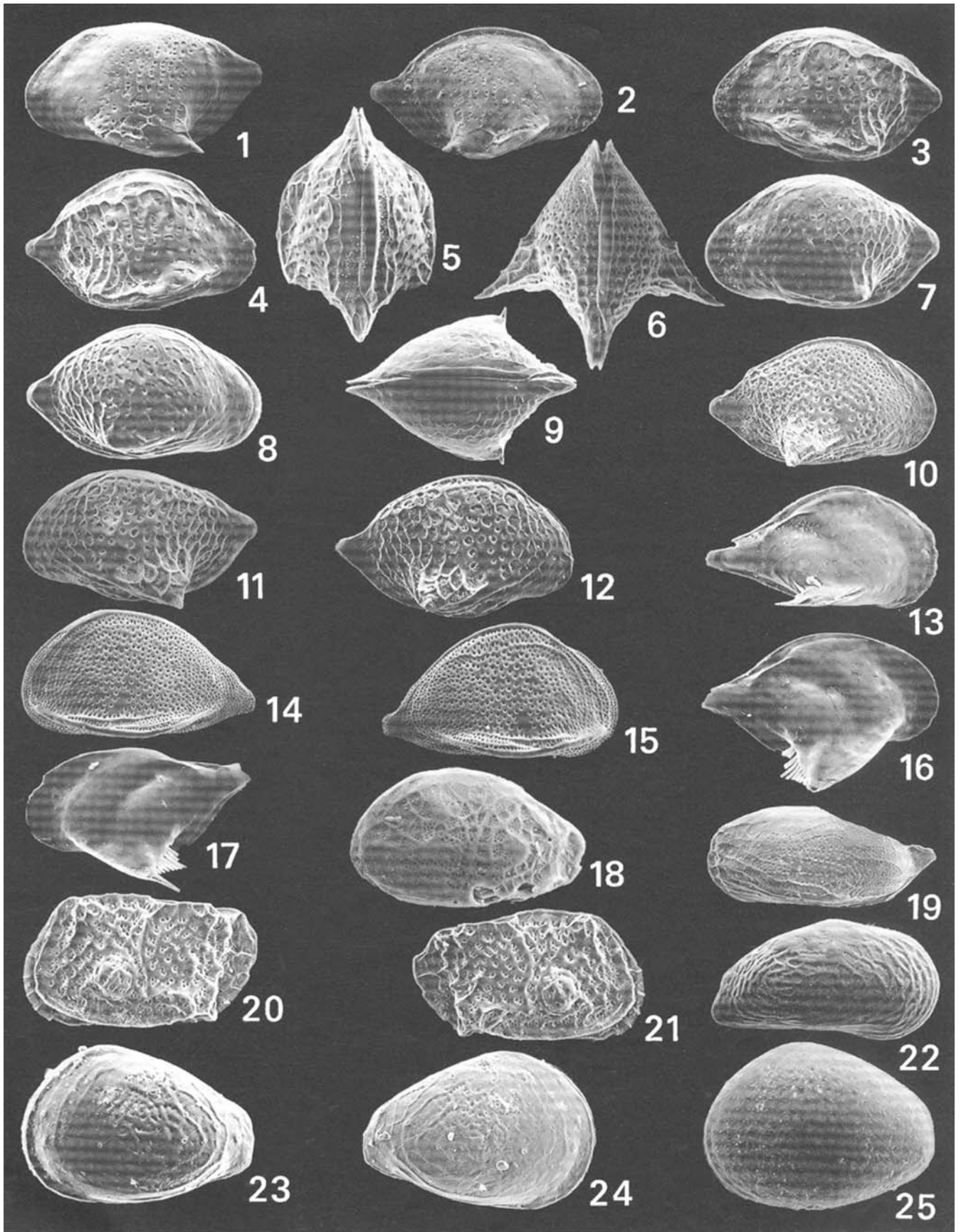**Cytheropteron sedovi* Schneider, 1969
*Cytheropteron scoresbyi Whatley & Eynon, 1996
Cytheropteron syntomoalatum Whatley & Masson, 1979
*Cytheropteron testudo Sars, 1869

Explanation of Plate 1

All external lateral views unless otherwise stated. **fig. 1.** *Argilloecia conoidea* Sars, 1923. Female RV, ME/1/P3, ×62.5. **figs 2, 3.** *Argilloecia cylindrica* Sars, 1923; fig. 2. RV, ME/2/T, ×76; fig. 3, LV, ME/2 /P1, ×76. **figs 4, 5.** *Propontocypris trigonella* (Sars, 1866); fig. 4, LV, ME/4/T, ×93; fig. 5, RV, ME/4/P1, ×95. **figs 6, 7.** *Bythoceratina scaberrima* (Brady, 1886); fig. 6, LV, ME/6/T, ×42; fig. 7, RV, ME/6/P1, ×54.5. **figs 8, 9.** *Pseudocythere caudata* Sars, 1866; fig. 8, RV, ME/7/P1, ×55.5; fig. 9, LV, ME/7/T, ×53. **fig. 10.** *Haplocytheridea bradyi* (Norman, 1865); LV, ME/8/T, ×58. **figs 11, 12.** *Cytheropteron arcticum* Neale & Howe, 1973; fig. 11, LV, ME/21/T, ×85; fig. 12, RV, ME/21/P1, ×74. **figs 13, 14.** *Cytheropteron carolinae*, Whatley & Coles, 1987; fig. 13, RV, ME/22/T, ×85; fig. 14, LV, ME/22/P1, ×85.5. **figs 15, 16.** *Cytheropteron groenlandicum* Whatley & Eynon, 1996; fig. 15, holotype RV, BMNH 1992.603, ×72; fig. 16, paratype LV, BMNH 1992.604/1, ×72. **figs 17–19.** *Cytheropteron hamatum* Sars, 1869; fig. 17, carapace dorsal view, ME/24/P2, ×105; fig. 18, LV, ME/24/T, ×75.5; fig. 19, RV, ME/24/P1, ×70. **figs 20, 21.** *Cytheropteron inflatum* Brady, Crosskey & Robertson, 1874; fig. 20, LV, ME/25/T, ×91; fig. 21, RV, ME/25/P1, ×76. **figs 22, 23.** *Cytheropteron neali* Cronin, 1981; fig. 22, LV (Juv.), ME/27/T, ×85.5; fig. 23, RV (Juv.), ME/27/P1, ×97.5. **fig. 24.** *Cytheropteron nodosum* Brady, 1868; LV (Juv.), ME/28/T, ×97.5.

Cytheropteron vespertilio (Reuss, 1850).
Eucythere argus Sars, 1866
Eucythere sp. A
Eucythere sp. B
Eucytherura delineata Whatley & Eynon, 1996
Finmarchinella barentzovensis Mandelstam, 1957
Hemicytherura clathrata (Sars, 1866).
Henryhowella dasyderma (Brady, 1880).
Krithe glacialis Brady, Crosskey & Robertson, 1874
Krithe minima Coles, Whatley & Moguilevsky, 1994
Krithe sp. A
Krithe sp. B
Krithe sp. C
Krithe sp. D
Krithe sp E
Krithe sp. F
Microcythere sp.
Muellerina abyssicola (Sars, 1865).
Nannocythere sp.
Swainocythere nanseni (Joy & Clark, 1977).
Paracytherois flexuosum Müller, 1894
Paradoxostoma productum Brady & Norman, 1889
Polycope areolata Sars, 1923
Polycope clathrata Joy & Clark, 1977
Polycope orbicularis Sars, 1866
Propontocypris sp.
Pseudocythere caudata Sars, 1866
Rabilimis mirabilis (Brady, 1868).
Haplocytheridea bradii (Norman, 1865)
Semicytherura affinis (Sars, 1865)
Thaerocythere crenulata (Sars, 1865)

This fauna represents an interesting mixture of high latitude shallow water Arctic species and those known from bathyal and abyssal depths in the North Atlantic, which include some species which are virtually world wide (the major exception being the Arctic Ocean) at these depths. Since it is temperature, a secondary function of depth which, except in most unusual circumstances, is the primary controlling feature on the bathymetrical distribution of all marine benthos, at such high latitudes with such low temperatures, it is not surprising to encounter some considerable difference in the depth distribution of ostracod species between the Greenland Sea and further south in the North Atlantic, although this has not been previously documented.

For example, six species whose depth range extends below

1000 m and which are common to the North Atlantic (data from the compilation of Dingle Lord, 1990) and the area of the present study in the Greenland Sea, are seen to occur in shallower water in the latter area. Two of the species (*Cytheropteron porterae* and *C. testudo* actually occur within the adjacent Scoresby Sund Fjord system on the East coast of Greenland at depths between 277 and 1262 m (Whatley *et al.*, 1996). The implications for the recognition of palaeo-watermass using ostracods is obvious. The comparative depth distribution (in m) of the six species in the two areas is given in Table 1.

Table 1. Differential depth distribution of six ostracod species in their dual occurrences in the Greenland Sea and the North Atlantic Ocean.

Species	North Atlantic	Greenland Sea
Cytheropteron testudo	1380–3526	256–1090
Cytheropteron porterae	2417–3884	256–1091
Cytheropteron syntomoalatum	2417–3884	812–1470
Bythoceratina scaberrima	3427–4780	1090–1927
Cytheropteron carolinae	3022–3427	812–3065
Argilloecia conoidea	400–3210	377–3065

The relationship of the fauna to depth is shown in Tables 2 and 3 which plot the species in depth order by first appearance of upper and lower limit, respectively. These two tables also show at what levels various species are represented by live individuals. Figures 3 and 4 depict graphically the appearance and disappearance of species with increasing depth, respectively.
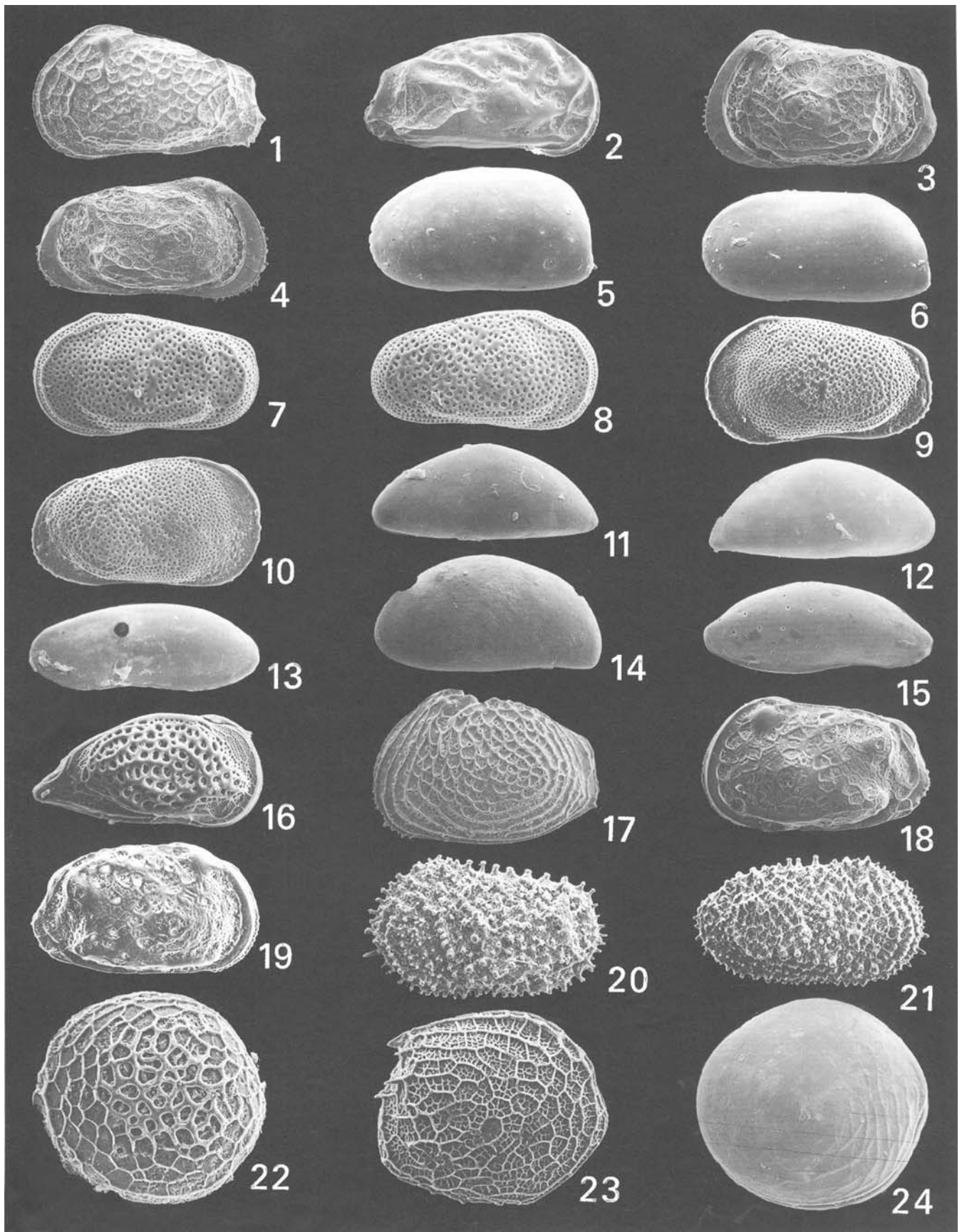
The depth ranges of the ostracods plotted in Tables 2 and 3 show that certain taxa are restricted to the shelf/upper slope, the slope and the lower slope/Greenland Basin abyss. Some species, however, range across the entire bathymetry of the East Greenland continental margin. The various depth categories of these associations are given below:

The shelf/upper slope association

Species	Depth range (m)
Krithe glacialis	274–279
Cluthia cluthae	274–651
Cytheropteron arcticum	274–651
Cytheropteron inflatum	274–651
Thaerocythere crenulata	274–651
Cytheropteron sedovi	279–812
Cytheropteron groenlandicum	651–1090

Explanation of Plate 2

All external lateral views unless otherwise stated. **figs 1, 2.** *Cytheropteron porterae* Whatley & Coles, 1987; fig. 1, LV, ME/29/T, ×61; fig. 2, RV, ME/29/P1, ×59.5. **figs 3–5.** *Cytheropteron pyramidale* Brady, 1868; fig. 3, LV, ME/30/T, ×66.5; fig. 4, RV, ME/30/P1, ×67.5; fig. 5, carapace dorsal view, ME/30/P2, ×69. **figs 6, 10.** *Cytheropteron scoresby* Whatley & Eynon, 1996; fig. 6, carapace dorsal view (Juv. A-2), paratype BMNH, 1992.609, ×77; fig. 10, RV, paratype, BMNH 1992.608, ×77. **figs 7–9.** *Cytheropteron pseudoinflatum* Whatley & Eynon, 1996; fig. 7, RV, holotype, BMNH 1992, ×79; fig. 8, carapace, paratype BMNH 1992.603/3, ×79; fig. 9, carapace, paratype BMNH 1992.603/3, ×75.5. **figs 11, 12.** *Cytheropteron sedovi* Schneider, 1969; fig 11, LV, ME/33/T, ×78.5; fig. 12, RV, ME/33/P1, ×80. **fig. 13.** *Cytheropteron syntomoalatum* Whatley & Masson, 1979; RV, ME/33/P1, ×114. **figs 14, 15.** *Cytheropteron testudo* Sars, 1869; fig. 14, LV, ME/36/T, ×80; fig. 15, RV, Me/36/P1, ×83. **figs 16, 17.** *Cytheropteron vespertilio* (Reuss, 1850); fig. 16, RV, ME/37/P1, ×52.5; fig. 17, LV, ME/37/T, ×51. **fig. 18.** *Hemicytherura clathrata* (Sars, 1866); LV (Juv.), ME/38/T, ×124. **fig. 19.** *Semicytherura affinis* (Sars, 1865) broken LV (Juv.), ME/40/T, ×52.5. **figs 20, 21.** *Eucytherura delineata* Whatley & Eynon, 1996; fig. 20, LV, holotype BMNH 1992.612, ×95; fig. 21, RV, paratype BMNH 1992.613, ×94. **fig. 22.** *Eucythere argus* Sars, 1866; male RV, ME/10/T, ×45. **figs 23, 24.** *Eucythere* sp A; fig. 23, LV, ME/10/T, ×94; fig. 24, RV, ME/10/P1, ×100. **fig. 25.** *Eucythere* sp B, RV (Juv.), ME/11/P1, ×105.

Species	Depth range (m)
Cytheropteron testudo	274–1090
Cytheropteron pyramidale	256–1090
Muellerina abyssicola	279–1090
Cytheropteron porterae	256–1091
Eucytherura delineata	651–1090

The slope association

Species	Depth range (m)
Krithe sp. B.	812–1470
Cytheropteron syntomoalatum	812–1470
Argilloecia cylindrica	279–1735
Bythoceratina scaberrima	1090–1927
Nannocythere sp.	1090–1927
Krithe minima	1091–2687
Henryhowella dasyderma	1735–2687

Slope and abyssal association

Species	Depth range
Cytheropteron carolinae	812–3065
Krithe sp. A.	1464–3065
Cytheropteron vespertilio	651–3355
Cytheropteron hamatum	651–3355
Cytheropteron scoresbyi	1090–3355

The taxa whose depth ranges embrace the entire or virtually the entire bathymetry sampled are:

Species	Depth range
Paracytherois flexuosum	256–2687
Polycope orbicularis	279–2687
Pseudocythere caudata	274–3065
Argilloecia conoidea	377–3065

Faunal turnover
The Greenland Sea is characterized by a faunal turnover which occurs in the depth range of the upper slope. This is shown in Tables 2 and 3 of species distribution by depth, arranged by upper and lower limit, respectively, and by Figs 3 and 4 showing the appearances and disappearances of species against depth.

They show that there is an increase in both the number of species disappearing and appearing between the depths of 600 m and 1100 m, which is exhibited in two major peaks at 650 and 1090 m respectively. The majority of taxa which inhabit the continental slope first appear on the upper slope, between c. 600 m and 1100 m. Only seven species which occur on the shelf, range through to the middle and lower slope. This is probably to some extent a function of the fact that the thermocline, which is such a formidable ecological barrier in lower latitudes, is much less important in the Greenland Sea. A further peak in the number of disappearing taxa occurs at 2687 (Figs 3 and 4) but here, unlike the upper slope peak, the fauna is not replaced by newly appearing taxa.

The ostracod counts for each sample when converted to percentage data are shown in Fig. 5. This illustrates the upper slope faunal turnover and also shows that possibly the most important correlative is the oxygen minimum zone. Figure 6. represents, in depth order of the samples, the abundance, the species diversity, the number of live specimens recovered, the percentage of live specimens and generic diversity across the East Greenland continental margin. Table 4 gives most of this data numerically. The greatest number of specimens was recovered from the continental slope, although the lowest number of specimens was also recorded from this depth zone. The greatest number and percentage of live specimens were from the shelf and upper slope samples, above 651 m, while a localized peak of live specimens occurs on the lower slope at 1735 m.

Generic and specific diversity shows a decline with increasing depth, although some shelf samples were of very low diversity. Diversity remains reasonably high, but fluctuating, on the continental slope, but decreases into the abyss.

THE *KRITHE* PROBLEM
Peypouquet (1975, 1977, 1979) formulated the hypothesis that there exists a relationship between the size and shape of the anterior vestibulum of *Krithe* species and the amount of dissolved oxygen in the water. This led to the widespread belief that *Krithe* with large vestibula corresponded to areas depauperate in oxygen and vice versa. This has been considered in some detail and systematically rejected by Whatley Zhao (1993) and Coles *et al.* (1994). In the Greenland Sea, where high dissolved oxygen levels are relatively constant with depth, the unnamed *Krithe* species include two with large, two with medium sized and 3 with small vestibula which occur together along the continental rise and slope and, therefore, no relationship between vestibulum size and shape and oxygen levels was found (Figs 7 and 8).

Explanation of Plate 3
All external lateral views. **fig. 1.** *Baffinicythere howeii* Hazel, 1967; LV, ME/41/T, ×54. **fig. 2.** *Finmarchinella barentzovoensis* Mandelsatam, 1957; RV, ME/43/T, ×49. **figs 3, 4.** *Muellerina abyssicola* (Sars, 1865); fig. 3, female LV, ME/44/P2, ×44.5; fig. 4, male RV, ME/44/P1, ×44. **figs 5, 6.** *Krithe glacialis* Brady, Crosskey & Robertson, 1874; fig. 5, female LV, ME/12/P2, ×54; fig. 6, male RV, ME/12/T, ×51. **figs 7, 8.** *Cluthia cluthae* Brady, Crosskey & Robertson, 1874; fig. 7, female LV, ME/45/T, ×100; fig. 8, male RV, ME/45/P1, ×105. **figs 9, 10.** *Nannocythere* sp; fig. 9, LV, ME/47/T1, ×109; fig. 10, RV, ME/47/P1, ×110. **figs 11, 12.** *Microcythere* sp; fig. 11, LV, ME/52/T, ×133; fig. 12, RV, ME/52/P1, ×143. **fig. 13.** *Cytherois pusilla* Sars, 1928; LV, ME/49/T, ×81.5. **fig. 14.** *Acetabulostoma hyperboreum* (Scott, 1899); RV, ME/48/T, ×71. **fig. 15.** *Paracytherois flexuosum* (Brady, 1867); RV, ME/50/T, ×50.5. **fig. 16.** *Swainocythere nanseni* (Joy & Clark, 1977); RV, ME/53/P1, ×149. **fig. 17.** *Rabimilis mirabilis* (Brady, 1868); LV, ME/54/T, ×32. **figs 18, 19.** *Thaerocythere crenulata* (Sars, 1865); fig. 18, female LV, ME/56/T, ×42; fig. 19, female RV, ME/56/P2, ×43. **figs 20, 21.** *Henryhowella dasyderma* (Brady, 1880); fig. 20, female LV, ME/55/T, ×39; fig. 21, male RV, ME/55/P1, ×38. **fig. 22.** *Polycope areolata* Sars, 1923; LV, ME/57/T, ×172. **fig. 23.** *Polycope clathrata* Joy & Clark, 1977; RV, ME/59/T, ×115. **fig. 24.** *Polycope orbicularis* Sars, 1866; RV, ME/62/T, ×81.

Table 2. The depth distribution of ostracod species in the Greenland Sea by upper limit:. xxxxx equals occurrence as dead specimens; LLLLL indicates the occurrence of live specimens of a species.

Sample / Depth (m)	1923 256	1916 274	1924 279	1947 377	1948 651	1925 812	1918 1090	1949 1091	1951 1464	1950 1470	1926 1495	1927 1735	1919 1927	1920 2687	1921 3065	1922 3355
Cytheropteron neali	XXXXX															
Eucythere sp. B.	XXXXX															
Semicytherura affinis	LLLLL															
Cytheropteron pyramidale	XXXXX				XXXXX		XXXXX									
Cytheropteron porterae	XXXXX		XXXXX	XXXXX	XXXXX			XXXXX								
Paracytherosis flexuosum	XXXXX		LLLLL	XXXXX			XXXXX			XXXXX		XXXXX	LLLLL			
Cytheropteron nodosum		XXXXX														
Eucythere sp. A		XXXXX														
Rabilimis mirabilimis		XXXXX														
Krithe glacialis		LLLLL	LLLLL													
Cluthia cluthae		LLLLL		LLLLL	LLLLL											
Cytheropteron testudo		LLLLL	LLLLL	LLLLL	LLLLL	XXXXX	XXXXX									
Polycope orbicularis		LLLLL	LLLLL	XXXXX	LLLLL	XXXXX	LLLLL					LLLLL	LLLLL	LLLLL	XXXXX	
Pseudocythere caudata		LLLLL	LLLLL	XXXXX	LLLLL	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX		LLLLL	XXXXX	XXXXX	
Finmarchinella barentzovoensis		XXXXX														
Cytheropteron arcticum		XXXXX	XXXXX	XXXXX												
Cytheropteron inflatum		XXXXX	XXXXX	XXXXX												
Thaerocythere crenulata		XXXXX	XXXXX	XXXXX												
Cytheropteron sedovi		XXXXX	XXXXX	XXXXX												
Muellerina abyssicola		XXXXX	LLLLL	LLLLL			XXXXX									
Argilloecia cylindrica		XXXXX		XXXXX	XXXXX	LLLLL			XXXXX	XXXXX	LLLLL	XXXXX				
Argilloecia conoidea			LLLLL	LLLLL	XXXXX	LLLLL	XXXXX		XXXXX	XXXXX	XXXXX	XXXXX		XXXXX		
Cytheropteron simplex					XXXXX											
Krithe sp. D.					XXXXX											
Polycope areolata					XXXXX											
Cytheropteron groenlandicum					XXXXX		XXXXX									
Eucytherura delineata					XXXXX	XXXXX	XXXXX									
Polycope clathrata					XXXXX							XXXXX				
Cytheropteron pseudoinflatum					XXXXX	XXXXX			XXXXX	XXXXX	XXXXX		XXXXX	XXXXX		
Eucythere argus					XXXXX				XXXXX	XXXXX		XXXXX			XXXXX	
Cytheropteron hamatum					XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	LLLLL	XXXXX	XXXXX	LLLLL	XXXXX
Cytheropteron vespertilio					XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Cytheropteron syntomoalatum					XXXXX	XXXXX	XXXXX	XXXXX		XXXXX						
Krithe sp. B					LLLLL	LLLLL	XXXXX	XXXXX	XXXXX							
Cytheropteron carolinae					XXXXX	XXXXX	XXXXX						XXXXX	XXXXX		
Acetabulastoma hyperborea							XXXXX									
Paijenborchella sp.							XXXXX									
Paradoxostoma productum							LLLLL									
Cytherois pusilla							LLLLL	LLLLL								
Krithe sp. C							XXXXX		XXXXX							
Microcythere sp.							LLLLL			LLLLL						
Bythoceratina scaberrima							XXXXX	XXXXX					XXXXX			
Haplocytheridea bradii							XXXXX						XXXXX			
Nannocythere sp.							XXXXX	XXXXX		XXXXX	XXXXX	XXXXX	XXXXX			
Cytheropteron scoresbyi							XXXXX		XXXXX		XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Krithe sp. F.								XXXXX				LLLLL				
Krithe minima								XXXXX				XXXXX		XXXXX	XXXXX	
Krithe sp. A.									XXXXX	XXXXX	XXXXX	LLLLL	XXXXX	XXXXX	XXXXX	
Propontocypris sp.										XXXXX						
Krithe sp. E.												XXXXX				
Henryhowella dasyderma												XXXXX		XXXXX		
Baffinicythere howei														XXXXX		
Hemicytherura clathrata														XXXXX		

The fauna of station 1918

Maddocks & Steineck (1987) and Steineck *et al.* (1990) considered the ostracod association living on experimental wood islands (between 1800 and 4000 m) in various areas of the World Ocean. They discovered a unique assemblage of podocopid ostracods including the cytherurid genus *Xylocythere* [subsequently also encountered by Van Harten (1994) associated with vent faunas] and several species of *Cytherois, Paradox-ostoma* and *Propontocypris* all concentrated on the wood but absent from the surrounding sediment.

Station 1918, at a depth of 1090 m, yielded the highest number of ostracod specimens from East Greenland, with *Paradoxostoma, Cytherois* and *Propontocypris* being well represented. Although no wood fragments were present in the sediment and *Xylocythere* was absent, the possibility of an adjacent wood parcel cannot be ruled out.

Table 3. The depth distribution of ostracod species in the Greenland Sea by lower limit: xxxxx equals occurrence as dead specimens; LLLLL indicates the occurrence of live specimens of a species.

Sample Depth (m)	1923 256	1916 274	1924 279	1947 377	1948 651	1925 812	1918 1090	1949 1091	1951 1464	1950 1470	1926 1495	1927 1735	1919 1927	1920 2687	1921 3065	1922 3355
Cytheropteron scoresbyi							XXXXX		XXXXX		XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Cytheropteron hamatum				XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	LLLLL	XXXXX	XXXXX	XXXXX
Cytheropteron vespertilio					XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Krithe sp. *A.*									XXXXX	XXXXX	XXXXX	XXXXX	LLLLL	XXXXX	LLLLL	
Eucythere argus									XXXXX	XXXXX		XXXXX			XXXXX	
Cytheropteron carolinae					XXXXX	XXXXX	XXXXX							XXXXX	XXXXX	
Argilloecia conoidea				LLLLL	LLLLL	XXXXX	LLLLL			XXXXX	XXXXX	XXXXX	XXXXX		XXXXX	
Pseudocythere caudata		LLLLL	LLLLL	XXXXX	LLLLL	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX		LLLLL	XXXXX	XXXXX	
Baffinicythere howei														xxxxx		
Hemicytherura clathrata														XXXXX		
Henryhowella dasyderma												XXXXX		XXXXX		
Krithe minima								XXXXX			XXXXX			XXXXX	XXXXX	
Haplocytheridea bradii							XXXXX							XXXXX		
Cytheropteron pseudoinflatum					XXXXX	XXXXX			XXXXX	XXXXX	XXXXX			XXXXX	XXXXX	
Polycope orbicularis		LLLLL	LLLLL		LLLLL	XXXXX	LLLLL					LLLLL	LLLLL	XXXXX		
Paracytherois flexuosa	XXXXX	XXXXX	XXXXX	XXXXX			XXXXX			XXXXX				XXXXX	LLLLL	
Nannocythere sp.							XXXXX	XXXXX		XXXXX	XXXXX	XXXXX	XXXXX			
Bythoceratina scaberrima							XXXXX	XXXXX					XXXXX			
Krithe sp. *E.*												XXXXX				
Krithe sp. *F.*								XXXXX				LLLLL				
Polycope clathrata						XXXXX						XXXXX				
Argilloecia cylindrica		XXXXX			XXXXX	XXXXX	LLLLL		XXXXX	XXXXX	LLLLL	XXXXX				
Propontocypris sp.										XXXXX						
Microcythere sp.							LLLLL			LLLLL						
Cytheropteron syntomoalatum						XXXXX	XXXXX	XXXXX		XXXXX						
Krithe sp. *B.*						LLLLL	LLLLL	XXXXX	XXXXX	XXXXX						
Krithe sp. *C.*							XXXXX		XXXXX							
Cytherois pusilla							LLLLL	LLLLL								
Cytheropteron porterae	XXXXX		XXXXX	XXXXX	XXXXX			XXXXX								
Acetabulastoma hyperborea							XXXXX									
Paijenborchella sp.							XXXXX									
Paradoxostoma productum							LLLLL									
Cytheropteron groenlandicum					XXXXX		XXXXX									
Eucytherura delineata					XXXXX	XXXXX	XXXXX									
Muellerina abyssicola			XXXXX	LLLLL	LLLLL		XXXXX									
Cytheropteron testudo		LLLLL	LLLLL	LLLLL	LLLLL	XXXXX	XXXXX									
Cytheropteron pyramidale	XXXXX				XXXXX		XXXXX									
Cytheropteron sedovi			XXXXX	XXXXX	XXXXX	XXXXX										
Cytheropteron simplex					XXXXX											
Krithe sp. *D.*					XXXXX											
Polycope areolata					XXXXX											
Cytheropteron arcticum			XXXXX	XXXXX	XXXXX											
Cytheropteron inflatum			XXXXX	XXXXX	XXXXX											
Thaerocythere crenulata			XXXXX	XXXXX	XXXXX											
Cluthia cluthae		LLLLL		LLLLL	LLLLL											
Finmarchinella barentzovoensis		XXXXX														
Krithe glacialis		LLLLL	LLLLL													
Cytheropteron nodosum		XXXXX														
Eucythere sp. *A.*		XXXXX														
Rabilimis mirabilis		XXXXX														
Cytheropteron neali	XXXXX															
Semicytherura affinis	LLLLL															

DISCUSSION AND CONCLUSIONS

The most significant result from this study is the pronounced faunal turnover which takes place between 600 and 1100 m, where shelf species are replaced by bathyal and abyssal taxa. The Greenland Sea is characterized by fairly constant temperatures and generally little variation in nutrient levels. Several possible causes exist for the faunal turnover, such as change in temperature salinity or oxygenation at a water mass boundary.

Aagaard (1981) recognised a zone of reduced salinities in the Greenland Sea between 1000 and 1600 m and Belanger Streeter (1980) noted that the oxygen minimum zone occurs between 800 and 1200 m. However, although both of these phenomena occur at depths which render it possible to allow one to invoke their agency in causing the faunal turnover, the reductions in salinity and oxygen levels are very small scale.

Dingle & Lord (1990) identified the water mass boundaries in the Atlantic as a cause of the depth zonation of certain deep sea ostracods. The upper limit of the Greenland Sea Deep Water occurs at 900 m, which correlates with the faunal turnover as shown by the first peak in Figs 3 and 4, and probably exerts
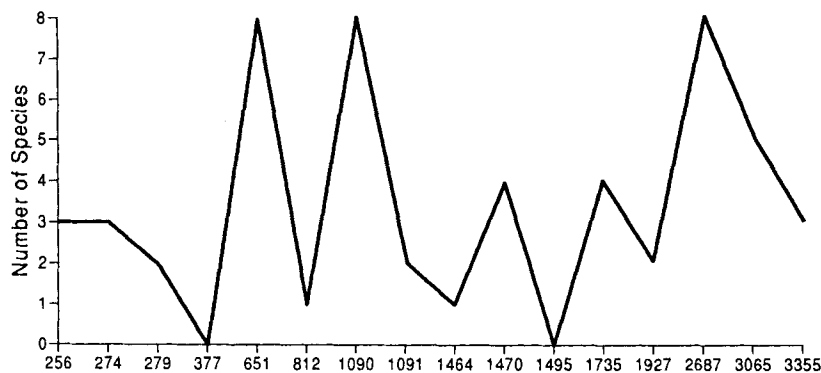
Fig. 3. Graphical representation of the number of species disappearing with depth in the various transects across the Greenland Sea.
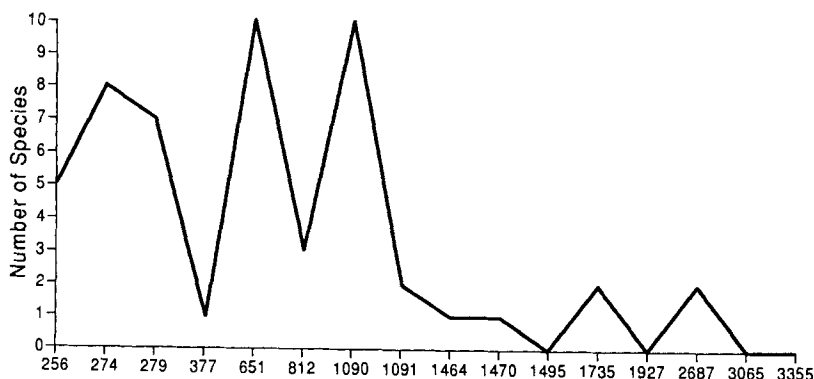
Fig. 4. Graphical representation of the number of species appearing with depth in the various transects across the Greenland Sea.

some influence on the shelf, and on the distribution of the North Atlantic fauna.

Studies such as that of Rosenfeld & Bein (1978), and Barkham (1985, unpublished MSc Thesis, Aberystwyth) off the coast of Northwest Africa and Cronin (1983) off Cape Hatteras, have recorded a faunal turnover below the shelf break. The East Greenland continental margin is characterized by a very deep continental shelf, with the shelf break occurring at *c.* 500 m and, therefore, the change in fauna occurs in a similar position to these other studies (second peak, Figs 3 and 4).

Such Arctic shelf taxa as *Thaerocythere crenulata*, *Muellerina abyssicola* and *Krithe glacialis* have their lower depth limit at 1100 m. Water temperature does not decrease here significantly with depth below 200 m (see Appendix) so that temperature alone cannot be the sole barrier to downslope migration of species into the deep sea. Because of the absence of an effective thermocline at these latitudes, theoretically they are where we should expect to encounter a 'backdoor' means of entry into the deep sea and it is very likely this route has been of significance in the past and may still be operative today. It is not easy to prove that the High Latitude Doorway hypothesis has been a major route of access into the deep sea, rendered so difficult by the inception of the thermocline in the late Palaeogene (Benson, 1975; Whatley, 1996) and from that time virtually impossible in lower latitudes, but the temperature controlled stenotopic depth distribution differences between Arctic and North Atlantic assemblages of the same species (Table 1) is possible evidence

in the case of certain species. Certainly, in the present study, the clear distinction between shelf and bathyal/abyssal taxa in the Greenland Sea demonstrates the significance of the ecological barriers that exist between them.

The deep sea fauna of the Arctic Ocean lacks many of the taxa which are virtually pandemic elsewhere in the world's oceans. As early as 1969, Benson after examining 'a few samples from the Arctic' was able to state that this area does not have 'a normal deep-water fauna at the present time'. We note the absence from the Greenland Sea of such genera as *Bradleya* Hornibrook and *Poseidonamicus* Benson, members of the pandemic deep sea fauna. Also, Coles (pers. comm. 1992) commented that the *Krithe* spp. from the Greenland Sea '. . .seem to be distinct from 'true' deep sea North Atlantic faunas further south and in deep sea water areas'.

Joy & Clark (1977) in their study of the deep water ostracods of the Canadian Basin, recorded three species which are common with the fauna of the Greenland Sea. These are: *Henryhowella dasyderma* (1351–3193 m), *Pseudocythere caudata* (1531–3198 m) and *Polycope punctata* (1351–2810 m). These authors also described 13 species which were then confined to the Canadian Basin and these figures indicate the importance as a barrier to migration of the Lomonosov Ridge.

More species (at least ten), are common with the fauna described from the Quaternary of the deep Arctic Basin by Cronin *et al.* (1994). It is not possible to be more precise since neither *Krithe* nor *Polycope* are speciated in the latter work.
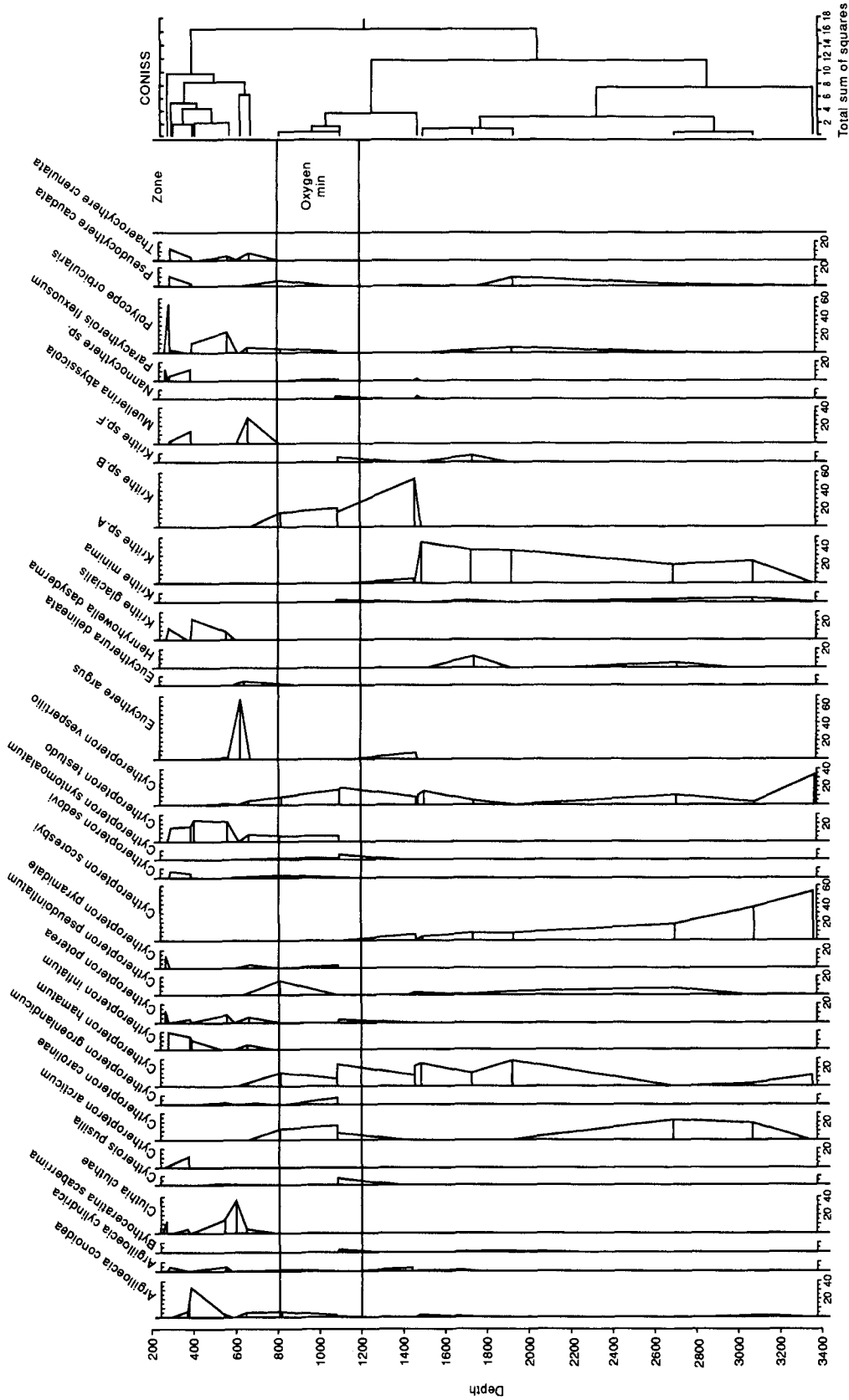
Fig. 5. The percentage distribution of the various ostracod species by depth in the Greenland Sea, showing the influence of the Oxygen Minimum zone on the relative importance of certain species.
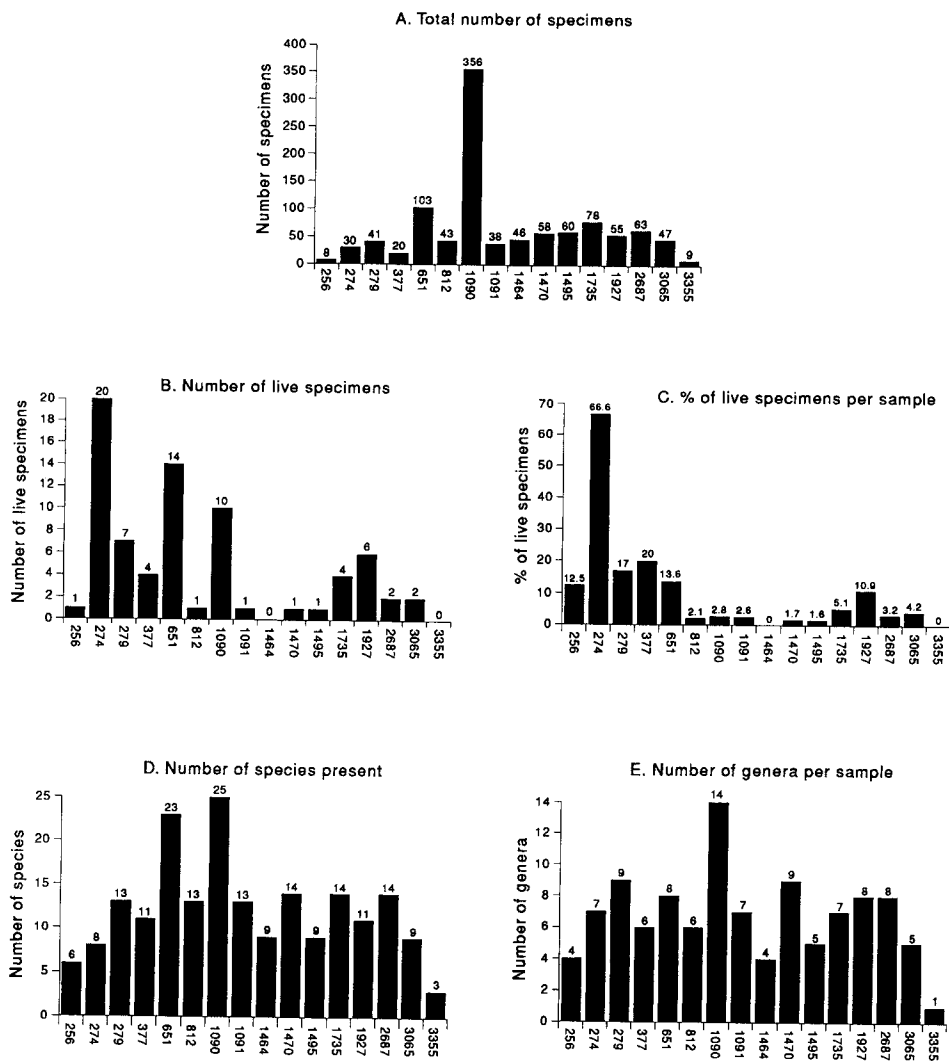
27

A. Total number of specimens

B. Number of live specimens

C. % of live specimens per sample

D. Number of species present

E. Number of genera per sample

Fig. 6. The total number of specimens, number of live specimens, percentage of live specimens, number of species and number of genera per sample by depth.

Table 4. The number of specimens, number of live species, total number of species, depth in metres per sample in depth order.

Sample	No. spp.	No. live	No. spp.	Depth m
1923	8	1	6	256
1916	30	20	8	274
1924	41	7	13	279
1947	25	4	11	377
1948	103	14	23	651
1925	48	1	13	812
1918	356	10	25	1090
1949	38	1	13	1091
1951	46	0	9	1464
1050	58	1	4	1470
1926	60	1	9	1495
1927	78	4	14	1735
1919	50	6	11	1927
1920	63	2	14	2687
1921	47	2	9	3065
1922	9	0	3	3355

These species, all from coretops, are *Acetabulastoma arcticum, Bythoceratina scaberrima, Cytheropteron alatum, C. carolinae, C. hamatum, Henryhowella asperrima, Krithe* spp., *Polycope* spp., *Pseudocythere caudata.*

Table C of Cronin *et al.* (1994) shows very clearly the important difference between the characteristic ostracods of the Arctic deep ocean basin and those of the Greenland Sea. This very clearly shows the extent to which the Greenland Sea fauna is not typically High Arctic in character and that it represents a Low Arctic fauna with strong connections to the faunas of the Norwegian Sea and to the northern North Atlantic.
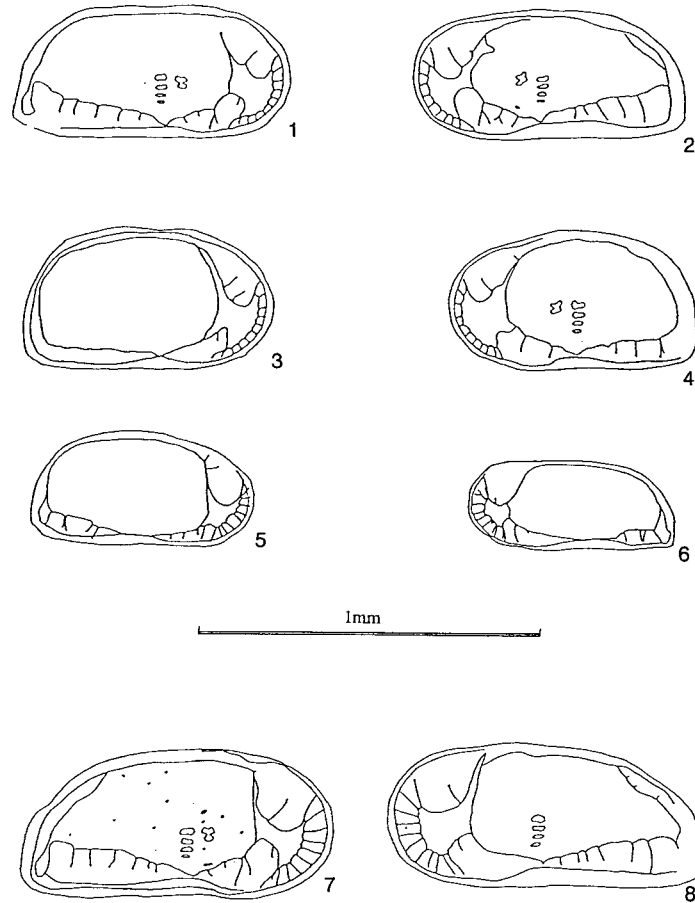
Fig. 7. Projectina drawings of *Krithe* spp. (all internal views). **fig. 1**, *K. glacialis*, male LV, ME/12/T; **fig. 2**, *K. glacialis*, male RV, ME/12/T; **fig. 3**, *K. glacialis*, female LV, ME/12/P2; **fig. 4**, *K. glacialis*, female RV, ME/12/P3; **fig. 5**, *K. minima*, female LV, ME/13/T; **fig. 6**, *K. minima*, male RV, ME/13/P1; **fig. 7**, *K.* sp. A, male LV, ME/14/T; **fig. 8**, *K.* sp. A, male RV, ME/14/P1.

APPENDIX
A synopsis of the location, depth and environmental data of the sampling localities.

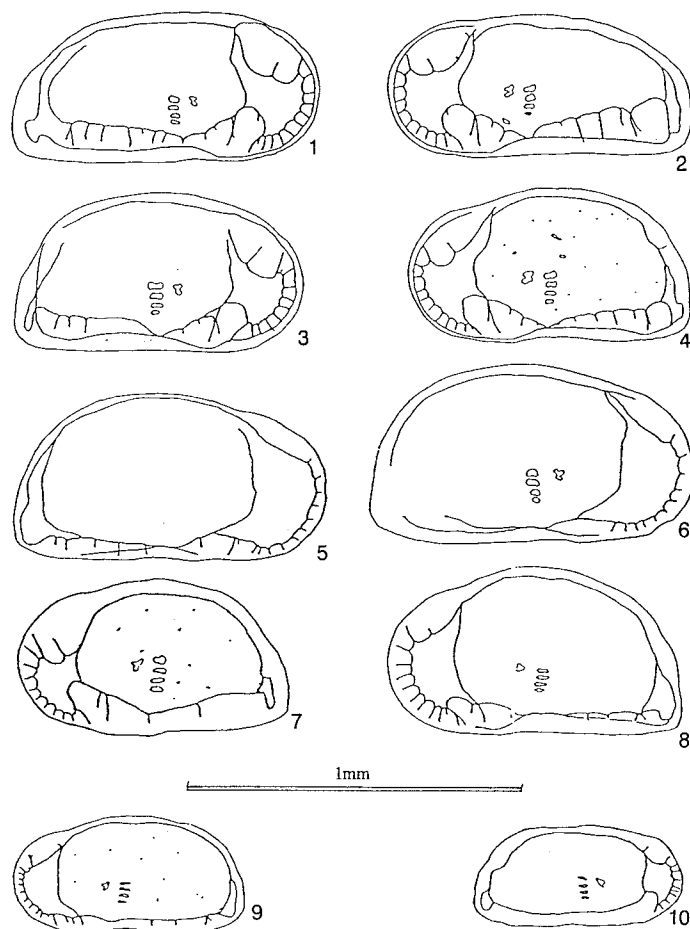| Stn	Coordinates (Lat/Long)	Location	Depth	Sediment
1916	74°48.89'N;18°43.75'W	Fjord mouth	274 m	Clay
1918	75°00.00'N;12°28.06'W	Upper slope	1090 m	Silty clay dropstones
1919	74°59.76'N:11°51.55'W	Continental slope	1927 m	Sandy clay
1920	74°59.88'N;11°05.60W	Lower slope	2687 m	Clay planctonic forams
1921	75°00.22N;10°36.26'W	Lower slope	3063 m	Clay planctonic forams
1922	74°59.92'N;20°29.99'W	Continental rise	3355 m	Clay planctonic forams
1923	71°28.82'N;20°29.99'W	Shelf	256 m	Sandy clay with ice rafted debris
1924	71°29.95'N;19°11.55'W	Shelf	279 m	Sandy clay with ice rafted debris
1925	71°29.93'N;18°43.29'W	Upper slope	812 m	Sandy clay with ice rafted debris
1926	71°29.47'N;18°16.58'W	Continental slope	1419 m	Silty clay
1927	71°29.78'N;17°08.81'W	Mid-slope	1735 m	Clay
1947	69°16.34'N;21°46.41'W	Shelf	377 m	Sandy clay with ice rafted debris
1948	69°04.05'N;21°17.03'W	Upper slope	651 m	Sandy clay with ice rafted debris
1949	68°59.65'N;21°10.08W	Upper slope	1091 m	Clay with ice rafted debris
1950	68°53.62'N;20°58.57'W	Continental slope	1470 m	Clay with ice rafted debris
1951	68°50.03'N;20°49.72'W	Continental slope	1464 m	Clay with ice rafted debris

Fig. 8. Projectina drawings of *Krithe* spp. (all internal views). **fig. 1**, *K.* sp. B, male LV, ME/15/T; **fig. 2**, *K.* sp. B, male RV, ME/15/P1; **fig. 3**, *K.* sp. B, female LV, ME/15/P2; **fig. 4**, *K.* sp. B, female RV, ME/15/P3; **fig. 5**, *K.* sp. C, female LV, ME/16/T; **fig. 6**, *K.* sp. C, female LV, ME/16/P1; **fig. 7**, *K.* sp. D, female RV, ME/17/T; **fig. 9**, *K.* sp. E, female RV, ME/18/T; **fig. 9**, *K.* sp. F, female RV, ME/19/T; **fig. 10**, *K.* sp. F, male LV, ME/19/P1.

Some stations have temperature and salinity data:

Station	Salinity ‰	Temperature °C
1921	34.9	-1.0
1927	34.9	-0.75
1949	34.9	-0.25
1951	34.9	-0 60

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