DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/104

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The ENAM (I, II) projects (European North Atlantic margin) financed by the EU were initiated in 1993 with the purpose to study the development of the European North Atlantic margin. Focus was on the Quaternary. Within the framework of the ENAM-II project (1996–1999) a cruise with R/V *Dana* was carried out in 1997 as a Danish contribution to the project. The ship time was financed through the Danish Natural Research Council (SNF). The sediment core presently discussed was taken during this cruise.

The aim of this report is to inform about new data, which provide basis for consideration of the surface water variability in the NE Atlantic region during the Holocene period. This study is based on the core DAPC03 of the ENAM Project, taken by R/V *Dana* in 1997 on the shelf near the Hebrides at latitude 58° 08.20'N, longitude 06° 18.03'W (Fig. 1), where water depth is around 58 m. In the year 2000 studies of the dinoflagellate cysts flora were completed and results compared with the magnetic susceptibility data of this core. The seven meter long piston core recovered an excellent succession of Holocene sediments. This study examines the entire sequence, and provides a correlation between the dinoflagellate cyst record and the magnetic susceptibility profile, and links these data to the hydrographic regime.

Information from other studies elsewhere in the NE Atlantic (e.g., Harland & Howe 1995; Kroon *et al.* 1997) was combined with this study in order to reconstruct the more large-scale current variability of the NE Atlantic.

The alternating assemblages of cold versus relatively warm water dinoflagellate cysts at this site illustrate that the North Atlantic Water (Fig. 1) current pattern changed during the Holocene period. This clearly demonstrates a fluctuating oceanic circulation pattern also elsewhere in the NE Atlantic. However, because there was only carried out one AMS ^{14}C dating, we are not able to give a more precise relationship of the identified phases to the chronology.

The climate and ocean current patterns have fluctuated during the last glacial period. Oscillations between warm and cold climate occur with a period of 2–3 kyr and are known from the Greenland ice cores as Dansgaard-Oeschger cycles (Dansgaard *et al.* 1993). A corresponding cyclic pattern is also documented in the Holocene marine climate records from the NE Atlantic (e.g. Bianchi & McCave 1999; Chapman & Shackleton 2000).

The magnetic susceptibility signal is controlled by the sediment mineralogy, grain size and amount of magnetic minerals, by the type and concentration of paramagnetic (Fe- and Mn-bearing) clays and by the sediment void ratio. Thus it reflects changes in the sedimentary environment that can be linked to hydrographic changes reflecting climate variability. These changes may involve the local bottom water dynamics, i.e. wind turbulence, bottom currents, temperature, salinity, and water depth changes induced by global Holocene sea level rise.

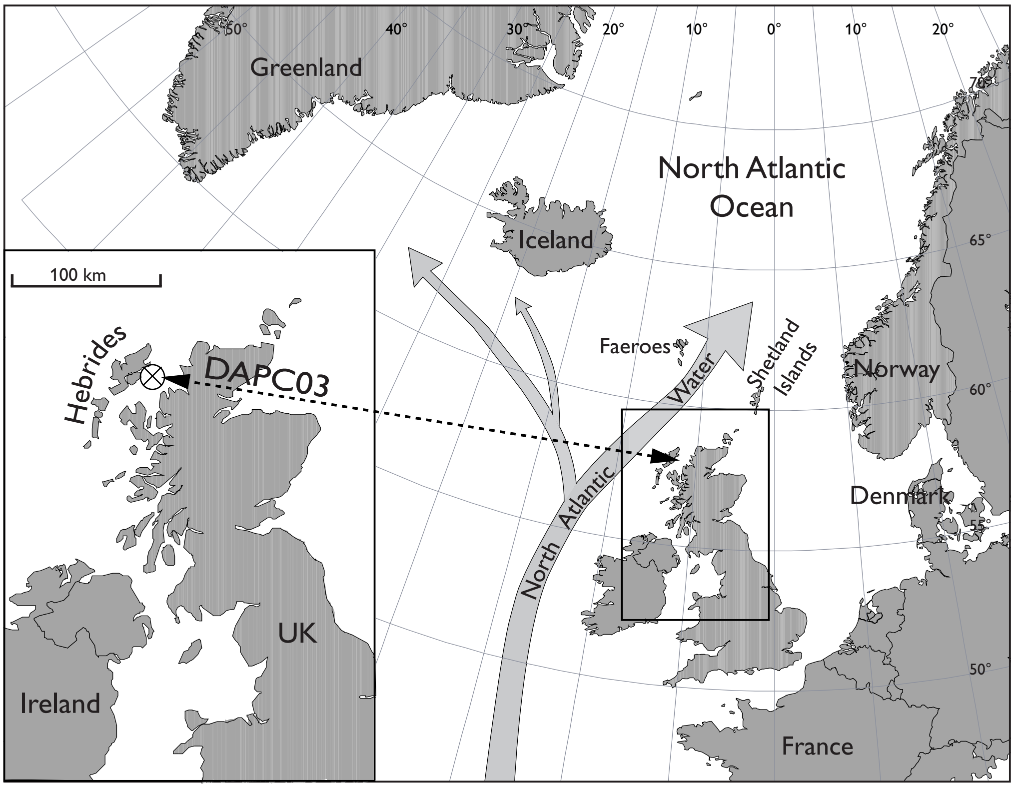

Fig. 1. Major surface currents indicated in the studied region of the North Atlantic (after Kroon et al. 1997). The core DAPC03 of the ENAM Project is located on the shelf near the Hebrides at latitude 58° 08.20'N, longitude 06° 18.03'W.

Environmental setting

The surface water circulation in the NE Atlantic is characterised by two main transport pathways of the North Atlantic surface water masses. The North Atlantic current displays two branches, one to the north-west transporting relatively warm and saline waters to the Iceland region and the other towards the north-east through the passage of the Faeroe Shetland Channel (Hansen & Østerhus 2000). In addition, a persistent poleward flow over the continental slope region transports water of somewhat higher salinity from the region off the west coast of northern France to the area west of Shetland (Pingree & le Cann 1989; Turrell et al. 1992). The water masses transported by this 'Continental Slope Current' are known as 'North Atlantic Water' (Fig. 1).

The location of the coring site was selected based on information from the British Geological Survey (D. Evans, personal communication 1997) describing the presence of larger, relatively thick deposits of fine-grained Holocene sediments in the study area east of the Hebrides.

Dinoflagellate cysts

Dinoflagellate cyst ecological distribution patterns have been studied for a long time in order to interpret palaeoenvironments (e.g. Wall 1967; Wall et al. 1977; Edwards &

Andrle 1992). Environmental affinities are interpreted for a large number of species and genera (e.g. Wall *et al.* 1977; Bujak 1984; Dale 1986; Corradini & Biffi 1988; Powell *et al.* 1990; Brinkhuis *et al.* 1992; Edwards 1992; Eshet *et al.* 1993; Rochon *et al.* 1999): Some species characterise the oceanic environment, some represent middle-outer neritic environments, some occur in a wide range of environments, or are cosmopolitans.

Most living peridiniod dinoflagellates flourish under conditions of high quantities of nutrients available such as in up-welling systems and high-latitude regions. They are heterotrophic, feeding mainly on diatoms (Gains & Taylor 1984; Jacobsen & Anderson 1986) which are the primary producers in up-welling systems. Variation in abundance of peridiniod cysts seems thus to reflect changes in primary diatom production (Bujak 1984; Dale 1986). Gonyaulacoids are autotrophic forms (e.g. Harland 1988a) that flourish in regions of low productivity (Wall *et al.* 1977; Dale 1986). Comparison with diatom population densities indicates that the ratio between the number of peridiniod and gonyaulacoid cysts is related to productivity changes (Bujak 1984; Powell *et al.* 1990). Dale (1986) has emphasised the significant differences between oceanic and shelf dinoflagellate cyst assemblages following the work of Wall *et al.* (1977) and Harland (1983). These differences reflect the division between generally nutrient-poor waters in the open ocean and nutrient-rich waters on the shelf. Only a few cyst types are indigenous to the ocean in contrast to the many cyst types indigenous to the neritic environment.

Edwards (1992) found from distribution plots of different sea-water depths that a number of dinoflagellate cyst species were especially common within rather narrow winter temperature intervals (e.g. *Operculodinium centrocarpum*, *Brigantedinium simplex*). Recognition of oceanic, temperate (but not tropical or subtropical) environments can be based on the numerical presence of specimens of the genus *Impagidinium*, especially the two species *I. aculeatum* and *I. strialatum* (Edwards 1992).

The dinoflagellate *Protoceratium reticulatum* (formerly *Gonyaulax grindleyi*) produces two well known cysts, *Operculodinium centrocarpum* and *Operculodinium israelianum*. Edwards & Andrle (1992) presented a summary of their reported distributions: The distribution of *O. israelianum* is from the warm-temperate to tropical estuarine to outer neritic sea, with most abundant occurrence at water depths of 30–50 metres in the present-day Mediterranean; it is also abundant in lagoonal environments with reduced salinity (Edwards & Andrle 1992). McMinn (1991) did not record any relation in its distribution to salinity. The distribution of *O. centrocarpum* is estuarine to oceanic and with a broad thermal tolerance, the highest abundance occurs at the continental slope, decreasing both seaward and shoreward (Edwards & Andrle 1992). The proportion between these two cysts appears to be a temperature and depth sensitive indicator within estuarine-neritic environments. *O. centrocarpum* is often regarded as being oceanic in character because of its distribution in bottom sediments (Harland 1983; Dodge & Harland 1991).

Materials and methods

The sediments consist of alternating olive-grey silty clay with few isolated burrows and few *Turritella* shells. At ÷426 cm a *Turritella* layer is present (Fig. 2). The layer has been dated at 5280 BC (BC5330–5260) (J. Heinemeier, unpublished data 1998).

Measurements of magnetic susceptibility were carried out at GEUS using a portable Bartington MS2 measuring device with loop sensor.

All the analysed samples from DAPC03 have been subjected to palynological processing in washing machine treated with citric acid and washing powder in 10 µm filter cloth bags and heavy liquid separated (Poulsen *et al.* 1990). All samples yielded dinoflagellate, however, they were not equally common in all samples (Fig. 2).

Results and discussion

The magnetic susceptibility profile of the core (Fig. 2) shows three phases of different water mass properties, which may be linked to 1) the early cool period after the last glaciation, 2) to the Holocene climatic optimum about 5000–3000 BC, and 3) the following cooling period ('Neoglaciation') up to present time. From the bottom of the core (÷680 cm below sea floor (bsf)) to a depth of ÷465 cm bsf (phase 1) the magnetic susceptibility of the sediments record a general increase from about 60 to 300 CGS indicating a gradual change to possibly increased deposition of slightly coarser and more (para)magnetic material associated with more turbulent conditions. On the nearby Faeroe margin it was found that in this area high CGS values were typically found under cold climate conditions (Kuijpers *et al.* 1998). Thus, tentatively we may conclude relatively cold climate, or hydrodynamically turbulent conditions, in the upper part of this phase 1. In fact, widespread evidence has been found in the North Atlantic that after relatively warm surface water conditions around 7000 BC (Koc *et al.* 1993), a marked cooling event occurred at 6500–6200 BC (Gudmundsson 1997; Klitgaard-Kristensen 1998; Barber *et al.* 1999). Alternatively, a relative sea level fall due to regional isostatic rebound after glaciation would favour a high-energy sedimentary environment and contribute to higher CGS values in the upper part of phase 1. A transition phase is recognised from ÷465 to ÷410 cm bsf with abrupt falling CGS values from 300 to 50 indication raising sea level and/or, warmer climate. A dense concentration of the gastropod *Turritella* at ÷426 cm bsf can be compared with its occurrence in the Scandinavian area, where *Turritella* spp. have become marker species for water depth exceeding about 20 m (Kaj Strand Pedersen, personal communication 2001). It is concluded that the water depth at the site during the transition phase increased from very shallow to more than 20 m. The layer has been dated 5280 BC (BC5330–5260) (J. Heinemeier, unpublished data 1998).

The interval from ÷410 cm to ÷210 cm bsf has low CGS values (around 50) and almost no fluctuations (phase 2) may be interpreted to indicate stable, relatively warm, and low-energy hydrographic conditions. The upper part of the core from ÷210 cm to 0 cm bsf (phase 3) shows a somewhat fluctuating CGS values (between 100–150), suggesting a return to presumably cooler climate with enhanced current and wave-action. The dinoflagellate cyst data also reveals phases which correspond to the three magnetic susceptibility phases. Most of the samples, in fact, contain only few species and often also low numbers of specimens. Although cyst recovery cannot be directly linked to plankton productivity (Evitt 1985) there is a likely relationship between plankton productivity and cyst numbers. Transport through the action of surface currents and bottom water transport, and reworking, do also influence the number of specimens found in the sediments.

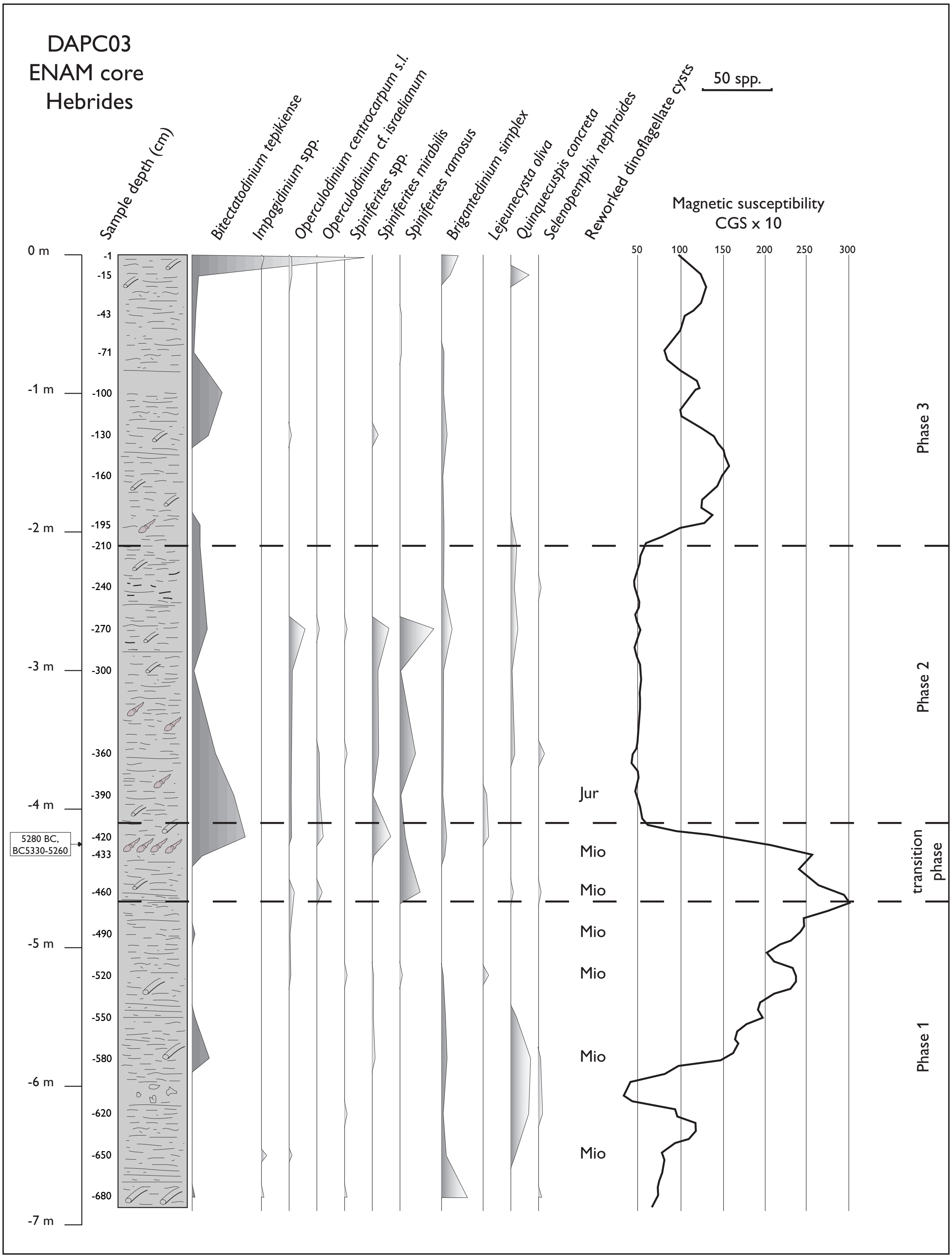

Fig. 2. Correlation of dinoflagellate cyst biostratigraphy with magnetic susceptibility. Samples horizons indicated as sample depth in cm below sea floor. Dinoflagellate cyst proportions indicated as counted specimens. At ÷426 cm a Turritella layer is present. The layer has been dated at 5280 BC (BC5330-5260) (J. Heinemeier, unpublished data 1998).

Characterisation of dinoflagellate cysts in the three phases

Phase 1 (÷680 cm to ÷465 cm bsf)

The samples from phase 1 recorded relatively low cyst recovery and were dominated by heterotrophic dinoflagellate (protoperidiniod cysts) "round browns" *Brigantedinium simplex* and other, mainly *Quinquecuspis concreta.* Assemblages dominated by "round browns" indicate cold environment with possible ice cover (Graham *et al*. 1990). All samples also contained *Bitectatodinium tepikiense* in low numbers, whereas other autotrophic dinoflagellate cysts, e.g. *Operculodinium centrocarpum* or *Spiniferites* spp. comprised more minor proportions of the assemblage. In addition to the dominant elements of the assemblages there is apparently a partition of *Impagidinium* species at the start of this phase (Fig. 2). The assemblages of phase 1 and the transition phase differ from the two following phases in containing reworked Neogene dinoflagellate cysts.

Low diversity dinoflagellate cyst assemblages with high quantities of *Brigantedinium* spp. are often a characteristic of polar to sub-polar environments (e.g. Rochon *et al.* 1999). However, assemblages dominated by *Brigantedinium* spp. are also common in temperate regions, especially in coastal up-welling areas (Wall *et al.* 1977). The latter assemblages, differ from polar to sub-polar ones in having a high diversity especially of protoperidiniod cysts (Mudie 1992; Matthiessen & Brenner 1996). Together with the presence of *Impagidinium* cysts at the base of this phase, which have an oceanic distribution and more southerly distribution (Wall *et al.* 1977; Harland 1983; Dodge & Harland 1991), this may indicate a northward transport of North Atlantic Water or ameliorating climate at the beginning of this phase. Most probably the common reworked material in this phase suggest strong bottom currents, maybe associated with a relatively low sea level.

Transition phase (÷465 cm to ÷410 cm bsf)

During this transition phase the dinoflagellate cysts assemblage increases both in cyst recovery as well as number of species (Fig. 2). At the base of the transition phase the assemblage is dominated by *Spiniferites ramosus,* whereas in the top of this transition phase the assemblages becomes dominated by *Bitectatodinium tepikiense, Spiniferites ramosus* and *S. mirabilis* is present at the top of this phase. *Operculodinium centrocarpum* and *O.* cf. *israelianum* occur infrequently through this phase (Fig. 2).

Mudie & Harland (1996) described *S. mirabilis* as typical cool-temperate to tropical species. Evidence of outer neritic shelf is more likely provided by species of *Spiniferites*, in particular *S. ramosus* and *S. mirabilis*, together with *Operculodinium* cysts (Wall *et al.* 1977; Dale 1983; Harland 1983). The income of these neritic forms probably reflects some oceanographic changes affecting the disposition of the eastern North Atlantic gyre. Hence the transition phase is interpreted as a period with gradual warming prior to phase 2, during which the sea water depth also increased from shallow shelf (below 20 m) to at least about 20 m, indicated by the dense concentration of the gastropod *Turritella* at ÷426 cm bsf (see above).

Phase 2 (÷410 cm to ÷210 cm bsf)

The samples of the lower two third of phase 2 contain more rich dinoflagellate cyst assemblages with a relative high cyst recovery. The assemblages are dominated through this part by *Spiniferites ramosus, S. mirabilis and Bitectatodinium tepikiense. Operculodinium centrocarpum* is present throughout, and *O.* cf. *israelianum* occur sporadically through this part of the phase (Fig. 2).

Although it is demonstrable that dinoflagellate cysts respond to climatic change and that this is seen in shelf successions (Harland 1988b), the recovered assemblages are not unique in character. Species of *Spiniferites* (*S. ramosus, S. mirabilis*) and *Operculodinium centrocarpum* are giving evidence of an outer neritic shelf environment (Wall *et al.* 1977; Dale 1983¸Harland 1983). The assemblages with common *O. centrocarpum* herein are consistent with a northern temperate climate and a hydrography comparable to that of present-day. *S. mirabilis* is largely confined to the eastern North Atlantic off the south-west coast of Ireland (Harland 1983; Dodge & Harland 1991). The occurrence of these neritic forms reflects a stable, relatively warm environment, and perhaps more important the extent and strength of both offshore and deep-water currents.

The peak values of *O.* cf. *israelianum* suggest a distinct inflow of warm water into what is interpreted above as temperate environment. These influxes of *O.* cf. *israelianum* coincide with contemporaneous influx of *S. mirabilis.* Matthiessen & Brenner (1996) interpreted influx of *O. israelianum* (as *O. crassum*) as warm-water influxes. In contrast, *Bitectatodinium tepikiense* has a broad thermal tolerance, but is absent or rare today in the Arctic Ocean (Mudie 1992; Matthiessen & Brenner 1996). In the north-western Atlantic, *B. tepikiense* appears to prefer environments with cold winter and warm summer sea-surface temperatures (de Vernal *et al.* 1992). According to Matthiessen & Brenner (1996), high percentage abundances of *B. tepikiense* are attributed to mixing of polar-influenced oceanic waters with cold, brackish melt waters from ice, and are associated with a salinity around 30‰ and a relatively short seasonal sea-ice cover or even ice-free conditions. *B. tepikiense*, which shows low percentages of the assemblages in the beginning of this phase but is otherwise common to abundant, is here regarded as a component of cold, and perhaps less saline waters.

The upper third part of this phase, the dinoflagellate cyst assemblages becomes less diverse and reduced in numbers of specimens, but the magnetic susceptibility does not reflect any changes. It is, however, shown that changes in larger scale surface ecology may be evident in the flora before it can be traced in the bottom sedimentary record (Gudmundsson 1997), perhaps due to relatively little surface water mixing in the beginning. On Iceland an early cooling period (3.000–2.500 BC) is recorded (Gudmundsson 1997), which may correspond to this upper part of phase 2.

The combined dinoflagellate evidence suggests a period with inflow of temperate to warm North Atlantic water masses into the Hebrides shelf followed by an early cooling preceding the more significant Neoglaciation (see phase 3).

Phase 3 (÷210 cm to 0 cm bsf)

This phase is represented by samples with a poor cyst recovery. In most of the samples, dinoflagellate cyst assemblages are dominated by *Bitectatodinium tepikiense* with only the occasional specimen of *Spiniferites* and *Brigantedinium simplex* ("round browns") and *Quinquecuspis concreta* and rarely *Operculodinium centrocarpum* (Fig. 2).

The occurrence of these neritic and cold water forms (see phase 2) probably reflects some oceanographic changes affecting the disposition of the eastern North Atlantic gyre, and perhaps more important the extent and strength of both offshore and deep-water currents. In particular *B. tepikiense* may prove to be a marker for the presence of cold waters of relatively low salinity (Matthiessen & Brenner 1996).

Fluctuations in the abundance of *B. tepikiense, Spiniferites* spp., and *O. centrocarpum* and low abundances and diversities of dinoflagellate cysts in general suggest periods with cold conditions and low productivity during deposition of the sediments. The increased abundance of *Brigantedinium* spp. near the end of this phase (that is sub-recent to recent strata) may be attributed to increased nutrient levels.

Conclusions

Dinoflagellate cyst analysis of the Holocene succession at site DAPC03 provides information that aids interpretations of the magnetic susceptibility. This information can be used to interpret changes in depositional environments and palaeoceanographic conditions on the Hebrides shelf.

The dinoflagellate assemblages suggest a relatively strong influence of highly saline North Atlantic Water especially during phase 2, as relatively warm water was transported along Ireland and England toward the Hebrides shelf. These periods of warm-water inflow must have alternated with periods characterised by relatively cold water of relatively low salinity.

In summary a tentative interpretation for the phases is as follows:

Phase 1: strong northward Continental Slope Current and an ameliorating climate at the beginning of this phase. Most probably the common reworked material in this phase suggest strong bottom currents associated with a relatively low sea level

Transition phase: a period with gradual warming during which the water depth increased from shallow shelf (below 20 m) to at least about 20 m

Phase 2: a period with inflow of temperate to warm North Atlantic Water masses to the Hebrides shelf, however also with some admixture of colder waters. The hydrographic regime was probably characterised by stable and low-energy (e.g. wave-action) conditions.

Phase 3: greater oceanographic variability affecting the eastern North Atlantic gyre, and perhaps more important the extent and strength of both warm and cold water transport. Fluctuations occurred with periods characterised by cold conditions and low productivity. Near the end of this phase possibly increased nutrient levels have been noted.

Acknowledgements

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