



# A new age model for the Pliocene–Pleistocene Tjörnes section on Iceland: Its implication for the timing of North Atlantic–Pacific palaeoceanographic pathways

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## ABSTRACT

The Plio–Pleistocene outcrops of the Tjörnes peninsula in northern Iceland present a unique section in which near-shore and terrestrial deposits alternate with lava flows. This section plays an important role in the correlation of climate signals from around the North Atlantic, but a solid age model has not been available for the entire sequence due to problematic K/Ar dating and incompletely recorded palaeomagnetic signal.

A palynological analysis with dinoflagellate cysts of 68 samples from the Tjörnes beds and twenty samples from the younger Breidavík Group was carried out in order to establish an age model for the Tjörnes section, independent of the available K/Ar ages. The dinoflagellate cyst record of the Tjörnes beds consists mainly of Pliocene taxa and indicates most probably a post-Miocene age for the *Tapes* and *Macra* Zones of the Tjörnes beds. Both *Operculodinium tegillatum* and *Batiacasphaera minuta*, which have a highest occurrence near the top of the Zanclean at c. 3.8 Ma, were present in the section up to the middle of the *Serripes* Zone. *Reticulatosphaera actinocoronata*, with a highest occurrence around 4.4 Ma, was recorded in situ at the base of the *Serripes* Zone. This suggests that the entire *Serripes* Zone was deposited between c. 4.0 and 4.5 Ma. Further, the normal polarities below and above the Skeifá lavas in the *Serripes* Zone were consequently linked to the Nunivak and Cochiti Subchron respectively. The entire Tjörnes beds were likely deposited in the Early Pliocene, before c. 4.0 Ma. The Breidavík Group is deposited much later in the Quaternary, from just before the Olduvai Subchron at c. 2.2 Ma.

The Gilbert/Gauss transition is located between the Tjörnes beds and the Höskuldsvík lavas and the Gauss/Matuyama transition between the Furuvík and Hörgi Formations. The exact position of both reversals is not preserved because two appreciable hiatuses of c. 600 kyr up to maximally 900 kyr occur at these locations. According to the new age model, the major invasion of Pacific molluscs at the base of the *Serripes* Zone took place before 3.8 Ma. In combination with the palaeopolarity data, this event can be placed in the Nunivak Subchron at c. 4.5 Ma. The invasion is likely a result of the northward flow of Pacific waters through the Bering Strait to the North Atlantic, which may have been caused by the shoaling of the Central American seaway between 4.7 and 4.2 Ma (Sarnthein et al., 2009).

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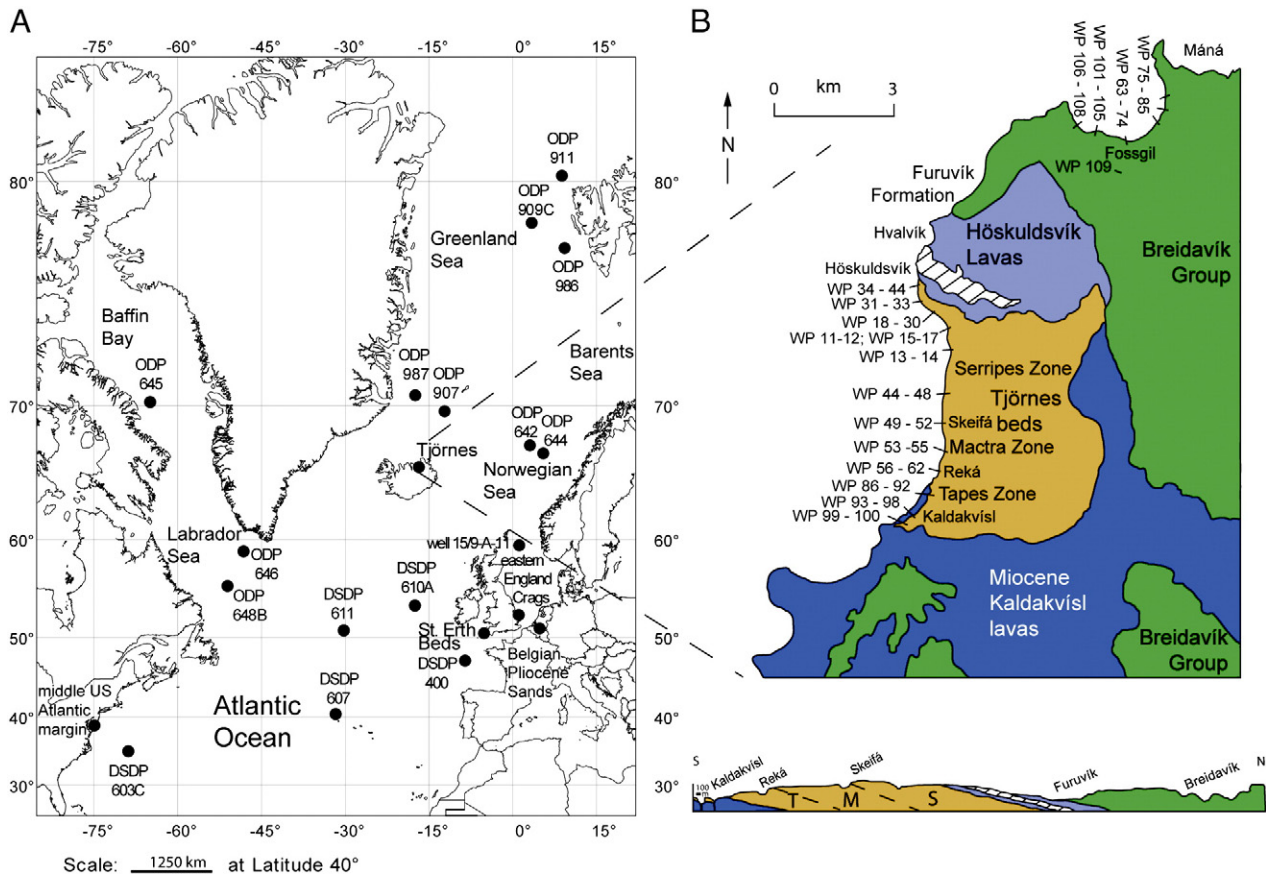
## 1. Introduction

The geological section at Tjörnes in northern Iceland (Fig. 1A and B) is an excellent natural archive to obtain insight into Icelandic and North Atlantic palaeoclimate and palaeoceanography during the Pliocene and Early Pleistocene (e.g. Cronin, 1991; Eiríksson et al., 1992; Buchardt and Símonarson, 2003; Símonarson and Eiríksson, 2008). The Pliocene is characterised by a climate warmer than today (e.g. Dowsett et al., 1996; Dowsett, 2007) and towards the end of the Pliocene by severe climate deterioration which marks the dawn of the Quaternary (e.g. Head et al., 2008 and references therein; Gibbard et al., 2010). Several palaeonto-

logical studies have focused on the Tjörnes section to document and understand the palaeoclimatic variability: e.g. studies on ostracods (Cronin, 1991), pollen (Schwarzbach and Pflug, 1957; Willard, 1994; Verhoeven and Louwye, 2010), plant macrofossils (Windisch, 1886; Akhmetiev et al., 1975, 1978; Denk et al., 2005) and molluscan assemblages (Bárdarson, 1925; Strauch, 1972; Norton, 1975, 1977; Gladenkov et al., 1980; Símonarson and Eiríksson, 2008). Molluscan research allows division of the Tjörnes beds in three biozones: the *Tapes* Zone, *Macra* Zone and *Serripes* Zone (Figs. 1B and 2). The molluscan fauna from the *Tapes* Zone have an Atlantic character, but a few warm-water species with Pacific ancestry occur also. At the boundary between the *Macra* Zone and the *Serripes* Zone, a massive invasion of cold-water (boreal) North Pacific molluscs occurs. This is explained by the re-opening of the Bering Strait (Einarsson et al., 1967), and later by the shoaling of the Central American seaway (Marincovich, 2000;

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**Fig. 1.** A: Location of the Tjörnes section and the North Atlantic Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) sites. B: Geological map and cross section of the Tjörnes Peninsula, including sample locations and numbers (WP numbers). Modified after Einarsson et al. (1967) and Eiríksson (1981b). The reversely magnetised middle part of the Höskuldsvík lavas is indicated in white with diagonal lines.

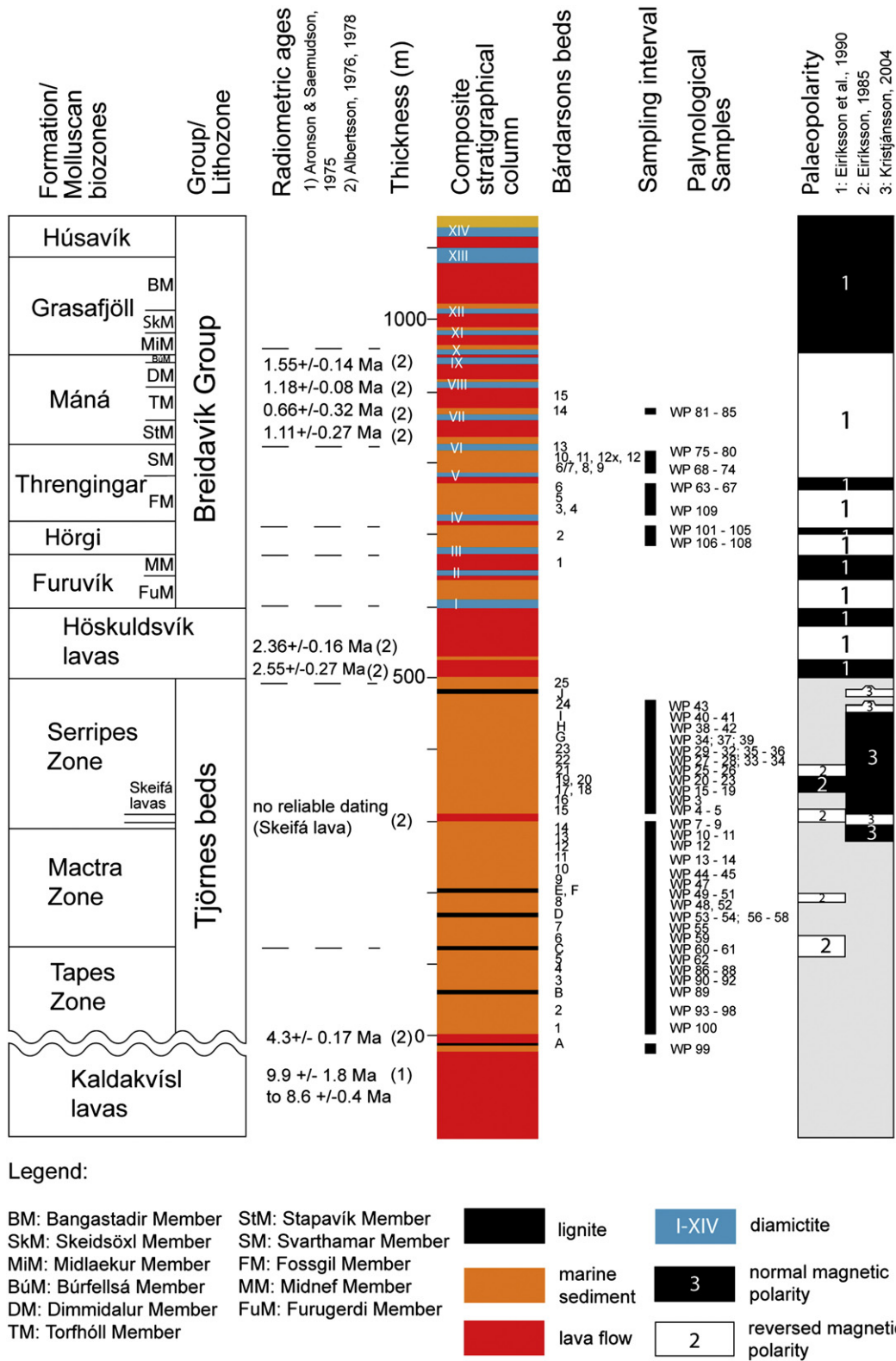
Simonarson and Eiríksson, 2008). The shoaling limits the exchange between equatorial Pacific and Atlantic waters and fauna and leads to a changed ocean circulation pattern (e.g. Driscoll and Haug, 1998). The Bering Strait then remained the only connection between both oceans in the northern hemisphere. Another consequence of the shoaling of the Central American seaway is that water flowed unidirectionally through the Bering Strait from the Pacific over the Arctic to the Atlantic and caused a faunal migration (Marincovich, 1999, 2000). Stable isotope studies on bulk samples of molluscan shells in the *Serrripes* Zone of the Tjörnes beds (Buchardt and Simonarson, 2003) demonstrate that the massive invasion of cold-water Pacific species is not related with a sudden climate deterioration, as previously suggested by Strauch (1972). The invasion is therefore not simply a climatological signal, but rather a consequence of a changed ocean circulation pattern in which the Bering Strait opened and the cold Arctic Ocean worked as a filter (Simonarson and Eiríksson, 2008): only cold-water species could migrate and cross the Arctic Ocean.

Previous age models for the Tjörnes section have been based primarily on biostratigraphic correlations of the molluscan assemblages, magnetostratigraphy, and on bulk K/Ar datings of the lavas intercalated between the sedimentary units. Simonarson and Eiríksson (2008) demonstrate inconsistencies between the radiometric dating and magnetostratigraphic interpretation. Radiometric ages (K/Ar) are available from several lava flows in the section (Aronson and Sæmundsson, 1975; Albertsson, 1976, 1978; Fig. 2). According to these authors, the basaltic lavas of the Tjörnes sequence are difficult to date due to extremely low potassium content and hydrothermal alteration. The ages of the lavas, which are probably minimum ages according to Aronson and Sæmundsson (1975), give only indirect information about the time of deposition of the entire sedimentary

sequence because the magnitude of hiatuses between the lava flows and sedimentary deposits was not determined. The Tjörnes Peninsula lies in a tectonically active region which experienced subsidence during the Early Pliocene, followed by substantial uplift during the Late Pliocene and Pleistocene (e.g. Sæmundsson, 1974). Consequently, the sequence of the strata is interrupted by numerous faults and structural unconformities as well as erosional disconformities.

Due to the absence of reliable age tiepoints, earlier age models did not consider hiatuses. Consequently, the age model for the entire section requires verification with an independent dating method, which tests the concept of continuous sedimentation/accumulation and a complete palaeomagnetic record. For this purpose we analysed the dinoflagellate cyst assemblages from the Tjörnes section. Organic-walled dinoflagellate cysts have a dinosporin wall (Versteegh and Blokker, 2004) and are resistant to most chemical weathering, except that protoperidinioids are very susceptible to oxidation (e.g. Zonneveld et al., 2007). Furthermore, it is relatively easy to extract cysts from different marine sediment types, including heavily silicified deposits. During the last decades it has emerged that dinoflagellate cysts are an excellent tool for refining the Neogene stratigraphy and palaeoenvironmental reconstruction in the higher latitudes (e.g. Head, 1996; De Schepper and Head, 2009). Several dinoflagellate cysts identified as reliable stratigraphical markers in the Norwegian-Greenland Sea (69–80°N; Poulsen et al., 1996; Smelror, 1999; Channell et al., 1999b), the southern North Sea Basin and the eastern North Atlantic (50–54°N; De Schepper and Head, 2009; De Schepper et al., 2009; Head, 1993, 1996, 1998a,b; Louwey et al., 2004) occur also in the Tjörnes section and allowed accurate dating of the section.

The aim of this dinoflagellate cyst study is twofold. First, we attempt to constrain better the age of deposition of the sedimentary



**Fig. 2.** Schematic stratigraphical column of the Tjörnes sequence including the radiometric K/Ar dates ((1) Aronson and Sæmundsson, 1975; (2) Albertsson, 1976, 1978), the corresponding Bårdarsons beds, the sample position and number, and the palaeopolarity of (1) Eiríksson et al. (1990), (2) Eiríksson (1985) based on a compilation of data from Hospers (1953), Einarsson et al. (1967) and Gladenkov and Gurari (1976), and (3) Kristjánsson (2004). The lithology and stratigraphy of the Tjörnes beds are after Eiríksson (1981b); the lithology and stratigraphy of the Höskuldsvík lavas and the Breidavík Group are after Eiríksson et al. (1990).

units in the Tjörnes section. The dinoflagellate cyst biostratigraphic framework is consequently combined with the available palaeomagnetic polarity data and radiometric ages of the intercalated lava flows

in order to construct a new age model. Secondly, the precise timing of the Pacific molluscan invasion in the Tjörnes area is assessed and correlated with the climatic and palaeoceanographic changes.



## 2. Geological setting and previous age models for the Tjörnes section

### 2.1. Geological setting

A 1200 m thick sequence of Pliocene to Late Pleistocene sediments is exposed on the Tjörnes Peninsula in northeast Iceland (Eiríksson, 1981b, 1985; Thordarson and Höskuldsson, 2006). During the Plio-Pleistocene, subsidence near the Tjörnes Fracture Zone, which is part of the Mid-Atlantic Rift zone, created accommodation space in a tectonic graben structure, which is uplifted by 500–600 m during Late Pleistocene times (Einarsson et al., 1967; Sæmundsson, 1974). As a result, continental swamps to estuarine and littoral depositional environments are formed during the Pliocene and Pleistocene.

The deposits of the Tjörnes section crop out mainly north of a tectonic fault zone separating the sequence from a series of Miocene basalt flows, the Kaldakvísl lavas. A first lava bed is observed at the very base of the sedimentary sequence near the fault zone. A second Pliocene lava bed (dated  $4.3 \pm 0.17$  Ma; Albertsson, 1976) occurs higher, but still near the base of the Tjörnes section north of the faults at the Kaldakvísl river (Eiríksson, 1981b). The Tjörnes section itself can be divided into three units: two sedimentary units, the Tjörnes beds and the Breidavík Group, separated by basaltic lava flows, the Höskuldsvík lavas (Figs. 1 and 2). The Tjörnes beds consist of an alternation of marine sediments (sandstones, mudstones, and conglomerates), terrestrial deposits (lignites, sandstones, and shales) and magmatic deposits (basalt lava). The Tjörnes beds generally display a dip of 5–10° NW. The Tjörnes beds have a thickness of about 520 m and consist mainly of marine coastal sediments (Buchardt and Simonarson, 2003). Bárðarson (1925) divides the Tjörnes beds into 25 distinct shell-bearing beds (1–25) and ten terrestrial or estuarine beds (A to J) (Fig. 2). Molluscan biostratigraphy divides the Tjörnes beds into three easily recognised biozones: the *Tapes* Zone (beds 1–5 of Bárðarson, 1925), the *Macra* Zone (beds 6–12) and the *Serripes* Zone (beds 13–25). With time, these biozones became established as informal lithostratigraphical units.

Buchardt and Simonarson (2003) and Simonarson and Eiríksson (2008) reconstruct the regional sea level changes during the Pliocene based on the palaeoenvironmental interpretation of the molluscan assemblages and a lithofacies analysis. The interplay between basin subsidence and sedimentation gave rise to shallow marine environments such as marshes and tidal flats. Estuarine and shallow sublittoral environments developed when subsidence increased and the sediment supply reduced. Most probably, water depths during deposition of the Tjörnes beds are never more than c. 50 m (Buchardt and Simonarson, 2003; Simonarson and Eiríksson, 2008). The entire *Tapes* Zone and the lower half of the *Macra* Zone consist of shallow tidal flat and continental swamp deposits (Simonarson and Eiríksson, 2008). Sandstones, lignites and a few conglomerates occur within this interval. Increased subsidence during the deposition of the upper *Macra* Zone and the lower *Serripes* Zone gave rise to the deepest sedimentary environments of the Tjörnes beds, with cross-bedded sandstones deposited in a sublittoral environment. During the deposition of the upper *Serripes* Zone, the subsidence decreased as a result of uplift of the area, and an estuarine environment with muddy and sandy sediments developed.

The Breidavík Group was deposited during the cooler conditions of the Pleistocene. Based on sedimentological studies and interpretation of marine faunal assemblages, Eiríksson et al. (1990, 1992) recognised 14 glacial–interglacial sedimentary cycles in the group (Fig. 2). In these cycles diamictites from different glacial processes alternate with interglacial marine deposits and basalts. An angular unconformity where the strike changes from 40° to 90° and the dip from 8° NW to 2° N is observed at the base of Hörgi Formation within the Breidavík Group, changing to a NW strike and a dip of 4° NE above the Hörgi Formation. Reworked clasts from the Pliocene Tjörnes beds occur in

the Breidavík Group sediments above the Hörgi unconformity (Bárðarson, 1925) indicating uplift and erosion.

### 2.2. Palaeomagnetic studies and existing age models for the Tjörnes section

The Tjörnes section has been studied since the 18th century (see Eiríksson, 1981a for an overview). The earliest palaeomagnetic studies on the magmatic deposits of the Tjörnes sediments were done by Hospers (1953). The measurements of the thermo-remnant magnetism of the lava flows were carried out in the field with a small portable magnetometer on oriented hand specimens, without demagnetising the rocks. Later, palaeomagnetic investigations using modern techniques were carried out to re-examine the Tjörnes section (Einarsson et al., 1967; Doell, 1972). Einarsson et al. (1967) develops the first age model based on the correlation of palaeopolarity data with the international palaeomagnetic timescale (Fig. 3). The lack of calibrated tie-points within the section allowed alternative interpretations. A first interpretation assumes a complete palaeomagnetic record, whereas a second assumes that the Jaramillo normal Subchron is missing. The only normally magnetised lava flow low in the Breidavík sequence, corresponding to the upper part of the Fossgil Member, is correlated with the Jaramillo Subchron in the first alternative but with the Olduvai Subchron in the second alternative (Fig. 3). Einarsson et al. (1967) propose their second alternative to be most plausible, because the sedimentary sequence and the assumed time of deposition correspond best. One problem with both alternatives is that they infer a period of about 800 ka for the deposition of the Fossgil Member, which has a thickness of only about 50 m (Eiríksson, 1981b). With the exception of the second alternative of Einarsson et al. (1967), the existing age models (Albertsson, 1978; Simonarson and Eiríksson, 2008) start from the idea of a nearly continuous sedimentation without major hiatuses.

The K/Ar dates obtained by Aronson and Sæmundsson (1975) and particularly Albertsson (1976, 1978) provide the necessary tie-points for more recent age models. However, some of these ages are difficult to reconcile with the palaeomagnetic data (Simonarson and Eiríksson, 2008). The first K/Ar dating of the Kaldakvísl lavas in the Tjörnes Peninsula indicates a Miocene age of  $9.9 \pm 1.8$  and  $8.6 \pm 0.4$  Ma (Fig. 2; Aronson and Sæmundsson, 1975). A large time gap between the Kaldakvísl lavas and the unnamed lava layer ( $4.3 \text{ Ma} \pm 0.17$ ) at the base of the *Tapes* Zone was demonstrated by Albertsson (1976). The Skeifá pillow lavas below in the *Serripes* Zone could not be dated with the K/Ar method. For the Máná basalt, Albertsson (1976, 1978) records four age estimates between  $0.66 \text{ Ma} \pm 0.32$  and  $1.55 \text{ Ma} \pm 0.14$ . In the Höskuldsvík lavas, the reversed magnetised basalt at Hvalvík and the normal magnetised basalt at Höskuldsvík have ages of respectively  $2.36 \text{ Ma} \pm 0.16$  and  $2.55 \text{ Ma} \pm 0.27$ . As a consequence, the Matuyama/Gauss boundary is placed in between both lava flows (Albertsson, 1976, 1978). Although the age of the Tjörnes beds was not mentioned, stratigraphic continuity between the Höskuldsvík lavas and the Tjörnes beds was assumed.

Albertsson (1976, 1978) correlates the Skeifá pillow lava either with the Kaena ( $3.032$ – $3.116$  Ma; Lourens et al., 2005) or the Mammoth reverse Subchron ( $3.207$ – $3.330$  Ma). Albertsson (1976, 1978) does not identify the Jaramillo Subchron in the Tjörnes section, but supposes it to be present somewhere in the Máná Formation. The uppermost normal magnetised lavas from the Höskuldsvík lavas are correlated with the Réunion Subchron. In Albertsson's scheme, part of the Furuvík Formation and the Hörgi Formation correlate most likely with the Olduvai Subchron. The normal polarity in the Fossgil Member can then possibly be correlated with the Cobb Mountain Subchron ( $1.173$ – $1.185$  Ma, Lourens et al., 2005). This implies a long depositional time for the Fossgil Member, comparable with both correlations of Einarsson et al. (1967).

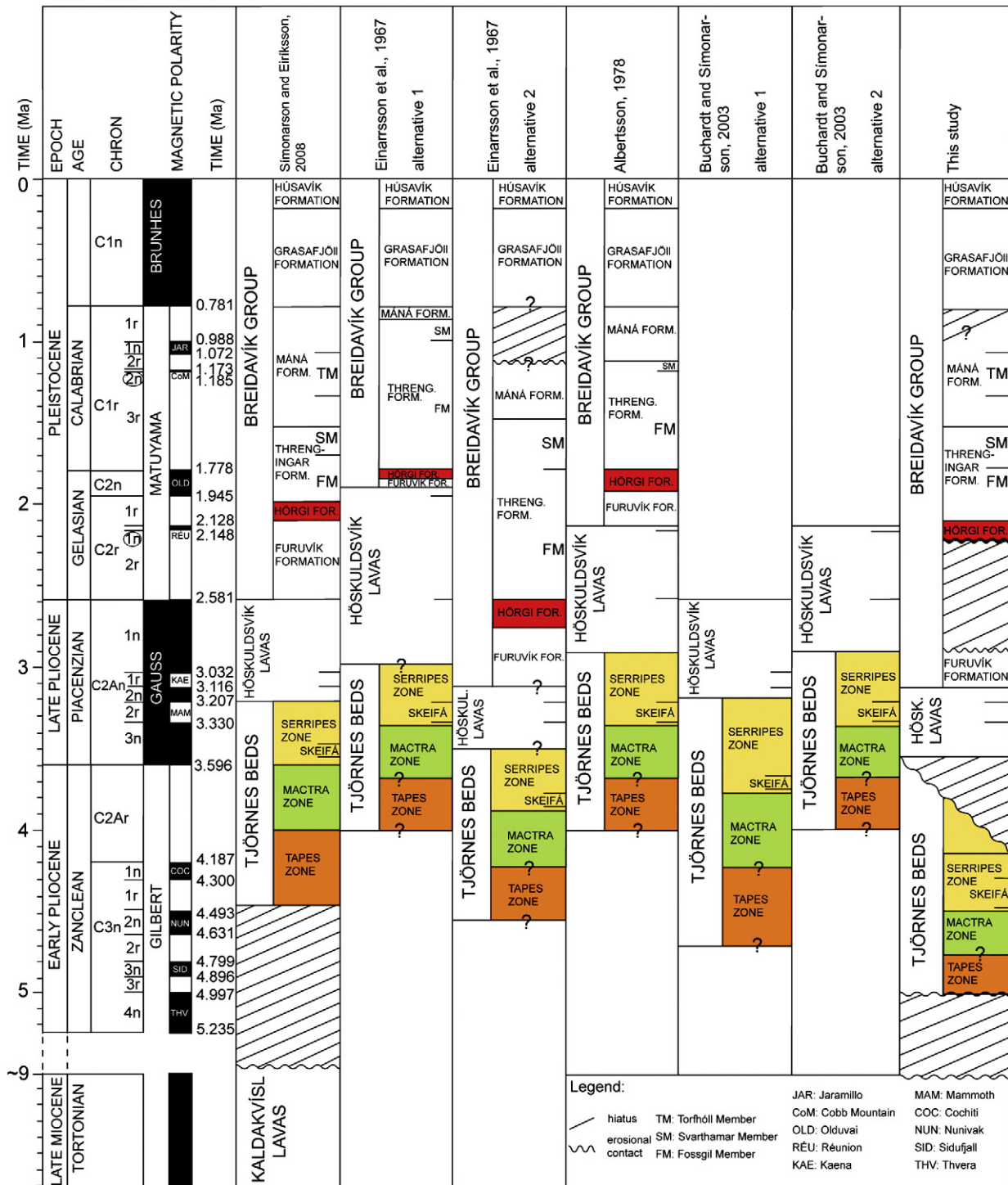


Fig. 3. Comparison of former age models from the Tjörnes section with the new age model. The units are correlated with the Astronomically Tuned Neogene Time Scale (ATNTS2004, Lourens et al., 2005) based on the palaeomagnetic polarity correlations of each author.

Eiríksson et al. (1990) indicate for the first time a reversed magnetic signal for the siltstones of the Furugerdi Member (lowermost part of the Furuvík Formation, Breidavík Group). This unit is situated in between the above-lying Midnef Member and under-lying Höskuldsvík lavas, which both contain a normal polarity magnetic signature (Fig. 2). This polarity reversal between the Höskuldsvík lavas and the base of the Breidavík Group is correlated by Simonarson and Eiríksson (2008) with the Gauss/Matuyama boundary (2.581 Ma; Lourens et al., 2005). As a consequence, the reversely magnetised Höskuldsvík lavas at the Hvalvík locality are correlated with the Kaena

Subchron, the upper part of the Serripes Zone corresponds to the Mammoth Subchron and the reversely magnetised Skeifá pillow lavas to the uppermost part of the Gilbert Chron. Eiríksson et al. (1990) also detect a normally magnetised sandstone just below the lava layer above the Hörgi Formation. This normally magnetised interval is not taken into account in the correlation of Simonarson and Eiríksson (2008). They place the Hörgi Formation in the reversed interval between the Réunion and Olduvai Subchron. In this correlation, the Höskuldsvík lavas at Hvalvík and Höskuldsvík appear to be c. 650 Ky older than what the K/Ar ages indicate.

Eiríksson et al. (1990) provide a detailed record of the magnetic polarities of the Breidavík Group and Höskuldsvík lavas, but such a record is not available for the underlying Tjörnes beds. Only few lava layers occur in the Tjörnes beds, limiting magnetostratigraphic interpretations. In order to complete the palaeomagnetic record, Kristjánsson (2004) made several reliable measurements from non-magmatic sediments from the *Serripes* Zone and *Macra* Zone, notwithstanding a less stable and intense signal compared to measurements of the Breidavík Group lavas. In layers I & J of the *Serripes* Zone, reversed polarities were measured and the reversed magnetisation of the Skeifá lavas as measured by Doell (1972) was confirmed (Fig. 2). Also, the sediments a few metres below the Skeifá lavas showed a reverse polarity, whereas the lower sediments in the *Serripes* Zone have a normal polarity. In total, four polarity reversals were observed by Kristjánsson (2004), from which the upper three were already known from the work of Gladenkov and Gurari (1976). Kristjánsson (2004) does not propose an age model, but suggested that the magnetic polarity of the sediments between the Höskuldsvík and Skeifá lavas is not in conflict with the suggestion by Buchardt and Símonarson (2003) that these sediments belong to the Gauss Chron.

### 3. Materials and methods

The samples for palynological analysis were collected during a field campaign in September 2007 from the cliffs of the Tjörnes Peninsula and from the Fossgil brook valley (Figs. 1B and 2). The NW dipping layers were sampled from successive vertical sections along the cliffs. The precise stratigraphic position of the samples was determined with the guide horizons from the litholog of Buchardt and Símonarson (2003, Fig. 2) and the stratigraphical framework of Bárðarson (1925). The sampling locations were positioned with a Garmin® GPS II Plus receiver (see Supplementary data).

Each layer was sampled at least once, with the exception of the difficult accessible uppermost lignite layer J and the littoral layer 25. The average stratigraphical distance between two successive samples within a formation is 6.5 m, with a minimum of 0.4 m and a maximum of 45.8 m, depending on the stratigraphical thicknesses of the different layers. A total of 68 samples were analysed from the Tjörnes beds and twenty samples from the interglacial sediments of the Breidavík Group (Fig. 2). From the fourteen glacial/interglacial cycles, four cycles were selected for palynological study because of their distinct marine lithofacies: the near-shore marine interglacial sediments from the third cycle (Hörgi Formation), the fourth cycle (Fossgil Member), the fifth cycle (Svarthamar Member) and the seventh cycle (Torfhóll Member) (Fig. 2).

Samples of 50 to 90 g were crushed into fragments of maximum 0.5 cm in a mortar and oven-dried for 24 h at 58 °C. One *Lycopodium clavatum* marker tablet (Batch 483216;  $n = 18,583 \pm 1708$  spores/tablet) was added to the dried sample. Carbonates were removed with cold 2 M HCl (6.1%) and the residue was rinsed until neutral. Silicates were dissolved with 100 ml cold 40% HF for a maximum of four days. Between three and seven cycles of 500 ml cold 2 M HCl were needed to remove the newly formed silica gel. When necessary, the cold HF and 2 M HCl cycle was repeated. For three sets of samples (Table 1) specific gravity separation with  $ZnCl_2$  ( $\rho = 1.93$  kg/l) was used for the separation of newly formed insoluble minerals from the organic residue. The residues were sieved on a 10  $\mu$ m nylon screen to prevent the loss of small palynomorphs.

The eight lignite samples (Table 1) were treated with acetolysis, which is the standard maceration technique for pollen analysis. These slides will also be used for future pollen studies. A volume of 2 ml lignite with one *Lycopodium clavatum* marker tablet was treated with cold 10% KOH in order to desintegrate the humic acids. Carbonate and silicate minerals were removed with cold 2 M HCl and cold 40% HF before the acetolysis, which followed the classic Erdtmann methods with 1/10 sulphur acid ( $H_2SO_4$ ) and 9/10 acetic anhydride ( $C_4H_6O_3$ ).

After rinsing with ethanol, the residue was stained with safranin-O and mounted on slides with glycerine gelatin. The slides were investigated with a Zeiss® Axio Imager A1 light microscope. Photomicrographs were taken with an AxioCam MRC5 digital camera. When possible, a minimum of 300 dinoflagellate cysts was counted.

The nomenclature of the dinoflagellate cysts follows DINOFLAJ2 (Fensome et al., 2008) and De Schepper et al. (2004) for *Barssidinium pliogenicum*. The relative abundances of dinoflagellates are based on the sum of all in situ dinoflagellate cysts excluding the indeterminata. We follow the Astronomically Tuned Neogene Time Scale (ATNTS 2004) of Lourens et al. (2005) throughout the manuscript for all ages of the magnetic reversals in the Neogene and Quaternary. The recently ratified boundary of the base of the Quaternary at 2.581 Ma and the subdivision of the Pliocene into the Zanclean and the Piacenzian stages is adopted (Gibbard et al., 2010) (these references are not repeated below). All stratigraphic events from the literature were recalculated to the ATNTS 2004 of Lourens et al. (2005) in order to allow a regional comparison of the lowest and highest occurrences (LO and HO) of dinoflagellate cyst species (see Supplementary data for the species list).

### 4. Results

#### 4.1. General

Of the 88 analysed samples, 44 yielded less than 25 dinoflagellate specimens per sample (Table 1). Samples with almost no dinoflagellate cysts come from the lignites of the *Tapes* Zone and the *Macra* Zone, from the interval between halfway bed 7 and the top of bed 10 (*Macra* Zone), from the interval between beds 22 and 23 until the top of bed 24 (*Serripes* Zone) and from the Fossgil Member (Fig. 2). Twenty-four samples yielded between 25 and 100 dinoflagellate cysts per sample, only twenty samples contained more than 100 dinoflagellate cysts. The highest observed absolute abundance was 1,148 cysts/g in sample WP 55 from the *Macra* Zone (Fig. 2, Table 1), but the majority (78%) of the samples have an absolute abundance below 50 cysts/g.

A selective taphonomic process was most probably not responsible for the low dinocyst concentrations. We based this on the fact that the heterotrophic, protoperidinioid cysts – taxa which are well preserved in the Tjörnes section – are prone to selective degradation through oxidation (Zonneveld et al., 2007). Furthermore, the heterotrophic species recorded in the Hörgi Formation still possess their brown, original colour of the cyst wall, and thus did not show any signs of bleaching through oxidation.

The low concentrations contrast sharply with the present-day observations on the northern and western Icelandic shelf. Marret et al. (2004) observed variable concentrations only occasionally below 1,000 and up to 256,920 cysts/g in sediment surface samples from the Icelandic shelf. Those samples were all collected in water depths between c. 104 and 1,800 m, considerably deeper than the inferred water depth of maximum 50 m for the Tjörnes beds (see Section 2.1). It is possible that a marginal marine environment shallower than 50 m constitutes an unfavourable environment for dinoflagellates. Indeed, two test samples (not reported here) from the Flatey borehole (Eiríksson et al., 1987) located c. 5 km off coast the Tjörnes cliffs, and thus representing a slightly deeper depositional environment, already yielded higher dinocyst concentrations of 1,135 cysts/g and 4,259 cysts/g.

It has also been demonstrated that comparing dinoflagellate cyst concentrations based on different laboratory methods can be problematic (Mertens et al., 2009), but given the large concentrations differences between Marret et al. (2004) and this study we assume the low concentrations in the Tjörnes section to be a true signal. This is most likely attributed to environmental factors, more specifically the shallow water depth. The estuarine deposits in the upper *Serripes* Zone are barren. Apart from the unfavourable estuarine environment



for dinoflagellates, the high energy in such an environment most probably prevented sedimentation of small particles such as dinocysts.

A total of 54 in situ dinoflagellate cyst species from 27 genera are recognised in the Tjörnes section (see Supplementary data for the species list). Limited reworking of Cretaceous to Miocene species is identified from the *Serripes* Zone upwards (Table 1). Reworked specimens of *Areoligera* sp. (Cretaceous–Miocene; Plate 2, Fig. O), *Spinidinium* sp. (Cretaceous–Oligocene), *Spiniferites* sp. (Cretaceous–recent) and *Cleistosphaeridium placacantha* (Miocene) may be due to the erosion of Cretaceous to Miocene sediments on Iceland. However, there are only few pre-Pliocene marine sediments on Iceland and reworked species such as *Chatangiella* sp. (Plate 2, Fig. P) and *Sepispinula anconiferum* have a restricted range in the Upper Cretaceous. These are too old to originate from the maximally 25 Ma old island (Thordarson and Höskuldsson, 2006). Therefore, it is very likely that all reworked taxa were brought to the depositional area via marine currents or as ice rafted debris.

#### 4.2. Stratigraphically significant dinoflagellate cysts

The stratigraphic range of dinoflagellate cyst species is rarely synchronous on a global scale and therefore comparison with regional biostratigraphic events in the North Atlantic is preferred (Fig. 4). The record of DSDP Hole 610A (Rockall Trough, eastern North Atlantic) offers a good reference biozonation (De Schepper and Head, 2008, 2009), which is directly correlated with calcareous microfossil biozonations, the  $\delta^{18}\text{O}$ -isotope record and the magnetostratigraphical timescale. This zonation is used as a basis for correlations, but additional information was obtained from records in the Norwegian–Greenland Sea (e.g. Mudie, 1989; Channell et al., 1999b; Smelror, 1999; Eidvin et al., 2007), western Europe (Head, 1993, 1996, 1998a, b; De Schepper et al., 2004; Louwye et al., 2004; De Schepper et al., 2009; Louwye and De Schepper, 2010), the central Atlantic (Mudie, 1987) and western Atlantic (de Vernal and Mudie, 1989a,b; Head et al., 1989; de Verteuil and Norris, 1996; Head and Norris, 2003).

##### 4.2.1. Tjörnes beds

As mentioned before, the Tjörnes beds are divided into three molluscan biozones: the *Tapes* Zone, *Maetra* Zone and *Serripes* Zone. Although dinoflagellate cyst stratigraphy could not differentiate these zones, it was possible to demonstrate that the Tjörnes beds are most likely younger than Miocene, and older than c. 3.8 Ma (Fig. 5). This dating places the entire unit in the Zanclean (Early Pliocene).

The genera *Barssidinium* and *Brigantedinium* – both recorded in the Tjörnes beds – are characteristic elements of shallow water dinoflagellate cyst assemblages. In this way, the dinoflagellate cyst assemblage (Plate 1, Table 1) from the Tjörnes beds resembles the Pliocene palynoflora of the southern North Sea Basin (Head, 1998a,b; Louwye et al., 2004; De Schepper et al., 2009). The assemblage in the base of the *Tapes* Zone consists of long-ranging species such as *Spiniferites ramosus* and *Brigantedinium cariacense*, and species with a HO in the Pliocene or Pleistocene such as *Barssidinium pliogenicum*, *Batiacasphaera minuta*, *Echinidinium euaxum*, *Filisphaera filifera* subsp. *filifera*, *Habibacysta tectata* and *Trinovantedinium glorianum*.

Noteworthy is the absence from the Tjörnes beds of species with a known Miocene HO in the North Atlantic region. *Labyrinthodinium truncatum* subsp. *truncatum*, *Hystrichosphaeropsis obscura* and *Selenopemphix armageddonensis* are considered to be reliable markers for the Miocene. *Labyrinthodinium truncatum* subsp. *truncatum* is a good marker for the Upper Miocene (see review in Louwye and De Schepper, 2010) with a HO at c. 7.5 Ma (US Atlantic margin; de Verteuil and Norris, 1996), at c. 9.6 Ma (Norwegian–Greenland Sea, ODP Hole 909C; Poulsen et al., 1996) and at 6.46 Ma (off East Greenland, ODP Site 987; Channell et al., 1999b). *Hystrichosphaeropsis obscura* has a HO at c. 7.5 Ma (de Verteuil and Norris, 1996), at c.

6.4 Ma (Poulsen et al., 1996) and at c. 5.4 Ma (off NW Morocco; Warny, 1999). Around the Miocene/Pliocene boundary, the HO of *Erymnodinium delectabile* (c. 6 Ma; de Verteuil and Norris, 1996), and *Achomosphaera* sp. 1 (c. 5.7 Ma; Poulsen et al., 1996; c. 5.3 Ma, M. Smelror, pers. communication 2010) are recorded in the Atlantic and/or Norwegian–Greenland Sea. *Barssidinium evangelinae* has a HO in the Tortonian at c. 7.2 Ma, offshore Eastern Canada (Lentin et al., 1994). *Selenopemphix armageddonensis* is recorded in the Tortonian (11.61–7.25 Ma) of Italy (Zevenboom, 1995), and probably persists until the end of the Miocene. The few Pliocene records of the latter species are considered as reworking by Louwye and De Schepper (2010). *Pyxidinospis pastiliformis* is common in the Upper Miocene of the Labrador Sea (Matsuoka and Head, 1992), and absent in the Pliocene. A HO of the latter species is known just below the Miocene–Pliocene boundary in the Western North Atlantic in DSDP Hole 603C (M. J. Head, pers. communication 2011). The absence of the above-mentioned dinoflagellate cysts suggests a post-Miocene age for the Tjörnes beds. However, a terminal Miocene age cannot entirely be excluded since our reasoning relies on the absence of index species, or – in other words – on a negative evidence. However, the assumption about an Early Pliocene age is corroborated by the K/Ar age of the unnamed lava bed at the base of the *Tapes* Zone (4.3 Ma  $\pm$  0.17; Albertsson, 1976).

In the Tjörnes beds, the biostratigraphically indicative species *Reticulatosphaera actinocoronata*, *Operculodinium tegillatum* and *Batiacasphaera minuta* were recorded. *Reticulatosphaera actinocoronata* was recorded up to bed 17 of the *Serripes* Zone (WP 16), two beds higher than the Skeifá lavas, but stratigraphically lower than the recorded HO of *B. minuta* and *O. tegillatum*. The latter species were present up to the middle part of the *Serripes* Zone (Fig. 4), up to sample WP 28 (between beds 21 and 22 of Bárðarson, 1925; Fig. 2).

*Reticulatosphaera actinocoronata* occurred until the top of bed 17 in the lower part of the *Serripes* Zone. *R. actinocoronata* is considered as a biostratigraphical marker for the Zanclean ranging no higher than c. 4.4 Ma (Louwye et al., 2004). *R. actinocoronata* is recorded near the top of the Molo Formation (mid-Norwegian continental shelf) in the Lower Pliocene (4–5.3 Ma; Eidvin et al., 2007). Mudie (1989) records the HO of *R. actinocoronata* in the Gilbert Chron (C2Ar) around 4.14 Ma in ODP Hole 642 C (Vøring Plateau, Norwegian Sea). As Mudie (1989) only provides presence/absence data, it is not possible to judge whether this highest appearance might be caused by reworking or not. The age of 4.14 Ma however is probably too young since comparable HO datums of c. 4.5 and 4.44 Ma are observed in the middle latitudes (DSDP Site 611; Mudie, 1987) as well as in the higher latitudes near Greenland (ODP Site 987; Channell et al., 1999b). In ODP Site 907, Poulsen et al. (1996) recorded a HO at c. 10.0 Ma in the C5n.2n Chron (9.987–11.040 Ma; Channell et al., 1999a). The discrepancy of this record may be attributable to an incorrect palaeomagnetic interpretation. Near Svalbard in the northernmost Atlantic, a HO of 5.05 Ma is found in ODP Hole 909C (Poulsen et al., 1996). In the Pliocene of northern Belgium, *R. actinocoronata* is recorded until the top of the Kattendijk Formation (Louwye et al., 2004; De Schepper et al., 2009). Beds 13–17 of the *Serripes* Zone, in which *R. actinocoronata* was recorded, were deposited in a much more energetic environment compared to the top of the *Maetra* Zone (Eiriksson, 1981b). Reworking of the species from the *Maetra* sediments however appears unlikely. The basin was at the time not subjected to uplift and it is not very likely that wave currents alone caused a reworking of *Maetra* sediments.

*Operculodinium tegillatum* has a HO at 3.71 Ma in the North Atlantic (DSDP Hole 610A; De Schepper and Head, 2008; ODP 646B; de Vernal and Mudie, 1989a). This species has a highest common occurrence of 3.98 Ma in the western Atlantic at DSDP Hole 603C, but occurred in low abundances until its HO of 3.59 Ma (De Schepper and Head, 2008). In eastern England, *O. tegillatum* occurs in the top of the Sudbourne Member of the Corraline Crag, but is absent from the

**Table 1**  
Raw counts of the in situ and reworked dinoflagellate cysts and fresh water algae in the Tjörnes section. Details about the applied laboratory treatments are given. Lignites are indicated with horizontal light grey bars.

		stratigraphy and molluscan biozones		G.P.S. Way Point: sample number		Bardonsöns beds		thickness, m		sediment		Laboratory		Dinoflagellate cysts					
		Torhöll Member		Svarthamar Member		Fossgil		Hörgi Formation		Serrripes Zone		Mactra Zone		Tapes Zone					
		WP	no.	depth	unit	lit.	type	no.	unit	lit.	type	no.	unit	lit.	type	no.	unit	lit.	type
		WP 82	14	889.8	S	x		1	55.6	587	2								
		WP 83	14	888.5	M	x		1	54.4	1185									
		WP 84	14	883.5	M	x		1	50.7	1360									
		WP 85	14	878.9	M	x		1	63.1	307	4	1							
		WP 77	12	835.0	C	x		1	63.8	565	4	2							
		WP 69	10	823.4	M	x		1	44.3	190	4								
		WP 70	10	819.8	M	x		1	54.2	281	11	4							
		WP 71	10	817.2	M	x		1	46.6	2643	4								
		WP 73	8	816.3	M	x		1	66.7	4227	1								
		WP 68	8	813.0	S	x		1	53.1	3848	5	3	1						
		WP 67		782.0	M	x		1	58.1	1347									
		WP 109		778.0	M	x		1	62.3	2242	13								
		WP 101		769.0	M	x		1	48.0	2697	12	2							
		WP 108		765.0	S	x		1	56.9	1506	28	7							
		WP 102		762.1	M	x		1	48.5	2471	1	1							
		WP 107		758.0	S	x		1	58.6	833	14								
		WP 103		753.0	M	x		1	41.9	1072	4								
		WP 104		752.5	M	x		1	54.6	1161	6	1							
		WP 106		750.0	S	x		1	52.1	450	1	2							
		WP 105		744.0	M	x		1	40.7	1529	3								
		WP 43	24	478.0	CSW	x		1	39.1	1716									
		WP 40		477.6	M	x		1	60.0	3864									
		WP 42	H	476.7	M	x		1	48.6	1005									
		WP 38	H	462.8	CSW	x		1	72.3	2003									
		WP 37	G	452.6	M	x		1	41.8	895									
		WP 36	23	449.8	SH	x		1	43.6	1411									
		WP 31	22/23	447.0	CS	x		1	63.6	1187									
		WP 27	22	442.6	S	x		1	37.8	2361	1								
		WP 28	21/22	439.4	S	x		1	59.4	2137	1	10							
		WP 32	?	439.3	S	x		1	51.6	204									
		WP 24	21/22	427.2	S	x		1	62.2	1474	5								
		WP 33	?	426.5	SH	x		1	62.1	2489	2								
		WP 25	21	424.8	SH	x		1	66.5	3992	13	4							
		WP 26	20/21	424.4	S	x		1	52.1	2375	1	1							
		WP 23	20	423.7	SH	x		1	50.0	1269	15	2							
		WP 22	19/20	422.9	S	x		1	39.2	764	1	1							
		WP 21	19	422.2	SH	x		1	82.8	929	22								
		WP 20	18/19	420.0	S	x		1	49.0	2253	6								
		WP 19	18	417.6	SH	x		1	40.3	1262	7								
		WP 18	17/18	415.8	S	x		1	52.6	1261	18	1							
		WP 17	17/18	406.5	S	x		1	47.1	1176	3	1							
		WP 16	17	402.2	S	x		1	53.5	2397	4	1							
		WP 3	16	379.3	SH	x		1	44.1	1383									
		WP 4	15/16	375.8	S	x		1	48.7	617	9	3							
		WP 5	15	368.8	SH	x		1	50.5	1808	3								
		WP 6	14/15	367.9	S	x		1	67.8	488	5	12							
		WP 7	14	363.9	SH	x		1	53.9	591	2								
		WP 8	13/14	360.1	S	x		1	45.2	191	7	7							
		WP 9	13	359.2	S	x		1	70.5	151	24	35							
		WP 10	12/13	357.2	S	x		1	72.1	361	4	2							
		WP 11	12	356.0	S	x		1	56.0	1393									
		WP 12	11	350.0	SH	x		1	51.7	3139									
		WP 13	11	340.0	CS	x		1	41.7	3572	3	1							
		WP 14	11	330.0	S	x		1	69.0	3676	1								
		WP 44	10	295.0	SH	x		1	34.4	253									
		WP 45	10	291.2	S	x		1	52.3	288	1	1							
		WP 48	9	286.1	SH	x		1	41.6	1029	1								
		WP 46	9	277.8	SH	x		1	57.2	1282									
		WP 47	?	272.0	SH	x		1	46.8	184									
		WP 49	F	260.5	L	x		1	2.4	17									
		WP 50	F	252.0	M,P	x		1	33.8	5									
		WP 51	E	244.0	CS	x		1	50.0	478									
		WP 52	8	230.0	SH	x		1	74.3	656	4								
		WP 53	D	211.1	M,W	x		1	3.2	128	1	2							
		WP 56	D	207.9	L	x		1	3.5	35									
		WP 54	D	203.7	L	x		1	34.2	77	1								
		WP 57	7	195.3	S	x		1	46.8	566									
		WP 58	7	188.0	M,W	x		1	3.4	1080									
		WP 55	7	185.0	S	x		1	38.2	25	8	9							
		WP 59	6	183.0	S	x		1	42.8	428	9	13							
		WP 60	C	145.0	L	x		1	2.4	51									
		WP 61	C	144.0	S	x		1	31.7	1248	5								
		WP 62	5	129.0	S	x		1	43.9	1620									
		WP 86	4	83.2	S	x		1	47.7	1306	2								
		WP 87	4	78.0	S	x		1	49.7	846									
		WP 88	4	69.0	S	x		1	49.5	697									
		WP 89	B	68.0	L	x		1	2.4	2									
		WP 90	3	66.2	S	x		1	49.9	149	6								
		WP 91	3	65.1	S	x		1	38.0	531	3								
		WP 92	c	45.0	L	x		1	2.5	6									
		WP 93	2,b	36.2	L	x		1	2.6	6									
		WP 94	2	35.3	S	x		1	48.7	343	18								
		WP 95	2	29.4	S	x		1	38.4	1850									
		WP 96	2,a	22.4	L	x		1	2.4	8									
		WP 97	2	20.4	S	x		1	32.5	222	3								
		WP 98	2	13.7	S	x		1	60.2	516	2								
		WP 100	1	5.0	S	x		1											





overlying Walton Crag (Fig. 6; Head, 1998a). In the Pliocene of northern Belgium, *O. tegillatum* is recorded in the Kattendijk Formation, but absent in the overlying Lillo Formation (Louwye et al., 2004; De Schepper et al., 2009).

*Batiacasphaera minuta* has a HO in the eastern North Atlantic at 3.83 Ma in DSDP Hole 610A (De Schepper and Head, 2008, 2009). In the Belgian Pliocene the species is considered in situ in the Kattendijk Formation (De Schepper et al., 2009). de Vernal and Mudie (1989a) report *B. minuta* in the Labrador Sea DSDP Hole 646B until c. 3.7 Ma, and in the western North Atlantic *B. minuta* shows a HO at 3.74 Ma (DSDP Hole 603C, De Schepper and Head, 2008).

The biostratigraphical significant dinoflagellate cysts placed the studied part of the Tjörnes beds into the RT1 and/or RT2 biozones of De Schepper and Head (2009) as defined in the Rockall Trough (DSDP Hole 610A, Fig. 4). The upper boundary of the RT2 biozone corresponds with an age of 3.83 Ma, which is therefore the minimum age for the interval between beds 21 and 22, that is the highest stratigraphical level in which *Batiacasphaera minuta* and *Operculodinium tegillatum* are recorded together. As the uppermost layers J and 25 of the Tjörnes beds (Fig. 2) were not sampled, and the layers in between layers J and 21 are barren of dinoflagellate cysts, we cannot unquestionably demonstrate a Zanclean age for the top of the Tjörnes beds based on the dinoflagellate cyst stratigraphy.

#### 4.2.2. Breidavík Group: Hörgi Formation

A clear shift was observed between the Early Pliocene palynoflora of the Tjörnes beds and the early Quaternary flora of the Breidavík Group. The dinoflagellate assemblage from the Hörgi Formation, up to bed 10 of Bárðarson (1925) of the Svarthamar Member (Fig. 2), was dominated by *Operculodinium centrocarpum* s.s. (average 43%), *Spiniferites* spp. (average 8%) and *Lingulodinium machaerophorum* (average 6%). From bed 10 of Bárðarson (1925) on, the assemblage became dominated by cysts of *Pentapharsodinium dalei* (average 52%), *Bitectatodinium tepikiense* (average 15%), *O. centrocarpum* sensu Wall and Dale (1966) (average 11%) and *S. elongatus* (average 2%) (Plate 2J–L). Heterotrophic protoperidinioid species were present up to the Hörgi Formation (Plate 2A–H, Table 1). These fragile species did not occur in large quantities but were nevertheless well preserved (Plate 2A–E). The good preservation of these non-dominant species and their corresponding stratigraphical range are indicative of an in situ occurrence. Reworked Neogene dinoflagellate cysts were present in small quantities in the Breidavík Group: one single badly preserved specimen of *Operculodinium tegillatum* (sample WP 103; Plate 2H), some specimens of the robust species *Reticulatosphaera actinocoronata* (samples WP 106, 108, 102; Plate 2F) and one specimen of *Melitasphaeridium choanophorum*, sample WP 106.

Age diagnostic dinoflagellate cysts indicated that the Hörgi Formation have an Early Pleistocene Gelasian age, older than the Olduvai Subchron, likely around ca. 2.0 Ma (Fig. 5). *Barssidinium pliogenicum* was conspicuously present up to the upper Hörgi Formation. In the southern North Sea Basin, *B. pliogenicum* occurs up to the top of the Piacenzian Lillo Formation (De Schepper et al., 2009; Fig. 6). Younger Gelasian marine deposits are absent in northern Belgium (Laga et al., 2001). In the same basin *B. pliogenicum* is recorded only at the base of the late Piacenzian Walton Crag, the lowermost subdivision of the Red Crag (Fig. 6) at Walton-on-the-Naze, eastern England (Head, 1998b). In the adjacent Channel Basin in southwest England, it is found in the Gelasian St. Erth Beds which were deposited in a short period sometime between c. 2.1 and

1.95 Ma (Head, 1993). Head et al. (2004) finds the species in the Gelasian Nordland Group mudstones in the northern North Sea, dated with foraminifera to 2.4–1.8 Ma. Together with *Echinidinium euaxum*, the same authors consider the species in the Nordland Group as reworked. This interpretation may need to be revised, given the range of this species in southeast England up to 1.95 Ma. Furthermore, Smelror (1999) records *B. pliogenicum* continuously until seismic reflector 6 on the Svalbard-Barents Shelf margin (ODP Site 986). Applying the age model of ODP Site 986 (Knies et al., 2009) this record provides a HO of 2.17 Ma for the species.

Other heterotrophic species regularly occurring in the Tjörnes beds were found sporadically in the Hörgi Formation. *Selenopemphix dionaeacysta* and *Trinovantedinium glorianum* (Plate 2B) both have a HO in the Gelasian and do not occur higher than the base of the Olduvai Subchron in the northern hemisphere mid-latitudes. In the Ludham borehole both species are present during the Early Pleistocene Thurnian pollen stage around 2.2 Ma (Head, 1996, 1998a). In the Channel Basin, *S. dionaeacysta* is recorded in the St. Erth Beds which have a comparable Thurnian/Tiglian age (2.1–1.95 Ma; Head, 1993). In the eastern North Atlantic, *S. dionaeacysta* is recorded sporadically and in small numbers within the Gauss Chron at ODP Hole 610A up to 2.69 Ma (De Schepper and Head, 2009). On the Svalbard margin (ODP Site 986), Smelror (1999) recorded the HOs of *S. dionaeacysta* at c. 3.05 Ma and *T. glorianum* at c. 3.13 Ma according to the age model of Knies et al. (2009). *T. glorianum* occurs sporadically at DSDP Hole 610A and its HO is located at 2.30 Ma in the lower Matuyama Chron (De Schepper and Head, 2009).

*Echinidinium euaxum* occurs in the St. Erth Beds in the Channel Basin (2.1–1.95 Ma, Head, 1993). The species is also found in the Deurganck Dock and in the Verrebroek Dock up to the Piacenzian Kruisschans Sands Member (Louwye et al., 2004). Head et al. (2004) found a HO of the species in the Upper Gelasian deposits (1.8–2.4 Ma) of well 15/9-A-11 in the northern North Sea. It appears to be characteristic for inner neritic/shallow marine environments (Head, 1993).

A single specimen of *Operculodinium? eirikianum* var. *eirikianum* was observed in the Hörgi Formation. The species has a HO at c. 2.3 Ma in the Ludhamian of eastern England (Ludham borehole; Head, 1996) and in the base of the St. Erth Beds (2.1–1.95 Ma; Head, 1993). Versteegh (1997) recorded a comparable HO of c. 2.34 Ma in DSDP Site 607 in the central North Atlantic Ocean. De Schepper and Head (2009) recorded a slightly older HO at 2.62 Ma in DSDP Hole 610A.

The record of *Habibacysta tectata* in the Hörgi Formation seemed to exclude a post-Olduvai age for the unit since a HO of the species is found at 1.77 Ma in DSDP Hole 603C (Head and Norris, 2003), at c. 2.1 Ma in ODP Hole 911A (Matthiessen and Brenner, 1996) and at 2.08 Ma in DSDP Hole 610A (De Schepper and Head, 2009). However, rare and isolated finds of the species are known from DSDP Hole 610A up to c. 0.76 Ma and from ODP Hole 911A up to c. 1.1 Ma. It is not clear whether the latter records are due to reworking (De Schepper and Head, 2008). In the Norwegian Sea DSDP Hole 642B, the species occurs sporadically as high as MIS 19 (c. 0.75 Ma; Lourens et al., 2005) at the base of the Brunhes Chron (Mudie, 1989; De Schepper and Head, 2008).

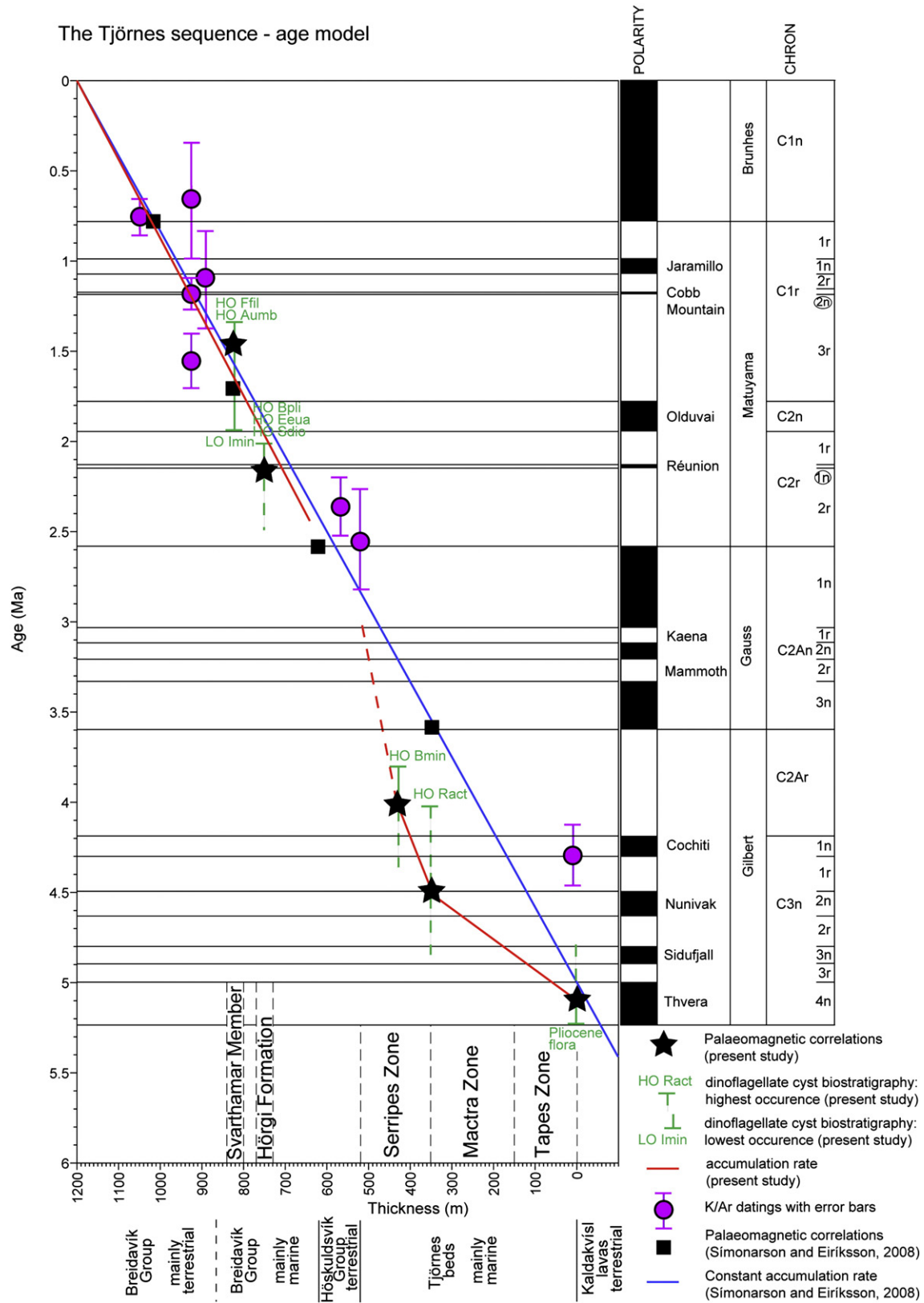
#### 4.2.3. Breidavík Group: Svarthamar Member (Threngingar Formation) and Torfhóll Member (Máná Formation)

Dinoflagellate cysts from both units suggested a Pleistocene age younger than the Olduvai Subchron. The Svarthamar Member is

**Fig. 4.** Age estimates for the lithological units of the Tjörnes sequence based on the biostratigraphical data of dinoflagellate cysts (right) and the magnetic palaeopolarity data (left). The position of selected biostratigraphical marker species in the Tjörnes section is compared with the biostratigraphical ranges of these species from northern hemisphere studies. Upward arrows = lowest occurrence, downward arrows = highest occurrence. DSDP Hole 607A, Mudie (1987) and Versteegh (1997); DSDP Site 611, Mudie (1987); ODP Hole 642C, Mudie (1989); DSDP Hole 603C, Head (unpubl. data in De Schepper and Head, 2008); ODP Site 986, Smelror (1999); DSDP Hole 610A, De Schepper and Head (2009); ODP Site 644, Mudie (1989); ODP Hole 645B, de Vernal and Mudie (1989b); ODP Hole 646B, de Vernal and Mudie (1989a).







**Fig. 5.** Combined dinoflagellate cyst and palaeomagnetic age model (in red, this study) for the Tjörnes section compared with the combined K/Ar and palaeomagnetic age model of Simonarson and Eiriksson (2008) (in blue). Dinoflagellate cysts: Ffil: *Filissphaera filifera* subsp. *filifera*; Aum: *Amiculosphaera umbraculum*; Bpli: *Barsidinium pliocenicum*; Eeua: *Echinidinium euaxum*; Sdio: *Selenopemphix dionaeacysta*; Imin: *Islandinium minutum*; Bmin: *Batiacasphaera minuta*; Ract: *Reticulatosphaera actinocoronata*.

possibly older than c. 1.4 Ma based on the HO of *Amiculospaera umbraculum* and *Filisphaera filifera* subsp. *filifera* (Fig. 5).

*Islandinium minutum* was recorded from the top of the Svarthamar Member (sample WP 69) to the base of the Torfhóll Member. de Vernal and Mudie (1989b) recorded in Baffin Bay (DSDP Site 645) the LO of the latter species in the Early Pleistocene. In the Labrador Sea (DSDP Site 646), the LO of *I. minutum* coincides most probably with the base of the NN19 calcareous nannofossil zone, at c. 1.95 Ma (de Vernal and Mudie, 1989a; Lourens et al., 2005). In the Norwegian Sea, Mudie (1989) finds a much younger LO around the Jaramillo Subchron (ODP Hole 643A, 1.072–0.988 Ma).

A single specimen of *Amiculospaera umbraculum* occurred at the base of the Svarthamar Member in the upper part of the Threngingar Formation (Figs. 2 and 4). The species has a HO in the Lower Pleistocene (DSDP Hole 400A, Harland, 1979), at 1.44 Ma in the eastern Atlantic Ocean (ODP Hole 610A; De Schepper and Head, 2008) and at c. 1.54 Ma in the Norwegian Sea (ODP Hole 644A; Mudie, 1989).

*Filisphaera filifera* subsp. *filifera* was rare in the Breidavík Group, and occurred for the last time in the middle of the Svarthamar Member in sample WP 71 (Figs. 2 and 4). Its HO in the Greenland–Norwegian Sea is at c. 1.4 Ma (M. Smelror, pers. comm. 2010). Channell et al. (1999b) record a HO at c. 2.0 Ma in the Greenland Sea at ODP Site 987.

The cold-water species *Spiniferites elongatus* occurred intermittently in the *Tapes* Zone and in the Hörgi Formation, but continuously from the upper part of the Svarthamar Member onwards (Fig. 4, Table 1). On the western Svalbard margin (ODP Site 986), the continuous occurrence of *S. elongatus* starts at c. 1.24 Ma (Smelror, 1999) using the age model of Knies et al. (2009), whereas the LO of *S. elongatus* in the eastern North Atlantic (DSDP Hole 610A; De Schepper and Head, 2009) is at c. 1.34 Ma. The species is already known from the Upper Miocene of the Pacific (Bujak and Matsuoka, 1986) and the Gelasian of eastern England (Head, 1996, 1998a), and may be under strong environmental control (De Schepper and Head, 2009).

## 5. Discussion

### 5.1. New age model for the Tjörnes section

#### 5.1.1. Dinoflagellate cyst data

The dinoflagellate cysts indicated an early to mid Early Pliocene (Zanclean) age for the Tjörnes beds. The base of the *Tapes* Zone is most likely post-Miocene (Table 2) and the middle part of the *Serripes* Zone is as young as 3.83 Ma (RT2 biozone of De Schepper and Head, 2009). This implies that the Tjörnes beds are considerably older than previously thought (Fig. 3).

An Early Pleistocene age older than the Olduvai Subchron (possibly c. 2.0 Ma) is proposed here for the Hörgi Formation (Breidavík Group), and corresponds well with the age estimate of Simonarson and Eiríksson (2008). The Early Pleistocene age of the Hörgi Formation is also corroborated by studies of the foraminifera and molluscs. Together with reworked Pliocene forms, K. Knudsen (pers. comm., 2010) found typical Quaternary foraminifera in the Hörgi Formation. The arctic bivalve *Portlandica arctica* occurs within the molluscan assemblage of the Hörgi Formation. The presence of this bivalve in the formation gives an extra argument for its Quaternary age as the species indicates rather cold temperatures at the time of deposition (Simonarson and Eiríksson, 2008). Nowadays, it is found only in cold waters around Greenland. The Hörgi Formation contains pre-Pliocene and Pliocene reworked dinoflagellate cysts. The presence of freshwater algae, such as *Pediastrum* sp. and *Botryococcus* sp., suggests that reworking may have been caused by riverine input in the near-shore depositional environment. The relative abundance of heterotrophic taxa is substantially lower than in the Tjörnes beds, indicating probably a changed depositional environment.

The extremely poor palynological record from the Fossgil Member, the lowest member of the Threngingar Formation, hampers a precise relative dating. In the overlying Svarthamar Member (Breidavík Group), the record of *Amiculospaera umbraculum* suggests a minimum age of this unit of ca. 1.44–1.54 Ma (Table 2). This age assessment is broadly corroborated by the HO of *Filisphaera filifera* subsp. *filifera* (c. 1.4 Ma in Norwegian Greenland Sea; M. Smelror, pers. comm. 2010) in bed 10 of the Svarthamar Member.

Abundant cysts of *Pentapharsodinium dalei*, *Bitectatodinium tepikiense*, *Spiniferites elongatus* and *Islandinium minutum* in bed 10 of the Svarthamar Member and higher in the sequence are indicative of an assemblage as found today in the region, where the appearance of *I. minutum* indicates cooling. The LO of *I. minutum* falls in the Olduvai Subchron in the Baffin Bay (de Vernal and Mudie, 1989b). This implies a post-Olduvai age for the upper part of bed 10 of the Svarthamar Member.

#### 5.1.2. A new correlation of the palaeomagnetic data

The new biostratigraphical dinoflagellate cyst data from the Tjörnes section enables a more precise correlation of the available palaeomagnetic data with the international polarity time scale (Fig. 4). Although the boundaries do not coincide exactly, both Gladenkov and Gurari (1976) and Kristjánsson (2004) recognise a reversed/normal/reversed polarity alternation between the Skeifá lavas and the top of the *Serripes* Zone (Fig. 2). The dinoflagellate data suggest a minimum age of 3.83 Ma for the middle part of the *Serripes* Zone, thus the normal polarity observed between the Skeifá lavas and layer I of the central part of the *Serripes* Zone can be correlated with the Cochiti normal polarity Subchron (4.187–4.300 Ma, C3n.1n). A correlation with the C2An.3n interval of the Gauss Chron (3.596–3.330 Ma, Fig. 4) is unlikely based on the dinoflagellate cyst evidence. The reversed polarity of the Skeifá lavas near the base of the *Serripes* Zone probably corresponded to the C3n.1r interval (4.493–4.300 Ma), in between the Cochiti and Nunivak normal polarity Subchrons. Although the magnetic signal is weak, beds 11 to 14 immediately below the Skeifá lavas (Fig. 2) have a normal polarity (Kristjánsson, 2004) and may correspond to the Nunivak Subchron (C3n.2n; 4.631–4.493 Ma). The boundary between the *Maetra* Zone and *Serripes* Zone was accordingly placed at c. 4.5 Ma (Table 2).

The reversed polarity signal at the top of the *Serripes* Zone (layers I & J of Bárðarson, 1925; in Kristjánsson, 2004; Fig. 4) was correlated with the C2Ar Subchron. The top of this zone thus has an age between 4.187 and 3.596 Ma. Based on the limited stratigraphical thickness of these sediments (c. 40 m on a total of 520 m for the entire Tjörnes beds) and the assumption of a continuous sedimentation rate, the top of the *Serripes* Zone could be dated to c. 4.0 Ma (Table 2). A concordant transition is observed between the Tjörnes beds and Höskuldsvík lavas and the sedimentology indicates increasing terrestrial input in the upper part of the *Serripes* Zone, induced by an increasing uplift of the area (Simonarson and Eiríksson, 2008). So alternatively, there was a very reduced sedimentation with negligible erosional gaps in the upper *Serripes* Zone, starting with layer I.

The palaeomagnetic reversals detected in the Höskuldsvík lavas were correlated with reversals within the Gauss Chron and more precisely with the reversed polarity interval corresponding to the Mammoth Subchron. The lava started to flow during early Piacenzian times (normal polarity Chron C2An.3n; 3.596–3.330 Ma), but could not be precisely determined. Nevertheless, this implies that an appreciable hiatus of c. 600 kyr up to maximally c. 900 kyr is present between the Early Pliocene Tjörnes beds (>4.187 Ma) and Höskuldsvík lavas (<3.330 Ma). If there was a reduced sedimentation rate for the upper *Serripes* Zone, this hiatus would be shorter. However, in both cases the exact Gilbert/Gauss boundary is not preserved in the Tjörnes section.

The Furuvík Formation lies concordant on the Höskuldsvík lavas and contains reversed polarity marine sediments at its base

corresponding to the Kaena Subchron, and normal polarity lavas at the top corresponding to the upper part of the Gauss Chron (C2An.1n, 3.032–2.581 Ma). According to the proposed correlation with the palaeomagnetic time-scale, the Furuvík Formation is older than 2.5 Ma. The lower marine part of the Furuvík Formation with a reversed polarity (Furugardi Member) was likely deposited during a (much) longer time span than the normally magnetised upper Furuvík lava (the Midnef Member). Although the latter lava bed is approximately 40 m thick, its deposition took probably not much time as it is to be expected for this kind of magmatic deposits. The top of the Furuvík Formation is therefore estimated to be situated between 2.6 and 3.0 Ma, but a precise age cannot be given.

The angular unconformity observed between the Furuvík Formation and the mainly reversely polarised Hörgi Formation (Einarsson, 1958) represents a hiatus that likely includes the Gauss/Matuyama boundary. The Hörgi Formation is estimated to be c. 2.0 Ma based on dinoflagellate cysts and the normally magnetised upper part of the Hörgi Formation could be correlated with the Réunion Subchron (2.128–2.148 Ma). A considerable time gap of 600 kyr up to c. 900 kyr would therefore separate the Furuvík Formation from the Hörgi Formation. The erosion is probably caused by a change in the uplift direction of the sedimentation basin (Einarsson et al., 1967).

Minor angular unconformities as a result from a gradual shift from a westerly to easterly tilt direction are also observed below the Svarthamar Member and the Bangastadir Member (Fig. 2), but the magnitude of the corresponding hiatuses is uncertain (Eiríksson, 1981b). Erosional unconformities are present at the base of each Breidavík Group cycle (Fig. 2) but are likely of little importance because of the completeness of the cycles (Eiríksson, 1981b).

The lava and siltstones with normal polarity of the Fossgil Member can be correlated to the Olduvai Subchron (C2n, 1.945–1.778 Ma). The overlying Svarthamar Member with a reversed polarity would hence have a post-Olduvai age, in agreement with the dinoflagellate data and consistent with the interpretation of Eiríksson et al. (1992). The absence of deposits with a normal polarity corresponding with the Jaramillo Subchron in the Máná Formation can be explained by erosion of the upper part of this formation or by the non-detection of the subchron as it represents only a rather short period of 84 kyr.

Throughout the whole Grasafjöll and Husavík Formation, Eiríksson et al. (1990) recognise normal polarities. Although these are not marine and thus barren of dinoflagellate cysts, a correlation to the Brunhes Chron is logical when taken into account their stratigraphical position.

### 5.1.3. K/Ar dated lava layers

The Early Pliocene age for the *Tapes* Zone (Tjörnes beds) based on dinoflagellate data identifies a marked hiatus with the underlying Kaldakvísl lavas, which are K/Ar dated to 9.9 ± 1.8 Ma and 8.8 ± 0.4 Ma (Aronson and Sæmundsson, 1975). The lava bed located close to the base of the Tjörnes beds in unit 1 of Bárðarson (1925) has a K/Ar age of 4.3 ± 0.17 Ma (Albertsson, 1976) but according to Eiríksson (1981b) this age should be considered as a minimum age. The age of 4.3 Ma does not conflict with the dinoflagellate cyst data, but

combined with the palaeomagnetic data the age seems to be a few hundred thousand years too young, leaving some uncertainty about the maximum age of the Tjörnes beds.

The dinoflagellate cyst record of the Tjörnes beds and Hörgi Formation broadly constrain the Höskuldsvík lavas between c. 3.8 and 2.0 Ma. The K/Ar ages from the Höskuldsvík lavas at the localities of Höskuldsvík (2.55 ± 0.27 Ma) and Hvalvík (2.36 ± 0.16 Ma) (Figs. 1B and 2; Albertsson, 1976, 1978) fall within this range. However, our correlation of the palaeomagnetic polarity data puts the reversed middle part of the Höskuldsvík lavas in the Mammoth Subchron (3.330–3.207 Ma), with an age of about 700 kyr older.

The K/Ar ages of the unnamed lava layer in the base of the Tjörnes beds and the Höskuldsvík lavas are too young compared to our palaeomagnetic correlation based on the dinoflagellate cyst biostratigraphy. This may be attributed to post-depositional argon loss caused by weathering. Furthermore, the K/Ar dating method has limitations because of the very different chemical affinities of potassium and argon and both elements must be measured on different samples with a different method. The K/Ar dating method is also less reliable when whole rock samples, rather than single minerals, are dated as it was the case with the low K-content samples from the Tjörnes basalts (Faure and Mensing, 2005).

### 5.2. Age model comparison

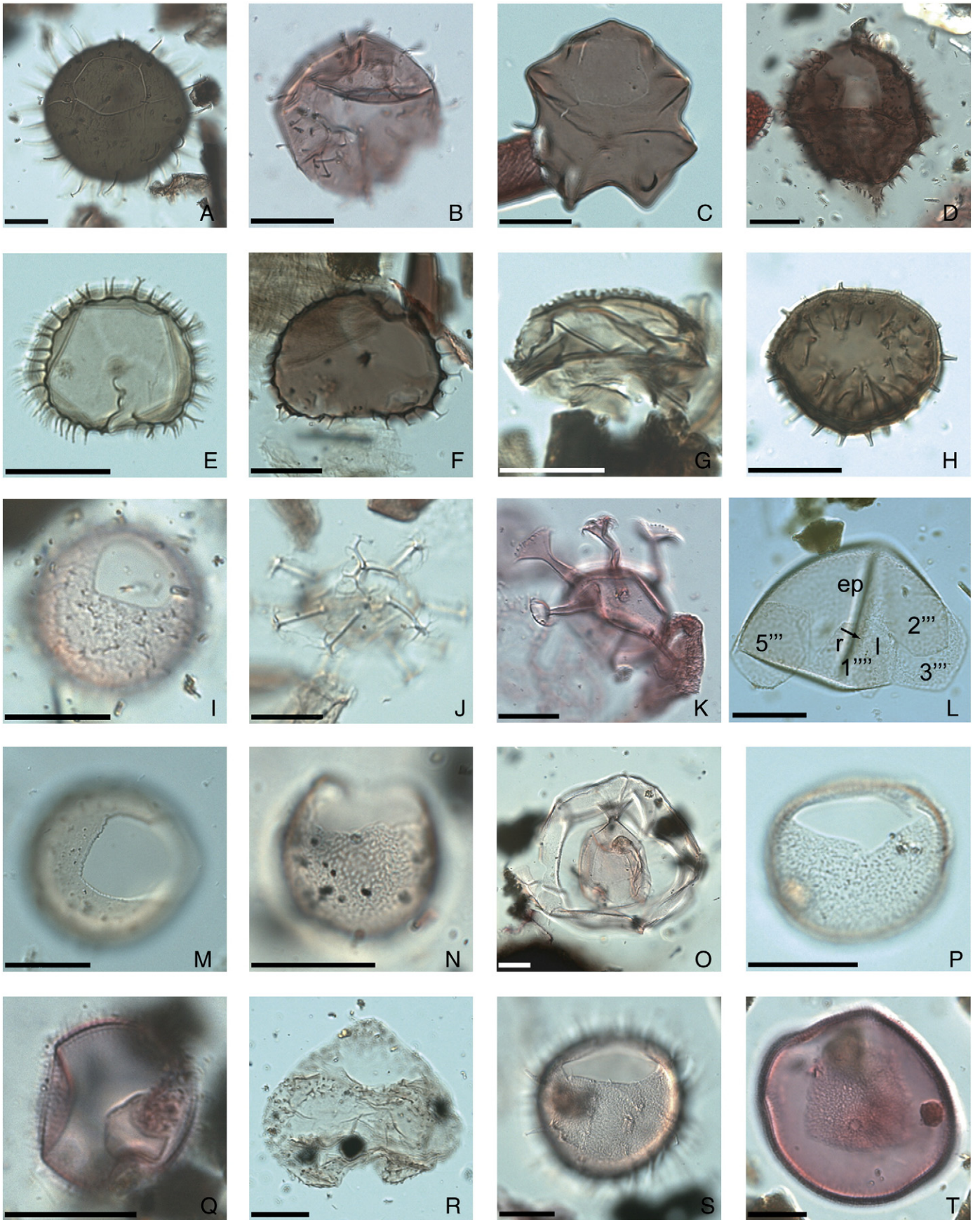
Our dinoflagellate cyst study indicates that the Tjörnes beds are likely considerably older than previously thought (Fig. 3). The new age model also identifies two major hiatuses of c. 600 kyr up to maximally c. 900 kyr, one between the Tjörnes beds and Höskuldsvík lavas, and one between the Furuvík and Hörgi Formations. Only the hiatus between the Furuvík and Hörgi Formations is confirmed by field observation by an angular unconformity between both formations. The large time gap between the middle part of the *Serripes* Zone (>3.83 Ma, upper Tjörnes beds) and the Höskuldsvík lavas can be attributed to an erosional hiatus, although a shorter time gap due to a very low sedimentation rate for the upper *Serripes* Zone could not be excluded (see Section 5.1.2). In any case, the assumption of a steady continuous sedimentation for the entire Tjörnes section (Einarsson et al., 1967; Albertsson, 1978; Buchardt and Símonarson, 2003) can no longer be supported (Fig. 6).

The proposed stratigraphic position of the Breidavík Group and the Höskuldsvík lavas corresponds best with the second alternative of Einarsson et al. (1967) (Fig. 3), with the notable exception of the introduction of a large hiatus between the Furuvík Formation and the Hörgi Formation in our study. Both alternatives of Einarsson et al. (1967) assume a long time of deposition for the Fossgil Member without hiatuses. According to our age model a hiatus is present between the Furuvík Formation and the Hörgi Formation.

The age models of Albertsson (1978), Buchardt and Símonarson (2003) and Símonarson and Eiríksson (2008) which use the K/Ar ages of Aronson and Sæmundsson (1975) and Albertsson (1976, 1978) as tie-points for the magnetostratigraphy always experience problems to fit their models to the geopolarity time scale. For example, the suggestion of Albertsson (1978; Fig. 3) to correlate the normal

**Plate 1.** Photomicrographs of selected biostratigraphical important dinoflagellate species from the Tjörnes beds. Scale bar: 20 µm. E.F.: England Finder coordinates. A: *Barssidinium pliocenicum*, sample WP97, E.F.: M46/0, *Tapes* Zone; B: *Trinovantedinium harpagonium*, sample WP6, E.F.: E31/0, *Mactra* Zone; C: *Lejeunecysta catomus*, sample WP59, E.F.: Y39/3, *Tapes* Zone; D: *Trinovantedinium glorianum*, sample WP4, E.F.: U37/0, *Tapes* Zone; E: *Selenopemphix dionaeocysta*, sample WP98, E.F.: H52/4, *Tapes* Zone; F: *Selenopemphix brevispinosa* subsp. *brevispinosa*, sample WP9, E.F.: Z54/3, *Serripes* Zone; G: *Selenopemphix brevispinosa* subsp. *conspicua*, sample WP55, E.F.: T52/0, *Mactra* Zone; H: *Echinidinium euaxum*, sample WP22, E.F.: Q50/0, *Serripes* Zone; I: *Operculodinium tegillatum*, sample WP5, E.F.: S39/0, *Serripes* Zone; J: *Reticulosphaera actinocoronata*, sample WP9, E.F.: E55/2, *Serripes* Zone; K: *Melittasphaeridium choanophorum*, sample WP6, E.F.: N29/2, *Serripes* Zone; L: *Capisocysta* sp. *C. lyellii?*, sample WP28, E.F.: P37/0, *Serripes* Zone, the epicyst = ep, the second, third and fifth postcingular plates (2", 3", 5") and the left and right first antapical homologues (1"l -1"r) and indicated. An arrow indicates the boundary between these two homologues; M: *Bitectatodinium? serratum*, sample WP23, E.F.: R48/0, *Serripes* Zone; N: *Batiacasphaera minuta*, sample WP4, E.F.: P39/0, *Serripes* Zone; O: *Amiculosphaera umbraculum*, sample WP4, E.F.: Q36/4, *Serripes* Zone; P: *Habibacysta tectata*, sample WP87, E.F.: Q62/4, *Mactra* Zone; Q: *Batiacasphaera hirsuta*, sample WP47, E.F.: W54/0, *Mactra* Zone; R: *Cristadinium* sp., sample WP5, E.F.: L31/0, slide2, *Serripes* Zone; S: *Operculodinium centrocarpum* s.s., sample WP59, E.F.: D51/2, *Mactra* Zone; T: *Filipsphaera filifera* subsp. *filifera*, sample WP18, E.F.: E41/1, *Serripes* Zone.







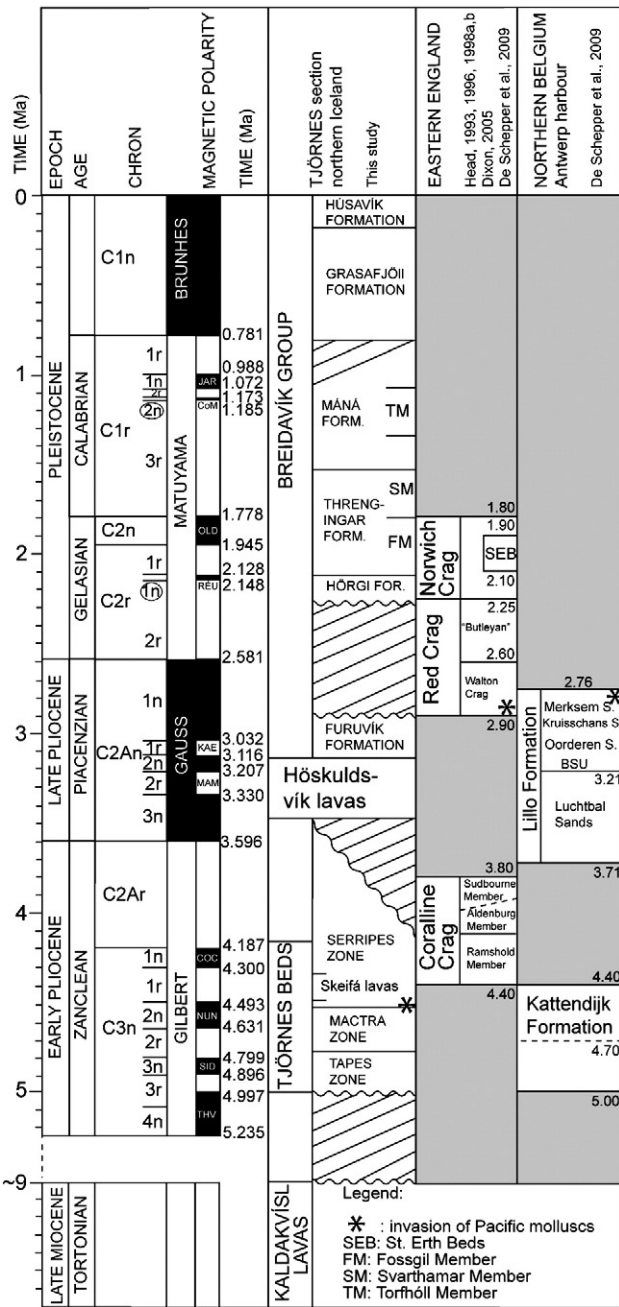


Fig. 6. Comparison of the Pliocene and Early Pleistocene deposits from the southern North Sea basin (northern Belgium and eastern England) with the Tjörnes section. Asterisks indicate the appearance of Pacific molluscs into the local assemblages.

polarity sediments of the upper Fossgil Member with the Cobb Mountain Subchron calls for a very rapid sedimentation of the Svarthamar Member and a condensed Fossgil Member. This suggests that the Fossgil Member may incorporate hiatuses although sedimentological data do not supported this idea.

Based on the Breidavík Group palaeomagnetic data of Eiríksson et al. (1990), Símonarson and Eiríksson (2008) correlate the normal to reverse polarity reversal at the base of the Breidavík Group in Furuvík with the Gauss/Matuyama boundary. As a consequence, the reversely magnetised lavas of Hvalvík correlate with the Kaena Subchron (3.032–3.116 Ma). The uppermost reversely magnetised sediments of the *Serripes* Zone were correlated with the Mammoth Subchron (3.207–3.330 Ma) and the top of the Skeifá lavas with the Gilbert/Gauss boundary (3.596 Ma). This correlation seems implausible based

on the dinoflagellate cysts which propose a minimum age of c. 3.8 Ma for the middle of the *Serripes* Zone.

That model also does not take into account the normal polarity at the base of the *Serripes* Zone and the top of the *Maetra* Zone (Kristjánsson, 2004). It also shows, but did not explain, the discrepancy in time between the radiometric age of 2.55 +/- 0.27 Ma for the lavas at Hvalvík and their correlation with the Kaena Subchron (3.032–3.116 Ma).

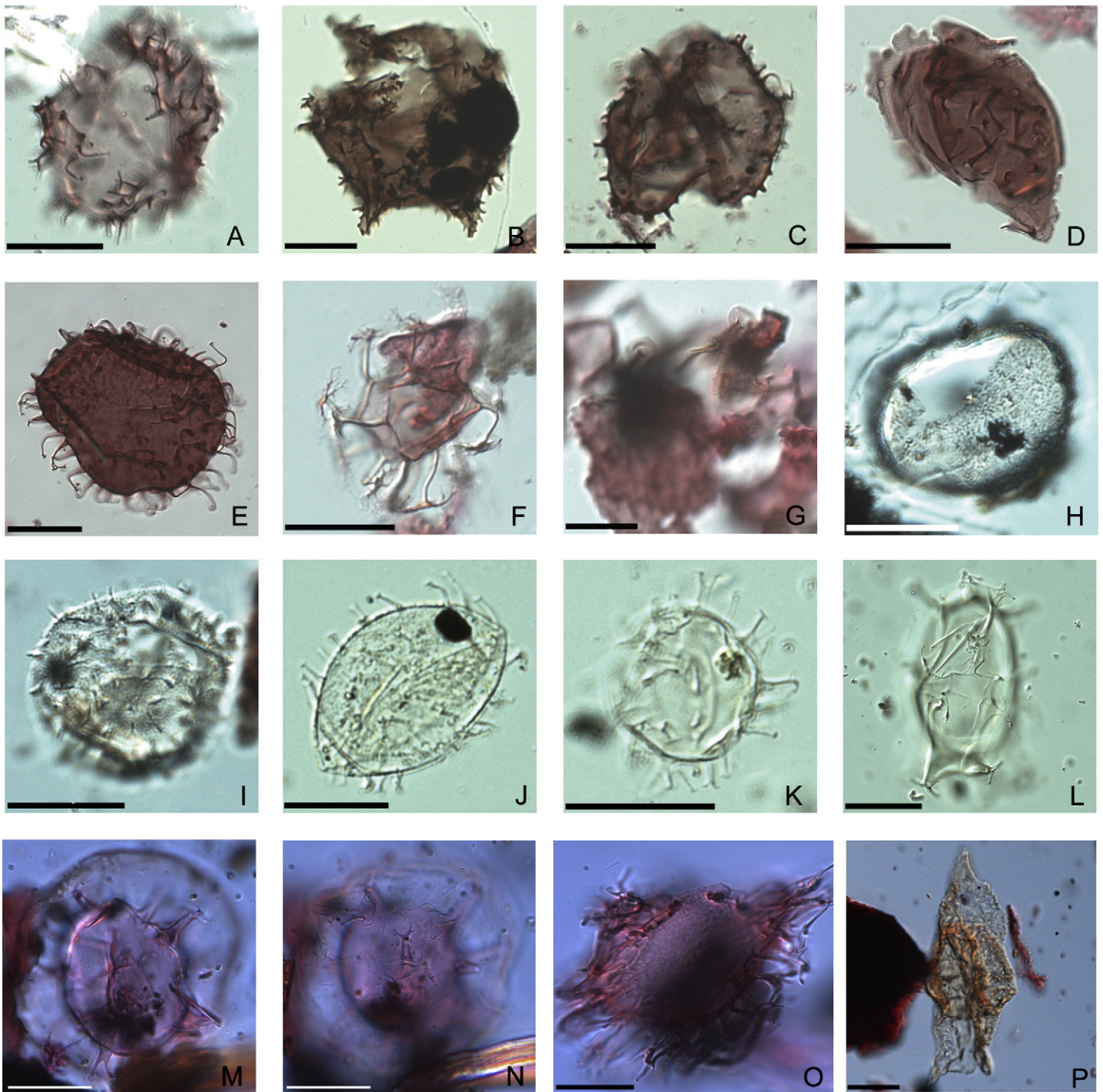
In summary, our new age model placed the Tjörnes beds in the Early Pliocene. Although no dinoflagellates from the Furuvík Formation were studied, a major hiatus between the Furuvík and the Hörgi Formation was proposed based on re-correlation of the palaeomagnetic data. The position of the Höskuldsvík lavas and the Furuvík Formation was based on the correlation of its palaeomagnetic data and the dinoflagellate cyts age estimates for the Tjörnes beds and Hörgi Formation.

5.3. Correlation with other North Atlantic units

The Pliocene marine deposits in northern Belgium and eastern England are bound by unconformities and are often deposited during short time intervals (Louwye et al., 2004; Dixon, 2005). Biostratigraphical analysis with dinoflagellate cysts in combination with sequence stratigraphy successfully shed light on the stratigraphical position of Pliocene deposits in England (Head, 1993, 1996, 1998a,b) and Belgium (Louwye et al., 2004; De Schepper et al., 2009; Louwye and De Schepper, 2010).

Several authors (Baden-Powel, 1955; Áskelsson, 1960a,b; Strauch, 1963; Durham and MacNeil, 1967; Norton, 1975, 1977) correlate the molluscan assemblage of the Pliocene deposits of eastern England with the *Tapes* and *Maetra* Zone of the Tjörnes beds. This correlation is based on the comparable Atlantic molluscan fauna, although a few warm-water molluscs of Pacific origin also occur in the Tjörnes beds. Einarsson et al. (1967) attribute the presence of these warm water molluscs to a Late Miocene migration from the Pacific to the Atlantic Ocean. The molluscs *Lentidium complanatum* and *Spisula arcuata* occur in the *Tapes* Zone and *Maetra* Zone and are considered by Harmer (1914–1925) as typical for the Coralline Crag, although in truth both species are also found in the younger Walton Crag (Norton, 1975, 1977). The dinoflagellate cysts suggested a correlation of the *Tapes* and *Maetra* Zones with the Kattendijk Formation (Belgium), but not with the younger Coralline Crag of eastern England (3.8–4.4 Ma in De Schepper et al., 2009; Fig. 6). In this study, we correlated the Coralline Crag with the *Serripes* Zone. The contradiction between mollusc and dinoflagellate cyst correlations is probably due to the absence of truly age-diagnostic molluscs in both units, the tendency of molluscs to be restricted to small faunal provinces bounded by latitudinal climate differences and climate-related diachronous appearances of molluscs (A. Johnson, pers. comm. 2010). This discrepancy was also observed in the North Sea Basin, where the molluscan assemblages of the Belgian Kattendijk Formation, Luchtbal Sands and the eastern England Coralline Crag compare well (Marquet, 1998), but their age estimates based on dinoflagellate cyst and sequence stratigraphy differ significantly (Louwye et al., 2004; De Schepper et al., 2009, Fig. 6).

The *Serripes* Zone is correlated with the Red Crag based on the LO of Pacific molluscs such as *Macoma praetenuis* and *Serripes groenlandicus* (Baden-Powel, 1955; Áskelsson, 1960a; Norton, 1977) and with the Merksem Sands Member of the Lillo Formation (Belgium) based on the LO of *M. praetenuis* (Norton, 1977). Our study demonstrated that the *Serripes* Zone is of mid-Zanclean age, whereas the Merksem Sands Member and Red Crag are of late Piacenzian age (Fig. 6; De Schepper et al., 2009). The latter two units both contain Pacific molluscs, which likely only arrived in the southern North Sea Basin around c. 2.9 Ma. This is about 1.6 Ma later than what is observed in the Tjörnes beds (Fig. 6). The idea of Norton (1977) of synchronous deposition within one wide-ranging faunal province can no longer be



**Plate 2.** Photomicrographs of selected biostratigraphically important dinoflagellate species from the Breidavík Group. Scale bar: 20  $\mu\text{m}$ . E.F.: England Finder coordinates. A: *Trinovantedinium harpagonium*, sample WP108, E.F.: Z63/3, Hörgi Formation; B: *Trinovantedinium glorianum*, sample WP107, E.F.: Q65/3, slide 2, Hörgi Formation; C: *Trinovantedinium ferugnomatum*, sample WP106, E.F.: X39/1, Hörgi Formation; D: *Echinidinium euaxum*, sample WP106, E.F.: Z59/0, Hörgi Formation; E: *Barssidinium pliocenicum*, sample WP108, E.F.: E42/2, Hörgi Formation; F: *Reticulosphaera actinocoronata*, sample WP106, E.F.: Y40/3, Hörgi Formation; G: *Melitaspheeridium choanophorum*, sample WP106, E.F.: V48/3, Hörgi Formation; H: *Operculodinium tegillatum*, sample WP103, E.F.: D53/0, Hörgi Formation; I: *Operculodinium? eirikianum* var. *eirikianum*, sample WP103, E.F.: E49/1, Hörgi Formation; J: *Operculodinium centrocarpum* sensu Wall & Dale (1966); sample WP84, E.F.: Z41/2, Torfhóll Member, Máná Formation; K: cyst of *Pentapharsodinium dalei*; sample WP84, E.F.: V49/0, Torfhóll Member, Máná Formation; L: *Spiniferites elongatus*, sample WP84, E.F.: D49/0, Torfhóll Member, Máná Formation. Reworked specimens: M–P; M–N: *Achromosphaera* sp., sample WP4, E.F.: T29/0, *Serripes* Zone; O: *Areligera* sp., sample WP105, E.F.: M49/0, Hörgi Formation; P: *Chatangiella* sp., sample WP103, E.F.: P34/0, Hörgi Formation.

maintained. More likely, the molluscan associations of the Tjörnes beds migrated southward towards the North Sea Basin during Late Pliocene times, when northern hemisphere cooling became more intense and likely also reached the North Sea.

The dinoflagellate cysts from the Hörgi Formation warranted a correlation with the St. Erth Beds (southwestern England). The latter beds have been dated with calcareous nannofossils, pollen and

planktonic foraminifera as of Gelasian age (2.1–1.95 Ma; Head, 1993). An equivalent in Belgium did not exist.

#### 5.4. Consequences for the Early Pliocene palaeoceanography

The molluscan fauna in the *Tapes* Zone and *Macra* Zone has a boreal North Atlantic character, but during deposition of the *Serripes*



**Table 2**

Age assessment of Pliocene and Pleistocene Formation/Member units and boundaries based on dinoflagellate cyst biostratigraphy in combination with a re-correlation of the palaeomagnetic polarity data.

Formation	Member	Dinoflagellate cyst biostratigraphy	Dinoflagellate cyst biostratigraphy + Palaeomag.	K/Ar
Máná	Torfhóll			1.55 +/- 0.14 Ma 1.18 +/- 0.08 Ma 0.66 +/- 0.32 Ma 1.11 +/- 0.27 Ma
Threngingar	Svarthamar	> 1.4 Ma < 1.95 Ma	1.78 Ma	
	Fossgil		2.13 Ma	
Hörgi		> 1.95 Ma		
Höskuldsvík lavas			c. 4.0 Ma	2.36 +/- 0.16 Ma 2.55 +/- 0.27 Ma
Serripes Zone		> 3.83 Ma > 4.40 Ma	c. 4.5 Ma	
Mactra Zone		?	?	
Tapes Zone				4.3 +/- 0.17 Ma
Kaldakvisl lavas		> 5.32 Ma		9.9 +/- 1.8 Ma 8.6 +/- 0.4 Ma

Zone, the fauna strongly diversified through the immigration of Pacific molluscs with arctic affinities (Símonarson and Eiríksson, 2008). Several species found in the lowermost part of the *Serripes* Zone have an obvious North Pacific origin and migrated via the Arctic Ocean into the North Atlantic (Durham and MacNeil, 1967). Such migrations must have taken place at a time when the Arctic Ocean was ice-free and warmer than today, because nowadays some of the migrating taxa do no longer range far north (Einarsson et al., 1967; Símonarson and Eiríksson, 2008).

Early molluscan migrations are identified in the *Tapes* Zone and *Mactra* Zone of the Tjörnes beds, but the numbers of warm-water Pacific species are limited (Einarsson et al., 1967; Símonarson et al., 1998; Marincovich and Gladenkov, 1999). During this initial phase some species arrive gradually through the northern route from the Pacific to the Atlantic Ocean. An abrupt invasion of Pacific molluscs in the Tjörnes section is observed a few metres below the Skeifá lavas at the *Mactra/Serripes* Zone boundary (Fig. 2; Maier-Reimer and Mikolajewicz, 1990; Marincovich, 2000). Einarsson et al. (1967) link this invasion to the opening of the Bering Strait at c. 3 Ma. Símonarson and Eiríksson (2008) in turn place this invasion event in their age model around 3.6 Ma.

An intermittent connection between the Arctic Ocean and the Pacific via the Bering Strait existed probably already in the Early Miocene (Polyakova, 2001). The first complete flooding of the strait is dated to 5.5–5.4 Ma (Marincovich and Gladenkov, 1999; Gladenkov et al., 2002; Gladenkov, 2006), when global sea-level was considerably higher than today, up to some 50 m above present-day level (Miller et al., 2005). At first, the flow through the Bering Strait was southwards, from the Atlantic over the Arctic to the Pacific, but after 3.6 Ma a northward flow becomes evident through the sudden appearance of molluscs with Pacific affinity in the North Atlantic (Marincovich, 2000; Marincovich and Gladenkov, 2001; Matthiessen et al., 2009).

Marincovich (2000) estimates the appearance of the bivalve *Mya arenaria* in the Pliocene North Sea Basin deposits of Belgium (Lillo Formation; Vermeij, 1989), The Netherlands (van der Burg, 1987), England (Coralline Crag; Jenkins and Houghton, 1987) and the Tjörnes beds in Iceland (alternative 1 of Einarsson et al., 1967) at around 3.6 Ma. As discussed above, dinoflagellate cyst stratigraphy indicated that the Pliocene deposits within the southern North Sea are not time equivalent (De Schepper et al., 2009; Fig. 6) and that both the

Coralline Crag and Tjörnes beds are of Zanclean age, i.e. older than 3.6 Ma. The invasion of Pacific molluscs into the North Atlantic occurred near the *Mactra/Serripes* Zone boundary, dated to c. 4.4–4.5 Ma according to our age model. Thus, the invasion occurred considerably earlier than assumed until now.

Strauch (1972) believed that the molluscan invasion in the Tjörnes beds was caused by a major cooling event, but isotopic research on molluscs in Tjörnes do not confirm this hypothesis (Buchardt and Símonarson, 2003). Our new age estimate of c. 4.4–4.5 Ma for the invasion of Pacific molluscs near the *Mactra/Serripes* Zone boundary is more in tune with the major oceanic circulation changes observed in the Early Pliocene. Between 4.7 and 4.2 Ma, a salinity contrast between the Pacific and Caribbean is established because the shoaling of the Central American seaway passes a critical threshold (Haug et al., 2001; Steph et al., 2006). This resulted in a major reorganisation of the northern hemisphere ocean circulation, increased thermohaline circulation (e.g. Haug and Tiedeman, 1998) and possibly doubled the Arctic through-flow from the Bering Strait to the Norwegian–Greenland Sea (Sarnthein et al., 2009). Moreover, between 4.5 and 4.4 Ma, sea level remained c. 20 m higher than today (Miller et al., 2005), facilitating a continuous migration through the Bering Strait.

In summary, North Pacific molluscs arrived gradually in Iceland during the deposition of the Early Pliocene *Tapes* Zone and *Mactra* Zone as a result of the northward flow of Pacific waters through the Bering Strait to the North Atlantic. The major invasion of Pacific molluscs is recorded at the base of the *Serripes* Zone at c. 4.5 Ma. The timing corresponds well with the changed ocean circulation in the northern hemisphere related to the shoaling of the Central American seaway.

## 6. Conclusions

Our biostratigraphic analysis with dinoflagellate cysts from the Tjörnes beds and the Breidavík Group allowed a relative dating of the deposits and a comparison with biozones from the Atlantic realm. Biostratigraphic key species (*Batiacasphaera minuta*, *Operculodinium tegillatum* and *Reticulosphaera actinocoronata*) and palaeomagnetic data demonstrated that the Tjörnes beds were deposited between c. 5.3 Ma (post-Miocene) and c. 3.8 Ma, possibly even 4.0 Ma. The age of the base of the Tjörnes beds was most probably post-Miocene, but this hypothesis was based on negative evidence whereby a latest Miocene age cannot be excluded. This date is nevertheless considerably older than previously assumed for the Tjörnes beds (Fig. 3). The Breidavík Group is of Quaternary age and its dinoflagellate cyst assemblage is dominated by *Operculodinium centrocarpum* s.s., *O. centrocarpum* sensu Wall and Dale (1966), *Bitectatodinium tepikiense*, *Spiniferites elongatus* and cysts of *Pentapharsodinium dalei*. The presence of *Barssidinium pliogenicum*, *Trinovantedinium glorianum* and *Selenopemphix dionaeacysta* in the Hörgi Formation gives a minimum age of c. 2.0 Ma to the formation. A post-Olduvai, Early Pleistocene age can be proposed for the Svarthamar Member of the Threngingar Formation based on the LO of *Islandinium minutum*. The latter unit is likely older than 1.4 Ma, based on the HO of *Filisphaera filifera* subsp. *filifera* and *Amiculosphaera umbraculum*.

A new age model was constructed based on the dinoflagellate cyst data and the re-interpretation of the palaeomagnetic data. It became evident that the assumption of a continuous sedimentation for the Tjörnes section (Einarsson et al., 1967; Albertsson, 1978; Buchardt and Símonarson, 2003; Símonarson and Eiríksson, 2008) can no longer be supported (Fig. 6). Two intervals of strongly reduced deposition rates or even hiatuses occur in the Tjörnes section: a lower hiatus between the Tjörnes beds and the Höskuldsvík lavas and a second hiatus between the Furuvík and Hörgi Formations. Both hiatuses represent a span of time of c. 600 kyr up to maximally c. 900 kyr.

The massive invasion of Pacific molluscs at the base of the *Serripes* Zone was located in the Nunivak Subchron, around 4.5 Ma. This

implies that Pacific waters flowed northward through the Bering Strait into the Arctic and North Atlantic already during the Zanclean, almost 1 Myr earlier than previously assumed (c. 3.6 Ma). The dating of the invasion by Pacific molluscs at 4.5 Ma fits well with other observed changes in northern hemisphere ocean circulation that are related to the shoaling of the Central American seaway between 4.7 and 4.2 Ma (Haug and Tiedeman, 1998; Haug et al., 2001; Steph et al., 2006; Sarnthein et al., 2009).

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## References

- Akhmetiev, M.A., Golubeva, L.V., Skiba, L.A., 1975. Palaeobotanical characteristics of the main section of the Plio-Pleistocene deposits on Tjörnes peninsula, North Iceland. Proceeding of the USSR Academy of Sciences, Geological Series 7, 100–107 (in Russian).
- Akhmetiev, M.A., Bratoeva, G.M., Giterman, R.E., Golubeva, L.V., Moiseyeva, A.I., 1978. Late Cenozoic stratigraphy and flora of Iceland. Transactions Academy of Sciences of the USSR Soviet Geophysical Committee. 316 pp.
- Albertsson, K.J., 1976. K/Ar ages of Pliocene–Pleistocene glaciations in Iceland with special reference to the Tjörnes sequence, northern Iceland. PhD thesis University of Cambridge, 268 pp.
- Albertsson, K.J., 1978. Um aldur jarðlaga á Tjörnesi. Náttúrufróedingurinn 48, 1–8.
- Aronson, J.L., Sæmundsson, K., 1975. Relatively old basalts from structurally high areas in central Iceland. Earth and Planetary Science Letters 28, 83–97.
- Áskelsson, J., 1960a. Fossiliferous xenoliths in the Móberg Formation of South Iceland. Acta Naturalia Islandica 2 (3) 30 pp.
- Áskelsson, J., 1960b. Pliocene and Pleistocene fossiliferous deposits. In: Thorarinsson, S. (Ed.), On the Geology and Geophysics of Iceland, 21st International Geological Congress (Copenhagen): Guide to Excursion, A2, pp. 28–32.
- Baden-Powell, D.F.W., 1955. The correlation of the Pliocene and Pleistocene marine beds of Britain and the Mediterranean (with discussion). Proceedings of the Geologists' Association 66 (4), 271–292.
- Bárdarson, G.G., 1925. A stratigraphical survey of the Pliocene deposits at Tjörnes, in northern Iceland. Det Kongelige Danske Videnskaberne Selskabs, Biologiske Meddelelser IV, 5, 118 pp.
- Buchardt, B., Simonarson, L.A., 2003. Isotope palaeotemperature from the Tjörnes Beds in Iceland: evidence of Pliocene cooling. Palaeogeography, Palaeoclimatology, Palaeoecology 189, 71–95.
- Bujak, J.P., Matsuoka, K., 1986. Late Cenozoic dinoflagellate cyst zonation in the western and northern Pacific. In: Wrenn, J.H., Duffield, S.L., Stein, J.A. (Eds.), Papers from the First Symposium on Neogene Dinoflagellate Cyst Biostratigraphy: American Association of Stratigraphic Palynologists Contributions Series, 17, pp. 7–25.
- Channell, J.E.T., Amigo, A.E., Fronal, T., Rack, F., Lehman, B., 1999a. Magnetic stratigraphy at sites 907 and 985 in the Norwegian–Greenland Sea and a revision of the site 907 composite section. In: Raymo, M.E., Jansen, E., Blum, P., Herbert, T.D. (Eds.), Proceedings of the Ocean Drilling Program: Scientific Results, 162, pp. 131–148.
- Channell, J.E.T., Smelror, M., Jansen, E., Higgins, S.M., Lehman, B., Eidvin, T., Solheim, A., 1999b. Age models for glacial fan deposits off East Greenland and Svalbard (sites 986 and 987). In: Raymo, M.E., Jansen, E., Blum, P., Herbert, T.D. (Eds.), Proceedings of the Ocean Drilling Program: Scientific Results, 162, pp. 149–166.
- Cronin, T.M., 1991. Late Neogene marine ostracods from Tjörnes, Iceland. Journal of Paleontology 65, 767–794.
- De Schepper, S., Head, M.J., 2008. Age calibration of dinoflagellate cyst and acritarch events in the Pliocene–Pleistocene of the eastern North Atlantic (DSDP Hole 610 A). Stratigraphy 5, 137–161.
- De Schepper, S., Head, M.J., 2009. Pliocene and Pleistocene dinoflagellate cyst and acritarch zonation of DSDP hole 610A, Eastern North Atlantic. Palynology 33 (1), 179–218.
- De Schepper, S., Head, M.J., Louwye, S., 2004. New dinoflagellate cyst and incertae sedis taxa from the Pliocene of northern Belgium, Southern North Sea Basin. Journal of Paleontology 78, 625–644.
- De Schepper, S., Head, M.J., Louwye, S., 2009. Pliocene dinoflagellate cyst stratigraphy, palaeoecology and sequence stratigraphy of the Tunnel-Canal Dock, Belgium. Geological Magazine 146, 92–112.
- de Vernal, A., Mudie, P.J., 1989a. Pliocene and Pleistocene palynostratigraphy at ODP sites 646 and 647, eastern and southern Labrador Sea. In: Srivastava, S.P., Arthur, M.A., Clement, B.M., Aksu, A.E., Baldauf, J.G., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 105. Ocean Drilling Program, College Station, Texas, pp. 401–422.
- de Vernal, A., Mudie, P.J., 1989b. b. Late Pliocene to Holocene palynostratigraphy at ODP Site 645, Baffin Bay. In: Srivastava, S.P., Arthur, M.A., Clement, B.M., Aksu, A.E., Baldauf, J.G., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 105. Ocean Drilling Program, College Station, Texas, pp. 387–399.
- de Verteuil, L., Norris, G., 1996. Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. Micropaleontology 42, 1–172 (supplement).
- Denk, T., Grímsson, F., Kvaček, Z., 2005. The Miocene floras of Iceland and their significance for late Cainozoic North Atlantic biogeography. Botanical Journal of the Linnean Society 149, 369–417.
- Dixon, R.G., 2005. Field meeting: coastal Suffolk Crag weekend, 23–25 April 2004. Proceedings of the Geologists' Association 116, 149–160.
- Doell, R.R., 1972. Palaeomagnetic studies of Icelandic lava flows. Geophysical Journal of the Royal Astronomical Society 26, 459–479.
- Dowsett, H.J., 2007. The PRISM palaeoclimate reconstruction and Pliocene sea-surface temperature. In: Williams, M., et al. (Ed.), Deep-time Perspectives on Climate Change: Marrying the Signal From Computer Models and Biological Proxies. Micropaleontological Society Special Publications, vol. 2. Geological Society of London, pp. 459–480.
- Dowsett, H.J., Barron, J.A., Poore, R.Z., 1996. Middle Pliocene sea surface temperatures: a global reconstruction. Marine Micropaleontology 27, 13–25.
- Driscoll, N.W., Haug, G.H., 1998. A short circuit in thermohaline circulation: a cause for northern hemisphere glaciation? Science 282, 436–438.
- Durham, J.W., MacNeil, F.S., 1967. Cenozoic migrations of marine invertebrates through the Bering Strait Region. In: Hopkins, D.M. (Ed.), The Bering Land Bridge. Stanford University Press, Stanford, pp. 326–349.
- Eidvin, T., Bugge, T., Smelror, M., 2007. The Molo Formation, deposited by coastal progradation on the inner Mid-Norwegian continental shelf, coeval with the Kai Formation to the west and the Utsira Formation in the North Sea. Norwegian Journal of Geology 87, 75–142.
- Einarsson, T., 1958. A survey of the geology of the area Tjörnes-Bárdardalur in northern Iceland, including paleomagnetic studies. Vísindafélag Íslendinga 32, 1–79.
- Einarsson, Th., Hopkins, D.M., Doell, R.R., 1967. The stratigraphy of Tjörnes, northern Iceland, and the history of the Bering Land Bridge. In: Hopkins, D.M. (Ed.), The Bering Land Bridge. Stanford University Press, Stanford, pp. 312–325.
- Eiríksson, J., 1981a. Tjörnes, North Iceland: A Bibliographical Review of the Geological Research History. Jökull 30, 1–20. [imprinted 1980].
- Eiríksson, J., 1981b. Lithostratigraphy of the upper Tjörnes sequence, North Iceland: the Breidavík Group. Icelandic museum of natural history. Acta Naturalia Islandica 29, 1–37.
- Eiríksson, J., 1985. Facies analysis of the Breidavík Group sediments on Tjörnes, North Iceland. Acta Naturalia Islandica 31, 1–56.
- Eiríksson, J., Gudmundsson, A.I., Simonarson, L.A., 1987. Setmyndun í Tjörnesbrotabeltinu í ljósi kjarnaborunar í Flatey á Skjálfanda. Raunvísindastofnun Háskólans, Reykjavík. RH-07-87, 85 pp.
- Eiríksson, J., Gudmundsson, A.I., Kristjánsson, L., Gunnarsson, K., 1990. Palaeomagnetism of Pliocene–Pleistocene sediments and lava flows on Tjörnes and Flatey, North Iceland. Boreas 19, 39–55.
- Eiríksson, J., Knudsen, K.L., Viljálmsón, M., 1992. An early Pleistocene glacial–interglacial cycle in the Breidavík Group on Tjörnes, Iceland: sedimentary facies, foraminifera, and molluscs. Quaternary Science Reviews 11, 733–757.
- Faure, G., Mensing, T.M., 2005. Isotopes. Principles and Applications, Third edition. J. Wiley & Sons, Hoboken, New Jersey, pp. 897.
- Fensome, R.A., MacRae, R.A., Williams, G.L., 2008. DINOFLAJ2, Version 1. American Association of Stratigraphic Palynologists, Data Series no. 1.
- Gibbard, P.L., Head, M.J., Walker, M.J.C., The Subcommittee on Quaternary Stratigraphy, 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. Journal of Quaternary Science 25 (2), 96–102.
- Gladenkov, A.Y., 2006. Neogene diatoms from the Sandy Ridge section, Alaska Peninsula: significance for stratigraphic and paleogeographic reconstructions. Stratigraphy and Geological Correlation 14, 79–97.
- Gladenkov, Y.B., Gurari, G.Z., 1976. Paleomagnetic characteristics of the Plio-Pleistocene in Iceland (Tjörnes Peninsula). Doklady Akademii Nauk SSSR 230, 1173–1175.
- Gladenkov, Y.B., Norton, P., Spink, G., 1980. Upper Cenozoic of Iceland (in Russian). Trudy Geologicheskogo Instituta, Akademii Nauk SSSR 345, 1–116.
- Gladenkov, A.Y., Oleinik, A.E., Marinovich Jr., L., Barinov, K.B., 2002. A refined age for the earliest opening of Bering Strait. Palaeogeography, Palaeoclimatology, Palaeoecology 183, 321–328.
- Harland, R., 1979. Dinoflagellate biostratigraphy of Neogene and Quaternary sediments at Holes 400/400A in the Bay of Biscay (Deep Sea Drilling Project Leg 48). In: Montadert, L., Roberts, D.G., et al. Initial Reports DSDP, 48: Washington (U.S. Govt. Printing Office), 531–545.
- Harmer, F.W., 1914–1925. The Pliocene Mollusca of Great Britain. Vol. 1 (1914, 1915, 1918, 1919), Vol. 2 (1920, 1921, 1923, 1925). Paleontographical Society, London.
- Haug, G.H., Tiedeman, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393, 673–676.
- Haug, G.H., Tiedeman, R., Zahn, R., Ravelo, A.C., 2001. Role of Panama uplift on oceanic freshwater balance. Geology 29 (3), 207–210.

- Head, M.J., 1993. Dinoflagellates, sporomorphs and other palynomorphs from the Upper Pliocene St. Erth Beds of Cornwall, southwestern England. *Journal of Paleontology*, *Memoirs* 31, 1–62.
- Head, M.J., 1996. Late Cenozoic dinoflagellates from the Royal Society borehole at Ludham, Norfolk, eastern England. *Journal of Paleontology* 70, 543–570.
- Head, M.J., 1998a. Marine environmental change in the Pliocene and early Pleistocene of eastern England: the dinoflagellate evidence reviewed. *Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO. The Dawn of the Quaternary* 60, 199–226.
- Head, M.J., 1998b. Pollen and dinoflagellates from the Red Crag at Walton-on-the-Naze, Essex: evidence for a mild climatic phase during the early Late Pliocene of eastern England. *Geological Magazine* 135 (6), 803–817.
- Head, M.J., Norris, G., 2003. New species of dinoflagellate cysts and other palynomorphs from the latest Miocene and Pliocene of DSDP Hole 603C, western North Atlantic. *Journal of Paleontology* 77, 1–15.
- Head, M.J., Norris, G., Mudie, P.J., 1989. New species of dinocysts and a new species of acritarch from the upper Miocene and lowermost Pliocene, ODP Leg 105, Site 646, Labrador Sea. In: Srivastava, S.P., Arthur, M.A., Clement, B.M., et al. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*, 105. College Station, Texas, pp. 453–466.
- Head, M.J., Riding, J.B., Eidvin, T., Chadwick, R.A., 2004. Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Norland Group mudstones at Sleipner, northern North Sea. *Marine and Petroleum Geology* 21, 277–297.
- Head, M.J., Gibbard, P.L., Salvador, A., 2008. The Quaternary: its character and definition. *Episodes* 31 (2), 234–238.
- Hospers, J., 1953. Palaeomagnetic studies of Icelandic rocks. Ph.D. thesis. University of Cambridge, 172 pp.
- Jenkins, D.G., Houghton, S.D., 1987. Age, correlation and paleoecology of the St. Erth Beds and the Coralline Crag of England. *Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie* 24, 147–156.
- Knies, J., Matthiessen, J., Vogt, C., Laberg, J.S., Hjelstuen, B.O., Smelror, M., Larsen, E., Andreassen, K., Eidvin, T., Vorren, T.O., 2009. The Plio-Pleistocene glaciation of the Barents Sea-Svalbard region: a new model based on revised chronostratigraphy. *Quaternary Science Reviews* 28, 812–829.
- Kristjánsson, L., 2004. A reconnaissance study of paleomagnetic directions in the Tjörnes Beds, northern Iceland. *Jökull* 54, 57–63.
- Laga, P., Louwye, S., Geets, S., 2001. Paleogene and Neogene lithostratigraphic units (Belgium). *Geologica Belgica* 4 (1–2), 135–152 (Lithostratigraphic scale of Belgium).
- Lentin, J.K., Fensome, R.A., Williams, G.L., 1994. The stratigraphic importance of species of *Sumatradinium*, *Barssidinium*, and *Erymmodinium*, Neogene dinoflagellate genera from offshore eastern Canada. *Canadian Journal of Earth Sciences* 31 (3), 567–582.
- Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2005. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), *A Geological Time Scale 2004*. Cambridge University Press, Cambridge, U.K., pp. 409–440. [imprinted 2004].
- Louwye, S., De Schepper, S., 2010. The Miocene–Pliocene hiatus in the southern North Sea Basin (northern Belgium) revealed by dinoflagellate cysts. *Geological Magazine* 147 (5), 760–776. doi:10.1017/S001675810000191.
- Louwye, S., Head, M.J., De Schepper, S., 2004. Dinoflagellate cyst stratigraphy and palaeoecology of the Pliocene in northern Belgium, southern North Sea Basin. *Geological Magazine* 143, 353–378.
- Maier-Reimer, E., Mikolajewicz, U., 1990. Ocean general circulation model sensitivity experiment with an open Central American isthmus. *Paleoceanography* 5, 349–366.
- Marincovich Jr., L., 1999. Late Pliocene trans-Arctic molluscan migration synchronous with closure of the Central American seaway: Geological Society of America Abstracts with Programs 31 (7), A473.
- Marincovich Jr., L., 2000. Central American paleogeography controlled Pliocene Arctic Ocean molluscan migrations. *Geology* 28, 551–554.
- Marincovich Jr., L., Gladenkov, A.Y., 1999. Evidence for an early opening of the Bering Strait. *Nature* 397, 149–151.
- Marincovich Jr., L., Gladenkov, A.Y., 2001. New evidence for the age of Bering Strait. *Quaternary Science Reviews* 20, 329–335.
- Marquet, R., 1998. De Pliocene gastropodenfauna van Kallo (Oost-Vlaanderen, België). *Belgische Vereniging voor Paleontologie, Publicatie* 17, 1–246.
- Marret, F., Eiriksson, J., Knudsen, K.L., Turon, J.-L., Scourse, J.D., 2004. Distribution of dinoflagellate cyst assemblages in surface sediments from the northern and western shelf of Iceland. *Review of Palaeobotany and Palynology* 128 (1–2), 35–53.
- Matsuoka, K., Head, M.J., 1992. Taxonomic revision of the Neogene marine palynomorph species *Cyclopsella granosa* (Matsuoka) and *Battiacasphaera minuta* (Matsuoka), and a new species of *Pxydinopsis* Habib (Dinophyceae) from the Miocene of the Labrador Sea. In: Head, M.J., Wrenn, J.H. (Eds.), *Neogene and Quaternary Dinoflagellate Cysts and Acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 165–180.
- Matthiessen, J., Brenner, W., 1996. Dinoflagellate cyst ecostratigraphy of Pliocene–Pleistocene sediments from the Yermak Plateau (Arctic Ocean, Hole 911A). In: Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., Ruddiman, W.F. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*, 151. College Station, Texas, pp. 243–253.
- Matthiessen, J., Knies, J., Vogt, C., Stein, R., 2009. Pliocene palaeoceanography of the Arctic Ocean and subarctic seas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 367, 21–48.
- Mertens, K.N., Verhoeven, K., Verleye, T., Louwye, S., Amorim, A., Ribeiro, S., Deaf, A.S., Harding, I.C., De Schepper, S., González, C., Kodrans-Nsiah, M., de Vernal, A., Henry, M., Radi, T., Dybkjaer, K., Poulsen, N.E., Feist-Burkhardt, S., Chitolie, J., Heilmann-Clausen, C., Londeix, L., Turon, J.-L., Marret, F., Matthiessen, J., McCarthy, F.M.G., Prasad, V., Pospelova, V., Kyffin Hughes, J.E., Riding, J.B., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C., Soliman, A., Van Nieuwenhove, N., Vink, A., Young, M., 2009. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments: the Lycopodium marker-grain method put to the test. *Review of Palaeobotany and Palynology* 157, 238–252.
- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. *Science* 310 (5752), 1293–1298.
- Mudie, P.J., 1987. Palynology and dinoflagellate biostratigraphy of Deep Sea Drilling Project leg 94, sites 607 and 611, North Atlantic Ocean. In: Ruddiman, W.F., Kidd, R.B., Thomas, E., et al. (Eds.), *Initial reports, Deep Sea Drilling Project*, 94, pp. 785–812.
- Mudie, P.J., 1989. Palynology and dinocyst biostratigraphy of the Late Miocene to Pleistocene, Norwegian Sea: ODP Leg 104, Sites 642 to 644. In: Eldholm, O., Thiede, J., Taylor, E., et al. (Eds.), *Proceedings of the Ocean Drilling Programme: Scientific Results*, 104, pp. 587–610.
- Norton, P.E.P., 1975. Paleocology of the Molluscs of the Tjörnes sequence, Iceland. *Boreas* 4, 97–110.
- Norton, P.E.P., 1977. Neogene mollusca of the Tjörnes sequence, Iceland: paleoecology, zonation, correlation. *Malacologia* 16 (1), 211–213.
- Polyakova, Y.I., 2001. Late Cenozoic evolution of northern Eurasian marginal seas based on the diatom record. *Polarforschung* 69, 211–220.
- Poulsen, N.E., Manum, S.B., Williams, G.L., Ellegaard, M., 1996. Tertiary dinoflagellate biostratigraphy of sites 907, 908, and 909 in the Norwegian-Greenland Sea. In: Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., Ruddiman, W.F. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*, 151, pp. 255–287.
- Sæmundsson, K., 1974. Evolution of the axial rift zone in northern Iceland and the Tjörnes Fracture zone. *Geological Society of America Bulletin* 85, 495–504.
- Sarnthein, M., Bartoli, G., Prange, M., Schmittner, A., Schneider, B., Weinelt, M., Andersen, N., Garbe-Schönberg, D., 2009. Mid-Pliocene shifts in ocean overturning circulation and the onset of Quaternary-style climates. *Climate of the Past* 5, 269–283.
- Schwarzbach, M., Pflug, H.D., 1957. Beiträge zur Klimageschichte Islands VI. Das Klima des jüngeren Tertiärs in Island (in German). *Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen* 104, 279–298.
- Simonarson, L.A., Eiriksson, J., 2008. Tjörnes – Pliocene and Pleistocene sediments and faunas. *Jökull* 58, 331–342.
- Simonarson, L.A., Petersen, K.S., Funder, S., 1998. Molluscan palaeontology of the Pliocene–Pleistocene Kap København Formation, North Greenland. *Meddelelser om Grønland, Geoscience* 36, 1–103.
- Smelror, M., 1999. Pliocene–Pleistocene and redeposited dinoflagellate cysts from the western Svalbard margin (site 986): biostratigraphy, paleoenvironments, and sediment provenance. In: Raymo, M.E., Jansen, E., Blum, P., Herbert, T.D. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*, 162, pp. 83–97.
- Steph, S., Tiedeman, R., Prange, M., Groeneveld, J., Nürnberg, D., Reuning, L., Schulz, M., Haug, G., 2006. Changes in Caribbean surface hydrography during the Pliocene shoaling of the Central American Seaway. *Paleoceanography* 21 (4), PA4221. doi:10.1029/2004PA001092.
- Strauch, F., 1963. Zür Geologie von Tjörnes (Nord-Island). *Sonderveröffentlichungen des Geologischen Instituts der Universität Köln*, 7, 129 pp. (in German).
- Strauch, F., 1972. Zum Klima des nordatlantisch-skandischen Raumes im jüngeren Känozoikum. *Zeitschrift der Deutschen Geologischen Gesellschaft* 123, 163–177 (in German).
- Thordarson, T., Höskuldsson, A., 2006. Iceland, classic geology in Europe 3, second impression. 200 pp.
- van der Burg, W.J., 1987. The stratigraphic distribution of Pliocene molluscs from deposits of the northern Peel district in The Netherlands. *Basteria* 51, 25–32.
- Verhoeven, K., Louwye, S., 2010. Form variability within the *Polygonum bistorta* pollen type: a comparison between Pliocene and recent material. In: Bakels, C., Fennema, K., Out, W.A., Vermeeren, C. (Eds.), *Van Planten en Slakken/Of Plants and Snails*. Sidestone Press, Leiden, pp. 229–237.
- Vermeij, G.J., 1989. Invasion and extinction: the last three million years of North Sea pelecypod history. *Conservation Biology* 3, 274–281.
- Versteegh, G.J.M., 1997. The onset of major Northern Hemisphere glaciations and their impact on dinoflagellate cysts and acritarchs from the Singa section, Calabria (southern Italy) and DSDP Holes 607/607A (North Atlantic). *Marine Micropaleontology* 30 (4), 319–343.
- Versteegh, G.J.M., Blokker, P., 2004. Resistant macromolecules of extant and fossil microalgae. *Phycological Research* 52, 325–339.
- Warny, S., 1999. Mio-Pliocene palynology of the Gibraltar Arc: a new perspective on the Messinian Salinity Crisis. Unpublished PhD thesis, 307 pp.
- Willard, D.A., 1994. Palynological record from the North Atlantic region at 3 Ma: vegetational distribution during a period of global warmth. *Review of Palaeobotany and Palynology* 83, 275–297.
- Windisch, P., 1886. Beiträge zur Kenntniss der Tertiärflora von Island. (in German) *Zeitschrift für Naturwissenschaften* 59, 215–262.
- Zevenboom, D., 1995. Dinoflagellate cysts from the Mediterranean late Oligocene and Miocene. Ph.D. thesis. Univ. Utrecht, The Netherlands. 221 pp.
- Zonneveld, K.A.F., Bockelmann, F., Holzwarth, U., 2007. Selective preservation of organic-walled dinoflagellate cysts as a tool to quantify past net primary production and bottom water oxygen concentrations. *Marine Geology* 237, 109–126.