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A reconstruction of the depositional history and palaeoenvironment of the Plio-Pleistocene of northeast Iceland

A combined terrestrial and marine palynological approach

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Front cover:

Picture taken by the author in september 2007 in Tungubakkar on the eastcoast of the Skjálfandi Bay, northeast Iceland. The picture gives a view of the coastal cliffs of the Tjörnes Peninsula in the direction of Höskuldsvík. The marine sediment of the *Serripes* Zone are visible and have a NW dip.

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Acknowledgements

The present PhD dissertation is the result of my scientific endeavours during the past six years as a research assistant at the Department of Geology and Soil Sciences (DGSS), Ghent University. Six years is a long period to remain focussed, especially when time for research has to be wedged in between educational and other supporting tasks. Anyhow, completing this work would not have been possible without the support of many persons, whom I thank in what follows.

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Preface

This dissertation is the result of the work carried out by the author as an assistant in the Research Unit of Palaeontology, Ghent University, in the period spanning three times two years. As a member of the staff, half of the time was reserved for student support of various bachelor and master projects and for the assistance of both professors in the research unit by their educational tasks.

The research project of the dissertation was set up to investigate the combined response of terrestrial vegetation and marine algae to climate cooling effects. The geological period most suitable for the analysis of such a cooling is the transition from the Pliocene to the Quaternary, for it represents the greatest cooling event in recent history. Geologically speaking, the Pliocene epoch is not that far away in time, which as a result that most of the marine and terrestrial fauna and flora is near to the recent ones. Present-day ecological characteristics such as temperature sensitivity and nutrient dependency can therefore be used to reconstruct the Pliocene environment. In earlier geological epochs, the connection with recent fauna or flora decreases drastically and modern analogues are difficult to find. The Pliocene moreover knew much warmer environments than today and clear faunal and floral changes can be expected at the transition into the Quaternary. We selected the coastal geological outcrops of the Tjörnes Peninsula in northern Iceland for our study, as their northern location makes them very sensitive to the shifts of the climate zones. Also, their location central in the northern Atlantic should allow to detect possible changes in palaeoceanography. Therefore, the reconstruction of the sedimentary history of the Tjörnes sequence will help to decipher that of the global climate. The marine and terrestrial sediments of Tjörnes were studied for more than 200 years, but until now no coherent palynological study was made. Scientists knew the potential of the site, but the disadvantages of extreme low concentrations of palynomorphs and the difficulties to extract them from the sediments dissuaded intense research on the Tjörnes sequence. Thus, the study of the palynology was limited and mostly restricted to studies of the pollen and spores from the lignites, while a dinoflagellate study had not yet been carried out. The aim of our study was to combine both terrestrial and marine palynology of the marine sediments as well as the lignites. The extraction of the palynomorphs and the low concentrations of them hampered indeed the analysis, but in the end the analysis provided reasonable insight.

All our research during the past six years focused on palynological studies with marine dinoflagellate cysts in combination with terrestrial pollen and spores from sediments deposited during the past five million years. Several studies of Pliocene and Pleistocene outcrops of the Tjörnes Peninsula, but also of the succession on Flatey Island, situated 2.5 km out of the coast in the same bay, were made, as they combine into a meaningful whole. Other research, such as the study of the deep marine sediments of Porcupine, a deep sea drilling southwest of the Irish coast, and ODP 985, a comparable deep sea drilling in the Atlantic northeast of Iceland, are not included in this memoir, but will be the subject to later publications. The present text concerns peer-reviewed articles of which the general contents are summarized in what follows.

Chapter 1 gives a general introduction to the research questions and the specific characteristics of the study area. The Pliocene period is a period transitional from the warm Miocene to the glaciations of the Quaternary and the study of the Pliocene climate, still warmer than today but subject to cooling, is of major importance to understand the present-day climate changes. Background information concerning the Pliocene, climate, plate tectonics, ocean currents and the terrestrial and marine palynological tools is provided, as well information of the Tjörnes and Flatey locations. A general overview of the vegetation history and study of Iceland is given, together with a list of plants now extinct on the island and encountered in our study.

In **Chapter 2** we describe the previous age models of the Tjörnes section and the development of a new one based on the dinoflagellate cysts biostratigraphy and a reinterpretation of the palaeomagnetic polarity signals. Although the Tjörnes beds were studied already for more than two centuries, a solid age model was not available up to now. The K/Ar dates, previously the sole reference points for the age model, did not fit with the palaeomagnetic reversal signals. The best existing age model placed the entrance of Pacific molluscs in the Tjörnes area wrongly around 3.6 Ma. Dinoflagellate cysts are known to be good stratigraphical tools and provided new reference points for dating the Tjörnes sequence. The Tjörnes assemblages have been compared with those of all available deep sea drillings as well as coastal sections of the northern Atlantic Ocean; these have a good independent age control. We were able to reinterpret the magnetic reversals and propose a new age model in which the entrance of Pacific molluscs fit with the global palaeoceanographical context.

Next to be good biostratigraphical tools, dinoflagellates also reflect well their palaeoenvironment and can therefore be used to reconstruct past ecological parameters. **Chapter 3** deals with the ecological reconstruction of the Tjörnes region with the dinoflagellate cysts, focusing mainly on estimates of past temperatures and past nutrient availability. The temperature sensitivity of particular extant and extinct dinoflagellates made it possible to render a restricted cooling visible in the Early Pliocene Tjörnes beds and a distinct cooling in the Early Pleistocene Breidavík Group. Nutrient dependent heterotrophic dinoflagellates disappeared for almost the entire *Mactra* Zone in the middle of the Tjörnes beds. Two major changes in the palaeoceanography lie at the base of the retreat of nutrients from the area. After the nutrient poor period, heterotrophic species suddenly re-enter the area, partly preceding the entrance of Pacific molluscs at the *Mactra/Serripes* boundary higher in the Tjörnes beds.

Chapter 4 describes a new dinoflagellate cyst species from the genus *Selenopemphix*. It was given the name *Selenopemphix islandesis* sp. nov., as the first finds come from the Tjörnes beds in Iceland. Its earliest occurrence coincides with the base of the *Serripes* Zone in top of the Tjörnes beds and thus the entrance of nutrients and Pacific species. The chapter examines the stratigraphical and ecological significance of this new heterotrophic dinoflagellate cyst. Probably, the species has a Pacific origin and can be used as a biostratigraphical marker in the Pliocene of the Atlantic, postdating 4.5 Ma. Unfortunately, it is easily overlooked because it has a pale, thin wall; it is therefore not well visible. Its main characteristics are the large fan-shaped processes around the sulcus and the small processes positioned on the cingulum.

Chapter 5 deals with the relation between the vegetation history of Tjörnes and the sea level fluctuations as revealed by the molluscan ecology and the sedimentology. The study is based on the pollen content of both marine and terrestrial sediments of the Tjörnes beds and the Breidavík Group. Not only the lignites yield valuable pollen signals, but the marine sand- and mudstones also. Six pollen zones were established, of which one devoid of pollen and spores was confined to energetic estuarine sediments. Although the pollen types mostly contain several species with a variety of ecological preferences, the combination of the pollen record with the sea level reconstruction allowed to establish the location of certain groups of plants in the coastal area. Gymnosperm trees (*Pinus*, *Abies* and *Picea*) apparently were located on higher situated plateaus, while *Larix* and *Ilex aquifolium* preferred a location close to the coastal hills. The angiosperm trees *Juglans* and *Acer* most likely were present in small angiosperm forests on levees in the coastal area.

One aberrant pollen type was found and studied in **Chapter 6**. Although it looks quite similar to the *Polygonum bistorta*-type already known from the literature, it differs in size and development of its pores. The pollen seems to accompany the sedges (Cyperaceae) and no doubt originated from the coastal marshes. The chapter compares this pollen with representatives of the *Polygonum bistorta*-type in recent reference material from France, Belgium and Iceland, in order to figure out whether its morphological variability has to do with the northern position of Iceland or with different growth parameters during the Pliocene. The fossil pollen have a great size range, is much smaller than the *Polygonum bistorta*-type described in the literature, but has a comparable form.

Chapter 7 discusses the palynological potential of the Pleistocene succession on Flatey Island. The core taken on the island was not accessible during our PhD research because of storage problems in the core repository. Only two samples could be examined, the first came from an outcrop on the island, the second was the only sample available from the core, but its exact position is not clear. The position of the Flatey deposits close to the coastal Tjörnes section and their comparable sedimentary history on the shallow shelf make them of major interest for understanding land-sea relations. Much larger dinoflagellate cyst concentrations are found which suppress the pollen signal at least in the core sample. Both proxies however are present in sufficient quantities to provide insight in the terrestrial and marine climate evolution of the region. A cooling is seen and a tentative correlation of the Flatey and Tjörnes sequences is offered.

Chapter 8 offers a synthesis of all the results and proposes topics for further investigations. Although our study present appreciable contribution to unravel the geological history of the Tjörnes and Flatey sections, many questions are still not answered. The Flatey core released its first palynological secrets and showed its potential to decypher the time setting of the upper Breidavík Group sediments. An intensive biostratigraphical study of the marine sediments of the Breidavík Group and the Flatey succession will place the Quaternary glacial history of Iceland in a solid time frame and contribute to the understanding of the glacial history of our globe.

Introduction: Tjörnes and Flatey as key localities to understand Plio-Pleistocene cooling in the northern hemisphere

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This study focuses on microfossil assemblages formed in the transition period from the Neogene to the Quaternary. Two climate related signals were investigated: changes in the resting cysts of marine organic-walled algae known as dinoflagellates and changes in pollen and spores representing terrestrial vegetation. In what follows, the exact aim of the study, the geological background, the selected time period and location of the studied area are discussed as well as the concerned microfossil groups.

1. Geology

1.1 Tectonic framework

Iceland is situated in the middle of the Atlantic Ocean and its formation post-dates the genesis of the ocean. Some 300 Ma ago, the supercontinent Pangaea was formed. The formation of the Central Atlantic Ocean and the Thethys Ocean around 200 Ma resulted in the splitting of Pangaea into Laurasia in the north and Gondwana in the south. During Cretaceous times, Laurasia splitted by the formation of the North Atlantic Ocean and the Norwegian Sea in Laurentia, the combination of North America and Greenland, in the west and Eurasia in the east (Ziegler, 1990). At the latitude of Iceland, the Mid Atlantic Rift system (MAR) with active spreading was formed around 55 Ma ago, and the plates diverge here slowly at a half-spreading rate of 0.9 cm/year (DeMets *et al.*, 1990, 1994; Bourgeois *et al.*, 2005; Grímsson *et al.*, 2007).

The formation of proto-Iceland started already c. 24 Ma ago, but the oldest rocks exposed on the surface of Iceland are 14-16 Ma old (Thordarsson and Hoskuldsson, 2006). Iceland is indeed located on the junction of the MAR and the Greenland-Iceland-Faeroes Ridge between 63°23’N and 66°30’N. Not only its formation, but also its ongoing growth, is driven by active geological processes. Seismic profiles indicate the presence of magmatic material below Iceland, upwelling from a depth of 400 km below the sea bottom. This structure is called the North Atlantic Mantle Plume, and its position right below the MAR brought the rift system to the surface and formed Iceland. The mantle plume or hotspot has been active for the past 80 Ma and causes the formation of a large belt of basaltic provinces between Greenland and Scotland of which Iceland is the youngest, centrally located and still active (Bourgeois, 2005; Thordarson and Hoskuldsson, 2006). The hotspot is assumed to be stationary, while the MAR outside of Iceland moves west-northwest at a constant rate of 0.3 cm/year with respect to the hot spot (Sæmundsson, 1974; Thordarson and Hoskuldsson, 2006).

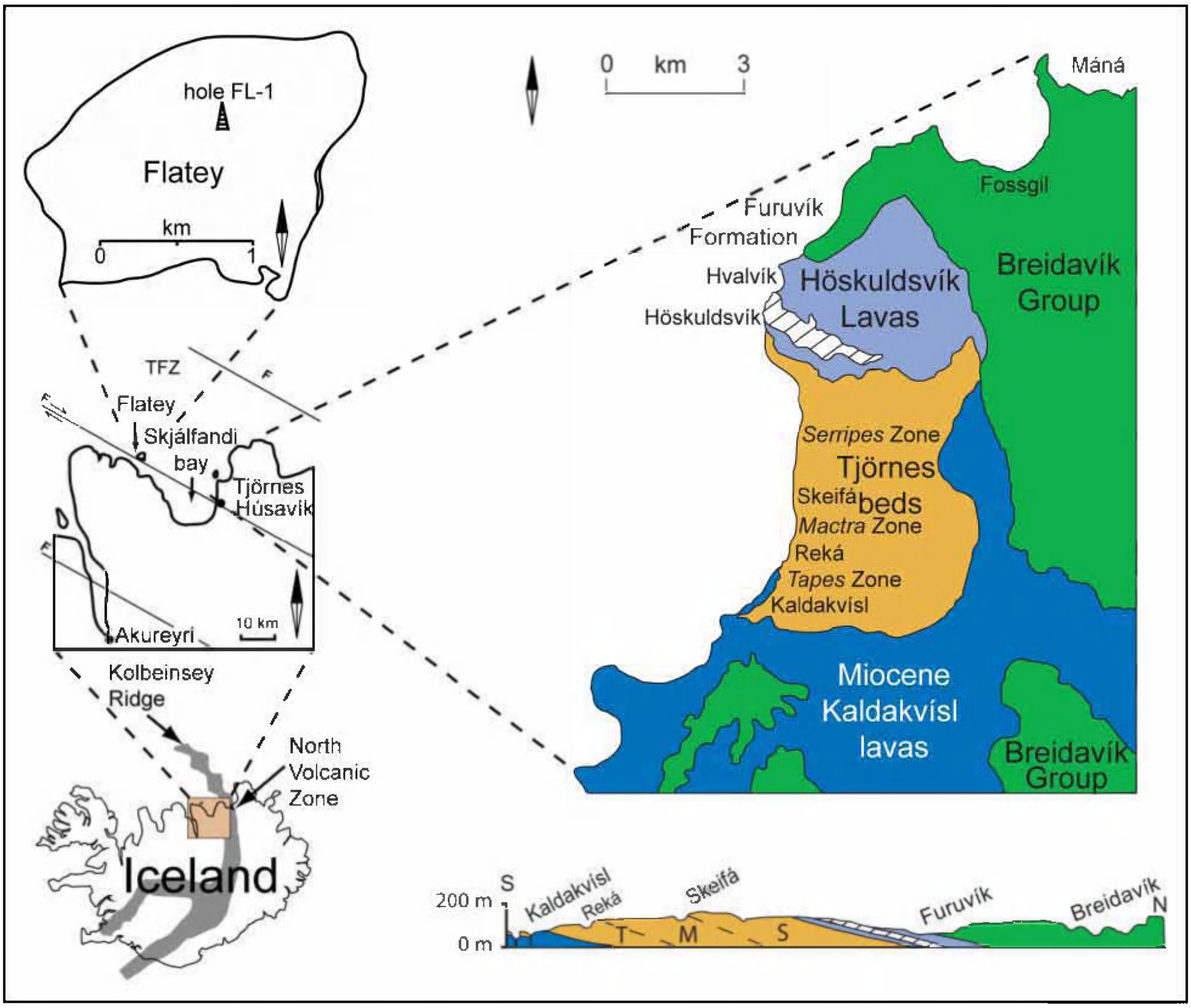

Figure 1.1: **Localisation of the study area. The geological map of Tjörnes is adapted from Einarsson *et al.* (1967) and Eiríksson (1981b). Within the Höskuldsvík lavas, the field with the diagonal lines indicate the laves with a reversed geopolarity, the other lavas of this group have a normal polarity.**

As a result the position of the MAR at the location of Iceland is constantly moving from west to east, and makes a jump relative to the submarine rifting of the ocean north and south of Iceland. Large transform faults or active volcanic belts, connect the different rifting zones. The Tjörnes Fracture Zone (TFZ) in the north is a 70 km wide and 120 km long belt of currently inactive transform faults that connects the offshore Kolbeinsey Ridge with the North Volcanic Zone in northeastern Iceland. They became active as transform faults around c. 7 Ma ago, but as active movements are no longer present here they are now indicated as parts of the fracture zone (Sæmundsson, 1974; Thordarsson and Hoskuldsson, 2006; Figure 1.1). The right-lateral, west-northwest trending Husavík-Flatey fault is a still active transform fault, situated at the southern boundary of the TFZ. The total cumulative displacement along the fault has been 60 km since its activation (Sæmundsson, 1974).

A large hiatus of 3 to 4 Ma is observed between the older “Tertiary” Basalt Formation and the deposits in the newly formed subsidence basin related to the TFZ (Sæmundsson, 1974). In the Tjörnes section, this hiatus is observed between the Kaldakvísl lavas (8.6 ±0.4 Ma, 9.9±1.8 Ma) and the unnamed lava layer in the base of the *Tapes* Zone (Aronson and Sæmundsson, 1975; Albertsson, 1976; Figure 1.2). The top of the island of Flatey situated just north of the Husavík-Flatey fault and of which two samples were studied, is composed of undisturbed interglacial lava flows (Figure 1.1). Its basalt layers have most probably their origin in an eruption on the fault and not in volcanic areas to the south-east, on the northern

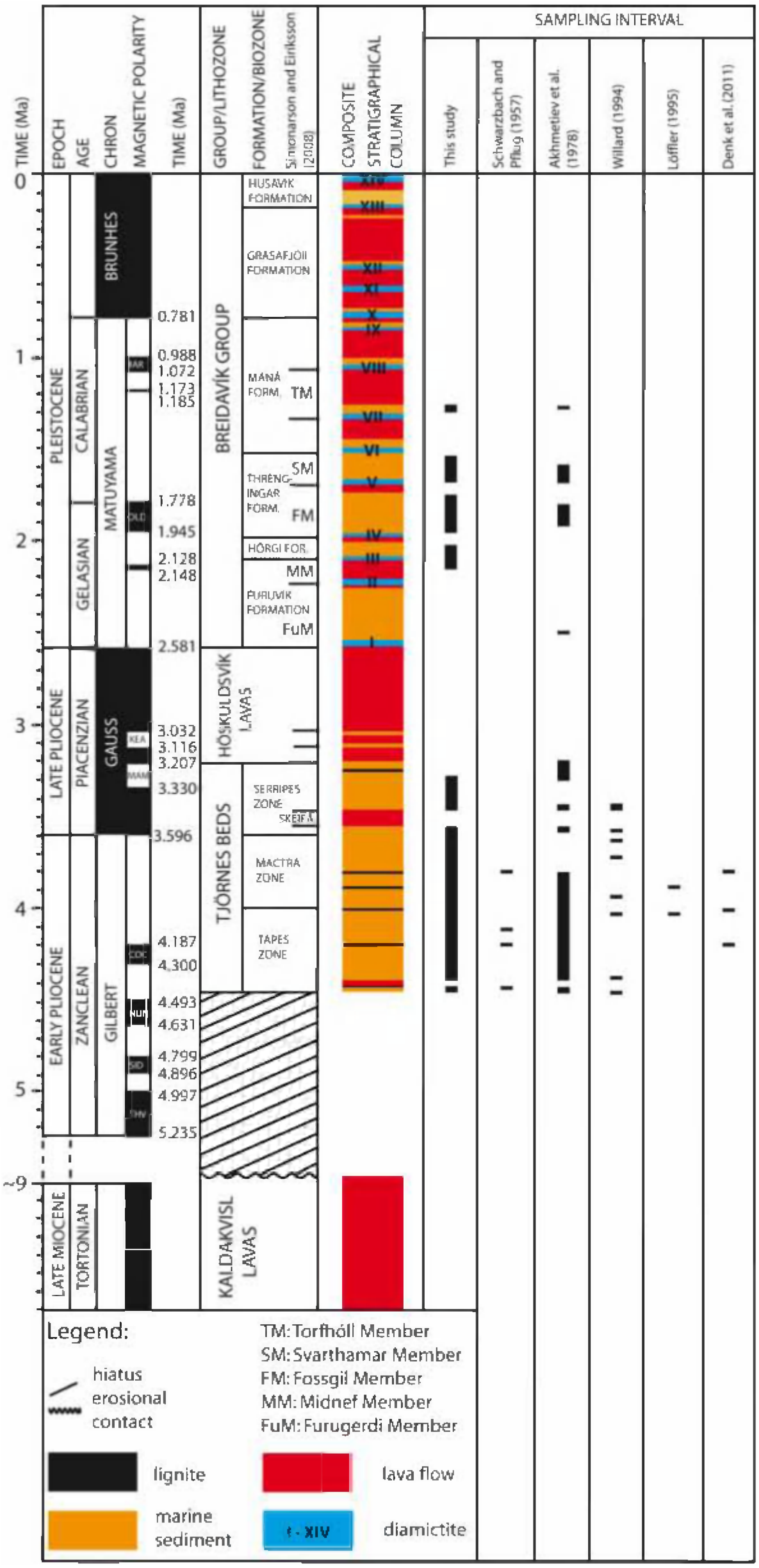

Figure 1.2: Lithostratigraphical schema of the Tjörnes section, with correlations with palaeomagnetostratigraphy and K/Ar ages. According to Símonarson and Eiríksson (2008). Composite stratigraphical column according to Eiríksson (1981b) and Eiríksson *et al.* (1990). Roman capitals indicate glacial periods. Black bars indicate the palynological and macrobotanical sample intervals.

part of Iceland (Sæmundsson, 1974). The drilled Flatey sequence consists of Pleistocene marine sediments, glacial remains and three lava flows of which the upper one forms the surface of the island. As to the Tjörnes section, the sedimentation basin of Flatey was uplifted at the end of the Pleistocene. In 1982, the National Energy Authority of Iceland drilled this 550 m long core at the north side of the island during a prospection campaign for hydrocarbon sources (Eiríksson *et al.*, 1987). The coalified layers at the base of the Early Pliocene laid at the base of the observation of escaping bubbles in the ocean, but are situated at the locality of Flatey at a depth of c. 2000 m. The initial aim to study these layers was not attained, as the drilling depth was not deep enough (Eiríksson, personal communication 2007). The core was not available during this study because of storing difficulties in the Icelandic core repository.

The vegetation of Iceland is poor and therefore the volcanic layers are exposed to atmospheric agents such as frost, wind and water. The erosion of the magmatic rocks is therefore much stronger than elsewhere in the world. As a result, huge amounts of sediment are transported to the coastal areas by rivers and glaciers, and together with the active volcanism the island is constantly growing since its birth. Lava layers can cap the already deposited succession and protect them from further erosion. The combination of the steady supply of sediments with quite appreciable sedimentation rates near formerly active faults of the TFZ, resulted in the formation of a highly detailed geological record in the northern part of Iceland, nowadays uplifted in cliffs along the coast. An almost 1200 m thick sedimentary sequence occurs in the western part of the Tjörnes Peninsula, formed in a subsiding trough related to the TFZ and, as mentioned above, uplifted at the end of the Pleistocene (Figure 1.2). Sediment supply came from the south in a trough, interpreted as a graben, dipping slightly to the north (Strauch, 1963).

The TFZ has been active since the Late Miocene around c. 7 Ma. Since the start of the Pliocene, the most complete nearshore geological record in the northern Atlantic has here been deposited. Our study however indicates that the generally accepted view that we are dealing with a near-continuous stratigraphical section (Einarsson *et al.*, 1967; Albertsson, 1978; Símonarson and Eiríksson, 2008) is not correct, as possibly three marked hiatuses exist (chapters 2, 8). Only alternative 2 of Einarsson *et al.* (1967) mentioned the possible missing of sediments in top of the Matuyama chron in Tjörnes, all other former studies at least give the impression of a continuous record. These authors were aware of erosional events at, for example, the base of the Breidavík sedimentation cycles, but no major concerns is given to erosional events in the total composition of the section. Nevertheless, the record in Tjörnes is the most complete nearshore record in the northern Atlantic and will remain the key section to study climate related processes of the period considered in the area. This unique geographical setting in combination with the available ecological information of molluscs, ostracods, pollen/spores and plant macrofossils together with palaeomagnetic polarity measurements, sedimentological analyses and K/Ar dating provide us with a good reference section for the study of the pollen/spores and dinoflagellates in the sequence. The available radiometric ages of the basalts, however, are considered to be minimum ages, as only low K values are measured. Mafic basalts, formed by partial melting of the mantle, are characterized by a low SiO_2 (<52%), K, Na and Al content but are rich in Mg, Fe and Ca. The low K content makes it difficult to date these basalts, as the $^{40}K/^{40}Ar$ or $^{40}Ar/^{39}Ar$ absolute dating methods are the only ones appropriate for the geologically relative young basalts. Large basalt expanses developed only during ice free periods and volcanism during glacial periods resulted in the deposition of local subglacial pillow lavas, volcanoclastic breccias and tuffs. The sequence of lithologies in the upper part of the Tjörnes section allows the reconstruction of a succession of palaeoenvironments, but a chronological framework was until now not available, which would allow to estimate the significance of the events and to effect a meaningful comparison of areas in Iceland and elsewhere (Eiríksson, 1981b).

1.2 Stratigraphy of the Tjörnes section

The Tjörnes section comprises three major stratigraphical units: the Pliocene Tjörnes beds, the basaltic Höskuldsvík Group, and the Pleistocene Breidavík Group (Figures 1.1, 1.2). Based on the molluscan assemblages found, the Tjörnes beds have been divided by Bárdarson (1925), from below to above, in the *Tapes*, *Mactra* and *Serripes* Zone. This informal stratigraphy with 25 shell bearing units (1–25) and 10 lignites (A–J) has been generally adopted and is still in use. The changing interplay of the subsidence rate of the basin and a varying sediment supply from the island resulted in an alternation of terrestrial lignites with intertidal sandstones, subtidal mudstones and estuary sediments (Símonarson and Eiríksson, 2008). Apart from the marine and terrestrial sediments, two basalts were deposited in the Tjörnes beds, the oldest near the base of the *Tapes* Zone and the youngest in the base of the *Serripes* Zone.

The Höskuldsvík Group, capping the Tjörnes beds, consists of c. 250 m of basalts. The Breidavík Group holds c. 500 m of glacial-interglacial cycles with various rock types. In this group, fourteen tills or tillites represent fourteen glacial periods (roman capitals in Figure 1.2). These glacier deposits distinguish themselves from other sedimentary deposits by the unstratified, chaotic mixture of clay to boulder size debris. Tills or tillites belong to the group of the diamictites, which also contains gravity induced heterogenic sediments. The glacial striae found in rocks in the Tjörnes Peninsula all have an uniform northerly to north-westerly direction and indicate the presence of an extensive ice cap of regional shape (Eiríksson, 1981b). The last author records several glacial-interglacial cycles in the Breidavík Group, based on the already mentioned succession of glacial tills, various late glacial sediments such as outwash gravels and glacio-lacustrine sediments, interglacial marine sediments and lava flows, followed by glacial erosion surfaces. Erosional unconformities are present at the base of every Breidavík Group cycle and hiatuses are no doubt present at these levels, but most cycles are quite complete; major time gaps seem here to be absent (Eiríksson, 1981). However, the angular unconformities at the base of the Hörgi Formation, the Svarthamar Member and the Bangastadir member halfway the Grasafjöll Formation are considered to represent major time gaps (Eiríksson, 1981b).

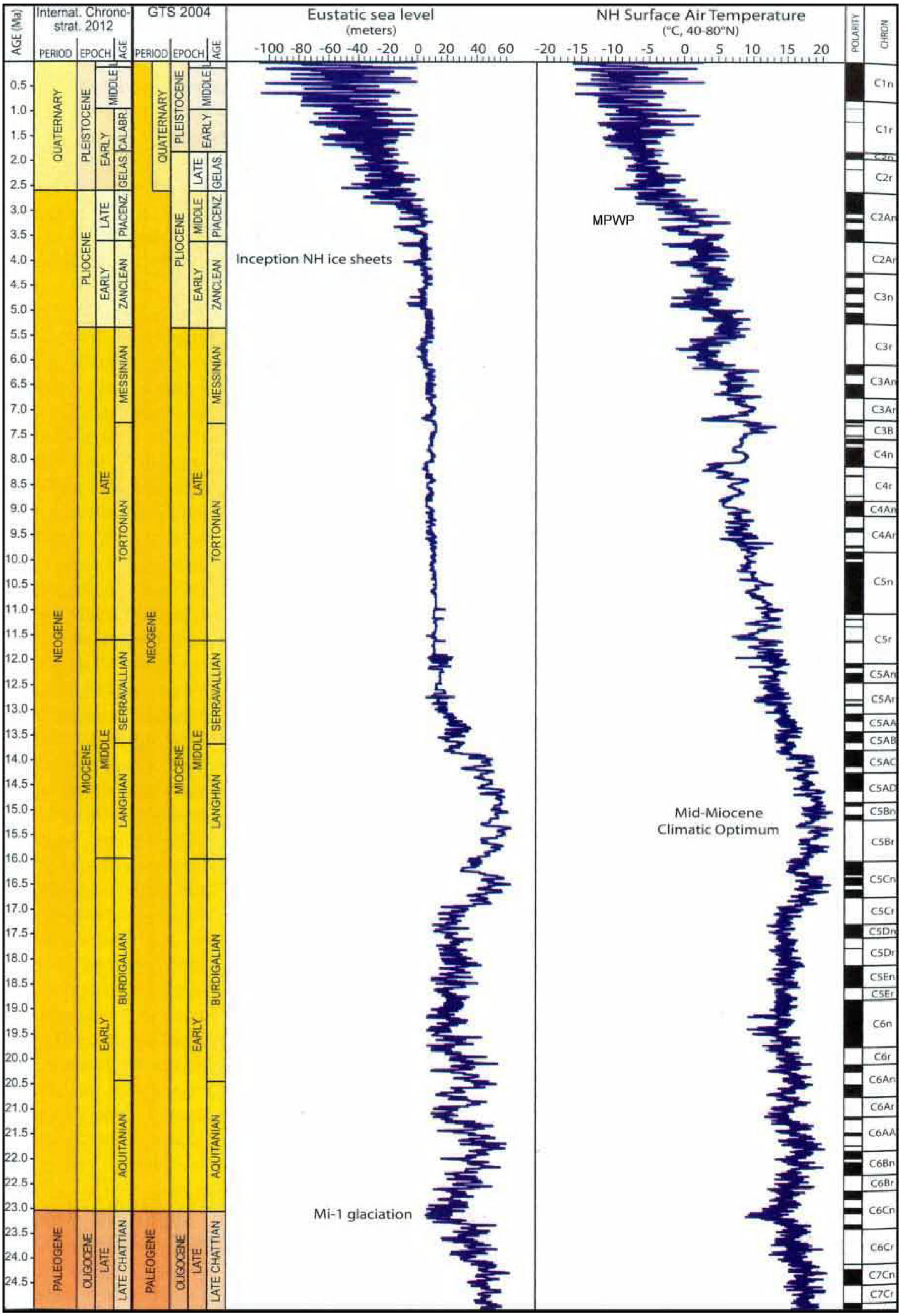

Figure 1.3: Modeled sea level and northern hemisphere temperature changes during the Late Oligocene and the Neogene (De Boer *et al.*, 2010; Gradstein *et al.*, 2012). The stacked benthic δ^{18}O record of Zachos *et al.* (2008) was smoothed by the authors, rescaled to ATNTS2004 and interpolated to obtain a continuous record with a time resolution of 100 years.

In our study, we selected the four most prominent marine interglacial deposits of the Breidavík Group, together with the entire record of the Tjörnes beds. From the Flatey island, only two samples were available: a marine sandstone from an outcrop of the island and a mudstone sample from the FL-01 core, situated in the northern part of the island (Figure 1.1). This restricted sampling nevertheless helped to understand the Tjörnes section and its history.

2. The geological time period studied

Many geological studies focus on the reconstruction of the Pliocene, as it may provide insights into the nature of warmer-than-modern climates and the mechanisms and effects of global warming (Raymo *et al.*, 1996; Bennike *et al.*, 2002; Kleiven *et al.*, 2002; Dodson and Macphail, 2004; De Schepper *et al.*, 2009; Robinson, 2009; Sarnthein *et al.*, 2009; Williams *et al.*, 2009; Naafs *et al.*, 2010). The unique combination of near modern atmospheric CO_2-concentrations, palaeogeography and palaeobiology makes it the most studied pre-Quaternary period in geology (Raymo *et al.*, 2011; Salzman *et al.* 2011). Calculations of temperatures and sea levels over the past 25 Ma based on 1-D ice-sheet models indicate higher Pliocene temperatures and sea levels compared to the present-day situation (De Boer *et al.*, 2010; Hilgen *et al.*, 2012; Figure 1.3). The ice-sheet models are based on stacked isotope curves of oxygen (Zachos *et al.*, 2008) or carbon (Lisiecki and Raymo, 2005; Figure 1.4), both derived form the $CaCO_3$ skeletons of in most cases fossil benthic foraminifera. The

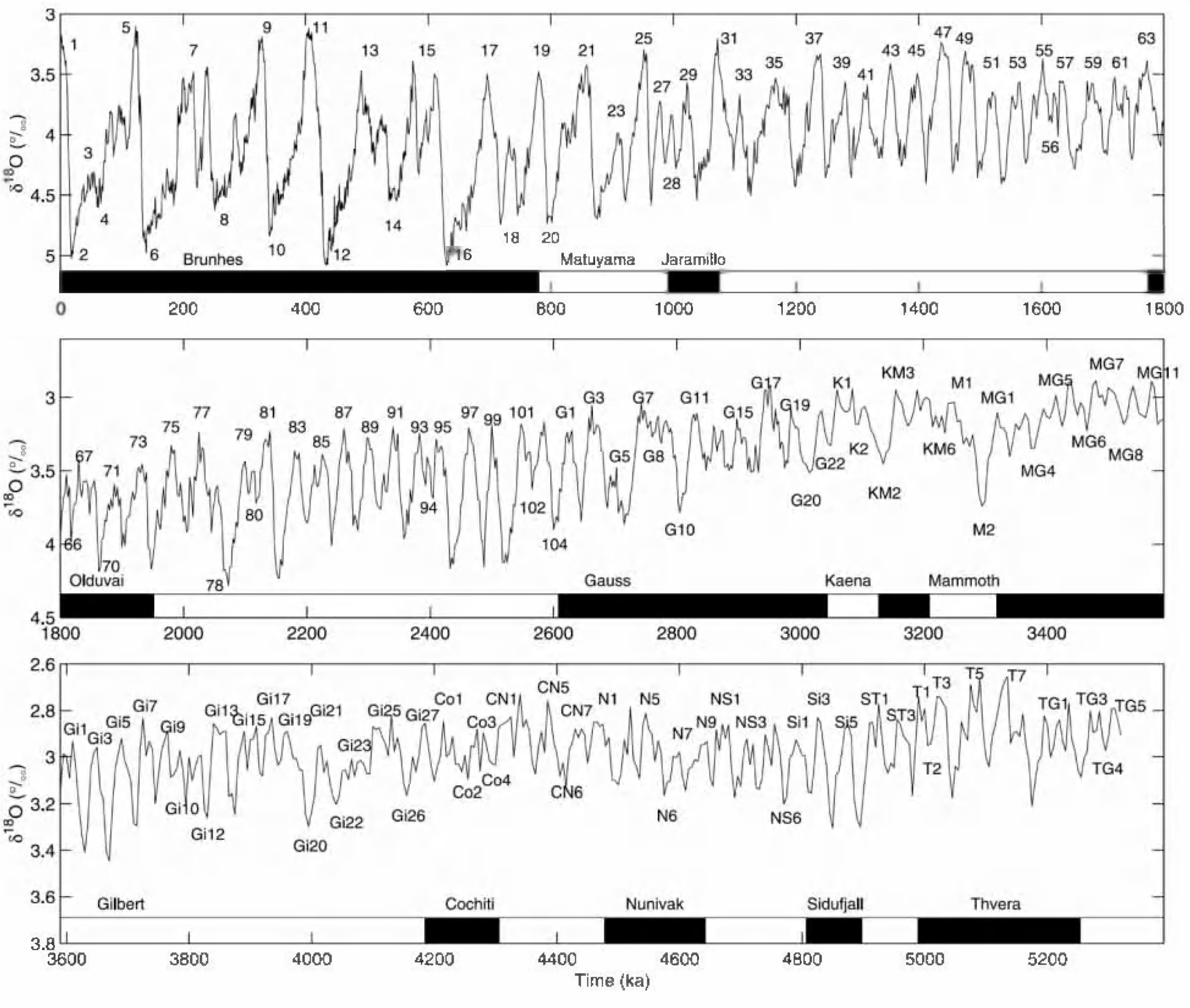

Figure 1.4: **The LR04 bethic $\delta^{18}O$ stack constructed by the graphic correlation of 57 globally distributed benthic $\delta^{18}O$ records. The stack covers the entire Pliocene to recent (Lisiecki and Raymo, 2005).**

reconstruction of past atmospheric CO_2-values and of the diffracted oxygen isotopes in sea water or ice cores, measured as the $\delta^{18}O$-ratio, allow to visualize the ongoing Neogene cooling (Figure 1.3). The Pliocene in general is warmer than today, but especially one particular period, the PRISM-interval, became studied with the aim to understand futher climate warming. The various programs of the United States Geological Survey's Pliocene Research, Interpretation and Synoptic Mapping Group (PRISM), focus on this stratigraphical interval corresponding to the Mid Piacenzian Warm Period (MPWP; c. 3.3–3.0 Ma; Dowsett *et al.*, 1996, 1999; Thompson and Fleming, 1996; Haywood and Valdes, 2006; Haywood *et al.*, 2009; Salzman *et al.* 2011; Figure 1.3).

The most conservative estimates of our future climate suggest a global warming of 1-2°C in the near future, even when the emission of greenhouse gasses is markedly reduced (Raymo *et al.*, 2009). The understanding of climate and ice sheet dynamics under warmer conditions than today is therefore crucial. The MPWP is the most recent period in which Earth's climate was consistently and for an extended period warmer than the Holocene, with global temperatures elevated by as much as 2 to 3°C with respect to modern values (Dowsett, 2007; Raymo *et al.*, 2009; Salzman *et al.*, 2011; Figure 1.3).

Our initial aim to reconstruct the environment during the MPWP in the northern Atlantic however, had to be abandoned, as it turned out that almost no suitable sediments of this period were preserved in the Tjörnes area. Our focus changed towards (1) the reconstruction of the Early Pliocene warm climate, as preserved in the Tjörnes beds, (2) the cooling announcing the onset of the glaciations at the transition of the Quaternary in the Breidavík Group and (3) temperature indications obtained by our study to calibrate climate models.

Global cooling started in the Oligocene at the base of the Rupelian, c. 30 Ma ago, and continued in the Miocene and Pliocene to result in the Ice Ages of the Quaternary (Figures 1.3, 1.4). The Pliocene (5.333–2.588 Ma) is divided in two stage: the Zanclean (5.333–3.600 Ma) and the Piacenzian (3.600–2.588 Ma) (Gradstein *et al.*, 2012; Figure 1.3). Before the revision of the base of the Quaternary in 2009 (Gibbard *et al.*, 2010), the Pliocene also included the Gelasian stage, now part of the Pleistocene. The beginning and the end of the Pliocene lack well marked and easy recognisable strata, as no major geological events such as important extinctions are present. The Pliocene Epoch was a generally warmer and wetter interval than today, and the major differences in climate are found in the higher latitudes where temperatures were markedly higher and where temperate and boreal vegetation zones showed a northward shift at that time (Dowsett *et al.*, 1996; Thompson and Fleming, 1996; Salzmann *et al.*, 2011). The position of the continents and the fauna and flora were in the Pliocene much comparable to today.

The Quaternary, the most recent period of the geological time scale, extend from 2.588 Ma to now; its base is marked by the major onset of the so-called Northern Hemisphere Glaciations (NHG), and global cooling. As known, the Quaternary comprises the Pleistocene (2.588–0.0117 Ma) and the Holocene (0.0117 Ma–recent). During the Pleistocene, large glacial periods alternate with small interglacial periods. The glacial-interglacial cycles of the Quaternary are driven by astronomical parameters related to changes in the orbit of the Earth around the sun and are known as the Milankovitch cycli (Milankovitch, 1941; Berger *et al.*, 1984, 1999). Three climate regulating processes are distinguished: (1) the eccentricity of the orbit with a duration of 100 ka, (2) the obliquity of the elliptic with a duration of 41 ka and (3) the precession of the equinoxes with a duration of 19 and 23 ka. The combination of these astronomical cycles determine the amount of radiation of the sun received by the Earth and long-term climatic variations. Fourteen of these cyclic phenomena were detected by Eiríksson (1981b) in the succession of the Pleistocene Breidavík Group (Figure 1.2). Up to now, 52 cold phases with glacial status have been distinguished in the marine oxygen isotopic records during the Pleistocene (Lisiecki and Raymo, 2005; Figure 1.4).

Since the Miocene, some 30 different glacial periods have been detected in Iceland, but the correct dating of all these tillites proved to be difficult (Ehlers and Gibbard, 2008). The oldest glaciers in Iceland date back to the late Miocene, according to Geirsdóttir (2004) at c. 5 Ma or according to Ehlers and Gibbard (2008) to 7–6 Ma (Figure 1.5). Between 4 and 3 Ma in the Pliocene, a second cooling phase began, glaciers started to nucleate in the mountains and rivers grew because of increased precipitation.

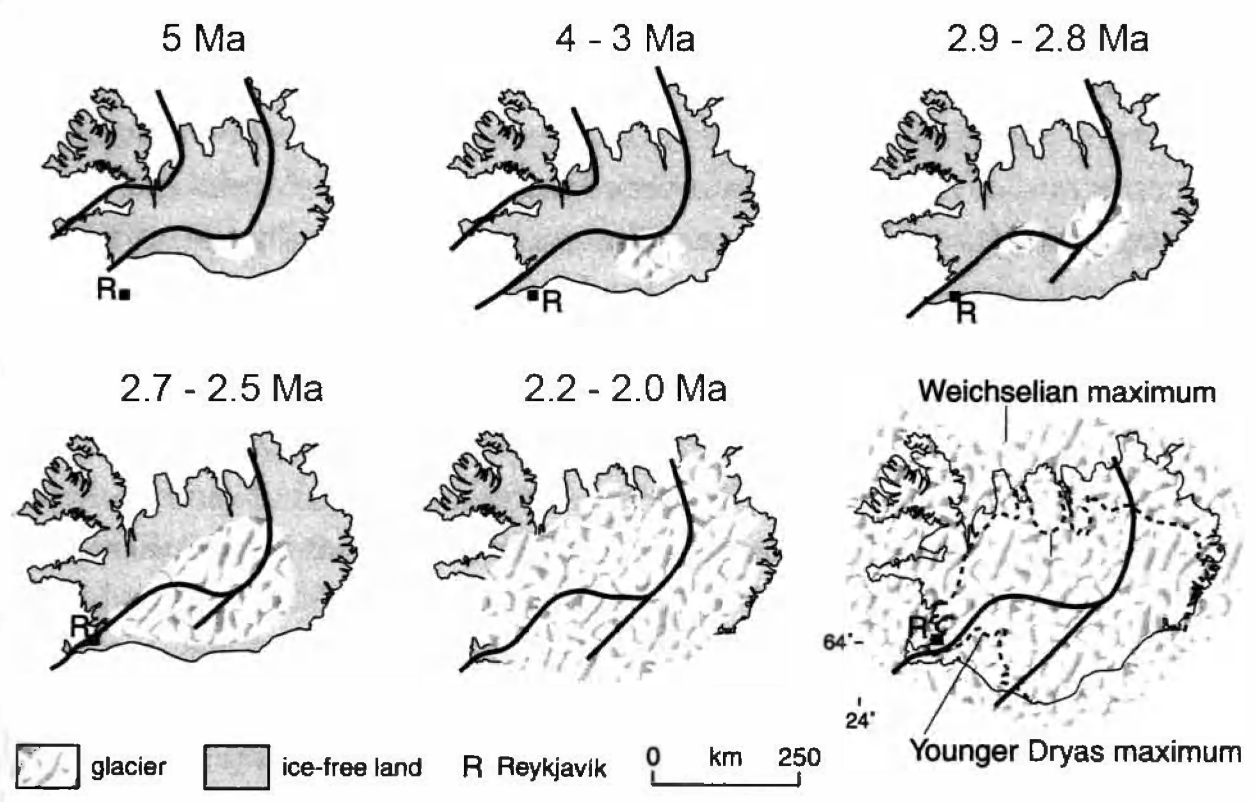

Figure 1.5: The growth of the ice sheet in Iceland during the past 5 Ma with indication of the evolution of the Icelandic rift (solid lines) during the same period (Geirsdóttir and Eiríksson, 1994; Thordarson and Hoskuldsson, 2006).

The progressive cooling resulted in the northwards and westward growth of the Quaternary ice sheet from its nucleus in southeast Iceland (Geirsdóttir and Eiríksson, 1994; Geirsdóttir, 2004; Thordarson and Hoskuldsson, 2006). By about 2.5 Ma almost half of the island was probably covered by ice and around 2.2 Ma most of Iceland for the first time (Figure 1.5). The tillites preserved within the Furuvík Formation just above the Höskuldsvík lavas on the Tjörnes Peninsula, are taken to mark the onset of full glaciation in Iceland and were up to now believed to be 2.2 Ma old (Thordarson and Hoskuldsson, 2006; roman capital I in Figure 1.2). The cooling or glacial phases alternated with interglacials, when marine sediments were deposited in the Breidavík Group.

3. Area of interest and palaeoceanography

Our study area is situated on the north Icelandic coast. As the PRISM studies clearly showed that climate changes in the Pliocene were more pronounced on higher latitudes, our preference went to such a highly situated study area. The Tjörnes section in the north of Iceland is located in an area that could be sensitive to possible changes in ocean currents, and their signals could be preserved in its marine sediments. This particular area in the Northern Hemisphere plays an important role in the thermohaline circulation (THC, Figure 1.6). This phenomenon, also called global conveyer belt or Atlantic Meridional Overturning Circulation, drives the temperature dispersal on Earth and thus the climate. This natural water and heath transport system is driven by temperature and salinity differences of oceanic water, and redistributes solar warmth around the world. For example, warmth accumulating on the equator will be transported to the north by the Gulf Stream (Figure 1.6). This is a powerful wind driven surface current, originating at the southern tip of Florida in the Gulf of Mexico and following the eastern coastline of North America up to Newfoundland, before crossing the Atlantic Ocean. In the centre of the Atlantic Ocean, the Gulf Stream evolves into the North Atlantic Drift (NAD), which splits in two branches at about 40°N 30°W:

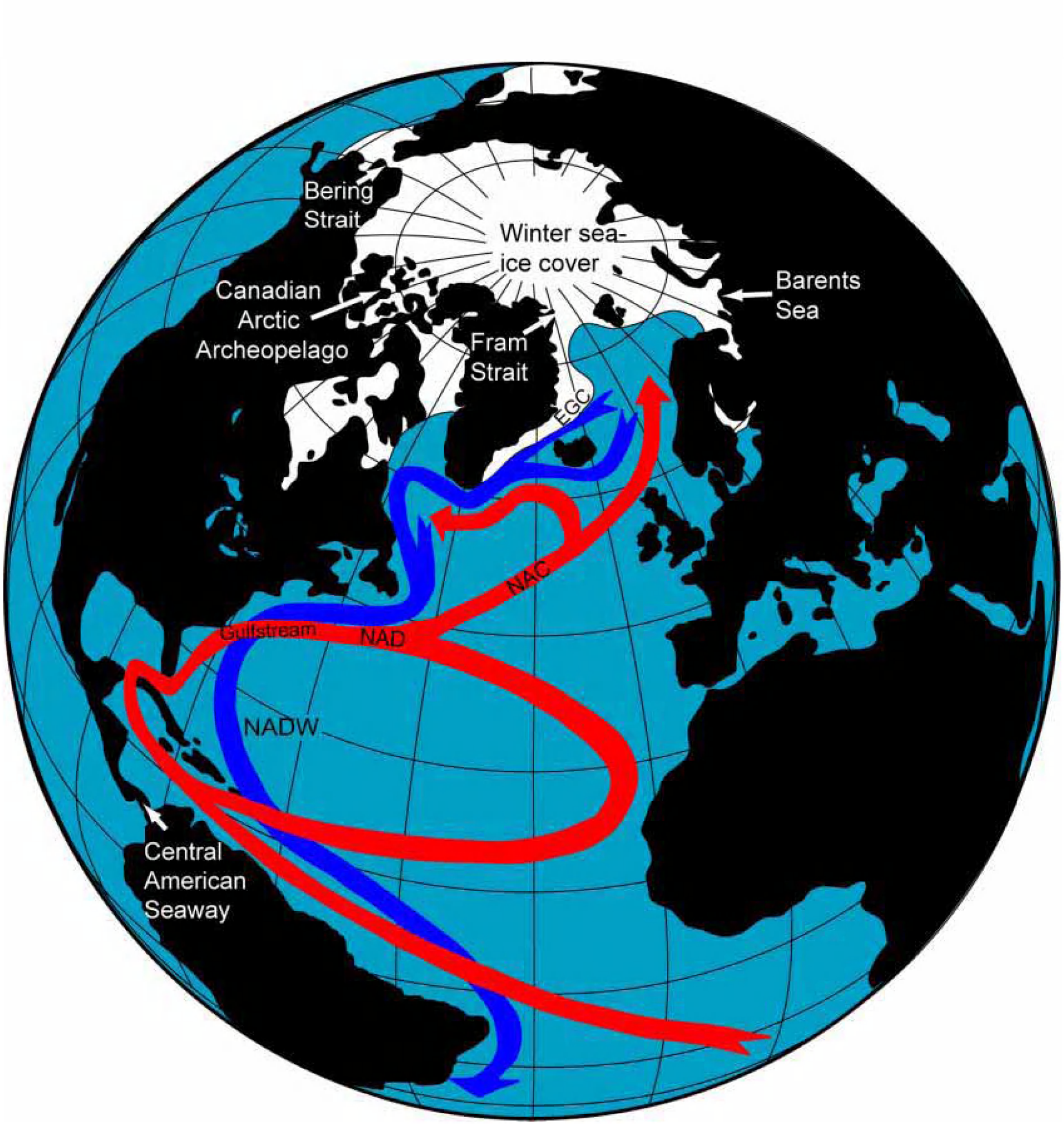

Figure 1.6: Europe's heating system. Highly symplified cartoon of Atlantic currents, with warmer currents in red (NAD: North Atlantic Drift; NAC: North Atlantic Current) and cold North Atlantic Deep Water (NADW) in blue. The thermohaline circulation heats the North Atlantic and Northern Europe, pushing back the winter sea-ice margin. The Central American Seaway and the Bering Strait are indicated with white arrows. After Rahmstorf (1997).

the North Atlantic Current (NAC) going to the north and a southern stream recirculating off West Africa. The warm Atlantic surface water cools during its transport and eventually sinks in higher latitudes to form the North Atlantic Deep Water (NADW). Polar ice, derived partly from evaporated seawater, further cools the initially warm surface water that becomes more saline. This cold, salty brine sinks and flows in the direction of the equator, forming the motor of the worldwide THC.

At present time and also during the Pliocene, all ocean basins are in connection with each other. The large-scale water transport of the THC allowed not only the transport of heat around the world, but also of marine organisms. Yet the marine realm during the Pliocene was characterized by a reconfiguration of ocean gateways, particularly the narrowing of the Indonesian Seaway and the closure of the Central American Seaway (CAS) resulting in the modern pattern of ocean circulation (Salzman *et al.*, 2011; Figure 1.6). The CAS forms the connection between northern and southern America through which Pacific water could mix with Atlantic water (Figure 1.6). However uncertainty exists concerning the timing of the ocean gateway changes.

The Tjörnes section is important in dating these changes, as at the *Mactra/Serripes* transition a major influx of Pacific molluscs has been observed (Bárdarson, 1925; Figure 1.2). During the Pliocene, only the deep Fram Strait between Greenland and Svalbard together with the shallow Bering Strait formed connections with the Arctic (Matthiessen *et al.*, 2009; Figure 1.6). The Bering Strait, situated between Alaska and Russia, connects the Arctic with the Pacific Ocean. After c. 100 Ma of closure, it reopened between 5.5 and 5.4 Ma (Marincovich and Gladenkov, 2001; Gladenkov *et al.*, 2002). The conduits through the Canadian Arctic Archeopelago and the Barents Sea were closed during the Pliocene (Matthiessen *et al.*, 2009; Figure 1.6). Before the shoaling of the CAS between 4.7 and 4.2 Ma (Haug *et al.*, 2001; Steph *et al.*, 2006), less saline water of the Central Pacific came into the Central Atlantic. Haug *et al.* (2001) demonstrated that the Caribbean surface-salinity between 4.7 and 4.2 Ma increased as a result of the shoaling of the CAS and the gradual diminished imput of less saline Pacific water. At 4.2 Ma, the modern Atlantic-Pacific salinity contrast of c. 1‰ became established (Haug *et al.*, 2001). The shoaling of the CAS and its final closure at about 2.7 Ma (Schmidt, 2007) strongly changed the North Atlantic oceanography by cutting of the entrance of less saline buoyant water from the Central Pacific in the Central Atlantic. Transport of more saline waters to the North Atlantic led to increased production of North Atlantic Deep Water (NADW) and thus a more vigorous Atlantic THC with more warmth transport to the north (Haug and Tiedeman, 1998; Haug *et al.*, 2001; Steph *et al.*, 2006; Poore *et al.*, 2006 *in* Salzman *et al.*, 2011). A possible intensification of Mediterranean outflow water at c. 3.3 Ma may also have brought warm salty water to the north-east Altantic, further intensifying the NADW formation (Khélifi *et al.*, 2009). The THC increased and more warmth and moisture was transported to the North-east Atlantic (Lunt *et al.*, 2008; Salzmann *et al.*, 2011). It was believed that this increased evaporation and precipitation in the Northern Hemisphere high latitudes culminated in the intensification of Northern Hemisphere Glaciations (NHG) during the Piacenzian (3.2–2.7 Ma) as a result of the closing of the CAS (“Panama Hypothesis”). Lunt *et al.* (2008) however could conclude that although the closing of the CAS may have slightly enhanced or advanced the onset of NHG, it was not a major forcing mechanism. More likely, the decreased levels of pCO_2 during the Neogene, coupled with fluctuating orbital configurations culminated it the crossing of a critical threshold (e.g. Berger *et al.*, 1999; Lunt *et al.*, 2008).

The reopening of the Bering Strait around 5.5/5.4 Ma initiated a southwards flow from the Atlantic to the Pacific (Gladenkov *et al.*, 2002). Short-term

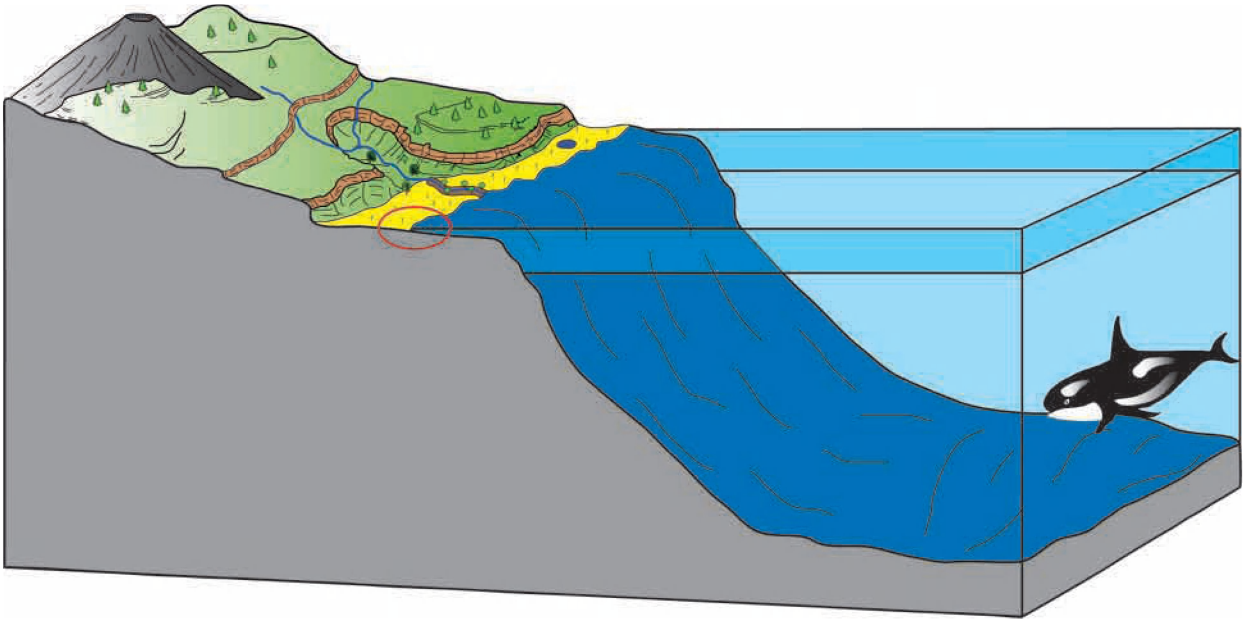

Figure 1.7: Schematic cross section from the north Icelandic hinterland to the beginning of the deep-sea during the Pliocene. The red ellipse shows the coastal sedimentation area, which became uplifted in a later phase.

closure of the Bering Strait might have occurred during pronounced sea-level lowstands at 4.9, 4.0, 3.3 and 2.5 Ma (Miller *et al.*, 2005 *in* Matthiessen *et al.*, 2009), but the sea level was often higher in the Early Pliocene than today. Since 3.6 Ma, the sea level steadily decreased and the Bering Strait might have been closed more frequently (Matthiessen *et al.*, 2009). Less data are available from the Arctic region, but it is believed that part of the Arctic was seasonally ice-free during the Pliocene, allowing transport when the gateways to the Arctic Ocean opened (Cronin *et al.*, 2008; Robinson, 2009). The central part of the Arctic Ocean located at the Lomonosov Ridge accommodated undisturbed perennial sea ice during the period from the Miocene till recent (references in Salzman *et al.*, 2011). It was supposed that the closing of the CAS induced a reversion of the flow direction in the Bering Strait; the detection of Pacific molluscs in Tjörnes played a major role in this hypothesis (Matthiessen *et al.*, 2009). The actual timing and closure history of the Panama Seaway was recently still controversial (Haug and Tiedemann, 2008), but the demonstrated connection with the migration event in Tjörnes and the isotope changes in the Caribbian Sea could make this history more clear (chapter 2). The northward transport of less saline Pacific water into the Arctic Ocean increased also the formation of polar ice at the time and reduced the THC (Matthiessen *et al.*, 2009). During the Early Pliocene, an appreciable global sea-level drop has been recorded, resulting in a hiatus in the circum-Arctic outcrops between 5.2 and 3.5 Ma (Matthiessen *et al.*, 2009; Figure 1.3).

Sea-level reconstructions based on for instance the elevation of fossil-shorelines indicate for the Mid Piacenzian Warm Period a 25 m higher sea-level suggesting a significantly reduced polar ice sheet (Dowsett and Cronin, 1990; Haywood *et al.*, 2009; Dowsett *et al.*, 2010), although the 1-D ice-sheet modeling of De Boer *et al.* (2010) only indicate c. 8 m sea level rise for the same period (Figure 1.3). The estimates for the MPWP sea level range from 10 to 40 m, but for numerical climate modelling a value of + 25 m is often adopted, implying the complete deglaciation of the West Antarctic and Greenland ice sheets and significant loss of the East Antarctic ice sheet (Raymo *et al.*, 2011). In the climate model of the PRISM, the Tjörnes section is the most northerly situated location in which Sea Surface Temperature (SST) estimates could be made (Dowsett *et al.*, 1996). Ostracod research by Cronin (1991) indicate a SST of 5°C warmer than today during the deposition of the Early Pliocene Tjörnes beds.

It is believed that the Greenland-Scotland Ridge was markedly lower during the MPWP, and warm Atlantic surface water could extend much further to the north in the Arctic (Robinson *et al.*, 2011). Much warmer Mid-Piacenzian SST's are recorded compared to today: SST's in the Beaufort Sea, situated north of the Bering Strait, were c. 2 to 4°C warmer, while SST's in the Fram Strait, situated between Greenland and Svalbard, were c. 13 to 18°C warmer (Robinson, 2009).

The preceding findings indicate the importance of the Tjörnes section in the understanding of the Pliocene global oceanography. A major palaeoceanographical event has already been detected in this section, but probably more signals can be found. Moreover the former sedimentation environment of Tjörnes was situated in the coastal area, increasing its palynological potential (Figure 1.7, the red ellipse indicates former sedimentation area). Macro- as well as microfossils from the land as well as the sea are here preserved. Both proxies, dinoflagellate cysts and pollen/spores, could thus be studied from the same outcrop, allowing a combined marine and terrestrial palaeoecological study.

4. Palynology

The following notes are based on textbooks, such as Armstrong and Brasier (2005) and Lee (2008) for dinoflagellate cysts and Moore *et al.* (1991) and Fægri and Iversen (1989) for pollen and spores. The references will not be repeated.

4.1 Dinoflagellate cysts

4.1.1 Ecological significance

Dinoflagellates are a large group of flagellate unicellular microplankton mostly living in a marine environment, but also occurring in fresh water. The living organisms usually have two flagella, one transversal flagellum lying in the cingulum and propelling the cell and one longitudinal coming out from the sulcus and acting mainly as a rudder (Figure 1.8).

Both flagella permit active movement in the water column. The dinoflagellate body wall is called theca with various plates oriented in a certain pattern, called tabulation.

Dinoflagellates are the third most important primary producers in oceans after the diatoms and calcareous nanoplankton, playing thus an important role in the food chain. Most dinoflagellates are photosynthetic or autotrophic producers (e.g. the gonyaulacoids) or heterotrophic consumers (e.g. the peridinoids). Autotrophic dinoflagellates produce complex energy-rich organic compounds (fats, carbohydrates, proteins) from simple substances using the energy of light or inorganic chemical reactions. Heterotrophic dinoflagellates cannot fix carbon and use for the construction of their cells organic molecules assimilated by autotrophic organisms or derived from other heterotrophic organisms. Heterotrophic organism are thus dependent on other organisms. The feeding strategies include endosymbiosis and parasitism.

The size of dinoflagellate cysts varies between 20 and 150 µm and thus falls in the same size classes as pollen and spores, creating the advantage that both proxies can be extracted with a same laboratory preparation technique and studied by a same magnification under a light transmission microscope. As their distribution is subject to parameters such as temperature, nutrients, salinity, water depth and sea ice cover, they can be used to reconstruct past ecological conditions and climates. Their geological record begins in the Upper Triassic (Norian; 216.5–203.6Ma). As dinoflagellates are planktonic with a broad distribution, they can also be used as biostratigraphical markers. Moreover, dinoflagellates evolve very rapidly, allowing for the Neogene Period a zonation scheme with a resolution of c. 100.000 a. The Highest Occurrence (HO) age is the age of the highest sediments in which a species occurs before it evolved, moved elsewhere or became extinct; the Lowest Occurrence (LO) age of a species gives the oldest age of the sediments in which it has been found.

Meroplanktonic dinoflagellates produce during their life cycle highly resistant resting cysts or dinocysts (Figure 1.9) and are therefore of major interest in geology. During periods when environmental parameters are not favourable, the free swimming algae produce a diploid zygote that remains immobile in a cyst on the bottom of the basin. When the living conditions are again acceptable the organisms can germinate, leaving an empty cyst in the sediments. The germination opening is called the archeopyle and reflects the tabulation pattern of the cyst. The tabulation can also be seen in the body of the swimming form, called theca, of which the cyst is some kind of a duplicate or copy (Figure 1.8).

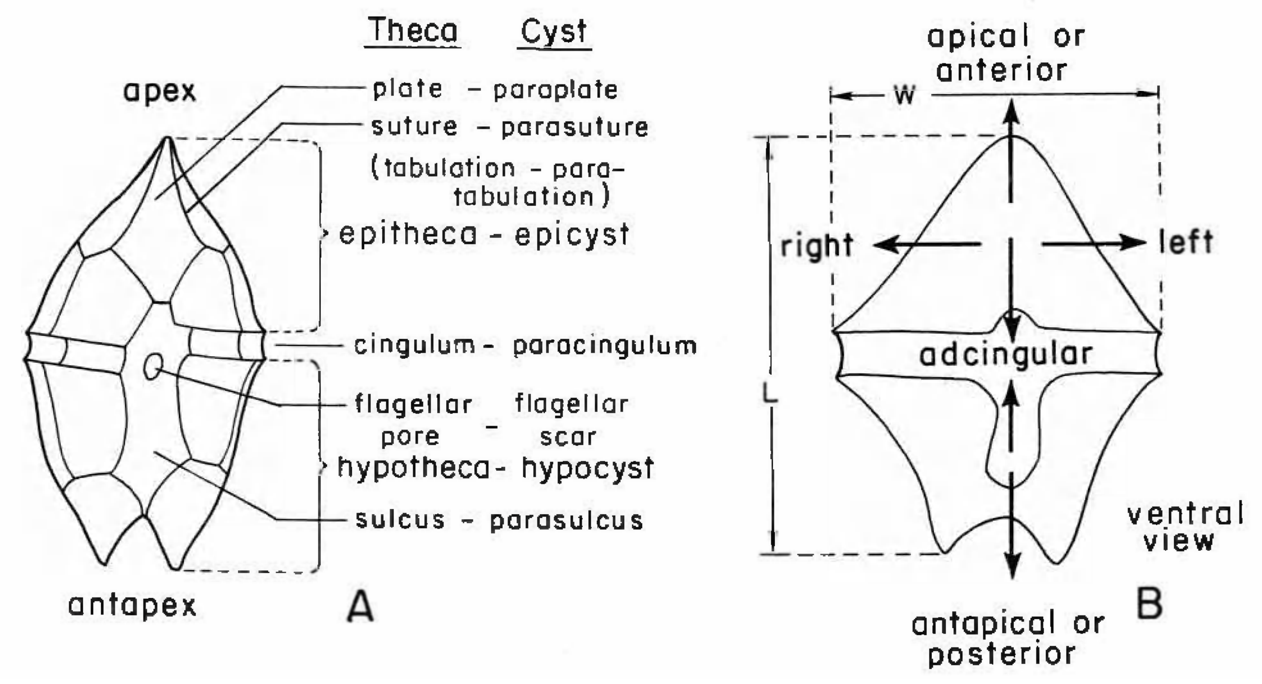

Figure 1.8: Basic terminology of the theca and cyst from dinoflagellates (Evitt, 1985).

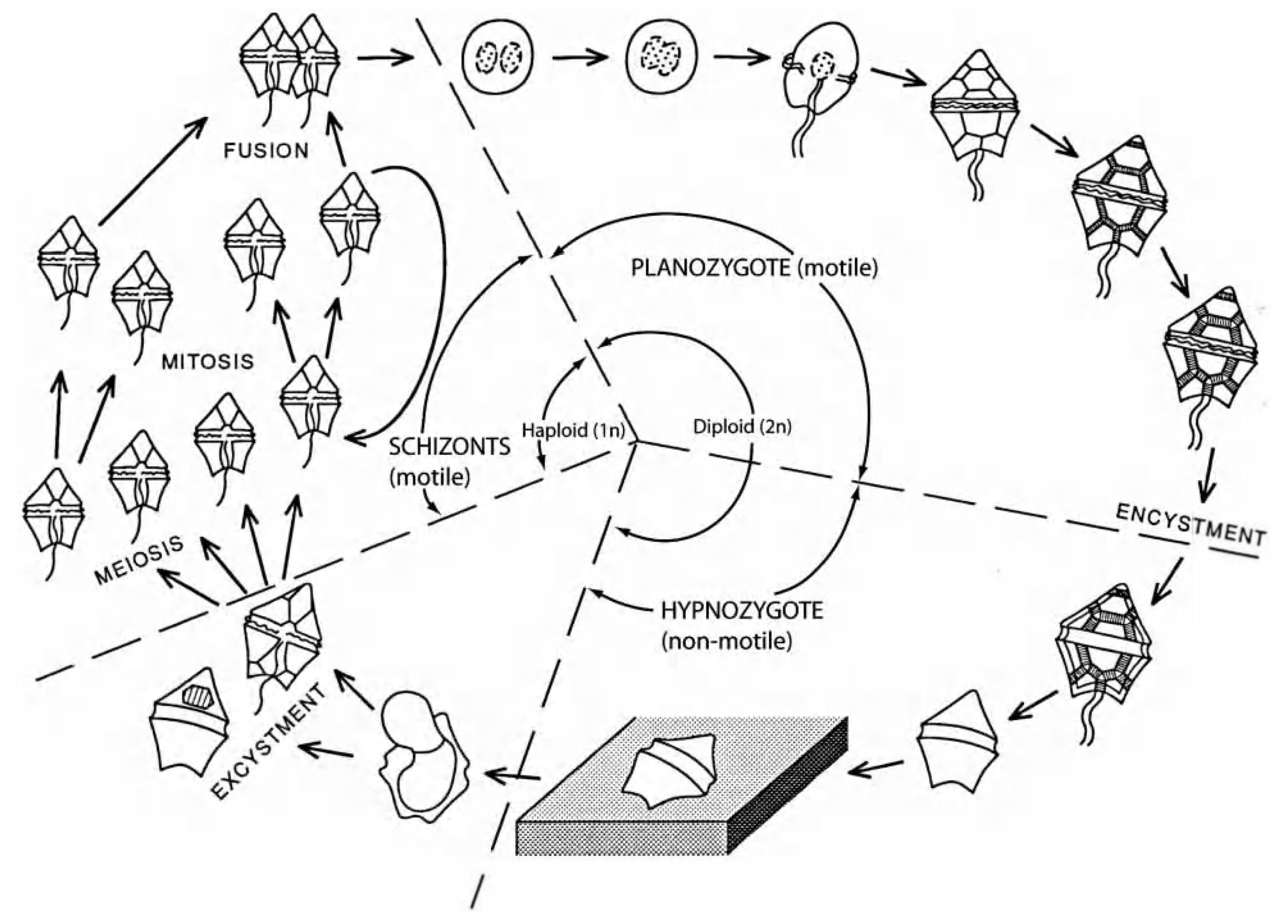

Figure 1.9: Idealized life-cycle involving sexual reproduction and cyst formation (after Evitt, 1985 and Fensome *et al.*, 1993).

The presence of an angular archeopyle and a body composed of well-organised plates (tabulation) are major diagnostic features allowing to distinguish dinoflagellates from acritarchs. The latter group consists of organic-walled marine microfossils of uncertain biological affinity. They are probably hollow resting structures of marine phytoplanktonic algae, which open with an irregular split instead of an archeopyle. Acritarchs have a form similar of that of dinoflagellate cysts. Most of them are probably green algae or coppepods eggs, others possible dinoflagellates.

Most dinoflagellate cysts or dinocysts have an organic wall and can easily be extracted from the sediment. These resting cysts are studied within the discipline of palynology s.l. Some dinoflagellates produce toxines and can poison bivalves amongst other organisms. Blooms of dinoflagellates may colour the water and are known as red tides. The term dinosporin is used to describe the chemical composition of the organic-walled dinocysts and is a complex aromatic biopolymer, resistant to both strong acids and bases. Cysts are quite resistant but show species specific resistance to aerobic degradation. Heterotrophic species such as *Echinidinium* sp. and *Brigantedinium* sp. are very sensitive to oxidation, while autotrophic species such as *Lingulodinium machaerophorum* and *Operculodinium centrocarpum* are moderately sensitive. Other autotrophic species such as *Impagidinium* sp. and *Nematosphaeropsis labyrinthus* appear to be very resistant (Marret and Zonneveld, 2003). As selective preservation may occur, dinocyst assemblages have to be carefully interpreted.

4.1.2. Preparation method

The marine sediments are macerated in the laboratory in order to dissolve the different minerals and to concentrate the organic material following a standard procedure. Solid rocks are washed, broken into c. 0.5 cm large pieces and decalcified with cold 2M HCl (c. 6%).

One *Lycopodium clavatum*-spore tablet is added as a marker at the beginning of the chemical treatment in order to allow absolute concentration calculations. Repeated washings with demineralised water removes the Ca^{2+} ions and prevents the formation of fuorosilicates later on. Cold HF (40%) dissolves the silica and silicates in the rocks, transforming it into a kind of gel. Repeated cycles with cold or even warm (60°C) 2M HCl are needed to dissolve this gel. The residue is then washed and neutralised over a 10 µm sieve. As the sediments of our study are saturated with silica of volcanic origin, they were difficult to dissolve and even warm HF treatments were needed. In case of insoluble particles, decanting separated these from the residue. No ultrasonicifaction or oxidation was used. After the final washing, the residue is stained with safranin-o and mounted with glycerine-gelatine jelly on microscopy slides.

Lignites were treated with acetolysis and KOH (see the preparation of pollen and spores below). As not all dinocysts have a same preservation potential, this treatment may disturb the dinocyst signal. Boiling with 5% KOH, necessary to decay humus acids in peat and lignite, will affect mostly the heterotrophic dinocysts.

Some dinoflagellate species form calcareous resting cysts. They generally disappear completely as a result of the standard laboratory treatment with HCl, used to decalcify the sediment. The inner layer of some of the calcareous species however is organic and can be found in residues treated by the standard maceration technique.

4.2. Pollen and Spores

4.2.1 Ecological significance

Pollen are structures produced during the life cycle of higher plants, conifers and angiosperms. They contain the male gametophyte with two cells, one with the genetic material and one which will form the pollen tube, necessary to make the connection to the ovule of the female gametophyte. The germination occurs through an opening of the pollen, called pore or colp, through which the pollen tube transports the male genetic material (Figure 1.10). Monocotyle plants such as grasses have one pore, while dicotyle plants have mostly tree pores, colps or a combination of both aperture types. The pollen contain the male haploid genetic material. Meiosis of the pollen mother cell forms a tetrad of unripe pollen which separate in four haploid pollen grains. After fertilisation of the female ovule, a diploid seed is formed resulting in a new sporophyte (tree, shrub or herb).

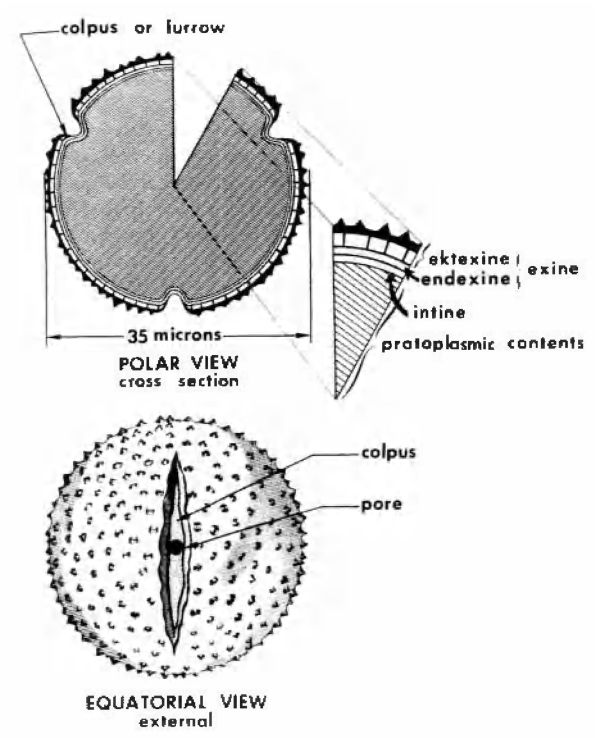

Figure 1.10: Diagrammatic view of typical tricolporate pollen grain in section, above, and external view, below (Traverse, 2007).

The wall of the pollen is very resistant, as it is composed of sporopolenine. This biopolymer is a very stable organic molecule present in the outer wall layers (exine) of pollen and spores. Only this wall layer has a very good preservation potential; the inner wall made of cellulose can decay very soon. Pollen are of great biostratigraphical value as large amounts of it are formed by the plants, become dispersed and afterwards good preserved in wet sediments.

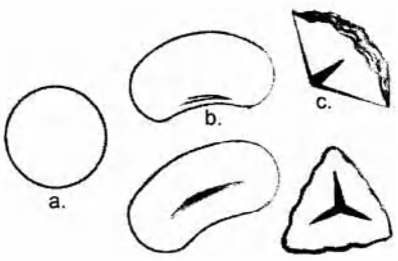

Figure 1.11: The major spore types of vascular plants. a: Alete; b: Monolete, two views; c. Trilete, two views (Kapp *et al.*, 2000).

Reconstructions based on pollen must keep in mind that pollen transported by wind, mostly derived from tree species, will be more widely distributed than those of insect pollinated plants.

Spores are structures of lower plants such as bryophytes and ferns used to transport male as well as female genetic material. Lower plants can produce large female megaspores and small microspores and are called heterosporous. Some lower plants produce only microspores and are called homosporous. The spores are in fact haploid gametophytes containing half of the chromosome compliment of the diploid sporophyte (2n). Spores are formed in sporangia and are ejected in damp areas after explosion to form gametophytes which in turn form the gametes that fertilize and form a diploid sporophyte again. Two major morphological groups occur: the monolate spores with one germination slit and the trilete spores with an Y-formed germination opening (Figure 1.11).

Fossil pollen and spores assemblages reflect former vegetations, but the proportions of the plants present in a pollen sample and in the vegetation are not comparable at all. The different dispersal mechanisms and availabilities of pollen or spores of various taxa have to be taken into account. Their small sizes and good preservation allow their extraction from lignites and marine sediments. Pollen however can rarely be attributed to a particular species. A pollen-type or pollen-group mostly contains various species and even families. It is therefore difficult to reconstruct particular temperatures and habitats, as the types often group taxa with different ecological parameters. Plant macrofossils such as leaves, seeds and woods are mostly species specific and can give more precise ecological information. Pollen studies in lignites are also hampered by the large amounts of amorphous organic material, making the observations of pollen more difficult.

4.2.2. Preparation method

For marine sediments, the same method is followed as described for dinocysts. Acetolysis is used only for the lignites as they are composed of 100% organic material, mainly cellulose. Acetolysis is a maceration method developed by Gunnar Erdtman, through which cellulose is dissolved. The chemical mixture used is composed of 9/10 acetic anhydride ($C_4H_6O_3$) and 1/10 sulphuric acid (H_2SO_4). Its effect is the removal of the inner content of the pollen and a more clearly visible pollen wall morphology. The method is used to diminish the amorphous organic material. The disadvantage however is the restricted resistance of heterotrophic dinoflagellate cysts such as *Brigantedinium* sp. to the technique. Before acetolysis, the lignites were treated with 5% KOH in order to dissolve the humic acids present and to break down the lignites. Carbonates are removed with cold 2M HCl (c. 6%), silicates with 40% KOH. One *Lycopodium clavatum*-tablet was added to the lignite samples in order to make counting of the absolute concentrations possible. No staining with safranin-o was applied. The residues of the lignites were mounted in the same way as the ones of the marine sediments.

5. Vegetation overview in Iceland from the middle Miocene to recent

About 55 Ma ago, when the opening of the North Atlantic began, this early ocean was still a narrow inland sea and plants could migrate freely from North America/Greenland and from Eurasia to Iceland (Grímsson *et al.*, 2007; Figure 1.12). This inland sea evolved into an open and vast ocean and around 36 Ma, plants could cross the ocean only along two routes: a northern one via Svalbard and a second route between Greenland and Scandinavia via the Faeroes and proto-Iceland, known as the North Atlantic Land Bridge. When the ocean widened further around 24 Ma, the migration between the Faeroes and proto-Iceland became difficult, but the migration route between proto-Iceland and Greenland was still open. In the Middle Miocene around 15 Ma, the connection with the Faeroes was lost. Around c. 4 Ma, the connection with Greenland also stopped and Iceland became totally isolated (Grímsson *et al.*, 2007).

Warm–temperate tree taxa with a clear North American affinity, such as *Sequoia*, *Magnolia*, *Sassafras*, *Glyptostrobus* and many other taxa were present on Iceland during the Middle Miocene (15 Ma; Windisch, 1886; Akhmetiev *et al.*, 1978; Grímsson and Símonarson, 2008; Denk *et al.*, 2011).

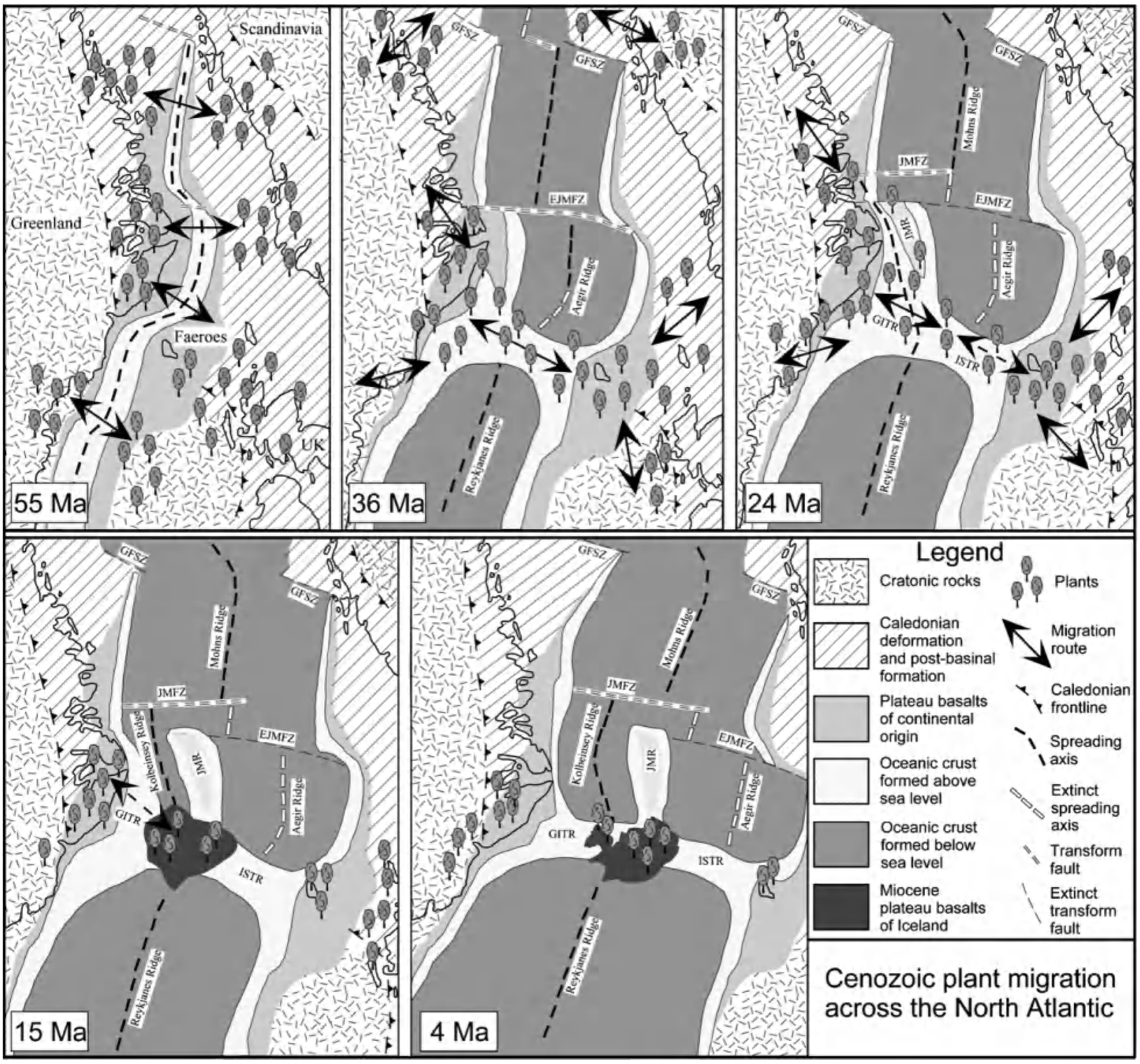

Figure 1.12: Reconstruction showing the opening of the North Atlantic Ocean and possible migration routes during the Cenozoic. GSFZ: Greenland-Senja Fracture Zone, EJMFZ: East Jan Mayen Fracture Zone, JMFZ: Jan Mayen Fracture Zone, JMR: Jan Mayen Ridge, GITR: Greenland-Iceland Transverse Ridge, ISTR: Iceland-Scotland Transverse Ridge. (Grimsson *et al.*, 2007)

The diversification of the flora started already during the early stages of the formation of Iceland, when broadleaved deciduous and partly evergreen beech forest with *Fagus* as dominant taxa grew on the highlands, and conifers, such as *Sequoia* and *Glyptostrobus*, in the lowlands (Grímsson *et al.*, 2007; Grímsson and Símonarson, 2008). The North Atlantic Land Bridge between proto-Iceland and the European and American continents allowed a direct colonisation and diversification of the vegetation (Figure 1.12).

After 12 Ma, during the Serravallian, the vegetation changed drastically, reflecting the increased isolation of the island and a partial break up of the land bridge (Grímsson and Denk, 2007). Plants with restricted dispersal potential did not migrate to Iceland after 9 Ma (Late Miocene); migration from the west may have been hampered earlier (Grímsson and Denk, 2007). Pollen of *Quercus* morphotype 2, with a clear similarity to recent North American species, appears however for the first time in Iceland during the latest Miocene at Selárgil (5.5 Ma), and suggest continued immigration from the west at that time (Denk *et al.*, 2010). *Quercus* pollen morphotype 1 was found in the 9–8 Ma Hrútagil locality (Skarðsströnd–Mókollsdalur Formation). This first morphotype has a general northern hemisphere distribution and its origin is not clear.

Late Miocene Icelandic floras are quite different from Middle Miocene floras, as warm-temperate taxa are lacking. Taxa adapted to colder conditions dominate and reflect gradual cooling (Heer, 1868; Akhmetiev *et al.*, 1978, Grímsson and Símonarson, 2008). *Betula* mainly, but also *Alnus*, *Salix* and *Acer* are present in the sediments deposited around lakes, while conifers such as *Abies*, *Picea*, *Pinus*, *Pseudotsuga* and *Larix* dominate the highlands. The vegetation during Late Miocene times reflects a temperate to cool–temperate mixed boreal forest (Grímsson and Símonarson, 2008).

From the Miocene/Pliocene transition onwards, the vegetation shows close similarities to European floras. During this period, *Betula* and *Salix* shrubs and grasses become more and more common and form a tundra-type of vegetation, whereas the taiga-type forest with *Picea* and *Abies* declines (Akhmetiev, 1991). The Quaternary glacial periods reduced severely the number of taxa of the Icelandic flora. *Pinus* disappeared 1.1 Ma ago and *Alnus* is only found during interglacial periods until 0.5 Ma ago (Eysteinsson, 2009). The cooling resulted in an arctic climate with no real summers, a climate very similar to that of today. The only forest forming native tree species nowadays are the downy birch (*Betula pubescens*), the uncommon rowan (*Sorbus aucuparia*), the extremely rare aspen (*Populus tremula*) and the tea–leaved willow (*Salix phylicifolia*). All recent tree species are quite small, and the presence of the fourth one is even mostly restricted to the shrub form. Rundgren and Ingólfsson (1999) postulate that half of the present day flora in Iceland must have survived in Weichselian refugia on the island itself, while a maximum of 20% is introduced by man, and 30% can be explained through long distance transport by ocean currents or birds. The first settlers on Iceland around 870 AD found a birch (*Betula*) forest covering about 25 to 40% of the island, shrubs mainly along the coast and in the wetlands, and trees in sheltered valleys below 400 m (Eysteinsson, 2009). Higher altitudes were covered with willow (*Salix*) tundra. By the start of modern monitoring in 1950, it became clear that logging, slash-and-burn and grazing sheep reduced the original tree cover to less than 1%. As a result, the Icelandic vegetation appears at first sight as a treeless boreal tundra with arctic-alpine elements. With exclusion of the genera *Hieracium* and *Taraxacum*, the present vegetation consists of only 440 species of vascular plants (Einarsson, 1963). A total of 365 species are widespread, 98% of the recent taxa are of European affinity, and only 64% are present in Greenland (Einarsson and Albertsson, 1988; Kristinsson, 2005; Denk *et al.*, 2011). As a consequence of the scarce vegetation, pollen dispersal is nowadays very low. A comparison of the recent Icelandic vegetation map (Gudjónsson and Gíslason, 1998) with the reconstructed vegetation map of Iceland during the earliest colonization settlement (Einarsson and Gíslason, 2000) points to an anthropogenic reduction of the vegetation on the Tjörnes Peninsula: the birch and woodland of the coastal border were replaced by a treeless dryland vegetation border.

6. Previous palynological s.s. research in the Tjörnes Peninsula

Earlier palynological analyses of the Tjörnes section focused mainly on lignites and clayey gyttja (Schwarzbach and Pflug, 1957). These authors investigated a total of seven horizons from the Early Pliocene *Tapes* Zone (layers A, B and 4 from Bárdarson, 1925), the *Mactra* Zone (layers E and F) and the Pleistocene Fossgil Member (below unit 3 of Bárdarson, 1925; Figure 1.2). The pollen concentration was low and the data is mostly presented as present/absence data. Nevertheless, a diverse flora could be recognized, dominated by tree and shrub gymnosperm taxa (*Abies, Ephedra*-type, *Larix*, *Picea*, *Pinus*; possibly *Pseudotsuga*) and angiosperm taxa (*Alnus*, *Betula*, cf. *Carya*, *Corylus*, *Cyrilla* or *Castanea*-type, Ericaceae, *Fagus silvatica*-type, *Hedera*, *Ilex*, *Juniperus*, *Myrica gale*-type, cf. *Platanus*, cf. *Quercus*, *Phellodendron*, cf. *Rhamnus* and *Salix*). Angiosperm herbs (Rubiaceae/Lamiaceae, Cyperaceae), water plants (*Nymphaea*) and spore plants (Polypodiaceae, *Sphagnum*, *Pteridinium*) are present in low numbers. Layers E and F from the *Mactra* Zone contain pollen of the more warmth-demanding plant *Ilex*; they were therefore interpreted as deposited during a climatic optimum. According to Schwarzbach and Pflug (1957), the climate during the deposition of the Tjörnes beds was generally warmer than today, but definitely cooler than the Pliocene climate of Central Europe. The Pleistocene Fossgil spectrum is still composed of mainly tree and shrub species, but *Salix* (29%) and *Alnus* (23%) are now the two dominant species.

The warmer taxa have disappeared and the other tree pollen such as *Pinus*, *Picea*, *Abies*, *Larix*, *Myrica gale*-type, *Fagus*?, *Populus*? and *Juniperus*? are interpreted as partly introduced from the south.

Einarsson (1977) *in* Eiríksson *et al.* (1992) analysed a pollen sample of the Breidavík Group and inferred a forest vegetation characterised by *Pinus* and *Alnus*, accompanied by *Betula*, *Salix* and *Juniperus*.

Akhmetiev *et al.* (1978) studied the plant macrofossils and the pollen and spores from lignites and marine sediments from the Tjörnes section (Figure 1.2). The results of the analysis of 57 samples from the cliffs of the Tjörnes beds and 9 from the Breidavík Group were published. They did not sample the interval between unit F and unit 14 at the top of the *Mactra* Zone and the interval between unit 15 and unit 23 in the lower part of the *Serripes* Zone. The Breidavík samples are situated in the Furugerdi Member (1 sample), the Fossgil Member (3 samples), the Svarthamar Member (4 samples) and the Thorfhóll Member (1 sample). The pollen was often poorly preserved and the extraction from the silica-rich sediments proved difficult. The Upper Pleistocene deposits yielded a very poor pollen and spores assemblage, most probably because of the extremely low vegetation cover at the time. Compared to contemporaneous assemblages from the continents, the Icelandic ones only contain 1/3 to 1/5 of their number of taxa, illustrating the isolated position of the island. Pollen from wind pollinated plants such as *Salix*, *Betula* and *Pinus* are extensively represented in the pollen slides, while insect pollinated plants such as *Acer* can be dominant in the macrofossils, but are quite scarce in the pollen slides. The wind pollinated *Populus* and the insect pollinated *Dryas* were present to a lesser extent in the macrofossil remains compared with *Acer*, but are also absent or very rare in the pollen record. In contrast to the findings from Tjörnes by Schwarzbach and Pflug (1957), tree and shrub pollen of gymnosperm and angiosperm plants play here a less prominent role and have maximum values of approximately 30% in unit D and 40 to 50 % in the upper part of unit F. The presence of the gymnosperm pollen of *Larix*, *Pinus* and *Abies* is restricted to the Tjörnes beds; they are absent in the Breidavík Group. A large number of conifer pollen is recorded in unit 15, but was interpreted as re-deposited pollen. *Alnus*, trees and shrubs, and *Betula* are the most abundant angiosperm wood plants in the pollen signal, with peaks in lignite D, E and F, followed by Ericaceae, *Salix* and *Myrica*. Akhmetiev *et al.* (1978) did not record warmth-loving trees such as *Quercus*, *Ilex*, *Juglans* and *Castaneae* in the Tjörnes beds. *Alnus*, *Betula*, *Salix* and Ericaceae are the only remaining tree and shrub species found in the Breidavík Group. Cyperaceae are moderately present in the *Tapes* Zone, but become the most prominent species in the Tjörnes beds from the top of this zone on, together with Polygonaceae (*Polygonum bistorta*-type) and, to a lesser amount, Rosaceae (*Sanguisorba officinalis*) and Ranunculaceae. Poaceae play a moderate role until the upper part of the *Serripes* Zone in lignite J, later becoming the dominant species. Spore plants such as Polypodiaceae, *Sphagnum*, *Lycopodium* and *Selaginella selaginoides* are in the study by Akhmetiev and collaborators included in the pollen sum, which is normally not done, but they are never dominant (range mainly between 5 and 7%). In the *Tapes* and *Mactra* Zones, the relative amount of herbaceous and arboreal plants and shrubs show major fluctuations, while from the upper part of the *Serripes* Zone on, herbaceous plants are dominant, mainly because of the high numbers of Poaceae.

Willard (1994) examined ten marine sediment samples from the Tjörnes beds in the framework of a vegetation study of the North Atlantic region around 3.0 Ma ago (Figure 1.2). The age model of the Tjörnes section by Verhoeven *et al.* (2011) however dates these beds as Early Pliocene between *c.* 5 Ma and *c.* 4 Ma and no longer as Middle Pliocene. The pollen was sparse in most of the Tjörnes samples. Next to non-arboreal pollen, mainly Cyperaceae, warm-temperate tree taxa were recorded in the *Tapes* Zone (*Quercus*, *Acer*, *Castanea*, *Ilex*) and in the *Mactra* Zone (*Picea*, *Quercus*, *Betula*, *Acer*). Some of these warmth-demanding taxa such as *Castanea* and *Ilex* are no longer present in the lower part of the *Serripes* Zone; this suggested warmer conditions during deposition of the *Tapes* and *Mactra* Zones, in contrast to more temperate conditions during the deposition of the *Serripes* Zone. Willard (1994) described the vegetation as a mixed coniferous and hardwood forest vegetation with no close modern representant. According to the same author, the most similar, recent vegetation is that of the *Tsuga*-northern hardwood forests of Newfoundland and

Nova Scotia; this would indicate cooler winters and warmer summers than today on the Tjörnes Peninsula. The presence of warmth-demanding taxa in Tjörnes would allow a reconstructed January temperature of at least 4°C to possibly 10°C warmer than today during the Early Pliocene. Present January temperatures in Newfoundland and Nova Scotia however average around -5°C and are too cold for a vegetation with, for example, *Ilex*. The comparison with Newfoundland and Nova Scotia as a best modern analogue is considered doubtful.

Löffler (1995) studied remains of wood from unit 5 of the *Tapes* Zone at Reká and observed the presence of *Larix*, *Ilex*, *Alnus* and *Quercus/Fagus*. The same author recorded wood remains of *Picea glauca*, *Picea sitchensis*, *Tsuga*, *Pseudotsuga*, *Ilex* and *Salix* in unit D of the *Mactra* Zone at Hringvershvilft (Figure 1.2). Tree species with modern analogues, e.g., *Tsuga heterophylla* and *Picea sitchensis*, suggest conditions found in the present-day North American Pacific coast from California to southern Alaska. Analysis of tree rings and tracheids of the Reká samples indicate furthermore a mild temperate climate with sufficient precipitation during the growth season and a relatively dry period during the winter (Löffler, 1995 *in* Denk *et al.*, 2011). Slightly cooler conditions are suggested during the deposition of the Hringvershvilft bed (*Mactra* Zone) based on narrower tree rings, a large variation in their widths and other growth related features. Denk *et al.* (2011) postulate that tree ring morphology is more sensitive to small-scale climate shifts than pollen assemblages. The slight cooling between the Reká sample in the upper part of the *Tapes* Zone and the *Skeifá* sample in the middle *Mactra* Zone, seen in the isotope record (Buchardt and Símonarson, 2003) can be detected in the wood anatomy from the intermediate Hringvershilft bed.

Denk *et al.* (2011) investigated the pollen, the leaves and the reproductive structures of plants from the Tjörnes beds in two sections from the *Tapes* Zone (Egilgjóta, unit B and Reká, unit C of Bárdarson, 1925) and a section in the middle part of the *Mactra* Zone (Skeifá, unit F; Figure 1.2). The flora of the three localities is diverse and highly similar, with Pinaceae, Betulaceae and Ericaceae as dominant elements among the woody plants. Warm elements such as *Ilex*, *Viscum* cf. *album*, aff. Calycanthaceae, *Euphorbia*, *Pterocarya* and the extinct Fagaceous genus *Trigonobalanopsis* are recorded in the three localities. Using present-day plant ecological preferences, the authors distinguish several vegetation types, ranging from an aquatic and swamp vegetation, over levee and well-drained lowland vegetation with angiosperm hardwood, to mountain forests with conifers and evergreen shrubs in the understorey. The fossil plant evidence indicates a cool Cfb climate (Peel *et al.*, 2007) during deposition of the *Tapes* and the first half of the *Mactra* Zone, that is, a temperate climate without dry season but with warm summers, possibly similar to that of present-day southern Norway. It would seem that during the entire Tjörnes beds, no substantial change of vegetation occured.

7. Plants from the Tjörnes section no longer present on Iceland

The Pliocene vegetation in Tjörnes was clearly different from the modern situation. We found a total of 28 pollen types of tree and shrub species in the fossil record of Tjörnes that are nowadays absent in Iceland. These are: *Abies, Picea, Pinus, Cedrus, Acer, Alnus, Buxus, Carpinus betulus, Castaneae, Corylus, Fagus, Fraxinus, Hedera, Hippophaërhamnoides, Ilex, Juglans, Myrica, Nyssa, Pterocarya, Quercus, Rhamnus*-type, *Sambucus nigra, Sobus*-group, *Tilia, Ulmus, Viburnum opulus* and *Viscum album.* Furthermore, 16 pollen types of herbs from the fossil Tjörnes section are also no longer present: *Aconitum*-type (Ranunculaceae), *Agrostemma githago* (Carylophylaceae), *Aquilegia* (Ranunculaceae), *Campanula trachelium*-type (Campanulaceae), Cannabinaceae, *Circaea* (Onagraceae), *Drosera intermedia* (Droseraceae), *Euphorbia* (Euphorbiaceae), *Helleborus foetidus* (Ranunculaceae), *Helianthemum nummularium*-type (Cristaceae), *Helianthemum oelandicum* (Cistaceae), *Jasione montana*-type (Campanulaceae), *Plantago coronopus*-type (Plantaginaceae), *Polygonium oxyspermum* subsp. *raii* (Polygonaceae), *Solanum nigrum*-type (Solanaceae) and cf. *Trollius europaeus.* A few water plants and spore plants also disappeared since the Pliocene: *Nymphaea, Nuphar* and *Sagittaria sagittifolia* (3 pollen types) and *Sphagnum, Lycopodium clavatum* and *Osmunda regalis* (3 spore types).

8. Rationale of the study

The Pliocene is nowedays the most studied pre-Quaternary period of the geological history, but it is still not well known. Before it became clear in the nineties of the past century that we urgently need to know more about the effects of possibly human-induced climate warming, the Pliocene was studied only by individual scholars (Norton, 1975, 1977; Cronin, 1991). The interest of large research groups for this time period grew as it became clear that the warm Pliocene can provide more information regarding climate and ice-sheet evolution in a warmer-than-present world. The position of the continents, the ocean configuration and the concentration of greenhouse gases are in the Pliocene well comparable to today, what makes it the most obvious period for the study of the impact of future global warming. Climate modelers however need well dated ecological input data to calibrate their models; such data are not always available. In models reconstructing past sea surface temperatures and vegetation, the ecological data of the Tjörnes Peninsula is used since it has a unique location central in the northern Atlantic (Dowsett, *et al.*, 1996; Thompson and Fleming, 1996; Haywood and Valdes, 2006; Salzmann *et al.*, 2011). Many proxies such as botany, molluscs, oxygen isotopes and sedimentology provided until now already much information about the past climate of the Tjörnes section (Bárdarson, 1925; Norton, 1975, 1977; Akhmetiev *et al.*, 1978; Eiríksson, 1981b, 1985; Akhmetiev, 1991; Cronin, 1991; Willard, 1994; Buchardt and Símonarson, 2003; Denk *et al.*, 2011). Moreover, the record of continental glacial remains in the Tjörnes section is the most complete of the Early Pleistocene in the northern hemisphere. Serious efforts were made to establish and understand the palaeomagnetic record of the section (Einarsson *et al.*, 1967; Doel, 1972; Gladenkov and Gurari, 1976; Eiríksson *et al.*, 1990; Kristjánsson, 2004), but the age models until now were based only on the position of the palaeomagnetic reversals with the aid of some K/Ar dates as reference points (Aronson and Sæmundsson, 1975 and Albertsson, 1975, 1978).

We were aware of the importance of the Tjörnes section for validation of present-day climate models, but we had doubts about the age model of the section. Therefore we chose this location for a combined dinoflagellate cyst and pollen/spores study. Dinoflagellate cysts have proven in the past to be a strong biostratigraphical tool, but had not yet been studied in Tjörnes. Their small size and resistant organic wall allow extraction in reliable numbers from most marine sediments. Another advantage is that the sediments can be relatively dated, independently of the capping basaltic lava flows dated with the K/Ar technique. The dinoflagellates might help to date the marine sediments and the geological events preserved in the Tjörnes section. The ecological preferences of dinoflagellates for temperature and feeding strategy also can inform us about the evolution of the climate deterioration, changes in ocean currents and the presence of the Polar Front in the area.

Previous studies in Tjörnes indicate the presence of pollen and spores in the section, which allows to study the combined response of the vegetation and the marine algae to climate changes. Coastal environments are not favourable for dinocysts or pollen, but they are in our case the only setting in which both proxies could be studied together. We opted for a high resolution palynological study of all lignites and marine sediments of the Tjörnes beds, in combination with that of the four most pronounced interglacials of the Breidavík Group. The analysis of samples of the Flatey Island might help to better understand the Tjörnes sequence, as both depositional basins are located next to each other. It was hoped that the combination of a pollen and dinocyst biozonation of both sections would clarify our understanding of the regional climate variability and contributes to the global climate story.

CHAPTER - 2

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

2

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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 *Tapes* and *Mactra* 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. 4.0–4.5 Ma. Further, the normal polarity 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 Breidavik Group is deposited much later in the Quaternary, from just before the Olduvai Subchron at c. 2.2 Ma till recent.

The Gilbert/Gauss transition is located between the Tjörnes beds and the Höskuldsvík lavas and the Gauss/Matuyama transition between the Furuvík and Hörgi Formation. 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).

Keywords: Pliocene, dinoflagellate cysts, Tjörnes, Iceland, biostratigraphy, age model, Bering Strait

1. Introduction

The geological section at Tjörnes in northern Iceland (Figure 2.1A, 2.1B) 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).

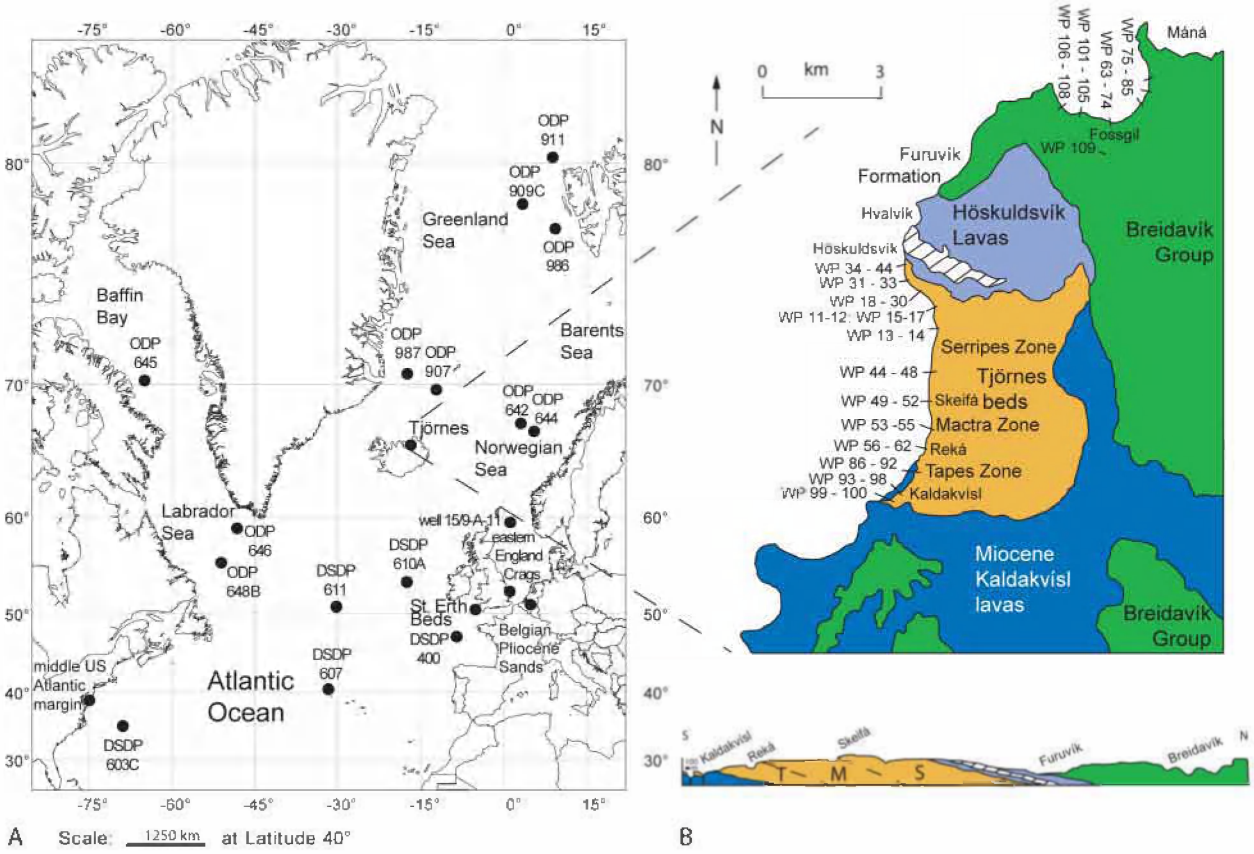


Figure 2.1A: Location of the Tjörnes section and the North Atlantic Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) sites. **B:** Geological map and cross section of the Tjörnes Peninsula, including sample locations and numbers (WP numbers). Modified after Eiríksson (1981b) and Einarsson *et al.* (1967). The reversely magnetised middle part of the Höskuldsvík lavas is indicated in white with diagonal lines.

Several palaeontological studies have focused on the Tjörnes section to document and understand the palaeoclimatic variability: e.g. studies on ostracods (Cronin, 1991), pollen (Schwartzbach 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, *Mactra* Zone and *Serripes* Zone (Figures 2.1B, 2.2). The molluscan fauna from the *Tapes* Zone have an Atlantic character, but a few warmwater species with Pacific ancestry occur also. At the boundary between the *Mactra* 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; Símonarson 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 *Serripes* Zone of the Tjörnes beds (Buchardt and Símonarson, 2003) demonstrates 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 (Símonarson and Eiríksson, 2008): only cold-water species could migrate and cross the Artic Ocean.

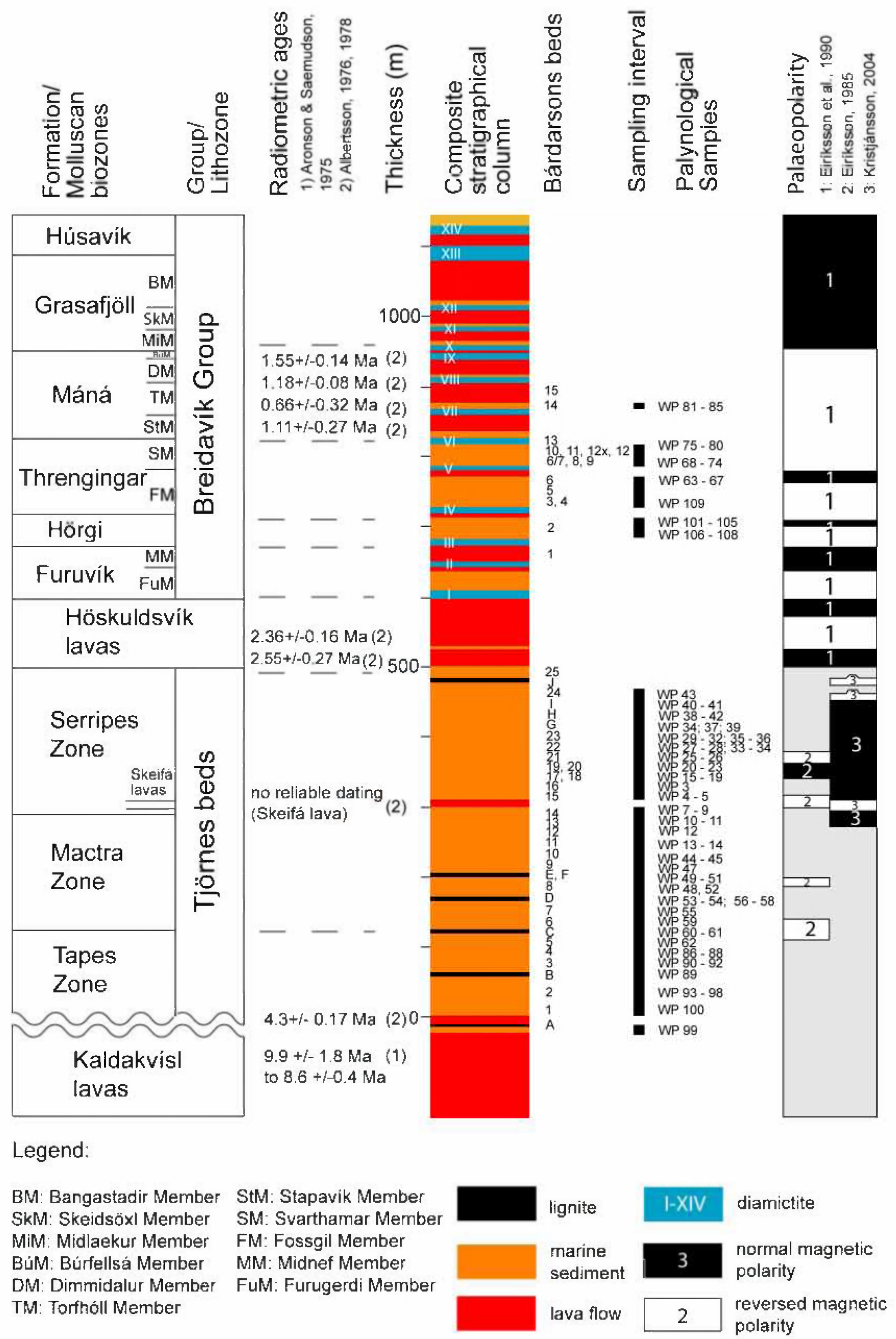


Figure 2.2: Schematic stratigraphical column of the Tjörnes sequence including the radiometric K/Ar dates ((1) Aronson and Sæmudson, 1975; (2) Albertsson, 1976, 1978), the corresponding Bárdarsons beds, the sample position and number, and the palaeopolarity of (1) Eiríksson *et al.* (1990), (2) Eiríksson (1985) based on a compilation of data from Hospers (1953), Gladenkov and Gurari (1976) and Einarsson *et al.* (1967), 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).

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. Símonarson 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; Figure 2.2). 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; Louwye *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 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 stucture, 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 ± 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 (Figures 2.1, 2.2). The Tjörnes beds consist of an alternation of marine sediments (sandstones, mudstones, conglomerates), terrestrial deposits (lignites, sandstones, 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 Símonarson, 2003). Bárdarson (1925) divides the Tjörnes beds into 25 distinct shell-bearing beds (1–25) and ten terrestrial or estuarine beds (A to J) (Figure 2.2). Molluscan biostratigraphy divides the Tjörnes beds into three easily recognised biozones: the *Tapes* Zone (beds 1–5 of Bárdarson, 1925), the *Mactra* Zone (beds 6–12) and the *Serripes* Zone (beds 13–25). With time, these biozones became established as informal lithostratigraphical units.

Buchardt and Símonarson (2003) and Símonarson 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 sub-littoral 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 Símonarson, 2003; Símonarson and Eiríksson, 2008). The entire *Tapes* Zone and the lower half of the *Mactra* Zone consist of shallow tidal flat and continental swamp deposits (Símonarson and Eiríksson, 2008). Sandstones, lignites and a few conglomerates occur within this interval. Increased subsidence during the deposition of the upper *Mactra* 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, 1992a) recognised 14 glacial-interglacial sedimentary cycles in the group (Figure 2.2). 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 a bove the Hörgi Formation. Reworked clasts from the Pliocene Tjörnes beds occur in the Breidavík Group sediments above the Hörgi unconformity (Bárdarson, 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-remanent 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 (Figure 2.3). 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 magnetized 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 (Figure 2.3). Einarsson *et al.* (1967) propose their second alternative to be most plausible, because the sedimentary sequence and the assumed time of deposition correspond best.

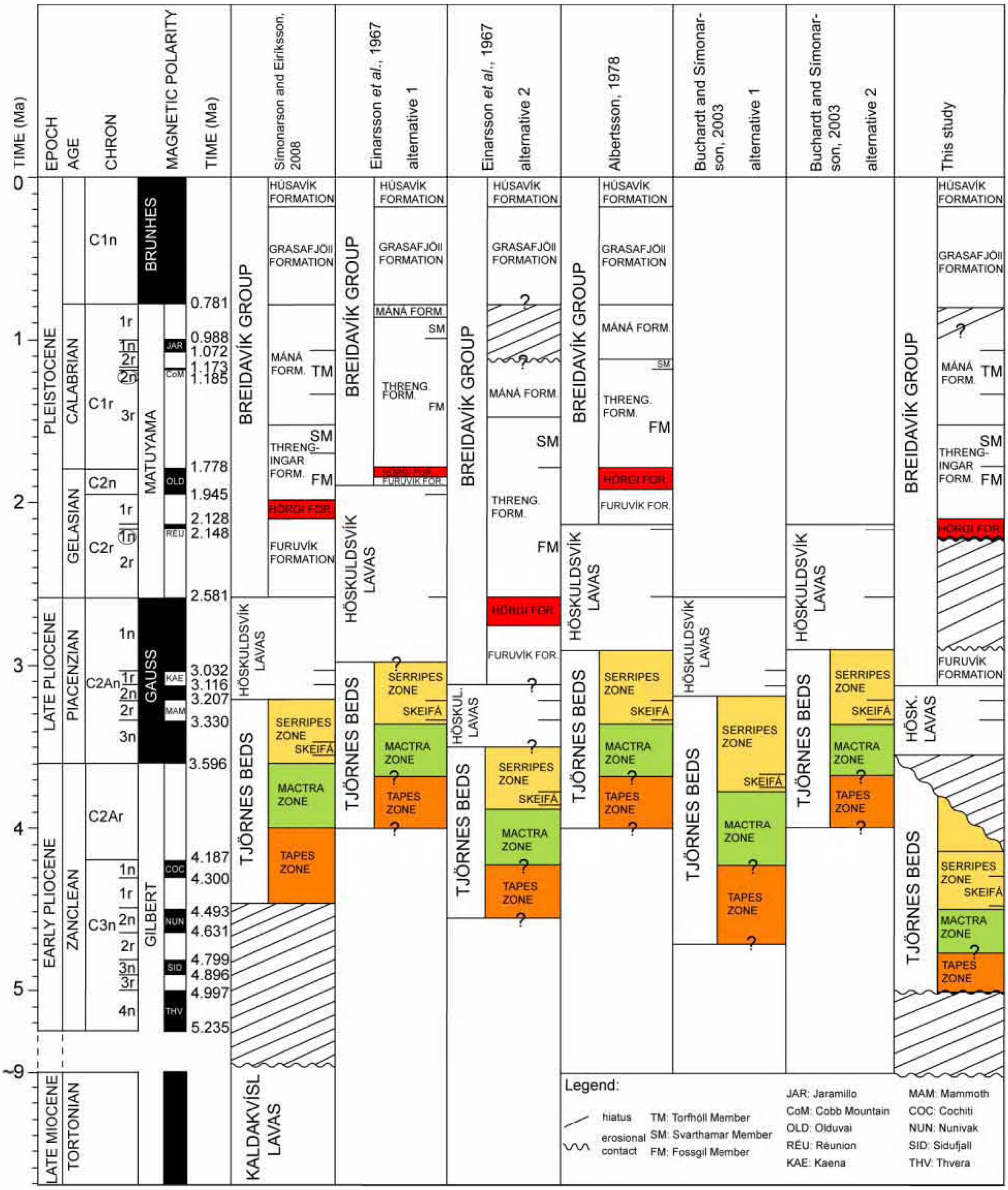


Figure 2.3: Comparison of former age models from the Tjörnes section with the new age model. The units are correlated with the Astronomically Tuned Neogene Time Scale (ATNTS2004, Lourens *et al.* 2005) based on the palaeomagnetic polarity correlations of each author.

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; Símonarson 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 (Símonarson and Eiríksson, 2008). The first K/Ar dating of the Kaldakvísl lavas in the Tjörnes Peninsula indicate a Miocene age of 9.9 ± 1.8 and 8.6 ± 0.4 Ma (Figure 2.2; Aronson and Sæmundsson, 1975). A large time gap between the Kaldakvísl lavas and the unnamed lava layer (4.3 Ma ± 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 Ma ± 0.32 and 1.55 Ma ± 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 Ma ± 0.16 and 2.55 Ma ± 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 notmentioned, 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).

Eiríksson *et al.* (1990) indicates for the first time a reversed magnetic signal for the siltstones of the Furugerdi Member (lowermost part of the Furuvík Formation, Breidavik 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 (Figure 2.2). This polarity reversal between the Höskuldsvík lavas and the base of the Breidavík Group is correlated by Símonarson 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 and the upper part of the *Serripes* Zone corresponds to the Mammoth Subchron. The reversely magnetised Skeifá pillow lavas are in Símonarsson and Eiríksson (2008) wrongly correlated to the lowermost part of the Gauss Chron, which has a normal polarity. 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 Símonarsson 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 *Mactra* Zone, notwithstanding a less stable and intense signal compared to measurements of the Breidavík Group lavas. In layers I and J of the *Serripes* Zone a reverse polarity was measured and the reversed magnetisation of the Skeifá lavas measured by Doell (1972) was confirmed (Figure 2.2). Also, the sediments a few meters 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 Símonarsson (2003) that these sediments belong to the Gauss Chron.

Table 2.1: 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 gray bars.

						LABORATORY						DINOFLAGELLATE CYSTS																																		
stratigraphy and molluscan biozones		G.P.S. Way Point; sample number	Bardarsons Beds	thickness, m	sediment	standard treatment (HCl, HF, HCl)	KOH, Acetolysis	Heavy liquid separation, $ZnCl_2$	# *Lycopodium clavatum* tablets, batch 483216, x=18583 +/- 1708	dry weight sediment, g	*Lycopodium clavatum* (spike)	dinocyst spp. indet.	*Achomosphaera* sp.	*Amiculosphaera umbraculum*	*Barssidinium pliocenicum*	*Batiacasphaera hirsuta*	*Batiacasphaera minuta*	*Bitectatodinium tepikiense*	*Bitectatodinium? serratum*	*Brigantedinium cariacoense*	*Brigantedinium simplex*	*Brigantedinium* spp.	*Capisocysta* sp. *C. lyellii?*	*Cristadinium* sp.	*Echinidinium euaxum*	*Echinidinium karaense*	*Echinidinium* sp.	*Filisphaera filifera* subsp. *filifera*	*Habibacysta tectata*	*Impagidinium aculeatum*	*Impagidinium patulum*	*Impagidinium plicatum*	*Impagidinium* sp.	*Islandinium minutum*	*Lejeunecysta catomus*	*Lejeunecysta marieae*	*Lejeunecysta oliva*	*Lejeunecysta sabrina*	*Lejeunecysta* sp.	*Lingulodinium machaerophorum*	*Melitasphaeridium choanophorum*	*Nematosphaeropsis labyrinthus*	*O. centrocarpum* sensu W. & D. (1966)	*O. centro.* sensu W. & D. short processes	Bardarsons Beds	thickness, m
Breidavik Group	Torfholl Member	WP 82	14	889,8	S	x			1	55,6	587	2						1																									7	1	14	889,8
		WP 83	14	888,5	M	x			1	54,4	1185							1																											14	888,5
		WP 84	14	883,5	M	x			1	50,7	1360	2						5				2					1													1			18		14	883,5
		WP 85	14	878,9	M	x			1	63,1	307	4	1					12			1	5									1			1									5		14	878,9
	Svarthamar Member	WP 77	12	835,0	C	x			1	63,8	565	4	2					82																27						1			1		12	835,0
		WP 69	10	823,4	M	x			1	44,3	190	4						3																3									2	1	10	823,4
		WP 70	10	819,8	M	x			1	54,2	281	11	4					35				3																		1			24		10	819,8
		WP 71	10	817,2	M	x			1	46,6	2643	4						7										1												2		1	1		10	817,2
		WP 73	8	816,3	M	x			1	66,7	4227	1																																1	8	816,3
		WP 68	8	813,0	S	x			1	53,1	3848	5	3	1																										2					8	813,0
	Fossgil	WP 67		782,0	M	x			1	58,1	1347																																			782,0
		WP 109		778,0	M	x			1	62,3	2242	13																																		778,0
	Hörgi Formation	WP 101		769,0	M	x			1	48,0	2697	12	2																											6						769,0
		WP 108		765,0	S	x			1	56,9	1506	28	7		5							1							1							1				1						765,0
		WP 102		762,1	M	x			1	48,5	2471	1	1																																	762,1
		WP 107		758,0	S	x			1	58,6	833	14			2	2																										1				758,0
		WP 103		753,0	M	x			1	41,9	1072	4																1											1	4						753,0
		WP 104		752,5	M	x			1	54,6	1161	6	1		2																									1						752,5
		WP 106		750,0	S	x			1	52,1	450	1	2		3	4									1															2	1					750,0
		WP 105		744,0	M	x			1	40,7	1529	3																												3						744,0
Tjörnes beds	Serripes Zone	WP 43	24	478,0	CS,W	x			1	39,1	1716																																		24	478,0
		WP 40	I	477,6	M	x			1	60,0	3864																																		I	477,6
		WP 42	H	476,7	M	x			1	48,6	1005																																		H	476,7
		WP 38	H	462,8	CS,W	x			1	72,3	2003																																		H	462,8
		WP 37	G	452,6	M	x			1	41,8	895																																		G	452,6
		WP 36	23	449,8	SH	x			1	43,6	1411																																		23	449,8
		WP 31	22/23	447,0	CS	x			1	63,6	1187																																		22/23	447,0
		WP 27	22	442,6	S	x			1	37,8	2361	1			2						1	3			5											1									22	442,6
		WP 28	21/22	439,4	S	x			1	59,4	2137	1	10		15		1					9	4					16								1									21/22	439,4
		WP 32	?	439,3	S	x			1	51,6	204																																		22/23	439,3
		WP 24	21/22	427,2	S	x		x	1	62,2	1474	5			66		1			2					5			9								1									21/22	427,2
		WP 33	?	426,5	SH	x			1	62,1	2489	2			2					1	3	20			5			5											1						22	426,5
		WP 25	21	424,8	SH	x		x	1	66,5	3992	13	4		1						1	2			7			6								1							1		21	424,8
		WP 26	20/21	424,4	S	x			1	52,1	2375	1	1		15		1			1	1	13			2			2											1						20/21	424,4
		WP 23	20	423,7	SH	x		x	1	50,0	1269	15	2		17		4		1		2	11			18											6									20	423,7
		WP 22	19/20	422,9	S	x		x	1	39,2	764	1		1	67	2	5		1	8		64		1	39			2								7			4				1		19/20	422,9
		WP 21	19	422,2	SH	x		x	1	82,8	929	22			74	1			3	2	4	29		2	2			7											1						19	422,2
		WP 20	18/19	420,0	S	x			1	49,0	2253	6			27	3	2					36		5	37	1		3								1									18/19	420,0
		WP 19	18	417,6	SH	x		x	1	40,3	1262	7			4			1				1						1					1				1								18	417,6
		WP 18	17/18	415,8	S	x			1	52,6	1261	18	1	1	26		48	1	1	8	8	76		5	74			18									4	3	3						17/18	415,8
		WP 17	17/18	406,5	S	x		x	1	47,1	1176	3	1		6							3			5			3																	17/18	406,5
		WP 16	17	402,2	S	x		x	1	53,5	2397	4	1		5					1	2	12		1	9			2								1		1	1						17	402,2
		WP 3	16	379,3	SH	x			1	44,1	1383																																		16	379,3
		WP 4	15/16	375,8	S	x			1	48,7	617	9	3	51	2	1	21				5	27			26			17						5	4	2	1								15/16	375,8
		WP 5	15	368,8	SH	x			1	50,5	1808	3		14	1		13				6	36		1	12			1					1			1			1						15	368,8
		WP 6	14/15	367,9	S	x		x	1	67,8	488	5	12	3	5		49		5	1	2	3						2	2											3	1				14/15	367,9
		WP 7	14	363,9	SH	x			1	53,9	591		2				1					6			3			1																	14	363,9
		WP 8	13/14	360,1	S	x			1	45,2	191	7	73		11						1	1			1										1	2			1						13/14	360,1
		WP 9	13	359,2	S	x			1	70,5	151	24	35		44	1	5			2	2	39			67										2	16	1	1	5		2	1			13	359,2
		WP10	12/13	357,2	S	x			1	72,1	361	4	2		1	1						3						17	2							2			3	2					12/13	357,2
	Mactra Zone	WP 11	12	356,0	S	x			1	56,0	1393				1																1												3		12	356,0
		WP 12	11	350,0	SH	x		x	1	51,7	3139			1	1													3																	11	350,0
		WP 13	11	340,0	CS	x			1	41,7	3572	3	1		1	1													1											4			72	6	11	340,0
		WP 14	11	330,0	S	x			1	69,0	3676	1					4																												11	330,0
		WP 44	10	295,0	SH	x			1	34,4	253					1	1												1	1												1			10	295,0
		WP 45	10	291,2	S	x			1	52,3	288	1	1		1	3																												10	291,2
		WP 48	9	286,1	SH	x			1	41,6	1029	1				2													2	1															9	286,1
		WP 46	9	277,8	SH	x			1	57,2	1282					2																														9	277,8
		WP 47	?	272,0	SH	x			1	46,8	184					6																														8	272,0
		WP 49	F	260,5	L		x		1	2,4	17																																		F	260,5
		WP 50	F	252,0	M,P	x			1	33,8	5																																		F	252,0
		WP 51	E	244,0	CS	x		x	1	50,0	478																																		E	244,0
		WP 52	8	230,0	SH	x		x	1	74,3	656	4				5													1																8	230,0
		WP 53	D	211,1	M,W	x			1	3,2	128	1	2		1														23																D	211,1
		WP 56	D	207,9	L	x			1	3,5	35																																		D	207,9
		WP 54	D	203,7	L	x			1	34,2	77	1																																	D	203,7
		WP 57	7	195,3	S	x		x	1	46,8	566																																		7	195,3
		Wp 58	7	188,0	M,W	x			1	3,4	1080																																		7	188,0
		WP 55	7	185,0	S	x		x	1	38,2	25	8	9		3							1			3				4			1			2									2	7	185,0
		WP 59	6	183,0	S	x		x	1	42,8	428	9	13		6							11			18				24		1		1		1						1				6	183,0
	Tapes Zone	WP 60	C	145,0	L		x		1	2,4	51																																		C	145,0
		WP 61	C	144,0	S	x		x	1	31,7	1248	5			1										4																				C	144,0
		WP 62	5	129,0	S	x		x	1	43,9	1620						1																												5	129,0
		WP 86	4	83,2	S	x		x	1	47,7	1306	2			3		27	2											1											1					4	83,2
		WP 87	4	78,0	S	x		x	1	49,7	846				3														32																4	78,0
		WP 88	4	69,0	S	x		x	1	49,5	697				4		2					1														1									4	69,0
		WP 89	B	68,0	L		x		1	2,4	2																																		B	68,0
		WP 90	3	66,2	S	x		x	1	49,9	149	6			1		6			1	2	15			23											3	1			1					3	66,2
		WP 91	3	65,1	S	x		x	1	38,0	531	3					1			1		6			2				2																3	65,1
		WP 92	c	45,0	L		x		1	2,5	6																																		c	45,0
		WP 93	2, b	36,2	L		x		1	2,6	6																																		2, b	36,2
		WP 94	2	35,3	S	x		x	1	48,7	343	18			134		12	2		4		19						4	1						3	9	2		1						2	35,3
		WP 95	2	29,4	S	x		x	1	38,4	1850							4				1							2																2	29,4
		WP 96	2, a	22,4	L		x		1	2,4	8																																		2, a	22,4
		WP 97	2	20,4	S	x		x	1	32,5	222	3			13					2		7			9			2	1						2	1									2	20,4
		WP 98	2	13,7	S	x			1	60,2	516	2				1									3				2					1		1				1					2	13,7
		WP 100	1	5,0	S	x			1	42,7	38	5			16													1																	1	5,0
		WP 99	A	3,0	L		x		1	4,0	10																																		A	3,0

Legend: L = lignite; M = mudstone; S = sandstone; CS = coarse sandstone; W = wood; P = plant remains; C = conglomerate; SH = shell remains

																															REWORKED DINOCYSTS											FRESHWATER										
Operculodinium centrocarpum	*Operculodinium? eirikianum* var. *eirikianum*	*Operculodinium* sp.	*Operculodinium tegillatum*	cyst of *Pentapharsodinium dalei*	*Quinquecuspis concreta*	*Reticulatosphaera actinocoronata*	*Scrippsiella trifida*	*Selenopemphix brevispinosa*	*Selenopemphix conspicua*	*Selenopemphix* sp. 1	*Selenopemphix dionaeacysta*	*Selenopemhix nephroides*	*Selenopemphix quanta*	*Selenopemphix* sp.	*Spiniferites bulloideus*	*Spiniferites delicatus*	*Spiniferites elongatus*	*Spiniferites membranaceus*	*Spiniferites mirabilis*	*Spiniferites ramosus*	*Spiniferites* spp. indet.	*Tectatodinium pellitum*	*Trinovantedinium applanatum*	*Trinovantedinium ferugnomatum*	*Trinovantedinium glorianum*	*Trinovantedinium harpagonium*	*Trinovantedinium* sp.	*Tuberculodinium vancampoae*	total *in-situ* dinocysts	richness (number of taxa)	*Achomosphaera* sp., reworked	*Areoligera* sp.	*Cleistosphaeridium placacanthum*	*Chatangiella* sp.	*Sepispinula anconifera*	*Spinidinium* sp.	*Spiniferites* spp., reworked	unknown reworked	Total reworked dinocysts	Bárdarsons Beds	thickness, m	Botryococcus sp.	cfr. Mougeaotia zygospore	Pediastrum sp.	chlamydospores	Type 128, globose microfossil	zygospores of Zygnemataceae	cfr. Zygnema	Total fresh water	Total acritarch	# dinocysts/g sediment	**# reworked dinoflagellates/g sediment**
				3																									14	4			1						1	14	889,8								0	0	8	1
				1																									2	2										14	888,5			1					1	0	1	0
2				34													2			1	3								71	10			1						1	14	883,5	1		6		1	1		9	0	19	0
6				276									1				11			1	7								332	13								2	2	14	878,9	7		29		1			37	1	319	2
				228													1			1	3								350	9										12	835,0			1					1	0	180	0
				325											1		19			11	23								392	9										10	823,4	3		4					7	1	865	0
1				247			22										1			3	33								385	11										10	819,8	2		16			2		20	0	469	0
11				3																	1								31	8							2	3	5	10	817,2	16		9			1		26	3	5	1
16																					2								20	3										8	816,3	17		5					22	0	1	0
8																					3								22	5								2	2	8	813,0	1		23					33	3	2	0
																													0	0											782,0								0	0	0	0
2																					2								17	2											778,0	6	1	6		4			17	0	2	0
55															1						6								82	5											769,0	13		11					24	0	12	0
28		2		1		1					1				1		1				6					2			87	15							1	2	3		765,0	2		97		7			106	1	19	1
1						1																							4	3											762,1	3		3					6	0	1	0
32				3												1					6				2				63	8											758,0	8		41		1			50	0	24	0
8	1		1																		1								21	7		1	3	1	1		1	6	13		753,0	2		3		3			8	3	9	5
11																					6								27	5											752,5			1		1			2	0	8	0
5				5		2		1											1		4		1	1					34	14							1	1	2		750,0	5		52		3			60	0	27	2
24																				1									31	3		1						2	3		744,0	3		1		3			16	0	9	1
																													0	0										24	478,0	11		2		1			14	0	0	0
																													0	0										I	477,6								0	0	0	0
																													0	0										H	476,7	4				6			10	0	0	0
																													0	0										H	462,8								0	0	0	0
																													0	0										G	452,6	2				1			3	0	0	0
																													0	0										23	449,8								0	1	0	0
																													0	0										22/23	447,0	3				1			4	0	0	0
										2										1									16	7										22	442,6					3	1		4	13	3	0
1			5	1						2										4	15								85	13										21/22	439,4	16		4		1		1	22	4	12	0
																													0	0										22/23	439,3								0	0	0	0
										3		1								4	2		1		3		2		105	13								1	1	21/22	427,2	4		1					5	5	21	0
11				4				1		2		2								1	1		3	1	3				68	17										22	426,5	4		2		3		2	11	43	8	0
12				4				1		1											1				2		1		58	15										21	424,8	14		3		1			18	26	4	0
6			2	6				3		5		2												1	3				66	17								6	6	20/21	424,4	7				5			12	69	10	1
5				11				2		9		1								3	3		2	2	1	1			116	19										20	423,7	8		2		2			12	20	34	0
			11	74						17		4								8			2	5	3	1			328	22										19/20	422,9	2		2		1			5	16	204	0
3			4	79						22		8								4	1		1	1	6				276	20										19	422,2	1		4		1			6	12	67	0
			2	7						3		2								11	1				1	3			151	17								8	8	18/19	420,0	8		6					14	82	25	1
2			2	4								3									2								29	11										18	417,6	4							4	2	11	0
5			2	11	1				2	4		11	11							2	2		1	4	7				358	28						1		11	12	17/18	415,8	3		8		4			15	65	100	3
												4	1																26	7										17/18	406,5	2		1		2			5	29	9	0
1			1	3		1			2				1							3	2			1	1				56	21										17	402,2	9		2		1			12	120	8	0
																													0	0										16	379,3	2							2	0	0	0
12			46	1						6	1	5								4	5		15	5	53		1		328	25	1									15/16	375,8	1		3		64		1	69	54	203	0
3			1	3	1					3		2								1			2		9				115	20										15	368,8	1		7		3			11	63	23	0
38			11	2		2		3		6										4	1		1	1		2			164	23										14/15	367,9	4		2					6	47	92	0
5																									1				19	7										14	363,9								0	9	11	0
				4		1		3	4	22	17	5	7	4						2	14		1	23					205	21										13/14	360,1	13		4		8			25	39	441	0
24			1	9		8		22		5	6	5	51	3						1	19		12	2	13	4			432	31										13	359,2	5		199		12			216	79	754	0
3				4				3			4							1		4	1		5	1					63	18								1	1	12/13	357.2	3		3					6	5	45	1
																													5	3										12	356,0	3				2			5	9	1	0
			4																	1									10	5										11	350,0	11		3					14	0	1	0
9		1		2		1														3	4								109	13										11	340,0	4		4					8	11	14	0
6			7	4																1	3								26	6										11	330,0	7		9		1		5	22	3	2	0
1				2																									8	7										10	295,0	1							1	1	17	0
3				2		1															3								15	7										10	291,2			3		1			4	0	19	0
																													6	3										9	286,1			1					1	0	3	0
7						2																							11	3										9	277,8								0	1	3	0
4																													10	2										8	272,0			1					1	0	22	0
																													0	0										F	260,5					1			1	0	0	0
																													0	0										F	252,0				52	26			78	0	0	0
																													0	0										E	244,0								0	1	0	0
2																					1								13	4										8	230.0	1				3			4	1	5	0
				6		1												3		1	2								40	8										D	211,1	4		36		1			41	0		0
																													0	0										D	207,9					1			1	0	0	0
								1																					2	1										D	203,7	3		1			1		5	0	14	0
																													0	0										7	195,3			1					1	0	0	0
																							1						1	1										7	188,0								0	0	5	0
27		1				8		14	1		1									4	53			4	3				149	18										7	185,0	4				5			9	4		0
224				6											1					4	13		1		12				346	16										6	183,0					6			6	26	351	0
																													0	0										C	145,0								0	0	0	0
																									3				13	3										C	144,0	2		72		1			75	0	6	0
																													1	1										5	129,0	4		1		1			6	0	0	0
				3																	1								40	7										4	83,2			5		4			9	14	12	0
37						4									1													3	80	6										4	78,0	4		1		1			6	0	35	0
1											1													5					15	7										4	69,0					2			2	0	8	0
																													0	0										B	68,0								0	0	0	0
8				2	12			5			6							1	1	1	2		2	5	2				106	21										3	66,2	2					1		3	0	265	0
				1	2			4			2														6				30	10										3	65,1	5		2		5			12	4	28	0
																													0	0										c	45,0								0	0	0	0
																													0	0										2, b	36,2	7							7	0	0	0
5				25	1			12			8				1		1			7	18		4	9	19		2		321	24										2	35,3	1		6	1				8	5	357	0
				3																									10	4										2	29,4	2		3					5	0	3	0
																													0	0										2, a	22,4					2			2	0	0	0
				3	2						2											2		1	6				56	14										2	20,4	7		3					10	0	144	0
1											2									1	1				2				18	11										2	13,7	3		11		4			18	3	11	0
3				1	2			2													2			1	2				35	9										1	5.0	4		1		2			7	2	400	0
				1																	1								2	2										A	3,0								0	1	941	0

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 (Figures 2.1B, 2.2). 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, Figure 2.2) and the stratigraphical framework of Bárdarson (1925). The sampling locations were positioned with a Garmin® GPS II Plus receiver (see Supplementary Data).

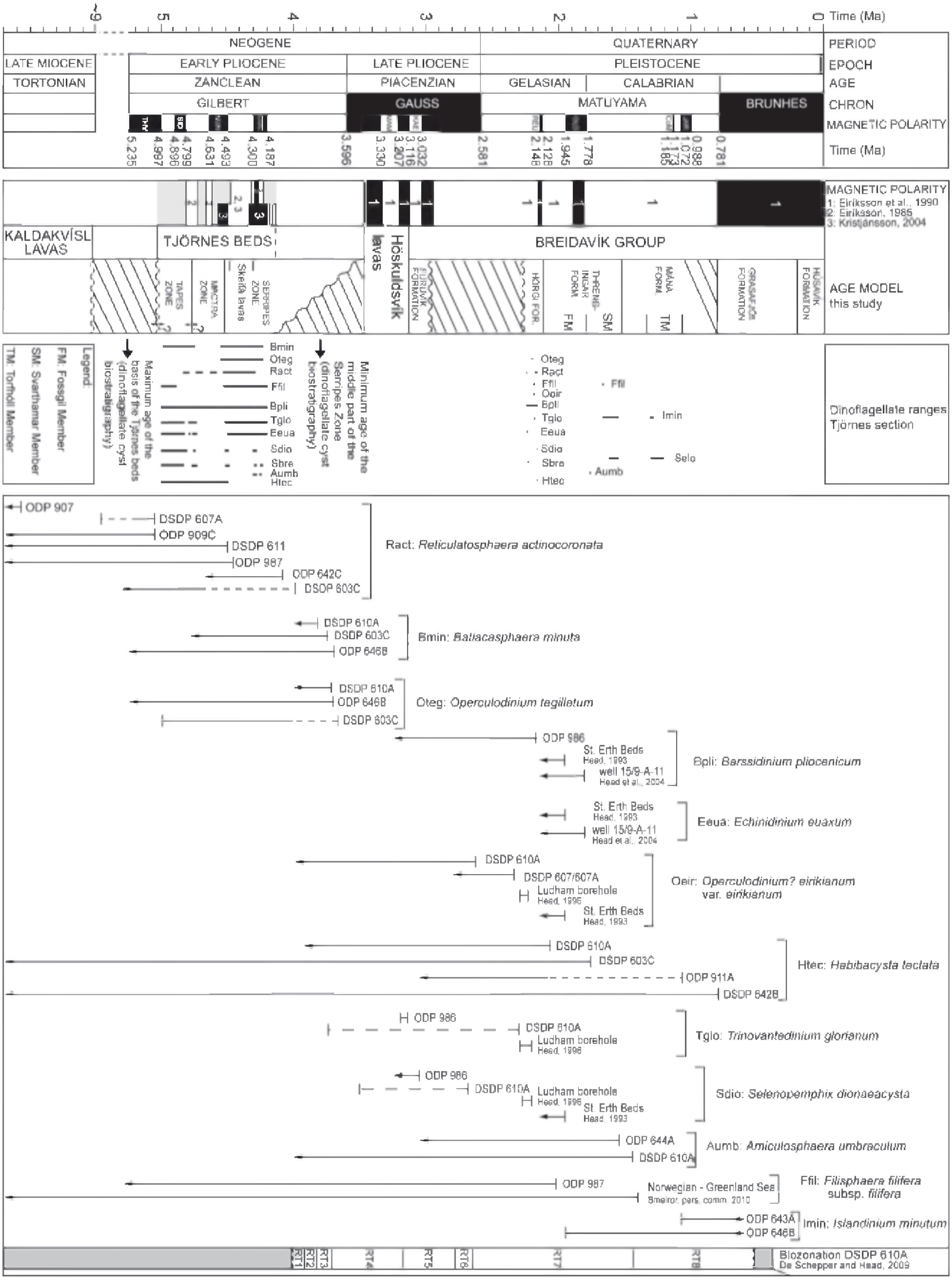
Each layer was sampled at least once, with the exception of the difficult accessible uppermost lignite layer J and the littoral layer 25. The average stratigraphical distance between two successive samples within a formation is 6.5 m, with a minimum of 0.4 m and a maximum of 45.8 m, depending on the 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 (Figure 2.2). 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) (Figure 2.2).

Samples of 50 to 90 g were crushed into fragments of maximum 0.5 cm in a mortar and oven-dried for 24 hours at 58° C. One *Lycopodium clavatum* marker tablet (Batch 483216; n = 18583 ± 1708 spores/tablet) was added to the dried sample. Carbonates were removed with cold 2M 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 2M HCl were needed to remove the newly formed silica gel. When necessary, the cold HF and 2M HCl cycle was repeated. For three sets of samples (Table 2.1) specific gravity separation with ZnCl2 (ρ=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 µm nylon screen to prevent the loss of small palynomorphs.

The eight lignite samples (Table 2.1) 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 2M 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 pliocenicum*. 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 occurences (LO, HO) of dinoflagellate cyst species.

Figure 2.4: 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 of 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, Versteegh, (1997) and Mudie (1987); DSDP Site 611, Mudie (1987); ODP Hole 642C, Mudie (1989); DSDP Hole 603C, Head (unpubl. data in De Schepper *et al.*, 2009); 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).


Time (Ma)
~6
5
4
3
2
1
0
NEOGENE
QUATERNARY
PERIOD
LATE MIOCENE
EARLY PLIOCENE
LATE PLIOCENE
PLEISTOCENE
EPOCH
TORTONIAN
ZANCLEAN
PIACENZIAN
GELASIAN
CALABRIAN
AGE
GILBERT
GAUSS
MATUYAMA
BRUNHES
CHRON
MAGNETIC POLARITY
5.235
4.997
4.896
4.799
4.631
4.493
4.300
4.187
3.596
3.330
3.207
3.116
3.032
2.581
2.148
2.128
1.945
1.778
1.185
1.173
1.072
0.988
0.781
MAGNETIC POLARITY
1: Eiríksson et al., 1990
2: Eiríksson, 1985
3: Kristjánsson, 2004
KALDAKVÍSL LAVAS
TJÖRNES BEDS
Höskuldsvík lavas
BREIDAVÍK GROUP
TAPES ZONE
MACTRA ZONE
Skeifá lavas
SERRIPES ZONE
FURUVÍK FORMATION
HÖRGI FOR.
THRENGINGAR FORM.
FM
SM
MÁNÁ FORM.
TM
GRASAFJÖLL FORMATION
HÚSAVÍK FORMATION
AGE MODEL this study
Legend:
FM: Fossgil Member
SM: Svarthamar Member
TM: Torfhóll Member
Maximum age of the basis of the Tjörnes beds (dinoflagellate cyst biostratigraphy)
Minimum age of the middle part of the Serripes Zone (dinoflagellate cyst biostratigraphy)
Bmin
Oteg
Ract
Ffil
Bpli
Tglo
Eeua
Sdio
Sbre
Aumb
Htec
Oeir
Imin
Selo
Dinoflagellate ranges Tjörnes section
ODP 907
DSDP 607A
ODP 909C
DSDP 611
ODP 987
ODP 642C
DSDP 603C
Ract: Reticulatosphaera actinocoronata
DSDP 610A
DSDP 603C
ODP 646B
Bmin: Batiacasphaera minuta
DSDP 610A
ODP 646B
DSDP 603C
Oteg: Operculodinium tegillatum
ODP 986
St. Erth Beds Head, 1993
well 15/9-A-11 Head et al., 2004
Bpli: Barssidinium pliocenicum
St. Erth Beds Head, 1993
well 15/9-A-11 Head et al., 2004
Eeua: Echinidinium euaxum
DSDP 610A
DSDP 607/607A
Ludham borehole Head, 1996
St. Erth Beds Head, 1993
Oeir: Operculodinium? eirikianum var. eirikianum
DSDP 610A
DSDP 603C
ODP 911A
DSDP 642B
Htec: Habibacysta tectata
ODP 986
DSDP 610A
Ludham borehole Head, 1996
Tglo: Trinovantedinium glorianum
ODP 986
DSDP 610A
Ludham borehole Head, 1996
St. Erth Beds Head, 1993
Sdio: Selenopemphix dionaeacysta
ODP 644A
DSDP 610A
Aumb: Amiculosphaera umbraculum
ODP 987
Norwegian - Greenland Sea Smelror, pers. comm. 2010
Ffil: Filisphaera filifera subsp. filifera
ODP 643A
ODP 646B
Imin: Islandinium minutum
RT1
RT2
RT3
RT4
RT5
RT6
RT7
RT8
Biozonation DSDP 610A De Schepper and Head, 2009

4. Results

4.1 General

Of the 88 analysed samples, 44 yielded less than 25 dinoflagellate specimens per sample (Table 2.1). Samples with almost no dinoflagellate cysts come from the lignites of the *Tapes* Zone and the *Mactra* Zone, from the interval between halfway bed 7 and the top of bed 10 (*Mactra* Zone), from the interval between beds 22 and 23 until the top of bed 24 (*Serripes* Zone) and from the Fossgil Member (Figure 2.2). 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 1148 cysts/g in sample WP 55 from the *Mactra* Zone (Figure 2.2, Table 2.1), but the majority (78%) of the samples have an absolute abundance below 50 cysts/g.

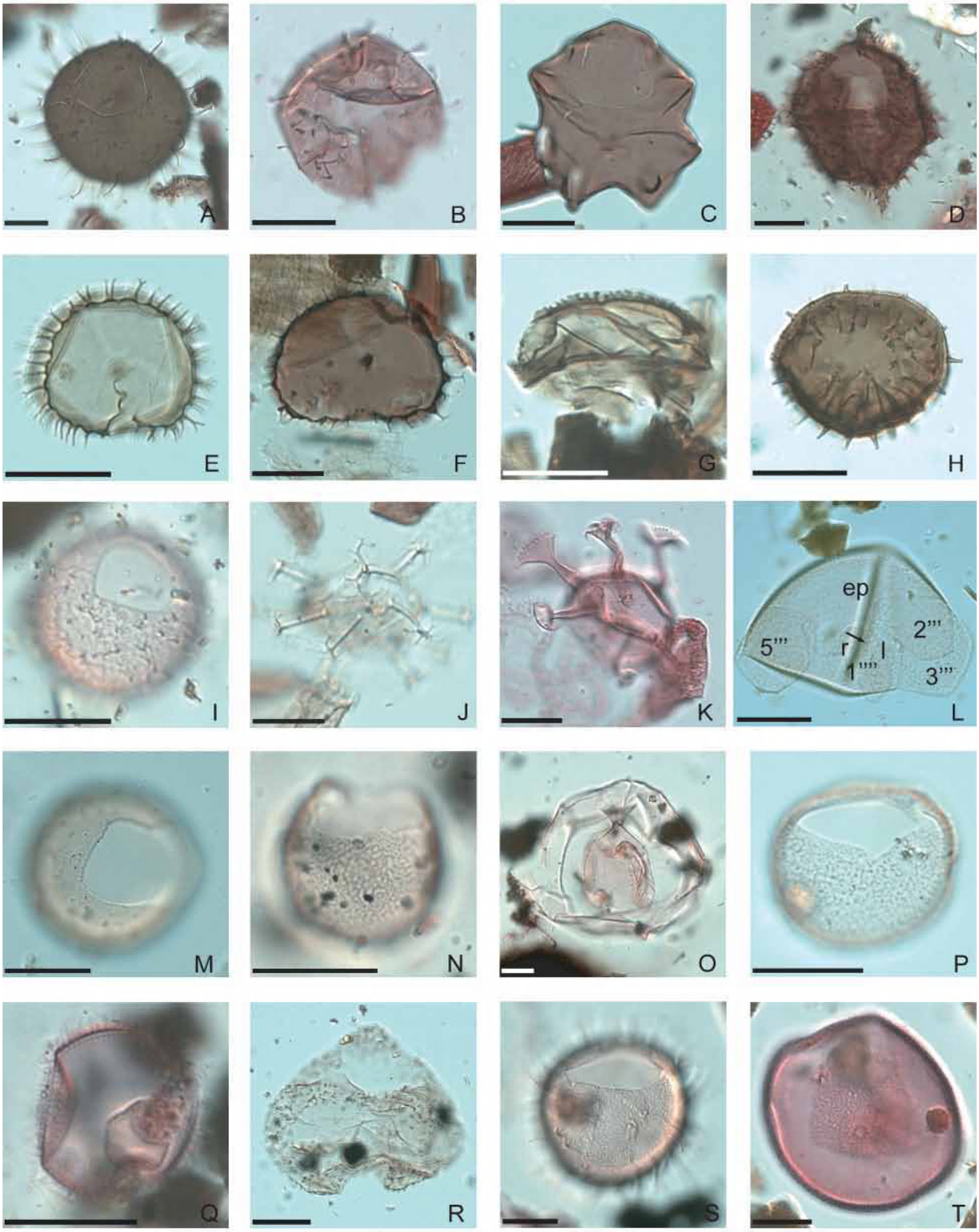
A selective taphonomic process was most probably not responsible for the low dinocyst concentrations. We based this on the fact that the heterotrophic, protoperidinioid cysts – taxa which are well preserved in the Tjörnes section – are prone to selective degradation through oxidation (Zonneveld *et al.*, 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 1000 and up to 256.920 cysts/g in sediment surface samples from the Islandic shelf. Those samples were all collected in water depths between c. 104 and 1800 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 1135 cysts/g and 4259 cysts/g.

It has also been demonstrated that comparing dinoflagellate cyst concentrations based on different laboratory methods can be problematic (Mertens *et al.*, 2010), but given the large concentrations differences between Marret *et al.* (2004) and this study we assume the low concentrations in the Tjornes 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. Limited reworking of Cretaceous to Miocene species is identified from the *Serripes* Zone upwards (Table 2.1). Reworked specimens of *Areoligera* sp. (Cretaceous–Miocene; Plate 2.2O), *Spinidinium* sp. (Cretaceous–Oligocene), *Spiniferites* sp. (Cretaceous–recent) and *Cleistosphaeridium placacantha* (Miocene) may be due to the erosion of Miocene sediments on Iceland itself. However, there are only few pre-Pliocene marine sediments on Iceland and reworked species such as *Chatangiella* sp. (Plate 2.2P) 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

Plate 2.1: 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*, sample WP9, E.F.: Z54/3, *Serripes* Zone; G: *Selenopemphix 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: *Reticulatosphaera actinocoronata*, sample WP9, E.F.: E55/2, *Serripes* Zone; K: *Melitasphaeridium 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: *Filisphaera filifera* subsp. *filifera*, sample WP18, E.F.: E41/1, *Serripes* Zone



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.

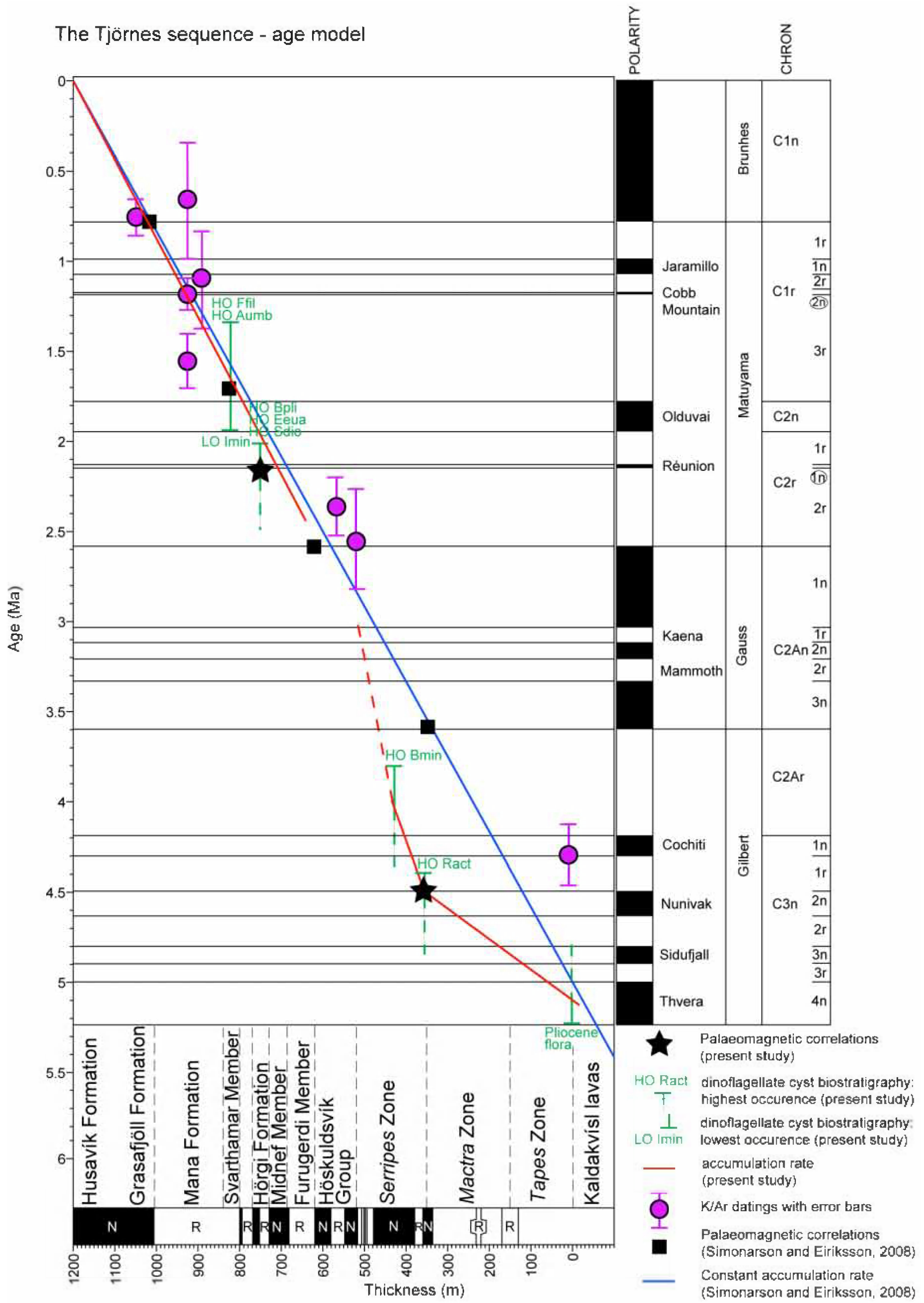


Figure 2.5: Combined dinoflagellate cyst and palaeomagnetic age model (in red, this study) for the Tjörnes section compared with the combined K/Ar and palaeomagnetic age model of Símonarson and Eiríksson (2008) (in blue). Dinoflagellate cysts: **Ffil:** *Filisphaera filifera* subsp. *filifera*; **Aum:** *Amiculosphaera umbraculum*; **Bpli:** *Barssidinium pliocenicum*; **Eeua:** *Echinidinium euaxum*; **Sdio:** *Selenopemphix dionaeacysta*; **Imin:** *Islandinium minutum*; **Bmin:** *Batiacasphaera minuta*; **Ract:** *Reticulatosphaera actinocoronata*.

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 (Figure 2.4). 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 δ^{18}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; Smelror, 1999; Channell *et al.*, 1999b; Eidvin *et al.*, 2007), western Europe (Head, 1993, 1996, 1998a,b; De Schepper *et al.,* 2004, 2009; Louwye *et al.*, 2004; 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, *Mactra* 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 (Figure 2.5). 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 2.1, Table 2.1) 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.*, 2008). The assemblage in the base of the *Tapes* Zone consists of long-ranging species such as *Spiniferites ramosus* and *Brigantedinium cariacoense*, and species with a HO in the Pliocene or Pleistocene such as *Barssidinium pliocenicum*, *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 evangelineae* 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). *Pyxidinopsis 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 ± 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 *Batiacasphaera minuta* and *Operculodinium tegillatum*. The latter species were present up to the middle part of the *Serripes* Zone (Figure 2.4), up to sample WP 28 (between beds 21 and 22 of Bárdarson, 1925; Figure 2.2).

Reticulatosphaera actinocoronata is in the North Atlantic region considered as a biostratigraphical marker for the Zanclean, ranging no younger than c. 4.4 Ma (Louwye *et al.*, 2004). This species is also 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 *Reticulatosphaera actinocoronata* in the Gilbert Chron (C2Ar) around 4.14 Ma in ODP Hole 642C (Vøring Plateau, Norwegian Sea). As Mudie (1989) only provides presense/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, *Reticulatosphaera 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 *Reticulatosphaera actinocoronata* was recorded, were deposited in a much more energetic environment compared to the top of the *Mactra* Zone (Eiríksson, 1981b). Reworking of the species from the *Mactra* 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 *Mactra* 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 Atlanic at DSDP Hole 603C, but occurred in low abundances until its HO of 3.59 Ma (De Schepper and Head, 2008). In eastern England, *Operculodinium tegillatum* occurs in the top of the Sudbourne Member of the Corraline Crag, but is absent from the overlying Walton Crag (Figure 2.6; Head, 1998a). In the Pliocene of northern Belgium, *Operculodinium tegillatum* is recorded in the Kattendijk Formation, but absent in the overlying Lillo Formation (De Schepper *et al.*, 2009; Louwye *et al.*, 2004).

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 *Batiacasphaera minuta* in the Labrador Sea DSDP Hole 646B until c. 3.7 Ma, and in the western North Atlantic *Batiacasphaera 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, Figure 2.4). 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 bed 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 (Figure 2.2) were not sampled, and the layers in between layer 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 Bárdarson (1925) of the Svarthamar Member (Figure 2.2), was dominated by *Operculodinium centrocarpum* s.s. (average 43%), *Spiniferites* spp. (average 8%) and *Lingulodinium machaerophorum* (average 6%). From bed 10 of Bárdarson (1925) on, the assemblage became dominated by cysts of *Pentapharsodinium dalei* (average 52%), *Bitectatodinium tepikiense* (average 15%), *Operculodinium centrocarpum* sensu Wall and Dale (1966) (average 11%) and *Spiniferites elongatus* (average 2%) (Plate 2.2J-L). Heterotrophic protoperidinioid species were present up to the Hörgi Formation (Plate 2.2A-H, Table 2.1). These fragile species did not occur in large quantities but were nevertheless well preserved (Plate 2.2A-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 2.2H), some specimens of the robust species *Reticulatosphaera actinocoronata* (samples WP 106, 108, 102; Plate 2.2F) and one specimen of *Melitasphaeridium choanophorum*, sample WP 106).

Age diagnostic dinoflagellate cysts indicate that the Hörgi Formation has an Early Pleistocene Gelasian age, older than the Olduvai Subchron, and likely around c. 2.0 Ma (Figure 2.5). *Barssidinium pliocenicum* was conspicuously present up to the upper Hörgi Formation. In the southern North Sea Basin, *Barssidinium pliocenicum* occurs up to the top of the Piacenzian Lillo Formation (De Schepper *et al.*, 2009; Figure 2.6). Younger marine deposits from the Gelasian are absent in northern Belgium (Laga *et al.*, 2001). In the same basin *Barssidinium pliocenicum* is recorded only at the base of the late Piacenzian Walton Crag, the lowermost subdivision of the Red Crag (Figure 2.6) 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 some time between c. 2.1 and 1.95 Ma (Head, 1993). Head *et al.* (2004) found 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 interpretiation may need to be revised, given the range of this species in southeast Engeland up to 1.95 Ma. Furthermore, Smelror (1999) records *Barssidinium pliocenicum* 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 2.2B) 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, *Selenopemphix 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, *Selenopemphix 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 *Selenopemphix dionaeacysta* at c. 3.05 Ma and *Trinovantedinium glorianum* at c. 3.13 Ma according to the age model of Knies *et al.* (2009). *Trinovantedinium 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 possibly older than c. 1.4 Ma based on the HOs of *Amiculosphaera umbraculum* and *Filisphaera filifera* subsp. *filifera* (Figure 2.5).

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 *Islandinium 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 *Amiculosphaera umbraculum* occured at the base of the Svarthamar Member in the upper part of the Threngingar Formation (Figures 2.2 and 2.4). 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).

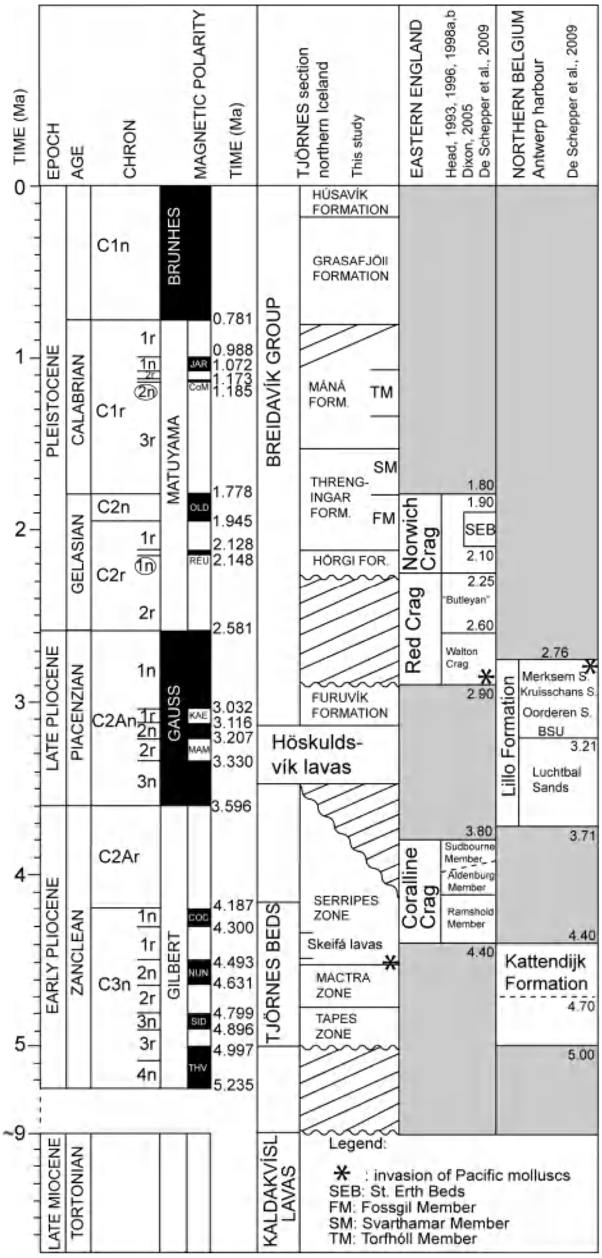


Figure 2.6: **Comparison of the Pliocene and Early Pleistocene deposits from the southern North Sea basin (northern Belgium and eastern England) with the Tjörnes section. Asterisks indicate the appearance of Pacific molluscs into the local assemblages. BSU = Basal Shelly Unit (Louwye *et al.*, 2004).**

Filisphaera filifera subsp. *filifera* was rare in the Breidavík Group, and occured for the last time in the middle of the Svarthamar Member in sample WP 71 (Figures 2.2 and 2.4). 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* occured intermittently in the *Tapes* Zone and in the Hörgi Formation, but continuously from the upper part of the Svarthamar Member onwards (Figure 2.4, Table 2.1). On the western Svalbard margin (ODP Site 986), the continuous occurrence of *Spiniferites elongatus* starts at c. 1.24 Ma (Smelror, 1999) using the age model of Knies *et al.* (2009), whereas the LO of *Spiniferites 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 2.2) 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 (Figure 2.3).

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 Símonarson 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 (Símonarson 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 (Breidavik Group), the record of *Amiculosphaera umbraculum* suggest a minimum age of this unit of c. 1.44–1.54 Ma (Table 2.2). This age assessment is broadly corroborated by the HO of *Filisphaera filifera* subsp. *filifera* (c. 1.4 Ma in Norwegian Greenland Seas; 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 *Islandinium minutum* indicates cooling. The LO of *Islandinium 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 (Figure 2.4). Although the boundaries do not coincide exactly, both Gladenkov and Gurari (1976) and Kristjánsson (2004) recognise a reversed/normal/reversed polarity alternation between the top of the Skeifá lavas and the top of the *Serripes* Zone (Figure 2.2). The dinoflagellate data suggest a minimum age of 3.83 Ma for the middle part of the *Serripes* Zone, thus the normal polarity observed

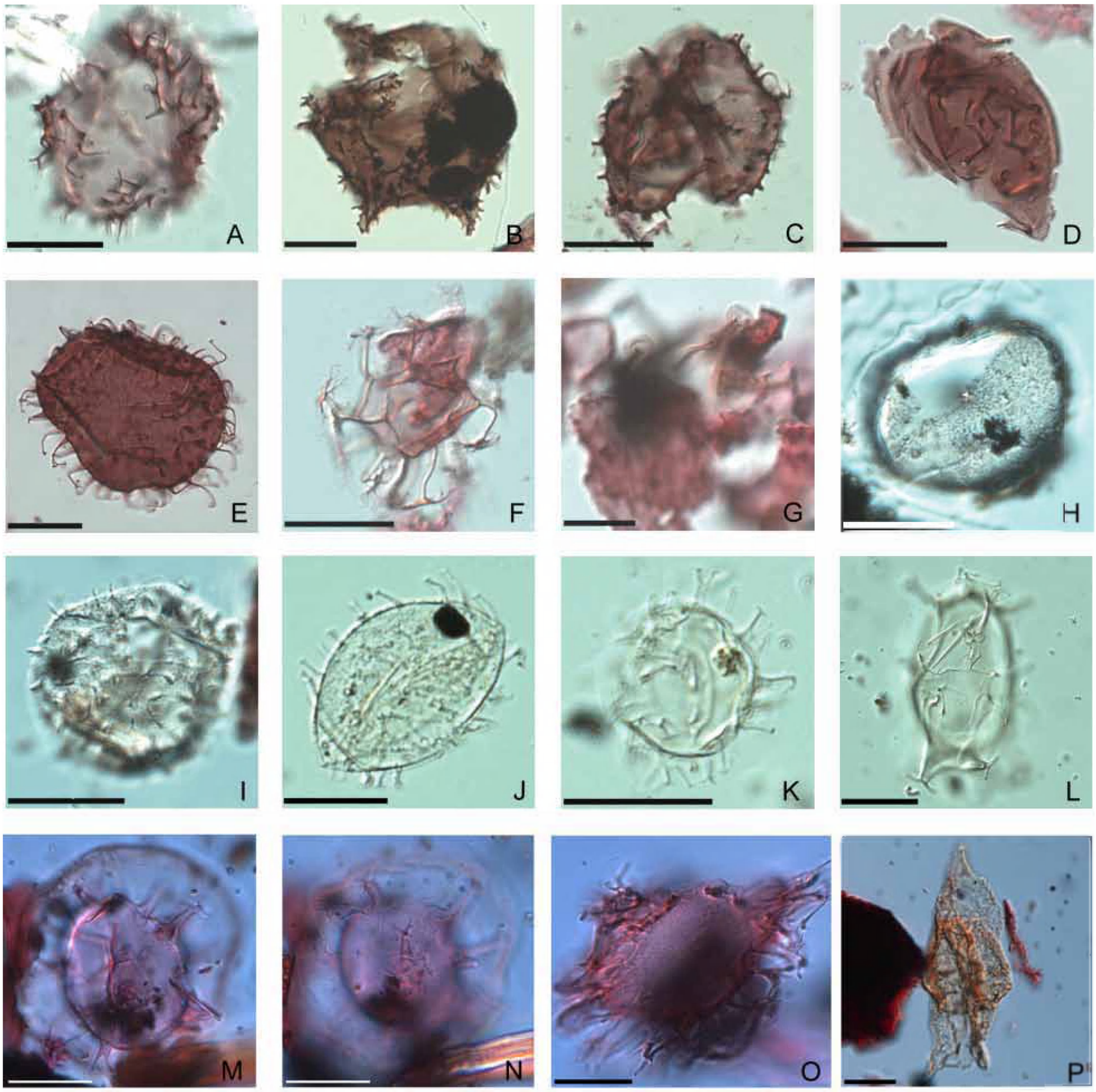
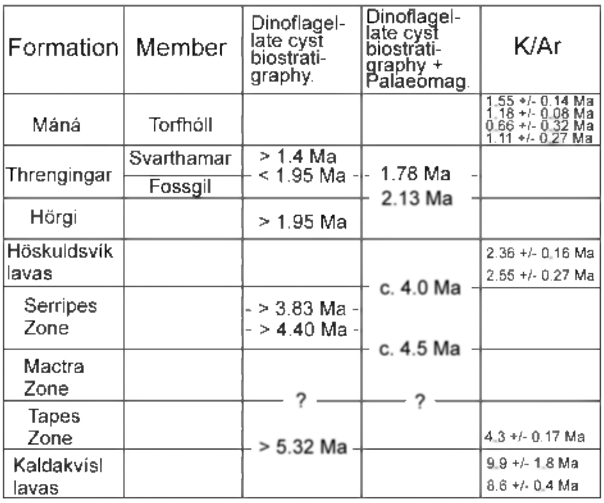


Plate 2.2: Photomicrographs of selected biostratgraphical important dinoflagellate species from the Breidavík Group. Scale bar: 20 µm. E.F.: England Finder coordinates. A: *Trinovantedinium harpagonium*, sample WP108, E.F.: Z63/3, Hörgi Formation; B: *Trinovantedinium glorianum*, sample WP107, E.F.: 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: *Reticulatosphaera actinocoronata*, sample WP106, E.F.: Y40/3, Hörgi Formation; G: *Melitasphaeridium 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: *Achomosphaera* sp., sample WP4, E.F.: T29/0, *Serripes* Zone: O: *Areoligera* sp., sample WP105, E.F.: M49/0, Hörgi Formation; P: *Chatangiella* sp., sample WP103, E.F.: P34/0, Hörgi Formation.

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, Figure 2.4) 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 immediatly below the Skeifá lavas



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		
	Fossgil	< 1.95 Ma	1.78 Ma	
Hörgi		> 1.95 Ma	2.13 Ma	
Höskuldsvík lavas				2.36 +/- 0.16 Ma 2.55 +/- 0.27 Ma
Serripes Zone		> 3.83 Ma > 4.40 Ma	c. 4.0 Ma	
Mactra Zone		?	c. 4.5 Ma ?	
Tapes Zone		> 5.32 Ma		4.3 +/- 0.17 Ma
Kaldakvisl lavas				9.9 +/- 1.8 Ma 8.6 +/- 0.4 Ma

Table 2.2: 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.

(Figure 2.2) have a normal polarity (Kristjánsson, 2004) and may correspond to the Nunivak Subchron (C3n.2n; 4.631–4.493 Ma). The boundary between the *Mactra* Zone and *Serripes* Zone is accordingly placed at c. 4.5 Ma (Table 2.2).

The reversed polarity signal at the top of the *Serripes* Zone (layers I and J of Bárdarson, 1925; *in* Kristjánsson, 2004; Figure 2.4) is correlated with the C2Ar Subchron. The top of this zone thus has an age between 4.187 to 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 2.2). 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 (Símonarson 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 are 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. 857 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 Gilbert/Gauss boundary itself 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 (Furugerdi 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 can not 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. As a result, the normally magnetised upper part of the Hörgi Formation could than 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 sedimentary 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 (Figure 2.2), but the magnitude of the corresponding hiatuses is uncertain (Eiríksson, 1981b). Erosional unconformities are present at the base of each Breidavík Group cycle (Figure 2.2) 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.* (1992a). 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 Húsavík Formation, Eiríksson *et al.* (1990) recognises 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 Bárdarson (1925) has a K/Ar age of 4.3 +/- 0.17 Ma (Albertsson, 1976) but according to Aronson and Sæmundsson (1975), 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) (Figures 2.1B, 2.2; 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 of 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 (Figure 2.3). 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 (Figure 2.6).

The proposed stratigraphic position of the Breidavík Group and the Höskuldsvík lavas corresponds best with the second alternative of Einarsson *et al.* (1967) (Figure 2.3), 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 Albertsson (1976, 1978) and Aronson and Sæmundsson (1975) 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; Figure 2.3) to correlate the normal 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 incoporate 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 *Mactra* 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-Powell, 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 *Mactra* 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 *Mactra* Zone and are considered by Harmer (1920) as typical for the Coralline Crag, although in reality both species are also found in the younger Walton Crag (Norton, 1975, 1977). The dinoflagellate cysts suggested a correlation of the *Tapes* and *Mactra* 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; Figure 2.6). 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 really 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, Figure 2.6).

The *Serripes* Zone has been correlated in former studies with the Red Crag based on the LO of Pacific molluscs such as *Macoma praetenuis* and *Serripes groenlandicus* (Baden-Powell, 1955; Áskelsson, 1960a, Norton, 1977) and with the Merksem Sands Member of the Lillo Formation (Belgium) based on the LO of *Macoma praetenuis* (Norton, 1977).

In contrast, 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 (Figure 2.6; 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 that what is observed in the Tjörnes beds (Figure 2.6). The idea of Norton (1977) of synchronous deposition within one wide-ranging faunal province can no longer be 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 eventually 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 unit in Belgium does not exist.

5.4 Consequences for the Early Pliocene palaeoceanography

The molluscan fauna in the *Tapes* Zone and *Mactra* Zone has a boreal North Atlantic character, but during deposition of the *Serripes* 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 (Figure 2.2; Maier-Reimer and Mikolajewiez, 1990; Marincovich, 2000). Einarsson et al. (1967) links 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, 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; Jenskins 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; Figure 2.6) 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 occured 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 4.7–4.2 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 Tiedemann, 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 *Reticulatosphaera 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 is 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 (Figure 2.3). The Breidavík Group is of Quaternary age and its dinoflagellate cyst assemblage is dominated by *Operculodinium centrocarpum* s.s., *Operculodinium centrocarpum* sensu Wall and Dale (1966), *Bitectatodinium tepikiense*, *Spiniferites elongatus* and cysts of *Pentapharsodinium dalei*. The presence of *Barssidinium pliocenicum*, *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 reinterpretation 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 (Figure 2.6). 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 Tiedemann, 1998; Haug *et al.*, 2001; Steph *et al.*, 2006; Sarnthein, 2009).

7. Author contribution

The samples were taken from outcrops in the coastal cliffs from the Tjörnes Peninsula in northern Iceland by KV. JE helped with the organization of the field trip, the localization of the samples in the Tapes Zone and the Breidavík Group and the general interpretation of the geology. The palynological maceration in the laboratory of the rocks, the preparation of the slides, counting and interpretation was done by KV. The chapter was mainly written by KV, taking into account the palaeoceanographic and biostratigraphical remarks of SDS, the remarks on the geology by JE and the general remarks and language corrections by SL. All figures and photomicrographs were made by KV.

8. Acknowledgements

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Palaeoenvironmental reconstruction with marine palynomorphs of the Plio-Pleistocene in Tjörnes, Northern Iceland

3

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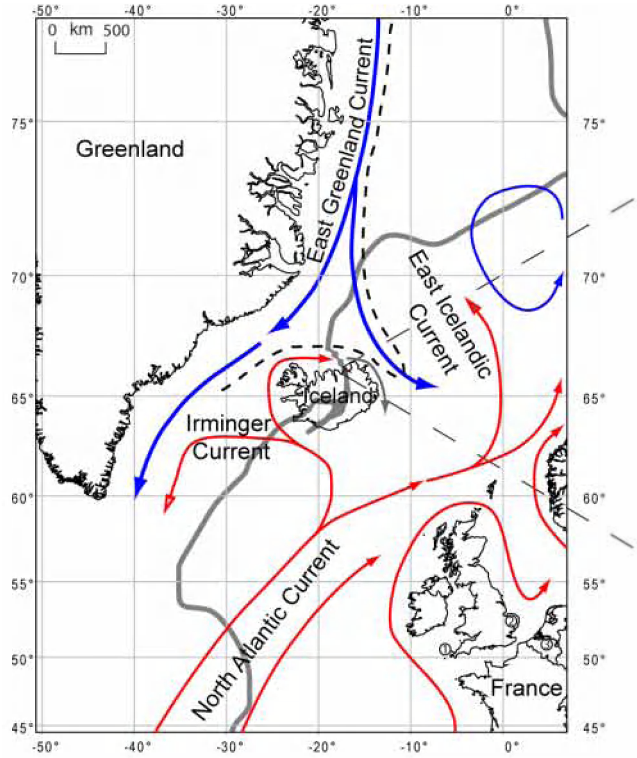
Abstract

Deposits from the Tjörnes Peninsula in northern Iceland permit to assess past ocean currents and the influence of the nearby island. Most palaeoecological studies with dinoflagellate cysts focus on deep marine or shelf settings and deal with outer neritic and oceanic species. Dinoflagellate cyst studies of marginal marine settings are scarce and represent only short time intervals. The Tjörnes section however accommodates 1200 m sediments which are mainly shallow marine. The sediments are attributed to the Early Pliocene Tjörnes beds and also signal the onset of the Quaternary cooling in the overlying Breidavík Group. We studied the dinoflagellate cysts from 68 samples from the Tjörnes beds and 20 samples from the Breidavík Group. The dinoflagellate assemblages are grouped into six biozones (DZ). The changes in the assemblages proved to be independent of the changes in bathymetry of the sedimentary environment. Heterotrophic dinoflagellate cysts dominate during DZ1. An abrupt impoverishment in species diversity is observed during DZ2 when autotrophic species dominate the assemblage. Slightly preceding the entrance of Pacific molluscs in the area in unit 14 of the *Serripes* Zone, heterotrophic species (unit 12/13) re-enter the area in DZ3. The marked decrease and return of the heterotrophic species does not relate to conditions of preservation, but may result from the loss of nutrients and prey organisms. The top of DZ1 and the base of DZ3 reflect major changes in the palaeoceanography and span a period in which the polar front may have been moved temporarily from the area. The first event situated at the top of DZ1 occurred in unit 4 halfway the Tapes Zone between 5 and 4.5 Ma. The second event at the top of unit 12 around 4.5 Ma has been linked to the shoaling of the Central American Seaway. Heterotrophic dinoflagellates disappear almost completely from the area during the deposition of the Pleistocene Breidavík Group (DZ5-6). A transition from a heterotrophic dominated assemblage to an autotrophic dominated assemblage is observed in the Hörgi Formation (DZ5a). An assemblage dominated by autotrophic cold water species comparable to the present-day assemblage of the area north of Iceland, occurs from unit 10 in the Pleistocene Svarthamar Member on (DZ6). This study underscores that the distribution of temperature sensitive dinoflagellate cysts is influenced by the availability of nutrients and changes in ocean currents.

Keywords: Pliocene, dinoflagellate cysts, Tjörnes, Iceland, ecology, sea currents

1. Introduction

A shallow sedimentation basin formed during Early Pliocene and Pleistocene times near the Tjörnes Fracture Zone, a fault zone related to the Mid Atlantic Ridge passing through Iceland (Figure 3.1A). The basin was interpreted as a fjord open to the north with sediment supply from the land to the south (Strauch, 1963). Shallow marine sediments as well as terrestrial sediments and lava flows accumulated and resulted in a 1200 m thick sequence. In later Pleistocene times the Tjörnes basin was uplifted as a horst structure and the beds are now exposed in the coastal cliffs.



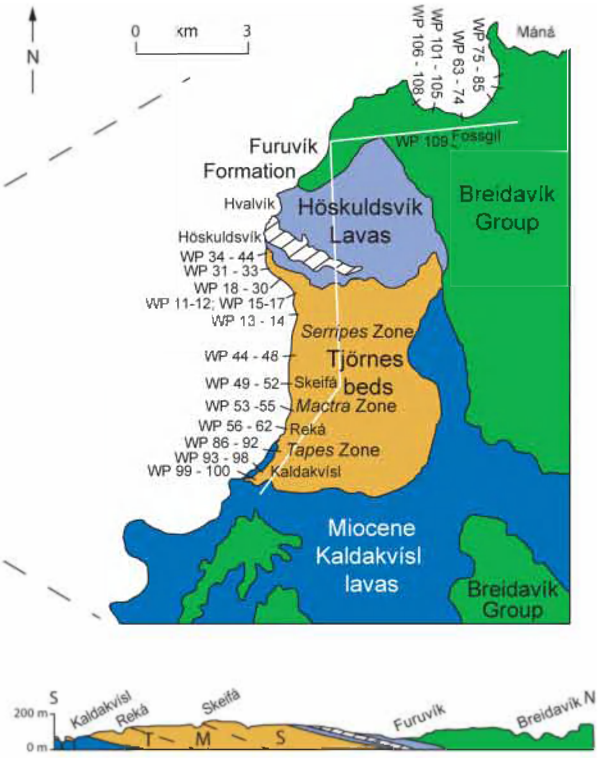


Figure 3.1A (Left): Overview of the present-day surface currents of the North Atlantic Ocean with indication of the study area in northern Iceland. Warm water currents are indicated with red arrows, cold water currents with broader blue arrows (adapted from Marret *et al.*, 2004). The Mid-Atlantic Ridge is indicated with a gary line. The position of the Polar Front around Iceland (dashed line) is after Knudson and Eiríksson (2002). The encircled numbers 1–3 indicate shallow marine Pliocene deposits: (1) the St. Erth Beds, (2) the England Crags and (3) the Belgian Pliocene sands.

Figure 3.1B (Right): Detailed geological map of the study area, located on the western part of the Tjörnes Peninsula. A cross section (white line) of the area is given below, modified and simplified after Einarsson *et al.* (1967) and Eiríksson (1981b), together with the sample locations and numbers. T = *Tapes* Zone; M = *Mactra* Zone; S = *Serripes* Zone.

The oldest part of the sequence is the Early Pliocene Tjörnes beds consisting mainly of marine sandstones alternating with terrestrial lignites. Lava flows occur sporadically. The Höskuldsvík lavas separate the Early Pliocene Tjörnes beds from the overlying Pleistocene Breidavík Group (Figures 3.1B, 3.2). This group encompasses fourteen glacial-interglacial cycles consisting of glacial till sediments, late-glacial outwash gravels and interglacial marine sediments (Figure 3.2; Eiríksson, 1981b). Recent lava flows cover the Quaternary glacial-interglacial deposits.

The position of the Tjörnes cliffs central in the northern Atlantic and their easy accessibility make them an unique location for palaeontological, palaeoclimatical and palaeoceanographical studies. Bárdarson (1925) described in the Tjörnes beds 25 shell bearing marine units (1-25) and 10 lignites (A-J), and divided the sequence into three molluscan taxon-range biozones: the *Tapes*, *Mactra* and *Serripes* Zones (Figure 3.1). Other palaeontological studies focussed on marine molluscs (Strauch, 1972; Norton, 1975, 1976; Gladenkov *et al.*,1980; McCoy, 2007, Símonarson and Eiríksson, 2008; Símonarson and Leifsdóttir, 2008), ostracods (Cronin, 1991) and dinoflagellate cysts (Verhoeven and Louwye, 2012; Verhoeven *et al.*, 2011). Cronin (1991) recorded foraminifers but stated that these are difficult to extract from the consolidated siliciclastic matrix. Akhmetiev *et al.* (1978) made a preliminary study of the diatoms from lignites C and F, respectively in the *Tapes* and *Mactra* Zone. The organisms however are poorly preserved, of mixed age and ecological preference and therefore the analysis was not pursued. Past sea water temperatures of the Tjörnes beds were estimated with oxygen isotopes (Buchardt and Símonarson, 2003). Eiríksson (1981b, 1985) studied in detail the sedimentology of the Breidavík Group.

The organic-walled dinoflagellate cysts (dinocysts) from the Tjörnes beds and the overlying Breidavik Group were studied by Verhoeven *et al.* (2011)

and allowed a more refined age attribution than the earlier ones (Einarsson *et al.*, 1967; Albertsson, 1978; Buchardt and Símonarson, 2003; Símonarson and Eiríksson, 2008) and the reconstruction of the depositional history. It was established that the base of the Tjörnes beds is of post-Miocene age. The entire Tjörnes beds are of Early Pliocene age, with the top of the *Serripes* Zone has been deposited around 4.0 Ma. The Pacific molluscan invasion around the *Mactra*/*Serripes* Zone boundary is dated c. 4.5 Ma. Two major hiatuses of c. 600–900 ka occur, one between the top of the *Serripes* Zone and the Höskuldsvík lavas and one between the Furuvík Formation and the Hörgi Formation, the last formation being dated around 2.2 Ma (Figure 3.2). The rest of the Breidavík Group extends from then on to recent times. The Tjörnes beds and Breidavík Group also contain pollen and spores, the study of which contributed to our knowledge of the vegetation, the water depth and the coastal landscape (Verhoeven *et al.*, in press).

Only a few other shallow marine deposits of comparable age are known from the northern and central Atlantic (Figures 3.1A, 3.2). The Tjörnes assemblages have been compared with these of the St. Erth Beds in southwest England (+- 2.1–1.95 Ma), several crag deposits in southeast England (4.4–1.8 Ma) and the Belgian Pliocene sands (5–2.76 Ma).

In the present study, the ecological preferences of the dinocysts of the sequence are discussed, in order to understand Plio-Pleistocene palaeoceanographical and climatological changes in the northern Atlantic realm.

2. Molluscs and palaeobathymetry

A combined sedimentological/malacological study of the Tjörnes beds by Buchardt and Símonarson (2003) indicated a slightly fluctuating sea level during deposition of the *Tapes* Zone and the lower part of the *Mactra* Zone. Sediment supply was more or less in sync with the subsidence rate and intertidal sandstones and beach gravels alternating with lignites, remnants of coastal marshes, were deposited. Strong bottom currents transported molluscan shells of deeper water to the coastal area as revealed by the allochthonous taphocoenoses of epi- and infaunal molluscs present in the entire Tjörnes beds (Norton, 1975).

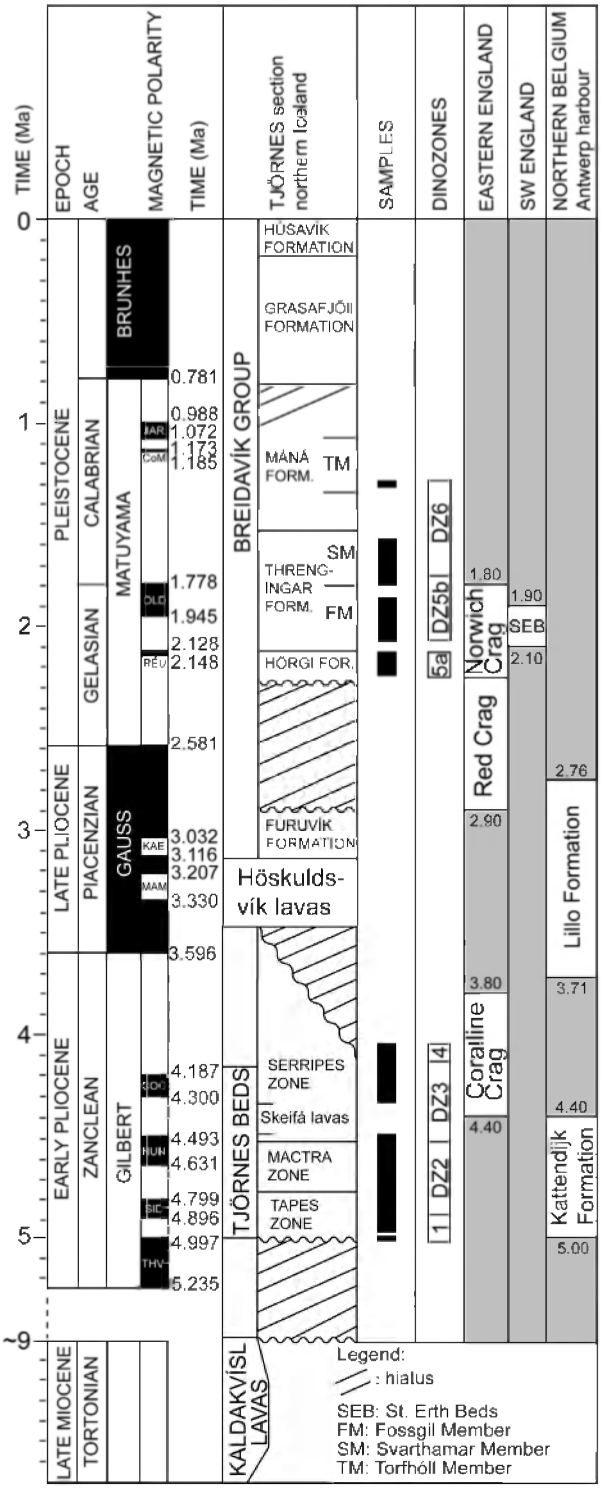


Figure 3.2: Age model of the Tjörnes section with indication of the sampled intervals (modified after Verhoeven *et al.*, 2011). The stratigraphical position of shallow marine sediments from Eastern England (Head, 1996, 1998a,b; De Schepper *et al.*, 2009), Southwest England (Head, 1993) and Northern Belgium (De Schepper *et al.*, 2009) are given.

Table 3.1: **Relative abundances of dinocysts and marine Non Pollen Palynomorphs from the Tjörnes section. Lignites are indicated with horizontal grey bars.**

stratigraphy and molluscan biozones							LABORATORY						DINOFLAGELLATE CYSTS																																					
			G.P.S. Way Point; sample number	Bardarsons Beds	thickness, m	sediment	standard treatment (HCl, HF, HCl)	KOH, Acetolysis	Heavy liquid separation, ZnCl2	# *Lycopodium clavatum* tablets, batch 483216, x=18583 +/- 1708	dry weight sediment, g	*Lycopodium clavatum (spike)*	dinocyst spp. indet.	*Achomosphaera* sp.	*Amiculosphaera umbraculum*	*Barssidinium pliocenicum*	*Batiacasphaera hirsuta*	*Batiacasphaera minuta*	*Bitectatodinium tepikiense*	*Bitectatodinium? serratum*	*Brigantedinium cariacoense*	*Brigantedinium simplex*	*Brigantedinium* spp.	*Capisocysta* sp. *C. lyellii?*	*Cristadinium* sp.	*Echinidinium euaxum*	*Echinidinium karaense*	*Echinidinium* sp.	*Filisphaera filifera* subsp. *filifera*	*Habibacysta tectata*	*Impagidinium aculeatum*	*Impagidinium patulum*	*Impagidinium plicatum*	*Impagidinium* sp.	*Islandinium minutum*	*Lejeunecysta catomus*	*Lejeunecysta marieae*	*Lejeunecysta oliva*	*Lejeunecysta sabrina*	*Lejeunecysta* sp.	*Lingulodinium machaerophorum*	*Melitasphaeridium choanophorum*	*Nematosphaeropsis labyrinthus*	*O. centrocarpum* sensu W. & D. (1966)	*O. centro.* sensu W. & D. short processes	*Operculodinium centrocarpum* s.s	*Operculodinium? eirikianum* var. *eirikianum*	*Operculodinium* sp.	*Operculodinium tegillatum*	cyst of *Pentapharsodinium dalei*
Breidavík Group	Torfhóll Member		WP 82	14	889,8	S	x			1	55,6	587	14						7.1																									5	7.1					21
			WP 83	14	888,5	M	x			1	54,4	1185							5																															5
			WP 84	14	883,5	M	x			1	50,7	1360	2.8						7.4				2.8					1.5													1.5			25		2.8				48
			WP 85	14	878,9	M	x			1	63,1	307	1.2	0.3					3.6			0.3	1.6									0.3			0.3									1.6		1.9				83
	Svarthamar Member	DZ6	WP 77	12	835,0	C	x			1	63,8	565	1.1	0.6					23																7.7						0.3			0.3						65
			WP 69	10	823,4	M	x			1	44,3	190	1.2						0.8																0.8									0.5	0.3					83
			WP 70	10	819,8	M	x			1	54,2	281	2.9	1.4					10				0.8																		0.3			6.2		0.3				64
			WP 71	10	817,2	M	x			1	46,6	2643	13						23										3.2												6.5		3.2	3.2		35				9.7
			WP 73	[illegible]	816,3	M	x			1	66,7	4227	5																																5	8				
		DZ5b	WP 68	8	813,0	S	x			1	53,1	3848	23	14	4.5																										10					36				
	Fossgil		WP 67		782,0	M	x			1	58,1	1347																																						
			WP 109		778,0	M	x			1	62,3	2242	76																																	12				
	Hörgi Formation		WP 101		769,0	M	x			1	48,0	2697	15	2.4																											7.3					68				
			WP 108		765,0	S	x			1	56,9	1506	32	8.5		5.7							1.1							1.1							1.1				1.1					32		2.3		1.1
			WP 102		762,1	M	x			1	48,5	2471	25	25																																25				
			WP 107		758,0	S	x			1	58,6	833	22			3.2	3.2																										1.6			5.8				4.8
		DZ5a	WP 103		753,0	M	x			1	41,9	1072	19																4.8											4.8	19					39	4.8		4.8	
			WP 104		752,5	M	x			1	54,6	1161	22	3.7		7.5																									3.7					4.7				
			WP 106		750,0	S	x			1	52,1	450	2.9	5.9		8.8	12									2.9															5.9	2.9				15				15
			WP 105		744,0	M	x			1	40,7	1529	9.7																												9.7					77				
Tjörnes beds	Serripes Zone		WP 43	24	478,0	CS,W	x			1	39,1	1716																																						
			WP 40	I	477,6	M	x			1	60,0	3864																																						
			WP 42	H	476,7	M	x			1	48,6	1005																																						
		DZ4	WP 38	H	462,8	CS,W	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	6.3			13						6.3	19			31											6.3													
			WP 28	21/22	439,4	S	x			1	59,4	2137	1.2	12		18		1.2					1.6	4.8					19								1.2									1.2			5.9	1.2
			WP 32	7	439,3	S	x			1	51,6	204																																						
			WP 24	21/22	427,2	S	x		x	1	62,2	1474	4.8			63		1			1.9					4.8			8.6								1													
			WP 33	7	426,5	SH	x			1	62,1	2489	2.9			2.9					1.5	4.4	29			7.4			7.4											1.5						16				5.9
			WP 25	21	424,8	SH	x		x	1	66,5	3992	22	6.9		1.7						1.7	3.4			13			1.3								1.7							1.7		2.7				6.9
			WP 26	20/21	424,4	S	x			1	52,1	2375	1.5	1.5		23		1.5			2.4	1.5	20			3.3			3.3											1.5						10			3.3	10
			WP 23	20	423,7	SH	x		x	1	50,0	1269	13	1.7		15		3.4		0.9		1.7	9.5			16											5.2									4.3				9.5
			WP 22	19/20	422,9	S	x		x	1	39,2	764	0.3		0.3	2.4	0.7	1.5		0.3	0.7		20		0.3	12			0.7								2.1			1.2				0.3					3.4	23
			WP 21	19	422,2	SH	x		x	1	82,8	929	8			27	0.4			1.9	2.2	1.4	1.6		0.7	0.7			2.5											0.4						1.9			1.4	29
			WP 20	18/19	420,0	S	x			1	49,0	2253	4			18	2	1.3					24		3.3	25	0.7		2								0.7												1.3	4.6
		DZ3	WP 19	18	417,6	SH	x		x	1	40,3	1262	24			14			3.4				3.4						3.4					3.4				3.4								6.9			6.9	14
			WP 18	17/18	415,8	S	x			1	52,6	1261	5.3	0.3	0.3	7.3		13	0.3	0.3	2.2	2.2	21		1.4	2.7			5.3									1.1	0.8	0.8						1.4			0.6	3.7
			WP 17	17/18	406,5	S	x		x	1	47,1	1176	12	3.8		24							12			19			12																					
			WP 16	17	402,2	S	x		x	1	53,5	2397	7.1	1.8		8.9					1.8	3.6	21		1.8	17			3.6								1.8		1.8	1.8						1.8			1.8	5.4
			WP 3	16	379,3	SH	x			1	44,1	1383																																						
			WP 4	15/16	375,8	S	x			1	48,7	617	2.7	0.9	16	0.7	0.3	6.4				1.5	8.2			7.9			5.2							1.5	1.2	0.7	0.3							3.7			14	0.3
			WP 5	15	368,8	SH	x			1	50,5	1808	2.7		12	0.9		11				5.2	31		0.9	1.4			0.9					0.9			0.9			0.9						2.7			0.9	2.7
			WP 6	14/15	367,9	S	x		x	1	67,8	488	3.5	7.3	1.8	3.5		30		3.5	0.7	1.2	1.8						1.2	1.2											1.8	0.7				23			6.8	1.2
			WP 7	14	363,9	SH	x			1	53,9	591		1.5				5.3					32			16			5.3																	26				
			WP 8	13/14	360,1	S	x			1	45,2	191	3.4	36		5.4						0.5	0.5			0.5										0.5	1			0.5										2
			WP 9	13	359,2	S	x			1	70,5	151	5.6	8.1		1.2	0.2	1.2			0.5	0.5	9.3			16										0.5	3.7	0.2	0.2	1.2		0.5	0.2			5.6			0.2	2.8
			WP10	12/13	357,2	S	x			1	72,1	361	6.3	3.2		1.6	1.6						4.8						27	3.2							3.2			4.8	3.2					4.8				6.3
	Mactra Zone		WP 11	12	356,0	S	x			1	56,0	1393				2																2												6						
			WP 12	11	350,0	SH	x		x	1	51,7	3139			1	1													3																				4	
			WP 13	11	340,0	CS	x			1	41,7	3572	2.8	0.9		0.9	0.9													0.9											3.7			67	5.5	8.3		0.9		1.8
			WP 14	11	330,0	S	x			1	69,0	3676	3.8					15																												24			27	15
			WP 44	10	295,0	SH	x			1	34,4	253					13	13												13	13												13			13				25
			WP 45	10	291,2	S	x			1	52,3	288	6.7	6.7		6.7	2																													2				13
			WP 48	9	286,1	SH	x			1	41,6	1029	17				33													33	17																			
			WP 46	9	277,8	SH	x			1	57,2	1282					18																													64				
			WP 47	7	272,0	SH	x			1	46,8	184					6																													4				
			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		x	1	50,0	478																																						
		DZ2	WP 52	8	230,0	SH	x		x	1	74,3	656	3.8				38													7.7																15				
			WP 53	D	211,1	M,W	x			1	3,2	128	2.5	5		2.5														58																				15
			WP 56	D	207,9	L	x			1	3,5	35																																						
			WP 54	D	203,7	L	x			1	34,2	77	5																																					
			WP 57	7	195,3	S	x		x	1	46,8	566																																						
			Wp 58	7	188,0	M,W	x			1	3,4	1080																																						
			WP 55	7	185,0	S	x		x	1	38,2	25	5.4	6.4		2.1							0.7			2.1				2.7			0.7			1.3									1.3	18		0.7		
			WP 59	6	183,0	S	x		x	1	42,8	428	2.6	3.8		1.7							3.2			5.2				6.9		0.3		0.3		0.3						0.3				65				1.7
	Tapes Zone		WP 60	C	145,0	L		x		1	2,4	51																																						
			WP 61	C	144,0	S	x		x	1	31,7	1248	38			7.7										3.8																								
			WP 62	5	129,0	S	x		x	1	43,9	1620						1																																
			WP 86	4	83,2	S	x		x	1	47,7	1306	5			7.5		68	5											2.5											2.5									7.5
			WP 87	4	78,0	S	x		x	1	49,7	846				3.8														4																46				
			WP 88	4	69,0	S	x		x	1	49,5	697				27		13					6.7														6.7									6.7				
			WP 89	B	68,0	L		x		1	2,4	2																																						
			WP 90	3	66,2	S	x		x	1	49,9	149	5.7			0.9		5.7			0.9	1.9	14			22											2.8	0.9			0.9					7.5				1.9
			WP 91	3	65,1	S	x		x	1	38,0	531	1					3.3			3.3		2			6.7				6.7																				3.3
			WP 92	c	45,0	L		x		1	2,5	6																																						
			WP 93	2, b	36,2	L		x		1	2,6	6																																						
		DZ1	WP 94	2	35,3	S	x		x	1	48,7	343	5.7			42		3.7	0.6		1.2		5.9						1.2	0.3						0.9	2.8	0.6		0.3						1.6				7.8
			WP 95	2	29,4	S	x		x	1	38,4	1850							4				1							2																				3
			WP 96	2, a	22,4	L		x		1	2,4	8																																						
			WP 97	2	20,4	S	x		x	1	32,5	222	5.4			23					3.6		13			17			3.6	1.8						3.6	1.8													5.4
			WP 98	2	13,7	S	x			1	60,2	516	11				5.6									17				11					5.6		5.6				5.6					5.6				
			WP 100	1	5,0	S	x			1	42,7	38	14			46													2.9																	8.6				2.9
			WP 99	A	3,0	L		x		1	4,0	10																																						

Legend: L = lignite; M = mudstone; S = sandstone; CS = coarse sandstone; W = wood; P = plant remains; C = conglomerate; SH = shell remains

																								MARINE PALYNOMORPHS																	INDICES														
Quinquecuspis concreta	*Reticulatosphaera actinocoronata*	*Scrippsiella trifida*	*Selenopemphix brevispinosa*	*Selenopemphix conspicua*	*Selenopemphix islandensis*	*Selenopemphix dionaeacysta*	*Selenopemhix nephroides*	*Selenopemphix quanta*	*Selenopemphix* sp.	*Spiniferites bulloideus*	*Spiniferites delicatus*	*Spiniferites elongatus*	*Spiniferites membranaceus*	*Spiniferites mirabilis*	*Spiniferites ramosus*	*Spiniferites* spp. indet.	*Tectatodinium pellitum*	*Trinovantedinium applanatum*	*Trinovantedinium ferugnomatum*	*Trinovantedinium glorianum*	*Trinovantedinium harpagonium*	*Trinovantedinium* sp.	*Tuberculodinium vancampoae*	Crustacean egg	Foram lingings: planispiral	Foram lingings: trochospiral	Invertebrate mandibles	*Tasmanites* sp.	Total non acritarch marine	Acritarch sp. indet.	*Cyclopsiella? trematophora*	*Cyclopsiella* sp.	*Cymatiosphaera invaginata*	*Halodinium minor*	*Halodinium scopaeum*	Acritach type 1 (this study)	*Paralecaniella indentata*	Algae type A De Schepper (2006)	Algae cyst type 1 Head (1996)	Total acritarch	Shannon-Wiener Index (dinocysts)	Evenness (dinocysts)	Dinocyst conc. (# cysts/g sediment)	Terrestrial palynomorph concentration	# warm dinocyst species (n)	# cold dinocyst species (n)	W/C index (n warm/ (n warm + n cold))	Heterotrophic species (n)	Autotrophic species (n)	nH/(nH+nA)	IN/ON=nIN/(nIN + nON)	P (total recent pollen)	S (total recent spores)	nP/(nP+nD)	(nP+nS)/(nP+nS+nD)
																																									0.73	0.53	7.97	0.93	0	4	0	0	2	0	1	1	0	0.1	0.1
																																									0.48	0.69	0.58	3.29	0	2	0	0	1	0	1	39	5	1	1
												2.8			1.5	4.2																									1.04	0.45	19.1	1.00	1	41	0	3	14	0.2	0.9	37	8	0.3	0.4
								0.3				3.3			0.3	2.2																	0.3							0.31	0.53	0.21	319	1.82	1	300	0	8	39	0.2	0.9	88	27	0.2	0.3
												0.3			0.3	0.9									0.6					0.6											0.66	0.3	180	0.19	1	338	0	27	90	0.2	1	3	8	0	0
										0.3		4.8			2.9	5.9																	0.3							0.26	0.49	0.22	865	1.56	0	350	0	3	58	0	0.9	63	6	0.1	0.1
		5.7										0.3			0.8	8.6									0.3					0.3											0.85	0.35	469	0.83	1	283	0	3	78	0	0.9	21	23	0.1	0.1
																3.2																							9.7	9.66	1.07	0.52	4.68	2.92	2	11	0.2	0	23	0	0.9	101	28	0.8	0.8
																1																									0.39	0.35	1.32	4.01	0	0	0	0	19	0	0	169	91	0.9	0.9
																14									4.5					4.5				4.5						10	13.6	0.88	0.55	2	6.18	2	0	1	0	17	0	0.3	169	154	0.9	0.9
																																									0	0	0	5.75	0	0	0	0	0	0	0	261	60	1	1
																12																									0.35	0.5	2.26	5.04	0	0	0	0	4	0	0	220	75	0.9	0.9
										1.2						7.3									1.2		1.2		2.4												0.55	0.34	11.8	7.06	6	0	1	0	70	0	0.5	207	120	0.7	0.8
	1.1					1.1				1.1		1.1				6.9					2.3																		1.1	1.15	1.08	0.4	18.9	6.10	6	3	0.7	10	47	0.2	0.5	239	107	0.7	0.8
	25																								25					25											0.72	0.66	0.62	2.08	0	0	0	0	2	0	0	60	40	0.9	1
											1.6					9.5				3.2					7.9					7.9											0.81	0.39	24	6.14	2	4	0.3	4	42	0.1	0.4	240	117	0.8	0.9
																4.8																							14	14.3	0.98	0.5	8.69	7.95	5	1	0.8	1	16	0.1	0.7	257	69	0.9	0.9
																22																									0.79	0.49	7.92	1.39	3	0	1	2	19	0.1	0.3	45	31	0.6	0.7
	5.9		2.9											2.9		12		2.9	2.9																						1.67	0.62	26.9	8.52	8	5	0.6	7	18	0.3	0.7	258	183	0.9	0.9
															3.2																										0.37	0.34	9.26	10.30	3	0	1	0	28	0	0.8	290	123	0.9	0.9
																																									0	0	0	0.33	0	0	0	0	0	0	0	4	1	1	1
																																									0	0	0	0.03	0	0	0	0	0	0	0	2	0	1	1
																																									0	0	0	2.68	0	0	0	0	0	0	0	2	0	1	1
																																									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																																									0	0	0	0.38	0	0	0	0	0	0	0	15	1	1	1
																																									0	0	0	0.07	0	0	0	0	0	0	0	2	1	1	1
																																									0	0	0	1.71	0	0	0	0	0	0	0	9	0	1	1
					13										6.3									6.3	131				138					6.3	69	13				87.5	1.19	0.61	3.33	6.35	7	0	1	14	1	0.9	0.7	61	178	0.8	0.9
					2.4										4.8	18									1.2				1.2				4.8							4.76	1.5	0.59	12.5	39.72	15	17	0.5	27	56	0.3	0.6	281	2071	0.8	1
																																									0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0
					2.9		1								3.9	1.9		1		2.9		1.9			4.8				4.8		1				3.9					4.76	0.96	0.37	21.3	8.44	72	9	0.9	84	16	0.8	0.9	22	503	0.2	0.8
			1.5		2.9		2.9								1.5	1.5		4.4	1.5	4.4					8.8	1.5			10.3		5.9		1.5		51				1.5	6.29	1.6	0.56	8.17	14.32	9	9	0.5	44	18	0.7	0.8	48	821	0.4	0.9
			1.7		1.7											1.7				3.4		1.7			14				14				5.2		40					44.8	1.37	0.51	4.06	25.77	8	10	0.4	17	23	0.4	0.9	69	1645	0.5	1
			4.5		7.6		3.3												1.5	4.5				3.3	71				74				10		10	4.5				14.5	1.65	0.58	9.92	30.07	19	8	0.7	47	11	0.8	1	126	1440	0.7	1
			1.7		7.8		0.9								2.6	2.6		1.7	1.7	0.9	0.9				20				20	0.9			2.6		14					17.2	1.61	0.55	34	18.14	36	11	0.8	72	18	0.8	0.8	79	828	0.4	0.9
					5.2		1.2								2.4			0.7	1.5	0.9	0.3				9.8				9.8		0.3		1.8			2.7				4.88	1.54	0.5	204	3.01	110	76	0.6	222	30	0.9	0.9	22	94	0.1	0.3
					8		2.9								1.4	0.4		0.4	0.4	2.2					7.7				7.7	0.7			2.5		1.9					4.35	1.33	0.44	66.6	2.62	84	86	0.5	152	23	0.9	1	30	183	0.1	0.4
					2		1.3								7.3	0.7				0.7	2				158				158		3.3		3.3		31	7.3	1.3			46.4	1.43	0.5	25.4	15.59	66	10	0.9	116	22	0.8	0.8	132	628	0.5	0.8
							1.3									6.9									24				24				6.9							6.9	1.33	0.55	10.6	6.92	7	6	0.5	9	9	0.5	0.8	20	258	0.4	0.9
0.3				0.6	1.1		3.7	3.7							0.6	0.6		0.3	1.1	2					7.4			0.3	7.7		8.7		1.7		2.5	0.6	0.6		4.2	18.2	1.66	0.5	100	13.87	111	30	0.8	248	81	0.8	0.9	93	635	0.2	0.7
							15	3.8																	24				24		12		15		8.8		3.8			112	1.17	0.6	8.72	10.67	15	3	0.8	19	4	0.8	1	65	437	0.7	1
	1.8			3.6				1.8							5.4	3.6			1.8	1.8					123				123		170		7.1		38					214	1.73	0.57	8.12	14.57	14	5	0.7	38	10	0.8	0.7	124	655	0.7	0.9
																																									0	0	0	3.06	0	0	0	0	0	0	0	67	68	1	1
					1.8	0.3	1.5								1.2	1.5		4.6	1.5	16		0.3			5.2				5.2	0.9	14		0.3						1.2	16.5	1.77	0.55	203	10.24	33	18	0.6	158	160	0.5	0.3	341	150	0.5	0.6
0.9					2.7		1.7								0.9			1.7		7.8					1.7				1.7		50		1.7		3.5					54.8	1.56	0.52	23.4	10.78	15	4	0.8	75	34	0.7	0.3	342	197	0.7	0.8
	1.2		1.8		3.7										2.4	0.7		0.7	0.7		1.2				0.7			0.7	1.2		21		1.8		0.7		1.2		3.7	28.7	1.57	0.5	92.1	10.9	9	6	0.6	24	131	0.2	0.6	357	382	0.7	0.8
																				5.3					79				79		32				16					47.4	1.18	0.61	11.1	6.21	3	1	0.8	10	9	0.5	1	156	177	0.9	0.9
	0.5		1.5	2	1.7	8.3	2.4	3.4	2						1	6.8		0.5	11												2.9		4.4						12	19.2	1.5	0.49	441	89.94	17	4	0.8	104	89	0.5	0.5	1300	2765	0.9	1
	1.9		5.9		1.2	1.4	1.2	12	0.7						0.2	4.4		2.8	0.5	3.9	0.9				3.7		0.5		4.2		1.9	0.2	2.3		0.7				13	18.3	1.86	0.54	754	8.41	118	9	0.9	302	89	0.8	0.7	289	295	0.4	0.6
			4.8			6.3							1.6		6.3	1.6		7.9	1.6						1.6			1.6	3.2										7.9	7.94	1.68	0.58	45	8.33	4	23	0.1	22	33	0.4	0.8	331	270	0.8	0.9
																									62				62				6		6				6	18	0.66	0.6	1.19	18.28	2	0	1	1	1	0.5	1	547	473	1	1
															1																										0.98	0.61	1.15	19.59	1	3	0.3	1	9	0.1	0.7	509	498	1	1
	0.9														2.8	3.7											0.9		0.9										1.9	1.92	0.91	0.35	13.6	29.20	5	3	0.6	1	30	0	0.5	615	601	0.8	0.9
															3.8	12																							12	11.5	1.14	0.58	1.9	19.81	0	4	0	0	20	0	0.5	497	870	1	1
																																							13	12.5	1.32	0.68	17.1	166	0	3	0	0	6	0	1	14	43	0.6	0.9
	6.7															2																									1.23	0.63	18.5	7.04	1	2	0.3	1	10	0.1	0.5	70	298	0.8	1
																									33				33												0.71	0.65	2.6	0.96	0	2	0	0	5	0	0	10	30	0.6	0.9
	18																																					10		10	0.63	0.57	2.79	2.59	0	0	0	0	9	0	0	41	107	0.8	0.9
																																									0.47	0.67	21.6	7.12	0	0	0	0	10	0	0	27	305	0.7	1
																																									0	0	0	144.7	0	0	0	0	0	0	0	332	0	1	1
																																									0	0	0	13.46	0	0	0	0	0	0	0	439	16	1	1
																																									0	0	0	0.14	0	0	0	0	0	0	0	5	2	1	1
																7.7																							7.7	7.69	0.73	0.53	4.96	2.29	0	1	0	0	9	0	0	49	120	0.8	0.9
	2.5												7.5		2.5	5																									0.95	0.46	1809	114.6	4	29	0.1	1	31	0	0.5	313	53	0.9	0.9
																																									0	0	0	107.7	0	0	0	0	0	0	0	379	0	1	1
			5																																						0.24	0	14.1	19.39	0	0	0	1	0	1	0	101	563	1	1
																																									0	0	0	0.58	0	0	0	0	0	0	0	9	18	1	1
																		1																							0	0	5.11	6.23	0	0	0	1	0	1	0	21	0	1	1
	5.4		9.4	0.7		0.7									2.7	36			2.7	2.1					6.7				6.7				2.1						0.7	2.68	1.41	0.49	2899	8.85	0	4	0.6	32	101	0.2	0.1	200	131	0.6	0.7
										0.3					1.2	3.8		0.3		3.5					15				15				3.8					0.3	3.5	7.51	0.96	0.35	351	2.20	26	30	0.5	49	282	0.1	0.4	58	36	0.1	0.2
																																									0	0	0	120.7	0	0	0	0	0	0	0	256	26	1	1
																				24					154			7.7	162												0.52	0.57	6.11	11.24	5	0	1	8	0	1	1	58	298	0.8	1
																																									0	0	0.26	9.76	0	0	0	0	1	0	0	61	367	1	1
																2.5																	5						3	35	0.75	0.38	11.9	7.44	4	6	0.4	3	32	0.1	0.9	152	201	0.8	0.9
	5									1.3													3.8																		0.81	0.45	35.4	7.65	6	32	0.2	3	73	0	0.9	71	307	0.5	0.8
						6.7													33						13				13												1.18	0.61	8.08	6.69	4	0	1	12	3	0.8	1	291	40	1	1
																																									0	0	0	6.81	0	0	0	0	0	0	0	14	0	1	1
11			4.7			5.7							0.9	0.9	0.9	1.9		1.9	4.7	1.9					1.9				1.9												1.7	0.56	265	7.79	27	2	0.9	78	20	0.8	0.4	78	310	0.4	0.8
6.7			13			6.7														2					63				63				13							13.3	1.37	0.59	27.6	9.52	2	3	0.4	23	3	0.9	1	58	303	0.7	0.9
																																									0	0	0	170.1	0	0	0	0	0	0	0	174	218	1	1
																																									0	0	0	134.2	0	0	0	0	0	0	0	329	20	1	1
0.3			3.7			2.5				0.3		0.3			2.2	5.7		1.2	2.8	5.9		0.6											1.6							1.56	1.48	0.47	357	8.23	134	33	0.8	227	51	0.8	0.9	114	286	0.3	0.6
																									1				1												0.89	0.64	2.62	8.63	0	9	0	1	6	0.1	1	40	291	0.8	1
																																									0	0	0	150.4	0	0	0	0	0	0	0	364	3	1	1
3.6						3.6											3.6		1.8	1.7					3.6				3.6												1.54	0.58	144	11.62	24	6	0.8	45	5	0.9	1	87	287	0.6	0.9
						11									5.6	5.6				11					44				44			5.6							11	16.7	1.49	0.62	10.8	8.37	4	3	0.6	9	7	0.6	0.3	82	418	0.8	1
5.7			5.7													5.7			2.9	5.7																			5.7	5.71	1.06	0.48	400	10.74	16	2	0.9	23	6	0.8	0.9	234	220	0.9	0.9
																5																							5	5	0.48	0.69	941	3.54	0	1	0	0	1	0	0.5	10	3	0.8	0.9

The low-diversity and monotonous molluscan assemblages in the *Tapes* and *Mactra* Zones are indicative of a coast entirely open to the sea with few molluscan habitats. Small numbers of Pacific molluscs such as *Mytilus edulis*, *Modiolus modiolus* and *Zirfaea crispata* invade the depositional area (units 1, 6, 8, 10, 12) during deposition of the *Tapes* and *Mactra* Zones (Figure 3.5; Gladenkov *et al.*, 1980; Buchardt and Símonarson, 2003). These early introductions were possible as the Bering Strait began to open around 5.4-5.5 Ma (Símonarson *et al.*, 1998, Marincovich and Gladenkov, 1999; Marincovich, 2000; Gladenkov *et al.*, 2002; Símonarson and Eiríksson, 2008). Comparable Boreal to low-Arctic molluscan assemblages are present in both the *Tapes* Zone and *Mactra* Zone and indicate no significant environmental or climatic change between both zones (Norton, 1975).

At the transition of the *Tapes* to the *Mactra* Zone, the intertidal mollusc *Tapes* (*Venerupis* today) *aurea*, disappears and is replaced by the now extinct *Spisula arcuata*. The latter species and *Arctica islandica* are indicators of deeper sub-littoral environments; together with *Lentidium complanatum* they are the marker species for the *Mactra* Zone. A significant deepening of the depositional area is observed in the upper part of the *Mactra* Zone (unit 10) until unit 22 in the upper part of the *Serripes* Zone as indicated by the progressively more diverse and new molluscan fauna characteristic for the *Serripes* Zone (Norton, 1975).

In unit 14, in the base of the *Serripes* Zone a major introduction (25% of the assemblage) of sublittoral Pacific molluscs such as *Serripes groenlandicus* and *Macoma calcarea* occurs (Bárdarson, 1925; Norton, 1975, 1977; Gladenkov *et al.*, 1980; Símonarson and Eiríksson, 2008).

The invasion is linked to the shoaling of the Central American Seaway around 4.5 Ma and led to the introduction of Pacific water through the Bering Strait into the Atlantic realm (Verhoeven *et al.*, 2011). The introduction of many Arctic elements in the Tjörnes area is however not indicative of a sudden cooling, for the O^{16}/O^{18} record does not show such an event (Buchardt and Símonarson, 2003). It has been suggested that the Arctic Ocean acted as a filter, allowing only cold water molluscs to migrate to the Atlantic (Einarsson, 1967; Símonarson and Eiríksson, 2008). Furthermore, new entrances of Atlantic Boreal and Lusitanian species, probably brought in by the Gulf Stream, are noted in the *Serripes* Zone (Bárdarson, 1925). The open coast setting during deposition of the *Tapes* and *Mactra* Zones was replaced in the *Serripes* Zone by a more sheltered and deeper water basin in which a wide range of molluscan communities thrived (Norton, 1975). *Serripes groenlandicus, Bela borealis* and *Macoma praetenuis* define the base of the *Serripes* Zone (Norton, 1975). The sedimentary environment became estuarine and intertidal in the upper part of the *Serripes* Zone.

3. Material and methods

A total of 68 samples from the Tjörnes beds and 20 samples from the Breidavík Group were analysed for dinocysts, pollen and spores (Figures 3.1B, 3.2). Four interglacials from the Breidavík Group were studied: the Hörgi Formation, Svarthamar Member, Fossgil Member and Torfhóll Member (Figure 3.2). Every bed of the Tjörnes beds as defined by Bárdarson (1925) was sampled at least once, except units J and 25. The average sampling interval was 6.5 m. Samples are taken in vertical transects out of the cliffs. When the exact allocation to a certain Bárdarson unit was ambiguous, an interpolated position was taken. For example, the notation 15/16 comprehends a sample situated in between two distinct molluscs accumulation layers attributed respectively to unit 15 and to unit 16. Quite large samples of minimum 40-50 g (Table 3.1) were mechanical crushed with a mortar into pieces of c. 0.5 cm and oven dried for 24 hour at 58°C. One *Lycopodium clavatum* tablet (batch 483216; n=18583+/-1708) was added before the chemical treatment for the calculation of absolute concentration of palynomorphs. The marine sediments were treated according to the standard maceration procedure involving demineralisation with 2 M cold HCl (6.1%) followed by 40% cold HF for the removal of carbonates and silicates respectively (Louwye *et al.*, 2007). Repeated cycles of the acid treatment proved necessary for the dissolution of the silicates and the newly formed fluorosilicates. The residues were sieved on a 10 µm nylon mesh, stained with safranin-O and mounted on glycerine-gelatine slides. Lignites were processed following the standard Erdtmann maceration protocol for pollen analysis (Fægri and Iversen, 1989). Only small samples of c. 2 g were oven dried, treated with 10% KOH and an acetolysis mixture (9/10 H_2SO_4 and 1/10 $C_4H_6O_3$). The lignite residues were mounted on fixed slides without sieving and staining. Microscopy work was carried out on a Zeiss® AxioImager A1 transmitted light microscopy under 400x and 1000x magnification. Photomicrographs were taken with a Zeiss® Axiocam MRc5 digital camera. Taxonomy of the dinocysts follows DINOFLAJ2 (Fensome *et al.*, 2008), except for *Barssidinium pliocenicum* for which De Schepper *et al.* (2004) was followed. Taxonomy also follows Louwye *et al.* (2004) (*Selenopemphix brevispinosa* and *S. conspicua*) and Verhoeven and Louwye (2012) (*S. islandensis*).

4. Results

4.1 Dinoflagellate cyst analysis

A total of 54 different dinocyst species belonging to 27 genera were counted in 88 samples from the Tjörnes and Breidavik sections (Plate 3.3, 3.4, 3.5; Figure 3.3; Table 3.1 for relative abundances and Table 2.1 for raw data). Acritarchs and freshwater green algae are present in moderate numbers, especially in the *Serripes* Zone (Plate 3.4). Less than 25 dinocysts were counted in a total of 44 samples. The poorest samples come from the lignite layers, the interval between unit 8 and 10 in the *Mactra* Zone, the interval between unit 22/23 and 24 in the upper part of the *Serripes* Zone and the Fossgil Member. Twenty-four samples contained between 25 and 100 cysts and only 20 samples yielded more significant counts of more than 100 cysts. Consequently the relative abundances have to be treated with caution and a semi-quantitative and qualitative analysis was performed instead of a biostatistical analysis. Reworking of Cretaceous and Paleogene/Neogene species is limited in the entire section (Verhoeven *et al.*, 2011).

4.2 Palaeoecological indices

Versteegh (1995) and De Schepper (2006) detected and characterised palaeoenvironmental changes by means of various palaeoecological indices based on the composition of dinocyst assemblages.

Concentration (number of dinocysts/gram) and richness (number of different species/sample) are calculated, together with the Evenness (E_H) and Shannon Wiener diversity index (H′, Table 3.1, Figure 3.4). The latter two indices indicate the distribution of the various species within a sample. The Shannon Wiener index has a rather constant value of c. 1.5 in the Tjörnes beds, with the exception of the central part in which a clear decrease has been noted. During the successive interglacials of the Breidavík Group, the index gradually decreases towards values around 0.7 in the Tórfholl Member. The evenness and the richness show the same trend. Concentrations are always low and have a highest value in the upper Pleistocene of 924 dinocysts/gram.

The inner neritic/outer neritic-ratio (IN/ON= nIN/[nIN+nON]) gives an indication of the position of the depositional area on the shelf, and the proximity to the coast. Typical inner neritic species are *Lingulodinium machaerophorum*, *Melitasphaeridium choanophorum*, *Barssidinium pliocenicum*, *Bitectatodinium tepikiense*, cysts of *Pentapharsodinium dalei*, *Filisphaera filifera*, *Tectatodinium pellitum* and *Tuberculodinium vancampoae*. Typical outer neritic species are *Amiculosphaera umbraculum* and *Operculodinium*? *eirikianum* var. *eirikianum*. The IN/ON-ratio through the section is moderate to high and indicates a constant near coast position of the sedimentary basin (Figure 3.4). Another indication of the palaeobathymetry is provided by the pollen and spores and will be discussed elsewhere (Verhoeven *et al.*, in press; chapter 5).

The P/D-ratio (=nP/[nP+nD]) in which P= pollen and D= dinocysts gives an indication of the proximity to the coast or the cooling effects on the land. This ratio remains very high during the entire section, except in the uppermost Breidavík Group and in some minor relapses in the upper part of the *Mactra* Zone and the base of the Serripes Zone. When spores are added to the index, the minor relapses disappear (Figure 4; (P+S)/[(P+S)+D]). These minor changes in the P/D-ratio thus do not indicate a slightly diminished influence of the land, but a changed vegetation composition.

An indication of the transport of dinocysts from an open marine environment into the shallow shelf area is given by the oceanic/neritic index (O/N=(nO/[nO+nN]), with N representing the inner and outer neritic species (see above) and O the oceanic species *Nematosphaeropsis labyrinthus* and *Impagidinium* spp.

The number of oceanic species is low throughout the studied section. The O/N-ratio suggests limited transport from the ocean into the depositional area, restricted to the upper part of the *Mactra* Zone and the base of the *Serripes* Zone (Figure 3.4).

Heterotrophic dinoflagellates are dependent of nutrients derived from upwelling or transported from the land. The H/A-ratio (nH/[nH+nA]) with H representing heterotrophic species (mainly protoperidinoid species) and A autotrophic species (gonyaulacoids and goniodomacoids) is used as a measure for upwelling. It should be noted that heterotrophic species are more sensitive for oxidation (Marret, 1993) and this may influence the ratios. Heterotrophic species are distinctly present in the Tjörnes beds, but show an abrupt regression during the second half of the *Tapes* Zone and the *Mactra* Zone (Figures 3.3, 3.4). Heterotrophic species are of minor importance in the Breidavík Group, where autotrophic species predominate. During the first half of the *Serripes* Zone, autotrophic species became already quite important.

The ecological preferences of recent dinoflagellates can be deduced from their present day distribution. Marrett and Zonneveld (2003) distinguish recent species by their preference to warm (W) or cold (C) surface water. A qualitative analysis relying on the warm/cold-ratio (W/C=nW/[nW+nC]) is a first indication of past Sea Surface Temperatures (SST), assuming for species with a distinct present-day distribution related to surface water temperature a comparable distribution during the Pliocene. Thus, *Impagidinium aculeatum*, *Impagidinium patulum*, *Lingulodinium machaerophorum*, *Selenopemphix nephroides*, *Spiniferites belerius*, *Spiniferites membranaceus*, *Spinifertes mirabilis*, *Tectatodinium pellitum* and *Tuberculodinium vancampoae* are considered to indicate warm surface water. *Bitectatodinium tepikiense*, *Islandinium minutum*, cyst of *Pentapharsodinium dalei*, *Spiniferites delicatus* and *Spiniferites elongatus* would indicate cold surface water. For extinct species however, we can assume temperature sensitivity only when independent proxies show that this is the case. De Schepper *et al.* (2011) quantified the spring/summer temperature ranges of extant and extinct dinoflagellate species through a calibration of Mg/Ca measurements of *Globigerina bulloides* from the same samples. Temperature distributions of extant species are broadly comparable for the Pliocene and modern oceans, with the Pliocene species clustering in the warmest part of the present-day distribution range. Head (1993) found large numbers of *Barssidinium pliocenicum* and *Echinidinium euaxum* in the interglacial Sint Erth Beds of southwest England and could link these occurrences to a warm winter SST of 15°C and the presence of the Gulf Stream at the time. *Melitasphaeridium choanophorum* and *Operculodinium*? *eirikianum* var. *eirikianum* are also linked to warm Pliocene SST (Head, 1997; De Schepper *et al.*, 2011). Many authors (Head, 1994, 1996; Versteegh, 1995; De Schepper *et al.*, 2011) also found evidence for the Pliocene cold water affinity of *Filisphaera filifera* and *Habibacysta tectata.* The W/C-ratio during the Tjörnes beds is rather high, except in the second half of the *Tapes* Zone and in the *Mactra* Zone. During the first half of the *Serripes* Zone, a dip is observed which runs more or less parallel with a dip in the H/A-ratio. A clear cooling is observed in the second half of the Svarthamar Member and in the Tórfholl Member, both in top of the Breidavík Group.

4.3 Dinocyst assemblage zones

4.3.1 Dinocyst zone 1 (DZ1)

The first zone (0-75 m), of Early Pliocene age, ranges from the base of the *Tapes* Zone to halfway unit 4 of the same molluscan zone and is defined by the dominance of the heterotrophic species *Barssidinium pliocenicum* (average of 10.6%; Plate 3.3C, D), *Trinovantedinium ferrugnomatum* (average 3.5%; Plate 3.1B; 3.1C,D), *Trinovantedinium glorianum* (average 2.2%; Plate 3.1E, F), *Selenopemphix dionaeacysta* (average 2.8%), *Quinquecuspis concreta* (average 2.1%, Plate 3.1O) and *Lejeunecysta marieae* (average 1.5%; Plate 3.1M, N). Autotrophic species are of minor importance. *Filisphaera filifera* subsp. *filifera* (average 0.6%; Plate 3.3S, T) occurs together with *Habibacysta tectata* (average 1.7%; Plate 3.3I, J; 3.3K), although the first species is much less well represented. The tropical species *Tectatodinium pellitum* (3.6%; Plate 3.2B) is recorded in unit 2 in the lower part of DZ1.

The average richness amounts to 15.6 species/sample, while the average dinocyst concentration is 118 dinocysts/g.

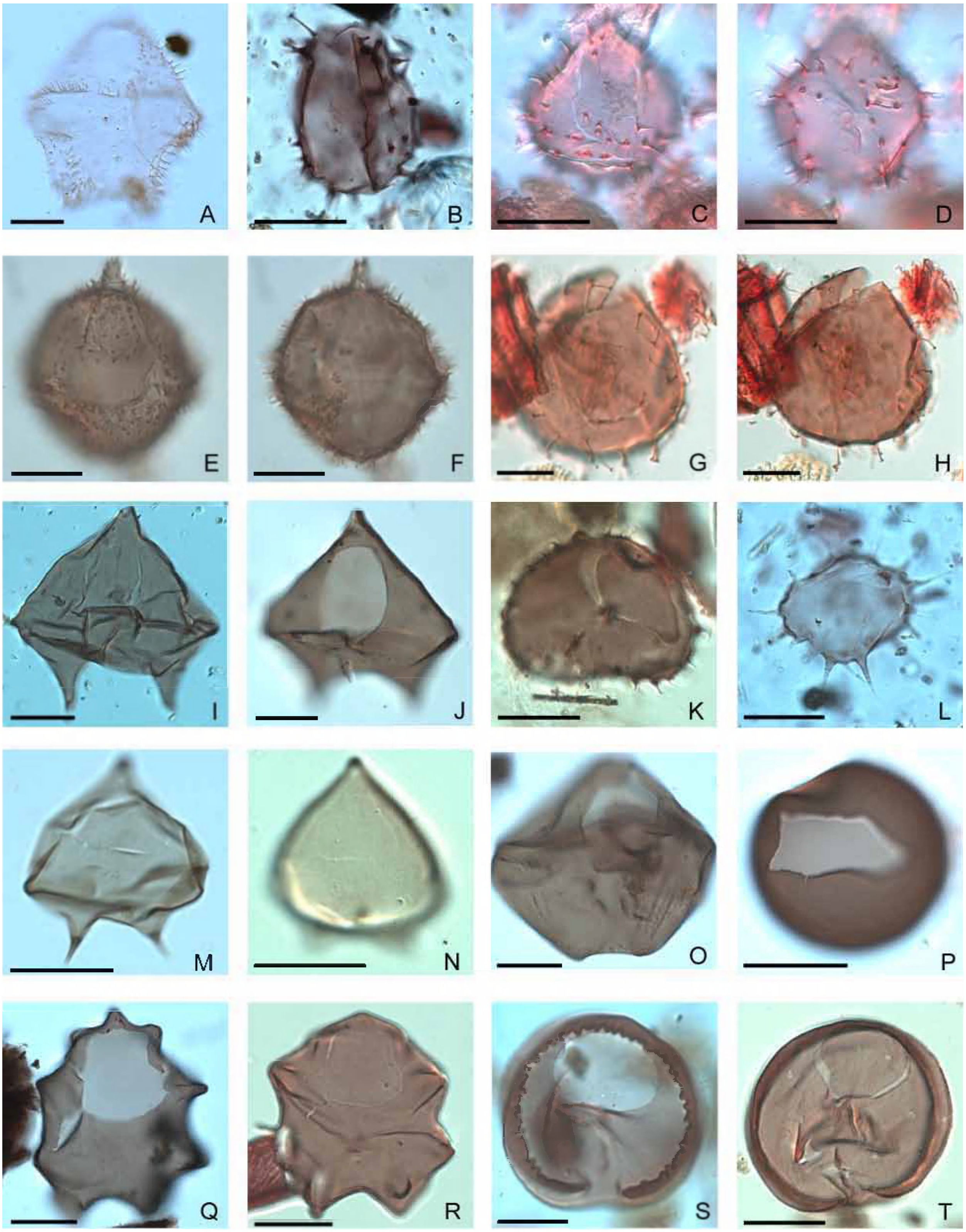


Plate 3.1: **Photomicrographs of selected heterotrophic dinoflagellate species. Scale bars indicates 20 µm. E.F.= England Finder coordinate.** **A**: *Trinovantedinium applanatum*, sample WP10, *Serripes* Zone, E.F.: T33/4; **B**: *Trinovantedinium ferugnomatum*, sample WP8, *Serripes* Zone, E.F.: X47/2; **C–D**: *Trinovantedinium ferugnomatum*, sample WP18, *Serripes* Zone, E.F.: X38; **E–F**: *Trinovantedinium glorianum*, sample WP21, *Serripes* Zone, E.F.: T50/3; **G–H**: *Trinovantedinium variabile*, sample WP9, *Serripes* Zone, E.F.: X56/3; **I, J**: *Lejeunecysta* sp., sample WP21, *Serripes* Zone, E.F.: L33/1 (I), sample WP5 (slide 2), *Serripes* Zone, E.F.: T31/1–2 (J); **K**: *Selenopemphix brevispinosa*, sample WP9, *Serripes* Zone, E.F.: Z54/3; **L**: *Selenopemphix quanta*, sample WP8, *Serripes* Zone, E.F.: T44; **M, N**: *Lejeunecysta marieae*, sample WP98, *Tapes* Zone, E.F.: U51/4 (M), sample WP22, *Serripes* Zone, E.F.: H56/2 (N); **O**: *Quinquecuspis concreta*, sample WP97, *Tapes* Zone, E.F.: M52/4; **P**: *Brigantedinium cariacoense*, sample WP21, *Serripes* Zone, E.F.: K38/3; **Q, R**: *Lejeunecysta catomus*, sample WP97, *Tapes* Zone, E.F.: M39 (Q), sample WP59, *Mactra* Zone, E.F.: X39/3 (R); **S**: *Selenopemphix nephroides* (undulate morphotype), sample WP18, *Serripes* Zone, E.F.: Z47/3; **T**: *Selenopemphix nephroides* (normal morphotype), sample WP18, *Serripes* Zone, E.F.: L52/0. Both morphotypes are grouped as *Selenopemphix nephroides*.

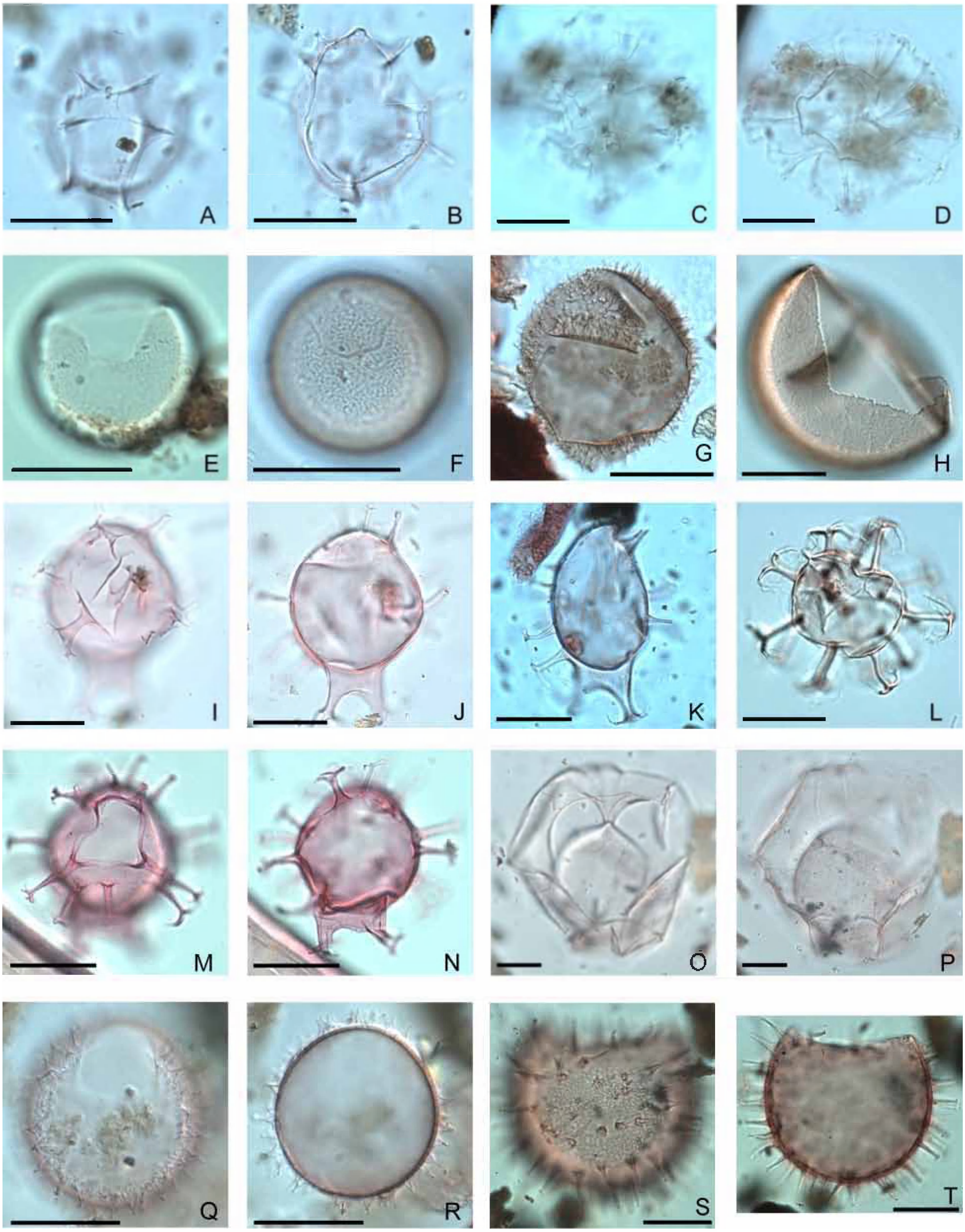


Plate 3.2: Photomicrographs of selected autotrophic dinoflagellate species. Scale bars indicates 20 µm. E.F.= England Finder coordinate. **A–B**: *Impagidinium aculeatum*, sample WP48, *Mactra* Zone, E.F.: X52; **C–D**: *Nematosphaeropsis labyrinthus*, sample WP44, *Mactra* Zone, E.F.: E37/2.; **E, F**: *Batiacasphaera micropapilata*, sample WP14 (slide 1), *Mactra* Zone, E.F.: X37/2 (E), sample WP26, *Serripes* Zone, E.F.: V58/3 (F); **G**: *Batiacasphaera hirsuta*, sample WP9, *Serripes* Zone, E.F.: K61; **H**: *Bitectatodinium*? *serratum*, sample WP21, *Serripes* Zone, E.F.: T48/1; **I–J**: *Achomosphaera* sp., sample WP28, *Serripes* Zone, E.F.: M45; **K**: *Spiniferites mirabilis*, sample WP8, *Serripes* Zone, U42/3; **L**: *Reticulatosphaera actinocoronata*, sample WP13, *Mactra* Zone, E.F.: E55/1; **M–N**: *Spiniferites bulloideus*, sample WP 101, Hörgi Formation, E.F.: M61; **O–P**: *Amiculosphaera umbraculum*, sample WP5, *Serripes* Zone, E.F.: R47/4; **Q–R**: *Operculodinium tegillatum*, sample WP18, *Serripes* Zone, E.F.: Z47/4; **S–T**: *Operculodinium centrocarpum* s.s., sample WP4, E.F.: E55/1.

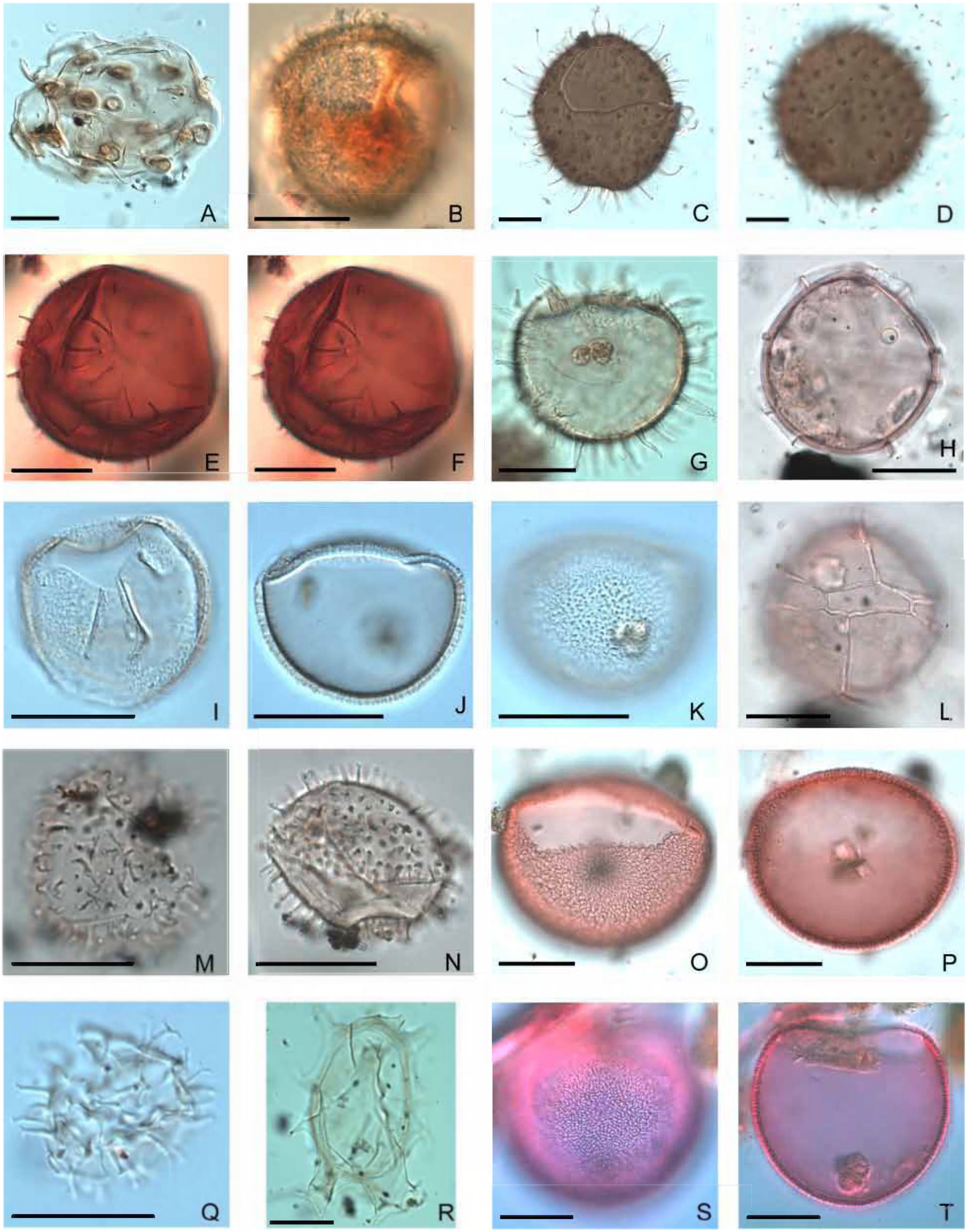


Plate 3.3: Photomicrographs of temperature sensitive dinoflagellate species. Scale bars indicate 20 µm. E.F.= England Finder coordinate.
A: *Tuberculodinium vancampoae*, sample WP87, *Tapes* Zone, E.F.: J59/2; **B**: *Tectatodinium pellitum*, sample WP97, *Tapes* Zone, E.F.: P48/1, **C–D**: *Barssidinium pliocenicum*, sample WP21, *Serripes* Zone, E.F.: S44/3–4; **E–F**: *Echinidinium euaxum*, sample WP18, *Serripes* Zone, E.F.: R50/3; **G**: *Lingulodinium machaerophorum*, sample WP13, *Mactra* Zone, E.F.: B37; **H, L**: *Impagidinium patulum*, sample WP11, *Mactra* Zone, S35/4; **I**: *Habibacysta tectata*, sample WP87, *Tapes* Zone, E.F.: B58; **J–K**: *Habibacysta tectata*, sample WP87, *Tapes* Zone, E.F.: M39/3–4; **M–N**: *Islandinium minutum*, sample WP77, Svarthamar Member, E.F.: Z50/1; **O–P**: *Bitectatodinium tepikiense*, sample WP26, *Serripes* Zone, E.F.: O61/3; **Q**: cyst of *Pentapharsodinium dalei*, sample WP21, *Serripes* Zone, E.F.: K34/1; **R**: *Spiniferites elongatus*, sample WP84, Torfhóll Member, E.F.: D49; **S–T**: *Filisphaera filifera* subsp. *filifera*, sample WP18, *Serripes* Zone, E.F.: Y51/2.

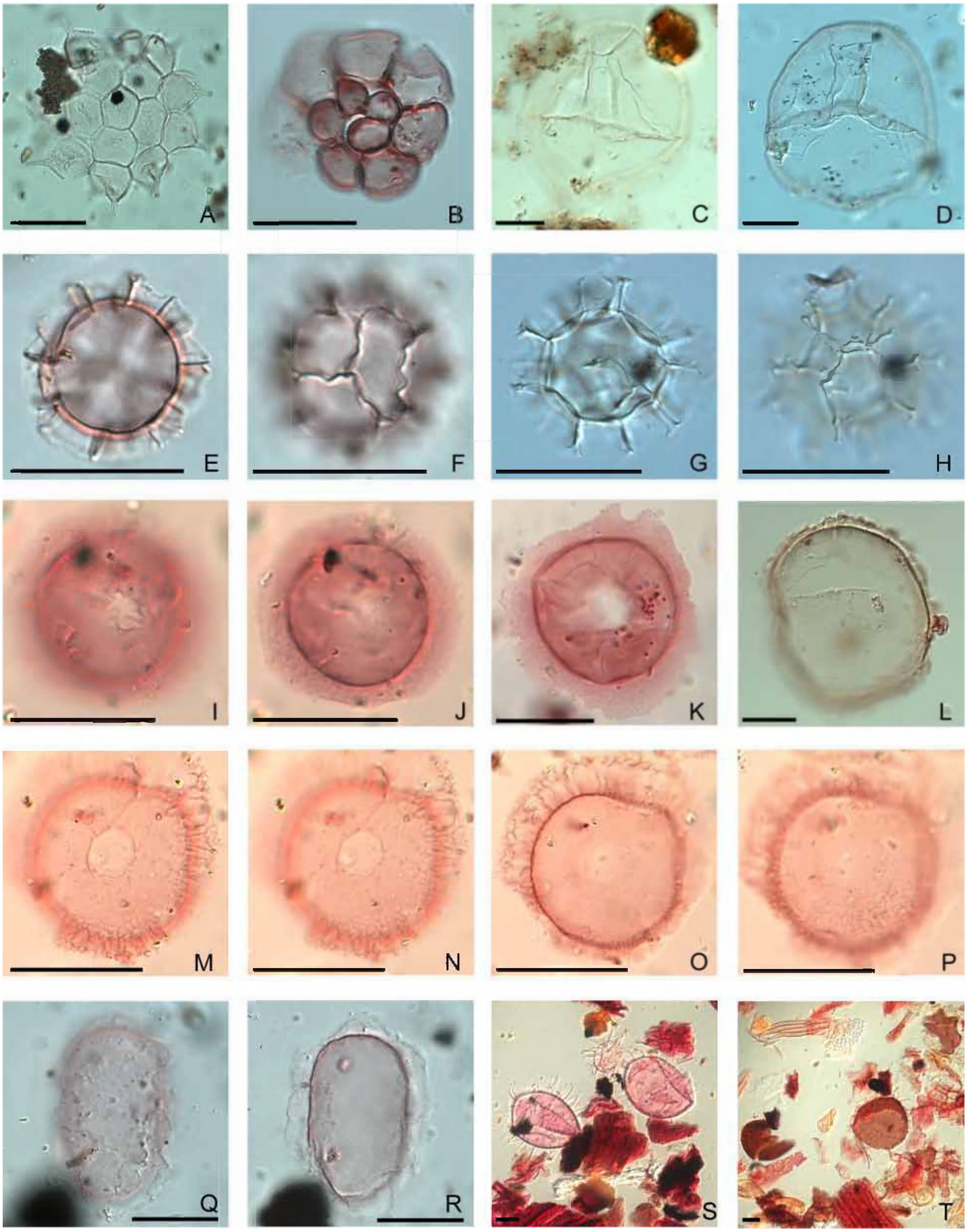


Plate 3.4: Photomicrographs of fresh water algae, acritarchs and linings of foraminifers and calcareous dinoflagellates. Scale bar indicates 20 µm. E.F.= England Finder coordinate. **A**: *Pediastrum* sp., sample WP4, *Serripes* Zone, E.F.: Q53; **B**: Foraminifera lining, planispiral, sample WP18, *Serripes* Zone, E.F.: N54/2; **C, D**: *Cyclopsiella*? *trematophora*, sample WP18, *Serripes* Zone, E.F.: M59/3 (C), sample WP4, *Serripes* Zone, E.F.: 33/2 (D); **E–F**: *Cymatiosphaera invaginata*, sample WP26, *Serripes* Zone, E.F.: O47; **G–H**: Algae cyst sp. 1 Head (1996), sample WP9, *Serripes* Zone, E.F.: K61/4; **I–K**: *Halodinium scopaeum*, sample WP26, *Serripes* Zone, E.F.: U43; **L**: *Paralecaniella indentata*, sample WP18, *Serripes* Zone, E.F.: N56/3; **M–P**: Acritarch sp.1, sample WP20, *Serripes* Zone, E.F.: Y55/4; **Q–R**: *Scripsciella trifida*, sample WP70, Svarthamar Member, E.F.: V48/1; **S**: assemblage dominated by autotrophic species such as *Operculodinium centrocarpum* s.s., sample WP59, E.F. K35; **T**: assemblage dominated by heterotrophic species such as *Barssidinium pliocenicum*, sample WP9, E.F.: X46/3.

The average pollen concentration (72.290 pollen/g) and spores concentration (22.910 spores/g) are noticeable higher. Heterotrophic species clearly dominate the assemblage as can be seen in the average H/A-ratio of 0.82. The average W/C-ratio amounts to 0.77 and indicates a rather warm SST.

4.3.2 Dinocyst zone 2 (DZ2)

Zone DZ2 (75-356.5 m) is also of Early Pliocene age and spans the sediments from the middle part of unit 4 in the upper part of the *Tapes* Zone to unit 12 in the upper part of the *Mactra* Zone. The base of the zone is defined by the sudden decrease of heterotrophic species. Heterotrophic species such as *Barssidinium pliocenicum* (average 1.4%), *Trinovantedinium* sp. (average 1.3%), *Echinidinium euaxum* (average 0.4%; Plate 3.3E, F) and *Lejeunecysta* sp. (average 0.1%) are much less represented during DZ2 and are replaced by the autotrophic species *Operculodinium centrocarpum* s.s. (average 10.3%, Plate 3.2S, T), *Habibacysta tectata* (average 5.1%), *Impagidinium* sp. (average 1.3%) and *Spiniferites* spp. (average 0.9%). *Filisphaera filifera* subsp. *filifera* is notably absent (average 0.1%). The warm water species *Tuberculodinium vancampoae* (3.8%, Plate 3.2A) is recorded in unit 4 at the base of DZ2.

The average H/A-ratio (0.08) and the W/C-ratio (0.34) are much lower than in DZ1. The average dinocyst concentration (109.4 dinocysts/g) is only slightly lower than in DZ1 and DZ3. Parallel with the regression of the heterotrophic species, the average richness decreases to 10.4 species/sample. The same decline is also visible in the Shannon-Wiener diversity index (H’) and the Evenness (E_H). The average concentration of pollen and spores amount respectively to 13.632 pollen/g and 717 spores/g. In units 11 and 12, just under the transition from DZ2 to DZ3, we see the appearance of the cosmopolitan species *Operculodinium centrocarpum* sensu Wall & Dale (1966).

4.3.3 Dinocyst zone 3 (DZ3)

The Early Pliocene DZ 3 (356.5-445 m) begins at the base of the *Serripes* Zone at 4.5 Ma and is defined by the re-entrance of heterotrophic species in the assemblage. The upper boundary, placed in the top of unit 22, is characterised by the transition to a barren assemblage. Heterotrophic species such as *Barssidinium pliocenicum* (average 10.8%), *Echinidinium euaxum* (average 8.3%), *Brigantedinium* spp. (average of 4.6%), *Trinovantedinium glorianum* (average 2.5%) and *Lejeunecysta marieae* (average 1.02%) re-appear in DZ3 and dominate the assemblage. *Selenopemphix islandensis* appears at the base of DZ3 and is in the Tjörnes section restricted to this zone with an average of 2.8%. *Trinovantedinium variabile* (average 0.2%; Plate 3.1G, H) arrives in the section in unit 13 and maintains its limited presence in DZ3. *Filisphaera filifera* subsp. *filifera* re-appears and *Operculodinium tegillatum* (Plate 3.2Q, R) appears already in unit 11 in the top of DZ2; both are now prominently present (average 4.5% and 2%). Notable is the dominant occurrence (up to 16%) of *Amiculosphaera umbraculum* (Plate 3.2O, P) in the lower part of the zone (units 15 and 15/16).

DZ3 has the highest average richness (18.8 species/sample) of the entire section but still a quite low average dinocyst concentration of 118.6 dinocysts/g. The heterotrophic species are again dominant with an average H/A-ratio of 0.62. The average W/C-ratio in DZ3 is also high (0.65). The terrestrial input during DZ3 is very low with an average pollen concentration of 171 pollen/g and an average spores concentration of 365 spores/g.

The acritarchs *Cyclopsiella*? *trematophora* (average 14%), *Halodinium scopaeum* (average 12.6%), *Cymatiosphaera invaginata* (average 3.2%; Plate 3.4E, F), and *Paralecaniella indentata* (average 0.3%) occur for the first time and are relatively abundant. An acritarch provisionally labelled Acritarch type 1 (average 1.2%; Plate 3.4M–P) appears for the first time in unit 17/18 of the *Serripes* Zone. Linings of Foraminifera (average of 30.3%, Plate 3.4B) are very abundant.

4.3.4 Barren interzone (DZ4)

The estuarine sediments from unit 22/23 to unit 24 (445-480 m) still Early Pliocene with a final date of c. 4.0 Ma. They did not yield organic-walled phytoplankton and only a few pollen and spores. The intertidal sediments of unit 25 together with the underlying lignite J on top of the *Serripes* Zone were not sampled, but can probably be included in this zone.

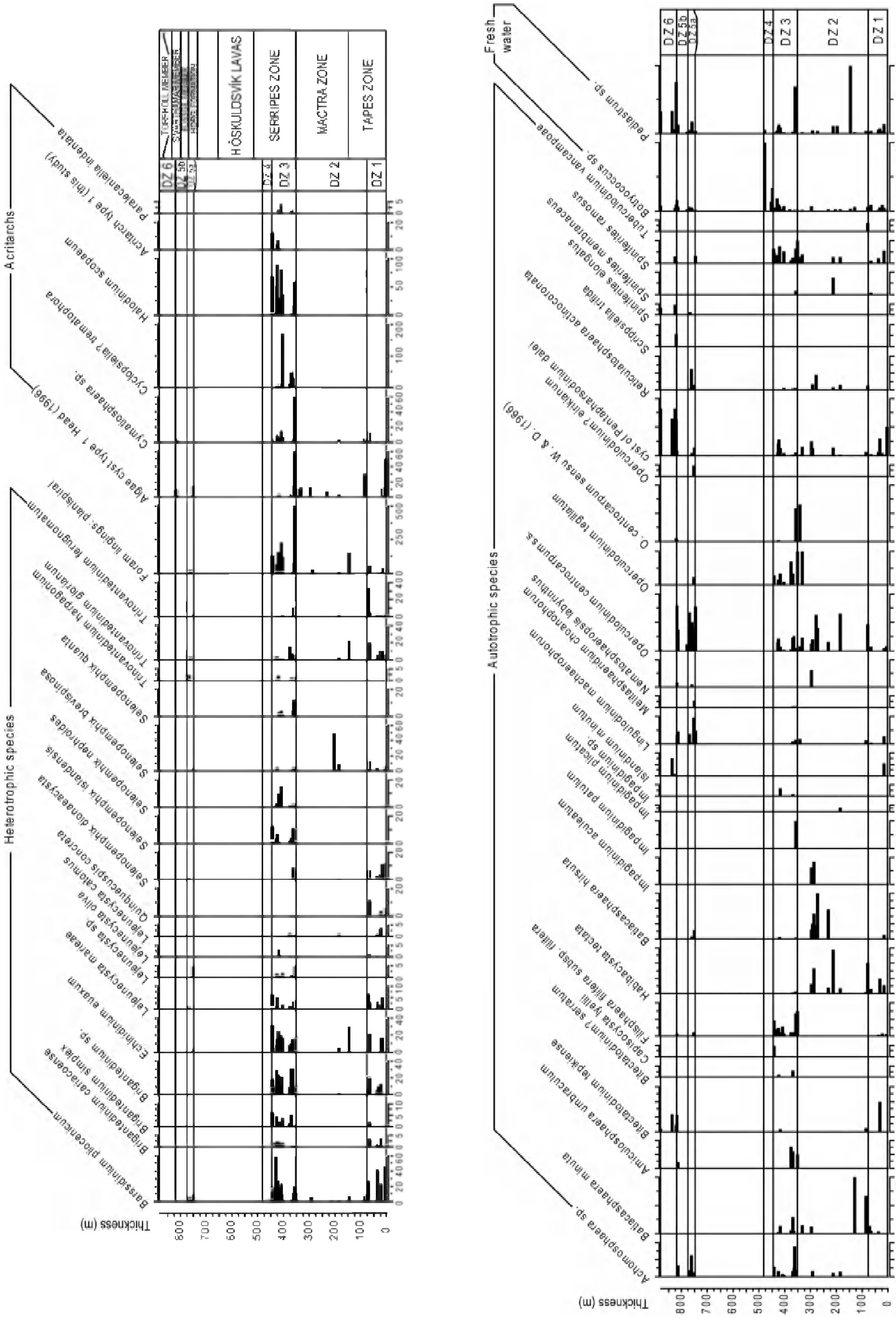


Figure 3.3: Relative abundances of selected autotrophic and heterotrophic dinocyst species and acritarchs. The Dinocysts Zones (DZ) are positioned against the stratigraphical scheme. Following Eiríksson (1981b), the top of the Kaldakvísl lava's was taken as zero-value for the thickness scale.

4.3.5 Dinocyst zone 5 (DZ5)

The lower boundary of DZ5 is defined by the low numbers of heterotrophic species and the onset of the nearly continuous presence of *Lingulodinium machaerophorum* and *Operculodinium centrocarpum* s.s. The diversity of the other dinocysts and differences in richness permit to divide DZ5 in two subzones.

4.3.5.1 Dinocyst subzone 5a (DZ5a)

This subzone is of Early Pleistocene age and dated around 2.2 Ma. It corresponds to the sediments of the Hörgi Formation (744-773 m) and has a low average richness of 8.3 species/sample and an average dinocyst concentration of 15.4 dinocysts/g. *Operculodinium centrocarpum* s.s. dominates the assemblage (average 33.3%), together with *Lingulodinium machaerophorum* (average 5.9%), *Batiacasphaera hirsuta* (average 1.9%, Plate 3.2G) and *Achomosphaera* sp. (average 5.7%; Plate 3.2I, J). The presence of *Batiacasphaera hirsuta* so late in the Gelasian (2.581–1.778 Ma) has to be treated with caution (Head, personal communication 2012). Reworking of the species is plausible as in the same sediments reworked specimens of *Reticulatosphaera actinocoronata* and *Operculodinium tegillatum* have been recorded (Verhoeven *et al.*, 2011). Heterotrophic species such as *Barssidinium pliocenicum* (average 3.2%), *Trinovantedinium glorianum* (average 0.4%), *Lejeunecysta marieae* (average 0.14%) and *Selenopemphix brevispinosa* (average 0.4%) are recorded, albeit in lower numbers compared to the situation in DZ3 (average H/A-ratio 0.10). Remarkable is the excellent preservation of the heterotrophic cysts, indicating that they have not been reworked (Verhoeven *et al.*, 2011). The presence of *Lingulodinium machaerophorum* (Plate 3.3G) and *Barssidinium pliocenicum* explains the high average W/C-ratio of 0.77. The cold water species cyst of *Pentapharsodinium dalei* (average 2.6%, Plate 3.3Q) shows low abundances comparable to those in the preceding dinocyst zones. Terrestrial influx is very low with an average pollen concentration of 74 pollen/g and an average spores concentration of 39 spores/g.

4.3.5.2 Dinocyst subzone 5b (DZ5b)

This subzone, still Early Pleistocene, is dated around 2.1-1.8 Ma. It encompasses the sediments of the Fossgil Member and the lower part of the Svarthamar member (unit 8 and the beginning of unit 10; 773-818 m) (Figure 3.3, Table 3.1), and is characterised by a very low palynomorph content. As in DZ5a, the dominant species are *Operculodinium centrocarpum* s.s. (average 18.3%) and *Lingulodinium machaerophorum* (average 1.6%). The upper part of the subzone sees the first appearance of *Bitectatodinium tepikiense* with a value of 22.6% (Plate 3.3O, P). Heterotrophic species are now absent. The average richness (8.0 species/sample) and the average dinocyst concentration (2 dinocysts/g) are at their lowest value. The cold water species gain importance compared to the previous zone (average W/C-ratio 0.15). The average pollen and spores concentration is extremely low: 26 pollen/g and 10 spores/g.

4.3.6 Dinocyst zone 6 (DZ6)

Of Middle Pleistocene age, this biozone is dated between 1.8-1.4 Ma. It corresponds to the sediments of the middle part of unit 10 at 818 m in the Svarthamar Member to the top of the Torfhóll Member at 885 m (Figure 3.3, Table 3.1), and is characterised by the high numbers of cysts of *Pentapharsodinium dalei* (average 53%), *Bitectatodinium tepikiense* (average 8.2%) and *Operculodinium centrocarpum* sensu Wall & Dale (1966) (average 5.5%) and to a lesser extent *Spiniferites elongatus* (average 1.6%, Plate 3.3R) and *Islandinium minutum* (average 1.3%; Plate 3.3M, N). The species diversity is rather low with an average richness of 10.4 species/sample. Cysts of thermophilic species are scarce, only a few specimens of *Lingulodinium machaerophorum* and *Impagidinium patulum* (Plate 3.3H, L) occur. Cold water forms such as cyst of *Pentapharsodinium dalei*, *Bitectatodinium tepikiense*, *Spiniferites elongatus* and *Islandinium minutum* occur in high numbers and dominate the zone (W/C-ratio 0.01). DZ6 has the highest average dinocyst concentration (383 dinocysts/g) with a maximum of 924. The zone is dominated by autotrophic species (H/A-ratio 0.05). The concentrations of spores (11 spores/g) and pollen (39 pollen/g) are low and testify to fully marine conditions with low terrestrial input.

5. Discussion

5.1 Transition to the present-day dinocyst assemblage

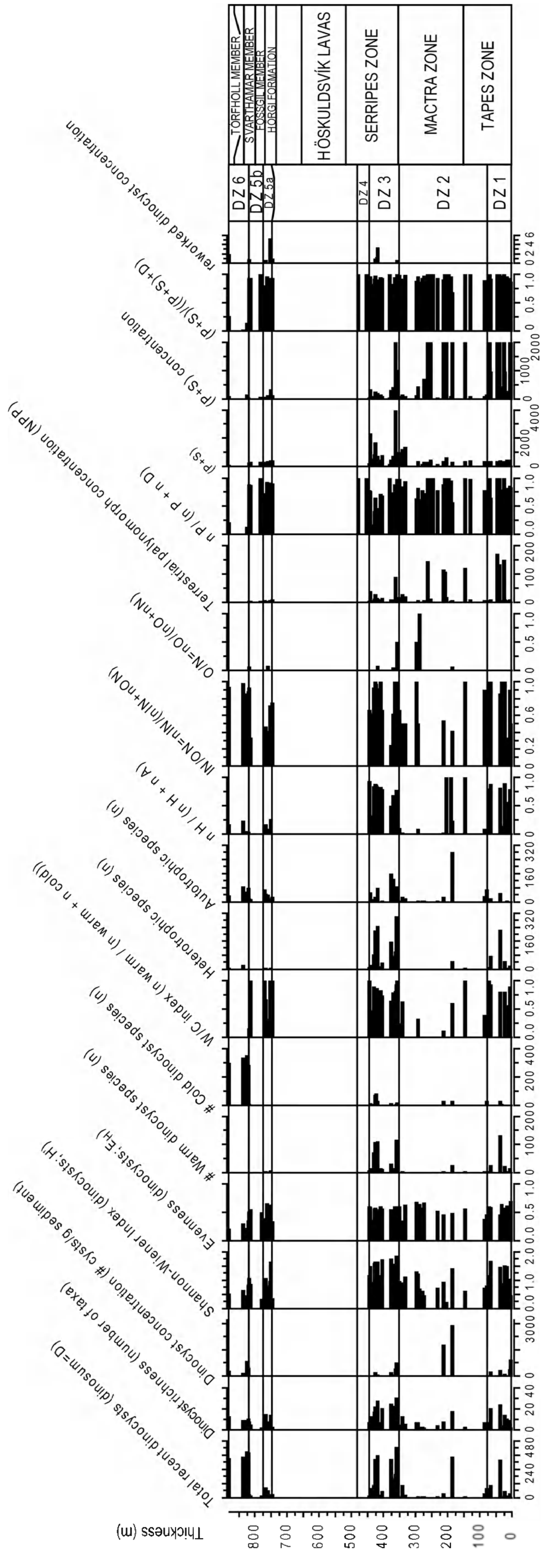
The assemblages recorded in the Tjörnes beds (DZ1-3) show much similarity with those of the Pliocene deposits from northern Belgium and England (De Schepper *et al.*, 2009; Louwye *et al.*, 2004; Head, 1998a,b). Stratigraphically, they correspond to the Kattendijk Formation and the lower part of the Coralline Crag (Verhoeven *et al.*, 2011; Figure 3.2). In the deposits of the southern North Sea, comparable large numbers of heterotrophic genera such as *Barssidinium*, *Lejeunecysta*, *Trinovantedinium* and *Selenopemphix* occur. Encrusting acritarch species such as *Cyclopsiella*? *trematophora* and *Halodinium scopaeum* are also a significant part of the spectrum. These acritarchs in combination with the important abundance of heterotrophic dinoflagellate species might be indicative for comparable shallow sedimentation environments during the Early Pliocene in northern Iceland and in the southern North Sea basin.

The sediments of DZ4 do not contain dinocysts. Findings of the sedimentological and malacological studies support the inference that these sediments were deposited in an estuarine environment (Buchardt and Símonarson, 2003). An energetic environment of this kind will prevent small particles such as resting cysts of dinoflagellates to settle. The pollen study of the sediments gave a comparable very poor signal (Verhoeven *et al.*, in press).

DZ5 is a transitional assemblage with few heterotrophic species in subzone DZ5a. Subzone DZ5b already resembles much the late Pleistocene assemblage DZ6, from which it differs by the minor importance of cold water species such as cyst of *Pentapharsodinium dalei* and *Bitectatodinium tepikiense.* DZ6 is dominated by cyst of *Pentapharsodinium dalei* accompanied by *Operculodinium centrocarpum* sensu Wall & Dale (1966), *Bitectatodinium tepikiense*, *Islandinium minutum* and *Spiniferites elongatus*. Marret et al. (2004) examined recent surface sediments from the western and northern margin of Iceland. DZ6 resembles strongly the authors' group II or IIIa assemblage dominated by cysts of *Pentapharsodinium dalei* accompanied by *Operculodinium centrocarpum* sensu Wall & Dale (1966). The recent assemblages straddle the Polar Front (Figure 3.1), which runs parallel to the Atlantic shelf to the west and northeast of Iceland (Marret *et al.*, 2004). The Polar Front represents a sharp oceanographic boundary between north of it the cold East Greenland Current (EGC) and its branch the East Icelandic Current (EIC) and south of it the warm Irminger Current (IC). Because of the mixing of both waters, the area is very productive today and very high dinoflagellate concentrations (up to 256.920 cysts/g) have been counted by Marret *et al.* (2004). Our study recorded much lower concentrations but those of DZ6 are particularly higher compared to the older ones. The assemblage identified in DZ6 and the relatively high dinocyst concentrations invite to place the Polar Front close to the Tjörnes area during the onset of the deposition of DZ6, halfway unit 10 of the Svarthamar Member. According to the age model of Verhoeven *et al.* (2011) this situation suggests a pre-Olduvai age of around 1.7 Ma for the positioning of the recent Polar Front. Marret *et al.* (2004) explained the dominance of cyst of *Pentapharsodinium dalei* on the northern Icelandic shelf to the preference of the species for a seasonally varying SST caused by the presence of the Polar Front and the enriching influence of cold and warm currents.

5.2 Dinocyst concentration variability

As already stated, the dinocyst concentrations recorded in the Tjörnes section are clearly lower than in the present-day surface sediments studied by Marret *et al.* (2004). The difference can be explained by the location on the shelf and the continental slope of the samples analyzed by the latter authors. Compared to the coastal and intertidal depositional environments of the Tjörnes area, these settings are much less energetic and permit excellent preservation as small particles will settle easily. Moreover, these environments are usually nutrient-enriched and associated with phytoplankton blooms (Le Fèvre, 1986; Walsh, 1988). During deposition of the first three dinozones of the Tjörnes beds, the concentrations are low and vary around 110 cysts/g. Although the richness shows a clear decline during DZ2 (Figure 3.4), this is not reflected in changes of the concentration.



The change from a heterotrophic dominated assemblage (Plate 3.4T) to one dominated by autotrophic species (Plate 3.4S) suggests changing water characteristics which influenced only the heterotrophic species and not the dinolagellates in general. The average concentrations during deposition of the Pleistocene DZ5a and DZ5b are very low, 15.4 and 2 cysts/g respectively, but increase again during DZ6 to 383 cysts/g (Figure 3.4). The first decline at the base of the Breidavík Group (DZ5) can be explained by the general cooling caused by the onset of the glaciations, while the maximum values of DZ6 most probably indicate the arrival of the Polar Front in the area.

5.3 Changes in nutrient supply: two major oceanographic events

The biozonations of the Tjörnes beds based on molluscs and ostracods run stratigraphically almost parallel; this is not entirely the case for the dinocyst zonation (Figure 3.5). A clear decline of heterotrophic species occurs in the base of DZ2. Such a regression is not observed in the numbers of the freshwater green algae *Botryococcus* and *Pediastrium* (Figure 3.3) or in the pollen and spore concentration (Figure 3.4). The presence of green algae, brought in from the island in the depositional area can be used as a measure of the terrestrial input. Green algae are somewhat better represented in DZ1 and DZ3, but these differences do not militate for distinct changes in the nutrient supply from the land. Also, the P/D-ratio do not show a changing input of pollen and spores. Moreover as the heterotrophic species are well preserved (Plate 1R), selective degradation of such dinocysts in the DZ2 sediments can be ruled out; the pollen are also well preserved (Verhoeven *et al.*, in press).

According to us the transition from a heterotrophic dominated DZ1 to an autotrophic dominated DZ2 marks an important oceanographic event, apparently not registered by the molluscs or ostracods. The ostracod analysis however has to be considered with caution, as the resolution in this part of the section was certainly too low to register this event.

Figure 3.4: Overview of palaeoecological indices with indication of the dinozones. The highest values of the pollen and spores concentration are levelled off to 2000 specimens/g for visualization of the lower values variations. H= heterotrophic species (n); A: autotrophic species (n); IN= inner neritic species (n); ON= outer neritic species (n); P= pollen (n); S= spores (n), D= dinocysts (n).

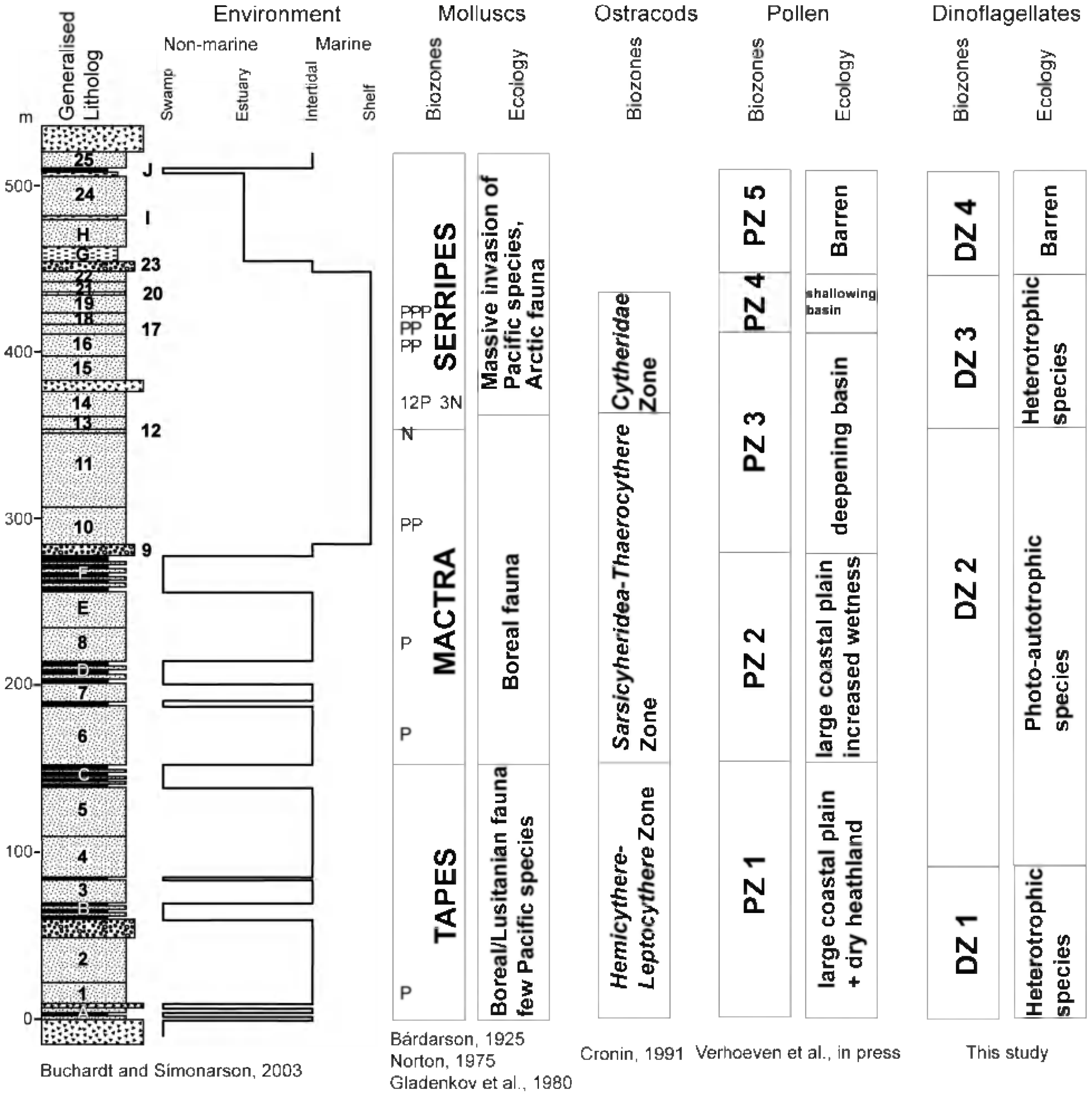


Figure 3.5: The biozonations of the Tjörnes beds versus the lithology and the environmental interpretation of the depositional basin. The levels of introduction of Pacific mollusc species ("P" in general and "N" for naticids) are given (Gladenkov *et al.*, 1980; McCoy, 2007).

Cronin (1991) had but two samples of the *Tapes* Zone with ostracods and only the unit 5 sample yielded a significant number of specimens. Most of the molluscan studies (a.o. Bárdarson, 1925; Norton, 1975) considered the units of the *Tapes* Zone in their entirety and no differentiations within the units were made. This could explain why the transition recorded within unit 4 by the dinocysts, may have been overlooked. The *Tapes*/*Mactra* transition, in which an assemblage dominated by *Tapes* is replaced by an assemblage dominated by *Mactra* occurs in the top of the lignite C. This lignite separates the marine units 5 and 6. Unit 5 appears to be a transitional zone, for Bárdarson (1925: p. 26) found already frequent *Mactra* shells in the *Cyprina* horizon of the unit at the Reká locality. He excluded however unit 5 from the *Mactra* Zone as this first occurrence of *Mactra* coincides with the highest occurrence of *Tapes*, the key species of the *Tapes* Zone. In our view, the onset of DZ2 halfway unit 4 and the first occurrence of *Mactra* in unit 5 may be penecontemporaneous, signalling the same palaeoceanographic change. Most probably the decrease in nutrients during

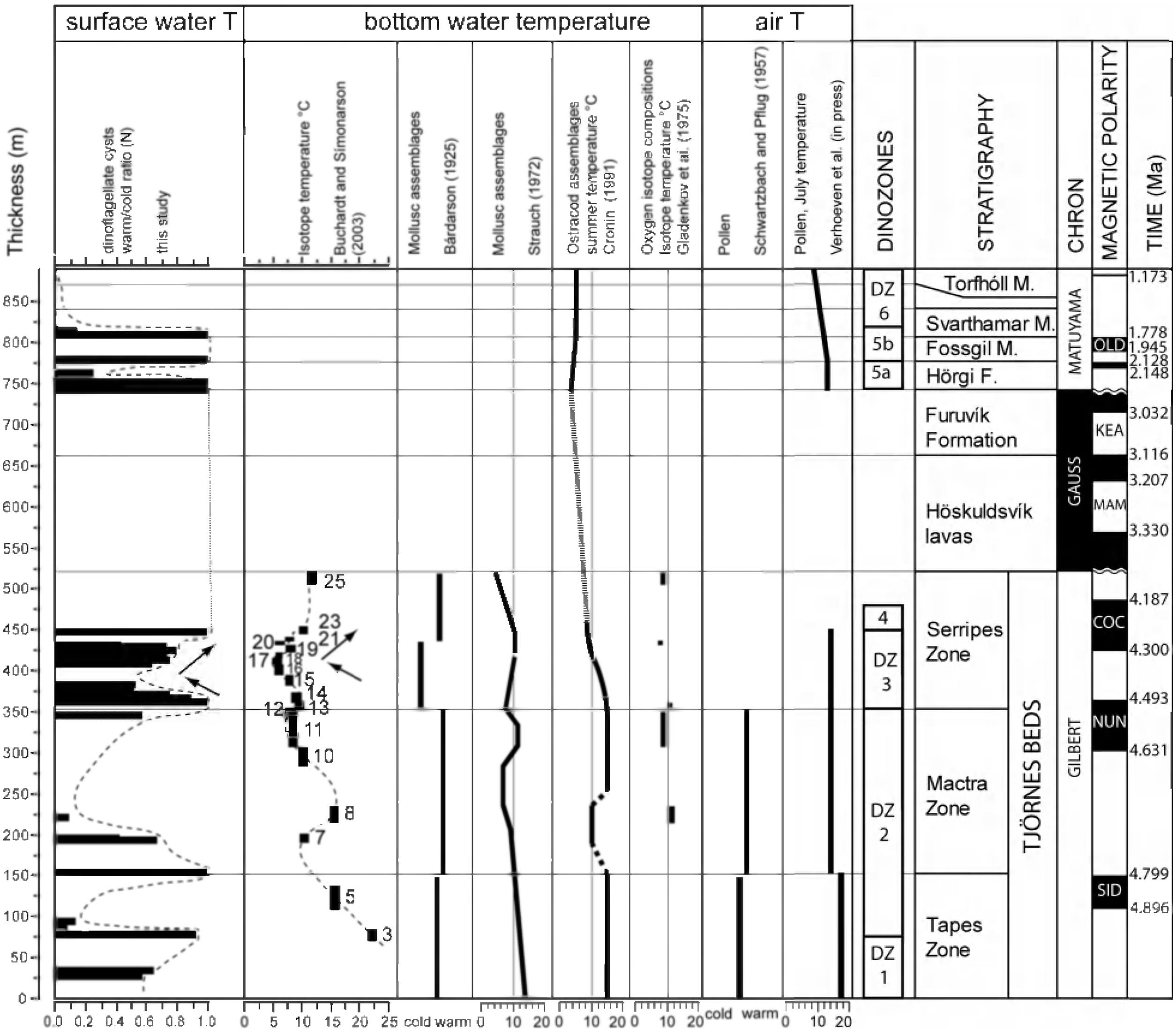


Figure 3.6: The W/C-ratio of the dinocysts compared with the available temperature proxies of the Tjörnes section. Modified after Buchardt and Símonarson (2003) and according to the age model of Verhoeven *et al.* (2011).

deposition of DZ2 caused the change in the molluscan assemblage at the transition from the *Tapes* Zone to the *Mactra* Zone.

The invasion of cold water Pacific organisms around 4.5 Ma in the study area (Verhoeven *et al.*, 2011) is a major environmental event, marked by the arrival of: (1) molluscs in unit 14 of the base of the *Serripes* Zone, (2) ostracods in unit 14 at the base of the *Cytheridae* zone and (3) dinocysts in unit 12/13 at the base of DZ3 (Figure 3.5). The dinocyst record shows at the base of DZ3 (unit 12/13) an abrupt return of heterotrophic species. The renewed dominance of heterotrophic species may indicate an increased influx of nutrients, and a repression of the autotrophic dinoflagellates. The arrival of the Pacific species *Selenopemphix islandensis* in unit 13 marks this event (Verhoeven and Louwye, 2012). From its first arrival on, *Selenopemphix islandensis* is always an important part of the assemblage (average 4.1%) and remains restricted to DZ3. *Trinovantedinium variabile* as well as the normal and undulate morphotype of *Selenopemphix nephroides* (Plate 3.1S, T) enter the assemblage at the beginning of DZ3; these species were probably not present in the Tjörnes area before DZ3. A Pacific origin can be suggested for *Trinovantedinum variabile* as it is a cold tolerant species common in the Pliocene of the northern Pacific (Head, personal communication 2012). However, de Verteuil and Norris (1992) recorded both *Trinovantedinium variabile* and *Selenopemphix nephroides* also in the Miocene of the coastal plain in Maryland and Virginia on the east coast of North America.

Northward transport of these taxa by the Gulf Stream can therefore not be excluded. The shoaling of the Central American Seaway between 4.2 and 4.7 Ma forced not only Pacific water northwards through the Bering Strait but intensified at a same time the Gulf Stream (Steph *et al.*, 2006).

The heterotrophic species *Barssidinium pliocenicum*, *Echinidinium euaxum* and *Brigantedinium* spp. flourish during deposition of DZ3, but were already present earlier in the Tjörnes area. The arrival of Pacific waters at the *Mactra*/*Serripes* boundary in the base of DZ3 was preceded in unit 11 by the brief appearance of *Operculodinium centrocarpum* sensu Wall & Dale (1966). This reflects changing water conditions preceding the transport of trans-Arctic water, since the species is an opportunist immediately occupying available ecological niches (Dale, 1996).

Unit 14 in the base of the *Serripes* Zone and DZ3 is the first horizon of the zone in which Pacific invasive molluscs abound. Gladenkov *et al.* (1980) recognised at this level the entrance of 15 of the 22 invasive molluscs of the *Serripes* Zone (Figure 3.5). The base of the *Serripes* Zone does not exactly corresponds with the major invasion of Pacific molluscs, but rather to the upper limit of the presence of *Mactra* in the preceding zone. In the period between the extinction of *Mactra* in unit 12 and the entrance of Pacific molluscs in unit 14, the heterotrophic dinoflagellates dominate already in unit 12/13. Hence, the major invasion of Pacific molluscs post-dates the initial transport of Pacific water and nutrients through the Bering Strait. Although migration of Pacific molluscs was already possible during the time of unit 12/13, it was delayed for some reason.

As already mentioned, the invasive Pacific mollusc species have Arctic affinities (Bárdarson, 1925; Gladenkov *et al.*, 1980; Símonarson and Eiríksson, 2008). As the isotope record of Buchardt and Símonarson (2003) does not show an abrupt temperature decline at the time (Figure 3.6), the migration of cold water species cannot be explained by a cooling of the climate, more likely it may relate to a northward transport of water through the Bering Strait induced by the shoaling of the Central American Seaway (Verhoeven *et al.*, 2011 and references therein). Only species adapted to cold water could cross the cold Arctic environment which acted as a filter (Einarsson *et al.*, 1967). The opening of the Bering Strait facilitating the Trans Arctic Invasion could be dated between 5.5 and 5.4 Ma (Gladenkov *et al.*, 2002). The age model of Verhoeven *et al.* (2011) dates the Trans Arctic Invasion at around 4.5 Ma; it may coincide with the shoaling of the Central American Seaway, dated between 4.7 and 4.2 Ma (Haug *et al.*, 2001; Steph *et al.*, 2006).

Coeval with the dominance of heterotrophic species, acritarch species such as *Cyclopsiella*? *trematophora*, *Cymatiosphaera invaginata* and *Halodinium scopeaum* appear in DZ3. According to Matsuoka and Head (1992), the genus *Cyclopsiella* has an epilithic or encrusting form of life, and prefers shallow habitats as the organisms live in clusters on the sea floor with the pylome oriented upwards. High numbers and acmes of *Cyclopsiella* and *Paralecaniella* were recorded in the photic zone of energetic, shallow marine and nearshore deposits of the Upper Miocene Diest Formation in northern Belgium (Louwye and Laga, 2008). The restricted occurrence of these acritarchs in relatively high numbers only in DZ3 is thus remarkable since the palaeobathymetry of the Tjörnes beds is quite low throughout the sequence and theoretically suitable for these acritarchs. The sudden appearance of acritarchs in DZ3 is most probably caused by a combination of environmental factors such as a low water depth, high energy and the degree of trophication.

5.4 Temperature reconstruction based on dinoflagellate cysts

Clearly warmer dinocyst assemblages than today are recorded in the Early Pliocene zones DZ1 to DZ3, although some warm water heterotrophic species such as *Barssidinium pliocenicum* and *Echinidinium euaxum* are still present in the early Pleistocene DZ5a. The warmest species are present in the top of DZ1 and in the base of DZ2. *Tectatodinium pellitum* is regarded as an extremely warm species, nowadays confined to subtropical to tropical environments (range 14–30°C) (Marret and Zonneveld, 2003), and is used as an indicator of warm intervals as far back as the Danian (Head and Nøhr-Hansen, 1999). *Tuberculodinium vancampoae* also has a recent warm distribution (range 12.7–29.5°C) and is restricted to latitudes between 45°N and 45°S. Both species are confined to DZ1 and the base of DZ2 and this period can be regarded as the warmest of the studied interval at Tjörnes. No temperature maximum is however expressed in the W/C-ratio, as only a few specimens of both species were found (Figure 3.6). Nevertheless the presence of these tropical species demonstrates sufficiently that the warmest period must have been during the early deposition of the Tjörnes beds. Buchardt and Símonarson (2003) found the highest temperatures (15 to 20°C) in the same interval of their oxygen isotope curve. The pollen study by Verhoeven *et al.* (in press) is in agreement with these findings and suggests summer air temperatures of at least 8°C warmer than today during deposition of the *Tapes* Zone and 5°C during deposition of the rest of the Tjörnes beds and the early Pleistocene interglacials.

As already said, during the deposition of the Tjörnes beds and the lower part of the Pleistocene Breidavík Group, a mix of warm and cold water species occurs. Near the top of DZ5b and DZ6, the mixed dinocyst temperature signal changes into a distinct cold water signal indicated by cysts of *Pentapharsodinium dalei*, *Bitectatodinium tepikiense*, *Spiniferites elongatus* and *Islandinium minutum*. *Bitectatodinium tepikiense* has the broadest thermal tolerance, but does not occur in the Arctic. The species prefers cold winter and warm summer SST. *Islandinium minutum* has a bipolar distribution, above 30°N and below 30°S. It is characteristic of subpolar and polar areas but has a broad temperature range. The species prefers large seasonal and inter-seasonal fluctuations of parameters such as temperature, salinity and insolation (Marret and Zonneveld, 2003). Cysts of *Pentapharsodinium dalei* have a very broad temperature range, but occur mainly in the temperate/subpolar regions of the northern hemisphere (Marret and Zonneveld, 2003). *Spiniferites elongatus* can be characterised as a cold to temperate species, accepting a broad range of temperatures (Marret and Zonneveld, 2003). The Pleistocene cooling registered from DZ5a to DZ6 shows a gradual trend (Figure 3.3) with a continuous decrease of the warm water species *Lingulodinium machaerophorum*, a very rare species in areas with SST below 10°C, and an increase of the cold water species cyst of *Pentapharsodinium dalei* and *Spiniferites elongatus*. Simultaneously the cold tolerant species *Bitectatodinium tepikiense* shows a decrease from c. 20% to c. 6% near the top of DZ6. The recent assemblage around Iceland (Marret *et al.*, 2004) contains only c. 1% of this species. *Bitectatodinium tepikiense* most probably migrated southward during Middle Pleistocene times as it became too cold. Based on the modern distribution of *Bitectatodinium tepikiense* (Marret and Zonneveld, 2003), the mean summer temperature decreased from c. 15°C to c. 10/12°C, and the mean winter temperatures ranged between 0°C and 12°C. Sea Surface Temperatures comparable to the present-day ones can thus be suggested for DZ6. Today on the same latitude, the Irminger Current transports relative warm water of c. 6°C in winter to c. 11°C in summer from the western side of Iceland to the northern part (Marret *et al.*, 2004).

The extinct cold tolerant species *Habibacysta tectata* and *Filisphaera filifera* show a remarkable signal in the Tjörnes beds. Head (1994) suggest a broad thermal tolerance for *Habibacysta tectata*, as it is found in the upper Miocene of the Gulf of Mexico as well as in Pleistocene sediments post-dating the northern hemisphere cooling. The species tolerates a broad range of water temperatures, from cool temperate to subtropical or tropical, but high numbers are mostly associated with cooler conditions. De Schepper *et al.* (2011) stated that Pliocene abundances in excess of 30% correspond to $SST_{Mg/Ca}$ values between 10 and 15°C, confirming the cool-water affinities of the species. *Habibacysta tectata* has a Highest Occurrence (HO) in unit 14/15 of the *Serripes* Zone, but does show such high values in the Tjörnes beds except in two samples with very few dinocyst counts. *Filisphaera filifera* has a maximum Pliocene $SST_{Mg/Ca}$ range of 10.7-25.2°C (De Schepper *et al.*, 2011) and is also considered to be cold tolerant (Head, 1996). *Filisphaera filifera* is present in the base of the *Tapes* Zone and then disappears from the record. The species re-appears in unit 11 (upper part of DZ2) and has a HO in unit 21/22. *Habibacysta tectata* and *Filisphaera filifera* thus occur together in the Tjörnes beds only in the base of the *Tapes Zone* and in the base of the *Serripes* Zone (Figure 3.3). In the sediments between, only *Habibacysta tectata* is present, while in the upper part of the *Serripes* Zone only *Filisphaera filifera* occurs. This may be caused by a temperature rise during the second half of the *Tapes* and the *Mactra* Zone and a temperature decline in the upper part of the *Serripes* Zone.

According to this hypothesis, both species have a rather restricted latitudinal range with *Filisphaera filifera* more adapted to cold water. During the temperature rise, this species occurred north of Iceland, while during the temperature decline *Habibacysta tectata* occurred below Iceland. The isotope record by Buchardt and Símonarson (2003) however does not point to such an explicit warming (Figure 3.6); their temperature curve shows rather a gradual decline with a restricted warming during the *Mactra* Zone. As no major warming is registred, the interruption of *Filisphaera filifera* during the second half of the *Tapes* Zone and the *Mactra* Zone has possible to do with another parameter than temperature. The interruption also pre-dates the impoverishment of the dinoflagellates during DZ2 and is hence not related to the relapse of nutrient supply.

The W/C-ratio (Figure 3.6) is used to follow temperature variations, but in our study it may also be influenced by changing water currents influencing the supply of nutrients. For example, the appearance of the cold water tolerant species *Filisphaera filifera* and *Trinovantedinium variabile* in the base of DZ3 co-occurs with high abundances of the warm water species *Barssidinium pliocenicum*, *Echinidinium euaxum* and *Brigantedinium* spp. This can be explained by the introduction of cold and nutrient rich Pacific water, favourable for heterotrophic warm water species but introducing cold tolerant species at the same time. The distribution of warm and cold water species would thus be driven not only by temperature changes of the local water masses, but also by incoming nutrients. The W/C-ratios during the *Tapes* and *Mactra* Zones (DZ1 and DZ2) are rather irregular and seem also to be influenced not only by temperature as registered by the O^{16}/O^{18} curve (Figure 3.6). The impoverishment of the assemblage during DZ2 resulted in the decrease of mainly warm heterotrophic species. This resulting decline in the W/C-ratio is not recorded by other marine or terrestrial temperature proxies (Figure 3.6) and is apparently not an indication of cooling. During deposition of DZ3 (*Serripes* Zone), a certain decrease in the W/C-ratio preceding that of the oxygen isotope temperature curve occurs as recorded by the decline of *Echinidinium euaxum* and *Barssidinium pliocenicum* (Figures 3.3, 3.6). Although cold water species enter in DZ3, their influence is restricted and the W/C-ratio seems to follow the water temperature. However, the W/C-ratio changes precede slightly that of those based on the isotopes recovered from the molluscs.

6. Conclusions

Dinocysts from 68 samples of the Tjörnes beds and 20 samples of four Lower and Middle Pleistocene interglacial sediments of the Breidavík Group were studied, and allowed to divide the sedimentary sequence into six dinocyst zones DZ1–DZ6, but DZ4 is barren.

The assemblages defining dinozones DZ1 to DZ3, corresponding to the Tjörnes beds, are quite similar to those of the shallow marine Early Pliocene of the southern North Sea Basin. The uppermost part of DZ4 contains no dinocysts, as the depositional environment shallowed into an energetic estuarine environment. DZ5 can be regarded as an ecologically transitional zone during the early Pleistocene, in which the heterotrophic species disappeared and extant cold water species are introduced. The uppermost DZ6 starts in the middle of unit 10 of the Svarthamar Member around 1.7 Ma and resembles much the present-day assemblage of northern Iceland. The assemblage of DZ6, dominated by cysts of *Pentapharsodinium dalei* and accompanied by *Operculodinium centrocarpum* sensu Wall & Dale (1966) can be linked to a position near the Polar Front and suggests that the present-day palaeoceanography came into being at that time.

The dinocyst assemblages signal two important ecological events in the Tjörnes beds, separated by impoverished dinocyst assemblages. DZ1 is dominated by heterotrophic dinocysts and is abruptly followed by DZ2, dominated by autotrophic species. This event can be explained by a sudden decrease of nutrient supply, probably caused by a shift of the Polar Front. Although not entirely coincident, this event can be correlated to the change from a *Tapes* dominated molluscan assemblage to a *Mactra* dominated molluscan assemblage. The drastic decline in nutrients can be the cause of the disappearance of *Tapes* and the transition to the *Mactra* assemblage. The second event coincides with the *Mactra*/*Serripes* transition (base DZ3) and can be explained by the introduction of Pacific water in the northern Atlantic via the Bering Strait. This event has been linked to the shoaling of the Central American Seaway around 4.5 Ma which pushed water northwards through the Bering Strait. The cold nutrient rich water caused the heterotrophic species to thrive and introduced cold water tolerant species in the Tjörnes area. *Selenopemphix islandensis*, *Trinovantedinium variabile* and *Filisphaera filifera* subsp. *filifera* are now clearly present in the assemblage. A major migration wave of Pacific molluscs, observed in unit 14, apparently post-dates the opening of the northern passage through the Bering Strait by some ten thousand years.

The changes in the curves of temperature sensitive dinoflagellates show a clear relation with the presence of nutrients and changed ocean currents and W/C-ratios have thus to be evaluated with caution.

7. Author contribution

The study is fully designed and carried out by KV and includes the sampling, palynological preparation in the laboratory, counts, interpretation of the data, writing of the paper and preparation of the figures and photo plates. The scientific content has been thoroughly discussed with SL, who also made language corrections of the chapter.

8. Acknowledgements

Friðgeir Grímsson provided test samples from the Tjörnes beds. Margrét Hallsdóttir and the staff of the Islandic Institute of National History in Reykjavík helped with the preparation of the fieldtrip and gave access to the library of the institute. Jón Eiríksson assisted in the sampling on the cliffs and the interpretation of the local stratigraphy. Achilles Gautier helped to tailor the manuscript in its final form.

Selenopemphix islandensis sp. nov.: a new organic-walled dinoflagellate cyst from the Lower Pliocene Tjörnes beds, northern Iceland

4

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Abstract

A new protoperidiniacean dinoflagellate cyst species recorded from the Lower Pliocene *Serripes* Zone of the Tjörnes beds in northern Iceland is formally described and its palaeoecological preferences are evaluated. *Selenopemphix islandensis* sp. nov. is a thin-walled cyst with strong polar compression and a reniform outline in apical view. The wide cingular margins are dorsally ornamented with processes of varying morphology and ventrally with large fan-shaped processes. A distinct size difference between the dorsal and ventral cingular processes is a major diagnostic characteristic of this species. A differential diagnosis for *Selenopemphix islandensis* sp. nov. is presented. Within the Tjörnes section, *Selenopemphix islandensis* sp. nov. is restricted to the uppermost *Serripes* Zone of the Tjörnes beds. The base of this zone corresponds to the invasion of cold-water molluscs of Pacific affinity through the Bering Strait into the northern Atlantic. The sudden appearance of *Selenopemphix islandensis* sp. nov. from this level can possibly be related to this northern migration through the Bering Strait, and suggest a Pacific origin. The new species is not recorded in the underlying Lower Pliocene *Tapes* Zone and *Mactra* Zone of the Tjörnes beds, and is also absent in the superjacent Pleistocene Breidavík Group. *Selenopemphix islandensis* sp. nov. has a first and last appearance in the Tjörnes region at c. 4.5 Ma and 4.2 Ma, respectively. Palaeoecological studies on molluscs, ostracods, plants and oxygen isotopes indicate an average summer temperature of 5–10°C for the *Serripes* Zone, which is comparable to the present-day situation in northern Iceland.

Keywords: Pliocene, dinoflagellate cysts, taxonomy, *Selenopemphix*, Tjörnes, Iceland, Bering Strait

1. Introduction

The outcrops in the Tjörnes Peninsula in northern Iceland (Figure 4.1) consist of an alternation of marine deposits (mudstones, sandstones and conglomerates) and continental deposits (lignites and diamictites) interspersed with lavas (Símonarson and Eiríksson, 2008). The well-exposed and easily accessible deposits of the Tjörnes Peninsula are the subject of many multidisciplinary studies, since its unique location in the northern Atlantic Ocean is well-suited for regional palaeoceanographic studies (Einarsson *et al.*, 1967; Marincovich 2000; Vermeij, 2005; Símonarson and Leifsdóttir, 2008). Palaeoenvironmental, palaeoclimatic and biogeological studies have focused on, for example, molluscs (Bárdarson, 1925; Strauch, 1972; Norton, 1975, 1977; Gladenkov *et al.*, 1980; Símonarson and Eiríksson, 2008), ostracods (Cronin, 1991), macro plant remains (Windisch, 1886; Akhmetiev *et al.*, 1975, 1978; Denk *et al.*, 2005), dinoflagellate cysts (Verhoeven *et al.*, 2011) and pollen (Schwartzbach and Pflug, 1957; Willard, 1994; Verhoeven and Louwye, 2010).

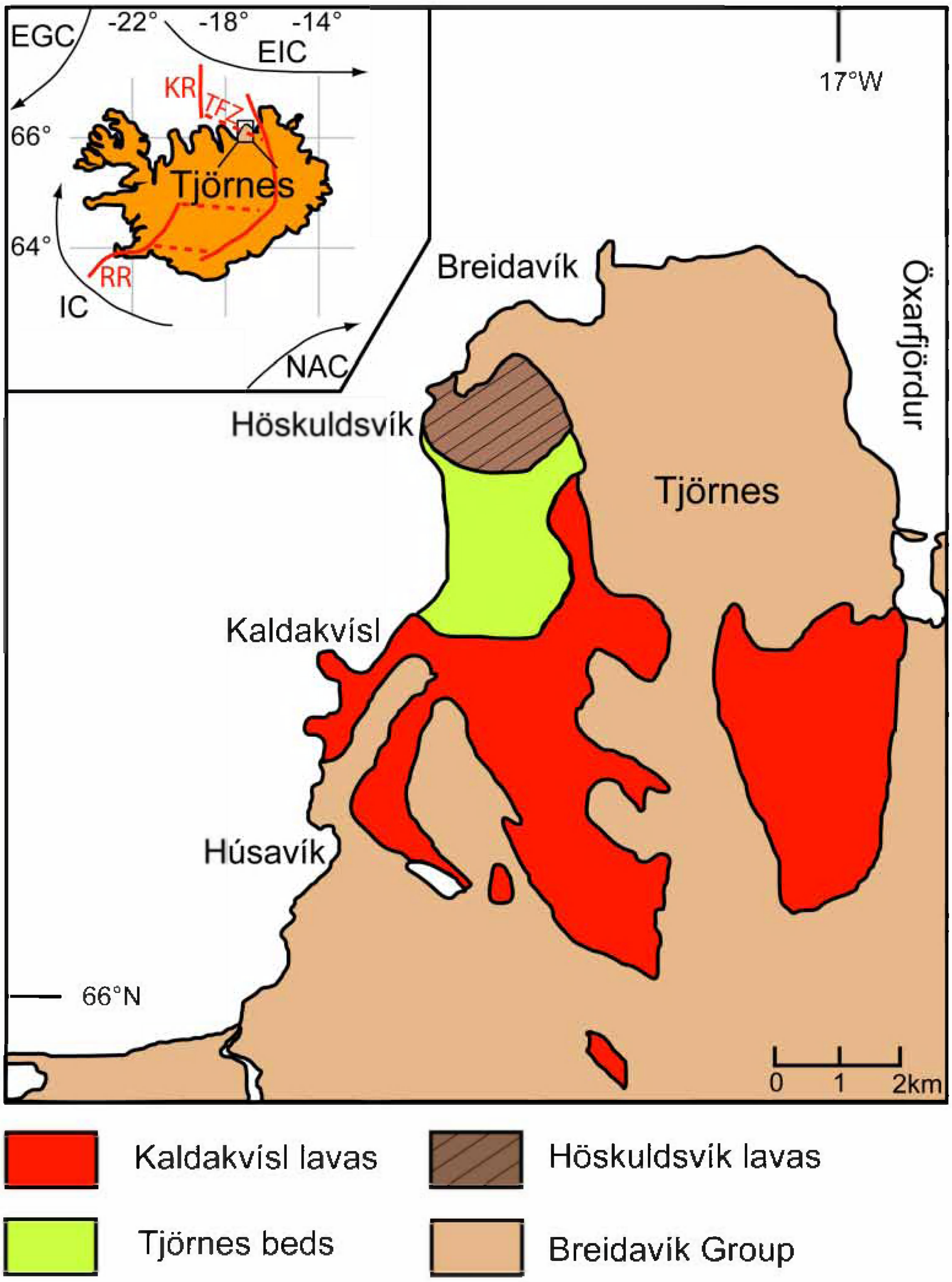

Figure 4.1: Geological map of the Tjörnes Peninsula, northern Iceland. Modified after Eiríksson (1981b). The surface circulation patterns around Iceland are adapted from Marret and Zonneveld (2003). EGC: East Greenland Current; EIC: East Icelandic Current; IC: Iceland Current; NAC: Norwegian Atlantic Current. The location of the Mid Atlantic Rift zone through Iceland is indicated, modified after Thordarson and Höskuldsson (2006). TFZ: Tjörnes Fracture Zone; RR: Reykjanes Ridge; KR: Kolbeinsey Ridge.

A high-resolution palynological analysis of the Neogene and Quaternary deposits from the Tjörnes Peninsula revealed the presence of well-preserved marine palynomorph assemblages, albeit in variable and rather low concentrations. The goal of the palynological analysis was twofold. Firstly, a refinement of the chronology of the depositional history in northern Iceland during Neogene and Early Quaternary times was envisaged (Verhoeven *et al.*, 2011) and, secondly, an attempt was made to reconstruct the regional marine palaeoenvironment. During the palynological analysis, a previously undescribed dinoflagellate cyst species with a restricted stratigraphic range in the upper part of the Tjörnes beds was observed. The new species *Selenopemphix islandensis* is herein formally described and its stratigraphic range and ecological preferences are discussed.

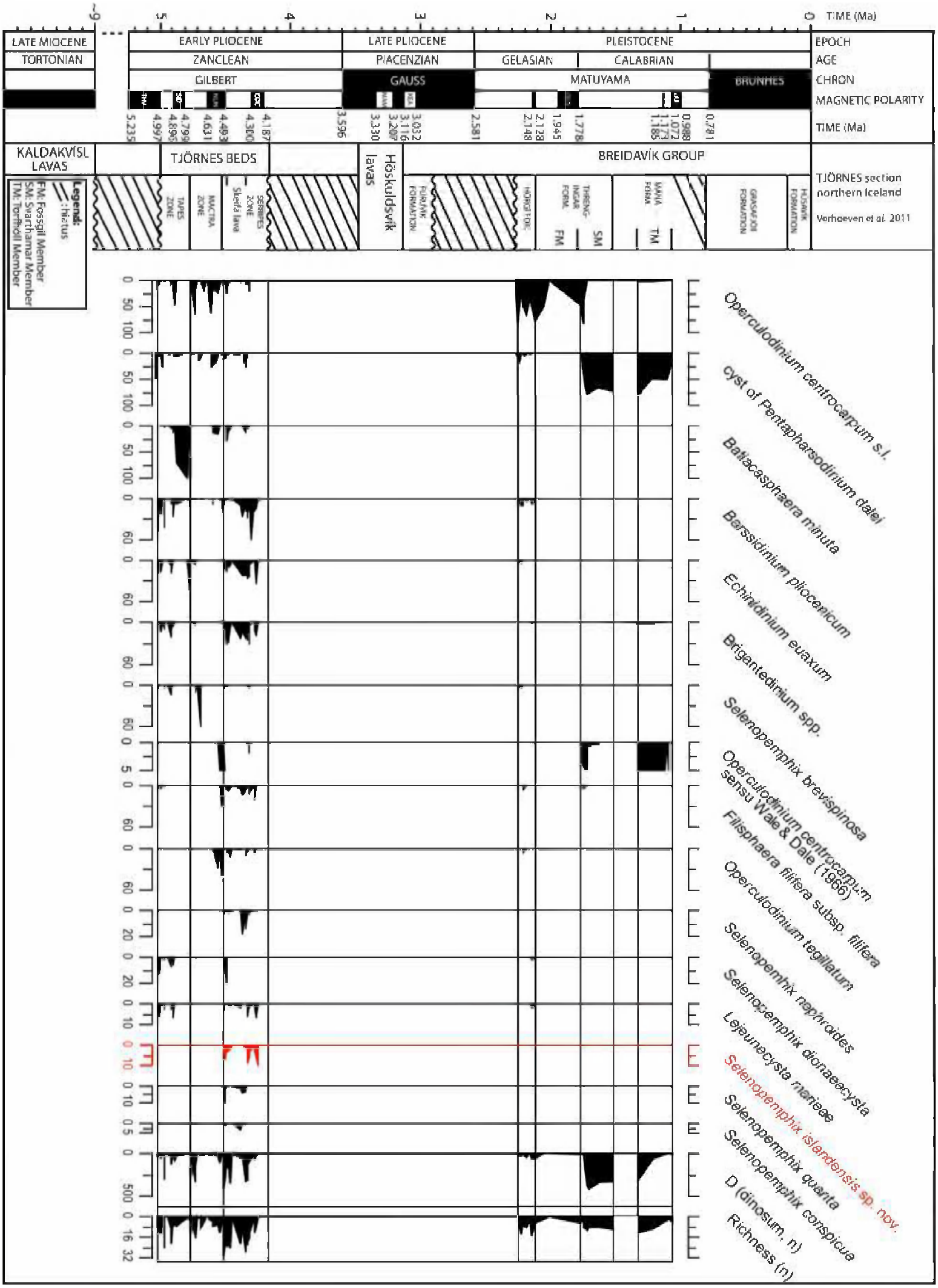

Figure 4.2: Stratigraphic distribution of selected dinoflagellate cysts from Tjörnes, including *Selenopemphix islandensis* sp. nov. (in red).

2. Geological background

The sediments of the Tjörnes Peninsula were deposited in a subsiding basin in the vicinity of the Tjörnes Fracture Zone (Figure 4.1), which is related to the dynamics of the Mid Atlantic Rift Zone (MAR; Sæmundsson, 1974). Subsidene occured near transform faults that connect the Kolbeinsey Ridge, the oceanic part of the MAR northwest of Iceland, with the MAR on Iceland itself, known as the north volcanic zone (Figure 7.1). Sediments could accumulate in subsiding basins near the transform faults during the period from the Early Pliocene to Late Pleistocene. According to Thoroddsen (1902) this basin is a graben/horst structure that became uplifted over 500 to 600 m during Late Pleistocene times (Einarsson *et al.*, 1967). The tectonic uplift resulted in the present-day easily accessible Neogene and Quaternary outcrops in the northern cliffs of the Tjörnes Peninsula.

Eiríksson (1981b) divided the Neogene and Quaternary sequence of the Tjörnes Peninsula into four lithostratigraphic units: the Kaldakvísl lavas, the Tjörnes beds, the Höskuldsvík lavas and the Breidavík Group (Figures 4.1, 4.2). A large hiatus is present between the Miocene Kaldakvísl lavas (Aronson and Sæmundsson, 1975) and the Lower Pliocene Tjörnes beds. The Tjörnes beds are traditionally divided into three mollusc zones: the *Tapes* Zone, the *Mactra* Zone and the *Serripes* Zone (Bárdarson, 1925; Norton, 1977; Símonarson and Eiríksson, 2008). Age diagnostic dinoflagellate cysts in combination with a renewed correlation of the palaeomagnetic polarity data resulted in a new age model for the Tjörnes section (Verhoeven *et al.*, 2011). The entire Tjörnes beds are of Early Pliocene age, and were deposited between c. 5.0 Ma and 4.1 Ma (Figure 4.2). The boundary between the *Mactra* Zone and the overlying *Serripes* Zone, which corresponds to a distinct turnover in the mollusc assemblage, was dated at c. 4.5 Ma (Verhoeven *et al.*, 2011). An Atlantic mollusc fauna, including a few warm-water species of Pacific ancestry, is present in the *Tapes* Zone and the *Mactra* Zone. The Pacific affinities of some of these molluscs result from a first migration through the Bering Strait during Miocene times (Símonarson and Eiríksson, 2008). A second, massive invasion of Pacific molluscs with cold-water affinities is observed at the boundary between the *Mactra* Zone and the *Serripes* Zone (Einarsson *et al.*, 1967). The second migration through the Bering Strait was, according to Marincovich and Gladenkov (1999) and Marincovich (2000), possibly induced by the shoaling of the Central American Seaway.

The reconstruction of the depositional environment of the Tjörnes beds is based on a sedimentological analysis and the palaeoecology of the mollusc assemblages (Símonarson and Eiríksson, 2008). The sediments of the *Tapes* Zone and the lower part of the *Mactra* Zone were, according to this reconstruction, deposited in a shallow marine area. The sedimentation was in pace with the subsidence and resulted in the deposition of tidal flat deposits, lignites and lacustrine sediments. Deposition of the upper part of the *Mactra* Zone and the lowermost part of the *Serripes* Zone took place in a slightly deeper marginal marine or sublitoral environment as the subsidence exceeded the sedimentation. Subsidence decreased again during deposition of the upper part of the *Serripes* Zone and resulted in deposition of estuarine and littoral sediments.

The overlying Höskuldsvík lavas and the lower part of the Breidavík Group (the Furuvík Formation) are of Late Pliocene age and a significant hiatus is present at the base and the top of both units (Figure 4.2). The upper part of the Breidavík Group consists of an alternation of glacial and interglacial deposits. A total of 14 glacial/interglacial cycles could be detected within the Pleistocene upper part of the Breidavík Group (Eiríksson *et al.*, 1990).

3. Materials and methods

A total of 88 samples for palynological analysis were collected from the cliffs of the Tjörnes Peninsula during a field campaign in 2007. The 68 samples from the Tjörnes beds and the 20 samples from the Breidavík Group consist of marine and terrestrial deposits (lignite layers).

About 50 g of marine mudstones and sandstones were washed and crushed into small fragments of c. 0.5 cm. The samples were oven-dried at 60°C and subsequently treated with cold 2M (6%) HCl and cold 40% HF for the removal of carbonates and silicates, respectively. A final chemical treatment involved repeated cycles with 2M HCl for the removal of fluorosilicates. One *Lycopodium clavatum* marker tablet (batch 483216; 18586 + 1708 spores/tablet) was added at the beginning

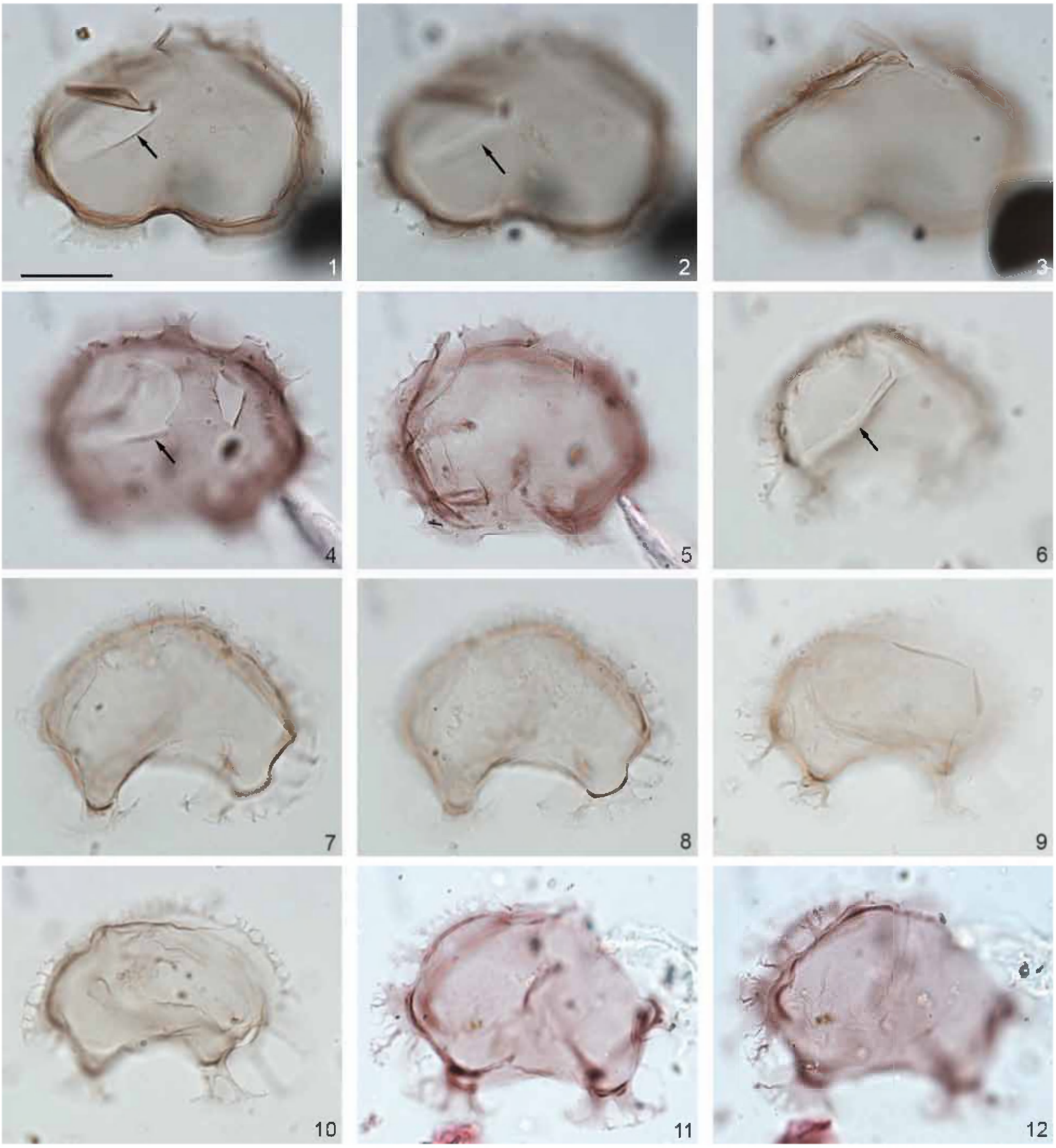

Plate 4.1: Photomicrographs of *Selenopemphix islandensis* sp. nov., all specimens from the *Serripes* zone of the Tjörnes beds. Scale bars indicate 20 µm and arrows show the archeopyle. EF: England Finder co-ordinates. Figures 1–3. Holotype, slide WP22, EF: K48/1, antapical view. Figures 4–5. Slide WP6, EF: X56/2, antapical view. Figures 6–8. Slide WP23, EF: X41/4, antapical view. Figures 9–10. Slide WP23, EF: R32/2, apical view. Figures 11–12. Slide WP20, EF: A64/3, apical view.

of the maceration process for the calculation of absolute abundances. Nylon sieves with a mesh diameter of 10 µm were used during every step in order to prevent loss of palynomorphs. The residue was coloured with safranine-red and mounted with glycerine gelatine on microscope slides. The microscope study was carried out with a Zeiss© Axio Imager A1 transmitted light microscope equipped with differential interference contrast. Photomicrographs were taken with an AxioCam MRc5 at 400x and 1000x magnification. The taxonomy of the dinoflagellate cysts follows DINOFLAJ 2 (Fensome *et al.*, 2008).

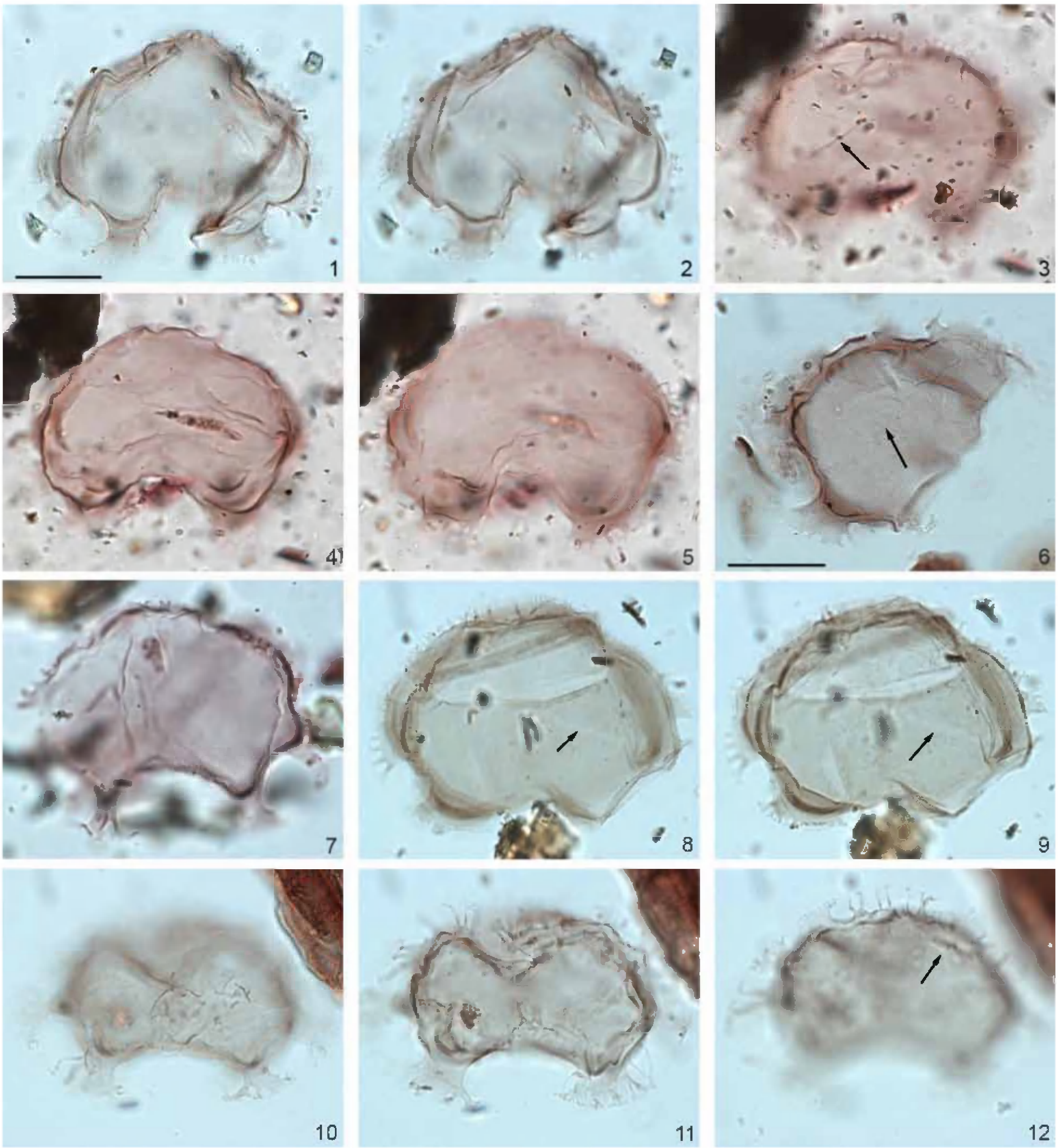

Plate 4.2: Photomicrographs of *Selenopemphix islandensis* sp. nov., all specimens from the *Serripes* zone of the Tjörnes beds. Scale bar of figure 1 indicates 20 µm for all figures except figure 6. Arrows show the archeopyle. EF: England Finder co-ordinates. Figures 1, 2. Slide WP5, EF: J 48/1, apical view. Figures 3–5. Slide WP8, EF: X48/1, antapical view. Figure 6. Slide WP18, EF: O60/4, antapical view. Figure 7. Slide WP4, EF: Y34/0, orientation uncertain. Figures 8, 9. Slide WP16, EF: Z54/4, apical view. Figures 10–12. Slide WP21, EF: Z47/4, antapical view.

4. Systematic palaeontology

Division DINOFLAGELLATA (Bïtschli, 1885);
Fensome *et al.* (1993)
Subdivision DINOKARYOTA Fensome *et al.* (1993)
Class DINOPHYCEAE Pascher (1914)
Subclass PERIDINIPHYCIDAE Fensome *et al.* (1993)
Order PERIDINALES Haeckel (1894)
Suborder PERIDINIINEAE (Autonym)
Family PROTOPERIDINIACEAE Balech (1988)
Subfamily PROTOPERIDINIOIDEAE Balech (1988)
Genus SELENOPEMPHIX (Benedek, 1972)
emended Bujak in Bujak *et al.* (1980)
Species *Selenopemphix islandensis* sp. nov. (Plates 4.1, 4.2)

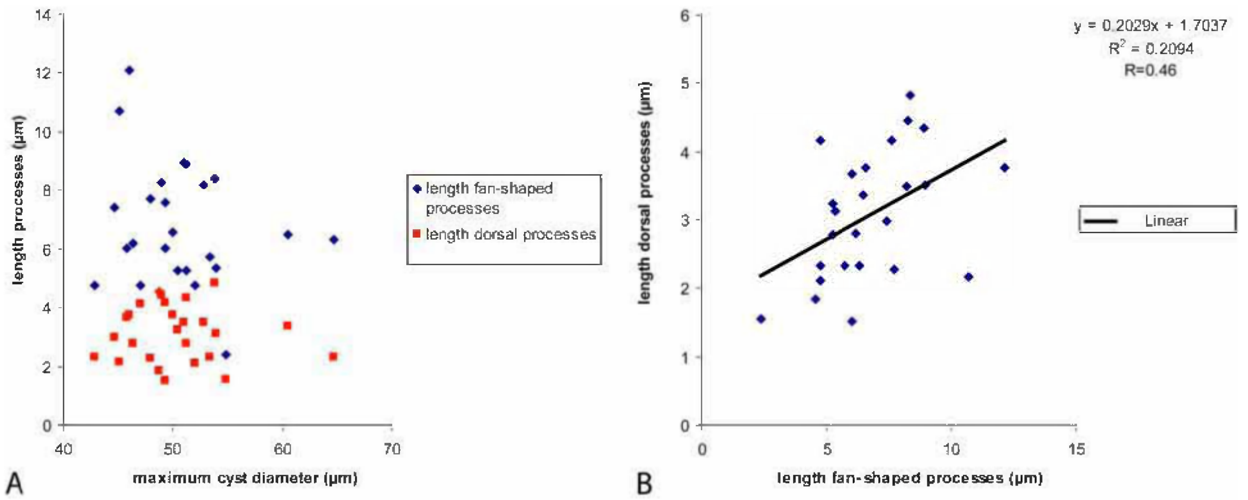

Figure 4.3: (A) Relation between the process length and the maximum cyst diameter of 25 specimens of *Selenopemphix islandensis* sp. nov. and (B) relation between the length of the first fan-shaped process and the length of the dorsal processes of 25 specimens of *Selenopemphix islandensis* sp. nov.

Holotype. Plate 4.1; figures 1–3, slide WP 22 (England Finder co-ordinates: K48-1), *Serripes* Zone, Tjörnes beds, northern Iceland.

Repository. Royal Belgian Institute of Natural Sciences (Brussels, Belgium), catalogue number IRSNB b5759

Derivation of name. '*Islandensis*' refers to 'derived from Iceland'. The new species is observed for the first time in the marine deposits of the *Serripes* Zone in the Tjörnes section.

Diagnosis. An autophragmal, thin-walled protoperidiniacean cyst with a blunt apical horn. The cyst is polar compressed and has a reniform ambitus in apical view. The cyst wall is psilate. The cingular margin is well developed and dorsally and ventro-laterally ornamented with simple or occasionally bifurcating processes which are distally serrate, acuminate or expanded. The ornamentation of the cingular margin is typically absent over a short distance at the ventro-lateral sides, where the cingular margin is also considerably reduced. Cingular margins at the ventral sides are well developed and ornamented with a large, fan-shaped process. The tabulation is only reflected by the broad cingulum and the anterior intercalary archeopyle with rounded angles. Operculum adnate, occasionally free.

Description. The cyst possesses a thin psilate wall with a thickness of less than 0.5 µm. The wall is autophragmal and usually has a pale-brown colour. However, hyaline specimens are often encountered when the preservation was not optimal. The cyst is polar compressed and has a reniform outline in apical/antapical view. A narrow, blunt apical horn is present on the epicyst (Plate 4.1, figures 2, 5 and 8; Plate 4.2, figure 6). Antapical horns are absent. The well-developed cingulum is broad and has a width of c. 10–15 µm, and accounts for almost 50% of the total cyst height. The cingulum appears planar and is clearly interrupted in the sulcal area. The wide cingular margins are for the greater part of the circumference ornamented with processes of varying size and shape. The greater part of the processes is to a varying degree joined proximally. The morphology of the processes is tapering to nearly cylindrical. The distal ends of the processes are slightly serrated, acuminate or expanded. Processes bifurcate occasionally. The ornamentation is typically absent over a short distance of 5–10 µm at the ventro-lateral sides and in the sulcal area. The cingular margin between the ventro-lateral sides and the sulcal area is more strongly developed and is ornamented with a wide and large, sometimes asymmetrical, fan-shaped process. The process is distally irregular indented. Two pairs of asymmetrical processes are occasionally observed on a few specimens. No correlation is observed between the size of the cysts and the size of the latter processes (Figure 4.3A), but a clear size difference between the small dorsal processes and the larger fan-shaped processes is always present although no exact ratio between the two sizes is found (Figure 4.3B). The archeopyle is formed by the release of a single anterior intercalary plate. The operculum is mostly adnate and only occasionally free.

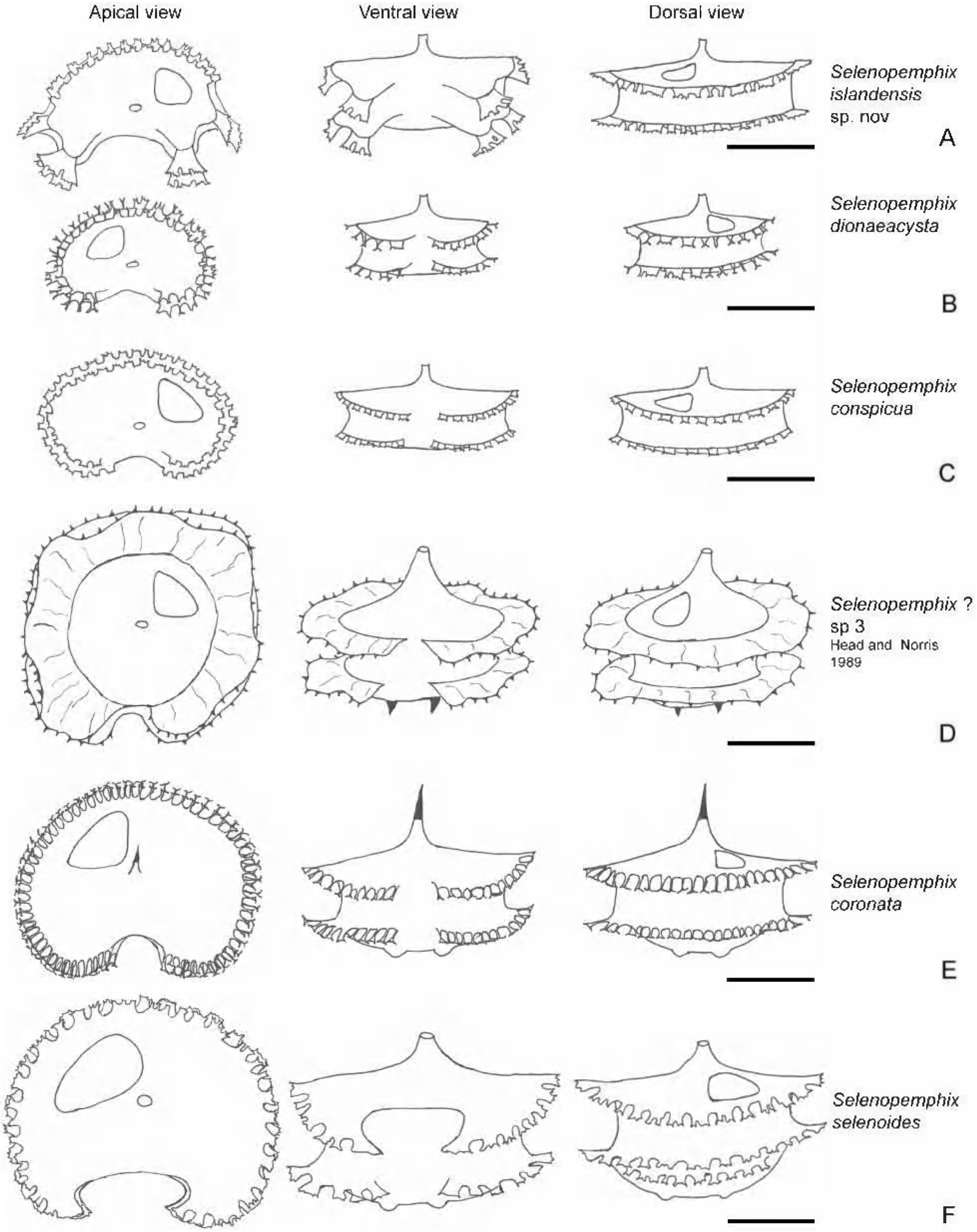

Figure 4.4: **Schematic representations based on light microscopy observations and literature study of (A)** *Selenopemphix islandensis* sp. nov., **Tjörnes. (B)** *Selenopemphix dionaeacysta* **with different processes on the left and right half indicating the large morphological variability of the processes, Tjörnes and de Verteuil and Norris (1992). (C)** *Selenopemphix conspicua*, **Tjörnes and de Verteuil and Norris (1992); (D)** *Selenopemphix*? sp. 3 **in Head and Norris (1989); Kallo –92.6m, De Coninck (1999); Head and Norris (1989); (E)** *Selenopemphix coronata*, **Kallo –115m, De Coninck (1995), and (F)** *Selenopemphix selenoides*, **Kallo –96/–106m, De Coninck (1999). All drawings are at the same scale. Scale bars indicate 20 µm.**

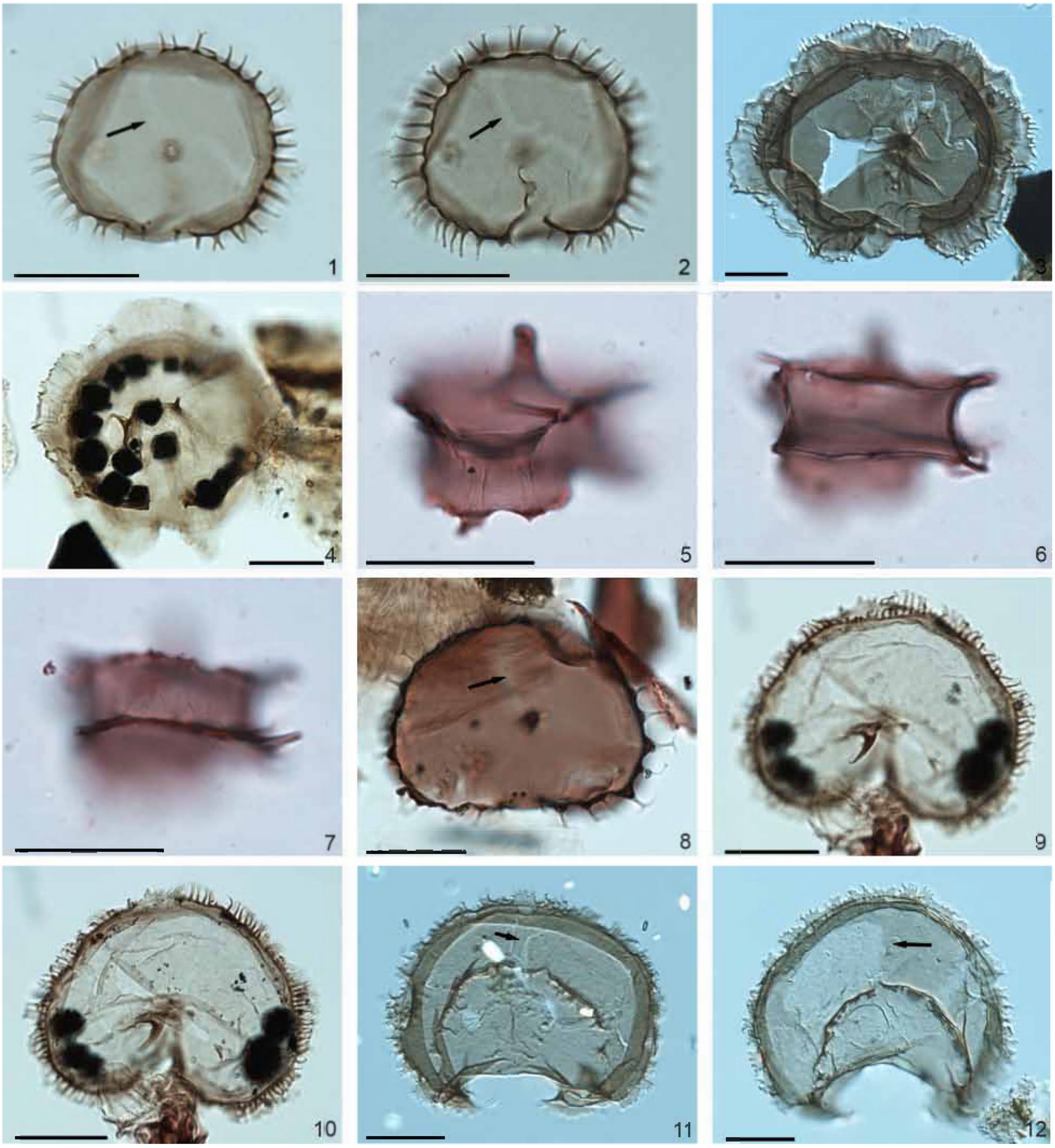

Plate 4.3: Photomicrographs of *Selenopemphix* species with a comparable morphology to *Selenopemphix islandensis* sp. nov. Scale bars indicate 20 µm and arrows show the archeopyle. EF: England Finder co-ordinates. Figures 1, 2. *Selenopemphix dionaeocysta*, Tjörnes beds, *Tapes* Zone, slide WP 98, EF: H52/4, apical view. Figure 3. *Selenopemphix*? sp. 3 Head and Norris (1989); Kallo –92.6m, slide 2, EF: Q58/1, antapical view, De Coninck (1999). Figure 4. *Selenopemphix*? sp. 3 Head and Norris (1989); Kallo, –92.6m, slide 2, EF: O39/3, De Coninck, (1999). Figures 5–7. ?*Selenopemphix brevispinosa*, Tjörnes beds, *Serripes* Zone, slide WP 10, EF: E42/3, equatorial view. Figure 8. *Selenopemphix brevispinosa*, Tjörnes beds, *Serripes* Zone, slide WP 9, EF: Z41/0, antapical view. Figures 9, 10. *Selenopemphix coronata*, Kallo, –115 m, slide 5, R46/0, antapical view, De Coninck (1995). Figure 11. *Selenopemphix selenoides*, Kallo, –106 m, slide 1, EF: U41/3; antapical view, De Coninck (1999). Figure 12. *Selenopemphix selenoides*, Kallo, –96 m, slide 1, EF: D46/2, antapical view, De Coninck (1999).

The angles of the operculum are rounded. The archeopyle is offset to the left on the dorsal side. The archeopyle and the cingulum are the only indications of tabulation.

Dimension. Maximum equatorial cyst diameter without processes: 42.8 (50.5) 64.7 µm. Minimum equatorial cyst diameter without processes: 25.1 (33.6)44.1µm. Dorsal process length: 1.5(3.1)4.8µm. Width of the base of the first ventral arch, closest to the sulcus: 3.0 (9.6) 16.9 µm.

Length of the first fanshaped process: 2.4 (6.8) 12.1 µm. The well-developed cingulum is broad and has a width of c. 10–15 µm.

Measurement based on 25 specimens.

Remarks. *Selenopemphix islandensis* sp. nov. is often overlooked during microscopic analysis because of its very pale, thin wall which folds readily.

Type locality. Lower Pliocene *Serripes* Zone, Tjörnes beds, Tjörnes Peninsula, northern Iceland. *Selenopemphix islandensis* sp. nov. is recorded in the upper part of the Tjörnes beds from the base (unit 13 of Bárdason, 1925) to halfway through the *Serripes* Zone (unit 22 of Bárdason, 1925).

Comparisons. The general outline and process morphology of *Selenopemphix islandensis* sp. nov. is reminiscent of the outline and the process morphology of *Selenopemphix brevispinosa*, *Selenopemphix conspicua*, *Selenopemphix coronata*, *Selenopemphix dionaeacysta* and *Selenopemphix selenoides* (Figure 4.4; Plate 4.3). The new species has the strong polar compression, the reniform outline in apical/antapical view, the narrow apical horn and the presence of processes restricted to the cingular margins in common with the latter species. The adcingular processes of *Selenopemphix* sp. 3 of Head and Norris (1989) are comparable to the fanshaped processes of *Selenopemphix islandensis* sp. nov., but the latter species possesses a more circular outline in apical/antapical view (Plate 4.3, figures 3–4; Figure 4.4).

Selenopemphix islandensis sp. nov. is typified by the arch-like protrusions symmetrical to the sulcal area and two size classes of processes.

Selenopemhix brevispinosa differs from the new species in its smaller size (maximum cyst diameter: 35 (48) 57 µm; de Verteuil and Norris, 1992) and the presence of only a single type of small, simple processes (Plate 4.3, figures 5–8). The width of the cingulum is comparable to the cingulum observed on specimens of *Selenopemphix brevispinosa* (Plate 4.3, figures 5–8), where the cingulum accounts for almost 50% of the cyst height.

The relatively wide processes (3–4 µm breadth) of *Selenopemphix conspicua* (de Verteuil and Norris, 1992; Figure 4.4) are morphologically more or less comparable to the processes present on the dorsal side of *Selenopemphix islandensis* sp. nov. However, the processes of *Selenopemphix conspicua* are more or less equally spaced and continuously present over the entire cingular margin, which however is not the case on *Selenopemphix islandensis* sp. nov.

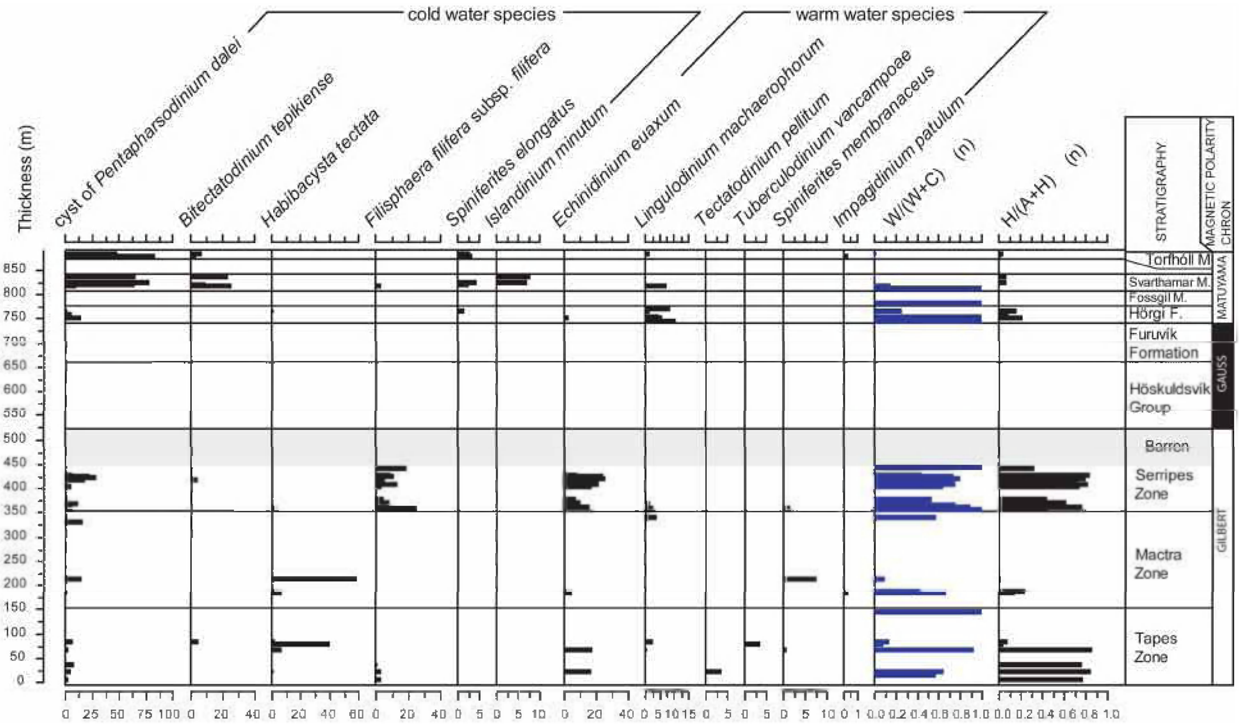

Figure 4.5: The warm/cold ratio based on the distribution of the warm (W) and cold (C) water indicating dinoflagellate cysts. The distribution of the heterotrophic (H) and autotrophic (A) dinoflagellate cysts is given.

Selenopemphix dionaeacysta (Plate 4.3, figures 1, 2; Figure 4.4) possesses a broad range of process morphologies, but the processes are more or less of equal dimensions.

The cingular ornamentation of *Selenopemphix* sp. 3 of Head and Norris (1989) is formed by a continuous ridge with only an interruption in the sulcal area (Plate 4.3, figures 3–4; Figure 4.4). In contrast, the presence of the fan-shaped membranes on *Selenopemphix islandensis* sp. nov. is limited to the ventral side and never forms a continuous membrane. Furthermore, only small, simple processes are observed on *Selenopemphix* sp. 3 of Head and Norris (1989). *Selenopemphix* sp. 3 of Head and Norris (1989) also possesses two small, sharp antapical horns (Plate 4.3, figure 4; Figure 4.4), whereas no antapical horns are observed on *Selenopemphix islandensis* sp. nov. *Selenopemphix coronata* possesses simple, evenly distributed, distally bifurcating processes of equal length. The distal tips of the bifurcations are typically joined (Plate 4.3, figures 9–10; Figure 4.4). The latter species furthermore possesses a well-pronounced apical horn and two small, antapical horns.

The cingular ornamentation of *Selenopemphix islandensis* sp. nov. is comparable to the ornamentation of *Selenopemphix selenoides*. The latter species however possesses a deep sulcus (Plate 4.3, figures 11–12; Figure 4.4) and a supplementary perforate ridge on the hypocyst.

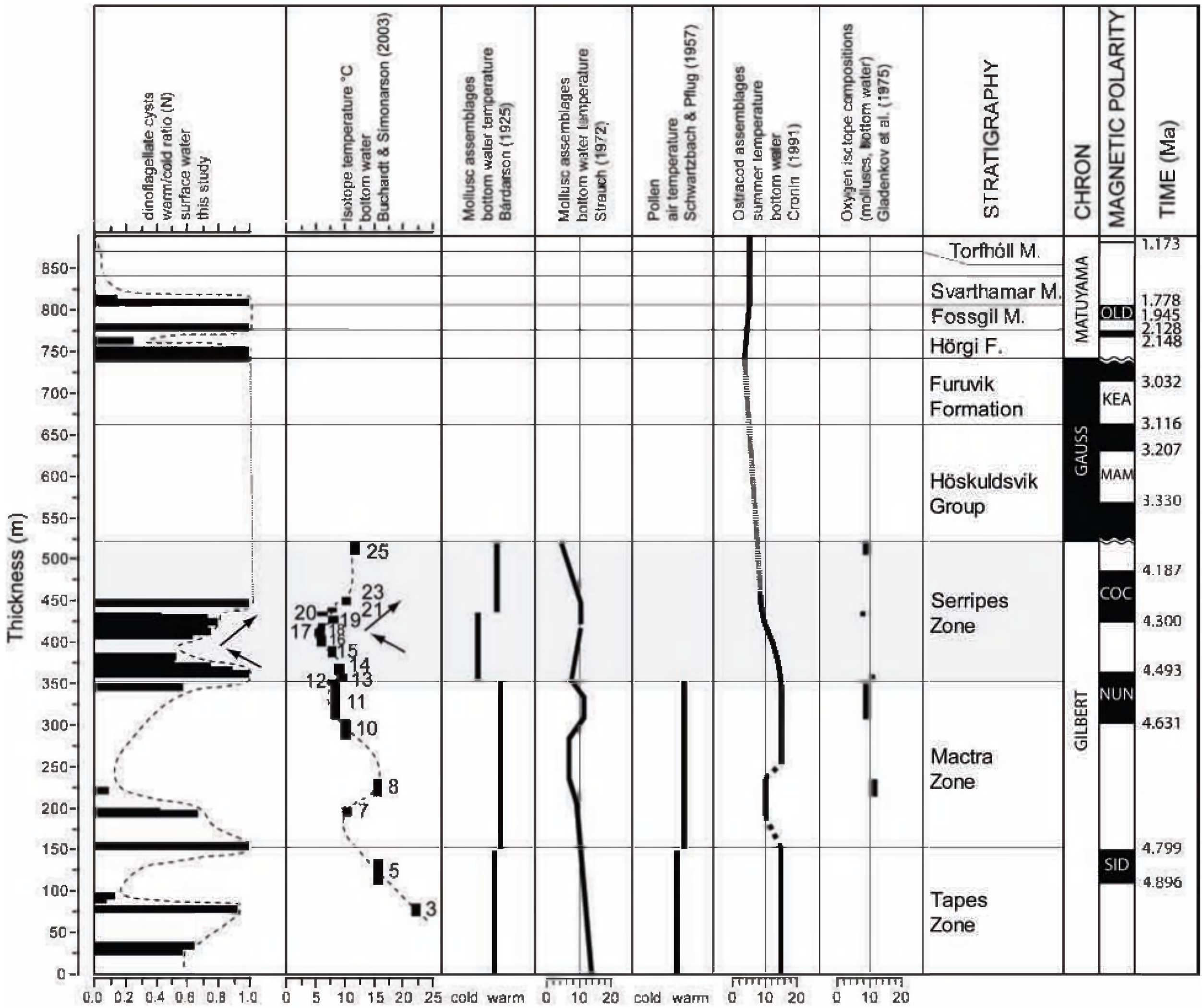

Figure 4.6: The warm/cold ratio of temperature sensitive dinoflagellate cysts (this study) compared to other palaeoclimatic studies of the Tjörnes section. Modified after Buchardt and Símonarsson (2003). The age correlation of the stratigraphy to the magnetic polarity timescale of Lourens *et al.* (2005) is based on Verhoeven *et al.* (2011).

5. Stratigraphic range and relation to palaeoceanography

Marine and terrestrial palynomorphs were recovered from the entire Tjörnes beds and the four most distinct marine interglacial sediments of the Breidavík Group (the Hörgi Formation, the Fossgil Member, the Svarthamar Member and the Torfhóll Member; Figure 4.2). Only the upper part of the *Serripes* Zone proved to be barren in palynomorphs, most probably caused by the energetic estuarine environment during deposition. *Selenopemphix islandensis* sp. nov. is only recorded in the *Serripes* Zone which forms the upper part of the Tjörnes beds. The latter zone was deposited during Early Pliocene times between c. 4.5 and 4.0 Ma. *Bitectatodinium*? *serratum*, *Cristadinium* sp., *Lejeunecysta sabrina*, *Selenopemphix nephroides* and *Selenopemphix quanta* are also restricted to the *Serripes* zone. Other representatives of the heterotrophic genus *Selenopemphix* such as *Selenopemphix dionaeacysta* and *Selenopemphix brevispinosa* are present in the underlying *Mactra* Zone and in the superjacent Lower Pleistocene Hörgi Formation. Palaeoecological conditions such as the throphication state are most probably not responsible for the restricted occurrence of the new species to the *Serripes* Zone.

Malacological studies demonstrated the abrupt appearance of cold-tolerant, boreal, mollusc species of Pacific origin at the boundary between the *Mactra* Zone and the *Serripes* Zone (Bárdarson, 1925; Strauch, 1963; Einarsson *et al.*, 1967; Símonarson and Eiríksson, 2008). Oxygen isotope analysis allowed the reconstruction of the growth temperature of the molluscs *Arctica islandica* and *Pygocardia rustica* from the Tjörnes beds (Buchardt and Símonarson, 2003). Instead of a cooling, a rather limited temperature increase of the bottom waters from 7°C to 10°C at the *Mactra*/*Serripes* Zone boundary is inferred, followed by a gradual cooling to 5°C for the middle part of the *Serripes* Zone. According to the new age model for the Tjörnes beds (Verhoeven *et al.*, 2011), this cooling phase during deposition of the middle part of the *Serripes* Zone can be correlated with the first Pliocene cooling around 4.5 Ma (Zagwijn, 1960; Suc *et al.*, 1995). The abrupt change in mollusc assemblage observed at the *Mactra*/*Serripes* Zone boundary is therefore probably unrelated to a sudden climatic deterioration, but can readily be explained by an influx of Pacific mollusc species via an open Bering Strait in the north through which cold-water-tolerant species migrated (Einarsson *et al.*, 1967).

A marked change in the dinoflagellate cyst assemblage is also observed near the *Mactra*/*Serripes* Zone boundary, where a distinct increase in heterotropic species is noted (Figure 4.5). *Operculodinium centrocarpum* sensu Wall and Dale (1966) peaks just below the *Mactra*/*Serripes* Zone boundary and is even more prominent higher up in the Breidavík Group (Figure 4.2). Palaeoecological studies revealed a clear correlation between strong signals of the latter species and unstable palaeoceanographic conditions (Dale, 1996; De Schepper and Head, 2009). The high relative abundance of *Operculodinium centrocarpum* sensu Wall and Dale (1966) in unit 11 of Bárdarson (1925) below the *Mactra*/*Serripes* Zone boundary can be an indication for a major palaeoceanographic change, e.g. the arrival of Pacific waters in the Icelandic area via the Bering Strait. The sudden appearance of *Selenopemphix islandensis* sp. nov. in the *Serripes* Zone might indicate a Pacific ancestry. It should however be noted that this species has not been recognized in the Pacific before, and that the hypothesis of a Pacific ancestry is only based on its coeval introduction with Pacific molluscs at the base of the *Serripes* Zone. The pale appearance of this particular species however can have hampered the detection of it in previous palynological studies of the Pacific.

6. Palaeoecology of *Selenopemphix islandensis* sp. nov.

According to Buchardt and Símonarson (2003), summer water temperatures during deposition of the Early Pliocene *Tapes* Zone and *Mactra* Zone varied between (?22°C/) 15°C and 7°C. Water temperatures decreased during deposition of the superjacent *Serripes* Zone to an average summer water temperature between 5 and 10°C (Figure 4.6), which is comparable or only slightly lower than the present-day temperatures. The recent average surface water temperature for the period July–September is c. 7°C in the area above the Tjörnes Peninsula in northern Iceland, while the average January–March water temperature measures c. 2°C (sea-surface temperature data from Locarnini *et al.*, 2010). At a depth of 50 m, the average summer water temperature is reduced to 4.8°C because of the presence of cold arctic water underneath the warm water transported by the Icelandic Current (Figure 4.1). Buchardt and Símonarson (2003) interpreted the $\delta^{18}O$ values as a gradual change from warm-water conditions during the deposition of the lower part of the Tjörnes beds to cold-water conditions at the top. The boundary between the *Mactra* Zone and the *Serripes* Zone, which is characterised by a major shift of the mollusc faunal composition, does not coincide with a major cooling. The abrupt change in the molluscan assemblage is related to a changed oceanic circulation pattern rather than to a sudden climatic deterioration (Buchardt and Símonarson, 2003). The coldest values during the first half of the *Serripes Zone* (5–8°C) are interpreted by these authors as a cooling event prior to the Mid Pliocene Warm Period (c. 3.3–3.0 Ma; Dowsett *et al.*, 1999). The age model of Verhoeven *et al.* (2011) made however clear that we are dealing with older sediments of the Early Pliocene and that this detected cooling phase is much older.

Mollusc assemblages indicate a gradual development from warm-water conditions during deposition of the *Tapes* Zone and *Mactra* Zone to arcto-boreal conditions during the deposition of the *Serripes* Zone (Buchardt and Símonarson, 2003). Einarsson and Albertsson (1988) suggested that the *Tapes* Zone and *Mactra* Zone were characterised by lusitanic and low boreal molluscan assemblages, characteristic of water temperatures of 10°C (5–3°C higher than present). The latter faunas were replaced by boreal assemblages in the *Serripes* Zone, characteristic of water temperatures of 7–8°C, comparable to the present-day situation near Iceland. The cold-water mollusc *Portlandica arctica* is recorded from the Hörgi Formation onwards (Símonarson and Eiríksson, 2008) and indicates, together with other cold-water molluscs, a further cooling during the Late Pliocene and Pleistocene (Cronin, 1991).

Cronin (1991) presented a detailed reconstruction of the (bottom) water temperature evolution based on ostracods during deposition of the Tjörnes beds and the central part of the Breidavík Group (Hörgi Formation, Threngingar Formation, basal Máná Formation; Figure 4.6). A gradual cooling is inferred from summer water temperatures of c. 15°C during deposition of the *Mactra* Zone (unit 9–10 of Bárdarson, 1925) to temperatures of c. 8°C during deposition of unit 23 of Bárdarson (1925) in the upper part of the *Serripes* Zone. Summer water temperatures in the Breidavík Group were significantly lower and varied between 4 and 5°C. The mean summer water temperature during deposition of the *Tapes* Zone is relatively high (c. 17°C) and is based on the presence of warm-water genera *Paracytheridea*, *Tetracytherura* and *Aurila*. Pollen studies indicated that the basal part of the Tjörnes beds was deposited under climatic conditions markedly warmer than today (Schwarzbach and Pflug, 1957; Willard, 1994). Schwarzbach and Pflug (1957) suggested water temperatures during the deposition of the *Tapes* Zone and *Mactra* Zone that are 5°C higher than today. Pollen also indicated higher air temperatures. Willard (1994) found pollen of the warm-temperate taxon *Ilex aquifolium* only within the base and top of the *Tapes* Zone, but Schwarzbach and Pflug (1957) recorded this taxon also in lignite F (Bárdarson, 1925) in the middle part of the *Mactra* Zone. Pollen of the warm-temperate taxa *Quercus*, *Acer*, *Castanea*, *Picea* and *Betula* were recorded by Willard (1994) in the *Tapes* Zone and *Mactra* Zone. Some warm-temperate taxa such as *Quercus* are still found in the *Serripes* Zone, but the distinct warm taxa *Castanea* and *Ilex* are, according to the data of Willard (1994), absent in this zone. Based on this record, Willard (1994) considered the *Tapes* Zone and *Mactra* Zone to be deposited under warmer conditions than the *Serripes* Zone. In this study, however, pollen of the warm-temperate taxa *Ilex*, *Juglans*, *Ulmus*, *Acer* and *Fagus* were recorded also in the *Serripes* Zone and also in the Lower Pleistocene interglacial deposits of the Breidavík Group. The *Serripes* Zone and the interglacial deposits of the Hörgi Formation, Fossgil Member, Svarthamar Member and Torfhóll Member contain pollen of temperate deciduous trees, which indicate warmer conditions than presently observed in Iceland. The cooling inferred from oxygen isotope analysis during deposition of the *Serripes* Zone (Buchardt and Símonarson, 2003) is apparently not reflected in the published pollen records (Schwarzbach and Pflug, 1957; Akhmetiev *et al.*, 1978; Willard, 1994). A higher sampling resolution is most probably needed for elucidation of this issue.

The present-day environmental preference of the climatic sensitive taxon *Ilex* – recorded for instance in the basal part of the *Serripes* Zone – indicates a mean January air temperature higher than 0°C as *Ilex* does not show a distribution higher than the January 0°C isoline (Iversen, 1944; Walther *et al.*, 2005). Notwithstanding the fact that the mixed conifer/hardwood vegetation which is found in the entire Tjörnes beds has no close modern analogue (Willard, 1994), it indicates higher temperatures than today for Iceland based on the present-day preferences of the individual taxa. According to Willard (1994), the Early Pliocene vegetation in the Tjörnes beds shows a close similarity to the present-day vegetation of Nova Scotia, although the presence of Ilex in the basal part of the *Serripes* Zone indicates that the mean January temperatures had to be significant higher in Tjörnes compared to Nova Scotia. The present-day January temperature in Nova Scotia averages around -5°C and July temperatures are c. 15–20°C (Hare and Hay, 1974), while in northern Iceland the average January temperatures range from -1° to -2°C and the July temperature averages 10°C (Eythorsson and Sigtryggsson, 1971). The vegetation in Iceland shows a significant change from the open mixed coniferous–deciduous forest of the Early Pliocene to the recent tundra vegetation. Air temperatures during the beginning of deposition of the *Serripes* Zone had to be at least a few degrees (1–2) higher than today.

The dinoflagellate cyst assemblage of the Tjörnes section provides an indication of the former sea-surface temperature. According to Marret and Zonneveld (2003), the cysts of *Pentapharsodinium dalei* are commonly recorded from subpolar to even temperate environments. *Bitectatodinium tepikiense* has temperate to cold-water affinities (Marret and Zonneveld, 2003). A preference for a cold-water environment is attributed to the two extinct species *Habibacysta tectata* and *Filisphaera filifera*. According to Louwye *et al.* (2008), *Habibacysta tectata* has a lowest appearance in site 1318 of the Integrated Ocean Drilling Program in the Porcupine Basin at c. 13.6 Ma. This datum is linked to the distinct cooling related to the short-lived glaciation Mi3b following the Middle Miocene Climatic Optimum. The base of the Diest Formation in the Wijshagen borehole in northern Belgium (southern North Sea Basin) is also typified by a sudden appearance of *Habibacysta tectata*. This appearance of *Habibacysta tectata* coincides with the cooling effects related to the climatic transition between 14.2 and 13.8 Ma (Louwye and Laga, 2008). Head (1994) recorded *Habibacysta tectata* in the Lower Pleistocene, Ludham borehole in eastern England and associated its presence with the cooling at the beginning of the Quaternary. Mudie (1987) and Head (1996) considered the species *Filisphaera filifera* as a moderately cold tolerant species common at middle and high northern latitudes during the Late Pliocene and Early Pleistocene.

Barssidinium pliocenicum and *Echinidium euaxum* are dinoflagellate cyst species abundantly present in the *Serripes* Zone. *Echinidium euaxum* is recorded from the St Erth Beds in western England (Head, 1993), the Gulf of Mexico (Duffield and Stein, 1986) and in recent subtropical sediments of northwest Australia (Bint, 1988). The latter occurrences led to the assumption of a warm-water preference for this species. According to Head (1997, 1998a) and De Schepper *et al.* (2004), *Barssidinium pliocenicum* is a cold-intolerant species based on the presence in the Neogene of England. However, the presence in the St Erth Beds (2.1–1.95 Ma; Head, 1993 following the Astronomically Tuned Neogene Time Scale of Lourens *et al.*, 2005) rather indicates a tolerance to colder water as the cooling at the beginning of the Quaternary had already started. *Barssidinium pliocenicum* is furthermore present in the interglacial deposits of the Hörgi Formation of Early Quaternary age (c. 2.25–2.12 Ma; Verhoeven *et al.*, 2011). Since it is unclear whether this species has a preference for temperate–warm waters or not, the Warm/Cold ratio (Versteegh and Zonneveld, 1994) was calculated without *Barssidinium pliocenicum* (Figure 4.5). The ratio is calculated as follows:

$$W/C = nW/(nW + nC)$$

where n is the number of specimens counted, W is the warm-water-indicating dinoflagellate cysts (*Echinidinium euaxum*, *Lingulodinium machaerophorum*, *Tectatodinium pellitum*, *Tuberculodinium vancampoae*, *Spiniferites membranaceus* and *Impagidinium patulum*) and C is the cold-water-indicating species (cysts of *Pentapharsodinium dalei*, *Bitectatodinium tepikiense*, *Habibacysta tectata*, *Filisphaera filifera*, *Spiniferites elongatus* and *Islandinium minutum*).

We follow Marret and Zonneveld (2003) for temperature affinities of the recent dinoflagellate cyst species. The ratio indicates a relatively warm-water environment for the entire Tjörnes beds and the Hörgi Formation followed by a gradual but pronounced cooling from the Hörgi Formation onwards. Despite the fact that the entire Tjörnes beds were sampled with the same resolution, the results from the *Mactra* Zone are probably less significant because of the low palynomorph concentrations. A decrease of the ratio is observed in the lower part of the *Serripes* Zone, and precedes only slightly the cooling detected by the oxygen isotope study (Buchardt and Símonarson, 2003; Figure 4.6). *Selenopemphix islandensis* sp. nov. occurs in a zone in which both cold-intolerant as cold-tolerant dinoflagellate species are observed. Its absence in the Lower Pleistocene could probably indicate intolerance for subpolar conditions, or extinction near the end of the Pliocene. Its sudden appearance in the Tjörnes section on the base of the *Serripes* Zone (from unit 13 onwards) therefore coincides with a minor temperature rise but cannot be explained through a drastic climatic change. The lowest occurrence coincides precisely with the appearance of molluscs of Pacific origin in the Tjörnes area. As the mollusc migration only was possible due to the opening of the Bering Strait, only species adapted to cold (arctic) conditions could migrate (see above). A tolerance for cold to subpolar environments is thus assumed for *Selenopemphix islandensis* sp. nov. Its disappearance out of the Tjörnes area, probably already during the late Zanclean, might be regarded as an extinction. The reason herefore is not clear, as the species has to be adapted to the lower temperatures of the Quaternary. As up to now, only a record of this species has been found in the Tjörnes section, less can be said about its regional or global appearence.

In summary, the *Serripes* Zone was deposited during cold-water conditions with summer temperatures of 5–10°C. The arctic-boreal mollusc assemblage indicates comparable water temperatures of 7–8°C. The average water temperature during the deposition of the *Serripes* Zone is comparable to the present-day average summer temperature of 7°C. Slightly colder conditions must have occurred during deposition of the lower part of the *Serripes* Zone. At least air temperature during the beginning of the *Serripes* Zone was slightly warmer than today. *Selenopemphix islandensis* sp. nov. probably migrated from the Pacific Ocean into the Atlantic Ocean during Early Pliocene times, and a tolerance for cold– subpolar environments is assumed.

7. Conclusions

The new dinoflagellate cyst species *Selenopemphix islandensis* was recorded for the first time within the Tjörnes section in northern Iceland. The stratigraphic distribution of the new species is restricted to the Lower Pliocene *Serripes* Zone. The three main diagnostic features are its often pale and folded thin autophragm, the occurrence of one or two pairs of constrictions of the cingular margin symmetrically around the sulcus and the presence of two size classes of adcingular processes. The species is recorded in deposits with an average summer temperature of 5–10°C, comparable to the present-day situation. Its sudden appearance right at the base of the *Serripes* Zone indicates that this species possibly migrated from the Pacific Ocean into the Atlantic Ocean, together with the distinctive mollusc assemblage of Pacific origin in the Tjörnes beds. Since *Selenopemphix islandensis* sp. nov. migrated through the Bering Strait, a tolerance for cold–subpolar environments is assumed. *Selenopemphix islandensis* sp. nov. was not recorded higher in the Pleistocene sequence and probably became extinct near the end of Pliocene times.

8. Author contribution

Selenopemphix islandensis sp. nov. is recognized as a new species by KV during a palynological study fully designed by the same author. Drawings, figures and photo plates are from the hand of KV. SL helped with language corrections and the diagnosis of the species.

9. Acknowledgements

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CHAPTER - 5

Plio-Pleistocene landscape and vegetation reconstruction of the coastal area of the Tjörnes Peninsula, northern Iceland

5

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Abstract

Marine and continental deposits from the Tjörnes area in northern Iceland are studied for their pollen/spore content. Six Pollen Zones (PZ) were defined in the Early Pliocene Tjörnes beds and the Early Pleistocene Breidavík Group. The pollen is most diverse during the deposition of the lowest *Tapes* Zone (PZ 1) and the lower part of the overlying *Mactra* Zone (PZ 2). Local pollen from marshland, levee and foothill forests was deposited in a large coastal plain. The pollen spectrum reflects transgression and deepening during the second part of the *Mactra* Zone (PZ 3) and the lower part of the *Serripes* Zone (PZ 4). Gymnosperm pollen derived from the higher inland plateau increase in PZ 3. This background pollen was of minor importance during periods with an extensive coastal plain (PZ 1, 2, 4, 6). PZ 5 did not yield acceptable amounts of pollen. The pollen analysis allowed refinement of the sea level variations based on sedimentology and molluscs. Pollen of warmth-demanding plants are recorded throughout the Tjörnes beds and the Early Pleistocene interglacial deposits. Warmth-loving species indicate summers 8°C warmer than today during deposition of the *Tapes* Zone, and at least 5°C warmer during the rest of the Tjörnes beds. The Pliocene vegetation of Iceland matches well that of the present-day western European maritime temperate climate. The drastic cooling at the onset of the Quaternary led to a marked vegetation impoverishment, already noticeable in the Gelasian part of the Breidavík Group.

Keywords: Pliocene, pollen, Tjörnes, Iceland, ecology, landscape, sea level changes

1. Introduction

The Tjörnes Peninsula in northern Iceland holds the most complete marine geological section of Iceland. The location is unique since less than 10% of the Cenozoic strata of the island are sediments, the greater part having a volcanic origin (Einarsson and Albertsson, 1988). For more than two centuries, the geographical position of the Tjörnes Peninsula in the centre of the northern Atlantic Ocean has stimulated geological and palaeoecological studies, often in the context of global palaeoceanographic reconstructions (see Eiríksson, 1981a and Verhoeven *et al.*, 2011 for an overview). The Plio-Pleistocene sediments of the Tjörnes section have a total thickness of about 1200 m and are lithologically quite heterogeneous. Nearshore marine sandstones and mudstones alternate with lava flows, lignites and diamictites (Eiríksson, 1985). The sediments were deposited in a shallow marine environment with evidence of terrestrial influence from the nearby island, as indicated clearly by massive lignites mainly in the older part of the section.

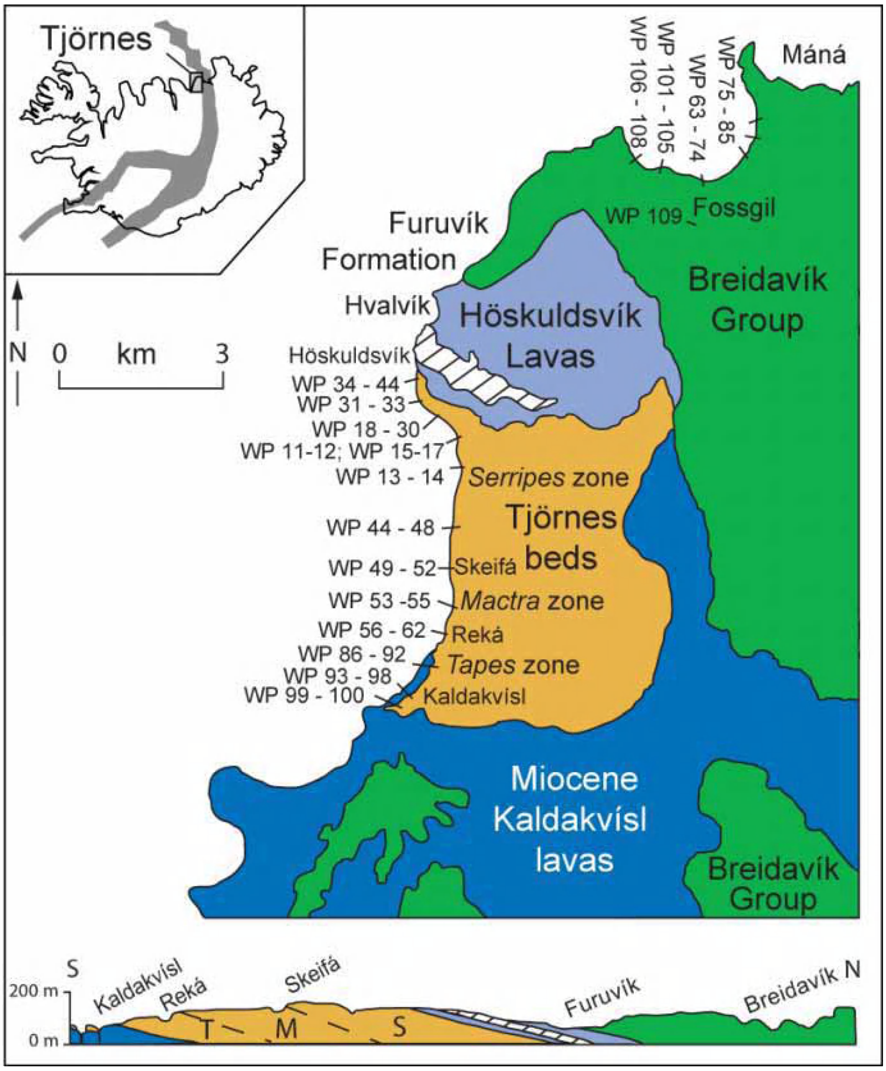


Figure 5.1: Location of the Tjörnes Peninsula in northern Iceland with indication of the Mid Atlantic Ridge in grey (left inset). Geological map of the study area, located on the western part of the Tjörnes Peninsula. A north-south cross-section of the area is indicated (details see figure 1.1). Also the sample locations and numbers are mentioned. The reversed magnetised lavas of the Höskuldsvík Group are indicated with diagonal lines. Modified after Einarsson *et al.* (1967) and Eiríksson (1981b). T = *Tapes* Zone, M = *Mactra* Zone, S = *Serripes* Zone.

These remnants of coastal forests have been intensively studied for plant macrofossils (Windisch, 1886; Schönfeld, 1956; Akhmetiev *et al.*, 1975, 1978; Löffler, 1995; Denk *et al.*, 2005, 2011) and pollen (Schwarzbach and Pflug, 1957; Willard, 1994; Verhoeven and Louwye, 2010; Denk *et al.*, 2010, 2011). An inventory of the pollen from 57 samples of the Tjörnes beds is given by Akhmetiev *et al.* (1978). Dinoflagellate cysts and organic-walled marine algae are preserved mainly in the shallow marine sediments throughout the entire Tjörnes section (Verhoeven *et al.*, 2011; Verhoeven and Louwye, 2011). Malacological studies in combination with sedimentological analyses indicate important environmental changes during Early Pliocene times, induced by a changing relative sea-level (Buchardt and Símonarson, 2003).

The samples of the Tjörnes section were concurrently analysed for marine palynomorphs (dinoflagellate cysts, acritarchs, prasinophytes), and terrestrial palynomorphs (pollen and spores). The dinoflagellate cyst stratigraphy allowed a re-evaluation of the Plio-Pleistocene magnetostratigraphy and the construction of a robust age model for the entire section (Verhoeven *et al.*, 2011).

The aim of this paper is to establish the detailed chronology of the vegetation changes in the Tjörnes area during Pliocene and Early Pleistocene times through a high-resolution pollen analytical study, and to relate the former coastal landscapes with its vegetation to sea-level movements and climate changes.

2. Geology

During Pliocene times sedimentation took place in a graben system appertaining to the Tjörnes Fracture Zone, a WNW/ESE-oriented fault zone caused by the passage of the Mid Atlantic Ridge system through Iceland (Figure 5.1). The Tjörnes beds accumulated in a depression, interpreted as a shallow fjord open to the north with sediment supply from the south (Strauch, 1963). The Tjörnes beds were divided by Bárdarson (1925) into 25 marine horizons or layers (1–25) and 10 lignite layers (A–J) (Figures 5.2, 5.3). The author also provided an informal stratigraphical scheme based on three mollusc biozones: the *Tapes* Zone (horizons 1–5), the *Mactra* Zone (horizons 6–12) and the *Serripes* Zone (horizons 13–25).

The interpretation of the sedimentation environment by Buchardt and Símonarson (2003) is shown in figure 5.3. The *Tapes* Zone was deposited in an intertidal environment and consists of sandstones and conglomerates. Lignite beds derived from coastal swamp forests in the *Tapes* Zone alternate with the marginal marine sediments. This alternation of marine and terrestrial deposits indicates a fluctuating balance between sediment supply and the subsidence rate. The intertidal depositional regime persisted during sedimentation of the lower part of the overlying *Mactra* Zone (horizons 6–9). The sedimentation rate during this period was high and the fjord rapidly filled in. The molluscan fauna indicates a transgression and deepening from an intertidal to a subtidal depositional environment during deposition of the upper part of the *Mactra* Zone (horizons 10 to 12) and the greater part of the superjacent *Serripes* Zone (horizons 13 to 22). However, at that time salinity decreased, most probably due to freshwater input from the land (Símonarson and Eiríksson, 2008). The subsidence exceeded the sediment supply during this period. It is noteworthy that horizons 13 to 16 in the base of the *Serripes* Zone are disturbed by storms and the molluscs from this interval are often broken as a result of post-mortem transport, reflecting a highly energetic environment.

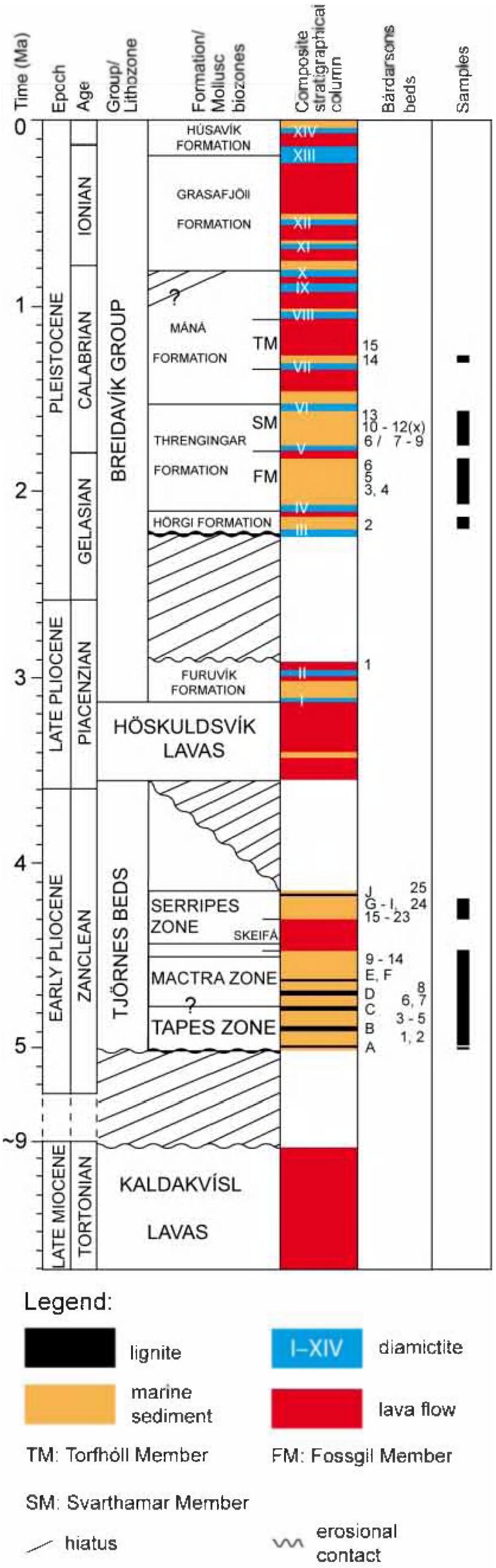


Figure 5.2: Stratigraphical column of the Tjörnes sequence based on the age model by Verhoeven *et al.* (2011). The lithology (after Eiríksson (1981b) and Símonarson and Eiríksson (2008)) and sample intervals are indicated. The formations and members discussed are given in the text, together with the labelling of the layers as defined in Bárdarson (1925). The positions of the 14 Quaternary diamictites are indicated by Roman capitals.

Table 5.1: **Raw data of the pollen, spores and terrestrial Non Pollen Palynomorphs from the Tjörnes section. Lignites are indicated with horizontal light gray bars.**

							LABORATORY						GYMNOSPERMS									ANGIOSPERMS, TREES AND SHRUBS																									
stratigraphy and molluscan biozones		pollen zonation	G.P.S. Way Point; sample number	Bárdarsons Beds	thickness, m	sediment	standard treatment (HCl, HF, HCl)	KOH, Acetolysis	Heavy liquid separation, $ZnCl_2$	# *Lycopodium clavatum* tablets, batch 483216, x=18583 +/- 1708	dry weight sediment, g	*Lycopodium clavatum* (spike)	*Abies*	*Cedrus*	*Larix*	*Picea*	*Pinus*	*Tsuga mertensiana*	bissacate pollen indet.	total gymnosperms	reworked bissacate pollen	*Acer*	*Alnus*	*Betula*	cf. *Buxus*	*Carpinus betulus*	*Castaneae*	*Corylus*	cf. *Fagus*	*Hedera*	*Hippophae*	*Ilex*	*Juglans*	cf. *Juniperus*	*Ostrya*	*Myrica*	*Nyssa*	cf. *Pterocarya* (small; <30µm)	*Quercus*	*Rhamnus*-type	*Rhus coriaria*-type	*Salix*	*Sambucus nigra*-type	*Tilia*	*Ulmus*	*Viscum album*	total deciduous trees and shrubs
Breidavik Group	Tofholl Member	Pollen Zone 6	WP 82	14	889,8	S	x			1	55,6	587								0			1																								1
			WP 83	14	888,5	M	x			1	54,4	1185					1			1				3																							3
			WP 84	14	883,5	M	x			1	50,7	1360					3		8	11			1	2												1			1				2		1		8
			WP 85	14	878,9	M	x			1	63,1	307	5				13		14	32			3	4																			1				8
	Svarthamar Member		WP 77	12	835,0	C	x			1	63,8	565			1					1																											0
			WP 69	10	823,4	M	x			1	44,3	190							3	3			1	1												1						1					4
			WP 70	10	819,8	M	x			1	54,2	281	1						1	2					6																				1			7
			WP 71	10	817,2	M	x			1	46,6	2643				3	53		10	66	2		5	4									3														12
			WP 73	?	816,3	M	x			1	66,7	4227	27		9	1	16		26	79	3		10	34		2			1				4			2		1	2								54
			WP 68	8	813,0	S	x			1	53.1	3848	33		6	2	17		23	81			4	13		1		1	1									1				1					24
	Fossgil		WP 67		782,0	M	x			1	58,1	1347	79			2	3		18	102	2		42	60				2					1			1	1					1		1			109
			WP 109		778,0	M	x			1	62,3	2242	40				11		83	134	1		46	13				9											1								69
	Hörgi Formation		WP 101		769,0	M	x			1	48,0	2697	35		2	9	42	1	32	121			14	18								1	1						1					1			36
			WP 108		765,0	S	x			1	56,9	1506	9				5		28	42			18	12				5					1						1								37
			WP 102		762,1	M	x			1	48,5	2471	12				17		12	41			5									1															6
			WP 107		758,0	S	x			1	58,6	833	8				3		36	47		2	18	9				1										1						1			32
			WP 103		753,0	M	x			1	41,9	1072	21		1	12	31		43	108			11	24				2					2												2		41
			WP 104		752,5	M	x			1	54,6	1161	7				5		14	26			1	4												1						1		1			8
			WP 106		750,0	S	x			1	52,1	450	28			2	2		33	65			21	12				1					2						1								37
			WP 105		744,0	M	x			1	40.7	1529	69			1	18		87	175	1		8	14				2										1									25
Tjörnes beds	Serripes Zone	PZ 5	WP 43	24	478,0	CS,W	x			1	39,1	1716					1			1				1																							1
			WP 40	I	477,6	M	x			1	60,0	3864								0				1																							1
			WP 42	H	476,7	M	x			1	48,6	1005					1			1																											0
			WP 38	H	462,8	CS,W	x			1	72,3	2003								0																											0
			WP 37	G	452,6	M	x			1	41,8	895							1	1																											0
			WP 36	23	449,8	SH	x			1	43,6	1411								0			1																								1
			WP 31	22/23	447,0	CS	x			1	63,6	1187					1			1			1																								1
		Pollen Zone 4	WP 27	22	442,6	S	x			1	37,8	2361					1			1			3	2														2					1				8
			WP 28	21/22	439,4	S	x			1	59,4	2137	19			5	57		7	88			14	5				2							1								1		1		24
			WP 32	?	439,3	S	x			1	51,6	204								0																											0
			WP 24	21/22	427,2	S	x		x	1	62,2	1474	1			1	4		2	8			1											3								1					5
			WP 33	?	426,5	SH	x			1	62,1	2489	2			1	10		1	14																											0
			WP 25	21	424,8	SH	x		x	1	66,5	3992	5			1	11		9	26				2									1														3
			WP 26	20/21	424,4	S	x			1	52,1	2375	5			4	20		10	39	1		5																				1				6
			WP 23	20	423,7	SH	x		x	1	50,0	1269	3		4	2	21			30			3	1									3									1					8
			WP 22	19/20	422,9	S	x		x	1	39,2	764	1		1		6		1	9				1																							1
			WP 21	19	422,2	SH	x		x	1	82,8	929				2	3		4	9			2																								2
			WP 20	18/19	420,0	S	x			1	49,0	2253	4			1	21		2	28			13	4															2			1			1		21
			WP 19	18	417,6	SH	x		x	1	40,3	1262				1	5		6	12																											0
			WP 18	17/18	415,8	S	x			1	52,6	1261	1				16			17			11	3																							14
			WP 17	17/18	406,5	S	x		x	1	47,1	1176	3				4		6	13		1	13	3																		1					18
			WP 16	17	402,2	S	x		x	1	53,5	2397	9			7	37		17	70			8	2									1											1	1		13
		Pollen Zone 3	WP 3	16	379,3	SH	x			1	44,1	1383	7			2	39		12	60			1																								1
			WP 4	15/16	375,8	S	x			1	48,7	617	5				246		9	260			5	2														1									8
			WP 5	15	368,8	SH	x			1	50,5	1808	35			6	214		42	297	1		5	4																				1			10
			WP 6	14/15	367,9	S	x		x	1	67,8	488	59			1	220		18	298	1		4	1						1		2				1						1		1		11
			WP 7	14	363,9	SH	x			1	53,9	591	32			2	46		55	135			6	1																							7
			WP 8	13/14	360,1	S	x			1	45,2	191	13			4	871		10	898	1		36	18				5				7				3			1								70
			WP 9	13	359,2	S	x			1	70,5	151	5			5	229		24	263			1									1		1		2									1		6
			WP10	12/13	357,2	S	x			1	72.1	361	109			2	165		6	282	2		8	1								2				1									2		14
	Mactra Zone		WP 11	12	356,0	S	x			1	56,0	1393	199			1	174		102	476	9		11	5		1							1			1		1									20
			WP 12	11	350,0	SH	x		x	1	51,7	3139	31			11	263		39	344	1		29	9				3				1	3			1									2		48
			WP 13	11	340,0	CS	x			1	41,7	3572	95			8	338	1	65	507	3		6	1				1										1									9
			WP 14	11	330,0	S	x			1	69,0	3676	67				274		36	377	3	1	4	1				2				1															9
			WP 44	10	295,0	SH	x			1	34,4	253	1				7			8																											0
			WP 45	10	291,2	S	x			1	52,3	288			1		35		4	40			4				1	2				3										1					11
			WP 48	?	286,1	SH	x			1	41,6	1029					3		1	4																											0
			WP 46	?	277,8	SH	x			1	57,2	1282				1	21		3	25			1																								1
			WP 47	?	272,0	SH	x			1	46,8	184					6		1	7			1	1																							2
		Pollen Zone 2	WP 49	F	260,5	L		x		1	2,4	17					3		4	7			2													2											4
			WP 50	F	252,0	M,P	x			1	33,8	5			27					27			2	1														1									3
			WP 51	E	244,0	CS	x		x	1	50,0	478							1	1																											0
			WP 52	8	230,0	SH	x		x	1	74,3	656	1				1			2			2	1												2											5
			WP 53	D	211,1	M,W	x			1	3,2	128			5					5			22																			1					23
			WP 56	D	207,9	L	x			1	3,5	35			4					4																								1					1
			WP 54	D	203,7	L	x			1	34,2	77	1		6	1	1		10	19			5	2	7								1														16
			WP 57	7	195,3	S	x		x	1	46,8	566			4				1	5																											0
			Wp 58	7	188,0	M,W	x			1	3,4	1080					3			3			3	11																							14
			WP 55	7	185,0	S	x		x	1	38,2	25	3		15	1			4	23			6	4												3						1					14
			WP 59	6	183,0	S	x		x	1	42,8	428	2		33		1		3	39				2																							2
	Tapes Zone		WP 60	C	145,0	L		x		1	2,4	51								0			1	2																		1					4
			WP 61	C	144,0	S	x		x	1	31,7	1248			11	2			6	19			2																								2
		Pollen Zone 1	WP 62	5	129,0	S	x		x	1	43,9	1620	1		4				8	13			9	5												3					1						18
			WP 86	4	83,2	S	x		x	1	47,7	1306	9			1	37	2	10	59	2		8	8				2			1	2				8									2		31
			WP 87	4	78,0	S	x		x	1	49,7	846	12		12	1	2		10	37			2	2									1			1											6
			WP 88	4	69,0	S	x		x	1	49,5	697					1		1	2		166	1					2					109			2										1	281
			WP 89	B	68,0	L		x		1	2,4	2								0																2											2
			WP 90	3	66,2	S	x		x	1	49,9	149	7		16	1	1	1	2	28	1		4	3					2					2												11
			WP 91	3	65,1	S	x		x	1	38,0	531			5		1		9	15			4																	1							5
			WP 92	c	45,0	L		x		1	2,5	6								0			9	5																		4					18
			WP 93	2, b	36,2	L		x		1	2,6	6	1			6	24		24	55			12	11																		3					26
			WP 94	2	35,3	S	x		x	1	48,7	343	3		13	2	24		10	52			5													8											13
			WP 95	2	29,4	S	x		x	1	38,4	1850			2		3		6	11				2																							2
			WP 96	2, a	22,4	L		x		1	2,4	8					10			10		3	24																			2					29
			WP 97	2	20,4	S	x		x	1	32,5	222	4		25				11	40			2	4									1														7
			WP 98	2	13,7	S	x			1	60,2	516	4	1			1		6	12			8						2							2											12
			WP 100	1	5,0	S	x			1	42,7	38	11		49	1			12	73			34	8									1			2											45
			WP 99	A	3,0	L		x		1	4,0	10	1						1	2			1	1																							2

Legend: L = lignite; M = mudstone; S = sandstone; CS = coarse sandstone; W = wood; P = plant remains; C = conglomerate; SH = shell remains

G.P.S. Way Point; sample number	pollen zonation	ANGIOSPERMS, HERBS																																												
		Aconitum-type	*Agrostemma githago* (Carylophylaceae > 50µm)	Apiaceae	*Aquilegia*-type	*Artemisia*	Asteraceae Liguliflorae-type	Asteraceae Tubiliflorae-type	*Ballota*-type	Brassicaceae	Cannabinaceae	Carylophyllaceae	*Cerastium*-type (Carylophylaceae)	Chenopodiaceae	*Circaea*	Cyperaceae	*Drosera intermedia*	Ericaceae-*Empetrum*-group	*Euphorbia*	*Filipendula*	*Galeopsis*-*Ballota*-group	*Gentiana pneumantha*-type	*Helleborus foetidus*	*Hellianthemum oelandicum*	*Jasione montana*-type	*Koenigia islandica*	*Lathyris*-type	*Mentha*-type	*Papaver rhoeas*-group	*Parnassia palustris*	*Persicaria maculosa*-type	*Plantaginaceae*	Poaceae	Poaceae (>50µm)	*Polygonum bistorta*-type	*Polygonium raii*	*Ranunculus acris*-type	Rosaceae	Rubiaceae	*Rumex acetosa*-type	*Sanguisorba officinalis*	*Saxifraga aizoides*-group	*Sedum*-type	*Solanum nigrum*-type	*Sorbus*-group	*Thalictrum*
WP 82	Pollen Zone 6																																													
WP 83							1	1				2		1		1		9															20													
WP 84												1				10		1															3		1		1							1		
WP 85						1	2	1				2				18		2								2							18		1											
WP 77																		2																												
WP 69							1	2						2		2		49																												
WP 70												1		2		5		3																	1											
WP 71							1	1								6		3													1		5		3						1					
WP 73							1	1								9		3															8		8		2	1								
WP 68								2							1	28		7						1		1							13		8					1	1	1				
WP 67				3		1						1		3		6		3															20		5		3			1						1
WP 109							2									10																	2		3											
WP 101						1	2	2				1				15	3	3											1				13	1	7						1					
WP 108							5	2				2				111		2										1					18		5		12								2	
WP 102																		3															8								1					
WP 107							2	1				1				66		2															61		14		7				3				3	1
WP 103							1									15		19															44		28						1					
WP 104																2		3							1								3		1		1									
WP 106						9	1			7		8				70		2															40		2	1	5			3	4					1
WP 105							2	5				1				32		4															14		28		3				1					
WP 43	PZ 5																																2													
WP 40												1																																		
WP 42																																	1													
WP 38																																														
WP 37							1	1																									12													
WP 36																						1																								
WP 31																																	6						1							
WP 27	Pollen Zone 4						3					1						7								1					1		22		2		5				7					2
WP 28								3				4				82		4							1			2					9		8		25				10				1	2
WP 32																																														
WP 24								1				1						1															2		1											
WP 33							5	5								4		1															1		1		6				4					
WP 25								3								2																	3	1	7		12				3					
WP 26						1		1								6					1												3		7		37				10		1			
WP 23										1						6		1															4		4		13			1	5					2
WP 22																1				1													2				2				4					2
WP 21												1				7																	1				2				4					
WP 20							1	1				2				20																	4		2		28				12		1			2
WP 19								2																									2				2				1					
WP 18		1						3			1					11													3	1			10		3		23				2					
WP 17								1						1		5																	4		1		14				3					
WP 16				1			1	2				2				5		2															4		3		8			1	9					
WP 3	Pollen Zone 3						1	1								1																	1				1									
WP 4							4	2				1				37		2															3		1		4				5					3
WP 5							7	1				2				3		3															11		4		1				3					
WP 6							5					2				14		4		1													3		5		3				2					
WP 7								1				1						3															3		2		1				1					
WP 8					1		30	1		2		1				61		20					1										29		13		12				16					
WP 9							3									5		2				1													3		2									
WP10						1	9	2				1				4		2								1							4		3											
WP 11							7	1				1				7		7															2		6		3				3					
WP 12							17					1				34		5															14		17		6			5	9				1	1
WP 13				1		1	25	3				2				4		13															5		22		7				7					
WP 14							28	8				2				4		13															9		32		1	1		1	5					
WP 44							2									2		1																												
WP 45							8											1								1							5		3						1					
WP 48							3																									1			1											
WP 46						2	4	2								4																	2													
WP 47							3									2																	6		1						1					
WP 49	Pollen Zone 2		2	1								1				259						2											9		43		2				2					
WP 50							2	1				26				236																	19		77		8				39					
WP 51																4																														
WP 52							1	3						1		21									1								3		4		2				3					
WP 53																223																	6		27		8				14					
WP 56																279		1															3		69		12				8					
WP 54							3	3								23																	16		7		1				2					
WP 57																1																	2								1					
Wp 58																1																	3													
WP 55						2		2								131																	3		8		5				2					
WP 59																10		1															3		2						1					
WP 60							1						4			222																	7				3				12					
WP 61							1									13		2															9		7		1				4					
WP 62	Pollen Zone 1						3					1				12																	5		7		2									
WP 86						1	5	1				1		2		10	1	7						2									7		13		4				5					
WP 87							2									10		1															4		4		4				1					
WP 88								1		2																1							2		2											
WP 89																3																			8											
WP 90								1				2				19		1	1														3		5		5				1					
WP 91						1			1							19																1	5		6		3									
WP 92				2				1				1				58									1								5		21		12				2					
WP 93				1		1		3			1	1		1		181		3															30		9						12					
WP 94							3					1				19	1								1								8		12						3					
WP 95							2									7																	2		15											
WP 96				5				2			1	1				114											4						8		121		32				29					8
WP 97										1						21		1								3							1		9		1				1					1
WP 98							2									24																	11		10		5									
WP 100						1	1	1		1						63																	15		11		7				5					
WP 99								1								7																	1				1				1					

Table 5.1: continuation

								ANG. HERBS						WATER PLANTS								SPORES																											
stratigraphy and mollusc biozones	pollen zonation	G.P.S. Way Point; sample number	Bárdarsons beds	thickness, m	sediment	dry weight sediment, g	*Lycopodium clavatum* (spike)	*Polycnemum*	*Trifolium*-type	Urticaceae, Moraceae	*Valeriana officinalis*-type	unknown periporate	total other angiosperm species	*Menyanthis trifoliata*	*Nuphar*	*Nymphaea*	*Persicaria amphibia*	*Potamogeton*	*Sparganium*-type	*Triglochin/Potamogeton*	total aquatic plants	*Dryopteris* sp.	Polypodiaceae	monolete; echinate (spores)	monolete; psilate (spores)	monolete; granular (spores)	monolete; reticulate (spores)	monolete; verrucate, small (spores)	monolete spores with perine	total monolete spores	*Bottrychium* sp.	*Huperzia* sp.	*Lycopodium annotinum*	*Lycopodium clavatum* (no spike)	*Osmunda regalis*	*Osmunda* sp.	*Selanginella selanginoides*	*Sphagnum* sp.	trilete;echinate (spores)	trilete; clavate (spores)	trilete; psilate (spores)	trilete; granular (spores)	trilete; verrucate (spores)	trilete; reticulate (spores)	trilete; rugulate (spores)	trilete; reticulate (>60µm; spores)	total trilete spores	trilete zonal	richness (number of spores taxa)
Breidavík Group, Torfhóll Member	Pollen Zone 6	WP 82	14	889,8	S	55,6	587						0								0									0																	0		0
		WP 83	14	888,5	M	54,4	1185						35								0		1							1			4														4		2
		WP 84	14	883,5	M	50,7	1360						18								0				3					3			1				2		1		1						5		5
		WP 85	14	878,9	M	63,1	307				1		48								0		1		19					20			1				3	3									7		5
Svarthamar Member		WP 77	12	835,0	C	63,8	565						2								0				2	1				3			1	3			1										5		5
		WP 69	10	823,4	M	44,3	190						56								0		1		3					4		2															2		3
		WP 70	10	819,8	M	54,2	281						12								0				11					11	5	3		2		1	1										12		6
		WP 71	10	817,2	M	46,6	2643				2		23								0		1		14					15					4	5	1		1	1			1				13	2	8
		WP 73	8	816,3	M	66,7	4227			1	2		36				1				0		4		19	1				24		1	4		10	38	4		9								66		9
		WP 68	8	813,0	S	53,1	3848						64								0		9		134		2			145					1	4	1	1			1	1					9		9
Fossgil		WP 67		782,0	M	58,1	1347						47							3	3				39					39			3		6	5		2	4					1			21		7
		WP 109		778,0	M	62,3	2242						17								0		5		16		1			22			4		28	20					1						53		7
Hörgi Formation		WP 101		769,0	M	48,0	2697						50								0		2		80					82			6		5	15			8	1	1		1	1			38		10
		WP 108		765,0	S	56,9	1506						160								0		16		63	2				81									26								26		4
		WP 102		762,1	M	48,5	2471			1			13								0		1		10					11			22				2		4		1						29		6
		WP 107		758,0	S	58,6	833						161								0		22		75	1				98			2						7	1	1		8				19		8
		WP 103		753,0	M	41,9	1072						108								0		4		33					37			13		5	4	1		3	2	2		2				32		10
		WP 104		752,5	M	54,6	1161						11								0		2		1					3			26						1		1						28		5
		WP 106		750,0	S	52,1	450						153					3			3		2		150		1			153			5				9		12		2		2				30		8
		WP 105		744,0	M	40,7	1529						90								0		3		50					53			13		8		4		28	15	1	1					70		9
Tjörnes beds, Serripes Zone	PZ 5	WP 43	24	478,0	CS,W	39,1	1716						2								0				1					1																	0		1
		WP 40	I	477,6	M	60,0	3864						1								0									0																	0		0
		WP 42	H	476,7	M	48,6	1005						1								0									0																	0		0
		WP 38	H	462,8	CS,W	72,3	2003						0								0									0																	0		0
		WP 37	G	452,6	M	41,8	895						14								0				1					1																	0		1
		WP 36	23	449,8	SH	43,6	1411						1								0		1							1																	0		1
		WP 31	22/23	447,0	CS	63,6	1187						7								0									0																	0		0
	Pollen Zone 4	WP 27	22	442,6	S	37,8	2361				1		52								0				172					172	3				1	2											6		4
		WP 28	21/22	439,4	S	59,4	2137				13	5	169								0				2004					2004	13	8	7	2	15	19		2	1								67		9
		WP 32	?	439,3	S	51,6	204						0								0									0																	0		0
		WP 24	21/22	427,2	S	62,2	1474				3		9								0		2		486					488		5	8			1					1						15		6
		WP 33	?	426,5	SH	62,1	2489				5	2	34								0				801					801	3	3	14														20		4
		WP 25	21	424,8	SH	66,5	3992				7	1	39			1					1				1617					1617		7	18			1					2						28		5
		WP 26	20/21	424,4	S	52,1	2375			2	5	7	81								0				1386					1386		9	39	1		1			1				2	1			54		8
		WP 23	20	423,7	SH	50,0	1269				4		41								0		11		805					816		4	4			2					1				1		12		7
		WP 22	19/20	422,9	S	39,2	764						12								0				90					90		1	1						2								4		4
		WP 21	19	422,2	SH	82,8	929				4		19								0		2		177					179			2						1				1				4		5
		WP 20	18/19	420,0	S	49,0	2253			2	8		83								0				605					605	11	3	2	2		2		1	1					1			23		9
		WP 19	18	417,6	SH	40,3	1262				1		8								0		4		250					254		1	2										1				4		5
		WP 18	17/18	415,8	S	52,6	1261				3	1	62								0	1			619			1		621	8		1		1	2		1	1								14		9
		WP 17	17/18	406,5	S	47,1	1176				5		34								0				426					426					3	4			1		1		2				11		6
		WP 16	17	402,2	S	53,5	2397				3		41								0				600					600			8	1	15	10		2	5		3		11				55		9
	Pollen Zone 3	WP 3	16	379,3	SH	44,1	1383				1		6								0				65					65			1						2								3		3
		WP 4	15/16	375,8	S	48,7	617				4	7	73								0				145					145			3					2									5		3
		WP 5	15	368,8	SH	50,5	1808						35								0				183					183			4		4	5			1								14		5
		WP 6	14/15	367,9	S	67,8	488				4	5	48								0				362				1	363		1		3		13			2								19		6
		WP 7	14	363,9	SH	53,9	591				2		14								0				170					170		1				5		1									7		4
		WP 8	13/14	360,1	S	45,2	191	9			11	120	327						5		5		1		2734					2735	2	2	11		1	10		4									30		8
		WP 9	13	359,2	S	70,5	151				4		20								0				285			5	1	291		2	1								1						4		6
		WP10	12/13	357,2	S	72,1	361				3	5	35								0				263					263			1			2		1	3								7		5
Mactra Zone		WP 11	12	356,0	S	56,0	1393				2	12	51								0		3		450			2		455	1	4	4			2		6			1						18		9
		WP 12	11	350,0	SH	51,7	3139				5	2	117								0		4		451					455	6	1	1		9	8		13	1			1		3			43		11
		WP 13	11	340,0	CS	41,7	3572				7	2	99								0		2		557					559	19	3	15			1		2		1				1			42		9
		WP 14	11	330,0	S	69,0	3676				6		110		1						1		1		794					795	29	5	32		2	4			2			1					75		9
		WP 44	10	295,0	SH	34,4	253				1		6								0				42					42			1														1		2
		WP 45	10	291,2	S	52,3	288						19								0		1		295					296		1										1					2		4
		WP 48	9	286,1	SH	41,6	1029			1			6								0				29					29		1															1		2
		WP 46	9	277,8	SH	57,2	1282				1		15								0		2		99					101					2	2			2								6		5
		WP 47	?	272,0	SH	46,8	184				1	4	18								0				302					302			1			1					1						3		4
	Pollen Zone 2	WP 49	F	260,5	L	2,4	17						321								0									0																	0		0
		WP 50	F	252,0	M,P	33,8	5				1		409								0				16					16																	0		1
		WP 51	E	244,0	CS	50,0	478						4								0				2					2																	0		1
		WP 52	8	230,0	SH	74,3	656				3		42								0		13		103					116		2	1								1						4		5
		WP 53	D	211,1	M,W	3,2	128				2		280						5		5		2		36					38			1					12					2				15		5
		WP 56	D	207,9	L	3,5	35				2		374								0									0																	0		0
		WP 54	D	203,7	L	34,2	77				11		66								0		10		542					552		4			4			1			2						11		6
		WP 57	7	195,3	S	46,8	566						4								0		2		16					18																	0		2
		Wp 58	7	188,0	M,W	3,4	1080						4								0									0																	0		0
		WP 55	7	185,0	S	38,2	25		1			1	155						8		8	1	4		125	1				131																	0		4
		WP 59	6	183,0	S	42,8	428						17								0				35					35						1											1		2
Tapes Zone		WP 60	C	145,0	L	2,4	51				1		250					2			2									0							26										26		1
		WP 61	C	144,0	S	31,7	1248						37								0		6		279					285		3	2				7					1					13		6
	Pollen Zone 1	WP 62	5	129,0	S	43,9	1620						30								0		11		324					335		6	10		1	4	7		1		3						32		9
		WP 86	4	83,2	S	47,7	1306				2		61	1							1		1		173					174		1	10				10		5				1				27		7
		WP 87	4	78,0	S	49,7	846				1		27			1					1		2		280					282		4	4		4		10		1	1			1				25		9
		WP 88	4	69,0	S	49,5	697						8								0				31					31			4				3		1		1						9		5
		WP 89	B	68,0	L	2,4	2						11					1			1									0																	0		0
		WP 90	3	66,2	S	49,9	149				1		39								0		2		294		1			297			4		3		4		2								13		7
		WP 91	3	65,1	S	38,0	531				1		37		1						1		2		275					277		3	8		8		3	1			3						26		8
		WP 92	c	45,0	L	2,5	6						103					53			53				203					203								4			11						15		3
		WP 93	2, b	36,2	L	2,6	6						243					5			5		1	1	15					17							1				2						3		5
		WP 94	2	35,3	S	48,7	343				1		49								0		3		266					269		2	3		3		3		5	1							17		8
		WP 95	2	29,4	S	38,4	1850				1		27								0		4		263					267		4	8			2	7	1					2				24		8
		WP 96	2, a	22,4	L	2,4	8						325								0				1					1											2						2		2
		WP 97	2	20,4	S	32,5	222				1		40								0		5		268					273		2	2		2	3	5										14		7
		WP 98	2	13,7	S	60,2	516						52					4		2	6		3		373	2				378			8		5		5		11	4	1			3	1	2	40		12
		WP 100	1	5,0	S	42,7	38				1		106						10		10	1	10		187					198			1		4	1	7	1	5	1			2				22		11
		WP 99	A	3,0	L	4,0	10						6								0	1			2					3																	0		2

Legend: L = lignite; M = mudstone; S = sandstone; CS = coarse sandstone; W = wood; P = plant remains; C = conglomerate; SH = shell remains

				INDICES											CLUSTERS										NON POLLEN PALYNOMORPHS																
stratigraphy and mollusc biozones		pollen zonation	G.P.S. Way Point; sample number	richness pollen	pollen indet.	spores indet.	total non reworked pollen (P)	total non reworked spores (S)	total non reworked pollen and spores (P + S)	*Lycopodium clavatum* (spike)	Total terrestrial palynomorphs (P+S+NPP)	Pollen concentration (# pollen/g dry sediment)	Spores concentration (# spores/g dry sediment)	Terrestrial palynomorph concentr. (P+S+NPP)	cluster of *Acer* pollen	cluster of Asteraceae Tubuliflorae pollen	cluster of *Betula* pollen	cluster of Cyperaceae pollen	cluster of *Juglans* pollen	cluster of Poaceae pollen	cluster of *Polygonum bistorta* pollen	cluster of monolete psilate spores	cluster of *Halodinium scopeum*	cluster of fungi	Arcella sp. T-352	Botryococcus sp.	zygospores of Mougeotia	Pediastrum sp.	cfr. T-128 (smooth)	T-128, globose microfossil	zygospores of Zygnemataceae	T-65, fungal spores	T-126, hyphopodia of Clasterosporium caricinum	Fungal germlings	Fungal mycelium	T-8B, fruit-body, Microthyrium sp.	leaf hair	stomata (leaf fragment)	scalariform perforation plate (woodvessel)	T-89, Tetraploa aristata, fungus	Total terrestrial NPP
Breidavik Group	Torfholl Member	Pollen Zone 6	WP 82	1	1		1	0	1	587	52	1	0	30																					51						51
			WP 83	9	6	0	39	5	44	1185	179	11	1	52															1							135						135
			WP 84	14	4	2	37	8	45	1360	51	10	2	14												1		6		1	1				6						6
			WP 85	15	10		88	27	115	307	115	84	26	110						1						7		29		1											0
	Svarthamar Member		WP 77	2	1		3	8	11	565	12	2	4	6															1											1		1
			WP 69	[illegible]			63	6	69	190	69	139	13	152												3		4													0
			WP 70	8	2	2	21	23	44	281	45	26	28	55												2		16			2								1		1
			WP 71	14	5	2	101	28	129	2643	136	15	4	21												16		9			1						1		6		7
			WP 73	22	20	13	169	90	259	4227	266	11	6	18												17		5											7		7
			WP 68	23	18	9	169	154	323	3851	328	15	14	30												10		23									2		3		5
	Fossgil		WP 67	23	28	3	261	60	321	1347	334	62	14	79																										13		13
			WP 109	10	24	17	220	75	295	2242	314	29	10	42												6	1	6		4				13					6		19
	Horgi Formation		WP 101	23	15	12	207	120	327	2697	339	30	17	49								1				13		11							2				10		12
			WP 108	17	42	26	239	107	346	1506	347	52	23	75												2		97		7									1		1
			WP 102	8	6	2	60	40	100	2471	101	9	6	16												3		3											1		1
			WP 107	19	78	39	240	117	357	833	360	91	45	137						1						8		41		1									3		3
			WP 103	15	23	8	257	69	326	1072	333	106	29	138												2		3		3					4				3		7
			WP 104	13	6	2	45	31	76	1161	76	13	9	22															1		1											0
			WP 106	22	48	37	258	183	441	450	444	204	145	352			1										5		52		3									3		3
			WP 105	16	49	10	290	123	413	1529	419	87	37	125		1		1									3		10		3									6		6
Tjörnes beds	Serripes Zone	PZ 5	WP 43	3			4	1	5	1716	13	1	0	4												11		2		1				8							8
			WP 40	2		1	2	0	2	3864	2	0	0	0																											0
			WP 42	2			2	0	2	1005	130	1	0	49												4				6				128							128
			WP 38	0			0	0	0	2003	0	0	0	0																											0
			WP 37	3			15	1	16	895	16	7	0	8												2				1											0
			WP 36	2			2	1	3	1411	3	1	0	1																											0
			WP 31	4	1		9	0	9	1187	109	2	0	27												3				1				100							100
		Pollen Zone 4	WP 27	16	6	7	61	178	239	2361	240	13	37	50								1			6					3	1								1		1
			WP 28	22	17	8	281	2071	2352	2137	2358	41	303	345												16		4		1	1								6		6
			WP 32	0			0	0	0	204	1	0	0	2																				1							1
			WP 24	12		3	22	503	525	1474	525	4	102	106												4		1													0
			WP 33	12	3	3	48	821	869	2489	890	6	99	107											2	4		2		3	2			14				7			21
			WP 25	14	11	19	69	1645	1714	3992	1714	5	115	120												14		3		1											0
			WP 26	16	26	5	126	1440	1566	2375	1566	19	216	235											13	7				5											0
			WP 23	18	8	2	79	828	907	1269	907	23	243	266												8		2		2											0
			WP 22	10	1		22	94	116	764	118	14	58	73												2		2		1								1	1		2
			WP 21	9		6	30	183	213	929	217	7	44	52												1		4		1								4			4
			WP 20	20	18	5	132	628	760	2253	764	22	106	129										1	12	8		6										2	2		4
			WP 19	7	3	4	20	258	278	1262	279	7	94	102								1				4												1			1
			WP 18	15	19	3	93	635	728	1261	729	26	178	204											1	3		8		4									1		1
			WP 17	14	7	7	65	437	502	1176	503	22	146	169									1			2		1		2									1		1
			WP 16	20	11	24	124	655	779	2397	779	18	95	113										1		9		2		1											0
		Pollen Zone 3	WP 3	10	2	3	67	68	135	1383	135	20	21	41												2															0
			WP 4	16	7		341	150	491	617	499	211	93	309												1		3		64	1							7	1		8
			WP 5	15	4	6	342	197	539	1808	544	70	40	111												1		7		3								4	1		5
			WP 6	20	4	6	357	382	739	488	739	201	215	415												4		2													0
			WP 7	13	6	6	156	177	333	591	335	91	103	195																									1	1		2
			WP 8	24	19	3	1300	2765	4065	191	4068	2796	5948	8751												13		4		8						1		1	1		3
			WP 9	15	5	2	289	295	584	151	593	504	515	1035												5		199		12								8		1	9
			WP10	18	4	1	331	270	601	361	601	236	193	429												3		3													0
	Mactra Zone		WP 11	19	7	3	547	473	1020	1393	1023	130	113	244												3				2									3		3
			WP 12	22	12	14	509	498	1007	3139	1012	58	57	116												11		3						1					4		5
			WP 13	20	11	11	615	601	1216	3572	1216	77	75	152								1				4		4													0
			WP 14	20	9	12	497	870	1367	3676	1367	36	64	100												7		9		1	5										0
			WP 44	6			14	43	57	253	57	30	92	122												1															0
			WP 45	13	14	50	70	298	368	288	368	86	368	454															3		1											0
			WP 48	5	4	11	10	30	40	1029	40	4	13	17															1													0
			WP 46	9	12	10	41	107	148	1282	148	10	27	37																											0
			WP 47	9	21	46	27	305	332	184	333	58	658	719															1							1						1
		Pollen Zone 2	WP 49	12	20		332	0	332	17	340	154432	0	158153																	1			5			1			2		8
			WP 50	12	65		439	16	455	5	455	48272	1759	50031																52	26											0
			WP 51	1	2		5	2	7	478	7	4	2	5																											0
			WP 52	15	10	2	49	120	169	656	170	19	46	65												1				3									1		1
			WP 53	10	34	6	313	53	366	128	368	14156	2397	16644												4		36		1									2		2
			WP 56	9	25	1	379	0	379	35	379	57167	0	57167							1									1											0
			WP 54	17	14	17	101	563	664	77	664	712	3968	4680												3		1			1										0
			WP 57	4			9	18	27	566	27	6	13	19															1													0
			Wp 58	5	2		21	0	21	1080	21	107	0	107																											0
			WP 55	16	12	6	200	131	331	25	338	3892	2549	6577												4				5									7		7
			WP 59	9	2	1	58	36	94	428	94	59	37	95																	6											0
	Tapes Zone		WP 60	**11**	**23**	**1**	**256**	**26**	**282**	**51**	**286**	**39358**	**3997**	**43971**				1																	3						1		4
			WP 61	10	5	4	58	298	356	1248	356	27	140	167												2		72		1											0
		Pollen Zone 1	WP 62	12	15	6	61	367	428	1620	428	16	96	112												4		1		1											0
			WP 86	26	5	11	152	201	353	1306	355	45	60	106															5		4									2		2
			WP 87	17	3	2	71	307	378	846	380	31	136	168												4		1		1									2		2
			WP 88	12	8	2	291	40	331	697	331	157	22	178	1				1												2											0
			WP 89	4	7		14	0	14	2	16	55354	0	63261																									2		2
			WP 90	19	8	9	78	310	388	149	389	195	775	972												2					1									1	1
			WP 91	13	19	16	58	303	361	531	362	53	279	333												5		2		5									1		1
			WP 92	13	32	23	174	218	392	6	432	212168	265820	526762																		1	39								40
			WP 93	18	49	3	329	20	349	6	349	391911	23824	415735												7															0
			WP 94	15	10	2	114	286	400	343	401	127	318	446												1		6	1										1		1
			WP 95	8	6	4	40	291	331	1850	331	10	76	87												2		3													0
			WP 96	15	58		364	3	367	8	367	346527	2856	349383																	2											0
			WP 97	15	10	5	87	287	374	222	378	224	738	972												7		3											4		4
			WP 98	13	23	23	82	418	500	516	504	49	250	302												3		11		4					3			1			4
			WP 100	18	10	6	234	220	454	38	459	2677	2517	5252												4		1		2									5		5
			WP 99	**8**	**5**		**10**	3	13	10	14	4705	**1411**	6566																									1			1

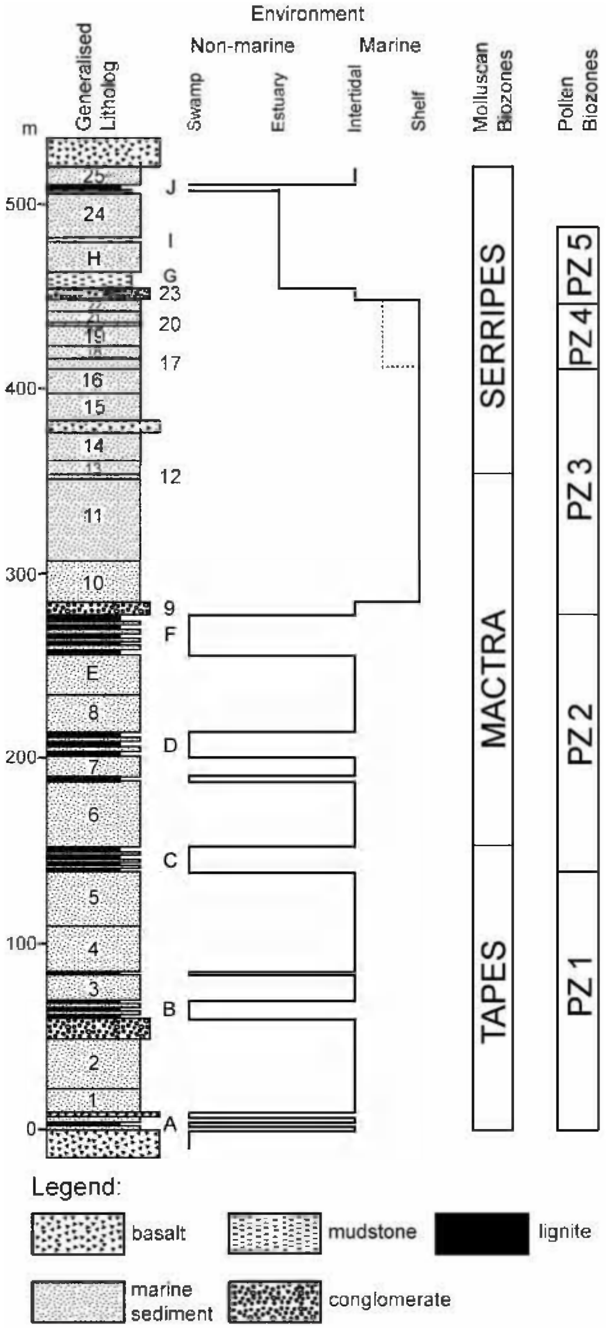


Figure 5.3: Palaeoenvironmental evolution of the depositional basin of the Tjörnes beds based on molluscs and lithology (after Buchardt and Símonarson, 2003). The inset of the dashed line represents the sea level lowering as indicated by PZ 4. PZ = Pollen Zone

Subsidence decreased during deposition of the upper part of the *Serripes* Zone (horizons 23 to 25) and led to the formation of a highly energetic estuarine depositional environment, later evolving into a swamp and littoral environment during deposition of the uppermost part of the *Serripes* Zone (Figure 5.3). In units H and 24, remains of tree trunks occur.

The relative dating with dinoflagellate cysts indicates a post-Miocene age for the *Tapes* and *Mactra* Zones, while the *Serripes* Zone was deposited sometime between c. 4.5 Ma and 4.0 Ma (Verhoeven *et al.*, 2011) (Figure 5.2). The entire Tjörnes beds were thus deposited during Early Pliocene times, apparently before 4.0 Ma. The Tjörnes beds emerged for the first time around c. 4.0 Ma and became covered by the Upper Pliocene basaltic Höskuldsvík lavas.

A glacial-interglacial alternation of tillites and marine sediments characterise the following Pleistocene Breidavík Group. Eiríksson *et al.* (1990, 1992) described a total of 14 glacial-interglacial cycles in this group. Later during Late Pleistocene times, the entire Tjörnes section was uplifted and is nowadays exposed in cliffs along the coast (Figure 5.1).

3. Material and methods

A total of 88 samples from the Pliocene Tjörnes beds and from four of the 14 interglacial deposits from the Breidavík Group (Hörgi Formation, Fossgil Member, Svarthamar Member and the Torfhóll Member) were analysed. All samples originate from the coastal cliffs on the western part of the Tjörnes Peninsula, except the Fossgil samples that came from a small valley. Each unit of the sequence as subdivided by Bárdarson (1925) has been sampled at least once with an average sampling interval of 6.5 m (Figures 5.2, 5.3; Table 5.1).

Rather large samples of 50 to 90 g of sediments were macerated as the marine sediments usually yield a poor pollen assemblage (Akhmetiev *et al.*, 1978; Willard, 1994). Lignites on the other hand consist entirely of organic material and small amounts of circa 2 cm^3 suffice. Notwithstanding the high pollen concentration in the lignites, large amounts of amorphous organic debris often hampered the counting of the pollen.

In order to make absolute concentration calculations possible, one *Lycopodium clavatum* marker tablet (batch 483216; 18583±1708 spores/tablet) was added to every sample. The standard treatment with 5% KOH, followed by an acetolysis with 1/10 sulphur acid (H_2SO_4) and 9/10 acetic anhydride ($C_4H_6O_3$), was applied to the eight lignite samples.

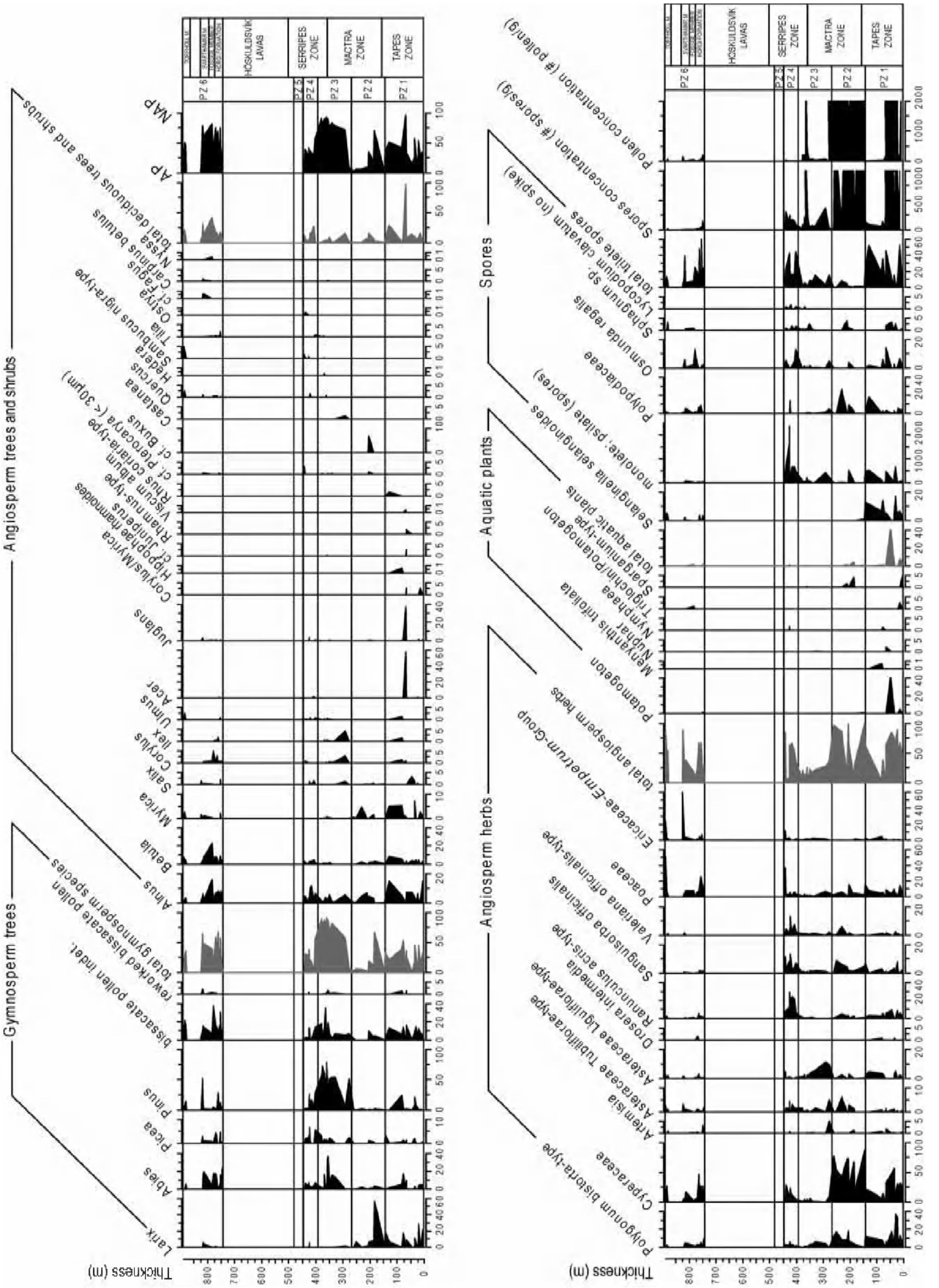


Figure 5.4: Pollen diagram with relative abundances of selected pollen and spore plants from the Tjörnes section. Percentages are calculated versus the total pollen sum. Only the samples with more than 30 pollen grains in the pollen sum are shown. The highest values of the pollen and spores concentrations are levelled off to 1000 and 2000 specimens/g for visualization of the lower values variations.

The marine sediments were crushed into fragments of maximum 1 cm diameter, washed, oven-dried (58°C) for one day and macerated with cold 2M HCl (6.1%) and cold 40% HF in order to remove respectively the carbonates and silicates. Repeated cycles (3 to 7) of hot (60°C) 2M HCl were needed to remove newly formed fluorosilicates, for the sediments were heavily saturated with silica derived from decomposed basalts as reported also by Akhmetiev, *et al.* (1978). Some of the rocks did not dissolve entirely, even after two cycles of HF treatments. Undissolved particles were removed from the residue through decanting. Heavy liquid separation with $ZnCl_2$ (ρ=1.93 kg/l) was applied three times for the removal of heavy minerals. The residues were sieved after every step on a nylon sieve with a 10 µm mesh size in order to avoid loss of palynomorphs. The residue was finally stained with safranin-o and mounted on glass slides with glycerine-gelatine jelly. The microscopic analysis was carried out with a Zeiss Axio Imager A1 microscope under 400x and 1000x magnification. Photomicrographs were taken with an Axiocam MR5c camera. For the identification of the pollen, the works by Fægri and Iversen (1989), Moore *et al.* (1991), Kapp *et al.* (2000), Reille (1998, 1999) and Beug (2004) were followed. The classification and nomenclature of pollen types of the latter author was used, except for the Asteraceae, which were subdivided into the Tubiliflorae and Liguliflorae-type according to Punt and Clarke (1984). The pollen sum includes all higher plants with the exception of the aquatic plants.

4. Results

More than 38000 terrestrial palynomorphs and almost 8400 marine palynomorphs were counted (Table 5.1). It proved difficult to obtain minimum counts of 300 dinoflagellate cysts and pollen in each sample, as the sedimentary environments were sometimes favourable for dinoflagellate cysts, sometimes for pollen, but seldom for both. The nearshore location of the samples is unique for it allows the reconstruction of a combined record of local pollen and dinoflagellate cysts.

A diverse flora with gymnosperms (6 pollen types), angiosperm trees and shrubs (25 pollen types), angiosperm herbs (50 pollen types), aquatic plants (7 pollen types) and spores (8 monolete and 17 trilete spores types) is recorded throughout the sequence (Figure 5.4). Most of the plants do not occur in Iceland today and indicate a warmer Pliocene and Early Pleistocene climate. Differences in the dominance of certain taxa were used to distinguish five pollen zones in the Tjörnes beds. The samples from the Breidavík Group can be grouped into a sixth pollen zone.

4.1 Pollen zone 1

This zone (0–140 m, 16 samples) spans the sediments from lignite A to horizon 5 of the *Tapes* Zone (Figure 5.3). It is characterised by a moderate numbers of Cyperaceae (c. 30%), the presence of a variety of aquatic plants (*Menyanthes trifoliata*, Plate 5.3F; *Nuphar*; *Nymphaea*; *Potamogeton*; *Sparganium*) and gymnosperms (*Abies*, Plate 5.1C; *Larix*, Plate 5.1F; *Picea*, Plate 5.1B; *Pinus*, Plate 5.1A and *Tsuga mertensiana*, Plate 5.1D). Cyperaceae (Plate 5.2L), *Polygonum bistorta*-type (Plate 5.2E, 5.2F), *Ranunculus acris* (Plate 5.2M, 5.2N), *Sanguisorba officinalis* (Plate 5.2C, 5.2D) and *Valeriana officinalis* are prominently present in the lower part of the zone but decline in the second part. *Selaginella selaginoides* (Plate 5.3S, 5.3T) occurs in PZ 1 with a fairly constant relative abundance (c. 10%). With the exception of lignite C in the base of PZ 2, it is restricted in the Tjörnes beds to the first pollen zone. Sample WP88 in the middle of PZ 1 is noteable as it is dominated by *Acer* (57%, Plate 5.1M, 5.1N) and *Juglans* (37%, Plate 5.1O, 5.1P). These pollen appear not only as individual grains, but also in clusters of unripe or less developed pollen. A minor occurrence of *Myrica* (Plate 5.1G), *Corylus* and *Viscum album* (Plate 5.1R) is also observed in this sample. The herbs in this sample represent only 3% and the gymnosperm trees are represented only by *Pinus* (0.3%). The warmth-loving plant *Ilex* (Plate 5.1I) occurs in the top of the zone, together with a single find of *Hippophae rhamnoides* (Plate 5.3D). *Drosera intermedia* (Plate 5.2K) was recorded in two levels of PZ 1.

4.2 Pollen zone 2

This zone (140–265 m, 13 samples) spans the top of the Tapes Zone (horizon C) up to lignite F in the *Mactra* Zone (Figure 5.3). Cyperaceae pollen increases in this zone to c. 60%, and becomes the dominant taxon. The base of this increase forms the lower limit of PZ 2. A distinct decline of the gymnosperm pollen is observed. *Abies* and *Pinus* disappear almost completely, only *Larix* and, to a limited extent, *Picea* are still present in this zone. Spores are also still present, but *Huperzia* (Plate 5.3I, 5.3J), *Lycopodium annotinum* (Plate 5.3O, 5.3P) and *Osmunda regalis* (Plate 5.3Q, 5.3R) show now lower values. Monolete psilate spores (Plate 5.3L) and *Polypodium* do not show a decline. The latter genus even reaches a maximum value of 20% in PZ 2.

Lignite beds occur mainly in the *Tapes* and lower part of the *Mactra* Zone (Table 5.1) and are an important component in PZ 1 and 2. These beds are characterised by high values of Cyperaceae (up to 88%) and *Polygonum bistorta*-type (up to 33%). Pollen of angiosperm trees such as *Alnus* (Plate 5.1S), *Myrica* and *Salix*, species adapted to wet environments, are also found in the lignites. The relative abundance of gymnosperms is variable, with *Larix* and *Pinus* constituting the most prominent species. Aquatic plants such as *Sparganium* and *Potamogeton* are present, but are not restricted to this type of sediments. They occur in small numbers in PZ 1 and 2, together with other aquatic plants such as *Nuphar*, *Nymphaea*, *Menyanthes trifoliata* and probably *Triglochin*. The lignite beds show a variable but remarkably higher pollen concentration (c. 700 – 400.000 pollen/g) than the marine sediments (c. 5 – 4000 pollen/g), as was expected.

4.3 Pollen zone 3

This zone spans the sediments from horizon 9 in the *Mactra* Zone to horizon 16 in the *Serripes* Zone (265–390 m, 17 samples) (Figure 5.3). *Pinus* (c. 50%), *Abies* (c. 15%) and *Picea* (c. 5%) dominate the zone, but *Larix* disappears almost entirely from the assemblages. Angiosperm herbs show a low relative abundance of c. 20%. The almost continuous presence of *Ilex* pollen through the zone is noteworthy. The Asteraceae Liguliflorae-type (Plate 5.2A) has a maximum abundance of c. 10% in the base of the zone but declines rapidly. *Myrica*, present with a relative abundance of 5 to 8% in the two preceding zones, disappears of the Tjörnes beds from this zone. Monolete and trilete spores have their lowest values in PZ 3.

4.4 Pollen zone 4

A major increase in the abundance of spores is observed in this zone (390–445 m, 15 samples), which spans the sediments from horizon 17 to horizon 22 (Figure 5.3). Monolete psilate spores dominate, with values up to 24 times that of the pollen. *Botrichium* (Plate 5.3K), *Huperzia*, *Lycopodium annotinum*, *Lycopodium clavatum* and undetermined trilete spores are also present. A remarkable increase and maximum values for *Ranunculus acris*, *Valeriana officinalis*, *Thalictrum* and *Sanguisorba officinalis* are observed. Up to this level, the Ericaceae–*Empetrum* group was apparently a minor element in the local vegetation, and manifests itself for the first time in PZ 4. The relative abundances of *Alnus* (10%) and *Betula* (5%) (Plate 5.1H) rise again. The pollen concentration plunges sharply in the zone.

In PZ 2 to 4, an unknown, small (c. 25 µm) periporate pollen was found (Plate 5.3G, 5.3H). The pollen has most of the times four pores which are not always well pronounced, without costae or annuli and without operculum. The c. 1.5 µm long and clearly visible columellae are individually placed. The wall consists of a thin nexine and a thick sexine that is not tectate. The pores are round and their diameters vary between 3 and 4 µm.

4.5 Pollen zone 5

This zone (445–480 m, 7 samples) spans the samples from unit 22/23 to unit 24 in the upper part of the *Serripes* Zone (Figure 5.3), but is almost devoid of pollen. A few spores and some pollen of *Alnus*, *Betula* and Poaceae (Plate 5.2I) were found, but their limited numbers preclude interpretation of their presence.

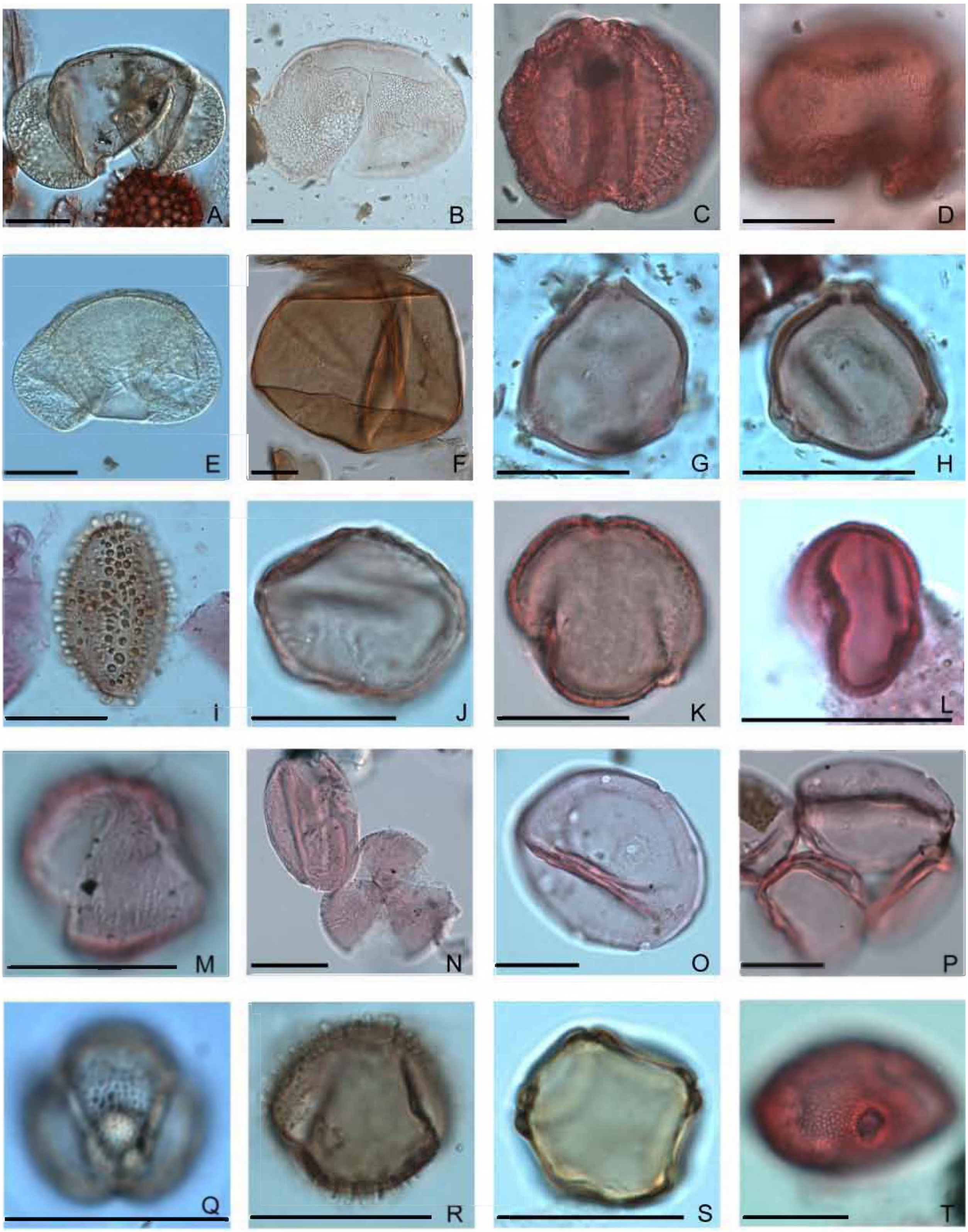


Plate 5.1: Photomicrographs of selected tree and shrub species. Scale bar equals 20 µm. A. *Pinus* sp., sample WP9, *Serripes* Zone, E.F.: J61. **B.** *Picea* sp., sample WP5, *Serripes* Zone, E.F.: D49/1. **C.** *Abies* sp., sample WP26, *Serripes* Zone, E.F.: G 49/1. **D.** *Tsuga mertensiana*, sample WP 86, *Tapes* Zone, E.F.: S52/4. **E.** *Cedrus* sp., sample WP98, *Tapes* Zone, E.F.: V50/2. **F.** *Larix* sp., sample WP100, *Tapes* Zone, E.F.: Q44. **G.** *Myrica* sp., sample WP8, *Serripes* Zone, E.F.: W53. **H.** *Betula* sp., sample WP8, *Serripes* Zone, E.F.: Y30. **I.** *Ilex* sp., sample WP10, *Serripes* Zone, E.F.: F31/1. **J.** *Ulmus sp.*, sample WP86, *Tapes* Zone, E.F.: Z40/2. **K.** *Quercus* sp., sample WP73, Svarthamar Member, E.F.: P39/2. **L.** *Castanea* sp., sample WP45, *Mactra* Zone, E.F.: W51. **M.** *Acer* sp., sample WP88, *Tapes* Zone, E.F.: W52/2. **N.** cluster *Acer* sp., sample WP 88, *Tapes* Zone, E.F.: X49. **O.** *Juglans* sp., sample WP88, *Tapes* Zone, E.F.: Z42/2. **P.** cluster *Juglans* sp., sample WP88, *Tapes* Zone, E.F.: M64/1. **Q.** *Sambucus nigra*-type, sample WP84, Torfhóll Member, E.F.: W54/4. **R.** *Viscum album*, sample WP88, *Tapes* Zone, E.F.: L49/2. **S.** *Alnus* sp., sample WP100, *Tapes* Zone, E.F.: Y49/4. **T.** *Tilia* sp., sample WP101, Hörgi Formation, E.F.: H32/1.

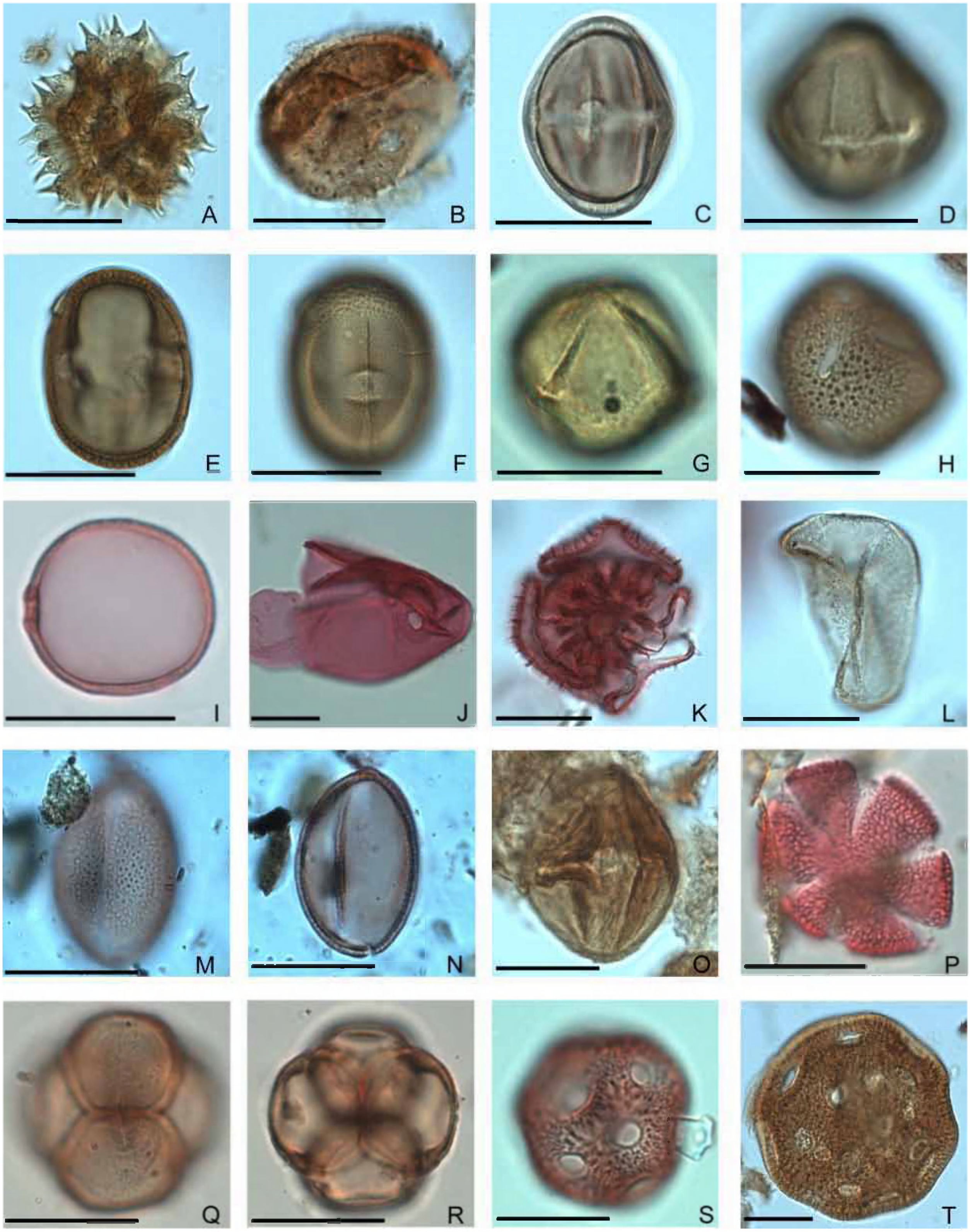


Plate 5.2: Photomicrographs of pollen of selected herbs. Scale bar equals 20 µm. A. Asteraceae Liguliflorae-type, sample WP100, *Tapes* Zone, E.F.: Z41/4. **B.** *Jasiona montana*-type, sample WP92, *Tapes* Zone, E.F.: Q29. **C.** *Sanguisorba officinalis*, sample WP97, *Tapes* Zone, E.F.: O40. **D.** *Sanguisorba officinalis*, sample WP100, *Tapes* Zone, E.F.: D46/2. **E–F.** *Polygonum bistorta*-type, sample WP61, *Tapes* Zone, E.F.: N42. **G.** *Solanum nigrum*-type, sample WP84, Torfhóll Member, E.F.: Y53/1. **H.** *Koenigia islandica*, sample WP97, *Tapes* Zone, E.F.: Z55/4. **I.** Poaceae sp., sample WP28, *Serripes* Zone, E.F.: Q42/1. **J.** Poaceae sp. >50 µm, sample WP101, Hörgi Formation, E.F.: X40/2. **K.** *Drosera intermedia*, sample WP86, *Tapes* Zone, E.F.: W60/2. **L.** Cyperaceae sp., sample WP91, *Tapes* Zone, E.F.: Z54/3. **M–N.** *Ranunculus acris*-type, sample WP8, *Serripes* Zone, E.F.: U53/3. **O.** *Gentiana pneumonanthe*-type, sample WP60, *Tapes* Zone, E.F.: Q34/1. **P.** *Mentha*-type, sample WP28, *Serripes* Zone, E.F.: T44/4. **Q–R.** Ericaceae-*Empetrum* group, sample WP24, *Serripes* Zone, E.F.: N47/1. **S.** Carylophylaceae sp., sample WP13, *Mactra* Zone, E.F.: X48/4. **T.** *Agrostemma githago*, sample WP49, *Mactra* Zone, E.F.: X47/4.

Plate 5.3: Photomicrographs of trees, herbs and spore plant. Scale bar indicates 20 µm. A–B. *Fagus* sp., sample WP14, *Mactra* Zone, E.F.: N39/3. **C.** *Juniperus* sp., sample WP24, *Serripes* Zone, E.F.: V43. **D.** *Hippophae rhamnoides*, sample WP24, *Serripes* Zone, E.F.: Y53. **E.** *Persicaria amphibia*, sample WP73, Svarthamar Member, E.F.: letter R from "Finder". **F.** *Menyanthes trifoliata*, WP86, *Tapes* Zone, E.F.: U55. **G–H.** unknown periporate, sample WP8, *Serripes* Zone, E.F.: G26. **I.** *Huperzia* sp., sample WP14, *Mactra* Zone, E.F.: E41/1. **J.** *Huperzia* sp., sample WP86, *Tapes* Zone, E.F.: Y50/2. **K.** *Botrychium* sp., sample WP12, *Mactra* Zone, E.F.: X56/4. **L.** monolete psilate, sample WP100, *Tapes* Zone, E.F.: Z55/2. **M.** *Sphagnum* sp., sample WP8, *Serripes* Zone, E.F.: U48/3–4. **N.** trilete spore verrucate?, sample WP90, E.F.: Z47. **O–P.** *Lycopodium annotinum*, sample WP26, *Serripes* Zone, E.F.: Q59/4. **Q–R.** *Osmuda regalis*, sample WP5, *Serripes* Zone, E.F.: T52. **S.** *Selanginella selanginoides* (tetrade), sample WP91, *Tapes* Zone, E.F.: T45/1. **T.** *Selanginella selanginoides* (monade), sample WP91, *Tapes* Zone, E.F.: V58/1.

4.6 Pollen zone 6

This zone (740–890 m, 20 samples) contains the interglacial sediments of the Breidavík Group (Figure 5.3). An increase in pollen of angiosperm herbs and a decrease in deciduous trees/shrubs and gymnosperms pollen can be observed in these deposits. *Pinus* and *Abies* are found in the four studied interglacials and their numbers decrease as one moves up the sequence. *Picea* displays the same trend and has a highest occurrence in the Svarthamar Member. *Larix* is recorded in the Hörgi Formation (0.3–1%) and the Svarthamar Member (4–5%). *Alnus*, *Betula*, *Quercus* (Plate 5.1K), *Salix*, *Myrica*, *Sambucus nigra*-type (Plate 5.1Q), *Tilia* (Plate 5.1T) and *Ulmus* (Plate 5.1J) are still present. Some *Ilex* (0.5 and 1.7%) was recorded in the uppermost part of the Hörgi Formation. The Cyperaceae decrease, but the Ericaceae–*Empetrum* group (Plate 5.2Q, 5.2R), typical for heathland, and the Poaceae show an increase in relative abundance. Heath pollen was already present in low numbers in the Tjörnes beds (PZ 1–4), becoming somewhat more frequent in the upper part of PZ 4, but the real manifestation of heath becomes visible in PZ 6. The pollen and spores concentration of this zone show a gradual upward decrease.

4.7 Clusters of pollen and spores

The preservation of the pollen throughout the entire section was good. Moreover, pollen clusters of *Acer* (Plate 5.1N), Cyperaceae, *Juglans* (Plate 5.1P), *Polygonum bistorta*-type and monolete psilate spores are recorded in the Tjörnes beds, as already noted for PZ 1. These clusters point to the presence of anthers in the sediment and no doubt limited transport. Clusters of Asteraceae Tubiliflorae, *Betula*, Poaceae, Cyperaceae and monolete psilate spores are recorded higher up in the Breidavík Group. The distribution of the clusters is indicated in Table 5.1.

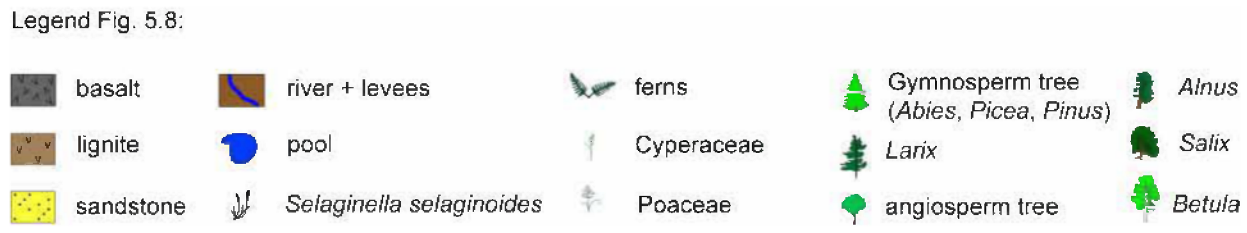
5. Discussion

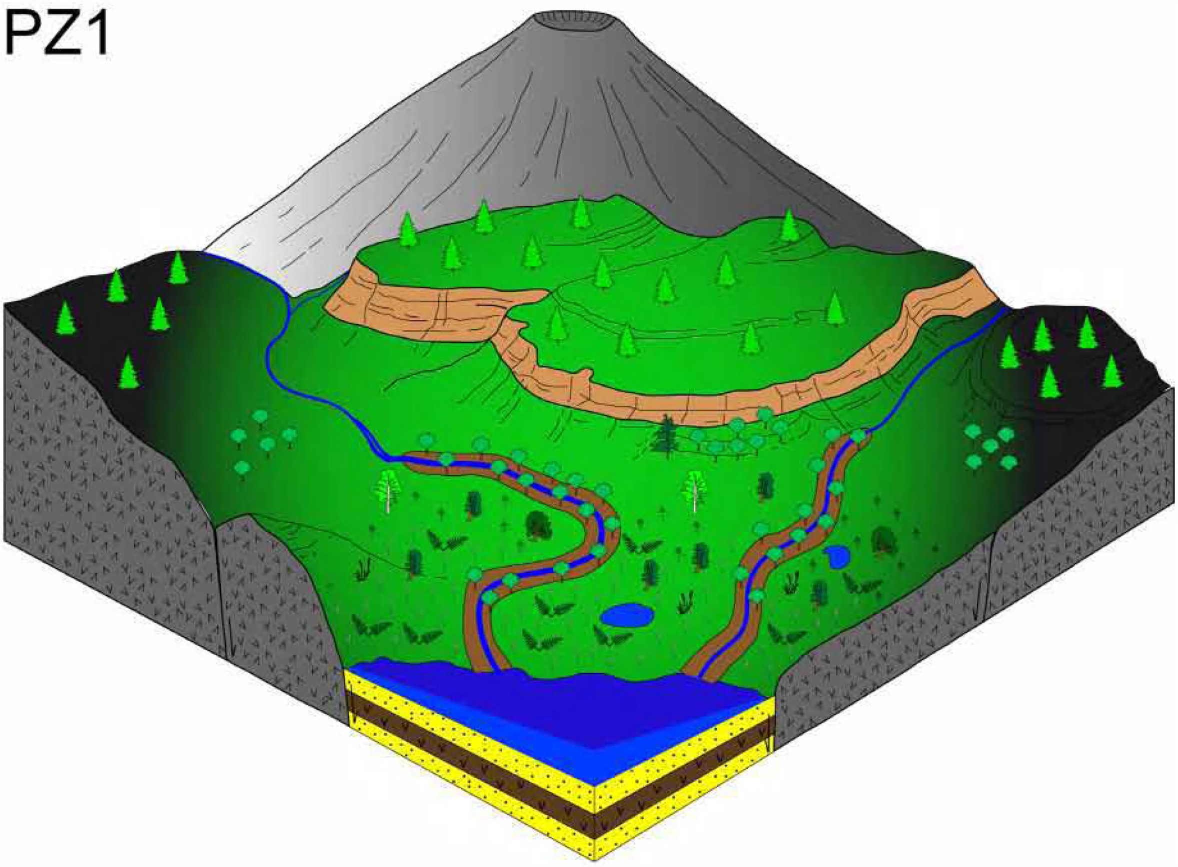
5.1 Vegetation reconstruction and sea-level changes

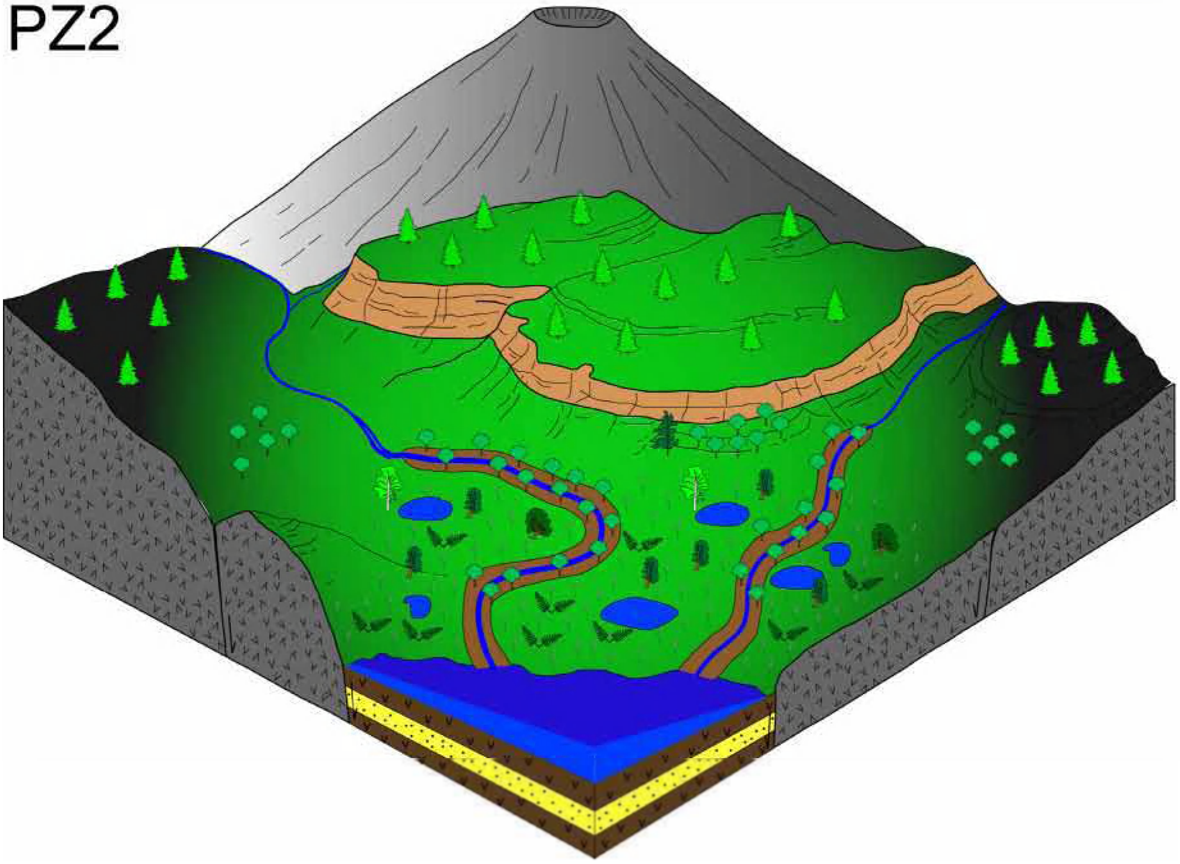
Selaginella selaginoides is continuously present in PZ 1 and in lignite C at the base of PZ 2, but absent in younger deposits of the Tjörnes beds, a fact already observed by Akhmetiev *et al.* (1978). This plant is today a very common element of dry heathland and pastures in Iceland (Kristinsson, 2005), habitats that probably disappeared or were drastically reduced in the Tjörnes area after deposition of PZ 1. *S. selaginoides* is a poor competitor and does not grow in areas with tall, dense vegetation. *S. selaginoides* indicates an open coastal landscape without other shrubs or trees. *Pinus* and *Betula* are not adapted to saline environments and would have been located landward of the coastal plain.

Pollen of the insectivorous plant *Drosera intermedia* is recorded in two levels of PZ 1. This quite rare plant is a key species of the *Lycopodium–Rhynchosporetum*–association (Bog Clubmoss–Beak-Sedge–association) and represents a pioneering vegetation on nutrient free soils without trees and shrubs, and with a poor but specific herb layer (*Erica tetralix*, Poaceae, mosses). *D. intermedia* thrives around pools in open sunny places in bogs and colonizes the wetter parts of the coastal plain. Today *D. rotundifolia* is the only representative of the genus in Iceland and found in comparable habitats of mossy hummocks in acid bogs and boggy edges below hillsides (Kristinsson, 2005).

Figure 5.5: Evolution of the Tjörnes area during Pliocene and Early Pleistocene times. The reconstructions reflect the six pollen zones. Schematic block diagram adapted from Denk *et al.* (2011).




PZ1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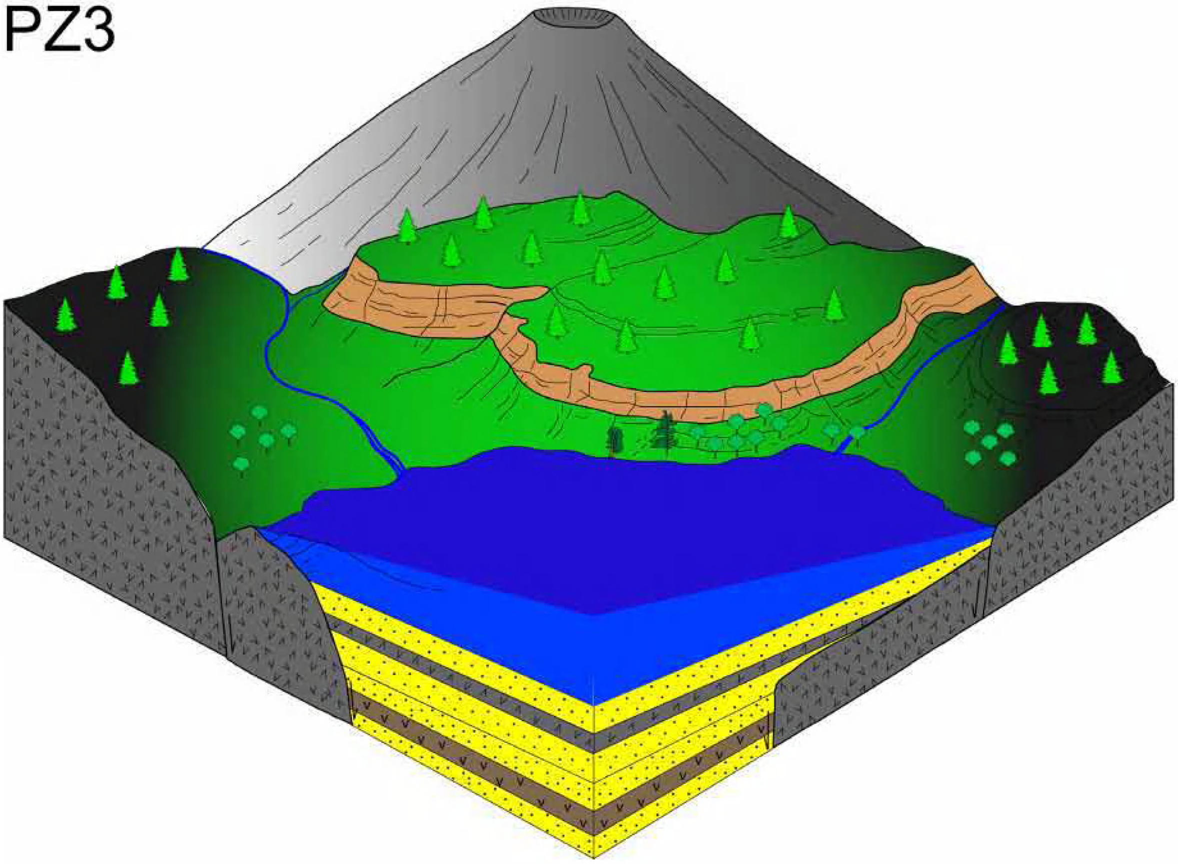
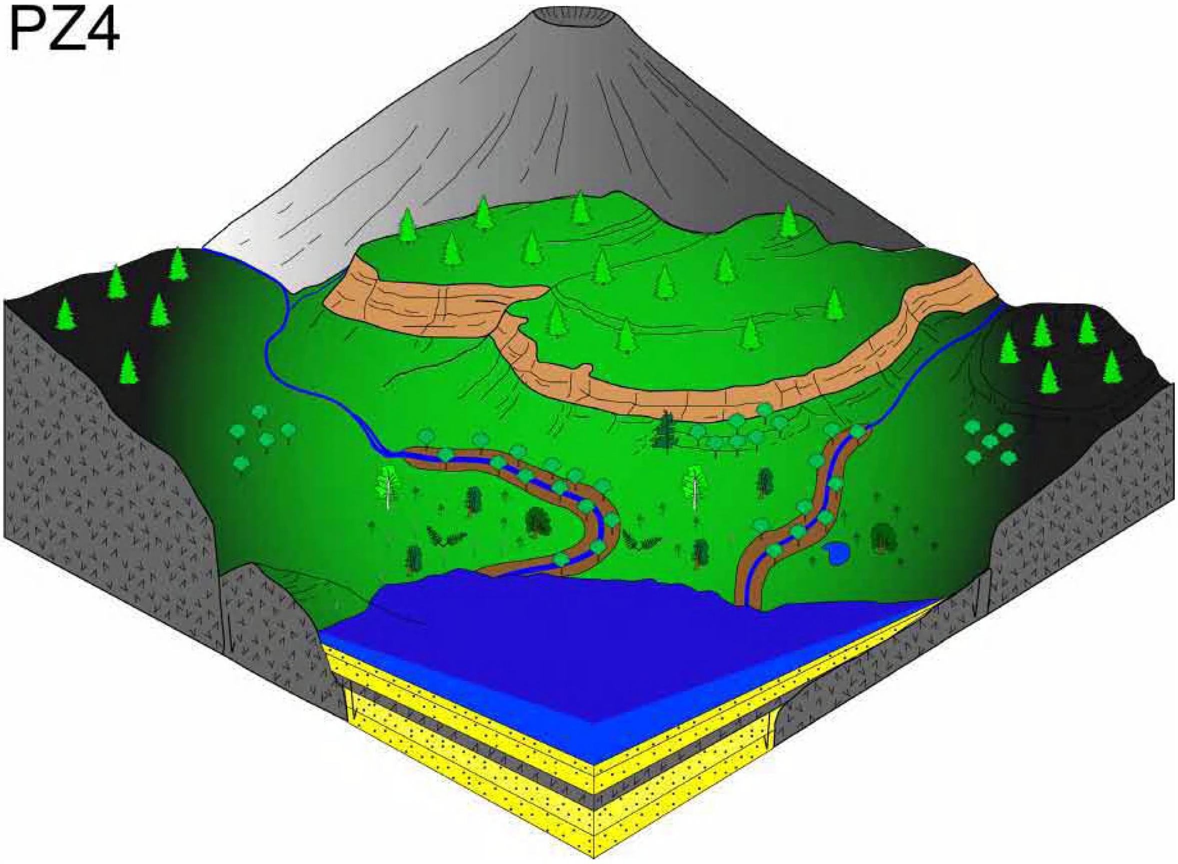
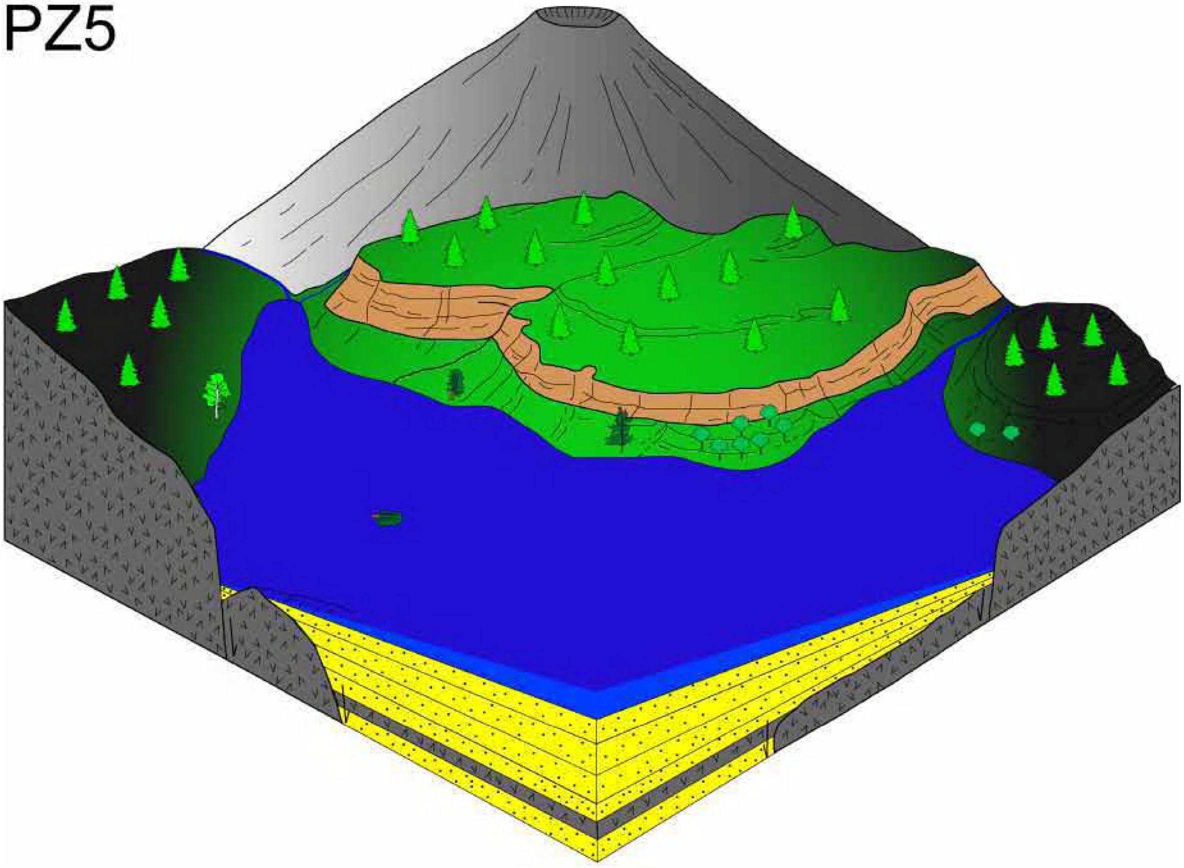


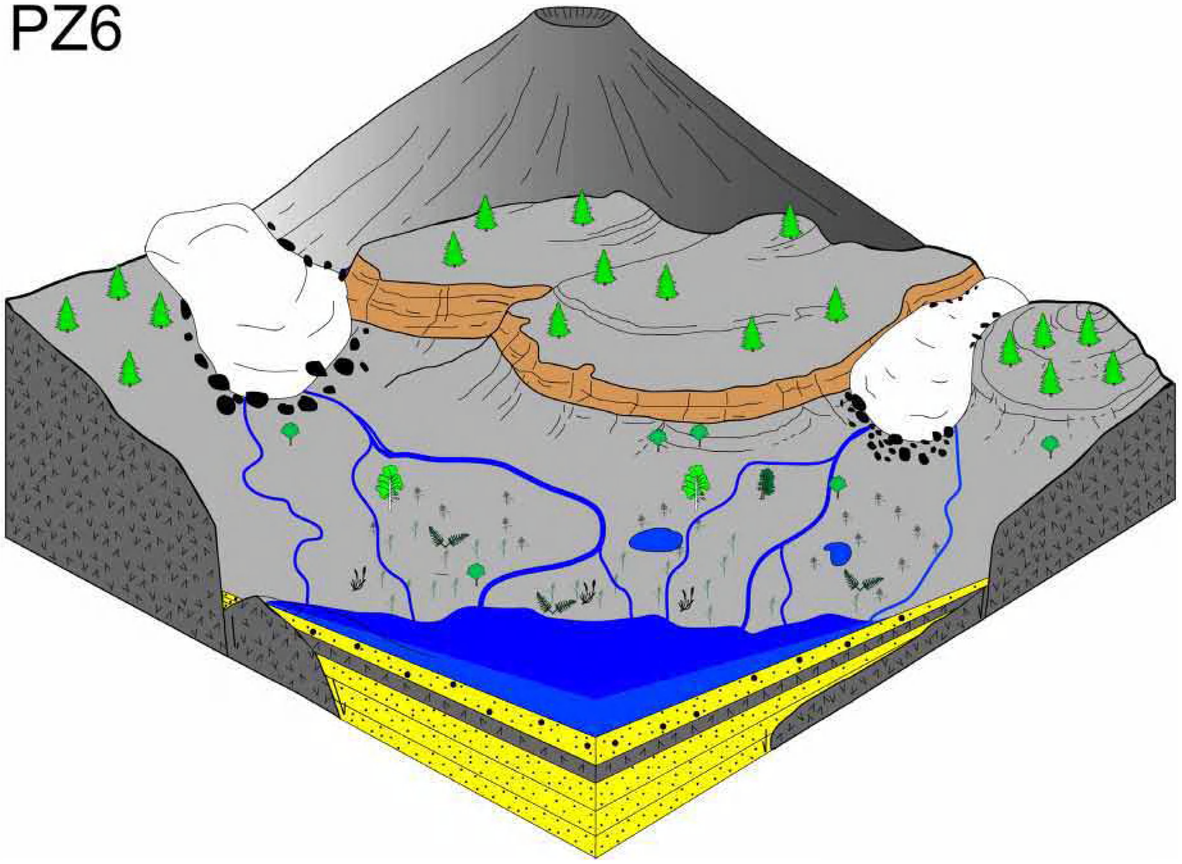
PZ4



PZ5



PZ6



The presence of aquatic plants in PZ 1 is indicative of shallow pools with stagnant water. Spore plants are also associated with these shallow pools, as clusters of monolete psilate spores occur in lignites higher up in the sequence.

Lignites occur as massive layers in PZ 1 and 2, and represent fossilised coastal marshes. The lignites provide an insight into the local pollen production of this habitat, while marine tidal flat sediments collect pollen from different habitats and provide a more regional pollen signal. The marshes were located in the wetter places of the vast coastal plain and were dominated by Cyperaceae while wetland trees such as *Alnus*, *Myrica* and *Salix* were present but do not dominate. Small-scale sea-level movements (Buchardt and Símonarson, 2003) would undoubtedly affect the marshes, but this type of vegetation remains a constant factor during the first two pollen zones. The presence of dinoflagellate cysts in the lignites (Verhoeven *et al.,* 2011) locates the marshes and pools close to the shoreline and testifies to marine incursions. Poaceae and possibly *Bistorta vivipara* are part of the marsh vegetation, as these pollen always accompany Cyperaceae pollen in the lignite. *Sanguisorba officinalis* and *Ranunculus acris* are not part of the marsh vegetation, but are, according to their modern representatives, present in meadows and on grassy slopes.

Abundant pollen of angiosperm trees and shrubs are recorded from PZ 1, but usually these trees do not grow in the coastal marshes or on the dry heathland. The need for well-drained moist soils most probably locates them on the levees and the well-drained lowland forests. The dominance of *Acer* and *Juglans* in sample WP88 gives a unique insight in the local forest vegetation for that part of the sequence (middle PZ 1). Clusters of immature pollen derived from anthers of *Acer* and *Juglans* are present and indicate nearby location on the levees. *Acer* and *Juglans* trees clearly dominate and most probably constitute the main part of the local forest, located on well-drained slightly elevated areas. Levees probably housed the deciduous forests and were bordered by brushwood (Figure 5.5; PZ 1, 2 and 4). Shrubs of *Corylus* and *Myrica* are shade intolerant and grow at forest borders. *Myrica* and *Alnus* prefer wet environments and were most probably located on the lower levee borders. Abundant pollen of *Pinus*, *Abies*, *Larix* and *Picea* are recorded in PZ 1 and these gymnosperms most likely thrived in the forests on the plateau and to a lesser degree on the steep hills.

Cyperaceae are prominently present in PZ 2 and form the key species. The co-occurrence in unit C of the highest occurrence of *Selaginella selaginoides* in the Tjörnes beds, marker species for PZ 1, and the lowest occurrence of Cyperaceae can be explained by an increasing wetness of the coastal plain, and, consequently, the beginning loss of dry heathland and pastures (Figure 5.5, PZ 2), as also noted by Akhmetiev *et al.* (1978). The local nearshore marsh and levee vegetation constitutes the major part of the pollen in PZ 2. Small-scale sea-level rises repeatedly affected the biotopes and the greater part of the marsh vegetation disappeared intermittently. Cyperaceae decline during the periods of elevated sea-levels, while the number of monolete psilate spores of ferns rises. The angiosperm trees on the levees were most probably not affected by the small sea-level rises for their pollen signal remains constant. The pollen signal of the gymnosperm trees in this and the preceding zone is less prominent, no doubt as the result of the greater distance between the place of sedimentation and the hinterland. The vegetation from the large area between the plateau and the coastline dominates the pollen influx, diluting the imports from the plateau. A general increase in wetness marks the transition from PZ 1 to PZ 2 and led to the disappearance of the drier heathland and pasture from the coastal plain.

The pollen signal of the gymnosperms rises in PZ 3, while a marked decrease of the Cyperaceae, Poaceae and Asteraceae pollen is noted. This can be explained by a deepening of the sedimentary basin that led to the inundation of the entire coastal plain (Figure 5.5, PZ 3). The angiosperm tree signal in PZ 3 is weak and indicative of the extensive inundation during which even the levees were flooded. Only *Alnus* persists while *Myrica*, situated on the border of the marshes, disappears. A restricted angiosperm forest most probably persisted on the foothills, as suggested by the presence of *Castanea* (Plate 5.1L), *Ilex*, *Corylus* and *Hedera*. The continued but low presence in PZ 3 of the poorly distributed *Ilex* pollen is an indication of its location at the foothills. The gymnosperm pollen signal is very distinct in PZ 3 and can be interpreted as an intensification of the background pollen signal during the inundation of the coastal plain.

Larix, however, almost disappears within this zone, most probably since it grew in the lowland and not higher up. Spore plants together with the herbaceous plants are scarce during PZ 3 since they were also affected by the sea-level rise. Akhmetiev *et al.* (1978) did not record elevated values for the gymnosperms in their samples corresponding to PZ 3. This may be an artefact of lower sampling resolution as only units 14 and 15 of this interval were examined. Moreover, the research by the foregoing authors focused strongly on the organic remains from the marshes in the *Tapes* and *Mactra* Zones. As a consequence, the local vegetation component was more expressed, compared to the background gymnosperm signal from the plateau as recorded in the marine deposits.

A distinctive increase of herbs such as *Valeriana officinalis*, *Ranunculus acris* and *Sanguisorba officinalis*, together with a slight increase in the Cyperaceae signal is observed in PZ 4. The richness and abundance of angiosperm trees and spore plants also rises. Especially *Alnus* and *Betula* show a clear recovery and represent the regeneration of swamps and dry heathland. Other taxa such as *Ulmus*, cf. *Pterocarya*, *Tilia*, *Sambucus nigra*, *Ostrya* and *Juglans* indicate the increasing importance of well-drained lowland habitats. The angiosperm trees were able to re-enter the coastal area from the refugia close to the hillsides. Apparently, the sea-level lowered and resulted in an expansion of dry heathland and levee forests (Figures 5.3, 5.5; PZ 4). The re-establishment of marshes is however restricted, as can be deduced from the restricted rise of the Cyperaceae. Modern representatives of *Ranunculus acris*, *Sanguisorba officinalis* and *Valeriana officinalis* can be found in Iceland on steep hillsides, but in the context of a regeneration of the levee forests and the marshes, a location on dry heathland appears more likely.

PZ 5 yielded almost no pollen. Akhmetiev *et al.* (1978) were however able to sample the units J and 25 which were deposited in a less energetic environment (top of the *Serripes* Zone). They recorded a dominance of herbs such as Poaceae (~40%), Cyperaceae (~30%) and Polygonaceae (~15%). The prominent presence of grasses in the pollen signal is indicative for a recovery of the marshes in the coastal plain. In this study, a distinct rise of the Poaceae pollen is recorded in the uppermost part of PZ 4. The sediments towards the top of the *Serripes* Zone (Figure 5.3) are interpreted by Buchardt and Símonarson (2003) and Símonarson and Eiríksson (2008) as deposited in an estuarine environment, a rather unfavourable place for the settling and preservation of microfossils and palynomorphs. This high-energy environment impeded the settling of small particles such as palynomorphs, and only large tree trunks could settle (e.g. unit H and 24; Figure 5.5, PZ 5).

PZ 6 contains interglacial sediments of the Lower Pleistocene. An increase in angiosperm herb pollen parallels a decrease of angiosperm and gymnosperm tree pollen throughout the entire zone. Tree species initially dominate the signal and indicate that the coastal plain, characterised by herbs, is reduced in size. A rise of the herbs typically indicates a cooling of the climate characterised by an impoverishment of the vegetation. The Cyperaceae signal becomes less important and the marshes were probably less extensive then during the deposition of PZ 1 and 2. Small ponds or lakes with stagnant to slow-moving water are present at least during the deposition of the Hörgi Formation, the Fossgil Member and the Svarthamar Member. *Selaginella selaginoides* reappears and indicates the recovery of the dry heathland habitat (Figure 5.5, PZ 6), underscored by the increased abundance of Ericaceae–*Empetrum* pollen. During PZ 6, the pollen and spores concentration has very low values (Table 5.1) and reflects a thin vegetation cover as a result of a deteriorating climate.

5.2 Vegetation as a proxy for air temperature

The Pliocene vegetation of Iceland is characterised by warmth-loving taxa such as *Juglans*, *Castanea* and *Hedera*. Some plants however have a well-defined temperature range and allow a more specific temperature reconstruction. *Ilex aquifolium* demands winter temperatures higher than 0°C (Iversen, 1944; Walther *et al.*, 2005) and summer temperatures of the warmest month higher than 12°C. This plant is present in PZ 1, 3 and 6 (*Tapes*, *Mactra*, *Serripes* Zones, and Hörgi Formation). The presence of *Ilex* in the Early Pleistocene Hörgi Formation (*c.* 2.15 Ma, Verhoeven *et al.*, 2011) indicates quite warm interglacial periods at the beginning of the Quaternary; this is supported by the finding of pollen grains of the warmth-loving genera *Pterocarya* up to the base of the Svarthamar Member (*c.* 1.7 Ma; Verhoeven *et al.*, 2011). Schwarzbach and Pflug (1957) and Denk *et al.* (2011) recorded *Ilex* pollen in lignite F of the *Mactra* Zone. The first authors interpreted the *Mactra* Zone as deposited during a climatic optimum, based on the limited presence of *Ilex* pollen. They however found also other warmth-loving plants such as *Castaneae/Cyrilla*, *Carya* and *Hedera* in the older *Tapes* Zone, where *Ilex* was absent. The temperature differentiation between the *Tapes* and *Mactra* Zone was thus based on negative evidence of *Ilex* pollen. Denk *et al.* (2011) did not observe such a temperature difference as warmth-loving taxa such as *Euphorbia*, *Pterocarya*, *Trigonobalanopsis*, *Viscum* cf. *album* and *Tsuga* are found in both zones. We recorded *Ilex* throughout the sequence and its increase in relative importance in PZ 3 is most probably related to the proximity of the lowland foothill forest to the sedimentary basin and not to climate amelioration.

The pollen of the epiphyte *Viscum album* is recorded from unit C of the *Tapes* Zone (Denk *et al.*, 2011) and in our study in unit 4, hence also in the *Tapes* Zone. This plant is adapted to temperate climates of less marked continental regions. The highest latitudinal record is at 59°38’N and is clearly temperature related. The mean January temperature has to be higher than -7.7°C, while the mean July temperature has to be higher than 15.6°C (Zuber, 2004).

The Pliocene vegetation of the Tjörnes area compares well to the vegetation of the western European maritime temperate climate with no dry season and with warm summers (Cfb). In such a temperate climate the average temperature of the coldest month lies between 0°C and 18°C, while the average temperature of the warmest month is higher than 10°C (Peel *et al.*, 2007).

Today the vegetation of Iceland is much less diverse than during Pliocene times since many trees, shrubs and herbs are no longer present in Iceland. Long-term meteorological observations indicate a present-day mean January temperature in northern Iceland of -1.3°C and a mean July temperature of 7.7°C (Hanna *et al.*, 2004). The greater part of Iceland’s current climate belongs to the Boreal taiga/cold climate (Köppen classification: Dsc and Dfc; Peel *et al.*, 2007). The Dfc Boreal taiga climate is a coastal climate with less than four months with temperatures higher than 10°C and a temperature of the coldest month lower than 0°C. The northern situated peninsulas such as the Tjörnes area belong to a colder polar tundra climate (ET).

A drastic cooling of the climate in Iceland thus occurred between the Pliocene and today. At first, the global cooling at the end of the Miocene is tempered in the Tjörnes area by an intensification of the Gulf Stream, as after the shoaling of the Central American Seaway around 4.7/4.2 Ma (Steph *et al.*, 2006), oceanic currents changed and transported warmer water to the north Atlantic. Today the intensified Gulf Stream is the cause of the more temperate climate of the west coast of Iceland, compared to other areas at the same latitude.

The ecological limitations of *Ilex* and *Viscum album* provide air temperatures during the deposition of the lower part of the Tjörnes beds. Compared with today, January and July temperatures were at least 1.3°C and 8°C higher, respectively. During the deposition of the rest of the Tjörnes beds and during the Early Pleistocene interglacials, summer temperatures of the warmest month were at least c. 5°C higher than today.

6. Conclusions

Six pollen zones are defined in the Tjörnes section on the basis of vegetation changes and interpreted in terms of presence or absence of specific vegetation habitats caused by relative sea-level changes. The observed variations in the pollen signal of the Tjörnes beds appear not to be linked to temperature variations, but can most likely be attributed to the loss and gain of local habitats.

The depositional basin was affected by faulting and this led to the development of a wide coastal plain sensitive to marine ingressions. Depending on the height of the water table, poorly drained marshes, dry pastures and heathland could have developed intermittently. The coastal marshes were mainly covered by Cyperaceae and some isolated trees such as *Hippophae* and *Alnus*. The dry heathland carried different angiosperm herbs and isolated *Betula* trees. Shallow pools with *Drosera* must have occurred in the coastal plain. Different angiosperm trees were present on the levees.

Probably a mixed gymnosperm/angiosperm forest occurred on the foothills with *Larix* and *Ilex*. The hinterland was composed of plateaus formed by basalt outflows; they were always exposed to sunlight and poor soils developed on them. Gymnosperm species such as *Picea*, *Pinus* and *Abies* preferred this habitat. The valleys incising the hills created umbrageous habitats, also found in the undergrowth of forests. Rivers discharging in the coastal plain deposited part of their sediment load and formed elevated levees along the channels. Such levees are usually well-drained and are places where angiosperm trees and shrubs thrive.

An alternation of non-marine swamps and sediments of tidal flats can be proposed as the depositional environment of the *Tapes* Zone and the lower part the *Mactra* Zone (PZ 1–2). A deepening of the depositional environment is observed in the upper part of the *Mactra* Zone and the lower part of the *Serripes* Zone (PZ 3–4). The upper part of the *Serripes* Zone was deposited in an estuary environment (PZ 5).

The vegetation of the Early Pliocene Tjörnes beds shows similarities with the present-day temperate, Western European vegetation corresponding to a Cfb climate. No air temperature changes could be detected in the vegetation sequence of the Tjörnes beds. Icelandic summers during Pliocene times were clearly warmer then today. The presence of *Ilex* and *Viscum album* in the *Tapes* Zone indicates July temperatures of at least 8°C higher than today. July temperature during deposition of the rest of the Tjörnes beds and the Early Pleistocene deposits were still at least 5°C higher than today. Contrary to previous research, the *Mactra* Zone is not interpreted as deposited during a climatic optimum since the key species *Ilex* is not restricted to this zone. The Early Pleistocene interglacials still contain warm vegetation elements, but the density of the vegetation clearly declines. A temperature decline is also visible throughout the successive interglacials of the Breidavík Group.

7. Author contribution

The study is fully designed and carried out by KV and includes the sampling, palynological preparation in the laboratory, counting, interpretation of the data, writing of the paper and preparation of the figures and photo plates. Remarks on the text by SL and JE were included. Where necessary, language corrections of the chapter were made by SL. JE helped with the practical organization of the field work in Iceland and the stratigraphical arrangement of the different samples.

8. Acknowledgements

This study was carried out by the first author in the framework of an assistantship in the Research Unit of Palaeontology of Ghent University. Friðgeir Grímsson provided test samples of the Tjörnes section. Margrét Hallsdóttir and the library staff of the Icelandic Institute of Natural History assisted in preparing the field campaign. Technical assistance in Ghent was kindly provided by Thomas Verleye. P. Cleveringa and an anonymous reviewer are kindly thanked for their constructive comments that greatly improved the manuscript. The grammatical and linguistic remarks by A. Gautier are kindly acknowledged.

Form variability within the *Polygonum bistorta*-pollen type: a comparison between Pliocene and recent material

Variabele vormkenmerken bij het *Polygonum bistorta*-pollentype: een vergelijking tussen Plioceen en recent materiaal

6

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Abstract

The NAP component in pollen spectra obtained from marine and estuarine Pliocene sediments in northern Iceland reveals an important, continuous presence of aberrant Polygonaceae pollen. The pollen grains show the morphology typical of the *Polygonum bistorta*-type, but are conspicuously smaller and have only in three out of five cases clear endopori. As the deviation from the normal may be due to the high latitude of the habitat, the pollen is compared with recent reference material collected in Iceland and Western Europe. The sizes of recent pollen from Iceland are really found to be smaller than the values found in the literature concerning the *Polygonum bistorta*-type. The partly absence of endoapertures was not seen in the recent material.

Samenvatting

Pollenonderzoek op Pliocene moeras- en kustnabije mariene afzettingen uit het noorden van IJsland toont in het kruidensignaal een belangrijk en continu voorkomen aan van afwijkend pollen uit de Polygonaceae familie. Het aangetroffen pollen heeft de typische vormkenmerken van het *Polygonum bistorta*-type, maar is beduidend kleiner en heeft slechts in drie van de vijf gevallen duidelijk ontwikkelde endopori. Om na te gaan of deze afwijkingen te wijten zijn aan het voorkomen van de plant op hoge breedtegraden, werd een vergelijking gemaakt met recent referentiemateriaal uit IJsland en centraal West-Europa. De afmetingen en wanddiktes van 54 pollenkorrels van enerzijds *Persicaria vivipara* uit IJsland en anderzijds *Persicaria bistorta* uit België en Frankrijk werden opgemeten. Zowel het fossiel als het recent pollen vertoont een brede range van korrelgroottes, waarbij de gemiddelde groottes en diktes van de wanden van het fossiel pollen steeds kleiner uitvallen dan bij het recent pollen. De hoogte/breedte verhouding en de verhouding van de wanddikte van het fossiele materiaal is echter gelijk aan het referentiemateriaal. Dit gegeven, samen met de overeenkomsten in de wandstructuur, versiering en apertuursysteem laat ons toe het fossiel pollen aan het *P. bistorta*-type toe te wijzen. De kleine afmetingen en het brede grootte interval van het fossiel pollen is mogelijks toe te schrijven aan het variabele aantal chromosomen.

Keywords: Pliocene, pollen, taxonomy, *Polygonum bistorta*, Tjörnes, Iceland

1. Introduction

Basin formation caused by fault activity in the vicinity of the Mid Atlantic Ridge near the Tjörnes fault in northern Iceland resulted in the deposition of fossil-bearing sediments during the Pliocene and the beginning of the Pleistocene (Thordarson and Hoskuldsson, 2006, Figure 6.1a). During this period, more than 1000 m of sediment accumulated in the Tjörnes and Breidavík Group (Símonarson and Eiríksson, 2008, Figure 6.1b).

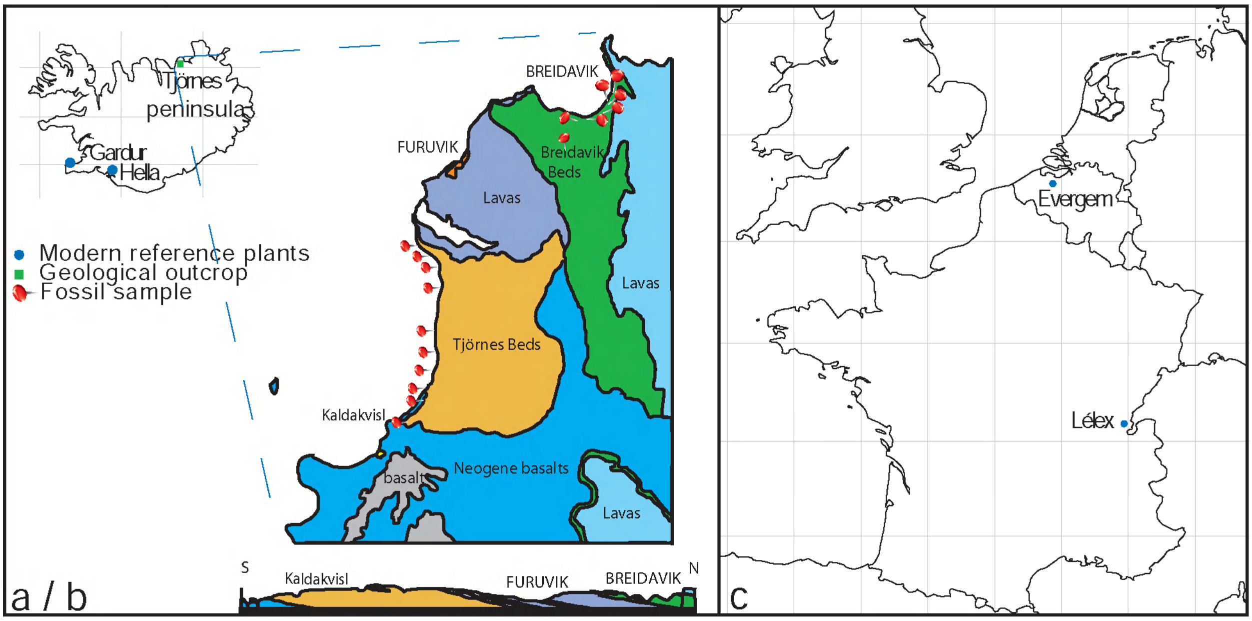


Figure 6.1: a: map of Iceland; b: the geological outcrop of Tjörnes enlarged (map adapted from Einarsson *et al.*, 1967); c: map of Belgium and France with indication of sampling locations of the recent pollen material.

a: kaart van IJsland; b: de uitvergrote geologische dagzoming van Tjörnes (kaart bewerkt naar Einarsson *et al.*, 1967); c: kaart van België en Frankrijk waarop de monsterlocaties van het recente pollen materiaal zijn aangegeven.

Palynological research in the Pliocene shallow marine and marsh sediments of the Tjörnes section in northern Iceland revealed in the herbaceous signal an important presence of pollen of the Polygonaceae family. During the Pliocene, a warmer-than-modern climate prevailed in Iceland. Willard (1994) described the former vegetation as a mixed conifer-hardwood vegetation. The pollen of the Polygonaceae family described here represents a major part of the non-arboreal pollen. Akhmietev *et al.* (1978) recognised the same pollen in the Tjörnes section and described them as *Polygonum* sp. Although the pollen looks very similar to that of the *Polygonum bistorta*-type according to Van Leeuwen *et al.* (1988) and Beug (2004), it differs in size and in the continuous presence of the endopori. To ascertain whether the observed differences in the fossil material are absent or present in recent pollen of Iceland, we compared the Pliocene material with recent material from Iceland, Belgium and France (Figures 6.1a, 6.1c).

2. Material and methods

2.1 Origin of pollen material

Fifty-four pollen grains of the supposed *Polygonum bistorta*-type from the Pliocene Tjörnes Beds were biometrically measured. In order to compare the fossil material with recent material, the same amount of recent pollen of the *Polygonum bistorta*-type from four different localities were measured. Today only one species of the *P. bistorta*-type, e.g. *P. vivipara* (Alpine Bistort), occurs in Iceland. This plant is very common in very diverse Icelandic habitats (Kristinsson, 2005). Two fresh *Persicaria vivipara* samples from Hella and Gadar (Iceland), one fresh sample of *Persicaria bistorta* from Evergem (Belgium), one herbarium species also of *Persicaria bistorta* from Lélex (France) were studied. To avoid taxonomic confusion, the used plant names follow the most recent Belgian taxonomic division of Lambimon *et al.* (2004).

2.2 Laboratory treatments

The lithology of the marine and estuarine Pliocene sediments consists of sand- and mudstones. The hard sediments were crushed and treated repeatedly with cold 10% HCl and cold 40% HF to dissolve the carbonates and silicates, respectively. In order to prevent selective loss of palynomorphs, each decantation was done over a nylon 10 µm sieve. The organic residue was stained with safranin-O for contrast enhancement of the palynomorphs. For the crushing of the lignite samples, it was necessary to treat the sediment with 10% KOH and to acetolyse the material following the method described in Faegri and Iversen (Faegri and Iversen, 1989). The mineral contents of these sediments were also dissolved with 40% HF and 10% HCl. Recent fresh and herbarium flower material was only briefly acetolysed. A drop of residue was mounted with Kaiser's glycerol gelatin on a glass slide for light microscopy. For scanning electron microscope (SEM) analysis, a drop of residue was mounted on a cylindrical stub and subsequently coated with gold. The material was studied with a Zeiss® Axio Imager A1 light microscope (LM) equipped with an AxioCam MRc5 camera which allows digital length measurements. Specimens were measured on 1000x magnification with immersion oil (n=1.518). From the reference slides, the first 54 equatorially well-orientated and unfolded grains were measured. The samples used for the fossil measurements are from various stratigraphical levels of the Tjörnes section.

2.3 The *Polygonum bistorta*-type in the literature

Polygonum bistorta-type includes the pollen of *Persicaria amplexicaulis*, *Persicaria vivipara* and *Persicaria bistorta* (Van Leeuwen *et al.*, 1988). The ratio of the legth of the polar axis (P) verus equatorial axis (E) of this pollen type lies between 1.13 and 1.38. This pollen-type is thus subprolate (P/E: 1.14 < < 1.33) to slightly prolate (P/E: 1.33< <2.00). It has a tricolporate aperture with slit-shaped outer colpi and large endopori (the range and terminology follows Punt *et al.*, 1994). The colpi are relative short and occupy approximately 2/3-3/4 of the distance between the poles (Moore *et al.*, 1991). Each endoporus is circular to transversely elliptic. The exine is thick to very thick and thickest in the apocolpium. The columellae are branched and coarser at the poles. The tectum shows scattered perforations situated above the branched columellae (Moore *et al.*, 1991). The wall surface is psilate, but small scabrae are visible under SEM. The outline in equatorial view is elliptic to slightly rectangular. The outline in polar view is triangular with the apertures in the convex sides.

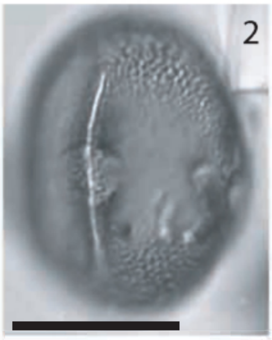
Moore *et al.* (1991) and Van Leeuwen *et al.* (1988) indicate that the grains of this pollen type are very variable in size (33-76 µm). However, the small sizes given by Van Leeuwen *et al.* (1988) derive entirely from the *P. amplexicaulis* species (33-37.5µm). This species originates from East-Asia and was recently introduced in Ireland and England (Jalas and Suominen, 1979), but Pliocene occurrences of this species are not known for Western Europe. The Faegri and Iverson (1989) pollen identification key indicate a large size, e.g. more then 50 µm, of the pollen. This large size, > 47.5 µm, is also observed by Van Leeuwen *et al.* (1988) when we disregard *P. amplexicaulis*. In Van Leeuwen *et al.* (1988), the measured specimens of *P. bistorta* originates from Central Europe (France, England, Germany, and the Netherlands), but for *P. vivipara* also specimens of higher latitudes are measured (Iceland, Norway and Sweden apart from Austria, England, and France). Exceptional observations of pollen without apparent endopori are mentioned by Van der Knaap (personal communication in van Leeuwen *et al.*, 1988). According to Van der Knaap, this aberrant pollen is found on plants with an arctic location.

3. Results

SEM photomicrographs of the fossil pollen show a psilate wall structure ornamented with small scabrae. Perforations occur towards the poles and the aperture system is located in the middle of the sides (see Plate 6.1, photomicrograph 8). The outer colpus is slit-shaped and rather long (±3/4 of the polar axis P). LM photomicrographs show a thick exine which is thickest in the apocolpium. The endopori of the fossil pollen are in approximately 60% of the cases distinct (Plate 6.1, photomicrographs 1-3).

POLYGONUM BISTORTA pollen type


1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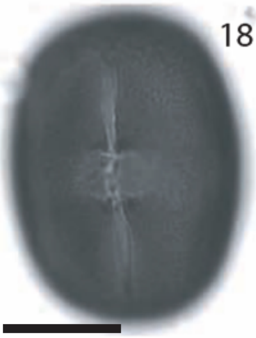
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		P			E			P/E		
		min.	max.	average	min.	max.	average	min.	max.	average
	Tjörnes	23	54	37	18	42	26	1,2	1,9	1,4
Persicaria vivipara	Gardar	41	56	48	30	46	36	1	1,5	1,3
Persicaria vivipara	Hella	36	58	46	27	43	34	1	1,6	1,4
Persicaria bistorta	Evergem	40	64	54	28	46	38	1,1	1,6	1,4
Persicaria bistorta	Lélex	36	63	45	26	56	37	1	1,5	1,2
▼										
P. bistorta-type	*	33	76		27	60		1,13	1,38	
P. amplexicaulis	*	33	37,5	35	27	30,5	29	1,13	1,22	1,29
P. bistorta	*	49,5	68,5	58,5	37,5	50,5	44,5	1,24	1,38	1,31
P. vivipara	*	47,5	76	55	36	60	43,5	1,16	1,28	1,37
		thickness exine polar			thickness exine equatorial			exine polar/exine equatorial		
		min.	max.	average	min.	max.	average	min.	max.	average
	Tjörnes	1,2	4,2	2,7	0,8	2,4	1,3	1,2	4	2,1
Persicaria vivipara	Gardar	2,4	4,5	3,6	1,2	2,8	2	1,2	2,9	1,9
Persicaria vivipara	Hella	1,7	4,3	3	1,2	2,9	1,8	1,1	2,7	1,7
Persicaria bistorta	Evergem	2,1	5,6	3,9	1	3,9	2,2	1,1	4,5	1,9
Persicaria bistorta	Lélex	1,8	4,8	3,6	1,3	3,5	2,1	1,2	2,7	1,7

Table 6.1: Measurements of different characteristics of the pollen grains; the measurements of three taxa published by van Leeuwen *et al.* (1988) are indicated below the symbol ▼

Metingen van verschillende kenmerken van de pollen korrels; de maten van drie taxa gepubliceerd door van Leeuwen *et al.* (1988) zijn te vinden onder het teken ▼

P = length polar axis; E = length equatorial axis

Plate 6.1 (left page): 1-12: Pliocene Icelandic pollen of the *P. bistorta*-type. 1: WP56, *Mactra* biozone; 2-3: WP88, *Tapes* biozone; 4: WP56, *Mactra* biozone; 5, 9: WP62, *Tapes* biozone; 6-7: WP49, *Mactra* biozone; 8: WP56, *Mactra* biozone; 10-11: WP98, *Tapes* biozone; 12: WP96, *Tapes* biozone; **13-20: Recent pollen of the *P. bistorta*-type.** Row 4: *P. bistorta.* (13-14) Lélex, France; 15-16: Evergem, Belgium; Row 5: *P vivipara.* 17-18: Gardar, Iceland; 19-20: Hella, Iceland. Scale bars indicate 20 µm. All pictures are taken with a light microscope with differential interference contrast at a magnification of 1000x, except for the right-hand column that shows SEM photos.

1-12: Pliocene IJslandse pollen van het *P. bistorta*-type. 1: WP56, *Mactra* biozone; 2-3: WP88, *Tapes* biozone; 4: WP56, *Mactra* biozone; 5, 9: WP62, *Tapes* biozone; 6-7: WP49, *Mactra* biozone; 8: WP56, *Mactra* biozone; 10-11: WP98, *Tapes* biozone; 12: WP96, *Tapes* biozone; **13-20: Recente pollen van het *P. bistorta*-type.** Rij 4: *P. bistorta.* 13-14: Lélex, Frankrijk; 15-16: Evergem, België; Rij 5: *P vivipara.* 17-18: Gardar, IJsland; 19-20: Hella, IJsland. De schaalstok geeft 20 µm weer. Alle figuren zijn gemaakt met een licht microscoop met differentieel interferentiecontrast bij een vergroting van 1000x, behalve voor de rechter kolom die SEM foto's laat zien.

Sometimes, they are poorly developed (Plate 6.1, photomicrographs 6-7, 10-11) or absent (Plate 6.1, photomicrographs 5, 9).

Measurements of the total length P of the pollen shows for the Icelandic fossil and fresh material an unimodal distribution with a rather broad range (Figure 6.2a).

The pollen from Lélex and Evergem display a bimodal distribution. The smaller specimens are more abundant in Lélex than in Evergem. The fossil pollen is clearly smaller than the recent pollen of *P. vivipara* from Iceland which in turn is smaller than known from the literature (van Leeuwen *et al.*, 1988). The average value of the fossil Tjörnes pollen is 37 µm compared to ±46 µm for the recent material from Iceland and Lélex. Evergem has the largest pollen with an average of 54 µm (Table 6.1).

The pollen form based on the length/width ratio is for the fossil and the recent pollen slightly prolate with a mean P/E value of 1.4. The pollen from Lélex is more rhombic than spherical and shows a more subprolate form with an average P/E value of 1.2 (Plate 6.1, photomicrographs 13, 14).

fig. a Lenght polar axis P

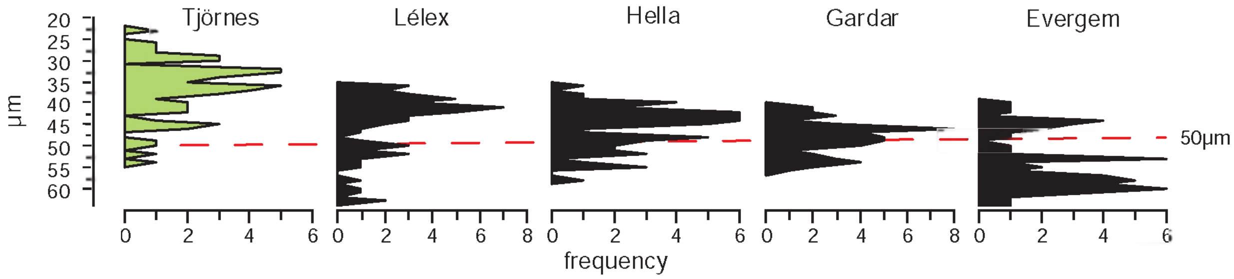

fig. b Length/width ratio

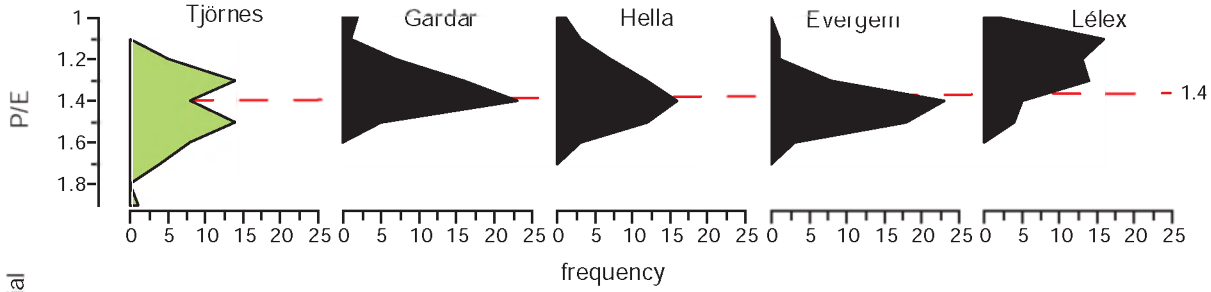

fig. c Exine polar / equatorial ratio

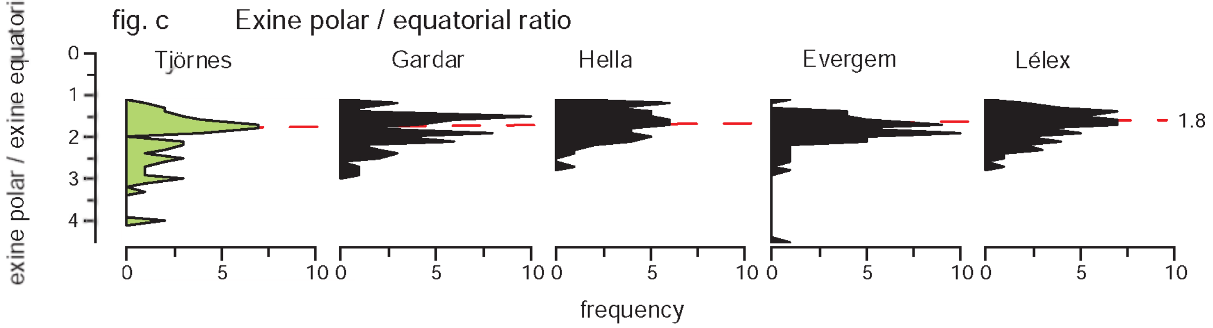

fig. d Thickness exine polar

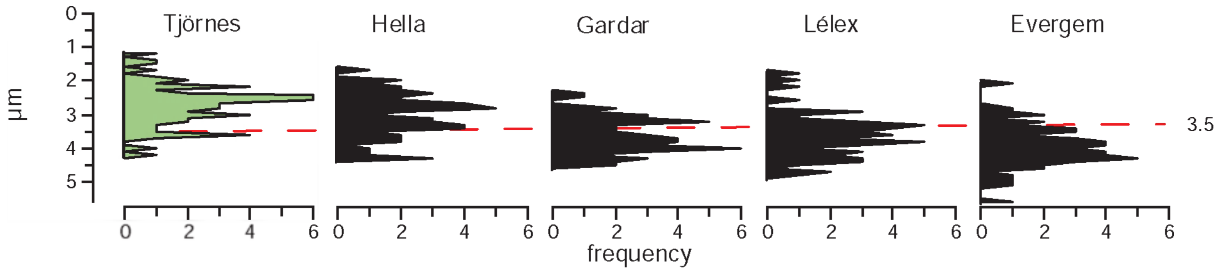

fig. e Thickness exine equatorial

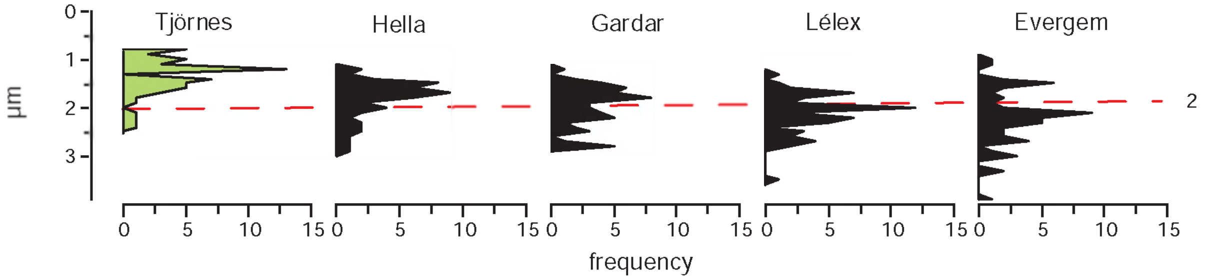

Figure 6.2: **Graphic representation of the measured characteristics of the pollen grains. The frequencies are based on 54 measurements of each sample/location.**

Grafische weergave van de kenmerken van de pollenkorrels. De frequenties zijn gebaseerd op 54 metingen van elk(e) monster/plaats.

Thickness measurements of both the equatorial and the polar exine show a broad range in values (Figures 6.2d, 6.2e). The value of the Tjörnes specimens is for both proxies smaller than for the recent ones, e.g. smaller than 3.5 µm for the polar thickness and smaller than 2 µm for the equatorial thickness. The ratio between both wall thicknesses is the same for all the measured samples with an average 1.8 thicker polar wall than the equatorial wall (Figure 6.2c).

4. Discussion

SEM and LM study allowed the investigation of the different characteristics of the pollen. Comparison of the wall surface/structure, aperture system and shape of the fossil pollen with recent material and literature data justifies the assignment of the fossil pollen to the *P. bistorta*-type as described in Van Leeuwen *et al.* (1988) and Beug (2004). However, the small size and the sporadic lack of well-expressed endopori are noteworthy, and differ distinctly from the general description of the pollen type.

Although it is suggested that the lack of endoapertures is characteristic of arctic plants, the recent Icelandic *P. bistorta* pollen do not show this feature contrary to the Pliocene ones. Such aberrant pollen is nevertheless not an exception within the *P. bistorta-type* (van Leeuwen *et al.*, 1988).

The small size and the broad size range of the pollen grains may be caused by the presence of different chromosome numbers (Beug, personal communication). As Áskell Löve (Icelandic botanist, °1916-†1994) shows a variable chromosome number of P. vivipara varying between 2n = 66-132, this is plausible.

Of the 54 measurements of Pliocene pollen, 16 measurements were done on lignite samples which were processed with acetolysis, while the other 38 measurements were only processed with cold HF and HCl. Within the results, there is no difference in size measured caused by the different laboratory treatment.

5. Conclusions

1. Although the size of the Pliocene pollen of the Polygonaceae family is smaller than known from literature data and measurements of recent pollen of the *Polygonum bistorta*-type, it has the form and all the characteristics of this pollen type. Because of this, the Pliocene pollen can be ascribed to the *P. bistorta*-type.
2. The endopori of the Pliocene material are in 40% of the cases not or badly developed. Although this lack of development of endopori can be caused by the arctic location, as suggested in the literature, this feature was not observed in the recent reference pollen from Iceland.
3. The studied recent Icelandic reference pollen of *P. vivipara* is smaller than known from the literature.

6. Author contribution

The study is fully designed and carried out by KV and includes the sampling of Belgian fresh plant material and the herbarium specimen, palynological preparation of the anthers in the laboratory, measurements, interpretation of the data, writing of the paper and preparation of the figures and photo plates. Where necessary, language corrections of the chapter were made by SL.

7. Acknowledgements

Ghent University is thanked for making this palynological study possible within the framework of an assistantship. Prof. emeritus Hans-Jürgen Beug and dr. Margrét Hallsdóttir are kindly thanked for sampling fresh flower material from Iceland. The Ghent division of the plant workgroup of the Belgian wildlife association “Natuurpunt” is thanked for helping to determine *Polygonum* species during summer walks. Prof. Paul Goetghebeur (Ghent University) is thanked for making pollen available from the herbarium of the Biology Department. Last but not least, Wim Kuijper is thanked to introduce me into the wonderful world of pollen and spores. His never-ending enthusiasm and devotion to (palaeo-)ecological research and education will always be a stimulus to me.

Land-sea signals from the Pleistocene on Flatey Island, northern Iceland: results of a combined dinoflagellate-pollen study

7

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Abstract

The island of Flatey is located close to the famous geological outcrops of the Tjörnes Peninsula, which has already been studied in the past by dinoflagellate cysts and pollen/spores. A drilling in 1982 on Flatey made a geological record available for the reconstruction of the climatological changes on the land and on the shelf. Although nowedays located 2.5 km out of the coast, the Quaternary glaciers deposited diamictites on the island and also lava flows reached it during ice-free periods. As the core itself was not available for study, only a sandstone from the island and a previously taken mudstone from the core were analysed. Both samples show a much higher dinoflagellate cyst concentration compared to the Tjörnes section. The assemblages indicate a cooling: the older sample is dominated by the cold water taxon *Bitectatodinium tepikiense* and *Brigantedinium* spp., the youngest sample by the cyst of *Pentapharsodinium dalei* accompanied with other cold water species such as *Islandinium minutum* and *Spiniferites elongatus*. The island sample corresponds to dinozone DZ6 in the Tjörnes section, the core sample most probably to the transition from DZ5b to DZ6, although correspondence to older Late Pliocene cold stages could not be excluded. The dinodata combined with the data concerning the palaeomagnetic reversals and the lithological sequence results in tree alternative correlations of the Tjörnes and Flatey section. The initial correlation by Eiríksson *et al.* (1987), which is mainly based on the corresponding occurrence of a set of tuff layers and the K/Ar dates of the three lava layers, can accord with the dinocyst assemblage of the core sample if this sample corresponds with a Late Pliocene cold stage. More samples however are needed to elaborate a more founded correlation. The Flatey vegetation is mainly composed of sedges and heath. This pilot study reveals a rich dinocyst and pollen and spores assemblage suitable for a detailed climatological study of the Pleistocene cooling on land and sea in northern Iceland.

Keywords: Pleistocene, dinoflagellate cysts, pollen, Flatey, Iceland, land-sea interactions

1. Introduction

Marine invertebrates, microfossils and palynomorphs are excellent proxies for the detection of changes in oceanographic pathways and exchange between oceans (Bárdarson, 1925; Verhoeven *et al.*, 2011). Single-celled algae such as dinoflagellates respond rapidly to adverse environmental conditions and migrate easily. Moreover, dinoflagellates occur in very high numbers in the neritic and oceanic realm, and circa 15–20% have a meroplanktonic life cycle. The latter species produce very resistant organic-walled resting cysts that are relatively easy to extract from the sediments. Dinoflagellate cysts or dinocysts are increasingly used as proxies in palaeoenvironmental studies and reconstructions of the depositional basin (Head, 1993, 1996, 1998a; Louwye *et al.*, 2004; Pospolova *et al.*, 2004; Louwye and Laga, 2008; Mertens *et al.*, 2009; De Schepper *et al.*, 2009, 2011; Verhoeven and Louywe, submitted).

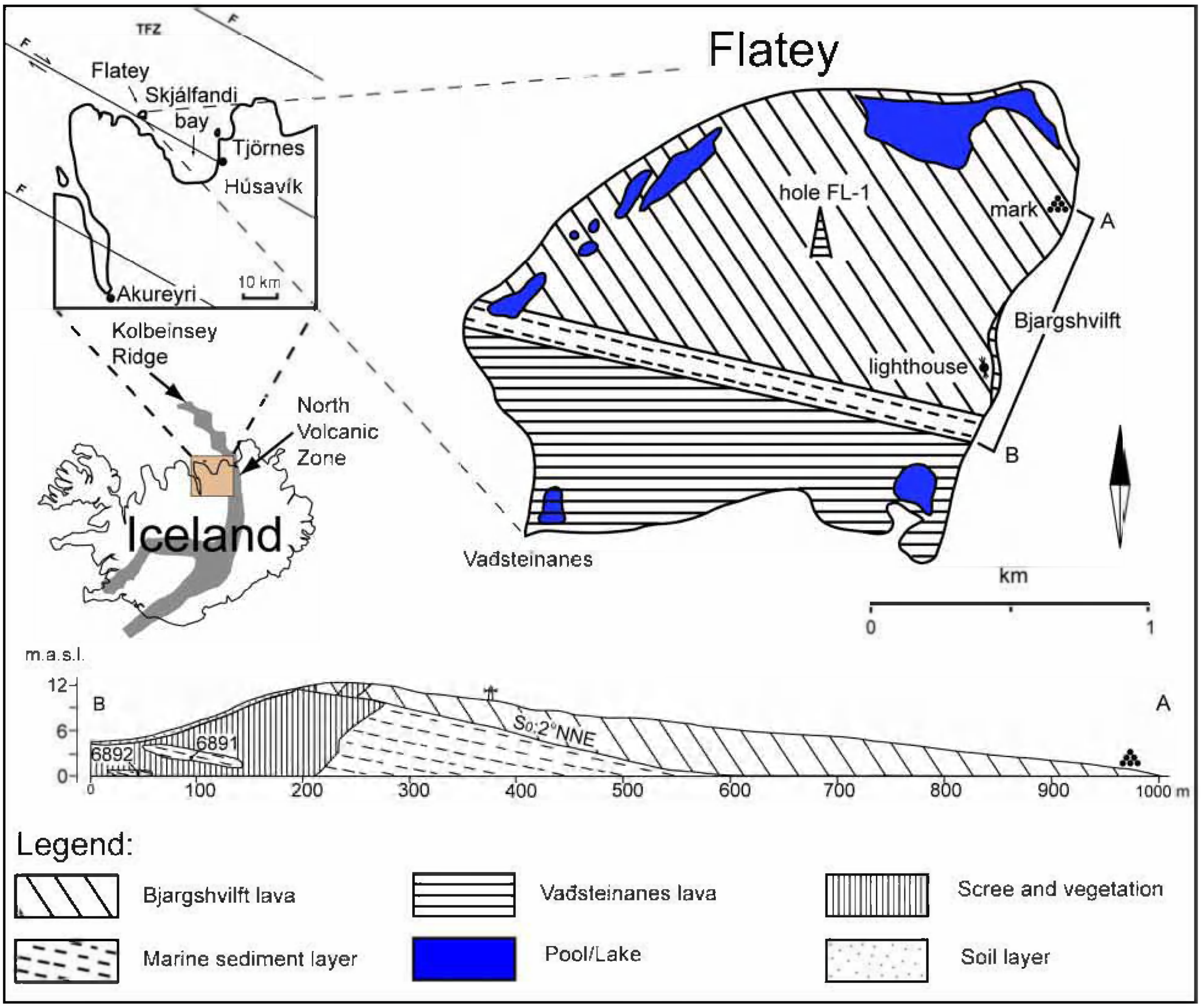

Figure 7.1: Localisation of the island of Flatey and the Tjörnes Peninsula in northern Iceland, with indication of the different major faults of the Tjörnes Fracture Zone (TFZ). The geological map of Flatey is given, with the location of borehole FL-1. Transect A-B shows the geological outcrop of the east coast with the position of the two samples mentioned in the text. The layers have a virtual dip of 2°NNE. (Modified after Birgisdóttir, 1982).

The location of the Polar Front north of Iceland, together with the supply of warm waters from the southwest by the Gulfstream, makes Iceland an unique location for the reconstruction of past oceanographic currents.

The shallow marine to terrestrial sediments from the Tjörnes area in northern Iceland have been studied for many decades for the elucidation of past oceanographic changes and the reconstruction of Polar Front shifts through time (references in Verhoeven *et al.*, 2011 and Eiríksson, 1981a). The Tjörnes beds comprise more than 550 m of Early Pliocene deposits, while the overlying Höskuldsvík and Breidavík Group consists of c. 570 m of Middle to Late Pleistocene marine lava layers, sediments, terrestrial lignites and glacial remains. These sequences are well exposed in the cliffs on the Tjörnes Peninsula (Figure 7.1). Increased subsidence, caused by fault activity and followed by recent uplift, explain the sedimentation and accessibility of this unique record in Tjörnes, but also the formation of the island of Flatey. This small island is located in the western part of the Skjálfandi Bay in northern Iceland, in front of the Tjörnes Peninsula, which is situated at the opposite eastern shore (Figure 7.1). The island is located c. 2.5 km from the coast and therefore sensitive to environmental changes occurring on the island as can be seen in the presence of pollen as well as glacial remains or diamictites. The Húsavík-Flatey fault is a parallel fault zone at the southern boundary of the Tjörnes Fracture Zone (TFZ). This fault complex connects the 120 km offset between two segments of the Mid Atlantic

Ridge (Figure 7.1). Movements along these faults created accommodation space during Pliocene and Early Pleistocene times. An uplift at the end of the Pleistocene gave birth to the present-day Plio-Pleistocene cliffs on the Tjörnes Peninsula and also created the island of Flatey. Accumulation of sediments occurred also in comparable active regions in the southwest of Iceland, but these sediment are not uplifted and exposed in cliffs.

A cored well of c. 550 m through the strata of Flatey recovered marine sediments of slightly deeper marine depositional setting than the Tjörnes sediments (Birgisdóttir, 1982; Eiríksson *et al.*, 1987). Sedimentological analysis in combination with magnetostratigraphy allowed a tentative correlation of the Flatey sediments with the coastal sediments of the Tjörnes Peninsula (Eiríksson *et al.*, 1987, 1990; Eiríksson and Geirsdóttir, 1991). These authors showed that the core sediments compare quite well with the exposed Breidavik Group at Tjörnes. The calibrated pollen and dinocyst biozonations (Verhoeven *et al.*, 2011; Verhoeven *et al.*, in press) of the Tjörnes section can be used as independent proxies to adjust the palaeomagnetic-based correlation. As diamictites are present in both sections, a solid stratigraphical correlation can elucidate more of the regional glacial history.

This study evaluates the palynological potential of the Flatey core and proposes three possible correlation alternatives. A robust correlation however could not be proposed as a more thoroughly investigation of both the Flatey and Breidavík section is needed.

2. Material and method

The National Energy Authority of Iceland drilled in 1982 a borehole in the northern part of the Island of Flatey. The cored borehole, labelled FL-1, reached a depth of 554 m, of which 517 m of rocks were recovered (Eiríksson *et al.*, 1987). The drilling campaign fitted within a prospection study for fossil carbon sources and had initially no scientific goal. Afterwards, the drilling came available for scientific study.

The sediments consist mainly of marine clay-, silt- and sandstones and numerous poorly sorted conglomerates (Figure 7.2). Three lava layers are present, of which the upper two, the Bjargshvilft lava (1.6–8.5 m) and the Vaðsteinanes lava (25.0–42.0 m), also crop out on the island itself (Figure 7.1).

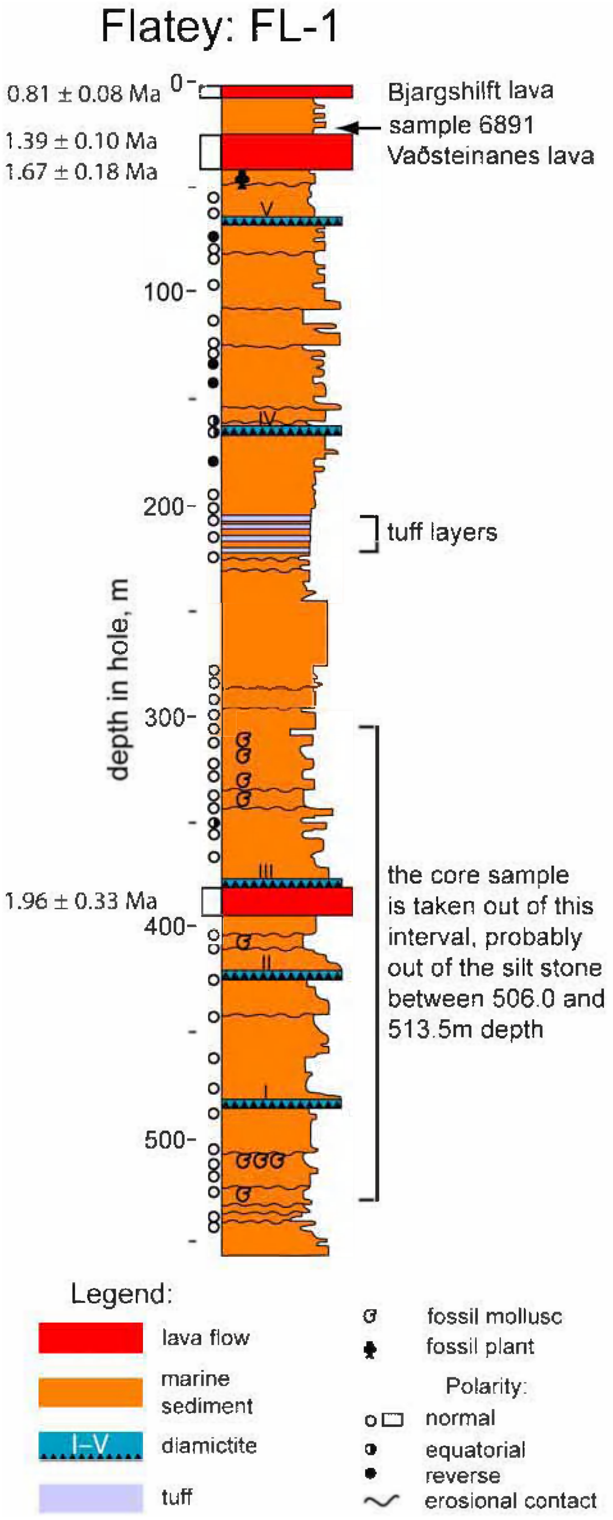

Figure 7.2: Simplified lithological column of the Flatey core FL-1 with indication of glacial remains (I–V), erosional horizons (19), fossils (molluscs and plants), K/Ar datings (Albertsson and Eiríksson, 1989), palaeomagnetic measurements and the probable positions of the two samples of this study. (Modified after Eiríksson *et al.*, 1987).

The third lava layer is found at a depth of 381.8–395.0 m. Immediately below the Vaðsteinanes lava layer, lenses and remains of unidentified coalified plants are recorded. These form the sole level with plant macro-remains. Shells of bivalves and gastropods occur below 300 m depth, at the intervals 309.0–312.1 m, 325.3–330.0 m, 335.0–337.0 m, 403.0–411.6 m, 506.0–513.5 m and 522.8–530.6 m. Shells are common only in the interval of 506.0–513.5 m, elsewhere only small shell fragments occur (Eiríksson *et al.*, 1987). The molluscs are *Portlandica arctica*, *Portlandica lenticula*, *Nucla tenuis*, *Natica* sp. and *Mya truncate*; they do not allow biostratigraphical interpretation of the core. K-Ar datings on the Flatey lava flows indicate eruption some time between 0.81 ± 0.08 and 1.96 ± 0.33 Ma (Matuyama chron) (Figure 7.2; Albertsson and Eiríksson, 1989) and an appreciable time gap between the upper two lavas. Eiríksson *et al.* (1987, 1990) state that the sediments accumulated in a cyclical way with diamictites, deformation structures, shear planes and associated erosional unconformities ascribed to glacial erosion typically being followed by poorly sorted conglomerates and sandstones interpreted as deglaciation assemblages. Mudstones with marine fossils are typically deposited during a following transgression. This in turn is followed by a regression during the cooling of the climate preceding a following glacial period which resulted in the deposition of sandstones, conglomerates and lava in still ice-free conditions. Thus, the facies cyclicity can been attributed to glacial-interglacial cycles.

The core sample analysed is said to be part of a molluscan sample most probably from the interval between 506.0 m and 513.5 m, and stored apart from the core (Jón Eiríksson, pers. comm. 2007). It consists of a greyish siltstone originated from at least 300 m depth, for higher up no shells seem to occur in the core (Eiríksson *et al.*, 1987; p. 12, figure 2). We found no shell debris in the sample during the processing of the sample. The provenance of the sample is therefore equivocal; it may come from higher in the core than the suggested depths. Remains of five different glacial periods are recorded at various levels within the core, together with 19 erosional surfaces (Figure 7.2). In the interval between 203.8 m and 226.2 m, sandstones alternate with thick (20–40 cm) and thin (5–10 cm) tuffaceous layers.

After the geological project concerned with the prospection for oil reservoir rocks, the core became available for scientific research and was initially stored in the repository of the energy authority. A rationalisation at the end of the past century centralized all geological cores of Iceland in a repository of the Islandic Institute of National History in Akureyri. This core storage facility however became soon overstocked and consulting of cores was therefore no longer possible. During our research, the movement to another and larger repository was not yet initiated and the only core sample available to analyse was a part of the higher described shell sample.

Two sedimentary rock samples originating from the island itself are stored (nr. 6891 and 6892) in the Islandic Institute of National History in Reykjavík. Both samples contain shell fragments and were collected by K. Sæmundsson in 2000 in an outcrop of 700 m near the locality of Bjargsvift at the east coast of the island (Figure 7.1). Sample 6891 is from the outcrop itself, c. 14 m below the base of the Bjargshvilft lava and thus c. 22.5 m below the surface. The other sample 6892 is part of a boulder thrown up by the sea from somewhat lower in the stratigraphy, but it was not selected for palynological analysis since its precise stratigraphical position is unknown. The studied sample 6891 is a sandstone with dropstones originating from a drifting iceberg. Molluscs are present, but their shells are partly dissolved.

The initial dry weight of sample 6891 was 65.16 g of which 56.31 g could be dissolved. The dried core sample initially weighted 45.16 g but 4.16 g of it did not dissolve. Large samples were needed as previous palynological studies of the area (Akhmetiev *et al.*, 1978; Willard, 1994; Verhoeven *et al.*, 2011, in press) indicate rather low concentrations of pollen and dinocysts. All previous studies experienced problems during the laboratory treatments, caused by the presence of undissolvable minerals of basaltic origin and the high degree of saturation with silica. Removal of these particles through decanting was necessary. The same maceration technique was followed for the pollen analysis as well as for the analysis of the dinocysts. The rocks were rinsed and fragmented into pieces of c. 0.5 cm and dried during 24 hour at 60°C. One *Lycopodium clavatum*-tablet (batch 483216; 18586±1708 spores/tablet) was added for the calculation of absolute abundances of the palynomorphs.

	Flatey core >500m below surface		**Flatey 6891** 22.5m below surface	
Dinoflagellate cysts	counts	%	counts	%
Indeterminate dinocysts	2	0,38	1	0,18
Achomosphaera sp.	/	/	v	/
cfr. *Alexandrium tamarensis*/calcareous cyst	v	/	/	/
Bitectatodinium serratum	v	/	/	/
Bitectatodinium tepikiense	267	50,95	22	3,96
Brigantedinium cariacoense	5	0,95	0	0,00
Brigantedinium simplex	3	0,57	0	0,00
Brigantedinium spp.	129	24,62	0	0,00
Round Brown Cysts	6	1,15	0	0,00
Impagidinium patulum	v	/	/	/
Impagidinium sp.	0	0,00	1	0,18
Islandinium minutum	4	0,76	v	0,00
Lejeunecysta sabrina	3	0,57	0	0,00
Nematosphaeropsis labyrinthus	v	/	v	/
Operculodinium centrocarpum sensu W. & D.	15	2,86	6	1,08
Operculodinium centro.s. W. & D. short proc.	1	0,19	0	0,00
Operculodinium centrocarpum s.s.	0	0,00	1	0,18
cyst of *Pentapharsodinium dalei*	22	4,20	421	75,72
Quinquecuspis concreta	5	0,95	0	0,00
Selenopemphix quanta	15	2,86	0	0,00
Spiniferites elongatus	v	/	17	3,06
Spiniferites mirabilis	v	/	/	/
Spiniferites ramosus	0	0,00	4	0,72
Spiniferites spp.	47	8,97	83	14,93
Total recent dinocysts (dino sum)	524	100	556	100
reworked Spiniferites sp. (scabrate)	/	/	v	/
# Warm water species (n)	0	/	0	/
# Cold water species (n)	293	/	460	/
# Heterotrophic species (n)	170	/	0	/
# Autotrophic species (n)	352	/	555	/
nH/(nH+nA)	0,33	/	0,00	/
dinocyst richness	13	/	8	/
dinocyst concentration (dinocysts/g)	66627	/	2628	/
Shannon Wiener index dinocysts (H')	1,05	/	0,59	/
Evenness dinocysts (EH)	0,41	/	0,28	/
Fresh water and Marine organisms				
Botryococcus sp.	6	1,15	4	0,72
Cyclopsiella sp.	v	/	/	/
Cymatiosphaera sp.	v	/	v	/
Desmidiales sp.	v	/	/	/
Halodinium scopeaum	v	/	/	/
Pediastrum sp.	0	0,00	37	6,65
Foram lingings: planispiral	13	2,48	0	0,00
Foram lingings: linear	3	0,57	0	0,00
Pollen				
Pinus	12	9,02	30	9,32
indeterminate bissacaat pollen	0	0,00	1	0,31
total gymnosperms	12	9,02	31	9,63
Alnus	0	0,00	1	0,31
Betula	12	9,02	0	0,00
Carpinus betulus	0	0,00	2	0,62
Juniperus	1	0,75	1	0,31
Salix	0	0,00	3	0,93
cf. *Ulmus*	1	0,75	0	0,00
total decidous trees and shrubs	14	10,53	7	2,17
Artemisia (Asteraceae)	0	0,00	2	0,62
Asteraceae liguliflorae-type	4	3,01	2	0,62
Asteraceae tubeliflorae-type	0	0,00	6	1,86
Carylophylaceae	3	2,26	9	2,80
Chenopodiaceae	0	0,00	5	1,55
Circaea (Onagraceae)	0	0,00	4	1,24
Cyperaceae	43	32,33	134	41,61
Ericaceae-*Empetrum*-group	45	33,83	69	21,43
Poaceae	12	9,02	51	15,84
Ranunculus acris-type (Ranunculaceae)	0	0,00	1	0,31
Rosaceae	0	0,00	1	0,31
total other angiosperms	107	80,45	284	88,20
Armeria maritima	0	0,00	1	0,31
Menyanthis trifoliata (Menyanthaceae)	0	0,00	2	0,62
Sparganium-type	0	0,00	1	0,31
total water plants	0	0,00	4	1,24
total pollen (pollen sum)	133	100	322	100
total pollen (pollen sum + water plants)	133		326	
Spores				
Spores: monolete; echinate	10	7,52	0	0,00
Spores: monolete; psilate	20	15,04	6	1,86
Dryopteris	32	24,06	0	0,00
total monolete spores	62	46,62	6	1,86
Spore: trilete; echinate	0	0,00	1	0,31
Spore: trilete; psilate	0	0,00	1	0,31
Botrychium	8	6,02	12	3,73
Huperzia	0	0,00	4	1,24
Lycopodium annotinum	4	3,01	8	2,48
Lycopodium clavatum (no spike)	0	0,00	6	1,86
Sphagnum	0	0,00	1	0,31
Selaginella selanginoides	1	0,75	8	2,48
total trilete spores	13	9,77	41	12,73
total spores	75	56,39	47	14,60
sporangium	1	0,75	0	0,00
pollen indet.	7	5,26	18	5,59
spores indet.	9	6,77	2	0,62
richness pollen	9	/	19	/
richness spores	6	/	9	/
pollen concentration (pollen/g)	655,19	/	95,51	/
spores concentration (spores/g)	369,47	/	13,77	/
P/D ratio = nP/(nP+nD)	0,01	/	0,04	/
Shannon Wiener index pollen and spores (H')	/	2,16	/	1,81
Evenness pollen and spores (EH)	/	0,80	/	0,56

Table 7.1: Raw data and absolute abundances of marine and terrestrial palynomorphs from the two Flatey samples. v indicates presence during scanning; / indicates absence during scanning or not calculated.

The sediments were decalcified with cold 2M HCl (6%). After neutralisation, the rock fragments are treated with warm (60°C) 40% HF during 2 to 3 days. As the sample 6891 was heavily saturated with silica, a second HF cycle proved necessary. Repeated cycles with warm 6% HCl were needed for the removal of the newly formed fluorosilicates. The residues were washed, stained with Safranin-O and mounted on slides with glycerine-gelatine jelly. The microscopic analysis was carried out at a 400x and 1000x magnification with a transmitted light Zeiss Axio Imager A1 microscope. Photomicrographs were made with a Zeiss MRc5 digital camera. The taxonomy of the dinoflagellates follows DINOFLAJ2 (Fensome *et al.*, 2008), that of the pollen Beug (2004). Apart, Fægri and Iversen (1989), Moore *et al.* (1991), Kapp *et al.* (2000) and Reille (1998, 1999) also helped for the determination of the pollen.

3. Results

Because of the low organic content, the sediments were treated with only a mild maceration technique without the use of acetolysis or potassium hydroxide. The relative abundances of the marine and fresh water algae, such as *Pediastrum* sp. (Plate 7.4, M) and *Botryococcus* sp. (Plate 7.4, N), are calculated versus the dinocyst sum. The counting of these algae stopped when a sufficient large dinocyst sum of more than 500 cysts was reached. The pollen and spores concentration was markedly lower. In both samples, the concentration of the dinocysts, 66627 cysts/g in the core sample and 2628 cysts/g in sample 6891, are much higher compared to the pollen concentration, which are 655.2 and 95.5 pollen/g respectively. Although the pollen concentration of sample 6891 was more than six times higher than in the core sample, a pollen sum of 300 pollen was here not reached.

3.1 Dinocyst analysis

A total of 14 dinocyst species belonging to 10 genera was recorded in both Flatey samples, but only three species were in common. The richness (number of species/sample) shows a decline from the core sample (10 species) to the higher sample 6891 (7 species) (Table 7.1). We made a distinction between the poorly preserved *Brigantedinium* species, noted as *Brigantedinium* sp., and the larger round brown cysts (RBC). In the core sample the group of the *Spiniferites* spp. refers in most cases to poorly preserved specimens of the species *Spiniferites ramosus*, in sample 6891 it refers most probably to *Spiniferites elongatus*. The deficient preservation did not allow determination to species level.

The two dinocyst assemblages are markedly different. The core sample contains following rare dinoflagellates only recorded during scanning: cfr. *Alexandrium tamarensis* / calcareous dinocyst lining, *Bitectatodinium serratum*, *Impagidinium patulum*, *Nematosphaeropsis labyrinthus*, *Spiniferites elongatus* and *Spiniferites mirabilis.* Also present are the acritarch species *Halodinium scopeaum* (Plate 7.4, O), *Cymatiosphaera* sp., *Cyclopsiella* sp. and the fresh water green algae *Desmidiales* sp. (Plate 7.4, P). Scanning of sample 6891 yielded the extra dinoflagellate cysts *Islandinium minutum*, *Achomosphaera* sp. (Plate 7.1, E–F), *Nematosphaeropsis labyrinthus* (Plate 7.1, I–L) and the acritarch *Cymatiosphaera* sp. In this sample, a large scabrate, probably reworked *Spiniferites* cyst was also recorded.

The core sample is dominated by *Bitectatodinium tepikiense* (50.9%; Plate 7.1, M–O) and *Brigantedinium* sp. (26.14%). Within the latter group, *Brigantedinium cariacoense* (0.95 %) as well as *Brigantedinium simplex* (0.57%) could be distinguished, but the poor preservation of the heterotrophic *Brigantedinium* species did not allow a specific determination. Other recorded heterotrophic species are *Selenopemphix quanta* (2.86%; Plate 7.1, P), *Quinquecuspis concreta* (0.95%; Plate 7.1, G), *Lejeunecysta sabrina* (0.57%), Round Brown Cysts (1.15%) and *Islandinium minutum* (0.76%). The heterotrophic species account for c. 33% of the assemblage. The autotrophic species, other than *Bitectatodinium tepikiense*, are unidentified *Spiniferites* spp. (8.97%), cyst of *Pentapharsodinium dalei* (4.20%), *Operculodinium centrocarpum* sensu Wall and Dale (2.86%) and the variety of this taxon with short processes (0.19%). According to the present-day dinocyst distribution (Marret and Zonneveld, 2003), almost 56% of the species have cold water affinities; these are *Bitectatodinium tepikiense*, cyst of *Pentapharsodinium dalei* and *Islandinium minutum*. The Shannon Wiener diversity index (H': 1.05) and the Evenness (E_H: 0.41), give an indication of the diversity and the spreading of the species within the sample; they are rather low. Only one specimen of the warm tolerant species *Impagidinium patulum* is recorded, together with one specimen of *Nematosphaeropsis labyrinthus*, an oceanic species. All other dinocysts have a neritic or an unspecific affinity.

Sample 6891 is clearly dominated by the cyst of *Pentapharsodinium dalei* (75.52%; Plate 7.1, D, H). Indeterminate *Spiniferites* spp. (14.93%), *Bitectatodinium tepikiense* (3.96%) and *Spiniferites elongatus* (3.06%; Plate 7.1, A–C) are the only other species that are regularly recorded. All other species have an abundance of maximum 1%: *Operculodinium centrocarpum* sensu Wall and Dale (1.08%), *Operculodinium centrocarpum* s.s. (0.18%; Plate 7.1, S–T), *Spiniferites ramosus* (0.72%; Plate 7.1, Q–R) and *Impagidinium* sp. (0.18%). The assemblage reflects a cold water environment for the most prominent species, c. 83% of the total assemblage, have recent cold water affinities (Marret and Zonneveld, 2003): cyst of *Pentapharsodinium dalei*, *Bitectatodinium tepikiense* and *Spiniferites elongatus.* No heterotrophic species were recorded in the sample. The Shannon Wiener index (from 1.05 to 0.59 now) and the Evenness (from 0.41 to 0.28 now) are much lower compared to the ones of the core sample.

3.2 Pollen and spores

Sample 6891 yields 19 pollen species and 9 spore species. The richness of the core sample was lower with 9 pollen species and 6 spore species, although the concentrations are much higher with about 7 times more pollen and about 27 times more spores. The difference in concentration in the core sample between the dinocysts (66627 cysts/g), and the pollen or spores (655.2 pollen/g and 369.5 spores/g, respectively) is remarkable and hampered the counting of the terrestrial palynomorphs. As a result, less than half the amount of pollen, 133 instead of 326, was reached in the core sample compared to sample 6891.

The core sample is dominated by Cyperaceae (32.3%) and the Ericaceae-*Empetrum*-group (33.9%). The angiosperm herbs constitute 80.5% of the assemblage together with Poaceae (9%), Carylophylaceae (2.3%) and *Asteraceae liguliflorae*-type (3%). Some angiosperm tree pollen are recorded in this sample: *Betula* (9%; Plate 7.2, E–F), *Juniperus* (0.8%) and cfr. *Ulmus* (0.8%; Plate 7.2, M–N). An almost comparable number of gymnosperm tree pollen is encountered (*Pinus*, 9%). Spore plants with *Dryopteris* (24%; Plate 7.4, K–L), monolete echinate (7.5%), monolete psilate (15%), *Botrychium* (6%), *Lycopodium annotinum* (3%), and *Selaginella selaginoides* (0.8%) account for 56.5% of the assemblage. A sporangium was observed in the sample, it indicates the nearby presence of spore plants.

Sample 6891 is dominated by the same groups, Cyperaceae (41.6%; Plate 7.3, G–H) and the Ericaceae-*Empetrum*-group (21.4%; Plate 7.2, I–J), but the Poaceae (15.8%; Plate 7.3, L) are now more important. The number of angiosperm herb pollen rises to 88.2%. Other angiosperm herbs are *Artemisia* (0.6%; Plate 7.3, I–J), Asteraceae liguliflorae-type (0.6%; Plate 7.3, A–B), Asteraceae tubiliflorae-type (1.9%; Plate 7.3, C–D), Carylophylaceae (2.8%; Plate 7.3, F), Chenopodiaceae (1.6%; Plate 7.3, E), *Circaea* (1.2%; Plate 7.3, M,N), *Ranunulus acris*-type (0.3%; Plate 7.3, K) and Rosaceae (0.3%; Plate 7.2, O–P). The number of gymnosperm pollen is comparable with the core sample, *Pinus* (9.6%; Plate 7.2, B) being also now the sole representative. The diversity of the angiosperm tree pollen increased with *Alnus* (0.3%; Plate 7.2, A), *Carpinus betulus* (0.6%; Plate 7.2, C–D), *Juniperus* (0.3%; Plate 7.2, G–H) and *Salix* (0.9%; Plate 7.2, K–L), but accounts for only 2% of the total assemblage. *Menyanthes trifoliata* (0.6%; Plate 7.3, O,P), *Armeria maritima* (0.3%; Plate 7.3, S–T) and *Sparganium*-type (0.3%; Plate 7.3, Q–R) represent water plants, accounting for 1.2% of the total assemblage. Spores plants constitute almost 15% of the assemblage compared to the pollen assemblage: monolete psilate (1.9%), trilete echinate (0.3%), trilete psilate (0.3%), *Botrychium* (3.7%; Plate 7.4, J), *Huperzia* (1.2%; Plate 7.4, A–B), *Lycopodium annotinum* (2.5%; Plate 7.4, E–F), *Lycopodium clavatum* (1.9%; Plate 7.4, C–D), *Sphagnum* (0.3%; Plate 7.4, I) and *Selaginella selaginoides* (2.5%; Plate 7.4, G–H).

The P/D-ratio (nP/(nP+nD) relates the number of pollen (P) and dinocysts (D). High values give an indication about the proximity to the coast or higher temperature on the land. In both samples the ratio is rather low with a value of only 0.01 in the core sample and 0.04 in sample 6891.

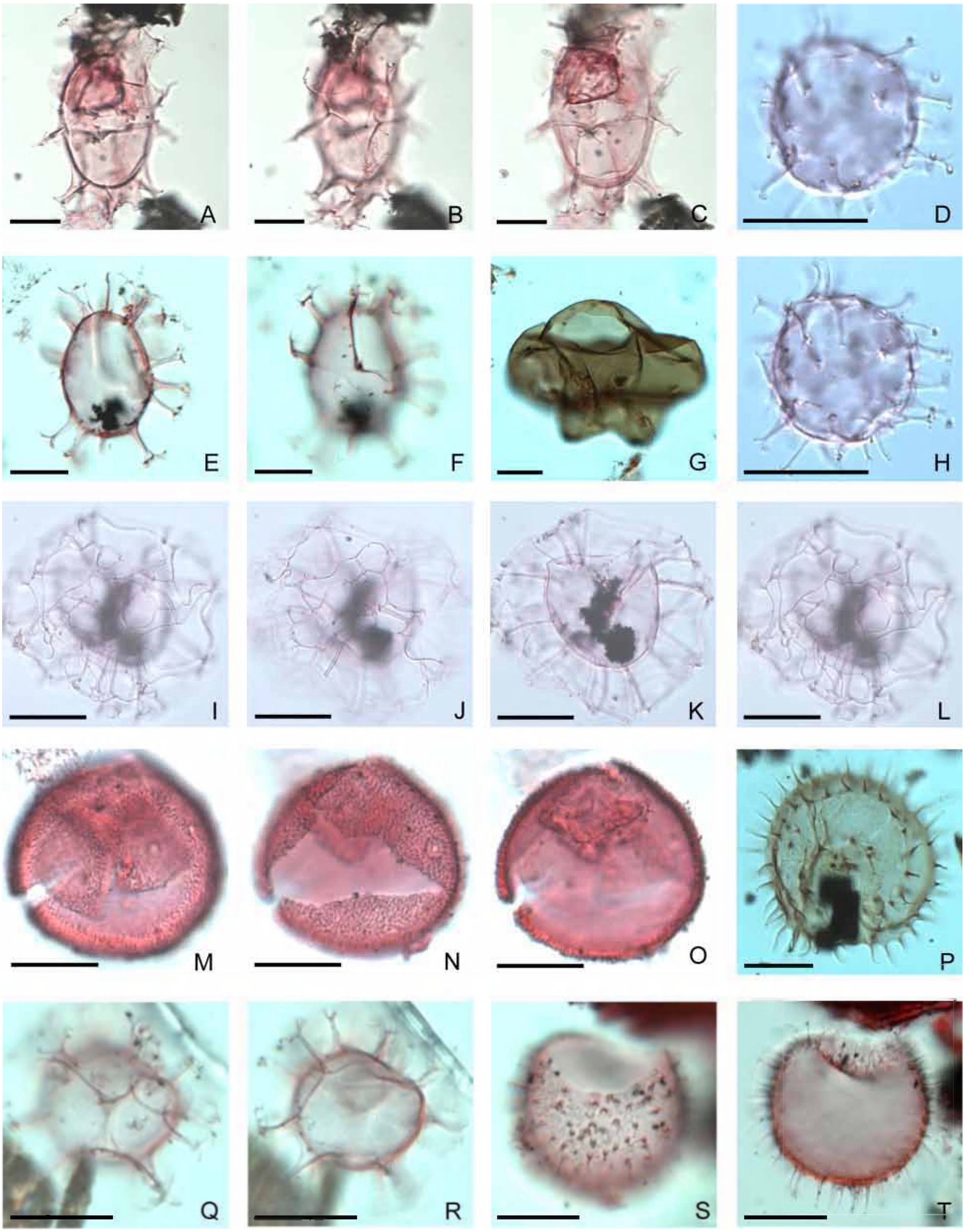

Plate 7.1: Photomicrographs of selected dinoflagellate species. Scale bars indicate 20 µm.

A–C: *Spiniferites elongatus*, Flatey sample 6891, E.F.: N39/1; **D, H**: cyst of *Pentapharsodinium dalei*, Flatey sample 6891, E.F.: Y53; **E–F**: *Achomosphaera* sp., Flatey sample 6891, E.F.: K32/4; **G**: *Lejeunecysta sabrina*, Flatey core, E.F.: V32/1 3; **I–L**: *Nematosphaeropsis labyrinthus*, Flatey sample 6891, E.F.: R34/2; **M–O**: *Bitectatodinium tepikiense*, Flatey sample 6891, E.F.: Y54/3,4; **P**: *Selenopemphix quanta*, Flatey core, E.F.: G55; **Q–R**: *Spiniferites ramosus*, Flatey sample 6891, E.F.: V52/2 4; **S–T**: *Operculodinium centrocarpum* s.s., Flatey sample 6891, E.F.: E45/3.

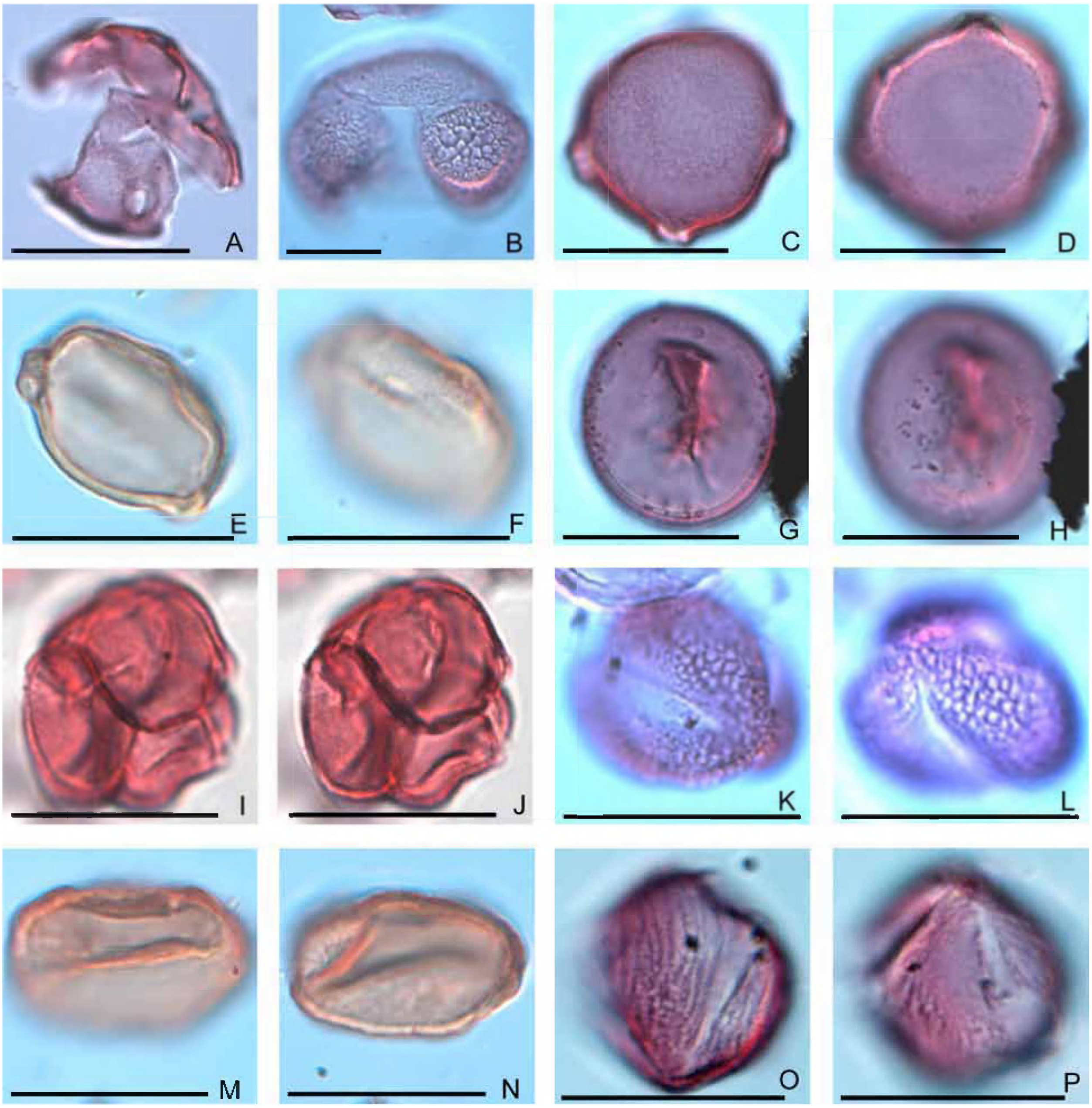

Plate 7.2: Photomicrographs of selected tree pollen. Scale bars indicate 20 µm.
A: *Alnus* sp., Flatey sample 6891, E.F.: Q61/4; **B**: *Pinus* sp., Flatey sample 6891, E.F.: Y50; **C–D**: *Carpinus betulus*, Flatey sample 6891, E.F.: W43/2; **E–F**: *Betula* sp., Flatey core, E.F.: R42/3; **G–H**: *Juniperus* sp., Flatey sample 6891, E.F.: W59; **I–J**: Ericaceae-*Empetrum*-group, Flatey sample 6891, E.F.: Z61/1; **K–L**: *Salix* sp., Flatey sample 6891, E.F.: S41/1; **M–N**: cf. *Ulmus* sp., Flatey core, E.F.: E55/1; **O–P**: *Rosaceae*, Flatey sample 6891, E.F.: W40/1.

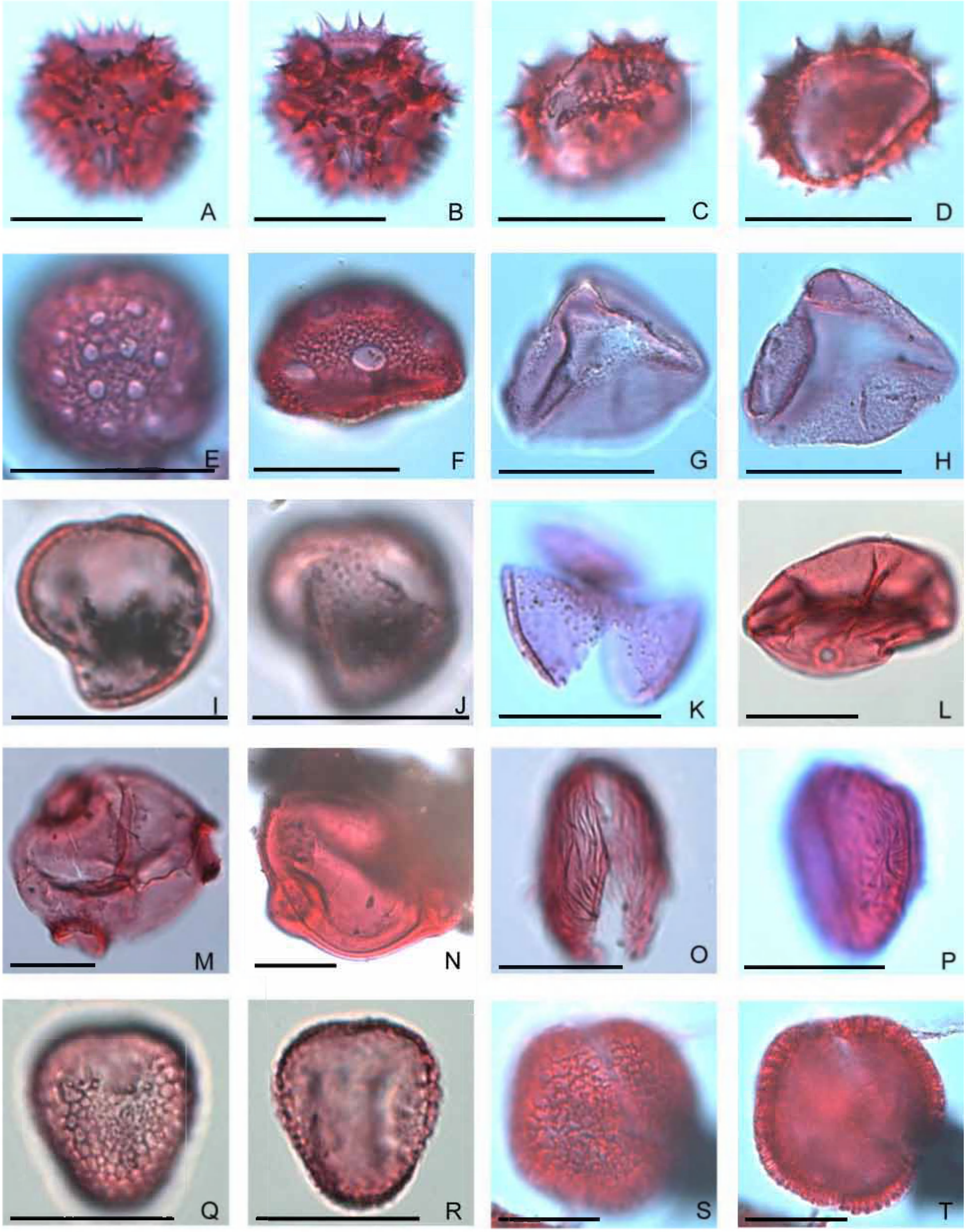

Plate 7.3: Photomicrographs of selected herb species. Scale bars indicate 20 µm.
A–B: *Asteraceae liguliflorae*-type, Flatey sample 6891, E.F.: W47/1; **C–D**: *Asteraceae tubiliflorae*-type, Flatey sample 6891, E.F.: X58; **E**: *Chenopodiaceae* sp., Flatey sample 6891, E.F.: Y37/4 ; **F**: *Carylophylaceae* sp., Flatey sample 6891, E.F.: X43; **G–H**: *Cyperaceae* sp., Flatey sample 6891, E.F.: W52/4; **I–J**: *Artemisia* sp., Flatey sample 6891, E.F.: L47/3; **K**: *Ranunculus acris*-type, Flatey sample 6891, E.F.: R35; **L**: *Poaceae* sp., Flatey sample 6891, E.F.: N39/4; **M, N**: *Circeae* sp., Flatey sample 6891, E.F.: M31 (M), E.F.:O57/2 (N); **O, P**: *Menyanthes trifoliata*, Flatey sample 6891, E.F.: V61/2; **Q–R**: *Sparganium*-type, Flatey sample 6891, E.F.: N39/3; **S–T**: *Armeria maritima*, Flatey sample 6891, E.F.: N34/1.

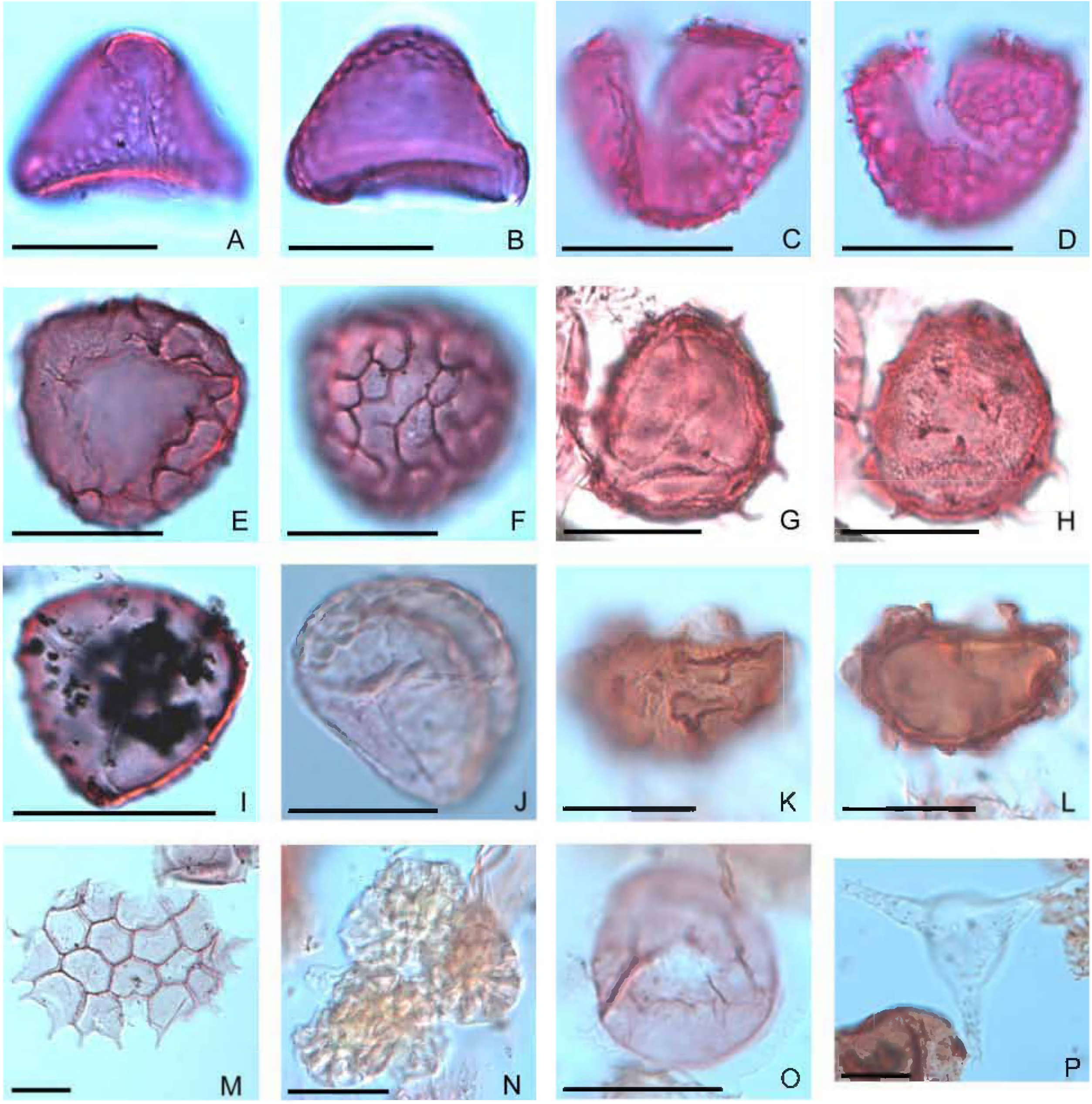

Plate 7.4: **Photomicrographs of selected spores, fresh water and marine algae. Scale bars indicate 20 µm.**
A–B: *Huperzia* sp., Flatey sample 6891, E.F.: S49/2 4; **C–D**: *Lycopodium clavatum*, Flatey sample 6891, E.F.: X54; **E–F**: *Lycopodium annotinum*, Flatey sample 6891, E.F.: W52; **G–H**: *Selaginella selaginoides*, Flatey sample 6891, E.F.: Z54/2; **I**: *Sphagnum* sp., Flatey sample 6891, E.F.: W57; **J**: *Botrychium* sp., Flatey sample 6891, E.F.: O52/2; **K–L**: *Dryopteris* sp., Flatey core, E.F.: X63/3; **M**: *Pediastrum* sp., Flatey sample 6891, E.F.: Y46/3; **N**: *Botryococcus* sp., Flatey core, E.F.: Y57/3; **O**: *Halodinium scopaeum*, Flatey core, E.F.: D54/4; **P**: *Desmidiales* sp., Flatey core, E.F.: T42.

The distance from the coast was apparently already great, but still allowed the deposition of a representative pollen assemblage. The increase in ratio probably reflects a shallowing of the area caused by an already started uplift. As a result of the shallowing, the area became less favourable for dinoflagellates.

4. Discussion

4.1. Correlation with the Tjörnes dinoflagellate zonation

Both Flatey samples have a poor richness. A total of only 14 species belonging to 10 genera was recorded, despite the enlarged dinocyst sum. The Early Pliocene Tjörnes assemblage, as a whole, is much richer with 54 dinocyst species belonging to 27 genera (Verhoeven *et al.*, 2011, in press). It is clear that the Flatey samples were deposited during much colder conditions than the Early Pliocene Tjörnes beds. Moreover within the Flatey succession a cooling trend can be suggested as the number of cold water species rises from c. 56% in the core sample to c. 83% in sample 6891. A correlation with the Early Pleistocene Breidavík Group is most obvious, as not only the low richness values but also the assemblages show much similarity.

The Flatey core sample consists of 33% extant heterotrophic species. Heterotrophic species with a Pliocene affinity such as *Echinidinium euaxum*, *Barssidinium pliocenicum*, *Selenopemphix brevispinosa* and *Trinovantedinium glorianum* do not occur. In the oldest dinozone of the Breidavík Group (DZ5a), corresponding to the Hörgi Formation, these Pliocene survivors still constitute 4% of the total assemblage. The dominant species of DZ5a, *Operculodinium centrocarpum* s.s. and *Lingulodinium machaerophorum* are not recorded in the core sample and a more recent, post-Hörgi age can at a first sight be attributed to it. In contrast to DZ5a, the Flatey core sample represents a much colder assemblage without warm elements such as *Barssidinium pliocenicum* and *Lingulodinium machaerophorum*. Subzone DZ5b encompasses the sediments of the Fossgil Member till halfway unit 10 of Bárdarson (1925) in the lower part of the Svarthamar Member. A comparable assemblage as the one of DZ5a is here observed, with the main difference that Pliocene heterotrophic species are lacking. *Bitectatodinium tepikiense* appears for the first time in the upper part of DZ5b in the coastal area and directly accounts for 23% of the assemblage. A few *Brigantedinium* species are found in the base of DZ6, the zone holding the sediments from the upper half of the Svarthamar Member and the Tórfholl Member. The numbers of heterotrophic species in the Tjörnes beds was never high. Poor preservation of the fragile cysts or differing nutrient availability of the coast and the shelf area can be the cause of this low occurrence. The corresponding high abundance of *Bitectatodinium tepikiense*, the co-occurrence of *Brigantedinium* species and the continuing dominance of cysts of *Pentapharsodinium dalei* correlate the Flatey core sample at first sight with the transition of DZ5b into DZ6 in the Tjörnes section, which corresponds with unit 10 from Bárdarson (1925) in the Svarthamar Member. However, as no Lower Pleistocene sediments older than c. 2.2 Ma are present in the Breidavík Group (Verhoeven *et al.*, 2012) and no Late Pliocene sediments of the Furuvík Formation were studied, it is hard to proof this hypothesis. Cold phases from that time period could also have resulted in a comparable dinoflagellate assemblage as found in the core sample. Therefore, caution has to be taken with the correlation of the core sample with the Breidavík Group. Not only the transition of DZ 5b to DZ6 can be considered as a possible correlation but also colder phases of the Late Pliocene / Early Pleistocene can be taken into account.

In sample 6891, the dominance of cysts of *Pentapharsodinum dalei*, together with the distinct presence of *Spiniferites elongatus* correlates the sample with DZ6 of the Tjörnes section. The lower boundary of DZ6 lies in the middle of unit 10 of the Svarthamar Member and the zone continues at least into the Tórfholl Member. Higher up in the Breidavík Group, no longer suitable marine sediments were detected, resulting in a lack of reference material for the last million year. The recent dinocyst assemblage in the northern part of Iceland (Marret *et al.*, 2004) however compares well with the DZ6 finds. Cysts of *Pentapharsodinium dalei* dominate also today the assemblage with values between 40 and 70%. *Operculodinium centrocarpum* sensu Wall and Dale (10–50%) and *Nematosphaeropsis labyrinthus* (10–20%) are today more abundant,

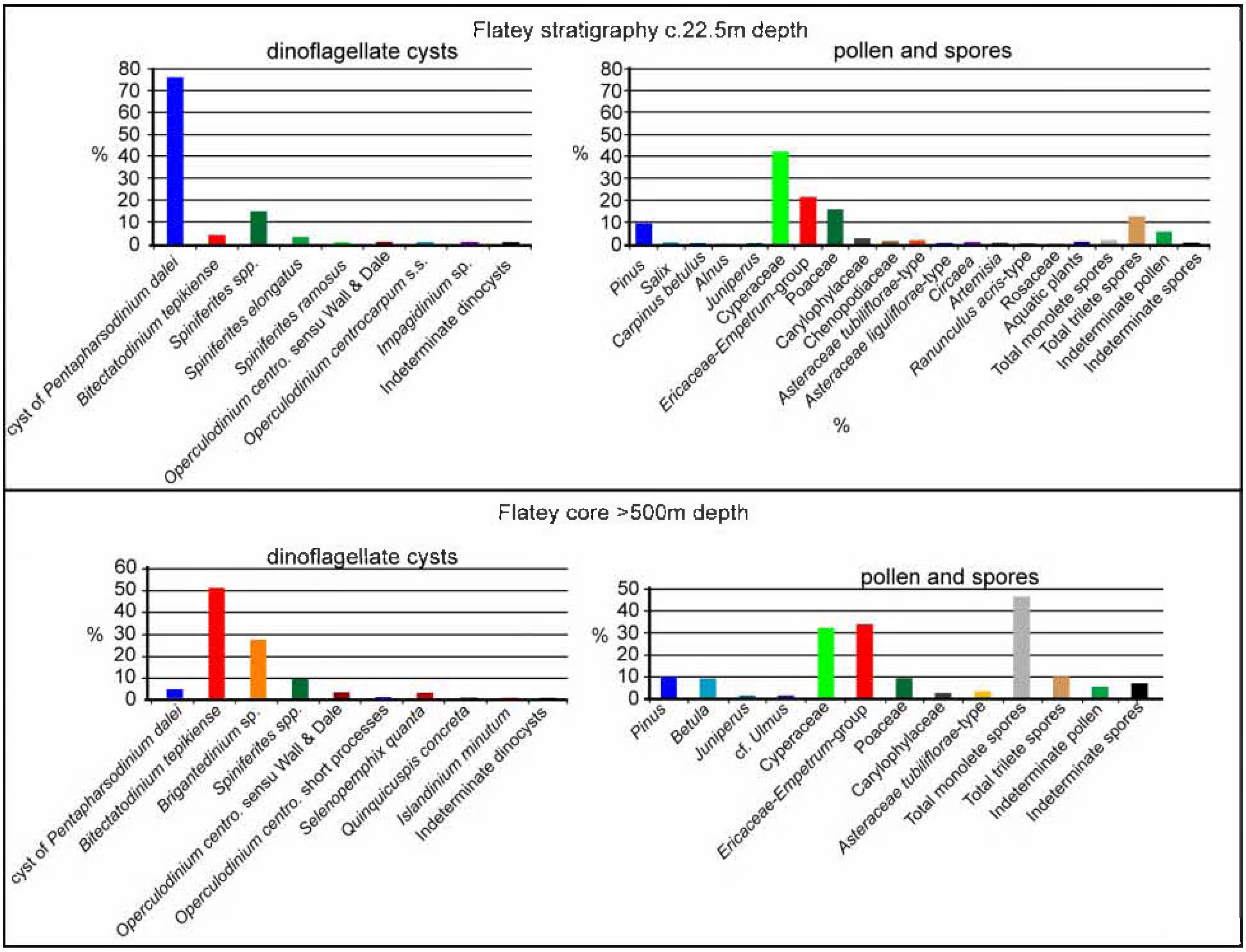

Figure 7.3: Vertical bar diagrams of the relative abundances of selected dinoflagellate cysts and pollen and spores of the analysed Flatey samples. Similar species are indicated with a same colour.

while *Bitectatodinium tepikiense* is present in low numbers (Dinocyst association II of Marret *et al.*, 2004). Sample 6891 correlates with the upper part of the Svathamar Member or with stratigraphical higher situated deposits.

4.2. Dinocyst paleoecology

The greater part of the dinocyst assemblage consists of neritic species or species without a specific environmental preference. *Bitectatodinium tepikiense* and cysts of *Pentapharsodinium dalei* for example are typical inner neritic species and dominate both assemblages. *Impagidinium* sp. and *Nematosphaeropsis labyrinthus* are oceanic species, and are observed only in very low numbers in sample 6891. Transport of dinocysts from the open ocean into the northern Icelandic shelf area was thus limited at the time.

The Shannon Wiener index of the core sample is low (1.05), and decreases to 0.59 in sample 6891. Compared to the average value of c. 1.5 during the Tjörnes beds, a clear decrease in diversity can be noted. Such a decrease was also observed during the successive interglacials of the Breidavík Group.

Heterotrophic dinoflagellates are dependent on nutrients delivered by upwelling or transported from the continent. During deposition of the lower part of the Flatey sequence, one third of the assemblage is composed of heterotrophic dinocysts, mainly *Brigantedinium* spp. Such large numbers of heterotrophic species have not been observed in the Breidavík Goup or in the recent assemblages (Verhoeven and Louwye, submitted; Marret *et al.*, 2004). The location of Flatey out of the coast seems to be favourable for heterotrophic species, and is probably related to a higher availability of nutrients. No single warm water species was recorded in both Flatey samples. This confirms the cold water conditions of both, and points to a Pleistocene origin.

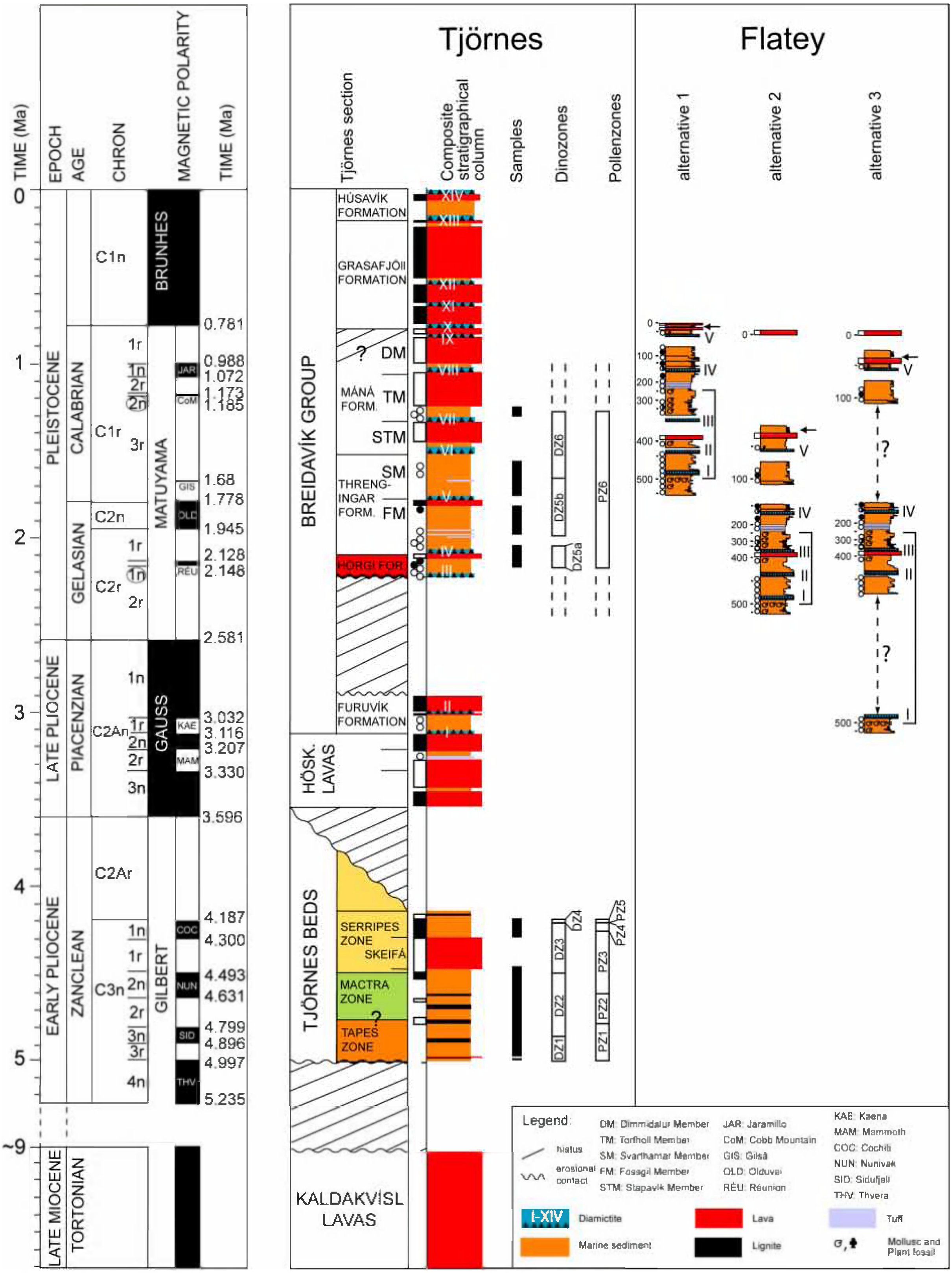

Figure 7.4: Correlation of the different strata of the Flatey and Tjörnes section in accordance with the dinoflagellate cyst assemblages, pollen and spores assemblages and the palaeomagnetic polarity measurements. Alternative 1 is based on the corresponding dino zones and pollen zones, alternative 2 and 3 on the corresponding occurrence of tuff layers. The age model of the Tjörnes section is based on Verhoeven *et al.* (2011), the dinoflagellate cysts zonation on Verhoeven and Louwye (submitted), the pollen and spores zonation on Verhoeven *et al.* (in press) and the palaeomagnetic measurements on Gunnarson *et al.* (1984). The arrow gives the location of sample 6891, the vertical brace the initial supposed location of the core sample.

The higher abundance of the cold water species cyst of *Pentapharsodinium dalei* in the uppermost sample represents a cooler environment compared to the assemblage of the core sample (see higher).

4.3. Pollen and spores

The relative high values of the Ericaceae-*Empetrum*-group in both Flatey samples clearly relates to the upper part of pollen zone PZ6 from the Tjörnes section. The upper part of PZ6 comprises the sediments from the top of unit 10 in the Svarthamar Member and the Torfhóll Member. A distinct decrease of the tree signal and an increase of the herbs are observed in this part of DZ6. A comparable trend marked by the increasing importance of Poaceae and *Selaginella selaginoides*, is visible in the Flatey sequence. It has to be noted that the vegetation in both Flatey samples already resembles closely the present-day vegetation with mainly *Empetrum* shrubs and herbs such as Poaceae. Spores of *Selaginella selaginoides* point to the presence of dry heathland and pastures. *Circaea*, previously in the Tjörnes beds incorrectly identified by Denk *et al.* (2011) as *Epilobium* sp., is characteristic of sheltered places in humid, mostly deciduous forests. As this pollen has been recorded several times in sample 6891, deciduous forests were apparently still part of the vegetation at the time. The extent of the forests was rather limited as the arboreal pollen total only accounts for c. 12% of the assemblage. The quite great variety of spore plants and the presence of a sporangium, locates these forests close to the coast. Ferns, as well as *Circaea*, need similar humid and sheltered locations probably in a coastal forest. *Circaea* is no longer present in Iceland. *Armeria maritima*, although mostly associated with a maritime influence, is a common herb species also present in the inland of Iceland. The finds in sample 6891 is the first fossil record of this plant in Iceland. Together with *Menyanthes trifoliata*, *Sparganium*-type and the many Cyperaceae, the plant indicates the presence of coastal marshes with fresh water pools. The presence of such pools is confirmed by the numerous records of the green algae *Pediastrum* sp. and *Botryococcus* sp. and the presence of the other green algae *Desmidiales*. In total, the vegetation in Flatey would be comparable to that of the Breidavík vegetation.

4.4. Palaeomagnetic correlation versus dinocyst biostratigraphy

Gunnarsson *et al.* (1984) initially measured the magnetic signal of the core succession on 25 fine-grained sediment samples and on eleven different levels of the three lava layers. Eiríksson *et al.* (1990) measured additionally 31 samples on fine-grained sediments. Forty-five of the 56 analysed samples yielded useful signals (Eiríksson *et al.*, 1990). All lava layers and the major part of the sediment layers (41 of the in total 48 reliable levels) have a reversed polarity (Figure 7.2). As a result, the entire core was attributed to the Matuyama chron (2.581–0.781 Ma; Lourens *et al.*, 2005). One sample with a normal polarity was observed below the uppermost glacial remains of diamictite V around 70 m core depth. The interval between 130 and 180 m core depth contains three normal and two equatorial signals. At 350 m depth, a sample with an equatorial signal was observed.

Eiríksson *et al.* (1987, 1990) suggested a correlation between the Flatey succession and the Breidavík Group based on the Matuyama age of Flatey and the corresponding occurrence of tuff layers. Between 206 and 223 m in the Flatey core, six tuff layers can be correlated to the tuff layers of the Fossgil Member. This last member contains seven tuff layers with a corresponding reversed polarity. As said, Eiríksson *et al.* (1990) proposed a Matuyama age to the entire Flatey sequence and also linked the normal remanence inclinations in the top of the core to the Réunion or Olduvai subchron or the Gilså geopolarity event, but a detailed correlation was not possible at the time.

Three possible correlations between Flatey and Tjörnes are proposed (Figure 7.4). The first correlation is based on the possible interpretation of the dinocyst results in which the Flatey core sample corresponds to the transition of DZ5b to DZ6 of the Breidavík Group, taken into account the diamictites and the palaeomagnetic reversals. The other two start from the correlation proposed by Eiríksson *et al.* (1987, 1990), based on the Matuyama age and the equivalence of the tuff layers found, the second alternative also uses the K/Ar dates of the lava layers (Albertsson and Eiríksson, 1989). We have to keep in mind that it is not certain whether the sedimentation history of both sites, Flatey and Tjörnes, is similar and that the same lava layers or diamictites are present at both localities.

Both basins are located close to each other, but differences in the tectonic regime may have existed. As the Flatey-Husavík fault passes through Flatey, much larger movements resulting in greater sedimentation rates can be advanced for the island compared to those of the section in Tjörnes. After all, seismic data showed here the presence of c. 2000 m of post-Miocene sediments, compared to c. 1200 m in the Tjörnes section (Eiríksson, pers. com. 2007).

The first alternative does not consider the correlation of the tuff layers or K/Ar dates, but it is based on a possible interpretation of the dinocyst correlation, diamictites and palaeomagnetic reversals. In this interpretation, the core sample corresponds to the uppermost part of zone DZ5b, halfway the Svarthamar Member. The normal magnetic signals around diamictite IV of the Flatey core then corresponds to the Jaramillo subchron (0.988–1.072 Ma, Lourens *et al.*, 2005). As no normal polarity signal is observed in the lowest part of the core, a post-Olduvai age can be assumed for the base. The first diamictite of the Flatey core does not seem to have a representative in the Tjörnes section and should be positioned between diamictite V and VI of Tjörnes. Diamictite II, III, IV and V of Flatey then probably correspond to diamictite VI, VII, VIII and IX of Tjörnes. Also, in this hypothesis the deposition of the tuff layers of Flatey coincides with the outflow of basalt lavas of the Torfhóll Member. The Tjörnes deposits corresponding to sample 6891 of Flatey are lava flows without dinocyst assemblage. It is however likely that zone DZ6 extends continues latest known occurrence, as the dinocyst assemblage is already similar to the recent assemblages of the area. In the first alternative, the Flatey Island was uplifted around 0.8 Ma and the oldest core sediments were 1.7 Ma old.

Eiríksson *et al.* (1987, 1990) suggested a correlation of the tuff layers of the Flatey succession with the tuff layers of the Fossgil Member, and of diamictite III of the Flatey core with diamictite IV at the base of the Fossgil Member. According to the age model of Verhoeven *et al.* (2011), the normal polarities measured around diamictite IV of the Flatey core correspond then to the Oluvai subchron (1.778-1.945 Ma; Lourens *et al.*, 2005; alternative 2; Figure 7.4). The correlation in this part of the succession appears acceptable for the alternation of lava flow, diamictite and tuff layers shows here great similarity. Diamictite I of Flatey has yet to correlate to a missing Lower Pleistocene part of the Breidavík Group (alternative 2), or, if a similar hiatus occurs in Flatey as in Tjörnes, to the lower part of the Furuvík Formation (alternative 3, Figure 7.4). The single normal polarity sample at 70 m depth can be related to the Gilså normal polarity event dated at 1.68 Ma (Lourens *et al.*, 2005); this results in the correlation of diamictite V of the Flatey core with diamictite VI of Tjörnes. In this hypothesis or alternative 2, the K/Ar dates indicate a major hiatus between the upper two lavas (Figure 7.2; Albertsson and Eiríksson, 1989). If the single normal magnetic signal in top of the core is younger, it may correspond to the normal polarity subchron of Cobb Mountain (1.173–1.185 Ma) or Jaramillo (0.988–1.072 Ma). This is the third alternative, with a second large hiatus between the highest normal polarity sample and diamictite IV.

Alternatives 2 and 3 do not match the suggested dinocyst correlation as used in alternative 1. No problems arise for the correlation of sample 6891, but the assemblage of the core sample does not show any similarity with the corresponding dinozones of the Tjörnes section (DZ5). In these alternatives, this core sample has to correspond to zone DZ5 or even to a Late Pliocene assemblage not yet known in Tjörnes. Although a correlation to the DZ5b / DZ6 transition seemed most logic at a first sight (alternative 1), cooling phases of Late Pliocene or Early Pleistocene age can also have resulted in the core sample assemblage (see higher). During such cold phases, the assemblage can be different and the absence of *Operculodinium centrocarpum* s.s. as the dominant species of DZ5 can be explained in this way. Cold water taxa as *Bitectatodinium tepikiense* and cyst of *Pentapharsidinium dalei* will probably also played a role in Early Pleistocene assemblages. Alternatives 2 and 3 are not in conflict with the dinocyst study, if the core sample corresponds to an Early Pleistocene cold phase. This cannot be excluded, but more palynological research on both sites is needed to solve this problem. Alternative 2 is the only alternative that is in total agreement with the K/Ar dates and suggests a marked hiatus between the uppermost lava layers of Flatey. Probably this hiatus is also present in the coastal section of Tjörnes between the Máná and Grasafjöll Formation. This would result in a more condensed Svarthamar Member and Máná Formation, which were then deposited before Olduvai and Cobb Mountain times. The position of the core sample however remains uncertain, but has to be placed in the interval between 300 and 530 m.

Preference can be given to the second alternative, since it provides better individual correlations of diamictites and lava flows. This alternative is only possible when the core sample originated from an Early Pleistocene glacial phase. Additional dinocyst studies of sediments from the Breidavík Group and the Flatey core are needed to improve the dinocyst zonation and correlation between Tjörnes and Flatey. This study however showed that a refinement of the palynological zonations of both sites will no doubt be useful to solve the correlation problem.

5. Conclusions

Two samples of the Flatey succession were analysed palynologically: a sandstone originating from the island, known as sample 6891, and a mudstone with a shell fragment in it from borehole Fl-01 in the northern part of the Flatey Island. The exact position of the core sample is not well known, but has to be situated between 300 and 530 m, as only in this part of the core mollusc shells are found. Both samples yield rich dinocyst assemblages of which the island sample was much colder and showed already similarities with the recent assemblage. The samples were assigned to the Pleistocene Matuyama chron. Moreover, sample 6891 can be referred to zone DZ6 of the Tjörnes section, while the core sample corresponds to the transition of zones DZ5b to DZ6 or to an Early Pleistocene cold phase. However, the dinocyst data of the two samples is too weak to allow an unambiguous correlation between the Flatey and Breidavík section. Three alternative correlations could be proposed based on correspondence in diamictites, lava flows and palaeomagnetic polarities. The first alternative follows a possible dinoflagellate correlation in which the core sample corresponds to the DZ5b/DZ6 transition. Two other alternatives are based on the published correlation with corresponding tuff layers, diamictites and palaeomagnetic polarities. They can also be in agreement with the diocyst data, if the core sample corresponds to an earlier cooling phase. The second alternative, based on the correspondence of the lava layers, diamictites and the K/Ar dates is most acceptable as much stratigraphical correspondance can be seen.

The Flatey succession is characterised by a sedimentation rate almost twice that of the Tjörnes section. The concentrations of the pollen and spores is much lower than those of the dinocysts, but nevertheless indicative of the coastal vegetation. The pollen concentration in Flatey corresponds to the ones in the marine Tjörnes sediments, but in the latter context the difference with the dinocysts concentration is negligible. The vegetation of Flatey comprises plants from deciduous coastal forests, dryland, pastures and marshes with fresh water pools. Except for the presence of some tree species, a close correspondence to the present-day vegetation of Iceland can be advanced. Both samples can be related to PZ6 from the Pleistocene part of the Tjörnes section.

In summary, the Flatey core represents a well-preserved palynological record documenting the Pleistocene cooling in northern Iceland, with the unique opportunity to study marine dinocysts and terrestrial pollen and spores in combination. It will allow a highly detailed climatological land-sea reconstruction in a future study. An intensive palynological study of the marine sediments of the Flatey core in combination with an additional study on the missing intervals in the Breidavík Group will no doubt allow for a more solid correlation.

6. Author contribution

The study is fully designed and carried out by KV and includes the subsampling of the island samples, palynological preparation in the laboratory, counting, interpretation of the data, writing of the paper and preparation of the figures and photo plates. Where necessary, remarks and language corrections of the chapter were made by SL.

7. Acknowledgements

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Conclusions and future perspectives

8

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1. Introductory conclusions

Our dissertation focusses on the coastal area of Tjörnes in northern Iceland, as this location harbours a key section for the understanding of the climate shifts of our hemisphere. However up to now, little was known about the concentrations, preservation and possible disturbances by reworking of palynomorphs in the deposits. Also, a solid age model for the Tjörnes section was not available, as the dominantly marine sediments yielded only weak palaeomagnetic signals and no absolute dating could be applied to them (Eiríksson *et al.*, 1990; Kristjánsson, 2004). The magnetic polarities and K/Ar ages of the lava layers (Aronson and Sæmundson, 1975; Albertsson, 1976, 1978) in sequence formed the fragile framework of the age model, and the low potassium content of the radiometric sample also introduced much uncertainty. Moreover the sedimentary rocks could only be positioned indirectly in the timeframe and hiatuses between lava and sediment layers could not be demonstrated. In our study, we analyzed the terrestrial and marine palynomorphs of the Tjörnes beds, of four interglacials of the Breidavík Group and of two levels of the Flatey succession on the homonymous island near the Tjörnes coastal area. Lignites as well as marine sediments were included in the analysis.

The preparation and study of the palynomorphs did not present particular problems. However, in the Tjörnes section, the concentrations of the dinoflagellate cysts is rather low, but the preservation is good and only a limited influx of reworked palynomorphs is observed (chapter 2). Although the concentrations were low, the number of species was quite large. Because of the coastal position of the sedimentation basin, a diverse heterotrophic flora could develop, yielding much ecological data (chapter 3). A new dinoflagellate cyst named *Selenopemphix islandensis* was found and appears to be useful as a biostratigraphical marker (chapter 4).

A large variety of pollen from plants, today generally extinct in Iceland, occurs in the Tjörnes section (chapter 1). A clearly warmer vegetation is recorded in the Pliocene and Early Pleistocene interglacials (chapter 5). As expected, the Pliocene pollen morphology is generally comparable with that of the present-day pollen. The *Polygonum bistorta*-type however presents an exception, as the Pliocene variant of this pollen is markedly smaller than the present-day ones and 40% of the variant has poorly or not developed pores (chapter 6). All recent reference pollen, including those from two Icelandic locations, show distinctly larger sizes than the Pliocene ones. As the Pliocene is warmer than today, one expects plants then to have grown to a larger size, with the *Polygonum bistorta*-type pollen of a corresponding size. It is not clear what caused the poorly developed pores in the Pliocene pollen of this type. Probably an evolution to a larger chromosome number from the Pliocene to the recent forms lies at the basis of the enlarged pollen size.

2. Land-sea signals in the coastal Tjörnes and Flatey shelf setting

The potential to study in combination terrestrial as well as marine palynology in the same samples is tested in Tjörnes and Flatey. The absolute concentrations and the richness of pollen, spores and dinoflagellate cysts have been compared (Table 8.1, Figure 8.2). Although it was not the subject of this memoir, the palynological potential of the deep sea drilling ODP 985A has been added to the comparison, as it forms a third environment in a land-sea transect (Figure 8.1). Pliocene and Pleistocene sediments of this core were palynologically tested on dinoflagellate cysts and pollen / spores in order to evaluate their potential in future research. The general findings of these tests are here included to make clear that the records in Tjörnes and Flatey are unique in combining both proxies in a meaningful way. The coastal section in Tjörnes contains both marine and terrestrial palynomorphs, but the dinoflagellate cysts concentrations are mostly too low to provide a statistically needed counting of 300 specimens/sample. Quantitative analysis of the assemblages however resulted in meaningful results concerning relative dating of the sediments, ecology and changes in ocean currents. The shallow shelf sediments of Flatey combined an abundant dinoflagellate presence with a still meaningful terrestrial palynomorph concentration and richness. Flatey and Tjörnes are both suitable for a pollen/dinoflagellate study, but marked concentration differences of both proxies in a same sample hamper the combined study. For example, dinocysts are present in the lignites of the Tjörnes beds, but they are so few with respect to the pollen and spores, that no signal could be obtained. The opposite happened in the more marine Flatey setting in which dinoflagellate cysts dominate. Acetolysis and KOH treatment may here help to destroy the dinocysts, in favour of a clear pollen slide and two separate laboratory treatments can here be useful. The diluted dinocyst signal in de lignites however cannot be made more dense, as pollen is more resistant than dinocysts and both have a comparable density. As to ODP 985, it is situated too far from the

		dinocyts		pollen				spores	
		average richness (species/sample)	average concentration (cysts/g)	average heterotrophic species	average richness (species/sample)	average concentration (pollen/g)	percentage gymnosperms	Average richness (species/sample)	Average concentration (spores/g)
ODP985	Pleistocene c. 1 MA	8,3	148,7	0%	3,5	88,9	88%	1,5	27,6
	Pliocene, 4–4.4 Ma	17,4	1614,4	19%	3,3	311,5	95%	3,5	63,6
Flatey	c. 1 Ma	8	2628	0%	19	95,5	9,50%	9	13,8
	c. 2.5 Ma	13	66627	33%	9	655,2	9%	6	369,5
Tjörnes	Early Pleistocene	6,9	99	7%	14	50	36%	6,3	22
	Pliocene, marine 4.5–5Ma	11,5	136,5	45%	13,6	250	45%	5,9	374
	Pliocene, lignite 4.5–5Ma	1,1	230	17%	11,6	110400	8,50%	2,6	25514

Table 8.1: Overview of the concentration and richness values of terrestrial and marine palynomorphs from the coastal section in Tjörnes, the shallow shelf section in Flatey and the deep marine section in ODP 985.

continent: the land signal is not well expressed as the pollen assemblage is rather poor and dominated by gymnosperms. Angiosperm pollen do not float well and are almost absent in the deep sea assemblage of ODP 985. Pollen studies on deep sea cores can be useful, but as the vegetation cover of the higher latitudes is extreme low during cold phases, the terrestrial signal will be barely preserved in these settings. This was the case for ODP 985 which showed a rather limited pollen content. The absence of much nutrients in the full oceanic setting of ODP 985 gives a rather monotonous dinoflagellate cyst signal dominated by autotrophic species. In contrast, the dinoflagellate cysts in the northern Icelandic coastal area are more diverse. Nutrient availability played here a major role and a rather large species diversity could be detected. Because of the low concentrations in the Tjörnes and Flatey sections, much efforts however has to been done in the palynological analysis. The comparasing with the deep sea record made clear that these effort were advantageous as much information could be derived out of the palynological study of this area, information which is not present in deeper settings as the distance to the land is too far.

3. Age model and glacial history

The dinoflagellate assemblages found in the Tjörnes beds as well as in the Breidavík Group provide new data to age the Tjörnes section. The Tjörnes beds seemed to be of post-Miocene age and the presence of the marker species *Batiacasphaera minuta*, *Operculodinium tegillatum* and *Reticulatosphaera actinocoronata* indicate an Early Pliocene age for the beds. In combination with the palaeomagnetic reversals, the top of the *Serripes* Zone could be placed around 4 Ma and the Pacific molluscan invasion at the *Mactra*/*Serripes* boundary around 4.5 Ma, immediately above the top of the Nunivak subchron.

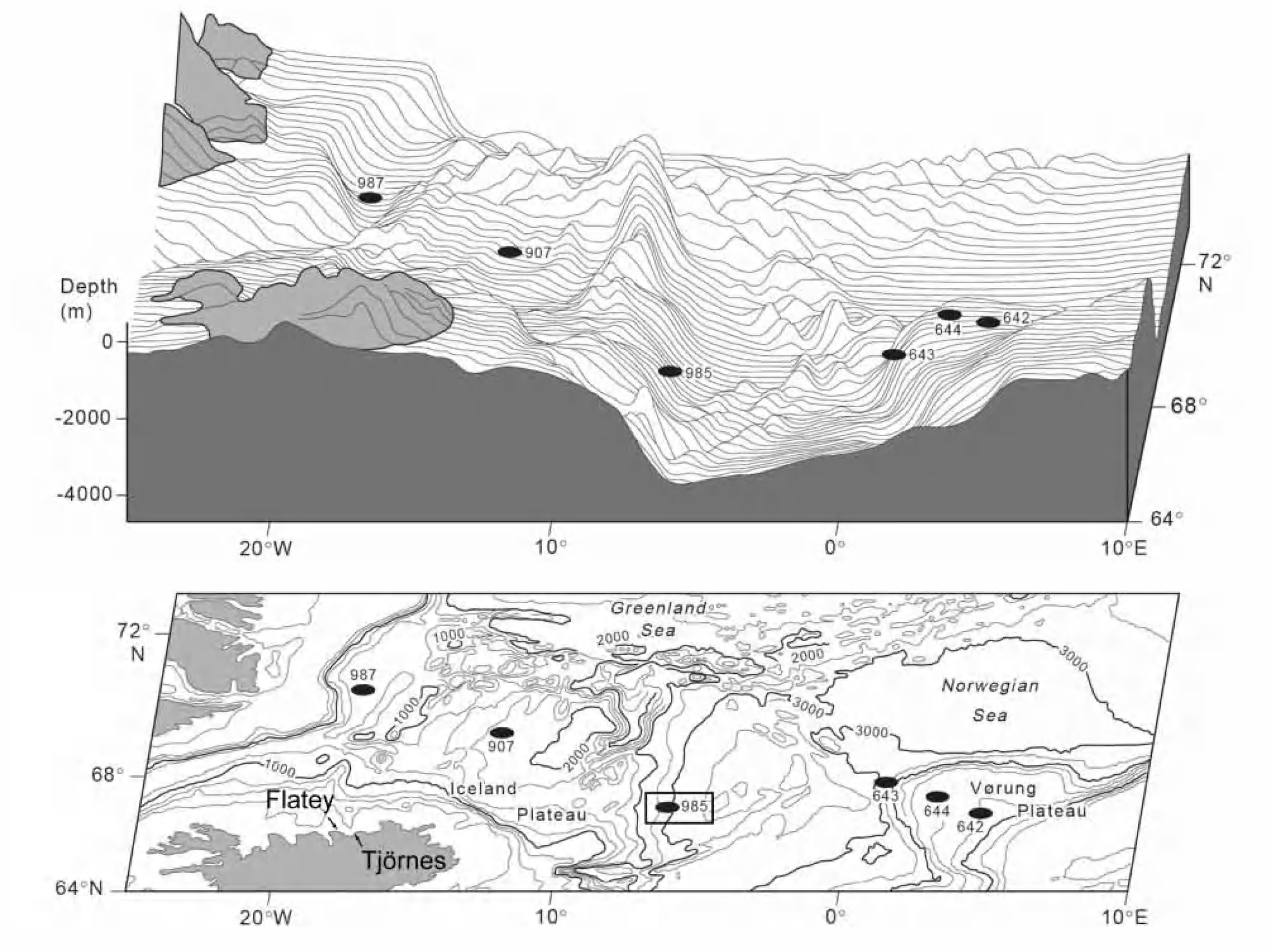

Figure 8.1: Localization of the Tjörnes section, Flatey drilling and ODP 985. Map adapted from Kaminski and Austin (1999).

The age model proposed in our study (chapter 2, Figure 2.3) reveal that the K/Ar dating of the Höskuldsvík lavas, situated between the Tjörnes beds and the Breidavík Group, were c. 0.7 Ma too young, while the K/Ar age of the unnamed weathered lava layer in the base of the *Tapes* Zone was c. 0.6 Ma too young. The ages of the Máná Formation lavas show a great range (0.66 ± 0.32 Ma – 1.55 ± 0.14 Ma; Albertsson, 1978), but the exact position of the sampled lavas was not clear to us and the correctness of these ages could not be well evaluated. However, they are not in conflict with the proposed age model of chapter 2. In the case of the ages which appear too young, we suppose that weathering may have led to argon loss. As to the basalts, they contain a very low potassium content and the ages may thus be seen as minimum ages.

In contrast to the older K/Ar ages of Tjörnes, those of Flatey seem to be reliable and the second alternative correlation proposed (chapter 7, Figure 7.4) probably comes close to what really happened in the Flatey area. Independent of the K/Ar ages of the Flatey basalts, the palaeomagnetic reversals and tuff layers as positioned in the alternative fit with the proposed age model of Tjörnes (chapter 2, Figure 2.3). This provides a separate argument that the normal polarities in the top of the Hörgi Formation effectively correspond to the Réunion subchron, while the normal polarities in the top of the Fossgil Member correspond to the Olduvai subchron (Figure 8.3). In this view, the Flatey succession corroborates the idea of a marked hiatus between the Hörgi and Furuvík Formation of the Breidavík Group. The start of the sedimentation in Flatey coincides with a period of non-deposition or even erosion at the Plio-Pleistocene transition in Tjörnes, spanning approximately 0.7 Ma and marked by an angular unconformity between the Furuvík and Hörgi Formation. The lowermost 135 m of sediments in Flatey are unique compared to those of the Tjörnes succession, and complete the glacial history of the area as they contain an extra diamictite. According to alternative 2 (Figures 7.4, 8.3), these oldest glacial remains of Flatey are not preserved in Tjörnes, for they correspond to the mentioned hiatus. As a result, a total amount of fifteen instead of fourteen demonstrable glacial periods are present in the Tjörnes area. As the time gap in Tjörnes between the second and third glacial period amounts to 0.7 Ma, probably more glacial periods are missing there. The oldest proof of a glaciation in the Tjörnes area, situated in the base of the Furuvík Formation, is dated around 3.1 Ma, instead of 2 or 2.48 Ma as previously stated (Eiríksson and Geirsdóttir, 1991; Geirsdóttir, 2004), and predates the onset of the Quaternary by 0.6 Ma. The first time that glaciers in northern Iceland reached the coastal area and had thus a large distribution on the island is thus older than previously thought. In northeastern and eastern Iceland, evidence of glaciation of a comparable age (3.0 Ma) has been recorded by McDougall and Wensink (1966) and Guðmundsson (1978). Mapping and dating efforts by Sæmundsson (1980), and Einarsson and Albertsson (1988) also suggest the onset of widespread glaciations in Iceland just over 3 Ma ago. At that time, the early Icelandic ice sheet that started to grow initially in the southeast of the island around c. 4.6 Ma, extended further to the west and the north and formed for the first time a major ice sheet (Geirsdóttir, 2004). Our study reveals that the start of the northern glaciation can be linked to the extension of the ice sheet in the eastern part at the Jökuldalur and Fljótsdalur valleys, and that the Icelandic ice sheet around 3.1 Ma had already a greater extent than previously accepted (Geirsdóttir, 2004).

The marked time gap between the upper two lava layers of Flatey (chapter 7, Figure 7.2) suggest a comparable hiatus in the top of the Flatey succession. As the sedimentation history of Tjörnes is closely related to that of Flatey, it is very plausible that a comparable hiatus also exists in Tjörnes. As between the normal polarities of the Fossgil Member and the Grasafjöll Formation, no other normal polarities have been measured, a hiatus or the non-detection of the Jaramillo and Cobb Mountain normal polarity subchrons has been proposed in chapter 2. After the study of the available K/Ar dates and the palaeomagnetic data of Flatey in chapter 7, which resulted in the correlation of the Flatey with the Tjörnes succession (Figure 7.4), the option of a hiatus between the Máná and Grasafjöll Formation in Tjörnes appears most acceptable (Figure 8.3). A hiatus of possible 0.6 Ma between diamictite IX and X in Tjörnes will no doubt increase the total number of glacial periods that affected Tjörnes. As said, the remains of fifteen glacial periods has be demonstrated, but probably much more cold phases affected the area.

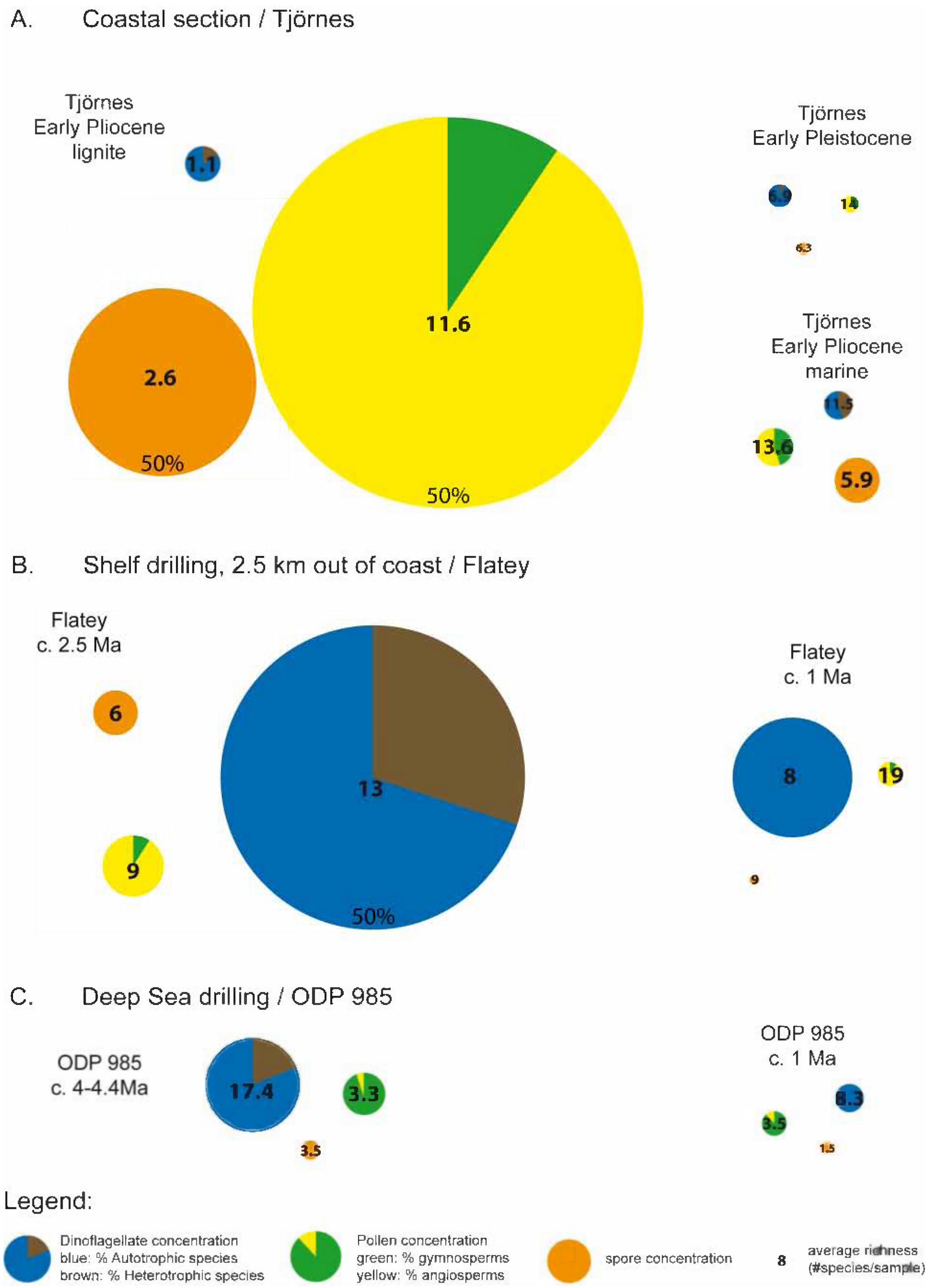

Figure 8.2: Potential of pollen, spores and dinoflagellate research in Tjörnes, Flatey and ODP 985. The size of the circles represent the absolute concentrations. The three circles with indication of 50% are drawn for only half the size as otherwize they became too big for this figure.

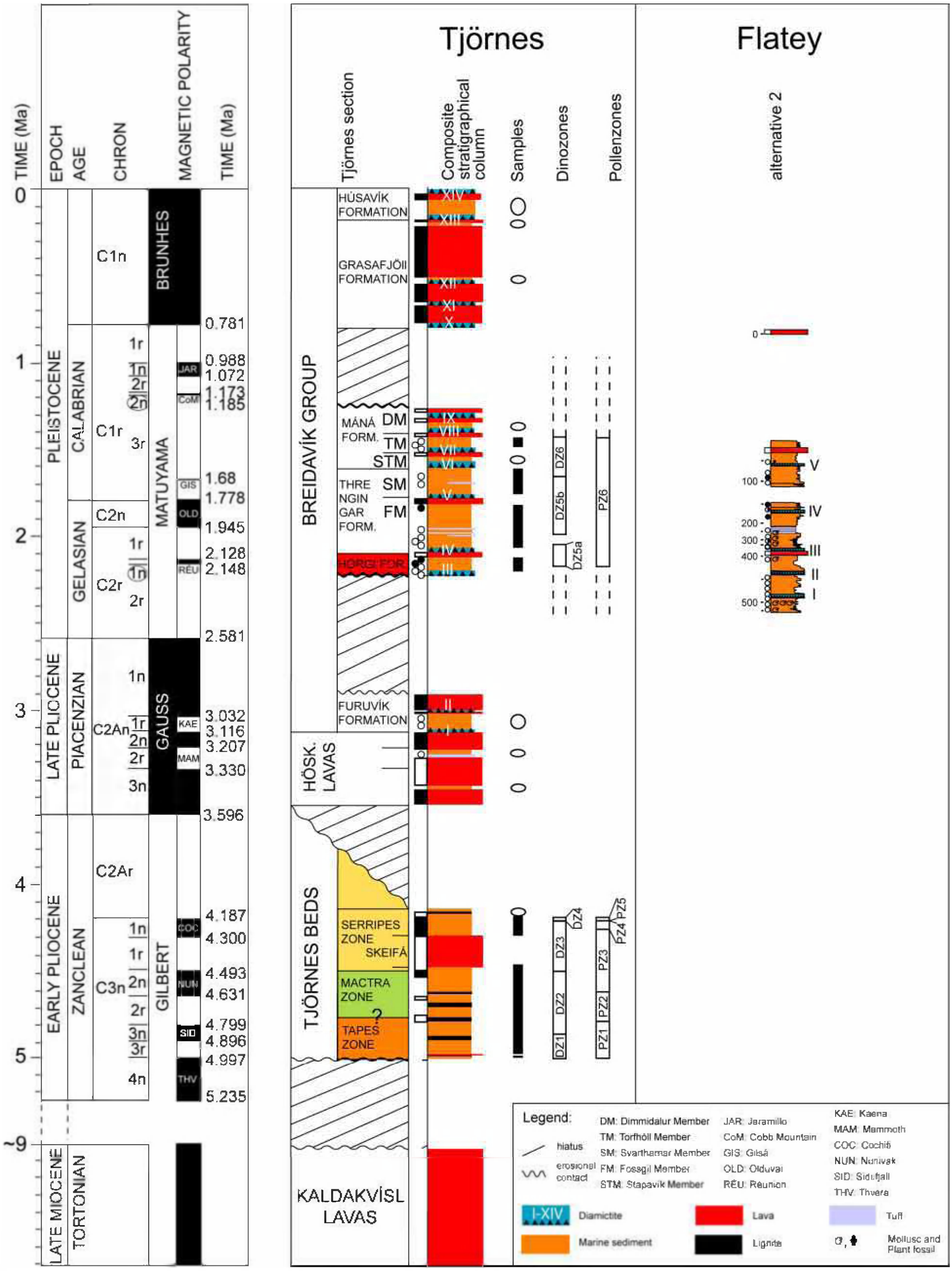

Figure 8.3: Age model of the Tjörnes and Flatey succession according to the latest insights. The circles in the column of the samples indicate the not studied marine sediments.

Ehlers and Gibbard (2008) state that the oldest tillites in the Icelandic mountains are of Miocene age, prior to 7–6 Ma, and a total of some 30 glacial events were detected in Iceland since that time. The section in Tjörnes is probably the best preserved terrestrial record for the Early and Middle Pleistocene glaciations anywhere in the North Atlantic region (Ehlers and Gibbard, 2008). Possibly two marked hiatuses are present in the glacial record, but a quite complete glacial stratigraphy from the earliest regional glaciations to the last glaciation is here recorded.

The second alternative correlation discussed in chapter 7 seems to be the most logical one, as the tuff layers, K/Ar ages and the palaeopolarity reversals fits with the age model of Tjörnes (chapter 2), but an independent control with dinoflagellate cysts was impossible. To elucidate whether our hypothesis is correct, at least knowledge of the dinoflagellate content of the marine Furuvík sediments and the sediments below 500 m depth in the Flatey core is needed.

4. Pliocene-Quaternary transition

The idea of a nearly continuous sequence of Pliocene and Pleistocene sediments in Tjörnes has to be abandoned, as three major hiatuses seem to be present. For instance, the top of the Early Pliocene is missing, as between the *Serripes* Zone and the Höskuldsvík lavas a first large hiatus is present. Although the fact that the Höskuldsvík lavas lay concordant on the sediments of the *Serripes* Zone, the relative dating with dinoflagellate cysts of this zone in combination with the reinterpretation of the palaeomagnetic data indicates a major age difference with the Höskuldsvík lavas. A very slow sedimentation rate or erosion may have caused this time gap. Also, the transition of the Pliocene to the Quaternary is missing in Tjörnes, but this hiatus is in contrast to the previous one underscored by an angular unconformity between the Furuvík and Hörgi Formation.

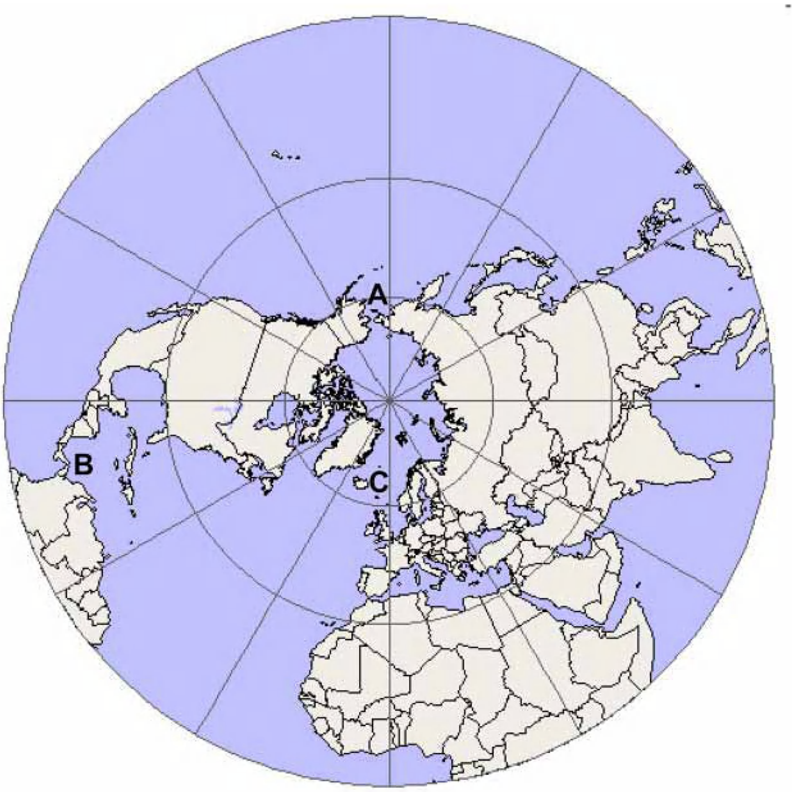

Figure 8.4: Overview of the connections between the Pacific and Atlantic Ocean with indication of the important geological changes in the palaeoceanography. A: Bering Strait, B: Central American Seaway, C: Tjörnes.

The idea of a complete record of the Calabrian in the middle of the Pleistocene has also to be abandoned as higher up in this chapter we present arguments for a third great hiatus, between the Máná and Grasafjöll Formation. The Tjörnes beds give insight in the Early Pliocene, while the Breidavík Group shows the cooling during the middle part of the Quaternary. The onset of the glaciations is preserved in Furuvík, but two major hiatuses hampered the total reconstruction of the glacial history. The generally adopted start from the global cooling at 2.581 Ma at the beginning of the Quaternary is not preserved in Tjörnes, but may be preserved in Flatey. Seismic profiles suggest a total sediment depth of c. 2 km in Flatey (Gunnarsson *et al.*, 1984), and thus the beginning of the Quaternary can therefore be present in this place. The Flatey FL-01 however did not reach further than 554m.

5. Pacific molluscan migration and changes in palaeoceanography

Before our study it was believed that the entrance of Pacific molluscs at the *Matra/Serripes* transition in the Tjörnes beds occured 3.6 Ma ago (Marincovich, 2000; Símonarson and Eiríksson, 2008). Comparable molluscan invasions at the base of the Red Crag Formation in England and in the Merksem Sand Formation in Belgium were thought to be contemporaneous with the invasion in Tjörnes, based on corresponding molluscan assemblages (Einarsson *et al.*, 1967; Marincovich, 2000). Various dinoflagellate studies (Head 1993, 1996, 1998a,b; De Schepper *et al.*, 2009) however show that the invasion in the English and Belgian part of the North Sea basin was indeed contemporaneous, but took place already around 2.8–2.9 Ma. Our study accords a much older age of 4.5 Ma to the invasion in the Tjörnes area. Although migration from the Pacific into the Atlantic was already possible from then on, it took 1.7 Ma for the molluscs to overcome ecological barriers between the coastal environment of Tjörnes and that of the southern North Sea. Biostratigrapical use of molluscs on a large geographical scale is indeed hampered by the limited migration capacities of the group; that is not the case by planktonic algae such as dinoflagellates.

Already in the *Tapes* and *Mactra* Zones, the immigration of some Pacific molluscs is recorded (Figure 3.5) and post-dates the opening of the Bering Strait in the northern Pacific (Figure 8.4). At the beginning of this opening, Atlantic water entered the Pacific and the presence of the Atlantic/Arctic bivalve *Astarte* in southern Alaska on the Pacific side of the Bering Strait, may date this opening to 5.4 Ma ago (Marincovich and Gladenkov, 2001). After the shoaling of the Central American Seaway, dated between 4.7 and 4.2 Ma, water took an unidirectional flow from the Pacific to the Atlantic (Marincovich and Gladenkov, 1999; Steph *et al.*, 2006). The massive migration of Pacific molluscs to Tjörnes at the base of the *Serripes* Zone can be linked to this shoaling, as an age of around 4.5 Ma is established for this migration (chapter 2). Migration of nutrient rich water inducing the bloom of heterotrophic dinoflagellate species slightly preceded the invasion of Pacific molluscs (chapter 3, Figure 3.5). The period before the invasion, corresponding the *Mactra* Zone, is devoid of heterotrophic species and it seems that upwelling systems bringing nutrients to the area are not present at that time. The period before, more or less corresponding to the *Tapes* zone, however, is dominated by heterotrophic species. During the *Mactra* Zone, the palaeoceanography changed apparently, probably because of the shift of the Polar Front with related upwellings of nutrients from the region. The reason of the molluscan change between the *Tapes* and *Mactra* Zone is until now unclear, but it has probably much to do with the change in algae and availability of nutrients, caused by a possible retreat of the Polar Front out of the area.

6. Future research perspectives

Our study makes clear that a better understanding of the depositional history of Flatey will contribute to unravel that of Tjörnes. Both sections are closely related, but the initial correlation with palaeomagnetic polarity reversals and K/Ar ages (Figure 8.2) needs to be tested with an independent proxy. A refinement of the dinoflagellate and pollen biozonation of the Breidavík Group in combination with a thoroughly study of the palynology of the Flatey core will no doubt made this possible. The K/Ar ages of the Flatey lava layers appear reliable and the palynological content of the marine Flatey sediments is of good quality and sufficiently rich, to allow the setup of a detailed biozonation in Flatey, which in turn can be used in Tjörnes. The palynological potential of the Breidavík Group is restricted compared to that of Flatey because of the much lower palynomorph concentrations, but still useful for biostratigraphical correlation. However, the presence of marine sediments in the Breidavík Group, especially in top of it, is restricted and can provide only fragmentary information. Nevertheless the marine incursion within the Höskuldsvík lavas and the marine sediments of the Furuvík Formation, Stapavík and Dimmidalur Member of the Máná Formation are worth to be studied, as they can give a better insight in the Tjörnes biozonation and the cooling effects of the Pleistocene. The study of these marine sediments in combination with the ones of the Flatey succession is crucial to construct a more solid correlation of the Breidavík Group with the Flatey succession. We need such a correlation to better understand the glacial successions in Iceland. Glacial remains in the outer parts of Iceland, as in Tjörnes and Flatey, represent marked cooling periods not only affecting the whole island but also with impact on a global scale. A further unravelling of the sedimentation and glacial history on the Tjörnes Peninsula will contribute to the knowledge of climate deterioration during the ice ages of the Quaternary. Furthermore, a link with the deep sea can be made by studying core drillings of the Icelandic Plateau. ODP 907 and 985 are suitable cores, as both have a good palaeomagnetic record and contain sediments of comparable ages. The distance of these cores from land however will make the pollen signal much less clear. Nevertheless, a combined study of dinoflagellate cysts with pollen is also here advisable. A dinocyst new to science was found and labelled *Selenopemhix islandensis* (chapter 4). It is supposed to originate from the Pacific and entered the Atlantic around 4.5 Ma. Therefore it can be used as biostratigraphical marker in the Atlantic. Its presence in the Pacific however has not been proved and a thorough dinoflagellate study of the sediments of higher latitudes of the Pacific origin is needed to evaluate the stratigraphical value of this species. A future study of Miocene Pacific sediments can elucidate the origin of the species. Furthermore the study of Miocene and Pliocene palynology in sediments on both sides of the Bering Strait can clarify migration directions between the northern Pacific and Atlantic. A future drilling in the total sequence of Flatey down to 2000 m instead of 554 m can greatly contribute to the unravelling the history of the terrestrial vegetation and glaciations in Iceland and elsewhere as well as their interactions with the marine realm.

Samenvatting (Summary in Dutch)

Inleiding

De geologie als wetenschap heeft zich sedert haar ontstaan bij Griekse filosofen verdiept in de processen die de Aarde vormden en de geschiedenis die deze Aarde doorliep. Het doorheen de geschiedenis veranderende klimaat is steeds bepalend geweest voor het uitzicht van deze Aarde, en dit zowel naar vegetatie, als naar zeespiegelstand en vorming van sedimentaire gesteenten toe. Sinds de 18de eeuw, bij de aanvang van de moderne geologie, werden geologische ontsluitingen steeds beter onderzocht en beschreven. Ook in IJsland, het geologische laboratorium bij uitstek, was dit het geval. De kliffen van het Tjörnes schiereiland aan de noordkust van IJsland konden reeds sinds 1749 op interesse van IJslandse natuurkundigen rekenen. Sedert de 19de eeuw erkenden ook wetenschappers van buiten IJsland het belang van deze ontsluitingen, en dit zowel vanuit stratigrafisch, klimatologisch als tektonisch oogpunt. De meeste onderzoeken gebeurden echter oppervlakkig; zorgvuldig gepland, doorgedreven onderzoek was eerder schaars. Op basis van de aanwezige schelpen, werden de afzettingen in Tjörnes verondersteld van Pliocene ouderdom te zijn, terwijl de afzetting in de noordelijker gelegen Breidavík Baai op basis van de aanwezige glaciale tillieten uit het Quartair zouden stammen. In Tjörnes zijn zowel mariene kustsedimenten, terrestrische organische lagen als basalt lavas afgezet, terwijl in Breidavík interglaciale mariene kustsedimenten afwisselen met glaciale afzettingen. In totaal zijn hier afzettingen van veertien ijstijden gevonden.

Voornamelijk de aanwezigheid van fossiele schelpen in Tjörnes trok de aandacht van wetenschappers. Op basis van overeenkomsten met afzettingen in Engeland en België werd een Laat-Pliocene ouderdom vermoed voor de afzettingen in Tjörnes, maar een nauwkeurigere datering bleek aan de hand van mollusken niet mogelijk. De eerste poging om een ouderdomsmodel voor de Tjörnes sectie op te stellen gebeurde door het opmeten van normale en inverse geopolariteiten, voornamelijk meetbaar in de aanwezige lavas. Het paleomagnetische signaal dat in de sedimenten en lavas vervat zit, kon wegens het ontbreken van exacte ouderdomspunten evenwel geen uitsluitsel geven omtrent de exacte timing van de afzettingsgeschiedenis van het gebied. Eind jaren 70 van vorige eeuw kwam hierin verandering toen er absolute ouderdomsdateringen van de sectie beschikbaar werden onder de vorm van K^{40}/Ar^{40}-ouderdommen. Toch moeten deze resultaten als minimum ouderdommen bekeken worden omwille van het laag potassium (K) gehalte, hetgeen een precieze meting bemoeilijkt. De gebruikte methode is daarenboven gevoelig aan verwering van het gesteente, omdat het door radioactief verval gevormde argon gas uit het systeem kan ontsnappen. De ijkpunten die zo ter beschikking kwamen, lieten twee mogelijke correlaties van het paleomagnetische signaal toe, maar slaagden er niet in de verschillende magnetische ompolingen eenduidig te plaatsen. Het toenmalige ouderdomsmodel was hoofdzakelijk gebaseerd op de basalten en niet op de mariene sedimenten. Op basis van dit ouderdomsmodel was het dan ook bijzonder moeilijk om uitspraken te doen betreffende de timing van gebeurtenissen die in de mariene sedimentatiereeks zelf gevonden werden. Omdat er een indrukwekkende stratigrafische successie van c. 1200 m aanwezig is, werd er vanuit gegaan dat hiaten in de sectie wel mogelijk waren, maar waarschijnlijk eerder verwaarloosbaar. De ouderdomsmodellen beperkten zich ook enkel tot het aangeven van mogelijke overeenkomstige magnetische ompolingen. Doordat de sedimentsuccessie nooit ten opzichte van de tijd uitgezet werd, vielen mogelijke hiaten ook minder op.

In de Tjörnes afzettingen komen er ook lignieten voor. Onderzoekers waren er aanvankelijk niet van overtuigd dat de aanwezige organische lagen van lokale origine waren, en het aandrijven van plantenresten werd vermoed. Zowel de botanische macroresten zoals bladeren, zaden en hout, als het fossiel pollen werd reeds sporadisch onderzocht in Tjörnes. Doorgedreven onderzoek dat alle lagen van Tjörnes en de meeste interglaciale afzettingen van Breidavík behandelt ontbrak echter tot nu toe. Meestal werden de mariene sedimenten in het vegetatieonderzoek buiten beschouwing gelaten.

Klimaatsverandering in het Plioceen

Dit onderzoek bestudeert de Plio-Pleistocene sedimenten van Tjörnes op basis van hun palynologische inhoud. De keuze voor het Plioceen als tijdsperiode kadert in de huidige interesse die er in de wetenschap heerst rond deze periode. Bij het ontstaan van een algemene consensus rond de recente opwarming van het klimaat, zochten wetenschappers naar een potentieel analoge situatie uit het verleden die ons de toekomstige warmere wereld beter kan leren begrijpen. De randvoorwaarden in het Plioceen betreffende de positie van de continenten en de aanwezige fauna en flora sluiten het sterkst van alle voorgaande geologische perioden aan met de voorspelde verwachting voor het einde van deze eeuw. Het klimaat in het Plioceen was beduidend warmer dan nu, en ook het gehalte aan CO_2 in de atmosfeer was hoger, zodat deze periode heel erg lijkt op het voorspelde toestand van de Aarde bij het einde van deze eeuw. Hoofdzakelijk in de hogere breedtegraden valt tijdens het Plioceen een verschuiving in de richting van de polen van klimaatgordels en vegetatiezones op. Om die uitgesproken veranderingen te kunnen waarnemen, kozen we ons studiegebied in het noordelijke deel van de Atlantische Oceaan, namelijk in het noorden van IJsland. Naast een duidelijk beeld over de Pliocene vegetatie en dinoflagellaten samenstelling, kan hier ook het effect van de Quartaire afkoeling op de terrestrische en mariene omgeving bestudeerd worden.

Belang van het studiegebied

Het Tjörnes schiereiland is gelegen aan de noordkust van IJsland. Doordat de afzettingen in de kustzone plaatsvonden, zijn zowel ijstijdafzettingen, lavas, resten van landvegetatie als mariene organismen bewaard gebleven. Het geheel van afzettingen weerspiegelt ontegensprekelijk het veranderend klimaat waaraan het noorden van IJsland onderhevig was. Door het gebrek aan een uitgebreide vegetatie zijn natuurlijke erosieve processen zoals wind, water en ijswerking hier maximaal en kent men een zeer hoge sedimentatiesnelheid van afbraakmateriaal aan de randen van het eiland. Breukwerking aan de Tjörnes Breuk Zone (TFZ) heeft sinds het begin van het Plioceen voor de nodige accomodatieruimte gezorgd om deze sedimenten te bergen. Het uitvloeien van basalten zorgde op zijn beurt voor preservatie van de eerder afgezette sedimenten, en beschermde deze tegen erosie en herwerking van fossielen. De unieke combinatie van zeer hoge sedimentatiesnelheden met een tektonisch actief dalingsgebied zorgt in Tjörnes voor het meest uitgebreide geologische archief uit het Plio-Pleistoceen van de hele noord Atlantische omgeving. Latere opheffing van het gebied zorgde voor de ontsluiting van deze gesteenten in de kustkliffen van het Tjörnes schiereiland. Naast het uitgebreid geologisch archief, is ook de strategische ligging interessant: dicht bij het Polair Front, en centraal tussen de kusten van Oost Amerika / Groenland en West Europa. Het Polair Front geeft de zone weer waar de koude, voedselrijke oppervlaktestroom uit het noorden, de Oostelijke IJsland Stroom als aftakking van de Oostelijke Groenland Stroom, botst met warm oppervlakte water afkomstig van de Irminger Stroom die op zijn beurt een aftakking is van de Noordelijke Atlantische Stroom die uiteindelijk zijn oorsprong vind in de Golf Stroom (Figuur 1.6). Momenteel is dit Polair Front slechts 50 km ten noorden van IJsland gelegen; positieveranderingen doorheen de geologische tijd worden geregistreerd door mariene fossielen. De positie van het zeer voedselrijke gebied gaat immers gepaard met het massaal voorkomen van heterotrofe micro-organismen, zoals sommige dinoflagellaten soorten, en organismen die dergelijke algen als voedsel gebruiken. In de Tjörnes lagen worden reeds sinds 1925 op basis van de aanwezige mollusken assemblages drie sedimentpakketten onderscheiden; van oud naar jong zijn dit: de *Tapes*, *Mactra* en *Serripes* Zone. Tijdens de *Tapes* en *Mactra* Zones komen sporadisch mollusken met een Pacifische oorsprong voor. Deze soorten konden via de Bering Straat de Pacific verlaten, de Noordelijke IJszee doorkruisen en via de Fram Straat de Atlantische Oceaan binnenkomen. Tijdens het Plioceen was de globale zeespiegel hoger dan nu, waardoor de ondiepe Bering Straat als doorgang kon dienen. De Noordelijke IJszee was daarenboven seizoengebonden ijsvrij; dit maakte waterstromen langsheen de noordpool mogelijk. Omdat reeds aan de basis van de *Tapes* Zone er een molluskensoort van Pacifische oorsprong gevonden is, blijkt de afzetting van de Tjörnes lagen achter te komen op de initiële opening van de Bering Straat. Dit laatste gebeurde rond 5.5 a 5.4 miljoen jaar geleden. Initieel zou hoofdzakelijk Atlantisch water naar de Pacific gestroomd hebben, maar aan de overgang van de *Mactra* naar de *Serripes* Zone wordt deze zuidelijke stroming door de Bering Straat omgepoold naar een noordelijke stroming. De massale aanwezigheid van Pacifische mollusken aan de basis van de *Serripes* Zone in Tjörnes is hier het bewijs van. Wat de exacte reden is van de overgang van de *Tapes* naar de *Mactra* Zone kon op basis van mollusken niet worden uitgemaakt. Mogelijk ligt de oorzaak hier in een veranderend oceaan stromingspatroon. De dinoflagellaten cysten tonen tijdens de *Mactra* Zone immers het verdwijnen van heterotrofe soorten aan. Dit zou erop kunnen wijzen dat het Polair Front in de omgeving van Tjörnes aanwezig was tijdens de *Tapes* Zone, maar bij de overgang naar de *Mactra* Zone uit het gebied verdween. De heterotrofe dinoflagellaten zijn dan weer massaal aanwezig sinds de basis van de *Serripes* Zone, en komen hier zelf iets eerder voor dan de mollusken, namelijk in laag 12 terwijl de massieve invasie van mollusken iets hoger in de stratigrafie in laag 14 wordt opgetekend. De heterotrofe dinoflagellaten zijn ofwel meegekomen met het Pacifische water, ofwel terug in het gebied geïntroduceerd door het opnieuw beschikbaar zijn van veelvuldig voedsel.

De aanwezigheid van biostratigrafische belangrijke dinocysten zoals *Reticulatosphaera actinocoronata*, *Batiacasphaera minuta* en *Operculodinium tegillatum*, geven aan de *Serripes* Zone een ouderdom van meer dan 3.8 miljoen jaar en voor de basis van de zone zelf een ouderdom van meer dan 4.4 miljoen jaar. De combinatie van de biostratigrafische ijkpunten met het paleomagnetische ompolingsignaal laat toe de *Mactra/Serripes* grens te correleren met de top van de Nunivák Subchron, rond 4.5 miljoen jaar geleden. De massale migratie van Pacifische soorten in Tjörnes kon hierdoor in verband gebracht worden met het ondieper worden van de Centraal Amerikaanse Zeeweg (CAS). Deze verbinding tussen de Pacific en de Atlantische Oceaan werd merkbaar ondieper tussen 4.7 en 4.2 miljoen jaar en sloot zich uiteindelijk rond 2.9 miljoen jaar geleden. Door het ondieper worden van deze centraal gelegen doorgang werd Pacifsch water in het noorden door de Bering Straat gestuwd. Voorheen was deze belangrijke paleoceanografische gebeurtenis rond 3.6 miljoen jaar gedateerd; ons onderzoek toont echter aan dat dit bijna een miljoen jaar eerder gebeurde. Het ouderdomsmodel dat opgesteld werd bracht ook twee, en mogelijks zelfs drie grote hiaten aan het ligt: tussen de Tjörnes lagen en de Höskuldsvík basalten, tussen de Furuvík en de Hörgi Formaties en mogelijks tussen de Máná en Grasafjöll Formaties. Opmerkelijk is ook het samenvallend voorkomen met de *Serripes* Zone van een nieuw gevonden dinoflagellates soort: *Selenopemphix islandensis*. Voorheen was deze soort in Tjörnes niet aanwezig en bijgevolg wordt een Pacifische oorsprong verondersteld. Deze soort kan als gidssoort gebruikt worden voor het Plioceen in de noordelijke Atlantische Oceaan.

De dinoflagellaten lieten ook toe om een idee van de watertemperatuur te krijgen. Zo is een duidelijk warmere assemblage gevonden tijdens de *Tapes* Zone, met zelfs de aanwezigheid van enkele specimen van de tropische soort *Tuberculodinium vancampoae* en *Tectatodinium pelitum*. Doorheen heel de Tjörnes lagen worden er warme assemblages aangetroffen. Een afkoeling wordt pas zichtbaar in de Breidavík Group. Vanaf halfweg het Svarthamar Member rond 1.7 miljoen jaar geleden vertoont de assemblage zeer veel gelijkenissen met de recente assemblage van het gebied.

Het pollensignaal van de Tjörnes lagen is duidelijk gerelateerd aan de relatieve zeespiegelveranderingen van het gebied dewelke op basis van de ecologie van de mollusken en de sedimentologie voorheen opgesteld was. Een grote, vochtige kustvlakte met hoofdzakelijk zegges en andere kruiden kwam in het gebied voor. In de kustvlakte hebben drogere oeverwallen vermoedelijk als ondergrond gediend voor het angiospermenbos. Angiospermenbomen komen ook voor aan de voet van de hellingen, terwijl bovenaan de basaltplateaus zich hoofdzakelijk gymnospermenbossen bevinden. Dit kon afgeleid worden doordat tijdens de maximale zeespiegelstand, het pollensignaal voornamelijk bestaat uit de regionale gymnospermen component, terwijl de lokale component wegviel door de overstroming van de kustvlakte. Een vernatting van de kustvlakte kon opgemerkt worden door het verdwijnen van de sporenplant *Selaginella selaginoides*, momenteel in IJsland een belangrijke component van het droge heidelandschap. De aanwezigheid van hulst (*Ilex aquifolium*) en maretak (*Viscum album*) in de *Tapes* Zone geven een zomertemperatuur weer die 7°C warmer is dan vandaag in IJsland. Ook tijdens de rest van de Tjönes lagen en in het eerste onderzochte interglaciaal van de Breidavík Group waren de zomer temperaturen met 5°C beduidend warmer dan vandaag de dag in IJsland.

De estuariene sedimenten zijn verstoken van zowel pollen/sporen als dinoflagellaten cysten. Het hoog energetische karakter van deze afzettingen verhinderde vermoedelijk de afzetting van de microfossielen. Het pollen van het *Polygonum bistorta*-type was in het Plioceen materiaal beduiden kleiner en ook minder ontwikkeld dan in recent vergelijkingsmateriaal. Bij recente vertegenwoordigers van dit pollen type is een variabel chromosoomaantal aangetoond. Mogelijks heeft deze plant evolutionair een verhoging van haar chromosoomaantal doorgemaakt sinds het Plioceen.

Hoewel slechts twee stalen van het geologische archief van het nabij Tjörnes gelegen eiland Flatey beschikbaar waren, bleek het aanwezige palynologische signaal erg waardevol. Voorlopige correlaties van de ondiepe shelf afzettingen van Flatey met de nabijgelegen kustafzettingen van Breidavík konden op basis van de aanwezige pollen/sporen en dinocysts gemaakt worden. Het dinocyst signaal was beduidend rijker in de ondiepe shelf dan in de kust sedimenten. Hoewel het aantal onderzochte stalen te laag was en het staal uit de boorkern niet exact geplaatst kon worden om een eenduidige correlatie mogelijk te maken, kon de Flatey sequentie toch aan het Matuyame chron worden toegewezen. Het beter op elkaar afstellen van de paleomagnetische ompolingen van de Breidavík Groep met de Flatey successie leidde tot het aantonen van een derde hiaat in de Tjörnes sectie en het aantonen van een uniek voorkomende ijstijdafzetting in Flatey. Het totaal aantal waargenomen ijstijden in het Tjörnes schiereiland vermeerderd hierdoor van veertien naar vijftien. Deze hypothese dient evenwel getest te worden door een doorgedreven palynologisch onderzoek uit te voeren op de Flatey boring en extra vergelijkbare interglaciale afzettingen van de Breidavík Groep te analyseren.

Toekomstige onderzoeksperspectieven

Seismisch onderzoek nabij Flatey geeft een opeenvolging van 2000 m sedimenten weer van vermoedelijk Plio-Pleistocene ouderdom; verder van de Flatey-Husavík breuk verwijderd zou deze accumulatie zelfs tot 4000 m oplopen. Van dit geologische archief werd slecht 554 m ter hoogte van het eiland opgeboord. Uit ons onderzoek blijkt dat de bewaring van pollen, sporen en dinoflagellaten in deze successie bijzonder goed is, en een correlatie mogelijk maakt met de kustafzettingen van het Tjörnes schiereiland. In eerste instantie zou het erg nuttig zijn om de beschikbare Flatey kern palynologisch nader te onderzoeken. Dit in combinatie met aanvullend werk in de Breidavík Groep zal toestaan om de voorgestelde correlatie tussen de twee sequenties te bevestigen of bij te stellen, wat een verduidelijking zal opleveren in verband met de glaciale ontwikkeling van het noorden van IJsland en bij uitbreiding van de globale afkoelingsgeschiedenis. Vermoedelijk bevat de nog niet aangeboorde sequentie in Flatey nog meer glaciale afzettingen en kan bij een toekomstige langere boring deze glaciale geschiedenis nog beter in kaart worden gebracht. Het belang van de dinoflagellatensoort *Selenopemphix islandensis* als gidsfossiel voor Atlantische sedimenten jonger dan 4.5 miljoen jaar geleden moet nog verder onderzocht worden en ook de aanwezigheid ervan in oudere Pacifische afzettingen kan nagegaan worden.

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List of abbreviations

a: anno, year

CAS: Central American Seaway

DIC: Differential Interference Contrast

EGC: East Greenland Current

EIC: East Iceland Current

HCl: Hydrogen chloride

HF: Hydrogen fluoride

HO: Highest Occurrence

IC: Irmiger Current

IODP: Integrated Ocean Drilling Program

KOH: Potassium hydroxide

Kyr: ka, kilo year, 1000 year

LO: Lowest Occurence

MAR: Mid-Atlantic Ridge

MPWP: Mid Piacenzian Warm Period

Myr: Ma, million year

NAC: North Atlantic Current

NAD: North Atlantic Drift

NADW: North Atlantic Deep Water

NPP: Non Pollen Palynomorphs

ODP: Ocean Drilling Program

PF: Polar front

PRISM: Pliocene Research, Interpretation and Synoptic Mapping group (3.264–3.025Ma; the PRISM interval)

SEM: Scanning Electron Microscopy

SST: Sea Surface Temperature

TAI: Trans-Arctic Invasion

THC: Thermohaline circulation

TFZ: Tjörnes Fracture Zone

Curriculum Vitae

Curriculum Vitae (last update December 11th, 2012)

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Biographical data

Place of birth	Ghent, Belgium
Date of birth	February 25, 1980
Nationality	Belgian
Marital Status	Not married, no children

Professional experience

2006-2012	Research Assistant for the department of Geology and Soil Sciences, Research Unit Paleontology at Ghent University 50% research, 45% education, 5% services to the department (October, 1st 2006 – October, 1st 2012)
2006	Teacher in Geography/Geology ("aardrijkskunde" and "tourism") in the second and third degree of two high schools: Koninklijk Atheneum Deurne (10/05–30/06) and Koninklijk Atheneum Etterbeek (19/04–02/05)
2005	Scientific researcher; Flemish Heritage Foundation (SVE) / Flemish Institute for Cultural Inheritance (VIOE) Palynological research on the abbey of Herkenrode (January, 2nd – December, 31st)
2004	Various jobs as temporary workman (Batibouw, Tower automotive/4-ce, Vyncolit, Citrosuco, Gasbotteling, Christeyns)
2003	Vegetation reconstruction of the direct vicinity of a Middle-Neolithic wetland site (Schipluiden, The Netherlands) Pollen analysis; company ArchOL (October 6th – December 19th)

CURRICULUM VITAE

Academic education

2006-2012	PhD student (assistant) at the Research Unit Palaeontology, department of Geology and Soil Sciences; Ghent University
2004-2006	A.I.L.O. ("Academic Initial Teacher Education") - option Geography; Ghent University Pedagogic degree / high school teacher training
2002-2003	Master of Arts in science-based Archaeology, option paleobotany; Leiden University
2000-2002	Licentiate/Master in Geology, option paleontology; Ghent University
1998-2000	Kandidate/Bachelor in Geology; Ghent University

Teaching experience

High school teaching

2005-2006	Geography/Geology ("aardrijkskunde"), 2nd and 3th degree

Course teaching assistant palaeontology (practical courses and field excursions)

2006-2012	First Semester Geology: system Earth (24 B-hours; 1st Bach. Geology); Palaeontology I (40 B-hours, 2nd Bach. Geology); Micropalaeontology and palaeoenvironmental reconstruction (30 B-hours, 1st Master Geology); Fieldcourse biosphere evolution and stratigraphy ("Boulonnais", 80 B-hours); Introduction to Geology (24 B-hours, 1st Bach. Geography and Geomatics); Palaeobiology of micro-organisms (30 B-hours, 1st Master Marelac)
	Second Semester Belgian Geology (40 B-hours, 2nd Bach. Geology); Fieldcourse I /Geological mapping ("Ronquières"; 80 B-hours, 2nd Bach. Geology); Structural geology and geological mapping (40 B-hours, 2nd Bach. Geology); Palaeontology II (40 B-hours, 3th Bach. Geology); Advanced Micropalaeontology (10/30 B-hours, 1st Master Geology); Geology system Earth (8/28 B-hours, 1st Bach. Biology); Palaeontology (30 B-hours, 3th Bach. Biology); Evolution of primates and palaeoantropology (4/24 B-hours, 1st Master Biology and Geology); Geology for archeologists ((4) B-hours, 2nd Bach. Archaeology); Palaeontology 2 (30B-hours, 1st master Biology)

Course guest lecturer

2006-2012	Palaeontology II: partim Pollen analysis; Advanced Micropalaeontology: partim Pollen analysis

Student supervision

2006-2012	6 master students (Holocene geology; palynology s.s.); 7 Bachelor students (Dinoflagellate cysts; palynologys s.s.)

Courses

- Having a feed-back conversation: some practical hints. Department of educational quality, Ghent University. 26/11/11
- Educational seminars: seminar 5; Learning digital. Association Ghent University, 25/05/2011
- Educational seminars: seminar 4; "Have a look over the wall". Association Ghent University, 05/05/2011
- Educational seminars: seminar 3; Working trans-disciplinary. Association Ghent University, 22/03/2011
- Educational seminars: seminar 2; Working with large groups. Association Ghent University, 25/02/2011
- Basic assistant training. Department of educational quality, Ghent University, 08/02/2011
- Educational seminars: seminar 1; Academic teaching: the basics. Association Ghent University, 27/01/2011
- Workshop on taxonomy of Quaternary and Neogene dinoflagellate cysts. Head M., Dino 8, Montreal, Canada, 07/05/08
- Workshop on quantitative treatment and paleoceanographical reconstructions based on dinocyst assemblages. de Vernal A. & Marret F., Dino 8, Montreal, Canada, 05/05/08
- Analysis of problematic pollen (Porcupine, Iceland). Lydie Dupont, Bremen, Germany, 08-10/04/08
- Study of the geology of Tjörnes, Iceland, Jón Eiríksson, 14, 22 and 25/09/07
- Discussion about Icelandic vegetation and study of the pollen reference collection, Margret Hallsdóttir, Icelandic Institute of Natural History, Reykjavik, 13-14 en 25/09/07
- Terrigenous climate signals in deep marine sediments. Jan-Berend Stuut, Lydie Dupont, et al. (NEBROC, RCOM), Bremen, Germany, 12 – 16/03/07
- Dinoflagellates - biological characteristics, ecology and their use for paleoclimate reconstruction. Karin Zonneveld, Gerard Versteegh (EUROPROX, RCOM), Bremen, Germany, 29/01 – 01/02/07

Fieldwork

- Sampling of the ODP 985, Core Repository, Bremen, Germany: 18/08/09-19/08/09
- Sampling of the Tjörnes beds and Breidavik Group, Iceland: 12/09/07 – 26/09/07
- Sampling for the absolute abundance project, Belgian Coastal Plain: 29/11/06
- Sampling of soft surface sediments in the North Sea (ms Zeeleeuw): collection of samples for the absolute abundance project: 19/12/06

Publication list

Articles

Articles in journals included in Science Citation Index (A1)

- Out, W. A., **Verhoeven, K.** Neolithisation at Dutch wetland sites: the case study of Hardinxveld-Giessendam De Bruin. (submitted to *Vegetation History and Archaeobotany*, Devember 2012)

- **Verhoeven, K.**, Louwye, S. (submitted). Land-sea signals from the Pleistocene; results from a combined dinoflagellate-pollen study in Flatey, northern Iceland (submitted to Jökull, Oktober 2012)

- **Verhoeven, K.**, Louwye, S. (submitted). Palaeoenvironmental reconstruction with marine palynomorphs of the Plio-Pleistocene in Tjörnes, Northern Iceland. (submitted to *Palaeogeography, Palaeoclimatology, Palaeoecology*; August 2012).

- **Verhoeven, K.**, Louwye, S., Eiríksson, J. (in press). Plio-Pleistocene landscape and vegetation reconstruction of the coastal area of the Tjörnes Peninsula, northern Iceland. *Boreas* 10.1111/j.1502-3885.2012.00279.x.ISSN0300-9483.

- **Verhoeven, K.**, Louwye, S. 2012. *Selenopemphix islandensis* sp. nov.: a new organic-walled dinoflagellate cyst from the Lower Pliocene Tjörnes beds, northern Iceland. *Palynology* 36, 10-25. DOI 10.1080/01916122.2011.593573.

- **Verhoeven, K.**, Louwye, S., Eiríksson, J., De Schepper S. 2011. A new age model for the Pliocene–Pleistocene Tjörnes section on Iceland: its implications for the timing of North–Pacific palaeoceanographic pathways. *Palaeogeography, Palaeoclimatology, Palaeoecology* 309, 33–52.

- Mertens, K., **Verhoeven, K.**, Verleye, T., Louwye, S., Amorim, A., Ribeireo, S., Deaf, A., Harding, I., De Schepper, S., Kodrans-Nsiah, M., de Vernal, A., Taoufik, R., Dybkjaer, K., Poulsen, N., Feist-Burkhart, S., Chitolie, J., Gonzalez Arango, C., Heilman-Clausen, C., Londeix, L., Ruron, J.-L., Marret, F., Matthiesen, J., McCarthy, F., Prasad, V., Pospelova, V., Hughes, J., Riding, J., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C., Soliman, A., Van Nieuwenhove, N., Vink, A., Young, M. 2009. The absolute abundance calibration project: the Lycopodium marker-grain method put to the test. *Review of Palaeobotany and Palynology* 157, 238–252. doi:10.1016/j.revpalbo.2009.05.004

A1 Articles in preparation

- **Verhoeven, K.**, Louwye, S., Reyes, M.P, Mertens, K.N. (in prep). New acritarchs from the Neogene of the southern North Sea Basin and the Atlantic realm. (to be submitted to *Palynology*)
- Gelorini, V., De Smedt, P., Bats, M., Court-Picon, M., Zwertvaegher, A., Boeckx, P., Bos, H., Boudin, M., Demiddele, H., Haas, J. N., Langohr, R., Van Asch, N., Van Damme, D., Van der Meeren, T., Verniers, J., Van Strydonck, M., Hoek, W., Heiri, O., De Reu, J., **Verhoeven, K.**, Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P., Van Meirvenne, M., Crombé, P. (in prep.). A multi-proxy, high-resolution palaeolimnological record of rapid environmental change during the Late Glacial in northwestern Belgium (to be submitted to *Quaternary Science Reviews*)

- **Verhoeven, K.**, Louwye, S. Climate changes in the Pocupine Seabight during the Late glacial - Holocene transition: a palynological study on the top sediments of IODP 1318B.

- **Verhoeven, K.**, Louwye, S, Crombe, P. Geographical source tracing of prehistoric flint in the Belgian area: relative dating with dinoflagellate cysts.

Dissertations (B1) / peer-reviewed book chapters (B2)

- **Verhoeven, K.**, Louwye, S. 2010. Form variability within the *Polygonum bistorta* pollen type: comparison between Pliocene and recent material. In: Van Planten en Slakken/Of Plants and Snails, Corrie Bakels, Kelly Fennema, Welmoed A. Out, Caroline Vermeeren (eds.), Leiden, Sidestone Press, pp. 229-237.

- **Verhoeven, K.** 2003. Palynological research on a peat drilling from the vicinity of a mesolithic donk settlement in Hardinxveld-Giessendam De Bruin (The Netherlands). (unpublished Master of Arts thesis, Faculty of Archaeology, University of Leiden, The Netherlands)

- **Verhoeven, K.** 2002. Source tracing of silex artefacts from prehistoric sites of Doel, Spiere and OEudeghien, by means of micropaleontological research with dinoflagellate cysts. (unpublished Msc scription in geology), Research Unit of Palaeontology, Ghent University, Belgium) 86 pp.

Other publications

Proceedings – abstracts

- **Verhoeven, K.**, Louwye, S. 2012. Land sea signals in three different marine settings: the strength and weakness of a combined pollen-dinoflagellate cyst research. 4th Geologica Belgica-symposium, Brussels, 12/09/12 (Abstract for poster presentation)

- **Verhoeven, K.**, Louwye, S., Eiríksson, J. 2012. Sea level changes interacting with vegetation: a palynological study on the Plio-Pleistocene Tjörnes beds (North Iceland). 4th Geologica Belgica-symposium, Brussels, 12/09/12 (Abstract for oral presentation)

- **Verhoeven, K.**, Louwye, S., Eiríksson, J. 2012. Reconstructing Iceland past landscape, air temperature and sea level by means of a pollen study in Tjörnes (northern Iceland). PhD-symposium, Faculty of Sciences, Ghent, 22/03/12. (Abstract for oral presentation) http://www.ugent.be/we/en/research (movie)

- **Verhoeven, K.**, Louwye, S., Eiríksson, E., De Schepper, S. 2011. Age diagnostic, oceanographic and ecological implications of a palynological research in Tjörnes, northern Iceland. MVP–PPMB meeting, Liège, 30/11/11 (Abstract for oral presentation)

- **Verhoeven, K.**, Louwye, S. 2011. Warm or Cold? Ecological signals of a Plio - Pleistocene pollen and dinoflagellate cyst record from the Tjörnes section (northern Iceland). APEX congres, Svalbard, 31/05-05/06/2011 (Abstract for poster presentation)

- **Verhoeven, K.**, Louwye, S., Eiríksson, J., De Schepper, S. 2011. Northern migration through the Bering Strait during Zanclean times: evidence from dinoflagellate cyst biostratigraphy in Tjörnes (northern Iceland). APEX congress, Svalbard, 31/05-05/06/2011 (Abstract for oral presentation)

- **Verhoeven, K.**, Louwye, S. 2010. *Selenopemphix islandensis* sp. nov.: a new dinoflagellate species from the Pliocene Tjörnes beds, northern Iceland. PALASS congress, Ghent, 17-20/12/2010 (Abstract for poster presentation)

- **Verhoeven, K.**, Louwye, S., Eiríksson, J., De Schepper, S. 2010. New age model for the Tjörnes section, northern Iceland. PALASS congress, Ghent, 17-20/12/2010 (Abstract for poster presentation)

- **Verhoeven, K.**, Louwye, S., Eiríksson, J. 2010. Dinoflagellate cysts and pollen from the Tjörnes / Breidavik section: a biostratigraphical and palaeoclimatological study of Plio-Pleistocene sediments from northern Iceland. European Geosciences Union General Assembly, Vienna, Austria, 02-07/05/2010, EGU2010-10611 (Abstract for poster presentation) (*solicited*)

- **Verhoeven, K.** 2009. Dinoflagellate cysts and pollen from the Tjörnes/Breidavik section, northern Iceland. In Gerrienne, P. & Steemans, P. (Eds). Miscelanea palaeontologica. Paleobotanique, paleopalynologie, Micropaleontologie, Université de Liège, Liège, Decèmbre 4, 2009: 30-31 MVP PPMB meeting. (Abstract for oral presentation)

- **Verhoeven, K.**, Louwye, S. 2009. Plio-Pleistocene land-sea correlation based on dinoflagellate cysts and pollen and spores from the Tjörnes peninsula, northern Iceland. Third International Conference Geologica Belgica: “Challenges for the Planet: Earth Sciences’ Perspective” Ghent, 14-15/09/09, (Abstract for poster presentation)

- **Verhoeven, K.**, Louwye, S. 2009. Plio-Pleistocene land-sea correlation based on dinoflagellate cysts and pollen and spores from the Tjörnes peninsula, northern Iceland. 2009. PhD symposium, Ghent, ICC, 28/04/2009 (Abstract for poster presentation)

- **Verhoeven K.**, Louwye, S. 2008. Late Quaternary dinoflagellate cysts and pollen from Porcupine Basin (IODP 307, Hole 1318B): indication of small-scaled climate variations. Dino 8, Montreal, 08/05/2008 (Abstract for oral presentation)

- **Verhoeven K.**, Louwye, S. 2008. Plio-Pleistocene land-sea correlations in the Icelandic region: a palynological approach. First results. Dino 8, Montreal, 07/05/2008 (Abstract for poster presentation)

- Mertens K., Amorim A., Ribeiro S., Deaf A.S., Harding I., De Schepper S., de Vernal A., Radi T., Dybkjaer K., Poulsen N., Feist-Burkhardt S., Chitolie J., Gonzalez C., Heilmann-Clausen C., Kodrans-Nsiah M., Londeix L., Turon J-L, Marret F., Matthiessen J., McCarthy F., Prasad V., Pospelova V., Hughes J.K., Riding J.B., Rochon A., Sangiorgio F., Marino G., Welters N., Sinclair N., Thun C., Soliman A., Zonneveld K., Van Nieuwenhove N., Vink A., **Verhoeven K.**, Verleye T., Louwye S., Young, M. 2008. The absolute abundace calibration project: the Lycopodium marker-grain method put to the test. Dino 8, Montreal, 09/05/2008 (Abstract for oral presentation).

Lectures without abstract

- **Verhoeven, K.** 2008. Vegetation changes recorded in Plio-Pleistocene sediments of northern Iceland (Tjörnes, Breidavik): preliminary results. Journée des doctorants "Lille-Liège-Gent". Université de Lille, France, 5 December 2008
- **Verhoeven, K.** 2007. Iceland: the onset of glaciations, the terrestrial and marine evidence. Journée des doctorants "Lille-Liège-Gent". Ghent University, Belgium, 4 December 2007
- **Verhoeven, K.** 2006. Palynological (s. l.) research of marine and continental interglacial deposits in Western Europe. (land-sea correlation, paleoecology, similarity with the Holocene).Journée des doctorants "Lille-Liège-Gent". Université de Liège, Belgium, 11 December 2006
- **Verhoeven, K.** 2003. Lezingenmiddag Palynologische Kring, Nationaal Herbarium, Leiden, The Netherlands
- **Verhoeven, K.** 2003. Paleolithische werktuigen en de microfossielen die ze bevatten. Maandelijkse bijeenkomst van de Belgische Vereniging voor Paleontologie, Antwerp, 3 July 2003

Organisation of geological excursions

2004 Geological building stones from Low and Middle Belgium. Excursion with guidance of Roger Neys, origanised for the Low Countries Sculpture Society, 28-30/10/04

Education committees

assistant representative at the education committee of the Department Geology and Soil Sciences (Bachelor and Master in Geology, Ghent University) (2010-2012)

assistant representative at the education committee for the Master of Geology (joint master Ghent University and University of Leuven (2010-2012)

Awards and honours

2012 BELQUA travel grant to attain to the 4th Geologica Belgica-symposium in Brussels, 12/09/12

Representative for the Department of Geology and Soil Sciences at the PhD symposium of the Faculty of Sciences, Ghent, 22/03/12

2010 Invited poster at the European Geosciences Union General Assembly, Vienna, Austria, 02-07/05/2010