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The pollen stratigraphy of late Quaternary lake sediments of South-West Greenland

by

Michael Kelly and Svend Funder

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The pollen stratigraphy of late Quaternary lake sediments of South-West Greenland

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4 plates in pocket

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Abstract

Pollen analysis and radiocarbon dating of lake sediment cores from four localities in the Frederikshåb district, South-West Greenland, provide a chronology of vegetation changes in the area since *c.* 10000 B.P. An initial pioneer phase with the early development of some heath communities is followed by a mid postglacial phase in which there is the successive appearance of woody scrub species. A final phase shows the decline of some of these. This is interpreted as a general response to a broad amplitude fluctuation in climate, with its optimal period lying between *c.* 7600 and 3200 B.P. The detailed composition of the vegetation however is influenced by immigration phenomena, with the appearance of many species lagging behind the attainment of their climatic thresholds. Detailed consideration is given to the possibility of *Alnus crispa* being present as a scrub component during the climatic optimum.

CONTENTS

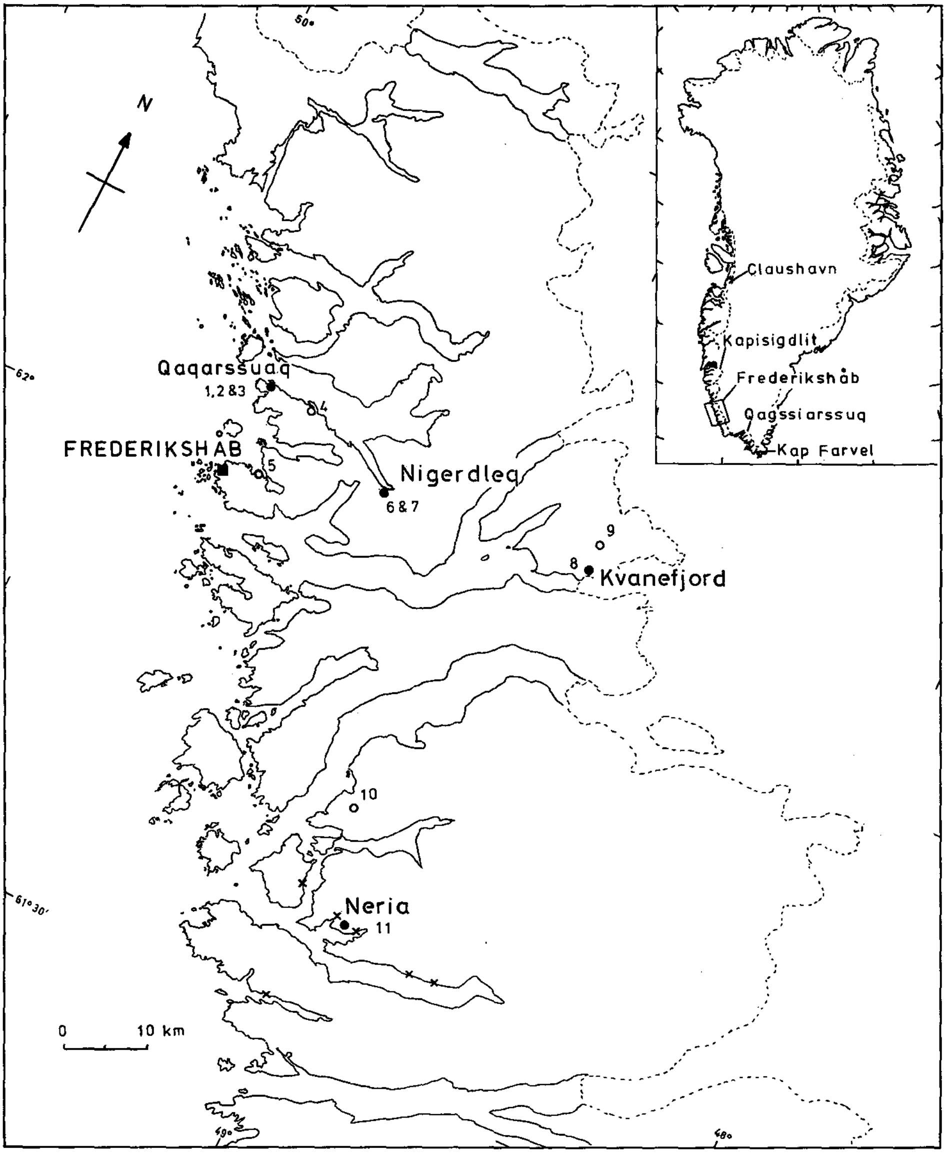

Fig. 1. Map of localities mentioned in the text. Solid circles: sites analysed in detail; open circles: other sites sampled; crosses: stations for *Alnus crispa*.

INTRODUCTION

General introduction

The pioneering pollen analytical work by the late Johannes Iversen (1934, 1953) showed that the evolution of the vegetation of Greenland since its partial deglaciation has been in response to the twofold influences of climatic change and the differential rate of immigration of species into this relatively isolated region. During geological mapping of the Frederikshåb district of South-West Greenland in 1964, 1965 and 1966, cores of lake sediments were obtained with the aim of determining the applicability of these conclusions to another part of Greenland, and of correlating this palaeo-climatic information with the geological evidence of the behaviour of the Greenland ice sheet. Subsequently a great deal of information has come from the detailed studies by Fredskild (1973) of lake sediments, mainly from south Greenland, and the present work has to be considered in the context of this also.

The Frederikshåb area is a rugged plateau around 500–1000 m high, deeply dissected by narrow valleys and fjords, with a small alpine area in the south-east. The bedrock is principally acid gneisses with local outcrops of amphibolite schists and dolerite dykes. Its vegetation is a mosaic of scrub, heath, herb and bog communities belonging to the low-arctic oceanic to suboceanic vegetation region (Böcher, 1954; Hansen, 1969). In addition to the important changes due to altitude there is a general contrast between the vegetation of the outer coast and inner fjords correlated with decreasing oceanicity. Table 1 gives climatic data for Frederikshåb, and for Grønnedal, which is an inland station to the south of the area. Thermal conditions in the inner fjords probably approximate to those at Grønnedal, though the precipitation will be lower.

Of the eleven sites sampled four have been analysed for their pollen and spore content in varying degrees of detail, and radiocarbon dates, for various purposes, have been obtained from eight. Fig. 1 gives their localities. The analysed sites comprise three at low elevations lying on an east-west line from the outer coast to close to the present ice margin, parallel to the present climatic gradient and to the direction of retreat of the ice sheet (Qaqarssuaq: plate 1, Nigerdleq: plate 2, Kvanefjord: plate 3), and a fourth site in the extreme south of the area (Neria: plate 4). Details of the sites are given in the appendix.

Table 1. Climatic data from south-west Greenland

	Temperature, °C			Precipitation
	Jan.	July	Annual	mm
Frederikshåb*	–5.0	5.6	–0.2	849
Grønnedal†	–3.3	8.5	1.8	1630

* Average mean values for 10 years (1961–1970) (from Provisional mean temperatures and total amount of precipitation in mm, Greenland. Publikationer fra Det Danske Meteorologiske Institut). †Average mean values for 10 years (1959–1968) (Forsvarets Vejrtjeneste, personal communication).

Methods

The cores were taken with a simple hand operated piston corer operated from a raft. The samples were prepared for pollen analysis using standard techniques, including the HF treatment of all samples. Absolute determination of frequencies were made for some of the sites but for others only conventional relative methods were used.

The pollen sum used for the relative frequencies comprises all angiosperms, gymnosperms and pteridophytes except water plants and exotic pollen definitely derived from areas outside Greenland (e.g., *Pinus, Picea, Corylus, Quercus* etc.). Pollen of doubtful origin are included in the sum, i.e. *Artemisia* and parts of the *Betula* and *Alnus* curves. This pollen sum is usually more than 500, excepting only those samples very poor in pollen.

The 'absolute' method used is analogous to that described by Jørgensen (1967) giving pollen concentration as no. mg^{-1} of dry sediment. Although dry weight concentration is affected by the rate of sediment deposition it is thought to be the simplest and best parameter available. It is not subject to the effects natural consolidation or artificial compaction following core extrusion or drying, unlike volume concentrations. Nor is it subject to the theoretical and practical problems associated with pollen deposition rates. At best these are pollen deposition rates at the sediment surface (no. cm^{-2} yr^{-1}), (i.e. pollen netto accummulation rates) which do not account for the geometry and contributing mechanisms of the catchment as a whole. They also require detailed dating of the sediments and are subject to the problems due to uncertainty about the deviations in atmospheric C^{14} content. Despite these comments, sediment surface pollen deposition rates are the best form for comparison with data from studies of present day atmospheric pollen concentrations and, where necessary, they have been calculated for Frederikshåb using measurements of sediment bulk densities and C^{14} dates to determine the sediment deposition rates.

The identification of pollen taxa is based on type material from Greenland. In general the criteria used for different groups was broadly similar to that detailed by Fredskild (1967). The consistent identification of Ericales and *Salix* proved to be most problematical with poor pollen preservation influencing the former in particular. Differentiation of the *Betula* species at selected levels from Nigerdleq and Kvanefjord was attempted by comparing the pollen size distribution of the fossil populations with those for modern material (see fig. 5).

The sediment types are given in the diagrams. The organic carbon curve from Nigerdleq was determined by loss of weight on ignition at 500°C.

BIOSTRATIGRAPHY

Zonation

The distribution of the major pollen and spore types at the four sites is shown in the pollen diagrams (plates 1–4). These pollen diagrams have been zoned on the criteria outlined below, which were first established for Nigerdleq and then applied as far as possible to the other sites.

Zone 1	– begins with the first pollen record	(pre–9600 B.P.)
Zone 2	– begins at the decrease of *Oxyria*	(9600–8950 B.P.)
Zone 3	– begins with the continuous *Salix* curve	(8950–7600 B.P.)
Zone 4	– begins with the increase of *Alnus*	(7600–5750 B.P.)
Zone 5	– begins with the increase of *Betula glandulosa*	(5750–3200 B.P.)
Zone 6	– begins with the decrease of *Alnus* and *Juniperus*	(3200–0 B.P.)

The dates given are based on the radiocarbon dates for the Nigerdleq core. The radiocarbon dates suggest that the period of organic sedimentation was of virtually the same duration at the three northern sites (9600–9800 years), whilst the zones present at Neria suggest that it was similar there too.

Fig. 2 shows that sedimentation was fairly uniform at most sites, with rates between 1.2–3.0 cm/100 yr. However departures from this has led to the anomalous development of zones at some sites. At Nigerdleq the exceptionally high rate in zone 3 might be associated with redeposition of sediment and is discussed later. At Kvanefjord the apparently low early rates, giving a very condensed initial zonal sequence, are less easy to account for.

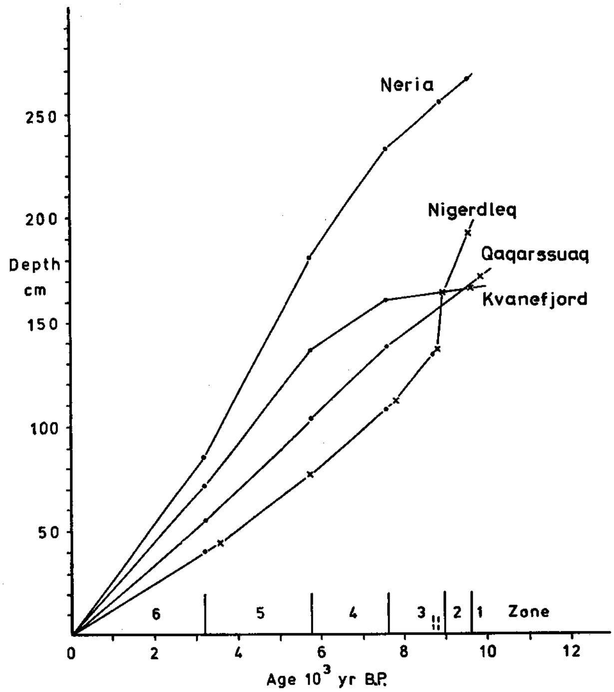

Fig. 2. Mean sedimentation rates of analysed cores. Crosses: dates based on C^{14} dates; dots: dates based on extrapolation and zonal correlation. For clarity depth and error ranges of C^{14} dates have been omitted (see plates for details).

Zonal development of the vegetation

Although the four diagrams show broadly comparable features the vegetation development is described for Nigerdleq, with the regional differences being treated separately.

Zone 1 (>9600 B.P.)

This zone occupies only the lowest 5–10 cm of the organic lake sediments. Total pollen concentrations are very low suggesting a low degree of vegetative cover, although an increased minerogenic content reduces the significance of this. A number of herb species and genera are conspicuously important: *Oxyria digyna, Saxifraga oppositifolia, Sedum* sp. (*S. villosum* or *S. rosea?*), *Potentilla* sp., *Chamaenerion* cf. *latifolium, Rumex acetosella, Campanula* cf. *rotundifolia,* Caryophyllaceae spp., together with Cyperaceae and Gramineae.

These are largely plants of habitats with low competition pressures in both dry exposed sites and snow patches. As such this assemblage represents a pioneer vegetation and therefore need not have any climatic significance. In fact all the species can be found today on fresh, less than 100 years old moraine along the ice margin in the Frederikshåb area.

Zone 2 (9600–8950 B.P.)

This zone is not clearly delineated from zone 1 as the species which characterise it e.g. Cyperaceae, Gramineae, *Empetrum* etc. had increased slowly during the pioneer stage of the earlier zone.

Although the first two dominate the pollen spectra the absolute data suggests that they played no greater role in the vegetation than they do today. This would be as components of many different communities, ranging from dry exposed habitats to moist herb-field habitats for Gramineae and from mesophilous to marsh habitats for Cyperaceae. Similarly *Empetrum hermaphroditum* heath appears to have been as common as at present.

Characteristically however, two ericaceous shrubs: *Harrimanella hypnoides* and *Loiseleuria procumbens,* and a range of herbs mostly continuing on from zone 1, were more abundant. *Harrimanella* is a typical snow-patch species, usually associated with *Salix herbacea.* Although there is a small amount of *Salix* pollen in this zone it is not known if it is indigenous. Also, many of the herbs are herb-field species requiring moderate snow cover.

Loiseleura, whilst also occurring in marginal snow patch habitats (Böcher, 1963) is more typical of dry wind exposed areas, with little snow cover.

An interesting component of the herb flora is *Angelica archangelica* which first occurs in zone 1. Today *Angelica* occurs in herb communities or willow copses on moist ground northwards to 70°N in West Greenland and was characterised by Böcher (1954) as a subarctic and suboceanic species. The early record of this species in the Frederikshåb region is consistent with observations by Iversen (1953) and Fredskild (1973) which showed that *Angelica* was also among the early immigrants in west and south Greenland (table 3). The occurrence of *Botrychium* in this zone has a comparable significance, with the Greenland *Botrychium* species today occurring in low arctic and subarctic herb communities, *Botrychium lunaria* reaching 73°N in West Greenland (Böcher, 1938).

The aquatic vegetation was probably mainly *Ranunculus confervoides,* as much of the *Ranunculus* pollen curve is thought to represent this species. Scattered records of *Potamogeton, Callitriche* and *Sparganium* suggest some occurrence of these.

Zone 3 (8950–7600 B.P.)

The early zone 3 vegetation differs from that of zone 2 only in the implied presence of abundant *Salix,* with a frequency similar to today's. The only clue as to which of the existing four species, *S. glauca* coll., *S. arctophila, S. uva-ursi, S. herbacea,* the rapid increase represents is that its magnitude would suggest it to be due to the most prolific pollen producer, *S. glauca.* This would presumably occur both as pure scrub and as a component of heath communities.

The major fluctuations in the curves, particularly that of *Salix,* which allows zone 3 to be subdivided, are only seen at Nigerdleq. Although several alternative explanations of this are possible the most likely one, supported by the anomalous sedimentation rate, is that zone 3b partly represents redeposited zone 2 sediments reworked from marginal areas of the lake.

The upper part (3c), however, shows an important reduction in the incidence of the snow-patch, herb-field and pioneer species of zone 2. In part this might be related to a decrease in snow cover most plausibly caused by increased snow melt. The effects of increasing competition however might also have an influence.

Although *Isoetes setacea* is never abundant at Nigerdleq it first joins the aquatic vegetation in zone 3, which is coincident with its appearance at other sites.

Zone 4 (7600–5750 B.P.)

As shall be discussed in detail below this zone probably saw the immigration of *Alnus crispa* into the area, to form isolated patches of scrub on slopes and stream banks in favourable localities.

Shortly afterwards *Juniperus* immigrated to become a minor component of dry dwarf shrub heaths. Another immigrant is *Selaginella selaginoides* which increases dramatically, presumably occurring in moist habitats which could have been close to the lake.

Other species show notable increases: *Thalictrum alpinum* which first occurred in zone 3c, and *Lycopodium dubium* and to a lesser extent *Diphasium alpinum,* both of which had been present since zone 2. Both lycopods occur in heath-associations with moderate to long snow cover respectively.

Even neglecting the possibility of the growth of *Alnus,* the occurrence of *Juniperus,* and particularly of *Selaginella* sets the minimum temperature requirements higher than in the preceding zones. *Juniperus* occurs north to 69°N in West Greenland and although found in oceanic coastal areas is most abundant in the continental interior. *Selaginella* has an even more southern distribution, south of 65°N (Böcher, 1938), which suggests a requirement for relatively high summer temperatures. Its northern limit in North America also closely parallels that of *Alnus crispa* (Hultén, 1958).

The lacustrine vegetation saw the addition of *Myriophyllum alterniflorum,* another species with a relatively southern Greenland distribution.

Zone 5 (5750–3200 B.P.)

A major change in the vegetation occurs with the immigration of *Betula glandulosa,* which would join a variety of heath associations from xeric lichen heaths to mesophilous mixed dwarf shrub heaths, as well as forming pure scrub stands. The evidence for the species identification is discussed later. However there is little sign of the effects of competition from it, with most other components retaining at least their zone 4 values, apart from *Selaginella.*

The minor components of the pollen flora at this time include two species which first appear in zone 5 or late zone 4: *Thymus drucei* and *Coptis trifolia,* both of which are relatively thermophilous species, with Greenland distribution south of 66°N.

Total pollen concentrations are highest in this zone and although this is strongly influenced by the addition of *Betula,* several species including *Betula* reach maximum values: *Alnus, Juniperus,* Gramineae. It is possible that this evidence of abundant flowering marks the period of optimum temperatures.

Zone 6 (3200–0 B.P.)

At Nigerdleq there are marked changes in several curves near the zone boundary, with reductions in the frequencies of *Alnus, Juniperus,* Gramineae, and lycopods. Coupled with this is a gradual decrease in the absolute frequency of *Betula.* Although at other sites these changes are less marked or more gradual, the overall implication of a climatic deterioration and the end of the optimal period of warmth is clear.

Assuming that *Alnus* grew locally, its decrease implies that the deterioration caused its extinction over most or all of the area. In the dwarf shrub heaths, whilst *Betula* was becoming less frequent, *Vaccinium* was apparently more abundant.

Regional variation in vegetation development

The systematic differences in vegetation which exist today between the more oceanic coast and the warmer and drier interior can be detected over most of the period covered by the pollen diagrams from the three northern sites. In the earliest zones Ericales, in particular *Loiseleuria* and *Harrimanella,* were more abundant at the coastal site (Qaqarssuaq) than the interior site (Kvanefjord). During the middle optimal period *Salix* and *Juniperus* were more abundant in the interior whilst *Empetrum* increased towards the coast. This greater frequency of *Empetrum* in the coastal area was maintained throughout the youngest zone and up to the present.

There are also differences between the sites in the degree to which the vegetation changes defining the zones of Nigerdleq can be recognised. Thus at Qaqarssuaq and Kvanefjord where the lowest zones are relatively condensed the appearance of *Salix* is not clearly separated from the increase of *Alnus.* Also, the zone 5–6 boundary is less easy to define precisely at other sites. Although the zones need not be synchronous over the area, the fairly uniform sedimentation rates this assumption gives (see fig. 2) suggests that they are at least nearly so.

The lacustrine vegetation shows a considerable variation between the sites, clearly shown by the diagrams. No two show a comparable development, apart from the uniformity in the date of appearance of *Isoetes* and in its persistence at Qaqarssuaq and Neria.

STATUS OF *ALNUS CRISPA* AND *BETULA* SPECIES

Special consideration has been given to the question of the occurrence of these species because of the implications this has for explaining their present Greenland distributions.

Alnus crispa

The curves for *Alnus* pollen from all the three northern Frederikshåb sites show roughly the same pattern: an intermediate period of high values between about 7600 and 3200 B.P. when it forms about 10–20% of the total pollen and spores, preceded and succeeded by periods with much lower frequencies. The question is in which of these periods, if any, *Alnus* was present in the area. Answering this is made difficult by the existence of an exotic pollen rain from North American sources, revealed for example by the conifer pollen in the diagrams; sources which Fredskild (1973) claims can contribute significant amounts of *Alnus* pollen.

At the present day *Alnus crispa* has its main area of distribution between 63° and 66°N in West Greenland, with isolated populations growing as far south as 61°N (Lægaard, 1971). It should be noted that in the Frederikshåb area (61½–62½°N) under consideration here, *Alnus* occurs only in Neria fjord in the southernmost part of the area, where it forms low copses on south facing slopes (fig.3). The position of these and the nearby Neria pollen site is shown in fig.1.

Within its main area of distribution *Alnus* is especially common in the interior parts where summer temperatures are high and the precipitation values low; in these areas it occurs in dence copses on moist soil near rivers and streams and also on well drained ground.

According to Böcher (1949, 1954) *Alnus* in Greenland prefers a subcontinental type of climate, its northern limit being dictated by decreasing summer temperature in coastal areas and increasing summer drought in the interior. The southern limit has been suggested as being due to increasing oceanity or competition with *Salix glauca* or both (Lægaard, 1971).

Fredskild considers that *Alnus* first appeared in the northern sector in Godt-

Fig. 3. *Alnus crispa* scrub, Kangerdlua, Neria fjord. This locality is adjacent to the Neria pollen site.

håbsfjord around 4000 B.P., in what is now one of the areas where it is most abundant. He came to this conclusion after reinterpreting Iversen's pollen data from that area, considering that the earlier much lower relative frequencies of *Alnus* were due to exotic pollen (Fredskild, 1973; Iversen, 1953). Furthermore he decides that *Alnus* has always been absent from south Greenland and that all the *Alnus* pollen recorded in his diagrams from there is exotic. This includes sites which give *Alnus* curves closely comparable with those from Frederikshåb.

Table 2 gives examples from the two areas of the absolute amounts of *Alnus* pollen involved. They show that there is a wide variation in *Alnus* concentrations in the sediment surface layer, which is some expression of the concentration in the modern pollen rain, and that this variation is not related to the distance the site lies from the area where *Alnus* grows today in Greenland. Thus there are low values at the Neria fjord locality. However it is possible that any relationship is obscured by the processes mentioned earlier which lead to differences between pollen concentrations in pollen rain and in sediments. The Canadian data on actual pollen rain concentrations suggests that there should be an order of magnitude difference between deposition rates for areas with or without *Alnus* in the vegetation. (Ritchie & Lichti-Federovitch, 1967). Other regional studies of pollen spectra from surface samples in Canada generally indicate the occurrence of long distance transported *Alnus* but they are less easy to assess since the fre-

Table 2. Concentrations and deposition rates of fossil and modern Alnus pollen

	Modern: surface sediment				Fossil: max. value *c.* 3000–7000 B.P.			
	Alnus		Total pollen and spores		*Alnus*		Total pollen and spores (at same horizon)	
	no/mg	no/cm²/yr	no/mg	no/cm²/yr	no/mg	no/cm²/yr	no/mg	no/cm²/yr
FREDERIKSHÅB								
Nigerdleq	1	(1.1)	45	(56)	10.6	(30.1)	114	(326)
Kvanefjord	2.5	(3.8)	83	(125)	8.6	(24.9)	129	(373)
Neria	0.5	(0.9)	22	(38)	2.0	(5.8)	25	(73)
S. GREENLAND*								
Isoetes Sø		20		400		108		510
Spongilla Sø		10		200		20		320
Kløft Sø		5		300		63		530
Comarum Sø		2		600		30		1200
CANADA†	all data: no/cm²/yr for *Alnus*							
Tundra stations (*Alnus* exotic)	0.02, 1.4, 3.3, 0.8, 1.6, 25.8							
Forest tundra stations (*Alnus* present)	14, 38, 27, 163, 95, 36, 119							

( ) denotes approximate values

* derived from diagrams in Fredskild (1973). † from Ritchie & Lichti-Federovitch (1967).

quencies quoted are only on a relative basis (e.g. Lichti-Federovitch & Ritchie, 1968; Terasmae, 1967; Wenner, 1947).

The values for the mid postglacial period of high *Alnus* frequencies at Frederikshåb and south Greenland although usually much higher than the surface values, are still within the same order of magnitude range and are therefore neither too large to be exotic nor too small to represent local scattered communities.

The increase of frequencies in the early postglacial has to be explained, if the exotic hypothesis holds, by a change in the character of the transport system by the operation, singly or in combination, of a number of factors:

(a) more effective transport mechanism e.g., shorter distance, greater precipitation, or stronger winds,

(b) change in location of source area to one where *Alnus* is an important component of the vegetation,
(c) increase of *Alnus* within a source area.

Fredskild invokes all three to some degree, linking them with changes in the atmospheric circulation pattern which Lamb, Lewis & Woodroffe (1966) suggested occurred with the waning of the Laurentide ice sheet. In particular, this suggests that the source of the exotic pollen bearing air masses should migrate northwards as the ice margin retreated, from the New England-Nova Scotia area at c. 10 000 B.P. to central Labrador in 5000 B.P. The information that is available about vegetation development in eastern Canada over this period indicates that there was a diachronous phase of deciduous scrub or wood of *Betula* species and *Alnus* which was followed by the northward spread af conifers (Richard, 1971; Terasmae, 1969; Morrison, 1970; Wenner, 1947).

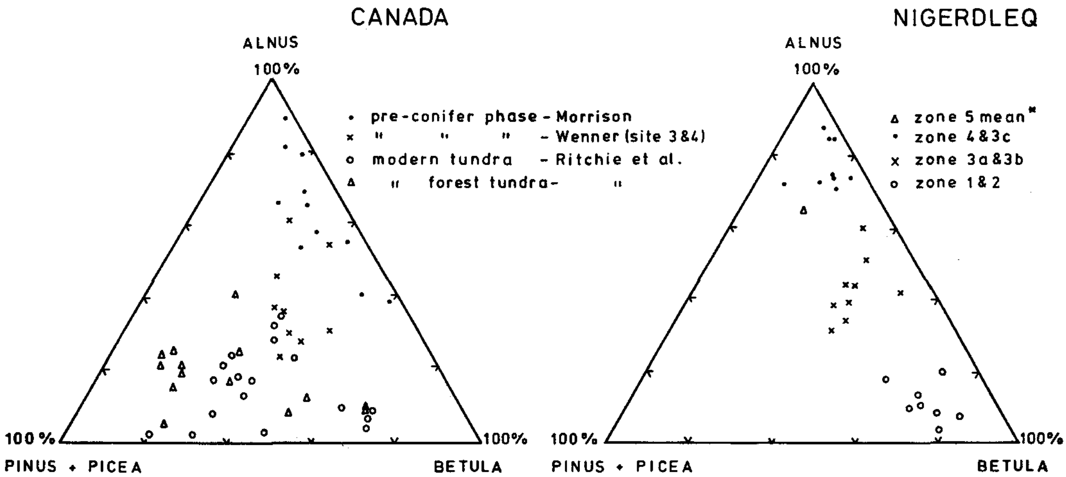

Fig. 4. Comparison of fossil pollen ratios from Nigerdleq, Greenland with those of modern and fossil assemblages from Canada.
*: mean value for zone 5 assuming exotic *Betula* has value equivalent to mean of zone 4.

This model provides another means of testing the status of the pollen at Frederikshåb, by considering the relative composition of the proposed exotic pollen rain and the likelihood of the above mechanism of providing it, as Fredskild in part has done. Fig. 4 shows diagramatically the changing character of the putative exotic populations of *Alnus* : *Betula* : *Pinus* + *Picea* in the pre-*Betula* immigration period. A mean value for the subsequent zone 5 at Nigerdleq is included in which an arbitrary value of 15 % for exotic *Betula* has been assumed (the mean in zone

4). As a whole the Nigerdleq ratios are low in conifers and could well be associated with the pre-conifer phase in eastern Canada. However in the final zone 4 population *Alnus* is enriched to a degree that requires explanation. Fredskild sought this in Morrison's diagrams from central Labrador which contain a short period of 200 years around 5600 B.P. when *Alnus* spread to the area before *Betula*. Certainly some of his analyses coincide with the required fossil ones (see fig. 4). However this vegetation phase does not appear to have developed in the earlier periods further east probably represented by Wenner's diagrams, though there are suggestions from other parts of Canada, outside of the likely source area, that such *Alnus* rich communities can occur e.g. Mackenzie delta N.W.T., 5400–3600 B.P. (Ritchie & Hare, 1971).

A further general difficulty is the relative lack of coniferous pollen at Frederikshåb in zone 5 when, with the conifers at their maximum extent in northern Canada, the *Alnus* : conifer ratio in the exotic pollen rain would at least be expected to resemble that of modern arctic Canada (fig. 4).

Thus although the Canadian evidence suggests that suitable communities for producing the required spectra did exist in certain periods it is difficult to imagine that they were widespread enough and persisted for long enough, even as a diachronous zone, to be able to dominate the exotic pollen transported to Greenland. Further work in Canada may clarify this point.

In conclusion, although the exotic pollen hypothesis is attractive there does not seem to be any firm evidence yet to preclude the possibility of the growth of *Alnus* copses in the Frederikshåb area, with the sharp rise of *Alnus* pollen at *c.* 7600 B.P. marking the immigration of the species into the area.

Betula glandulosa and *Betula pubescens*

In the present vegetation of Frederikshåb district *Betula glandulosa* var. *rotundifolia* Regel is a very important component of scrub and dwarf shrub communities. The 'tree' birch, *Betula pubescens* Ehrh. coll., also occurs but it is here close to its northern limit and is confined to single or small groups of individuals at isolated localities.

Analysis of the size distribution of the *Betula* pollen at various horizons (fig. 5) confirms that it is the small pollen species (*Betula glandulosa*) that is responsible for the high frequencies in zones 5 and 6. It is considered that the sharp rise in absolute amounts defining the 4–5 boundary marks the immigration of the species into the area at 5750 B.P. This should be compared with Fredskild's (1973) dates for its immigration into south Greenland of 4400 B.P. at Qagssiarssuk and 3800 B.P. in the Kap Farvel area (fig.1).

Frederikshåb is only about 1° south of the species northern limit in West Greenland, where it meets the other dwarf birch species, *Betula nana* L., whose distributional area lies to the north. Böcher (1972) has suggested this geo-

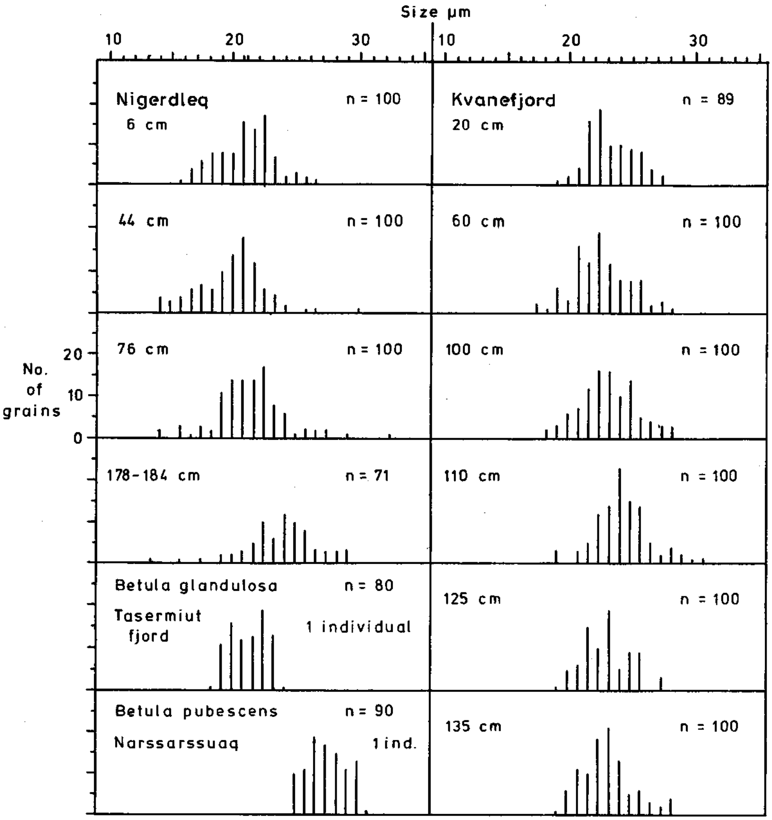

Fig. 5. Size distribution of fossil *Betula* pollen, compared with two examples from modern *Betula* species.

graphical separation of the two species may reflect ecological differences with *B. nana* being represented by continental races in Greenland and *B. glandulosa* by oceanic. In which case the expansion of *B. glandulosa* may indicate increasing oceanicity in south-west Greenland. However it seems equally likely that historical factors have played a part and that expansion of *B. glandulosa* does not carry any climatic implications. It is known that *B. nana* immigrated into central West Greenland at an early date, before 7850 B.P. in Disko Bugt, 69°N (Kelly, unpub.), spreading to Godthåbsfjord by about 7000 B.P. (Fredskild's (1973) estimate from Iversen (1953)). The present common boundary may thus be the zone of contact between two species spreading from different immigration centres.

There is no evidence from the pollen data of the growth of *Betula pubescens* in the area (fig.5). Large pored pollen populations are only clearly present in the earliest zones when all the *Betula* pollen is considered to be exotic. This contrasts with south Greenland where Fredskild proved its presence from 3600 B.P. It is therefore not certain that this species has ever had a self sustaining population in the area, and it is possible that at present it is maintained only by continued introduction of fruit from the south.

DISCUSSION

Comparison with the vegetation development of other parts of Greenland

In its broad outline the vegetation development at Frederikshåb follows that already known from west and south Greenland (Iversen, 1953; Fredskild, 1973). Their common features are:

(1) an initial pioneer phase during which there is a development of ericaceous, graminaceous and cyperaceous communities from more open communities,
(2) a mid-postglacial phase characterised by the successive appearance of woody scrub plants, and the replacement of pioneer herb species by other herbs and pteridophytes,
(3) a late postglacial period with declining frequencies of some scrub species and an increase in ericaceous.

It should be noted that a final phase recognised in both Godthåbsfjord and south Greenland covering the period of Norse settlement (*c.* A.D. 1000–1500) is not present at Frederikshåb, and that this is in agreement with the known distribution of Norse farms.

Although the overall pattern is consistent, the radiocarbon dates show that the phases are not synchronous, even when dates of deglaciation are comparable. This can be seen by comparing the dates of 'arrival' and the relative sequence of individual species in table 3.

Any pattern of dispersal which can be reconstructed from the geographical distribution of the dates suggests that there was a large fortuitous element in the introduction of species into Greenland and that their subsequent spread could be slow and random, dictated more by the dispersal mechanism or local factors than by climatic thresholds. Consequently relatively thermophilous species can appear earlier in the north than in the south e.g. *Thalictrum,* or more randomly e.g. *Thymus.* Nor does the obvious mobility of a propagule of a species necessarily lead to rapid spreading, e.g. *Salix* cf. *glauca.* However in the case of *Juniperus,* which has remarkably uniform dates of immigration, the explanation must be sought in the efficiency of the dispersal mechanism, presumably birds, since it was apparantly also not climatically determined (see below).

Vegetation changes due to edaphic factors such as progressive leaching, which are a feature of temperate latitudes, do not seem to be apparent in the terrestrial

Table 3. Approximate dates of appearance of species at localities in West Greenland

	Claushavn[1]	Kapisigdlit[2]	Frederikshåb	Qagssiarssuk[3]	Kap Farvel[3]
Salix cf. *glauca*	>7850	8000	8900	8000	7200
Alnus crispa		4000	7600	(7200)*	(7700–7000)*
Juniperus communis		7000	7000	6900	7000
Betula nana	>7850	7000			
Betula glandulosa			5700	4400	3800
Betula pubescens				3800	
Angelica archangelica		8500	>9580	8500	9000
Thalictrum alpinum		8000	8800	8000	7500
Selaginella selaginoides		7000	7500	6700	6500
Thymus drucei			5000	6000	3500
Isoetes setacea		>4300	7000	8000	7000
date of deglaciation	*c.* 8000	*c.* 8500	>10,000	*c.* 9000	>9500

Data from: 1. Kelly unpub.; 2. Iversen (1953), and Fredskild's (1973) interpretation of that data; 3. Fredskild, 1973 (* considered by Fredskild to be exotic).

vegetation. Although well developed podsols do occur, cryoturbation normally limits their development and the majority of developed soils are arctic brown earths (Hansen, 1969). Fredskild (1973) however has recognised their effect on lakes, leading to oligotrophication and acidification.

Development of the climate

The gradual and perhaps random spread of species in southern Greenland implies that the presence of an indicator species, for which a specific climatic requirement can be suggested, gives only a minimum date for the achievement of these conditions.

The botanical evidence from Frederikshåb suggests that at least by 9600 B.P. the climate had become low arctic, with *Angelica* and *Botrychium* being the key species. The later arrival of the less demanding *Salix* cf. *glauca* at *c.* 8900 B.P. is therefore an example of immigration or spreading lagging behind the climatic development. It is possible that the importance of chianophilous plants in this early period reflects oceanic low arctic conditions, with temperatures lower than today and a longer duration of snow cover.

If the interpretation that *Alnus* was indigenous is correct then its suggested arrival at *c.* 7600 B.P. marks the approach of subarctic conditions. This conclusion is backed up anyway by the occurrence of *Isoetes setacea* at *c.* 7900 B.P. and *Selaginella selaginoides* at *c.* 7500 B.P. since they are both considered to be southern elements in the Greenland flora (Böcher, 1938, 1963). With the indication that temperatures were comparable to those of the present, the date for the beginning of the climatic optimum can be set soon after 8000 B.P. Although the behaviour of the *Juniperus* pollen curve appears to characterise the optimal period, its first appearance at *c.* 7000 B.P. would therefore appear to be another example of immigration lag.

Whilst it has been suggested by others that *Betula glandulosa* is an oceanic species, as mentioned above, there is no other botanical evidence for a change in oceanicity around its arrival date of *c.* 5700 B.P.

The end of the optimum is seen as being around 3200 B.P. at Frederikshåb, marked by the beginning of a series of changes of the vegetation, some subtle but with the decline in *Juniperus* perhaps giving the clearest indication of a deterioration. However the relative role of temperature and precipitation changes is unclear.

No detail is available about the subsequent interval, the climate of which presumably continued to be oceanic with temperatures below those of the optimum.

This scheme of climatic development differs somewhat from Fredskild's (1973) reconstruction for other parts of Greenland. In particular, the onset of the optimal warm period is put 500–1000 years earlier than his estimate of *c.* 7000 B.P. However since the dates are based on the evidence of the same species, apart from *Alnus,* their relative merit depends upon the significance given to lag and delay in immigration and dispersal. The discrepancy in the date of the main post-optimal deterioration, which he puts at *c.* 2000 B.P. could be due to the critical thresholds being reached during different inclement phases in different localities. He does however record an important *Juniperus* decline at 3400 B.P. in south Greenland but interprets this as due to competition with *Betula pubescens* linked with a change to more humid and warmer conditions. He also recognises an increase in humidity at 3200 B.P. in West Greenland with the onset of peat growth at Itivnera in Godthåbsfjord.

However the Frederikshåb model is consistent with evidence from other sources, notably the oxygen isotope analysis of ice cores from north Greenland puts the optimum warm period between 4100 and 8000 B.P., with two subsequent cold spells centered around 3600 B.P. and 2800 B.P. (not C-14 years) (Dansgaard *et al.,* 1971).

The general behaviour of the western margin of the Greenland ice sheet described by Weidick (1972) shows a more complicated picture, with the period between 10 000 and 6000 B.P. being one of general retreat interrupted by short periods of readvance at *c.* 8700, 8100–8400 and 7200 B.P. (Avatdleq, Fjord and Mt. Keglen stages respectively), with the second probably having the most regional significance. Thus the periods around 8500, 8000 and 7000 B.P. are intervals of renewed amelioration in terms of ice margin response. The question of lag behind the climatic stimulus has not been considered. Weidick considers that the general retreat stage ended at 6000 B.P. when a readvance initiated the period of relative stability with minor fluctuations of the margin. This very important glaciological event falls within the period of optimal warmth according to the botanical evidence and anticipates by several thousand years a deterioration of climate sufficient to cause a vegetation response. His explanation is that the readvance was due to an increase in precipitation following a northward shift of low pressure areas during the climatic optimum. However this is not necessarily the case in the deglaciated coastal areas; Fredskild considers that the period is one of drier and less oceanic conditions whilst at Frederikshåb there is only the controversial evidence of the immigration of *Betula glandulosa*.

Evidence from other parts of the arctic, discussed in detail by Fredskild (1973), gives conflicting information about the duration of the climatic optimum and the character of subsequent climatic changes. Some of it is consistent with the interpretation of the Frederikshåb data e.g. the duration of the climatic optimum suggested by Ritchie & Hare (1971) and the existence of a deterioration at 3600 B.P. (Nichols, 1967). Andrews & Ives (1972) consider that in eastern arctic Canada glaciological evidence indicates that there was a major amelioration following the Cockburn readvance, in 8000 B.P. with the climatic optimum between 6000 and 4000 B.P. Readvances of the Neoglaciation followed this. In contrast they put the climatic optimum based on marine biological evidence between *c.* 8000 and 1000–3000 B.P.

To produce a unified picture of climatic development in the arctic will require not only the differences in the response thresholds and characteristics of the different systems to be understood, but for the botanical evidence, will require also the effects of dispersal phenomena to be unravelled from climatic responses.

Acknowledgements

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APPENDIX

Site descriptions

Qaqarssuaq
(site 1)

Qaqarssuaq peninsula, Nerutussoq fjord, Frederikshåb. 62°06'N, 49°37'W, fig. 6: lake at 52 m a.s.l., approx. 60 m diameter, maximum depth 3.5 m, at sample location. It lies on a rocky peninsula on the outer coast. The soils are shallow and patchy and there is consequently a low degree of vegetation cover. This is mainly small areas of snow-patch, marsh and dwarf shrub heaths especially with *Empetrum*. Vegetation in the lake includes *Isoetes setacea, Ranunculus confervoides*.

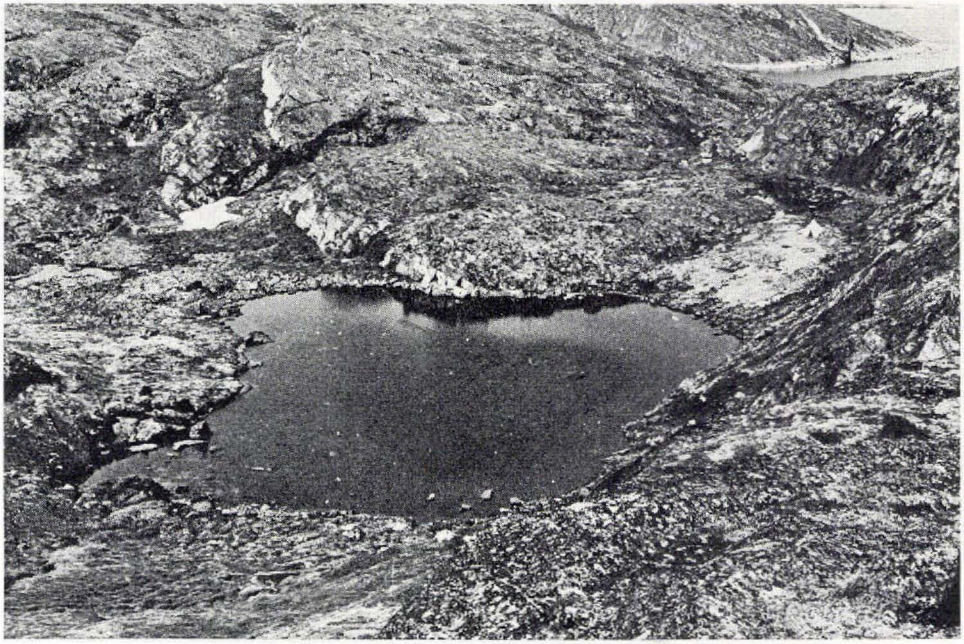

Fig. 6. Qaqarssuaq site 1.

Nigerdleq
(site 6)

Nigerdleq, a branch of Nerutussoq fjord, Frederikshåb. (At the site of the temporary GGU base 'Mellembygd'). 62°04'N, 49°20'W, fig. 7: lake at 92 m a.s.l., 75 × 105 m across, with a maximum water depth of 1.95 m at sampling location. It lies on a low ridge between Nigerdleq and the valley running east from Eqaluit fjord. The area is extensively vegetated on the valley floor and surrounding lower slopes. It is comprised of a mosaic of communities reflecting rapid spatial variation in soil moisture and snow cover duration. It includes major areas of xerophytic dwarf shrub and grass heaths, rich mesophytic dwarf shrub heaths, *Salix glauca callicarpaea* scrub on alluvial flats, dwarf shrub-herb tussock marsh and snow-patch

Fig. 7. Nigerdleq site 6. The arrows mark the sampling site.

communities. Lake vegetation comprise *Myriophyllum alterniflorum, Isoetes setacea* and *Potamogeton filiformis.*

Kvanefjord
(site 8)

At the Nigerdlikasik branch of Kvanefjord, Frederikshåb. 62°08′N, 48°50′W, fig. 8: lake at 152 m a.s.l., approx. 175 × 250 m across, maximum water depth 8 m, 5–6 m at sampling locations. The lake lies in a hollow on the south facing slope 1.5 km north of the edge of the glacier entering the fjord. The lower slopes are covered with thick morainic deposits which largely carry a xerophytic vegetation. Locally around the lake and in the neighbouring small valley to the west are *Salix glauca* scrubs, *Betula glandulosa* scrubs and dwarf shrub and snow-patch communities. No vegetation was recorded from the lake.

Neria
(site 11)

At the Kangerdlua branch of Neria Fjord, Frederikshåb. 61°39′N, 49°00′W, figs. 3 and 9: lake at 98 m a.s.l., 500 × 300 m across with a water depth at sample locality of 4 m. The vegetation around the lake includes extensive moist dwarf shrub heath and tussock marsh. On the slopes and ridges are major areas of disturbed soliflucted ground and also dry lichen heaths. Less than 0.5 km away on a south facing slope are scattered patches of *Alnus crispa,* occurring as pure dense scrub 1 m high, or in rich mixed scrub 0.5 m high with *Salix glauca, Betula glandulosa, Junipereus communis* and *Empetrum.* Lake vegetation comprise *Isoetes setacea.*

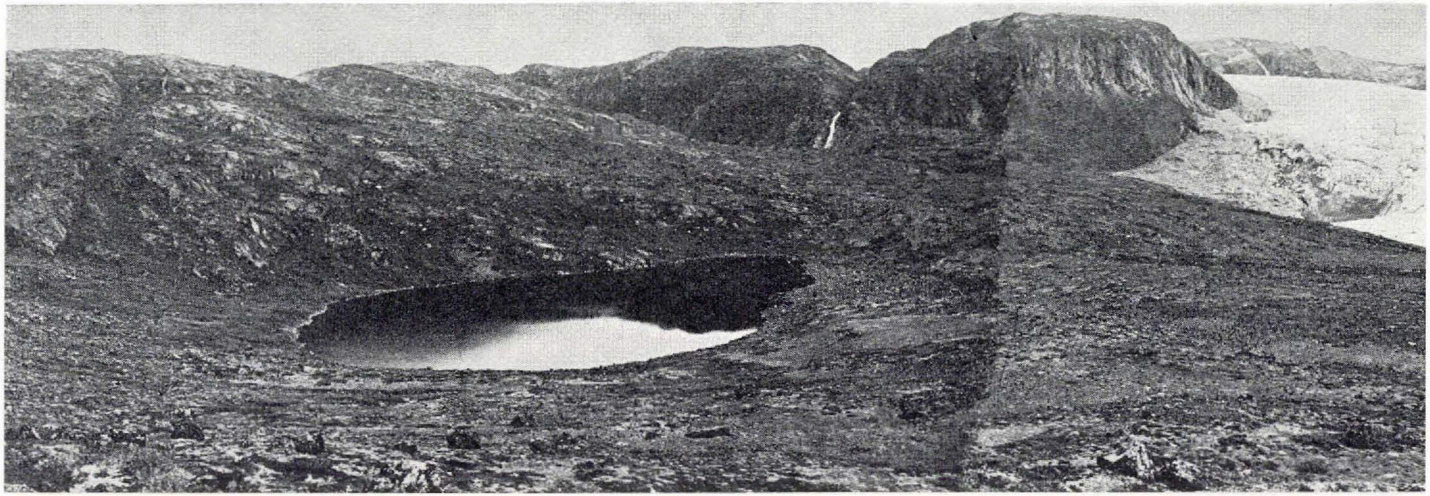

Fig. 8. Kvanefjord site 8.

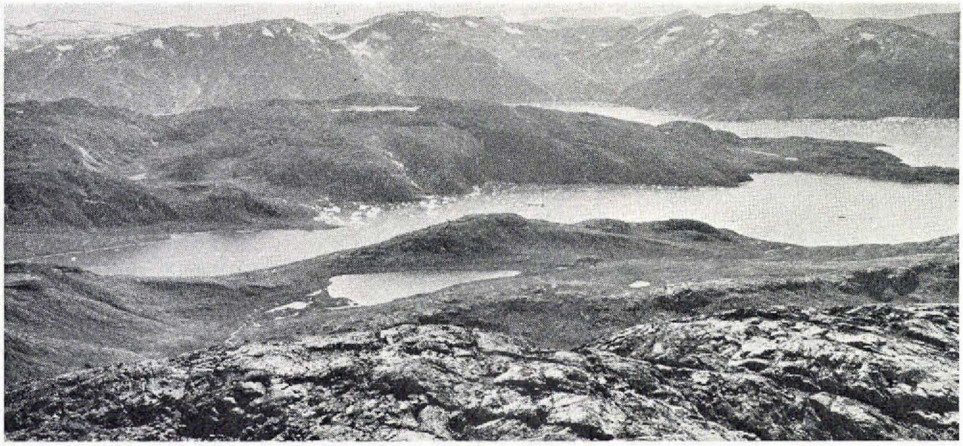

Fig. 9. Neria site 11. The *Alnus* locality shown in fig. 3 lies on the slope overlooking the fjord immediately behind the lake.

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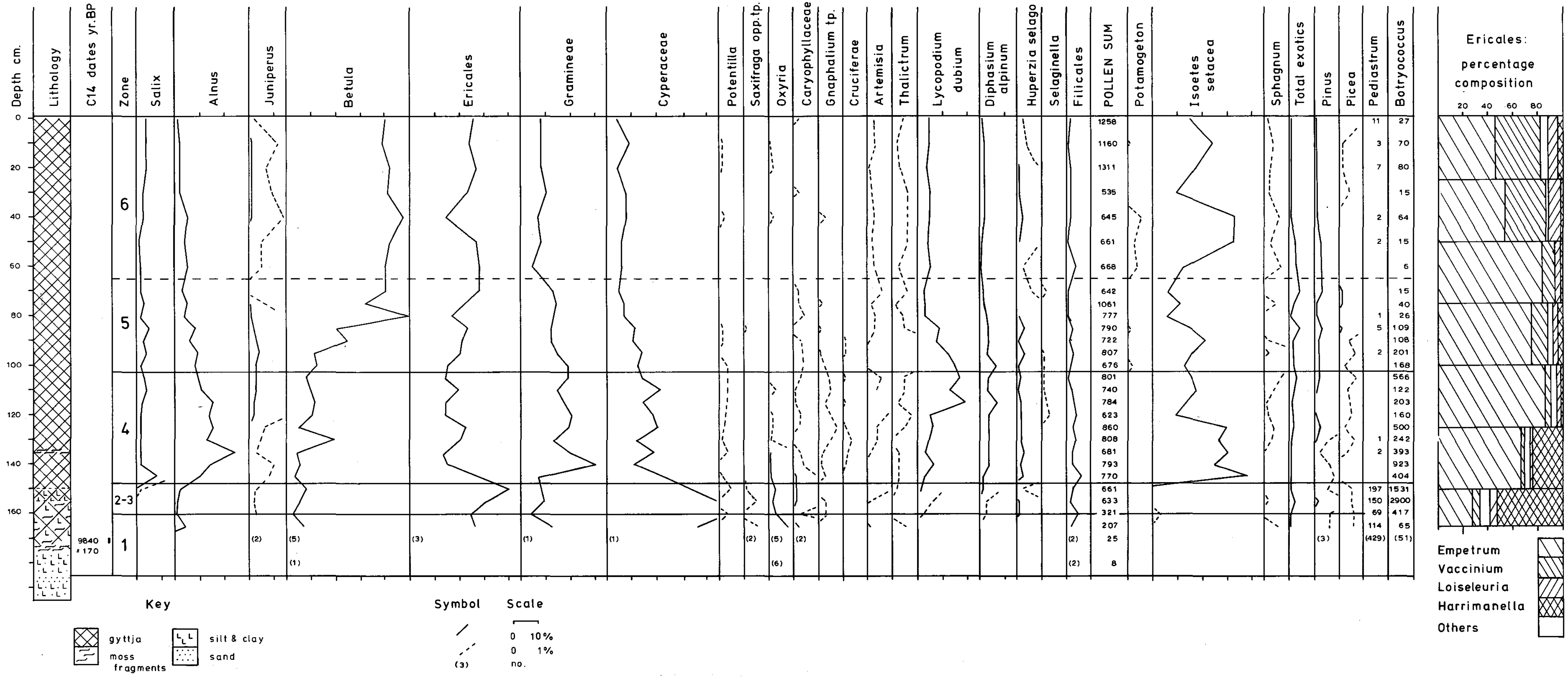

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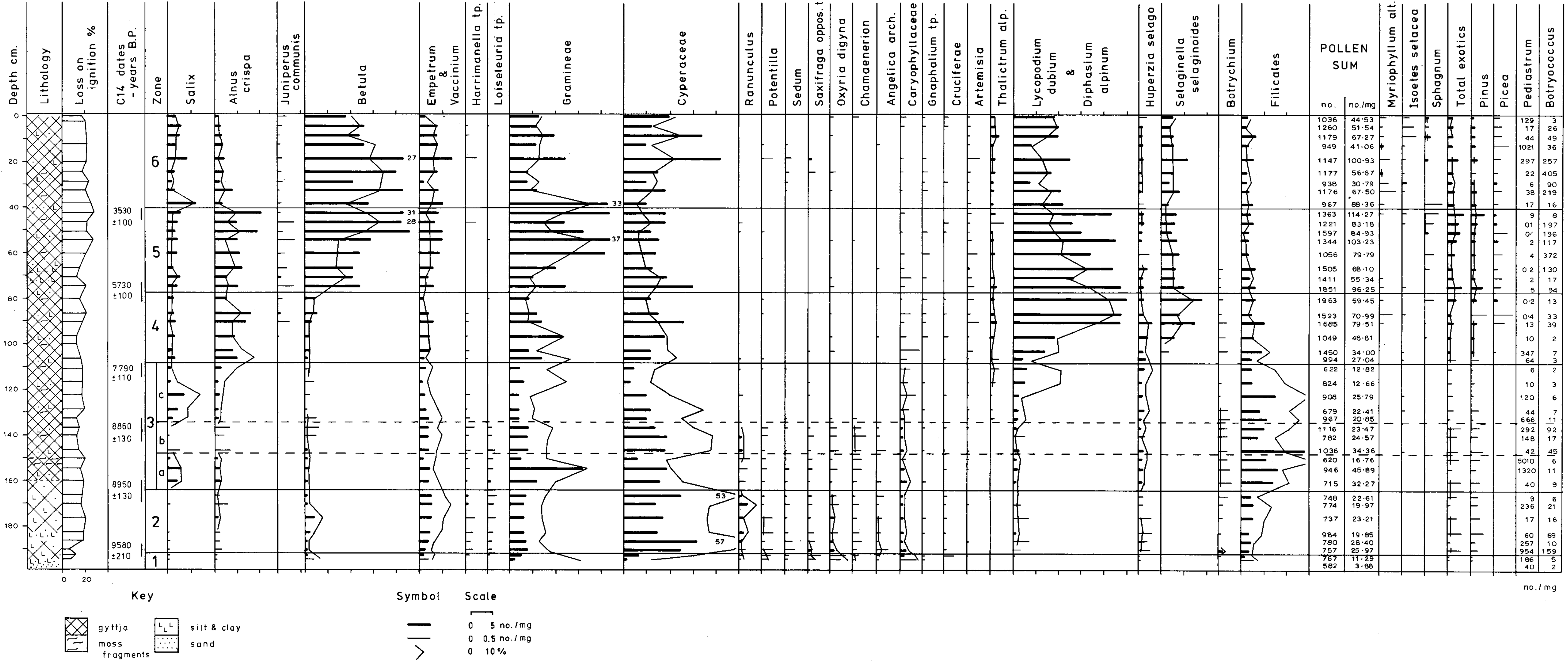
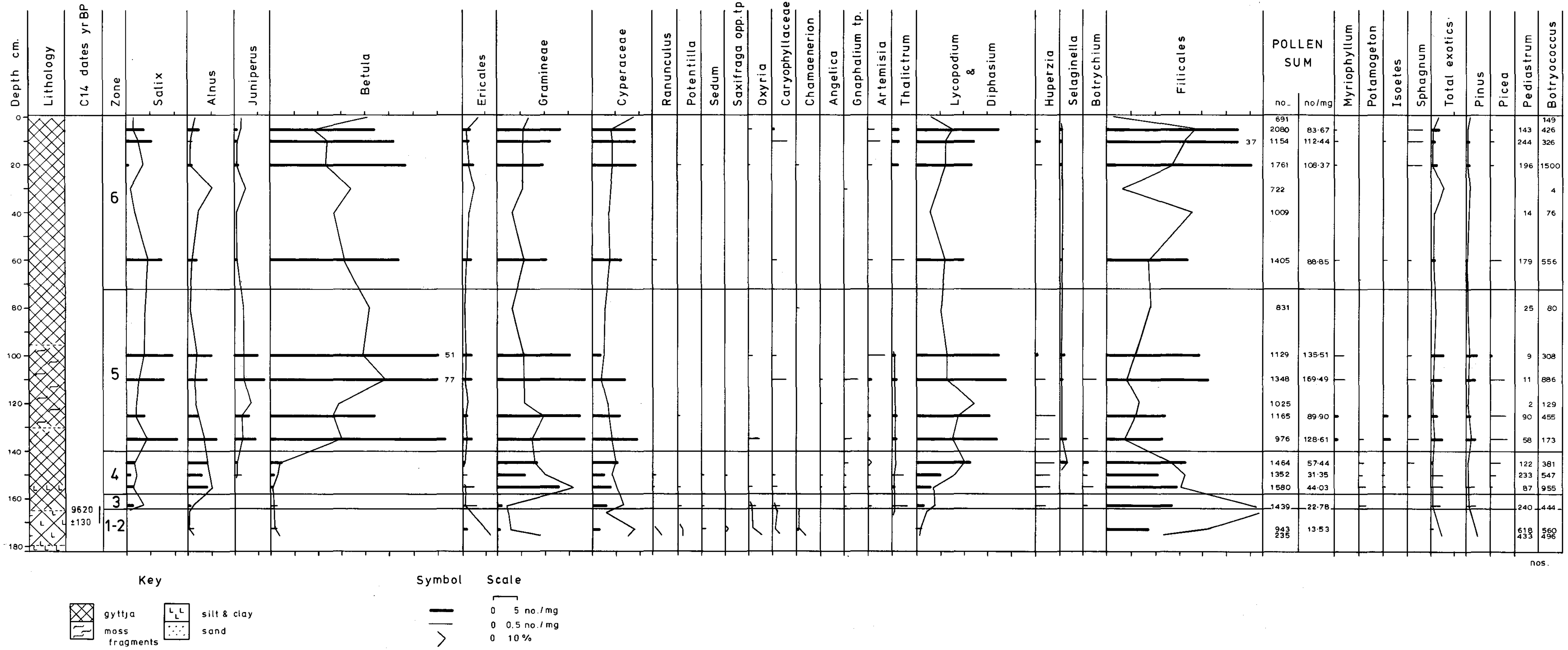


KVANEFJORD SITE 8.



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NERIA SITE 11.