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Sedimentology, palaeoecology and geochronology of Marine Isotope Stage 5 deposits on the Shetland Islands, Scotland

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ABSTRACT: New stratigraphical, palynological and dating evidence is presented for pre-Late Devensian/Weichselian sediments at Fugla Ness and Sel Ayre, Shetland. The Fugla Ness Peat rests on till and formed during an interglacial that saw the development of maritime heaths, with scattered trees and shrubs, including *Pinus* and possibly *Ilex*. A decline into stadial conditions is marked by overlying periglacial breccia and till. The Sel Ayre Organic Sands and Gravels lie between periglacial breccias and beneath till and appear to record a changing interstadial environment in which trees were absent and the vegetation comprised largely heaths, with *Bruckenthalia*, and grasslands. The Fugla Ness Peat is dated to 110 + 40/−35 ka by uranium series disequilibrium, suggesting that it formed during the Ipswichian/Eemian Interglacial (Marine Isotope Substage 5e). Luminescence ages of ca. 98–105 ka on intercalated sands within the Sel Ayre Organic Sands and Gravels place these deposits in Marine Isotope Substage 5c (Brørup Interstadial). The two sites provide the first detailed record of Marine Isotope Stage 5 environments on Shetland. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: sedimentology; palaeoecology; uranium series; luminescence; Marine Isotope Stage 5; Shetland.

Introduction

Shetland lies in a critical location for Quaternary studies through its position on the maritime margin of northwest Europe (Fig. 1). It is important for questions of the extent of Scottish and Scandinavian ice sheets, as a source of terrestrial palaeoclimatic information for comparison with marine records from surrounding seas (Sutherland, 1991; Sutherland and Gordon, 1993) and for the information it may provide on oceanic circulation in the North Atlantic. The glaciation of Shetland has a long history of investigation, dating from the ideas of Croll (1870) and their subsequent development in the seminal work of Peach and Horne (1879). This work established two principal phases of glaciation, initially by ice from external sources, probably in Scandinavia, moving westwards across the islands, then by a local ice cap. This basic two-stage model has been affirmed in subsequent studies, although the evidence for both the Scandinavian ice and the timing of glacial events is debatable (Hoppe, 1974; Mykura and Phemister, 1976; Flinn, 1977, 1978; Sissons, 1981; Sutherland, 1991; Gordon *et al.*, 1993; Ross, 1996). Although there is no direct dating or stratigraphical evidence, it generally is agreed that the local ice-cap glaciation occurred during the Late Devensian. The timing of any external glaciation from Scandinavian sources is uncertain.

Two sites in particular, at Fugla Ness and Sel Ayre (Fig. 1), have assumed critical importance for interpreting the Quaternary history of Shetland. The deposits at these sites include long sequences of sediments with interbedded organic materials of pre-Late Devensian origin. The organic deposits have been studied in some detail for pollen and plant macrofossils and are recognised to be of different ages. Conventionally, they have been ascribed on pollen-stratigraphical grounds to the Hoxnian Interglacial (Marine Isotope Stage (MIS) 7 or 9) and Ipswichian Interglacial (MIS 5e), respectively (Birks and Ransom, 1969; Birks and Peglar, 1979; Birks, 1993a, 1993b), but the basis for such correlation is questionable

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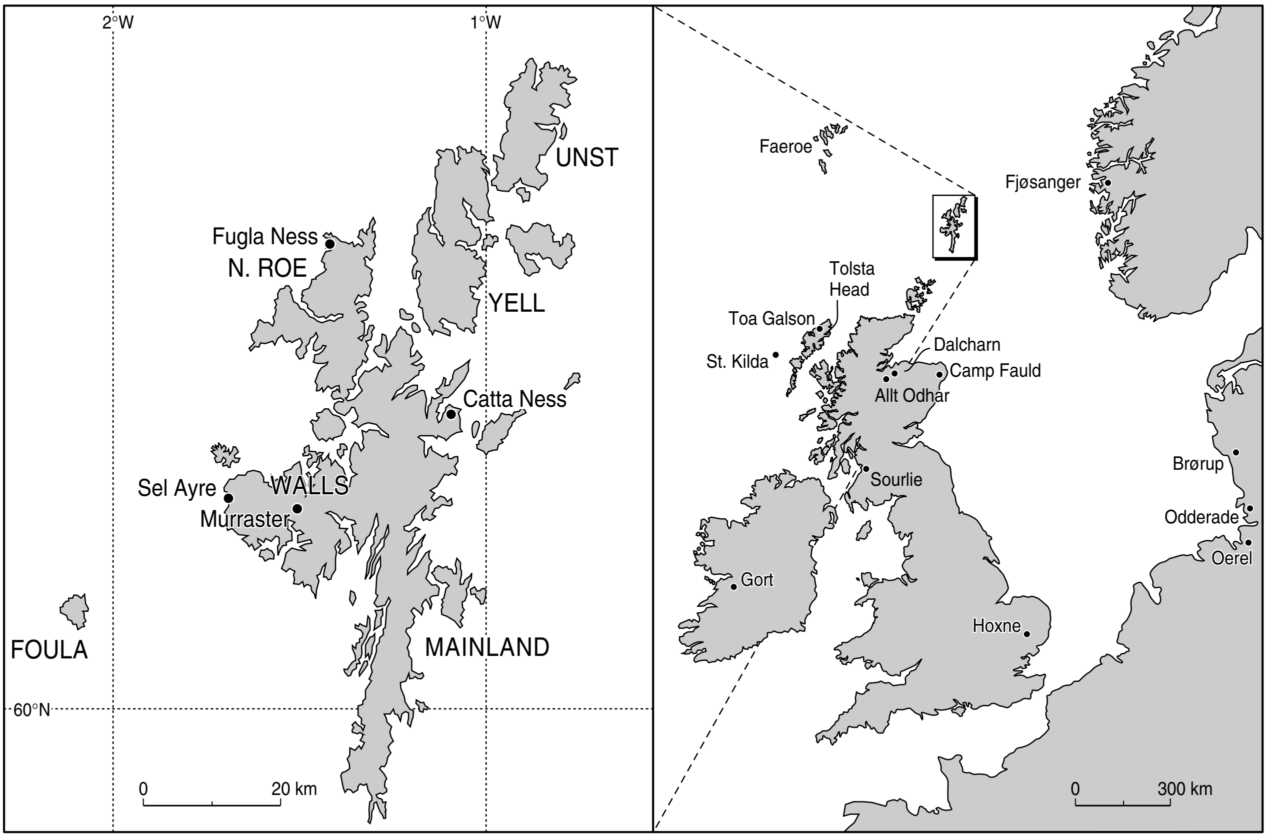

Figure 1 Location of Shetland and its northwest European context

(Lowe, 1984). Moreover, there have been no detailed studies of the sediment sequences in which the organic materials occur. This paper describes in detail these sediment sequences and reports the results of new biostratigraphical analyses and dating. We reassign the Fugla Ness Peat to MIS 5e and the organic sediments at Sel Ayre to MIS 5c and compare the environmental record for MIS 5 on Shetland with that from elsewhere in Scotland and northwest Europe.

Fugla Ness

Fugla Ness (HU 312913) is a low ice-moulded headland on the northwest coast of North Roe, Shetland Mainland. It is formed of ultrabasic rocks but granites occur 1 km to the southeast. The Quaternary sediments at Fugla Ness are exposed in a low cliff up to 5 m high and at the base of the section they pass below the level of the present storm beach. The sediments originally filled a small rock basin but marine erosion has exposed a prominent rock bar on the seaward side of the basin and largely removed the Quaternary fill.

Lithostratigraphy

Four stratigraphical units are recognised at Fugla Ness (Fig. 2). The sediments are described in greater detail elsewhere (Hall *et al.*, 1993a).

Fugla Ness Lower Till (thickness <1.6 m)

The Lower Till comprises a grey (Munsell 7.5YR N5) sandy, pebbly, matrix-supported diamicton with a strong NW–SE fabric (Fig. 3). Stone counts show a dominance of locally derived metagabbros and gneisses and a few granites (Hall *et al.*, 1993a). The till passes down into a lower, rip-block breccia derived from the immediately underlying bedrock.

Fugla Ness Peat (<1.0 m)

Peat is draped over the weathered, stony and concave surface of the Lower Till, conforming to the shape of the eastern margin of the rock basin, and thinning and pinching out towards the basin margins, where it is reworked into the base of the Fugla Ness Breccia (Fig. 2). In places, up to 3 cm of laminated, pale brown silt ('pond silt') underlie the peat and probably represent deposition within a shallow pool. The basal 5 cm of the peat are pebbly and show a faint laminar structure parallel to the surface of the Lower Till. Above, the peat is compacted, without clear structure, and minerogenic material is confined to minor lenses and thin beds of matrix-supported granules and laminated organic muds and sands and occasional isolated pebbles. A striking feature of the peat is the abundance of wood, dominantly roots of *Pinus sylvestris*. The abundance of organic material, including wood, in the overlying breccia indicates that the peat is truncated. The biostratigraphy of the peat is described below.

Fugla Ness Breccia (<2.2 m)

Overlying the Fugla Ness Peat is a light, yellow-brown (2.5Y 6/4), granular pebble breccia. The breccia shows parallel

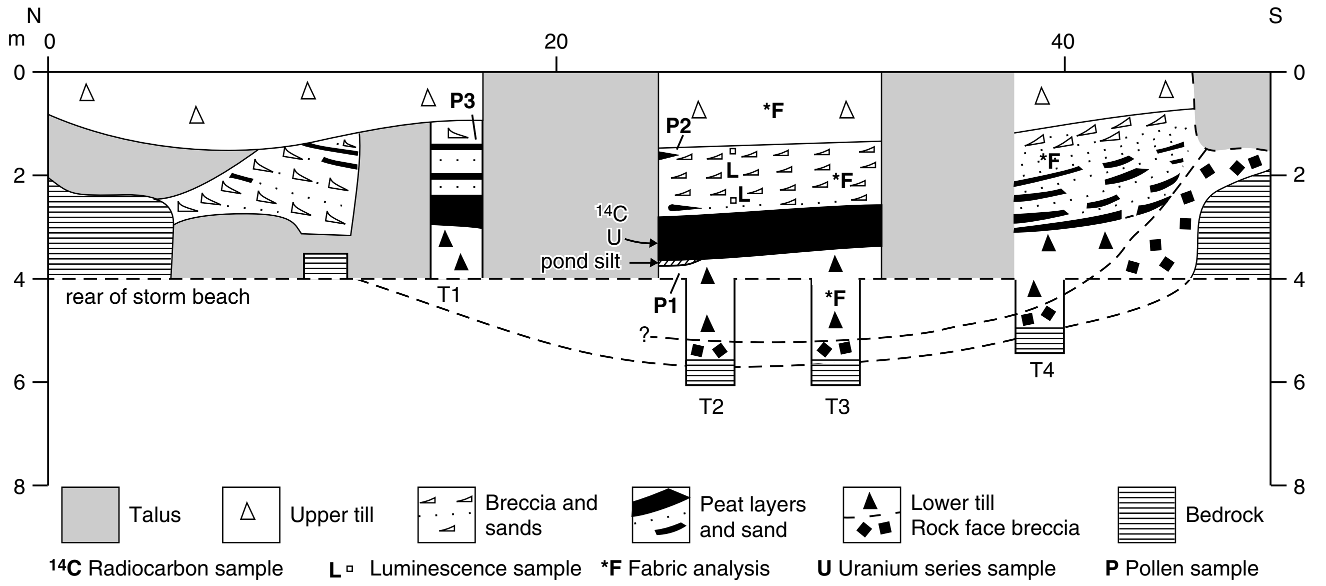

Figure 2 Lithostratigraphy of the deposits at Fugla Ness

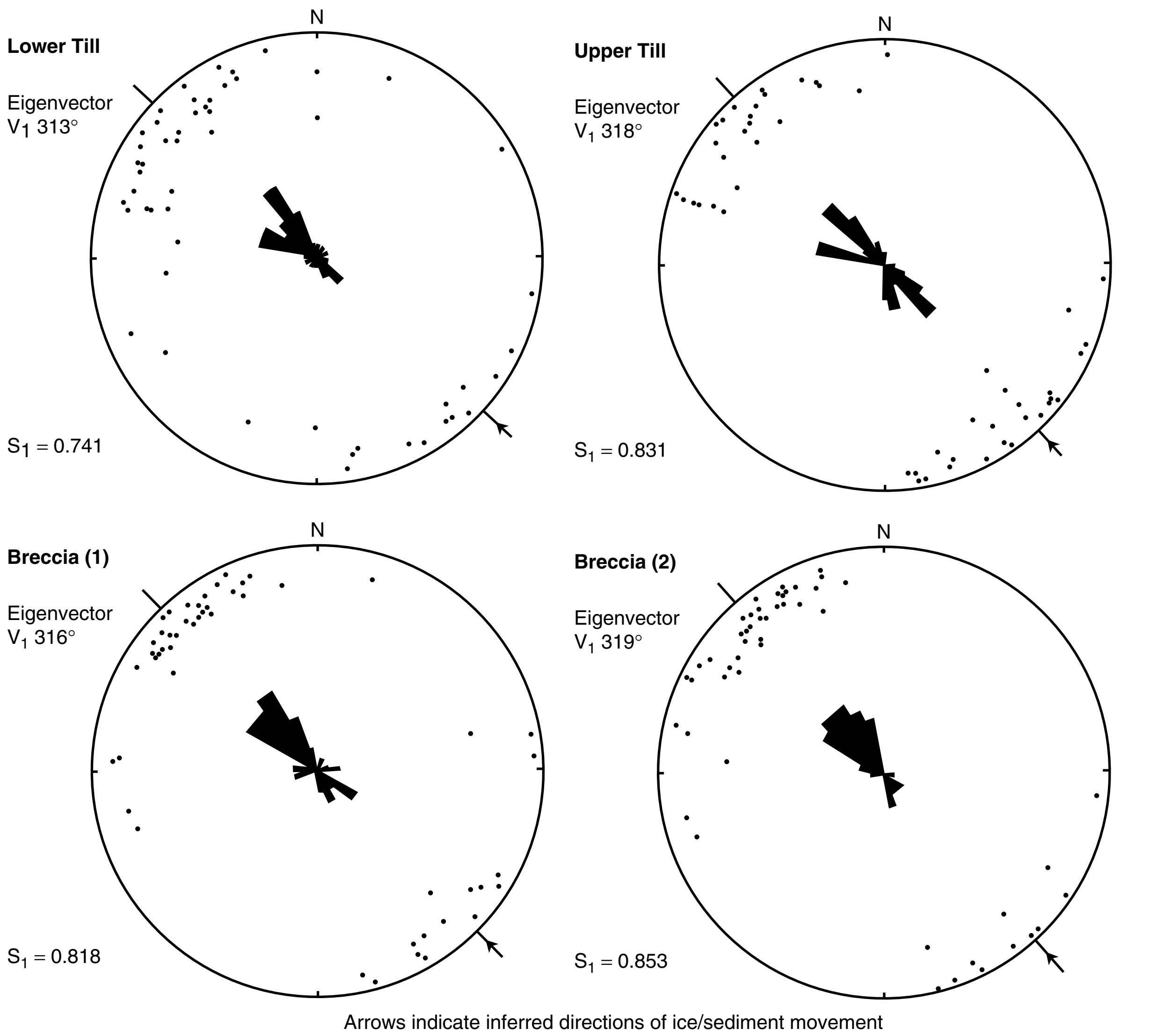

Figure 3 Fabric data for the Fugla Ness Lower Till, Fugla Ness Breccia (two sites) and the Fugla Ness Upper Till. Locations are indicated on Fig. 2

lamination that follows the concave upper surface of the peat, and a well developed, downslope clast fabric (Fig. 3). Clasts in the breccia comprise very largely angular, local, ultrabasic rock types. Many pebbles are bleached and show well developed weathering rinds; the occasional presence of broken clasts with bleached outer faces and fresh inner faces indicates that bleaching pre-dates deposition. In the central part of the section, the breccia matrix is in places rich in disseminated organic material. The proportion of organic material decreases upwards as the breccia coarsens, but organic lenses, including wood fragments, occur up to the base of the Upper Till. The breccia coarsens towards the margins of the basin and is interpreted as a bedded periglacial slope deposit produced by frost shattering of adjacent rock outcrops and solifluction and wash into the rock basin, with substantial erosion of the underlying peat bed. Previously, this bed was interpreted as till (Chapelhowe, 1965), but its bedded structure, angular pebbles and lack of erratic material give no support for a glacial origin.

Fugla Ness Upper Till (<3.0 m)

The Upper Till is a pinkish-grey (5YR 7/2), matrix-supported, massive, stony diamicton with a silty, sandy matrix. The diamicton shows boulder lags, with striated clasts, and has a well-developed NW–SE clast fabric (Fig. 3). On the northern margin of the basin, the till rests on a striated rock floor, with striae trending 298°. Clast types are dominated by local ultrabasics but include large numbers of granites derived from the west and southwest (Hall *et al.*, 1993a). The Upper Till is covered by up to 20 cm of peaty soil.

Biostratigraphy

The pollen and macrofossils within the Fugla Ness Peat have been described previously in detail (Birks and Ransom, 1969; Birks, 1993a). This work was not duplicated in the present study. However, the existence of organic materials in the pond silt (pollen sample P1) and within the Fugla Ness Breccia (pollen samples P2 and P3) has not been noted previously (Fig. 2). To ensure direct comparability with the original work, pollen counts were made in excess of 1000 grains at each level and results are presented in a similar fashion to the original study (Fig. 4), in which, owing to the dominance of the spectra by Ericaceae, the trees, shrubs and herbs are expressed as a percentage of the total dry land pollen (TDLP) minus the Ericaceae. The latter, together with the mire plants, aquatics and cryptogams, are given as a percentage of the TDLP plus the sum of the particular group.

Fugla Ness Peat

Birks and Ransom (1969) recognised two pollen zones within the peat (Fig. 4) and these are summarised below.

Pollen Zone F1 (616–691 cm). The dominant pollen type in this zone is Ericaceae (>70% TDLP). Arboreal types are present, *Pinus* and *Betula* being the most important, but also there are low, although consistent occurrences of *Quercus*, *Ulmus*, *Alnus*, *Picea* and *Abies* pollen. *Ilex* pollen also is present throughout the zone. The herbaceous taxa are dominated by Gramineae and Cyperaceae, and, of the cryptogams, *Osmunda* is the most prominent.

Pollen Zone F2 (536–616 cm). Ericaceae is still dominant but in decreasing amounts, falling to ca. 15% TDLP near the top of the zone. Of the arboreal pollen present, *Pinus* percentages increase to nearly double the values displayed in Zone F1, whereas *Betula* is almost two-thirds less. Other arboreal pollen taxa have lower percentages and are more sporadic in occurrence. Herbaceous pollen increase in type and amount, the most prominent still being Gramineae and Cyperaceae, along with Liguliflorae.

Birks and Ransom (1969) interpreted the pollen evidence as representing, in the Fugla Ness area, a coniferous woodland interspersed with heath and grassland communities. During the time over which the peat accumulated, however, there appears to have been an increase in *Pinus* representation, and the existence of pine roots in the upper part of the peat confirms its local growth. Whether the presence of the pollen of *Quercus*, *Ulmus*, *Abies* and *Ilex* does actually indicate the local occurrence of those taxa is perhaps debatable, given their extremely low percentages. What is of considerable importance, however, is that the pollen of those taxa shows some decline between Zones F1 and F2, most marked in the case of *Ilex*, probably indicating a lowering of temperature. The peat would appear to have accumulated around an area of open water. The pollen of taxa that inhabit wet land (e.g. *Filipendula*, *Succisa pratensis* and *Hydrocotyle vulgaris)* is present and probably is representative of the flora that fringed the water body. The occurrence, for example, of *Menyanthes trifoliata* and *Nuphar* and *Potamogeton* species, along with the megaspores of *Isoetes lacustris*, suggests that the water body displayed varying depths.

New Pollen Analyses

Pond Silt (P1). This deposit, apparently laid down very rapidly given its low pollen concentration value (97×10^3 grains cm^{-3} wet sediment), lies at the base of the Fugla Ness Peat. It contains ericaceous taxa as the dominant pollen type (72% TDLP), with Gramineae providing the only other substantial taxon (Fig. 4). The presence of *Potamogeton*, *Alisma plantago-aquatica*, *Littorella uniflora* and *Pediastrum* confirms the existence of a pond at the site. *Alnus* and *Salix* and some mire plants suggest there was a surrounding fen woodland.

Birks and Ransom (1969) described the earliest vegetation at Fugla Ness as being wet fen–woodland near the pond and, elsewhere, open woodland (*Pinus–Betula*) with Ericaceae providing a ground cover along with restricted grassland, the latter probably on steep slopes with shallow soils. The pollen taxa of P1 show an earlier stage when *Pinus* was less, and Gramineae more, abundant. The absence of *Osmunda regalis*, given that it shows strongly at the base of the Fugla Ness Peat, is interesting. It suggests there may have been a hiatus between the deposition of the pond silt and the formation of the peat.

Organic Bands within the Fugla Ness Breccia (P2 and P3). Pollen spectra from two organic bands within the Breccia were produced (Figs 2 and 4). The spectrum from P2 displays a major difference from the others at Fugla Ness, in that it is dominated by arboreal pollen, especially that of *Pinus*, whereas Ericaceae is at the lowest value recorded at the site. An examination of pollen exine reveals much of it to be perfectly preserved (*Pinus* 41%, *Empetrum* 38%), whereas the Gramineae has

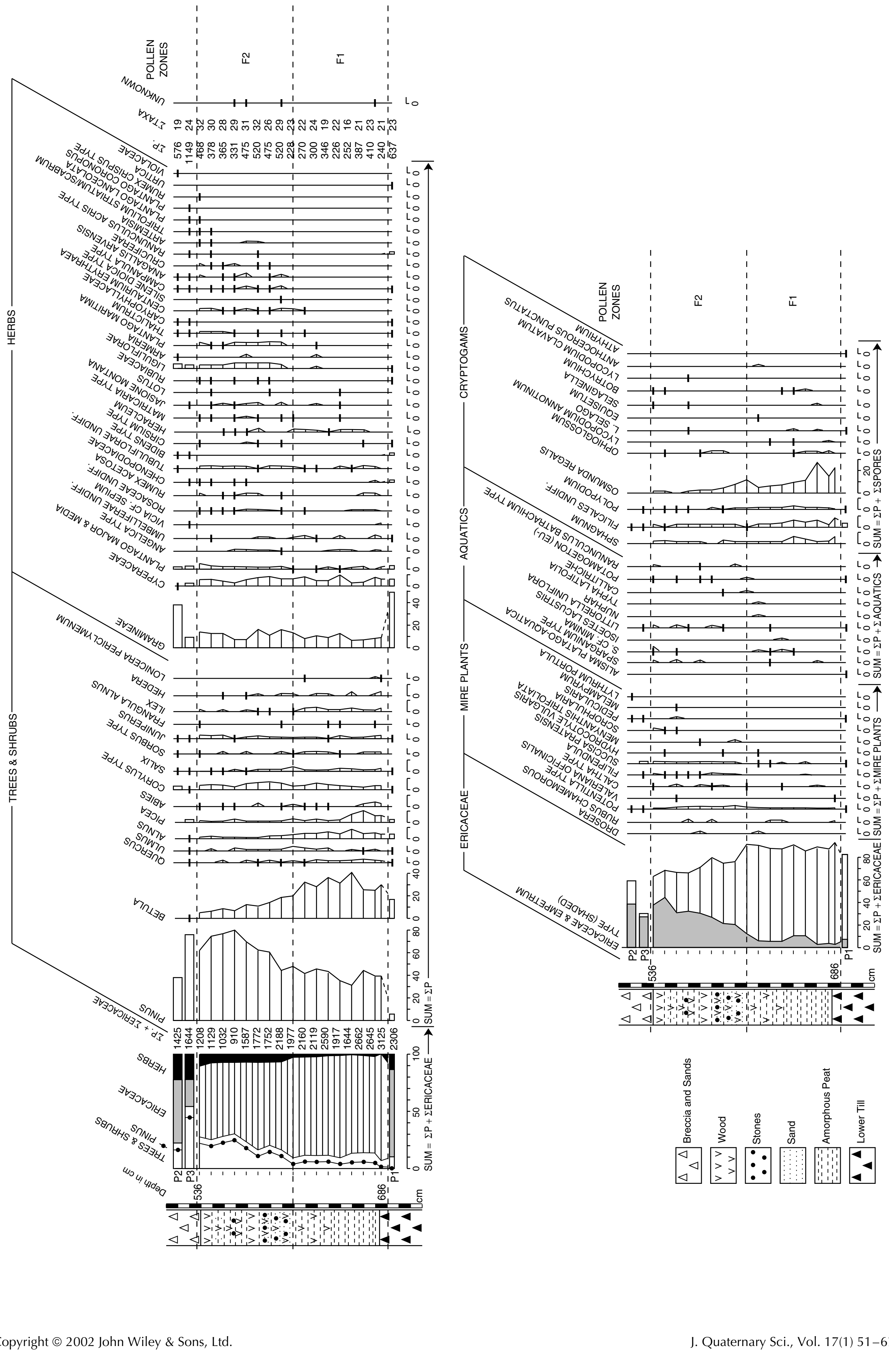

Figure 4 Percentage pollen diagram from Fugla Ness (after Birks and Ransom, 1969). The new pollen analyses are denoted by P1, P2 and P3. Reproduced by permission of Blackwell Science

Table 1 Preservation status of selected pollen taxa from samples P1, P2 and P3 at Fugla Ness. Values are by percentage and are in four categories: grains described as P are undamaged, B are broken, CRU are crumpled and COR are corroded, mainly thinned. Sample P1 is the Pond Silt and P2 and P3 are organic bands in the Breccia. Numbers in parentheses after those designations refer to the number of grains encountered in those samples

		P	B	CRU	COR
Pinus	P3 (223)	5.3	85.6	7.6	1.3
	P2 (891)	41.9	35.3	21.7	0.8
	P1 (33)	16.2	67.4	16.2	—
Betula	P3 (97)	3.2	25.8	54.8	16.1
	P2 (7)	14.2	—	—	85.7
	P1 (31)	4.1	10.3	39.1	46.3
Ericaceae	P3 (304)	14.1	31.2	29.9	24.6
	P2 (40)	17.5	10.0	50.0	22.5
	P1 (1511)	18.7	30.3	24.8	26.0
Empetrum	P3 (545)	27.7	30.0	33.3	8.8
	P2 (458)	38.2	14.4	44.7	2.6
	P1 (158)	43.0	10.1	43.6	3.1
Gramineae	P3 (214)	—	17.7	63.5	18.2
	P2 (113)	—	12.3	84.9	5.3
	P1 (309)	0.6	17.3	16.7	62.6

been crumpled; only the *Pinus* pollen has suffered breakage (35%) to any degree (Table 1).

Sample P3 shows Ericaceae as the dominant taxon (60% TDLP), comprising 38% *Empetrum* and 22% *Ericaceae*. Trees and shrubs provide 22%, to which *Pinus* contributes 16%. These percentages and the rest of the taxa bear a resemblance to spectra in F2, especially those near the top of the zone. The main difference lies in the much greater percentage of Gramineae, which occurs in P2 (38% as against 15% at the top of zone F2), and a much decreased value for *Pinus* (30% as against >70% in the upper part of F2). Pollen preservation in P3 (Table 1) for *Pinus* (85% broken) and for *Empetrum* and Ericaceae (mainly either broken or crumpled) provides a major contrast with that recorded for P2.

That samples P2 and P3 originated from the reworking of organic deposits is shown by the thermophilous nature of the pollen spectra, which contrasts so markedly with the periglacial character of the breccia. Reworking and selective destruction of pollen taxa is unlikely, however, to account for all the differences between samples P2 and P3 and Zones F1 and F2. In particular, the high levels of Gramineae in sample P3, when values for that taxon in Zones F1 and F2 rarely exceed 10%, suggest that the Fugla Ness Peat that is exposed today was not the only or even any part of the source of the pollen in Sample P3. The extreme variation in the *Pinus*–Ericaceae relationship in P2, compared with that in the rest of the spectra at Fugla Ness, also needs to be considered in the same context. The matrix containing the pollen in P2 and P3 would seem to have been incorporated into the breccia from higher levels in the Fugla Ness Peat, which are no longer extant. The differences in preservation status of the pollen in P2 and P3 are related to the nature of the materials into which it was incorporated and their subsequent reworking. Sample P2 is derived from a peat band that appears to have been severed from a peat deposit and incorporated into the breccia without further disruption. Sample P3 is a sandy peat lens that suffered comminution during reworking and thus, in contrast to P2, most of its pollen content underwent breakage.

Sel Ayre

The deposits at Sel Ayre are located on the western edge of the Walls peninsula (HU 176540) at the top of a 100 m high cliff facing west into the Atlantic. Land slip during cliff retreat has exposed about 10 m of Quaternary sediment, which fills a steep-sided gully cut into Devonian sandstone.

Lithostratigraphy

Four lithostratigraphical units are recognised at Sel Ayre (cf. Mykura and Phemister, 1976) (Fig. 5). The sediments are described in greater detail elsewhere (Hall *et al.*, 1993b).

Sel Ayre Lower Breccia (<4.0 m)

The Lower Breccia is a clast-supported, partly openwork rubble, with angular sandstone blocks, many over 10 cm in length, in a sand matrix. The breccia has a strong fabric, with clast orientation and dip towards the channel axis (Fig. 6). The highly angular and overwhelmingly local character of the constituent sandstone blocks indicates vigorous frost shattering of the channel walls and higher slopes. The Lower Breccia is a scree-like deposit formed during a period of periglacial conditions.

Sel Ayre Organic Sands and Gravels (<3.0 m)

At the base of this unit, at the centre of the gully, is a layer of pale green clay, 5–15 cm thick, which fills gaps between platy stones that form the upper surface of the Lower Breccia. Resting on the clay is a peat bed, up to 0.5 m thick, which dips eastward into the face and thins and splits laterally across the gully, becoming interbedded with sands. The peat is highly compressed and humified and contains inorganic debris throughout. It is the main peat band recognised by earlier workers (Mykura and Phemister, 1976; Birks and Peglar, 1979). In the central part of the gully these highly organic sediments pass upwards into horizontally bedded sands with occasional rubble bands and thin lenses and laminae of organic mud, which extend upwards for a thickness of at least 0.4 m. These sands pass laterally into dipping rubble bands. Notable features of these sands are their striking light grey (Munsell 10YR 7/1) colour, indicating strong bleaching, and the development of weathering rinds up to 2 cm thick on numerous clasts. Many stones show well-developed caps of silty sand.

On the northern wall of the gully (Fig. 5), bedded sands, sandy rubble layers and thin organic layers extend for up to 2.5 m above the top of the main peat. The organic layers are 1–2 cm thick beds and lenses of laminated organic sand and mud and extend for about 1.7 m above any of the organic sediments previously described at this site (Mykura and Phemister, 1976; Birks and Peglar, 1979). Sand layers are planar bedded and contain varying numbers of angular

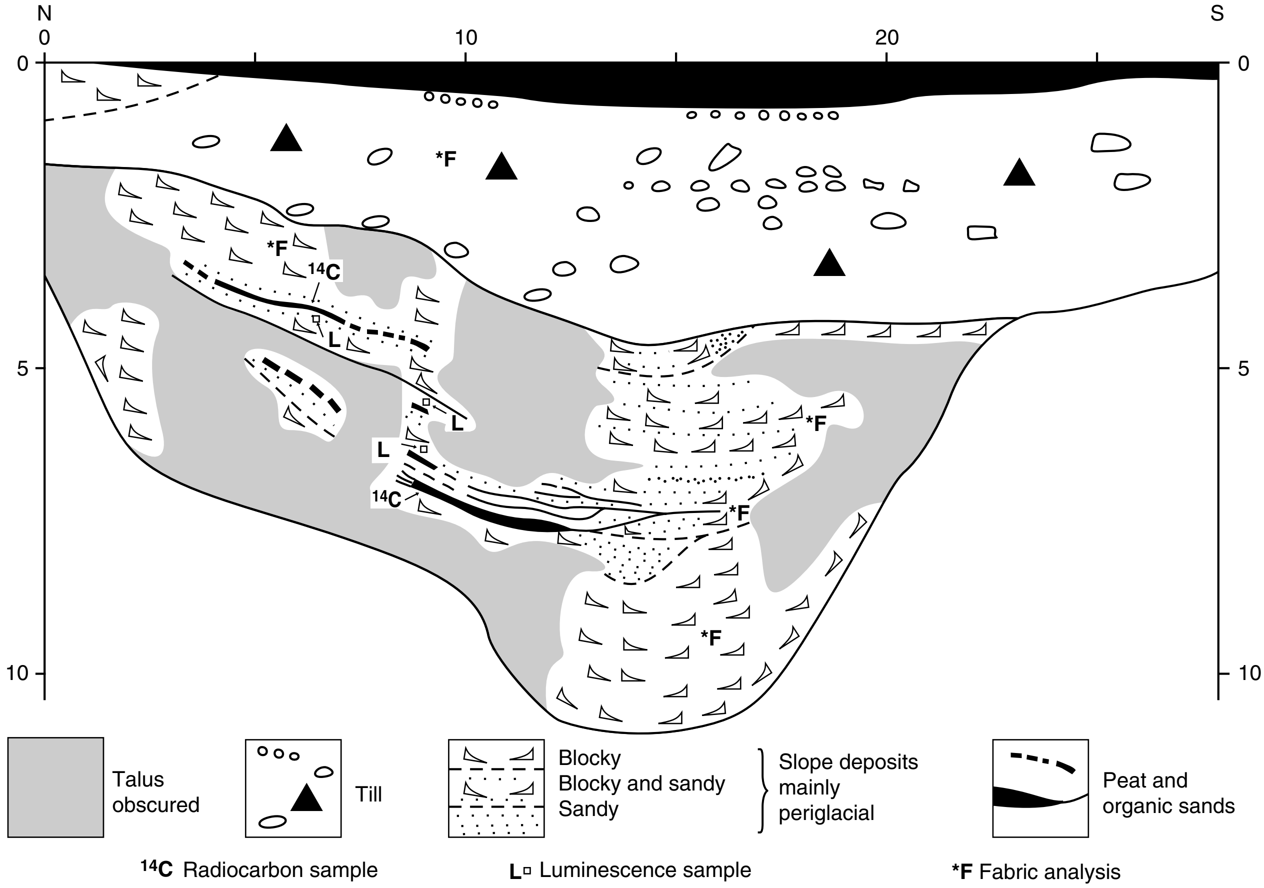

Figure 5 Lithostratigraphy of the deposits at Sel Ayre

sandstone clasts up to 4 cm in length. One feature of the sands is the repeated development of 2–5-cm-thick sequences of dark, organic, bleached and iron-stained sand, reflecting weathering of these sands during or after deposition. The sandy rubble layers comprise clast- and matrix-supported rubble, with clasts up to 15 cm in length. Scattered flecks of organic material occur in places within both the sand and sandy rubble bands.

Above the main peat, clastic sedimentation dominates and the growing influx of minerogenic material seems to record destabilisation of surrounding slopes, possibly in response to deteriorating climatic conditions. The character of the bleached sands overlying and partly interbedded with the upper part of the peat is instructive. Bleaching of sands and associated softening and development of weathering rinds on sandstone clasts occurred largely prior to deposition as weathered and unweathered stones occur side by side. A bleached horizon about 10 cm thick is common beneath Holocene peat in Shetland. It is suggested that a similar bleached horizon developed beneath peat on surrounding slopes at around the same time as the lower part of the main peat accumulated in the central gully. Vegetation loss from surrounding slopes then led to erosion of the peat and the underlying bleached horizon. Weathered scree deposits on the channel margins were remobilized, and slopewash led to the accumulation of thin planar-bedded sand units on the gully floor. An obvious corollary of this is that the organic bands above the main peat may include organic material reworked from surrounding soil and peat profiles. That this is the case is shown by the laminated and washed character of these bands, and by the frequent presence within them of flecks of organic material and of damaged pollen (Birks and Peglar, 1979).

Sel Ayre Upper Breccia (<3.0 m)

The Upper Breccia is mainly a matrix-supported and crudely stratified sandy and gritty rubble, with angular sandstone clasts up to 20 cm in length and strong downslope clast fabrics (Fig. 6). The Upper Breccia shows a number of features indicating weathering during or after deposition, namely localised iron-staining of sands, weathering rinds up to 3 mm thick on clasts, and caps of silty sand on clasts. The Upper Breccia formed during a period of periglacial conditions when intense frost weathering of adjacent rock slopes led to accumulation of debris on the gully floor as a result of rock fall and solifluction. The development of silt caps and thin weathering rinds on clasts indicates periods of incipient soil formation during deposition, but no organic material has been recovered from this unit.

Sel Ayre Till (<4.0 m)

The Sel Ayre Till is a brown (Munsell Colour 7.5YR 5/4), matrix-supported, sandy diamicton, with prominent boulder lags and lenses of subangular pebbles. Clasts range up to boulder size and include many that are facetted and striated. Clast lithologies are dominated by sandstone but there is a significant component of volcanic rock types derived from the east. The till has a well-developed clast fabric, indicating ice flow towards the northwest (Fig. 6). This direction of flow matches that of the last ice sheet over this part of the Walls peninsula, as shown by patterns of striae and erratic carry (Mykura and Phemister, 1976). The upper 1 m of the till is

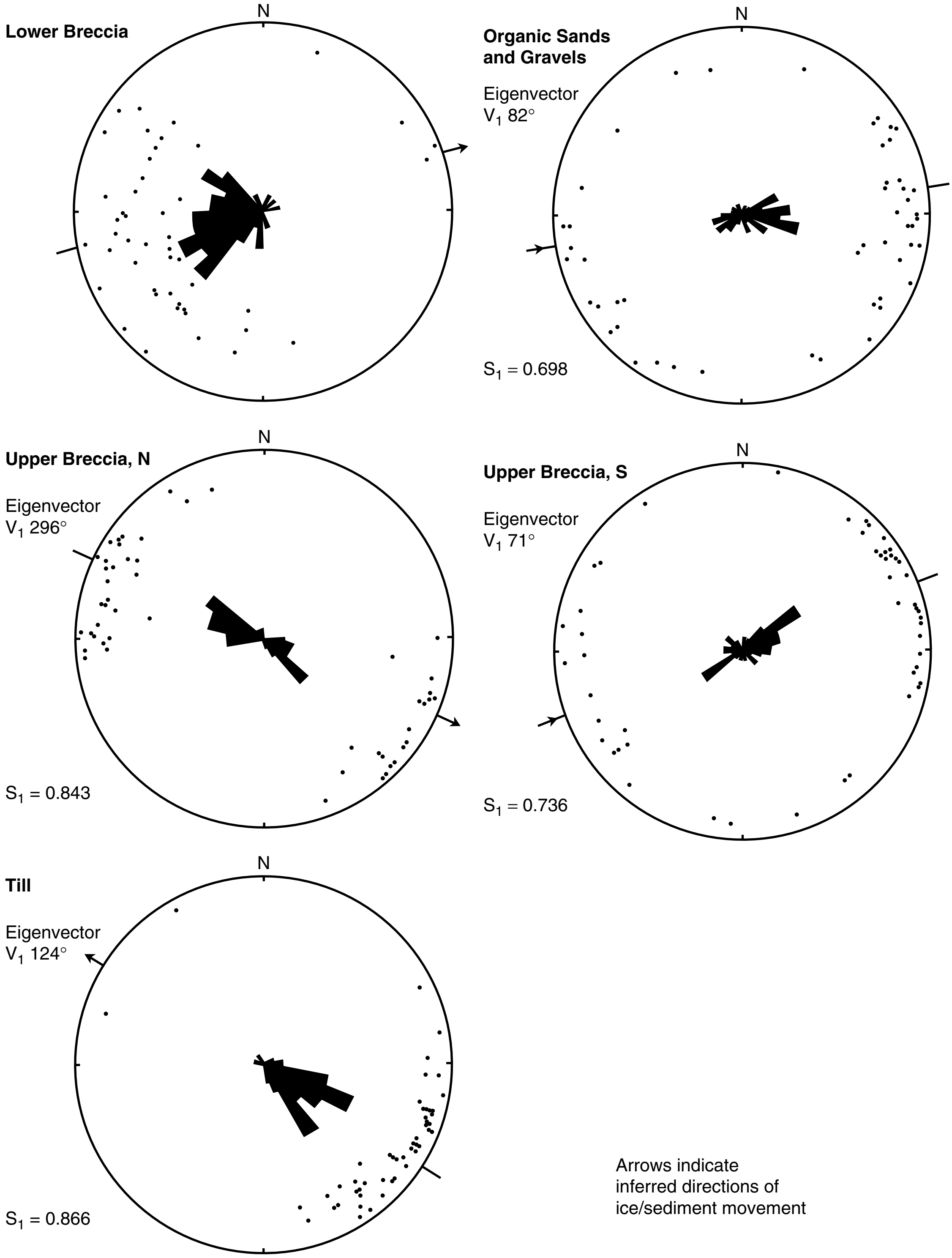

Figure 6 Fabric data for the Sel Ayre Lower Breccia, Sel Ayre Organic Sands and Gravels, Sel Ayre Upper Breccia (two sites on the north (N) and south (S) sides of the gully) and Sel Ayre Till. Locations are indicated on Fig. 5

disturbed, and on the northern margin of the section, rubbly slope deposits overlie the till. The sequence is capped by 0.4 m of Holocene peat.

Biostratigraphy

Birks and Peglar (1979) analysed pollen from the 48-cm-thick main peat band and from peaty laminae up to 80 cm above the top of the main peat. Three pollen zones were recognised (Fig. 7a) and the descriptions are summarised here. It also should be noted that individual taxa on the pollen diagram are expressed as a percentage of a sum that includes both pollen (including all indeterminate grains) and spores, whereas at Fugla Ness an entirely different representational system is used.

Zone SA1

This zone extends from the base of the main peat for a vertical thickness of 14 cm. Gramineae dominate the pollen spectrum; *Betula*, *Pinus*, *Quercus*, *Alnus* and *Fraxinus* are present at values of <5%. *Dryopteris*-type spores are common and indeterminable pollen is frequent, reaching 30%.

Zone SA2

This zone includes the upper 34 cm of the main peat and, 10 cm above it, one peat lamina. Ericaceae is totally dominant, being in excess of 60% throughout the zone, with Gramineae less than 10%. Arboreal pollen, with the exception of *Fraxinus*, repeats the pattern found in SA1 and additionally includes *Abies*, *Ulmus*, *Carpinus* and *Picea*. Notable is the presence of *Bruckenthalia spiculifolia*. Values for indeterminate pollen are <10%.

Zone SA3

This zone includes peat bands and laminae at 25 cm and 80 cm above the top of the main peat band. Levels of indeterminable pollen are comparable with those in SA2, except in the upper peat band. Gramineae pollen is dominant again (>50%) and Ericaceae provides 20%. Of the arboreal taxa present in SA2, only *Betula*, *Pinus*, *Alnus* and *Picea* are recorded and at very low values.

New Pollen Analyses

Organic materials unavailable to Birks and Peglar were recovered from a trench in the northern part of the gully located 10 m south from the north end of the section in Fig. 5 (pollen samples NPA 1-10, Fig. 7b). These were subjected to the same analytical methods as in the original investigation. Only three new pollen taxa were recovered—Chenopodiaceae, *Juniperus communis* and *Ephedra fragilis*.

NPA1 (791 cm), NPA2 (786 cm) and NPA3 (780 cm). Samples NPA1 and NPA2 come from organic sands resting on the Lower Breccia, and sample NPA3 is from the base of the peat in the trench. All pollen spectra are dominated by Gramineae (70%). Ericaceae is present and increases upwards (3–18%). *Betula* and *Alnus* are the only arboreal taxa. In contrast to Zone SA1, these samples have no *Dryopteris*-type spores and indeterminable grains do not exceed 5%. The pollen spectra seem to represent an earlier and developing phase of the vegetation of Zone SA1.

NPA4 (735 cm). Immediately above the main peat, and within Zone SA2, lies a narrow layer of grey/white sand with organic bands and lenses. The pollen in this sample is so severely fragmented that it is impossible to provide a meaningful count; recognisable taxa are indicated on Fig. 7b. Ericaceae is the dominant taxon and Gramineae is also important, as is the case in Zone SA2. Pollen concentration is high but not calculable. Charcoal fragments dominate the palynomorphs.

NPA5 (722 cm). The pollen from this organic band has a very high concentration value (28×10^5 grains cm^{-3} wet sediment), and the number of indeterminate grains contrasts with that in NPA4, being similar to that in the main peat. The majority of grains are broken, charcoal levels are high and the taxa represented correspond closely in type and percentage to those in Zone SA2.

NPA6 (706 cm) and NPA7 (676 cm). Samples from two newly located organic bands in Zone SA3 (Fig. 7a) were devoid of pollen.

NPA8 (662 cm), NPA9 (612 cm) and NPA10 (520 cm). Three higher, thin organic bands contained pollen. Although the bands are widely separated, they all show similar pollen spectra. Gramineae is dominant (>75%) and Ericaceae is present in low quantities in NPA8 and 9. *Salix* (16% in NPA9) and Compositae tubuliflorae (16% in NPA10) are at their most prominent for the whole site. These pollen spectra are similar to those of Zone SA3.

Geochronology

Radiocarbon dating

A number of finite radiocarbon age determinations between 47 500 and 34 800 ^{14}C yr BP exist for the Fugla Ness Peat (Table 2). The climate in northwest Europe during this period ranged from full stadial to cool interstadial conditions (Behre and van der Plicht, 1992) and this clearly is incompatible with the thermophilous vegetation micro- and macrofossils found within the peat. Accordingly, most writers have dismissed these radiocarbon age determinations as too young (Sutherland, 1991), an interpretation supported by a further date of >51 700 ^{14}C yr BP (Table 2).

The main peat at Sel Ayre originally yielded a finite age determination of 36 800 ^{14}C yr BP (Table 2). A new date of >52 200 ^{14}C yr BP (humin fraction) suggests that the earlier peat sample was contaminated by younger carbon. The upper organic band, equivalent to pollen sample NPA10, in the Sel Ayre Organic Sands and Gravels gave a date of 22 450 ^{14}C yr BP. The organic band lies within highly permeable sands and gravels and the possibility of contamination by younger carbon in groundwater seems high. In addition, luminescence ages for sands just below the organic band suggest that this radiocarbon date is too young. It is concluded that all the organic sediments known at Fugla Ness and Sel Ayre are beyond the range of radiocarbon dating.

Luminescence dating

In luminescence dating, the age of the sample is determined by dividing the equivalent radiation dose (ED) that the sample has received since deposition by the annual radiation dose (Duller, 1996). In this study, luminescence measurements on potassium-rich feldspars were used to calculate the ED. Luminescence measurements were made on a Risø automated TL/OSL reader through a combination of Corning 5-58 and Schott BG-39 glass filters. An assumption implicit in standard luminescence dating procedures is that sediment grains were exposed to sufficient daylight at deposition to remove any pre-existing luminescence signal. In depositional environments such as those at Fugla Ness and Sel Ayre, this assumption may not be valid. Hence the methods of ED determination used were designed explicitly to test this assumption. One approach was to exploit the significant difference in the rate at which the thermoluminescence (TL) and infrared stimulated

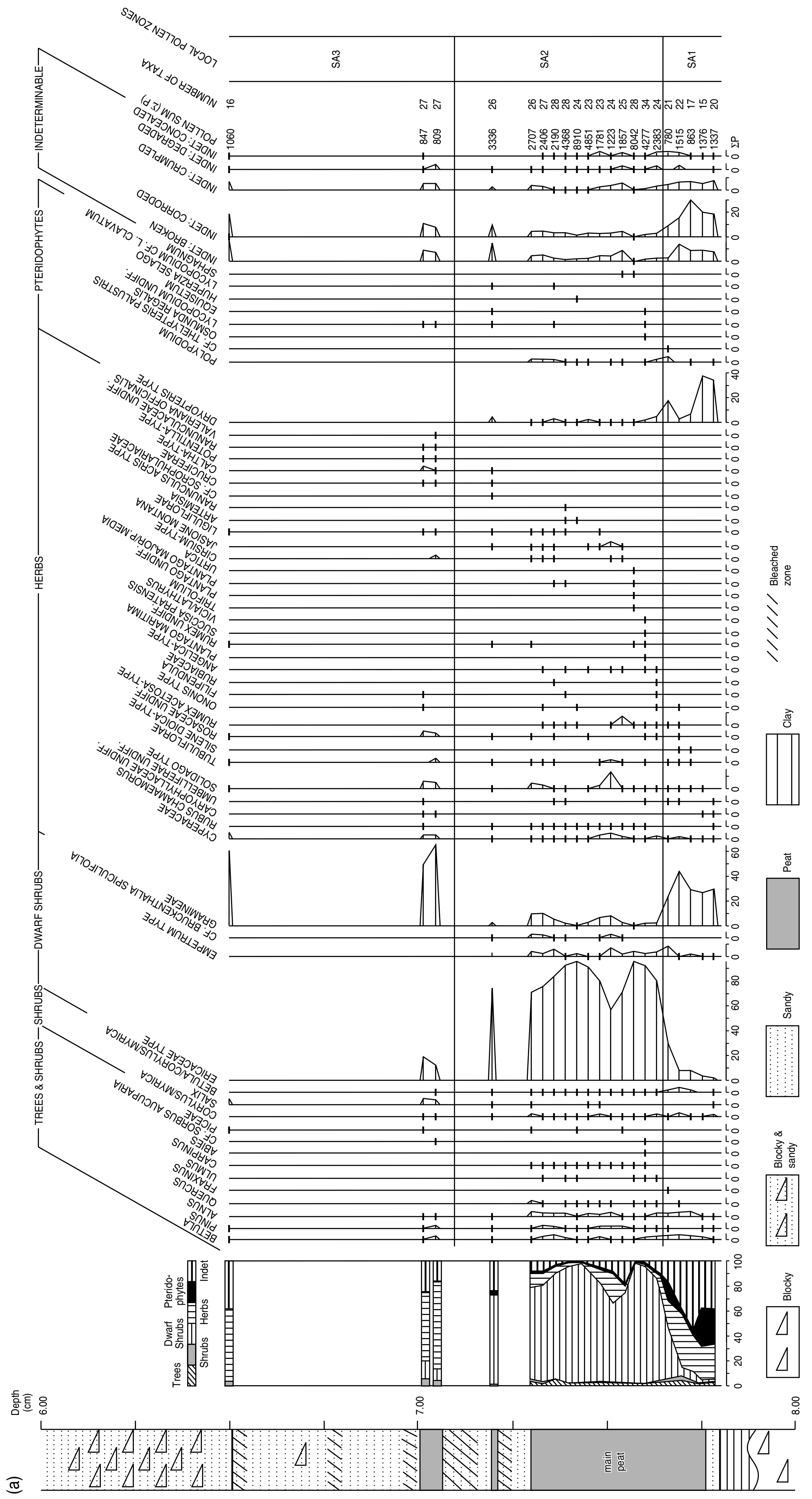

Figure 7 (a) Percentage pollen diagram from Sel Ayre (after Birks and Peglar, 1979). (b) Percentage pollen diagram derived from analyses of newly recovered organic deposits at Sel Ayre. Reproduced by permission of Blackwell Science

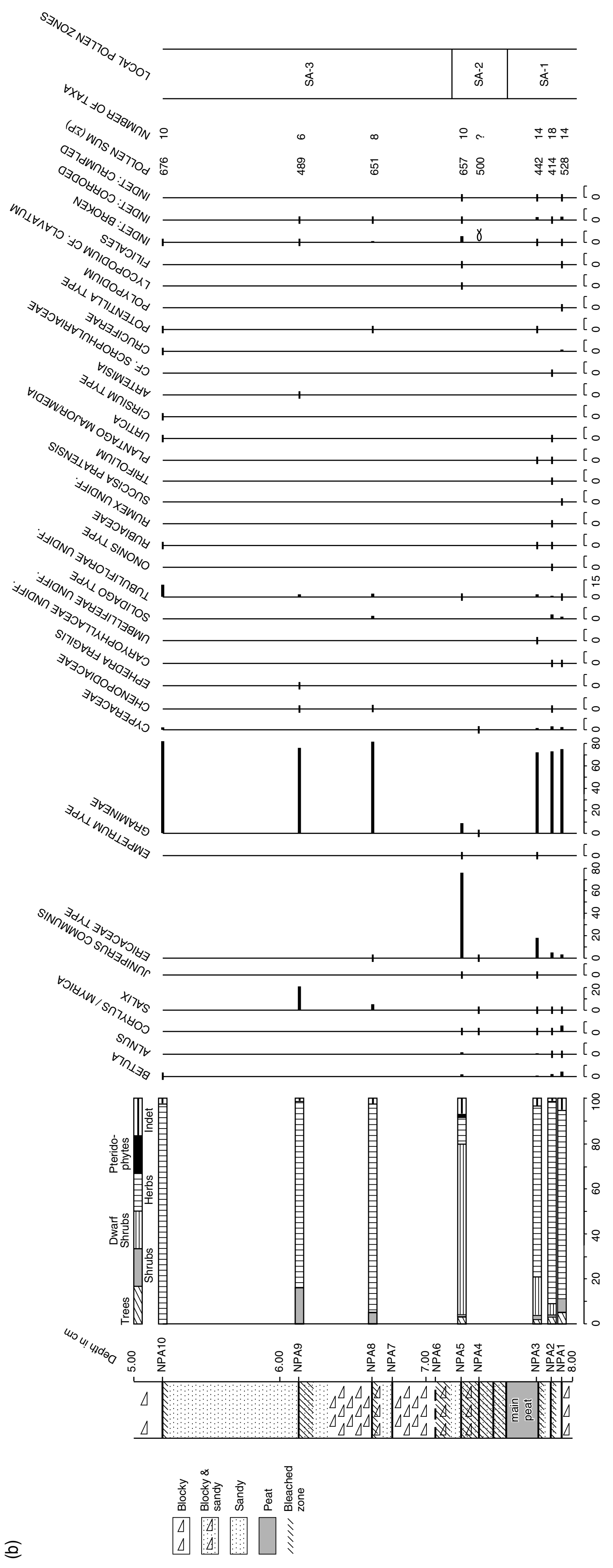

Figure 7 (*continued*)

Table 2 Radiocarbon ages for organic materials from Fugla Ness and Sel Ayre

Unit	Material	Laboratory number	Age (^{14}C yr BP)	Reference
Fugla Ness Peat	Wood	T-1092	34 800 + 900/−800	Page, 1972
Fugla Ness Peat	Peat	T-1093	37 000 + 1200/−1100	Page, 1972
Fugla Ness Peat	*Pinus* wood	SRR-59	40 100 + 2000/−1600	Harkness and Wilson, 1974
Fugla Ness Peat	*Pinus* wood	SRR-490	38 980 + 950/−850	Harkness, 1981
Fugla Ness Peat	Wood cellulose (same sample as SRR-59)	SRR-666	>33 300	Harkness, 1981
Fugla Ness Peat	*Pinus* cellulose (same sample as SRR-490)	SRR-667	43 970 + 1270/−1020	Harkness, 1981
Fugla Ness Peat	*Erica* cellulose	SRR-758	Humic: 44 970 + 1450/−1230	Harkness, 1981
Fugla Ness Peat	*Erica* cellulose prepared for SRR-758	GrN-7634	Humin: 47 500 + 2900/−2100	Harkness, 1981
Fugla Ness Peat	*Pinus* wood	SRR-4770	Humic: 33 320 + 230/−220 Humic-free wood: 42 050 + 590/−550 Cellulose component: >53 800	This paper
Fugla Ness Peat	*Pinus* wood cellulose	SRR-5365	>51 700	D. D. Harkness, personal communication 1994
Sel Ayre Organic Sands and Gravels—'main peat'	Peat	SRR-60	36 800 + 1950/−1560	Harkness and Wilson, 1974
Sel Ayre Organic Sands and Gravels—'main peat'	Peat	SRR-4768	Humic: 43 790 + 740/−680	This paper
Sel Ayre Organic Sands and Gravels—'main peat'	Peat	SRR-4768	Humin: >52 200	This paper
Sel Ayre Organic Sands and Gravels	Organic mud (NPA 10)	SRR-4769	22 450 ± 80	This paper

luminescence (IRSL) signals are removed by exposure to daylight. A series of experiments was undertaken to simulate the exposure of the sediments to sunlight for varying lengths of time and determine which period of exposure best matched that received at the time of deposition. This approach is described fully in Duller (1994).

An alternative approach is to see whether replicate measurements of ED on small subsamples (aliquots) are reproducible. Where a sample has been exposed to sufficient daylight at deposition to remove completely any pre-existing luminescence signal, all aliquots would be expected to yield similar values of ED. In contrast, where a sediment has been incompletely exposed to daylight, certain mineral grains will have had all their luminescence signal removed, whereas others will not. The effect is to create a distribution of ED values in different aliquots (Li, 1994; Duller, 1995; Duller and Murray, 2000). The annual dose rate to the samples was measured using a combination of thick-source alpha counting, thick-source beta counting and *in situ* gamma dosimetry. Full experimental details are given in Duller *et al*. (1995).

Fugla Ness

Sample FN1 was collected from the Fugla Ness Breccia (Fig. 2). The sample had a coarse grain size, and it was difficult to extract sufficient feldspar within the working grain size range (180–250 μm). The ED was measured using the method described above to compare results obtained using TL and IRSL. A multiple aliquot additive dose growth curve was constructed, and ED values calculated using residual levels measured for aliquots exposed to a SOL2 solar simulator for varying lengths of time (Fig. 8). The ED is the value on the *x*-axis where the growth curve fitted to the data intersects the residual level. Figure 8 contrasts the slow decrease in the TL signal with exposure to the SOL2, with the far more rapid decrease seen for the IRSL signal. The laboratory bleaching time at which both the IRSL and TL EDs are the same, will be that which most closely mimics the exposure of the sample at deposition (Duller, 1994).

The second method of ED determination applied at Fugla Ness is the single aliquot regeneration method (Duller, 1991) using IRSL measurements. This technique may suffer from changes in luminescence sensitivity, but other studies applying the method to samples that have been exposed to daylight for only a short time at deposition, and which probably retain a large proportion of their TL signal, suggest that it may give reliable results (Wintle *et al*., 1993).

The multiple aliquot TL/IRSL ED (763 ± 14 Gy) and the single aliquot IRSL ED (387 ± 14 Gy) for FN1 are significantly different (Table 3). The scatter in both sets of luminescence measurements is relatively low and, on the basis of these data, there is no obvious means of deciding which of the two results is nearer the correct ED corresponding to the age of deposition.

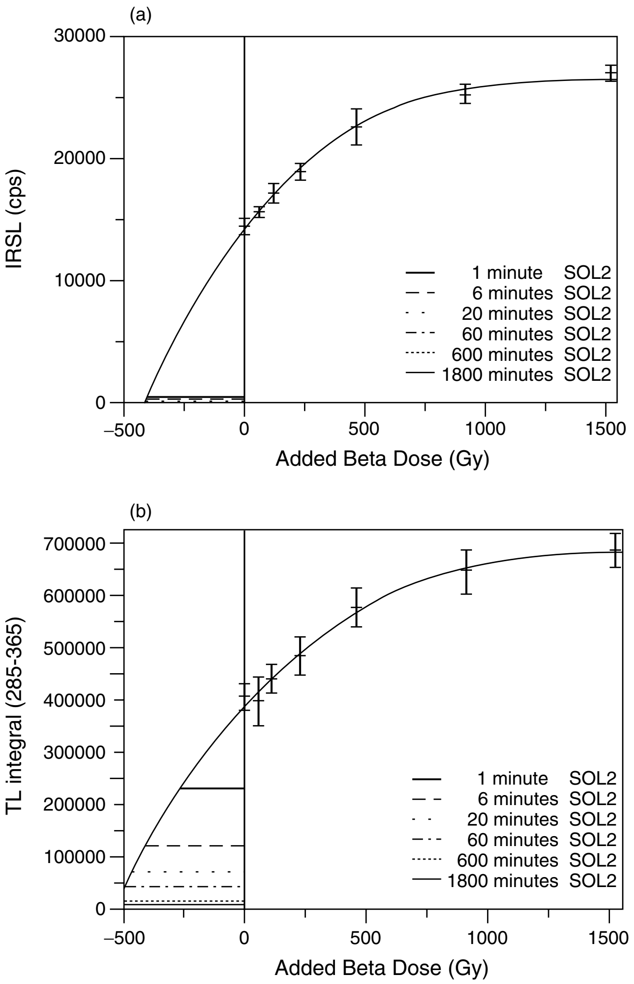

Figure 8 Multiple aliquot growth curve for sample SA1 (from Sel Ayre) using (a) IRSL measurements and (b) TL measurements. The residual levels after 1, 6, 20, 60, 600 and 1800 minutes exposure to a SOL2 solar simulator are shown on each graph. The correct residual level, and hence the correct ED, was calculated as being that where the ED given by both TL and IRSL measurements, for a given bleaching time, were identical. See text for further details

Sel Ayre

Sample SA1 was collected from the upper part of the Sel Ayre Organic Sands and Gravels (Fig. 5), and potassium-rich feldspars from 180 to 211 μm were separated for luminescence analysis. Identical multiple aliquot additive dose and single aliquot regeneration methods as used for FN1 were applied to SA1 (Table 3). For SA1, the multiple aliquot ED (415 ± 10 Gy) and the single aliquot regeneration ED (402 ± 35 Gy) overlap within errors.

For SA1, a single aliquot additive dose method was also applied (Duller, 1995). Unlike the regeneration procedure, the single aliquot additive dose method does not suffer from changes in sensitivity. The ED produced (388 ± 33 Gy) also overlaps with the other two estimates within the error limits.

Discussion relating to luminescence ages

A critical assumption in luminescence dating is that sediments are exposed to sufficient daylight at deposition to remove any prior signal. In spite of the approaches used, the apparent ages for the sample from Fugla Ness using the two methods described differ by almost a factor of two (Table 3). This disagreement is difficult to explain, except by suggesting that the sample was exposed to insufficient daylight to have even reduced its IRSL signal significantly. For this reason, the ages produced are both believed to be unreliable, and they probably overestimate the true age of deposition.

At Sel Ayre, the situation is very different. Here, three different methods of ED determination yielded consistent results for SA1, implying that the luminescence signal was sufficiently bleached at deposition to make dating possible. Li (1994) has suggested that one can explicitly test for the degree of bleaching by analysis of the distribution of the single aliquot data. Such an analysis on the Sel Ayre data gives an equivocal result (Duller *et al.*, 1995). However, the consistency between the three ED methods gives confidence in the age estimate (98–105 ka) produced.

Uranium-series disequilibrium dating

Disequilibrium between naturally occurring ^{234}U and its radioactive daughter product ^{230}Th (both members of the ^{238}U decay series) can be used to date materials up to approximately 350 ka. Referred to as U/Th disequilibrium dating, this method is based on the fact that uranium, due to its relatively high solubility when compared with thorium, is selectively taken up by certain materials, such as corals, travertine and speleothems from surface or ground water (Ivanovich and Harmon, 1992). The insoluble thorium is not taken up, so that its concentration in these materials should ideally be zero at the time of their formation. The present-day activity of ^{230}Th can be attributed solely to the *in situ* decay of its parent ^{234}U. The $^{230}Th/^{234}U$ ratio is therefore a good measure of the age of the material, provided there was no ^{230}Th present at time zero and the material was a geochemically closed system with respect to uranium and thorium.

The first attempts at dating interstadial and interglacial peats using this method were unable to correct for thorium present at the time of peat formation (Vogel and Kronfeld, 1980; van der Wijk, 1987; van der Wijk *et al.*, 1988), nor did they involve investigations into suspected open-system behaviour of the peat layers (which were assumed to be closed systems). However, Heijnis and van der Plicht (1992) have addressed both these problems. To correct for any thorium present at the time of formation, Heijnis and van der Plicht (1992) applied the method of Schwarcz and Latham (1989), using a series of samples to create an isochron-correction plot. The slope of the isochrons provides the Th-corrected ratios for age calculation. The second problem of open-system behaviour was avoided by using samples from the centre of the peat layer only (Heijnis and van der Plicht, 1992). The standard chemical and analytical procedures are described in Heijnis and van der Plicht (1992) and Dowling *et al.* (1998).

Fugla Ness

A monolith of peat was collected from the Fugla Ness Peat (Fig. 2). It was analysed using a sequence of 11 samples. The analyses focused on the centre of the peat layer containing woody peat, compressed peat and little sand. Some samples that were much sandier than the average were omitted from the age calculations. From the remaining samples, an isochron plot was constructed and yielded corrected ratios for $^{230}Th/^{234}U$ (0.83 ± 0.05) and $^{234}U/^{238}U$ (0.99 ± 0.05). These corrected ratios give an approximate age of 110 + 40/−35 ka.

Table 3 Summary data derived from the luminescence analyses of samples from Fugla Ness and Sel Ayre

Sample	Grain size (μm)	Water content[a] (%)	External alpha dose (Gy kyr^{-1})	External beta dose (Gy kyr^{-1})	Gamma dose (Gy kyr^{-1})	Internal beta dose (Gy kyr^{-1})	Cosmic dose (Gy kyr^{-1})	Total dose rate (Gy kyr^{-1})
FN1	180–250	25 ± 10	0.18 ± 0.10	1.15 ± 0.18	0.76 ± 0.01	0.40 ± 0.08	0.15 ± 0.02	2.63 ± 0.22
SA1	180–211	10 ± 5	0.30 ± 0.16	1.88 ± 0.14	0.96 ± 0.01	0.65 ± 0.08	0.15 ± 0.02	3.94 ± 0.23

Sample	Total dose rate (Gy kyr^{-1})	Single aliquot ED[b] (Gy)	Age (ka)	Single aliquot ED[c] (Gy)	Age (ka)	Multiple aliquot ED (Gy)	Age (ka)
FN1	2.63 ± 0.22	387 ± 14	147 ± 14	n.d.	n.d.	763 ± 14	290 ± 25
SA1	3.94 ± 0.23	402 ± 35	102 ± 11	388 ± 33	98 ± 10	415 ± 10	105 ± 7

[a] The water content was estimated from measurement of the sample in the laboratory.
[b] Single aliquot EDs were determined using the single aliquot regeneration method, giving the largest doses first.
[c] Single aliquot ED was determined using the single aliquot additive dose method, with dose correction.

Sel Ayre

A monolith of peat was collected from the main peat band of the Sel Ayre Organic Sands and Gravels (Fig. 5). It was sampled and analysed in the same fashion as the Fugla Ness Peat. However, the Sel Ayre peat was much thinner, making the central parts more susceptible to open-system behaviour. For this reason, the top and bottom samples (out of a series of five samples) were excluded from the isochron correction. Even the corrected ratio of $^{230}Th/^{234}U$ was >1, indicating that either the organics are in excess of 350 ka in age or the whole layer has been subject to post-depositional uranium uptake. The latter is very likely given the thin and sandy nature of the organic layer.

Discussion relating to uranium-series disequilibrium dating

The likelihood of open-system behaviour is indicated by the sandy nature of some of the organic materials and the presence of overlying and underlying coarse-grained sediments. This makes accurate dating impossible using the U/Th disequilibrium method. The correction for thorium present at the time of peat formation assumes that all samples have the same age, which of course is incorrect. Given the large uncertainties in the corrected ratios, resulting from some scatter in the isochrons, this does not greatly affect the final calculated average age of the Fugla Ness Peat.

Discussion

Ages of the organic sediments at Fugla Ness and Sel Ayre

Discussion of the ages of the deposits at Fugla Ness and Sel Ayre has centred on pollen-stratigraphical correlation. Such correlation is made very difficult by the highly distinctive maritime climatic environment of Shetland, with its warm winters, cool summers, high rainfall and exposure to high winds and sea-spray. Direct vegetational comparisons are probably most reliable with areas along the Atlantic margins of the British Isles and, possibly, with Faeroe. In these areas, however, there are few well-dated organic deposits older than 40 k ^{14}C yr BP (Lowe, 1984; Jóhansen, 1985; Coxon, 1993).

The pollen spectra for the main peat beds at Fugla Ness and Sel Ayre are distinct from each other (Birks and Peglar, 1979) and from the Holocene spectra from Murraster (Jóhansen, 1975) and Catta Ness, Shetland (Bennett *et al.*, 1992) (Fig. 1). The development of coniferous woodland at Fugla Ness in an area where *Betula* was the overwhelmingly dominant taxon during the wooded phase of the Holocene leaves little doubt that the peat here is of interglacial origin (Birks and Ransom, 1969; Lowe, 1984; Sutherland, 1991). Birks (1993a) suggests an interglacial equivalent to the English Hoxnian stage based on the presence of pollen of *Abies* and heaths, including *Daboecia cantabrica* and *Erica mackiana,* which were also known to occur at sites supposedly of this age in southern Ireland (the 'Gortian' stage) (Watts, 1967; Coxon, 1993).

In Scotland, there are no organic deposits dated reliably to the last interglacial (Lowe, 1984). Similarities have been noted between the pollen record at Fugla Ness and that from Dalcharn, near Inverness, ca. 400 km to the south (Fig. 1), which provides evidence for the establishment of an open, *Pinus–Betula* woodland, with *Ilex*, during an interglacial period of unknown age (Walker *et al.*, 1992). Interstadial/interglacial sites at Toa Galson, Lewis (Sutherland and Walker, 1984), and Abhainn Ruaival, St Kilda (Sutherland *et al.*, 1984), show grassland or heathland floras and are not comparable with Fugla Ness, nor are the *Alnus*-rich interglacial organic muds, associated with soil profiles, from Teindland (Edwards *et al.*, 1976; Hall *et al.*, 1995) and Kirkhill (Connell *et al.*, 1982) in northeast Scotland. The closest firmly dated last interglacial site to Fugla Ness is at Fjøsanger, Bergen, ca. 380 km to the east (Mangerud *et al.*, 1981). Similarities between the pollen records at the two sites include the presence of the thermophilous taxa, *Ilex*, *Quercus*, *Ulmus*, *Corylus*, *Picea* and *Hedera*, but there are also differences and, in particular, the absence of *Abies*. An interglacial peat near Klaksvik, Faeroe, shows *Betula* and *Pinus*, but also, notably, *Buxus*, suggesting an Ipswichian/Eemian age (Jóhansen, 1985). The mild climate implied by the reconstructed pollen assemblages at Fugla Ness is consistent with existing environmental reconstructions for the Ipswichian/Eemian interglacial. Temperate mixed-oak forest extended across northwest Europe at this time, and evidence from both Coleoptera and pollen analysis indicates that temperatures were rather higher than those of the present day (Aalbersberg and Litt, 1998). The uranium-series date of

110 + 40/−35 ka also supports the case that the Fugla Ness Peat formed during the last interglacial (MIS 5e), rather than an earlier interglacial. This is consistent with its stratigraphical position beneath a periglacial breccia and a single till unit.

The main peat band at Sel Ayre has been regarded as an interglacial deposit on the basis of its stratigraphical position and on similarities of its pollen spectra with those from Holocene sites on Shetland (Birks and Peglar, 1979). However, the contrasts between Sel Ayre and the undoubted interglacial peat at Fugla Ness are so striking, particularly in view of the similar locations of these sites on the exposed Atlantic coast of Shetland, as to call into question the interglacial status of the Sel Ayre peat. At Sel Ayre, tree pollen percentage values vary between 0.2 and 4.6% and may result entirely from a windblown origin (Birks and Peglar, 1979). This implies a lack of tree cover on Shetland at the time the Sel Ayre peat formed, yet, in the early Holocene, prior to the arrival of humans, a range of trees grew on the islands (Hawkesworth, 1969; Bennett *et al.*, 1992).

The three age determinations for sands from the upper part of the Sel Ayre Organic Sands and Gravels of ca. 105–98 ka indicate deposition during MIS 5c. During this stage, boreal forests with pine, spruce and birch grew in lowland Britain, Denmark and northern Germany (Behre, 1989). In Scandinavia, open birch woodlands developed (Berglund and Lagerlund, 1981; Helle *et al.*, 1981). In Scotland, an interstadial peat at Allt Odhar, Inverness, has yielded a uranium-series date of 106 ka BP, indicating an MIS 5c age. The pollen flora indicates an open birch woodland at an elevation of 370 m OD on the Scottish mainland (Walker *et al.*, 1992). At Camp Fauld, Peterhead, peat of probable MIS 5c age contains pollen showing development of pine–birch woodland. Inferred mean July temperatures were 12–14°C (Whittington *et al.*, 1993). There seems no reason on climatic grounds why a rich, tree-less heathland should not have developed on Shetland during MIS 5c or 5a. The presence at Sel Ayre of the exotic shrub, *Bruckenthalia spiculifolia*, today confined to the mountains of southeast Europe, is significant (Whittington, 1994). *Bruckenthalia* generally is missing from Eemian sites in northwest Europe but present at sites of Brørup and Odderade Interstadial age (Ambrosiani and Robertsson, 1992; Beaulieu and Reille, 1992), including Camp Fauld (Whittington *et al.*, 1993), Crossbrae (Whittington *et al.*, 1998) and Burn of Benholm (Auton *et al.*, 2000) in Scotland. Its presence in the peat at Sel Ayre is therefore consistent with an MIS 5c age.

Late Quaternary environments on Shetland

The oldest Quaternary sediment recognised on Shetland is the Fugla Ness Lower Till, which rests on the floor of a rock basin beneath the Fugla Ness Peat and which probably represents glaciation of the site during MIS 6.

The early stages of the interglacial represented at Fugla Ness are not present in the pollen record. The rich maritime heath indicated in Pollen Zone F1, in which *Pinus* and possibly *Ilex* and other trees occurred locally in sheltered areas, shows the establishment of a mild, oceanic climate, possibly with wind speeds lower than today. The change in vegetation from Zone F1 to Zone F2 suggests a drop in annual temperature and an increased frequency of frosts (Birks and Ransom, 1969). The high representation of grasses in the pollen reworked into the overlying Fugla Ness Breccia may reflect a continuation of this climatic deterioration. The breccia developed under conditions of intense granular and blocky disintegration of the local ultrabasic rock due to frost action, with wash and solifluction of debris into the basin. The breccia therefore marks a phase of periglacial conditions following the interglacial. The apparent continuity of deposition suggests formation of the breccia during MIS 5d, equivalent to the Herning Stadial, when periglacial conditions prevailed throughout northwest Europe (Aalbersberg and Litt, 1998).

The Sel Ayre Lower Breccia also records a periglacial phase, apparently prior to MIS 5c. These coarse sediments retain no record of any vegetation cover but are tentatively assigned to MIS 5d.

The Sel Ayre peat and associated organic deposits are attributed to MIS 5c on the basis of pollen stratigraphy and of luminescence ages from intercalated sands. The vegetation at the time of the lowest pollen zone (SA1) was grassland, initially with a restricted range of other vegetation types but subsequently including a varied fern and herb flora. Ericaceae dominated the vegetation of the succeeding pollen zone (SA2). Sediment input from the surrounding slopes during the period represented by zones SA1 and SA2 was low, implying a full vegetation cover. The changes in vegetation between these zones suggest the replacement of brown earths by more podzolic soils (Birks, 1993b). The latter are represented by the reworked bleached sands above the main peat. Pollen zone SA3 shows open, grass-dominated vegetation, with a variety of herbs characteristic of skeletal mineral soils. The greatly increased input at this time of coarse sediment, by wash, frost weathering, rockfall and solifluction, demonstrates marked climatic deterioration. The Sel Ayre sequence appears to record major environmental changes through the MIS 5c interstadial on Shetland.

The overlying Sel Ayre Upper Breccia is devoid of organic material, but apparent continuity of deposition suggests that it may date from the succeeding cold interval, MIS 5b, the Rederstall Stadial, when periglacial conditions returned to the lowlands of northwest Europe (Aalbersberg and Litt, 1998).

Fabric data from the near-surface tills at Fugla Ness and Sel Ayre conform to patterns of ice flow during the local ice-cap phase of glaciation (Hall *et al.*, 1993a,b). This usually is attributed to MIS 2, the Late Devensian/Weichselian, although firm dating evidence is lacking (Gordon *et al.*, 1993; Ross *et al.*, 1993; Ross, 1996). Despite suggestions on geomorphological criteria that ice-free areas existed during the Late Devensian/Weichselian maximum on northern Unst and Yell (Flinn, 1983; Long and Skinner, 1985; but see Ross, 1993), offshore data indicate that the Late Devensian/Weichselian ice-cap extended well beyond the current landmass to the east and north, and possibly near to the edge of the continental shelf west of Shetland (Johnson *et al.*, 1993; Stoker *et al.*, 1993; Ross, 1996).

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