THE LAST GLACIATION OF SHETLAND

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Abstract

Evidence of the last glaciation of the Shetland Islands, UK, is re-examined and combined with new data on terrestrial glacigenic deposits and recent offshore data from the continental shelf to produce a dynamic, integrated model of the history of the whole ice cap.

- It is shown that evidence which has previously been attributed to last glacial, or earlier, Scandinavian ice incursion, might be explained by the eastwards migration of local ice sheds.
- At its maximum, the ice sheet reached the continental shelf edge to the west of the islands, at least 75 km east, at least 50 km north and might be seen as a peninsular extension of the Scottish ice sheet to the south.
- The changing patterns of ice flow during deglaciation are reconstructed, implying an early phase of deglaciation at the west and northwest margins (possibly accounting for the suggested eastern migration of the ice shed), followed by retreat at more northern, then eastern, then southern margins.
- It is suggested that the above pattern reflects tidewater calving controlled by bathymmetric variation around the ice sheet.
- During a later phase of deglaciation, the margin of the ice cap may have grounded at around the current -100m bathymmetric contour and from there retreated terrestrially.
- The importance of topographic control on patterns of deglaciation as ice retreated towards the island group is clearly established.
- Some minor moraines in parts of Shetland are due to active ice margins but their age is unknown.
- Radiocarbon dates reported here show that the last glaciation was Late Weichselian and that the maximum northern extent was at least 50 km north of the islands.
- The concepts of an eastwards migrating ice shed and an early, extensive ice cap retreating to a grounding point, could have parallels elsewhere in Scotland during the last glaciation.
- The methodology applied in this study of Shetland - integrating onshore and offshore data, and developing a dynamic picture of the whole ice cap - needs to be applied to the last Scottish ice sheet also.

Declarations

I, Hamish Ross, hereby certify that this thesis, which is approximately 60,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

2/8/96

I was admitted as a research student in January 1993 and as a candidate for the degree of Doctor of Philosophy in January 1993; the higher study for which this is a record was carried out in the University of St Andrews between 1993 and 1996.

2/8/96

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of Doctor of Philosophy in the University of St Andrews and that the candidate is qualified to submit this thesis in application for that degree.

2/8/96.

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1. Introduction

1.1. Background and aims

Shetland lies on the margins of a crucial location within the northwest European and global climate system, to the south and southeast of key components of the oceanographic circulation system. What occurred in this area during the last glaciation of this northwest continental shelf zone is of some importance therefore. However understanding of the last glaciation of the Shetland Islands and surrounding shelf area is limited. Much ice movement direction data has been collected from the islands and this has been interpreted in the context of regional issues relating to the influence or otherwise of Scandinavian ice upon them. Generally, reconstructions have attempted to incorporate all available data into a single, temporal, snapshot or ice configuration. New offshore datasets have great potential for furthering understanding but the use of these has been limited to date. Little dating has been undertaken and the chronostratigraphy of the last glaciation of the area is tentative. This study aims to draw together this limited knowledge, add to it and interpret it in the wider context of northwest European glaciation. More specifically, the aims are:

1. To comprehensively re-examine and re-interpret published data relating to the last glaciation of the islands from terrestrial and offshore areas.

2. As far as possible, to establish a sequence of events during the last glaciation - combining relevant data, interpreting it in greater detail than previously and identifying patterns that can be morphochronologically resolved to present a stage-by-stage reconstruction for the first time.

3. To provide a new dataset of glacial sediments across the islands to assist in the interpretation of events.

4. For the first time to combine offshore interpretation with the terrestrial reconstruction to establish an integrated regional pattern covering the whole of the Shetland ice cap and its history, not just that part of it that is manifest in the rather limited terrestrial evidence.

5. To contribute to the temporal context of the last regional glaciation by dating key sediments for the first time.

6. To develop a reconstruction that is, as far as possible, testable, and to recommend courses of action that may confirm or refute it.

1.2. Limitations

The difficulties that the writer has encountered in reconstructing the last glaciation of the Shetland islands are outlined here to inform both this study and the discussions of previous work undertaken.

Reconstruction of the last terrestrial glaciation of Shetland is not straightforward. The islands form a narrow, Caledonian remnant, just a few kilometres from east to west in places. The last ice sheet may have been 150 km in diameter, so only a fraction of the former bed is represented terrestrially. Reconstruction of former glacial environments requires both evidence of the glaciation and some way of accounting for the varied effects that the substrate over which it developed might have upon the pattern of evidence. Both of these requirements are hard to satisfy on terrestrial Shetland. Evidence of glaciation on Shetland includes striae, stoss and lee landforms, erratics, some glacigenic landforms and drift geology. The terrestrial solid geology is highly variable, including intrusive and extrusive igneous rocks, sandstones and a wide variety of metamorphics. The writer has found the identification of striae on many rock types difficult: extrusive igneous types and sandstones provide the clearest record but striae are much more difficult to locate on coarse grained granites and granodiorites and schistose metamorphics. Although roches moutonées are identifiable in some areas, micro- stoss and lee data are less convincing in most because of the effect that the structure of the rock has on its pattern of disintegration under glacial erosion. Although the broadly north-south strike of the solid geology on Shetland offers considerable potential for the study of erratic movements in the east-west plane, the sheer diversity of rock types makes reliable identification from weathered hand specimens, particularly of metamorphic varieties, extremely difficult. The present writer has only been able to conduct useful erratic studies in areas where the available sources are limited and easily distinguishable. Across most of Shetland a thorough working knowledge of the solid geology would be advantageous, and the acquisition of such, a major project in its own right.

Shetland continues to sink relative to sea-level. Many of the valley floors in which glacial landform assemblages might be anticipated are now submarine and may have suffered erosion during this transgression. What little depositional glacigenic morphology there is, largely in central Mainland, is often difficult to interpret due to its small size, peat cover and erosion by postglacial drainage. The absence of major drainage basins and rivers and the high base-level that results from rising sea-level means that there are few natural exposures of glacial drift inland. Conversely, coastal exposures are excellent throughout the islands. Recent economic development due to the oil industry continues to open up new sections inland particularly during road building. Unfortunately the program is so large that major quarries have been established and the more numerous and widespread local roadside pits are less well maintained.

The recent development of data from offshore is potentially of enormous significance. Maps of Quaternary sediments at the 1:250 000 and 1:10 000 000 scales have been published together with regional reports. Little in-depth discussion of the data and its correspondence or otherwise with terrestrial interpretations has been attempted. In general, the interpretation of the data that has been undertaken is provisional and there is scope for widespread detailed analysis of seismic traces, sidescan sonar traces, and core material. Published interpretations are tentative. The considerable task of looking at the available data in greater depth has begun and exciting developments can be expected in coming years, both from analysis of the marginal areas of the continental shelf edge and the more limited sediments, sea bed sediments and sea bed morphology of inshore areas.

The difficulty in reliably distinguishing between glacimarine and subglacial sediments is a major problem in the interpretation of offshore sediments and the collection and analysis of widespread micropalaeontological data would be beneficial. More importantly still, the dating of sequences would provide a much needed temporal context for reconstruction. The sequences of relevance to this study were undated to the west and north of the islands and are only recently dated to the east.

It is clear when terrestrial data is considered in detail that not all of it can be accommodated without the establishment of some sequence of events. It is difficult, if not impossible, to construct an ice shed configuration that accounts at one time for all the observed data. This study uses morphochronology to assign different time periods to ice movement patterns. Morphochronolgy is the the assignment of morphological evidence to relative timescales based on the juxtaposition of landforms. In particular, it is assumed that more peripheral areas reflect earlier ice movements and that as deglaciation progresses, ice becomes increasingly topographically contained. It is also assumed that where multiple events are overlain or adjacent, that the stronger pattern is more recent. Finally, 'negative evidence,' - evidence for an event based on the absence of something rather than its presence and open to the criticism that the absence may be due to random or post-event processes - is treated with cautious open-mindedness.

This study attempts to build from detailed local interpretation, to a general pattern for the last Shetland ice cap as a whole, and ultimately to the implications for northwestern European continental shelf. This range of focus has been difficult to achieve given the timescale over which the study must be conducted. In all chapters compromise is attempted - between the detail in which the employed knowledge or observation was collected and the area over which it is being applied. No site, or local area, provides sufficient information to extrapolate usefully to the wider picture. However, published data and interpretation are largely at the scale of the islands themselves and have focused on regional issues such as the influence or otherwise of Scandinavian glaciation. There is therefore a need for some level of examination between these two scales and that is the level of new interpretation offered in the regional chapters of this thesis.

Conducting the investigation at this level does not allow direct observation of the data throughout the area. For the avoidance of confusion the writer has attempted wherever possible to refer to his own new observations as such, but cannot claim responsibility for finding, and must disclaim responsibility for the accuracy of, much of the data employed in the reconstruction. While the writer has always sought verification of observations recorded by other workers while in the field, only a limited amount of time is available for this activity and the fact that direct verification was not made of particular evidence obviously does not mean that such evidence does not exist. The writer does not therefore record instances of positive verification except in areas of particular controversy. Suffice to say, however, that sufficient positive verification has been made to confirm the broad reliability of the datasets used.

1.3. Conclusions

The results of the study show that terrestrial patterns of ice flow can indeed be assigned to some temporal sequence and that this is a more appropriate model than a static ice configuration. The established sequence reveals a pattern of deglaciation that can be explained by the relationship of the ice cap to regional bathymmetry and demonstrates the influence of sea level rise. After an initial maximum ice margin had retreated to approximately the -100 m bathymmetric contour, sea level ceases to control deglaciation and rose *following* ice retreat across inshore areas to the present terrestrial landmass.

2. The last glaciation of Northwest Europe

Shetland lies in an important position with respect to the climatic and oceanographic history of northwest Europe. The glacial history of this wider area is, therefore, both important to, and can be illuminated by, understanding of the glacial history of Shetland. The glacial history of northwest Europe is reviewed here. 'Devensian,' is usually used to refer to the last British glacial phase and, 'Weichselian,' to the Scandinavian. However, for simplicity, 'Weichselian,' only is employed in this study, regardless of the location under consideration.

2.1. The last glaciation of Scotland

2.1.1. Glacial build-up (englaciation) and maximum extent

Although pre- Quaternary events have contributed significantly to the physiography of Scotland[1], the radial trough pattern seen around Rannoch Moor suggests that this has repeatedly been an ice centre. Late Weichselian ice directional indicators across the country show a complex overall configuration with a number of major and minor centres of dispersion (figure 2.1) and the relative stratigraphic positions of tills bearing key erratics demonstrates that different centres developed diachronously[2].

Much, if not all, of the maximum margins of the last ice sheet around Scotland now lie offshore (figure 2.2). Difficulties in distinguishing between proximal glacimarine and subglacial sediments in cores, and the absence of chronostratigraphic data that reliably resolves Late Weichselian and earlier Weichselian events, remain considerable obstacles to confident reconstruction. Accordingly, better offshore interpretation in these areas will probably resolve the 'minimalist' versus 'maximalist' maximum ice extent debate that has polarised the literature to date (for example, compare figures 2.3 and 2.4). In terms of vertical extent, while Scottish trimlines exist and their interpretation is becoming increasingly sophisticated[3] their chronostratigraphic significance remains ambiguous. Theoretically, vertical and lateral limits can be linked by surface profile determinations[4] but such calculations can only be tested against the geological record and have further served to highlight the need to resolve the difficulties in that record.

In **eastern** Scotland, the age of the last major glaciation of Caithness, Orkney and Buchan is controversial. There is evidence of extensive ice moving from the Moray Firth across Caithness,

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[1] Hall, 1991
[2] e.g. Kirby, 1969
[3] Ballantyne, 1994
[4] Boulton et al., 1991

Orkney and coastal Buchan, perhaps due to pressure from Scandinavian ice, subsequent west-east movement across Caithness, and the possibility of ice-free periglacial zones in both Caithness and Buchan. Interpretation of these eastern areas therefore has implications for the extent of the last Scandinavian ice sheet also. Widely varying conclusions can be drawn from the available data, polarising between limited Late Weichselian glaciation, with Buchan, Caithness and Orkney being ice free[5], and extensive glaciation with all these areas glaciated[6]. Off-shore in the Moray Firth area[7], the Bosies Bank Moraine complex may form the eastern margin of the last Scottish ice sheet[8], from where it retreated by tidewater calving, and the Wee Bankie moraine further south[9] may also be of Late Weichselian age. North Sea data is discussed further below.

The **western** Scottish ice sheet subsumed those of the inner Hebrides[10], but was deflected, northwestwards and particularly southwestwards, by the Lewis ice cap and topography. The southern arm created an erosion surface to the continental shelf edge[11] and a margin also lay grounded close to the shelf edge southwest of St Kilda[12]. The Lewis ice sheet is thought to have had its ice shed to the west of the islands[13], presumably due to aggradation in the direction from which precipitation was being delivered. There is widespread evidence of the influence of an undated Scottish ice sheet on St Kilda but Sutherland et al.[14] suggest only limited glaciation during the Late Weichselian. Another possible Late Weichselian erosion surface extends 40 km north-northwest of the Butt of Lewis. In contrast, a restricted Late Weichselian western ice margin is implied by Von Weymarn[15] who argued that the Outer Hebrides ice sheet did not cover the extreme north of Lewis, and Sutherland and Walker[16] who suggest that the area was not glaciated at all, although evidence for ice free zones on north Lewis has recently been criticized[17]. There is however a morainic feature in the Minches, referred to as the Greenstone Ridge[18] which supports theoretical ice profiles consistent with maximum vertical extent reconstructions on the Trotternish peninsula of Skye[19]. Elsewhere, the vertical extent of the ice sheet at its maximum may be represented by trimlines in Easter and Wester Ross[20]. Much of this observation has been assembled into a possible temporal sequence in figure 2.5[21] which highlights the idea of more than one phase of glaciation, as yet temporally unresolved. By

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[5] e.g. Sutherland, 1984
[6] Hall and Bent, 1990; Hall and Whittington, 1989
[7] Bent, 1986; Andrews et al., 1990
[8] Hall and Bent, 1990
[9] Holmes, 1977
[10] Sutherland, 1984
[11] Davies et al., 1984
[12] Peacock et al.,1992
[13] Selby, 1989
[14] Sutherland et al., 1984
[15] Von Weymarn, 1979
[16] Sutherland and Walker, 1984
[17] Hall, 1995
[18] Fyfe et al., 1993
[19] Ballantyne, 1990, 1994
[20] Ballantyne, 1990
[21] Stoker et al., 1994

comparison with events to the north, the logical morphochronological implication that the more extensive margin is the older[22] is confirmed. This more extensive glaciation may be Early Weichselian[23] (as shown in figure 2.5), but this is inconsistent with global ice volume events and radiocarbon dates on glacimarine sediments immediately west of the moraines southwest of St Kilda which indicate that these, at least, are Late Weichselian[24]. It is possible that the evidence reflects two temporally distinct Late Weichselian phases, or a single, spatially complex, Late Weichselian ice configuration.

2.1.2. Deglaciation

Where the Scottish ice sheet reached the western continental shelf edge, transported material was reworked by submarine slope processes to further the progradation of the shelf itself[25]. On the shelf the pattern is characterized by glacimarine sequences, submarine end-moraines and ice contact fans[26]. The features are indicative of grounded ice rather than a grounded ice-shelf and reflect glacial retreat punctuated by periods of stasis. Foraminiferal and sedimentological data beyond the retreating ice on the outer shelf area[27] suggest shallow water (circa 30 m) high-arctic and probably sea-ice dominated conditions prior to the Windermere interstadial. The widespread raised shorelines, some revealing glacimarine material, of the Inner Hebrides and surrounding areas show that retreat was associated with glacimarine conditions well onto the present land area due to rising eustatic sea-levels and relatively slow glacio-isostatic recovery. Glacimarine sequences associated with grounded tidewater glaciers are also characteristic off the east coast[28] and extend into Buchan[29].

Due to the apparent lack of lowland moraine systems, glacial retreat is generally reconstructed on the assumption that ice directional indicators reflect ice flow immediately prior to deglaciation and perpendicular to palaeomargins[30]. A series of recessional moraines in the Dee valley of northeast Scotland indicate that at least east coast deglaciation was active and included the development of supraglacial land systems at a cold based margin[31]. The position of these moraines appears topographically controlled and evidence for climatically significant periods of stasis or readvance in Scotland, such as the Aberdeen-Lammermuir and Perth readvances, has been rejected except in Wester (and possibly Easter) Ross[32]. Periods of stasis at the mouths of sea lochs during rapid ice-calving retreat from the west coast seas also probably reflect topographic

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[22] Stoker and Holmes, 1991
[23] Stoker, 1988
[24] Peacock et al., 1992
[25] Stoker et al., 1994; Stoker, 1995
[26] Stoker and Holmes, 1991
[27] Peacock et al., 1992
[28] Bent, 1986
[29] Hall and Jarvis, 1989; Hall and Bent, 1990
[30] Boulton et al 1991
[31] Brown, 1993
[32] Perth and Aberdeen-Lammermuir: Sissons, 1967; Wester Ross: Robinson and Ballantyne, 1979; Sissons and Dawson, 1981;

rather than climatic control[33]. The nature of subsequent deglaciation, which may or may not have been completed through the Windermere interstadial, cannot yet be determined due to the eradication of evidence by the subsequent Loch Lomond stadial ice field.

Referred to as the Loch Lomond stadial glaciation, and the equivalent of the Scandinavian Younger Dryas stadial glaciation, the subsequent ice field of the Northwest Highlands and Western Grampians was contained within topographic boundaries, and elsewhere smaller ice caps and ice fields and many corrie glaciers developed. As the most recent evidence of glaciation, the lateral and vertical limits of the ice field and corries have in places been mapped in detail, allowing reconstruction of ice sheet surfaces and palaeoclimates[34]. Beyond these limits there is abundant evidence of periglacial activity[35]. Although Loch Lomond stadial glacial ice did not reach the outer continental shelf, the distribution and grain size of volcanic ash in continental shelf cores from a number of different eruptions suggests that sea ice was an important part of the offshore environment at that time[36]. Deglaciation is represented by hummocky moraine, a widespread landform within the Loch Lomond stadial ice field limits. Originally thought to be associated with rapid stagnation and subsequently seen as ice marginal and indicative of active retreat[37] the detailed analysis of this polygenetic morphology on Skye shows that retreat was initially active, probably driven by precipitation starvation, and latterly by stagnation due to increased temperature[38]. On the mainland ice field the pattern is repeated but the stagnation terrain is less widespread[39]. Despite this evidence of active retreat, palynological work thought to demonstrate glacial recession[40] has been criticised on theoretical grounds by Tipping[41] who also found no evidence of the expected pattern in the Awe valley.

2.1.3. Chronology

The chronology of the last glaciation is imprecise. Glaciation appears to have commenced *circa.* 26 ka BP: dates on reindeer (*Rangifer tarandus*) and woolly rhinoceros bones at Sourlie, Bishopbriggs and Inchnadamph show that lowland Scotland was ice free around 30-26 ka BP[42]; uranium series dates for speleothem deposition in Assynt show that neither glacial ice nor continuous permafrost were present in the area from 40-25 ka BP[43]; and no interstadial radiocarbon dates are younger than 25 ka BP on mainland Scotland or 23 ka BP on the Outer Hebrides[44].

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[33] Sutherland, 1984; Greene, 1992
[34] e.g. Ballantyne, 1989
[35] Boulton et al., 1991
[36] Peacock et al., 1992
[37] Bennet, 1994
[38] Benn et al., 1992
[39] Bennet and Boulton, 1993a,b
[40] e.g. Walker and Lowe, 1985
[41] Tipping, 1988
[42] Jardine et al., 1988; Rolfe 1966; Lawson 1984
[43] Atkinson et al., 1986; Gordon et al., 1989
[44] Boulton et al., 1991: table 15.3, p.522

Timing of the maximum ice extent is presumed to have coincided with maximum global ice volume, i.e. around 20-18 ka BP. The maximum in England is radiocarbon dated to around 18-17 ka BP[45] and speleothem deposition halted *circa.* 18 ka BP in north-west Yorkshire[46], although the English maximum may not be synchronous with the Scottish[47] one.

For deglaciation there are dates on the arctic marine fauna of the glacimarine Errol beds of the Forth and Tay valleys, and the glacimarine silts around St Fergus[48]. The latter are dated to *circa* 15.3 ka BP and the former between 18 and 13 ka BP. The interstadial Clyde Beds were deposited after deglaciation of the Clyde area, commencing at about 13 - 12.8 ka BP[49]. Radiocarbon dating of immediately postglacial sediments onshore is prone to error[50] and there is no reliable radiometric chronology, however the pattern of glacial retreat may be temporally constrained by intersection with the raised sea-level record. There are considerable difficulties in combining the independent factors involved however[51]. It has been suggested that by c. 13 ka BP ice had retreated to within the Highland boundary[52]. The Wester Ross end moraine, a possible readvance feature, is undated, but predates a radiocarbon date of 12,800 ± 155 BP at Loch Droma[53]. The many dates published for the Loch Lomond stadial suggest that it lasted approximately from 11 ka to 10 ka BP with considerable variation[54]. The quoted error margins are usually 100-200 years. These must be at least doubled for reliability (so that the true age has a two standard deviation (98%) probability of lying within the quoted margins and also to account for inter-laboratory variations) and the resolution therefore is not high. Equally significant is the decrease in atmospheric CO_2 during this time (the radiocarbon calibration plateau) resulting in the tendency for true ages in this range to map to around 10,000 radiocarbon years before present[55]. The early Holocene *Juniperus* maximum occurred at around 9.6 ka BP and it is thought likely that complete deglaciation had occurred by this time[56]. Insect evidence shows abrupt climatic amelioration at 13.5-13 ka BP and climate was analogous to the present day until about 12.2 ka BP when a sudden decline to cool-temperate conditions occurred at around 12.0-11.0 ka BP. From 11.0-10.0 ka BP a tundra environment is inferred[57].

Offshore radiocarbon dates from fossil marine mollusc assemblages suggests that an interstadial marine circulation was established off Scotland by about 12.8 ka BP, that polar waters had

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[45] e.g. Penny et al., 1969
[46] Atkinson et al.,1986; Gordon et al., 1989
[47] Sissons, 1981
[48] Errol beds: Peacock, 1981; St Fergus: Hall and Jarvis, 1989
[49] Peacock and Harkness, 1990
[50] Sutherland, 1980
[51] Lambeck, 1994
[52] Sutherland and Gordon, 1993c
[53] Kirk and Godwin, 1963
[54] Walker et al., 1994
[55] Amman and Lotter, 1989
[56] Boulton et al., 1991
[57] Coope, 1977

returned by about 10.85 ka BP, and that warming was once again occurring by about 10.1 ka BP[58]. However, these data cannot be used to constrain patterns of glacier extent or recession.

2.2. Northwest European and Scandinavian Glaciation

The timing and extent of northwest European and particularly Scandinavian ice sheets is of considerable importance in interpreting the last glaciation on Shetland, since evidence of external ice influence on the glacial history of the islands has been suggested.

2.2.1. Englaciation and maximum extent

Near the southern edges of the Eurasion ice sheet in Sweden and Germany, there is stratigraphic evidence that indicates extremely rapid ice build up. Advance rates across Sweden, which appears to have remained ice free as far north as Gothenberg until 24 ka BP, are estimated to be in the region of 75 - 100 ma^{-1} [59]. More geographically central Ålesund interstadial dates[60] show that much of Norway was ice free at this time, resulting in the conclusion that much of the Scandinavian ice sheet developed over just 10,000 years[61]. The maximum extent of the Eurasian ice sheets during the last glaciation has long been controversial and reflects the absence of unequivocal evidence and the mutual dependence of oxygen isotope, isostatic, and marginal morphological and stratigraphic data interpretation. There is disagreement over the question of whether the Scandinavian ice sheet was coalescent with extensive ice sheets over the former USSR, major ice sheets and shelves in the Barents Sea and Arctic Ocean, forming a large mass that crossed the North Sea to western Britain, or whether the Eurasian glaciation was much more restricted with only sea ice over much of the Arctic and independent ice sheets over Scandinavia, Spitsbergen and the UK[62]. Nearly all of the Late Weichselian glacial margin around Iceland is offshore and there is little information available for this time[63].

The core area of the Fennoscandian ice cap appears to have remained cold-based throughout its lifetime, a fact that has been interpreted as either evidence of extensive, more eastern, Gulf of Bothnia-centred Late Weichselian glaciation (largely supported by isostatic recovery patterns), or evidence of relatively thin, more west-centred glaciation (requiring reinterpretation of isostatic recovery patterns but offering more flexibility of geomorphological and geological interpretation particularly at the eastern margins of the ice sheet)[64]. Either way it is probable that the last glaciation of northwest Europe, and of Scandinavia, was the most extensive since the last interglacial[65]. It has been generally accepted that the maximum western limit is represented

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[58] Peacock and Harkness, 1990
[59] Ehlers, 1990
[60] Bergersen et al., 1991; Lauritzen, 1991;
[61] Baumann et al., 1995
[62] Dawson, 1992
[63] Ingólfsson and Norddahl, 1994
[64] Kleman and Borgström, 1994; Sollid and Sorbel, 1994; McCarroll and Nesje, 1993
[65] e.g. Larsen and Sejrup, 1990

by the Egga II series of moraines[66] which confines the margin to just west of the Norwegian trench, particularly in northern areas (figure 2.6). Some far northern islands, such as Andøya, have remained ice free altogether[67]. The Egga II moraines are undated and it is their proximity to dated advances on Andøya which suggests that they represent the maximum limit. A feature of the lake record in Andøya is the sparsity of minerogenic inwash which suggests low levels of precipitation, in keeping with more restricted northern glaciation. Despite such geological evidence, some workers suggest that a more extensive western Late Weichselian margin, 'seems plausible,'[68] and further interpretation of the North Sea deposits is required (see below).

2.2.2. Deglaciation

The global pattern of ice melting, and consequent changes in ocean and atmospheric circulation patterns, is highly complex. Even within the northwest European theatre the pattern may be asynchronous. Inevitably fundamentally different models of Eurasian ice sheet size dictate fundamentally different models of Eurasian ice sheet deglaciation. The deglaciation history of western Scandinavia is difficult to reconstruct, partially because of the uncertain extent of the glacial maximum. Dated pollen influxes and glacial advances on Andøya[69] suggest that ice reached its maximum about 18,500 BP with a series of ameliorations before about 16,000 BP. There then followed amelioration to around 13,700 BP when deterioration recurred[70]. Deglaciation is generally thought to have started at around 14 ka BP further south on the west coast and 13 ka BP in the Bergen area, with a minor readvance at 12.6 ka BP[71]. The generally recognized deglacial oscillations in Scandinavia (Bölling interstadial c. 13,000 - 12,000 BP; Older Dryas stadial c.12,000 - 11,800 BP; Alleröd interstadial c.11,800 - 11,000 BP) are followed by the major Younger Dryas stadial readvance (between c. 11,000 - 10,000 BP) that is well marked by moraines around coastal areas of Norway and in particular the Herdla ice-frontal marine delta near Bergen[72]. The ice domes of Spitsbergen[73] and Iceland[74] are also thought to have experienced pronounced readvance during the Younger-Dryas stadial, although on western Spitsbergen, following rapid deglaciation at 12,500 BP, it is not thought that there was any significant readvance[75]. The pre- Younger-Dryas oscillations are proving illusive in Britain but sufficient evidence is available elsewhere that an amphi-Atlantic climatic oscillation has been proposed for this time[76]. This informal namer refers to the correlation of cooling events affecting Europe, Greenland, the North Atlantic and eastern North America shortly before the Younger-

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[66] Andersen, 1979
[67] Alm, 1993
[68] Ehlers, 1990 (p.81)
[69] Alm, 1993
[70] Vorren et al., 1988
[71] Birks et al., 1994
[72] Mangerud et al., 1979; Nesje and Dahl, 1993
[73] Boulton, 1979
[74] Grosswald, 1984
[75] Birks et al., 1994
[76] Levesque et al., 1993

Dryas stadial (although better dating will be required to demonstrate that the various oscillations are indeed coeval.)

2.3. The North Sea Basin

There is a significant body of new data derived from investigations in the North Sea basin. A long chronological record is offered by the subsiding basin and the nature of deglaciation of adjacent areas must be examined in this context. There is much data and much interpretation, both past and ongoing but two important problems hinder the development of a complete picture: insufficient dating and the difficulty of distinguishing subglacial till from proximal glacimarine material on seismic traces and in cores.

The southern North Sea sequence is thinly capped by middle- to late- Pleistocene glacigenic and marine sediments. Interpretation of the these, together with sediments on the eastern coast of England as far south as The Wash, is relatively uncontroversial and leads to a lobate ice margin extending between 100 and 200 km into the North Sea from the English coast with the southern margin of the North Sea and western parts of the Netherlands being terrestrial at the Late Weichselian maximum[77]. Further north there is considerable uncertainty over Weichselian glaciation, some sense of which is summarized in figure 2.7[78]. The Wee Bankie moraine off the east coast of Scotland (figure 2.2) and the apparent absence of till beyond it are critical to the argument for a relatively limited Scottish ice excursion into the North Sea[79] and dry land is inferred for much of the area[80] beyond it (figure 2.7c). But the distribution of what are interpreted as Weichselian subglacial meltwater channels in the sediments of the North Sea implies extensive areas of ice both in the central and, more critically for the present study, northern areas (figure 2.7d), and the absence of till is explained by the erosive potential of postglacial marine transgressions[81]. The conflict between these two models of glaciation of the northern North Sea could be resolved by temporal resolution of Late Weichselian landforms and sediments. In this context, some progress has been made[82] (figures 2.8 and 2.9) which suggests that the Weichselian maximum in the central North Sea was earlier than conventionally believed and may lie between *circa* 29 ka - 23 ka BP. This contradicts the prevailing philosophy, based on oxygen isotope analysis, that the Late Weichselian became progressively more severely glaciated until 20-18 ka BP, and suggests that there was a more restricted glaciation at this stage.

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[77] Cameron et al., 1992
[78] Ehlers and Wingfield, 1991
[79] e.g. Hall and Bent, 1990
[80] Cameron et al., 1987
[81] Ehlers and Wingfield, 1991
[82] Sejrup et al., 1994

This important result is not (yet) reflected in the interpretation of deposits of direct significance to the present study. Sediments on the Shetland Platform itself are particularly thin and offer little assistance (figure 3.15). More extensive sediments occur further east, however, where a succession from Lower Pleistocene to Holocene is interpreted[83], dipping broadly west to east from the East Shetland Platform to the Norwegian trench (figure 2.10 - line of section is shown in figure 3.15 (line section 1)). The distinction between the early and late phases of glaciation identified above is not evident here. The British Geological Survey identify three seismostratigraphic units of presumed Weichselian age in the area - the Ferder, Cape Shore and Sperus formations. The Ferder Formation, includes the last interglacial and the early Weichselian. The overlying Cape Shore formation is thought to represent a firmly dated Mid-Weichselian marine environment[84]. The subsequent Sperus formation is interpreted as being a shallowing glacimarine unit deposited during the early Late Weichselian eustatic sea level regression and this is then overlain by the Tampen Formation which may be a lateral moraine deposit (northeast corner of figure 3.13) due to ice flowing northward in the Norwegian trench. Shells within it are radiocarbon dated to c. 18,860 ± 260 BP[85]. The Norwegian Trench Formation is also a till-like deposit but is apparently to be distinguished as having been deposited under differing glacial conditions as ice and water levels within the trench varied. The overlying Viking Bank Formation is thought to represent a pro-delta and delta-front environment draining ice overtopping the Norwegian trench, and infills some deep channels. with possible sandy, mobile, shallow water islands with aeolian input, on top. These units vary in age from 11, 350 ±120 BP to 8,530 ±110 BP[86]. Rising sea level is recorded on the edge of the Norwegian Trench by a thick beach deposit dated to between 12,500 and 10,800 BP[87].

What is crucial for our understanding of the timing and western extent of the maximum Late Weichselian Scandinavian ice sheet, and its possible impact on Shetland, is the absence of a discrete unit reflecting an early extensive glaciation between the Sperus Formation that represents the onset of global Late Weichselian glaciation, and the Tampen Formation representing glacial deposition of ice in the Norwegian trench and evidently part of the later, less extensive glaciation. There is no evidence that Scandinavian ice even crossed the Norwegian Trench, rather than flowing up it. It has been suggested that the high shear strengths and fabric characteristics near the sea bed noted in the Brae, Heather, Thistle and Magnus oil fields, which lie in a north-south line between Norway and Orkney, northern Shetland, and further north still, respectively, may be due to desiccation in subaerial permafrost conditions,

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[83] Johnson et al., 1993
[84] Johnson et al., 1993
[85] Rokoengen et al., 1982
[86] Rise and Rokoengen, 1984
[87] Johnson et al., 1993

rather than ice loading[88]. This subaerial state might have occurred had the area been on an isostatic forebulge between the Norwegian, Scottish and Shetland ice sheets.

The local absence of evidence for the two-phase Late Weichselian glaciation suggested above may be due to the absence or misinterpretation of evidence, the fact that it did not happen in this northern area, or that elsewhere in the North Sea the more extensive glaciation was due to Scottish rather than Scandinavian ice and that there should therefore be no reason to expect the same sequence between Shetland and Norway. However it is clear that as the sequences of the North Sea are examined and dated in detail, the better the last glaciation in northwest Europe will be understood.

2.4. Mechanisms

An important element of many studies of glaciation in northwest Europe is an attempt to determine the mechanisms of ice sheet development and decay as they relate to global atmospheric and oceanic circulation.

Glacier advance and maintenance requires low temperatures and/or high precipitation, both strongly influenced by oceanic and atmospheric conditions that are themselves influenced by adjacent ice sheets. The rate at which ice is transferred to situations in which it melts is important and is determined by the interaction between the base of the ice and the surface over which it moves. These range from cold based restricted movement to effectively frictionless water and the development of ice shelves which are sensitively related to sea-level. Sea water volume and sea level itself is locally and globally related to glaciation. Global and regional contexts are therefore interdependent and the overall climatic system is a complex arrangement of thresholds and feedback loops. This is evident in the fact that whilst Milankovitch orbital forcing cycles appear to control the tempo of Quaternary climate change, the magnitude and pace of that change requires that it is relayed and amplified throughout a global system[89].

Global, oceanic, thermohaline circulation is of great importance in transmitting heat around the globe (figure 2.11). In the current interglacial, warm surface waters flow north in the north Atlantic (the North Atlantic Drift), to the northeast margins, the Greenland, Icelandic and Norwegian Seas (GIN seas). Here, seasonal sea ice development increases salinity, the denser water sinks and returns south down the Atlantic (North Atlantic Deep Water). These northeastern areas are important therefore as a, 'pump,' in the maintenance of this global, 'conveyor belt,' (figure 2.12).

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[88] Johnson et al., 1993
[89] Imbrie et al., 1992

When open, the depth of the Bering Strait may have a profound effect on this mechanism, resulting in distinct differences between interglacials[90]. But during glacials, eustatic sea level fall results in the Bering land bridge, leaving only the North Atlantic connection to the GIN seas. The depth of this route is also reduced, and thus its capacity to exchange heat and salinity with the global oceans. The Wyville-Thomson Ridge across the Faeroe-Shetland channel (figure 3.4) is therefore a critical bathymmetric threshold, certainly in northwest Europe[91] and possibly in the global climate system. The failure of warm surface waters to reach the Arctic seas induces sea ice development in these areas[92].

Also of importance is the southern displacement of the polar atmospheric and oceanic fronts in the North Atlantic[93] (figure 2.13). Not only do precipitation bearing storm tracks follow this front, but sea ice develops north of it. During the winter months of the last glacial maximum, sea-ice may have extended as far south as 40-45° N (south of UK) and permanent pack ice may have extended to 60° N (exactly the line of latitude of Shetland)[94]. Cold surface waters and sea ice reduce the evaporative flux to the atmosphere and therefore precipitation to ice sheets, an effect especially enhanced by the high albedo of sea ice. The consequently reduced precipitation does not favour glaciation despite reduced temperatures and such factors suggest that maximum glaciation in Arctic areas may be out of phase with both Laurentide and Fennoscandian glaciation[95].

The relative rate of migration of these fronts and fluctuations in sea level around thresholds such as the Wyville-Thomson Ridge, are the most likely unifying keys to the pattern of the last glaciation and deglaciation of northwest Europe and Shetland.

The important issue of the timing of warm water advection into, and of evaporation and precipitation from, the GIN seas has often focused around the extent of ice in the Barents Sea. It has been suggested that the entire Barents Sea area was covered by grounded ice between 22 ka BP and 15 ka BP[96], but it has proved difficult to model circumstances that would allow such extensive glaciation[97]. Considerable precipitation is required to account for the rapidity of growth suggested by the above dates and it is therefore likely that the area cannot be treated as a closed cold-water cell as has been modelled previously[98]. Instead, deep sea sediment core analysis reveals that North Atlantic Drift water was advected into the area between 27-22.5 ka BP and also between 19.5 and 14.5 ka BP, the former being possibly responsible for the required

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[90] Shaffer and Bendtsen, 1994
[91] Peacock and Harkness, 1990
[92] Dawson, 1992
[93] Ruddiman and McIntyre, 1981
[94] CLIMAP, 1976
[95] Boulton, 1979
[96] Elverhoi et al., 1993; Gataullin et al., 1993
[97] Siegert and Dowdeswell, 1995
[98] CLIMAP, 1976

precipitation[99], and both showing some correspondence with Heinrich events 1 and 2 which are thought to represent ice sheet build-up. Raised shorelines and glacio-isostatic modelling however have been interpreted to suggest that, while there was indeed a major grounded ice sheet over the area at the last glacial maximum, it had mostly retreated by 15 ka BP[100].

A more general examination of ice-rafted debris input from the Norwegian Sea indicates several Late Weichselian oscillations on the shelf, at least four of which correspond to North Atlantic Heinrich events, suggesting that at least some major North Atlantic glacial advances were in phase[101]. This work again suggests that the Late Weichselian maximum was relatively early.

Subsequently, a north-south sea-ice-free corridor was already opened along the coast of Norway by 13,400 BP (figure 2.14) indicating the northward flow of North Atlantic Drift waters at this time, a switch that may partly reflect the re-establishment of an unsplit jet-stream due to the altitude reduction of the North American ice sheets[102]. This is earlier than the evidence suggests further south, where it has been shown that warm southerly water rapidly (within radiocarbon resolution) replaced polar water on the coast of northwest Europe and an interstadial marine circulation was fully established off southern Scandinavia by approximately 12,800 BP[103]. An important implication is that this water probably reached Scandinavia from north of Shetland, rather than between Scotland and Shetland.

Since maximum North Atlantic Deep Water (figure 2.11) return currents at the bottom of the Faeroe-Shetland channel may not have been in operation until the early Holocene[104], much global deglaciation probably occurred before the full interglacial oceanic circulation was operational.

Sea level during deglaciation of northwest European ice sheets is probably crucial given the quantities of Late Weichselian glacimarine deposits around their former margins and it is certainly likely that the deglaciation of ice shelves such as those hypothesised for the Barents Sea were sensitive to sea level[105]. Recent modelling has suggested that glacio-hydro-isostatic rebound during deglaciation is more significant than glacio-eustatic rise[106]. Around Shetland sea level is inferred to have been 40 metres below present at 16 ka BP, reached its lowest of -80 m at 13 ka BP, and has been rising progressively ever since. This corresponds to models that place

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[99] Hebbeln et al., 1994
[100] Lambeck, 1995
[101] Baumann, et al., 1995
[102] Koç et al., 1993; Jansen and Bjorkland, K.R., 1985
[103] Peacock and Harkness, 1990
[104] Stoker et al., 1989
[105] Elverhoi et al., 1993
[106] Lambeck, 1994

Shetland in a down-warping lithospheric part of the post glacial uplift pattern[107] and may suggest that Shetland lay on an isostatic forebulge from Scottish and/or Scandinavian ice sheets.

2.5. Conclusions

Areas to the north of Shetland are possibly of global importance during Late Weichselian times and an understanding of the timing of the englaciation, maximum, and deglaciation, as well as the maximum extent, of the last ice sheets in northwest Europe will assist understanding of the global climatic processes involved in such major environmental oscillations. These in turn are related to the position of precipitation-bearing storm fronts, the extent of evaporation-reducing sea-ice, relative sea-level and the movements of warm, North Atlantic waters. Confusion over the spatial arrangement of data relating to glaciation on the west coast of Scotland, the east coast of Scotland, the North Sea, Scandinavia, and the Barents Sea must be resolved. This may be achieved by applying a more complex temporal sequence of events that includes the glacial maximum between 29-22 ka BP followed by a more restricted glaciation between 20-18 ka BP. In general, however, it is probable that more detailed analysis of the offshore record on the northwest European continental margin, and more chronostratigraphic data, will make a major contribution to that effort.

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[107] Elverhoi et al., 1993

3. The last glaciation of Shetland

One of the major objectives of this study is the re-evaluation of existing datasets and publications relating to the last glaciation of Shetland on a region by region basis. Therefore, much of the literature discussed here is reviewed in greater detail in each of the region chapters to which it relates. This section gives a brief overview of the literature.

A number of broad reviews of the glacial history of the islands have been published[1]. There is also a series of summaries of the offshore sediments around the islands[2]. This latter data represents an enormous resource but has received superficial attention as regards interpretation. At the time of writing, it is being reviewed further by the British Geological Survey. The solid geology of the islands and surrounding continental shelf discussed in this study is taken from a number of publications[3] although it should be noted that there is a large literature on the subject and that the British Geological Survey is, at the time of writing, reviewing and re-mapping the area.

3.1. Solid geology, topography and bathymmetry

Shetland can be divided into east and west by the major north-south trending Walls Boundary Fault[4], a possible extension of the Great Glen fault. The terrestrial geology is highly complex (figure 3.1). Even at this generalized level the solid geology encompasses possible Precambrian (Lewisian) rocks of the Caledonian Foreland (A in figure 3.1), and subsequent meta-sediments resulting from regional orogenic metamorphism, Old Red Sandstone (Devonian) age sedimentary and volcanic rocks, and major subsequent igneous intrusions, all associated with the Caledonian orogeny. Lithological variation within the mapped units is considerable and is discussed on a region by region basis in subsequent chapters. The structural control of the Walls Boundary, Melby and Nesting Faults and the thrusts of east Mainland and Unst, together with the steeply dipping nature of the Caledonian metamorphic successions, impart a distinctive north-south lineation to the landscape that has not been significantly altered by subsequent agents of modification including glaciation. But since the exploitation of pre-existing structural weakness and topographic channels by ice is inevitable, those valleys aligned with ice movement, such as Colla Firth and Dales Voe, Delting (chapter 7, figure 7.2), may owe the perfection of their, "U-shapes," to glacial erosion[5]. The continuous seaward slope of the

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[1] Mykura, 1976; Flinn, 1977, 1978, 1980; Birnie et al., 1993; Sutherland and Gordon, 1994
[2] Johnson et al., 1993; Stoker, et al., 1993; Long, 1988; Stevenson, 1991; Chesher, 1984b; Evans et al., 1990;
[3] Mykura, 1976; Mykura and Phemister, 1976; Chesher, 1984a; Evans and Andrews, 1988
[4] Mykura, 1976; Mykura and Phemister, 1976
[5] Flinn, 1977

numerous drowned valleys prohibits a glacial explanation although some shallow seaward and may be glacially over-deepened (e.g. Ronas Voe - chapter 8, figure 8.2)[6].

Offshore, even close to the terrestrial landmass, there are significant additional solid geological outcrops (figure 3.2 and 3.3), including a number of fault-bounded Permo-Triassic sedimentary basins comprising sandstones with conglomerate bands including clasts of local terrestrial rocks (the Unst, Fetlar, St Magnus Bay, and West Fair Isle Basins in figure 3.5). The existence of these features as bathymmetric lows, and the possibility that a variety of local rock types might be exhumed from the conglomeritic bands, may have a profound influence on erratic distribution and the interpretation of ice flow during the last glaciation. With the exception of these basins, the offshore outcrops appear to be extensions of those identified onshore - although sequences are undivided, boreholes have proved similar rock types. The offshore bathymmetry is shown in figures 3.4 and 3.5.

The Permo-Triassic basins partly support the contention that the islands form part of a Caledonian erosional remnant which was partly or completely buried by proximal Devonian sediments, this cover being stripped during the Carboniferous[7]. Therefore, although the development of the Norwegian Graben and Faeroe-Shetland channel by the end of the Triassic led to the platform being sea-bound (figure 3.5), the erosional remnant of the present islands was probably in place and the surrounding platform peneplaned. The Mesozoic sediments in the Unst and Fitful basins, below the base of the present remnant, confirm this. Since the platform does not appear to have been a major source of Tertiary material it is likely that from the Jurassic onwards it remained fairly static and close to sea-level[8]. This supports the wider proposition that the main morphometric components of the Scottish Highlands, including the Orkney-Shetland Platform, were established by the end of the Palaeozoic, that several major erosional cycles were experienced during the Mesozoic, and that any deep weathering occurred during the pre-Quaternary Cenozoic[9]. If relics of past landscapes exist then east-west erosional features are of significance given the north-south structural control on the topography of the present islands. The gap at Quarff may relate to the Devonian landscape and there are also anomalous valleys at Voe and Mid-Yell (figure 3.6). Erosion surfaces on and around the islands (figure 3.6) have been tentatively identified by examining frequency histograms of Admiralty soundings and various Ordnance Survey map data[10]. The histograms suggest there may be terraces at 150 m, 100m, 60m, -15m, -45m, and -82m OD but the work is not conclusive. In particular the ages of the surfaces cannot be determined.

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[6] Flinn, 1977
[7] Flinn, 1977
[8] Flinn, 1977
[9] Hall, 1991
[10] Flinn, 1977

3.2. Previous work

3.2.1. The last terrestrial glaciation

At both regional and local level there are numerous direct conflicts and unexplained differences in both the evidence and interpretation of workers since the beginning of the century[11]. These are addressed directly in subsequent chapters. Only the major findings and issues are dealt with here.

The first major work on the last glaciation of the Shetland Islands showed that Scandinavian ice overran the entire archipelago from the northeast, turned upon it, and proceeded towards the northwest (figure 3.7), and that there was a subsequent local glaciation from the islands themselves[12]. These conclusions were drawn from striae, roche moutonée and stoss and lee observations, erratic movements (figure 3.7 also shows the solid geological interpretation with which the authors were working), and in places the asymmetry of till development around obstacles in the ice sheet's path. This scenario is consistent with the same authors' work in Orkney and Caithness (figure 3.8)[13]. At the time of publication, argument ensued over why a Scandinavian ice sheet should turn to the northwest[14] upon reaching Shetland and the authors proposed the impingement of a Scottish ice sheet from the south.

The possibility of Scandinavian glaciation was supported by the discovery of a large Tönsbergite boulder, originating near Oslo in Norway, at Dalsetter on the south Mainland peninsula[15] (chapter 5, figure 5.2). The boulder is discussed in detail in chapter 5 but its status as an erratic is open to question.

Subsequent authors have been unable to explain some of the sense of direction of striae data presented in the above work and also noted that erratic distributions strongly suggested only a local ice cap shedding ice radially from the islands[16]. The only evidence of Scandinavian ice was observed in the north of Unst and the southern peninsula of Mainland where erratics had crossed over the high ground and where the Dalsetter erratic is located. Local ice subsequently flowed from this high ground also however. The available data showed a pattern of northeasterly movement in central Mainland and Whalsay (figure 3.9) inconsistent with flow perpendicular to the axis of the islands and all the data was collated to produce a picture that involved a local ice sheet in confluence with Scandinavian ice to the east of central Mainland, with Scandinavian ice itself crossing south Mainland and Fair Isle, and possibly north Unst[17].

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[11] Ross et al., 1993
[12] Peach and Horne, 1879
[13] Peach and Horne, 1881
[14] Horne, 1880
[15] Finlay, 1932
[16] Robertson, 1935; Mykura, 1976
[17] Mykura, 1976

Variations in the radial pattern were also interpreted more subtly as being caused by ice flow shifting to new glacier margins, the orientations of which were being controlled by rapid ice calving into a rising sea level[18]. The conclusion thus reached was that the islands were indeed overrun by Scandinavian ice but as sea level rose at the end of the glaciation an independent ice cap was formed, possibly more dynamically active than climatically sustained, with the ice flow therefore controlled by rapid ablation by ice calving and ultimately bathymmetry (figure 3.10).

This interpretation was of course dependent on a knowledge of bathymmetry and it was subsequently observed that the pattern could equally be explained simply in terms of topographically contained ice flowing under gravity without any need to invoke iceberg calving[19]. By far the largest striae dataset and, given the extent to which it has been borrowed and passed on[20], more or less the only one, is that of D. Flinn who is responsible for re-mapping the solid geology of much of the Shetland islands and is therefore well placed to identify erratics. His major work on the subject[21] confirmed the radial pattern of ice movement (figure 3.11) from the islands and, while accepting evidence of Scandinavian ice crossing both south Mainland and Fair Isle, suggesting that it reflected, if not a previous glaciation altogether, an early stage in the last. This was reaffirmed with the regional addition of Foula and Fair Isle (figure 3.12)[22], a reversal of the conclusion previously reached on Fair Isle, where Scandinavian glaciation of the island was thought to be a relatively late, unimportant, event[23].

Broadly, interest in the issue of Scandinavian ice has taken prominence over the detailed interpretation of ice direction indicators on the islands and it is recognized that a more complex interpretation of the available data may be justified[24].

Given the small size of the islands, it is not surprising that references to terrestrial Late Weichselian ice margins are not abundant in the literature. One is reported across the island of Papa Stour[25], west Mainland (see figure 6.2), and another across north Unst and north Yell which may be that of the northern glacial maximum[26], or may not[27]. Various hummocky drift deposits have been reported[28] but it is not clear whether these represent active ice marginal deposits. Neither is it known whether they relate to a period of stasis or readvance during deglaciation of the Late Weichselian ice, or a Loch Lomond/Younger Dryas stadial readvance.

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[18] Hoppe, 1974
[19] Flinn, 1977
[20] to Mykura, 1976 (D. Flinn, pers. comm.) and from Mykura to Hoppe, 1974
[21] Flinn, 1977; and more or less reiterated, 1980
[22] Flinn, 1978
[23] Flinn, 1970
[24] Ross et al., 1993
[25] Mykura and Phemister, 1976
[26] Flinn, 1983, 1992b, 1994a
[27] Ross, 1993
[28] Mykura and Phemister, 1976; Flinn, 1982; May and Mykura, 1978; Gordon, 1993b

Numerous possible corrie glaciers are observed by one author[29] but subsequent writers[30] find little evidence of these (except for the hummocks mentioned above) and argue that they are hypothetical ice masses based on the likely locations of snow accumulation rather than on direct evidence.

3.2.2. The last offshore glaciation

There is potential for major improvements in understanding the last glaciation of the area since the development of enormous offshore sediment datasets. These have, as yet, only been interpreted superficially, and the results have been published during the course of this project. These interpretations are discussed here but it should be noted that combining the offshore and terrestrial conclusions to achieve this potential has not been attempted, other than briefly[31], prior to this study in which it is a major aim.

The summary conclusions regarding the last glaciation reached by the British Geological Survey are shown in figure 3.13[32] but the original 1:250 000 maps[33] show that the situation is complex, and even these are only initial interpretations. In particular, there are two possible margins in the north - the more restricted[34] fits well with the proposed terrestrial ice margin on Unst and Yell mentioned above[35]. However the more extensive is the limit of the Otter Bank sequence: sediments comprising over-consolidated diamicts forming ridges as well as mounded and sheet-like morphology across much of the shelf area[36]. They are interpreted as being deposited proximal to grounded glacial ice[37] and near the shelf edge in places form a series of parallel retreat moraines, indicative of ice retreat to the southeast. Between these ridges glacimarine deposits are visible on seismic traces[38]. The area marked in figure 3.13 as being of glacimarine sediments is also of interest. These are part of the Stormy Bank sequence, interpreted as being deposited during the waning stages of the last glaciation. They are well-layered, soft, glacimarine muds and clays with dropstones and are thought to be deposited in shallow conditions from icebergs or floating ice shelves[39].

Figure 3.14 shows the limit of the Stormy Bank sequence in inshore areas and to the east of the islands. These sediments are also related to the waning stages of the Late Weichselian and are of clear importance to the interpretation of the terrestrial data in this study. The relationship of the Otter Bank and Stormy Bank sequences in inshore areas is also shown in figure 3.15. To the

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[29] Charlesworth, 1956
[30] Mykura, 1976; Flinn, 1977
[31] Gordon et al., 1993; Ross et al., 1993
[32] Stoker et al., 1993
[33] Chesher, 1984b; Long, 1988; Stevenson, 1991; Holmes, 1991; Evans et al., 1990
[34] Long and Skinner, 1985
[35] Flinn, 1983
[36] Holmes, 1991; Stevenson, 1991
[37] Cockcroft, 1987
[38] Stoker and Holmes, 1991; R.Holmes (pers. comm. 1993)
[39] Johnson et al., 1993

northeast of Unst, beneath the area of Stormy Bank sediments, the Otter Bank sequence forms a possible morainal bank and both the Otter Bank and Stormy Bank sediments show some evidence of having been channelled here[40]. Beyond this, in an area that follows the shelf break from the north around to the west, between depths of around 150-300 m below modern sea-level (figure 3.4), is a zone where the seabed is characterized by iceberg scour marks[41].

The British Geological Survey have, at the time of writing, yet to publish an in-depth interpretation of the last glaciation of the area, however this work is underway[42].

The dispersal of heavy minerals in the sediments around the Shetland Islands have been studied and suggest a radial pattern of ice flow from the islands (figure 3.16)[43]. Comparing figures 3.16 and 3.9 reveals that the confluent Shetland and Scandinavian ice sheet, if such a situation existed, would have been further away from the islands than previously envisaged. The drawn limit is at the limit of the study, however, the presence of Scandinavian ice is derived from previous hypotheses and is not in any way demonstrated by the heavy mineral assemblages themselves.

3.2.3. Chronology

Dating is an objective of this study and the available terrestrial and offshore chronologies are reviewed in detail in chapter 10.

Fugla Ness in northwest Mainland includes organic materials overlain by two inorganic diamicts[44]. The age of the organic material is controversial and beyond radiocarbon determination but the thermophilous character of its constituents clearly indicate an interglacial, evidently not the present one. At Sel Ayre[45] a sequence of organic deposits is overlain by slope deposits and till and the age of the organic material, also beyond radiocarbon determination, based on pollen correlation, is contended to be either Ipswichian (last interglacial) or an Early Weichselian (Early Weichselian) interstadial, possibly correlated to oxygen isotope stage 5a or 5c[46].

The Stormy Bank and Otter Bank sequences have not been dated other than by the assumption that their uppermost stratigraphic position suggests that they are likely to be of Late Weichselian age. To the east of the islands, sediments are thin and patchy and are described as the East

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[40] Stevenson, 1991
[41] Stevenson, 1991
[42] A. Stevenson (pers. comm. 1995)
[43] Beg, 1990
[44] Chapelhowe, 1965
[45] Mykura and Phemister, 1976
[46] Hall et al., 1993b

Shetland Platform sediments[47] but are probably lateral equivalents of the Otter Bank and Stormy Bank sequences (as assumed in figure 3.15). Sediments associated with early deglaciation of ice from Shetland, near its assumed eastern maximum limit, have here been dated to early interstadial times at *circa* 13 ka BP[48]. These sediments are patchy and cannot be seismically traced to the Otter Bank and Stormy Bank sequences of the north and west shelf areas.

The oldest postglacial dates on Shetland are similarly dated to approximately 13 ka BP[49], discounting one of about 15 ka BP due to possible contamination[50]. A variety of projects relating to the timing of the late-glacial on Shetland have been completed or are underway but the overall situation is deemed, 'preliminary'[51]. Following the commencement of deposition of organic material there is a distinct late-glacial interstadial period followed by a return to more minerogenic deposition generally correlated with the Loch Lomond/Younger Dryas stadial.

3.3. Conclusions

There are a number of general points that can be made about work on the last glaciation of the Shetland islands to date.

Terrestrially, the issue of whether or not Scandinavian ice played any part in contributing to the last glaciation of the islands has been of importance. The question remains unresolved although it is clear that the most recent glacial activity involved a significant local ice cap which may or may not have reached its maximum extent on the northern isles of the group. More detailed interpretation of ice flows within this ice cap has not been undertaken and little attempt at establishing a sequence of events has been made. There is little terrestrial drift and this has also received no attention in terms of the timing of its deposition or its significance in relation to the subglacial environment.

Offshore interpretation around the area is at an early stage and no detailed description of the nature of the glaciation of the shelf area, and how or why this changed through time, has been published. However it appears that the maximum extent of the last ice cap reached 75 km to the east of the islands[52]. The extent to the north is controversial; and to the west, although there are clear morainic features on the shelf edge, these are not dated. Thus far, no attempt has been made to reconstruct the last ice sheet of the area in a way that accounts for both the onshore and offshore data.

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[47] Long, 1988
[48] Peacock and Long, 1994
[49] Birnie, 1993b; Birnie and Harkness, 1993
[50] Engstrand, 1967
[51] Birnie, 1993a (p.15)
[52] Long and Skinner, 1983

The last glaciation of the islands is assumed to be the Late Weichselian and dates from east of the islands suggest that this is indeed the case. A fuller timescale, taking account of variations around the islands and upon them, is yet to be developed. Although there is evidence of a Lateglacial climatic oscillation, and some depositional landforms on the islands, the oscillation is poorly dated and the landforms not at all. The timing, severity and geomorphological effects of the oscillation, and how closely it correlates with the Younger Dryas stadial are therefore uncertain.

4. The last glaciation of Fair Isle

4.1. Solid Geology, topography and bathymmetry

The solid geology and topography of Fair Isle are shown in figure 4.1 and comprise medium to coarse grained and occasionally pebbly sandstones of Middle and Lower Old Red Sandstone age with subsidiary bands of dolomitic mudstone and shale. The strata are steeply inclined to the east-south-east, except in the south-west where there is evidence of tectonic deformation or possibly thermal metamorphism[1]. No appropriate intrusions have been mapped[2] to support the latter hypothesis. There are a number of west-north-west trending faults cutting the island, some of which have dykes associated with them outcropping in the west. The geological structure is evident in the topography: the ground rises at the angle of dip of the sandstone to high cliffs in the west and less competent bands are readily identifiable in many places as shallow channels following the strike of the sequence. Offshore, Fair Isle lies close to the western edge of the Fair Isle ridge which is bounded to the West by the Walls Boundary fault and to the east by the East Fair Isle basin (figures 3.2 and 3.4). Boreholes in the ridge have proven sandstones and siltstones. On either side of the ridge, broad bands of Permo-Triassic sandstones and siltstones have also been mapped[3] (figure 3.2). Structurally, Fair Isle can be seen as an extension of the Caledonian erosional remnant that forms the archipelago of Shetland itself.

4.2. Previous work

Early authors have suggested that Fair Isle was overridden by ice moving from the east-south-east[4]. In support of this, strong ice moulding along fault lines in the south of the island and the azimuth of striae observations are referred to but no sense of *direction* evidence is given. Two supporting roche moutonée have subsequently been mapped[5] showing east to west ice movement. However Flinn[6] shows that striae azimuths form a bi-modal distribution - the majority associated with micro- stoss and lee features supporting north-west to south-east ice movement. The remainder, 'in several cases could be seen to be due to ice moving from the east towards the west.'[7] The superimposition of the two sets in some locations led to the inference that movement from the west preceded movement from the east, the latter being considered a, 'late and relatively unimportant phase'.[8] This conclusion was subsequently abandoned in favour of the opposite sequence of events[9] but it is not clear why.

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[1] Mykura ,1976
[2] Chesher, 1984a; Evans and Andrews, 1988
[3] Evans and Andrews, 1988
[4] Peach and Horne, 1881; Mykura, 1976
[5] May and Mykura, 1978
[6] Flinn, 1970
[7] Flinn, 1970
[8] Flinn, 1970 (p.275)
[9] Flinn, 1978

Evidence of the direction of ice movement has been sought in the nature of the till matrix and its colour and relative percentages of millet seed grains have been inconclusively investigated[10]: originally it was concluded that ice moved across Permo-Triassic basins to the north and east of the island[11], but such basins occur on both sides of the Fair Isle ridge (figure 3.2) and it has also been conceded that the Fair Isle till matrix might be derived from local rocks[12]. The low-lying distribution of the reddish till is thought to indicate westward movement followed by south-eastward movement of ice, although how this conclusion is deduced is not discussed by its author[13].

The most common non-local erratic on Fair Isle is a drusy granophyric granite similar to those intrusions encountered on the main island group but possibly from a late or post Devonian intrusion outcropping offshore[14]. No such outcrop has been identified[15] (figure 3.2) however and ice flow lines on Shetland make a Ronas Hill (north Mainland; figure 8.1) provenance[16] improbable. A possible alternative is the Sandsting Complex of the south Walls Peninsula (west Mainland; figure 6.1). The Spiggie plutonic complex (south Mainland; figure 5.1) is undoubtedly represented and Fair Isle till also includes a variety of igneous and metamorphic rocks compatible with but not matching Shetland suites and some gneisses that are incompatible and may have been derived from the basement of Norway[17].

Pre-Holocene Quaternary sediments offshore are limited (figure 3.15), possibly due to stripping by high bottom current velocities. Holocene sands usually overlie a shell hash and diamicton occasionally up to 3 m thick. The latter may include soft clays or well-sorted sands locally. Sidescan images indicate the presence of gravel ridges throughout an area approximately 30 km to the east of Fair Isle[18], which may represent an outwash plain, and the beginnings of a proglacial channel system draining into the Witch Ground Basin is perhaps identifiable[19] (figures 3.14 and 3.15). The south-eastern maximum of the Shetland ice sheet may therefore be represented by an area of stony clays of high undrained shear strength to the west of this area[20], these characteristics being possibly due to ice loading.

4.3. Outstanding issues

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[10] Flinn, 1970
[11] Flinn 1969; Evans and Andrews, 1988
[12] Flinn, 1978
[13] Flinn, 1978
[14] Flinn 1970, 1978
[15] Chesher 1984b; Evans and Andrews, 1988;
[16] Flinn 1970, 1978
[17] Flinn, 1978
[18] Evans et al., 1990
[19] Johnson et al., 1993; Flinn, 1967;
[20] Johnson et al., 1993

There remains confusion over the glacial history of Fair Isle. The following regionally crucial questions are considered here: Is there evidence of more than one glaciation? Were there multiple phases of ice movement within the last glaciation and is there any evidence of ice movement from an eastern source? What was the nature of the last glaciation and deglaciation and the mechanisms involved?

4.3.1. Multiple or single glaciation

The issues of ice direction and multiple glaciation are bound together on Fair Isle. Although there is no litho-/bio-stratigraphic evidence, multiple glaciation has been inferred as the simplest explanation for multiple striae azimuths, senses of direction inferred from stoss and lee data and complex erratic suites. Striae trending northeast-southwest and striae trending east-west must represent different ice movements and may be due to different glaciations[21]. The present author considers the latter to be improbable on the grounds of preservation. On Fair Isle sub aerial weathering of exposed surfaces since the last glaciation may be estimated from the pebbly grits and conglomerates through the extent to which the sandstone matrix has been denuded compared with sheared or planed pebbles of more resistant lithology. This can be up to 5 mm at various locations, such as the Bu Ness peninsula. In most parts of the island, joint block removal of many surfaces is evident (plate: figure 4.6), as it is over much of Shetland, so preservation of a striated surface both between and through subsequent glaciations is unlikely - indeed, only 43 observations have been made of striae. It is therefore simplest to assume that most of the erosional features reflects the last glacial period.

4.3.2. East-west and west-east ice movement

Even if there is evidence of only the most recent glaciation, it remains possible that multiple directions of ice movement occurred during that glaciation. In the case of Fair Isle, it has been suggested that the previously reported evidence supports two opposite movements: broadly, from the east and from the west[22]. It will be argued here that the evidence can be interpreted as being entirely due to ice moving from the west.

Near Bu Ness, the direction of glacitectonization of bedrock is offshore and towards the east or north-east (figure 4.3). This is incommensurate with glaciation from the east and the preservation of such structures (plate: figure 4.7) lying beneath 0 - 0.5m of till (figure 4.5) through a subsequent glacial phase is unlikely. It follows that the last ice movement here was broadly from the west and this direction can be reconciled with parts of the striae azimuth pattern (see below). It should be noted, however, that the precise orientation of glacitectonized bedrock may owe something to solid structure.

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[21] Flinn, 1978, 1980
[22] Flinn, 1970

The reported[23] sense direction of the two roches moutonées in the south of the island (figure 4.3) can be directly challenged. The more northerly (plate: figure 4.8) has a clearly smoothed western flank and more plucked eastern end, suggesting ice movement broadly from west to east, and there is no apparent reason why the sense of direction was previously interpreted to indicate the reverse flow. It is difficult to determine the sense of direction of the more southerly example, but the stoss and lee form of all smaller outcrops in the area suggests an eastward movement of ice. The author has been unable locate the striae and micro- stoss and lee observations showing east to west movement at Scroo and Head of Tind (figure 4.3) but it is worth noting that these are the only two striae that are attributed an east-to-west sense of direction by direct observation. They represent one of the reported, 'two sets of striated, ice-moulded surfaces'[24] on Fair Isle. It is possible that the stoss and lee observations were misinterpreted: stoss and lee, especially micro- stoss and lee, observations are not straightforward on Fair Isle where the bedrock is structured with an orthogonal joint system. Dilation is evident near the surface and removal of small blocks by non glacial processes readily achieved. The direction of glaciation under such circumstances is determined by dominant pattern not individual sites. The observations of this study leave little doubt that there is a dominant stoss and lee pattern indicative of ice movement from the west to the east. Occasional reverse observations are not locally consistent and probably do not owe their existence to ice moving in the other direction.

Till is generally thin and poorly developed on Fair Isle. However thicker till occurs at South Harbour (figure 4.3) and has a very clear fabric (plates: figures 4.9 and 4.10). The direction of dip, assumed to be up-glacier[25], suggests ice movement from the west. Although consistent, dip values were small and it is possible that this trend may have been due to ice moving locally up-slope. However the azimuth of clasts are clearly east-west and local stoss and lee observations suggest movement from the west. Fabric measurements were made elsewhere on the island but there were no sites of similar till thickness: the fabrics showed no strong azimuths and no evidence of the direction of ice movement.

Ice movement from the east might also be expected to result in a till distribution that reflected preferential lodgement against the western high ground due to pressure melting at the base of the ice. What little till exists, however, is best developed on the low ground in the south of the island (figure 4.5). Although it is possible that till which may have been previously lodged against the high ground was subsequently stripped away, it is difficult to reconcile that conclusion with the simultaneous preservation of former striae such as those discussed above at

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[23] May and Mykura, 1978
[24] Flinn, 1978 (p.116)
[25] Hambrey, 1994

Scroo and Head of Tind, on bedrock lithologies which prove highly susceptible to glacitectonization. The southerly distribution of till is more simply explained by a model in which the northeastern parts of the island lie in the shadow of the high ground that offers some protection from an east-flowing ice mass. Only at Bu Ness does the drift distribution show a distinctive preferential lodgement pattern on the up-glacier side of an obstacle, although no consistent fabric was identifiable, and here the implied ice direction is from west to east (figure 4.5) and may be associated with convergence around the high ground (see below and figure 4.4).

There is a distinct low ground striae azimuth pattern suggesting ice movement around the high ground (figure 4.4 - additional NW-SE observations (figure 4.3) are incompatible, and in places, cross this pattern) and the assumption has been made[26] that this reflects divergence of a westward moving ice mass of Scandinavian origin. The alternative hypothesis is that the pattern reflects convergence of an eastward moving ice mass on the lee side of the high ground. The low-ground pattern consists of only a few observations, which may reflect local topographic circumstances, and without clear directional information (see above) it is here concluded on the grounds of a combination of other evidence and preservation (see above) that the pattern reflects convergence of ice from the west. Such convergence of basal ice after flowing around the north and south flanks of the island is readily envisaged. The western, up-glacier, side of the island comprises near vertical cliff faces which could not be ascended by basal ice between the two flanks. The lee, or down-glacier, side of the island would become an area of low lateral pressure that would be filled by the convergence of northern and southern streams (figure 4.4).

The only remaining evidence that ice from a Scandinavian or any eastern ice shed passed across Fair Isle is the existence of exotic erratics. These are identified simply as being unlike Shetland suites. It is possible that the erratic content of till on Fair Isle is partly derived from offshore drift sequences and that their original deposition is the result of a previous glaciation. If these erratics were re-excavated from drift deposits in offshore areas then it might be reasonable to expect shell material, from the deposits themselves or from overlying interglacial or interstadial marine sediments, occurring in the same till sections on Fair Isle. No section on Fair Isle contains visible shell material and even crude, visual HCl experiments on the matrix of till samples taken from around the island suggest that the carbonate content is low. This implies that what drift did exist around Shetland prior to the last glaciation (and there is little there at present) was stripped early and that deposition on Fair Isle includes little or none of this material. The possibility that erratics on Fair Isle in general may be derived from glacial erosion of conglomeratic bands in the surrounding Permo-Triassic basins has not been considered. Such bands might contain remnants of basement rocks around Shetland that are no longer in outcrop. This hypothesis is difficult to demonstrate without detailed analysis both of Fair Isle erratics and

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[26] Flinn, 1970, 1978

conglomerate bands around the island offshore, and even then the particular conglomerate source bands probably no longer exist. Such alternative hypotheses are however at least sufficient to remove any *requirement* that Scandinavian ice reached Fair Isle from the east during the last glaciation.

In summary, the likelihood that evidence of more than one glaciation exists on Fair Isle is small. It is possible that an initial west-moving ice sheet was succeeded by an east moving one during the same glacial phase but the evidence of striae and drift geology can be most simply attributed to the eastward movement of glacial ice and there is no need to accept an eastern ice shed at any stage.

4.3.3. Western and north-western ice sheds

An implication of ice moulded landforms and striae on Fair Isle is that the ice shed lay directly to the west. However there is a strong northwest to southeast pattern of striae on Fair Isle suggesting a more northerly ice shed (figure 4.3). The aim of this section is to consider the sequence of ice shed configurations necessary to produce these variations. Erratic data does not contribute to this issue. Most erratics on Fair Isle have been attributed to Mainland Shetland which lies northeast. Flow lines on Shetland itself do not indicate that ice moved towards Fair Isle, however they do indicate movement of potential erratic material into areas west of Fair Isle at a late stage in glaciation. It is possible that similarly moved material from a previous glaciation was re-excavated and transported directly east or southeast during the most recent, or that the erratics derive from conglomeratic bands in the Permo-Triassic sedimentary sequences on either side of the island.

There is little doubt that ice moved directly from the west across southern Fair Isle at some stage. The fabric at South Harbour shows no northerly influence and neither do some striae azimuths (figure 4.3). These observations are likely to reflect regional basal ice movement as there is little relief in this southern area. The northwesterly set of striae, on the other hand, is broadly perpendicular to contours and may reflect topographic control of ice movement. The slight northwesterly alignment of the two mapped roches moutonées is the product of structural influence and stoss and lee observations are not of direct assistance in this context: in some areas orthogonal joint plucking perhaps suggests a more southerly direction of movement but systematic investigation did not reveal any trends.

There is no clear basis for conclusion here. It seems most probable that early ice movement was more directly from the northwest, followed by west to east movement. The reason for this conclusion is that much of the northwest-southeast pattern, though not all, is associated with high ground, over which ice may have become increasingly cold based, or even ice free, as the ice cap surface elevation was lowered during deglaciation. The alternative that the ice movements were contemporaneous is difficult to sustain: in places the northwesterly striae cross areas where the east-west set also exists, although it should again be noted that the present writer has been unable to make direct striae observations on Fair Isle.

The existence of striae on the high ground of the northwest (figure 4.3) is in itself curious. This is the western most part of the island, faced by high, vertical, cliffs, and it is therefore difficult to envisage where the basal material required to generate the striae has come from, particularly since it has been argued that basal ice moved around this area. We are left to conclude either that the ice movement indicated is *from* the south-east (which is contradicted by direction evidence), or that high level ice picked up material on the high ground and immediately used it to etch striae. The crucial part of this latter conclusion is that the ice shed would be to the west or north-west of Shetland and not centred on the Fair Isle high-ground itself.

4.3.4. Nature of englaciation and deglaciation

The presence of striations and ice moulding indicate that the last ice sheet to cross Fair Isle had a warm based temperature regime. Lodgement deposition is not easy to prove however. Stratigraphically, in places bedrock glacitectonization only is visible (plate: figure 4.6), and in others this has been succeeded by a more dispersed till (plate: figure 4.7). The vertical boundary is sharp and it is possible that the thin till mantle is melt-out and there are no locations where it is so thick that accretion is likely. An exception is at South Harbour (figure 4.5; plates: figures 4.9 and 4.10), where 2m of diamict is encountered and there are occasional striated clasts. In some locations clast clustering, sand stringers and shear structures suggest local lodgement. Elsewhere on Shetland, glacitectonization of bedrock is usually succeeded by lodgement. At the base of slopes on Fair Isle, more complex facies including gravelly material and fines bands that suggest a wetter depositional environment (plate: figure 4.11) and possibly flow till during deglaciation.

The absence of shells or much calcareous material in till on Fair Isle suggests that, by the time of till deposition, any antecedent offshore drift sequences containing such matter had been stripped and transported elsewhere; either those sequences were thin, as they are today, or till deposition occurred relatively late in the glacial cycle, or both.

The mechanisms of deglaciation around Fair Isle are difficult to determine due to the thin drift cover in the offshore areas. The record perhaps suggests that the maximum of the Shetland shelf glaciation lay 30 km or more to the east of Fair Isle and that meltwater drained, possibly subaerially, in a southeasterly direction. The sediments within that zone are thin however and, although there are hints of glacimarine sedimentation, any interpretation of the area would be difficult. To the west, shelf-edge end moraines interleave with glacimarine sediments[27] suggesting early deglaciation due to ice-calving (figure 3.13). The thin record nearer Fair Isle prevents the reconstruction of subsequent events.

4.4. Conclusions

Existing and new evidence is here interpreted to demonstrate a single, dominantly erosive, glaciation with possible multiple phases of ice movement. The latter may have included early ice moving from the east, but there is little, if any, conclusive evidence of this. Stoss and lee data clearly indicate that Fair Isle suffered glaciation from the west, broadly, and it is here suggested that this western ice shed may have been to the northwest at some early stage, and that it moved progressively to a more western position subsequently as a shelf-wide ice cap deteriorated. A residual ice mass may have existed independently of the Shetland ice sheet but there is no evidence of Fair Isle nourishing independent glaciers. The regional implications of these conclusions are considered in chapter 11 but of particular interest is the fact that the last major ice movement across Orkney was from the east.

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[27] R. Holmes (pers. comm. 1993)

5. The last glaciation of south Mainland

5.1. Solid geology, topography and bathymmetry

The solid geology, topography and bathymmetry of the area are shown in figure 5.1. The area comprises steeply dipping metasediments, primarily phyllites, overlain by Devonian sedimentary rocks outcropping along most of the east coast. The Spiggie granitic intrusion in the southwest of the area is probably part of a plutonic complex that also crops out in central Mainland (figure 7.1) and western Mainland (figure 6.1). Topography is closely related to structural control: the area is dominated by the Clift Hills ridge and its southern outlier, Fitful Head; most of Sumburgh, and a thin eastern coastal strip, is underlain by Devonian sedimentaries comprising sandstones and conglomerates, and is relatively flat and close to sea-level. Offshore[1] (figure 3.2) to the east the East Shetland Platform is composed largely of sandstones and siltstones, whereas immediately to the west undivided metamorphic rocks and also some granite intrusions occur to the Walls Boundary Fault, beyond which the West Fair Isle Basin contains Permo-Triassic sandstones and gives rise to a bathymmetric deep. The metamorphic rocks of the area are taken to have been metamorphosed during the Caledonian orogeny and may be correlated with the Dalradian of Scotland. The igneous intrusions are probably late Caledonian and the sedimentary rocks of Devonian age[2]. It has been suggested that the gap at Quarff may be a Devonian erosional remnant (figure 3.6)[3].

5.2. Previous work

This area is crucial since it offers the clearest evidence of possible Scandinavian ice moving onto the Shetland land mass. The pattern of striae in the area has generally been interpreted as indicating offshore ice movement from the spine of the Clift Hills[4]. Only Peach and Horne[5] interpret striae showing onshore movement (figure 3.7 - southeast corner) but these are disputed by subsequent authors[6]. However erratic data includes not only the movement of central Clift Hills phyllites east and west off the high ground, but also the transfer of sandstones from eastern source areas, across the high ground, to the west[7] (figure 5.2). This is interpreted as evidence for Scandinavian ice crossing the watershed prior to subsequent local glaciation from it. Some authors treat this as two phases of a single glaciation[8], others suggest that it may represent an earlier glaciation altogether[9]. Petrographic analysis of a single example of a large erratic near Dalsetter (figure 5.2) shows that it originated in the Tönsberg region of Norway but its original

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[1] Chesher, 1984a
[2] Mykura, 1976
[3] Flinn, 1977
[4] Peach and Horne, 1879; Flinn, 1977; Mylura, 1976
[5] Peach and Horne, 1879
[6] Flinn, 1977
[7] Peach and Horne, 1879; Mykura, 1976; Flinn, 1977;
[8] Peach and Horne, 1879; Hoppe, 1974; Mykura, 1976
[9] Flinn, 1977

stratigraphic position remains unclear despite anecdotal evidence that it may have been recovered from till[10]. No evidence is discussed for Scandinavian ice incursion north of Lerwick, although early authors believed it occurred nonetheless[11] (figure 3.7). Improved striae datasets suggest that ice flowed southeast across Dales Voe in the northeast of the area (figure 5.2), presumably from high ground to the northwest, and this is confirmed by erratic carry[12]. The sense of direction of striae on Bressay (figure 5.2) is controversial: since in the north of the island erratics include no evidence of Mainland metamorphic rocks, extra-local glaciation from the northeast, and Scandinavia, has been suggested[13] (figure 3.9); but other authors are convinced that the sense of direction of striae in this area indicates ice movement *to* the northeast[14]; and the possibility of a local ice-cap on the Ward of Bressay deflecting Mainland ice into Bressay Sound at a late stage in glaciation has been raised also[15].

Offshore (figures 3.14 and 3.15) sediments are thin but subglacial deposits associated with the last Shetland ice cap extend 75 km to the east[16] and probably to the shelf edge to the west[17], although the latter are not directly dated.

At Burn of Mail in the centre of the peninsula, localized hummocky topography has been described as morainic[18] although its extent is possibly confused by the presence of a nearby landslide[19]. Cored sediments in Aith Voe which drains the Veester catchment just to the north of Burn of Mail have been analyzed in detail[20]. There is no lithostratigraphic evidence that the catchment was glaciated during Loch Lomond stadial times, although there is clear evidence of reduced organic deposition and disturbed soils. The timing of these events by radiocarbon assay is discussed in chapter 10. Former corrie glaciers on the Clift Hills, on Bressay, and a valley glacier in Dales Voe have been mapped[21], but other authors[22] find no evidence of these and presume them to be partly hypothesised.

5.3. Outstanding issues

The following outstanding issues arise from the above. Did Scandinavian ice cross southern Mainland during the last glaciation? If not, how are the observations reviewed above to be interpreted? Can they be reconciled in a single phase of glaciation, or do they indicate major changes in ice shed configuration through the glacial cycle? What were the nature of glaciation

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[10] review: Gordon, 1993a; discovery and antecedence: Finlay, 1932; Flinn, 1992a; petrography: Le Bas, 1992
[11] Peach and Horne, 1879
[12] Robertson, 1935; Flinn, 1982
[13] Mykura, 1976
[14] Flinn, 1977
[15] Peach and Horne, 1879
[16] Peacock and Long, 1994
[17] Stoker et al., 1993
[18] Peach and Horne, 1879; Charlesworth, 1956; May and Mykura, 1978; Gordon, 1993b
[19] Flinn, 1977
[20] Birnie, 1993b; Birnie and Harkness, 1993
[21] Charlesworth, 1956
[22] Flinn, 1977

and the reasons for deglaciation? Is there hummocky moraine in Burn of Mail and does it represent Loch Lomond stadial glaciation?

5.3.1. Scandinavian glaciation

This area has received the most attention in terms of evidence of Scandinavian, as well as subsequent local, ice movement. It is clear that striae in the northeast of the area, including on Bressay, were not all formed at the same time, since their azimuth indicate mutually exclusive ice movements in close proximity (figure 5.2). Two possible explanations for this pattern exist:

(1) The Bressay striae reflect north-east to south-west ice movement from an extra-local source (i.e. Scandinavia)[23], and a local glaciation produced the more west-east pattern on the Kebister Ness peninsula.
(2) Alternatively, both patterns are of offshore movements and the change is due to ice-flow changes during deglaciation of a local ice cap only.

It has been argued[24] that the first hypothesis is supported by the absence of Mainland-derived metamorphic erratics in northern Bressay, suggesting that local ice did not cross that area. However, it can be seen from solid geology, topography and striae, that offshore ice passage in this direction would be almost exclusively across the sandstones of the Lerwick area (figure 5.3). The second hypothesis is supported by the author's observation of the drift distribution (figure 5.4) which suggests preferential lodgement on the upglacier side of the subglacial obstacle presented by the island - the west shore of the island supports a thin lodgement diamict up to 1.5 m thick, whereas only a thin glacitectonite or no drift was observed on the northeast coast. It has been suggested[25] that an ice stream flowed down Bressay Sound from the north, prevented from crossing the island by a local ice mass. Such a stream might account for the lodgement on the west shore, however all along this area the writer has identified northeast-southwest azimuth striae associated with the diamict and these observations are not consistent with an ice stream travelling down Bressay Sound. The pattern of lodgement against Ness of Sound may also be associated with offshore moving ice. The writer has observed northeast-southwest trending striae on the east side of Brei Wick and there is no evidence of metamorphic erratics in the till here either, although coastal protection has added many to the beach. This area is further west than the confluence zone of Mykura's[26] Scandinavian and local ice sheets (figure 5.3).

The striation of northern Bressay indicate erosion. This has a number of implications for the current argument. The first is that it is unlikely, this close to an apparent confluence with

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[23] Peach and Horne, 1879; Mykura, 1976
[24] Mykura, 1976
[25] Peach and Horne, 1879
[26] Mykura, 1976

another ice sheet, that Mykura's Scandinavian ice sheet would have the velocity and glacidynamic regime required for such erosion (figure 5.3). The second is that any early metamorphic erratics from Mainland might have been subsequently stripped by more recent ice flowing across areas that do not include metamorphic erratic sources.

Where the present writer has been able to identify micro stoss and lee patterns associated with striae near the disused quarry to the north of Hill of Setter on Bressay, Flinn's[27] conclusion that the sense of direction is to the northeast, offshore, is confirmed. Heavy mineral analysis of sediments offshore to the east and northeast of the area confirm that ice probably moved towards the northeast from the islands (figure 3.16)[28].

Further south on the peninsula, as far south as Ward of Scousborough (figure 5.2), ice direction indicators have been interpreted as showing Scandinavian ice crossing the peninsula from the east, followed by local ice flowing off both sides[29]. Here the two pieces of data suggesting Scandinavian ice are the Dalsetter erratic and the translocation of sandstone from the east to the west coasts. The former is a singular Scandinavian boulder and occurs near Boddom[30]. It is not known whether this is a glacial erratic, or an ornament transported to Shetland in Viking times. There is some evidence that the boulder was excavated from till[31], however the writer's search of all dry-stone built structures and till sections over an area of 7 km^2 in the vicinity revealed no further examples despite its striking visual appearance. If it is a glacial erratic, there is no way of determining whether it has been carried during the last glaciation only. Since its significance will probably always be determined by the context in which it is being used as evidence, the Dalsetter erratic is of questionable value in the present discussion.

The present writer confirms the existence of sandstone erratics in till sections on the west coast of the area. Since the West Fair Isle basin also comprises sandstones and conglomerates, and further west still there are Devonian sedimentaries, it might be hypothesised that these clasts were entrained and deposited by ice flowing west to east across the high ground rather than the conventional assumption of east to west. However the writer has observed sandstone clasts in till on Trondra where the till distribution (figure 5.4) suggests upglacier lodgement on the eastern face of the island. This, in turn, suggests that the ice lodging the till and carrying the erratics came from the east. It might be doubted that major erratics from Devonian outcrops further west than the West Fair Isle Basin could have reached the west coast of South Mainland without some other evidence of this movement, but it is also possible that erratics of all the local country rocks might have been exhumed from conglomeritic bands in the Permo-Triassic basin itself.

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[27] Flinn, 1977
[28] Beg, 1990
[29] Peach and Horne, 1879; Mykura, 1976; Flinn, 1977
[30] review: Gordon, 1993a; discovery and antecedence: Finlay, 1932; Flinn, 1992a; petrography: Le Bas, 1992
[31] Flinn, 1992a

Other authors, however, have been quite explicit in attributing erratics to source sandstones on the east coast[32], particularly in the far south where erratics and outcrops are not separated by high ground and the boulder train is easily traced. In the central part of this area however, there is a possibility that the erratics are derived from the west. It would take detailed spatial and petrographic analysis to further this argument.

5.3.2. Ice shed movements in the last glaciation

There may be evidence of a western ice shed at some stage. While Scandinavian ice, or ice from an eastern ice shed, may have moved sandstone erratics across the high ground early in the last glaciation, or during a previous one, the issue of their preservation during deglaciation, or subsequent glaciation, arises. If the deglaciation of the peninsula was highly erosive it is unlikely that previously deposited or entrained sandstone erratics could have survived this later stage on the narrow western coastal strip. There is no doubt that the most recent glacial phase on the eastern coast was highly erosive. What drift there is usually takes the form of a barely assimilated glacitectonite (figure 5.4). That this erosive situation reflects the most recent, local phase of glaciation, is shown by the involvement of metamorphic erratics from the high ground to the west (plate: figure 5.11). If this stripping also occurred on the west coast, it is difficult to explain the preservation of erratics in areas such as St Ninian's Isle (figure 5.2). One possible explanation is given in figure 5.5. If the central ice shed was displaced to the west of the high ground itself, and retreated towards it, then there may have been a zone of inactivity beneath its centre where previously deposited or entrained erratics would be preserved. This model would not account for erratics emplaced during a previous glaciation, since they would have suffered during englaciation of the most recent, but if, during the last glaciation, erratics were transported in basal ice to the west coast of the area, from whatever source, and then deglaciation progressively occurred in such a way as to limit erosion here, then their preservation is less remarkable. This discussion is inevitably speculative, but a western ice shed may be borne out by evidence from other areas (see chapter 6), also from the southern tip of the south Mainland peninsula (see below), and possibly even in consideration of the Burn of Mail moraine (see below).

On the southern tip of the peninsula, there are source areas for sandstone, schistose, and granitic erratics, and here again it is suggested that ice moved first from east to west across the area, and was subsequently shed from Fitful Head in the west[33] (e.g. figure 3.9). The present writer's survey suggests that the situation here is more complex than this. Although unable to confirm the sense of direction of the striae to the east of Ward Hill, the observations would appear to be consistent with an ice stream moving eastwards across the narrow strip of land here, and a clast

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[32] Peach and Horne, 1879

[33] Peach and Horne, 1879; Mykura, 1976; Flinn, 1977

fabric of lodgement till at Quendale suggests an even more northerly azimuth (figure 5.2). The till at Quendale includes sandstones, granite, and metamorphics, consistent with ice moving broadly west to east, although there are possible source areas for all these types offshore to the southwest (figure 3.2). The striae on the east coast around Voe may reflect east to west or west to east ice movement. Those on the west coast appear to show divergence around Fitful Head. The writer is not able to confirm the sense of direction of these, however the fabric at Noss Hill also suggests a broadly northwest-southeast azimuth of ice movement, consistent with the striae at the north end of Fitful Head. The clastic content of the till here is important, containing subsidiary quantities of both sandstone and metamorphics in the largely granitic composition. All along the coast between Spiggie Bay and Fitful Head there are erratics of all three rock types but in this particular location, if the fabric analysis is accepted, or assuming that ice from Fitful Head would have flowed under topographic constraints, then it is likely that the ice shed lay to the northwest, offshore, and crossed metamorphic outcrops to the northwest of Noss Hill. The sandstone clasts were either entrained earlier from the east, or from the West Fair Isle basin in the west. The implied western ice shed configuration reflects that suggested above (figure 5.5). Furthermore, to the northwest of Noss Hill, there is a dendritic pattern of now dry channels, running under the influence of topography, and converging on one channel containing a misfit stream running around the north side of the hill (figure 5.2; plate: figure 5.12). The heads of this system run close to the coastline and have no catchments commensurate with their size. It is difficult to explain these phenomena except as a proglacial meltwater system emanating from ice to the northwest of the coast. Although the metamorphic erratics at Noss Hill might have been transported by a piedmont-style glacier from Ward of Scousborough there is no other evidence of such a system and it does not explain the fabric analysis or the meltwater channel system. However, not only are there clear movements of particular sandstone erratics from east to west in this southern area[34], but the movement of sandstone and local syenite up Fitful Head is recorded and this must be due to an ice shed to the east, since basal ice from the west would be unlikely to ascend the sheer cliffs facing it.

There is, therefore, some evidence for ice crossing this southern area from both eastern and western or northwestern ice sheds. Clearly these movements did not occur at the same time but there is no evidence that they reflect discrete glaciations. At Quendale, for example, both metamorphic and granitic erratics are found in sediments associated with the most recent ice movement (plates: figures 5.13 and 5.14).

In the north of the area evidence of changes in ice movement direction is significant. When the evidence is considered as it is above, the second hypothesis of the glaciation of Bressay, that Mainland ice crossed northeast over it, is the more probable. This requires a relatively late ice

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[34] Peach and Horne, 1879

shed to the south-west of Lerwick. Topographically it might lie as in figure 5.3 (ice shed 2), leaving ice to travel across non-metamorphic rocks, although a more significant ice cap over or to the west of the main high ground might result in a zone of inactivity over potential western erratic sources. Either way, such an ice-shed is incompatible with the pattern around Gulberwick, where the northwest-southeast dominance is approximately perpendicular to submarine contours and also shows some correspondence with local topography (figure 5.2). The writer has observed the pattern into Brei Wick and, again on the morphochronological grounds of dominant pattern and the preservation of older, laterally more extensive patterns through deglaciation in an erosive context, these striae probably post-date those observed on the east shore of the bay. It can be reasonably argued therefore that the northeast Bressay pattern pre-dates that into Gulberwick and may reflect containment to a deeper bathymmetric contour than the Gulberwick pattern. The northern Bressay pattern may reflect regional northeasterly movement if a more considerable ice sheet's zone of erosion was restricted to source areas within the sandstone around Lerwick (as suggested above), or any further-travelled metamorphic erratics were swept off Bressay subsequently. Figure 5.3 attempts to combine the ice movements for which there is evidence, although the relative timing of ice shed 1 cannot be ascertained. It may be earlier because if there are striae corresponding to the Kebister Ness set on Bressay, they are not dominant and therefore probably older. If the two sets are unrelated and ice crossed Kebister Ness and did not reach Bressay, then ice shed 1 would be the most recent, a more reasonable explanation if the ice cap as a whole is retreating to the high ground of central Mainland.

Most of the rest of the evidence north of Channerwick is strongly suggestive of local ice moving under the influence of topographic and bathymmetric contours (figure 5.2). Striae are notably not perpendicular to topographic contours in the northwest of the area and as far south as West Burra. This can be explained by ice moving perpendicular to bathymmetric contours around the -100m level, i.e. into the West Fair Isle basin. There is no apparent shift to the -50m level, suggesting that by the time the ice front reached this location, little erosion was occurring. This is easily understood given the narrow spinal source area and steep slopes and may again suggest a late ice shed slightly west of the spine (see above and figure 5.5 - northeast). Around Gulberwick, it is suggested above that ice movement may reflect the influence of shallower bathymmetric contours. Continued supply of ice from the northwest to a later stage in deglaciation in this more northerly location (represented by a greater degree of topographic containment) is readily envisaged, with the ice cap retreating to the wider and (on average) higher altitude areas of central Mainland. The implication is that the southern spine of south Mainland may have been deglaciated earlier than central Shetland. To some extent this may be reflected in exposed possible solifluction deposits (figure 5.4 and plate: figure 5.15) on the hills above Burn of Mail (although it is not clear how widespread these are beneath peat) and rare cryoturbation structures near St Ninian's Isle (plate: figure 5.16). The age of these features is, however, not known, and their distribution may be limited. This latter point perhaps indicates that they are not of Lateglacial age since, there being no evidence of widespread glacial activity during this time, more widespread periglacial deposits would be anticipated if they were.

In the northwest of the area there is some evidence of changes in ice flow through the last glaciation (figure 5.2). Striae show that ice, at least at high level, crossed Whiteness and Stromness voes. However the distribution of drift suggests that ice has moved down Weisdale Voe (figure 5.4), in particular where a protrusion sticks out into the voe there is lodgement on the up Voe side and thin drift or glacitectonite on the down glacier side. This evidence of changing ice flow directions is more readily observed in the adjoining central Mainland area (figure 7.2).

In Dales Voe the golf course is built on a series of sloping, terrace-like, drift slopes. Sections are very limited but the upper surfaces appear to be underlain by diamict, whilst the lowest consists of fine gravels. A kilometre up valley from the coastline, a birdsfoot fan extends from a deep channel that drains a shallow enclosed basin above the valley to the west (figure 5.2 and plate: figure 5.17). The fan is clearly inactive and the minor stream in the voe flows around it. It is likely that it, and the lowest terrace of the valley, represents drainage from melting ice in the basin after the voe was deglaciated and the cutting passes through several metres of valleyside diamict. This assemblage of features suggests retreat of ice across Dales Voe to the west, possibly offering further evidence of a more western, late, ice shed.

5.3.3. The nature of glaciation and deglaciation

Only the evidence given above provides any suggestion of events occurring before the last period of deglaciation. This is not surprising: the last glacial ice cap is thought to have extended to the continental shelf edge to the west (more than 100 km from south Mainland) and perhaps 75 km or more to the east[35], and this part of the archipelago is only a few kilometres wide. The offshore sequence to the west suggests retreat and deposition of glacimarine sediments from the shelf edge to the Foula Ridge[36] (figure 3.13 and the Stormy Bank sequence (STB) in figure 3.15 (excluding the inshore basins)). To the east, across the East Shetland Platform, non-Holocene Quaternary sediments are patchily distributed and difficult to interpret (figure 3.15). The ice cap appears to extend 75 km to the east and initial deglaciation at least, may have also been through tidewater calving[37]. Only the terrestrial record, and the sediments in the West Fair Isle Basin are likely to give any indication of the nature of subsequent deglaciation.

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[35] Long and Skinner, 1985
[36] Stoker et al., 1993
[37] Peacock and Long, 1994

According to some reports the West Fair Isle Basin contains Quaternary sequences of 30m or more comprising compact grey clays with scattered pebbles[38]. The present writer has examined the borehole in a shallow part of the basin. Above the sandstone bedrock there is a thin (< 20 cm) gravel including weathered granitic clasts. Overlying this there are 4.75m of slightly sandy, soft, plastic, muds, with occasional shells in live position. This is overlain by 1.2m of Holocene shelly sands. The middle unit appears to be largely postglacial and there is no evidence of glacimarine deposition (such as dropstones, gravel, or laminated sediments). No detailed palaeontological work has been undertaken but it is likely, by comparison to other inshore basins (see chapters 6 and 7), that it represents a marine environment. The basal granite erratics could be from east or north of the basin and the weathering may suggest some subaerial exposure before sea level rose. It is clear that the basin deglaciated terrestrially and with little glacigenic sedimentation, possibly indicating *in situ* decay or subsequent erosion of any subglacial sediments. The subsequent low energy depositional regime suggests that significant marine erosion did not occur however. Finally, it should be observed that any significant preglacial sediments have been removed.

The erosive nature of deglaciation on terrestrial south Mainland is readily illustrated, although in northern parts of the area more prolonged ice streams have resulted in significant lodgement accretion (figure 5.4). This material is not melt-out till: four metres of diamict (such as that in Dales Voe) is unlikely to represent the consolidated thickness of the dispersed basal layer of the ice sheet, especially given the limited distance over which material can be incorporated into the layer. Occasional stone clusters support the lodgement interpretation in places. Preferential lodgement on the upglacier flanks of bedrock undulations is widely observed. In many sections, such as in Dales Voe, and on Bressay and Mousa, it is clear that lodgement has succeeded glacitectonization of the underlying bedrock. In some places the incorporation of the ripped material into the dispersed diamict is evident. Glacier, 'plucking,' is not a steady-state process, and this is illustrated here, where the plucked rocks increase frictional drag and become the basis of lodgement deposition. Differential lodgement against obstacles to ice flow demonstrates ice movement directions that can be independently associated with striae data of late stages in deglaciation. It is likely that much of this lodgement is therefore a relatively late development.

5.3.4. Burn of Mail

Morainic features of this valley have been reported and the author's 1:10 000 air photo interpretation is shown in figure 5.6.

The characteristics of hummocky moraine anticipated as an ice-marginal landform include planimetric bifurcations, down valley convexity, glacier-size-related lateral gradients (with

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[38] Chesher, 1984b

steeper gradients near valley heads), cross-sectional asymmetry, with gentler up-glacier faces (possibly with cuspate hollows due to inter-longitudinal-crevasse pressure), shear-folded, heterogeneous or homogenous diamictons, associated supraglacial and proglacial sediments and attendant landform assemblages[39]. At Burn of Mail there is only one small section (plate: figure 5.18) and this appears to be a homogenous diamict. There is evidence of bifurcation, and in places cross-sectional asymmetry: at the front of the main lower valley group, the distal slopes of the features reach 80° (plates: figures 5.19 and 5.20) whereas on the upglacier side they are less than 45° (plate: figure 5.21). Channels are cut through the moraine, in some places up-slope, suggesting hydrostatic pressure, although on the distal side they appear proglacial (plate: figure 5.20) and in all cases there is no commensurate drainage basin, indicating that they emanated from ice. These lower valley hummocks are the best developed and show all of the above features. They are up to 4-5 m high, larger than any of those further up valley and, with the channels as further evidence, probably represent a longer period of ice margin stasis.

There are abundant clasts of vein quartz on and within the features, possibly derived from a clear linear quartz vein further up the valley, showing that the ice responsible streamed through the valley rather than entering it tangentially. Two questions must be answered. Firstly, why is this evidence of valley glaciation so singular and localized? Secondly, when did it occur?

The glacier surface cannot be reconstructed in the absence of clear lateral moraines, evidence that the hummocky features represent its maximum advance, or ice-direction indicators within the valley, however even if the entire valley above the limits were filled wth ice, the equilibrium line altitude (ELA), must be less than 200 m at its highest. This is low relative to other western Scottish Loch Lomond Readvance ELA's, which on Skye are thought to range from 216m to 461m with a mean of 319m[40], average 357m on Rhum[41], and show an eastward rise across Scotland attributed to corresponding decline in precipitation[42], although on Hoy, Orkney, there are a number of undated corrie glaciers with ELA's in the region of 150m[43]. The low ELA's on Shetland and Orkney might be explained by extreme precipitation or lower temperatures. Both factors bear important relation to the position of the precipitation-bearing polar front. This is time-transgressive - it effects different places at different times as its position shifts from north to south and back through a glacial cycle - and such a low ELA would be anticipated early or late in the Younger Dryas episode, relative to the glaciation of northwest Scotland. The timing of the Loch Lomond stadial on Shetland is discussed elsewhere. It is likely that pack-ice

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[39] Bennet and Boulton, 1993a
[40] Ballantyne, 1989
[41] Ballantyne and Wain-Hobson, 1980
[42] Sissons, 1980
[43] Sutherland and Gordon, 1993b

extended as far south as St Kilda during the Loch Lomond/Younger-Dryas stadial[44]. This would have severely reduced the availability of moisture around Shetland.

If the features are attributed to the last ice sheet then comparison with Younger Dryas ELA estimates is of course irrelevant, but in either case such a low ELA would indicate glaciation in other locations, including the Laxdale basin immediately to the north. No similar features are evident in the south Mainland area, either on the ground or on 1:10 000 air photographs. We can do little more than speculate about this discrepancy. The combination of relief, valley shape and aspect, is unique in Shetland. The Mail catchment runs west-east, has a high amphitheatre-shaped upper valley and drops steeply to a relatively constrained lower valley. Lower altitude situations would prevent englaciation, wider valleys result in broader ice fronts, thinner glaciers and less dramatic morphological signatures, and protection from sun is naturally significant in determining the ELA of the glacier.

An alternative to the low ELA estimate would be allowed by a model in which the Late Weichselian ice shed was to the West of the Clift Hills and supplied ice from above them from the wasting ice cap itself (figure 5.5).

5.4. Conclusions

In summary, this section cannot claim to have resolved the issues surrounding Scandinavian glaciation and the configuration of ice sheds in south Mainland. It has however, demonstrated that it is not yet possible to propose a simple explanation for all the observed phenomena. On the southern tip there is good evidence of an easterly ice shed at some stage but only the Dalsetter erratic exists to imply that this was Scandinavian ice since the evidence on Bressay can be explained by shifting local ice sheds. Early deglaciation from the west could have the effect of shifting a linear ice shed centred over the central spine to the east, obviating any need for Scandinavian influence (figure 5.8). On the other hand, the reason why Scandinavian ice should overwhelm this southern spine but not areas further north (see central Mainland chapter 7) is easily modelled and this is explained in figure 5.7 in terms of topographic controls on the rapidity of englaciation. The strong north-south structure of the islands' geology part-justifies the use of a two dimensional illustration but where in the area the subsequent boundary between the Scandinavian and local ice sheets occurs would be dependent on the three-dimensional structure of the central mainland ice. The analysis given above indicates that this junction is not west of Bressay.

However it may only be on the southern tip of the area that ice from the east crossed the island at all, for erratics on the west coast further north may have sources offshore to the west. There is

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[44] Peacock et al., 1992; CLIMAP, 1976

other evidence of ice from a western ice shed flowing across the southern tip and deglaciation from such a position might explain the preservation of erratics on the west coast, ice direction indicators and channel heads around Noss Hill, the retreat pattern of ice across Dales Voe, and the morainic features of Burn of Mail. If it is accepted that precipitation sources were to the west, then *englaciation* would be expected ultimately to lead to the western movement of the ice shed as the ice cap itself topographically depleted precipitation from moist air masses travelling east. However it has been suggested that, subsequently, an eastern ice shed occurs in early deglaciation (figure 5.8) and a western ice shed later (figure 5.9). The mechanisms responsible for this are considered in Chapter 11. Although it is not possible to refute the premise of Scandinavian ice followed at some stage by a local ice shed flowing off the central spine and Fitful Head, it is possible to cast reasonable doubt on the accuracy, and certainly the simplicity, of these interpretations. Subsequent events include the streaming of topographically contained ice to both the southeast and southwest from the high ground of the northern part of the area and central Mainland.

Early deglaciation at the western margins, and possibly at the eastern, appears to have been glacimarine, but there is no evidence that this continued to the inshore West Fair Isle basin. The southern peninsula may have deglaciated relatively early, again due to the influence of topography, having a relatively low average altitude and steep slopes into surrounding offshore areas. Central Mainland appears to have continued to supply ice to northern parts of this area where it flowed, topographically contained, towards the -100m or -50m bathymmetric contours, specifically into the West Fair Isle basin. There is evidence of an earlier northeasterly ice movement across Bressay which may indicate that the deglaciation front reached northern areas before southeastern ones.

There is also little evidence of direct glacial activity in the area during the Younger Dryas period. If the characteristics of the Burn of Mail valley exceptionally resulted in a freak glacier at this time, then its ELA was very low. Similarly low ELA glaciers occurred on Orkney but, like the Burn of Mail glacier, these are undated.

6. The last glaciation of west Mainland

6.1. Solid geology, topography, and bathymmetry

The simplified solid geology[1], topography and bathymmetry of western Mainland are shown in figure 6.1. The oldest rocks in the area may be the acid and hornblendic gneisses that form the small group of islands (Ve Skerries) 6 km northwest of Papa Stour; these are potentially Precambrian (Lewisian). A band of metasediments across the top of the Walls peninsula, largely comprising muscovite-biotite-gneiss with some schist and occasional limestones, may be the result of the Caledonian orogeny. Much of the area is underlain by twice-folded sequences of Old Red sandstones with subsidiary rhyolites, basalts and tuffs. Granitic rocks outcropping in the south of the peninsula and on Muckle Roe are linked to plutonic complexes dated to late Caledonian times and much of the area is cut by dyke swarms. Offshore[2] (figure 3.2) to the west there are undivided sequences of sedimentary and extrusive igneous rocks with basins of Triassic and Permian sandstones to the north and south of the peninsula itself. Igneous intrusions are present around their terrestrial outcrops. The island of Foula lies southwest of the peninsula on a northeast-southwest trending bathymmetric ridge (figure 3.4) and is composed entirely of Upper Old Red sandstones except in the northeast where older, unclassed gneisses and schists outcrop with minor intrusions of microgranite of Old Red Sandstone age. The topographic significance of faulting is evident in Sandness, along Brindister Voe, and within the southern granitic intrusion (figure 6.1). Locally, sandstone dips dictate topography but regional trends are confused by multiple phases of folding. The northwest-southeast lineation on Muckle Roe does not appear to have any underlying structural control. The dominant bathymmetric feature (figures 3.4, 3.5 and 6.1) is the St Magnus Bay basin. Lying between the Walls peninsula, Esha Ness, and bounded to the west by a shallow sill, this is a fault-controlled basin[3]. There is also a basin to the south of the peninsula referred to as the West Fair Isle Basin. To the west of the Walls peninsula, the seabed rises to the Foula Ridge before dropping further westward to the continental shelf edge. The main voes deepen gradually seaward, to 10-20 m depth in places.

6.2. Previous work

Early authors noted that erratic carry across the area and onto Papa Stour shows that ice moved broadly east-west, and striae suggest more precisely from south-east to north-west[4] (figure 6.2). The idea that this northwesterly movement was due to the northward swing of a Scandinavian ice sheet[5] upon encountering the islands from the east was criticized on the grounds that there

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[1] Mykura, 1976
[2] Chesher, 1984a
[3] Chesher, 1984a
[4] Peach and Horne, 1879
[5] Peach and Horne, 1879

was no reason for an ice sheet to swing northwest under such circumstances[6]. The striae which indicate south-westerly movement of ice on the south coast are noted but not discussed by these writers. Subsequent account of these later brought the possibility that the last glacial maximum in the area involved ice movement off the peninsula[7] to the north-west, west, and south-west, with the ice shed lying in a southerly position (figure 6.2)[8]. However it is also recorded that erratic- and striae- founded interpretations of ice movement are in places divergent by 30° and there is evidence of due east-west erratic movement across Sandness[9] (figure 6.2). Multiple phases of ice movement may thus be in evidence and could be due to progressive deglaciation and shifts normal to bathymmetric contours as a result of rapid ablation at a calving marine margin[10]. The relationship of ice movement to bathymmetric contours is noted around Shetland as a whole by other authors[11] but no explanation for it given, probably implying that the pattern is due to gravitational topographic containment. On Foula (figure 6.3), early authors report northwest-southeast striae azimuth and interpreted northwesterly direction of ice movement, confirming the need for some agent to redirect Scandinavian glaciation to the northwest[12]. Later authors agreed, with the additional possibility of residual local ice from the island itself[13]. Subsequent work[14] has revealed more east-west striae and evidence of erratic carry both east to west across the north of the island and west to east across the south, as well as evidence of corrie glaciation. This data was interpreted as meaning that Foula supported local glaciers which were diverted both north and south by impinging Mainland ice. The existence of Spiggie granite erratics suggests that the impingement was from the south east, later supported by the additional observation of two northwest to southeast striae on the southeast coastline attributed to an earlier stage in glaciation[15]. The latter work also lists a considerable number of erratics derived from Mainland Shetland, including granodiorites almost certainly from the intrusive complex running from Bixter to Spiggie down the west coast of south Mainland (figure 3.1). These are reported on Foula at heights of at least 200 m and possibly higher. Metamorphic rocks from the Clift Hills and areas south are also reported, together with possible material from Walls and the Colla Firth Permeation belt of central Mainland. It is noted that striated surfaces are found beneath till sections containing these erratics and it is argued that ice completely covered the island with no nunataks being present, and further that, 'evidence,' of corries on the island is more accurately explained by recourse to other agents[16].

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[6] Horne, 1880
[7] Mykura, 1976
[8] Mykura and Phemister, 1976
[9] Mykura and Phemister, 1976; Mykura, 1976;
[10] Hoppe, 1974
[11] Flinn, 1977
[12] Peach and Horne, 1879
[13] Finlay, 1926
[14] Mykura, 1976; Mykura and Phemister, 1976
[15] Flinn, 1978
[16] Flinn, 1978

A belt of hummocks 1.6 km long is recorded across the island of Papa Stour[17] (figure 6.2) which must have been emplaced during overall deglaciation. The mounds trend north-south and individual cross sectional asymmetries are described as being slightly steeper to the east. The whole is interpreted as a terminal moraine attributed to a stillstand or readvance of the last glaciation. A number of possible residual glacier locations have been put forward[18] but only on the Sandness Hill plateau (figure 6.2) is there good evidence: a series of morainic mounds and sinuous ridges which contain only local material despite the proximity of erratic sources to the east; and meltwater channels terminating in small eskers. Both landform assemblages are thought to be evidence of late local glaciation[19].

The sedimentary infill of St Magnus Bay is up to 60 m deep in places. The borehole record is interpreted as containing about 4 m of till above the bedrock, 30 m of lacustrine material and 4 - 5 m of modern sands, with no other evidence of glacial or periglacial input[20]. Elsewhere this material is simply interpreted as Late Weichselian to early Holocene soft muds associated with the waning stages of the Weichselian glaciation[21]. The sedimentary infill of the West Fair Isle basin, which is up to 30 m thick in places, has not been examined in detail since there are few boreholes. The material is thought to be more clastic and may include till or glacimarine facies[22].

Immediately offshore to the west there is little in the way of Quaternary sediments over the Foula Ridge (figure 3.15) although there are pockets of glacimarine material (see below). The sea bed sediments of this area are sands and gravels. Beyond the ridge sub-glacial diamicts, 20 - 60 m thick, cover the shelf, forming a series of parallel shelf retreat moraines[23] on the outer shelf edge (figure 3.13) and grading into mass flow deposits that are at least partially glacigenic in origin on the shelf slope. The stratigraphic position of this deposit is post Eemian and, as the uppermost till sequence, generally supports a Late Weichselian age but no direct dating has been undertaken. Glacimarine sediments are identified in restricted embayments and may be up to 20 m thick. Ponded sediments are also seismically visible between the shelf edge moraines[24]. Again there is no direct chronostratigraphic data for these sediments (see chapter 10) but they are presumably Late Weichselian.

6.3. Outstanding issues

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[17] Mykura and Phemister, 1976
[18] Charlesworth, 1956
[19] Mykura and Phemister, 1976
[20] Cockcroft, 1987
[21] Stoker et al., 1993; Holmes et al., 1993
[22] Holmes et al., 1993
[23] Stoker and Holmes, 1991
[24] Stoker et al., 1993

The following issues arise in connection with the last glaciation of this area. Is the pattern of ice movement consistent with a single phase of glaciation or is it more probable that multiple movements are involved? What was the regional direction of ice movement at the last glacial maximum? What was the pattern of deglaciation, particularly into the St Magnus Bay basin? Was that pattern controlled by calving due to sea-level rise or not?. What evidence is there of stillstands or readvances in the area during deglaciation?

6.3.1. Single/Multiple phases of ice movement

The direction of ice movement across the area, inferred from striation, stoss and lee and erratic evidence, may reflect a broad regional ice movement of the glacial maximum or late local topographic containment associated with deglaciation, particularly into the St Magnus Bay basin, or both. The conclusion of this study is that there is evidence for both on the Walls peninsula and the reasons for this are clarified below where both regional maximum and late local ice movements are discussed.

6.3.2. Multiple phases of ice movement direction: glacial maximum

There are examples of striae on the Walls peninsula that show little or no relation to the topographic influence of the St Magnus Bay basin: near Voe of Dale, Vaila Sound, Seli Voe (a), on Papa Stour and the Ve Skerries to the northwest of Papa Stour, they show broadly northwesterly ice movement. On Esha Ness (figure 8.2) there are also northwesterly striae, as well as on high ground to the east of the Walls peninsula and elsewhere in northwestern Shetland (figures 7.2, 8.2). Up to 5 m of lodgement till has been deposited against the high ridge of Ward of Browland in the central area (figure 6.4). Like much till on the peninsula, this feathers out against the slope and is presumably lodged on the upglacier side of obstructions to west/northwest ice flow. Such a thickness of dispersed, matrix dominated lodgement till, in this location, is unlikely to reflect a short, deglacial phase of ice movement into the St Magnus Bay basin. Lodgement across Papa Stour thins westward, possibly for similar reasons and the pattern against eastern Muckle Roe and Aith Voe is also of interest (figure 6.4). The erosive topographic lineation of Muckle Roe must reflect prolonged, possibly repeated, northwesterly glaciation. Movement of erratics across Muckle Roe and central Walls, and from Sandness to Papa Stour, is also northwesterly. In the latter case, the topographic influence of St Magnus Bay may be discounted and across Sandness there are even metamorphic erratics from a directly eastern origin observed by the author and others[25].

It is therefore clear that some of the northwesterly trend is of regional significance rather than local streaming into St Magnus Bay. However, southwesterly ice movement is manifest in striae on the southern coast. The idea that these are contemporaneous with the northwesterly set and

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[25] Mykura, 1976

that an ice dispersion centre therefore existed on south walls with ice streaming both northwest and southwest from it has been put forward[26]. The required ice shed (figure 6.2) is an improbable and delicate configuration to maintain within an ice sheet that probably stretched to the shelf edge and may have been more than a kilometre thick. Its authors concede that the southwesterly striae could be due to a later phase of glaciation but consider this explanation unlikely due to the absence of, 'earlier,' northwesterly striae in the southern area. If, as contended in this study, northwesterly ice movement was regionally significant, why is no evidence of it preserved here as it is in north Walls? Two reasons can be given. The first is that solid geology on which the two sets are preserved is different: the relatively coarse-grained granitic substrate of the southern area is easily stripped whereas the relatively fine-grained gneissose northern peninsula is more resistant to erosion, a contrast evident in the landscape (plates: figures 6.8 and 6.9). Even though Muckle Roe is also an igneous intrusion outcrop, it is composed of finer-grained, harder, granophyre. There are areas where both sets of striae are preserved on the same bedrock type, i.e. sandstone, for example near Seli Voe (a), Vaila Sound and Voe of Dale, and indeed the proposed ice shed must be aligned broadly around the geological division (figures 6.1 and 6.2). The second reason for the, 'preservation,' of, 'earlier,' northwesterly striae in north Walls is that this is also the direction of later glaciation, so many of the observations may post-date those mentioned above.

Evidence of erratic carry westward across the southern area is potentially crucial to resolution of the issue. Observations of erratic carry onto the peninsula as a whole were noted at an early stage[27], but it is not clear how far south such observations are to be taken as being relevant and the present writer has not encountered any erratics of western provenance in the southeast Walls area. Staurolite schist erratics on the land between Sandsound Voe and Seli Voe (b) (figure 6.2) have eastern as well as northern sources[28] and are therefore unhelpful. The present writer has observed granitic erratics east of Seli Voe (a) and these again may be of eastern, northeastern, or southeastern provenance (figure 6.1). The direction of striation in the same area (figure 6.2) suggests that they came from the southeast and such evidence forces the hypothesised ice shed to run in a more north-south direction. This is incompatible with the movement of Staurolite schist mentioned above and would also result in southeasterly ice movement in the area south of Seli Voe (b), of which the writer can find no evidence. It is, of course, possible that the later southwestern glaciation of the south Walls peninsula, which was highly erosive, removed any erratics of eastern provenance.

It is here concluded that during the last glacial maximum of Shetland, or at an early stage of deglaciation, ice movement was broadly northwesterly across the whole of the area. It has been

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[26] Mykura and Phemister, 1976
[27] Peach and Horne, 1879
[28] Flinn, 1982

advanced that this reflects encroachment of a Scottish ice sheet to the west of Shetland[29] - erratics on Esha Ness are thought to indicate a consequent bending of local ice that has passed southwest over Hillswick[30] (figure 3.11). It is argued below that ice flow converged in the St Magnus Bay basin during deglaciation: the above erratic movement could be explained by divergence of ice upon leaving the basin at this stage or as the re-movement of erratics deposited in the basin at a late stage of a previous glaciation, or a more directly eastern ice movement. The present author prefers the latter explanation as discussed in chapter 8 on North Mainland, so that northwest movement across Esha Ness is seen as part of early regional glaciation. Offshore evidence implies that the Shetland ice cap extended to the shelf edge where a series of moraine ridges are identified in places[31] and there is no evidence of Scottish ice extending further north than Orkney (for example, on Fair Isle - see chapter 4). There is similarly no evidence for Scandinavian ice swinging north off southern Mainland. The absence of mainland schistose erratics in the southern areas of the Walls peninsula, even where the hypothesised local ice shed is not relevant, is crucial: the source of northwesterly movement across central Walls has, from erratic evidence, at some stage, been central Mainland; but across the southern coast, if the source was south Mainland, then any erratics have subsequently been removed. Alternatively, northwesterly moving ice neither crossed the south Mainland peninsula, nor, apparently, was shed from it. This suggests that the ice shed was just to the west of south Mainland and a summary reconstruction of these possibilities is shown in figure 6.5.

6.3.3. Multiple phases of ice movement direction: deglaciation

Following regional northwesterly glaciation, deglaciation resulted in changes in ice direction, very obviously on the south Walls peninsula, less so in the north.

On north Muckle Roe there are striae which diverge from the northwesterly topographic lineation and adopt a more westerly azimuth (figure 6.2). That pattern continues north from the area (figure 8.2) and striae observations around St Magnus Bay appear to converge on it. This convergence is improbable at the same time as a major ice stream crossing the bay in a northwesterly direction as described above. There are examples of striae of more northerly azimuth on the north east Walls peninsula which may also reflect a shift in ice movement into the basin but here the separation of the two trends, given the potential for minor variations due to local topographic conditions, makes this impossible to demonstrate conclusively.

Till distribution across northern Walls is also significant. In both east and west till development occurs (figure 6.4) but whilst it is well-developed as a sheet of dispersed lodgement in the west and on Papa Stour (plate: figure 6.10), it is patchy, locally derived, clastic, and found on the

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[29] Peach and Horne, 1879

[30] Peach and Horne, 1879; Flinn, 1977

[31] Stoker and Holmes, 1991; Stoker et al., 1993

upglacier side of obstacles in the east. Much of this latter area is severely ice-moulded (plate: figure 6.8) and even in central eastern Walls, where the author has examined bedrock beneath the blanket peat, around Sandsting for example, there is only a thin, clastic rubble, probably the remnants of a poorly sediment-laden ice mass, or no drift at all. The solid geology is similar and the difference in till development is anomalous. The explanation offered here is that ice moving northwest offshore from the northwestern coast does so over a relatively gentle gradient, whereas the gradient into the St Magnus Bay basin is high, basal velocities would have been greater and erosion more dominant than deposition except on the upglacier flanks of obstacles. This difference may not apply to earlier, regional, northwesterly glaciation. If ice were moving into the St Magnus Bay basin, and out the other side, across Esha Ness, towards the continental shelf edge as is suggested above, then the compression of ice in the basin itself would transmit reduced basal velocities back onto the Walls peninsula or other marginal areas. Alternatively the stream may have sheared across a block of largely inactive ice within the basin, also reducing basal velocities due to a reduction in the, 'bed,' gradient. In either case the absence of till around the basin would still require explanation. It is here proposed that at a late stage in glaciation, ice moved freely into the St Magnus Bay basin and either streamed out westward or disintegrated there. Such circumstances allowed the maintenance of basal velocities implied by the geomorphology, more so if ablation was occurring within the basin itself.

The ice movement southwest of southern Walls peninsula must have occurred when a sizeable ice mass remained over Shetland. There is no evidence of more southerly movement into the West Fair Isle basin. Such movement was presumably prevented by the existence of ice there already. However the southwesterly movement is not commensurate with an ice shed to the southeast, as discussed above for the glacial maximum, so ice must have been streaming into the West Fair Isle basin from central Mainland as it was streaming off the Walls peninsula. As discussed below, this is the beginning of the end of the ice mass over the peninsula itself.

It is concluded here that the regional trend of glaciation across the area at the last glacial maximum, or just after it, was northwesterly. The reasons for this are discussed briefly in the conclusion to this chapter, and then in the final synthesis, but the implied ice shed on the axis of central mainland may have run to the southwest, either west or east of the south Mainland topographic axis. An ice shed somewhere along the Walls peninsula with ice moving, erosively, southwest off the southern coastline, and possibly north into the St Magnus Bay basin, developed during deglaciation although it is unlikely to have been independent of central Mainland ice which also flows into the basin at a late stage.

6.3.4. The last glaciation of Foula

The peripheral island of Foula must be reconciled with the pattern described above. There do appear to be two senses of ice movement (figure 6.3): striae suggesting ice from the southeast diverging around the high ground of the island, with the exception of two in the south of the island which most probably reflect movement from the northeast; and erratics derived predominantly from the northeast and east. The author has not been to Foula and so can only advance the debate to a certain degree. Ice movement from the southeast to the northwest is consistent with the regional pattern discussed above, but the absence of erratics from southeasterly sources may again suggest that the ice shed latterly lay west of the south Mainland peninsula and that evidence of earlier ice movement from a more eastern ice shed has been removed. The movement of ice from the east, as suggested by some erratics, might also be responsible for a pattern of diverging striae around the high ground, particularly in northern areas. Erratics from the northeast, which may be associated with the striae on the southern tip of the island, are consistent with the northeast-southwest movement of ice discussed as a relatively late phase from the Walls peninsula (above). This overall interpretation however, is based on a sequence of events developed for the area as a whole and the author has not made any supporting local observations.

6.3.5. Nature of deglaciation

The seismically well layered sequences of sediment that are interpreted as being glacimarine occur widely across the western shelf, and shallow bores indicate that these probably occur more widely than mapped and are certainly glacimarine, comprising soft, well-layered muds, with dropstones. This would indicate glacier retreat into a marine margin at least as far east as the Foula ridge. The seabed sediments of the ridge itself are mostly gravels and sands of mixed provenance[32]. These are probably the clastic component of glacigenic material. Whether it has been winnowed by marine erosion and its original mode of deposition destroyed is not known. The British Geological Survey are currently investigating sea bed morphology around the Shetland Islands and there are possible morainic features to the west of the St Magnus Basin[33]. However, these have not yet been positively identified and the work is at an early stage.

The group of mounds that make up the moraine feature[34] on Papa Stour run north-northwest from Hamna Voe to Sholma Wick (figure 3.2). Individual mounds are visible on 1:10 000 air photos and the lineation is easily identifiable on the ground. The line is broadly parallel with striae and it could be argued that it represents a stream of drumlins rather than a terminal moraine. The former seems unlikely since the three hypothesised drumlin formation processes do not apply[35]: (1) moulding of previously deposited subglacial material - in this case the local, linear, nature of the feature is unexplained; (2) local variations in the textural properties of subglacial debris due to a variety of possible factors - none of which obviously relate to the

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[32] Stoker et al., 1993
[33] A. Stevenson (pers. comm. 1995)
[34] Mykura and Phemister, 1976
[35] Hambrey, 1994

formation of these linear features; and (3) the filling of basal meltwater cavities with a variety of stratified materials, particularly as a result of catastrophic flooding - and in this case the material appears to be massive diamict.

The hummocky form of the lineament is consistent with a variety of processes of end moraine production, but the report[36] that individual hummocks have a steeper eastern face is inconsistent since the ice contact side of terminal moraines is generally less steep[37] because the glacier has supplied material to the upglacier slope during progressive retreat or dammed slipped material, thus constructing a shallow slope, whereas on the downglacier side the slope is the angle of rest of the material of which the hummock is made. This model is not perfect and ice contact faces from residual inactive ice blocks may obscure the picture. However the present writer's observations suggest that the hummocks have steeper *western* slopes (plate: figure 6.11) and are only less steep on this side where the slope intersects a hummock or other relief further west (plate: figure 6.12). The slightly north-northwest trend may be the product of some topographic containment: although the relief of Papa Stour is not great, the feature broadly follows contours between Mauns Hill and Virda Field and can be seen in places to be adjacent to these topographic features (plate: figure 6.12). The larger hummocks, 5 to 8 m high and 20 m long, are found further west in the band, with smaller examples further east, suggesting that the ice front was stationary for longer in this western location. The composition of the hummocks is not known since there are no sections. In at least one location there is evidence of slipping of the material forming the hummock following retreat of ice, implying that the hummocks are at least partially composed of matrix sediments, although in all cases surficial large blocks of local rock are encountered. On the west shore of Hamna Voe there is a sequence of sediments including thin sands and gravels sandwiched between two tills which might represent an oscillating ice front (plate: figure 6.13). Overall, it is probable that the feature is indeed a terminal moraine, in which case its relationship with striae is contradictory (figure 6.2) and suggests a late ice front coming out of St Magnus Bay, possibly the extrusive divergence of flows converging on the basin discussed above (figure 6.7). The location of the moraine may be topographic: the sill at the western edge of the glacial basin, which includes Papa Stour, is a glacidynamically probable location for a stillstand, or, 'pinning point'[38]; the moraine would continue in an arcuate fashion and extend furthest west at the midpoint between Papa Stour and Esha Ness - here the greatest volume of ice would be streaming against the least elevated barrier. It will be interesting to discover whether the work being conducted by the British Geological Survey (above) coincides with this reconstruction. This reconstruction has two significant implications. The first is that the feature may have little or no climatic significance in terms of stillstands and readvances. The second is that it implies a less strong flow of ice from the Walls peninsula into the basin than

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[36] Mykura and Phemister, 1976
[37] Hambrey, 1994
[38] Greene, 1992

from elsewhere around it; the peninsula may not, therefore, be a major centre of ice dispersion, relative to central Mainland, at this stage. There may have been some blocking ice on the northwest peninsula but there are metamorphic erratics in Sandness which have an eastern origin and there are even two curious, southern pointing, striae on the island of Holm of Melby (figure 6.2) according to the 6" to 1 mile hand-drawn BGS drift map of the area. It is not known if ice was able to come onto Sandness from the northeast but if it is assumed that regional ice retreated to some consolidated core, then it is likely that the Walls peninsula was not part of it.

This latter point is consistent with the expected situation based on the average altitude of the peninsula relative to central Mainland. Ice on the peninsula would have lost mass considerably to the surrounding areas, at some stage both to the northwest and southwest (see above). At the same time, ice from central Mainland would also be diverted southwest into the West Fair Isle basin and northwest into St Magnus Bay (figure 6.6). The peninsula's supply would have been, ‘pinched out,’ and, if there was ice left, it may have stagnated. This situation is shown in figures 6.6 and 6.7 but it should be remembered that the relative timing of the events described above, including the formation of the Papa Stour moraine, is not known and they are shown on separate figures for simplicity only.

As across much of Shetland, there is little other evidence of the nature of terrestrial deglaciation. The lower parts of the Voe of Dale valley are clearly infilled with waterlain materials. Sections in this material (plates: figures 6.14 and 6.15) are, to the author's mind, clearly fluvioglacial: the discharges indicated are variable and higher than those occurring in the present channel which cuts through the infill creating terraces up to 2 m high (plate: figures 6.16). The upper part of the valley is dominated by bedrock with patches of diamict, possibly till, whereas till is more extensive in the lower valley (figure 6.4). The absence of fluvioglacial material in the upper valley may suggest that melting glaciers released large quantities of water but not such large quantities of sediment - the fluvioglacial material of the lower valley being largely reworked local lodgement till. This might again reflect a disintegrating, largely inactive, ice mass of some size, consistent with the, 'pinch-out,' of ice supply from the higher ground suggested above. Alternatively, the high discharges of the lower valley may be associated with drainage from a late, local ice cap on the Sandness Hill plateau to the north.

Sandness Hill is part of a relatively high plateau area, ideally suited to being a residual ice centre or corrie-glacier development site. The hummocky drift and fluvioglacial morphology identified[39] (figure 6.2) are restricted to its northern-facing slopes which, for reasons of aspect, are likely locations for residual or recrudescing ice. The mounds, which are generally orientated northwesterly and are composed of a sandy diamict with angular sandstone clasts, are

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[39] Mykura and Phemister, 1976

interpreted as being the product of a local glaciation. A crucial part of this interpretation lies in the absence of any metamorphic clasts despite metamorphic outcrops immediately to the east. These features are certainly associated with ice from Sandness Hill but it is not possible to determine whether they relate to the latter part of deglaciation, or a Loch Lomond re-glaciation. If the latter were the case, then the local equilibrium line altitude would again be less than 200 m above modern sea level (see chapter 5). The existence of an independent ice cap on the Sandness Plateau has been proposed as a possible explanation for the quantity of fluvioglacial material in the lower part of the Voe of Dale valley (above), however the proposal has not been investigated in detail and no other evidence of such an ice cap is offered here.

It is argued above that ice, at a late stage in the last glacial cycle, flowed rapidly into St Magnus Bay, converging from the southeast, east and northeast (see also chapter 8 on North Mainland). This continued for at least long enough to generate an identifiable erosive pattern on the flanks of the basin. It is also hypothesised that in order to achieve this, the ice must have been ablating within the basin at some stage. It is of regional significance, in terms of the extent to which sea-level controlled the demise of the last glaciation of Shetland, to know whether this ablation was glacimarine or otherwise.

The answer to this issue lies in the interpretation of the extensive Quaternary sediments of the bay which are up to 60 m thick. Cockcroft[40] has studied the BH 80/08 borehole (water depth 140 m.; depth drilled 47.75 m.; rockhead 34.6 m; percentage recovery 43%) and associated seismic data. He concludes that there is a small basal sequence of till, about 4 m thick, including metamorphic rocks from the surrounding landmass, beneath 29.5 m of low energy regime lacustrine sediments of interglacial aspect, and a Holocene, shelly, lag deposit on top of this. The extensive unit is interpreted as containing no outwash and no glacimarine sediments, nor evidence of active glaciation or periglaciation on the surrounding landmass. This proposed sequence is, in the clear sedimentary trap of St Magnus Bay, surrounded as it is by evidence of glaciation into it, somewhat implausible. Cockcroft's conclusion is that dead ice sat in the basin and routed meltout debris across it to the shelf areas beyond the western edge of the Walls peninsula. How the extensive sequence of low energy regime sediments, topped by a lag deposit, came to exist in St Magnus Bay over the Holocene, however, is not suggested. Indeed, Cockcroft concludes that the islands were not glaciated during the Late Weichselian at all. More recently[41] the sediments have been assigned to the Stormy Bank sequence, which is attributed to the waning stages of the Late Weichselian glaciation and which are, elsewhere, clearly glacimarine.

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[40] Cockcroft, 1987
[41] Stoker et al., 1993

The present author has examined the material in the core, records derived from it, and the interpretations of the above authors, in order to attempt to resolve the apparent difficulties of the sediment sequence and the terrestrial geomorphology (above).

The 4 m of basal material identified in the core is not identifiable as a seismostratigraphic unit, probably because it is within the resolution range of Sparker records and too deep for Pinger to penetrate. Crucially, it is not clear, therefore, whether the material is found only in the deepest part of the basin (which is penetrated by the borehole), or more extensively throughout. The recovered material represents only 25 cm and is a gravelly sand too disaggregated to determine its *in situ* fabric (plate: figure 6.17). It could be:

(a) a lag deposit derived from conglomeritic bands in the underlying Permo-Triassic sandstones;
(b) basal till;
(c) fluvioglacial outwash;
(d) glacimarine material;

The material comprises a gravel with some sandy matrix which is friable, but tough, and reddish brown. The gravel includes clasts up to 3 cm (a-axis) of sandstone and metamorphic rocks from the surrounding land. Although the sample size is extremely small, the absence of intrusive igneous rocks (granite/diorite) is noticeable. Clasts are sub-angular to rounded. Cockcroft[42] argues that the material is a terrestrial till, by tenuous comparison with extensive sequences on the other side of the islands (chapter 7). The present author's opinion is that the clasts are rounder than those in local terrestrial till but there is insufficient material available to conduct a well-controlled and statistically significant study.

A similarly washed sample from a conglomerate band in the Permo-Triassic sandstones of the same core contained some larger clasts (up to 5 cm) and possibly a more varied metamorphic suite, although again no granite. It should be noted, however, that the sample size was considerably larger than that available for the unit under investigation. Clasts were similarly sub-angular to rounded. With the available material, more detailed analysis is not possible and it is evident from the above comparison that the material could be an erosional lag from the underlying bedrock. If this were the case, however, then there is no glacigenic unit represented in this borehole at all and the lag deposit, which is 4 m thick in this location, must have survived glaciation since it is buried beneath sediments indicative of very low energy and possible gradual sea level rise (see below). Given the erosive nature of glaciation around the basin the outcrop of such a preserved deposit seems improbable.

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[42] Cockcroft, 1987

More significantly, it leaves no evidence of deglaciation itself. It has been suggested[43] that meltout material was routed across a dead-ice-filled basin. This is a doubtful explanation for the absence of fluvioglacial material - such an ice mass would not exist for long in a basin setting where ablation was occurring on the surrounding landmass. It is simpler to postulate that the basin does indeed contain deglacial material and that this is represented at the base of the core. The similarity with bedrock conglomeritic bands is quite consistent with a fluvioglacial explanation, since the clast source areas would be broadly similar as would the transport medium. No postglacial preservation issues arise. Hematite is mentioned on the core's ship log and may account for some of the redness in colour. Iron oxide development is common in fluvioglacial sands and gravels where water percolation is facilitated. It is not common in tills. It is not clear from seismic traces whether the material is more widespread but the conclusion of this study is that it is fluvioglacial in origin.

Regardless of interpretation, there is no evidence of glacimarine activity. Subsequent deposition is clearly very low energy - the material is almost entirely silts and clays - and the author has found no gravel or dropstones having examined the split core (plate: figure 6.18). Dinoflagellate cyst[44] analysis suggests a severe cold marine environment with two periods of amelioration (at 19 - 23 m, and much less significantly at 5 - 10 m). Below 10 m low cyst productivity and particular assemblages suggest a cold and severe climate in perhaps slightly less than full marine conditions. The presence of seasonal sea-ice is indicated and this may explain the low energy regime. At this point, perhaps, sea level was only just rising over the sill into the basin. Between 5 and 10 m conditions are perhaps more open but again with at least seasonal sea-ice cover. From 2.5 to 5.0 m there is a general warming, but not approaching modern temperatures. There were no significant findings below 25 m (i.e. within the fluvioglacial unit). Given the above, and whether or not the basal unit is a till, deglaciation at this stage was due to precipitation starvation or climatic warming, not rising sea level.

Less work has been undertaken on the sediments of the West Fair Isle basin to the south of the peninsula (see chapter 5). The author's own observations indicate that, at least sedimentologically, conditions were similar although no lamination is recorded and occasional molluscs in life position are observed. This may or may not imply the absence of sea ice and relatively warmer waters, leading to the tentative conclusion that the West Fair Isle basin was inundated later in deglaciation than the St Magnus Bay basin.

6.4. Conclusions

The simplest interpretation of ice directional evidence is that at the glacial maximum the Walls peninsula was crossed in its entirety by ice streams moving in a northwesterly direction that also

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[43] Cockcroft, 1987

diverged around Foula at its base and overtopped it by some margin. The ice shed lay at least as far east as central Mainland, if not further east at some stage (figure 6.5). The inshore shelf area and St Magnus Bay basin were stripped of sediment and substantial subglacial deposition commences to the west of the Foula Ridge, possibly due to the existence from that point of an unconsolidated substrate. Deglaciation was initially glacimarine across the outer shelf area to as far inshore as the Foula Ridge. Further inshore retreat appears to be terrestrial and rising sea level is then recorded in the St Magnus Bay. Deposition on land and inshore probably occurred during deglaciation but Walls is largely an eroded landscape. Ice sheds shifted dramatically. Ice converged into the St Magnus Bay basin, including from the Walls peninsula, and at some point the peninsula itself became a divide and ice flowed southwest from it as well. The supply of ice to the Walls peninsula from central Mainland probably, 'pinched out,' due to topography and what remained on the peninsula may have stagnated leaving a minor legacy of its little basal material (figure 6.9). Ice still flowing into and out of the basin dumped a moraine at the pinning point of the basin's western sill which included Papa Stour (figure 6.7). Subsequent retreat resulted in the deposition of fluvioglacial material in the basin but little or no till. It is possible that ice flow to the basin was also curtailed suddenly by increasing topographic containment in Sullom, Busta and Aith Voes. It may be that the Sandness Plateau maintained an independent ice mass for some time.

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[44] BGS internal report on borehole BH 80/08 (Harland - 1986)

7. The last glaciation of central Mainland

7.1. Solid geology, topography and bathymmetry

The solid geology[1], topography, and bathymmetry of the area are shown in figure 7.1. For reasons of scale the former is highly simplified: the principal components of the East Mainland Succession are shown but each of these contains a considerable mix of metamorphic rock types and some later igneous outcrops. The broad distinctions are evident in the strong influence of the north-south strike of the sequence on the topography of the area. The succession is divided into three divisions: the Yell Sound division (1, in figure 7.1) is composed almost entirely of migmatised psammites with quartzite bands; the Scatsta division (2, in figure 7.1) includes a lower (more western) group of pelitic Staurolite schists and an upper quartzitic group, the relative resistance of which is seen in the Scallafield ridge west of Weisdale Voe and Kergord valley as well as the high ground around Garder Hill. The Whiteness division (3, in figure 7.1) is composed of flaggy micaceous psammite with thinner bands of much less resistant crystalline limestone. The basal (most western) member is a 400 m thick example of the latter and is clearly identifiable as the north-south valley running between Weisdale and Dales Voes. The depression forming Whiteness Voe and Petta Dale as far as Hoo Kame is formed from another crystalline limestone member. The upper and easternmost members of the division include a limestone band that forms Lax Firth and the low ground between South Nesting and the South Nesting peninsula, and the psammites that form the Ward of Laxfirth peninsula, the South Nesting peninsula itself, and the high ground immediately to the east of the Nesting Fault from Clubb of Tronister in the north to Hill of Catfirth and Wadbister Voe in the south. The broad centre of the division is occupied by semi-pelitic and psammitic granulites with a major belt of migmatitic gneiss. Although the influence on topography is not as marked in this more homogeneous area, the trend of ridges follows the strike of these rocks and the effect is accentuated by high and often vertical dips. The metamorphic rocks forming Lunna Ness, Lunnasting and Whalsay are homogenous pelitic and semipelitic gneisses and are probably related to the Yell Sound (1) and Scatsta (2a) divisions. The Whiteness and Scatsta Divisions are tentatively correlated with the Dalradian of Scotland, and the Yell Sound Division with the Moinian.

There are three significant late Caledonian plutonic intrusions in the area, all forming relatively low ground. The area immediately west of Busta Voe is predominantly diorite and the areas north of Laxobigging and of East Hill of Gunnafirth are granodiorite but include large areas of the original metamorphic country rock which make up the high ground within these zones.

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[1] Mykura, 1976

Offshore around the area are undivided sequences of rocks, mostly schists, also believed to have been metamorphosed during the Caledonian orogeny[2] (figure 3.2). The igneous intrusion to the north of Laxobigging continues to outcrop some way into Yell Sound. A Permo-Triassic sandstone basin, referred to as the Fetlar Basin, is evident in the bathymmetry to the north of Whalsay (figure 7.1). The ridge on which Whalsay is situated continues northwest to include the Out Skerries, and then a trench is reached, the northern end of which is the Unst Basin and which is also infilled by Permo Triassic sandstones. Metamorphic rocks continue thereafter to the northeast onto the bathymmetrically raised Pobie Bank, sandstones and siltstones to the east and southeast across the East Shetland Platform.

The gap at Voe is a possible Devonian channel (figure 3.6)[3].

7.2. Previous work

Early authors[4] record striae azimuth in the east of the area, on Out Skerries, Whalsay, around Dury Voe, and Colla Firth, that are north-east to south-west, and interpret the direction of ice flow towards the southwest (figure 3.7). Excellent roches moutonées are referred to on Out Skerries, Lunna Ness and Lunnasting, generally in the manner: 'the *position* of the roches moutonées leaves no room for doubt as the direction of the ice-movement.'[5] On the high ground of the Weisdale Hill ridge in the west of the area, and further west (see chapter 6), striae of northwest-southeast azimuth are observed and interpreted as showing ice movement towards the northwest. Peach and Horne conclude that Scandinavian ice crossed the islands from the northeast and was diverted northwest by an impinging Scottish ice mass, the existence of which has been dismissed[6] as well as supported[7]. Striae not fitting the pattern, such as those observed on Whalsay showing northward ice movement, are attributed to later local glaciation.

Subsequent authors[8] attribute all the eastern coastal striae, and more, (see figure 7.2 for a complete inventory) to ice moving off the east coast of the area in various directions ranging from northeast to southeast. It is difficult to say how much this interpretation is influenced by crucial work on erratics (see below) but the conclusion directly contradicts the early interpretation. Although inferred ice flow lines on published figures are of offshore movement, mapped striae observation points are equivocal towards flow direction[9]. This caution is not evident in the early work discussed above. The correspondence between Peach and Horne and

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[2] Chesher, 1984a
[3] Flinn, 1977
[4] Peach and Horne, 1879
[5] Peach and Horne, 1879 (p.793) - present author's italics
[6] Horne, 1880
[7] Flinn, 1978
[8] Flinn, 1977; Mykura, 1976
[9] See, for example, Mykura 1976 (p.108, fig. 28), and compare Flinn 1977 (p. 140, fig 5) with Flinn 1982

Home[10] is instructive and suggests that the direction attributed to striae by the former authors may have little to do with the striae themselves, or supporting stoss and lee data. Others have argued, for example, with, 'absolute certainty,'[11] that the sense of direction on Out Skerries is the reverse of that suggested by Peach and Horne. The most considered striae dataset for the area is that of Flinn[12], where both azimuth-only and azimuth-and-direction striae and stoss and lee observations are given. In the latter cases ice flow is offshore. Such occurrences occur widely on Whalsay and the Out Skerries, less frequently on the Mainland. Flinn also maps, 'air photo striae,' which are lineations in drift or bedrock of a scale visible on 1:10 000 air photos. These correspond with local striae.

Between Swining Voe and Vidlin Voe in the northeast early workers[13] comment on roches moutonées with drift tails on the assumed downglacier side, again oriented northeast to southwest. Also mentioned are larger scale differences in till development: the greater volume of till on the eastern sides of Vidlin and Swining voes, in other words in the lee of the hypothesised southwesterly moving ice sheet, is compared with Dales Voe and Colla Firth which run parallel to ice flow and show no such drift asymmetry. This is taken as evidence that an ice sheet did indeed move on shore from the northeast, eroding the upglacier sides of Vidlin and Swining Voes but not the downglacier sides.

The early reported[14] clastic content of the drift on the eastern side of Swining Voe includes a nodular gneiss which outcrops on Lunna Ness to the northeast. This is the only erratic evidence offered for on shore ice movement in the central Mainland area. Much is made of the absence of dioritic clasts from the Busta Voe igneous intrusion in the west occurring east of that outcrop, permitting the inference that ice did not move from some ice shed to the west of Busta Voe, and of erratics being moved broadly westward onto and across the Walls peninsula (see chapter 6) and South Mainland (see chapter 5). But in this central area, although the same cross-island ice movement is favoured, no other erratic evidence is given. The erratic data of later authors[15] supports ice movement from central Mainland offshore to the east and west. In particular, the carry of erratics to the northeast as far as the Out Skerries conflicts with early theories of Scandinavian ice incursion. Instead it suggests that erosional ice movement information should be interpreted as offshore flow. Intriguingly, the, 'nodular gneiss,' used as evidence of the northwest to southeast passage of ice across Swining Voe, and with which this discussion of erratics began, is probably the, 'porphyroblast gneiss,' employed latterly[16] to demonstrate the reverse direction of flow (figure 7.2). Erratic movement from east to west onto the Walls

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[10] Home, 1880
[11] Hoppe, 1974 (p. 205)
[12] Flinn, 1982
[13] Peach and Horne, 1879
[14] Peach and Horne, 1879
[15] Robertson, 1935; Mykura, 1976; Flinn, 1982
[16] Flinn, 1982

peninsula from central Mainland is undoubted but there are no examples that can *unequivocally* be attributed to bedrock sources further east than the main Scallafield ridge[17].

The overall pattern of ice direction indicators in central Mainland is shown in figure 7.2. The northerly swing from Whalsay north has been attributed to the impinging influence of a Scandinavian ice sheet[18] and, alternatively, to the proximity of the -82m bathymmetric contour[19]. The causal relationship between the bathymmetry and ice flow is not specified. But elsewhere on Shetland, and around Whalsay in particular, inshore ice calving into a rising sea has been hypothesised[20].

Moraines are observed by Peach and Horne[21] at the heads of Dales Voe, Colla Firth, and Swining Voe, and near Voe, Voxter and Brae and are attributed to a late local ice mass flowing out of central Mainland. They have pointed out that they are more numerous where hypothesised ice streams converged such as at the head of Swining Voe: the spur between two streams is reported as being covered with lateral moraines which are distinct from the ground till in some sections. Others[22] describe the same features as 'hummocky drift,' and consider that they may relate to static accumulations of snow and ice possibly representing a minor Loch Lomond Readvance (figure 7.4). A number of boulder fields, terminal and lateral moraines identified near Loch of Voe, Olna Firth, and Colla Firth, and extensive fluvioglacial sediments in Kergord valley and Burn of Grunnafirth[23] are also thought to relate to this time, although the timing of the deposition of the fluvioglacial material is deemed uncertain[24]. Other possible Loch Lomond stadial glaciers[25] are dismissed as being based on the likely location of snow accumulation rather than on geological evidence[26].

Offshore Quaternary deposits in the inshore area east of Mainland and west of Out Skerries are less than 10 m thick except in the Fetlar basin where they reach 50 m. They are up to 20 m thick in parts of the Unst Basin but disappear onto the Pobie Bank further west[27]. They can be traced as patches across the East Shetland Platform as a reddish, stony, sandy, clay, and are interpreted as tills or glacimarine deposits[28] of Late Weichselian age and Shetland provenance[29] and reach an identifiable limit approximately 75 km to the east of the islands (figure 3.15). Dating from these sediments is discussed in chapter 10. The sediments of the inshore Fetlar Basin are

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[17] Mykura, 1976
[18] Mykura, 1976
[19] Flinn, 1977
[20] Hoppe, 1974
[21] Peach and Horne, 1879
[22] Flinn, 1977; Flinn, 1982
[23] Flinn, 1982
[24] Flinn, 1977
[25] Charlesworth, 1956
[26] Flinn, 1977
[27] Chesher, 1984b
[28] Long and Skinner, 1985; Long, 1988
[29] Peacock and Long, 1994

described as consisting of very soft, olive grey, silty clays rich in hydrogen sulphide, probably of post-glacial age, underlain by a compact grey till[30].

7.3. Outstanding issues

Some arguments put forward by proponents of Scandinavian glaciation have been ignored and these must be briefly mentioned. Also, the comparative wealth of information collected in the central Mainland area has not been fully scrutinized in terms of its interpretation: is only a single phase of ice movement represented by the directional evidence available, as suggested by later authors? How much of the glacial landscape is the product of the final period of ice movement? What were the mechanisms and patterns behind deglaciation? Is there any evidence of minor readvances or periods of stasis during or after deglaciation?

7.3.1. Scandinavian glaciation

The erratic evidence for a local ice cap of significant size streaming radially out from the area is convincing and the requirement for a nearby Scandinavian ice sheet to explain the northeasterly direction of striae and erratic carry is reasonably obviated when these are considered with respect to topography (see below). Although the observations made by proponents of the Scandinavian incursion[31] were a small subset of those now at hand, and although we may speculate on the influence of contemporary popular paradigm regarding northern European glaciation as a whole (see figure 3.8)[32], there are observations that seem inexplicable. On the Out Skerries all authors[33] are in no doubt about the direction of asymmetry of the roches moutonées but conclude totally different directions of ice movement. This is surprising, because the asymmetry and direction of ice inferred is described explicitly for other areas on Shetland where these authors concur (chapter 8). A brief examination reveals that the stoss and lee character in parts of the islands is by no means straightforward to interpret[34]. The asymmetry of drift development in key locations such as Vidlin Voe and Lunna Ness on a large scale, and the drumlinoid features between Vidlin and Swining Voes on a smaller scale, have also been ignored since they were proposed as evidence of onshore moving ice. In the section below on the nature of deglaciation, it is here argued that these are more probably evidence of offshore movement. The argument however is made on an understanding of glacial process-form relationships that is relatively recent. There remains the contradiction in the movement of erratics of gneiss from Lunna Ness to Swining Voe. The metamorphic rocks of this part of Shetland are highly variable and given the weight of evidence in favour of offshore movement,

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[30] Chesher, 1984b
[31] Peach and Horne, 1879
[32] see for example Peach and Horne, 1881
[33] Peach and Horne, 1879; Flinn, 1977;
[34] A Hall (pers. comm. 1995)

and the relative complexities of the local geological knowledge of the contending parties, the more recent data is favoured. However, the discrepancy remains unaccountable.

There is no clear evidence of Scandinavian or other eastern ice influence in this part of the islands. In the section on the nature of deglaciation (below) it is argued that much of the glacial landscape is the product of the final stages of glaciation, and that the processes were dominantly erosive. It is therefore conceivable that onshore ice movement did occur and evidence of it has been subsequently eradicated or is indistinguishable from evidence of offshore ice movement.

7.3.2. Multiple phases of ice movement

Recent reconstructions of ice movement off central Mainland[35] have sought to unify all the available spatial data in a single snapshot (figures 3.9 and 3.11). Others have argued for changes in ice movement direction during progressive retreat, especially around Whalsay (figure 3.10)[36].

Temporal reconstruction is based on the morphochronology of directions of ice movement and north and south central Mainland are treated separately in subsequent sections since there is little such evidence in the latter. It is reasonable to expect earlier directional information to be preserved in laterally and vertically peripheral locations, and it is the islands of the Out Skerries, Whalsay, Bigga and Little Roe in the north which present the greatest difficulty to the reconstruction of a single, all-encompassing, ice flow configuration. Such peripheral areas are not available for south Central Mainland (although see chapter 6).

Reconstructing changes in ice shed configuration is not straightforward. North of Dury Voe on the east coast, and on Whalsay, the pattern of ice direction indicators (figure 7.2) suggests convergence in the topographic low of the Fetlar Basin. Ice flow out of Dales Voe and across the island of Samphrey is also compatible with this, but striae azimuths on Bigga and the adjacent Mainland are northwest-southeast and granodioritic erratics on Linga suggest a more easterly, or even southeasterly movement. The pattern of striation of the Out Skerries is northeasterly which may represent movement into the Unst Basin or some regional phenomenon but not into the Fetlar Basin. Around Whalsay itself multiple directions of ice movement are evident in striae and these are incompatible with a single ice shed and published reconstructions either predate the discovery of all the evidence that is available now (figure 3.9)[37] or fail to discuss its implications[38]. Erratics from the granodiorite of Laxfirth appear on the Out Skerries and Whalsay, both to the northeast, yet the direction of ice movement across the source areas,

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[35] Mykura, 1976; Flinn, 1977;
[36] Hoppe, 1974
[37] Mykura, 1976
[38] Flinn, 1982

manifest in striae, air photo striae and the same erratics, is east to southeast. The islands of Nista and Moa off the east coast of Whalsay also suggest that the situation is complex: one is striated due east-west, the other contains an erratic which either came from the southwest, in which case the striation must post- or pre- date its arrival, or due west from the small outcrop on the north side of Dury Voe which is consistent with its neighbour's striation but not with those of the vast majority of Whalsay across which it must have journeyed (figure 7.2). The issue may be complicated by undetected offshore source outcrops (although none have been mapped and granitic intrusions within metamorphic country rocks are easily identified) or by multiple phases of erratic carry. Given the erosive nature of the glaciation (see below) it is likely that antecedent drift deposits were stripped and transported to the continental shelf before deposition occurred in these inshore areas so the multiple carry hypothesis between glaciations is less likely than changes in ice flow patterns at the end of the most recent.

In the southwest, on the Scallafield ridge, there are striae showing a broadly northwesterly direction of movement and, at lower elevations, southwesterly in the direction of the West Fair Isle basin (figures 7.2, 5.2). These are clearly not contemporaneous. Given the amount of evidence of multiple phases of ice movement elsewhere, the southeast coast of the area is remarkable in showing unidirectional ice flow. Questions nonetheless arise and these are dealt with in subsequent sections. An attempt is now made to reconstruct the last glaciation of the area through time.

7.3.3. North central Mainland ice shed movement

This kind of reconstruction is complex and must be broken down into discrete steps. The true impression is of a continuum of increasing topographic containment during deglaciation, yet there must have been some discrete scenarios maintained long enough to create a consistent impact on the landscape. It is difficult, however, to definitely correlate similar step changes between different areas and the precise sequence of events given below is tentative.

There were two ice movements across Whalsay, from the southwest and from the west, the latter being particularly but not exclusively evident in the southwest of the island (figure 7.2). Both striae and ice moulded bedrock show these movements and, accepting that they are not synchronous, we must ask which occurred first. Granodiorite has been entrained from Dury Voe and transferred to the Out Skerries, a northeasterly movement that must have passed over Whalsay and, assuming the Out Skerries deglaciated before areas closer to Mainland, was reasonably early. The wide spread of the erratics, and their occurrence on the east side of Whalsay suggests that their origin was the larger mass to the south of Dury Voe. The earliest identifiable ice shed therefore, must either have been southwest of here (evidence of its track subsequently destroyed), suggesting regional northeasterly ice movement, or due west of the source with some northerly diversion offshore (figure 7.5). Such a diversion might be due to the topographic influence of the Pobie Bank, Unst Basin, a more remote regional influence, or even the impingement of a Scandinavian ice sheet. In any event, for the stream to have reached the Out Skerries the Fetlar Basin and shelf area to the southeast of Whalsay must have supported ice to prevent reorientation normal to the bathymmetry of the Whalsay/Out Skerries ridge. It is argued below that, at a later stage, the ridge is a potential ice dispersion centre with ice moving both southeast and north. Topographic determination at this scale would also give rise to northwesterly movement across the Out Skerries into the Unst Basin but under these circumstances the transport of erratics from the distant Dury Voe is more difficult to envisage because the movement of ice southeast across the source area is unrestricted. In addition, while there is little to contradict the idea that ice flowed across the Lunna peninsula and along Colla Firth and Dales Voe at some stage, there is evidence of ice streaming northwest into Yell Sound, across the island of Bigga. This more northwesterly movement is consistent with striae on Yell (see chapter 9) and implies a stream of ice into Yell Sound. There is evidence of ice moving east from the adjacent Mainland into the Fetlar Basin, so this Yell Sound ice movement can be interpreted as further evidence of an early stage in which Fetlar basin was not as influential as it was subsequently (figure 7.5).

The idea that northeast movement was of regional significance and not due to the impingement of Scandinavian ice or the Pobie Bank is confirmed by heavy mineral analysis which shows the movement of terrestrial heavy minerals considerable distances offshore in this direction (figure 3.16 - compare with figure 3.9 but note that no evidence is given for the location or existence of Scandinavian confluence)[39].

The deglaciation of the Whalsay/Out Skerries bathymmetric ridge involves ice moving north into the Fetlar Basin and, since there are striae on south Whalsay aligned this way, the ice shed was perhaps somewhere to the south, implying broadly that deglaciation occurred in the northeast earlier than the southeast (figure 7.6).

Directional data across Lunnasting suggests predominantly northeasterly ice movement. Although the arguments below regarding the nature of deglaciation rather suggest that much of the pattern reflects late local glaciation into the Fetlar basin, the area contains granodiorite erratics probably from the small outcrop on the north side of Dury Voe which is an area latterly crossed by easterly moving ice topographically contained in the voe itself. This appears to be evidence of the progressive disintegration of an ice shed running broadly east-west down Dury Voe, probably contiguous with a linear ice shed on the Whalsay/Out Skerries ridge, and its progressive topographic containment within the voe. This is presumably accompanied by the deglaciation of the Whalsay/Out Skerries ridge. There are striae indicating southeasterly

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[39] Beg, 1990

movement, possibly even from an ice shed on the island itself and perhaps shown by the striae on Nista and some on Whalsay. Whalsay splits the broadly easterly ice stream passing down Dury Voe, which crosses its southeastern and possibly western edges in its passage to the southeast or the Fetlar Basin respectively. At some equivalently late stage, ice crossed the source area of the granodiorite erratics in an easterly or southeasterly direction (figure 7.8).

The picture in these peripheral areas is of more rapid deglaciation from the north and northeast than the southeast. If the stream of ice into Yell Sound is taken as being a relatively early event, perhaps contemporaneous with that crossing the Out Skerries in a northeasterly direction, then this further confirms the pattern. There appears to follow a shift in flow direction into the Fetlar basin but again from an ice shed to the south of Whalsay, then the development of the Whalsay/Out Skerries ice shed which demonstrates deglaciation in the southeast. Finally, progressive lowering until ice splits around Whalsay and deglaciation from the east and southeast occurs. This sequence is shown in figures 7.6 and 7.7. The position of the ice limits are not known at these stages and possibilities only are shown.

Reconstruction is less controversial once on Mainland because as the final ice shed is approached directional evidence is less diverse. Ice evidently moves into the Fetlar Basin across the Lunna Peninsula, although on the west side of the peninsula, and in Dales Voe and Colla Firth there may have been marginally more northerly movement once the peninsula can no longer be crossed and the Fetlar Basin loses its influence. Air photo striae inland of Hill of Vidlin may suggest similar reorientation once ice was unable to reach the Fetlar Basin from this more southerly area. Further south still, ice direction indicators show no dramatic late changes to the broadly easterly pattern. The evidence of both east and west moving ice from the area north of Dales Voe is of uncertain age but this relatively low northern area probably supported residual ice for a shorter period of time than more southerly parts.

The draw of ice into the St Magnus Bay basin on the west coast has been discussed in chapter 5. The broadly northwesterly direction of striation in the northwest of the area, particularly around Olna Firth, is most probably consistent with this and therefore reflects a stage in deglaciation during which that near-shore basin is topographically influential. It is unlikely that evidence exists of early ice directional movement at low elevations. Around Grobs Ness for example, the direction of glacitectonization of bedrock, in some cases associated with thin lodgement till development (plate: figure 7.11), is consistent with local high ground striae. There has therefore been an erosive northwesterly movement of ice in the area at some stage and the convergence pattern on St Magnus Bay suggests it was a late one. To account for this ice must be streaming as far as St Magnus Bay at least, suggesting that the ice cap at the time these indicators were created was thick. By simple comparison, at the same time it must have been streaming extensively into Yell Sound to the north, and have reached at least as far east as the Fetlar

Basin. It might be postulated therefore, that the pattern of glaciation into Yell Sound, or the Fetlar Basin, post-dates the commencement of that into the St Magnus Bay basin: erratic evidence shows ice moving westwards from at least as far east as Hill of Dale. Striae east of Voe suggest that the ice shed was further east than this also. Evidence of an earlier (thicker) eastern ice shed is evident in the clear stoss and lee forms observed by the writer at altitudes possibly up to 100m, again to the east of Voe (plates: figures 7.12 and 7.13). The overall impression is of deglaciation of a thick ice shed to the east of the central high ground (figure 7.5). Such conclusions are difficult to examine in detail since there is a broad gap in directional evidence, particularly erratic data, between western and eastern parts of the area.

7.3.4. South central Mainland ice shed movements

In south central Mainland reconstruction is more problematic because all directional evidence is remarkably consistent, prohibiting effective morphochronology, possibly due to the absence of peripheral areas upon which a longer record of directional data can be preserved from any but the most recent phase of deglaciation. Some relevant information is available from west Mainland (see chapter 5), regarding the regional northwesterly ice movement at an early stage in glaciation and curtailment of the supply of ice to the Walls peninsula over time. Bressay (chapter 5, figure 5.2) possibly also shows relatively early northeastern regional ice movement.

Erratics of Staurolite or kyanite schist (figure 7.2) are encountered to the east of their Scallafield ridge source area, on both the Mid- and East- Kame ridges. They also occur to the west on the Walls peninsula. The implication is that the ridge was an ice shed. However there are clearly striated and eroded surfaces on the ridge which have been interpreted as indicative of northwesterly moving ice on grounds of micro stoss and lee evidence[40], so an ice shed must also once have existed to the east of the ridge. Schistose granites of the central Colla Firth permeation belt are found as erratics further to the east of the Mid Kame source (figure 7.2) but there are no reports of Staurolite schists this far east, perhaps indicating that the Scallafield ridge ice cap did not extend further than Mid Kame, or that if it did any erratics were subsequently swept away. And while there are Scallafield erratics to the southwest of the source area on the other side of Sandsound Voe, there are none to the southeast, along Weisdale Voe, to where the schistose granites appear to have travelled slightly west. This is a complex and unresolved picture that does not lend itself to a single temporal snapshot reconstruction.

The cross-sections of figure 7.9 and 7.10 give two slightly different reconstructions. The Scallafield ridge rises to 280 m in places, considerably higher than the 160 m maximum of Mid Kame, and also higher than the highest point of the East Kame ridge, Hoo Kame, at 209 m. The differences in average heights are even more marked. It is reasonable to assume that ice build-

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[40] Hoppe, 1974; Flinn, 1982

up, particularly from westerly precipitation sources, was relatively rapid on the higher altitude ridge. Ice flowing from here may have overwhelmed the more easterly high ground, succeeded in transporting Staurolite schist erratics as far as East Kame, and possibly further. (The alternative hypothesis that the Staurolite schist erratics were deposited by a Scallafield Ridge ice cap near the end of deglaciation is discussed in the appropriate time sequence below.)

During deglaciation, ice must have moved across the Colla Firth belt that runs on East Kame, transporting erratics eastward. Ice must also have moved across the Scallafield ridge from the east in order to cause the erosion there. There are no eastern erratics on or beyond the ridge to the west so this ice acquired abrading materials from the ridge itself, and was probably clean prior to it. It is impossible to be precise, but these facts point to ice retreating from both the east and west, in the direction of an ice shed that lay somewhere to the east of the Scallafield ridge (figure 7.10). Here there may be evidence of earlier western deglaciation than eastern: assuming a westerly precipitation source, then any ice shed migration during englaciation would be towards the west; to achieve an easterly migration of the ice shed, western ablation is required.

Deglaciation also saw a significant southwesterly ice movement down Weisdale Voe, which transports schistose granites from eastern or northeastern sources. It is clear, from the glacitectonized bedrock, thin drift and marked striation on the sides of the voe, that this was a major ice stream (figures 7.2 and 7.3). No Staurolite schists, erratics of which are found southwest of Russa Ness Hill, appear in Weisdale Voe, although there are some examples of schistose granites on the more southerly, eastern side of the voe. There is no evidence, therefore, that this southwesterly ablation drew ice from the Scallafield Ridge down Weisdale Voe, rather that the source areas were further east and northeast. It seems probable that the Scallafield Ridge was a late, subsequent ice source for immediately western areas after the deterioration of a more eastern ice cap. This later ice cap may have been of sufficient dimension at its northern end to reach the other side of East Kame with a load of Staurolite schist erratics now attributed to a late phase of the cycle (figure 7.9). Since these have survived in a position to the east of the Colla Firth source area, from which schistose granites were transmitted further east still, this later time of deposition is the more likely.

However the morphological contrast between the areas immediately to the east and west of the Scallafield Ridge suggests an alternative circumstance. To the west there are large pockets of hummocky moraine (figure 7.4). These occur in linear bands, following the strike of valleys. Their nature and position is discussed below, however unless they represent a Loch Lomond stadial glaciation they confirm that ice retreated actively from the west. To the east of the ridge, no such constructional features exist and the largest quantity of fluvioglacial material on Shetland is located around Kergord in the Weisdale and Kergord valleys (figure 7.3). The more eastern Petta Dale is more difficult to interpret because of the extensive peat cover but appears to contain less drift. It could be argued that there is more material in Kergord because the valley was being fed by active ice for longer, whereas the Petta Dale valley contains only the basal meltout of the last resident ice which contained little debris. What is critical however, is that there is no evidence of constructional forms in either, suggesting that residual ice here decayed *in situ*. This asymmetry between the nature of deglaciation between the east and west sides of Scallafield may reflect the decay of an ice shed to the east of the Scallafield ridge rather than on top of it, as indicated in figure 7.10.

It is difficult to establish a clear sequence of events for this south central mainland area, but there is little doubt that the available evidence points to dynamic and significant changes in the ice configuration of the area. In particular, there is evidence of relatively early western deglaciation resulting in a more eastern ice shed that may have decayed *in situ*.

7.3.5. Nature of glaciation and deglaciation

Late Weichselian sediments appear to reach a limit about 75 km to the east of the area[41] (figure 3.15). Till or proximal glacimarine sediment, often forming positive bathymmetric features which might be end moraines, with high undrained shear strengths (>150 kPa), have been identified. A vibrocore 60 km from Mainland penetrates an interstadial marine mud (the chronology of the sequence is discussed in chapter 10), and below this a soft-sediment deformation till or subaqueous slope deposit with molluscs dating to the end of the last glaciation of the area[42]. The nature of this sediment is of concern for the present discussion. The authors assert that if it was a lodgement till then the shells would have been more damaged than they are. It is also probably the case, in the present writer's experience, that the vibrocore would not have penetrated 1.5 m of the material because lodgement till is generally too clastic for successful vibrocore penetration. The question arises as to whether these two observations should be any different for deformation till. The alternative hypothesis suggested by the authors is that the sediment is a glacigenic subaqueous debris flow although they feel that the slope of the platform is insufficient to support this interpretation. Presumbably this would be part of a glacimarine environment. The incorporation of shells that died at around the Late Weichselian maximum into the sediment suggests either a minor readvance, or burial in the proglacial setting. The latter corresponds to the subaqueous glacigenic debris flow interpretation of the diamict and a local ice margin may offer some topographic or hydrologic support for such a flow, but the establishment of deformation till conditions beneath a minor readvance is perhaps more questionable. At any rate, deformation till must have some pre-existing nature and, for the reasons outlined above, this was probably not lodgement till and therefore would have been glacimarine. This leads to the conclusion that early deglaciation of the Shetland ice sheet on this

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[41] Long and Skinner, 1985; Long, 1988;
[42] Peacock and Long, 1994

coast was probably glacimarine. It should be noted however that the molluscan assemblage of the unit predates the incursion of warm, north Atlantic waters into the North sea (see chapter 2).

Further west, across the East Shetland Platform to Mainland, there are generally either no Quaternary sediments or a very few areas with more than 0-5 m. The latter are difficult to resolve seismically and vibrocore logs suggest that they are muds and clays. The sea bed sediments are highly carbonaceous sands, in places organized into sandwaves, with some gravel lags, and are otherwise underlain by bedrock. The latter may partially be reworked Late Weichselian sediments and the British Geological Survey are currently working on possible morainic features evident in sea bed morphology[43]. This work is at an early stage however and the distinction between bedrock and drift morphology is not clearly resolved.

More extensive sequences have fortunately been preserved in the Fetlar and Unst Basins, and the topographic valley extending south from the latter (figures 3.4, 3.15 and 3.14). It is regionally important whether there is evidence of glacimarine processes in these areas. The Unst basin is discussed in chapter 9. The Fetlar Basin sediments are recovered in Borehole BH 80/02 and are described as soft muds of postglacial age, overlying a compact, grey, till or bedrock lag deposit[44]. The shipboard log shows:

0 - 3.5	Holocene muddy, very fine, sand with numerous shell fragments
3.5 - 4.6	Highly plastic, very soft, reddish brown clay
4.6 - 5.0	Grey, fine sand
5.0 - 6.75	No recovery
6.75 - 7.10	Fine micaceous, well sorted mud
7.10 - 7.5	Alternating laminae of fine and medium sand
7.5 - 7.6	Fine - medium sand; probably bedded
7.6 - 12.0	No recovery
12.0 - 12.2	Sand with angular to subrounded pebbles of quartz. Till or weathered bedrock
12.2	Rockhead - although difficult to identify with certainty. Bedrock is pebbly quartzose sandstone with conglomeritic bands including quartzite, schist, psammite, hematite stained quartz.

Quaternary calcareous tests above12.10 m are extremely sparse, showing increasing diversity up-borehole and generally shallow, cold, marine conditions, with a possible amelioration above 4.85m[45].

The present writer has also examined the core. The sediments at 12 m are difficult to interpret but washing the clastic content reveals that it is invariably quartzitic and this suggests that it is

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[43] A. Stevenson (pers. comm. 1995)
[44] Chesher, 1984b
[45] British Geological Survey internal report 95/501 - PDL 84/17

an erosional lag from the underlying bedrock. Difficulty in identifying the rockhead supports this but it should also be noted that conglomerate bands further downhole have more heterogeneous clast assemblages, including schists, and there is no recovery or data from the overlying 4.5 m, so it is dangerous to discount the existence of till or fluvioglacial material within the basin. The laminated sands and clays at 7.10 metres may indeed have a glacimarine origin controlled by rhythmic hydrologic variation (plate: figure 7.14). They are probably marine (although only 2 foram. tests were counted at this level) but do not appear to have any clastic component. If these sediments are related to glaciation then there were no icebergs calving into the basin and they are distal to the ice margin. An alternative possibility is that the variations are due to seasonal fluctuations in sea ice altering the energy regime of the basin and this may be evident up the rest of the core. The increasing diversity of the assemblages perhaps reflects rising sea level and the amelioration above 4.8m the beginning of the Holocene. Therefore the Fetlar basin was probably not a calving basin and ice converging in it must have exited to the east. As with St Magnus bay, retreat appears to have left little depositional evidence and was terrestrial. Sea level rises into the basin after ice has departed although it remained extremely cold. Like the St Magnus basin the retreat pattern of ice (discussed above) and topography might have conspired to cut ice supply to the basin suddenly, leaving ice decaying *in situ*. In this zone close to the ice shed, and as discussed below, it is not likely that the sediment transporting basal layer of the ice was very thick and the absence of much diamict in the core may be explained in this way. It is important to emphasize however that this borehole was not taken in the deepest part of the basin and seismic lines show an identifiable unit between the rockhead and the marine clays that can be traced into the Unst Basin to the east[46]. The sediments of the Unst basin are discussed in chapter 9 but this seismic correlation reveals that, over much of the Fetlar basin, the sediments described above may be underlain by subglacial diamict.

Borehole 77/60 (60-01/327) is located to the east of Out Skerries, in the tail end of the Pobie Bank trench. Recovery is extremely low and interpretation can only be based on trace materials. The rockhead appears to be at about 7 m and is overlain with pink clays, and shelly, sandy gravels. There are occasional metamorphic clasts up to 3 cm that are edge-rounded and faceted. However interpretation of this material is difficult in the absence of *in situ* superposition and fabric.

It is clear from terrestrial drift (figure 7.3) that the dominant processes are erosive. Tills are widely underlain by glacitectonized bedrock. This sequence implies early plucking and incorporation into a more dispersed matrix and ultimately a switch to lodgement deposition. The pattern is evident in all areas. Till is often thicker on central Mainland than elsewhere in Shetland and since the thickness of the dispersed layer of the basal ice in an area so close to the

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[46] Chesher, 1984b

ice shed would not be great enough to produce thick melt-out facies this material must be accretionary, i.e. lodgement. Stone clusters, stone pavements, and fines bands are all partially diagnostic of lodgement and can be identified in some areas. This lodgement is probably a relatively late, deglacial event. In places it occurs in positions on the up-glacier side of obstacles to flow such as at Lunna Ness and Lunnasting and the south Nesting peninsulas. Smaller scale examples have been observed by the writer in Weisdale Voe and Little Holm in Cat Firth. This pattern is in keeping with the direction of ice movement recorded by other means as due to a late stage in glaciation (see above). In some places the underlying glaciotectonized bedrock records the direction in which ice is moving and on Grobs Ness (plate: figure 7.11) this is in keeping with striae and erratic carry there. A similar conclusion can be reached on the east coast. Although the south side of Dury Voe evidently supplied erratics to the northeast that are preserved on Out Skerries and Whalsay, the direction of erosional indicators on the source area is east and southeast. Glacitectonization cannot be treated as a separate, earlier event than lodgement. Invariably it is found that the clasts in the lodgement till are dominantly local and that these are usually more angular than their further travelled neighbours. The transition from the glacitectonization of bedrock to the lodgement of till may be a rapid process associated with increased frictional resistance. In this respect lodgement and erosion are part of a continuum of processes bounded by intrinsic thresholds. These appear to occur relatively late, so evidence of earlier ice movement may have been removed.

The warm-based nature of the system is evident from all that has been said above, but additional evidence is available. At Cat Firth there are significant bands of sand and gravel within the diamict (although this section is now inaccessible behind coastal defences) and on the east coast of Swining Voe there are washed gravel bands 5-6 cm thick within the diamict. There is a small esker at Grobs Ness (plate: figure 7.15), not more than a metre high but clearly sinuous and containing a more gravelly material than the underlying diamict. In some locations there is evidence of meltout: north of Brae there is 0.5 m of more gravelly washed material above the diamict but the boundary is unclear and does not appear to be periglacial or subsequent wash; and at Foraness Voe, there is 0.5 m of deformed sand bands with large clasts (plate: figure 7.16). Some of these are relatively peripheral areas by contrast with the sands and gravels of Kergord. There are other areas with fluvioglacial material but none with quantities similar to those in Kergord or in the Voe of Dale valley on the Walls peninsula (see chapter 6; plates: figures 6.14 and 6.15). There is little evidence therefore of any considerable deglacial flux of material from the englacial to proglacial environment. This may indicate a low glacial sediment load, high deglaciation rate, or both.

The author has encountered no evidence of periglacial modification of the sediments in Central Mainland.

7.3.6. Hummocky moraine

Hummocky moraine has been mapped in various locations and it has been argued that it represents debris associated with static collections of snow and ice during the Loch Lomond stadial[47]. The areas are shown in outline in figure 7.4. There is no evidence of the age of these features, although for them to be associated with the Loch Lomond stadial then the regional equilibrium line altitude would need to be less than 200 m above modern sea level. They do not appear to be associated with static accumulations of snow and ice however. Their size and morphology is highly variable and some are certainly significant constructional features clearly associated with active ice margins. This is best illustrated with the two most well developed areas which are on the west side of the Scallafield Ridge, and west of Souther Hill. In the former case there are ridges 8-10 m high and up to 100 m long, parallel to the Scallafield ridge and with some cross sectional asymmetry (plate: figure 7.17) suggesting glaciation from that high ground and the formation of a series of terminal moraines. In the only section the author has been able to find, a coarse, angular, diamict was observed, again inconsistent with the washed sediments anticipated by formation associated with inactive ice. The hummocks in this case occur in topographic lows between north-south trending ridges. This is to be expected of the interaction between glaciers and cross-flow topography and the location of the moraines is not necessarily of climatic significance. Similarly to the west of Souther Hill there are examples of hummocks with clear cross-sectional asymmetry, the shallow side upslope and upglacier (plate: figure 7.18). These hummocks reach 5 m in height and 10 m long. Elsewhere the size of hummocks is much less significant and it is often difficult to tell what contribution peat, bedrock, hummock and post-depositional drainage channels make to the visible morphology. In places such as Dales Voe and Colla Firth, the broad disposition, as shown in figure 7.4 may again suggest debris accumulation from ice entering the valley from the side rather than at its head, consistent with glaciation from the highest ground. It seems likely that these features indicate progressive retreat to the highest ground in the area during a deglaciation but without dating control it is not possible to rule out a Loch Lomond stadial age. The chronostratigraphic issue as a whole is discussed in chapter 10 but the evidence given there cannot be related to the morphology discussed here.

7.4. Conclusions

There is widespread evidence of erosional activity in central Mainland and all observations of glacial action probably relate to the deglacial period. If Scandinavian ice crossed Shetland in the early part of the glaciation it is therefore not surprising that no evidence of its passage remains, although there is evidence of an early, relatively eastern, ice shed. Evidence of striae on the

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[47] Flinn, 1977, 1982

Scallafield ridge and other ice direction indicators further north and the pattern of ice movement into Yell Sound points to an ice shed to the east of the main high ground in Mainland (figure 7.5). If this is not Scandinavian glaciation then it probably reflects relatively early deglaciation from the west. Whilst a local ice cap would build up on the high ground and the ice shed would ultimately migrate west if precipitation was from the west, early western deglaciation would account for an eastern migration.

It is not possible to consistently account for all ice direction indicators on eastern peripheral areas in a single, atemporal, reconstruction. On the grounds that laterally and vertically peripheral locations preserve older patterns, a tentative reconstruction is given in figures 7.5 to 7.8. On the eastern coast early deglaciation was probably from the north and northeast (figures 7.6 and 7.7) and later from the south east (figure 7.7). The pattern suggests early deglaciation at the northern and northeastern margins of the ice sheet followed by increased topographic containment. The glacimarine sedimentation of the East Shetland Platform does not appear to be reflected in inshore areas. This again suggests glacimarine deglaciation to some limit following which deglaciation was terrestrial, with sea level rise to modern levels after the disappearance of ice at least to the high terrestrial ground. The step change in the nature of deglaciation may coincide therefore with bathymmetry and the British Geological Survey's work on sea bed morphology (above) also shows some correspondence with water depth. There are difficulties with this reconstruction. Firstly, it is unlikely that deglaciation occurred in the discrete steps shown - more likely there was some continuum of progressive deglaciation and topographic containment, although this does not preclude step changes. Given this, it is difficult correlate local patterns from different areas. This is particularly true of incorporating the west coast reconstruction into the time frame of the east. It has been suggested that deglaciation started here early but its progress at each point in the east coast story is difficult to assess.

There is evidence of morainic features around the high areas of central Mainland. Their location appears to reflect topographic control and they remain undated.

8. The last glaciation of north Mainland

8.1. Solid geology, topography and bathymmetry

The solid geology[1], topography and bathymmetry of the area are shown in figure 8.1. The oldest rocks are the acid and hornblendic gneisses of possible Precambrian (Lewisian) age that outcrop in the northeast corner (A in figure 8.1). The belt of younger metasediments associated with the Caledonian Orogenic Belt (B in figure 8.1) includes an older group of impure, quartzitic, hornblendic gneiss and muscovite schist and a younger group of greenschist and calcareous rocks. These rocks are dated to the Caledonian orogeny but cannot be equated with the metamorphic rocks of Mainland and no correlation with the Moine-Dalradian sequence of Scotland is possible. Their broadly north-south strike is responsible for the north-south lineation of the topography across the north of the area and down the east coast as well as the more northeast-southwest lineation to the west of Lamba and Gluss Isle. The existence of Hillswick suggests some relative resistance within the confines of St Magnus Bay. The peninsula of Esha Ness comprises a sequence of rhyolites, andesites and tuffs, and a small outcrop of sandstone. These are very evident as the low relief ground to the west of the Melby Fault and are part of the Melby Formation which also outcrops on Sandness in west Mainland (see chapter 6) where two fish beds are correlated to the Eday Fish Bed of Orkney. The sequence is therefore of Devonian age. The area is topographically dominated by the Ronas Hill Plateau which is part of the probably interconnected series of Late Caledonian plutonic intrusions of the islands. In this area most of the complex is granite although there is a major band of more dioritic aspect running southward from Ronas Voe and more minor outcrops in the northern part of the plateau. With the exception of the Melby Formation of Esha Ness, swarms of dykes cut the entire area.

The granitic part of the intrusion continues to outcrop some way into St Magnus Bay (figure 3.2), including all around Hillswick, but the bathymmetric depression of the bay is the product of the fault-controlled Permo-Triassic sedimentary basin (figure 3.2) discussed in chapter 6. Undifferentiated metamorphic and igneous rocks continue some way offshore immediately to the north of the area, but the Walls Boundary fault is delineated by the eastern coastline and Yell Sound is underlain by a granitic intrusion to the south of Colla Firth and undifferentiated metamorphic rocks of the Mainland series to the north (figure 3.2). Similarly to the west the Melby fault comes close to the shore of North Roe and west of this is a band of undivided Devonian rocks including extrusive igneous varieties (figure 3.2). The long profile of Ronas Voe, including a lip at its mouth, may be suggestive of glacial over-deepening[2]

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[1] Mykura, 1976
[2] Chapelhowe, 1965

8.2. Previous Work

On the east coast of the area the general azimuth of striae observed by early authors[3] (figure 3.7) between Ollaberry and North Roe is southwest-northeast, although at North Roe and on Fethaland point, southeast-northwest examples are noted. The main set are interpreted as having a southwesterly direction due to the main Scandinavian glaciation. The exception at North Roe is interpreted as showing a southeasterly direction of ice associated with a later movement of ice down the bay. The northwest-southeast azimuth striae at Fethaland are interpreted as being evidence of ice moving to the northwest on low ground while maintaining the general southwest movement on higher ground. A similar argument is given for the variation in striae azimuth along Ronas Voe, from west at its head, to northwest at its mouth. The striae south of these areas, as far as Mavis Grind, are described as indicating ice movement from the east to the west, and the description of stoss and lee faces around the area, 'the smooth slopes looking to the east, while the rough slopes face the west,'[4] confirm this. A detailed study has been undertaken of the glacial evidence of the North Roe area (north of Ronas Voe), including glacial striae[5] (see figure 8.2). Two sets are resolved, a northeast-southwest azimuth set dominating the east coast of the area, and a northwest-southeast set over the rest of the area. The first group are assumed to show ice movement from the northeast, 'coincident with the land ice from Scandinavia postulated by Peach and Horne (1879).'[6] The second group are taken to indicate ice moving to the northwest on the grounds of erratic evidence (see below).

The movement of erratics noted by early authors[7] includes: the absence of more western dioritic and extrusive varieties on the eastern coast of the area around Ollaberry; the western movement of the eastern metamorphics onto the intrusive igneous central area; and the translocation of intrusive igneous rocks to the lee of the Hillswick metamorphic area and further west to Braewick. Erratics from all areas to the east are found on the Esha Ness peninsula. Across North Roe[8] drift is reported highly variable. Along the east coast north of Ollaberry, except in Burra Voe and north and west Colla Firth, a grey clay is variably well-developed, containing no granitic erratics (which would have indicated ice movement from the west) and an assemblage otherwise suggestive of movement from the east to the west. A grey clay also infills Burn of Sandvoe on the northern coast and the low ground between Burra Voe and Sand Voe in the northeast but this includes granitic erratics from the south and west. In Colla Firth, and around the northwest coast of the area, till derived largely from the granitic mass is reported. Other authors identify the northwesterly erratic carry across the Ronas Hill plateau and the east-west carry across the southern part of the area[9].

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[3] Peach and Horne, 1879
[4] Peach and Horne, 1879 (p.792)
[5] Chapelhowe, 1965
[6] Chapelhowe, 1965 (p. 63)
[7] Peach and Horne, 1879
[8] Chapelhowe, 1965
[9] Mykura, 1976

Some[10] have ignored the complexity of the directional data in North Roe, indicating that ice simply flowed from the southeast to the northwest across the area (figure 3.11), and others[11] acknowledge it but do not offer any sense of the events necessary for its creation. Two works[12] suggest an early Scandinavian ice sheet responsible for the deposition of the grey till on the east coast of the area, followed by more local glaciation from the Ronas Plateau itself, followed by minor corrie glaciation on the plateau. This final event is inferred from corrie features on the northern face of Ronas Hill[13].

Offshore, Quaternary sediments are thought to reach 30 m thickness in an elongate basin running between and beyond this area and Yell[14] (figure 3.15) but there are no boreholes in the sequence. South of Esha Ness and Hillswick, in the St Magnus Bay basin, are Quaternary sediments up to 60 m in thickness and these are discussed in detail in chapter 6. Otherwise the surrounding inshore area is largely devoid of non-Holocene sediments. Further offshore to the northwest, Quaternary sediments thicken towards the continental shelf edge. The uppermost units are thought to be of last glacial age and comprise the stiff diamicts of the Otter Bank sequence, thought to represent subglacial or proximal grounded glacial till, and the overlying Stormy Bank sequence which in this area is glacimarine and contain dropstones - a zone of iceberg keel marks is evident near the shelf edge[15]. These data are shown in figures 3.15 and 3.13

8.3. Outstanding issues

A number of issues require resolution in this area. North of Ronas Voe more than one phase of glaciation is indicated but is it necessary to invoke Scandinavian influence and, if not, how are the various directions evident in striae and erratics to be explained temporally? South of Ronas Voe there is an evident change in ice direction from east-west in the east to northwest-southeast in the west. Erratics are taken as showing broadly east-west movement. How are these contrasting ice directions to be explained? If these changes occurred during deglaciation, what are the mechanisms responsible?

8.3.1. Evidence of Scandinavian glaciation

There is clear erratic evidence of ice movement from the east coast of the area across it in a broadly west or northwesterly direction including across the Ronas Plateau, if not the high point of Ronas Hill itself. Despite the fact that Ronas Hill is the highest ground on Shetland, the area

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[10] Flinn, 1977
[11] Mykura, 1976
[12] Peach and Horne, 1879; Chapelhowe, 1965;
[13] Charlesworth, 1956; Mykura, 1976; Flinn, 1977;
[14] Chesher, 1984b
[15] Stoker et al., 1993

is to the west of probable ice shed positions in recent reconstructions[16] (figure 3.11) and so this erratic movement itself does not provide conclusive evidence of Scandinavian glaciation, just as it does not in other western parts of the island (see chapter 6). What is significant, and ignored by recent reconstruction, is the northeast-southwest azimuth of some striae on the east coast of the area. Since areas to the northeast (i.e. Yell and Unst) are both more peripheral and of lower altitude, it is perhaps reasonable to invoke the external influence of a Scandinavian ice sheet from the northeast to explain these observations. The alternative hypothesis here suggested is that these azimuth reflect a relatively late movement of ice, in the opposite direction (northeast) into an ice stream formed in Yell Sound. The existence of such an ice stream at some stage is supported by ice movement from central Mainland (chapter 7) and south Yell (chapter 9). It is reasonable to expect that if north Mainland supported significant quantities of ice at the same time, and it is the highest area in Shetland, then some of this would be drawn into that stream. The theory requires that the sense of direction of the striae on the east coast of the area be the reverse of that suggested by previous authors and the present writer has been unable to identify convincing stoss and lee evidence that establish the direction of ice movement. The absence of granite erratics on the east coast of the area can be explained by the fact that the direction of striae would be consistent with basal ice movement along the metamorphic area only, although it is possible that basal ice from further west was drawn into an englacial position, thus passing over the narrow coastal strip. It has been suggested that the erratics in the till on the east coast are, 'fairly local in origin and suggest a movement from east to west, rather than from west to east'[17]. Given the banded nature of the solid geology along this area such a process would be particularly difficult to demonstrate. An unidentifiable quartz-feldspar pegmatite is mentioned occurring throughout till on the east coast and is thought to represent an unknown outcrop on the North Sea floor[18]. It is more likely, in the author's opinion, to originate locally, since it is reasonable to expect pegmatite as a constituent of the rocks around Yell Sound; the absence of a particular mapped outcrop and the widespread nature of the erratic rather suggests that it might occur in Yell Sound itself. These facts may indeed indicate an earlier east to west movement of ice. The pattern of striae around Quey Firth, Colla Firth and Bay of Ollaberry is less easily accommodated in this explanation since these areas are south of the high ground of Ronas Hill, however the streaming in Yell Sound noted in other areas (chapters 7 and 9) is morphochronologically assigned to a relatively early phase.

An earlier, broad, east to west movement may have been given a southwesterly azimuth by ice streaming around the high ground and the movement of erratics here does indeed confirm the sense of direction suggested by stoss and lee observations. South of Ronas Voe, ice movement is mostly east-west and is consistent with relatively late draw into the deep of the St Magnus Bay

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[16] Flinn, 1977
[17] Chapelhowe, 1965 (p.65)
[18] Chapelhowe, 1965

basin, except across Esha Ness. The relative timing and an explanation of these movements is discussed below - the purpose here is to demonstrate that Scandinavian ice is not necessary to explain the apparent northeast to southwest movement of ice on the eastern coast of the area.

8.3.2. Ice movement North of Ronas Voe

It is not possible to demonstrate whether or not ice from Ronas Hill flowed across Ronas Voe at any stage during the last glaciation. The writer has sought erratics that might conclusively suggest such a movement and has found none. If it did so, it would therefore most likely have been at an early stage. The significance of northwesterly movement is again discussed in this chapter in relation to the glacial maximum or early deglaciation (see chapter 6) and Ronas Hill's contribution to the convergent pattern around St Magnus Bay later would have been severely curtailed by the depth and steep northern side of Ronas Voe, as discussed below. For the purposes of this section, the areas to the north and south of the voe are treated separately.

Across the Ronas Plateau area there is again a preponderance of striae and erratic evidence suggesting ice movement to the northwest, with variations ranging from west-north-west to north-north-west. In areas such as to the south of the Beorgs of Uyea there are contrasting sets in close proximity, suggesting shifts in the predominant ice movement over time. The difficulty of identifying striae on the easily weathered granite of the area has been encountered by this study and certainly no sets have been revealed overlying each other in a way that might provide the correct temporal sequence. Some attempt at providing a time frame can be made however. The northwesterly striae in the area are consistent with those on Esha Ness (see below) and as discussed elsewhere on western extremities of the island group (see chapter 6). These are here attributed to the broad northwesterly movement of ice that appears to be related to the glacial maximum or early deglaciation (figure 8.4). The occurrence of erratics of eastern provenance on the eastern coastal strip also suggests some early movement from the east onto this area. There are sets of striae which are more north-south and more east-west than these however. The more northerly sets along the Beorgs of Housetter and between North Roe and Fethaland, and possibly on the low ground some way to the west of this area, may coincide with the north moving ice stream in Yell Sound (see above). It is logical to assert that this movement post-dates the northwesterly regional movement since an ice stream moving north up Yell Sound would remove the eastern source ice required to sustain the northwesterly movement, particularly on the high eastern areas such as the Beorgs of Skelberry (figure 8.5). The ice stream may have diverged and streamed through the gap between Sand Voe and Burra Voe although this area is affected by later ice movement from the Ronas Hill plateau (discussed below). If the more eastern striae on the low ground along the north of the area are not contemporaneous they are likely to be earlier, possibly reflecting the adjustment of the ice front to increasingly local bathymmetric contours that would draw ice to the northwest early on, and to the north and east later.

Heavy mineral analysis of offshore sediments (figure 3.16)[19] shows that this northwesterly movement is regionally dominant.

8.3.3. Plateau glaciation

Thus far, this adjustment from northwesterly ice movement to ice movements indicating more localized ice fronts and streams is similar to the situation discussed in other parts of Shetland (see chapters 5, 6, 7). The Ronas Plateau forms the highest ground on Shetland by a significant margin however and there is evidence of a plateau ice cap existing on the area and draining locally in all directions. To the east of the plateau area there appear to be only specific localities in which granite erratics are evident in till. These occur in Colla Firth and Burra Voe representing unique draining sites for ice from the plateau on the east coast (figure 8.6). A margin may be delimited by the A970 to the west of Ness of Queyfirth. Here granite erratics are evident to the west of the road but only metamorphic clasts are found to the east. In addition, to the southeast of Oxensetter there are small hummocky features which may represent a margin (plate: figure 8.7). Colla Firth and Burra Voe in particular are at the north and south ends of the Beorgs of Housetter and Skellberry which prevent ice streaming to the northeast. There are significant, now disused, drainage channels, particularly between the Beorgs of Housetter and Skelberry (plate: figure 8.8) that may be related to drainage associated with this plateau glaciation. The till bearing granitic erratics on the west shore of Colla Firth is overlain by fluvioglacial materials (plate: figure 8.9) (figure 8.3) and backed by minor channels and associated morphology, again suggesting progressive deglaciation of the plateau ice field. Further west, ascending Collafirth Hill, the area is hummocky but this can be largely attributed to bedrock forms.

Across the north coast of the area, all till contains granitic erratics, even as far east as the area between Sand Voe and Burra Voe. This till must relate to a northern or even northeastern movement of ice, again draining the plateau area. The previous movements discussed would not result in granite erratics appearing in sections in these areas. Together with the entire west coast, the above areas are topographically probable outlets for a plateau ice centre or field. As with Colla Firth, there is evidence of possibly fluvioglacial material in Burn of Sand Voe and terraces up to 1-2 m in height and these again demonstrate down-wasting of ice on the plateau area.

It is not possible to determine whether there was a re-expansion of ice from the plateau, or whether it represents continuing retreat. The thickness of till indicates that the ice remained active, and the underlying glacitectonite in places suggests that the streams were erosive, but

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[19] Beg 1990

pre-existing northwesterly striae have not been eradicated in some locations. On the higher ground of the plateau itself there is little striae evidence, largely due to peat cover and postglacial surface deterioration rather than inactivity since the area is of knock and lochan character.

8.3.4. Ice movement south of Ronas Voe

There are striae that suggest the possible movement of an ice stream along Ronas Voe itself. The inner voe is deep but becomes less so and has a shallow sill at its outflow which may reflect westward glacial over-deepening.

Again peripheral areas record a broad ice movement towards the northwest. This is especially noticeable on Esha Ness. The areas around St Magnus Bay are dominated by evidence of ice flow into it, except in places such as Ness of Olnesfirth where there are striae of northwest-southeast azimuth also. The picture that emerges from this area is again that of early northwesterly ice movement (figure 8.4), followed by greater topographic containment and the establishment of ice flow into the St Magnus Bay basin (figure 8.6). This may well be a step change caused by the Esha Ness peninsula itself dissecting further northwesterly flow, since there is little evidence of progressive variation. The present writer has mapped striae that are more or less due east on the south coast of Esha Ness, as well as crossing striae that vary between north and northwest. The till on Esha Ness overlies the above mentioned striae and contains metamorphics of assumed Hillswick origin as well as other eastern, widespread, erratics. Some authors[20] suggest that ice must have moved into the St Magnus Bay over the Hillswick peninsula and then been bent out over Esha Ness again (figure 3.11). The above data would seem to suggest the possibility of a more direct, eastern ice flow across both areas, post dating the northwesterly movement, and predating the pattern into St Magnus Bay. There is also evidence of a more north-south or northeast-southwest azimuth ice movement on Esha Ness which is difficult to place into this set of events. This may reflect local topographic containment of ice streams during the general northwesterly movement (although there is little topography) or an intermediate period that resulted in more northerly movement.

The late movement of ice into St Magnus Bay is strongly erosive. Substantial areas of ice moulding occur on the eastern fringe of the basin and what drift is evident is generally a glacitectonite with highly localized and insubstantial patches of more dispersed material (figure 8.3). More significant lodgement deposition is evident further east on the Sullom Voe side of the area. This may reflect preferential deposition on a large scale on the upglacier side of the subglacial obstacle presented by the isthmus, or alternatively the erosion of equally significant deposits on the downglacier side.

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[20] Flinn, 1977

Thick tills occur in the northwest corner of the Hillswick peninsula and at Braewick (plate: figure 8.10) as well as on the southeast coast of Ura Firth (figure 8.3). There is no erosive directional data in the area between Hillswick and Esha Ness and so it is not clear whether or not these thick sequences owe their existence to the absence of ice streaming into the St Magnus Bay at this locality, i.e. through preservation, or the presence of such streams, i.e. by enhanced lodgement. If the latter proves to be correct then the question arises as to why these should be the only locations around the basin where such tills have developed. The writer's preferred explanation is that they are the product of early westerly or northwesterly ice movement and that ice did not flow into the St Magnus Bay basin across the terrestrial area west and immediately east of the Hillswick peninsula. The clast pavements and surface of the till at Breiwick dips to the northwest, and contains metamorphic clasts of probable Hillswick derivation, suggesting that it was deposited beneath northwesterly moving ice. The fabric of the lodgement till in Ura Firth is orientated broadly northwest-southeast (figure 8.2) (although this may partially be due to the local slope, it certainly does not show northeast-southwest, along voe, movement) and overlies possible glacial grooves of similar azimuth. These observations are in keeping with striae on the high ground to the southeast of Ura Firth. It is here suggested, therefore, that when the switch into the basin occurred these areas had no source area of ice to the northeast due to the existence of Ronas Voe. The writer has sought erratic evidence of ice crossing Ronas Voe and has found none. The distribution of ice moulding, characteristic of ice streaming into the bay, extends only as far north as Ness of Olnesfirth (figure 8.3). There is evidence of striation into the basin in Hamar Voe, on which azimuth a direct stream into the centre of the basin would bypass Ronas Voe to its source area. The only observed striae on Hillswick are in the south of the peninsula, on a similar flow line (figure 8.2). Ronas Voe may have prevented ice from flowing into the basin over areas west of Ura Firth at the time the switch took place, either if it was deglaciated or if there was a late ice stream, by cutting supply from the northeast.

Further retreat may also be evident in the distribution of striae and ice moulding, although care should be taken in its analysis since the variable underlying substrate and overlying drift cover plays some role in that distribution. The absence of these erosional features on the east coast of this southern area may be due to topographic influence during retreat. Whilst considerable erosion demonstrates ice flow into the St Magnus Bay basin, ice may then have retreated across to Sullom Voe with much less activity since average bed gradients would have been significantly reduced.

8.3.5. The nature of deglaciation

The offshore record around the area again suggests a two stage deglacial process. To the northwest there are undoubtedly subglacial deposits overlain by glacimarine deposits (figure 3.15) and in this area there is swathe of the outer shelf that is scored by iceberg ploughmarks between 150 and 300 m below modern sea level[21]. The glacimarine sediments however end as the landmass is approached. As has been discussed at length in chapter 6, there is no evidence of glacimarine deposition in the deep St Magnus Bay, but it is unfortunate that the sediments of Yell Sound are not sampled since it would be interesting to know if the same may be said of this inshore area also. In St Magnus Bay there is evidence of rising sea level in a harsh environment with no terrestrial glacial input. This implies that, at some stage during deglaciation, there was a switch from glacimarine to non-glacimarine ablation. The British Geological Survey are currently working on sea bed morphology in inshore areas and there may be morainic hummocks to the west, possibly at this transition, and around the -100m bathymmetric contour line[22]. This work is in progress however and in particular the distinction between bedrock forms and sediment hummocks has not been examined in detail. The strong influence of topography on glacier movements is again observable around St Magnus Bay and in this location again extensive ice moulding provides further evidence of the warm-based temperature regime during deglaciation.

8.4. Conclusions

The northwesterly regional movement is probably the earliest ice movement recorded (figure 8.4). The next major shift is to the north, particularly with a major ice stream in Yell Sound, possibly sufficiently thick to cover the Beorgs of Skelberry and cause basal erosion there (figure 8.5). Ice may still have been flowing northwest across the southern area at this stage, or possibly in a more western direction, including around Ronas Voe. This is followed by the disappearance or substantial reduction of the Yell ice stream, to allow plateau drainage glaciers to cross the northeastern coastal strip, and the switch to ice moving into St Magnus Bay (figure 8.6). The convergent St Magnus Bay pattern does not occur west of Ura Firth, suggesting that, at some stage, ice supply from the northeast was diverted along or prevented by Ronas Voe. It is difficult to place these events into time sequence. The relative chronology of the Yell and Ronas Voe ice streams is difficult to resolve, since they probably issued from the same source area which may have become depeleted by one stream more rapidly than the other. Also, on the basis of altitude, it is probable that the plateau glaciation was the longest lived in the area, and may have been the last glacial event of significance in the entire island group. The nature of deglaciation again indicates early glacimarine followed by terrestrial retreat.

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[21] Stevenson, 1991
[22] A. Stevenson (pers. comm. 1995)

9. The last glaciation of Unst, Yell and Fetlar

9.1. Solid geology, topography and bathymmetry

The solid geology, topography and bathymmetry of the area are shown in figure 9.1. The entire area is underlain by metamorphic rocks. Figure 9.1 is highly simplified and the solid geology is heterogeneous. The island of Yell is underlain by a possible equivalent to the Yell Sound division of the East Mainland Succession discussed in chapter 7 (1a in figure 9.1 and 1 in figure 7.1) and tentatively correlated with the Moinian of Scotland. It consists of metamorphosed and migmatised gneisses with a number of poorly defined belts trending north-south to northeast-southwest. These can be seen to influence topography. Most notably: quartzite forming the high ground of the Hills of Arisdale and Reafirth ridge; and a belt of plane-foliated, granular gneiss between two broader areas of coarsely-foliated gneiss giving rise to the trough running from Mid Yell Voe to Gloup Voe. Western Unst and western Fetlar may correspond to the Dalradian Scatsta division discussed in the chapter 7 (2a in figure 9.1 and 2 in figure 7.1). The western high ground of Unst (Valla Field Ridge) represents a block, including north-south trending bands of a variety of gneisses, bounded to the east by the dislocation zone evident in the topography. The west coast of Fetlar, including the Lamb Hoga peninsula comprises similar basement rocks and is separated to the east by an equally clear fault line. The block comprising the Saxa Vord area ("?" in figure 9.1) is predominantly schistose and is difficult to place within the metamorphic history of the region. Eastern Unst and eastern Fetlar comprise the Unst-Fetlar Nappe Pile (UF in figure 9.1) - a series of major blocks of metamorphosed igneous and sedimentary rocks including serpentines, phyllites, metagabbros, schistose conglomerates and granites, that show a clear correspondence with topography in places. In addition, the serpentine blocks of Unst give rise to the brown weathering outcrops that characterise much of the Unst landscape. The metamorphism of the Nappe pile is associated with the Caledonian orogeny but is otherwise of unknown age[1]. Offshore around the area (figure 3.2) the solid geology is undivided but includes offshore equivalents of the terrestrial sequences. To the south of Fetlar, in the southeast of the area, is the Fetlar basin of Permo-Triassic sediments discussed in chapter 7, and to the east of the area the Unst basin and trough (figure 3.4 and 3.5) containing similar sediments and terminating to the east on the Pobie Bank that comprises metamorphic and igneous rocks. The Unst basin widens to an area of Cretaceous shales and mudstones, and to the north and northwest of the island there are undivided igneous rocks bounded to the west by a possible continuation of the Walls boundary fault[2] (figure 3.2).

The Mid Yell gap is a possible Devonian channel remnant (figure 3.6)[3].

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[1] Chesher, 1984a
[2] Chesher, 1984a
[3] Flinn, 1977

9.2. Previous work

It is interesting to note that, as a peninsular extremity of the Shetland archipelago, like south Mainland, this area has also been seen as a possible area of invasion by Scandinavian ice. Early authors[4] describe ice markings showing west-east or southwest-northeast azimuth across Unst, a similar pattern on Fetlar and on northeast Yell (figure 3.7). On the west coast of Unst and Yell, the trend described is northwest-southeast and the overall interpretation is of Scandinavian ice impinging from the east and northeast and swinging to the northwest on encountering the landmass. No reference to roches moutonées is made however, and it is not clear how the sense of direction of these striae is gathered. Maps based on a greater number of striae observations[5] and on more detailed analysis of stoss and lee data[6] show both a more complex pattern of striae and are interpreted, in some places on, 'absolutely clear evidence,'[7] as showing offshore ice movement (figure 9.2), incompatible with the Scandinavian theory. On the east coast, the interpretation for the northwesterly azimuth is variously thought to be due to the bending of local ice by impingement of a Scandinavian ice sheet[8], or to flow into bathymmetric lows[9]. The latter is assumed to be under gravity but the possibility of ice calving into rising sea level is offered as an explanation of the pattern[10] in other areas of Shetland. The data has been used to construct an ice shed for the last glaciation which runs across south Yell in a northeasterly direction to Unst where it continues due north in the centre of the island (figure 3.11). No stoss and lee evidence of ice moving from the east of the area is given in any of these later accounts.

Proponents of Scandinavian influence[11] support the argument for the incursion of Scandinavian ice on the grounds that erratics of serpentine and gabbro crossed the Vallafield ridge of Unst from Balta Sound in the east (and indeed that the relative percentages of the two in till sections up and down the west coast correlate with the relative outcrop areas on the east). Additional traverses by these authors, from Belmont to Muness, and across Saxa Vord hill (where the distinctive Lamba Ness granite is the erratic in question), revealed a similar pattern. A more recent[12] and wide-ranging survey of erratic distribution on Unst has also been conducted and the main elements of this are shown in figure 9.2. The conclusions are not dissimilar except that west to east ice movement is evident in places and the data is interpreted with the ice shed in the centre of the island, east of the high ground, rather than further west, thereby obviating any need for Scandinavian ice. Pebbles of flint, Tõnsbergite (petrographically identical to that found near Dalsetter in south Mainland (chapter 5)) and rhomb porphyry are found on a beach on the south

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[4] Peach and Horne, 1879
[5] Mykura 1976; Flinn, 1977
[6] Flinn, 1994a; Flinn, 1994b; Hoppe, 1974
[7] Hoppe, 1974 (p. 205)
[8] Mykura, 1976
[9] Flinn, 1977
[10] Hoppe, 1974
[11] Peach and Horne, 1879
[12] Flinn, 1994b

side of the island of Hascosay, but these rocks from London and Tönsberg (south of Oslo) are believed to be ballast from the ship Krageröe wrecked on Hascosay in 1803[13]. No Scandinavian erratics have otherwise been recorded. Erratics of gabbro and serpentine of Unst provenance are observed[14] on the northeast coast of Yell, implying ice movement across Bluemull Sound. Other erratic data from Yell, 'at best,'[15] are consistent with the ice flow on the island suggested by striae (figure 9.2). On Fetlar, gabbro and serpentine are reported to have been transported from the centre to the west coast of the island and also to the east coast of Yell between Mid Yell and Basta Voe[16]. Other authors describe many erratics from the Lamb Hoga peninsula lying on the central Serpentine areas of Fetlar and erratics from the latter on the eastern conglomerates[17], implying the reverse direction of ice movement, but do not discuss the earlier observations.

It has been proposed that an ice margin lay across or just to the north of northern Unst and Yell and in some papers that it represents the maximum limit of the last glaciation of the islands[18]. On Herma Ness in northern Unst there are meltwater channels that are variously described as subglacial, proglacial and supraglacial, and on both Herma Ness and Saxa Vord there is no till or striae and some solifluction, which facts are taken to indicate that ice did not cross the area during the last glaciation but that a periglacial environment prevailed[19]. A section through a possible fan into a hypothesised ice dammed lake north of Libbers Hill is also reported[20] (figure 9.2). On northern Yell there are observations of fluvioglacial sands and gravels, meltwater channels, solifluction deposits, local surficial erratics, as well as previously ice dammed lakes. Again there are no till or striae observations, particularly in the northwest[21]. Early offshore evidence[22] suggested that the distribution of till to the north of the area was varied and implied a lobate ice margin that fitted well with this hypothesised terrestrial limit, lobes extending well to the north off the east coast of Unst, between Unst and Yell, and west of Yell (figure 3.13). However, it has been argued that both the onshore and offshore evidence are equivocal and the existence of any kind of stable ice margin in general, and whether it represents the maximum of the last glaciation in particular, remain highly uncertain issues[23] (see, for example, figure 3.14).

Immediately offshore[24] there is little or no evidence of Quaternary sedimentation but the basins of Fetlar and Unst, and the trough areas running north of these contain Quaternary sequences up to 50 m in depth. A tongue of Quaternary sediments 30 m in depth exists in Yell Sound to the

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[13] Flinn, 1977
[14] Peach and Horne, 1879
[15] Flinn, 1994a (p. 95)
[16] Peach and Horne, 1879
[17] Phemister, cited in Mykura, 1976 (p.107)
[18] Flinn, 1983, 1992b, 1994a
[19] Flinn, 1983
[20] Flinn, 1992b
[21] Flinn, 1983, 1994a
[22] Long and Skinner, 1985
[23] Ross, 1993
[24] Chesher, 1984b

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[13] Flinn, 1977
[14] Peach and Horne, 1879
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[16] Peach and Horne, 1879
[17] Phemister, cited in Mykura, 1976 (p.107)
[18] Flinn, 1983, 1992b, 1994a
[19] Flinn, 1983
[20] Flinn, 1992b
[21] Flinn, 1983, 1994a
[22] Long and Skinner, 1985
[23] Ross, 1993
[24] Chesher, 1984b

north of West Sandwick but there are no boreholes in these sediments. Those in and around the Fetlar Basin are described in chapter 7. The sediments of the Unst Basin are reported as mainly compact grey clays with scattered pebbles[25] and the borehole has been interpreted as containing a till sequence with some evidence of interdigitated proglacial facies[26]. Quaternary deposits thicken to the north of the islands and become seismically distinct. The underlying units and chronology are discussed in chapter 10 in detail but the upper two units are of interest here: the Stormy Bank and underlying Otter Bank sequences[27] (figure 3.15). The latter are composed of over-consolidated diamicts and are generally less than 10m thick except where they become mounded. Such an area of mounding, that may represent a terminal moraine sequence, exists to the northwest of Unst and the sequence as a whole is considered to have been deposited proximal to grounded glacial ice. The overlying Stormy Bank sequence is a sediment drape on the Otter Bank sequence and also in channels, possibly meltwater channels, that cut down through both the Otter Bank and underlying sequences. It comprises soft muds with some gravel in places and is thought to represent the waning stages of the Late Weichselian glaciation. The boundaries of both sequences are not currently known precisely because seismic sparker interpretation allows only 5m vertical resolution. The author's own examination of core material (chapter 10) shows that the Stormy Bank sequence at least extends further north than shown in figure 3.15. Also observed to the northwest and northeast of the area, around the continental shelf edge, is an zone of iceberg scouring at a depth of 150-300 m (figure 3.4) below modern sea level[28].

Corrie glaciers are again discussed in various parts of Yell, Unst and Fetlar[29] and again treated by subsequent authors[30] as hypothetical features based on the likely locations of snow accumulation rather than direct evidence.

9.3. Outstanding issues

A number of regionally significant questions require resolution. Is there any evidence of Scandinavian ice movement across the area, or at least of regional ice movement from east to west? Can all ice direction indicators be related to a single ice shed model and, if not, how have ice sheds changed over time, particularly during deglaciation? What controlled deglaciation, in particular to what extent was rising sea level important? What is the evidence for a stable ice margin across northern Yell and northern Unst? What is the evidence that such an ice margin represented the maximum extent of the last ice sheet?

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[25] Chesher, 1984b
[26] Cockcroft, 1987
[27] Stevenson, 1991
[28] Stevenson, 1991
[29] Charlesworth, 1956
[30] Mykura, 1976; Flinn, 1977

9.3.1. Scandinavian Glaciation

There are a number of pieces of evidence attributed to Scandinavian glaciation by various authors (see above): the direction of erosional evidence on Unst; the east to west movement of erratics across Unst; the east to west movement of erratics across Fetlar and to Yell. Striae are discussed in the sections below and although it is necessary to invoke multiple phases of ice movement to account for the pattern, the author has not found any convincing evidence of stoss and lee that suggests onshore movement, particularly in the crucial area of east Unst. The movement of erratics from east to west across Unst is not contested although it is not necessary to invoke Scandinavian glaciation to achieve it. The only exception to this is in the far north, across Saxa Vord. Here, early authors describe a deposit that, 'occurs on the east bank of Burra fiord, about 300 feet above sea-level, where it reaches 50 feet in depth.'[31] The current author's observations allow clarification of the fact that it must be Burra Firth which is 50 feet in depth at this point, for it is certainly not the depth of drift on Saxa Vord, however the crucial point is the report of the preponderance of the Lamba Ness granite fragments which must have been transported from the east and across Saxa Vord. Some authors[32] mention the movement of erratics west across the island further south but do not discuss this particularly crucial example and the most recent work[33] is premised on the glacial maximum being to the south of the area and does not include Saxa Vord. The Lamba Ness granite is an easily identifiable rock amongst the largely schistose and quartzitic types that make up the hill and the present writer has found no sections on the hill that contain it. What drift there is appears to be a combination of weathered bedrock and possibly solifluction (plate: figure 9.7). No explanation for this discrepancy can be offered.

The other key erratic observation is the movement of serpentine and gabbro from the east to the west coast of Fetlar, and of Fetlar gabbro west to Yell between Basta and Mid Yell Voes[34]. Others[35] report blocks of western Lamb Hoga peninsula metamorphics on Fetlar lying on the centre-island serpentine and of serpentine on the conglomerates of the east coast. These represent the opposite direction of ice movement - west to east. The author's observations of till development on Fetlar are discussed below and suggest ice moving from west to east also. No erratic observations were made in this area in the course of the study and the evidence given and the failure to comment on early findings by subsequent authors leaves the issue somewhat unresolved, however the till sections in which the erratics are supposed to occur on Fetlar are, in the author's opinion, related to ice moving onto Fetlar from the west (see below). Once again it is assumed that the improved geological data available to later authors make their interpretation more probable.

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[31] Peach and Horne, 1879 (p.796)
[32] Mykura 1976
[33] Flinn, 1994b
[34] Peach and Horne, 1879
[35] Mykura, 1976

With this ambiguous exception, there is no reported evidence from the area that must be attributed to an external, eastern, source, such as from Scandinavia. Heavy mineral assemblages in offshore deposits again indicate movement of minerals to the northeast from areas south of Fetlar (figure 3.16).

9.3.2. Terrestrial glacial maximum

A number of arguments have been put forward to suggest that the maximum limit of the last glaciation of the islands lay across north Unst and just to the north of north Yell. The evidence and interpretation are considered here.

The absence of till and striae north of the proposed margin on north Unst has been suggested as being indicative of ice marginal conditions. The area outside the proposed limit, which itself has become increasingly crenulate with the discovery of till on the east side of Saxa Vord[36], is at high altitude. For striation and till development, ice must be thick above the subglacial substrate and basal ice must contain debris. North moving basal ice would probably have streamed around rather than over Saxa Vord and Herma Ness, and ice thickness over this high ground would have been less than surrounding low altitude areas so direct comparison of the presence or absence of till or striae is dubious. The writer has observed severely weathered bedrock and possibly periglacial solifluction on Saxa Vord (plate: figure 9.7), which may have destroyed both thin till and striated surfaces. On both Saxa Vord and Herma Ness there is little bedrock exposure at all, so striae observation is very unlikely. Metamorphic erratics occur on the granitic area of the lower altitude eastern flank of Saxa Vord (plate: figure 9.8) indicating that ice extended beyond the coastline here at least. The surficial material of Saxa Vord and Hermaness comprises *in situ* weathered bedrock possibly thinly reworked into periglacial slope deposits. The existence of these may be related to nunatak exposure of this area for protracted periods during retreat with ice streams passing north on either side. They do not necessarily imply that the area was ice free for the duration of the last glaciation.

Channels along the west side of Burra Firth (plate: figure 9.9) are undoubtedly meltwater channels since they run in places parallel or sub-parallel to contours. Such examples must be subglacial, sub-marginal or marginal but sub-classification on grounds of morphology is fraught with difficulty as the relationships between this and ice mass configuration, meltwater discharge, and bedrock characteristics are complex. On Unst they most probably reflect the existence of a temporarily stable ice margin but, as discussed above, there is no reason why this should be the glacial maximum. A possible ice dammed lake immediately to the north of Libbers Hill is inferred from the existence of meltwater channels tentatively classified as of overflow

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[36] compare Flinn, 1983 with Flinn, 1994b

type and a possible subaqueous fan emanating from two meltwater channels on the side of Libbers Hill itself (figure 9.3). Milldale burn cuts through this fan, revealing a deposit that has been variously described as solifluction[37] and subaqueous fan deposition[38].

The present writer has examined this section, possibly following further undercutting since there is no previously reported mention of the lowest unit observed. The stratigraphy comprises three units (plates: figures 9.10, 9.11, 9.12): approximately 1 m of low energy, laminated, fine to coarse sands, with ripple and cross-tabular bedding showing that water flow directions varied, and sharp contacts indicating repeated erosion and deposition; this is overlain with approximately 2m of massive, largely clast supported, diamict with a fine sandy matrix and varied clast fabric that in places is vertical; the sequence is overlain by peat. The contact at the base of the sequence is obscured.

The Milldale Burn cuts through sediments up to 3 thick in this upper area, which have themselves been incised by now dry re-entrants. It is not clear, however, whether this morphology is underlain by the same materials as those describe above. The author's examination of air photos suggests that the drift limit on the side of Libbers Hill is the most prominent feature of the proposed fan and the existence of the feature is not certain.

The lowest unit in the sequence is evidently a reflection of variable, low discharge, fluvial environment. The sediments are unconsolidated and may not be much deeper than those presently visible. It is probable that glaciation would have removed such sediments at an early stage and they are here attributed to subglacial or proglacial meltwater deposition, probably relatively close to the ice margin, variations in hydrological regime accounting for the variations in deposits. The overlying massive unit presents profound problems however due largely to the quantity of material involved. The writer has found some terracing by other streams on the east side of the Valla Field ridge, largely bedrock based, and in places with subaerial fan morphology at their exit, but in the upper reaches only thin till or periglacial solifluction deposits have been encountered. This massive unit appears too clastic to be either lodgement or meltout till. The absence of lower energy regime sediments suggests that if it was fluvioglacial then it was deposited catastrophically, but at this altitude it is difficult to envisage the glacial system providing such quantities of material in a short space of time. If it was deposited subaqueously as an accretionary fan, then lower energy sediments would also be expected to be interdigitated.

The subaqueous fan proposal leaves other issues unresolved. In order to create the Milldale glacial lake, an ice stream in Burra Firth is required. This is reasonable and the writer has

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[37] Flinn, 1983
[38] Flinn, 1992b

observed possible evidence of such a stream (discussed below). However, in order to create the fan with this quantity of material in the thus dammed lake, there must also be a significant thickness of ice on the highground of the Valla Field ridge, with its northerly terminus at Libbers Hill. Even assuming that the ice stream draws its ice surface down, the difference in altitude between the surfaces of the two is difficult to accept. If the lower energy sediments either occur near the margin or in a proglacial setting, and if the terraces are formed of the massive unit and the terraces are themselves eroded by water, and the massive unit is not till, then at least it can be said that it is probably a proglacial deposit. The writer is inclined to consider the deposit of periglacial solifluction origin, owing its unusual depth to the existence of a sediment trap. Such an explanation notably does not explain the apparent morphology to be seen on the 1:10 000 air photos but, ironically, is the same as Flinn's initial explanation[39].

The deposits and morphology of the Milldale area remain open to further investigation, but in the context of the wider issues with which this study is concerned, the evidence for a stable terrestrial ice margin of climatic significance is not overwhelming. The only proposed evidence that such a margin represents the maximum of the last glaciation is the absence of till and striae to the north of the area, and this can be alternatively explained (above).

A further contribution to the issue may be made by examination of offshore deposits to the north. Early reports suggested a lobate arrangement of till that fits well with the proposed terrestrial margins on or near Unst and Yell[40]. However till is also reported as the Otter Bank sequence further offshore, resulting in a much more northerly ice margin in keeping with the assumed extent of the Shetland ice cap to both the east and west[41]. A lobate margin may well have existed at some stage during deglaciation, but if the Otter Bank sequence represents the glacial maximum then the lobate deposits and terrestrial margins must post date this. The question of whether the Otter Bank sequence represents the last glacial maximum or not is discussed in chapter 10. There it is concluded it the sequence does relate to the last glaciation.

On Yell a series of meltwater channels and a further ice dammed lake are described[42]. The writer concurs that the channels are most probably the product of meltwater but the assertion that the zone between the present shore of Kussa Waters and the peat is indicative of drainage that took place at the end of the last glaciation (plate: figure 9.13) is improbable. The peat itself post-dates the glaciation and it is unlikely that it would not have spread across the bare surface since then. The drainage of Kussa Waters is probably much more recent. Although drainage channels to the southwest are clearly fluvioglacial in origin, since they are cut to some extent

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[39] Flinn, 1983
[40] Long and Skinner, 1985
[41] Stevenson, 1991
[42] Flinn, 1985

through bedrock, they are in places also cut through up to 4-5 m of peat, indicating that water continues to drain them in postglacial times. Sands and gravels reported in Burn of Gossawater are certainly fluvioglacial since the competence required to transport the material exceeds that presently indicated by the channel. Although the writer has been unable to find striae on the North Neaps in northeast Yell there are probable deposits of till up to 2m on the west shore of Gloup Voe (figure 9.3). A thin veneer of periglacial solifluction is otherwise recorded. If this area represented a stable ice margin at any time then it was probably not the last glacial maximum extent. Immediately to the east between Wick of Breacon and Bay of Brough the landscape is ice moulded and in Bay of Brough itself there is lodgement till up to 5m in depth (figure 9.3 and plate: figure 9.14). This kind of activity is the product of relatively thick ice and again it is difficult to envisage an ice free zone directly adjacent.

The existence of heavy mineral assemblages of Unst source in sediments all around the area to the north of the islands also suggests that, if there was a terrestrial ice margin, it was not that of the last glacial maximum[43] (figure 3.16). Although post-glacial deposition may affect heavy mineral assemblages, more so than with erratics, the research suggests that this effect is not significant.

9.3.3. Multiple phases of ice movement

It is difficult to envisage a single ice configuration that can account for all the ice direction data available. There are particular locations, such as on the island of Uyea and near Aywick on Yell that support crossing sets of striae; the observations of northwesterly erratic movement on Fetlar and some of the striae there are incompatible, and strong northwesterly sets of striae at the head of Basta Voe are difficult to reconcile with northeasterly striae in the same area (figure 9.2). Attempts to draw all encompassing ice shed configurations are prone to difficulty.

The idea that more peripheral data may reflect earlier movements of ice is difficult to apply here. The entire area is largely on the periphery of the island group as a whole. However something can be gained from looking at the vertical dimension. West-northwest striation of the highground of the Valla Field ridge on Unst, together with the movement of erratics from the east across it, suggests early west or northwestern ice movement from a significant ice shed east of this high ground. The vertical extent of that ice must have been considerable, even over the high ground itself, since there is evidence of widespread basal erosion at these elevations. Much of Yell shows evidence of northwesterly ice movement also. Reconstruction has generally shown the ice shed to be between these sets of striae and those further east (figure 3.11), however at an early stage the ice shed may have sat over eastern Unst, Fetlar and southeast Yell, or been further east still, the directional evidence of these areas being developed latterly. Such an ice

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[43] Beg, 1990

shed may explain the incorporation of rocks from the east and centre of Fetlar into basal ice that ultimately deposited them to the west, although evidence of this is uncertain (see above). The northwesterly movement in central and west Yell may be due to a later draw into an ice stream in Yell Sound (chapter 8) but the western shore of Yell Sound extends only as far as Whale Firth on the eastern shore (figure 3.5), and there are numerous striae north of Whale Firth and some way inland that suggest northwesterly ice movement that is locally topographically independent. There is also no evidence of an increasingly northerly swing in eastern coastal areas as might be expected if the dominant influence was a north flowing ice stream. This is only evident on the east coast south of West Sandwick. Once again, therefore, it is argued that the evidence suggests that the earliest movement of ice was in a broadly northwesterly direction from an ice shed that may have lain to the east of the northern isles.

From figure 9.2 subsequent events evidently produced the following at some stage: an ice stream passing up Bluemull sound between Unst and Yell; an ice stream passing up Yell Sound; ice crossing the east coast of Yell (at Sandwick and Basta), north Fetlar, Uyea and Muness to the northeast; ice moving directly east from Unst and Fetlar; ice moving into the Fetlar basin from southeast Yell and southeast from Fetlar. The relative timing of these events is difficult to ascertain.

At Norwick on Unst there are striae indicating northeasterly ice movement. These may reflect draw into a stream moving north between the island and the Pobie Bank, or more local northerly movement diverging around the Saxa Vord high ground. Although there is no clear directional evidence from the central low ground of Unst, near Baliasta the author observed possible evidence of till lodged around a bedrock obstacle in a manner that suggests northerly movement up the centre of the island to Burra Firth. There is only one minor section from which a striated stone was recovered. The above observations suggest that early retreat may have been to a northerly ice front. Evidence from the rest of the east coast of Unst suggests movement into the Unst basin largely perpendicular to bathymmetric contours with possible local topographic variations such as at Vord and Colvadale Hills. This ice movement appears to be directly east-west and associated with a north moving ice stream between the island and Pobie Bank and so probably post-dates that possible circumstance. Furthermore, if the earlier, significant, eastern ice shed (discussed above and capable of taking erratics across the western Valla Field ridge) is accepted then this eastern movement into the Unst Basin entails a reduction in size and shift to the west, of that ice shed. Therefore, this movement also post-dates the early northwesterly movement. The critical evidence of heavy minerals[44] in offshore deposits is relevant here, as they extend from Unst to northeast further than the Pobie Bank (figure 3.16).

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[44] Beg 1990

It is difficult to suggest when the ice stream through Bluemull Sound developed but the need for a further shift of ice centres to the south is required, which suggests a more advanced degree of retreat from the north.

Further draw down through Bluemull Sound and the Unst basin probably resulted in further ice centre movement to the south and west, progressively allowing northeasterly ice movement across Fetlar and southeast Unst in the direction of the Unst basin. The striae at Aywick in southeast Yell may also be part of this pattern. An ice shed running along the Arisdale highground and possibly further to the northeast, is implied by the switch to movement to the southeast across Fetlar and southeast Yell, into the Fetlar basin. This indicates that the Fetlar Basin has deglaciated and the movement into it probably post-dates those into Bluemull Sound and the Unst Basin but there is no direct morphochronological evidence of this. The movement probably post-dates the Yell Sound ice stream however, since evidence of this more eastern movement occurs south of Yell (chapter 7 - figures 7.2 and 7.6).

This is a complex sequence of events and it is tempting to resort to an explanation involving a number contemporaneous ice centres to explain all the data. This is the approach taken to some extent by Flinn[45]. An examination of the relevant figures (figures 3.11 and 9.2) however reveals that an equally complex set of extrapolated ice flow lines, bearing in places uncertain relationships to the main hypothesised ice masses, is required to support such a reconstruction.

9.3.4. Nature of glaciation and deglaciation

The nature of glaciation on Unst is largely erosive. Sizeable quantities of lodgement till are found on the western low ground around Bluemull Sound as far north as Wick of Collaster where up to 3-4 m of lodgement, including stone clusters, striated clasts and boulders up to 1m in diameter are deposited. Similar lodgement occurs on the other side of Bluemull Sound and this is probably related to ice stream development in the Sound (see above). The only other area where significant till is consistently developed on Unst is in the southeast corner over which a northeastern stream is thought to have passed. This till is also lodgement and includes boulder pavements in places. Elsewhere over much of the island, although there are surficial erratics, there is little drift development. Particularly on areas of serpentine the surface is bare and in places there are indications of solution weathering and microgelivation. It might be suggested that these bare areas, especially on high ground, such as at Keen of Hamar, represent periglacial environments during the last glaciation and that ice direction indicators on Unst are relics from a previous glaciation. This limited extent model does not fit with other data on the last glaciation of the islands to the north (see chapter 10). The more likely reason for the striking landscape is that the weathering of serpentine offers remarkably unsuitable nutrient material for

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[45] Flinn, 1978

vegetation. Climate, or a thin mantle of glacigenic material, since the end of the last glaciation may have allowed this limitation to be overcome but wherever the cover was subsequently stripped it has been unable to re-establish itself. Although not therefore a relic periglacial landscape, this state of affairs does allow the observation that very little till was deposited over most of Unst during the last glaciation where the landscape is dominantly erosive. Elsewhere on Shetland, and especially on Yell, thick peat often prohibits such observations.

On Fetlar there is a clear distinction between the west and east coasts. To the east there is little or no till development and colluvium with thrown beach gravels is developed on sheared bedrock surfaces with some evidence of glacitectonization. On the west coast up to 2-3 m of lodgement till is developed but extends only 10's of metres inland. This may reflect preferential lodgement on the up-glacier side of the obstacle presented by the island as ice passed to the northeast over it, but the rest of the island is again devoid of drift cover.

Much of the island of Yell is covered with a substantial thickness of peat, making it difficult or impossible to determine the character of the underlying drift. In most places where the peat is removed there is either bedrock or a thin veneer of clastic debris. The major exceptions are along the east coast, particularly on the fringes of Bluemull Sound, through which ice appears to have streamed to the north - at Bay of Brough, where up to 4-5m of lodgement is developed - and on the southeast coast which appears to have been passed over by an east-moving ice stream. There is also some evidence of lodgement on the flanks of the major voes.

In those areas on Unst, Yell and Fetlar where there is evidence of lodgement development there is also evidence of underlying glacitectonization, once again underlying the fact that lodgement and erosion are closely related processes. The absence of shell material in sections that are down-ice from areas that are now underwater, such as the northeast coast of Yell, the west coast of Fetlar, and the southeast coast of Unst, suggests that these inter-island inshore areas were swept clean before deposition of the lodgement occurred. The implied sequence of events is that considerable erosion took place, followed by a second phase of erosion and glacitectonization which in particular places crossed a glacidynamic threshold and led to deposition. This latter phase was probably relatively late in the cycle since the areas of deposition are associated with ice movements and streams that are identified as being relatively recent on the basis of morphochronology (above).

Offshore to the north the Otter Bank (subglacial) sequence extends to the shelf edge to the northwest and is hummocky and cut by channels in some areas. Overlying this, infilling some of the channels and partly channelized itself is the Stormy Bank sequence. The latter is glacimarine in origin and to the northwest there is an area of iceberg ploughmarks near the shelf edge at depths of between 150 - 300 m below modern sea level. As discussed above there are areas closer to the islands which do not appear to support these sequences and it has been suggested that till extends from Yell Sound, Bluemull Sound and between Unst and Pobie Bank in a lobate manner[46]. The sediments of Yell Sound and Bluemull Sound have not been cored but a borehole exists through the sediments of the Unst basin, between Unst and Pobie Bank. Here there are two seismic units, both of which extent from the inshore Fetlar basin and along the trough to the west of Pobie Bank.

The clastic nature of the material infilling the Unst Basin, the absence of significant micropalaeontological matter, the low calcium carbonate content, and the evidence of possible sub-aerial weathering, have all led to the conclusion that it is a terrestrial subglacial till with facies variations associated with possible proglacial environments[47]. The writer's examination of the till suggests that while the fabric could be proximal glacimarine the other evidence is in agreement with terrestrial deposition.

9.4. Conclusions

The last glaciation extended well to the north of Unst and Yell, probably to the shelf edge in the northwest and at least 50 km directly to the north. Early deglaciation resulted in ice flow to the northwest and an ice shed that may have been displaced to the east of Unst (figure 9.4). Ice direction evidence reveals that the deglaciating ice front must have become more northerly with time and the ice shed in the area moved south and west, ultimately feeding ice streams through Bluemull Sound, the Unst basin, and Yell Sound (figure 9.5). These may have resulted in a lobate offshore margin, possibly associated with terrestrial margins on north Unst and north Yell, Saxa Vord and Hermaness on Unst may have been nunataks for some time, shedding solifluction deposits. Further draw down through these exits resulted in further south and west movement of the ice source areas and ultimately flow into the Fetlar basin. There may have been a residual ice cap on Unst also (figure 9.6).

The pattern of northwestern and northern deglaciation and increased topographic containment is familiar but the relative timing of these events with those of the rest of the islands is discussed in chapter 11. The dating of the all important Otter Bank and Stormy Bank sequences is considered in chapter 10 and these are found to be of Late Weichselian age.

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[46] Long and Skinner, 1983

[47] Cockcroft, 1987

10. Chronology of the last glaciation

10.1. Previous work

10.1.1. On-shore Quaternary stratigraphy

Work on the pre-Holocene Quaternary of the Shetland Islands has resulted in the development of a stratigraphy extending at least as far back as the last interglacial, and has resolved the late-glacial interstadial and at least one other interstadial period.

10.1.1.1. Pre-last glacial maximum

The sedimentary sequence at Fugla Ness was first described[1] as comprising:

top	till
	till
	peat
	till
base	bedrock

More detailed analysis of the lithostratigraphy[2] resolved:

top	till
	periglacial slope deposits (organic bands at base)
	peat (in places resting on pond silts)
	till
base	bedrock

The biostratigraphy of the peat has been investigated[3] and is indicative of local open coniferous woodland, alternating with heath and grassland communities. The pollen assemblages of the organic bands in the slope deposits indicate a reversion to a harsher climate prior to the onset of the periglacial mass movement[4].

The age of the main peat is important. The presence of some thermophilous taxa, and macrofossil evidence of local pine woodland, suggest it is of interglacial character. Biostratigraphic correlation is difficult over long distances[5], especially given Shetland's unique position, but is attempted by two authors[6] who reach different conclusions. Firm geochronometric control is essential and missing. Most recently, the interglacial has been correlated with the Eemian (oxygen isotope stage 5e) on thermoluminescence dating and, 'count-from-the-top,' lithostratigraphy[7].

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[1] Chapelhow, 1965
[2] Hall et al., 1993a
[3] Birks and Ransom, 1969
[4] Hall et al., 1993a
[5] Lowe, 1984
[6] Birks and Ransom, 1969; Hall et al., 1993a
[7] Hall et al., 1993a

At Sel Ayre, the presence of peat beneath a number of deposits including till has been reported[8]. The lithostratigraphy, as more recently examined[9], comprises:

top	till
	breccia
	organic sands and gravels (including peat bed)
base	scree-like, brecciated, rock gully infill

The lower breccia is overlain by a thin, non-polleniferous, pond clay indicative of continuing climatic severity. The organic sands and gravels contain evidence of considerable local environmental change, but climatic amelioration from below, and through, the peat bed, is evident. The overlying upper breccia is a solifluction deposit, evidence of a return to a period of intense frost action prior to full glacial conditions.

The sequence at Sel Ayre represents a cold-warm-cold cycle. The pollen spectra of the main peat is statistically distinct from both the Fugla Ness peat and the Holocene assemblages[10] at Murraster[11], and is of interstadial character. The presence of *Bruckenthalia spiculifolia*, often associated with the Brørup and Odderade interstadials[12], equivalent to oxygen isotope sub-stages 5c and 5a, may be of some chronostratigraphic value. However, the number of interstadial/stadial cycles that may have occurred since the Eemian is considerable and the use of even such exotic species should be treated with caution. Geochronometry has proved inconclusive[13], although Uranium-series dating of the main peat[14] gives a very tentative maximum age of 100 ka BP. An interstadial post-dating the last interglacial, possibly of isotope sub stage 5a or 5c, is thought to be the likely age of the main peat[15].

For the present purposes, it should be noted that neither of these pre-glacial sites demonstrates that the last glaciation was of Late Weichselian age.

10.1.1.2. Late-glacial oscillation

Research into the stratigraphy of the late-glacial is at an early stage[16], but consists of lithostratigraphic, pollen and diatom analysis of lake basin sediments[17] and open sections[18] . Geomorphic evidence (discussed in the preceding regional chapters) has been presented[19] but is tentative and remains undated. Those sequences with dating control are discussed here.

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[8] Mykura and Phemister, 1976
[9] Hall et al., 1993b
[10] Johansen, 1975
[11] Birks and Peglar, 1979
[12] Beaulieu and Reille, 1992
[13] Hall et al., 1993b
[14] Heijnis, 1992
[15] Hall et al., 1993b
[16] Birnie, 1993a
[17] Hoppe, 1974; Hulme and Durno, 1980; Birnie, 1981, 1993b; Edwards et al., 1993
[18] Hoppe, 1974; Hall, 1993; Hall and Whittington, 1993
[19] Charlesworth, 1965; Mykura and Phemister, 1976; Flinn, 1982; Gordon, 1993b

Two cores at Aith Voe show a late-glacial interstadial lithostratigraphy[20]:

top	up incr. productivity;
	up decr. productivity; sediment virtually inorganic
	up incr. productivity; herbs, poss. *Salix*, *Betula*
	up incr. productivity but poss. disturbed soils
base	no/low organic productivity

Grain size variations in the sequence are thought to be due to changes in the location of stream input and do not indicate glacier input during the stadial.

Radiocarbon dating[21] suggests an early late-glacial oscillation (13,680 ± 80 BP and 12,190 ±80 BP delimiting the interstadial) compared to the Scottish mainland. Direct comparison is difficult, however, because radiocarbon dating of bulk samples from lake sediments suffers from the numerous and complex pathways by which C^{14} may reach the sediment. Accelerator Mass Spectrometry (AMS) dating of macrofossils, even microfossils, is a potential solution.

At Clettnadal[22] fine-grained organic lake sediments rich in macrofossils have been exposed in open section:

top	coarse breccia of unknown genesis
	brown gyttja with prominent leaf layers
	blue-grey organic silt
	brown gyttja with prominent leaf layer
	inorganic blue-grey silt (basal gravel lag)
base	glaciated rock surface

Four dates appear to confirm the late-glacial character of the lithostratigraphy. Deposition of the lower brown gyttja began at 11,650 ± 45 BP. The upper gyttja supports a sequence of three dates from 10,050 ± 45 BP at the base, to 9170 ± 45 BP at the top. These dates are inconsistent with the dates from Aith (above). However it would again be beneficial to conduct AMS dating, especially since macrofossils are abundant.

At Tresta[23] the following sequence is exposed:

top	peat
	grey diamict
	organic sediments
	grey diamict
base	till

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[20] Birnie, 1981
[21] Birnie and Harkness, 1993
[22] Hall, 1993
[23] Hoppe, 1974; Hall and Whittington, 1993

A date of 11,135 ±135 BP has been obtained from the organic sediments, although it is not clear where in the organic unit this was taken. If the base was dated, then the organic development might be conventionally placed during the late-glacial stadial and the diamict on either side may be associated with slope movement during the same period. The base of the overlying peat was dated to 5,865 ± 95 BP leaving a substantial hiatus at the commencement of the Holocene, so if the earlier date was from the top of the organic sediments, then a late-glacial interstadial assignation would again be reasonable. The uncertainties involved make it difficult to extend the significance of this site to the emerging picture of the late-glacial on Shetland.

An organic-inorganic-organic sequence from Clickhimin Loch has been reported[24], with dates of 12,090 ± 900 BP for the lower organic sediments, and 9,620 ± 750 BP at the base of the upper organic unit. This would appear to delimit the late-glacial oscillation. AMS dating would again be advantageous but recent workers have failed to recover a similar sequence[25].

A conventional lithostratigraphic late-glacial sequence was not recovered at Lang Lochs[26], but the base of the sequence comprised mineral in-wash with some organic content, succeeded by a gyttja. The base of the mineral in-wash was dated to 13,200 ±100 BP, and the base of the gyttja to 10,450 ±70 BP. Environmental change at c. 10.4 ka BP can be interpreted as the commencement of the Holocene interglacial, but the absence of a Lateglacial oscillation before this is anomalous.

Further evidence of the late-glacial environmental oscillation is reported at Grunna Water[27] but no chronostratigraphic data is available for this site.

The earliest date available for the commencement of the Holocene at Murraster is 10,400 ± 160 BP[28], and the onset of non-minerogenic sedimentation pre-dates 9,350 ± 90 BP at Dallican Water[29] and 9,785 ±80 BP at Gunnister Water[30].

In summary, pre-last glacial sites do not necessarily demonstrate that the last glaciation was Late Weichselian. Work on the late-glacial oscillation is at a preliminary stage, although it is clear that the oscillation is post- Late Weichselian and that environmental changes occurred, as they did elsewhere across northwest Europe. As yet there is no conclusive evidence of associated glacial activity. Tentative dates suggest that lowland parts of the islands were ice-free around 13

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[24] Hoppe, 1974
[25] G. Whittington (pers. comm. 1993)
[26] Hulme and Durno, 1980
[27] Edwards, et al., 1993
[28] Jóhansen, 1985; Bennett, 1993
[29] Bennet and Sharp, 1993
[30] Bennet et al., 1993

ka BP, and that environmental deterioration recommenced around 12 ka BP, terminating perhaps at 10 - 10.5 ka BP. The commencement of the interstadial may be relatively early but there are considerable anomalies, much work remains to be undertaken, and this broad sequence is highly tentative. Abundant macrofossils offer the potential of using AMS dating techniques to improve the chronostratigraphic sequence.

10.1.2. Off-shore stratigraphy

Longer and fuller Quaternary sequences are preserved offshore, particularly in the northern North Sea basin and in the progradation of the western continental shelf edge. However, climate change has major effects on the rate of sedimentation in these areas, particularly between glacial and non-glacial environments: much of the Quaternary cover on the shelf is glacigenic and, therefore, lithostratigraphic correlation between cores is not possible; interglacial sediments are richer in *in situ* biostratigraphic and geochronometric material, however such interglacial strata are thinner, may be missed or locally not present in core samples, and may not attain acoustic resolution on seismic traces. It should also be noted that biostratigraphic resolution is limited to, 'Early,' and, 'Late Pleistocene.'

Seismic correlation is therefore crucial, but in the inner shelf areas, both to the east and west of Shetland, the Quaternary cover is thin (and frequently impossible to differentiate due to the limitations of seismic resolution). The best sequences are preserved in basin settings but these cannot be traced from basin to basin, or to the outer shelf areas. Outer shelf sequences are better preserved but are bounded by unconformable erosion surfaces. While these provide the basis of seismic sequencing, chronological or environmental interpretation of such hiatuses is not possible and the erosion surfaces are potentially time-transgressive[31]. Seismic correlation between the West Shetland Shelf and the northern North Sea basin is largely prevented by the Orkney/Shetland ridge/platform, and between the northern North Sea basin and the main North Sea basin by the East Shetland Ridge. Between the West Shetland Shelf and the Hebrides Shelf, and the northern and main North Sea basins, other methods of correlation must be treated cautiously since these areas were affected by different ice centres. The West Shetland slope area appears to be beyond the limits of direct glaciation, except in places[32], and the chronology here is complicated by progradation and mass-movement[33]. The sediments of the deep Faeroe-Shetland Channel are distal, bioturbated, interdigitated with mass-flow from the slope area, and subjected to erosion by bottom-current activity which has varied significantly with marine circulation through the Quaternary[34]. Correlation between the Faeroe-Shetland Channel and the deep-sea basins to the south is limited by the Wyville-Thomson Ridge.

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[31] Stoker and Long, 1984
[32] D. Long (pers. comm. 1995)
[33] Stoker et al., 1993
[34] Stoker et al., 1989

The sequences identified by the British Geological Survey are shown in figure 10.1. Given the problems outlined above, however, the stratigraphy is to be taken as tentative. See also figures 2.10, 3.4, 3.13, 3.14, 3.15.

Only those sequences of direct relevance to this study are discussed below. Full discussions of the underlying sequences are available from a variety of sources[35].

The glacimarine Sperus Formation (SPE) conformably overlies the dated Cape Shore Formation (CSO) in the north-east shelf areas and is therefore Mid- to Late- Weichselian in age (figure 10.1). The overlying Tampen (TAM) Formation is a possible lateral moraine due to northward flowing ice in the Norwegian trench. Shells within this formation have been radiocarbon dated to 18 860 ± 260 BP[36]. The Viking Bank Formation overlies the Cape Shore Formation on the western side of the Viking Bank high and is associated with deltaic/pro-deltaic and shallow coastal processes. A stratigraphically consistent radiocarbon sequence from 11,350 ± 120 BP, to 10,420 ± 80 BP, to 8,530 ± 110 BP has been established[37].

The sediments of the inner, northern and western shelf areas are not as well dated. The inner shelf area is largely rockhead outcrop or thinly covered with Quaternary deposits. Exceptions occur in some basin settings (the St Magnus Bay (see chapter 6), Fetlar (chapter 7), West Fair Isle (chapter 5) and Unst (chapter 9) Basins), and to the north of the islands. The thin and patchy cover of the East Shetland Platform has been referred to as the Shetland Platform sediments[38]. They include sediments of glacial/glacimarine origin with some possible late-glacial/post-glacial soft clays infilling depressions. Until recently, only their relationship with the Ferder Formation (FDR in figure 10.1) and, 'count-from-the-top,' stratigraphy suggested that they may be of Late Weichselian age. Shells in either a glacigenic debris flow or soft-sediment deformation till from these sediments, are dated to 13, 315 ± 155 BP (adjusted for seawater apparent age of 405 ±40 years)[39], suggesting that ice covered these inner shelf areas at this time. An important feature of the sediments, widespread in this eastern continental shelf area, is the shelly strata beneath the Holocene sands that is associated with the late-glacial interstadial period. This is dated to 12,265 ± 135 BP (similarly adjusted).

Unfortunately the sediments of the East Shetland Platform are not seismically correlated with the more extensive glacigenic deposits of the Northern and Western Outer Shelf areas. Here the Otter Bank (OTB) sequence includes glacial diamicts with, in some places, overlying

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[35] Chesher, 1984b; Evans et al., 1990; Holmes, 1991; Johnson, et al., 1993; Long, 1988; Stevenson, 1991; Stoker et al., 1993;
[36] Rokoengen et al., 1982
[37] Rise and Rokoengen, 1984
[38] Long, 1988
[39] Peacock and Long, 1994

glacimarine deposits, and to the north there may be equivalent sediments within the Undifferentiated Upper Pleistocene sequence (UUP in figure 10.1). These sequences unconformably overly the Ferder (FDR) formation to the north and west of Shetland, suggesting that they are at least post-Eemian, and are the uppermost subglacial materials, therefore possibly of Late Weichselian age but there is no direct dating nor seismic relation to dated sequences elsewhere.

The Stormy Bank Sequence (STB) is glacimarine in origin and is identified in seismically isolated areas north and west of Shetland overlying the Otter Bank Sequence in many places. These areas are correlated on the basis of acoustic and lithological similarity and stratigraphic position. Within these locations the STB is invariably the uppermost non-Holocene unit and in places it merges with the underlying Otter Bank Sequence. No direct chronostratigraphic data exists for this sequence although it is again assumed to be Late Weichselian. The sediments of the inner basins have been examined in the preceding regional chapters. The most important finding is that, while there may be subglacial tills, there is no evidence of subsequent glacimarine activity. Instead, shallow, severe, marine conditions are indicated. It may, therefore, be appropriate to reconsider the validity of including these upper basin sediments in the Stormy Bank Sequence[40] (figure 3.15).

10.2. Outstanding issues

There are numerous outstanding issues related to the chronology of the last glaciation of the Shetland islands and this study does not attempt to cover them all.

Clearly the sediments of the northern North Sea basin are dated more effectively than those to the north, west and, to some extent, east of Shetland. Although the inner shelf sediments to the east have been dated[41], the thicker sequences to the north and west are in need of similar treatment. The assumed Late Weichselian position of these sediments has two bases, namely, 'count-from-the-top,' and their relation to the Ferder Formation. The Ferder Formation is therefore of considerable importance in regional correlation, but although seismostratigraphic correlation with the North Sea has been achieved, the interglacial data proved in boreholes there have not been observed north and west of Shetland. Since the Ferder Formation should include two cold episodes, the absence of the intervening warm episode confuses the stratigraphic position of overlying sediments such as the Otter Bank sequence. That is to say, the Otter Bank Sequence could be Early or Late Weichselian depending on whether the Ferder Formation includes both the cold episodes (Saalian and Early Weichselian) identified to the east. The need

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[40] Johnson et al., 1993
[41] Peacock and Long, 1994

for chronostratigraphic control on the Otter Bank sequence and further resolution of the Undifferentiated Upper Pleistocene deposits, therefore, is pressing.

The Stormy Bank sequence overlies the Otter Bank Sequence only and is not directly dated. The contact is generally conformable and this sequence may offer more useful organic dating material than the Otter Bank Sequence itself. The existing assignation to the, 'waning stages of the Late Weichselian,'[42] is highly probable given the sequence's stratigraphic position but the time span involved is not known.

10.3. Northern glacial chronology: aims

This study attempts to tackle some of these issues by examining and dating the sediments to the north of the islands. The northern area was selected over the western because: the date of the sediments here assists in the resolution of the extent of the northern glacial maximum (see chapter 9); and the western shelf edge sediments and morphology are currently under investigation at the British Geological Survey.

10.4. Northern glacial chronology: data and results

In order to contribute to the chronology of the region and also help resolve issues relating to the northern position of the last glacial maximum, a number of cores were examined from north of Unst and Yell. Those selected for initial examination were identified from the various British Geological Survey logs available for the region. Figure 10.2 shows the location of cores that were examined. All the cores were drilled in 1977 except 328 (1978), 275 (1980) and 9 (1984), and have been sealed and stored by the British Geological Survey since that time. Although some of the cores have been worked on subsequently, the details of these activities are not available.

The cores were examined and their fabric characteristics recorded. Due to poor borehole recovery and predominantly inadequate vibrocore penetration, only five of the examined cores contained useful sequences (figure 10.3), and only one a possible glacial-Holocene transition.

10.4.1. Seismic stratigraphy

A typical seismic line across the shelf area in figure 10.2 is shown in figure 10.4[43]. Despite the limited extent of the glacimarine (Stormy Bank) sediments mapped, most of the cores examined (figure 10.2) proved substantial glacimarine sequences (figure 10.3). This discrepancy is due to the resolution of 'Sparker' seismic records (about 5m) which is insufficient to show the top few

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[42] Stevenson, 1991

[43] After Stevenson, 1991

metres that the vibrocores penetrate. The veneer of glacimarine sediments may therefore cover much of the shelf area beyond that shown in figures 10.2 and 10.4.

10.4.2. Core quality

Of the cores marked on figure 10.2:

9, 328 and 275 are boreholes with *circa*. 10% recovery in the Quaternary or are extremely dried and have insufficient geotechnical and lithostratigraphic data to develop a reliable lithostratigraphic sequence;

65 is a vibrocore that recovered only bottle samples of 0.23m of sediment; there is therefore no geotechnical information and the lithostratigraphic sequence, sedimentary structures etc., are destroyed;

These cores were not considered further.

The remaining cores were 100% recovered and are logged in summary in figure 10.3. Of these, the detailed lithostratigraphy and other available data show 61-01 66ve to be a sequence including possible sub-glacial to Holocene units. The remaining cores generally showed no evidence of having penetrated possible sub-glacial materials or did not appear to have a possible Late-glacial unit[44]. Further data on vibrocore 61-01 66ve is given here.

10.4.3. Lithostratigraphy

Figure 10.5 shows the lithostratigraphy of core 61-01 66ve and the lettered units (1)-(4) are discussed below:

(1) Unconsolidated coarse shelly sand is almost invariably found at the top of vibrocore sequences in the area and represents Holocene marine deposition with much biogenic activity and some tidal winnowing of fines.

(2) This unit is common in most vibrocores from the surrounding shelf areas and characterizes the late-glacial oscillation[45]. The basal shell hash represents the amelioration of the late-glacial interstadial, with biogenic activity decreasing up-core until the commencement of the Holocene (unit 1).

(3) This unit is characteristic of glacimarine sedimentation: sandy muds and muddy sands suggest that marine influences are superseding ice-related processes but the singular occurrence of a large lithic is difficult to interpret as anything other than an iceberg dropstone. The bands of clay and fine silt may represent the distal tails of turbidity plumes or occasionally prolonged sea-

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[44] Peacock and Long, 1994

[45] J. D. Peacock (pers. comm. 1994); Peacock and Long, 1994

ice cover. Although the core has not been X-rayed for burrows, mottling of the sediments in parts of this unit is characteristic of bioturbation. More fines bands may have been destroyed by this mechanism.

(4) The lowest unit contains a coarser matrix, smaller shell fragments, lower biogenic productivity (more moderate visual HCl reactions on the sub 125 micron fraction), and is more gravelly. It is always difficult to distinguish lithologically between sub-glacial sediments and those released in a proximal glacimarine environment. The seismic interpretation of the area (figure 10.4), when allowance is made of the failure of the 2.5 m of glacimarine and Holocene sediment to be resolved on seismic traces, suggests that the vibrocore might well penetrate the Otter Bank Sequence. However it is possible that a proximal glacimarine unit is also seismically, "hidden," and that this is what is found at the base of 61-01 66ve.

10.4.4. Geotechnical data

The high undrained shear strength measurements at the base of 61-01 66ve (figure 10.5), which are also associated with higher values of hardness and lower values of plasticity, may be due to sub-glacial stress history[46]. Although the reduction in shear stresses up-core may be accounted for by reduced pressure of overlying sediments, the high value in the lower unit 4 is well above that of normally consolidated material. For comparison, shear stress measurements on Late Weichselian tills from the northern North Sea are generally in excess of 100 kPa[47], and the East Shetland Platform Sediments (figure 10.1) are frequently overconsolidated to undrained shear stresses of about 150 kPa[48]. Although high shear stress values have been recorded within mass movement sediments on the continental slope[49], in the shelf setting of this study the value of 450 kPa is unlikely to represent such a deposit.

10.4.5. Biostratigraphy

Although the available evidence supports a sub-glacial interpretation of unit 4, the lithostratigraphic difference between this and a proximal unit near the grounding line is probably not great.

No micropalaeontological data are available for this core although HCl reactions on the sub-125 micron fraction throughout the core indicate the presence of calcareous micro-biota. Such data for the upper sequences elsewhere in the study area are generally poor but, since the lithological sequence is well established, what data is available can be applied to 66ve and is here discussed in terms of lateral equivalents of the units described above. It is only possible to distinguish

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[46] e.g. Young et al., 1978

[47] e.g. Sejrup et al., 1994

[48] Long, 1988

[49] M. Stoker (pers. comm. 1994)

between, 'Early Pleistocene,' and, 'Later Pleistocene,' by assemblage, so correlation within the latter period is limited to palaeoenvironmental comparison. Early Pleistocene derived assemblages have not been reported in the upper sequences of the shelf regions around the study area. The two nearest cores for which data are available are discussed below.

Vibrocore 60-01 31ve lies approximately 30 km south of 66ve. The lithological sequence appears similar to 66ve although it is not clear whether the core penetrates substantially different material at the base. The macrofauna[50] is typical of modern sediments in the lateral equivalent of unit 1. Lower down the fauna is more restricted and includes the cold water species *Macoma calcarea* and *Nuculana pernula* suggesting that the equivalent of unit 2 may record the late-glacial stadial. Unfortunately samples were not examined below this depth. Dinoflagellate cyst data[51] again reveal a well-established Holocene sequence in the unit 1 equivalent but samples below this were too poor to give any clue as to the age of the older sediments (unit 2/3), although again a more severe environment is implied by this paucity.

Borehole 84/08, approximately 27 km southwest of 66ve, again penetrates Holocene sands and Stormy Bank glacimarine deposits. Dinoflagellate cyst data[52] do not cover the equivalent of units 1&2 but samples from the glacimarine (unit 3) sediments show a paucity typical of severe arctic conditions. At the top of this unit there is a possible amelioration or a change to a more open marine environment. This would suggest that unit 3 is increasingly distal up-core or possibly that downward bioturbation of late-glacial interstadial assemblages has occurred. Foraminifera[53] show a strong amelioration through the top of the unit 3 equivalent, which is otherwise unfavourable for the development of diverse assemblages.

A summary of Professor J D Peacock's examination of the macrofauna of the 61-01 66ve samples identified in figure 10.5, made for this study,. is as follows:

Unit 1 contains an assemblage to be expected at the present day at this water depth (160 m). This confirms the Holocene assignation of unit 1 and there is even some evidence of rising sea-level, confirming geomorphological evidence for the phenomenon on the Shetland Islands.

Unit 2 contains a characteristic late-glacial interstadial fauna, particularly including *Margarites costalis, Boreotrophon clathratus* and *Yoliella lenticula*, not currently found as far south as Scotland. The presence of *Nucula nucleus*, while not entirely incompatible with a late-glacial context, may indicate bioturbation of the overlying sediments into this unit. Sample 4 contains

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[50] British Geological Survey internal report: PDS 80/28
[51] British Geological Survey internal report: PDS 80/297
[52] British Geological Survey internal report: PDS 85/108
[53] British Geological Survey internal report: PDS 85/78

the more identifiable fauna and is more clearly within the late-glacial lithological unit (figure 10.5).

Unit 3, which is lithologically glacimarine, includes the anticipated cold water species. Some are abraded and possibly derived but others are unabraded and more probably *in situ*. The assemblage is not diagnostic of any particular environment, but *Nucula pernula* is a northern form not currently found in British seas.

The **unit 4** assemblage is difficult to interpret and probably includes derived species. The shoe sample (11) in particular contains rare fragments of species found in the Holocene assemblage (unit 1, above) which may be derived from pre-glacial circumstances. Unabraded fragments also exist and may not be derived.

10.4.6. Radiocarbon dates

The sequence within the selected core (61-01 66ve) has been dated in four places. AMS dating on single shell fragments has been undertaken since recovery of a sufficient bulk sample for conventional dating from cores is destructive and may result in a loss of stratigraphic resolution. The original samples comprised approximately 100 mm sections of half core, wet sieved through a 1000 micron sieve and oven dried overnight at 70^{o} C. The shell material to be dated was examined by Professor J. D. Peacock for his observations on sample quality, type, biostratigraphic significance (see above), and sample selection. *In situ* material has been selected for dating, although for units 3 and 4 the status is more probable than certain.

The results are as follows (see also figure 10.5) and include adjustments for the apparent age of seawater:

Lab No.	**Sample**	**Species**	**Measured Age with 2 SD limits**	**Adjusted age[1]**	**$\delta^{13}C_{PDB}$ ± 0.1‰**
AA16903	4	*Modiolus modiolus*	12860 ± 180	12445	0.1
AA16904	6	*Hiatella arctica*	13165 ± 180	12760	1.4
AA16905	9	*Hiatella arctica*	13390 ± 190	12985	1.3
AA16906	10	*Trodonta elliptica*	18230 ±280	17825	0.5

[1]Adjusted ages based on apparent age of seawater of 405 ± 40 years.[54]

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[54]Harkness, 1983

The effect of using the 2 standard deviation (95% confidence) limits on the resolution of these dates is as follows. The late-glacial date (unit 2; AA16903) cannot be resolved from the late glacimarine date (3; AA16904), the early glacimarine date (3; AA16905) cannot be resolved from the late glacimarine date (3; AA16904), but the early glacimarine date (3; AA16905) can be said to be significantly older than the late-glacial date (2; AA16903), and the sub-glacial/proximal glacimarine date (4; AA16906) can be said to be significantly older than all the others at the 95% confidence level. Note that atmospheric CO_2, ocean circulation, depth, and the location of areas of upwelling may be radically altered during full glacial times, so the apparent age of seawater given above may not be appropriate.

The date from unit 4 suggests that this is either a relatively proximal glacimarine unit, or that glacier ice fluctuated over the area, since the mollusc clearly did not die prior to the last glaciation. The question of whether the unit is glacimarine or subglacial is unresolved. However, either way, a nearby ice margin is indicated. This margin is considerably further north than Unst and the Otter Bank sequence continues further north still - it is therefore highly unlikely, even accepting a lobate northern margin, that the last glacial maximum was terrestrial on the northern isles (see chapter 9).

The site is close to a postulated ice margin and the date may suggest that deglaciation may have been underway in this northern area, as early as 17 - 18 ka BP, whereas, East of Shetland, although perhaps 30 km from the maximum eastern extent, ice-proximal deglaciation was occurring at around 13 - 14 ka BP[55]. It is possible that, by this time, much more distal glacimarine activity was underway at the northern site and that deglaciation commenced to the north of the islands earlier than to the east. However this cannot be conclusively stated on this evidence alone.

The timing of the late-glacial interstadial unit is comparable with that from the East Shetland Platform sediments (where an adjusted date of 12,265 ± 135 BP was obtained[56]).

Perhaps most significantly, these data suggest that the sediments north of the Shetland Islands are indeed associated with the Late Weichselian glaciation. Since the Otter Bank and Stormy Bank sequences can be seismically traced to the sediments and shelf edge moraines of the western continental shelf, it is likely that these too are of Late Weichselian age, although such a correlation does not imply that all the sediments were emplaced at the same time as those in this core.

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[55] Peacock and Long, 1994

[56] Peacock and Long, 1994

10.5. Conclusions

A number of conclusions are drawn from the investigation of the sediments north of Shetland made by this study: the Otter Bank and Stormy Bank sequences are associated with a glaciation of Late Weichselian age, that may have been more northerly extensive than currently mapped; since these sediments can be traced to the western shelf edge then these, too, are associated with Late Weichselian glaciation; although direct comparison is difficult, there may be evidence that deglaciation was underway considerably earlier in this northern location, than was the case for the eastern ice sheet margin; the late-glacial interstadial unit is identifiable in these northern areas, and is dated to around 12-13 ka BP, comparable with other late-glacial interstadial dates in the region.

11. Synthesis

This chapter synthesises the regional analyses, proposes a broad reconstruction of the last glaciation of the region, combines this with the wider context of northwest European glaciation and makes recommendations for future work. It is also intended to function as a sensible alternative to reading all the other chapters and offers brief reviews of previous work and the aims and limitations of the project. Since the existing literature is reviewed in chapters 2 and 3 and in relevant regional chapters specific publications are not referred to here.

11.1. Context

Problems and work to date on the last glaciation of the Shetland Islands are here reviewed briefly in the light of the author's own experience of the quality of the data available.

11.1.1. Terrestrial problems

Reconstruction of the last glaciation of Shetland on the current landmass is difficult. The islands form a narrow, Caledonian remnant, just a few kilometres from east to west in places and the last ice sheet may have been 150 km in diameter on this axis. Complex terrestrial solid geology[1] makes erratic analysis and, in many cases, the identification of erosional data such as striae and stoss and lee observations, difficult. Many of the valley floors in which glacial landform assemblages might be anticipated are now submarine and there is little - and generally poorly developed, preserved or exposed - morphological data. While coastal drift exposure is excellent, inland exposure is much more limited.

11.1.2. Terrestrial work to date

Given these difficulties a remarkable quantity of evidence has been collected from the Shetland islands since work began on their last glaciation a century ago. Striae and erratic data are particularly well documented[2] but the problems mentioned above are evident in the literature with a variety of authors being, 'convinced,' or, 'certain,' of the direction of ice movement implied by stoss and lee data but reporting contrasting conclusions. Even some early erratic reports are not compatible with later analyses and in these cases subsequent authors have ignored rather than directly refuted the suggestions.

Directional data has been used to discuss arguments relating to the influence or otherwise of Scandinavian ice on the islands. A number of models have been put forward, including: (1) early Scandinavian ice crossing the islands from the northeast and turning to the northwest

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[1] Mykura, 1976
[2] e.g. Flinn, 1982

followed by more limited local glaciation in which ice flowed both east and west off islands[3] (figure 3.7); (2) early Scandinavian glaciation from the east followed by the establishment of an independent remnant ice cap on the islands due to rising sea level, and the progressive reorientation of ice flow lines as ice calved into inshore areas[4] (figure 3.10); (3) an independent ice sheet flowing east and west off the islands but encountering a Scandinavian ice sheet to the east and flow lines being turned to the northeast and back across northern islands - the Scandinavian ice itself crossed the southern peninsula and Fair Isle[5] (figure 3.9); (4) and an independent ice sheet wholly unrelated to Scandinavian glaciation (although such glaciation is a possibility in an early stage or previous glaciation) in which ice flow lines are related to bathymmetric contours in inshore areas[6] (figure 3.11).

With the exception of the second, these have all been presented as atemporal models in which all the evidence has been fitted to a single ice sheet configuration at one point in time. This is not surprising since there is no obvious method of developing a stratigraphic framework into which erosional data, such striae and stoss and lee, can be placed. Till also usually occurs in thin, single units (see below) so observing changes in ice movement through erratics in stratigraphic sequence is not possible.

11.1.3. Offshore problems

The recent development of data from offshore[7] is potentially of enormous significance but to date has been interpreted for the last glaciation in only a limited manner, particularly with respect to its correlation with onshore events. Considerable work is now underway and new interpretation can be anticipated in coming years.

The difficulty in reliably distinguishing between glacimarine and subglacial sediments and the absence of chronostratigraphy are major impediments to offshore interpretation. The sequences of relevance are undated to the west, only recently dated to the east and, in this study, the north.

11.1.4. Offshore work to date

Offshore interpretation has provided some evidence of the size of the last ice cap of the area, stretching perhaps 75 km to the east of Shetland and as far as the continental shelf edge to the west[8] (figure 3.13). The northern glacial maximum has been more controversial largely due to the proposition that there may be a terrestrial maximum margin on northern Unst and Yell[9]. This is inconsistent with the extent of possible last glacial deposits to the north of the islands

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[3] Peach and Horne, 1879
[4] Hoppe, 1974
[5] Mykura, 1976
[6] Flinn, 1977, 1978
[7] Chesher, 1984b; Evans et al., 1990; Holmes, 1991; Johnson, et al., 1993; Long, 1988; Stevenson, 1991; Stoker et al., 1993
[8] Stoker et al., 1993; Johnson, et al., 1993
[9] Flinn, 1983, 1992b, 1994a; Long and Skinner, 1985

however[10]. The southern limit is also not known: although evidence of the glaciation of Fair Isle, possibly from Shetland and/or Scandinavia, has been put forward[11] much of this area is in shallow water and Quaternary sediments are reported as being thin and difficult to interpret[12]. To the north, east and west, subglacial tills have been identified in offshore zones although these are thin and patchily distributed in shallow inshore areas, especially on the East Shetland platform. The top pre-Holocene unit has been identified from the shelf edge and East Shetland Platform to inshore basins and has been attributed to the waning stages of the last glaciation[13] (figures 3.14 and 3.15). In places it is described as glacimarine indicating that deglaciation was associated with a marine margin. For the reasons outlined above, published interpretation of offshore data is provisional, cautious, and although there is much useful descriptive data, reconstruction is largely limited to what has been described above.

11.1.5. Chronological work to date

There is no separate section on the problems of chronology here since the largest relevant problem is its absence. The provision of a temporal context for the last glaciation, deglaciation, and late-glacial of the region is at a preliminary stage. The commencement of the last glaciation in the area is undated although there are two terrestrial sites[14] and extensive offshore sequences[15] that offer some evidence of pre- last glacial environments. Recently the sediments of the East Shetland Platform, which extend 75 km to the east of the islands, have been dated and these suggest that deglaciation of the last ice sheet commenced at or before 13 ka BP[16]. This work demonstrated for the first time that the last glaciation of the islands was during the Late Weichselian but only gives a date for the commencement of deglaciation from the eastern margin of ice sheet. The earliest accepted post-glacial dates from terrestrial Shetland[17] are not dissimilar to this age suggesting either exceptionally rapid deglaciation or some error in the chronology. A single late-glacial oscillation has been reliably identified in various parts of Shetland[18], although none of these have shown that the Younger-Dryas equivalent stadial period was associated with glaciation.

11.2. Aims and limitations of this study

This study aims to combine existing and new data sources to achieve a number of objectives: the reconstruction of the last glaciation of the islands over time, rather than as a single ice shed configuration; the inclusion of offshore interpretation and the integration of this to provide the

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[10] Ross, 1993; Gordon et al., 1993

[11] Flinn, 1970, 1978; Mykura, 1976

[12] Evans et al., 1990

[13] Stoker et al., 1993; Johnson, et al., 1993

[14] Hall et al., 1993a, 1993b

[15] Stoker et al., 1993; Johnson et al., 1993

[16] Peacock and Long, 1994

[17] Birnie, 1993a

[18] Birnie, 1993a

first interpretation for the whole ice cap; and the interpretation of the reconstruction in a wider, northwest European context. New observations have been made to augment existing datasets, and those existing datasets have largely been confirmed. A new data source is provided with preliminary observations on glacial sediments throughout the islands and these are used to assist in the reconstruction. This glacial drift generally relates to late periods in deglaciation, so the progress made in establishing a time sequence is largely due to new approaches rather than new data. These are: combining all relevant data cartographically to identify trends and patterns as well as exceptions to these; the morphochronological resolution of erosional data, particularly assuming earlier glaciation of vertically and horizontally peripheral locations and increasingly topographically contained ice flow through deglaciation and, in cases where two mutually exclusive ice direction patterns are adjacent or overlain, that the stronger is the more recent by virtue of greater preservation; and taking a cautious but open-minded approach to, 'negative evidence,' (interpretation arising from the absence of evidence rather than its presence).

The study attempts to focus on interpreting data from terrestrial Shetland at a new level of detail and also to expand the resulting reconstruction into the context of northwest European glaciation. Within the time period available some compromise is inevitable between these two scales of examination. The author has spent months in the field, partially verifying existing datasets and also collecting preliminary glacial sediment data but has not had time to conduct in-depth studies in local areas. This work has been essential in providing the understanding of published data required to interpret it, but much of the data here is cartographically transferred from existing sources.

11.3. Review of regional conclusions

For this study the Shetland area has been divided up into 6 regions, each corresponding to an earlier chapter with a further chapter on chronology. The conclusions relating to patterns of ice flow in each are briefly re-capitulated. These conclusions form a new hypothesis of the last glaciation of the islands - for details, and some sense of how tentatively they are made, the relevant chapter should be consulted. Interpretation of these conclusions for the glaciation of Shetland as a whole is considered in subsequent sections.

11.3.1. Fair Isle

It is has been suggested that there was an early ice movement east across Fair Isle[19] but there is no unequivocal evidence for this. Roches moutonées, the direction of glacitectonization of bedrock, till clast fabric and drift distribution are all used to show that ice crossed the island broadly from the west. In addition, there is possible offshore evidence for proglacial conditions,

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[19] e.g. Flinn, 1978

including an outwash plain and drainage channels into the Witch Ground Basin, 30 km to the east of Fair Isle[20], so any ice from the east must have been due to a phase in glaciation which predates this limit. Some of the directional evidence on Fair Isle suggests that ice moved due west-east, diverging around the island at low elevations, whereas on the high ground of the west coast, most striae indicate a broadly northwest to southeast movement. Although these patterns cross to some extent, they are difficult to resolve morphochronologically. The northwesterly pattern is found on the highest ground of the island and is therefore assumed to be the older. It is therefore here proposed that an earlier and more substantial ice sheet crossed Fair Isle from the northwest, followed by glaciation from more directly western sources.

11.3.2. South Mainland

For the south Mainland peninsula existing reconstructions involve Scandinavian ice crossing the central high ground from the east, followed by a smaller, local ice-cap flowing off the area to the west and east[21]. The transport of local rocks across the high ground and a single erratic of Norwegian provenance[22] is used as evidence of Scandinavian incursion, and other erratic evidence demonstrates the latter movement.

This study concludes that such a reconstruction is too simplistic. The local ice cap would extend 75 km to the east on the basis of offshore sediments[23]. The single, 'erratic,' of Norwegian provenance - the only evidence of specifically Scandinavian incursion - might have been transported to Shetland during a previous glaciation or by non-glacial means entirely. It is possible that earlier or faster deglaciation from the western margin of a major shelf ice cap would cause the eastward migration of the ice shelf, so that no Scandinavian incursion is required to carry local erratics across the high ground (figure 5.8). Latterly, this ice shed migrated west again, possibly lying just to the west of the peninsula and there finally decaying (figure 5.9).

On the northeast coast of the south Mainland area there is early evidence of northeasterly ice movement, superseded by a southeasterly pattern (figures 5.9 and 5.10). On the northwest coast there is a pattern of ice movement southwest into the West Fair Isle Basin. These later ice movements suggest ice feed from the relatively high central Mainland areas (figure 5.10).

There is some evidence of a terrestrially contained, active valley glacier at Burn of Mail on the southern peninsula. There is no evidence to indicate whether it relates to deglaciation or the

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[20] Evans et al., 1990
[21] Peach and Horne, 1879; Mykura, 1976; Flinn, 1977
[22] Gordon, 1993a
[23] Long and Skinner, 1985

Younger Dryas stadial. If the latter, then its estimated ELA is low compared with other Scottish sites.

11.3.3. West Mainland

Across the most western areas of Shetland there is a clear pattern of early, northwesterly moving ice. The ice shed was at least as far east as central Mainland (and probably further east (see below)) (figure 6.5). Increasing topographic containment is clearly indicated by ice movement into the St Magnus Bay basin, particularly from central areas. Ice was shed to the southwest from the Walls peninsula at or after this time and flow from central Mainland northwest and southwest - into the St Magnus Bay and West Fair Isle basins respectively - cut supply to the peninsula leaving the possibility of a Walls peninsula - centred ice cap (figure 6.6). At the western maximum, ice reached the continental shelf edge and retreated from there under glacimarine conditions[24] until it reached the relatively shallow Foula Ridge where there may have been a period of stasis and the development of morainal systems offshore and on Papa Stour (figure 6.7).

The nature of subsequent deglaciation is poorly, if at all, recorded in the sediments of the St Magnus Bay basin (this writer suggests there may be some fluvioglacial material) but there is no evidence of further glacimarine activity. Instead there is a record of postglacial sea level rise in the basin with poor biotic assemblages suggesting a severe environment and possible sea ice cover.

11.3.4. Central Mainland

In central Mainland there is evidence of early westerly and northwesterly ice movement. However there is no evidence of Scandinavian ice crossing the area. It is possible that an early ice shed lay east of the east coast and clear evidence that it at least lay to the east of the central Scallafield Ridge high ground (figure 7.5), possibly remaining there until the end of glaciation. The ice sheet extended up to 75 km offshore to the east[25].

There is evidence of subsequent ice movements towards the north and northeast, particularly with streams through Yell Sound and towards the Unst Basin (figure 7.6). These are followed by increasingly topographically contained movements, particularly to the east and into the Fetlar Basin (figure 7.7). Ice draining in more southerly directions appears to be a relatively late phenomenon but the high central Mainland area may have remained an ice dispersion centre for some time (figure 7.8).

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[24] Stoker et al., 1993

[25] Long and Skinner, 1985; Johnson et al., 1993

Like the St Magnus Bay basin, recovered sediments of the Fetlar Basin show evidence of rising sea level in severe climatic conditions, possibly with seasonal sea ice cover. There is no evidence of previous glacimarine activity, although it cannot be discounted. Just as with west Mainland, there may have been glacimarine retreat to some limit, followed by terrestrial deglaciation.

There is morphological evidence of individual, small, active, topographically contained glaciers in parts of central Mainland. The ages of these are not known.

11.3.5. North Mainland

The earliest ice movement across north Mainland is again towards the northwest (figure 8.4). Subsequent ice movement to the north is clearly indicated, particularly with the establishment of an ice stream in Yell Sound. There may also have been some eastern ice movement across the area south of, and presumably through, Ronas Voe before the strong containment effect of the St Magnus Bay is seen (figure 8.5). St Magnus Bay containment did not affect areas to the north of the bay where Ronas Voe curtailed ice supply from that direction. The ice stream in Yell Sound also disappeared, allowing a plateau glacier on Ronas Hill, the highest ground on Shetland, to drain, at particular sites, into the Sound (figure 8.6).

11.3.6. Unst, Yell and Fetlar

The northern maximum of the last glaciation extended to the shelf edge to the northwest and at least 50 km north of Unst. Again northwesterly ice flow is probably the earliest recorded in the northern isles area and again the ice shed was clearly east of the high ground, and possibly the east coast, of Unst (figure 9.4) - possibly a response to early western deglaciation rather than Scandinavian influence for which there is no evidence. As deglaciation progressed there is evidence that ice sheds moved south and west, ultimately feeding ice streams north and northeast through Bluemull and Yell Sounds and into the Unst basin (figure 9.5). This configuration may have resulted in a lobate offshore margin and possible terrestrial margins on Unst and Yell. There is no evidence, however, that the latter are associated with the glacial maximum as has been suggested[26]. Further topographic containment resulted in ice flow from the central Mainland area, and possibly Yell, into the Fetlar basin. There may have been a residual ice cap on Unst (figure 9.6).

11.3.7. Temporal relationships of regional patterns

There is little evidence that allows the stratigraphic relationship of the above regional reconstructions to be determined. A number of observations can be made however.

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[26] Flinn, 1983

The northwesterly movement of ice is a pervasive feature of many parts of Shetland and is found particularly on high ground and in peripheral parts of the landmass. It is clearly the earliest major movement for which there is evidence. Subsequent deglaciation resulted in ice movements that are seen to be increasingly topographically contained and the relative timing of these movements are considered next.

The ice stream in Bluemull Sound between Unst and Yell must have disappeared before the pattern of ice movement into the Fetlar Basin from Yell (figures 9.5 and 9.6). The Yell Sound ice stream must have substantially deteriorated or disappeared before ice movement into the Fetlar basin from north central Mainland because some striae suggest that the Yell Sound stream was partially fed from ice within the basin itself (figure 7.7). The pattern of ice movement into St Magnus Bay from central Mainland cannot be stratigraphically related to the Yell Sound stream but probably predates the pattern into the Fetlar Basin since there is evidence of a significant eastern ice shed associated with movement into the former (figure 7.5). It follows that the Yell Sound and St Magnus Bay patterns may be contemporaneous to some extent.

The northeasterly pattern of striae across Whalsay and Bressay (figures 7.6 and 5.9) both predate the southeasterly pattern of striae across east central Mainland and the Lerwick area as a whole (figures 7.8 and 5.10) and may suggest broad northeasterly ice movement at some stage during deglaciation, possibly at the same time as the streams between the northern isles or later, followed by more easterly and southeasterly movement from more central areas.

The southwesterly pattern on the south coast of the Walls peninsula (figure 6.6) predates the deglaciation of the West Fair Isle basin (figure 5.9), otherwise flow into the basin would be indicated, unless it occurred at approximately the same time as the significant stream from central Mainland into the basin (figure 6.6). This latter movement must itself be more recent than the deglaciation of the western ice shed over the west coast of the southern peninsula (figure 5.9). The northeast pattern across Bressay predates the deglaciation of the southern peninsula.

In summary, following regional northwesterly ice movement, there is evidence of north and northeasterly moving ice streams across the northern isles, increasing topographic containment into the St Magnus Bay basin on the west coast, and later movement from central areas to the east and into the Fetlar Basin. The final ice movements appear to be those to the southeast and southwest from the central high ground of Mainland. In all, a picture of a major ice cap with an eastern ice shed, shrinking to a core in the high ground of central Mainland, first revealing northern and western peripheral areas of Shetland, then eastern and finally southern parts. A plateau glaciation on the Ronas Hill plateau existed for an unknown period of time also. This sequence is summarized in figures 11.4 to 11.8 (discussed below).

11.3.8. Nature of englaciation and deglaciation

Offshore subglacial sediments show that ice reached the continental shelf edge to the west[27], at least 75 km to the east[28], at least 50 km to the north[29], and there may have been a margin at least 30 km east of Fair Isle[30] (figure 3.13). The subglacial deposits to the east are much thinner and more discontinuous than to the north and west[31]. This may be because of the existence of pre-Late Weichselian subglacial sediments to the north and west allowing the development of deformation till and the provision of material for other deposition there, whereas to the east ice flowed erosively over the East Shetland Platform - a solid substrate.

There are morainic forms parallel to parts of the continental shelf edge and widespread glacimarine deposits as well as areas of iceberg scour marks[32]. The glacimarine deposits continue inshore towards terrestrial Shetland, suggesting that deglaciation was into a rising sea level in its early stages. The inshore basins, however, show no evidence of glacimarine sedimentation and the sea level rise recorded within them is post-glacial although still related to severe climatic conditions. This implies some position at which the deglaciating ice margin became grounded. The ice margin on Papa Stour[33] and other possible hummocky bedforms currently under investigation at the British Geological Survey may relate to this transition and it is possible that this zone is in the region of the -100m bathymmetric contour around the island.

Subsequent deglaciation was topographically contained and highly erosive. These two contentions are mutually supportive. Evidence of erosion abounds and some of the strongest patterns shown by this erosion indicate topographic containment and are associated with very late ice movement. The glacial drift geology has been studied here for the first time. Almost everywhere there is evidence of glacitectonization of incompetent bedrock types, often showing a conformable contact with thin lodgement till. The direction of ice movement can be shown to be associated with late deglacial trends. The till is invariably deposited in a single unit and, where determinable, contains erratics associated with the most recent ice movement. In no sections were shells discovered, despite the likelihood that such material would have been entrained between islands and offshore during earlier stages, again suggesting that this evidence relates to the most recent period of deglaciation. In summary, the last glaciation was erosive in at least its late stages and, where lodgement deposition has occurred, it should be treated in most places be

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[27] e.g. Stoker et al., 1993
[28] Johnson et al., 1993
[29] Stevenson, 1991
[30] Evans et al., 1990
[31] Stoker et al., 1993; Johnson, et al., 1993
[32] Stoker et al., 1993
[33] Mykura and Phemister, 1976

seen as a glacidynamic process triggered by a friction threshold as erosion of the underlying bedrock entrains greater amounts of debris.

Finally, although what evidence there is of terrestrial ice margins is in most places too poor to interpret adequately, there is no doubt that in some locations there are constructional ice marginal forms[34] which indicate individual, small, active, glaciers, at a very late stage in the last deglaciation or during a recrudescence of ice during the Younger Dryas stadial.

11.3.9. Conclusions

There is evidence of ice retreat from the northwest, north, northeast and latterly from the east and southeast to a central Mainland core with a subsidiary core on the Ronas Hill plateau. It is likely that through much of deglaciation the main ice sheds were displaced somewhat to the east, and western areas of central Mainland were deglaciated earlier than eastern areas. However it is also likely that the ice shed was just to the west of south Mainland latterly.

There is, however, little evidence of an eastern displaced ice shed on Fair Isle at any time.

11.4. The last glaciation of Shetland

This apparently complex sequence can be explained in terms of a relatively simple hypothesis of the englaciation and deglaciation of the last ice cap of the area and this is outlined here and in figures 11.1 to 11.8.

11.4.1. Maximum

The limits of the last glaciation as best they are known are shown in figure 11.1. The orientation of the western margin is of significance since it explains the northwestern movement of ice that is seen across many parts of Shetland: from central and western Mainland to as far north as Unst. Early southeastern movement on Fair Isle might also be explained by a linear ice shed, parallel to the continental shelf edge. However, since this northeast-southwest trending ice shed is maintained through early deglaciation the pattern of ice movement described may relate to a later period than the glacial maximum shown in figure 11.1.

11.4.2. Early deglaciation

Glacimarine deposits between and within moraine systems, and iceberg scour marks, on the outer western continental shelf edge[35] suggest that deglaciation was associated with relative sea level rise. Bathymmetric asymmetry means that such a rise would have an immediate impact on the western margin of the ice sheet and a more delayed affect on the eastern margin. Assuming

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[34] Flinn, 1982; Mykura and Phemister, 1976; Charlesworth, 1956

[35] Stoker et al., 1993

that the linear ice shed was able to adjust to equilibrium, this disproportionate or wholly western ablation would cause it to migrate east. Note that it may have remained to the northwest of Fair Isle (figure 11.2).

11.4.3. Scandinavian influence?

The eastern ice shed discussed above explains the carriage of erratics from east to west across the southern peninsula of the islands. It has alternatively been hypothesised that early Scandinavian ice achieved this[36], since there is no evidence for such movement elsewhere on the islands because they were protected from the incursion by a local ice cap. This latter scenario has been modelled in this study (figure 5.7).

However the present writer believes the absence of eastern erratics across other parts of Shetland is instead due to their subsequent removal. Shetland has been severely glacially eroded. Even where lodgement deposition is evident it is often conformably underlain, and possibly triggered, by glacitectonization of the underlying bedrock. The direction of ice movement associated with this erosion is consistent with late, topographically contained, glaciation. Therefore, the little glacial drift on terrestrial Shetland is a late phenomenon associated with local ice from high ground areas. Since this movement was sufficiently prolonged to result in clear patterns of erosive evidence, it would be most unlikely that pre-existing erratics would survive in observable quantities on such a narrow archipelago. Widespread survey by this study did not reveal any multiple till sequences.

Some explanation is therefore required for why south Mainland alone should include erratic evidence of an earlier eastern ice shed. It is here suggested that a subsequent ice shed lay over, and decayed on, the west coast of south Mainland, preserving erratic evidence there (see below).

11.4.4. Later deglaciation

Figure 11.3 shows the situation when sea-level has risen to -100 m OD. Considerable deglaciation of the eastern margin has occurred but only a small movement in the western margin, so the eastern ice shed outlined above may have persisted for a considerable period. Deglaciation to the north and northeast has occurred but is less significant in the southeast and southwest. The conclusions reached from terrestrial Shetland (above) - that northern and northeastern margins were deglaciated earlier than southern margins - are therefore compatible with this model.

At -100m glacimarine sedimentation ceases, inshore basins between here and the current landmass have been shown in this and other studies not to contain glacimarine sediments. On-

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[36] Peach and Horne, 1879; Flinn, 1977; Mykura, 1976

going work at the British Geological Survey may reveal morainic morphology[37] at locations associated with this approximate depth. The development of a stable ice margin at, and terrestrial retreat from, this position might be due to a combination of eustatic and isostatic effects on relative sea level rise, or bathymmetry (around much of Shetland, a bathymmetric rise is observed at approximately -82 m[38]).

At this stage, bathymmetric asymmetry results in the position of the simple linear ice shed just to the west of south Mainland, continuing to shed ice to the northwest and southeast. Such a situation would explain the unexpected absence of south Mainland erratics on south Walls and Foula, the preservation of earlier erratics on the west coast of south Mainland (figure 5.5), and the most recent ice movement across Sumburgh. However at this stage the topography of the islands, relative to the size of the degraded ice cap, may be significant. Flow patterns now relate to a more complex three dimensional picture (discussed next) and the linear model is therefore simplistic.

The point at which terrestrial topographic containment of the last ice cap becomes significant can be determined very approximately. Assuming a maximum east-west ice sheet diameter of approximately 150 km a simple calculation[39] suggests that the ice shed, if centred over Shetland, reaches heights of approximately 1200 m. This assumes basal shear stresses associated with bedrock rather than deforming sediments. The assumption is appropriate to the east of the islands and some way to the west but last glacial sediments of the outer continental shelf to the west and north are underlain by unconsolidated Quaternary material. This may have had some effect in reducing the elevation of the ice cap but is unlikely to have resulted in topographic containment to an extent that would affect the conclusions given above.

With the ice extent associated with the -100 m bathymmetric contour (figure 11.3), subglacial deformation can be ignored since within this zone the substrate is almost entirely bedrock. Here the east-west extent is approximately 50 km and this results in an ice surface elevation over the centre of the ice cap of just 234 m. The analysis is simplistic but demonstrates significant topographic containment is relevant by this stage in deglaciation. The three dimensional nature of the ice cap becomes important and influences much of the terrestrial pattern of ice movement observed in this study and discussed now.

The early northwestern pattern of ice movement towards deglaciation on the northwestern margins of the ice sheet is observable in all areas except south Mainland (figure 11.4). As deglaciation occurred more significantly from northern margins, this movement over the

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[37] A. Stevenson (pers. comm. 1995)
[38] Flinn, 1964
[39] Nye, 1952

northern isles deteriorates and north moving ice streams in Yell Sound, Blue Mull Sound and the Unst Basin develop. Further south the ice shed continued to lie to the east side of central Mainland, although these northern ice streams may have drawn it westwards and reduced its elevation, furthering the topographic containment that becomes increasingly evident there (figure 11.5). A strong pattern of movement into the St Magnus Bay basin was underway by this time.

Further rises in sea level resulted in the first evidence of northeastern ice movement. The exact sequence of events is not clear but northeastern ice movement affected eastern coastal areas as far south as Bressay. By this time the ice shed must have migrated westwards onto central Mainland and possibly switched to the west coast of south Mainland (figure 11.6) and increasing draw down from northern streams resulted in the southern displacement of the ice shed zone also (figure 11.7).

Increasingly eastern and southeastern ice movements develop as deglaciation at eastern and southeastern margins becomes more significant (figure 11.8). Since the ice shed is likely to have been to the west of south Mainland, partly covering the west Fair Isle basin, deglaciation of the basin, and ice streams into it from central Mainland, may have occurred later still.

There is clear evidence of plateau glaciation north of Ronas Voe draining into Yell Sound (figure 11.8) and minor active glaciation of some high ground areas. Neither the timing or duration of these high ground glacial events is known.

The entire reconstruction, from bathymmetry-related early deglaciation, to inshore basin-related later deglaciation, and ultimately topographically contained terrestrial glaciation, demonstrates the overriding influence of topography at all scales. Ice flow associated with the ice cap at its maximum is controlled by regional bathymmetry, for example the orientation of the continental shelf edge, and appears unrelated to more local topography. Ice flow is subsequently towards major inshore basins, such as the St Magnus Bay and Fetlar basins, and eventually flows within local, terrestrial topography. It is the remnants of these different patterns and the relationship between the size of the ice cap and the scale at which it can be seen to be topographically contained, that has permitted this dynamic reconstruction. The heavily eroded nature of the Shetland landscape allows the writer confidence in attributing these patterns to different time sequences because it is possible to assume that earlier patterns of ice movement, associated with different scales of topographic containment, are removed by subsequent, more locally influenced, glaciers.

11.4.5. Chronology

The absence of extensive periglacial deposits has been used to infer that the most recent glaciation was of Late Weichselian age. However, although terrestrial chronological sites show the existence of at least two glaciations and one interglacial, their age remains uncertain[40]. An environmental oscillation that is clearly post Late Weichselian has also been recognized. Dates suggest the islands were ice free at *circa.* 13 ka BP and that there was a cold, although not necessarily glacial, spell between 12 ka BP and 10 ka BP. This chronological work is at a preliminary stage however[41].

Offshore sequences of sediments offer greater potential for establishing the chronology of the last glaciation of the area. Radiocarbon dates of 13, 315 ± 155 BP (adjusted for seawater apparent age of 405 ± 40 a) have been published from sediments near the eastern limit of the last ice sheet, thus indicating a Late Weichselian glaciation[42]. The end of the Lateglacial interstadial in this area is dated to 12, 265 ± 135 BP (adjusted for seawater apparent age of 405 ± 40 a). These sediments cannot be correlated with the more extensive last glacial sequences to the north and west of the islands and cannot, in themselves, assist in establishing the sequence of deglaciation suggested above.

However this study dated sediments on the northern continental shelf area, again illustrating that the last glaciation was Late Weichselian and extensive. It might also be suggested that deglaciation may have commenced much earlier than on the eastern margin, before 17,825 ± 280 BP, and that more distal glacimarine activity was occurring at around 13 ka BP, however this is simply consistent with the morphochronological sequence outlined above and is not conclusively demonstrated by the core logging and dating work undertaken. The late glacial interstadial unit examined in this study is of comparable age to that recovered from the East Shetland Platform.

11.4.6. Conclusions

In summary the last ice sheet of the Shetland Islands at its known maximum was perhaps 150 km wide and stretched northeast-southwest on the western edge of the continental shelf. Much of the ablation during deglaciation was due to ice calving into a rising sea level and the position of the ice cap relative to bathymmetry exerted a strong influence on the movement of the ice shed. Rapid deglaciation in the west and northwest moved the ice shed to the east of the island and, although it is to not possible to wholly resolve the issue, evidence previously attributed to Scandinavian glaciation could have resulted from this shift. Deglaciation commenced on the margins of the ice cap in a clockwise fashion: following early western deglaciation, the north, northeast, east, southeast and southwest margins began deteriorating in order, as sea level rose.

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[40] Hall et al., 1993a,b

[41] Birnie, 1993a

[42] Peacock and Long, 1994

Patterns of ice movement observed on Shetland demonstrate this sequence and preliminary dating may support it. The margin of the ice cap appears to have become wholly terrestrial at about the -100 m bathymmetric contour, due to a stabilization in relative sea level rise or a step-change in bathymmetry at -83m around parts of the island group. At this stage the Shetland Islands and surrounding topography were exerting influence in the containment of ice flow. This reconstruction demonstrates the influence of topography at different scales in relation to the size of the ice cap. Parts of Shetland may have been ice free by 13 ka BP but this date is uncertain. There is good evidence of plateau glaciation on the Ronas Hill plateau and of valley glaciers in other parts of the islands and these are undated.

The writer believes that this sequence of events offers a hypothesis that more robustly accommodates the evidence available than models providing a single ice shed configuration. The hypothesis requires further testing and recommendations for future work are given below.

11.5. The last glaciation of Shetland in northwest Europe

The last glaciation of northwest Europe as a whole was reviewed at the beginning of this study. This section briefly considers some of the conclusions reached by the study and highlights further questions that might be asked of the current models of northwest European glaciation.

Offshore work to the east of Shetland has shown that there is no evidence of Scandinavian glaciation extending further west than the western edge of the Norwegian trench during the last glaciation[43]. This study has provided a model in which evidence on Shetland may be interpreted in this context. However evidence from eastern Scotland, particularly Buchan, Caithness and Orkney also requires resolution in this respect (figures 2.3 and 2.4). In the case of Shetland, a linear ice shed migrated to the east of the islands due to significant ablation on one side, the west, of the ice sheet. Figure 2.4 (c1) refers to a Moray Firth ice divide. It is reasonable to ask whether a major ice shed developed here under similar circumstances and whether the linear, northeast-southwest trending ice shed discussed above in the context of the shelf-wide glaciation around the Shetland Islands, can be extended still further southwest, lying to the southeast of Orkney and Caithness, thus accounting for the northwestern pattern of ice movement across these areas.

The Shetland reconstruction also reveals that a more extensive glaciation retreated by sea-level rise induced glacimarine ablation to a more restricted margin where the ice appears to have become grounded. That point was around the -100m bathymmetric contour. Elsewhere in northwest Europe much debate surrounds the ideas of more extensive and less extensive Late

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[43] Johnson et al., 1993

Weichselian glaciations[44]. It is possible that this conflicting evidence can also be explained in terms of two phases of glaciation, possibly controlled by sea level rise.

Thus, 29-25 ka ago, as the result of an early, precipitation enhancing, incursion of warm north Atlantic waters into the northern seas[45], an extensive northwest European glaciation occurred. Regardless of the role played by Scandinavian ice, the maximum extent of Shetland ice itself is more compatible with the extensive glaciation of the North Sea that may have occurred at around 25 ka BP[46] (figures 2.8 and 2.9). The maximum eastern limit is improbably far east to be contemporaneous with the Bosies Bank moraine. Similarly on the western edge of the continental shelf, it is unlikely a Shetland ice cap would have reached the shelf edge[47] while a Scottish one was restricted to the Greenstone Ridge in the Minch[48]. The more extensive reconstruction is compatible with a recognized ice margin on the continental shelf edge to the west and northwest of Scotland (figure 2.5 and 11.9). The latter is thought to be early Weichselian in age but is undated[49] and may represent an early maximum of the Late Weichselian.

From this more extensive maximum, the Shetland ice cap retreated to a stable position associated with the -100m contour under the influence of sea level rise. The Bosies Bank moraine on the east coast of Scotland, and more restricted reconstructions on the west coast, including the Greenstone Ridge, demonstrate a striking relationship to the -100 m bathymmetric contour[50] (figure 2.5 and 11.9). South of St Kilda, a relative sea level minimum of approximately -80m is modelled to occur at between 18 and 13 ka BP[51], consistent with palaeoenvironmental evidence from dated vibrocores in this area[52]. These show that here sea level is relatively constant between 18 and 13 ka BP, during which time isostatic and eustatic contributions to sea level are therefore approximately equal and opposite. The result is a period of approximately 5,000 years during which sea level lay at or around the present -100m bathymmetric contour.

A pattern of deglaciation from an early extensive ice margin to a more restricted ice margin, then, can be reconstructed and might be achieved by the combination of sea level rise and bathymmetry. To apply such a hypothesis to the last glaciation of Scotland requires much consideration of eustatic and isostatic influences on relative sea level, of the significance of

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[44] e.g. Ehlers and Wingfield, 1991
[45] Hebbeln et al., 1994
[46] Sejrup et al., 1994
[47] Stoker et al., 1994
[48] Fyfe et al., 1993
[49] Stoker et al., 1994
[50] Hall and Bent, 1990
[51] Lambeck, 1993
[52] Peacock et al., 1992

trimlines and, above all, further dating of sediments. The writer has not investigated such parallels in detail but they certainly merit attention.

The Shetland study also suggests that these wider issues might be resolved by two complementary approaches: the integration of terrestrial and off-shore data in a non-superficial way; and the development of a robust chronostratigraphy. In the case of Shetland, a complex and confusing pattern of spatial data is resolved in this study by the introduction of a dynamic, temporal dimension and an effort to consider the ice cap as a whole, not simply its terrestrial expression. A similar approach needs to be taken with what is, after all, an even more complex and confusing pattern of spatial data around Scotland.

11.6. Summary and recommendations of this study

This study has demonstrated the following:

- that the last Shetland ice cap needs to be reconstructed as a dynamic entity if all available evidence is to be understood;

- that both terrestrial and offshore data need to be integrated if either is to be understood in the context of the whole Shetland ice cap;

- that bathymmetry and sea-level rise play an important role in determining the pattern of deglaciation of the last Shetland ice cap until its margins approached the current terrestrial landmass, that topography has constrained the pattern of deglaciation on and around terrestrial Shetland, and that, therefore, topography at a variety of scales has profoundly influenced the last Shetland ice cap throughout its history;

- that the last glaciation of Shetland can be explained without recourse to the influence of Scandinavian ice;

- that there are no multiple till sequences and that the last glaciation of Shetland was highly erosive, especially as ice became increasingly topographically contained during deglaciation, so that much of the terrestrial evidence pertains to later phases of deglaciation;

- that within this study lie important implications for the reconstruction of the last glaciation of Scotland, both in terms of the controlling influences on deglaciation and the methodology that permitted their reconstruction.

The wide ranging nature of this investigation has not allowed the full pursuit of all the implications of the reconstruction given. Whilst the writer believes it provides the most advanced consideration of the last glaciation of the islands to date it is best treated as an hypothesis awaiting testing. Numerous possibilities for future investigation arise. This study can make a number of challenging assertions that need to be investigated: high resolution stratigraphy and dating of offshore sediments around the islands will demonstrate the clockwise sequence of deglacial events suggested here; in-depth analysis of the clastic component of western offshore sediments or thicker lodgement till sections on western Shetland will prove that, at some stage, the last ice sheet crossed the entire Shetland archipelago from the east; however, terrestrial lodgement till fabrics will further demonstrate that much of the till on Shetland is associated with the most recent ice movements at the end of the last glaciation; modelling and further reconstruction of the development of the last Scandinavian ice sheet should not be constrained by any necessity that it need reach Shetland, and modelling of the Shetland ice cap that accounts for tidewater calving ablation will show an early eastern migration of the main ice shed zone and the pattern of deglaciation suggested above; further seismic and sidescan sonar analysis of the inshore area, some of which is already underway, will reveal more about the transition between glacimarine and terrestrial deglaciation around the -100m bathymmetric contour; and, in the case of Scotland, the integration of terrestrial and offshore data, the recognition of topographic influence at a variety of scales and the development of a dynamic framework, will further understanding of the last ice sheet.

The last Shetland ice cap should be treated as a sensitive focus of northwest European and, by extension, global climate change during the last glaciation. There are, of course, many ways in which the hypothesis outlined in this thesis might be challenged, tested and refuted. For the time-being, it is hoped that it serves to catalyse those activities.

12. References

Alm, T. 1993. Øvre Æråsvatn - palynostratigraphy of a 22,000 to 10,000 BP lacustrine record on Andøya, northern Norway. *Boreas,* 22, 171-188.

Amman, B. and Lotter, A.F., 1989. Late-glacial radiocarbon-dating and palynostratigraphy on the Swiss Plateau. *Boreas,* 18, 109-126.

Andersen, B.G., 1979. The deglaciation of Norway 15,000-10,000 years BP. *Boreas,* 8, 79-87.

Andrews, J.T., Erlenkeuser, H., Tedesco, K., Aksu, A.E. and Jull, A.J.T., 1994. Late Quaternary (Stage 2 and 3) meltwater and Heinrich Events, northwest Labrador Sea. *Quaternary Research,* 41, 26-34.

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. and McCormac, M., 1990. *United Kingdom offshore regional report: the geology of the Moray Firth.* London: HMSO for the British Geological Survey.

Atkinson, T.C., Lawson, T.J., Smart P.L., Harmon, R.S. and Hess, J.W., 1986. New data on speleothem deposition and palaeoclimate in Britain over the last forty-thousand years. *Journal of Quaternary Science,* 1, 1, 67-72.

Ballantyne, C.K., and Wain-Hobson, T. 1980. The Loch Lomond Advance on the Island of Rhum. *Scottish Journal of Geology,* 16, 1-10.

Ballantyne, C.K., 1987. The present-day periglaciation of upland Britain. In Boardman, J., 1987. *Periglacial landforms and processes in Great Britain and Ireland.* Cambridge: Cambridge University Press. 113-126.

Ballantyne, C.K., 1989. Loch Lomond readvance on the Isle of Skye, Scotland: glacier reconstruction and palaeoclimatic implications. *Journal of Quaternary Science,* 4, 2, 95-108.

Ballantyne, C.K., 1990. The late Quaternary glacial history of the Trotternish Escarpment, Isle of Skye, Scotland, and its implications for ice-sheet reconstruction. *Proceedings of the Geological Association,* 101, 3, 171-186.

Ballantyne, C.K., 1994. Gibbsitic soils on former nunataks: implications for ice sheet reconstruction. *Journal of Quaternary Science,* 9, 1, 73-80.

Baumann, K-H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf-welling, T.C.W., Henrich, R. and Kassens, H., 1995. Reflection of Scandinavian ice sheet fluctuations in Norwegian Sea sediments during the past 150,000 years. *Quaternary Research,* 43, 185-197.

Beaulieu, J.L.D. and Reille, M., 1992. The last climatic cycle at La Grande Pile (Vosges, France). A new pollen profile. *Quaternary Science Reviews,* 11, 431-438.

Beg, M.A., 1990. *The distribution and dispersal of heavy minerals on the continental shelf around the Shetland Islands.* Unpublished PhD Thesis, University of Strathclyde.

Benn, D.I., Lowe, J.J., and Walker, M.J.C., 1992. Glacier response to climatic change during the Loch Lomond Stadial and early Holocene: geomorphological and palynological evidence from the Isle of Skye, Scotland. *Journal of Quaternary Science,* 7, 125-144.

Bennet, K.D., 1993. Holocene vegetation history at Murraster, west Mainland, Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 119-120.

Bennet, K.D., Boreham, S., Hill, K., Packham, S., Sharp, M.J. and Switsur, V.R., 1993. Holocene environmental history at Gunnister, north Mainland, Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 83-98.

Bennet, M.R., 1994. Morphological evidence as a guide to deglaciation following the Loch Lomond readvance: a review of research approaches and models. *Scottish Geographical Magazine*, 110, 1, 24-32.

Bennet, M.R. and Boulton, G.S., 1993a. A reinterpretation of Scottish 'hummocky moraine' and its significance for the deglaciation of the Scottish Highlands during the Younger Dryas or Loch Lomond Stadial. *Geological Magazine*, 130, 301-318.

Bennet, M.R. and Boulton, G.S., 1993b. The deglaciation of the Younger Dryas or Loch Lomond Stadial ice-field in the Northern Highlands, Scotland. *Journal of Quaternary Science*, 8, 133-146.

Bent, A.J.A., 1986. *Aspects of pleistocene glaciomarine sequences in the North Sea.* Unpublished Phd Thesis, University of Edinburgh.

Bergersen, O.F., Thoresen, M., and Hougsnæ, R., 1991. Evidence for a newly discovered Weichselian interstadial in Gudbrandsdalen, central South Norway. *Striae*, 34, 103-108.

Birks, H.H., Paus, A., Svendsen, J.I., Alm, T., Mangerud, J. and Landvik, J.Y. 1994. Late Weichselian environmental change in Norway, including Svalbard. *Journal of Quaternary Science*, 9, 133-146.

Birks, H.J.B. and Peglar, S.M., 1979. Interglacial pollen spectra from Sel Ayre, Shetland. *New Phytologist*, 83, 559-575.

Birks, H.J.B. and Ransom, M.E., 1969. An interglacial peat at Fugla Ness, Shetland. *New Phytologist*, 68, 777-796.

Birnie, J.F., 1981. *Environmental changes in Shetland since the end of the last glaciation.* Unpublished PhD Thesis, University of Aberdeen.

Birnie, J.F. 1993a. The Late-glacial in Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association. 15-16.

Birnie, J.F. 1993b. The record of the late-glacial environment at Aith Voe, Cunningsburgh. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association, 27-38.

Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association.

Birnie, J.F. and Harkness, D.D., 1993. Radiocarbon dates on Late-glacial sediments at Aith Voe, Cunningsburgh, and adjustments for rock flower effects. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association, 39-43.

Boulton, G.S., 1979. A model of Weichselian glacier variation in the North Atlantic region. *Boreas*, 8, 373-396.

Boulton, G.S., 1990. Sedimentary and sea level changes during glacial cycles and their control on glacimarine facies architecture. In: Dowdeswell, J.A. and Scourse, J.D., 1990. *Glacimarine Environments: Processes and sediments.* p. 15-56.

Boulton, G.S., Peacock, J.D. and Sutherland, D.G., 1991. Quaternary. In Craig, G.Y. *Geology of Scotland.* London: The Geological Society. 503-543.

Brown, I.M., 1993. Patterns of deglaciation of the last (Late Weichselian) Scottish ice sheet: evidence from ice-marginal deposits in the Dee valley, northeast Scotland. *Journal of Quaternary Science,* 8, 3, 235-250.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. and Harrison, D.J. 1992. *United Kingdom offshore regional report: the geology of the southern North Sea.* London: HMSO for the British Geological Survey.

Cameron, T.D.J., Stoker, M.S. and Long, D. 1987. The history of Quaternary sedimentation in the UK sector of the North Sea basin. *Journal of the Geological Society*, 144, 43-58.

Chapelhowe, R., 1965. On the glaciation of North Roe, Shetland. *Geographical Journal,* 131, 60-70.

Charlesworth, J.K., 1956. The late-glacial history of the highlands and islands of Scotland. *Transactions of the Royal Society of Edinburgh*, 62, 769-928.

Chesher, J.A., 1984a. *Shetland Sheet 59° 50'N - 02°W British Geological Survey 1:250 000 Series Solid Geology.* Southampton: Ordnance Survey for the British Geological Survey.

Chesher, J.A., 1984b. *Shetland Sheet 59° 50'N - 02°W British Geological Survey 1:250 000 Series Sea Bed Sediments and Quaternary Geology.* Southampton: Ordnance Survey for the British Geological Survey.

CLIMAP Project Members 1976. The surface of the ice age Earth. *Science,* 191, 1131-1136.

Cockcroft, D.N., 1987. *The Quaternary sediments of the Shetland Platform and adjacent continental shelf margin.* Unpublished PhD thesis, University of Keele.

Coope, G.R., 1977. Fossil coleopteran assembalges as sensitive indicators of climatic change during the Weichselian (last) cold stage. *Philosophical Transactions of the Royal Society,* B280, 313-337.

Davies, H.C., Dobson, M.R., and Whittingon, R.J., 1984. A revised sesismic stratigraphy for Quaternary deposits on the inner continental shelf west of Scotland between 55°30'N and 57°30'N. *Boreas,* 13, 49-66.

Dawson, A.G. 1992. *Ice Age Earth - Late Quaternary Geology and Climate.* London: Routledge. pp.293.

Dunham, K.C., 1968. *Institute of Geological Sciences One Inch Series Scotland sheets 129, 130 & 131: Northern Shetland. Drift Edition.* Southampton: Ordnance Survey for Institute of Geological Sciences.

Dunham, K.C., 1971. *Institute of Geological Sciences One Inch Series Scotland sheet 127: Western Shetland. Drift Edition*. Southampton: Ordnance Survey for Institute of Geological Sciences.

Edwards, K.J., Moss, A.G. and Whittington, G., 1993. A Late-glacial pollen site at Grunna Water, Nesting. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 99-102.

Ehlers, J. 1990. Reconstructing the dynamics of the north-west European Pleistocene ice sheets. *Quaternary Science Reviews*, 9, 71-83.

Ehlers, J. and Wingfield, R. 1991. The extension of the Late Weichselian/Late Weichselian ice sheets in the North Sea Basin. *Journal of Quaternary Science*, 6, 313-326.

Elverhøi, A., Fjeldskaar, W., Solheim, A., Nyland-Berg, M. and Russwurm, L., 1993. The Barents Sea ice sheet - a model of its growth and decay during the last ice maximum. *Quaternary Science Reviews*, 12, 863-873.

Engstrand, L.G., 1967. Stockholm Natural Radiocarbon Measurements VII. *Radiocarbon*, 9, 387-438.

Evans, D. and Andrews, I.J., 1988. *Fair Isle Sheet 59°N - 02°W British Geological Survey 1:250 000 Series Solid Geology*. Southampton: Ordnance Survey for the British Geological Survey.

Evans, D., Long, D. and McElvanney, E.P., 1990. *Fair Isle Sheet 59°N - 02°W British Geological Survey 1:250 000 Series Sea Bed Sediments and Quaternary Geology*. Southampton: Ordnance Survey for the British Geological Survey.

Finlay, T.M. 1926. The Old Red Sandstone of Shetland. Part I: South-eastern area. *Transactions of the Royal Society of Edinburgh*, 54, 553-572

Finlay, T.M. 1932. A Tönsbergite boulder form the boulder-clay of Shetland. *Transactions of the Edinburgh Geological Society*, 12, 180.

Flinn, D., 1964. Coastal and submarine features around the Shetland Islands. *Proceedings of the Geologists' Association*, 75, 321-329.

Flinn, D., 1967. Ice front in the North Sea. *Nature*, 215, 1151-1154.

Flinn, D., 1969. A geological interpretation of the aeromagnetic maps of the continental shelf around Orkney and Shetland. *Geological Journal*, 6, 279-292.

Flinn, D., 1970. The glacial till of Fair Isle, Shetland. *Geological Magazine*, 107, 273-276.

Flinn, D., 1977. The erosion history of Shetland: a review. *Proceedings of the Geologists' Association*, 88, 129-146.

Flinn, D., 1978. The most recent glaciation of the Orkney-Shetland Channel and adjacent areas. *Scottish Journal of Geology*, 14, 109-123.

Flinn, D., 1980. Geological history. In Berry, R.J. and Johnston, J.L. (eds) *The Natural History of Shetland*. London: Collins. p. 31-59.

Flinn, D., 1982. *Institute of Geological Sicences One-Inch Series Scotland Sheet 128: Central Shetland Drift Edition.* Southampton: Ordnance Survey for the Institute of Geological Sciences.

Flinn, D., 1983. Glacial meltwater channels in the northern isles of Shetland. *Scottish Journal of Geology,* 19, 311-320.

Flinn, D., 1992a. A note on the Dalsetter erratic, Dunrossness, Shetland. *The Shetland Naturalist,* 1, 49-50.

Flinn, D., 1992b. The Milldale glacial lake, Herma Ness, Unst. *The Shetland Naturalist,* 1, 29-36.

Flinn, D., 1994a. *Geology of Yell and some neighbouring islands in Shetland. Memoir of the British Geological Survey, Sheet 130 (Scotland).* London: HMSO for the British Geological Survey

Flinn, D., 1994b. Ice flow in Unst during the last glaciation. *The Shetland Naturalist*, 1, 3, 73-80.

Folk,

Fyfe, J.A., Long, D., Evans, D. and Abraham, D.A., 1993.*United Kingdom offshore regional report: the geology of the Malin-Hebrides Sea area.* London: HMSO for the British Geological Survey.

Gatuallin, V., Polyak, L., Epstein, O. and Romanyuk, B. 1993. Glacigenic deposits of the Central Deep: a key to the Late Quaternary evolution of the eastern Barents Sea. *Boreas*, 22, 47-58.

Gordon, D., Smart, P.L., Ford, D.C., Andrews, J.N., Atkinson, T.C., Rowe, P.J. and Christopher, N.S.J., 1989. Dating Late Pleistocene interglacial and interstadial periods in the United Kingdom from speleothem growth frequency. *Quaternary Research,* 31, 14-26.

Gordon, J.E., 1993a. Dalsetter erratic. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide.* Cambridge: Quaternary Research Association., p.43

Gordon, J.E., 1993b. Burn of Mail. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide.* Cambridge: Quaternary Research Association., p.44

Gordon, J.E., Hall, A.M. and Ross, H.M., 1993. Introduction to the Quaternary of Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide.* Cambridge: Quaternary Research Association., p. 6-8.

Gordon, J.E. and Sutherland, D.G., 1994. *Geological Conservation Review Series Quaternary of Scotland.* London: Chapman and Hall for the Joint Nature Conservation Committee.

Greene, D., 1992. Topography and former Scottish tidewater glaciers. *Scottish Geographical Magazine*, 108, 3, 164-171.

Grosswald, M.G. 1984. Glaciation of the continental shelves (parts I and II). *Polar Geography and Geology*, 8, 194-258.

Hall, A.M., 1991. Pre Quaternary landscape evolution in the Scottish Highlands. *Transactions of the Royal Society of Edinburgh*, 82, 1-26.

Hall, A.M., 1993. Clettnadal, West Burra. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 48-50.

Hall, A.M. and Bent, A.J.A., 1990. The limits of the last British ice sheet in northern Scotland and the adjacent shelf. *Quaternary Newsletter*, 61, 1-12.

Hall, A.M., Whittington G., and Gordon, J.E. 1993a. Interglacial peat at Fugla Ness, Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 65-76.

Hall, A.M., Gordon, J.E., and Whittington G. 1993b. Early Weichselian interstadial peat at Sel Ayre. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 104-118.

Hall, A.M. and Jarvis, J., 1989. A preliminary report on the Late Weichselian glaciomarine deposits at St Fergus, Grampian Region. *Quaternary Newsletter*, 59, 5-7.

Hall, A.M. and Whittington, G., 1989. Late Weichselian glaciation of southern Caithness. *Scottish Journal of Geology*, 25, 307-324.

Hall, A.M. and Whittington, G., 1993. Tresta. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide*. Cambridge: Quaternary Research Association., p. 121-122.

Hambrey, M.J., 1994. *Glacial Environments*. London: UCL Press

Harkness, D.D., 1983. The extent of natural ^{14}C deficiency in the coastal environment of the United Kingdom. *Proceedings of the First International Symposium of C-14 and Archeology*. PACT 8, 351-364.

Hebbeln, D., Dokken, T., Andersen, E.S., Hald, M. and Elverhøi, A. 1994. Moisture supply for nothern ice-sheet growth during the Last Glacial Maximum. *Nature*, 370, 357-360.

Heijnis, H., 1992. *Uranium/Thorium dating of Late Pleistocene peat deposits in N W Europe*. Unpublished PhD Thesis, University of Groningen.

Holmes, R., 1977. Quaternary deposits of the central North Sea, 5. The Quaternary geology of the UK sector of the North Sea between 56° and 58°N. *Report of the Institute of Geological Sciences*, 77/14.

Holmes, R., 1991. *Foula Sheet 60°N - 04°W British Geological Survey 1:250 000 Series Quaternary Geology*. Southampton: Ordnance Survey for the British Geological Survey.

Holmes, R., Jeffrey, D.H., Ruckley, N.A. and Wingfield, R.T.R., 1993. Quaternary Geology Around the United Kingdom (North Sheet). 1: 1 000 000. Edinburgh: British Geological Survey.

Home, D.M. 1880. Valedictory address by President. *Transactions of the Edinburgh Geological Society*, 3, 23-26.

Hoppe, G., 1974. The glacial history of the Shetland Islands. *Transactions of the Institute of British Geographers, Special Publication*, 7, 197-210.

Hulme, P.D. and Durno, S.E., 1980. A contribution to the phytogeography of Shetland. *New Phytologist*, 84, 165-169.

Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J., Marinson, D.G., McIntyre, A., Mix, A.C., Molfino, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shacketon, N.J. and Toggweiler, J.R., 1992. On the structure and origin of major glaciation cycles. 1. Linear responses to Milankovitch forcing. *Palaeoceanography*, 7.

Ingólfsson O. and Norddahl, H. 1994. A review of the environmental history of Iceland, 13 000-9000 yr BP. *Journal of Quaternary Science*, 9, 147-198.

Jansen, E. and Bjørkland, K.R. 1985. Surface ocean circulation in the Norwegian Sea 15,000 BP to present. *Boreas*, 14, 243-257.

Jardine, W., Dickson, J.H., Haughton, P.D.W., Harkness, D.D., Bowen, D.Q. and Sykes, G.A. 1988. A late Middle Weichselian interstadial site at Sourlie, near Irvine, Strathclyde. *Scottish Journal of Geology*, 24, 288-295.

Jóhansen, J., 1975. Pollen diagrams from the Shetland and Faeroe Islands. *New Phytologist*, 75, 369-387.

Jóhansen, J., 1985. Studies in the vegetational history of the Faroe and Shetland Islands. *Annales Societatis Faeroensis Supplementum*, XI.

Johnson, H., Richards, P.C., Long, D. and Graham, C.C., 1993 *United Kingdom offshore regional report: the geology of the northern North Sea*. London: HMSO for the British Geological Survey.

Kirby, R.P., 1969. Till fabric analyses from the Lothians, central Scotland. *Geographiska Annaler, Stockholm*, 51A, 48-60.

Kirk, W. and Godwin, H., 1963. A late-glacial site at Loch Droma, Ross and Cromarty. *Transactions of the Royal Society of Edinburgh*, 65, 225-249.

Kleman, J. and Borgström, I., 1994. Glacial landforms indicative of a partly frozen bed. *Journal of Glaciology*, 40, 255-264.

Koç, N., Eystein, H. and Haflidason, H. 1993. Palaeoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian seas through the last 14 ka based on diatoms. *Quaternary Science Reviews*, 12, 115-140.

Lambeck, K., 1994. Glacial rebound and sea-level change in the British Isles. *Terra Nova*, 3, 379-389.

Lambeck, K., 1995. Constraints on the Late Weichselian ice sheet over the Barents Sea from observations of raised shorelines. *Quaternary Science Reviews*, 14, 1-16.

Larsen, E. and Sejrup, H.P., 1990. Weichselian land-sea interactions: Western Norway-Norwegian Sea. *Quaternary Science Reviews*, 9, 85-98.

Lauritzen, S.-E., 1991. Uranium series dating of speleothems: a glacial chronology for Nordland, Norway, for the last 600 ka. *Striae*, 34, 127-133.

Lawson, T.J., 1984. Reindeer in the Scottish Quaternary. *Quaternary Newsletter*, 42, 1-7.

Le Bas, M.J., 1992. The petrography of the Shetland tönsbergite. *The Shetland Naturalist*, 1, 51-56.

Levesque, A.J., Mayle, F.E., Walker, I.R. and Cwynar, L.C., 1993. The amphi-Atlantic oscillation: a proposed late-glacial climatic event. *Quaternary Science Reviews*, 12, 629-643.

Long, D., 1988. *Halibut Bank Sheet 60°N-00°W. British Geological Survey 1:250 000 Series Quaternary Geology.* Southampton: Ordnance Survey for British Geological Survey.

Long, D. and Skinner, A.C., 1985. Glacial meltwater channels in the northern isles of Shetland. *Scottish Journal of Geology*, 21, 222-224.

Lowe, J.J., 1984. A critical evaluation of pollen-stratigraphic investigations of pre-Late Weichselian sites in Scotland. *Quaternary Science Reviews*, 3, 405-432.

Mangerud, J., Larsen, E., Longva, O. and Sonstegaard, E., 1979. Glacial history of western Norway 15,000-10,000 BP. *Boreas,* 8, 179-187.

May, F. and Mykura, W., 1978. *Institute of Geological Sicences One-Inch Series Scotland Sheet 126: Southern Shetland Drift Edition.* Southampton: Ordnance Survey for the Institute of Geological Sciences.

McCarroll, D. and Nesje, A. 1993. The vertical extent of ice sheets in Nordfjord, western Norway: measuring degree of rock surface weathering. *Boreas*, 22, 255-265.

Mykura, W., 1976. *Institute of Geological Sciences British Regional Geology: Orkney and Shetland.* Edinburgh: HMSO.

Mykura, W. and Phemister, J., 1976. *Institute of Geological Sciences Memoirs of the Geological Survey of Great Britain (Scotland): The Geology of Western Shetland.* Edinburgh: HMSO.

Nesje, A. and Dahl, S.O. 1993. Late-glacial and Holocene glacier fluctuations and climate variations in western Norway: A review. *Quaternary Science Reviews*, 12, 255-261.

Nesje, A. and Sejrup, H.P. 1988. Late Weichselian/Weichselian ice sheets in the North Sea and adjacent land areas. *Boreas*, 17, 371-384.

Nye, J.F. 1952. A method of calculating the thickness of ice sheets. *Nature,* 169, 529-530.

Peach, B.N. and Horne, J., 1879. The glaciation of the Shetland Isles. *Quaterly Journal of the Geological Society of London*, 35, 778-811.

Peach, B.N. and Horne, J., 1881. The glaciation of Caithness. *Proceedings of the Royal Society of Edinburgh*, 6, 316-352.

Peacock, J.D., 1981. Scottish late-glacial marine deposits and their environmental significance. In Neale, J. and .Flenley, J., 1981. *The Quaternary in Britain.* Oxford: Pergamon Press. 222-236.

Peacock, J.D., Austin, W.E.N., Selby, I., Graham, D.K., Harland, R., and Wilkinson, I.P., 1992. Late Weichselian and Holocene palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science,* 7, 2, 145-161.

Peacock, J.D. and Harkness, D.D., 1990. Radiocarbon ages and full-glacial to Holocene transition in seas adjacent to Scotland and southern Scandinavia: a review. *Transactions of the Royal Society of Edinburgh*, 81, 385-396.

Peacock, J.D. and Long, D., 1994. Late Weichselian glaciation and deglaciation of Shetland. *Quaternary Newsletter*, 74, 16-21.

Penny, L.F., Coope, G.R. and Catt, J.A., 1969. Age and insect fauna of the Dimlington Silts, East Yorkshire. *Nature*, 224, 65-67.

Rise, L. and Rokoengen, K., 1984. Superficial sediments in the Norwegian sector of the North Sea between 60°30' and 62°N. *Marine Geology*, 58, 287-317.

Robertson, T. 1935. The glaciation of Aithsting, South Nesting, Whalsay and the Out Skerries. Unpublished: *Geological Survey Records (Edinburgh).*

Robinson, M. and Ballantyne, C.K., 1979. Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross. *Scottish Journal of Geology*, 15, 271-277.

Rokoengen, K., Løfaldi, M., Rise, L., Løken, T. and Carlsen R. 1982. Description and dating of a submerged beach in the northern North Sea. *Marine Geology*, 50, M21-M28.

Rolfe, W.D.I., 1966. Woolly rhinoceros from the Scottish Pleistocene. *Scottish Journal of Geology*, 2, 253-258.

Ross, H.M., 1993. North Unst and north Yell - evidence for an ice margin. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide.* Cambridge: Quaternary Research Association. 57-58.

Ross, H.M., Hall, A.M., and Gordon, J.E., 1993. Patterns of ice flow on Shetland. In Birnie, J.F., Gordon, J.E., Bennet, K.D. and Hall, A.M., 1993. *The Quaternary of Shetland Field Guide.* Cambridge: Quaternary Research Association. 9-14.

Ruddiman, F. and McIntyre, A. 1981. The mode and mechanism of the last deglaciation: oceanic evidence. *Quaternary Research*, 16, 125-134.

Seidenkrantz, M.-S., Kristensen, P. and Knudsen, K.L., 1995. Marine evidence for climatic instability during the last interglacial in shelf records from northwest Europe. *Journal of Quaternary Science*, 10, 77-82.

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D. and Rokoengen K. 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas*, 23, 1-13.

Selby, I., 1989. *The Quaternary geology of the Hebridean continental margin.* Unpublished PhD Thesis, Universtiy of Nottingham.

Shaffer, G. and Bendtsen, J., 1994. Role of the Bering Strait in controlling North Atlantic ocean circulation and climate. *Nature*, 367, 354-357.

Siegert, M.J. and Dowdeswell, J.A. 1995. Modelling ice-sheet sensitivity to Late Weichselian environments in the Svalbard-Barents region. *Journal of Quaternary Science*, 10, 33-44.

Sissons, J.B., 1967. *The Evolution of Scotland's Scenery.* Edinburgh

Sissons, J.B., 1981. The last Scottish ice-sheet: facts and speculative discussion. *Boreas*, 10, 1-17.

Sissons, J.B. and Dawson, A.G., 1981. Former sea-levels and ice limits in part of Wester Ross, NorthWest Scotland. *Proceedings of the Geological Association, London*, 92, 115-124.

Sollid, J.L. and Sørbel, L. 1994. Distribution of glacial landforms in southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler*, 76A: 1-2, 25-35.

Stevenson, A.G., 1991. *Miller Sheet 61°N-02°W British Geological Survey 1:250 000 Series Quaternary Geology*. Southampton: Ordnance Survey for British Geological Survey.

Stoker, M.S. 1988. Pleistocene ice-proximal glaciomarine sediments in boreholes from the Hebrides Shelf and Wyville-Thomson Ridge, Northwest UK continental shelf. *Scottish Journal of Geology*, 24, 3, 249-262.

Stoker, M.S. 1995. The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In Scrutton, R.A., Stoker, M.S., Shimmield, G.S. and Tudhope, A.W. (eds) 1995. *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region*, Geological Society Special Publication No. 90, 159-177.

Stoker, M.S. and Holmes, R. 1991. Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society of London*, 148, 431-434.

Stoker, M.S., Harland, R., Morton, A.C. and Graham, D.K., 1989. Late Quaternary stratigraphy of the northern Rockall Trough and Faeroe-Shetland Channel, northeast Atlantic Ocean. *Journal of Quaternary Science*, 4, 211-222.

Stoker, M.S., Hitchen, K. and Graham, C.C. 1993. *United Kingdom offshore regional report: the geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas*. London: HMSO for the British Geological Survey.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P, Evans, D., Ardus, D.A., 1994. A record of late Cenozoic stratigraphy, sedimentaion and climate change from the Hebrides Slope, Northeast Atlantic Ocean. *Journal of the Geological Society*, 151, 253-249.

Stoker, M.S. and Long, D., 1984. A relict ice-scoured erosion surface in the central North Sea. *Marine Geology*, 61, 85-93.

Sutherland, D.G., 1980. Problems of radiocarbon dating deposits from newly deglaciated terrain: examples from the Scottish Late-glacial. In Lowe, J.J., Gray, J.M. and Robinson, J.E., 1980. *Studies in the Late-glacial of North-West Europe*. Oxford: Pergammon Press. 139-149.

Sutherland, D.G., 1984. The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews*, 3, 157-254.

Sutherland, D.G., 1991. Late Weichselian glacial deposits and glaciation in Scotland and the adjacent offshore region. In Ehlers, J., Gibbard, P.L. and Rose, J., 1991. *Glacial Deposits in Great Britain and Ireland*. Rotterdam: Balkema. 53-60.

Sutherland, D.G., Ballantyne, C.K. and Walker, M.J.C., 1984. Late Quaternary glaciation and environmental changes on St Kilda, Scotland, and their palaeoclimatic significance. *Boreas*, 13, 261-272.

Sutherland, D.G. and Gordon, J.E., 1993a. The Shetland Islands - Introduction. In Gordon, J.E. and Sutherland, D.G. 1994. *Geological Conservation Review Series Quaternary of Scotland*. London: Chapman and Hall for the Joint Nature conservation Committee.

Sutherland, D.G. and Gordon, J.E., 1993b. The Orkney Islands - Introduction. In Gordon, J.E. and Sutherland, D.G. 1994. *Geological Conservation Review Series Quaternary of Scotland*. London: Chapman and Hall for the Joint Nature Conservation Committee.

Sutherland, D.G. and Gordon, J.E., 1993c. Introduction. In Gordon, J.E. and Sutherland, D.G. 1994. *Geological Conservation Review Series Quaternary of Scotland.* London: Chapman and Hall for the Joint Nature Conservation Committee.

Sutherland, D.G. and Walker, M.J.C., 1984. A Late Weichselian ice free area and possible interglacial site on the Isle of Lewis, Scotland. *Nature*, 309, 701-703.

Tipping, R.M., 1988. The recognition of glacial retreat from palynological data: a review of recent work in the British Isles. *Journal of Quatnernary Science,* 3, 3, 171-182.

Von Weymarn, J.A., 1979. A new concept of glaciation in Lewis and Harris, Outer Hebrides. *Proceedings of the Royal Society of Edinburgh,* 77B, 97-105.

Vorren, T.O., Vorren, K.D., Alm, T., Gulliksen, S. and Lovlie, R. 1988. The last deglaciation (20,000 to 11,000 BP) on Andøya, northern Norway. *Boreas*, 17, 41-77.

Walker, M.J.C., Bohncke, S.J.P., Coope, G.R., O'Connell, M., Usinger, H. and Verbruggen, C., 1994. The Weichselian/Weichselian Late-glacial in northwest Europe (Ireland, Britain, north Belgium, the Netherlands, northwest Germany). *Journal of Quaternary Science*, 9, 2, 109-118.

Walker, M.J.C., and Lowe, J.J. 1985. Flandrain environmental history of the Isle of Mull, Scotland. I. pollen-stratigraphic evidence and radiocarbon dates from Glen More, south-central Mull. *New Phytologist,* 99, 587-610.

Weaver, A.J. and Hughes, T.M.C., 1994. Rapid interglacial climate fluctuations driven by North Atlantic ocean circulation. *Nature*, 367, 447-450.

Young, A.C., Sullivan, R.A., Rybicki, C.A., 1978. Pile design and installation features of the Thistle Platform. *Proceedings of the European Offshore Petroleum Conference*, London.

Technical Appendix

This is the technical appendix.

Technical Appendix

Assumptions underlying evidence for reconstruction

The reconstruction of the last glaciation of Shetland offered in this thesis is based not only on newly observed terrestrial evidence but also on that collected from other sources. The latter is taken at face value and so it is appropriate to consider the assumptions upon which it is based.

Striation

Shetland's glacial history is dominantly erosive and striae are the most widely analysed indicators of ice movement. It may be possible to determine both the azimuth and sense of direction of ice movement from striae. The following assumptions are made in the interpretation of striae data in this study.

- Striae are the product of glacial abrasion rather than other floating or flowing masses which are capable of creating them, such as landslides, avalanches or iceberg scouring.

- Basal ice movement is sensitive to undulations in the bedrock over which it is flowing, as well as larger topographic controls at all scales. In general, wider, consistent patterns of striae azimuth are preferred to isolated observations as evidence of the azimuth of ice flow. However, this reconstruction is based on a recognition of patterns of topographic containment at varying scales and all observations, from all sources, are considered in this context.

- The distribution of striae is at least partially related to the distribution of appropriate lithologies upon which they can be etched and perserved, vegetation cover (concealment), postglacial erosion and observation and mapping. In this study, distribution is rarely used as evidence in itself.

- Although sense of direction of ice flow can be determined from striation morphology (Flint, 1971; Menzies and Shilts, 1996) the depth, width and length of are complexly related to basal stress, ice velocity, meltwater, debris content, effective stress, lithology of the indenter and indented and the angle of the indenter. This study, therefore, does not attempt to deduce sense of direction from striae observations. Sense of direction striae data from other sources are treated as being open to reversal unless clearly accompanied by consistent stoss and lee evidence.

Stoss and lee

Sense of direction of ice movement data is in places controversial on Shetland with different authors concluding different senses of direction for the same area. The following assumptions are made regarding stoss and lee data in this study.

- The distribution and pattern of individual and areal stoss and lee observations are strongly related to bedrock lithology (Rastas and Seppälä, 1981).

- Azimuth of ice movement is difficult to determine with precision because of this variation. Although Flint (1971) considers there to be only a 10 - 15° arc of variation, the heterogeneity of solid geology on Shetland is great and no attempt is made to determine azimuth of ice flow from such data in this study.

- Sense of direction from stoss and lee observations, particularly small scale (micro-) stoss and lee observations, can only be reliably established over an area in which consistent evidence exists. Single, small scale, observations are unreliable and can be the product of other weathering processes exploiting the same lithological weaknesses as a glacier.

Erratics

Clastic erratic data is used in the study as evidence of the direction of former ice movement. A number of assumptions are made in this regard.

- The presence of non-local rocks, surficially or in glacial sediments, is due to one period glacial transport from the source area. Other mechanisms (such as human carriage) would be readily identifiable. Most evidence of glaciation on Shetland indicates a high degree of erosion, especially in the later phases of glaciation, so multiple movements of erratics can reasonably be discounted.

- There is insufficient space on the islands, and insufficient data, to demonstrate the existence of indicator trains or fans. Core sampling of clastic debris is inadequate to mount such an investigation offshore.

- The percentage quantities of particular erratic assemblages are dependent on: area of upstream source outcrop; erodibility of upstream source outcrop; durability of rock type in transport; distance of transport. Some use of these assumptions on Shetland is made by other authors however this study treats these tentativelyand generally considers only the existence or otherwise of erratics of particular provenance, rather than their quantity.

- The variability of rock types on Shetland and the extent of weathering suffered by tranported clasts makes hand specimen identification of erratics from particular outcrops difficult. This study only identifies erratics in simple circumstances and accepts the superior knowledge of other workers at face value.

Heavy mineral analysis

A study on the heavy mineralogy of sand grade particles is referred to throughout this work as giving some evidence of the provenance of offshore glacigenic sediments. The following assumptions are made.

- The most influential control on heavy mineral assemblages sampled offshore is the petrography of the source materials.

- The stability of heavy minerals during weathering is highly variable (Bateman and Catt, 1985).

- Erosion, transport and deposition can affect the distribution of heavy minerals, particularly where grain density, size and shape are variable, but this has been little studied.

- Some heavy minerals may survive glacial abrasion more than others (Drewry, 1986).

- It is difficult to reliably analyse provenance where a variety of bedrock types are crossed by glaciers.

For these reasons, the study of heavy minerals is treated with some caution and detailed conclusions are not drawn from it in this reconstruction.

Fabric analysis

Fabric analyses are conducted in a number of locations. The following assumptions are noted.

- The study is concerned with a-type fabrics (a-axis declination parallel with ice flow and inclination slightly up-glacier) (Gale and Hoare, 1991).

- Lodgement and melt-out tills often display a-type fabrics.

- Fabric is not only controlled by depositional process but by: clast size and shape; till coarseness (interclast contact); local relief (extending ice flow may enhance a-type fabrics); ice flow velocity (Harris, 1968).

- Use of the horizontal reference plane may result in different fabrics than the plane of deposition which is not always possible to deteremine (Cornish, 1979).

- The character of till fabrics may change over very short horizontal and vertical differences (e.g. Hoare and Connell, 1981).

In this study, time did not permit widespread sampling of till faces and the fabrics presented are used as supplementary evidence unless clearly visible throughout the exposed till section.

References

Bateman, R.M. and Catt, J.A., 1985. Modification of heavy mineral assemblages in English coversands by acid pedochemical weathering. *Catena*, 12, 1-21.

Cornish, R., 1979. The statistical analysis of till fabric data: a review. *University of Edinburgh Department of Geography Research Discussion Paper*, 16. 46 pp.

Drewry, D., 1986. Glacial Geologic Processes. Edward Arnold: London

Flint, R.L., 1971. Glacial and Quaternary Geology. John Wiley and Sons

Gale, S.J. and Hoare, P.G., 1991. Quaternary Sediments. Belhaven Press: London

Harris, S.A., 1968. Till fabrics and speed of movement of the Arapahoe Glacier, Colorado. *The Professional Geographer*, 20, 195-198.

Hoare, P.G. and Connell, E.R., 1981. The chalky till at Barrington, near Cambridge, and its connection with other Quaternary deposits in Southern Cambridgeshire and adjoining areas. *Geological Magazine*, 118, 463-476.

Menzies, J. and Shilts, W.W., 1996. Subglacial environments. In Menzies, J. Past Glacial Environments - Sediments, Forms and Techniques. Butterworth-Heinmann:UK. 1-36.

Rastas, J. and Sepällä, M., 1981. Rock jointing and abrasion forms on roches moutonées, S.W. Finland. *Annals of Glaciology*, 2, 159-163.

Ground covered in field observation

Although this reconstruction is partially based on existing datasets, much of Shetland was covered by ground reconnaissance during the study. In all areas, new drift geology data was recorded and this is presented in summary in the figures accompanying this volume. Attention was paid to the depth, disposition with respect to the underlying substrate and topography, matrix colour, clast lithology, size and angularity, fabric, contacts and structure where these were evident, and probable genesis. Although many sections were cleaned for examination and photography, notes were made for whole exposures, where possible lateral and vertical extent were recorded, but individual sections were not formally logged in detail. Given the small scale maps in published work, it is difficult to determine whether recorded observations should be treated as new or confirmed. Specific striae observations made by the author are not recorded here. The author's field maps are largely at the 1:25 000 scale, however the major dataset is that of Flinn who has mapped striae throughout Shetland at 1:10 000.

To assist in the interpretation of the author's observations and in the planning of future work, the ground covered is recorded here. Much of the coastline was recorded because drift exposure is best here. Most roads and tracks, also liable to lead to exposures especially in quarries, were travelled by car. Many inland areas are peat-covered but the larger burns and valleys were explored, together with any areas that contained interesting drift or morphology previously published. In all, this amounts to six months work in the field.

Fair Isle

The entire coastline and much of the inland area was covered. All rock outcrops that might provide stoss and lee data were examined, as were all exposed drift sections. It is notable that despite particular efforts to verify striae evidence in this area none were observed. All roads and tracks were travelled and drift exposures examined.

South Mainland

The only coastlines not traversed were as follows: east coast of Bressay, east coast of Clift Sound, the West coast of West Burra, and the isles of Noss, Colsay, South Havra, Oxna, Papa and Hildsay. Much of the high ground of the Clift Hills is peat-covered but all available tracks were explored, together with the tributaries of the Burns of Laxdale, Mail and Sevdale. The areas of Dales Voe, Loch of Tingwall and west of Lerwick were covered. All roads and tracks were travelled and drift exposures examined.

West Mainland

Most of the southern coastline and associated voes were traversed, together with all of the west and northwest coasts. The voes and firths of the northern coast were explored although Vementry, Papa Little and the west coast of Muckle Roe were not visited. The entire coastline and inland area of Papa Stour was examined. Across the Walls peninsula, all roads and tracks were travelled and drift exposures examined, the Burn of Dale was traversed and Sandness Hill explored.

Central Mainland

The only coastlines not traversed were as follows: Aith Voe between East Burra Firth and Gon Firth; Sullom Voe west of Voxter Ness and North Ward; Garth's Voe to Orka Voe; Colla Firth to Sand Wick in Swining Voe; the east coast of Lunna Ness; Lunning Sound to Levaneap; parts of the east coast of South Nesting peninsula; parts of the east coast of Loch of Strom; the isles of Bigga, Samphrey, West Linga, Linga, Papa Little and Little Roe. Inland, East Kame, Mid Kame, West Kame, Petta Dale and the Valley of Kergord were covered. Also Burn of Laxobigging and tributaries, Burn of Valayre and Thieves Knowes. The area west of Lunnasting was not explored, but in North Nesting the Burns of Grunnafirth, Forse, Quoys and Laxo (to Grossawater) were. All roads and tracks were travelled and drift exposures examined.

North Mainland

The entire west coast of Sullom Voe and Yell Sound was traversed, along with the southern coast of the Esha Ness Peninsula, Hillswick, Ura Firth, Hamar, Gunnister and Mangaster Voes, and Hamna Voe and the south side of Ronas Voe. The coast and area north of Beorgs of Uyea was covered, as well as the Beorgs of Skellberry and Collafirth and Ronas Hill. The west coast of the Ronas Plateau, from Hevdadale Head to Uyea was traversed. All roads and tracks were travelled and drift exposures examined.

Unst, Yell and Fetlar

The only coastlines not traversed in this area were: parts of the northwest coast of Unst; the island of Balta; the island of Uyea; parts of the north and east coast of Fetlar; the island of Hascosay; the island of Linga; and the west coast of Yell between Whale Firth and West Sand Wick. On Unst, the Valla Field ridge, the Burns of Mailand and Caldback, the area of Virda Field and the areas around Saxa Vord and Hermaness were covered. On Fetlar, the inland areas of the west side of the island were widely covered. And on Yell, where much of the inland area is peat covered, the areas north of Hill of Vigon and Kussa Waters were explored, and the Laxa and Arisdale Burns were traversed. All roads and tracks were travelled and drift exposures examined.

The Last Glaciation of Shetland

Volume 2 - Figures and Plates

Hamish Ross
University of St Andrews
1996

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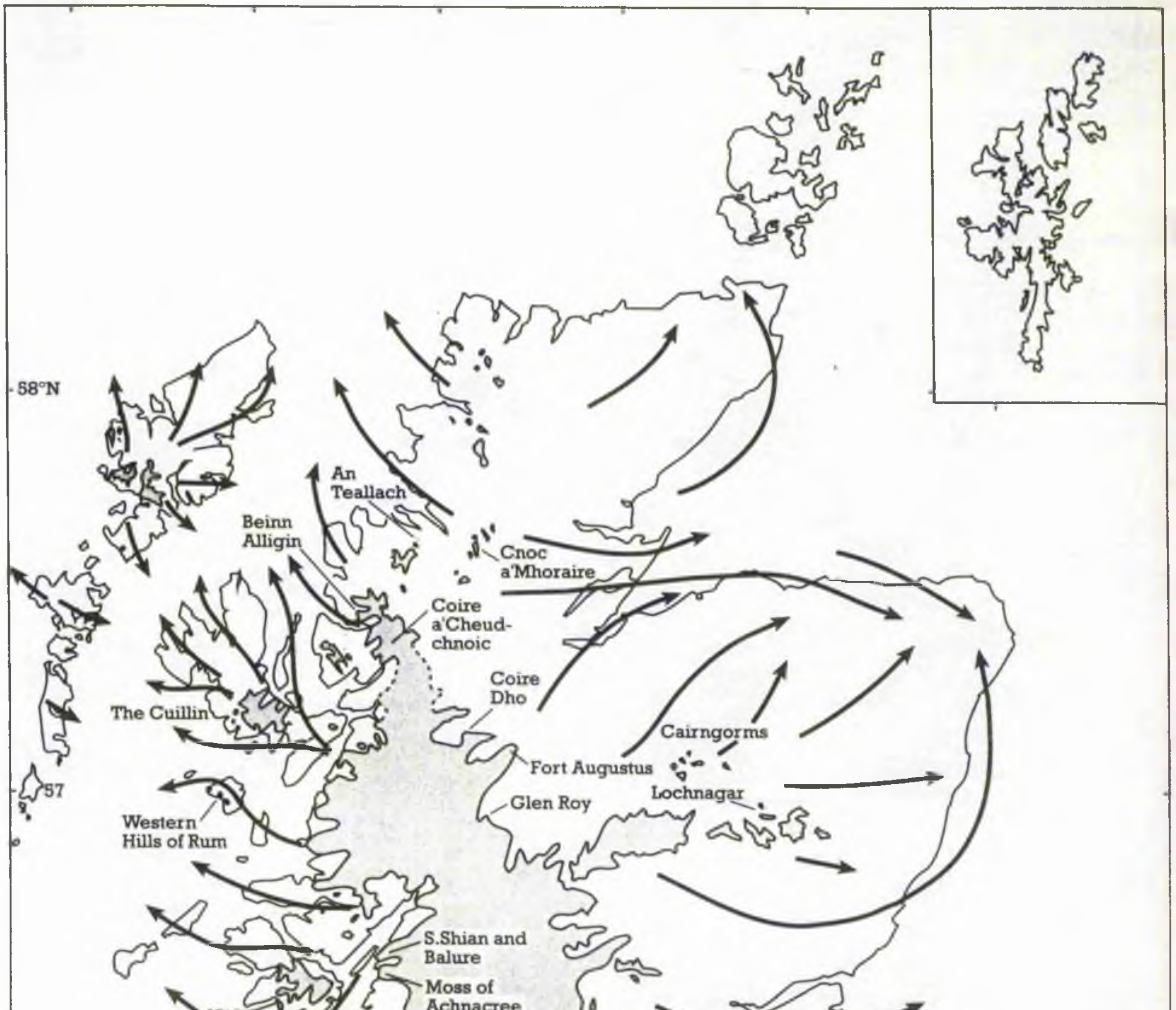


2.1 Major ice movements during the last glaciation, showing that ice flowed from a number of centres.
From Gordon and Sutherland, 1993

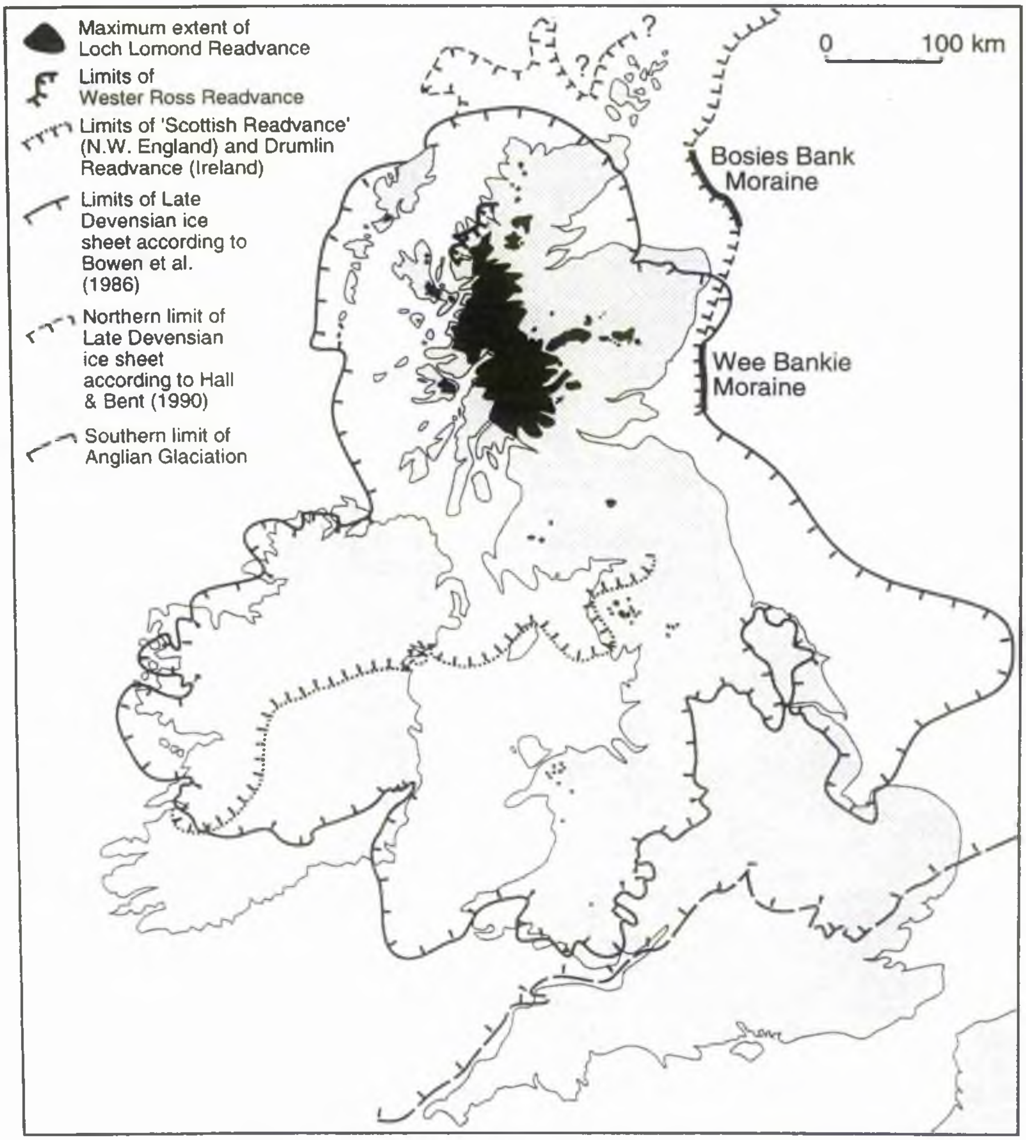


Figure 2.1 Extent of glacial limits in Great Britain and Ireland. Based on a map in Bowen *et al.* (1986), with modifications.

2.2 Maximum extent and ice limits for the Anglian, Late Devensian and Loch Lomond stadial glaciations.
From Ballantyne and Harris, 1994

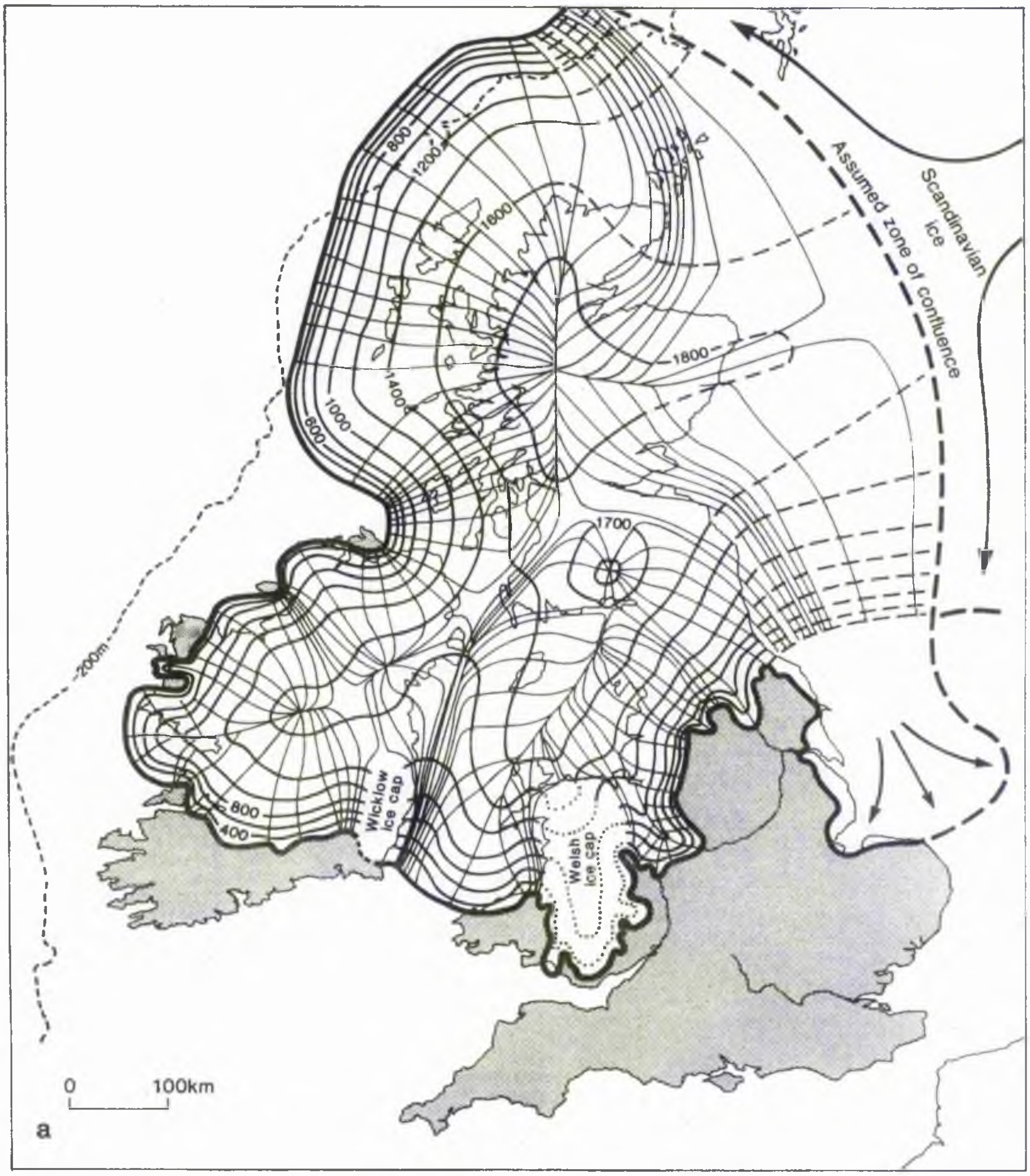


Fig. 15.16. Theoretical reconstructions of the maximum extent of the Late Devensian ice sheet over the British Isles. **a.** Model based on an ice sheet confluent with a Scandinavian ice sheet in the North Sea and using a 100 kPa basal shear stress. Contours (in metres) and flow lines are shown. No significant nunataks occur (Boulton *et al.* 1977).

2.3 Theoretical reconstruction of maximum extent of Scottish Late Devensian ice ('maximalist' version).
From Boulton et al., 1991

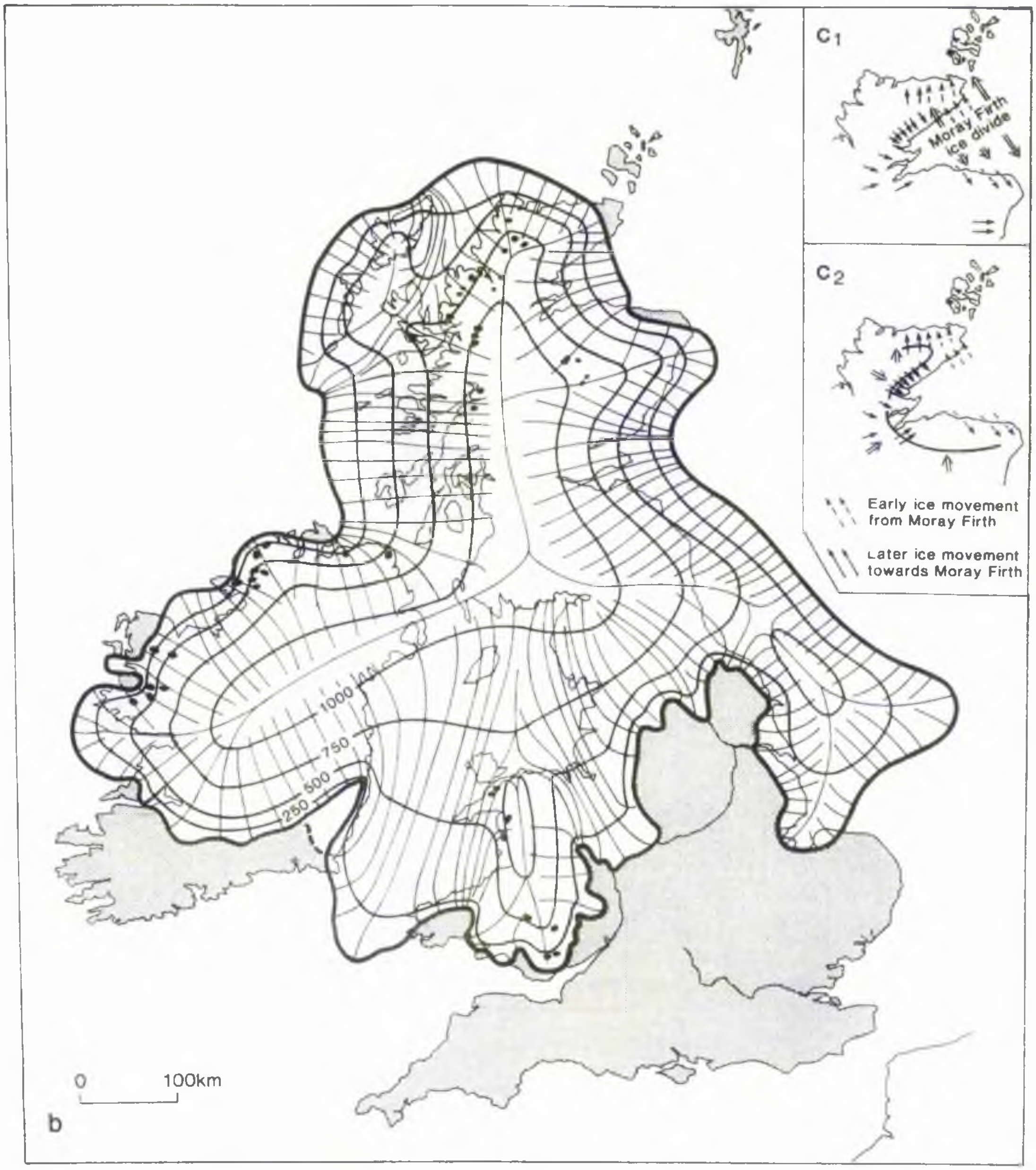


Fig. 15.16.

b. Reconstruction based on limited ice sheet extent in the North Sea, a basal shear stress of 70 kPa on the land area and 30 kPa in the sea area. Principal nunatak areas are shown as dots.

c. Explanation of the evidence of last ice flow directions in the Moray Firth area. Evidence of landward flow in the outer Firth suggests an ice divide in the Firth (C_1), whilst seaward flow in the inner Firth (C_2) must have occurred after collapse of the ice dome. The change could reflect a Wolstonian/Late Devensian contrast (e.g. Sutherland 1984) or stages in decay of the Late Devensian ice sheet (e.g. Boulton *et al.* 1985).

2.4 Theoretical reconstruction of maximum extent of Scottish Late Devensian ice ('minimalist' version) including possible scenarios for the northeast of Scotland. From Boulton et al., 1991

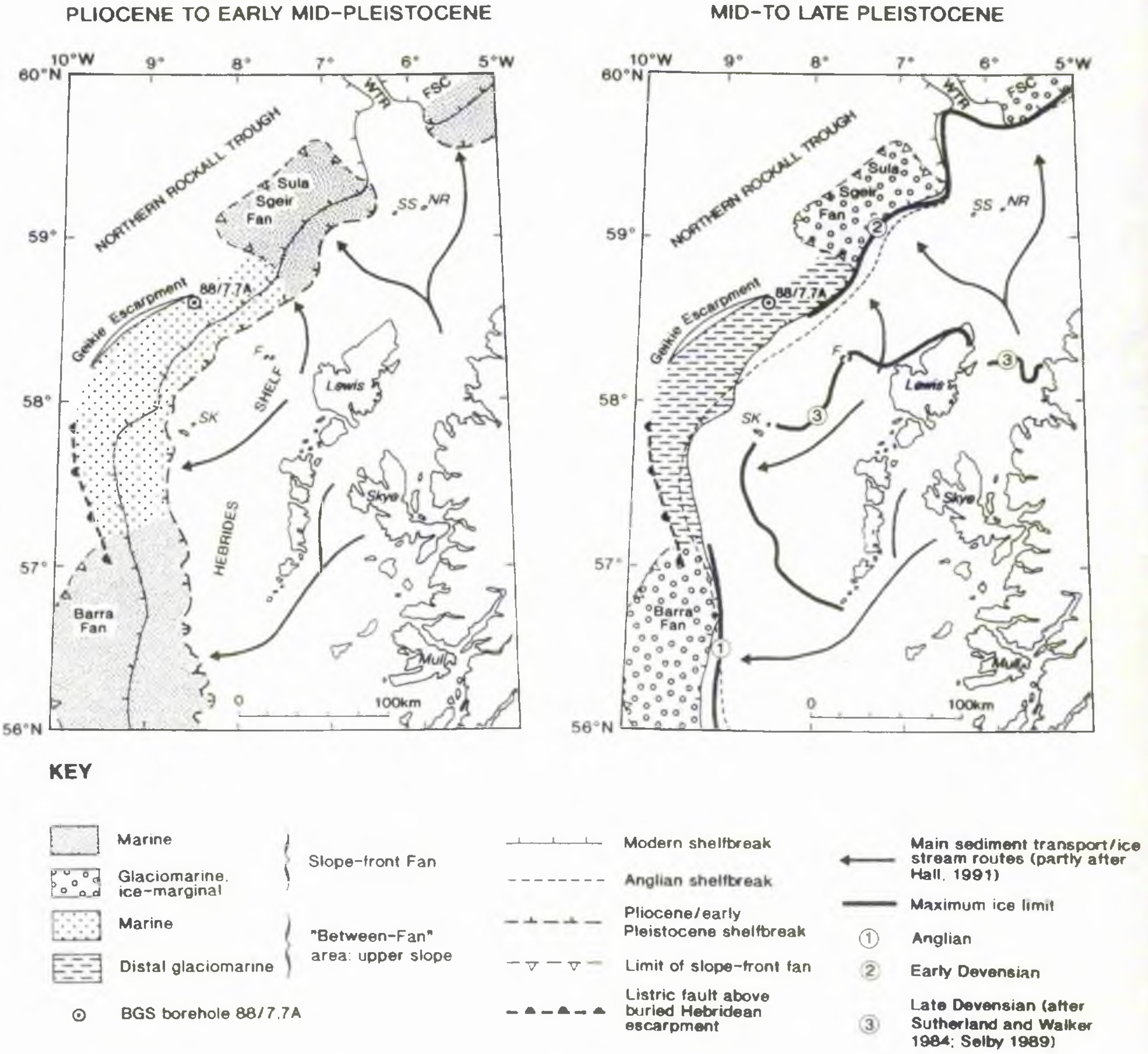


Fig. 9. Schematic palaeogeography of the Hebrides Slope during the Plio-Pleistocene (after Stoker *et al.* in press); Abbreviations: WTR, Wyville-Thomson Ridge; FSC, Faeroe-Shetland Channel; SS, Sula Sgeir; NR, North Rona; F, Flannan Islands; SK, St Kilda.

2.5 Schematic palaeogeography of the Hebrides Slope from the Plio-Pleistocene to Late Pleistocene. The right hand figure is of particular interest in this study.
From Stoker et al., 1994

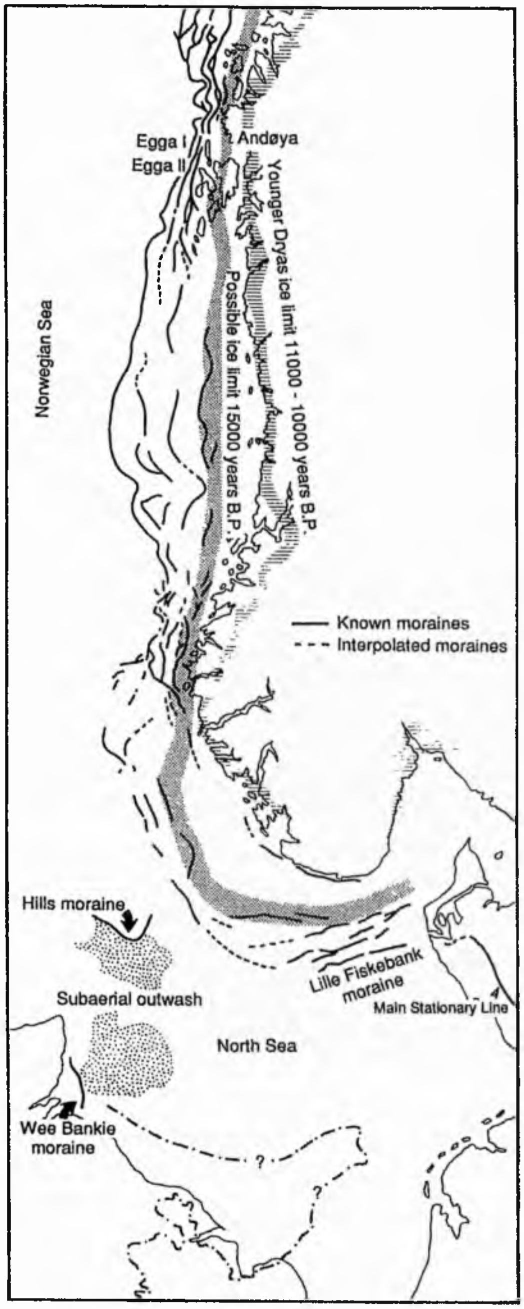


Figure 4.3 The distribution of glacier ice in the North Sea region during the last glacial maximum. The eastern limit of the British ice sheet is uncertain (dotted line). The distribution of ice-marginal moraines in Scandinavia is consistent with the view that much of the North Sea region was unglaciated during the last glacial maximum. The significance of the Hills moraine complex is not known (after Andersen 1979, Bowen 1978, Sutherland 1984; Long *et al.* 1988).

2.6 North sea ice distribution, including the Egga moraine sequences and the Wee Bankie moraine
From Dawson, 1992

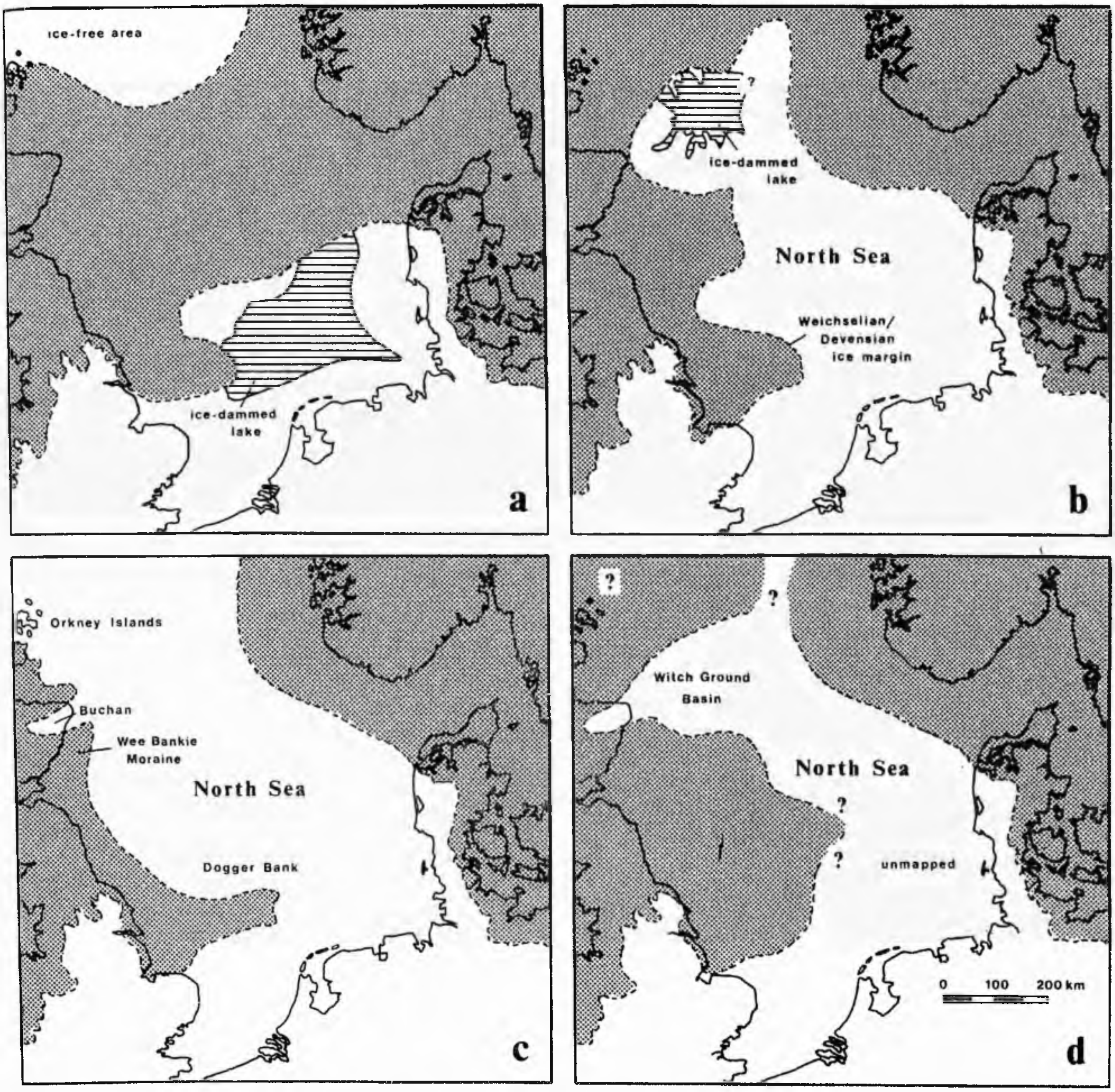


Figure 10 Weichselian/Devensian ice margins in the North Sea area as envisioned by (a) Valentin (1957), (b) Jansen (1976), (c) Long *et al.* (1988), and (d) Ehlers and Wingfield (this paper).

2.7 Various reconstructions of Weichselian/Devensian ice margins in the North Sea. From Ehlers and Wingfield, 1991

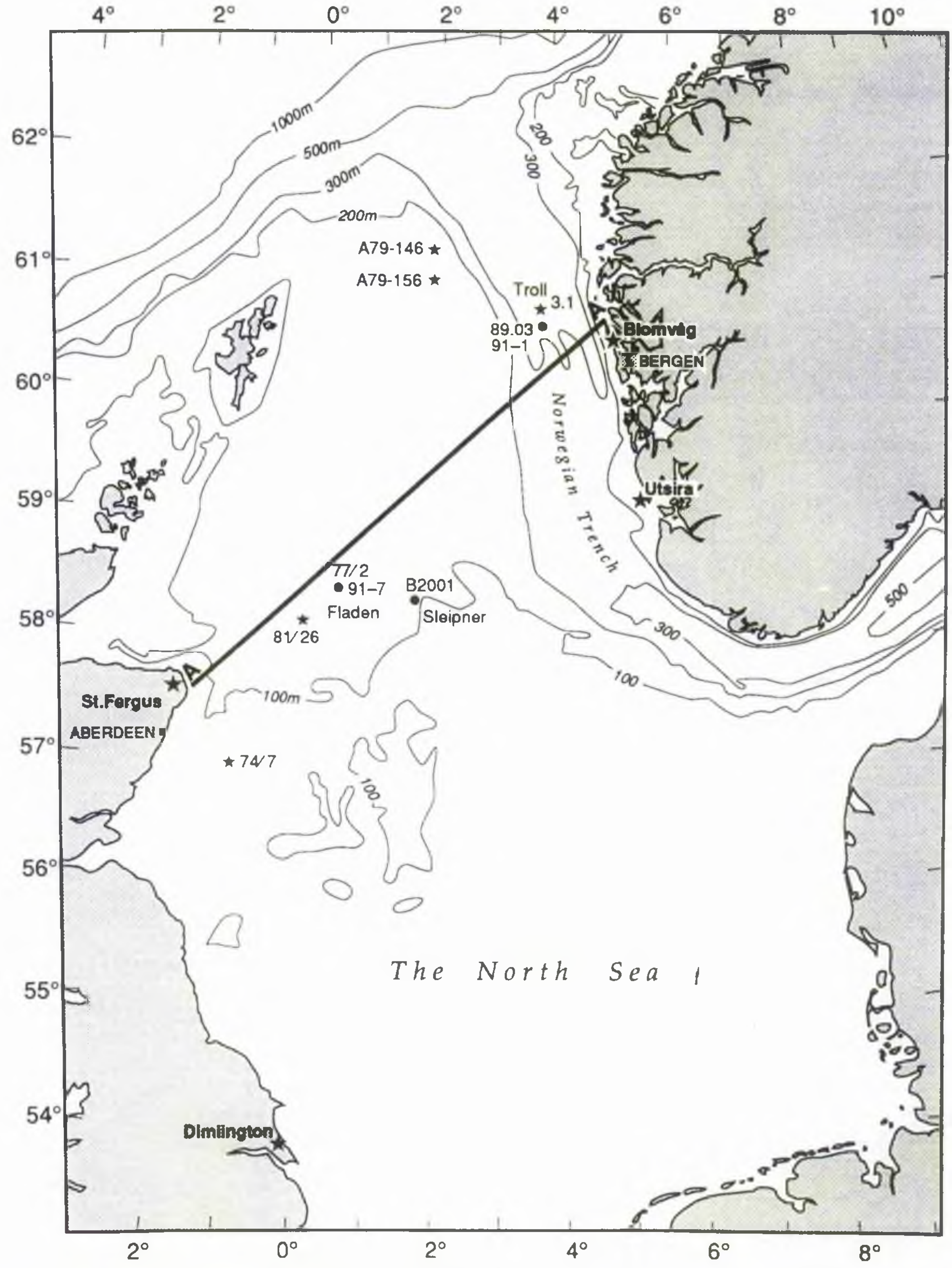


Fig. 1. Location map showing the position of the cores discussed in the text. Black dots: cores dated and described in this study. Stars: cores/sections previously described and dated (references in text). The line A–A' shows the profile along which the glaciation curve is constructed (see Fig. 12).

2.8 Transect across the North Sea relating to figure 2.9
From Sejrup et al., 1994

2.9 Glaciation curve for the northern North sea, along transect shown in figure 2.8. From Sejrup et al., 1994

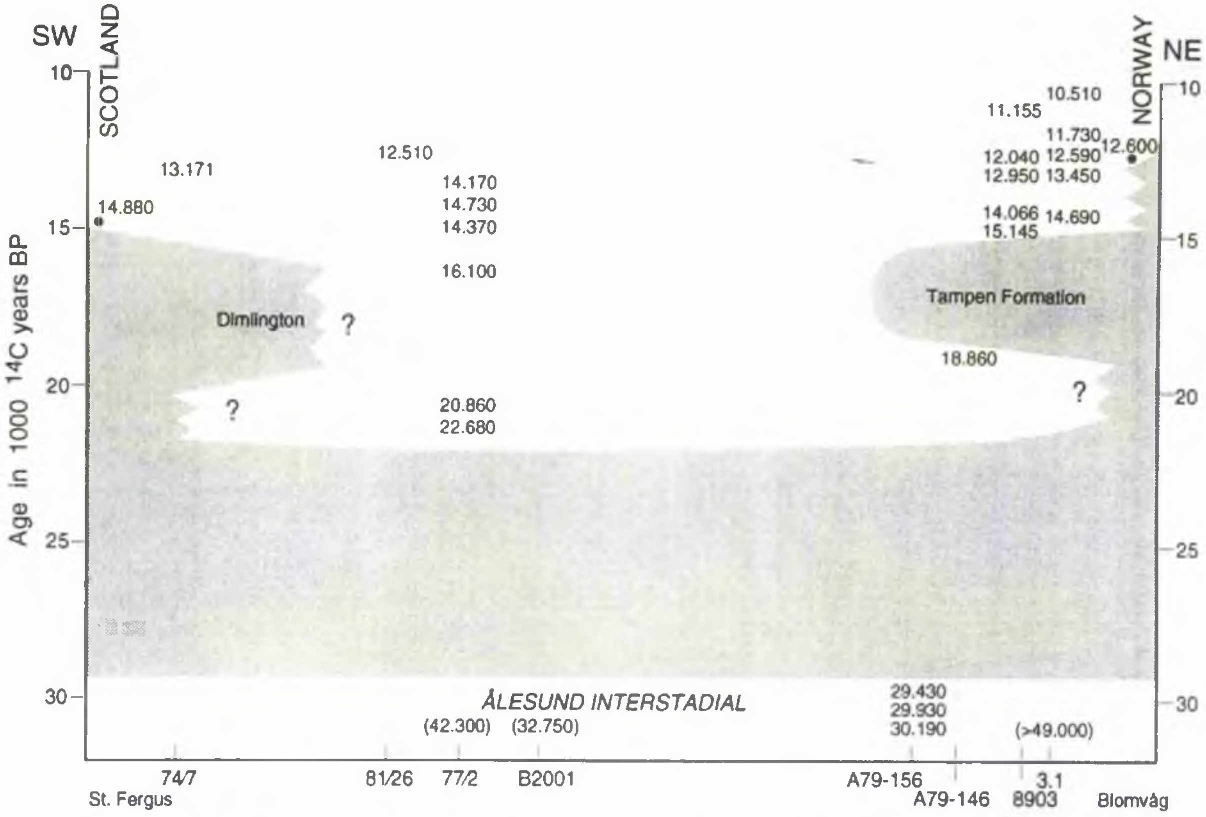
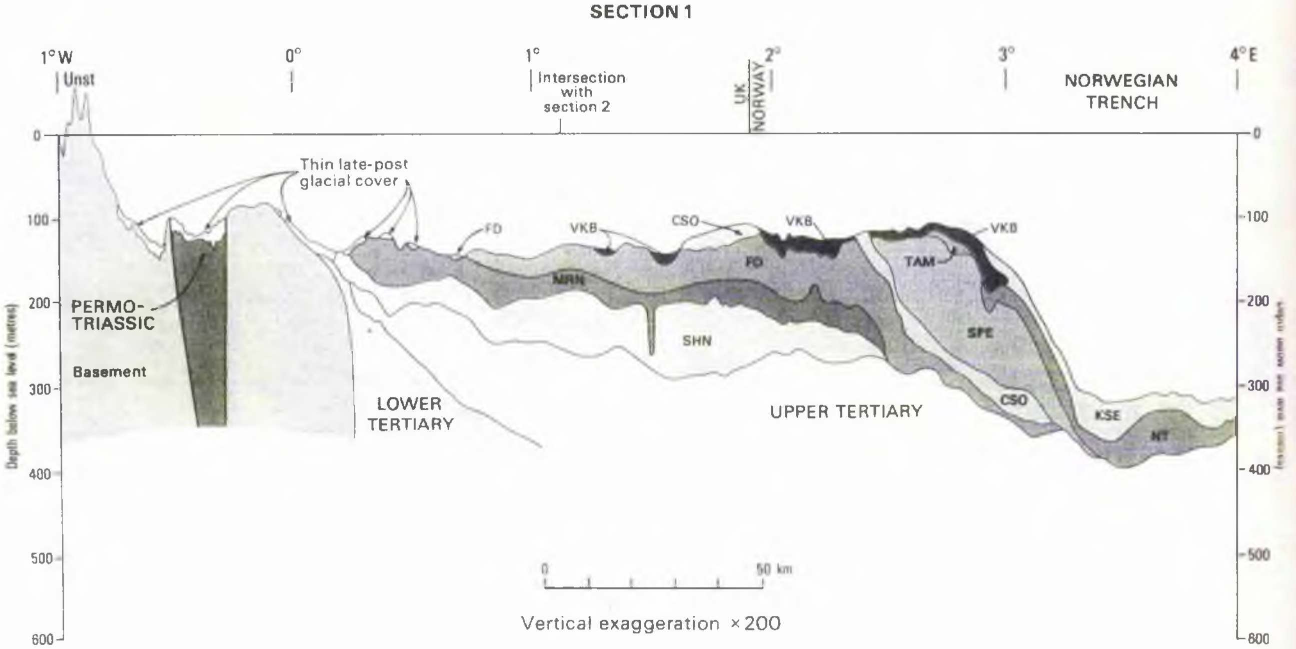


Fig. 12. Glaciation curve for the northern North Sea. The location of the cores/sites used in the diagram and the line on which they are projected are shown in Fig. 1. The shaded area represents periods of ice cover. The dates in parentheses were performed on foraminiferal samples from till units.



2.10 Cross section through Quaternary sediments between Shetland and Norwegian Trench, along transect shown in figure 3.15. Relevant deposits include: FD= Ferder Formation; SHN = Shackleton Formatio; MRN = Mariner Formation; CSO = Cape Shore Formation; TAM = Tampen Formation; NT = Norwegian Trench Formation; KSE = Kleppe Senior Formation. From Johnson et al., 1993

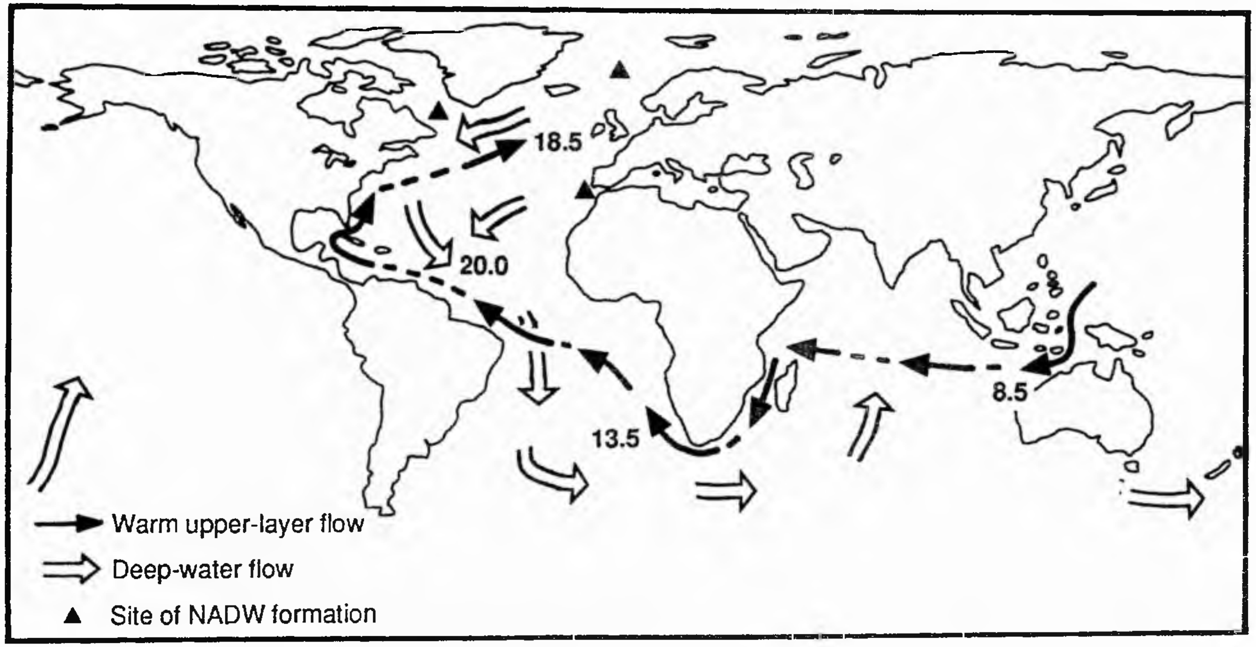


Figure 3.5 Global thermohaline circulation cell associated with North Atlantic deep water (NADW) production. Solid arrows show the inferred warm water route for return flow of upper-layer water to the North Atlantic. The suggested volume fluxes expressed as Sverdrup units (Sv) are based on a uniform upwelling of NADW with a production rate of 20 Sv (based on Street-Perrott and Perrott 1990). One Sverdrup unit is equivalent to 1×10^6 $m^3 s^{-1}$.

2.11 Global thermohaline circulation and North Atlantic Deep Water production.
From Dawson. 1992

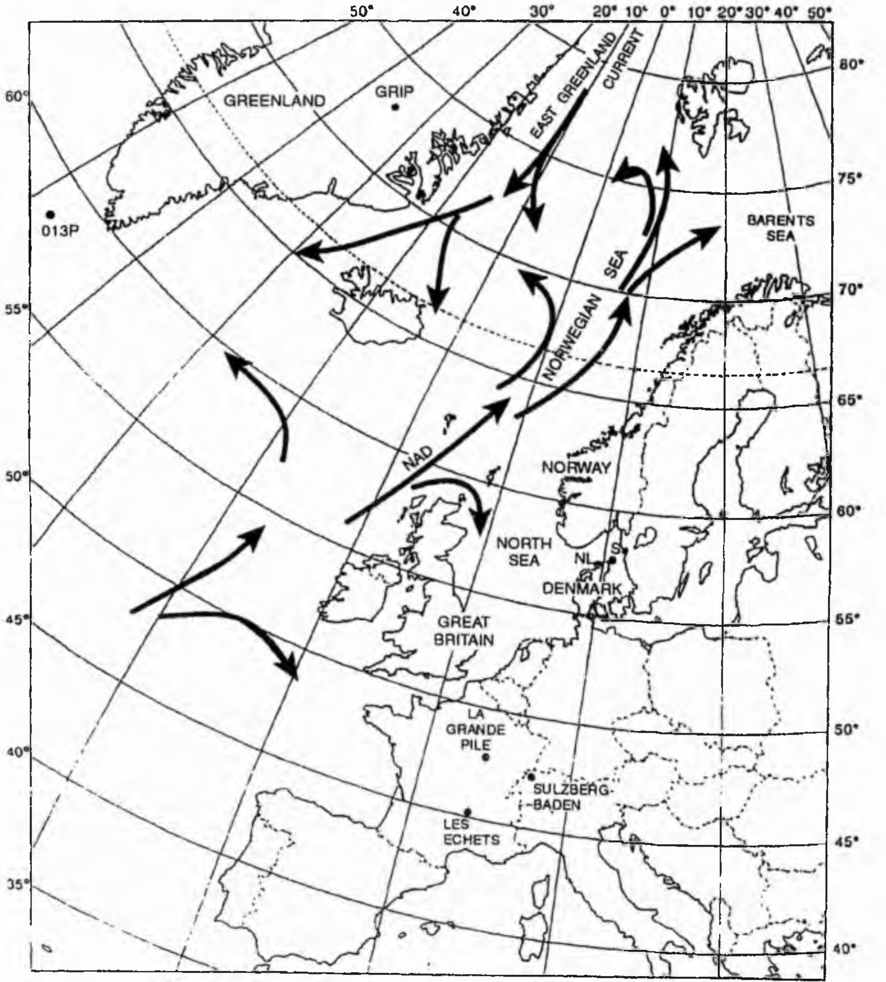
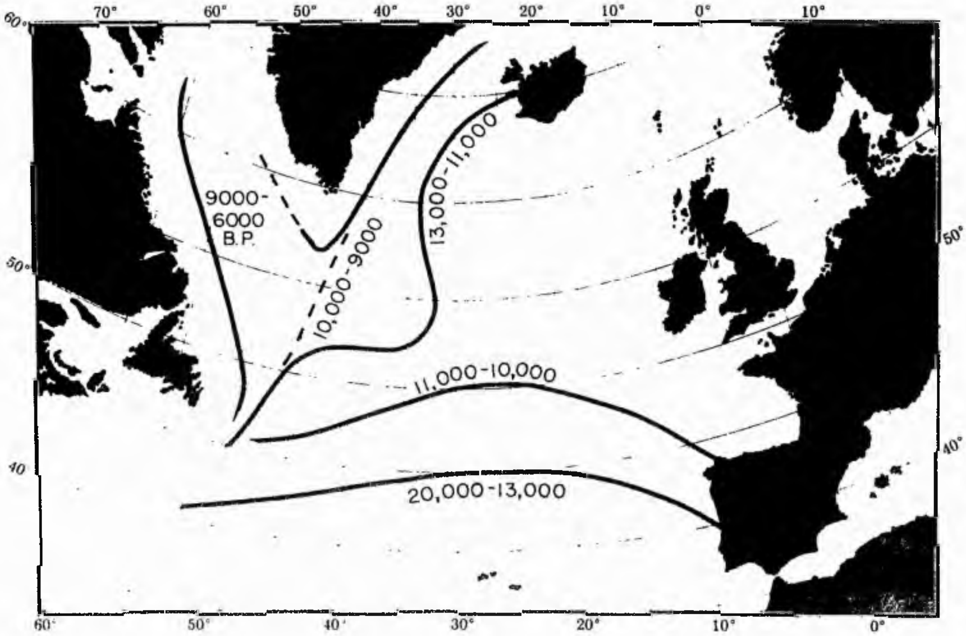


Figure 1 Location map showing the present current systems in the North Atlantic. S = Skagen 3, NL = Nørre Lyngby 2.

2.12 Present thermohaline current systems in the Northeast Atlantic, Greenland, Iceland and Norwegian Seas.
From Seidenkrantz and Knudsen, 1995

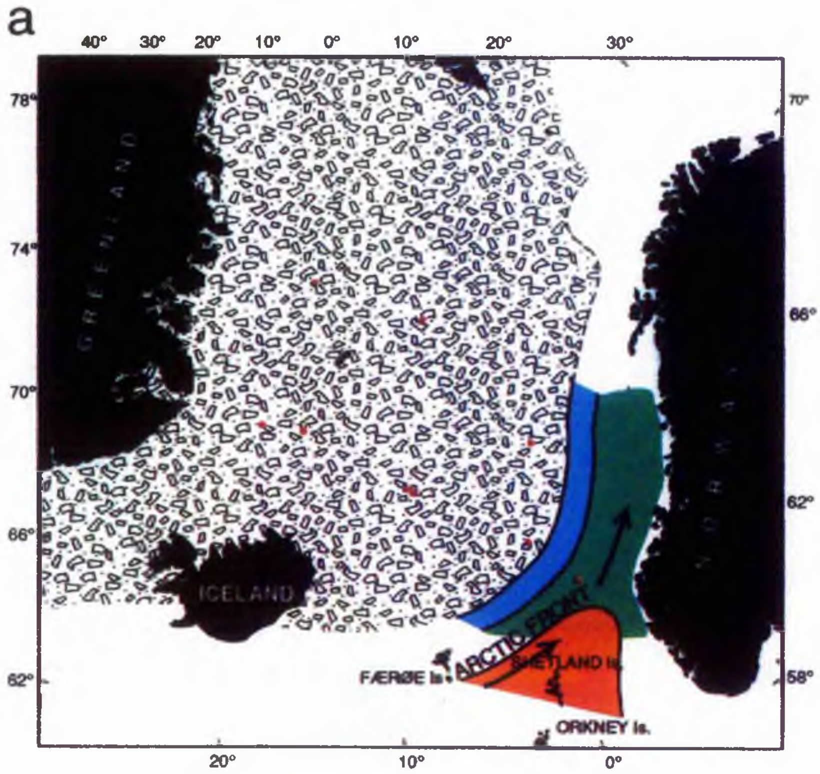


DEGLACIAL POLAR FRONT MOVEMENTS

FIG. 1. Retreat positions of the North Atlantic polar front from the glacial maximum position 18,000 yr ago to the modern interglacial location after 6000 yr B.P. Based on data in Ruddiman and McIntyre (in press).

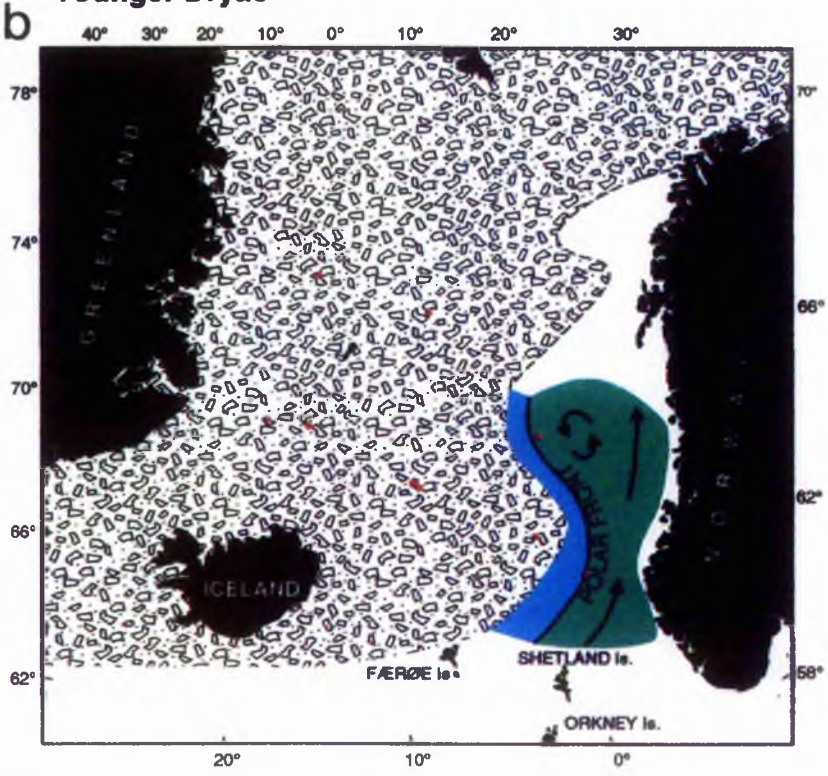
2.13 Deglacial polar front movements in the Atlantic Ocean.
From Ruddiman and McIntyre, 1981

13.4–11.2 KA

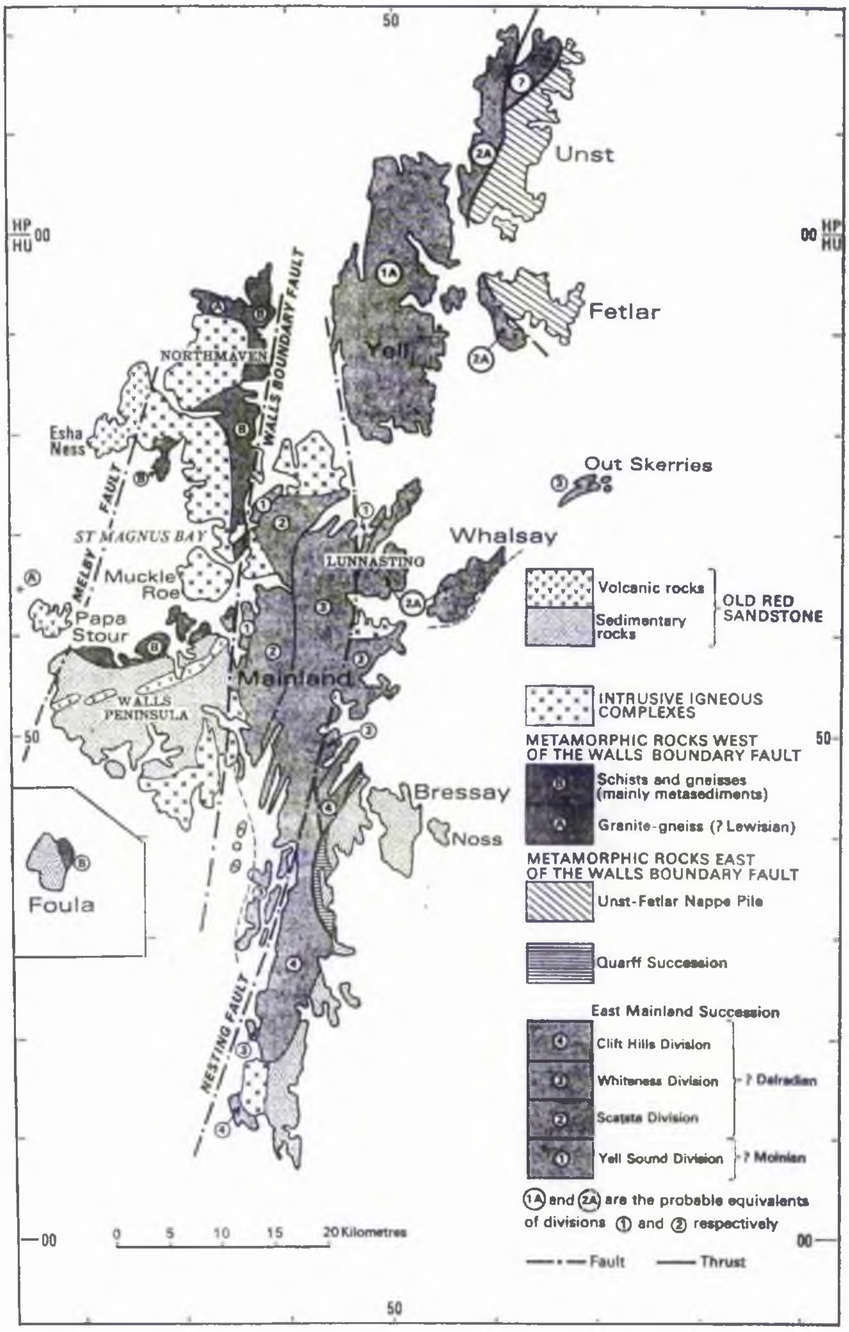


11.2–10.2 KA

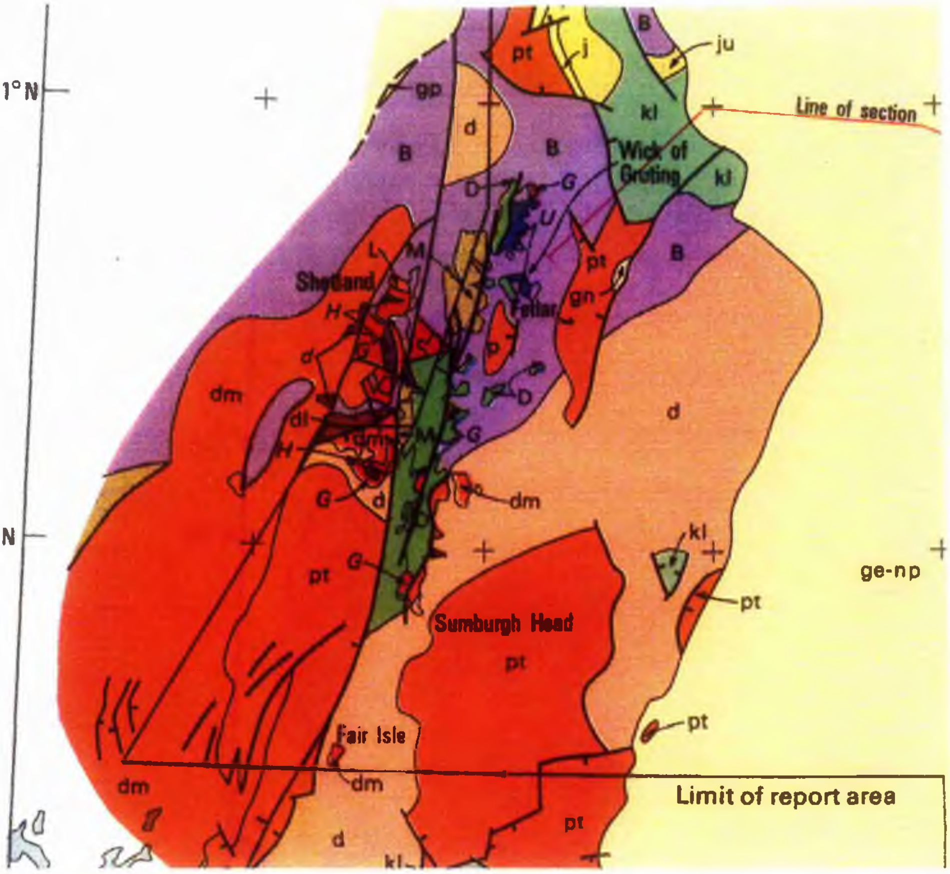
Younger Dryas



2.14 Reconstructions of palaeoceanographic conditions of the Greenland, Iceland and Norwegian seas, 13.4 - 10.2 ka BP. Arctic waters (green), sea ice (blue and broken pattern), mixed Norwegian/Arctic waters (brown).
From Koç et al., 1993



3.1 Summary sketch of terrestrial solid geology, Shetland. From Mykura, 1976



3.2 Summary sketch of offshore and terrestrial solid geology, Shetland. For key see figure 3.3. From Johnson et al., 1993

3.3 Key to summary of offshore and terrestrial solid geology shown in figure 3.2. From Johnson et al., 1993

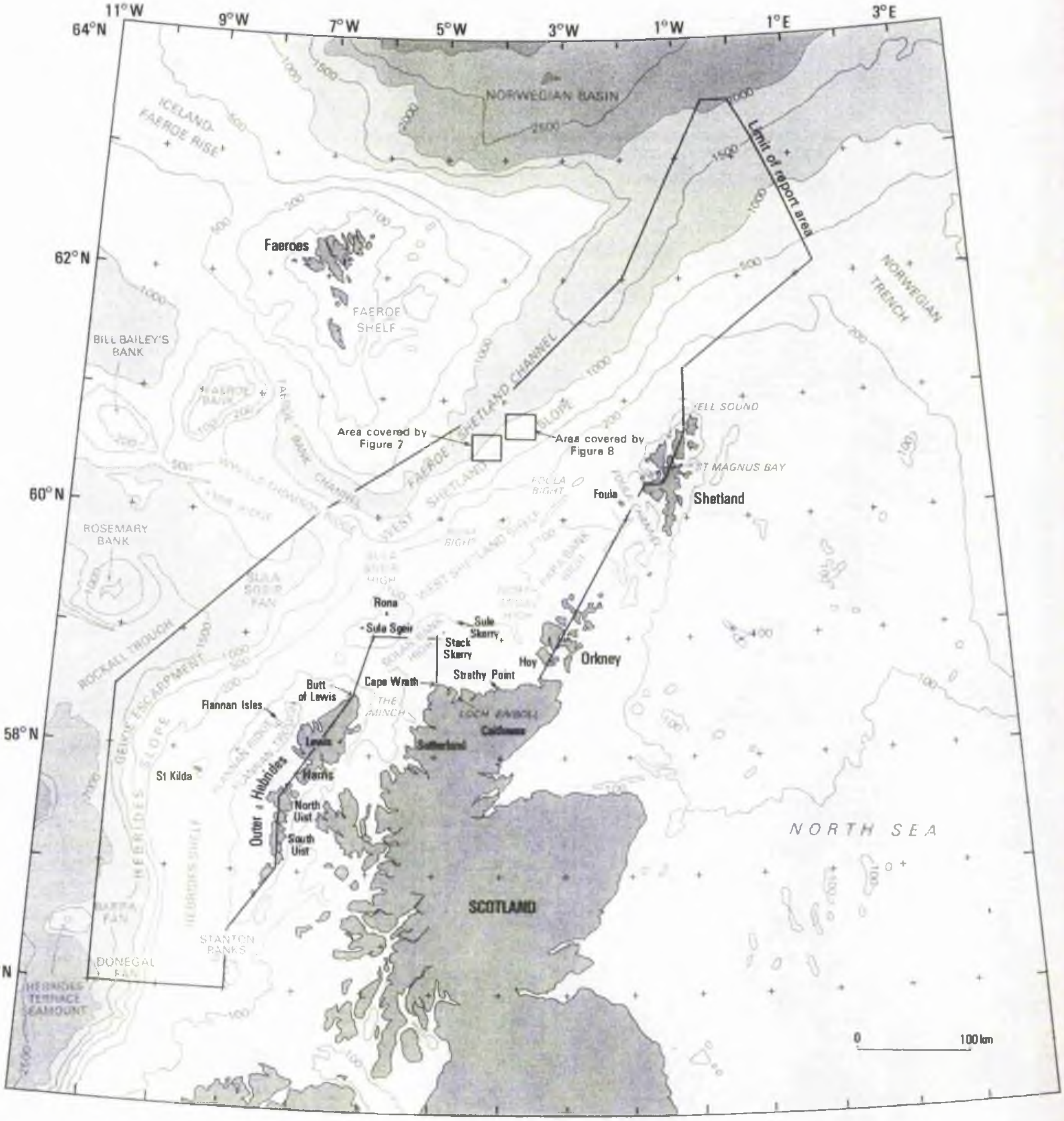


Figure 5 Bathymetry of the report area and surrounding regions. After Roberts et al. (1977).

3.4 Regional bathymmetry around Shetland.
From Johnson et al., 1993

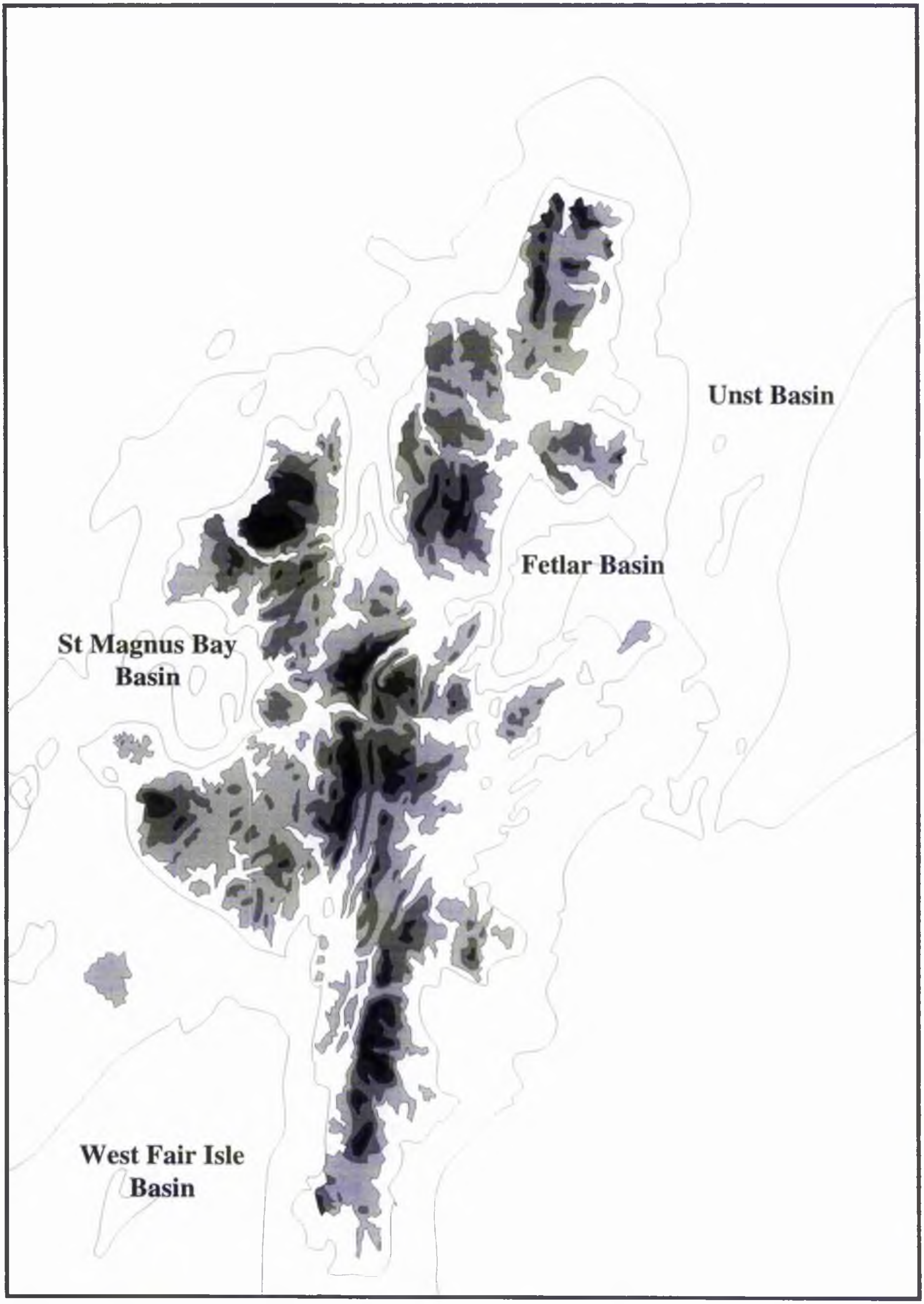


Figure 3.5. Outline of bathymmetry around Shetland. Bathymmetric contours are in -50 m intervals.

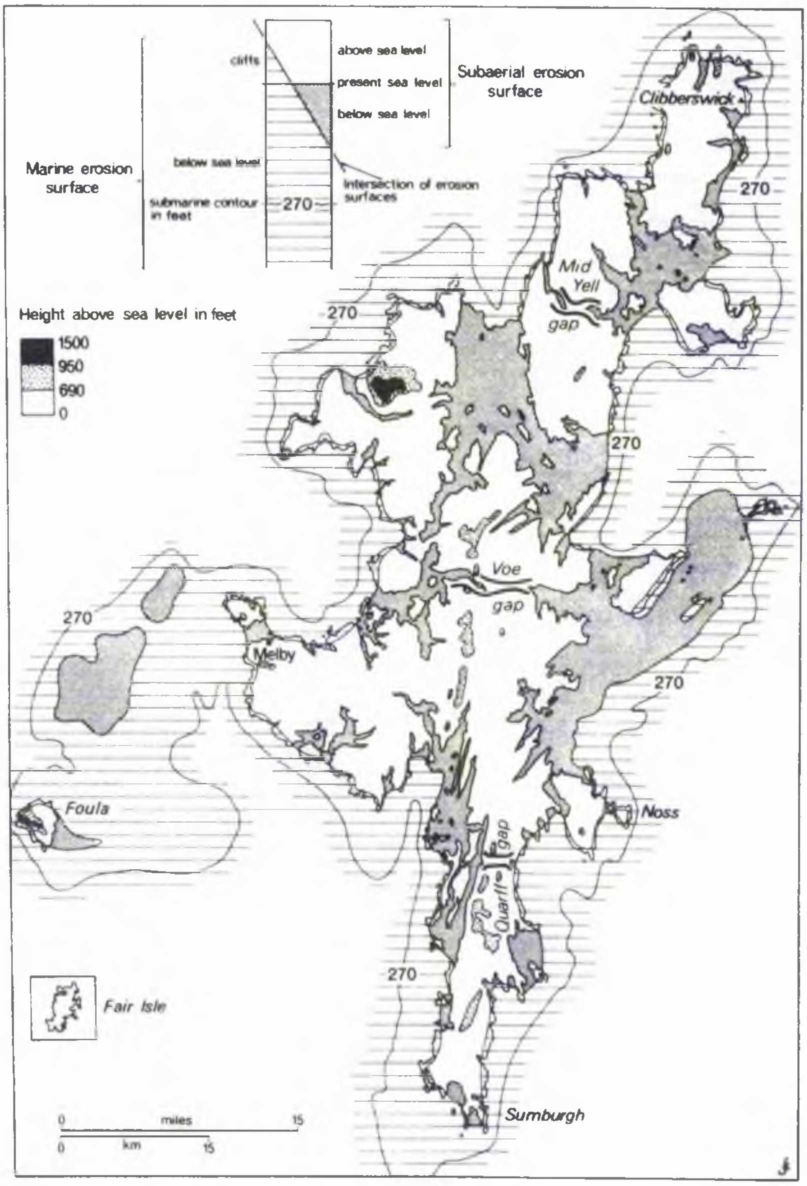
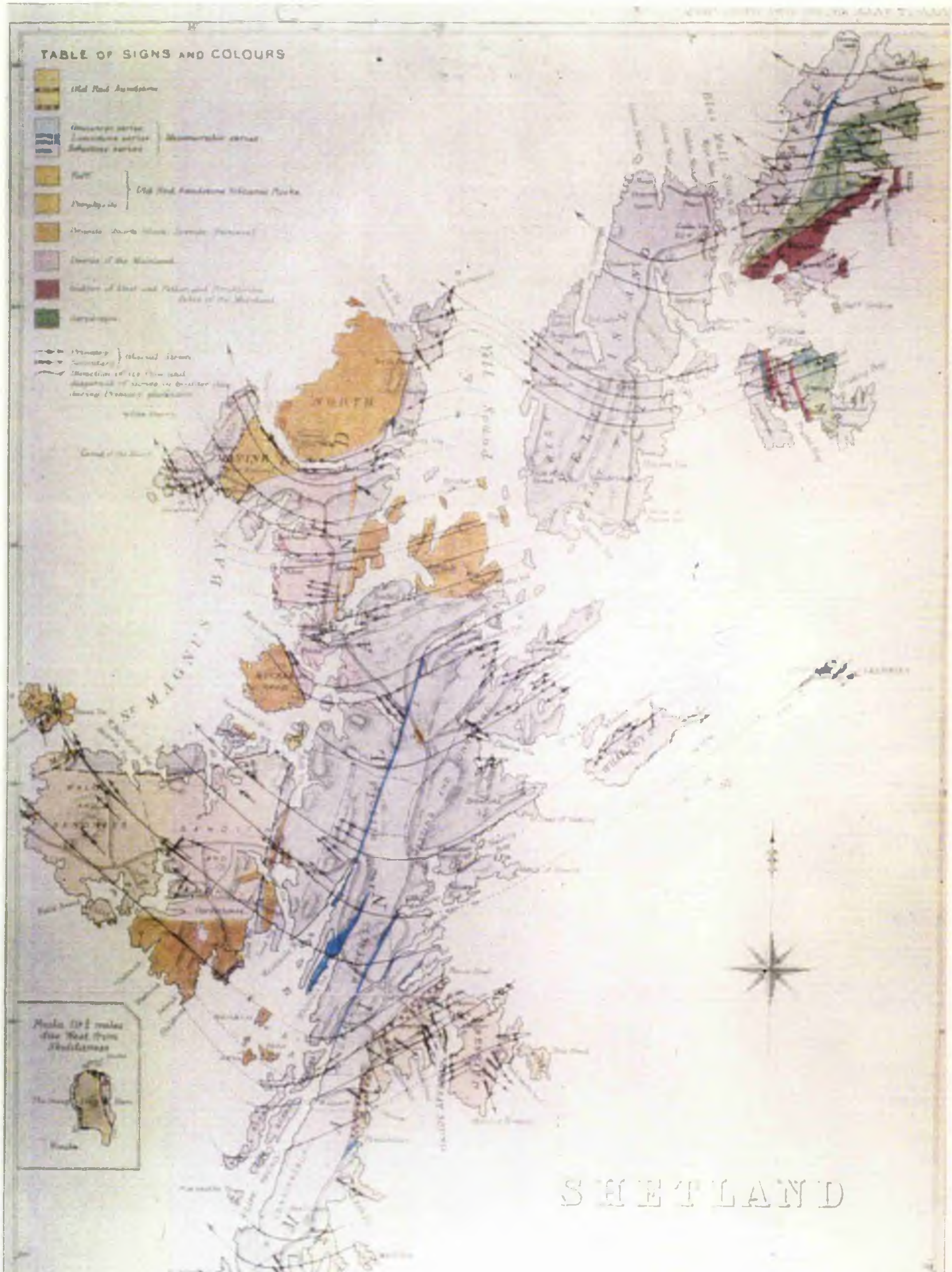
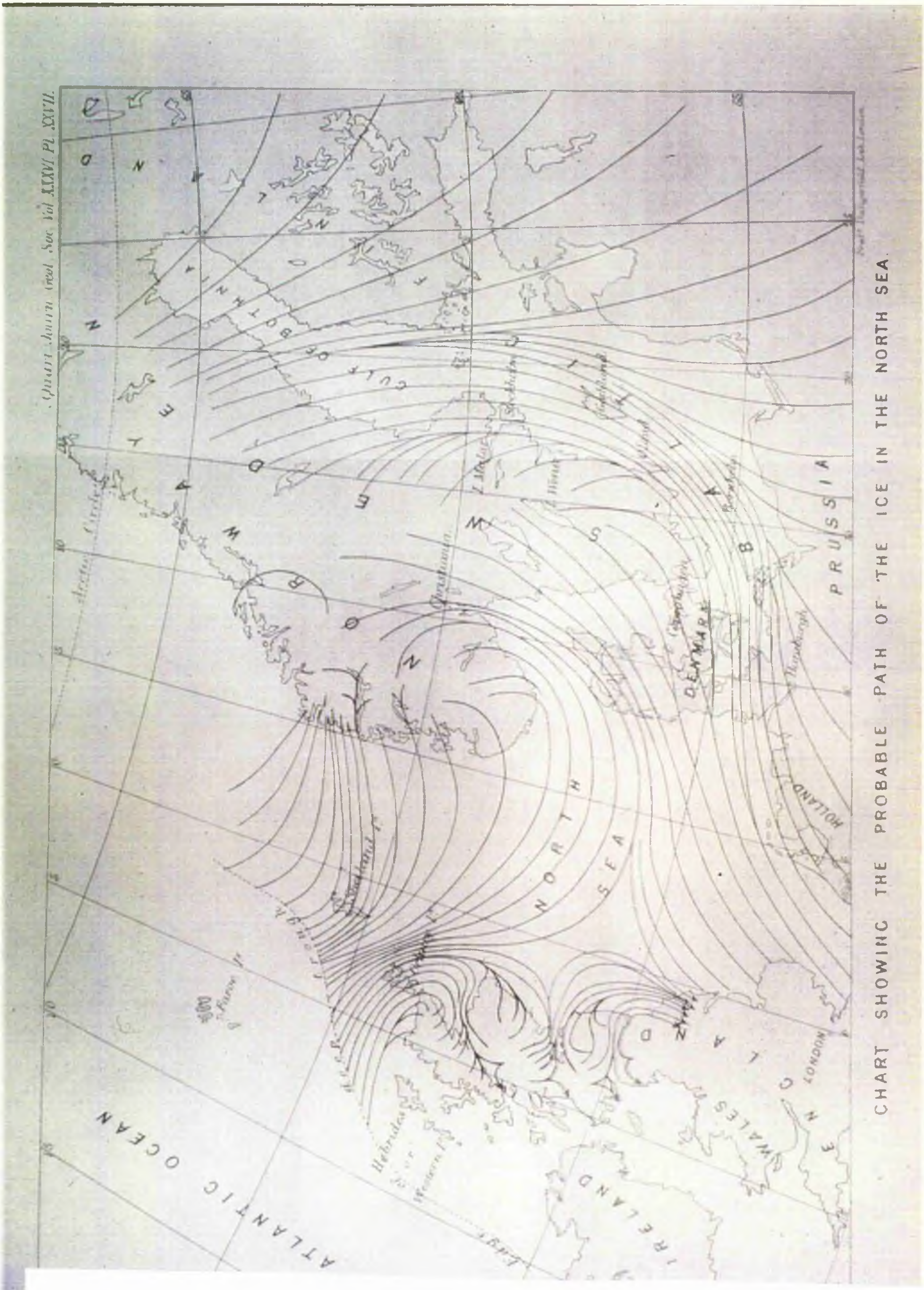


FIG 13. Erosion surfaces.

3.6 Erosion surfaces and possible major Devonian channels on Shetland. From Flinn. 1980



3.7 Peach and Horne's solid geology and reconstruction of the glacial history of Shetland. From Peach and Horne, 1879



3.8 Peach and Horne's reconstruction of the last glaciation of northwest Europe
From Peach and Horne, 1881

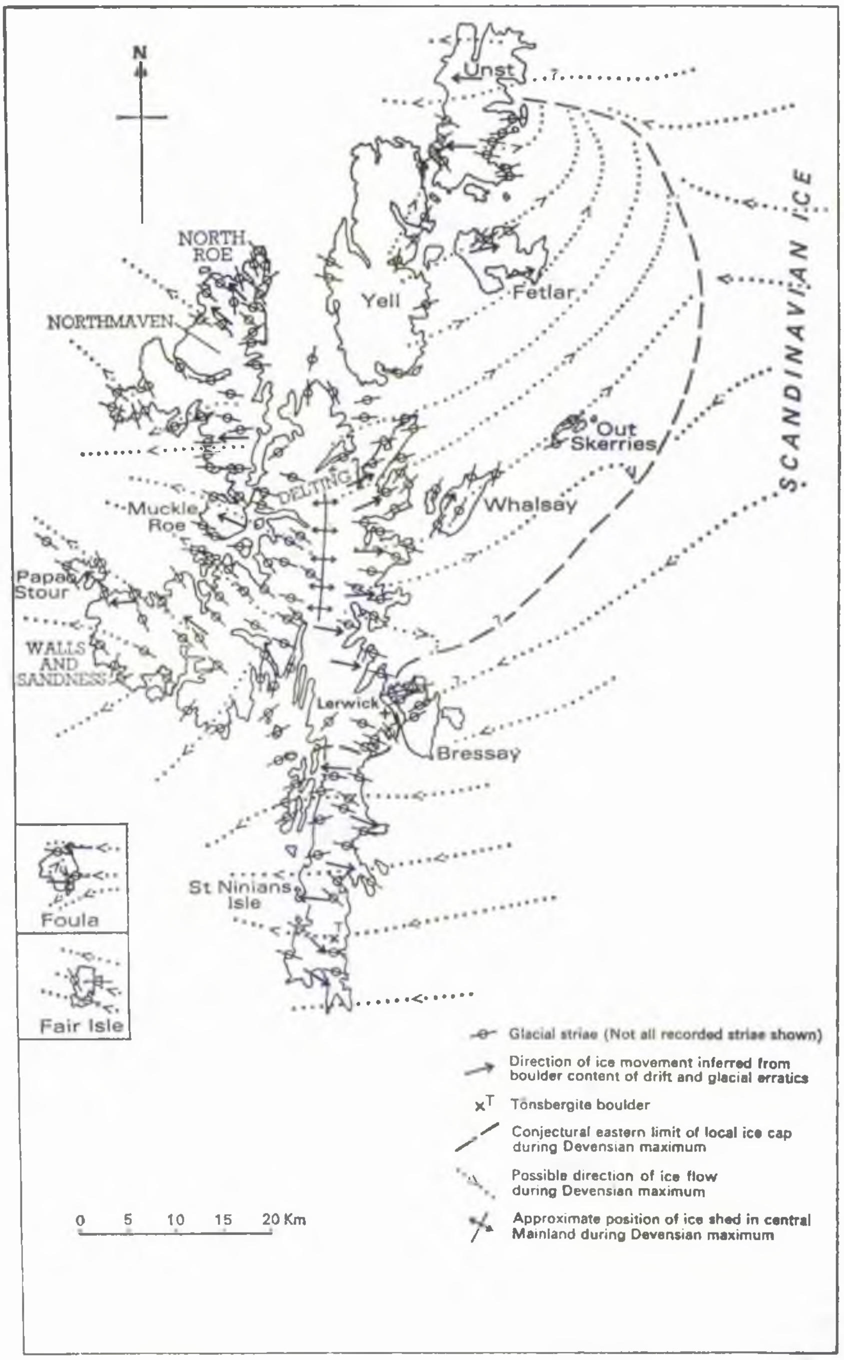


FIG. 28. *Directions of ice movement during the Devensian (Weichselian) in Shetland*

3.9 Mykura's reconstruction of the last glaciation of Shetland
From Mykura, 1976

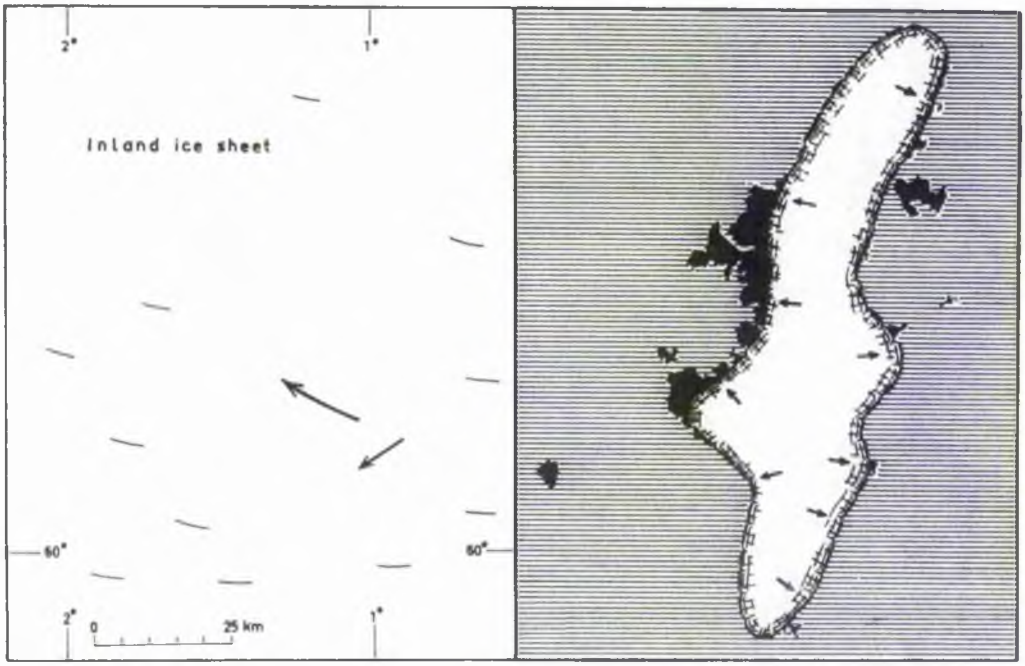


FIGURE 7. Glaciation of the Shetland Islands. During an early stage the Shetland Islands were most probably overridden by an ice sheet from the east (left map), whereas the later stage was characterized by radial flow from a local ice cap (right map)

3.10 Hoppe's reconstruction of the last glaciation of Shetland. From Hoppe, 1974

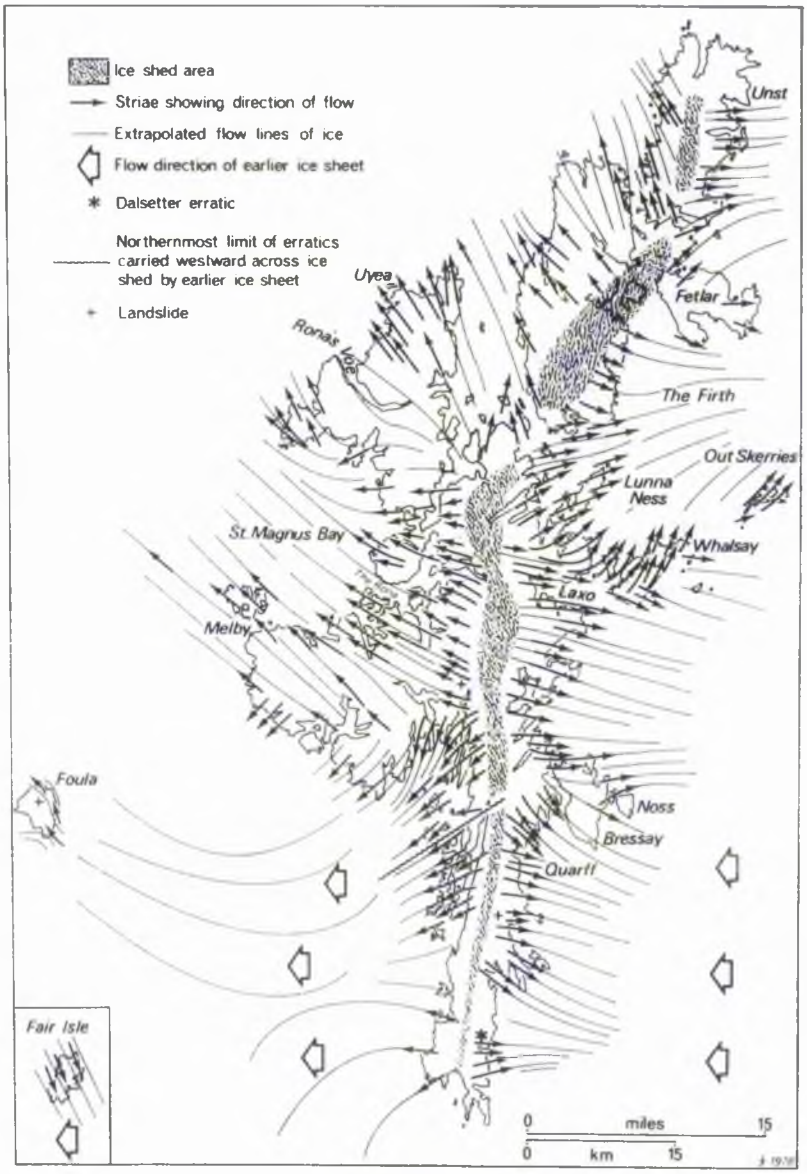


FIG 8. Flow pattern of the Shetland ice cap.

3.11 Flinn's reconstruction of the last glaciation of Shetland.
From Flinn, 1980

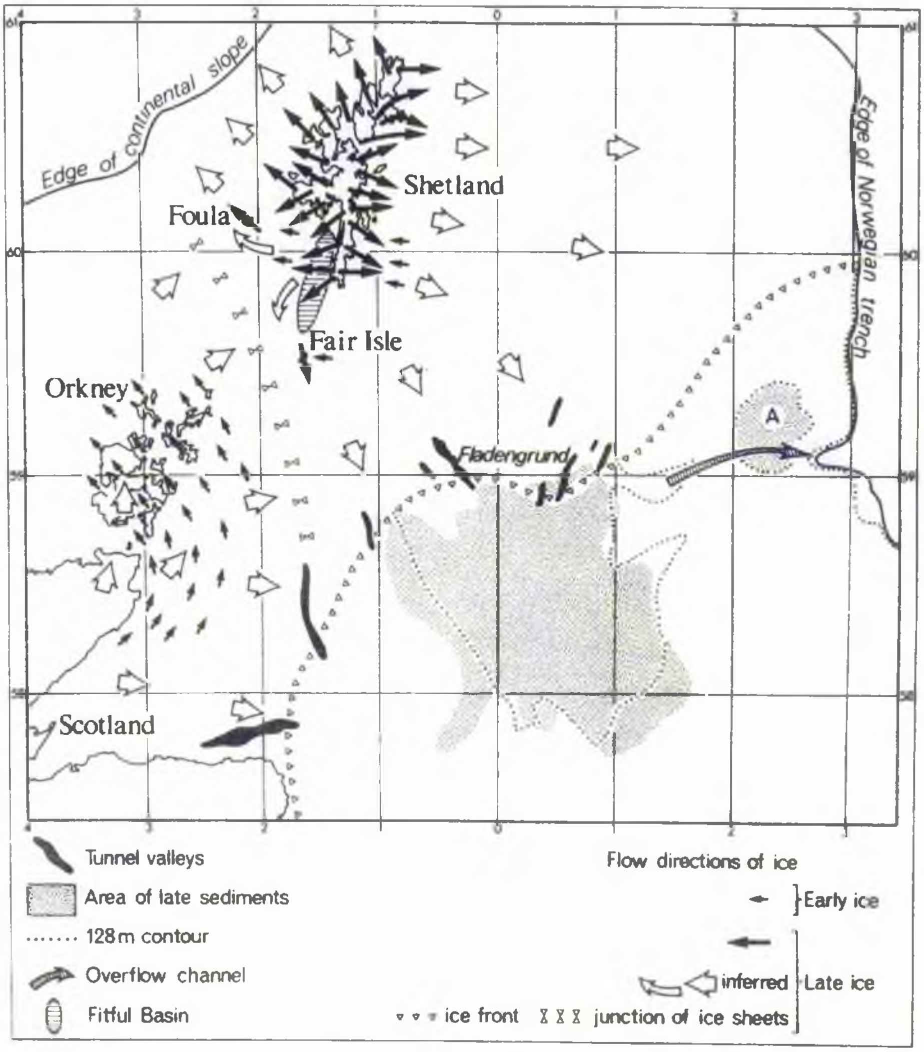


FIG. 5. A reconstruction of the last glaciation of Orkney, Shetland and the northern North Sea. Partly after Flinn (1967, 1973, 1978) and Jansen (1976). A—a locality referred to in the text (p. 120) and by Jansen (1976, p. 15).

3.12 Reconstruction of the last glaciation of Shetland, Orkney and the northern North Sea. From Flinn, 1978

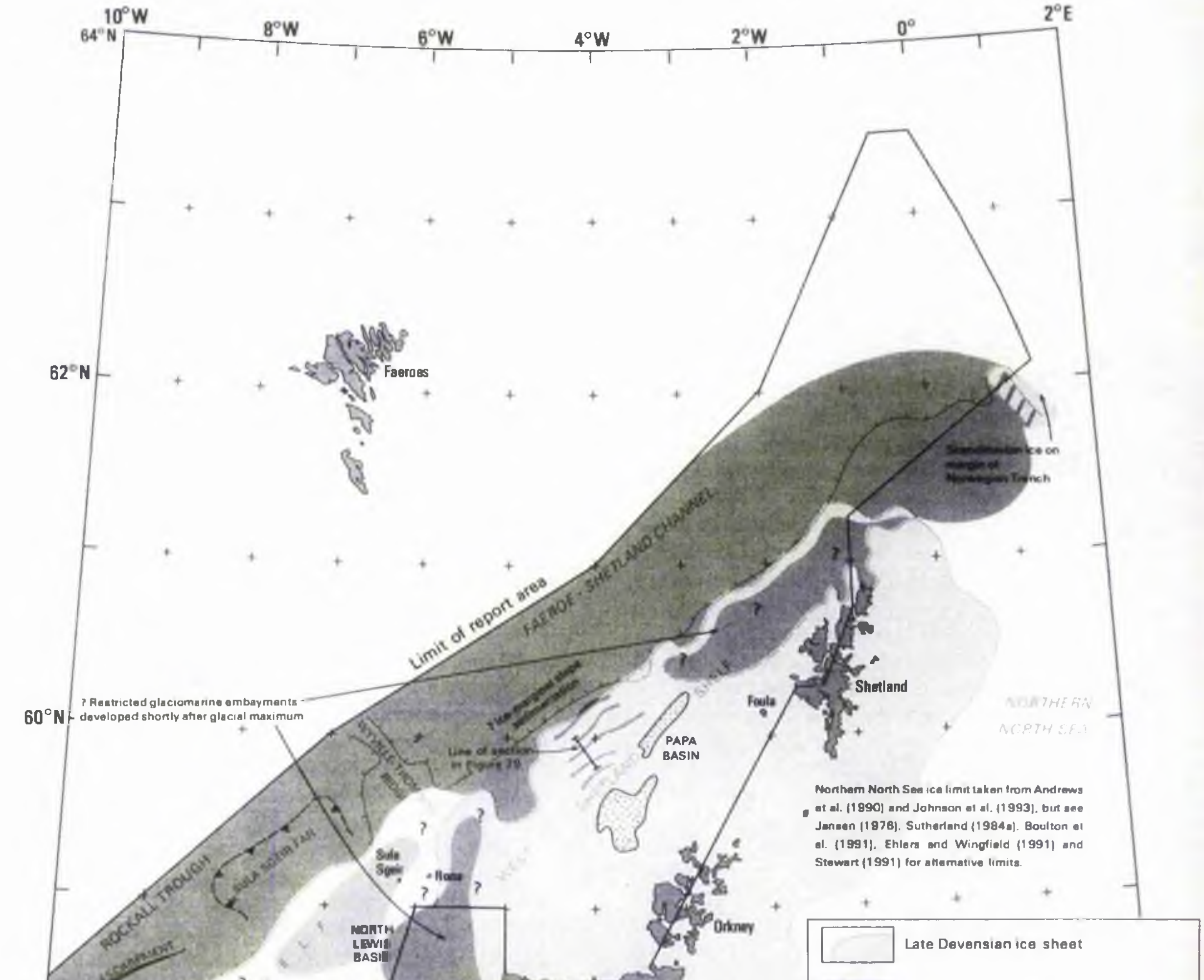


Figure 78 Schematic palaeogeographic reconstruction showing the inferred extent of the late Devensian ice sheet at, or shortly after, the glacial maximum.

3.13 Palaeogeographic reconstruction of the late Devensian ice sheet at the glacial maximum

From Stoker et al., 1993

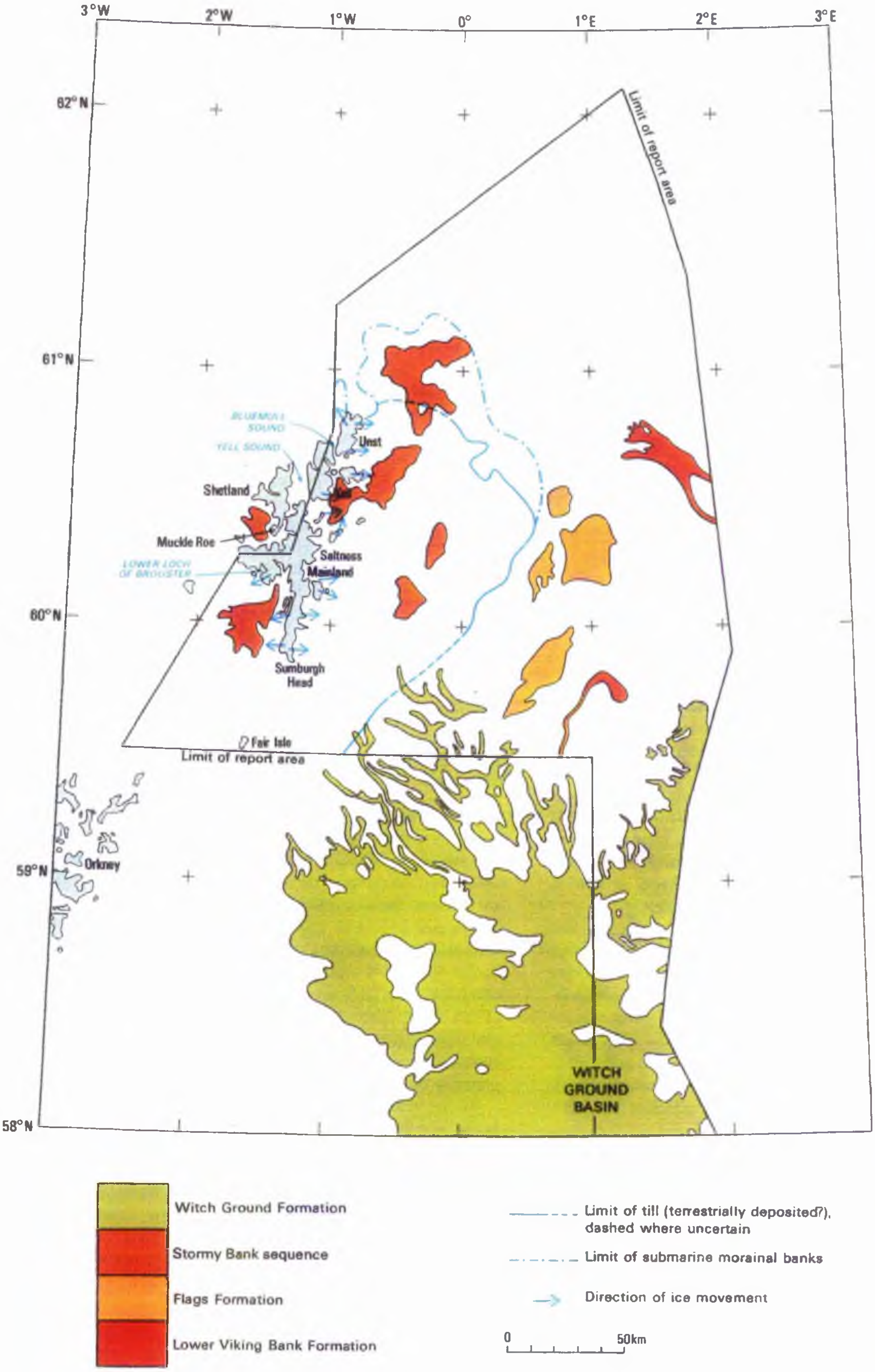


Figure 78 Map showing the distribution of acoustically well-layered, late-glacial deposits, with suggested limits of late Weichselian terrestrial and submarine tills.

3.14 Distribution of late-glacial deposits and suggested maximum limits of late Weichselian terrestrial and submarine tills on the East Shetland Platform and northern North Sea
From Johnson et al., 1993

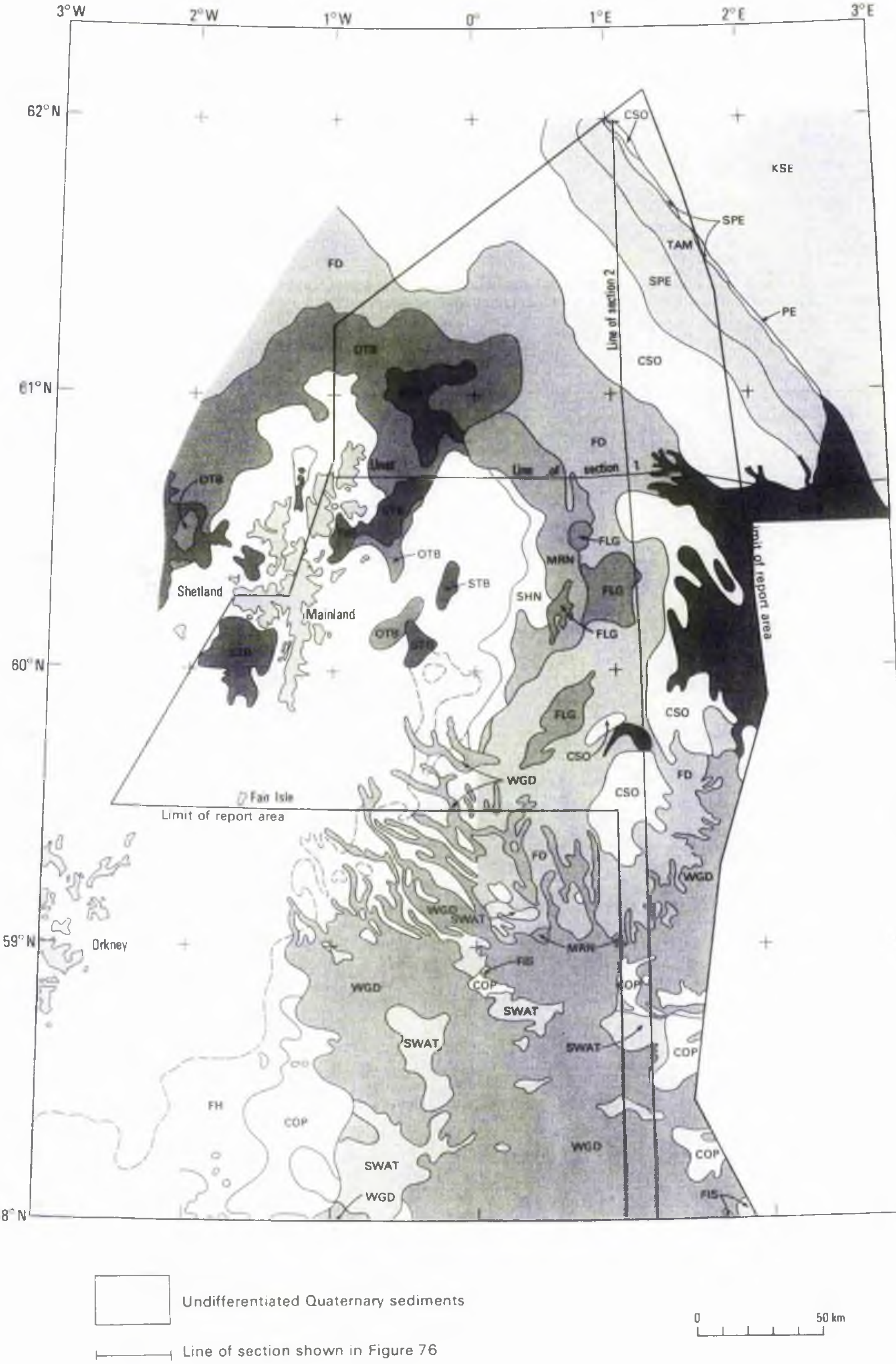


Figure 75 Outcrop map of Quaternary formations and sequences in and around the northern North Sea.

3.15 Distribution of Quaternary deposits around northern and eastern Shetland and the northern North Sea, see figure 2.10 for a cross section through these sediments. Relevant deposits include: OTB = Otter Bank Sequence; STB = Stormy Bank Sequence; FD= Ferder Formation; SHN = Shackleton Formation; MRN = Mariner Formation; CSO = Cape Shore Formation; SPE = Sperus Formation; TAM = Tampen Formation; FLG = Flags Formation; WGD = Witch Ground Formation;
From Johnson et al., 1993

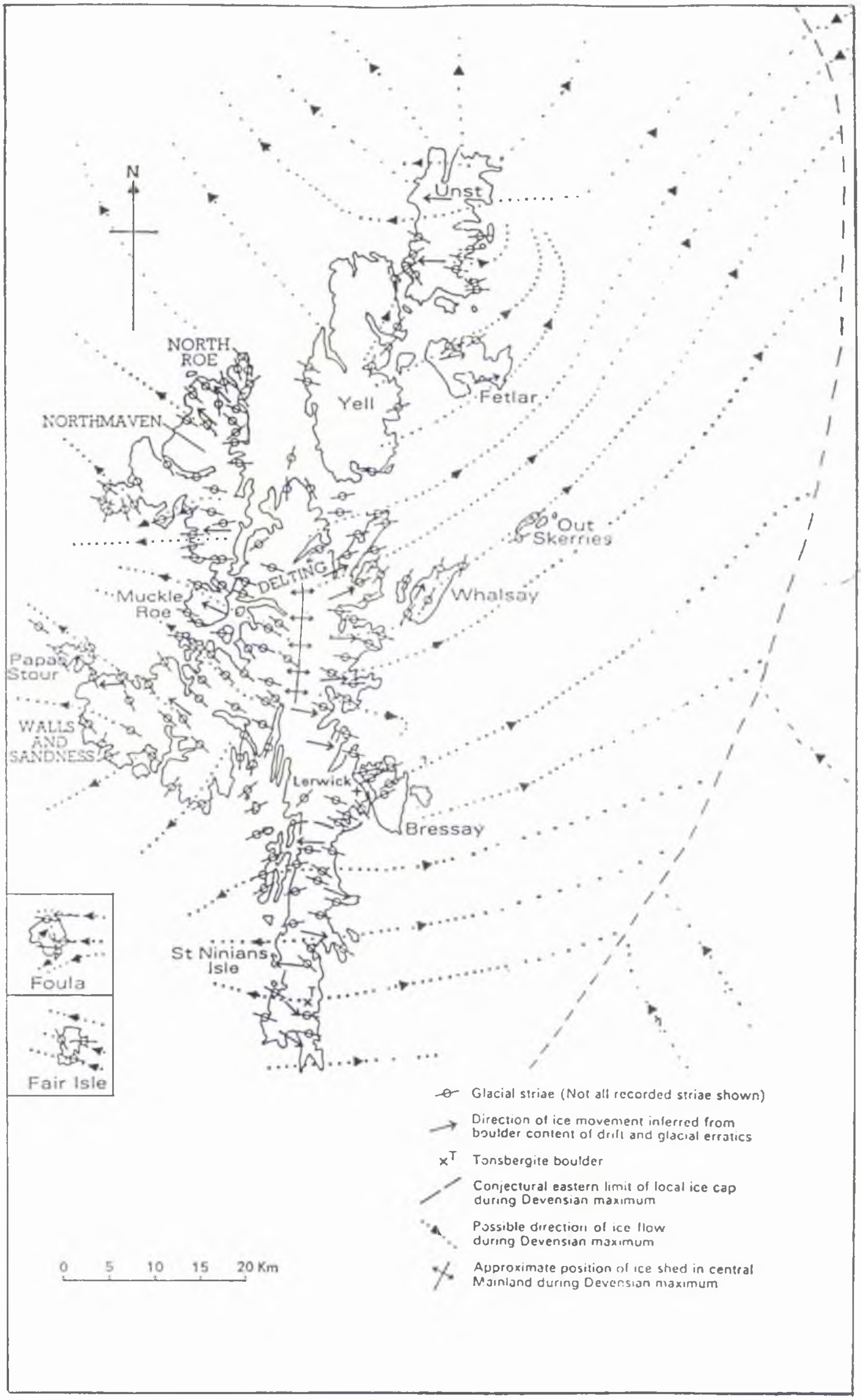


Fig.5.11 Probable transport paths of glacial material during the earlier phase of glaciation (Devensian) on the Shetland CS.

3.16 Probable transport paths of glacial material during earlier Devensian derived from analysis of heavy minerals in sea bed sediments.
From Begg, 1990

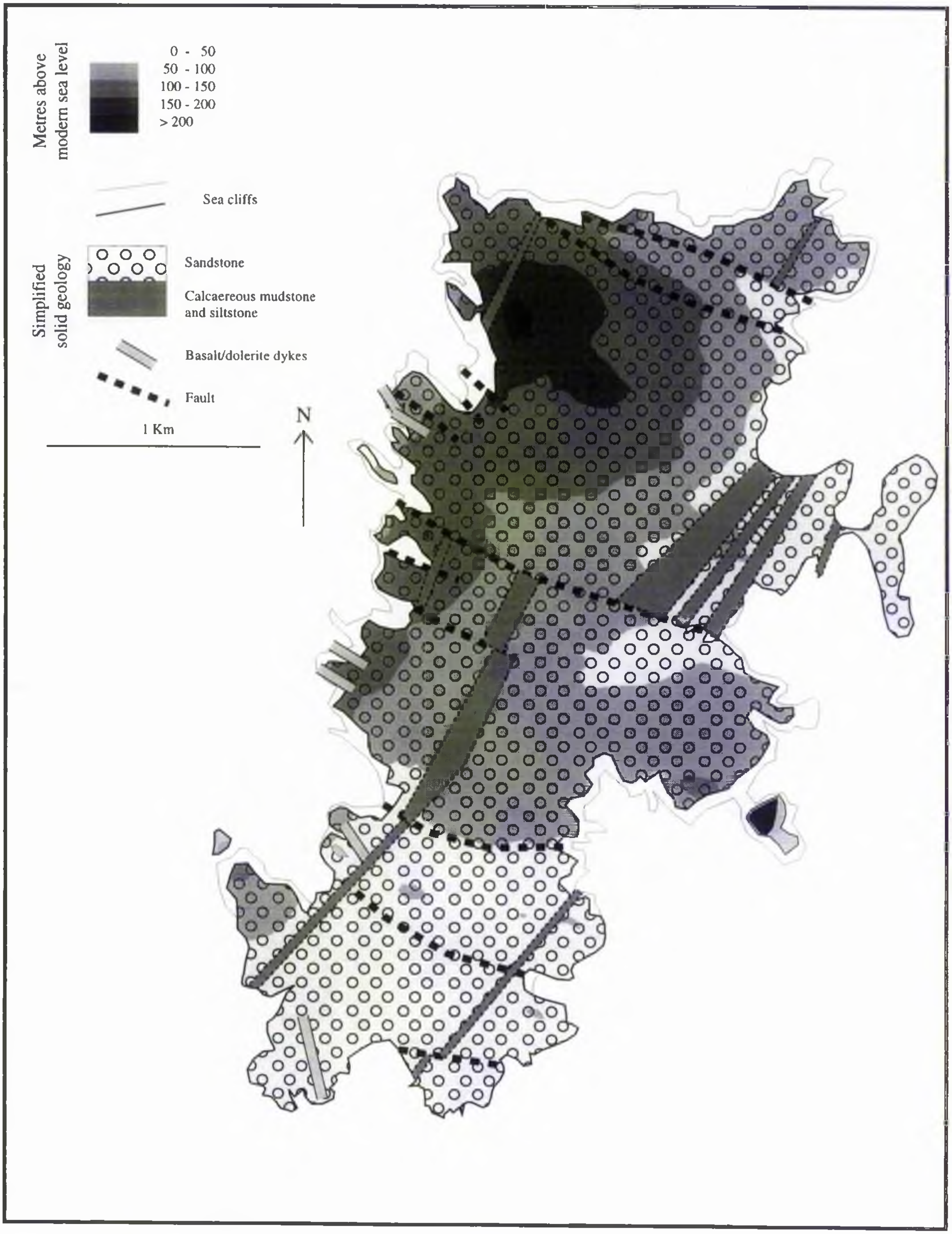


Figure 4.1. Solid geology and topography of Fair Isle, Shetland.

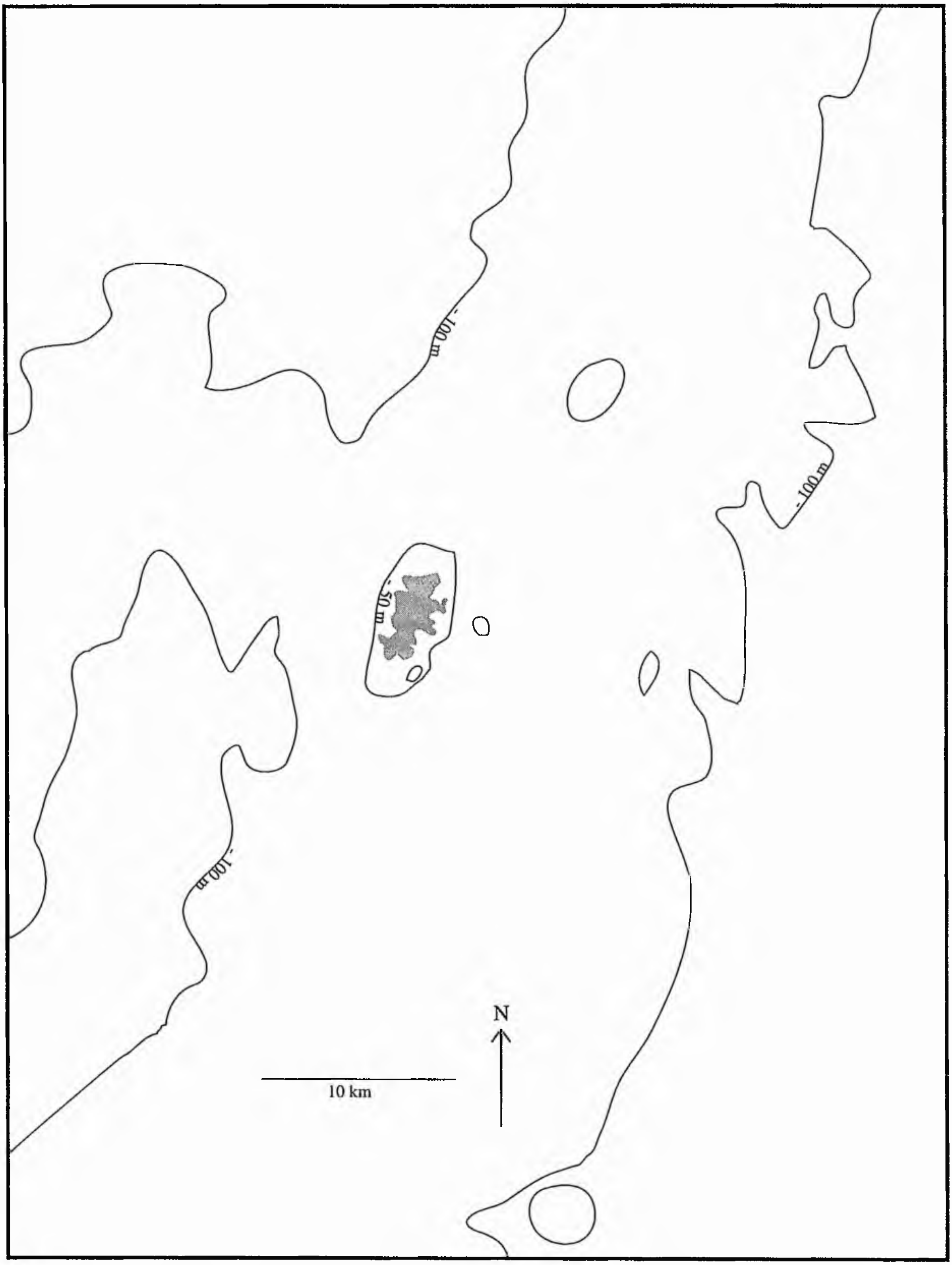


Fig ure 4.2. Bathymmetry around Fair Isle, Shetland (numbers on shallow side of bathymmetric contours).

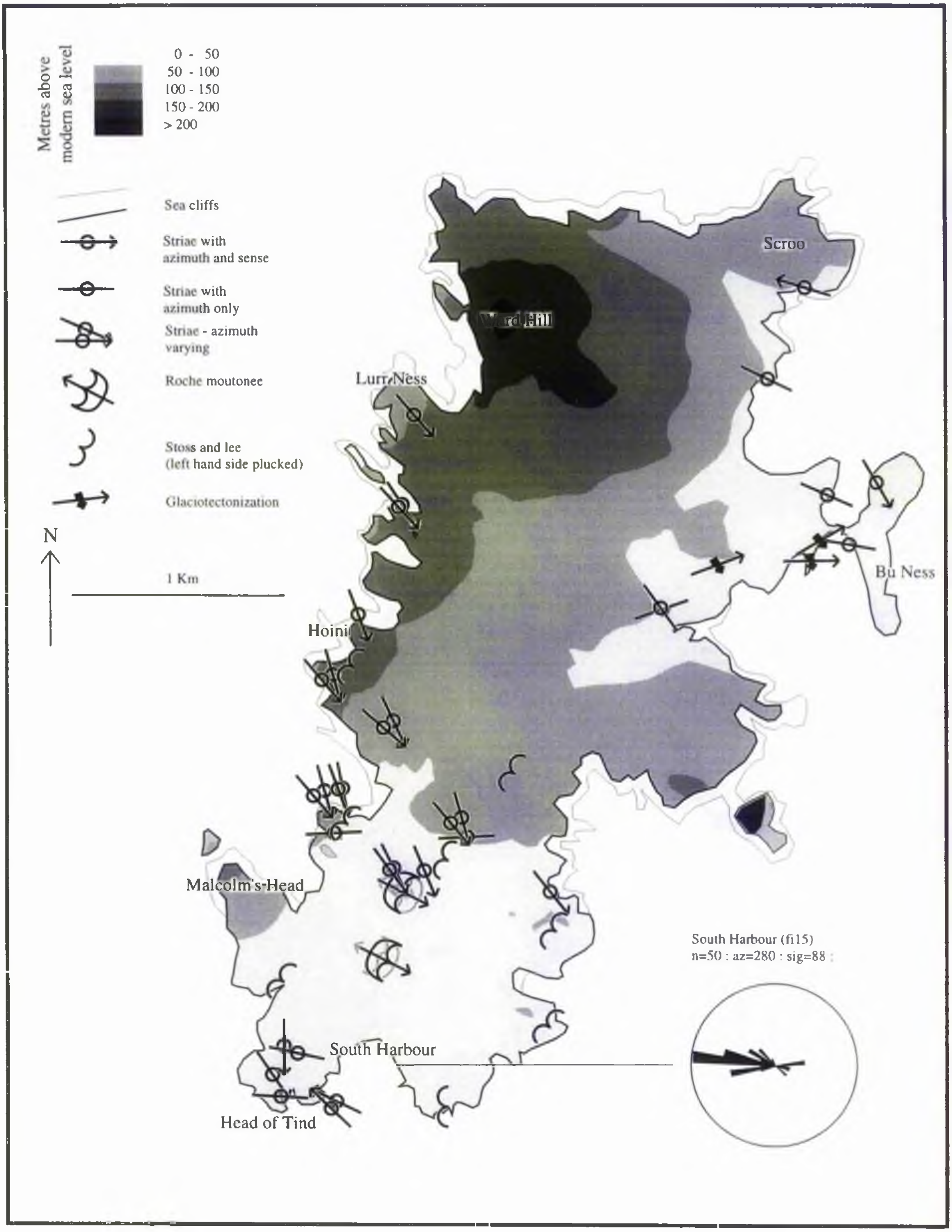


Figure 4.3. Ice direction indicators on Fair Isle, Shetland: striae after Flinn (1978) and May and Mykura (1978); roche moutonee (grey (May and Mykura (1978), black (this study)); stoss and lee observations (this study); and direction of glaciotectonization (this study). Fabric data (this study) include sample size (n clasts), maximum eigen vectors (az degrees) and values (sig %).

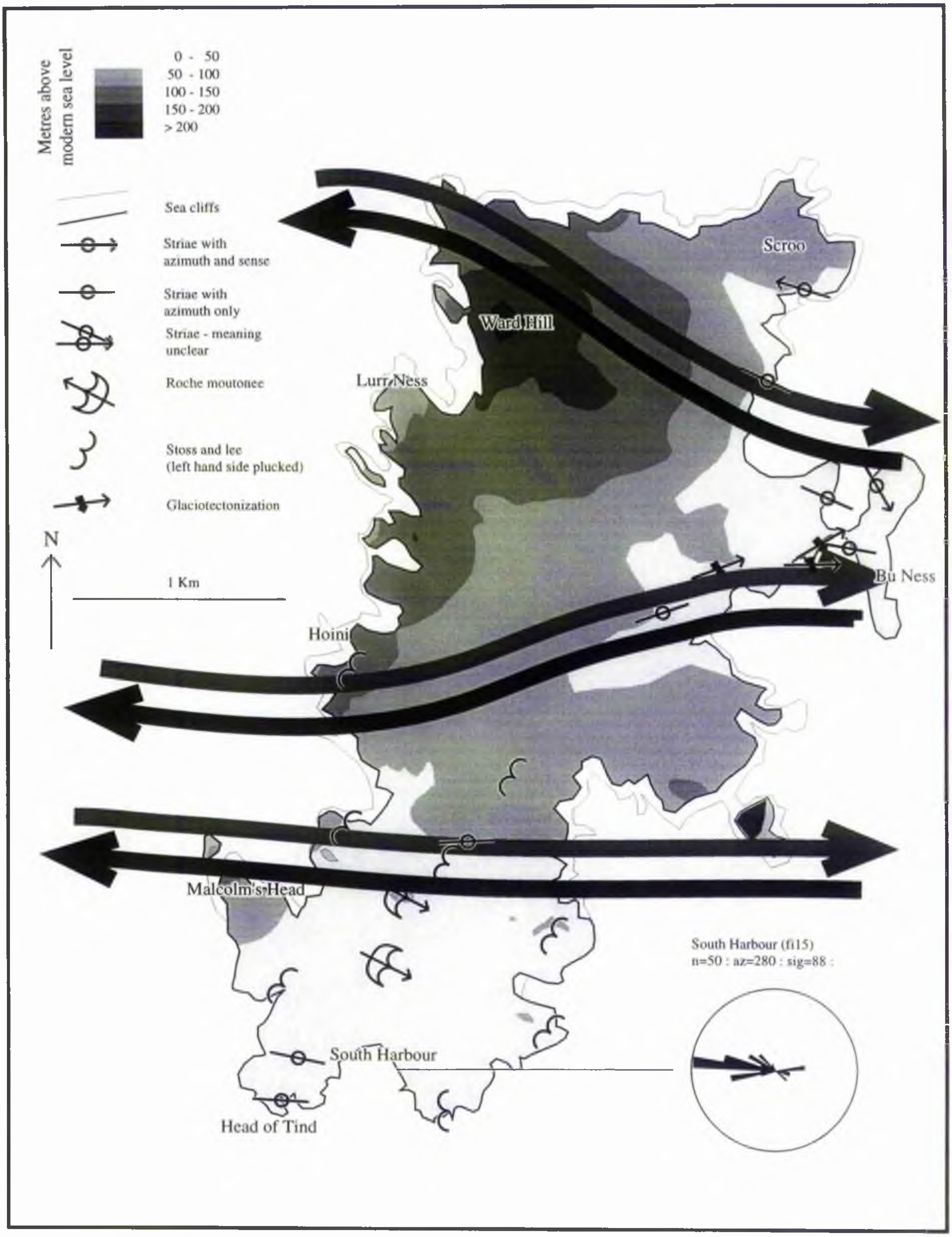


Figure 4.4. Ice direction indicators on Shetland, except NW-SE striae azimuth. The striae pattern has been interpreted as being indicative of ice from the east diverging around the high ground (thick black arrows). The interpretation of this study is of ice from the west converging on the lee side of the high ground (thick grey arrows). (See figure 4.3 for details of observation sources).

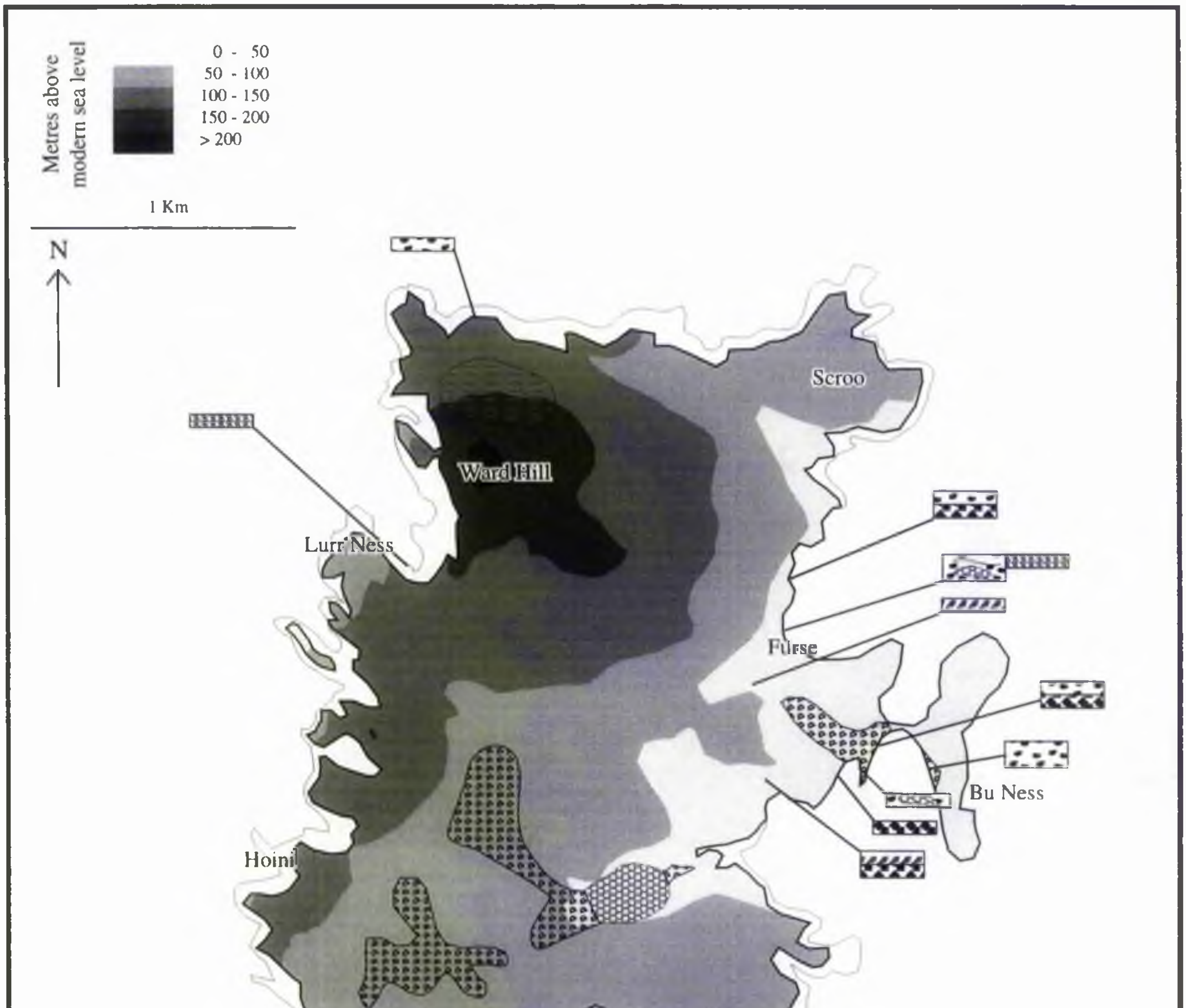


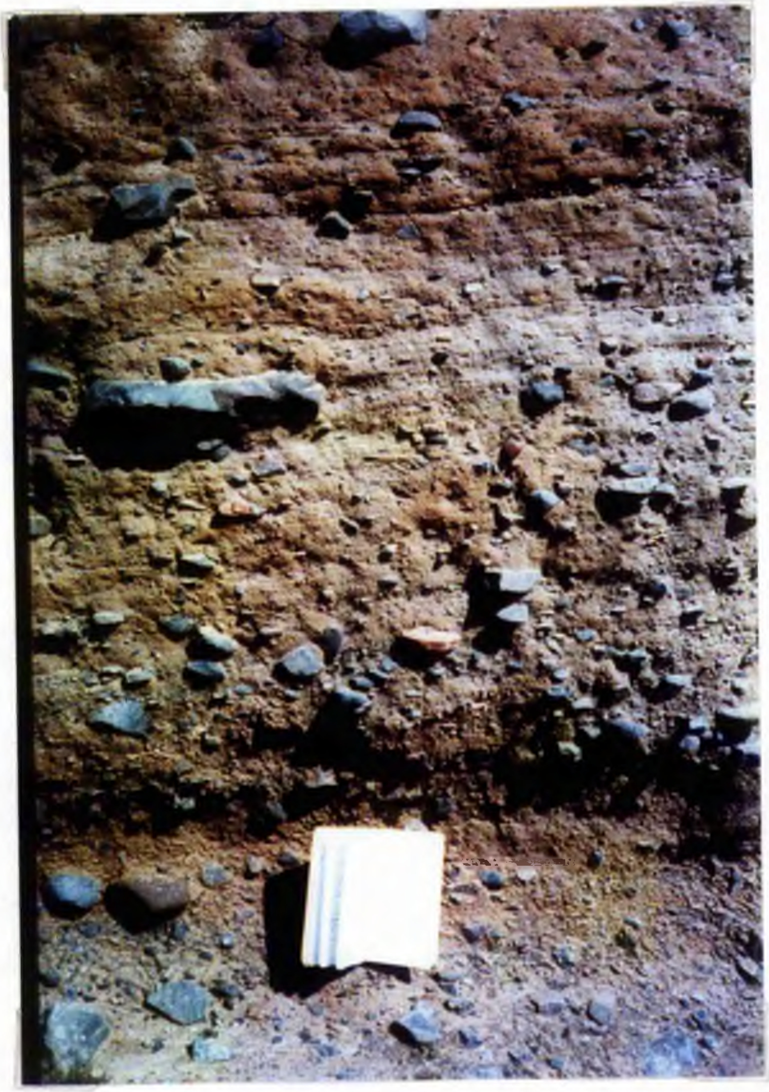
Figure 4.5. Drift distribution and glacial stratigraphy, Fair Isle, Shetland: drift distribution after May and Mykura (1978) and this study; glacial stratigraphy (this study).

4.6 Glacitectonization and joint-block removal, northeast Fair Isle, Shetland. (HU221730)

4.7 Glaciteconization near the Observatory, east Fair Isle, Shetland. (HU224723)

4.8 Roche moutonée, south Fair Isle, Shetland (centre horizon). Direction of ice movement from the left or west. (HU204706)

4.9 Lodgement till, South Harbour, Fair Isle, Shetland. (HU203699)



4.10 Lodgement till. South Harbour. Fair Isle. Shetland. Direction of ice movement probably left to right. or east to west. (HU203699)

4.11 Complex facies including gravels and sands, west Fair Isle, Shetland. (HU201708)

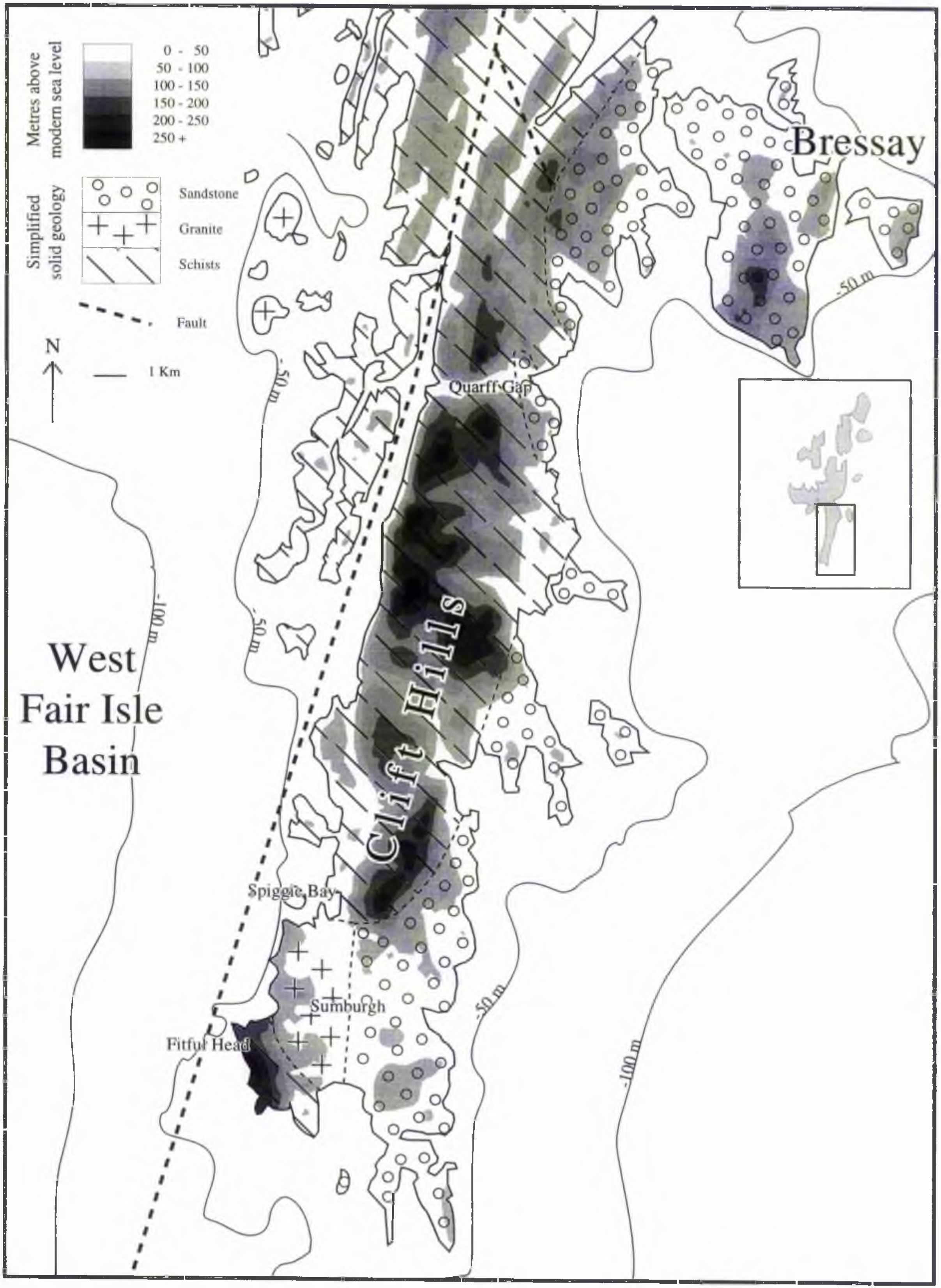


Figure 5.1. Solid geology, topography and bathymmetry, south Mainland, Shetland.

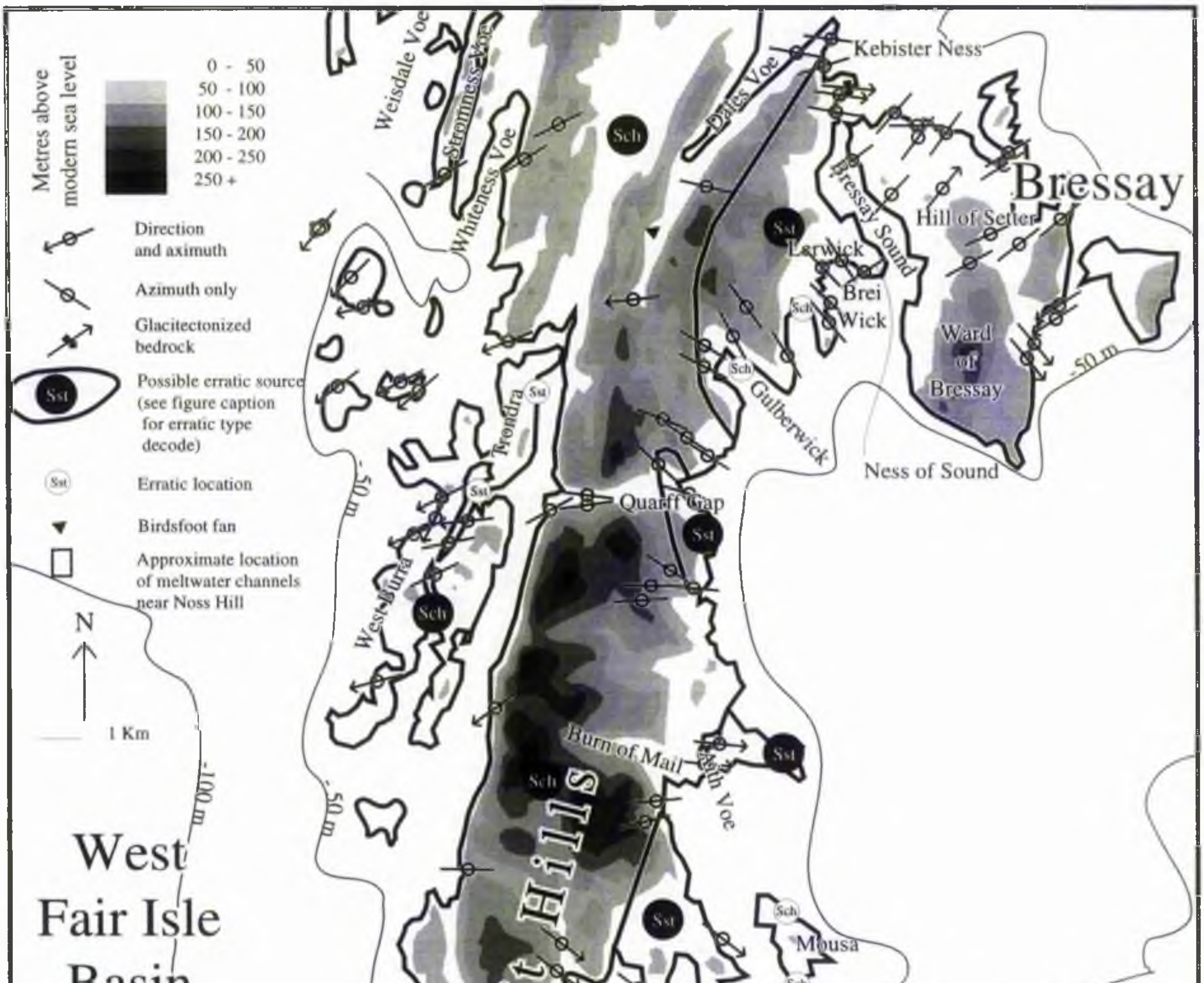


Figure 5.2. Ice direction indicators, south Mainland, Shetland: striae after May and Mykura (1978), Flinn (1977), Hoppe (1974) and this study; glacitectonized bedrock (this study); fabric data (this study), including sample size (n clasts), maximum eigen vectors (az degrees) and values (sig %) and azimuth of local slope angle shown by black line through fabric; erratic data from this study (but general trends established by previous authors): G - granite, Sch - schist, Sst - sandstones; birdsfoot fan and meltwater channels near Noss Hill (this study).

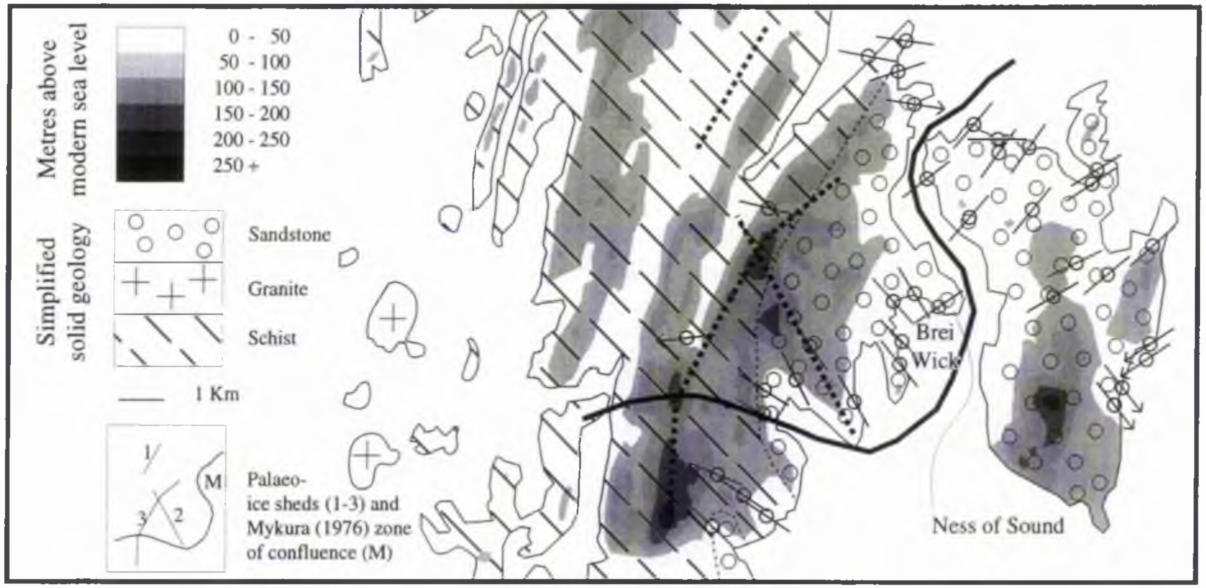


Figure 5.3. Possible ice shed configurations in the northeast of south Mainland, Shetland: the Mykura (1978) confluence between Scandinavian and Shetland ice sheets (M); and other possible ice sheds (1 - oldest/most recent - see text for explanation, 2 - older than 3).

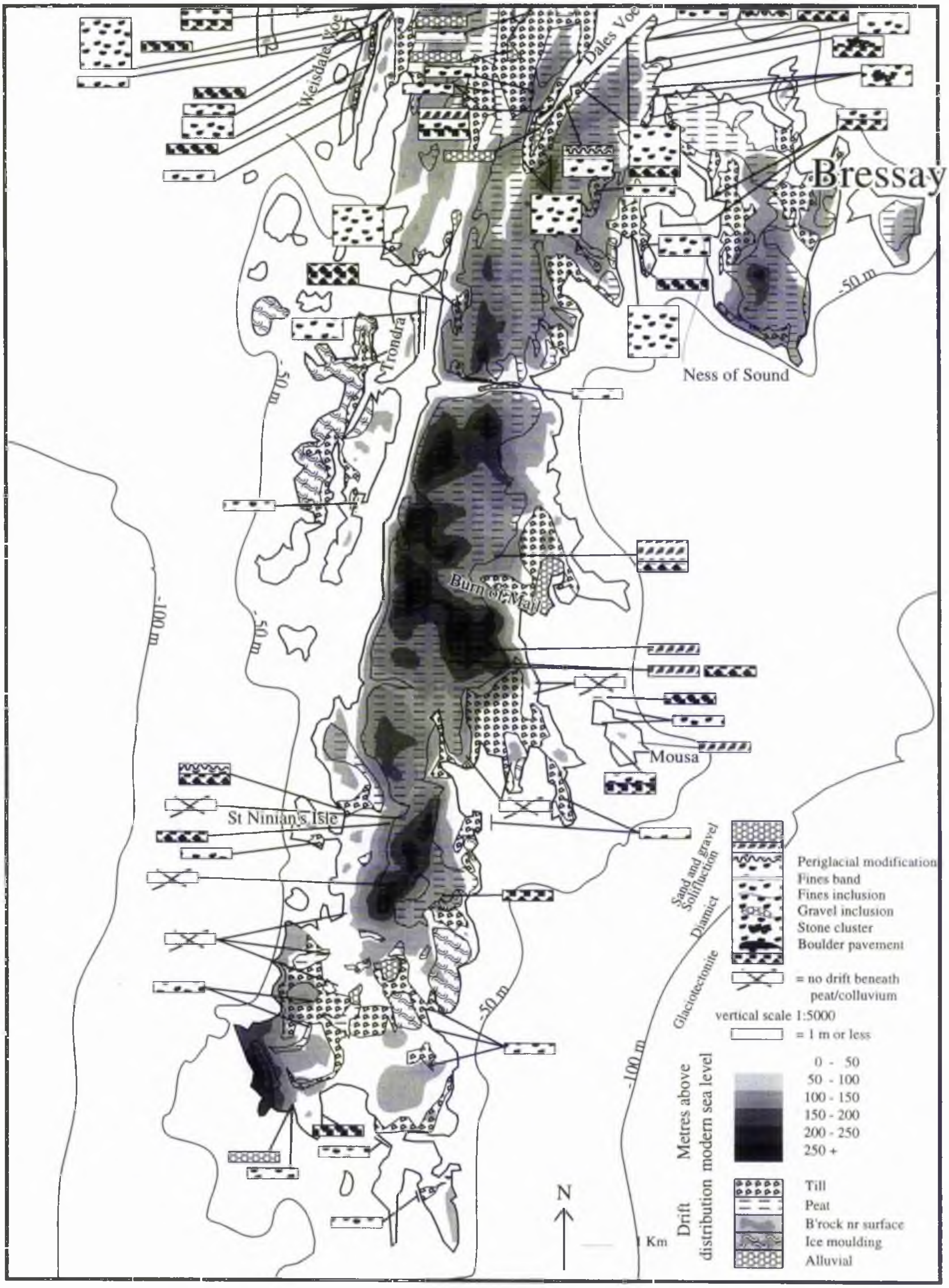


Figure 5.4. Drift distribution and glacial stratigraphy, south Mainland, Shetland: drift distribution after May and Mykura (1978) and this study; glacial stratigraphy (this study).

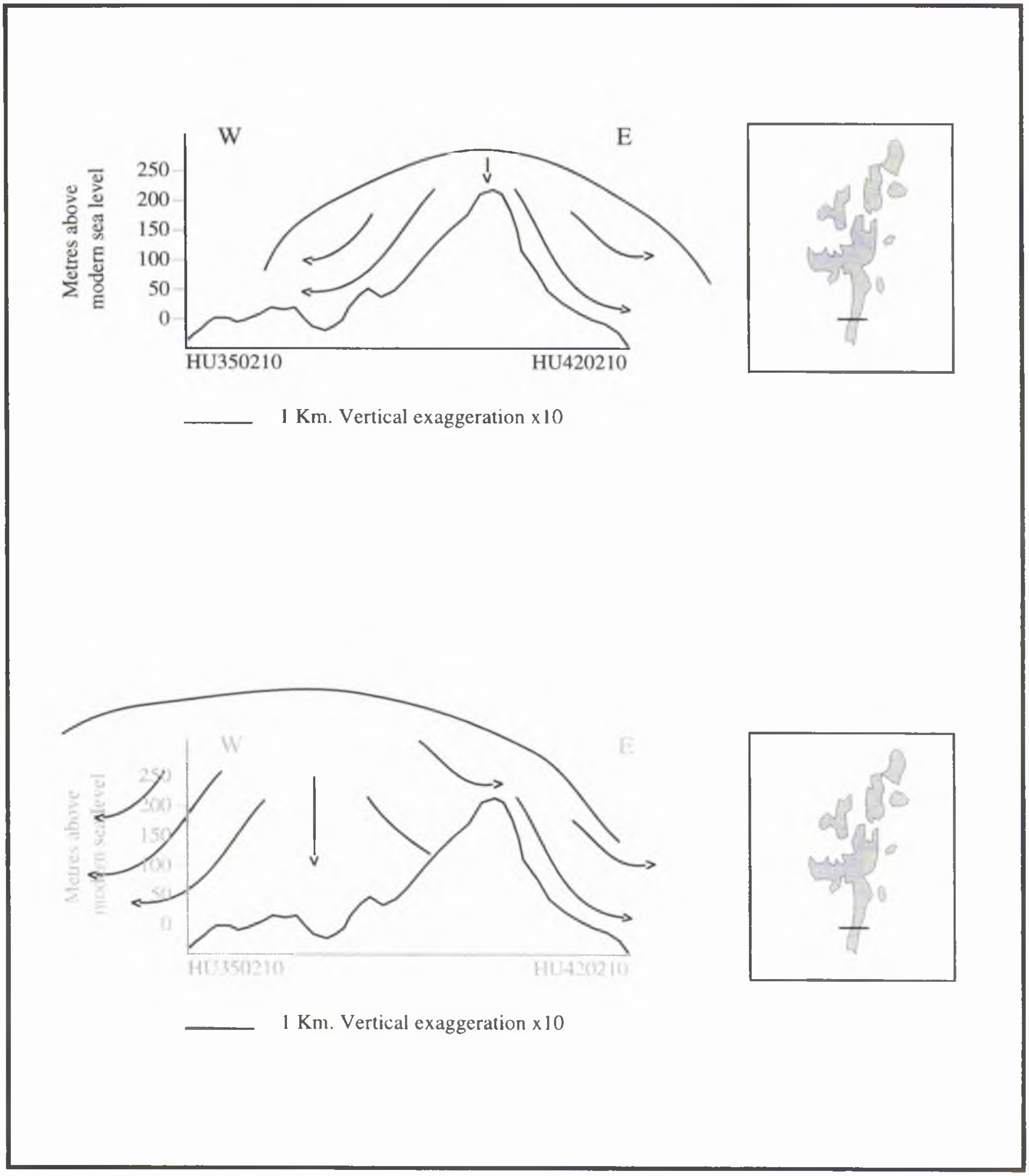


Figure 5.5. Schematic representation indicating a possible circumstance explaining the preservation of early-deposited erratics on the west coast of south Mainland, Shetland: in the top scenario, it is difficult to explain the preservation of these erratics under conditions of sever erosion on the west coast; in the lower, the erratics are preserved beneath a zone of limited or no erosion if the ice shed is displaced to the west of the high ground.

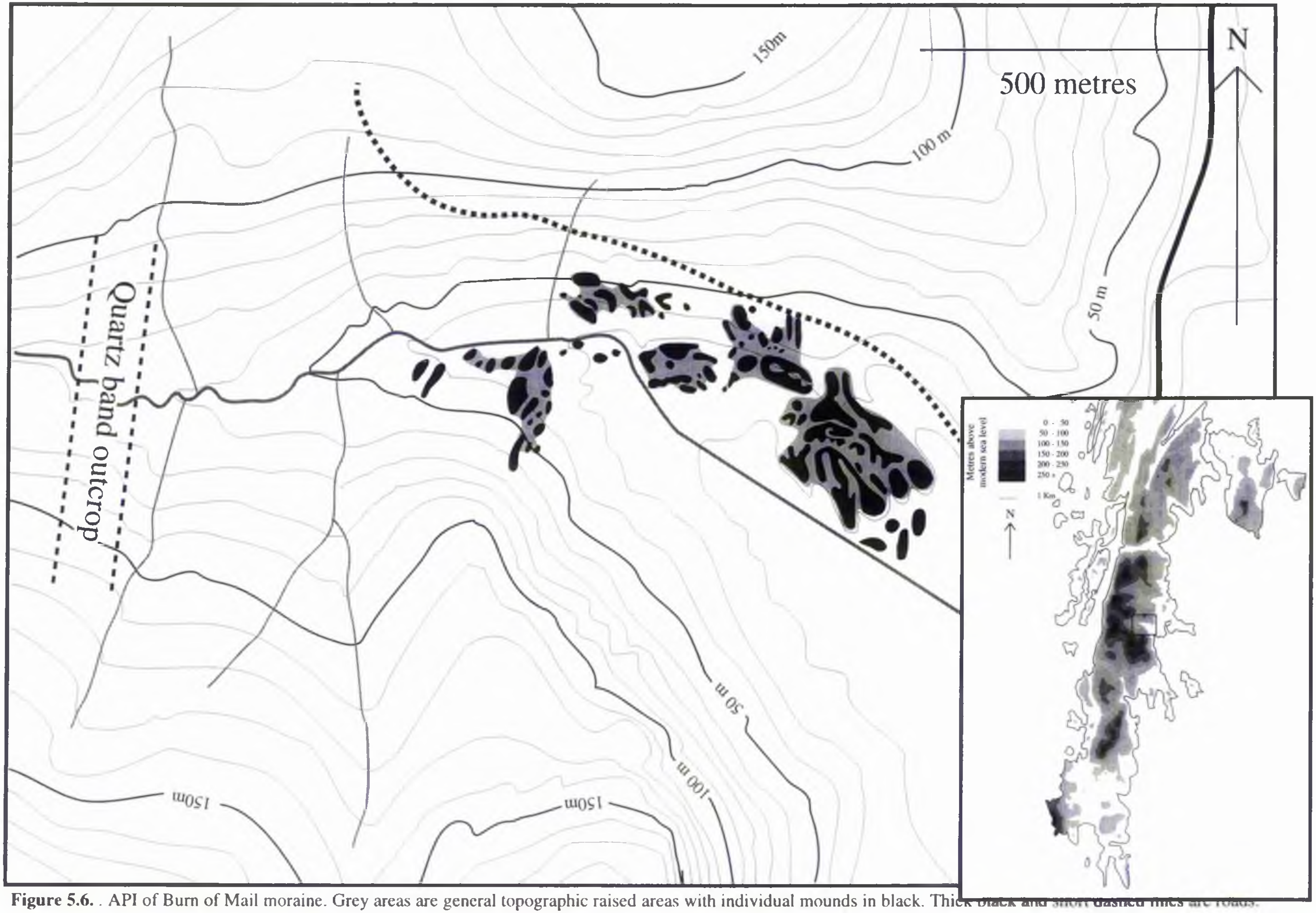


Figure 5.6. . API of Burn of Mail moraine. Grey areas are general topographic raised areas with individual mounds in black. Thick black and short dashed lines are roads.

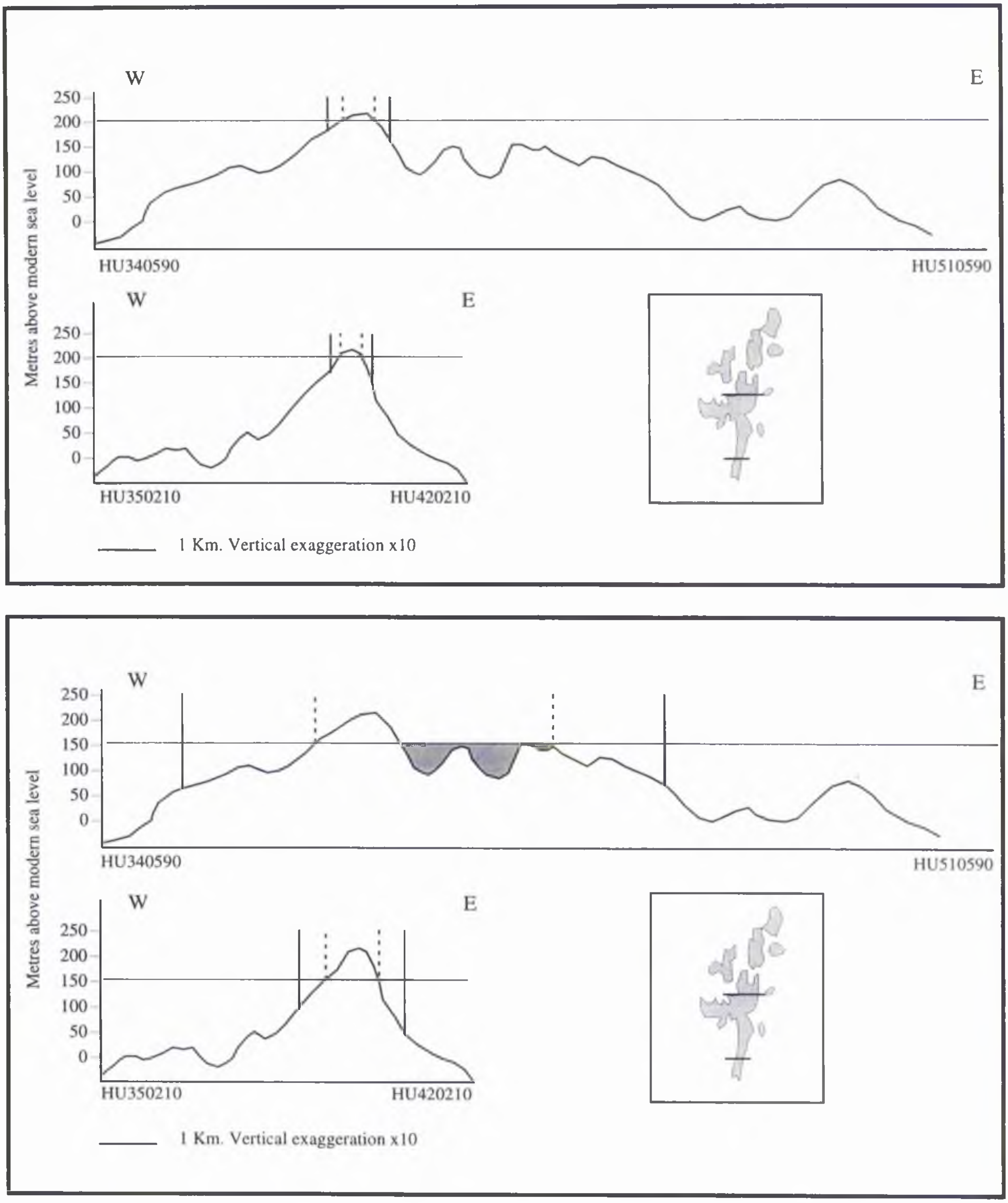


Figure 5.7. Possible circumstance explaining why Scandinavian ice could cross south Mainland but be deflected by local ice over central Mainland. The diagram compares central and south Mainland at two different regional equilibrium line altitudes (ELAs) (200 and150 m above modern sea level). Lateral extent of accumuation and ablation areas shown by dashed and solid lines respectively (these are schematic repsentations only). For the higher ELA there is little difference in ice extent as topography above ELA is similar. But for the lower ELA there is a dramatic difference. Note that the size of the ice cap has a non-linear relationship with surface area above the ELA. This is due to the infilling of valleys (grey shading) and the consequent topographic effect of the ice itself. The result is that as the ELA falls in englaciation, central Mainland develops a large ice cap relatively quickly.

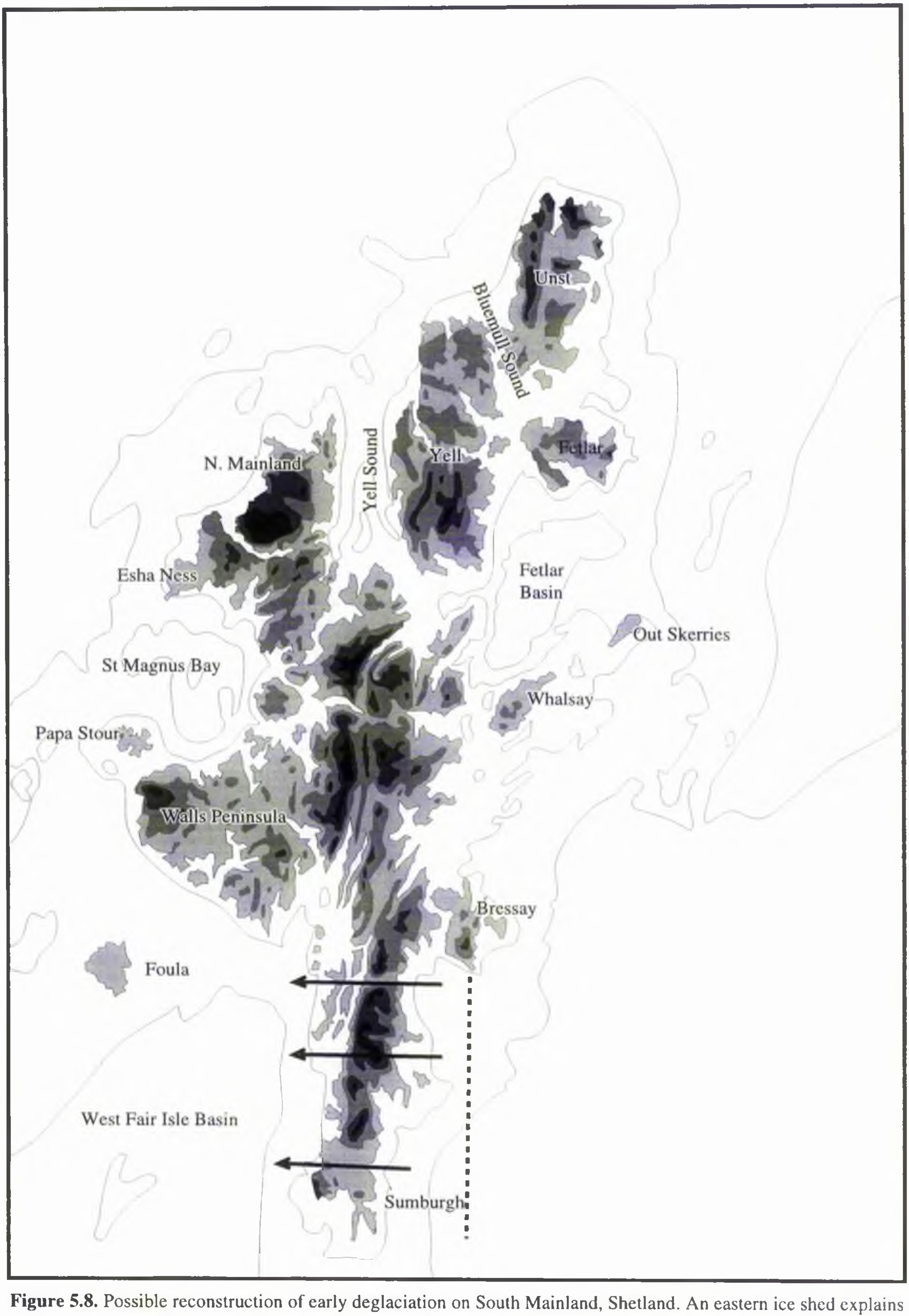


Figure 5.8. Possible reconstruction of early deglaciation on South Mainland, Shetland. An eastern ice shed explains the movement of erratics from the east to the west coasts of the area. It is not known whether this ice shed implies Scandinavian glaciation but this study argues that it need not. Ice movement shown by solid lines with arrows. Ice shed shown by dashed line. The ice shed lies to the east but the exact position is not known.

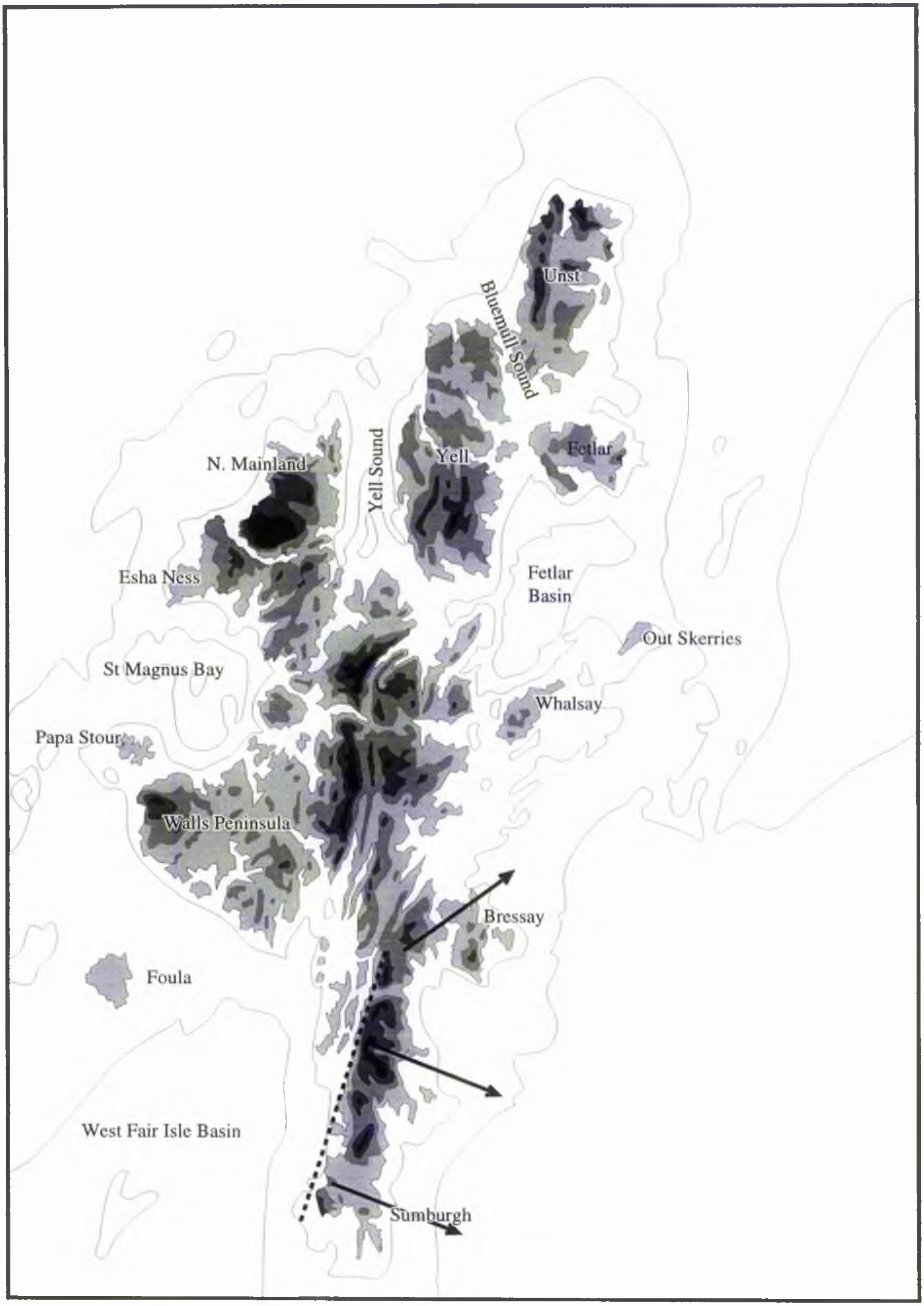


Figure 5.9. Possible reconstruction of early deglaciation of south Mainland, Shetland, following figure 5.8. The ice shed (dashed line) is placed in a relatively western location, explaining the preservation of early-deposited erratics on the west coast and the pattern of movement across the Sumburgh low ground. At this stage, ice is streaming to the southeast, but movement to the northeast, across Bressay, probably occurred earlier than this. Ice movement shown by solid lines with arrows.

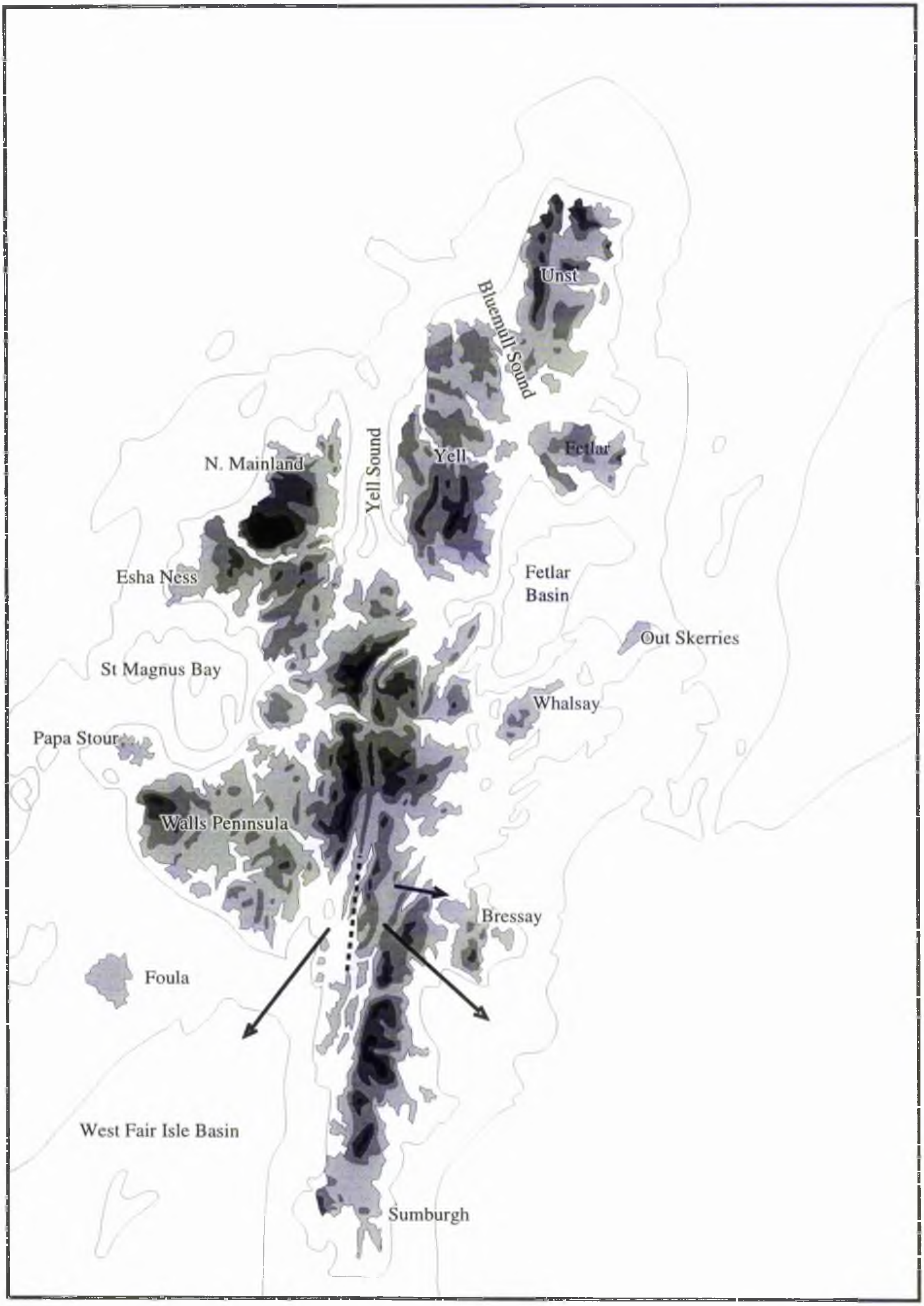
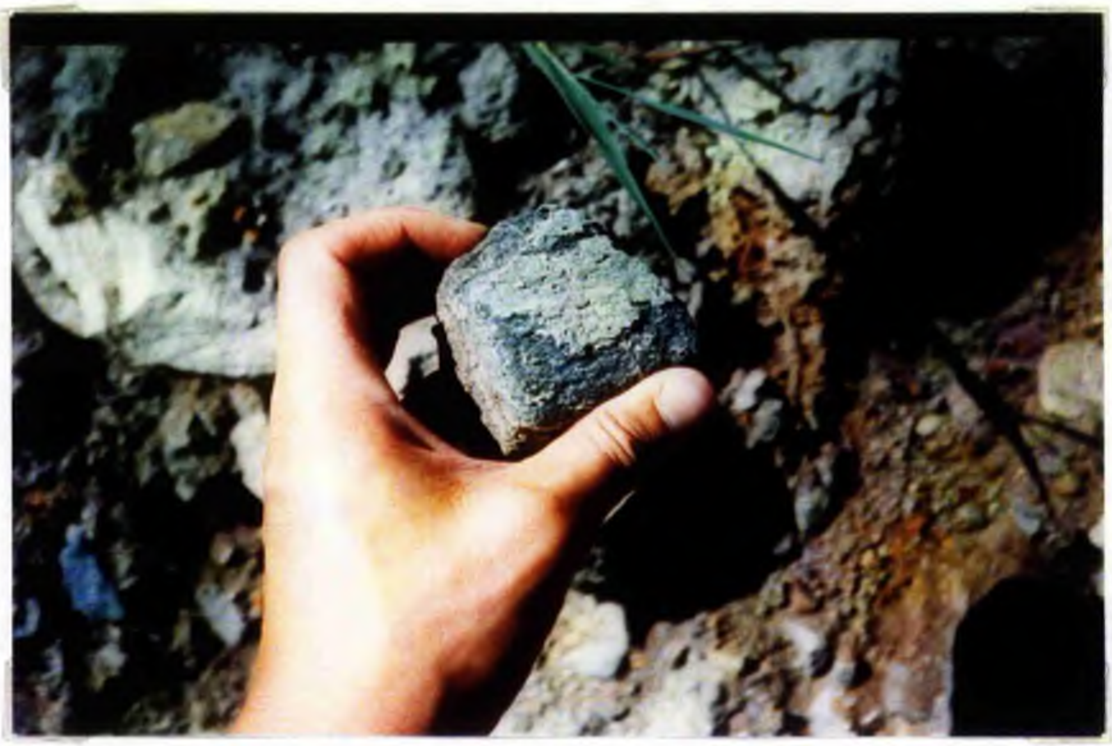


Figure 5.10. Reconstruction of the final deglaciation of south Mainland, Shetland. The main ice centre (dashed line) has retreated to the higher ground of central Mainland and ice is streaming both southwest and southeast from here. It does not appear to have reached Bressay. Together with the birdsfoot fan in Dales Voe, this perhaps suggests an overall pattern of retreat towards the west, so some element of the western ice shed identified in figure 5.9 may still be extant. Ice movement shown by solid lines with arrows.

5.11 Glacitectonized sandstone with metamorphic erratics, east coast of south Mainland, Shetland. (HU404188)

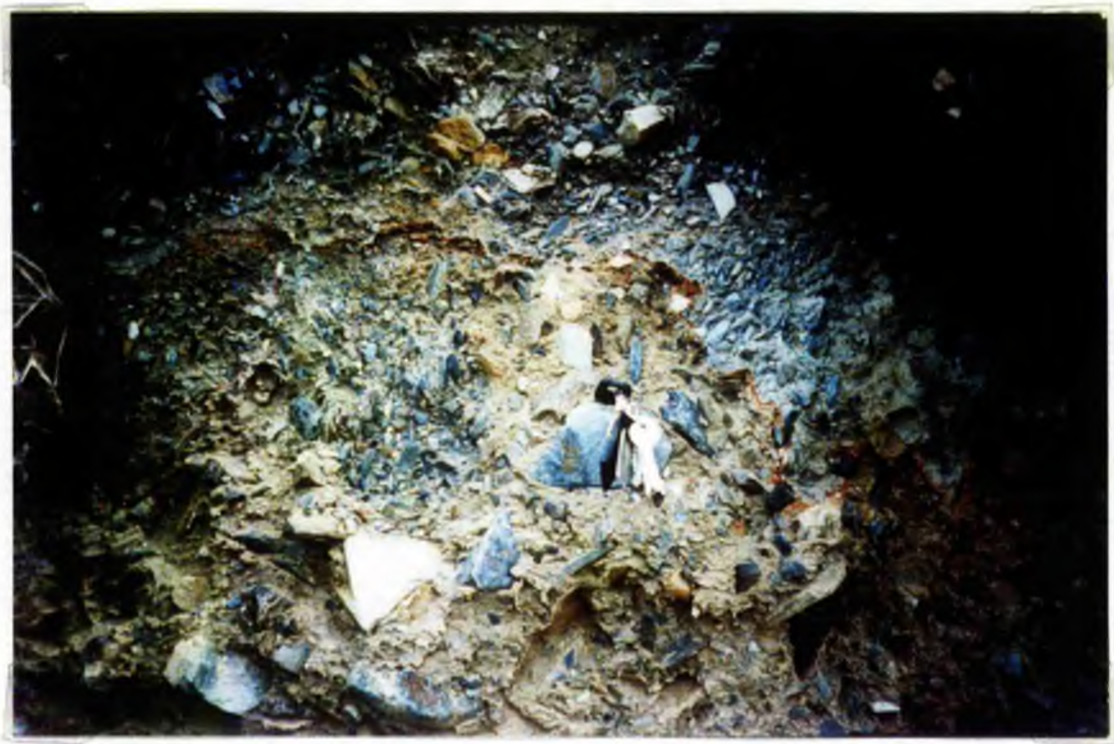
5.12 Dendritic pattern of dry channels, northwest of Noss Hill, south Mainland, Shetland. The channels are thought to represent flow from ice off the coast which can be seen in the background. (HU358161)

5.13 Weathered granite erratic associated with glacitectonized sandstone near the Sumburgh peninsula, south Mainland, Shetland. (HU388112)

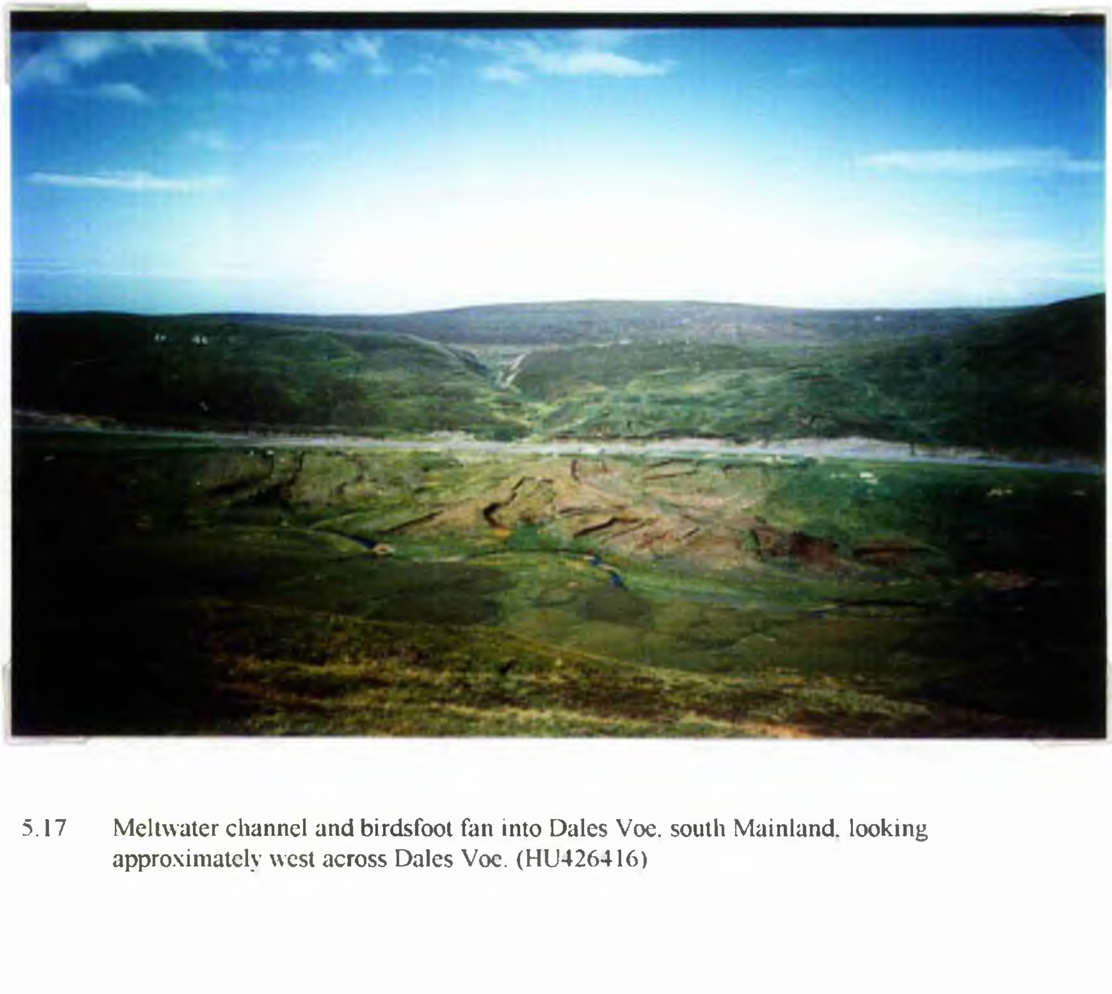


5.14 Metamorphic erratic taken from thin till to the east of Quendale Bay, south Mainland. Shetland. (HU388118)

5.15 Possible solifluction deposits on high ground above Burn of Mail, south Mainland. (HU415296)



5.16 Cryoturbation structures and frost-heaved clasts, near St Ninian's Isle, west coast of south Mainland, Shetland. (HU375216)



5.17 Meltwater channel and birdsfoot fan into Dales Voe, south Mainland, looking approximately west across Dales Voe. (HU426416)

5.18 Massive diamict in section through hummock. Burn of Mail, south Mainland, Shetland. (HU426286)

5.19 Distal slopes of main area of hummocky moraine. Burn of Mail, south Mainland, Shetland. (HU426286)

5.20 Distal slopes of main area of hummocky moraine, Burn of Mail, south Mainland, Shetland, showing proglacial channelization. (HU426286)

5.21 Proximal slopes of main area of hummocky moraine, ice to the right of the picture. (HU426286)

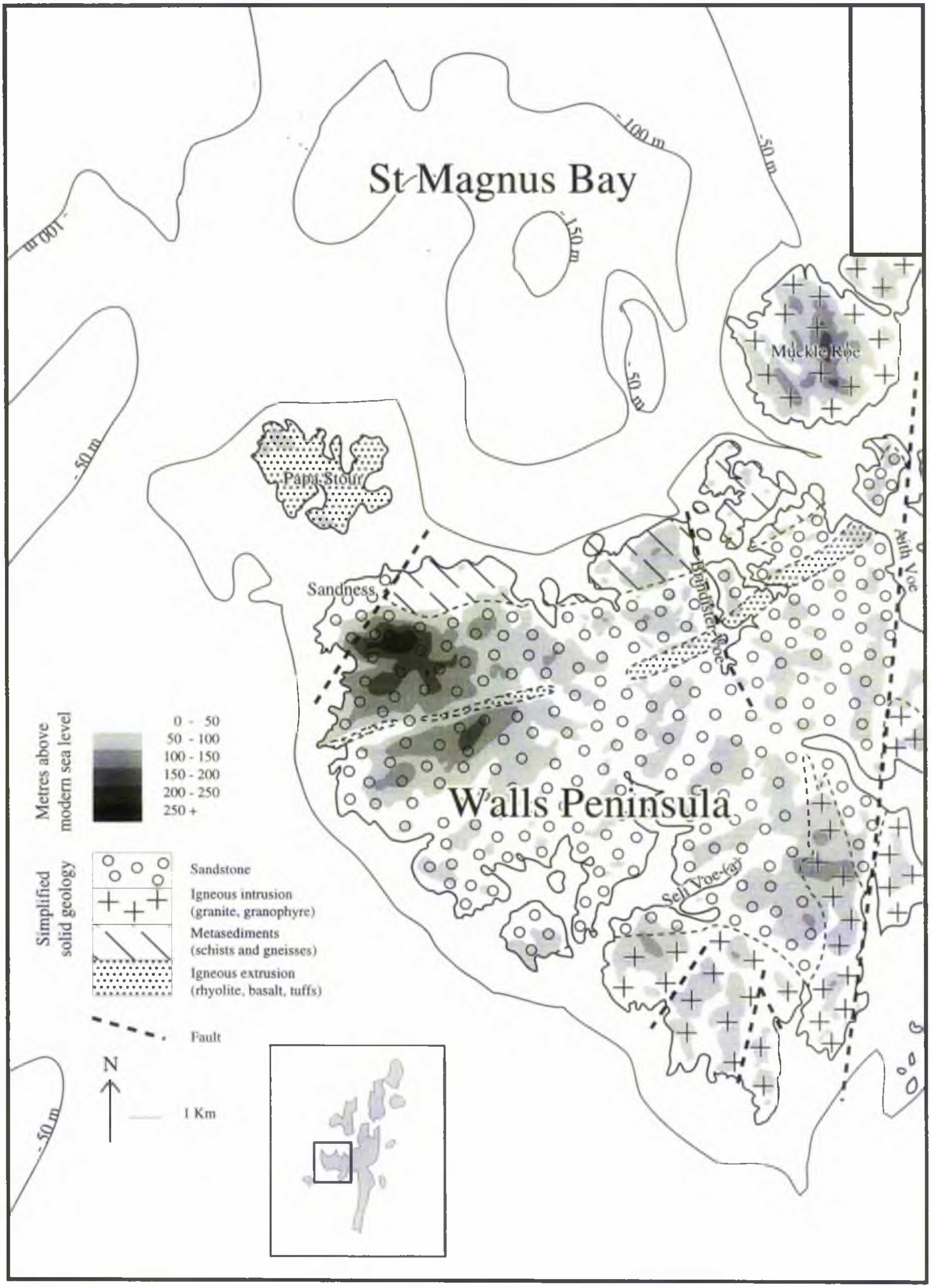


Figure 6.1. Solid geology, topography and bathymmetry (numbers on shallow side of bathymmetric contours) of west Mainland, Shetland.

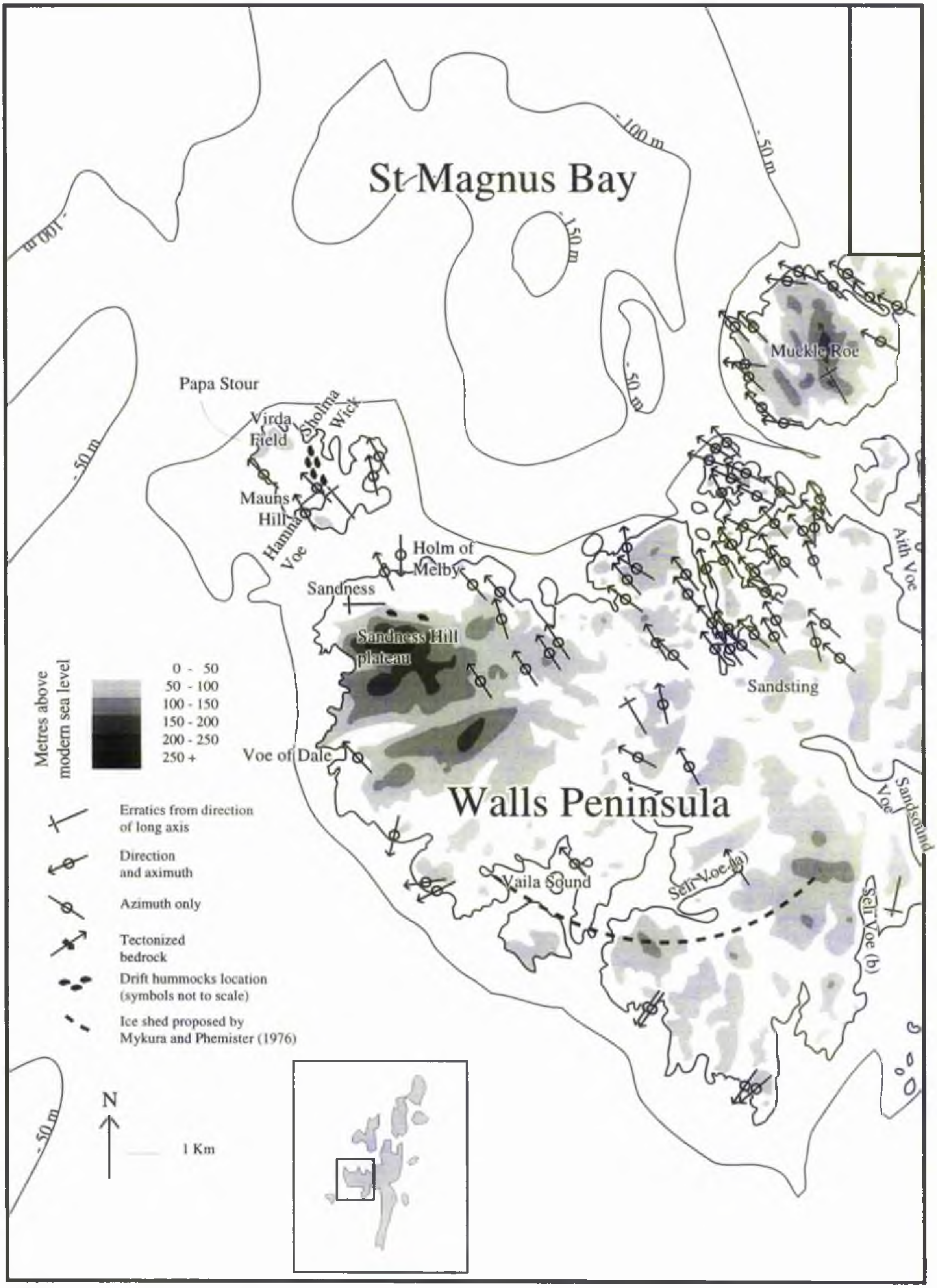


Figure 6.2. Ice direction indicators, west Mainland, Shetland: striae after Dunham (1971), Mykura and Phemister (1976) and this study; drift hummocks after Mykura and Phemister (1976); erratic carry after Mykura (1976), this study and Flinn (1982).

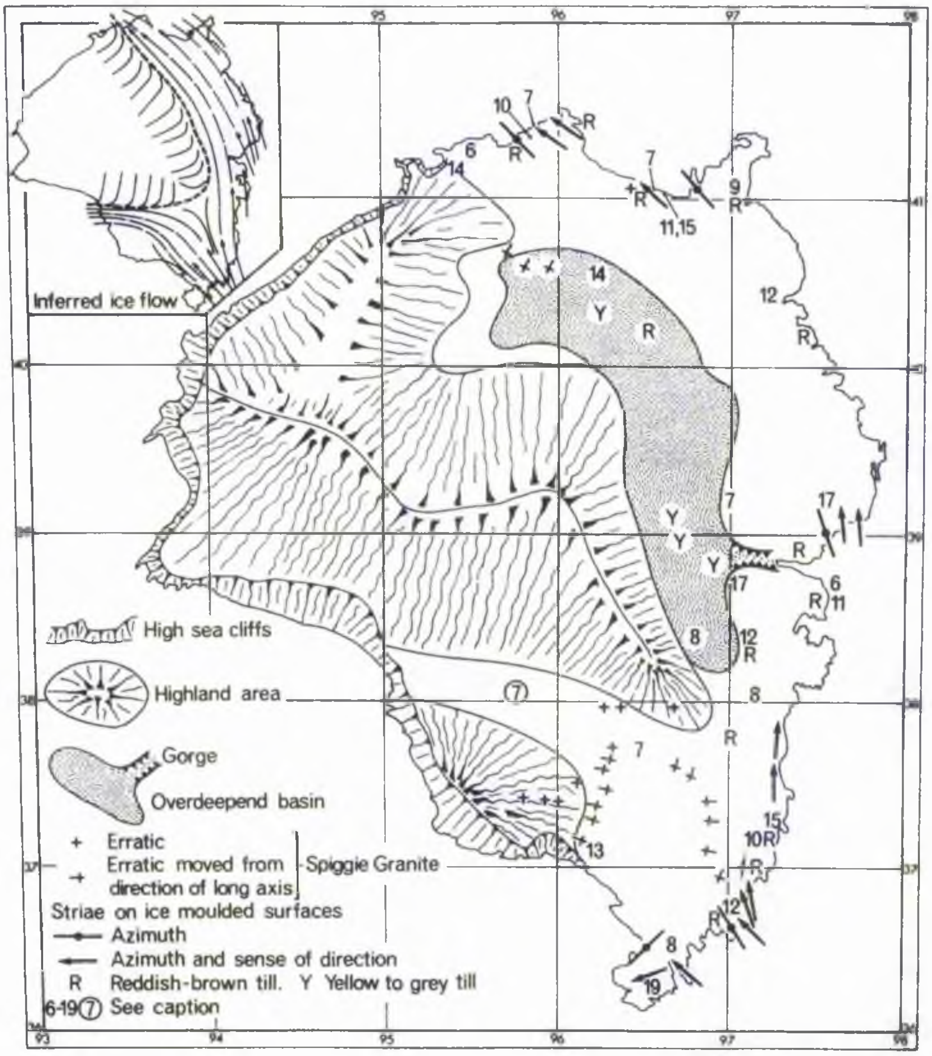


Fig. 2. The glacial geology of Foula. The figures 6 to 19 represent percentages of millet seed sand grains relative to quartz grains in the 1·0–0·5 mm fraction of the tills at the localities indicated. ⑦ditto in post glacial sand.

6.3 Glacial geology of Foula.
From Flinn, 1978

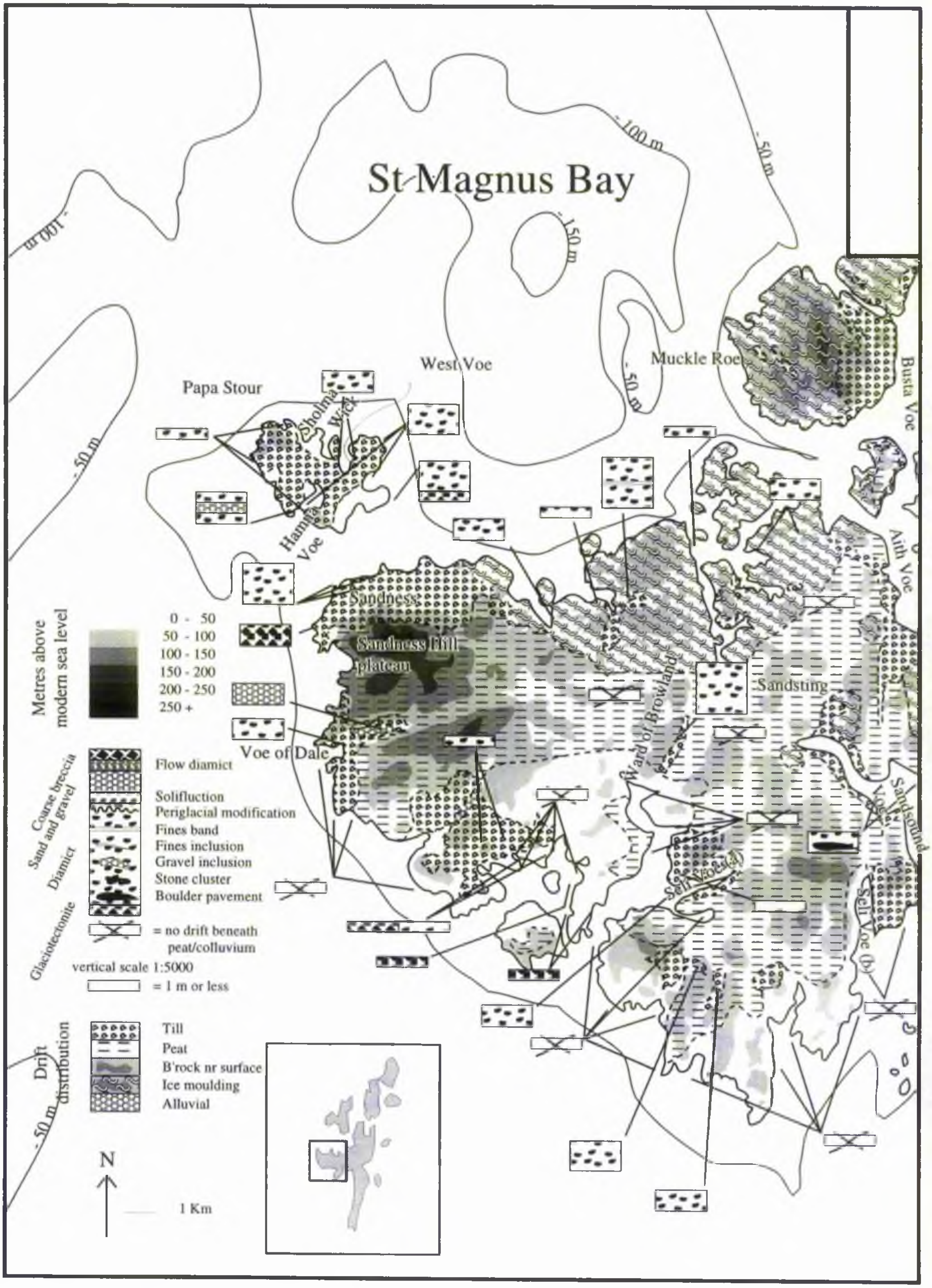


Figure 6.4. Drift distribution and glacial stratigraphy, west Mainland, Shetland: drift distribution after Dunham (1971) and this study; glacial stratigraphy (this study).

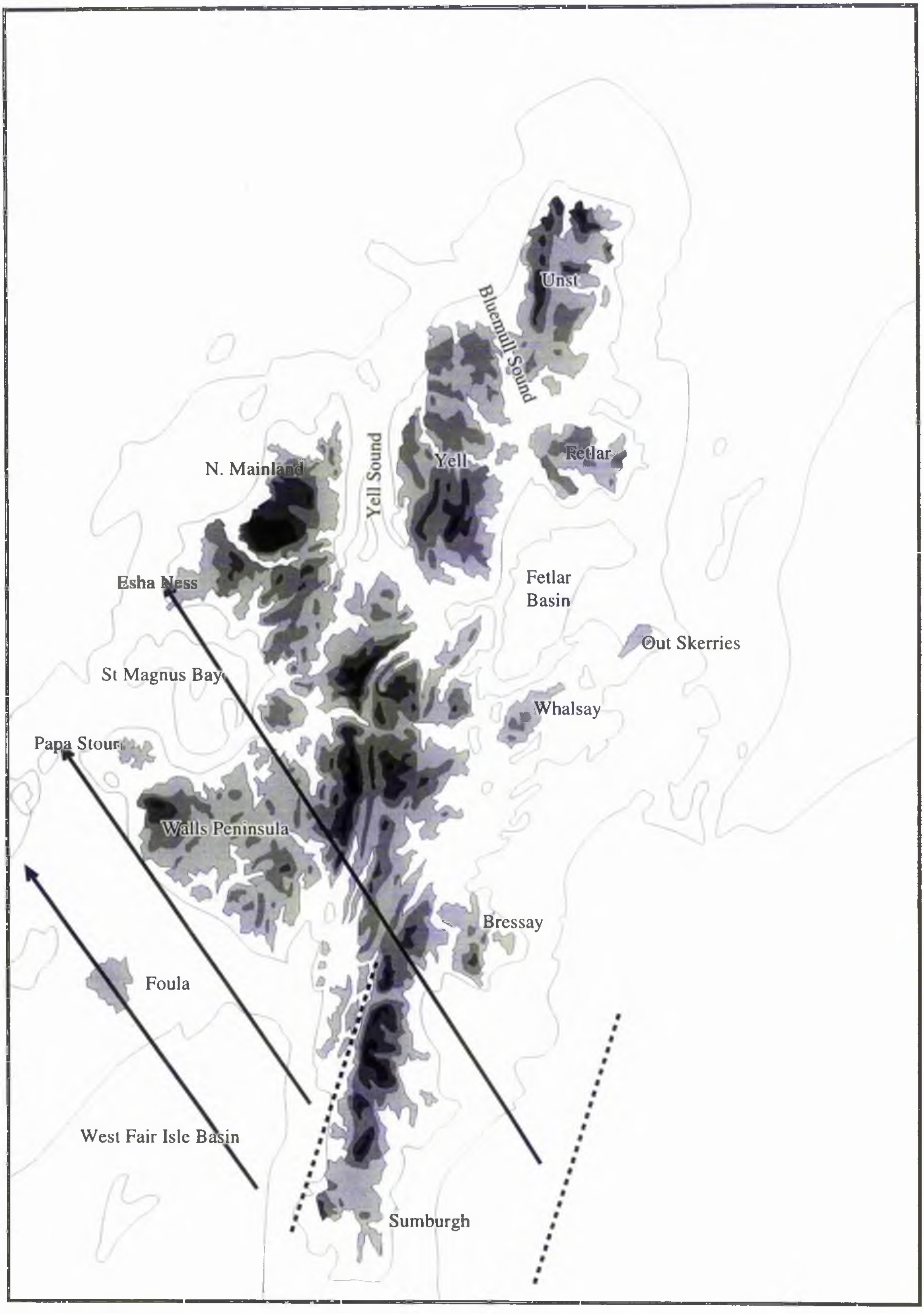


Figure 6.5. Possible reconstructions of early deglaciation of west Mainland, Shetland. The dominant northwesterly movement of ice is uncontroversial but the position of the ice shed is uncertain (dashed lines). The more western ice shed explains the reported absence of southern Mainland erratics on the Walls peninsula and Foula and is a possible reason for the preservation of earlier erratics on the west coast of south Mainland (see chapter 5). But the more eastern ice shed explains the existence of those erratics in the first place. Throughout this study, the northwesterly movement of ice has been shown to be an early condition and the author prefers the more eastern ice shed at this early stage in deglaciation. Ice movement shown by solid lines with arrows.

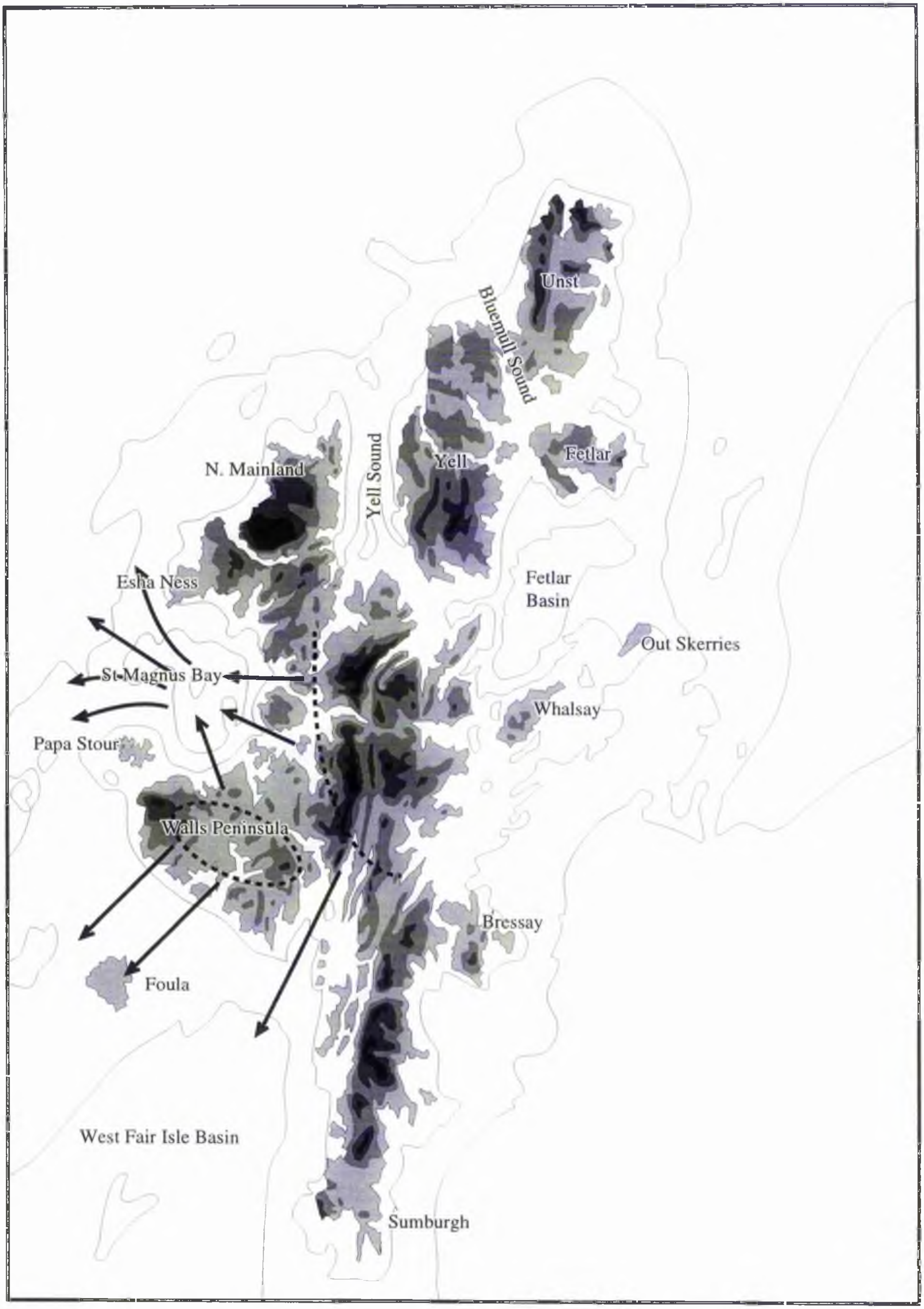


Figure 6.6. Reconstruction of the deglaciation of the Walls peninsula, west Mainland, Shetland, following the events shown in figure 6.5. The pattern of convergence into St Magnus Bay is shown, and streams into the West Fair Isle Basin. These, 'pinch out,' supply to the peninsula itself, leaving a remnant ice centre. Ice movement shown by solid lines with arrows. Ice shed zones shown with dashed lines.

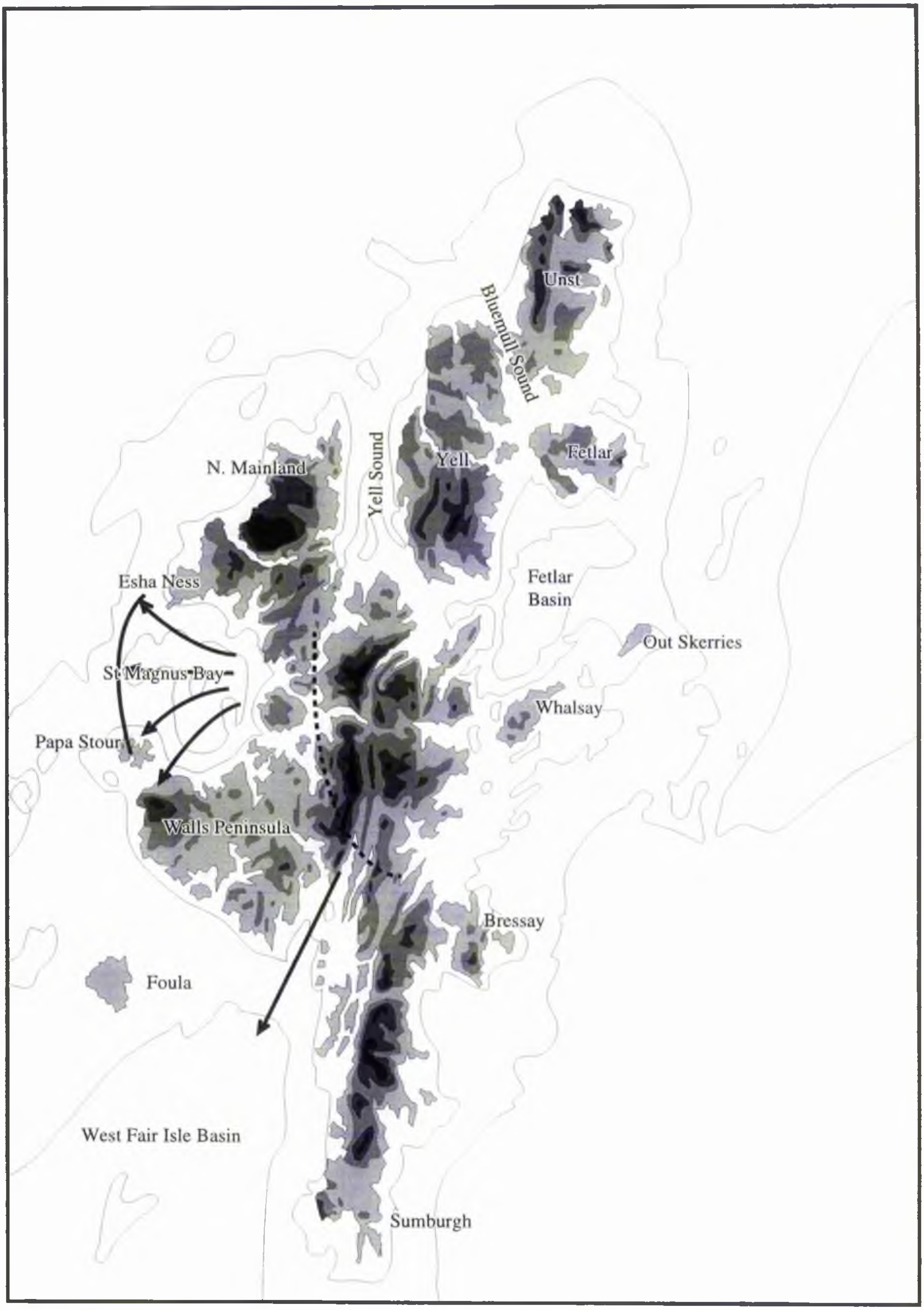
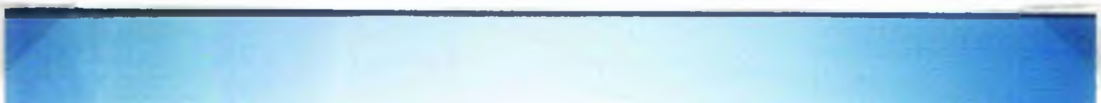


Figure 6.7. Reconstruction of the late deglaciation of west Mainland, Shetland. A possible ice margin is shown (solid line, no arrow), taking account of the moraine on Papa Stour and the possibility of the sill at the western margin of St Magnus Bay acting as a 'pinning point.' The timing of this reconstruction relative to that shown in figure 6.6 is not known and they may be contemporaeneous. Ice movement shown by solid lines with arrows. Western edge of hypothetical ice shed zone shown with dashed line.

6.8 Oblique aerial of the ice moulded landscape of northeast Walls, west Mainland, Shetland, (the island of Vementry in the midground (HU2960)). St Magnus Bay is to the top left of the photograph.

6.9 Planed landscape of the granitic area of the south Walls peninsula, Shetland. (HU3143)

6.10 Dispersed lodgement till, West Voe, east Papa Stour, Shetland. (HU178613)



6.11 Cross sectional form of morainic mound on Papa Stour, west Mainland, Shetland. The ice contact, eastern face, is to the left. (HU165613)

6.12 Hummocks against topography on Papa Stour, west Mainland, Shetland. Photo taken from the hummock shown in plate 6.11 - the ice contact side is to the right, or east, but the western side is shallower because the drift is emplaced against the hillslope.

6.13 Diamicts separated by thin sands at Hamna Voe, Papa Stour, west Mainland, Shetland. Their proximity to the Papa Stour moraine suggest that they may reflect and ice margin oscillation but this is not proven. (HU161600)

6.14 Fluvioglacial material, Voe of Dale, west Mainland, Shetland. (HU184527)

6.15 Fluvioglacial material, Voe of Dale, west Mainland, Shetland. (HU184527)

6.16 Fluvioglacial terrace, Voe of Dale, west Mainland, Shetland. (HU187527)

6.17 BH 80/08 from the St Magnus Bay basin, just above rockhead at 31-31.5 m, rounded gravel, disaggregated, *in situ* fabric not known.

6.18 BH 80/08 from the St Magnus Bay basin, 24.5-25 m, laminated silts and clays.

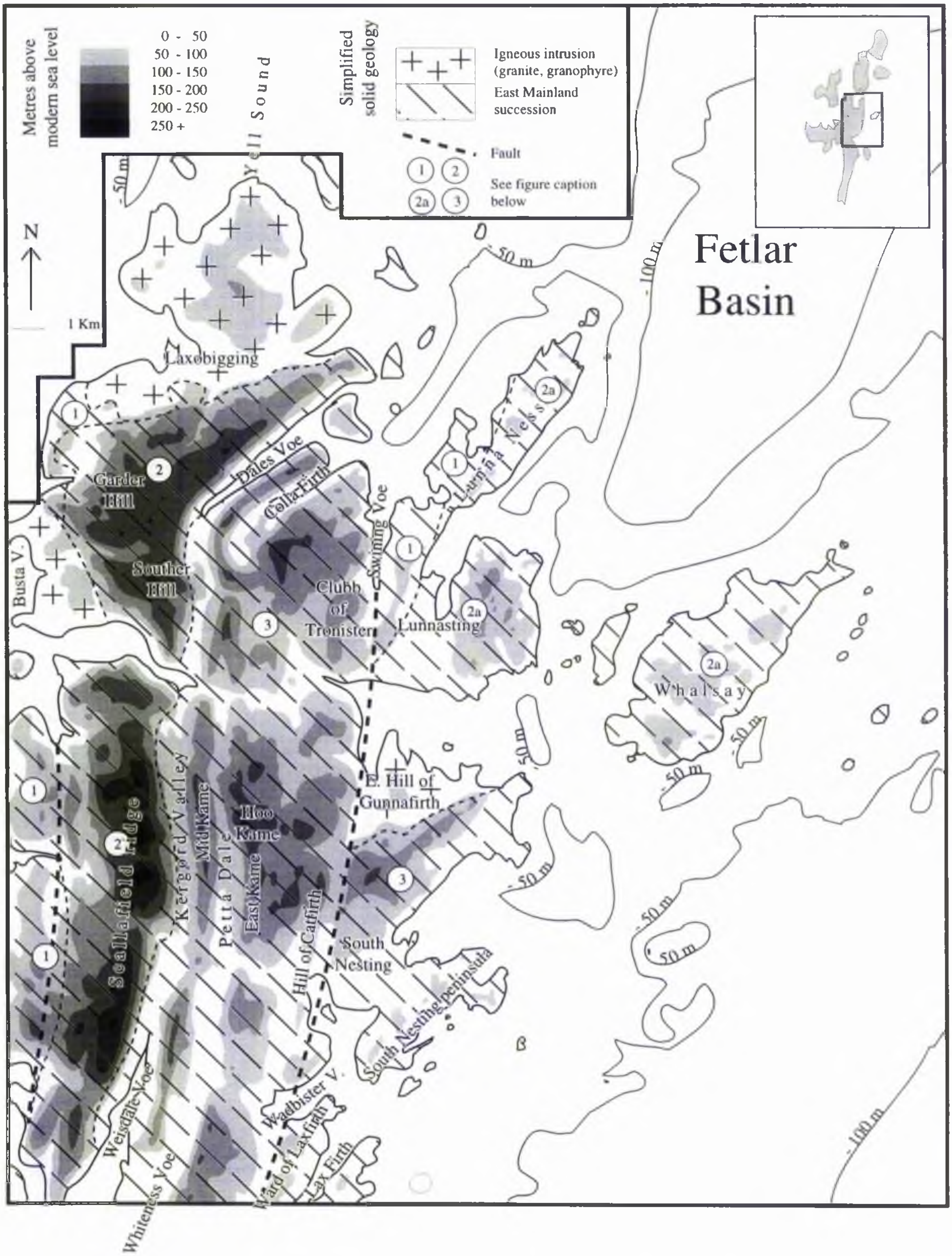


Figure 7.1. Solid geology, topography and bathymmetry, central Mainland, Shetland. No.'s 1-3 refer respectively to the Yell Sound, Scatsta and Whiteness Divisions of the East Mainland Succession of rocks metamorphosed during the Caledonian orogeny (their stratigraphic relation is youngest to the west and oldest to the east). Each division contains much heterogeneity and fuller details are discussed in the text.

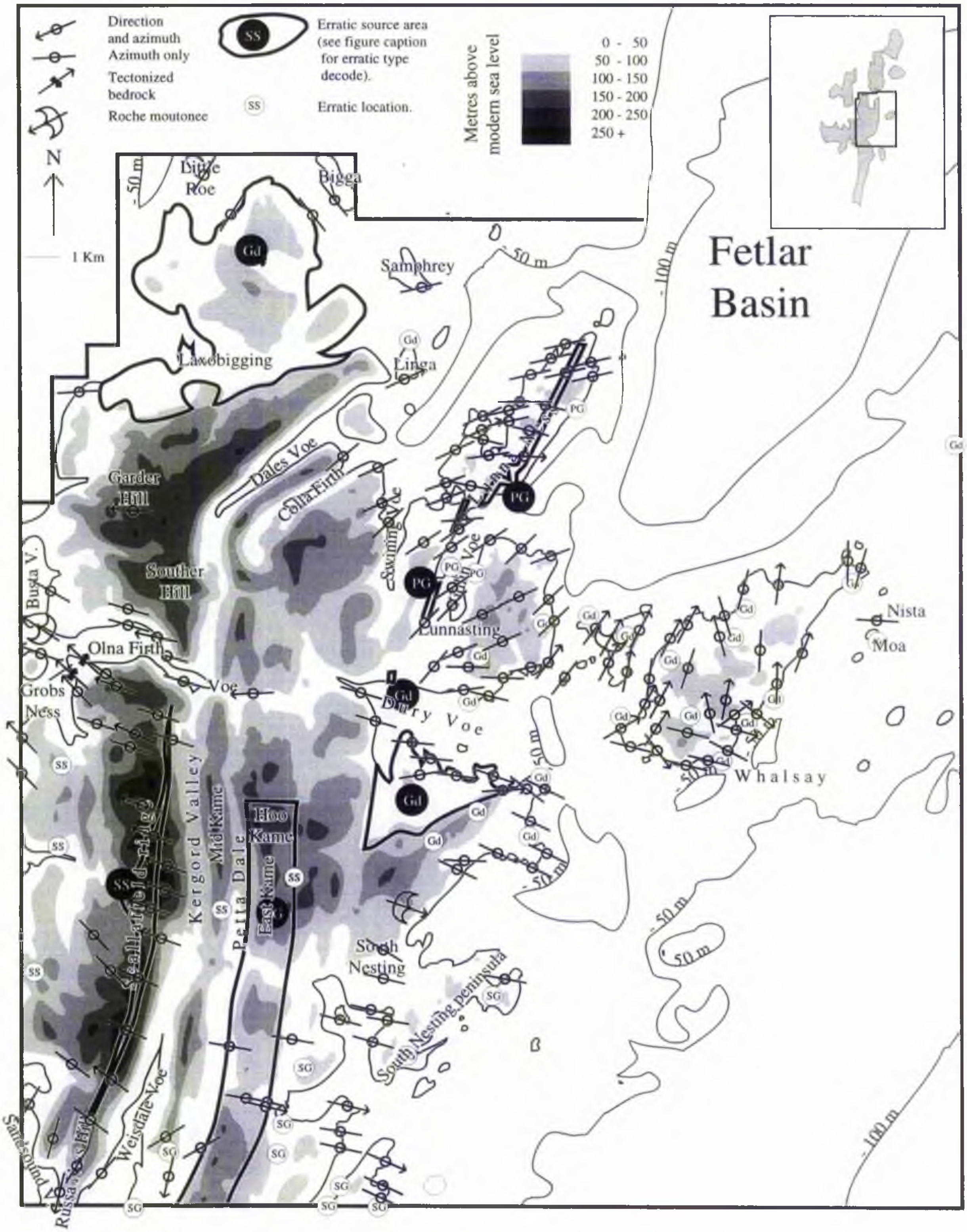


Figure 7.2. Ice direction indicators, central Mainland, Shetland: striae after Flinn (1982) and this study; glacitectonization (this study); erratic movement after Flinn (1982): Gd - granodiorite, PG - porphyroblast gneiss, SS - staurolite schists, SG - schistose granite of Colla Firth Permeation belt. Only erratic movements discussed in the text are shown.

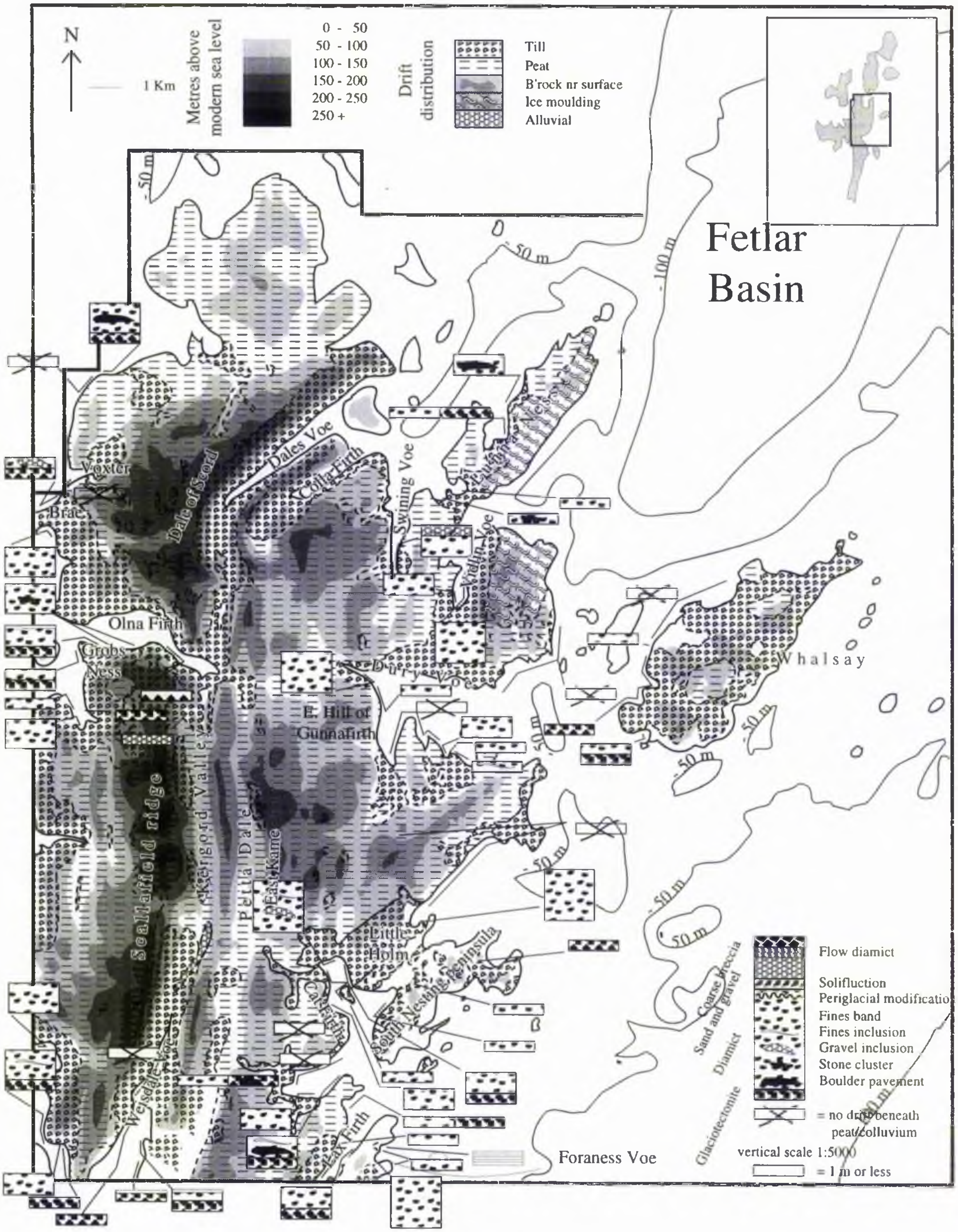


Figure 7.3. Drift distribution and glacial stratigraphy, central Mainland, Shetland: drift distribution after Flinn (1982) and this study; glacial stratigraphy (this study).

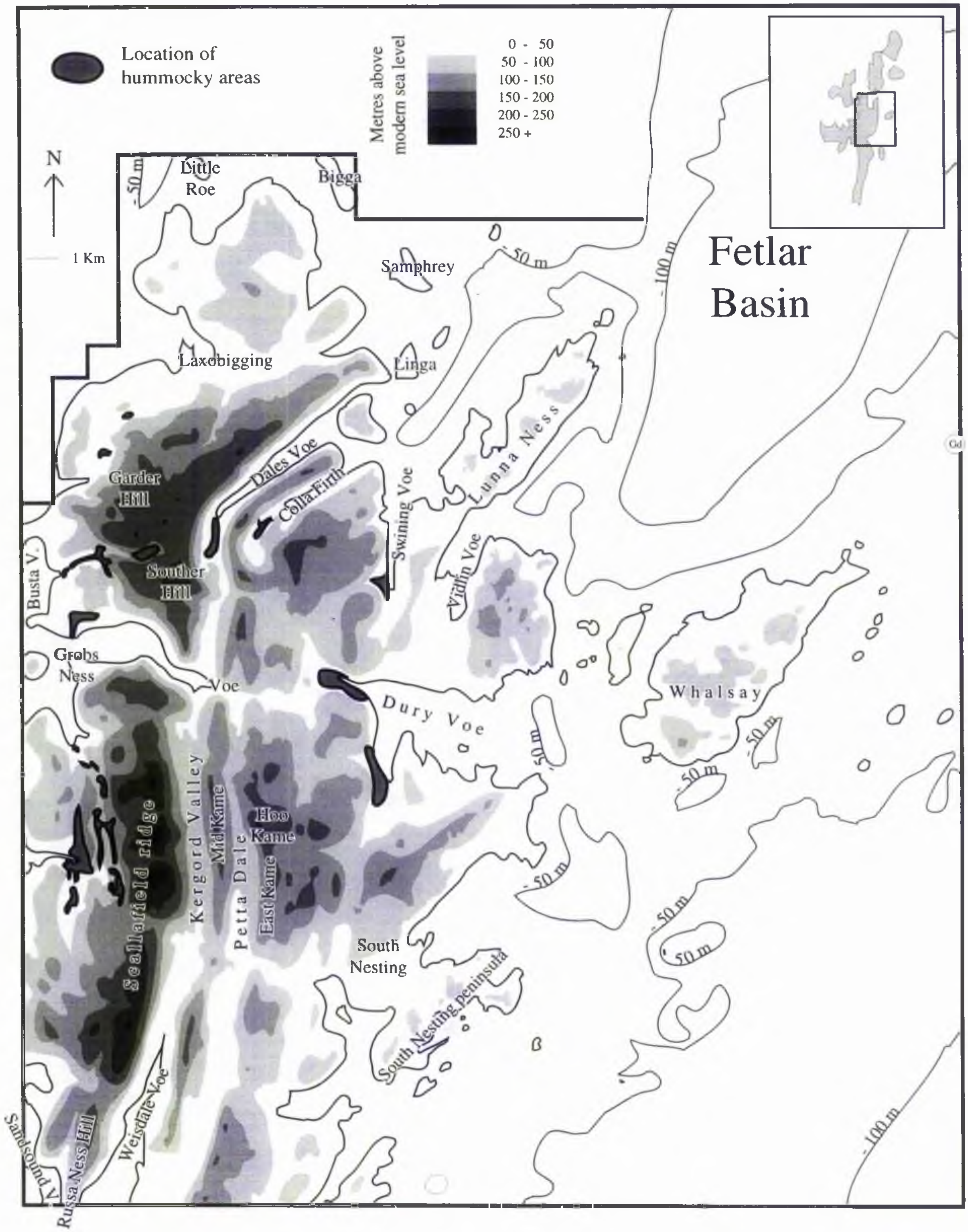


Figure 7.4. Approximate location and disposition of hummocky material, central Mainland, Shetland: after Flinn (1982).

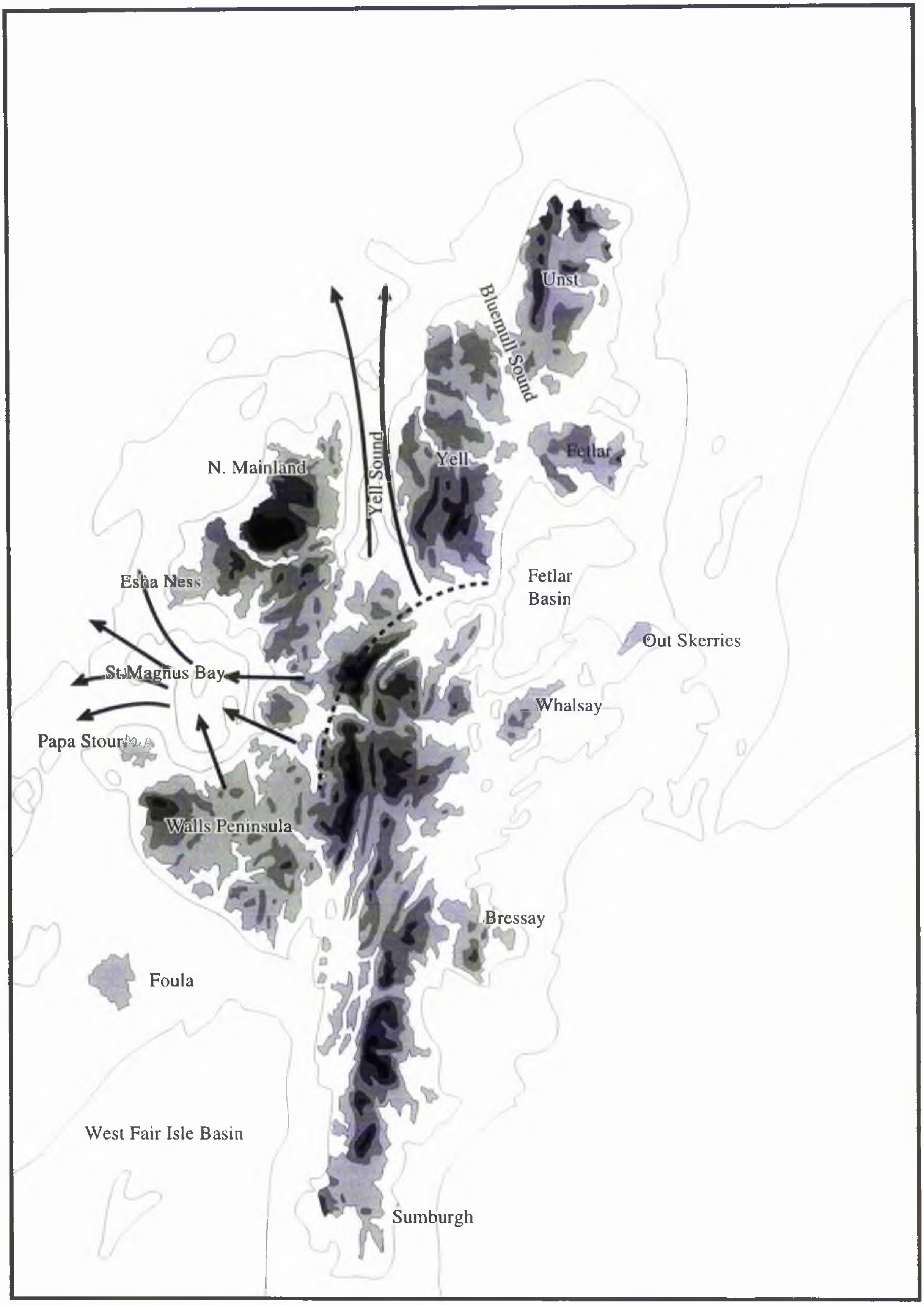


Figure 7.5. Reconstruction of the deglaciation of central Mainland, Shetland. The reconstruction shows the early establishment of ice streams into St Magnus Bay and Yell Sound (solid lines with arrows). The position of the ice shed zone (possible western edge shown by dashed line) cannot be drawn with certainty, although it is likely that it occupies a relatively eastern position, for the Fetlar Basin is not having a profound effect on ice movement at this time.

Figure 7.6. Reconstruction of the deglaciation of central Mainland, Shetland, following the events shown in figure 7.5. Clear patterns of northeasterly ice movement are shown, of sufficient dimension at least to transport erratics from Mainland to Out Skerries and beyond. This northeasterly movement may also be that identified on Bressay (see chapter 5). Ice movements shown by solid lines with arrows, possible ice shed zone shown with dotted lines.

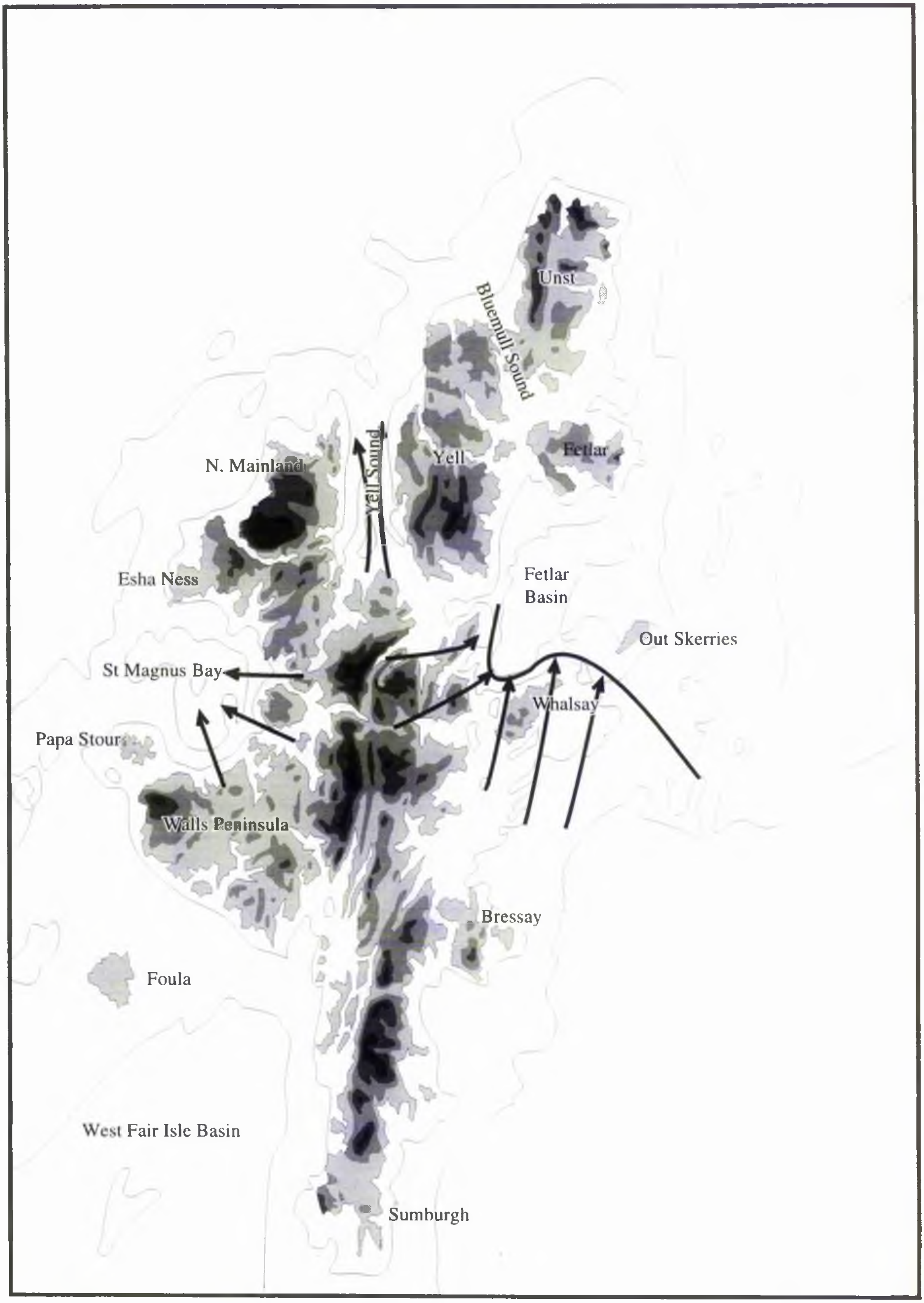


Figure 7.7. Reconstruction of the deglaciation of central Mainland, Shetland, following the events shown in figure 7.6. Northeastern deglaciation continues and the topographic influence of the Fetlar Basin becomes apparent. It follows that the Yell ice stream is diminished. The more northerly movement of ice over Whalsay towards the basin suggests ice is being supplied from the south. Ice movements shown by solid lines with arrows. Conjectural ice margin shown by solid line, no arrows.

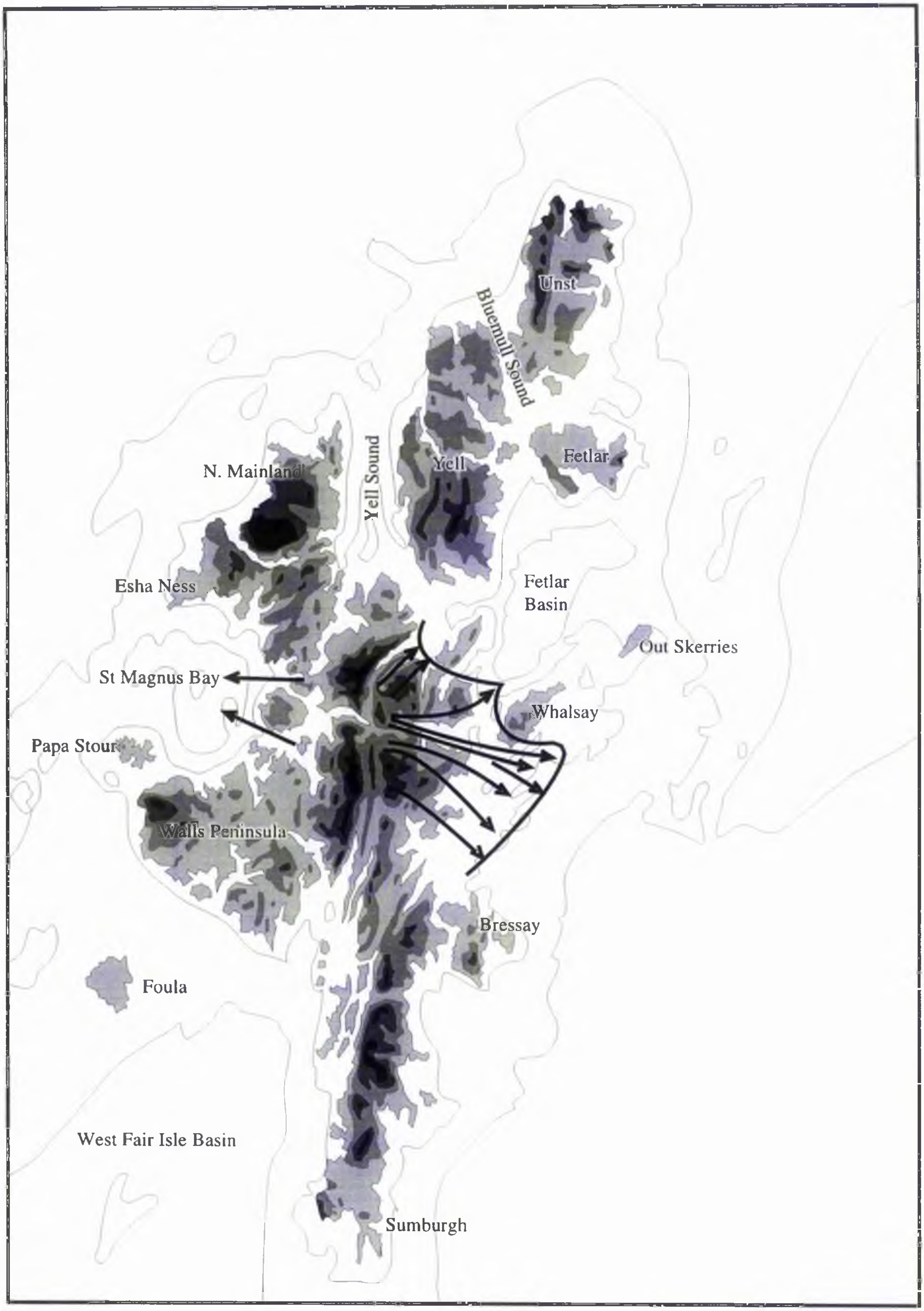


Figure 7.8. Reconstruction of the deglaciation of central Mainland, Shetland, following the events shown in figure 7.7. Southeastern deglaciation becomes apparent and and an ice stream splits around Whalsay. It is not known what continued northerly movement into Yell Sound is occurring. Evidently ice is now topographically contained and it is clear that the surface elevation of the ice cap has been diminished. Ice movements shown by solid lines with arrows. Hypothesised ice margins shown by solid lines, no arrows.

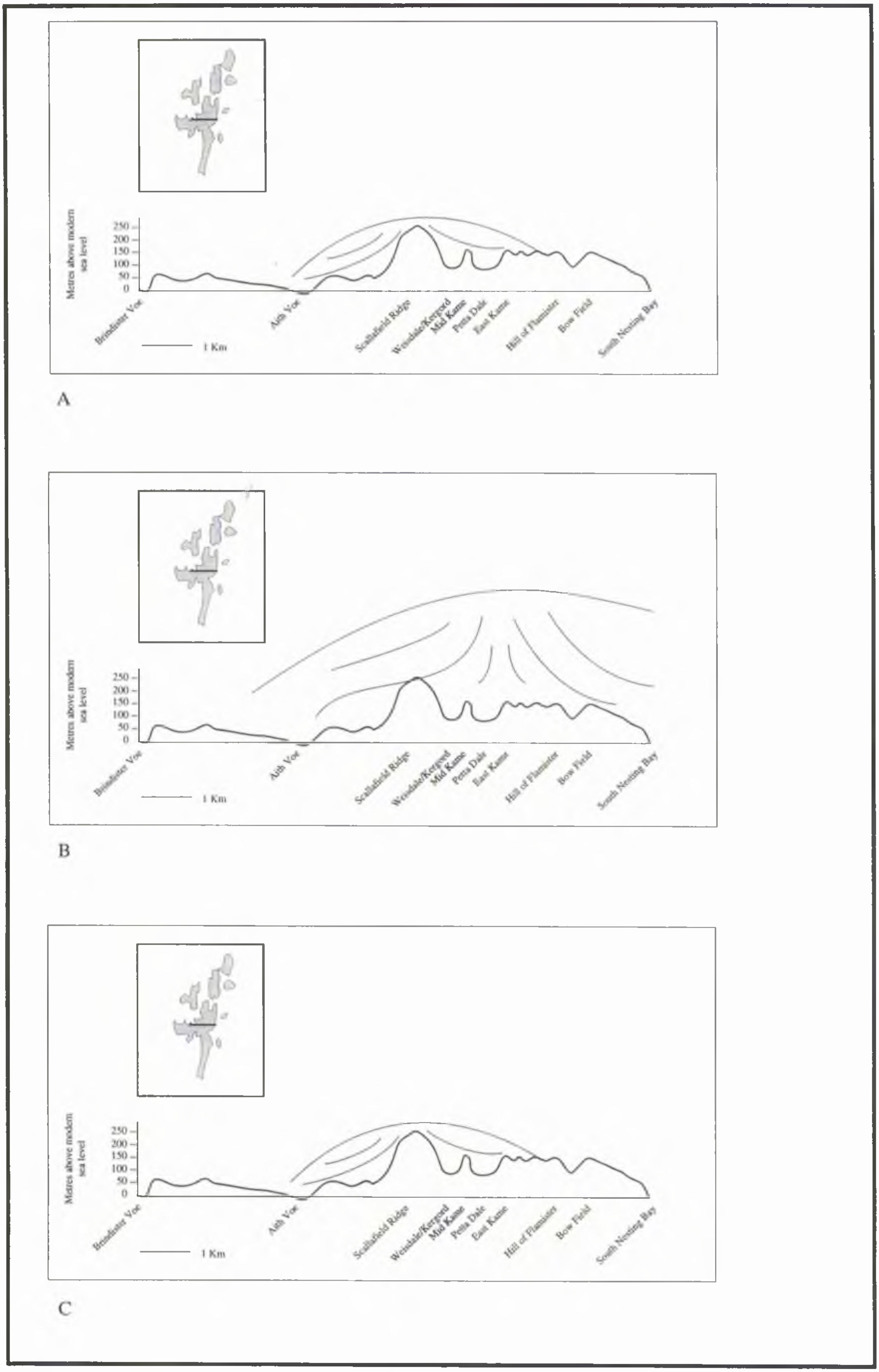


Figure 7.9. Glacial cycle in south central Mainland, Shetland - hypothesis 1: Staurolite schist erratics possibly carried east from Scallafield ridge during englaciation (A) and preserved later as ice striates ridge from east (B) with staurolite schists carried from Scallafield Ridge again during final stages of deglaciation from an ice shed centred on the ridge itself.

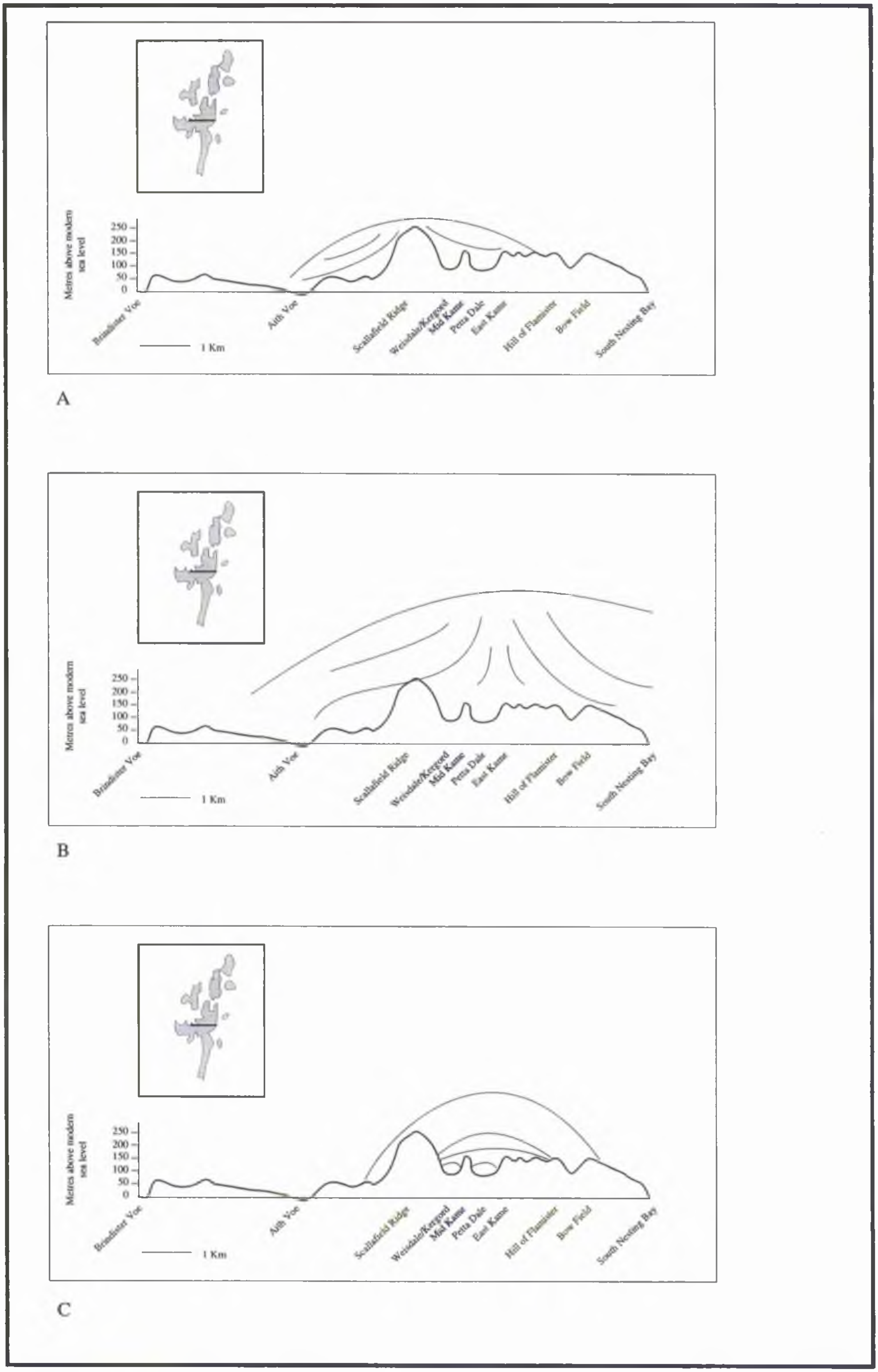


Figure 7.10. Glacial cycle in south central Mainland - hypothesis 2: Staurolite schist erratics are carried east from Scallafield ridge during englaciation (A) and are preserved later as ice striates ridge from east (B) and decays *in situ* (C).

7.11 Glacitectonization of bedrock on the south side of Grobs Ness, west central Mainland, Shetland. (HU367637)

7.12 Large scale stoss and lee assymetry southeast of Voe at South Filla Runnie (133m OD), central Mainland, Shetland. Assymetry in the background, ice moving from the left, or east. (HU420617)

7.13 Large scale stoss and lee assymetry at altitudes of 25m east of Voe, central Mainland, Shetland. Ice moving from the right, or east. (HU148632)

7.14 BH 80/02, from the Fetlar Basin, east central Mainland, Shetland: 7.10 - 7.30 m, knife pointing up core, showing laminated sands and clays.

7.15 Small esker with Grobs Ness, west central Mainland, Shetland, running left to right across the midground. The height of the feature is approximately 1 metre. (HU374638)

7.16 Deformed sands with large clasts, Foraness Voe, southeast central Mainland, Shetland. (HU456481)

7.17 View along linear hummock, immediately west of Scallafield Ridge, central Mainland, Shetland, running central foreground to background. Ice from the right, or east. (HU378568)

7.18 Small hummock in midground, west of Hill of Duddin, west central Mainland, Shetland, showing cross-sectional assymetry with ice from the highground to the left. (HU375673).

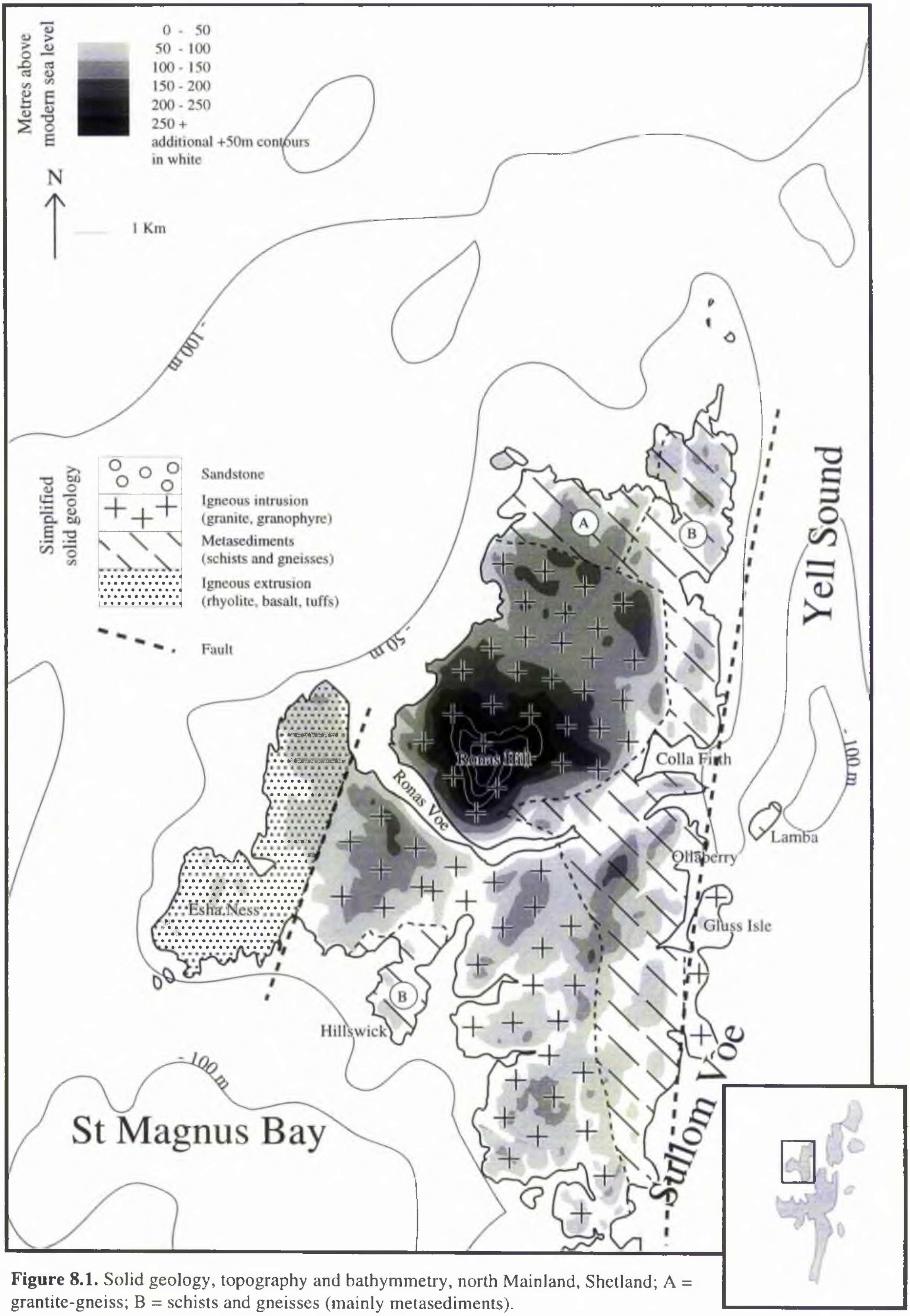


Figure 8.1. Solid geology, topography and bathymmetry, north Mainland, Shetland; A = grantite-gneiss; B = schists and gneisses (mainly metasediments).

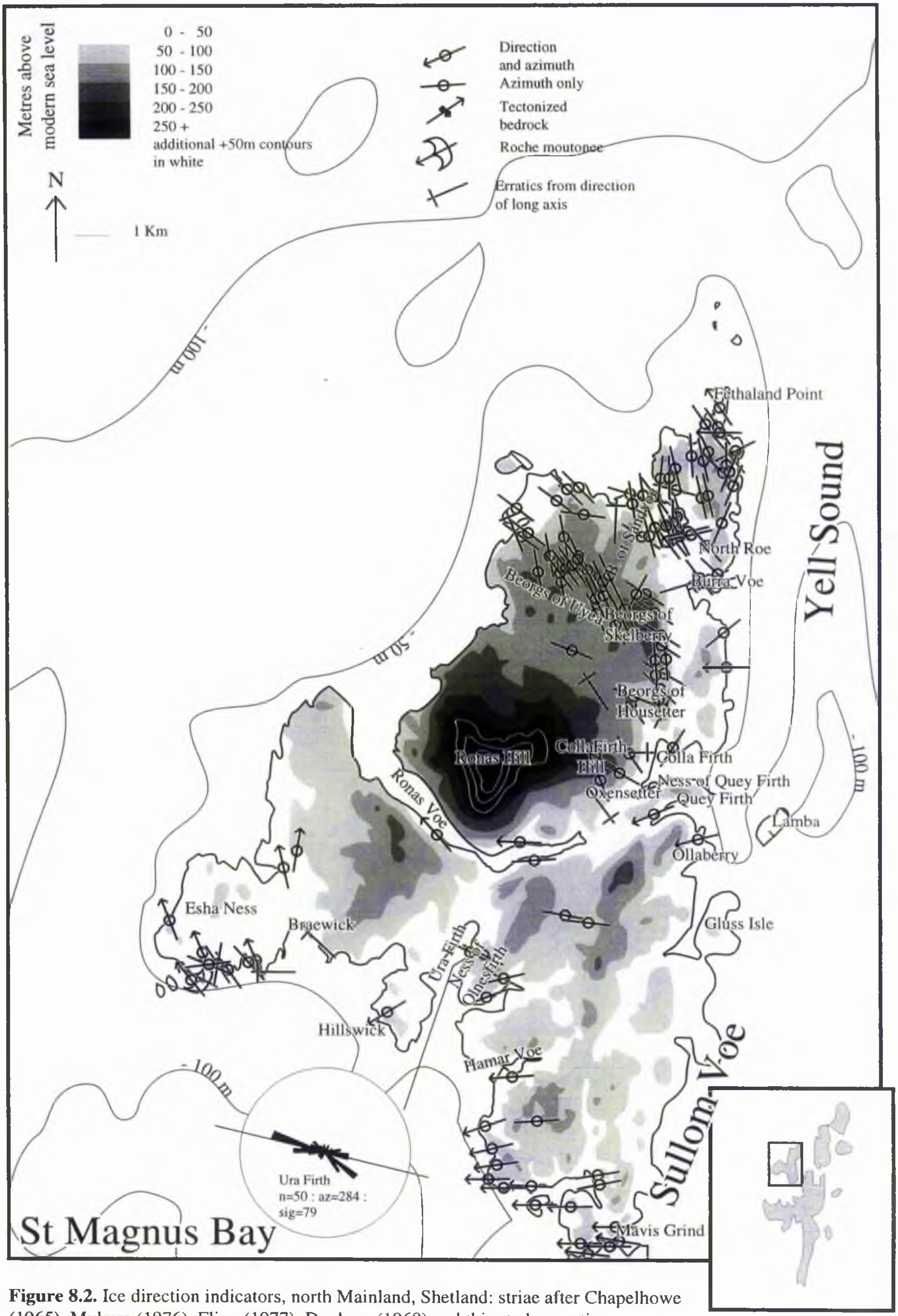


Figure 8.2. Ice direction indicators, north Mainland, Shetland: striae after Chapelhowe (1965), Mykura (1976), Flinn (1977), Dunham (1968) and this study; erratic movements after Mykura (1976) and this study; fabric data (this study), including sample size (n clasts), maximum eigen vector (az degrees) and value (sig %) and azimuth of local slope angle shown by black line through fabric.

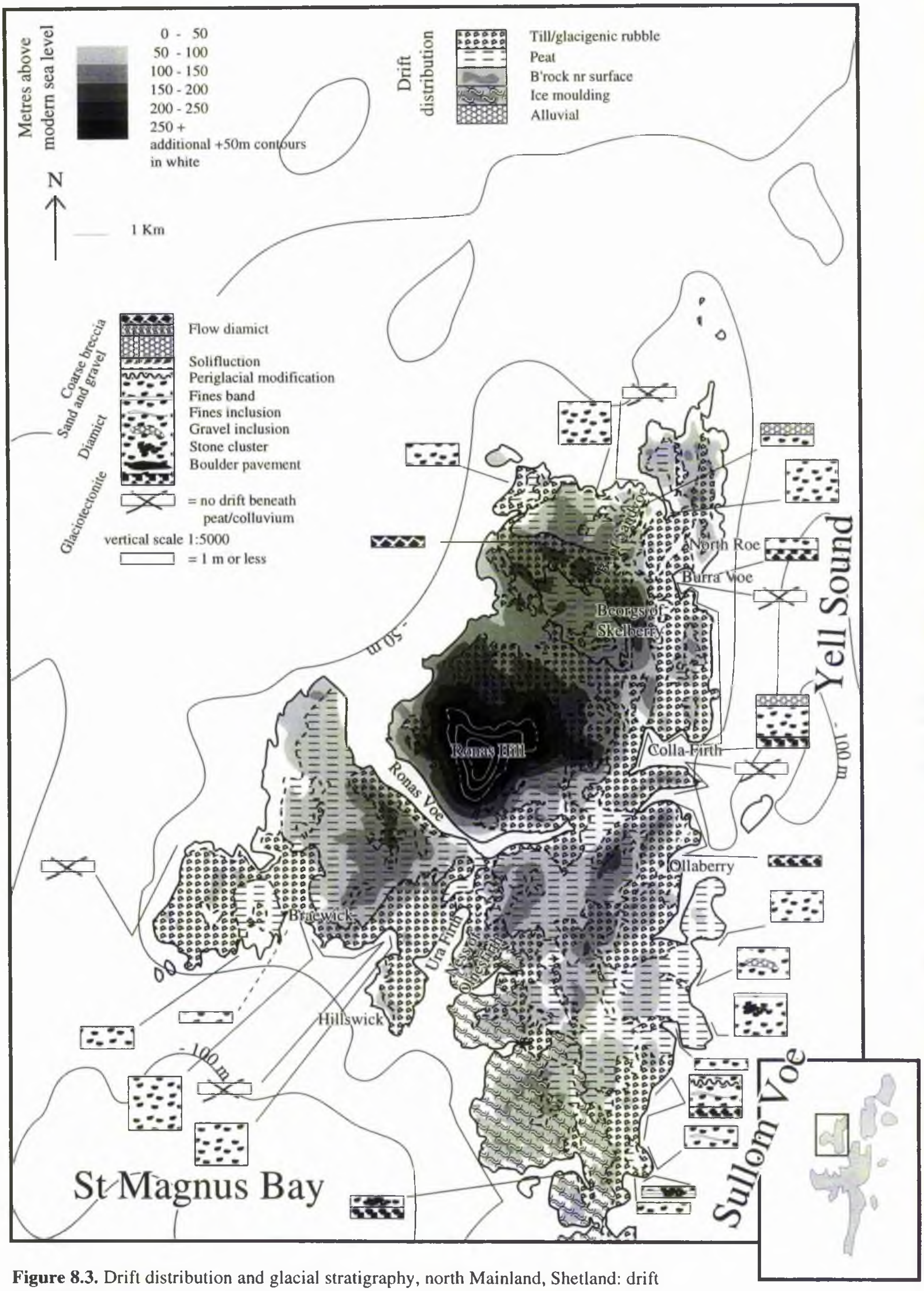


Figure 8.3. Drift distribution and glacial stratigraphy, north Mainland, Shetland: drift distribution: after Dunham (1968) and this study; glacial stratigraphy (this study).

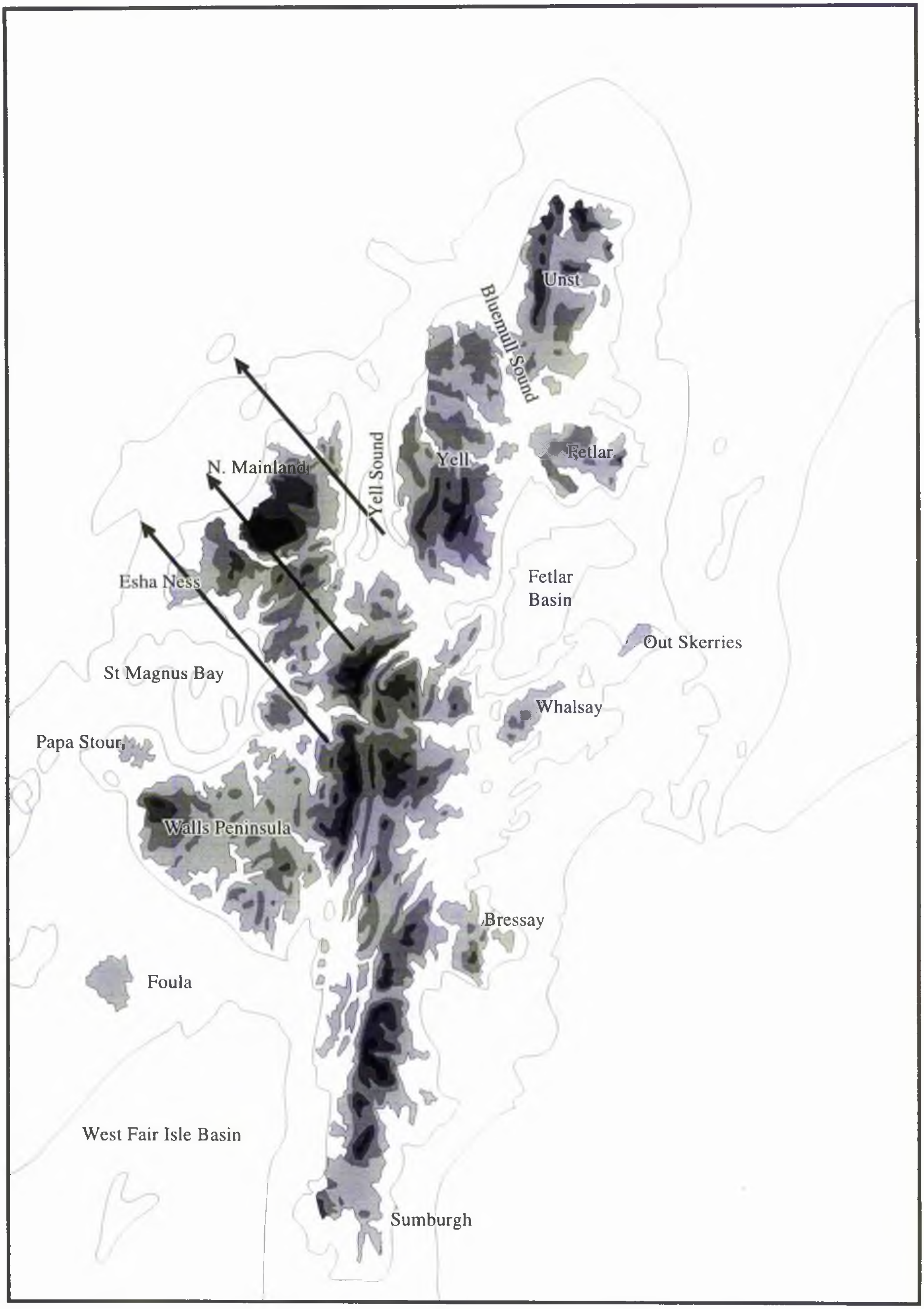


Figure 8.4. Reconstruction of the early deglaciation of north Mainland, Shetland. The position of the ice shed is not known. Ice movement shown by solid lines with arrows.

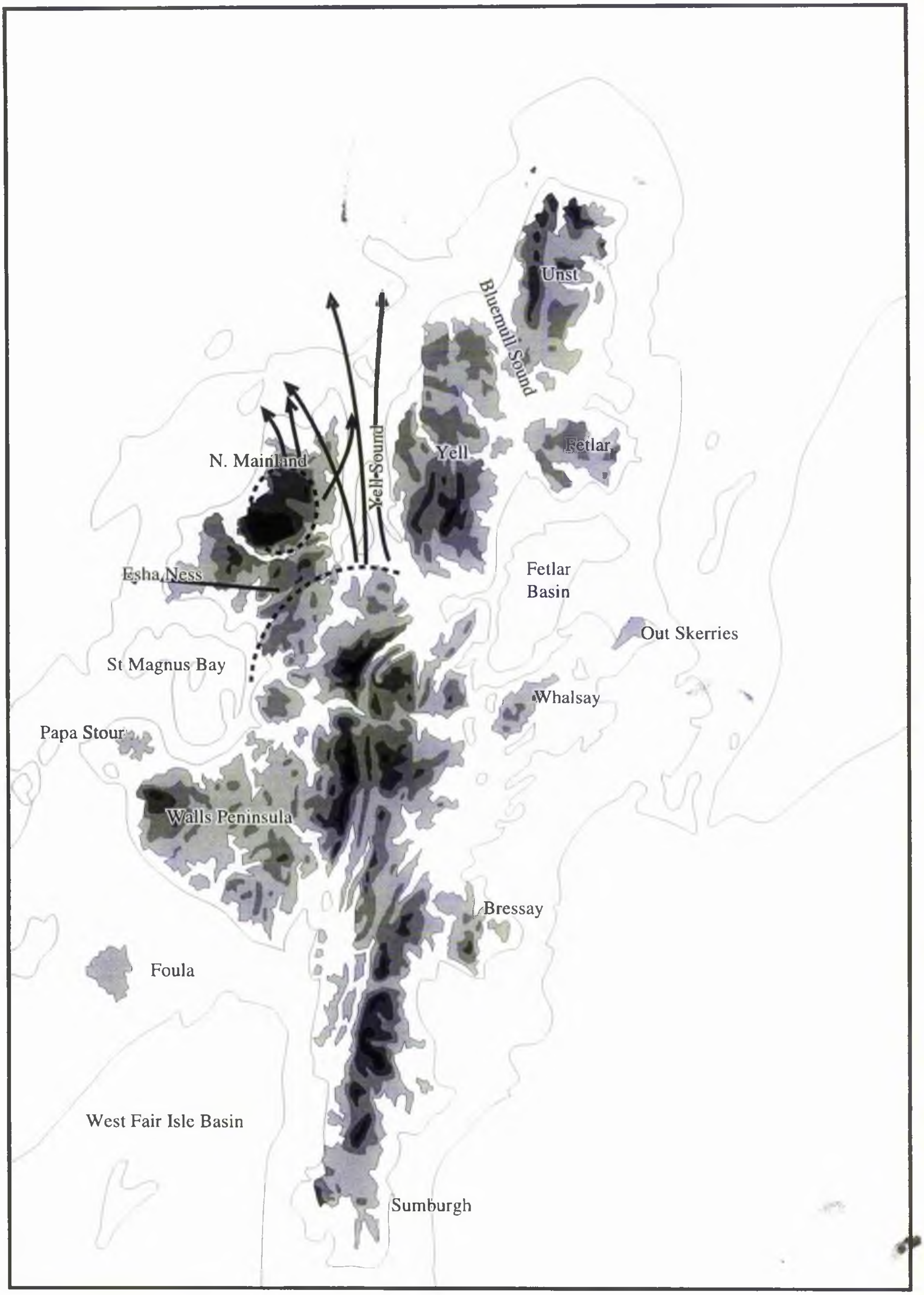


Figure 8.5. Reconstruction of the deglaciation of north Mainland, Shetland, following the events shown in figure 8.4. The position of the ice shed is not known. There is possibly an independent ice cap on the Ronas Plateau, feeding ice to the northwest and perhaps into the Yell Sound ice stream. At some stage, ice crosses the northern flank of St Magnus Bay in an easterly direction. Ice movement shown by solid lines with arrows. Ice shed zone and independent ice centre shown by dashed lines.

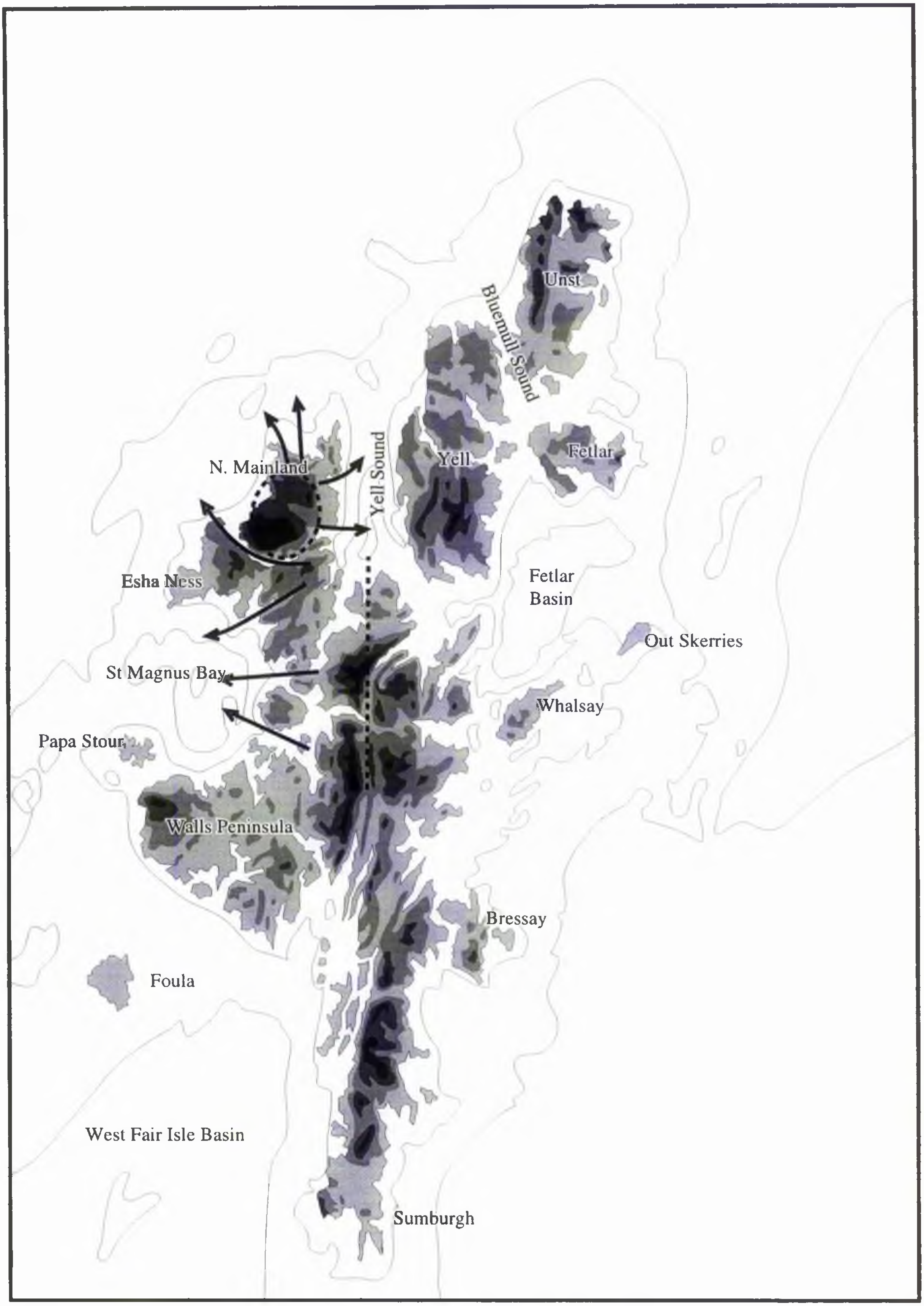


Figure 8.6. Reconstruction of the deglaciation of north Mainland, Shetland, following the events shown in figure 8.5. Ice streams into St Magnus Bay from the east but not the north as supply is not available because of Ronas Voe. Ice also streams radially from an independent ice centre on the Ronas Hill plateau, with identifiable drainage streams to the east into Yell Sound. It is not clear whether these two scenarios were contemporaeneous but if not it is likely that the Ronas Hill ice cap is the later of the two on altitudenal grounds. The position of the main ice shed is not known but the absence of more eastern erratics from this late stage suggests that it was relatively central. Ice shed/centre shown by dashed lines. Ice movement shown by solid lines with arrows.

8.7 Possible ice marginal morphology, southeast of Oxensetter, north Mainland, Shetland, representing margin of possible late plateau glaciation. (HU341819)

8.8 Meltwater channel draining the eastern margin of the Ronas Plateau, north Mainland, Shetland, between Beorgs of Skellberry and Housetter. (HU357864)

8.9 Fluvioglacial material overlying diamict, west Colla Firth, north Mainland, Shetland. (HU354834)

8.10 Thick lodgement facies at Breiwick, north Mainland, Shetland, dipping between west and northwest. The section is approximately 5 m thick at its thickest point. (HU249787)

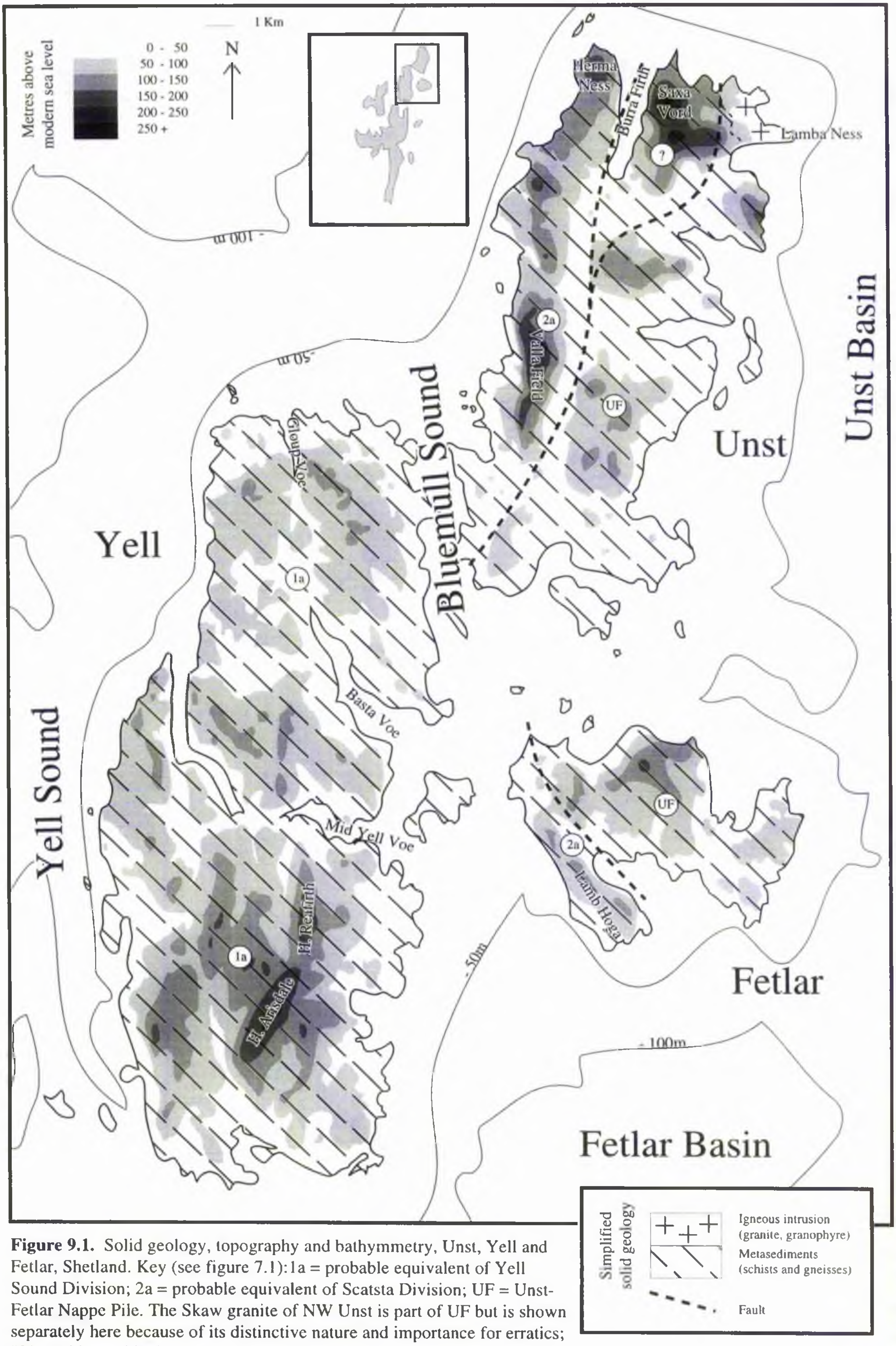


Figure 9.1. Solid geology, topography and bathymmetry, Unst, Yell and Fetlar, Shetland. Key (see figure 7.1): 1a = probable equivalent of Yell Sound Division; 2a = probable equivalent of Scatsta Division; UF = Unst-Fetlar Nappe Pile. The Skaw granite of NW Unst is part of UF but is shown separately here because of its distinctive nature and importance for erratics; "?" = schistose block of uncertain age.

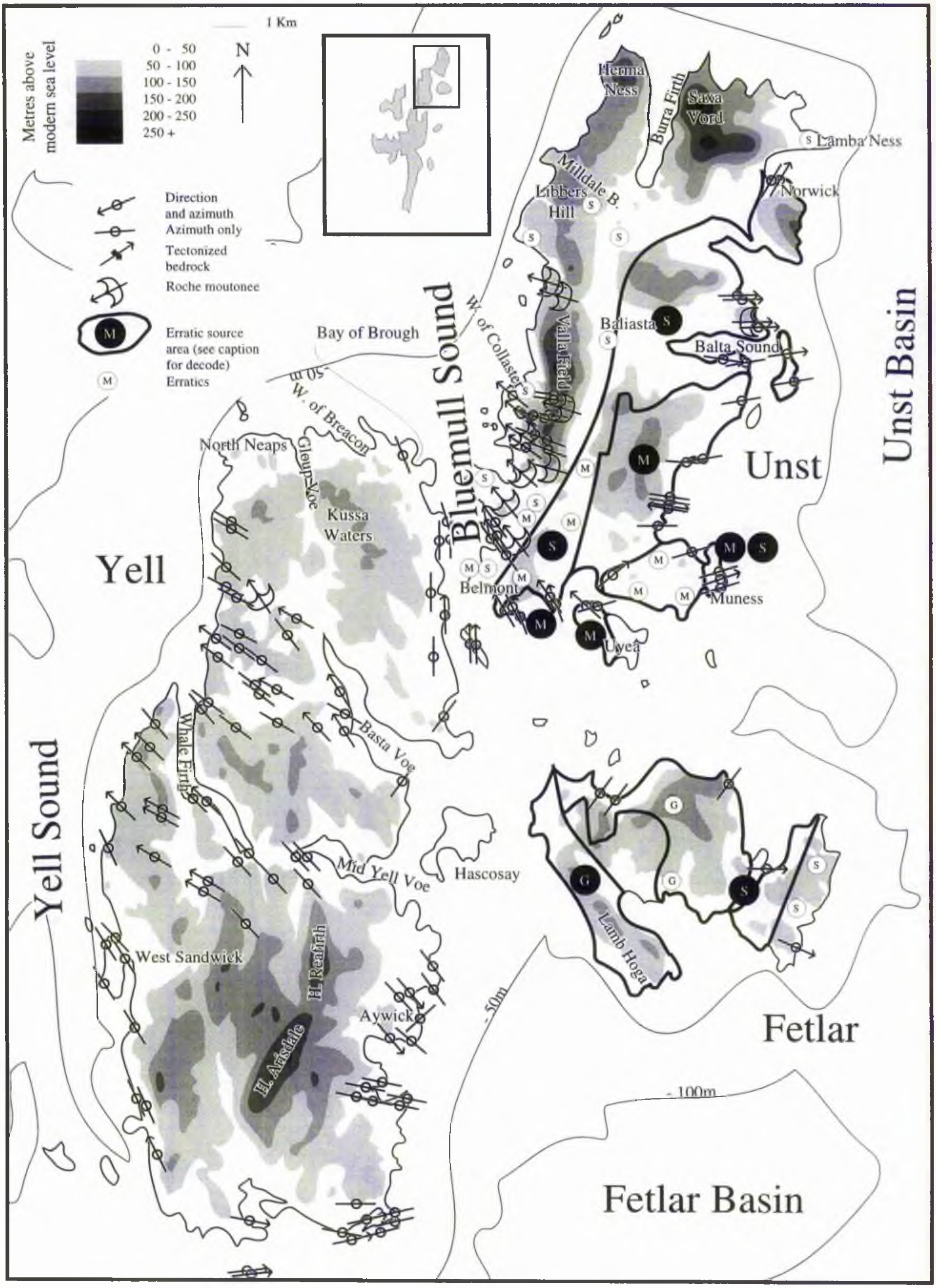


Figure 9.2. Ice direction indicators, Unst, Yell and Fetlar, Shetland: striae after Flinn (1977, 1994ab), Mykura (1976) and this study; erratics after Mykura (1976) and Flinn (1994b) - M = metagabbro, S = serpentine, G = gneiss;

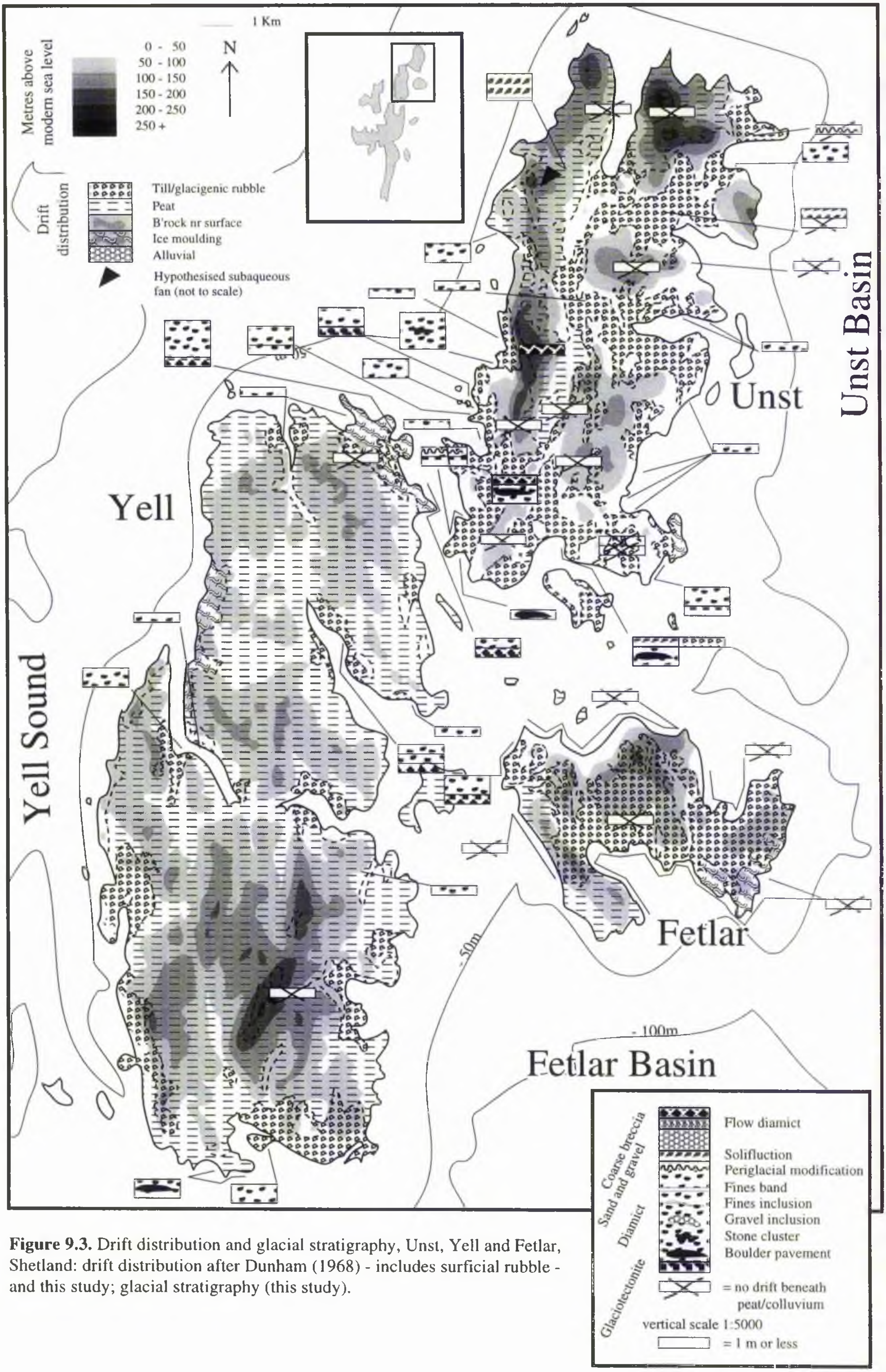


Figure 9.3. Drift distribution and glacial stratigraphy, Unst, Yell and Fetlar, Shetland: drift distribution after Dunham (1968) - includes surficial rubble - and this study; glacial stratigraphy (this study).

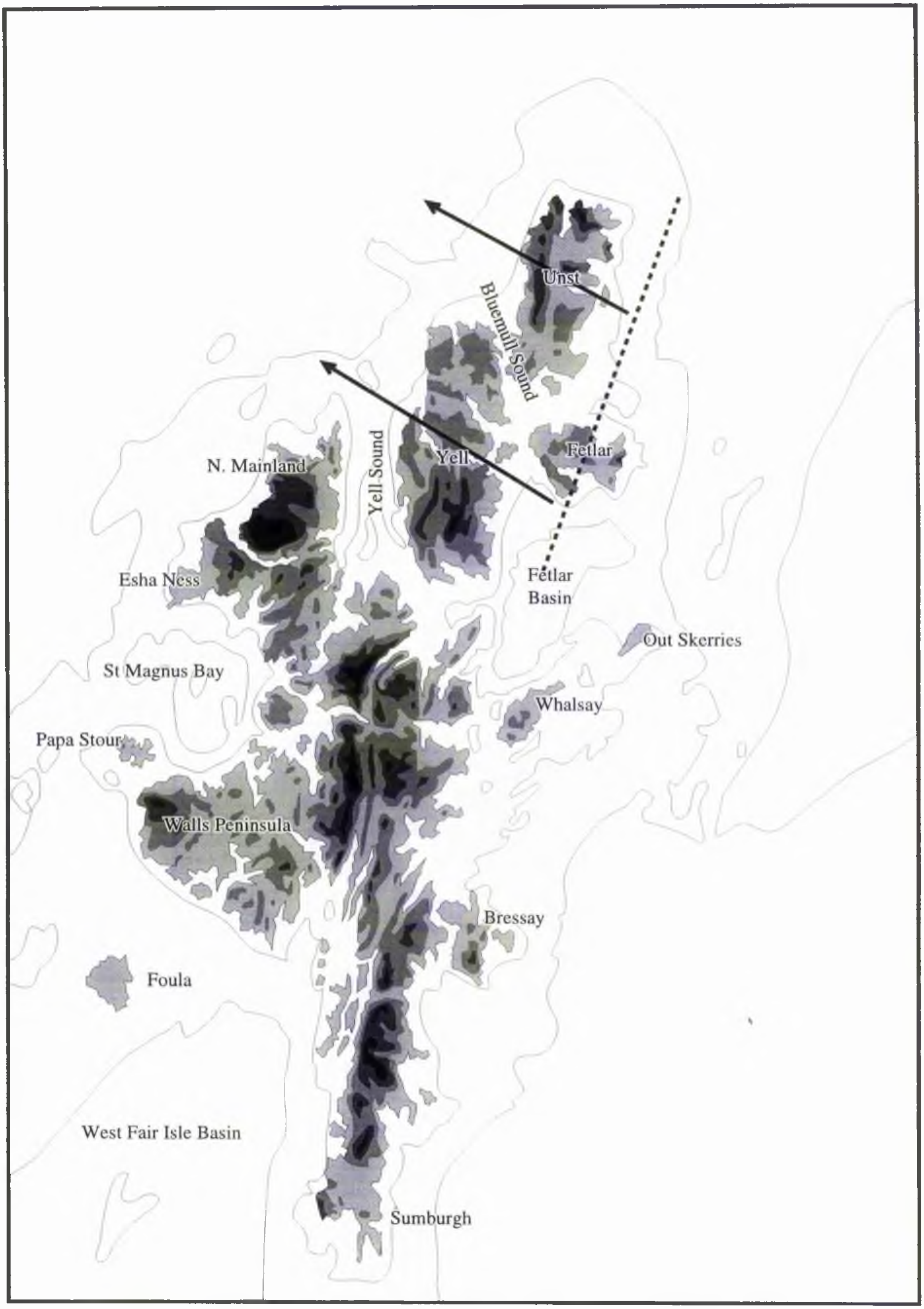


Figure 9.4. Reconstruction of early deglaciation, Unst, Yell and Fetlar, Shetland. The position of the ice shed (dashed line) is unknown but must be to the east, from which position the high ground of Unst is crossed. Ice movement shown by solid lines with arrows.

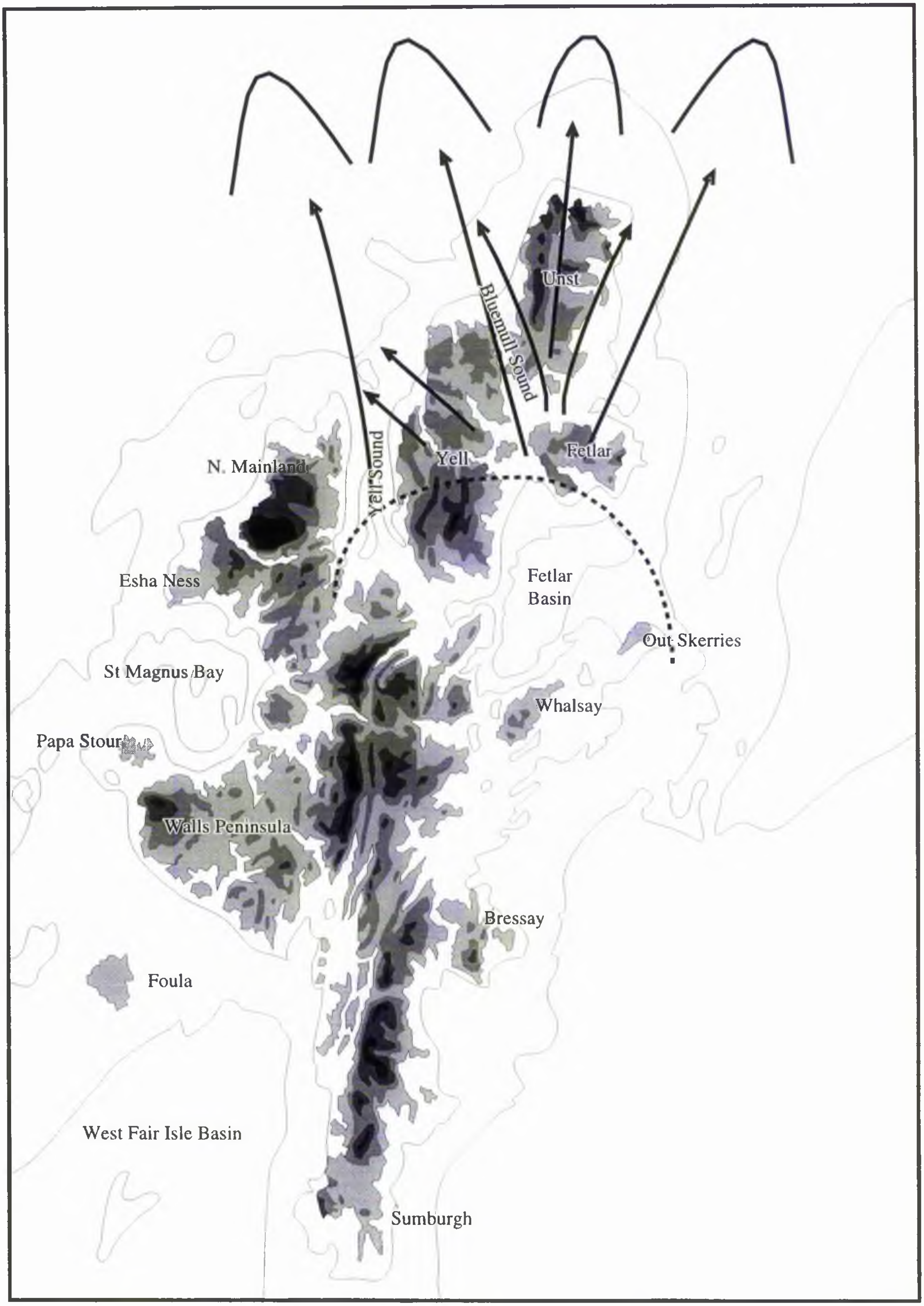


Figure 9.5. Reconstruction of early deglaciation, Unst, Yell and Fetlar, Shetland following that shown in figure 9.4. This reconstruction combines a number of elements that may not have been contemporaneous but the overall pattern strongly suggests a southwestward movement of the ice shed zone (shown by dashed line) from the position shown in figure 9.4. The northern ice margins (solid lines, no arrows) represent the possibility of a lobate pattern of stream termini, not the number or positions of them. Ice movement shown by solid lines with arrows.

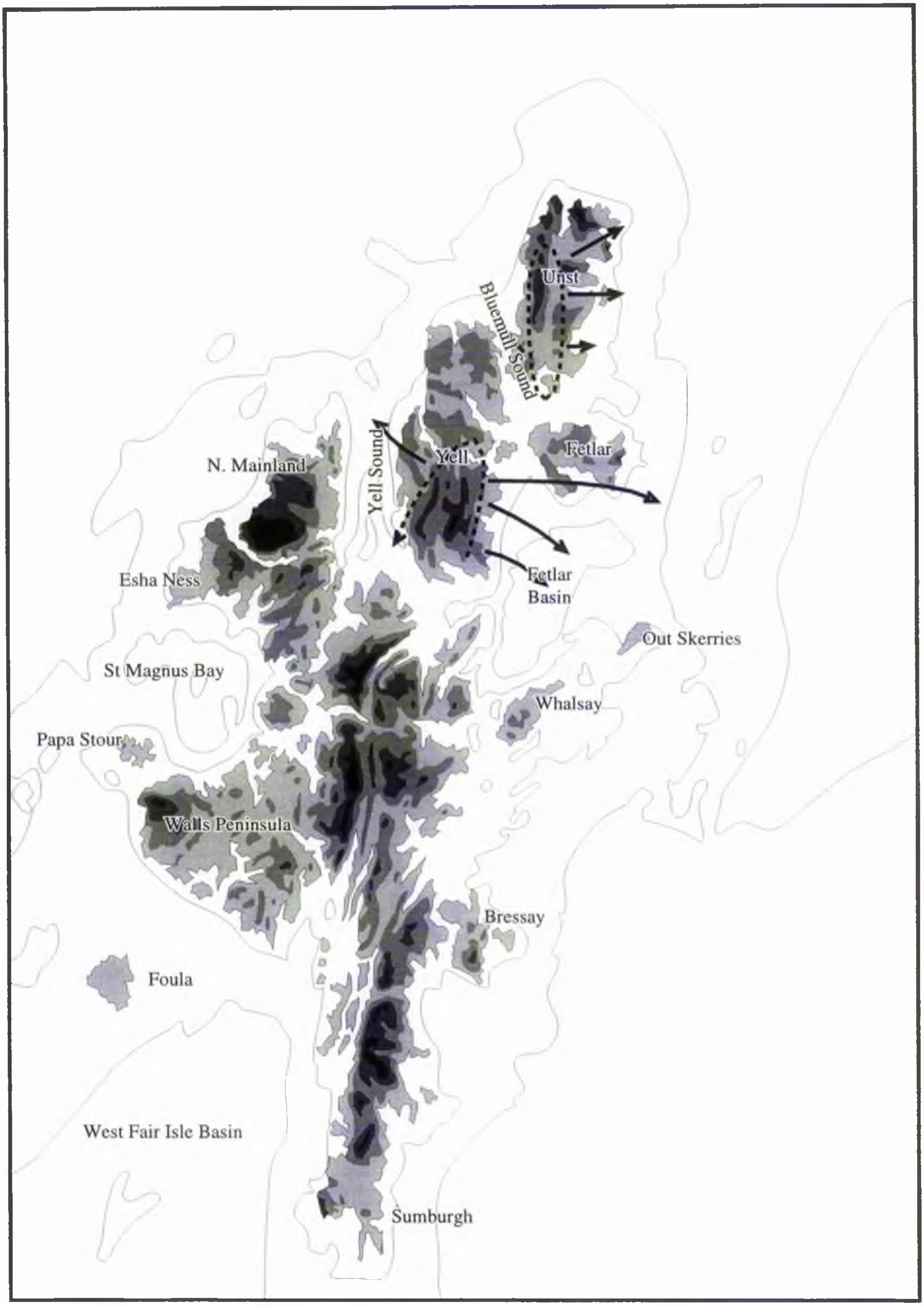


Figure 9.6. Reconstruction of final deglaciation of Unst, Yell and Fetlar, Shetland. Residual ice masses on the high ground of Yell and central Unst (dashed lines), appear to be indicated, and the pattern of flow into the topographically influential Fetlar and Unst Basins can be seen. Ice movement shown by solid lines with arrows.

9.7 Weathered bedrock and possible solifluction deposits on the east side of Saxa Vord. Unst. Shetland. (HP6515)

9.8 Metamorphic erratic in thin diamict developed on Lamba Ness granite. east of Saxa Vord. Unst. Shetland. (HP663168)

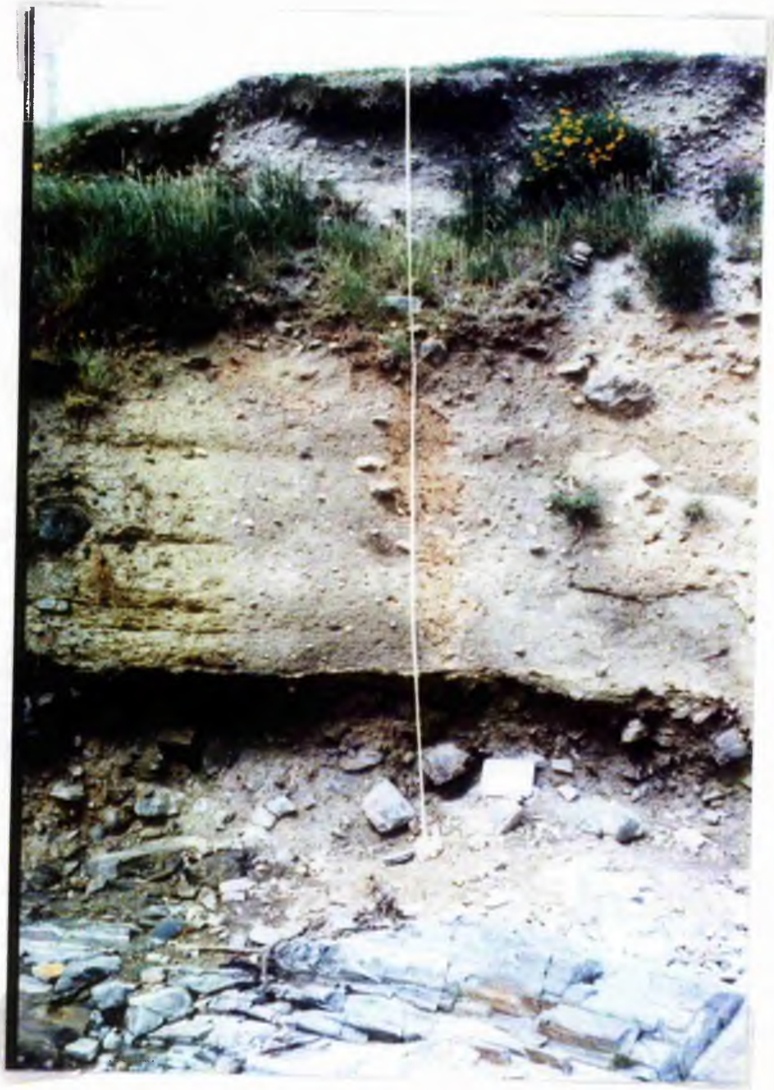
9.9 Meltwater channels on the side of Herma Ness, as seen from Saxa Vord to the east, Unst, Shetland. (HP612148)

9.10 Section through the sequence of sediments incised by Milldale Burn, Unst, Shetland. (HP597142)

9.11 Lower unit of sequence of sediments incised by Milldale Burn, Unst, Shetland. (HP597142)

9.12 Upper unit of sequence of sediments incised by Milldale Burn, Unst, Shetland. (HP597142)

9.13 Kussa Waters, Yell, Shetland, showing Flinn's (1983) proposed glacial lake shoreline. (HP518029)



9.14 Lodgement till on glacitectonized bedrock, Bay of Brough, Yell, Shetland. (HP538048)

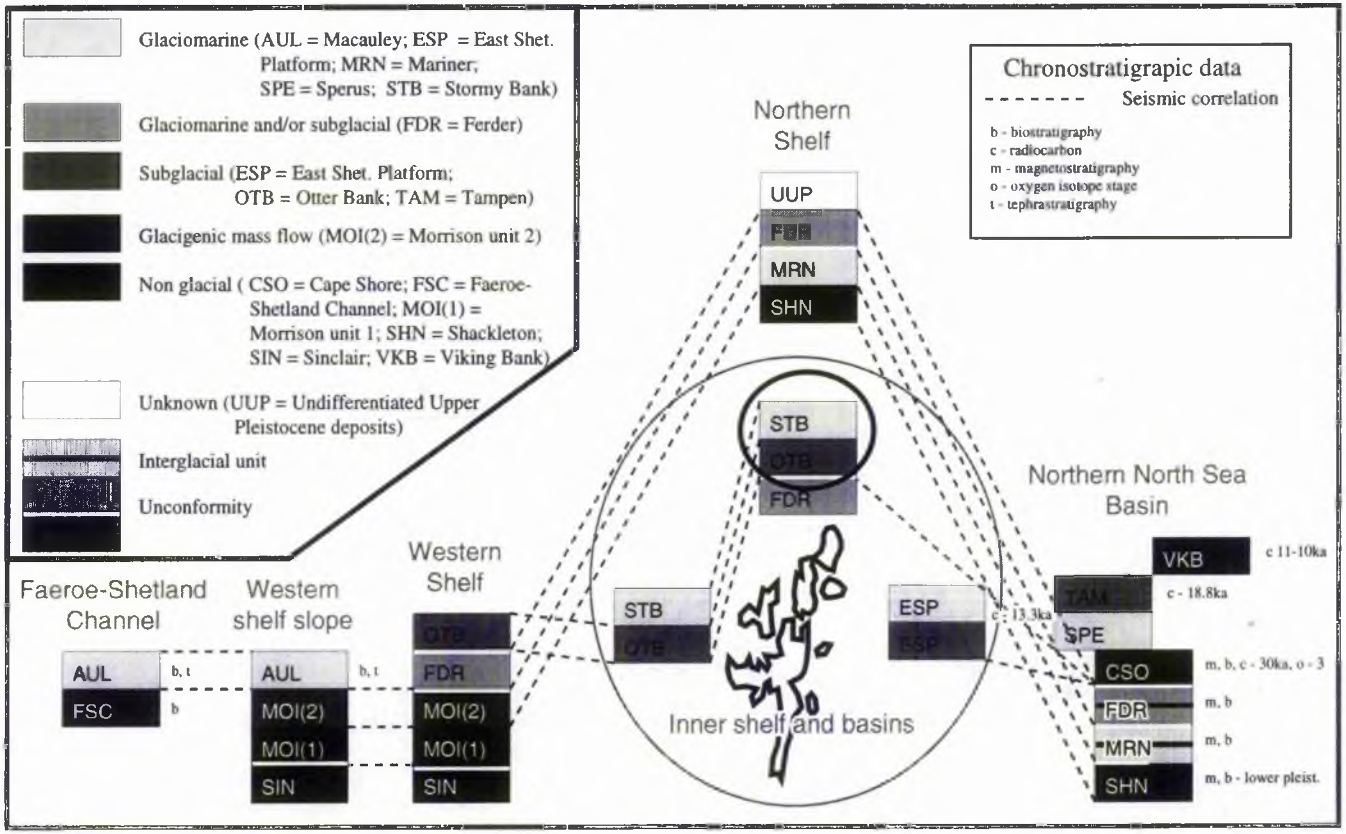


Figure 10.1. Schematic outline of British Geological Survey Quaternary stratigraphy around Shetland, including chronostratigraphic control. The location of the cores investigated in this study is circled in black.

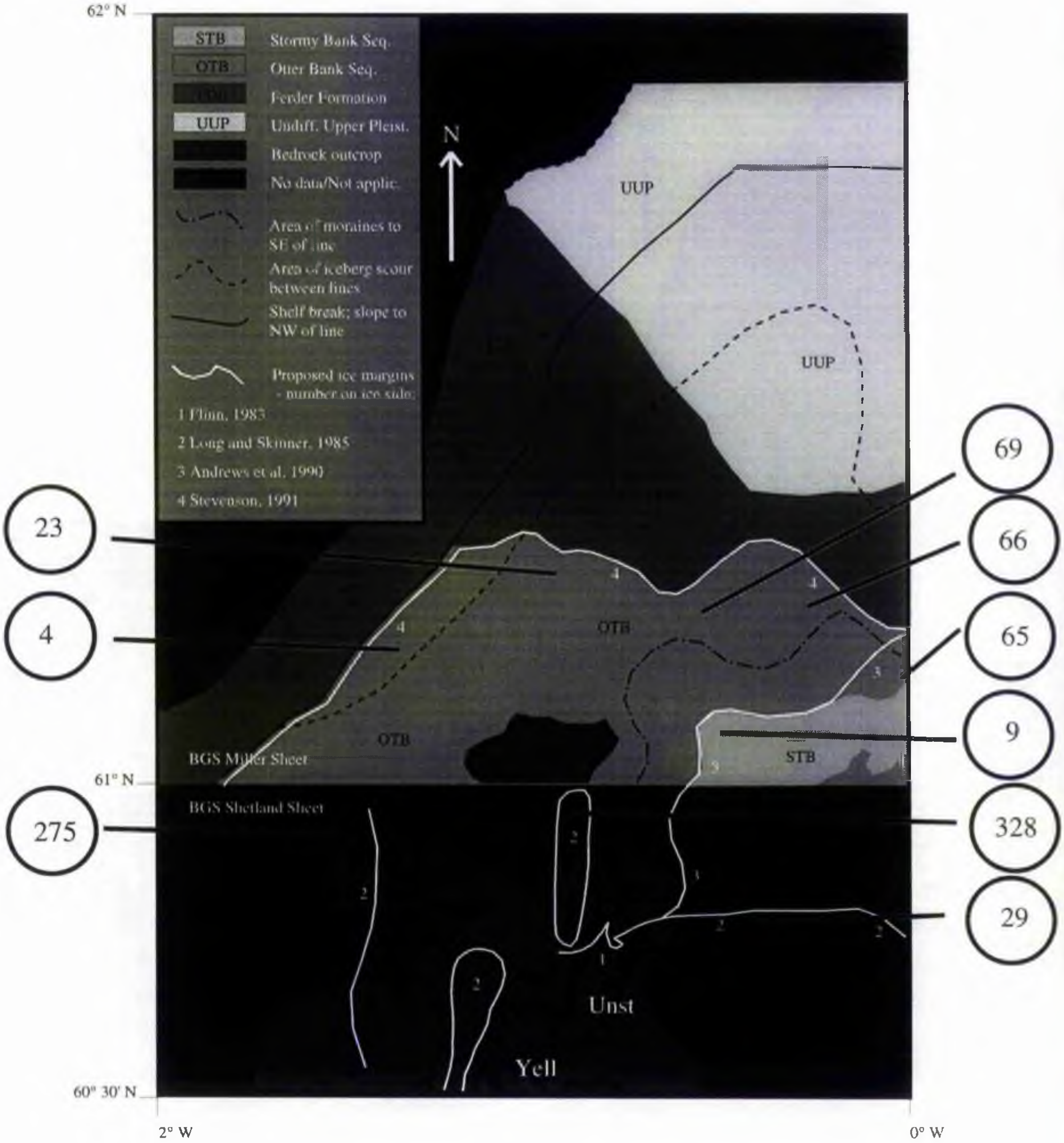


Figure 10.2. Location of this study's sample sites in British Geological Survey Miller and Shetland areas, north of Shetland, with various proposed maximum ice margins.

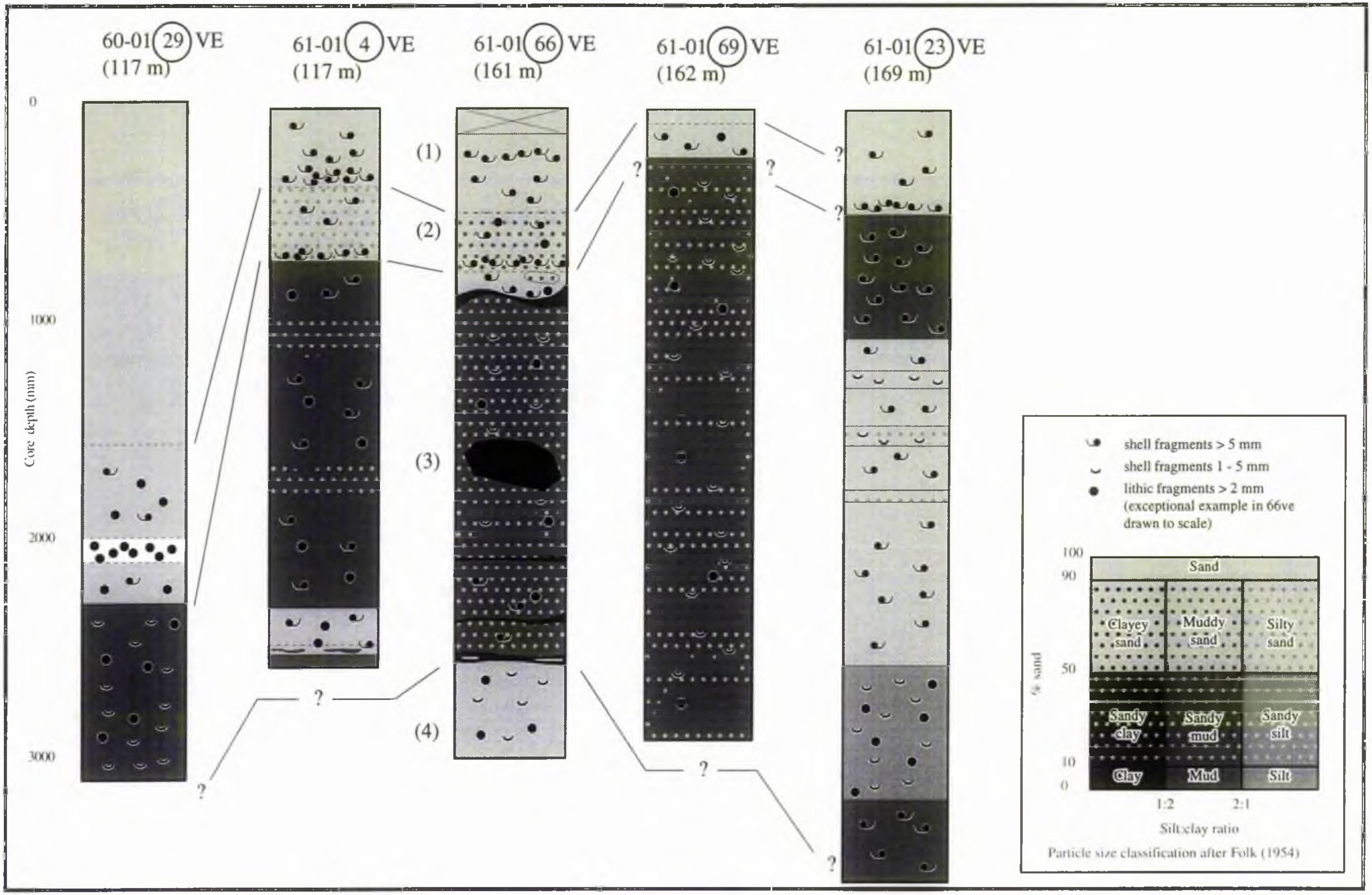


Figure 10.3. Summary vibrocore logs with probable lithostratigraphic ties: (1) coarse shelly sands (Holocene); (2) oscillation marked by ameliorative shell lag at base (Lateglacial); (3) glacimarine muddy sands and sandy muds (Late Weichselian); (4) subglacial/proximal glacimarine (Late Weichselian). Left to right is approximately North to South but there is no clear proximal to distal relationship (see figure 10.2 for core locations). Water depth in brackets.

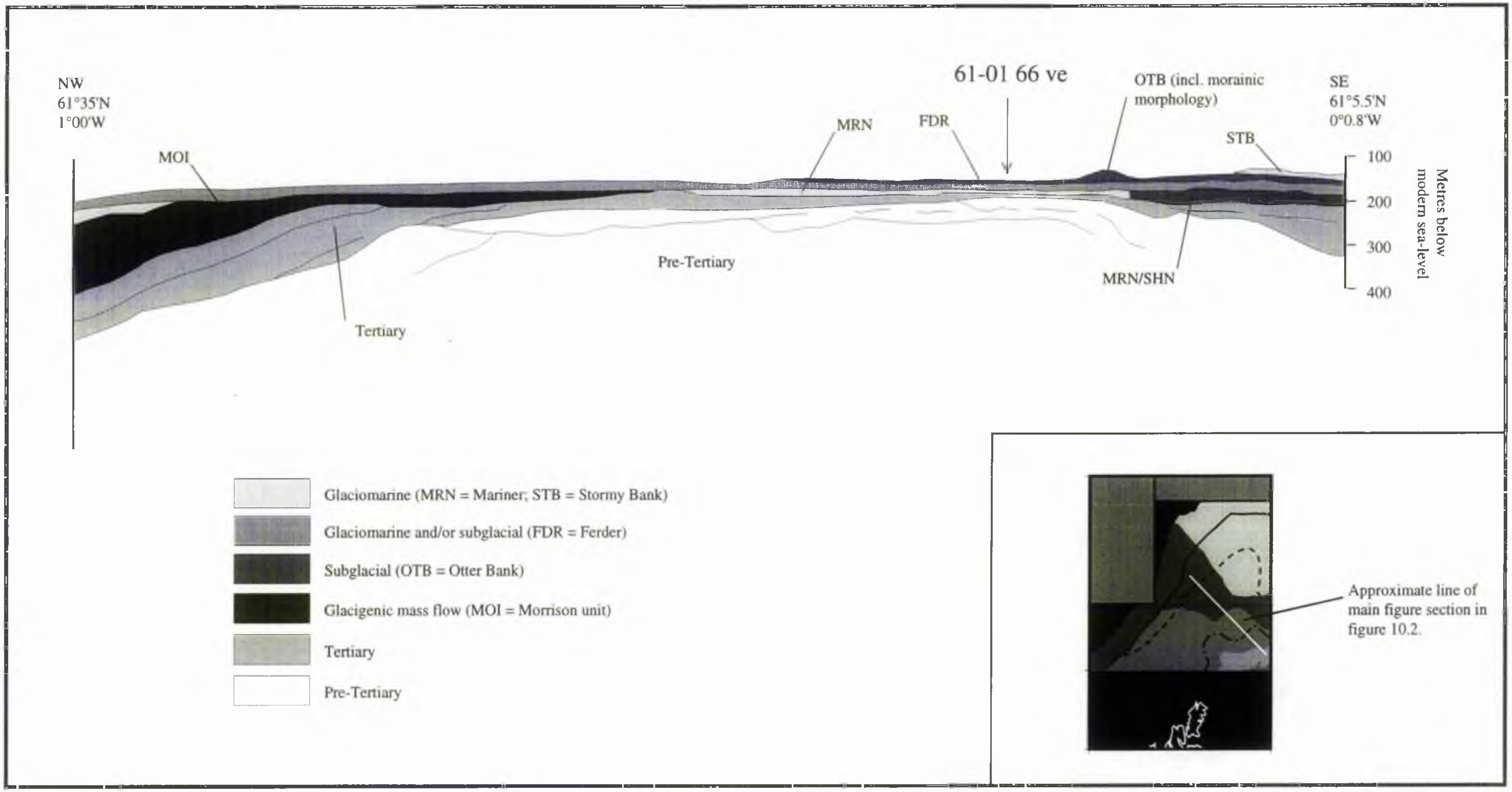
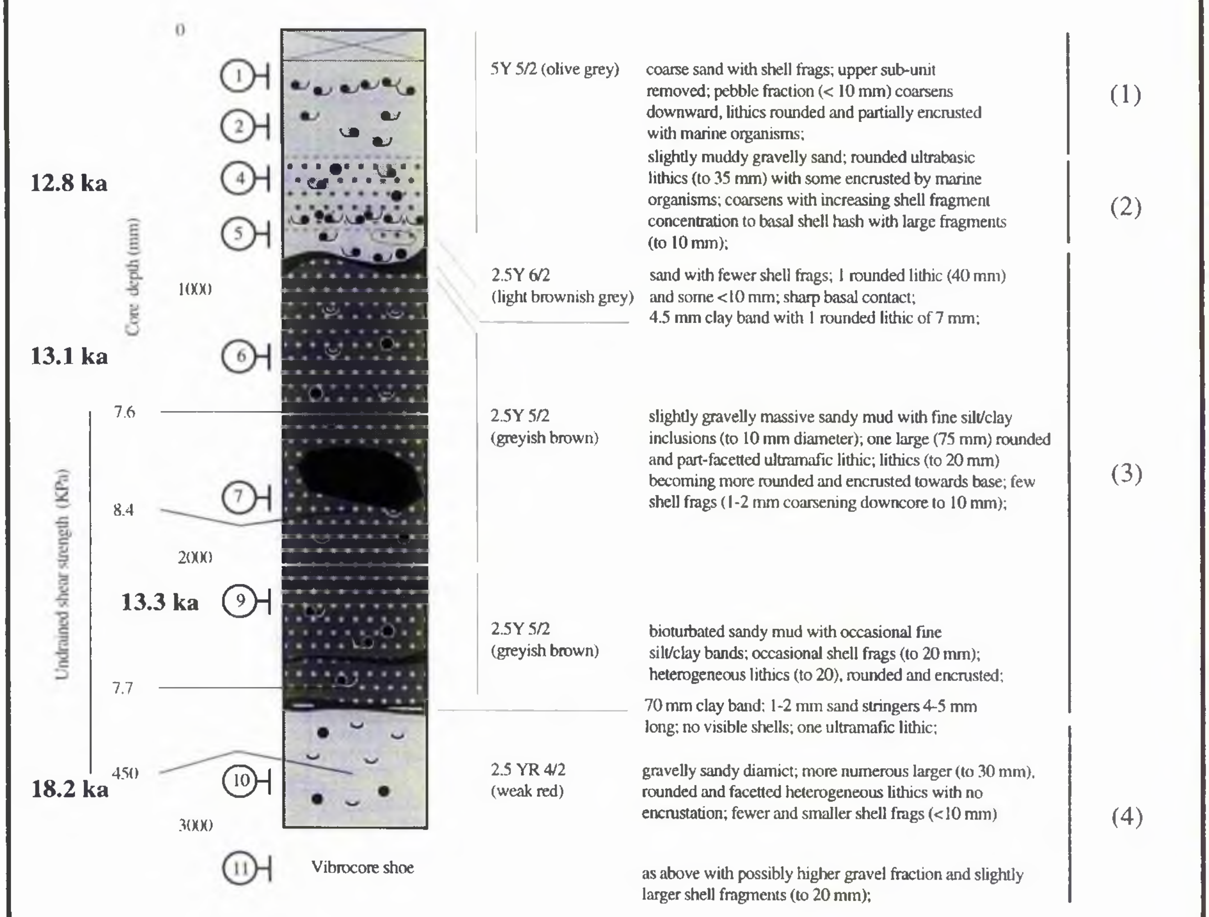


Figure 10.4. Seismic section across study area after Stevenson (1991). Inset shows position of section from figure 2. Vertical exaggeration is x25. Vibrocore 61-01 66ve lies directly on this seismic line at theposition indicated. Stormy Bank sequence (STB) glacimarine deposits extend further across the shelf area but beyond the area shown here and in figure 2 are too thin to be resolved at this seismic resolution (approx. 5 m).

61-01 66 VE (water depth: 161 m)



5Y 5/2 (olive grey)	coarse sand with shell frags; upper sub-unit removed; pebble fraction (< 10 mm) coarsens downward, lithics rounded and partially encrusted with marine organisms;	(1)
	slightly muddy gravelly sand; rounded ultrabasic lithics (to 35 mm) with some encrusted by marine organisms; coarsens with increasing shell fragment concentration to basal shell hash with large fragments (to 10 mm);	(2)
2.5Y 6/2 (light brownish grey)	sand with fewer shell frags; 1 rounded lithic (40 mm) and some <10 mm; sharp basal contact; 4.5 mm clay band with 1 rounded lithic of 7 mm;	(3)
2.5Y 5/2 (greyish brown)	slightly gravelly massive sandy mud with fine silt/clay inclusions (to 10 mm diameter); one large (75 mm) rounded and part-facetted ultramafic lithic; lithics (to 20 mm) becoming more rounded and encrusted towards base; few shell frags (1-2 mm coarsening downcore to 10 mm);	
2.5Y 5/2 (greyish brown)	bioturbated sandy mud with occasional fine silt/clay bands; occasional shell frags (to 20 mm); heterogeneous lithics (to 20), rounded and encrusted; 70 mm clay band; 1-2 mm sand stringers 4-5 mm long; no visible shells; one ultramafic lithic;	
2.5 YR 4/2 (weak red)	gravelly sandy diamict; more numerous larger (to 30 mm), rounded and facetted heterogeneous lithics with no encrustation; fewer and smaller shell frags (<10 mm)	(4)
	as above with possibly higher gravel fraction and slightly larger shell fragments (to 20 mm);	

Figure 10.5. Vibrocore 61-01 66VE. Sampling point numbers circled in black and the vertical bar represents the100 mm section of half core taken as a sample. Probable chronostratigraphic units numbered in brackets: (1) Holocene; (2) Lateglacial oscillation; (3) Late Weichselian glacimarine; (4) Late Weichselian proximal glacimarine/sub glacial. Radiocarbon determinations are shown in bold to the left of the sample location.

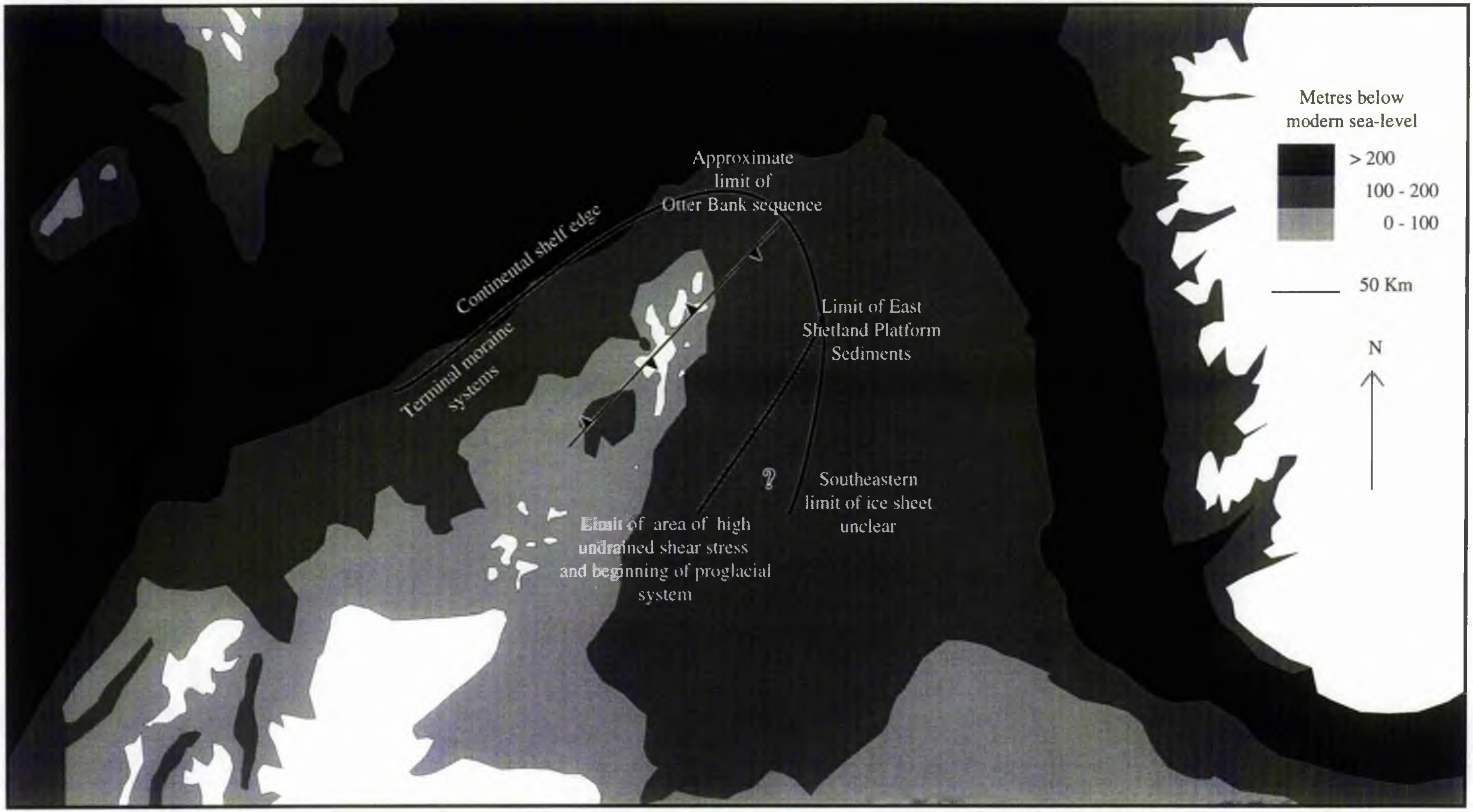
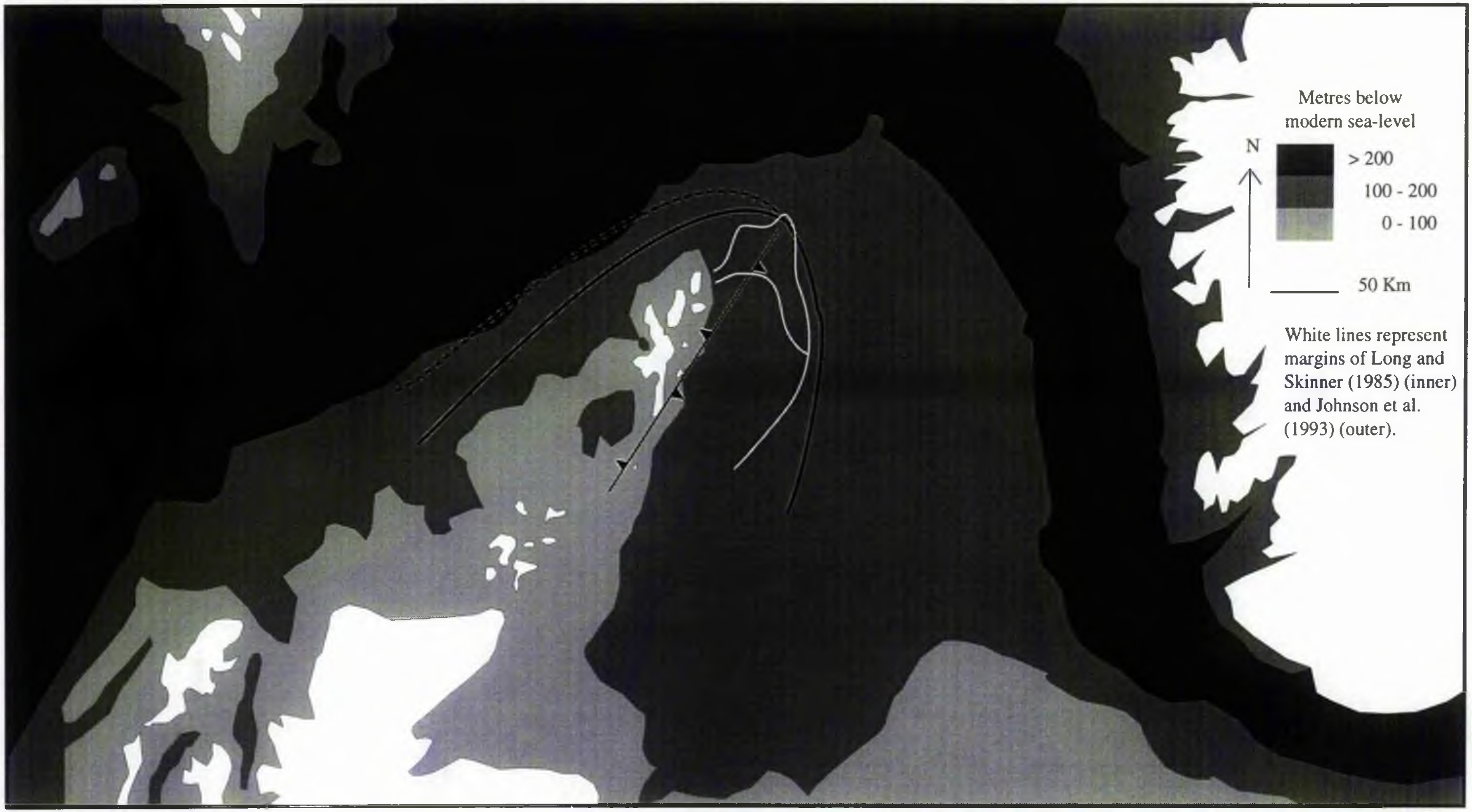


Figure 11.1. Suggested maximum limit of last ice sheet with associated evidence. There is possible evidence that ice tongues extended beyond the shelf edge in restricted areas (D. Long pers. comm. 1995) but the uppermost slope deposits are generally reworked glacigenic slope sediments. Note the relationship with the Scottish ice sheet is not known and neither is the southeastern limit. Sources for ice limit: Johnson et al., 1993; Stevenson, 1991; Stoker et al., 1993; Long, 1988; Evans et al., 1990.



White lines represent margins of Long and Skinner (1985) (inner) and Johnson et al. (1993) (outer).

Figure 11.2 Reconstruction of early deglaciation resulting in eastern migration of the main ice shed. It can be seen from the bathymmetric assymetry that sea level rise causes immediate glacimarine ablation of the western and northwestern margins earlier than northeastern and eastern margins (previous northwstern margin shown by dashed line - see figure 11.1 - new schematic margin shown by solid black line). Significant western deglaciation and little or no eastern deglacation would result in an eastern shift of the ice shed. Its exact position is not clear because with northern deglaciation a single plane ice shed reconstruction is highly simplistic.and a more southerly shift in ice shed might be anticipated. Note the eastern ice limits of Long and Skinner (1985) and Johnson et al. (1993) (white lines). If these represent distinct periods of stasis, then their confluence to the east supports the earlier northern deglaciation theory.

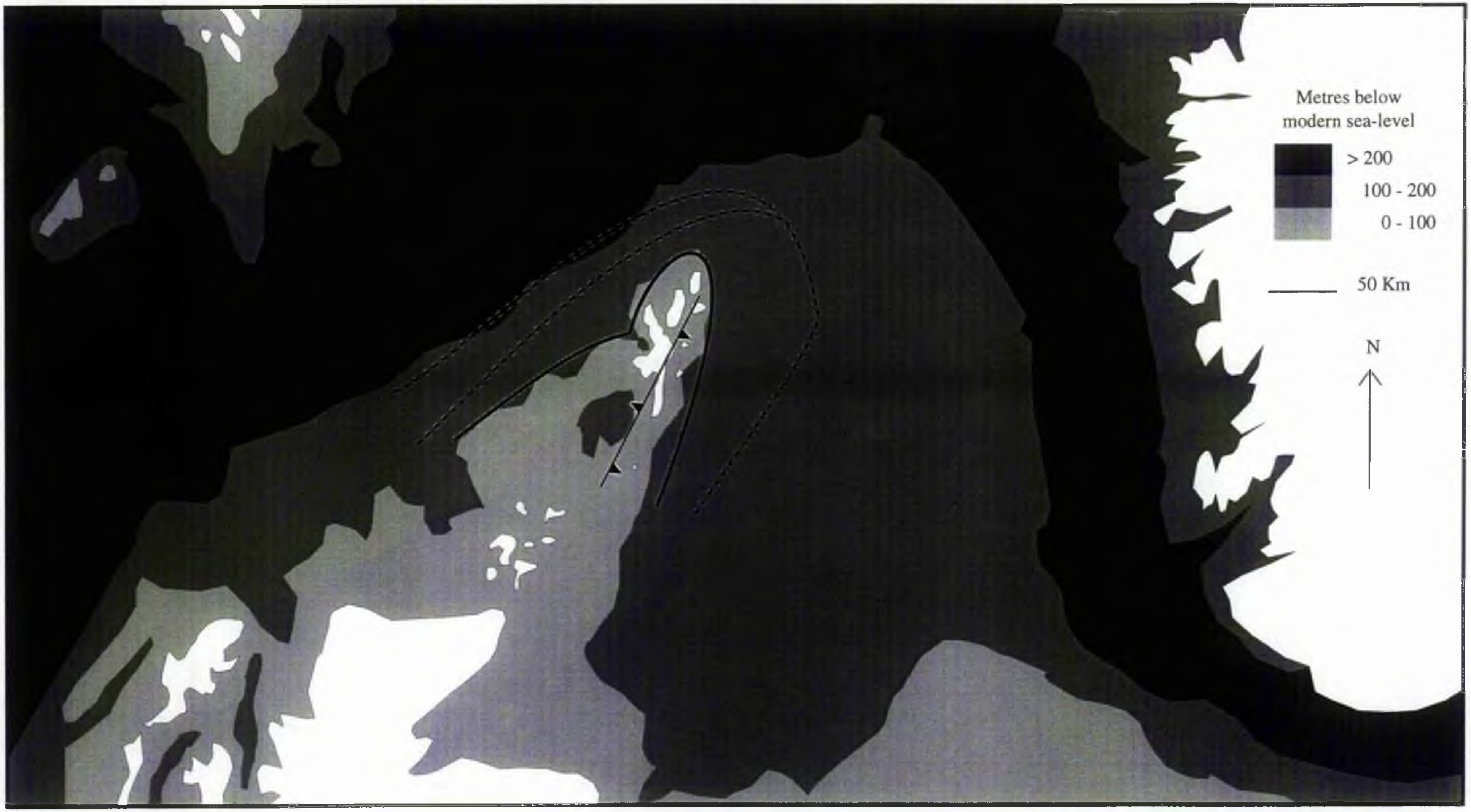


Figure 11.3. Reconstruction of glaciation as sea level rises to -100 m. This is approximately the position at which glacimarine deposits cease and possible sea-bed morainic morphology occurs. Note the continued assymmetry of the ice sheet across southern Mainland and the resultant ice shed marginally to the west of the peninsula. It is still to the west of Fair Isle but has shifted to a more directly western position (in figures 11.1 and 11.2 it is more northwest). Previous margins shown by dashed lines (see figures 11.1 and 11.2).

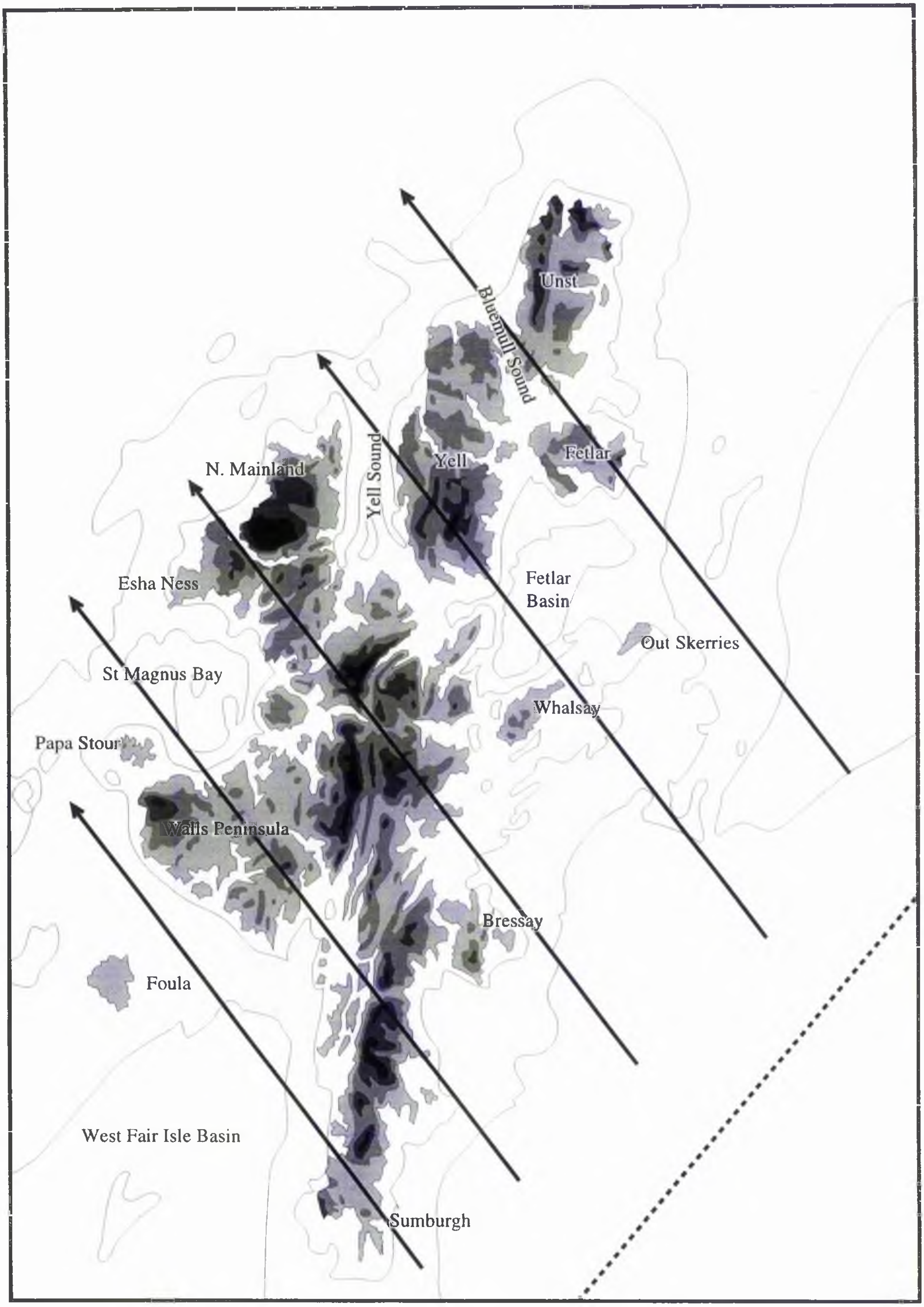


Figure 11.4. Reconstruction of glacial maximum/early deglaciation of Shetland. Differences in ablation between east and west result in the eastward movement of the ice shed (dashed line) on the continental shelf. Ice movement (solid lines with arrows) is perpendicular to the continental shelf edge (i.e. the ice margin). The exact position of the ice shed is not known.

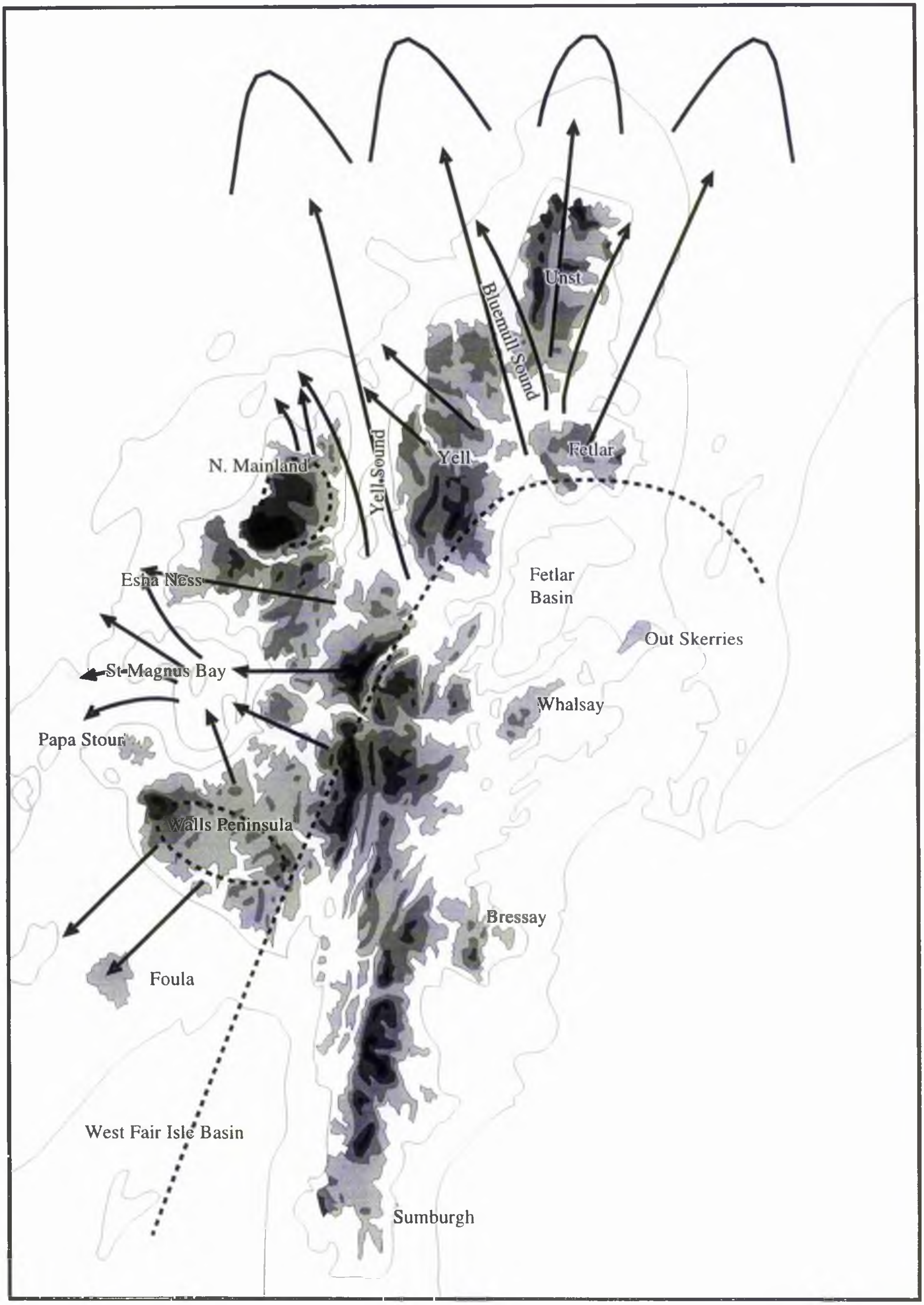


Figure 11.5. Reconstruction of deglaciation of Shetland following that shown in figure 11.4. Deglaciation at northern margins results in the southward movement of the ice shed zone (dashed lines) but it continues to remain largely east of central Mainland (and possibly south Mainland). Reduced surface elevations resulted in greater topographic containment, ice streaming and possibly the development of ice centres (dashed lines) on the Ronas Hill Plateau and Walls peninsula. Ice movement shown by solid lines with arrows.

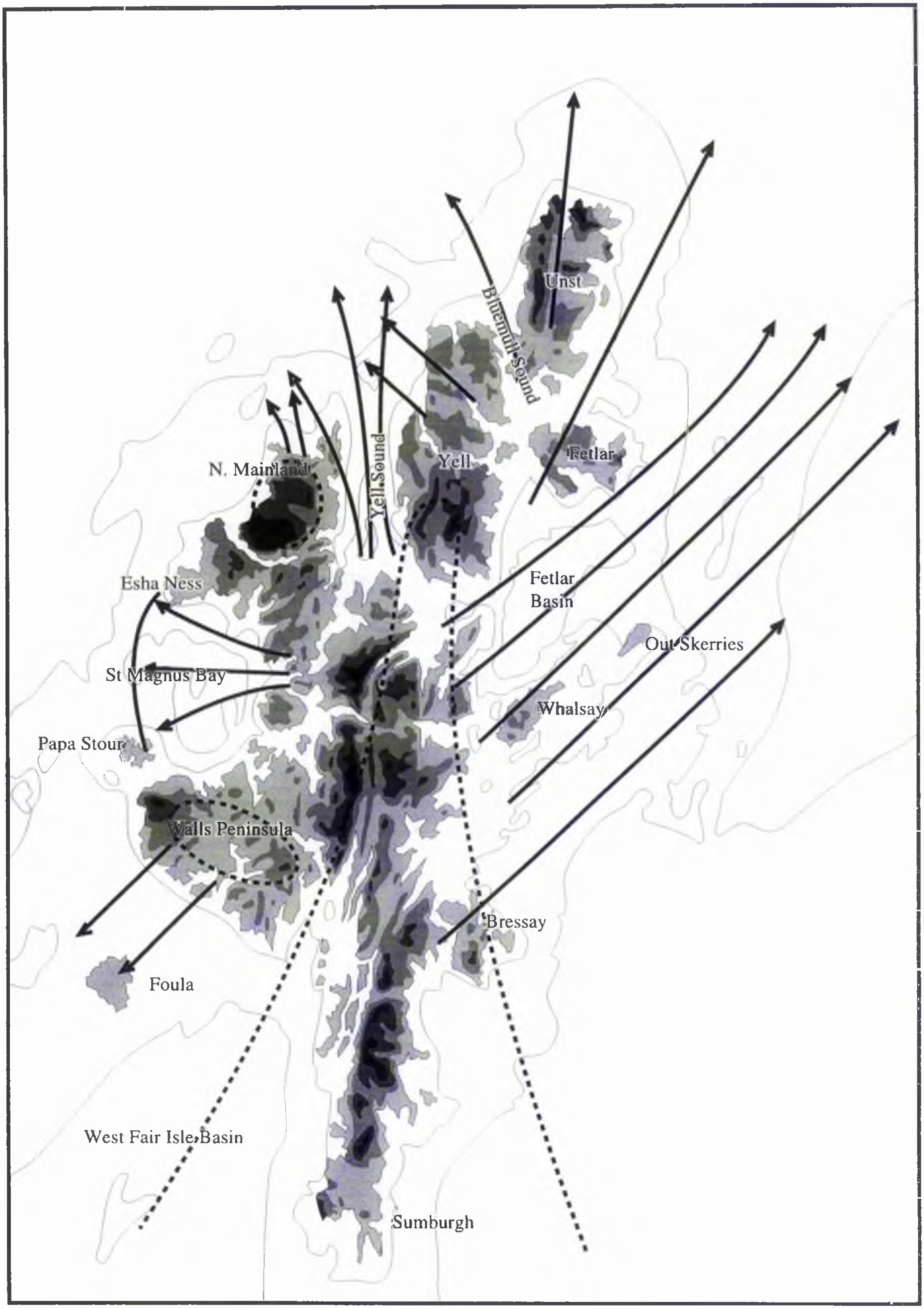


Figure 11.6. Reconstruction of deglaciation of Shetland following that shown in figure 11.5. Deglaciation at northeastern and eastern margins results in the westward movement of the ice shed over central Mainland (less so for south Mainland). Ice shed zones shown by dashed lines. Ice movement shown by solid lines with arrows. Ice margins shown by solid lines, no arrows.

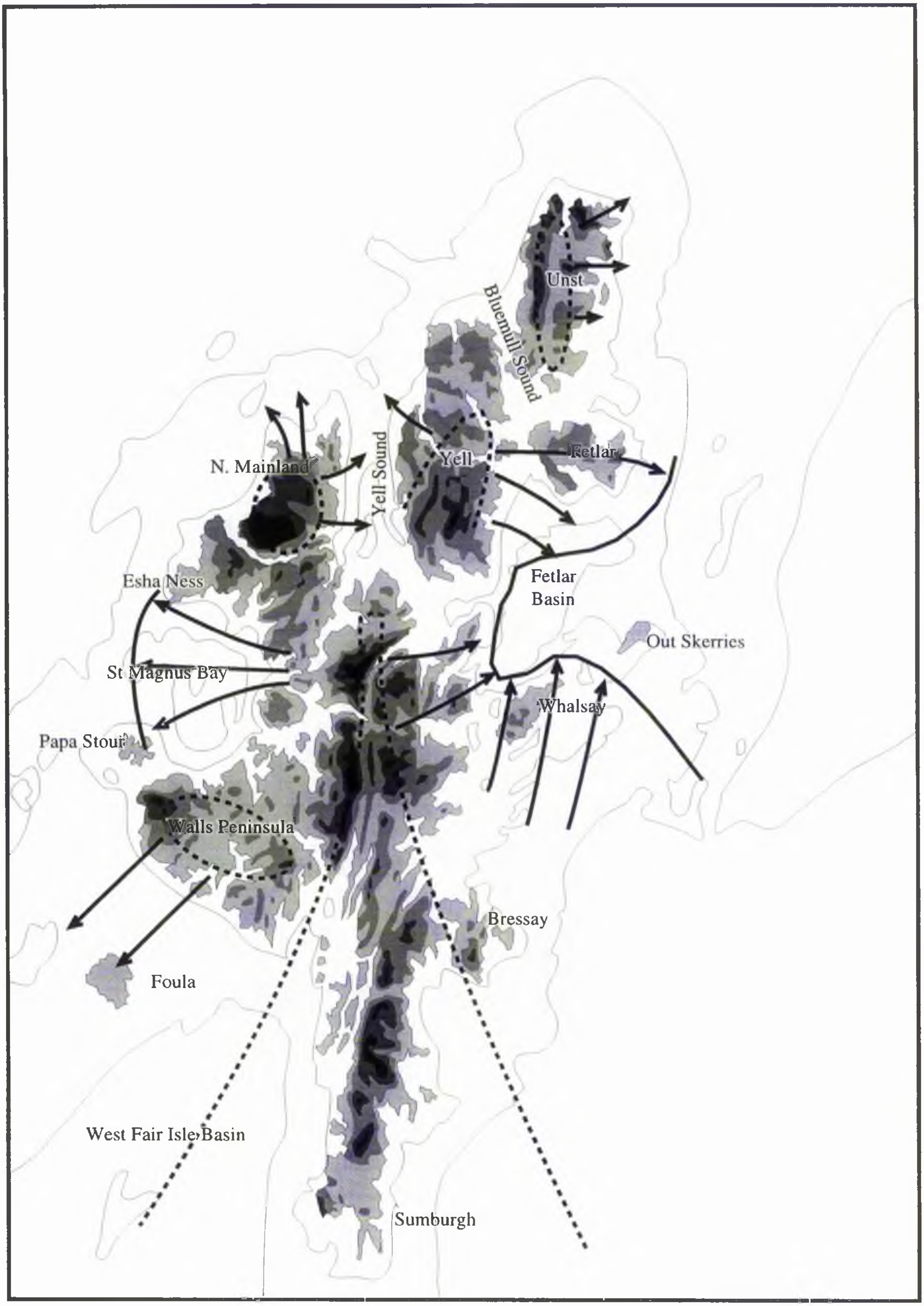


Figure 11.7. Reconstruction of deglaciation of Shetland following that shown in figure 11.6. Deglaciation at eastern margins is now evident in patterns of ice movement, but the ice shed is still substantial over the south. Remnant ice sheds over the Walls peninsula, Ronas Plateau, Unst and Yell may be present at this tim. Hypothesised ice shed zones and ice centres shown by dashed lines. Ice movement shown by solid lines with arrows. Hypothesised ice margins shown by solid lines, no arrows.

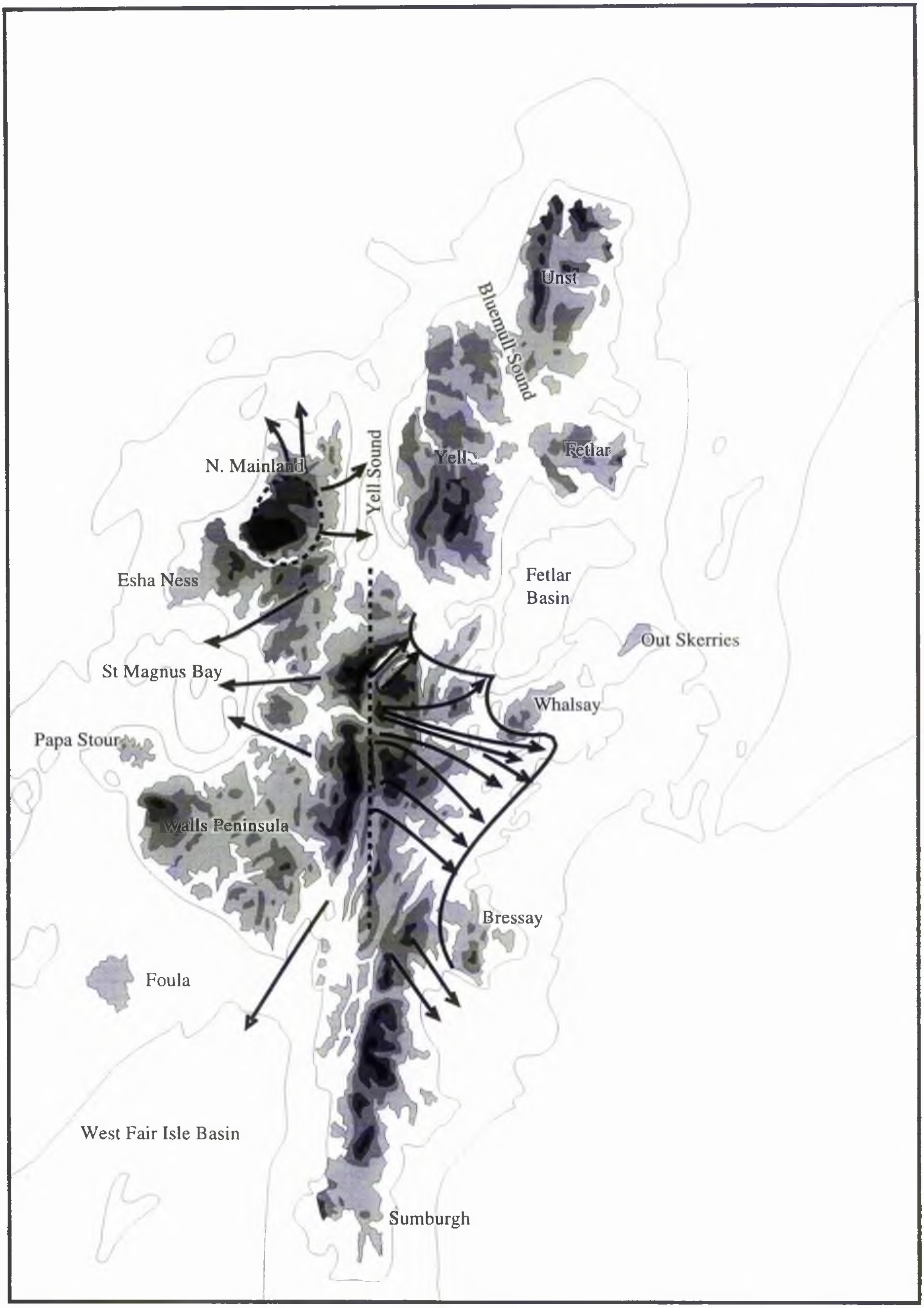


Figure 11.8. Reconstruction of deglaciation of Shetland following that shown in figure 11.7. Deglaciation at southeastern and southwestern margins now results in radial retreat to a core ice shed located over the central Mainland high ground. The Ronas Plateau ice cap probably persisted beyond this stage but it is not clear whether any other remnant ice caps existed. Ice sheds and ice centres shown by dashed lines. Ice movement shown by solid lines with arrows. Hypothesised ice margins shown by solid lines, no arrows.

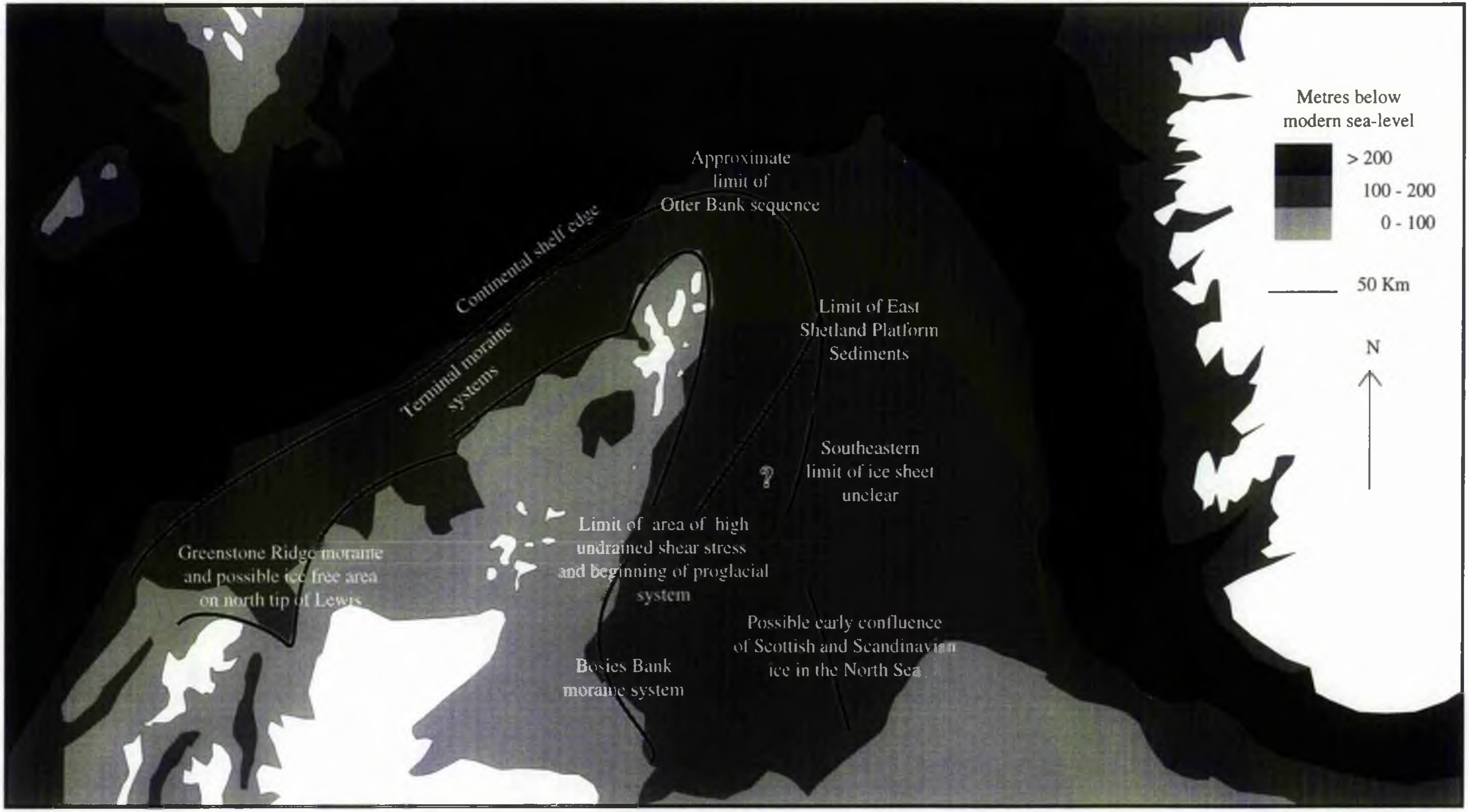


Figure 11.9. Possible extension of the resonstruction of the last glaciation of Shetland to include the Scottish ice sheet. The Shetland ice sheet is seen as a peninsular extension of the glaciation centred on Scotland, projecting out onto the northern continental shelf. While the maximum reached the continental shelf edge (and may have been confluent with Scandinavian ice to the east) the -100m bathymmetric contour may represent a grounding position during deglaciation that resulted in the establishment of a more restricted stable margin. Since deglaciation would have occurred first from the west and northwest, the ice shed may have moved east, possibly to the east of Shetland, Orkney and Caithness. Looking at the Shetland ice sheet as a peninsular extension of the Scottish explains why its ice shed remained in a southerly position until a late stage in deglaciation and also has implications for the routing and timing of warm, north Atlantic water incursions into the North Sea such as at the end of the last glaciation.