A Reconstruction of the Eastern Margin of the late Weichselian Ice Sheet in Northern Britain

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Doctor of Philosophy

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1991

CONTENTS

(VOLUME II)

ADDENDUM

Subsequent to the examination of this thesis, the following figures have been enlarged and are presented in the enclosure pocket in Volume II. The relevant figures have been marked in the text as shown:

Fig. 3.25*
Fig. 3.30*
Fig. 3.32*

Figure 3.39, which was omitted, is also in the enclosure pocket.

F. Stewart

3rd June 1991

FIGURES

(Volume II)

TABLES

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PLATES

(Volume II)

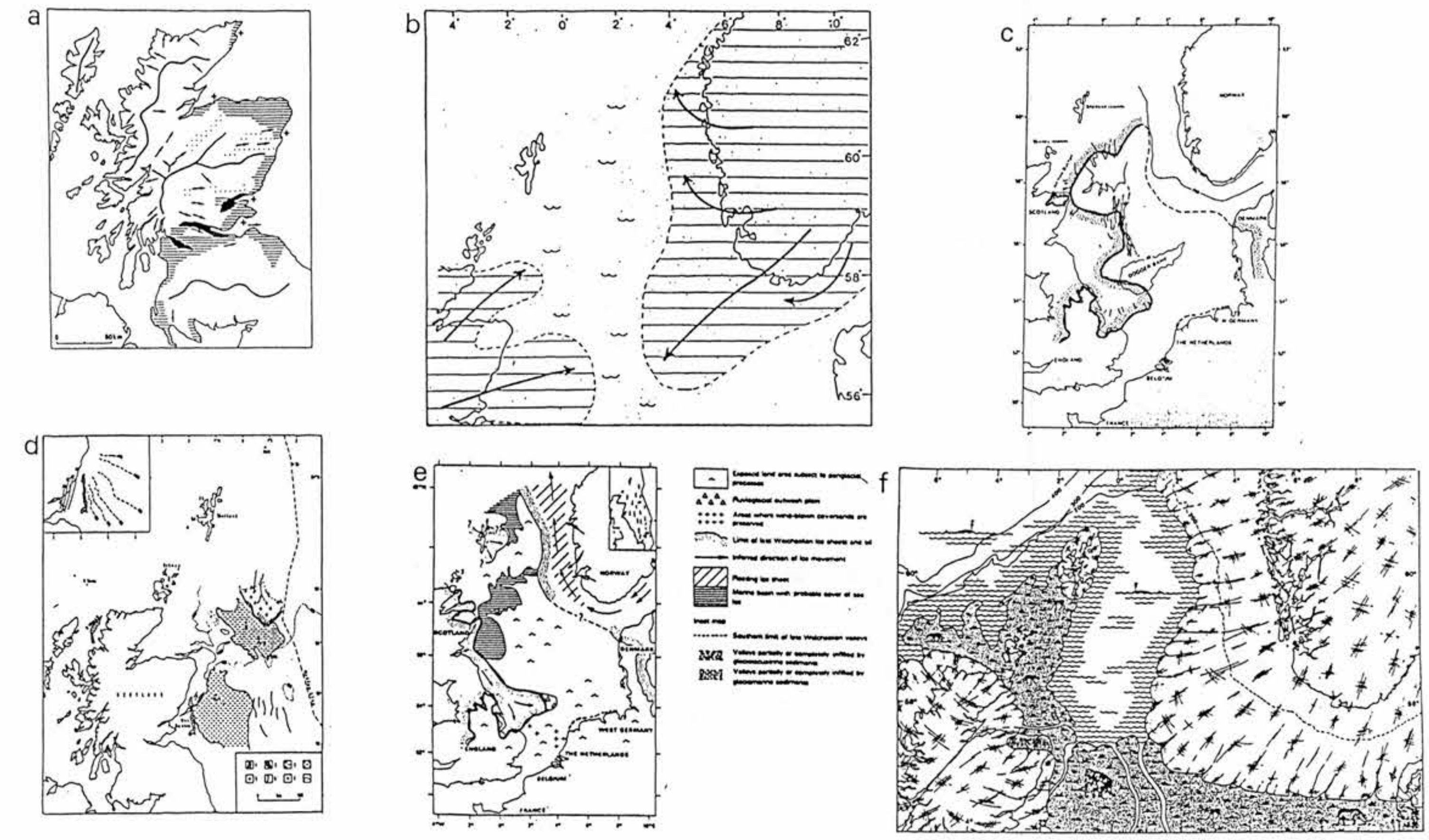
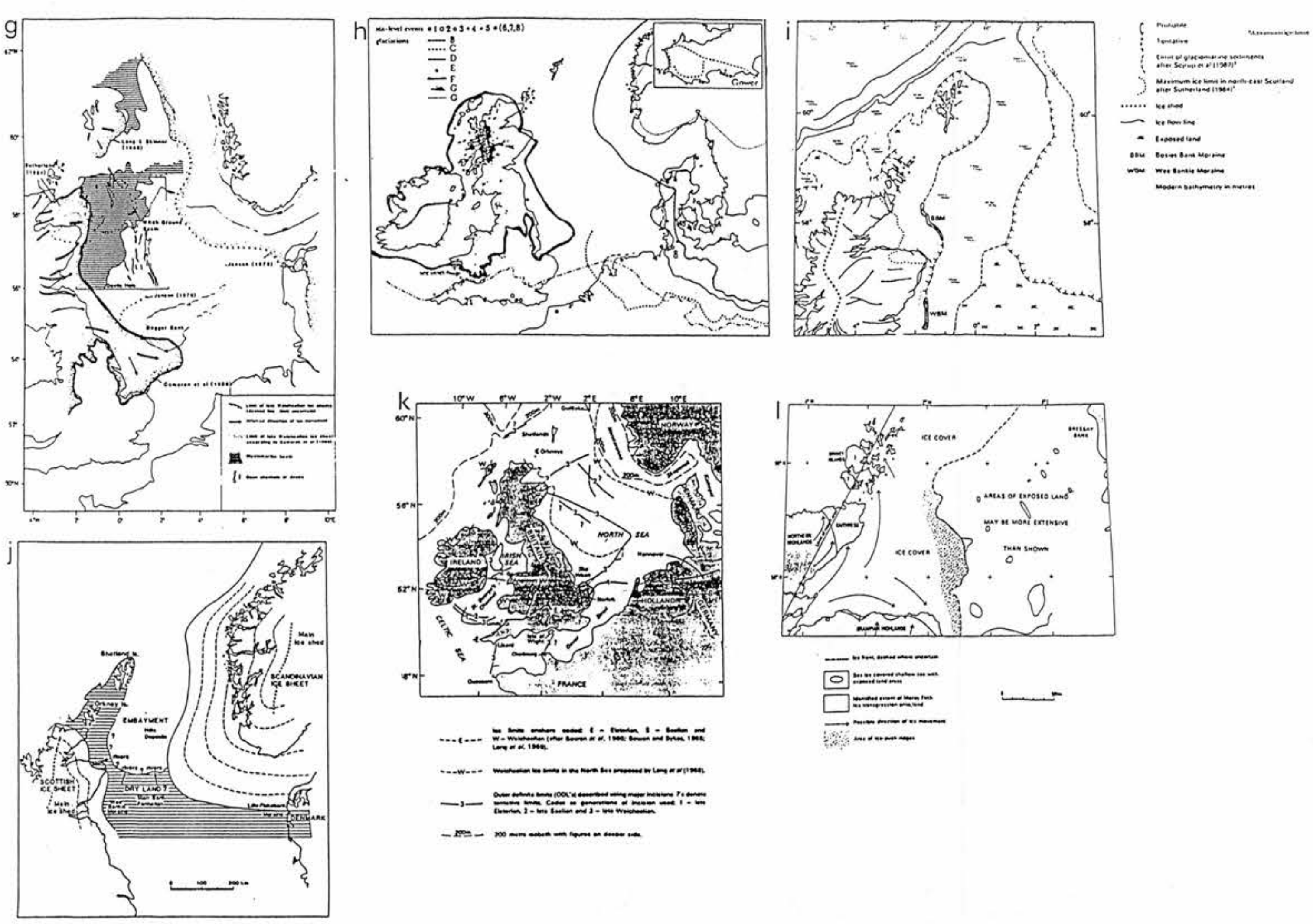
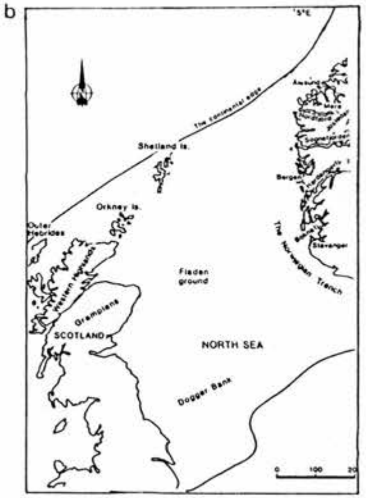


FIGURE 1.1b Reconstructions of limited ice extent of the late Weichselian ice sheet: a) Jamieson 1867, b) Redding 1976, c) Jansen *et al.* 1979, d) Sutherland 1984, e) Cameron *et al.* 1986, f) Sejrup *et al.* 1987, g) Bent 1986, h) Bowen 1988, i) Hall and Bent 1990 j) Nesje and Sejrup 1988 k) Ehlers 1990 and l) Andrews *et al* 1991.



a

b



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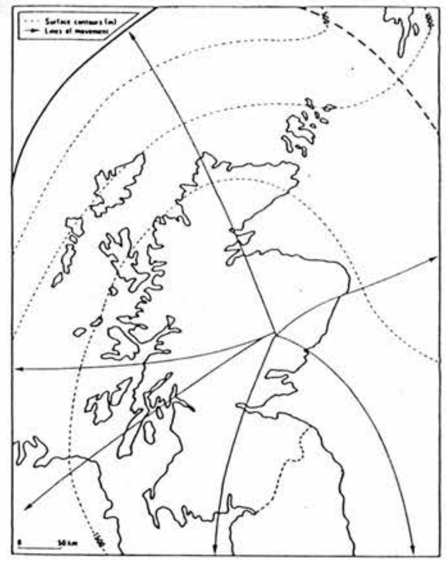

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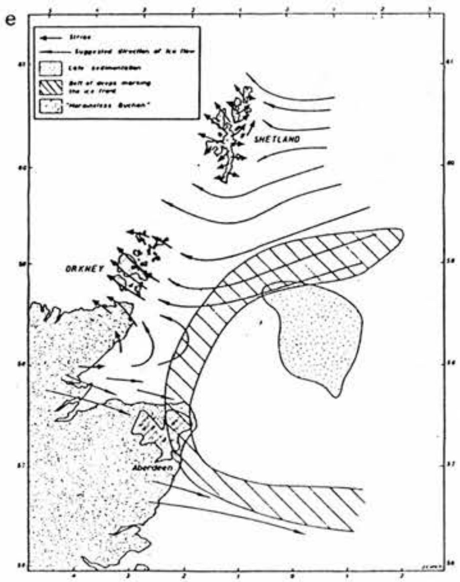
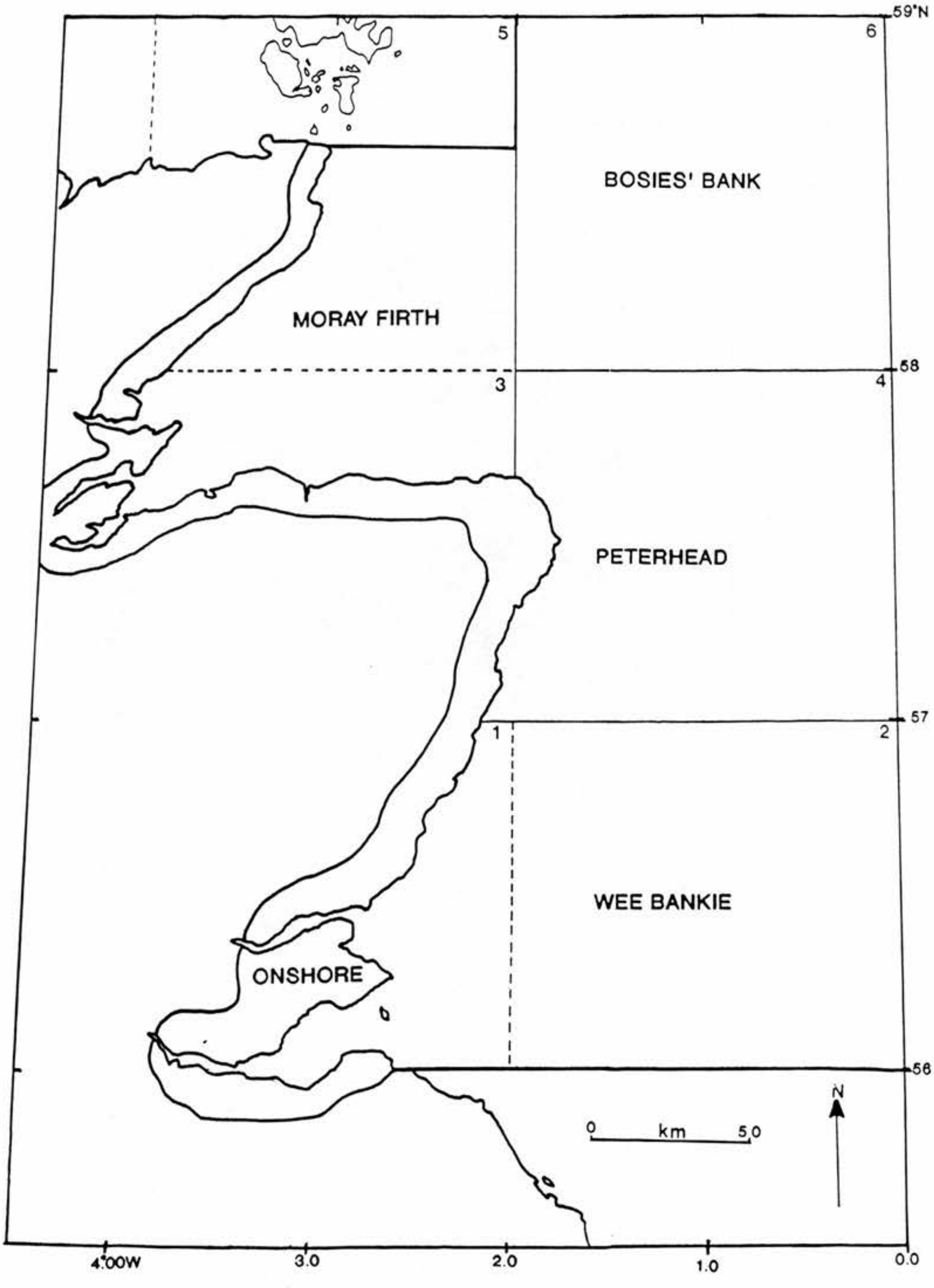


FIGURE 1.1a Reconstructions of the late Weichselian ice sheet:

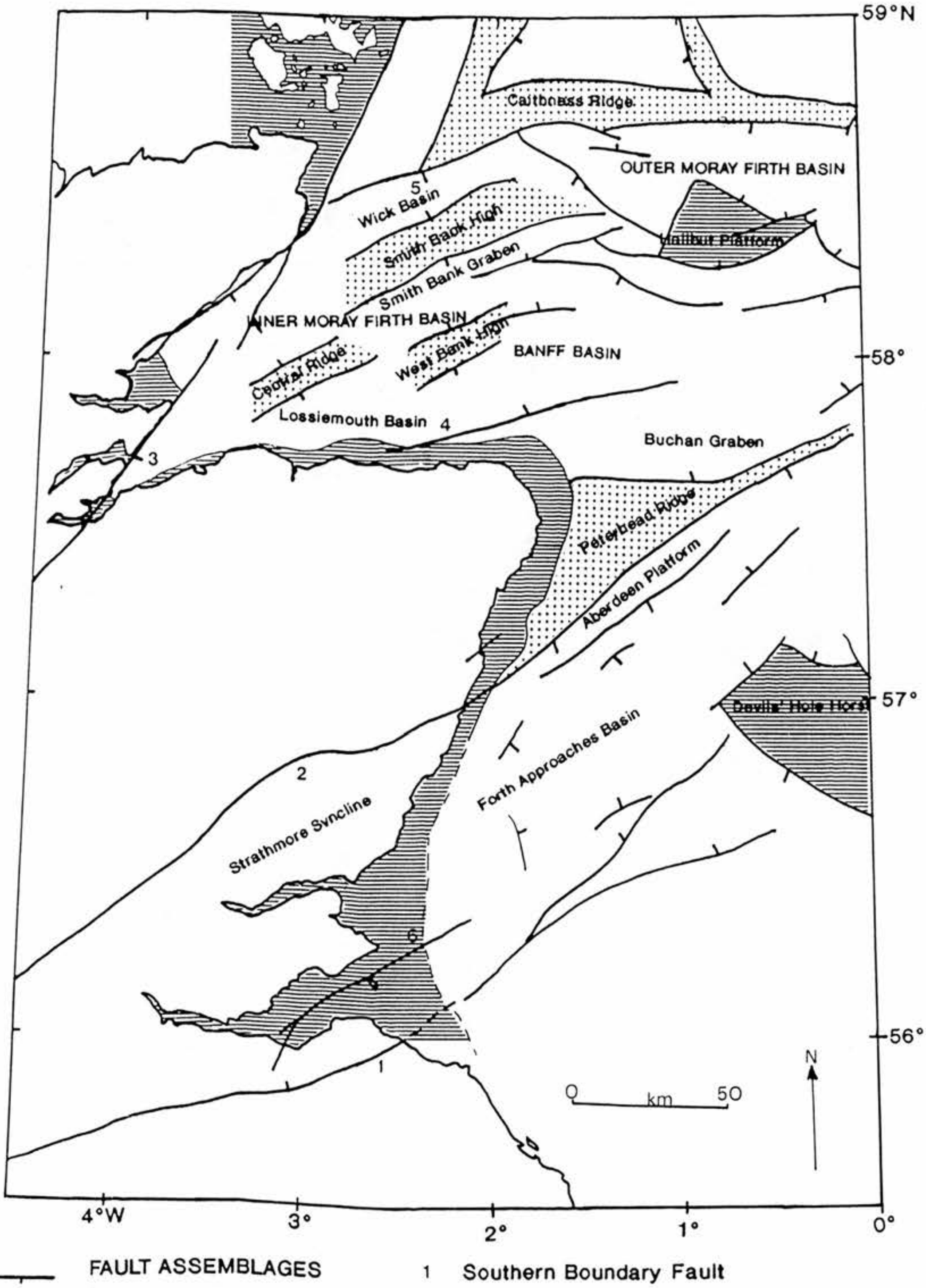
a) Boulton *et al.* 1977
b) Andersen 1981
c) Denton and Hughes 1981
d) Price 1983
e) Flinn 1967.



———	STUDY AREA
———	SUBDIVISIONS
- - - -	BGS MAP SHEETS

1 Tay-Forth (Stoker 1987)
2 Marr Bank (Stoker 1985a)
3 Peterhead (Stoker 1985b)
4 Moray-Buchan (Chesher 1984)
5 Caithness (Ruckley and Chesher 1987)
6 Bosies' Bank (Skinner and Bent 1988)

FIGURE 1.3 Map showing the offshore structural geology.



FAULT ASSEMBLAGES		1	Southern Boundary Fault
		2	Highland Boundary Fault
PLATFORMS		3	Great Glen Fault
HIGHS		4	Banff Fault
BASINS		5	Wick Fault
		6	Firth of Forth Fault

(compiled from the PESGB Structural Framework of the North Sea area (1990)).

FIGURE 1.4 Map of the pre-Quaternary Geology.

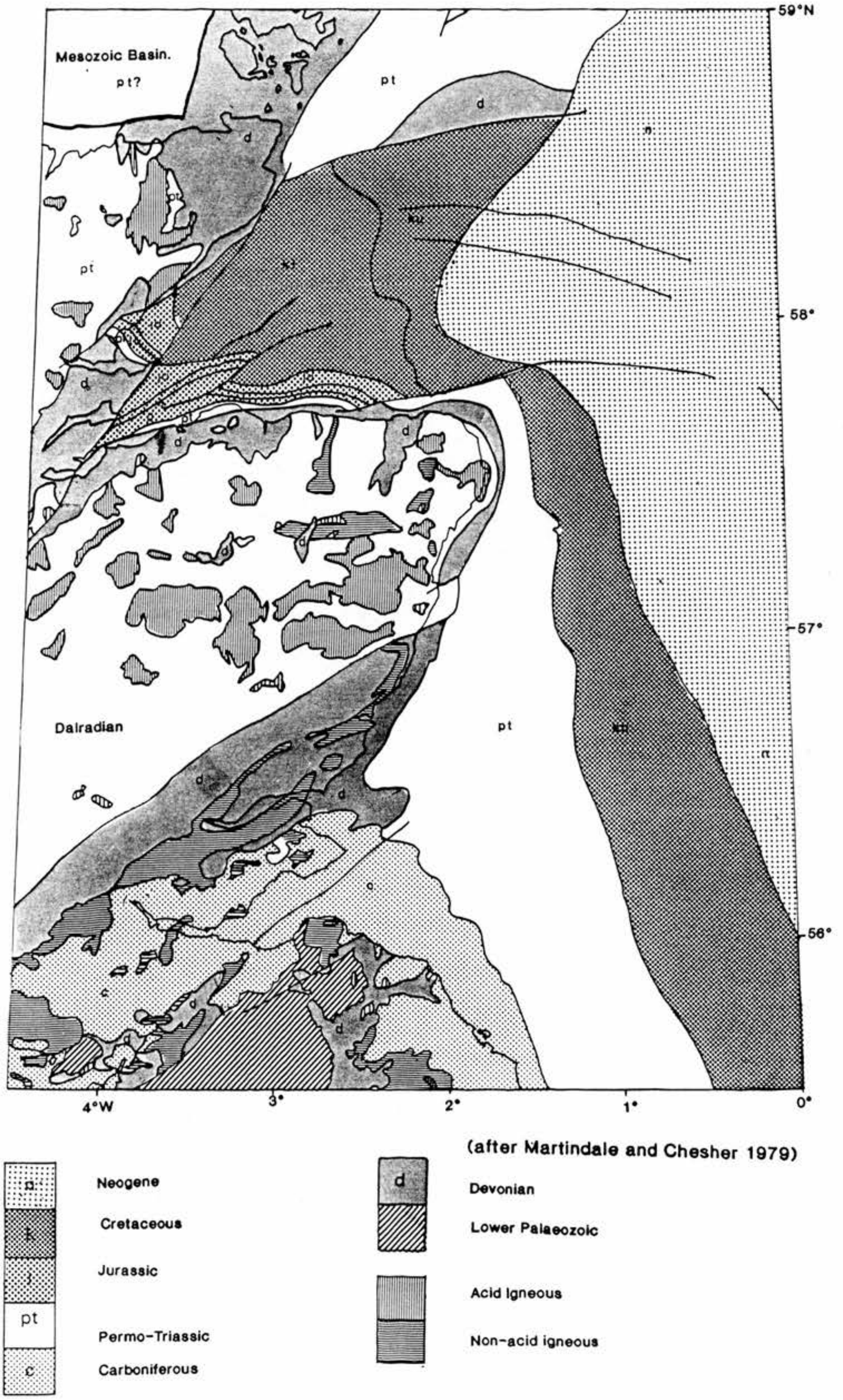
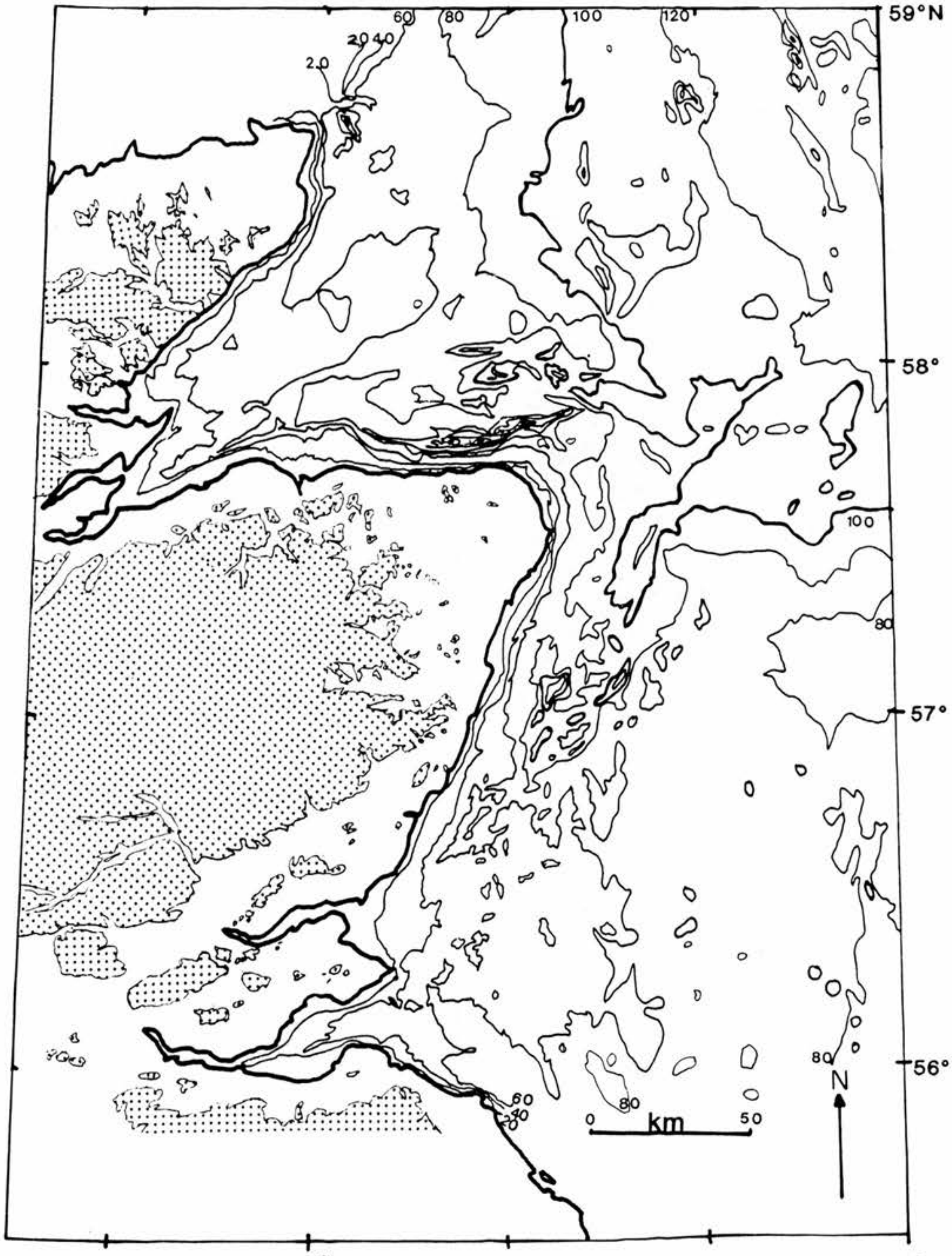


FIGURE 1.5 Map of the bathymetry and topography of the area.

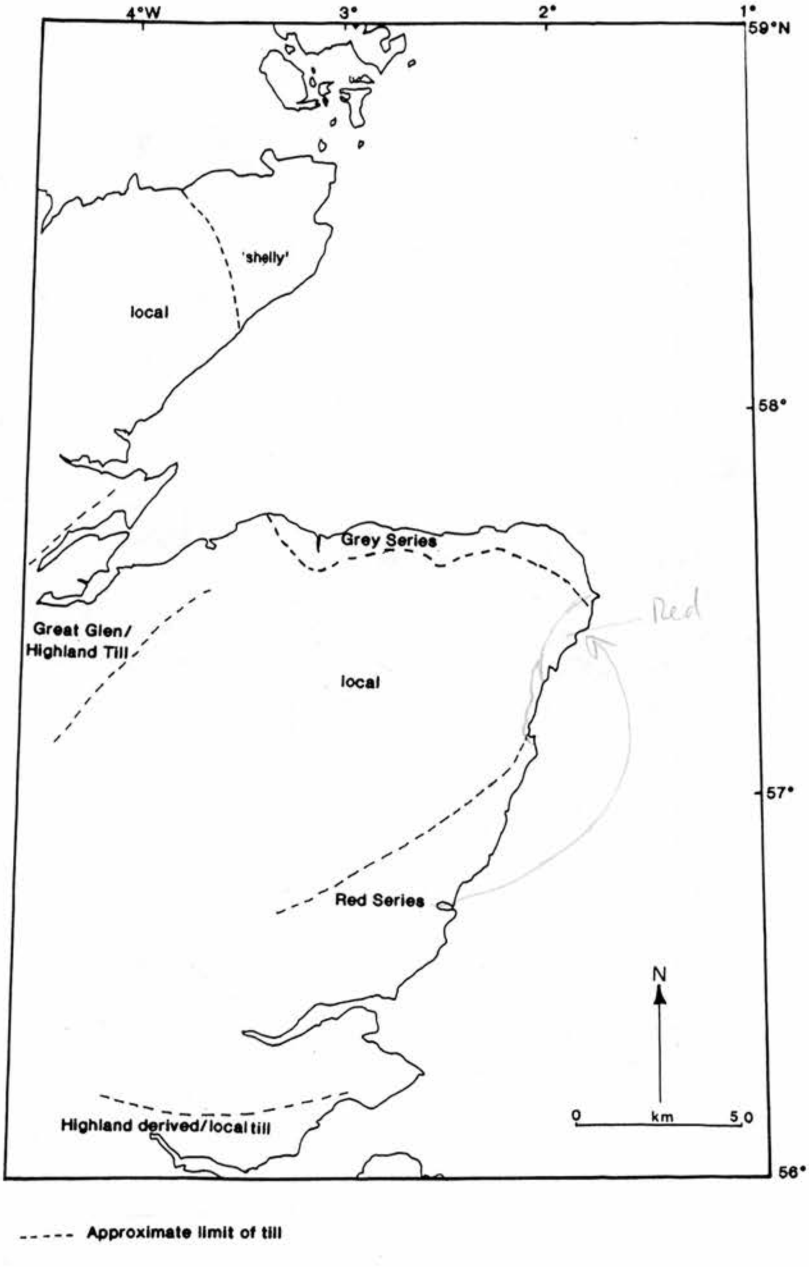


100m interval

20m interval

<250m high

FIGURE 1.6 Map showing the main onshore late Quaternary till cover (various sources).



----- Approximate limit of till

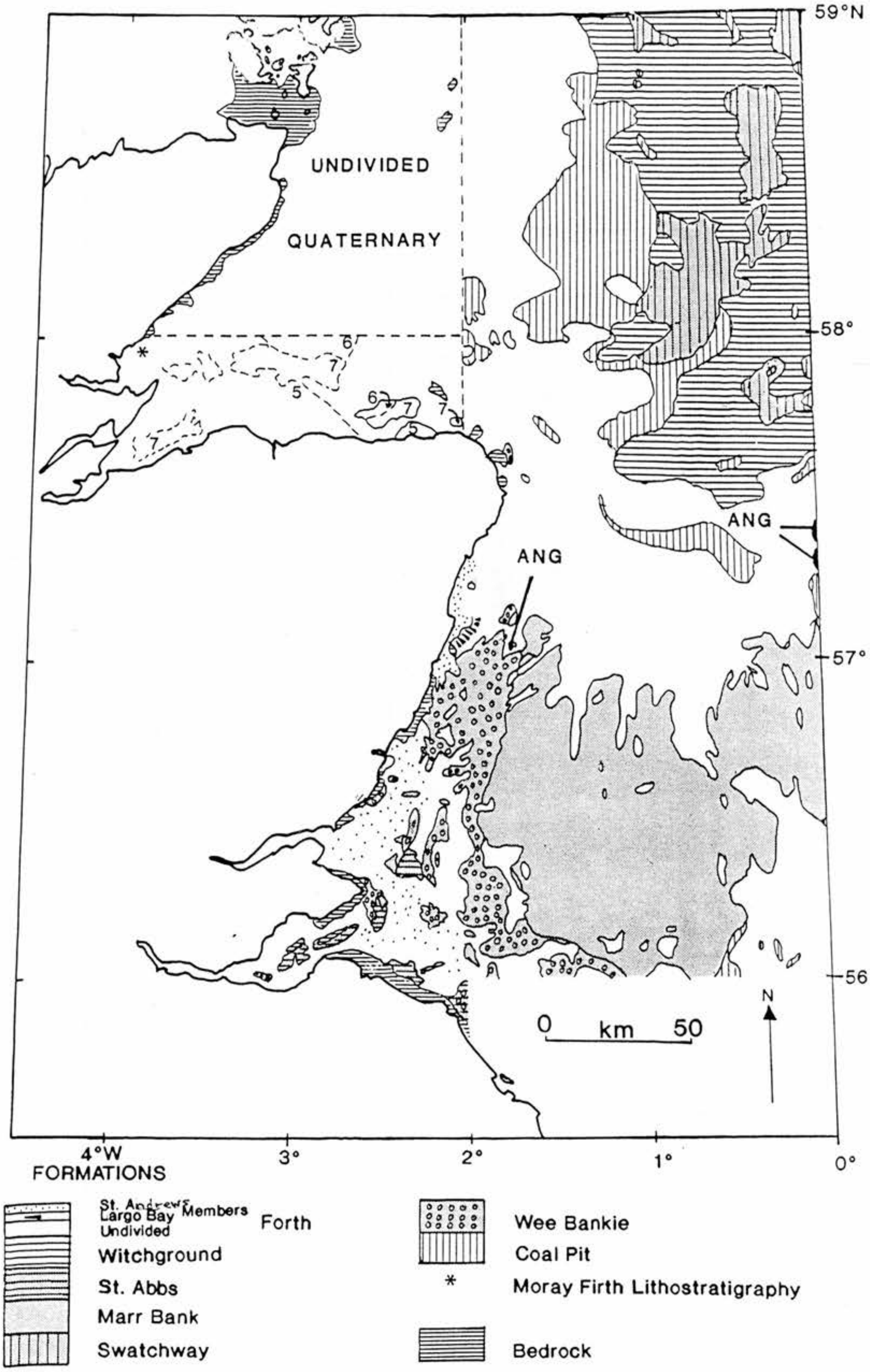
'local' Locally derived till

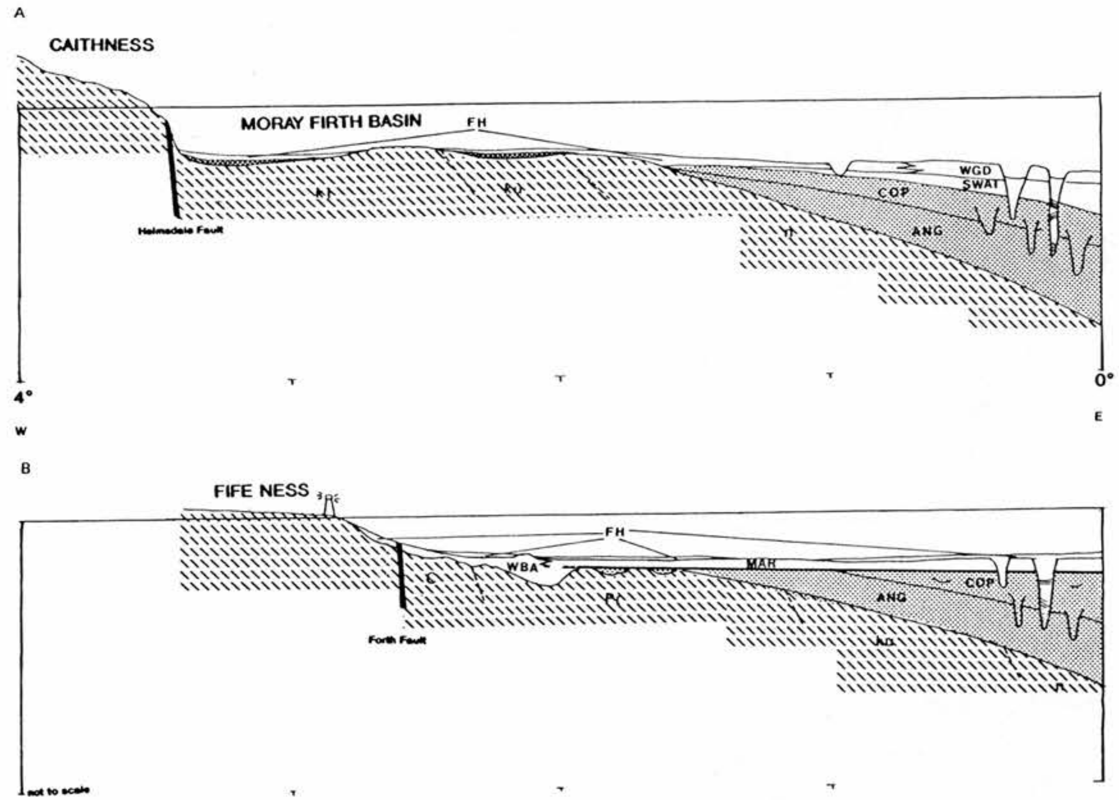
'shelly' shelly Till containing reworked offshore fauna (after Peach and Horne 1881)

Gray Series Till derived from the Moray Firth

Red Series Till derived from Strathmore Jamieson (1906)

FIGURE 1.7 Map showing the distribution of the Quaternary Formations.





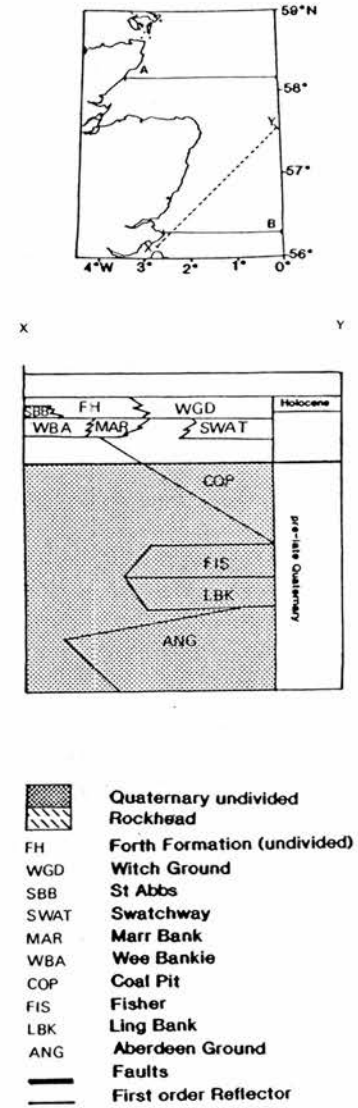
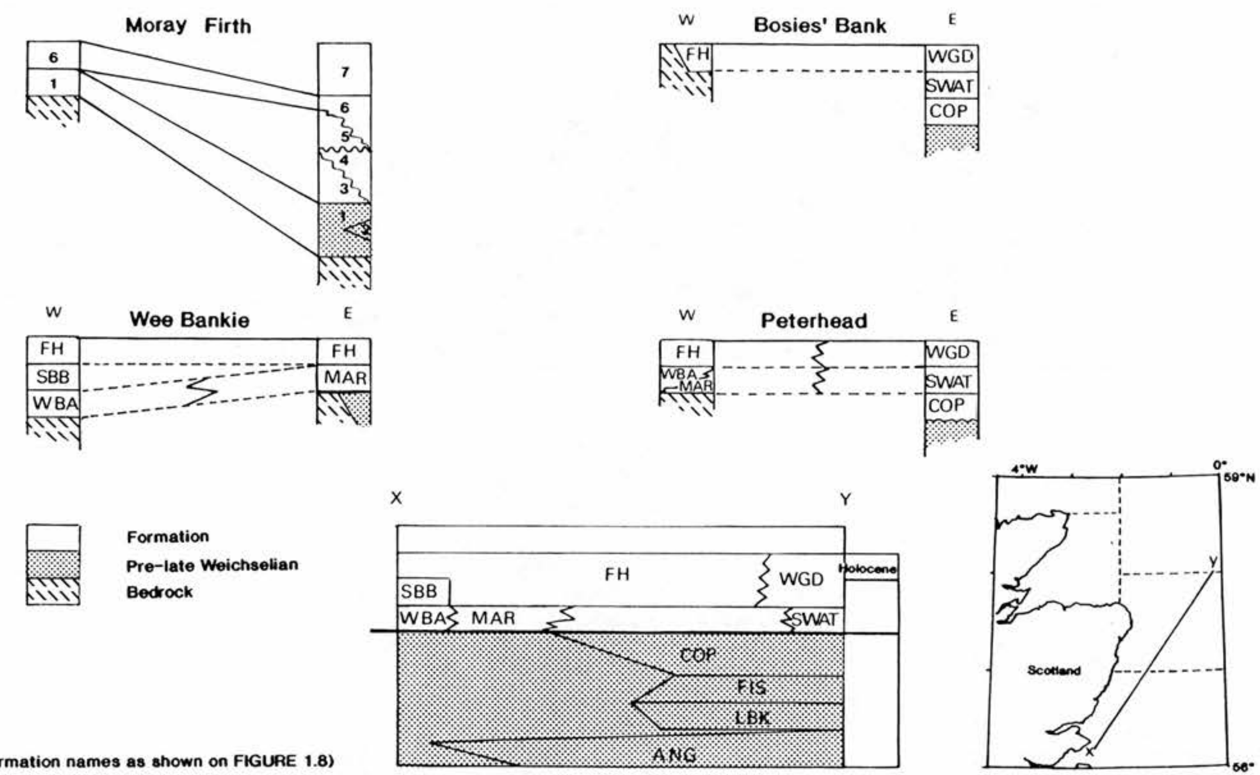


FIGURE 1.8 Composite Quaternary seismostratigraphy of the western margin of the central North Sea (after Stoker *et al.* 1985).

FIGURE 1.9 Offshore sedimentary succession (after Stoker 1985a,b, 1987, Skinner and Bent 1988, Chesher 1984, Ruckley and Chesher 1987).



(Formation names as shown on FIGURE 1.8)

FIGURE 1.10 A schematic framework of the thesis showing the relationships between the approaches.

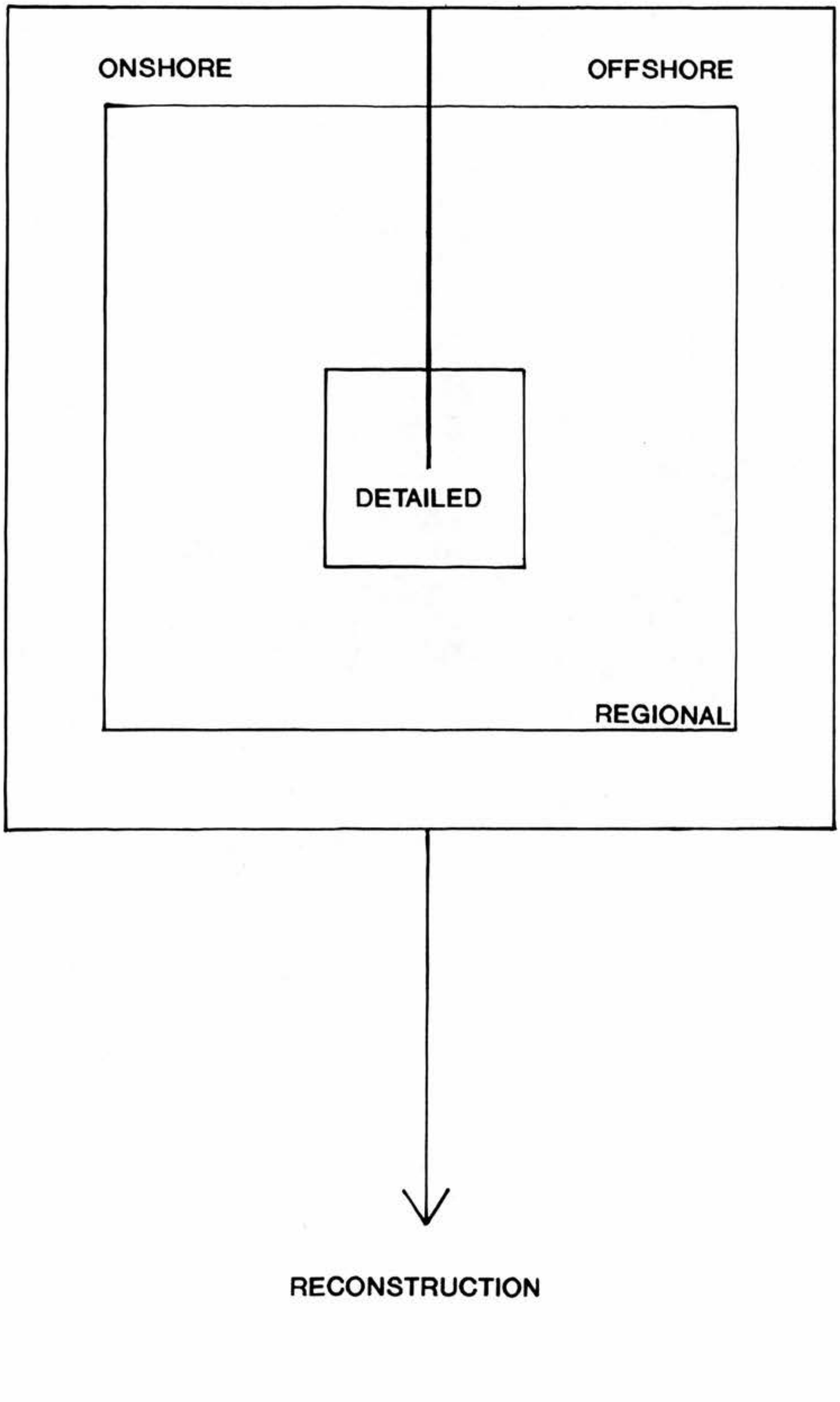


FIGURE 2.1 SCHEMATIC DIAGRAM OF THE METHODOLOGY. A Summary diagram of the work structure of the thesis.

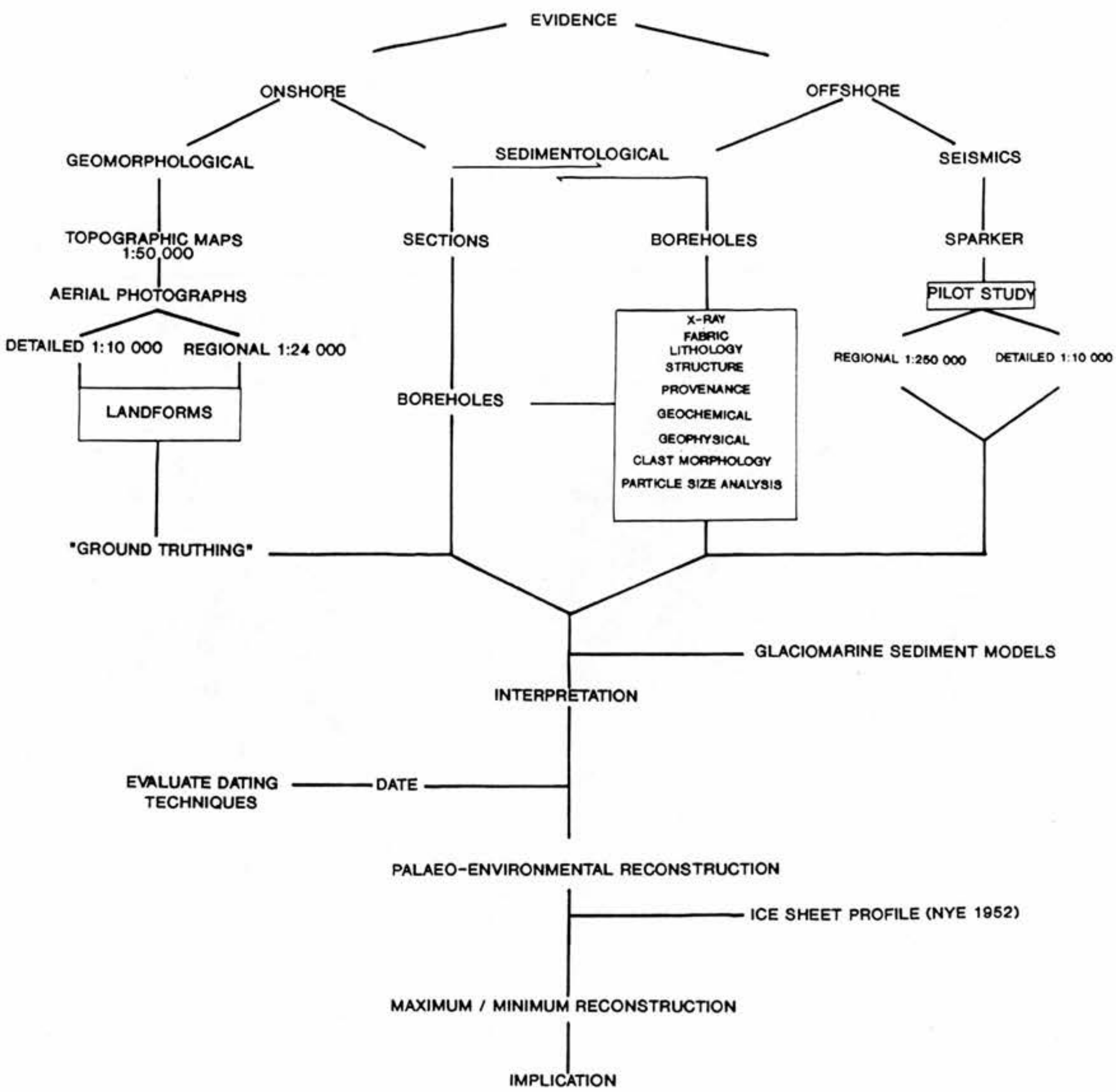
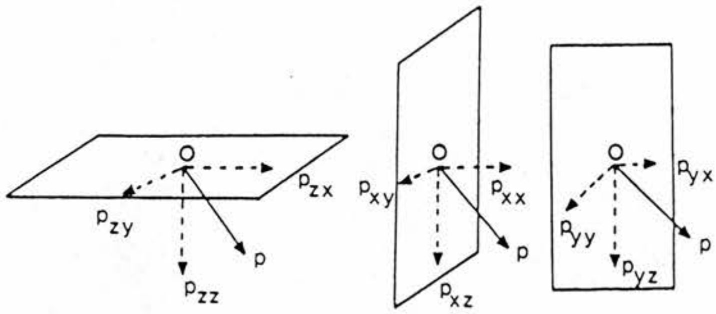


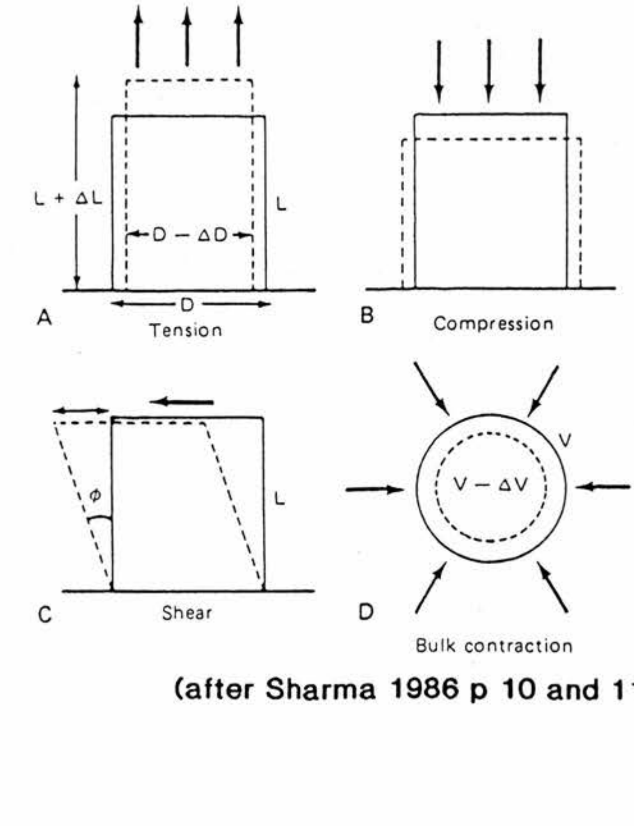
FIGURE 2.2 Schematic illustrations of Stress and Strain

STRESS The stress tensor at a point is specified by three normal and six shear components. Their attitudes with respect to the three mutually perpendicular planes intersecting at the point are shown by dashed lines with arrows.



STRAIN

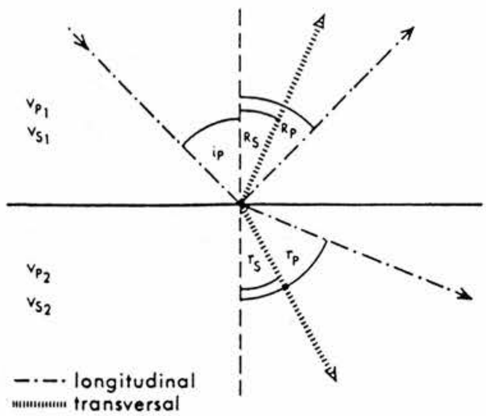
Common types of elastic strain



(after Sharma 1986 p 10 and 11)

FIGURE 2.3 Diagram showing reflection and refraction of a wave at a boundary, and Snell's Law.

Reflection and refraction of an incident longitudinal wave at a boundary separating two media with different velocities. In general, four new waves are generated at the boundary. Subscripts P and S denote longitudinal (push-pull) and transverse (shear) waves. *i* is the angle of incidence; *R* is the angle of reflection; *r* is the angle of refraction; *V* is the seismic velocity.



(from Sharma 1986, p 16 fig. 2.5).

Snell's law

$$\frac{\sin i_P}{V_{P_1}} = \frac{\sin R_P}{V_{P_1}} = \frac{\sin R_S}{V_{S_1}} = \frac{\sin r_P}{V_{P_2}} = \frac{\sin r_S}{V_{S_2}}.$$

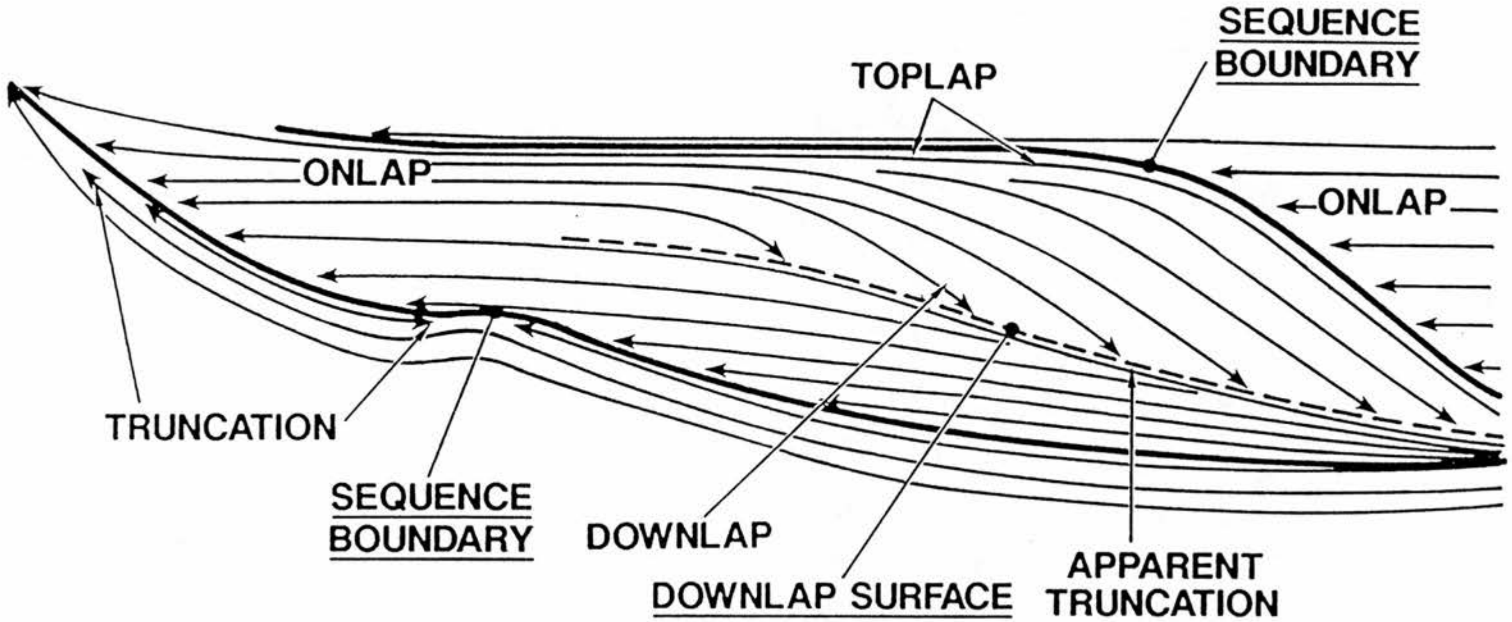


FIGURE 2.4 Seismic sequence reflectors, showing the reflector configurations identified in seismic stratigraphic analyses (after Vail 1987).

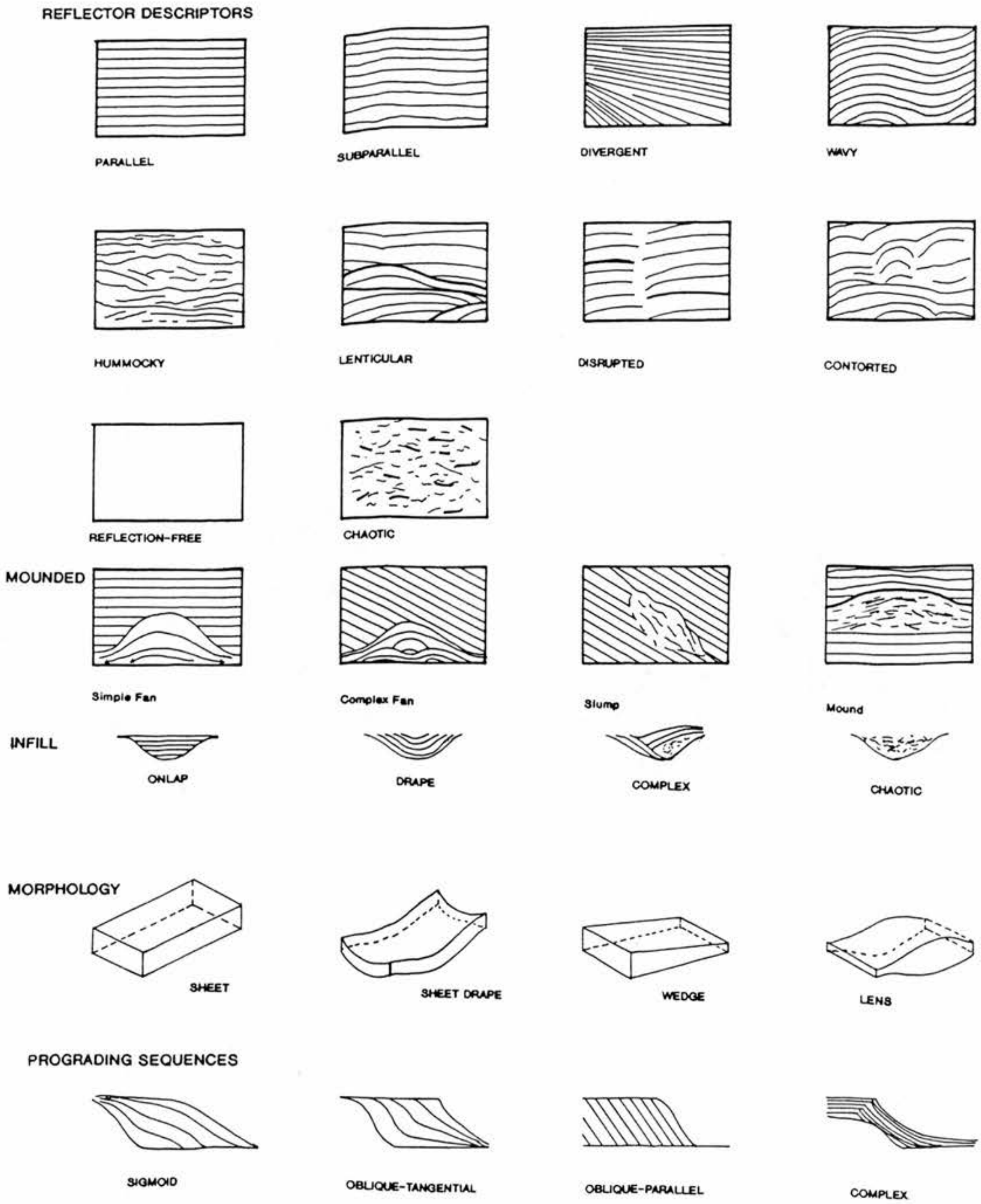


FIGURE 2.5 Reflector descriptors and seismic unit facies forms (after Mitchum *et al.*1977 and Sangree and Widmier 1977)

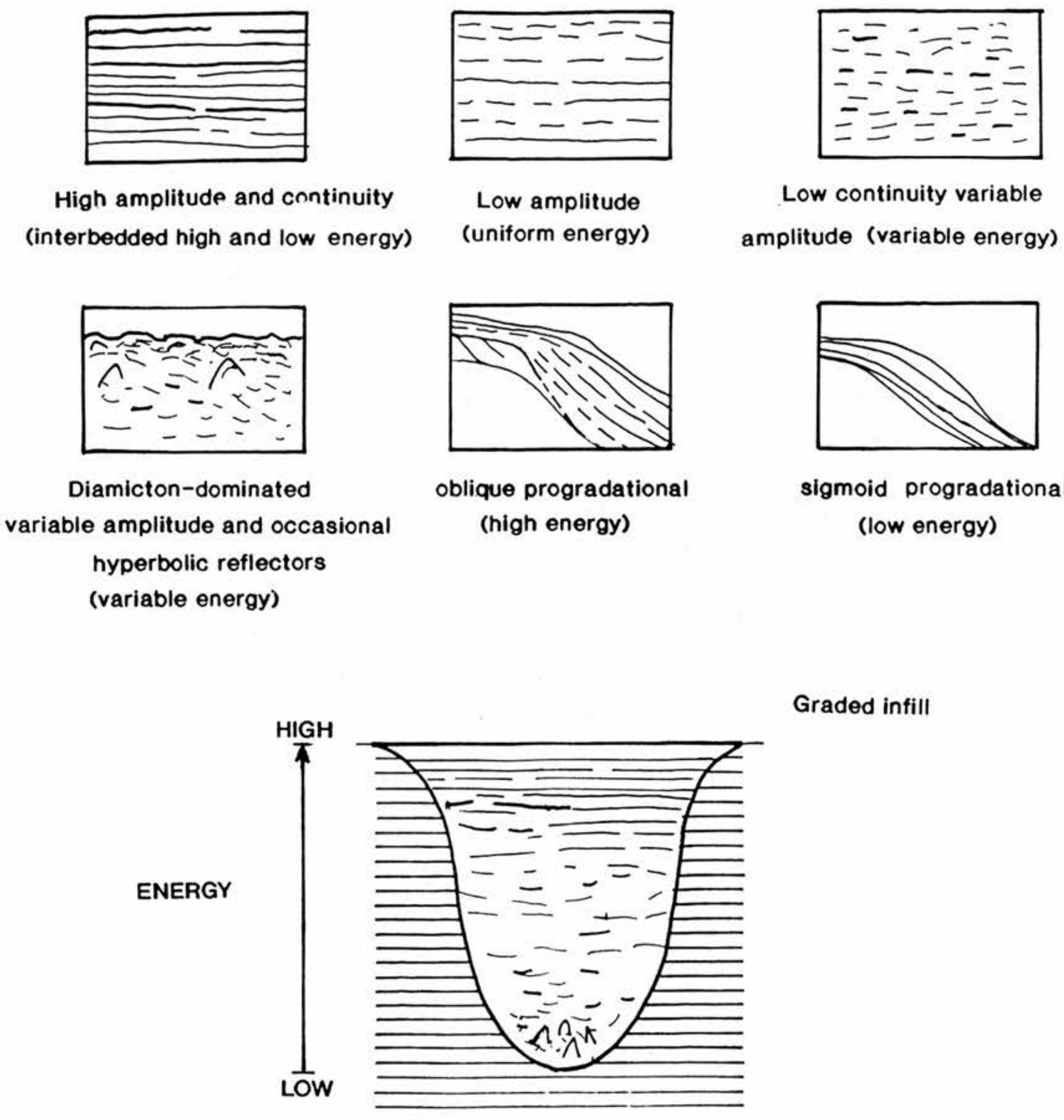
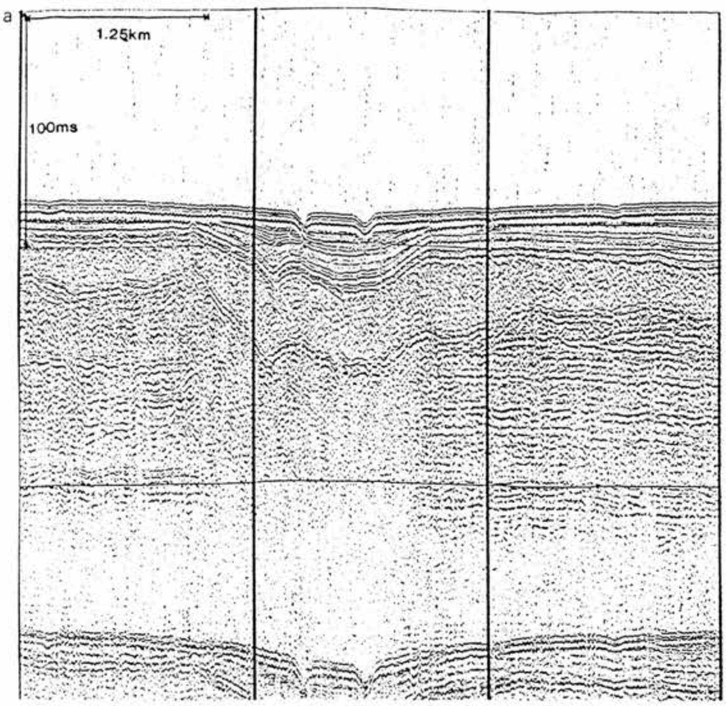
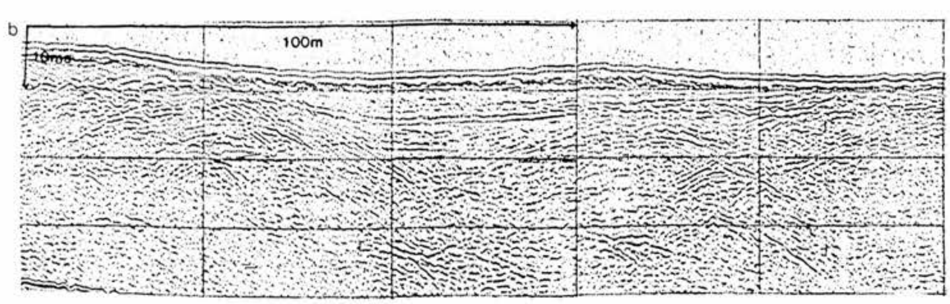


FIGURE 2.6 Shelf seismic clastic facies types, showing energy interpretations (Sangree and Widmier 1977 and Stewart and Stoker 1990).

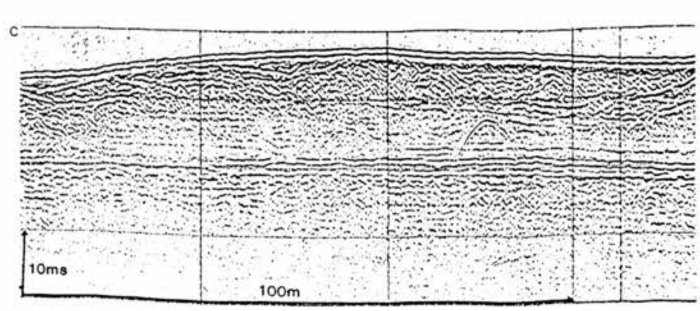
FIGURE 2.7 Examples of seismic interpretation problems : a) gas blanking and active pockmarks b) distortion by point-source reflectors at the junction between the sediment and rockhead and c) point-source reflectors within seismic facies unit.



courtesy of BGS Project 79/15 Line 8



Courtesy of BP.



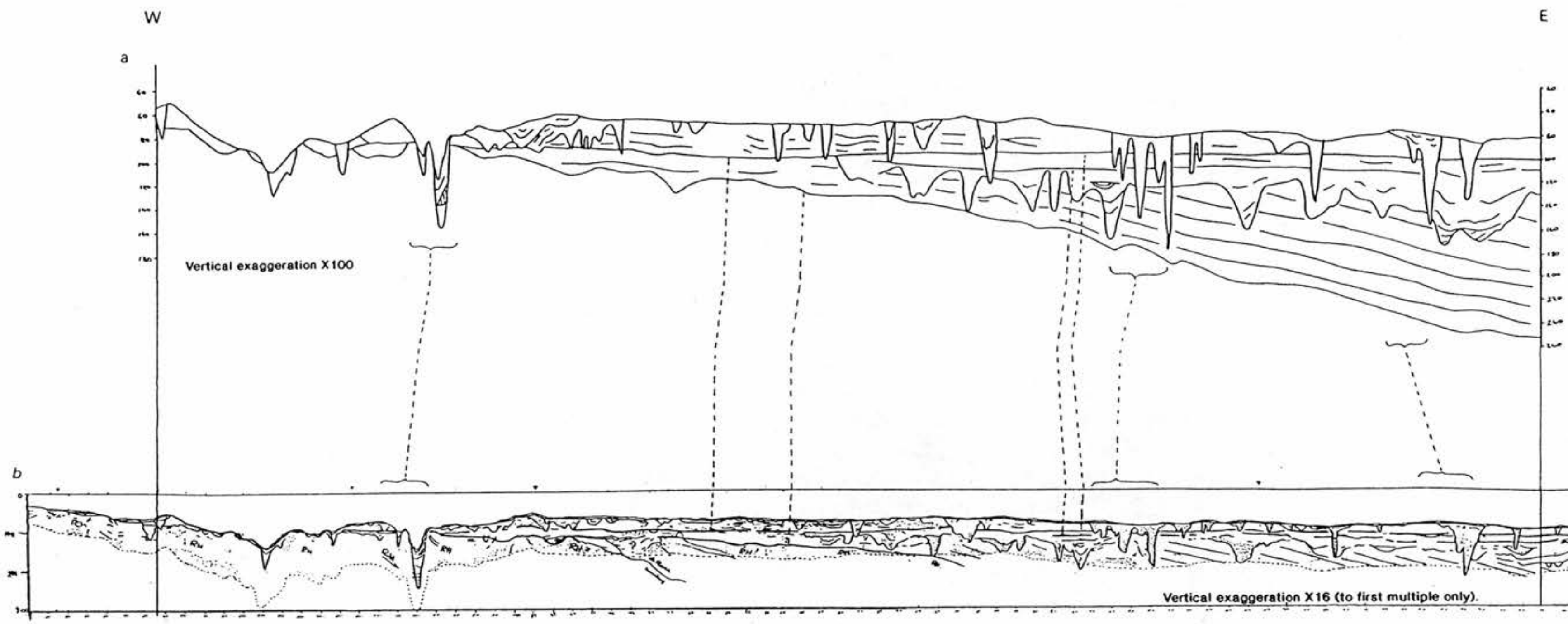


FIGURE 2.8 Comparisons between reflector identification and classification for BGS project 80/03 line 36 showing a) unpublished BGS data (Stoker) and b) the author.

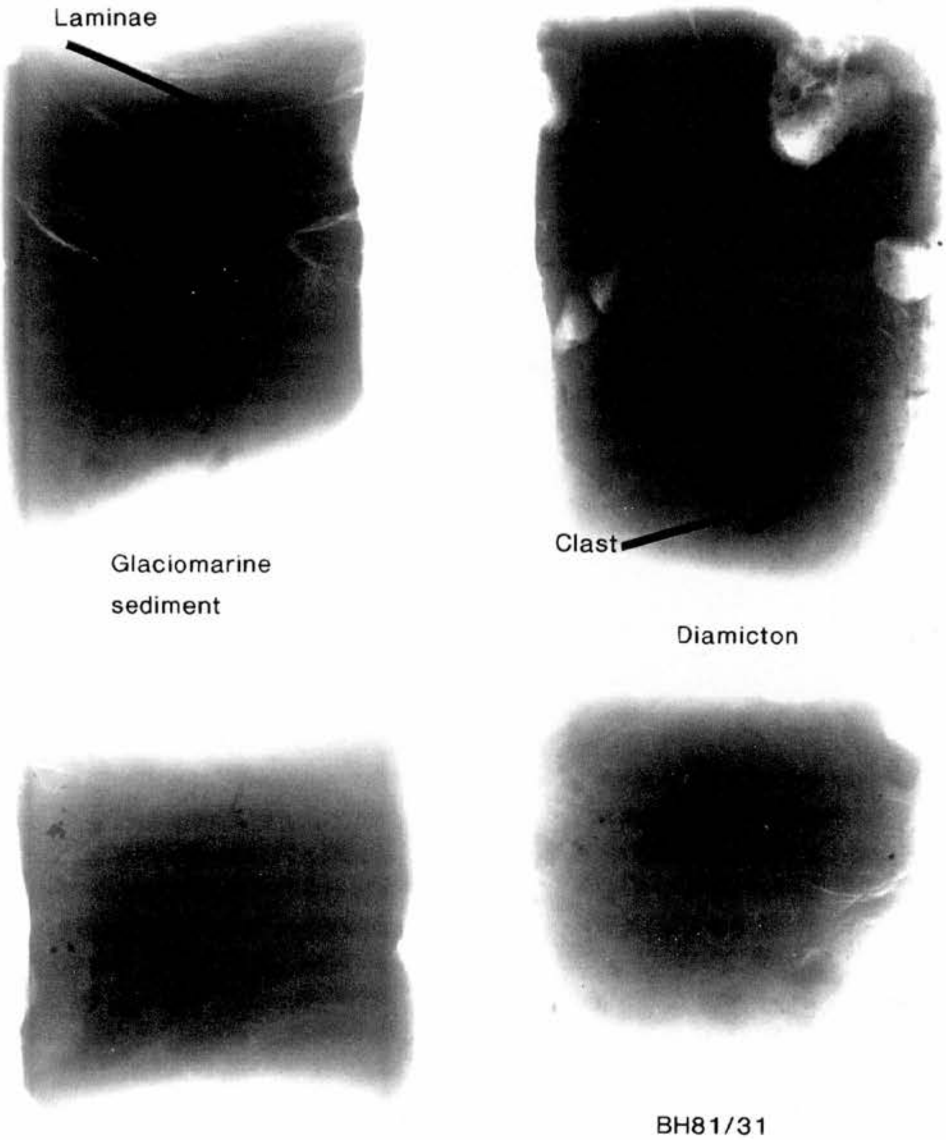
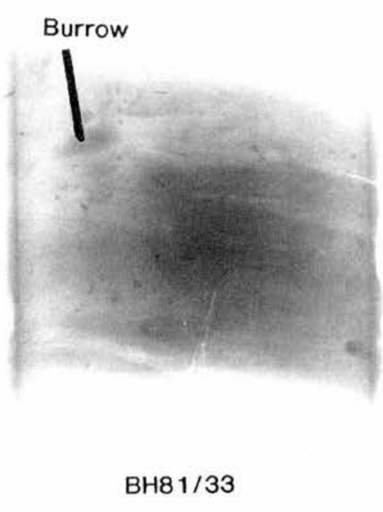
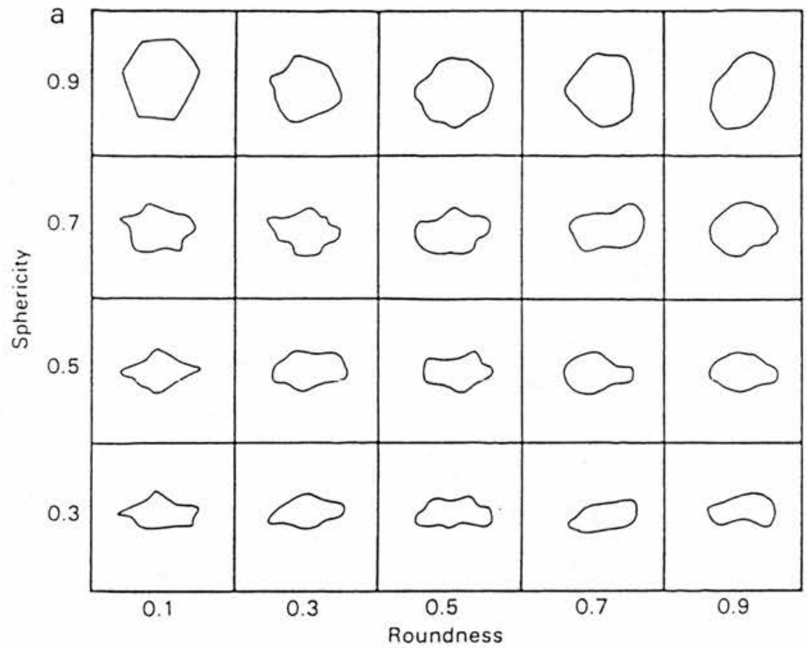


FIGURE 2.9

Examples of X-Radiograms showing diamicton and glaciomarine sediments.





b

Class name		Roundness indices
Very angular		0.12 - 0.17
Angular	(A)	0.17 - 0.25
Sub-angular	(SA)	0.25 - 0.35
Sub-rounded	(SR)	0.35 - 0.49
Rounded	(R)	0.49 - 0.70
Well rounded		0.70 - 1.00

(From Bridgland 1986, pp48 and 49).

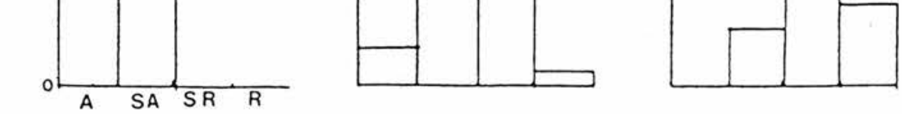
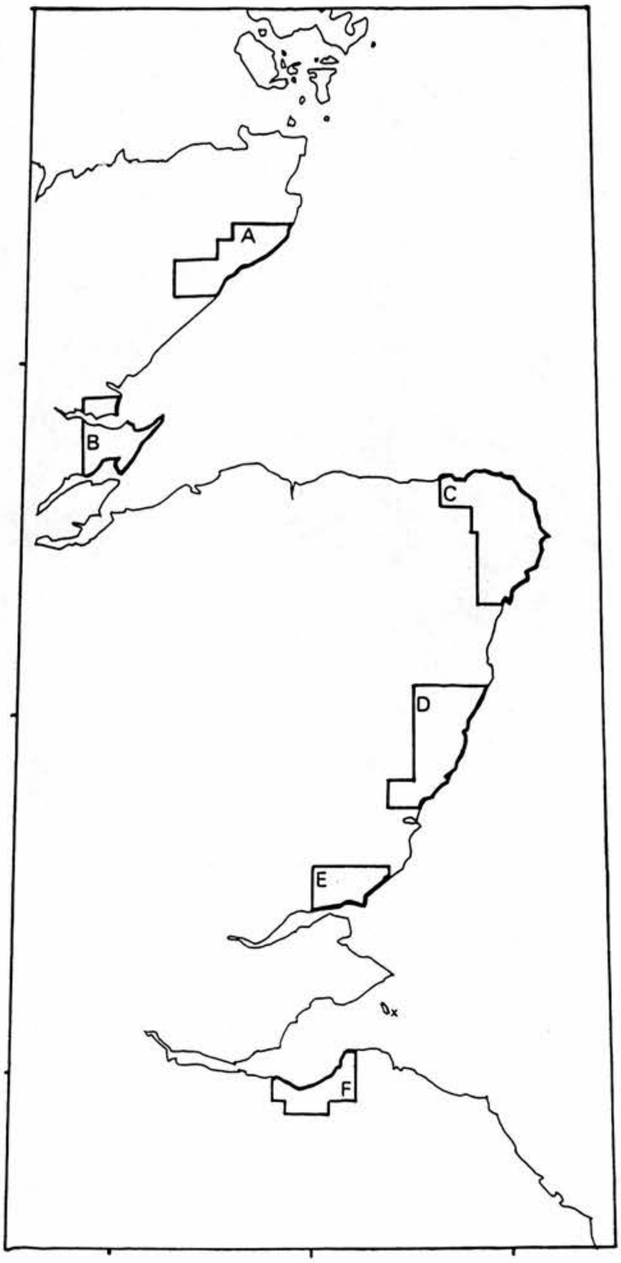


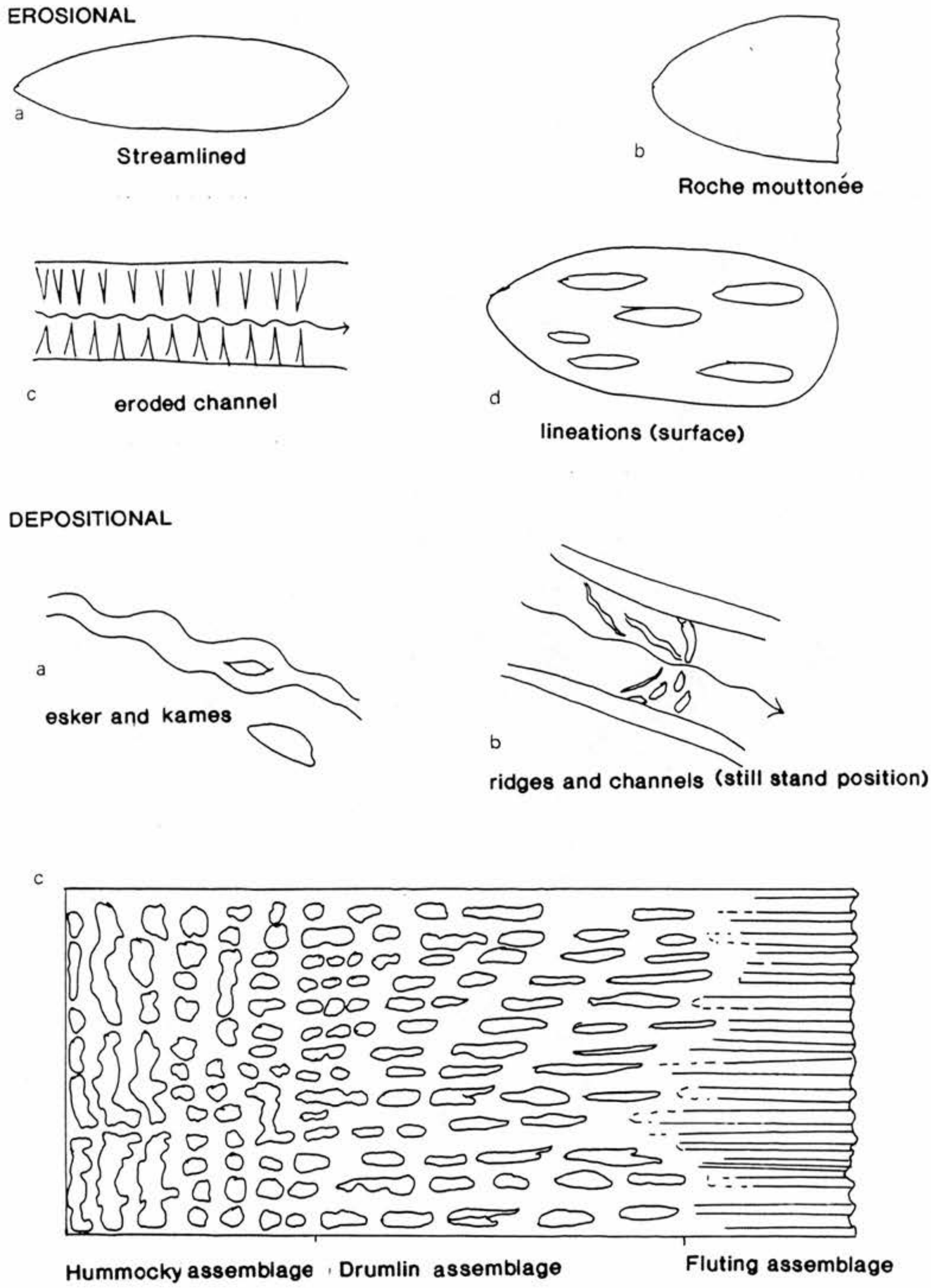
FIGURE 2.10 Illustrations of the clast shape classifications a) visual estimates of roundness and sphericity (after Krumbein and Sloss1955) and b) roundness classes and indices (after Powers 1953) and shows graphical illustrations of different glacigenic sediments

FIGURE 2.11 Locations of the 1:24 000 scale aerial photography detailed sites



A Lybster
B Invergordon
C Fraserburgh to Cruden Bay
x Isle of May (1:10 000).
D Portlethen to Inverbervie
E Dundee
F Edinburgh

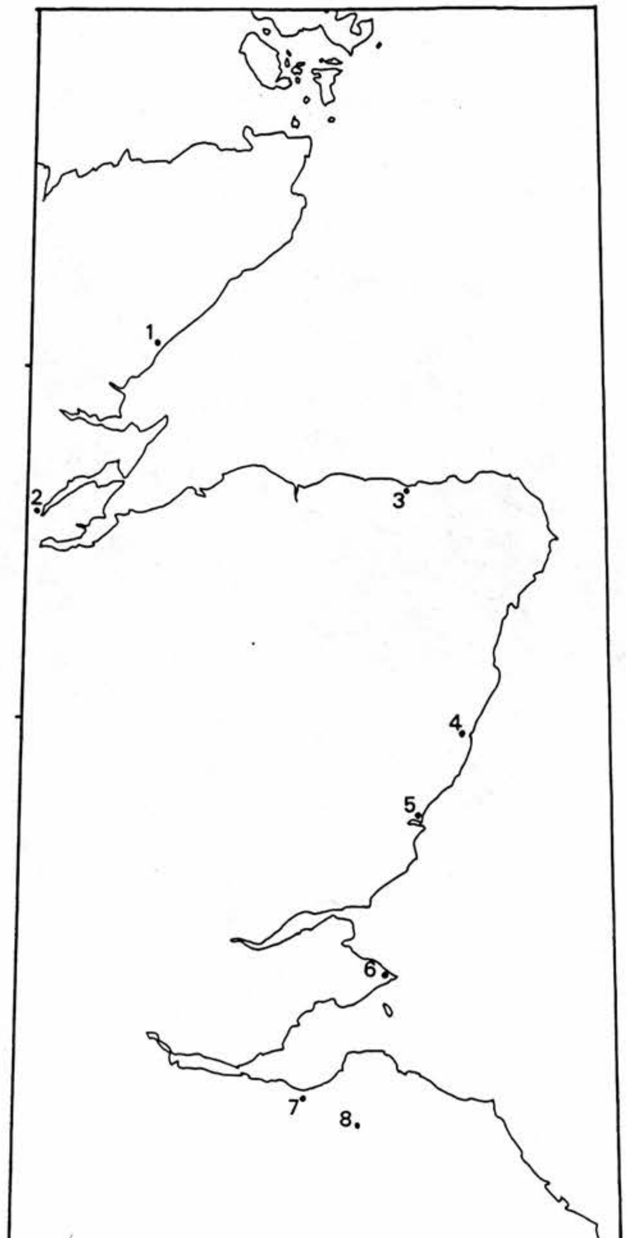
FIGURE 2.12 Planform criteria for aerial photograph interpretation.



A transitional series of active-ice assemblages (after Aario 1977).

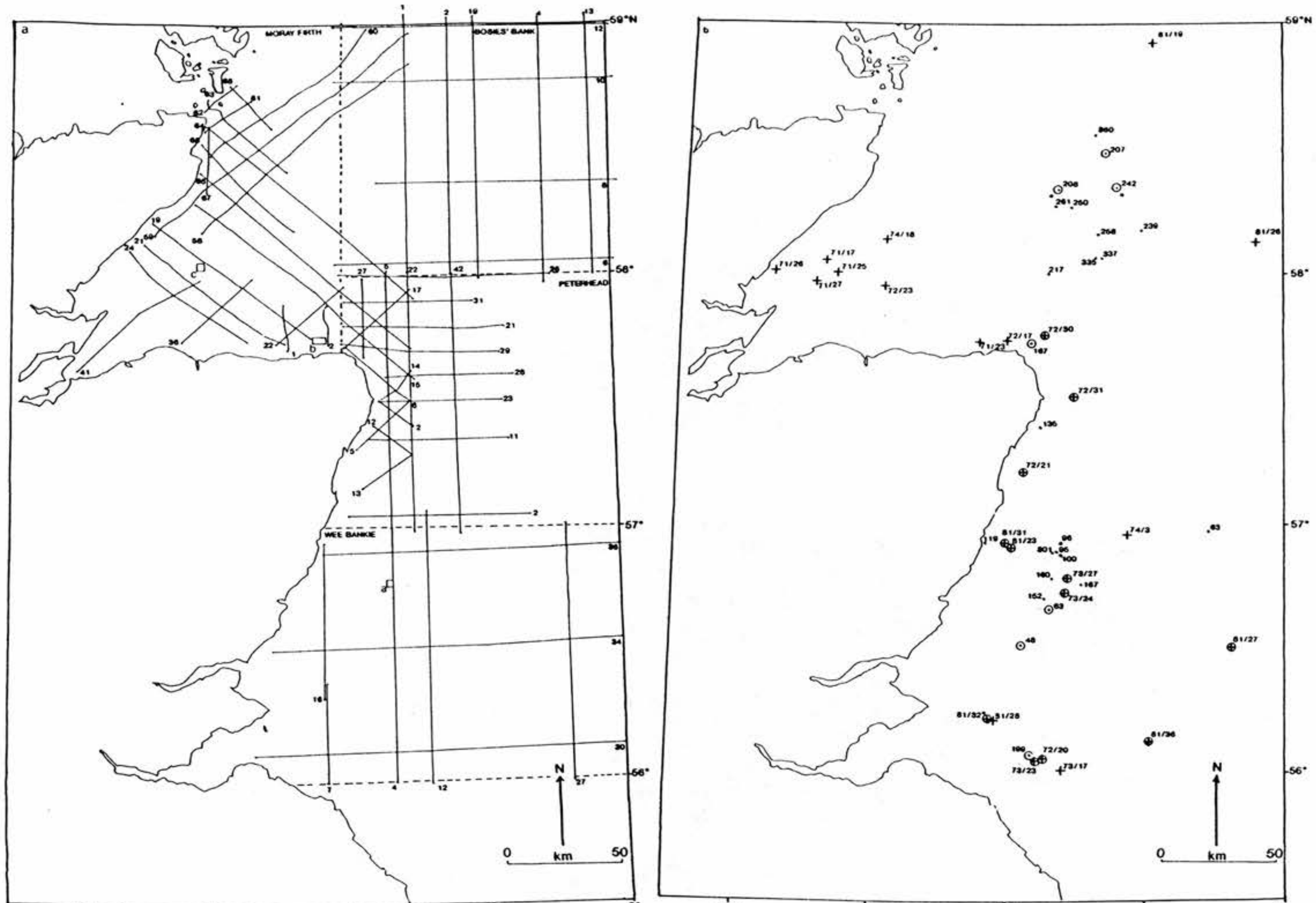
(Compiled from Dreimanis 1988)

FIGURE 2.13 Map showing the locations of the 1:10 000 scale aerial photography "ground truthing" sites.



1. Helmsdale
2. Strathpeffer/Dingwall
3. Banff
4. Stonehaven
5. Montrose
6. Fife Ness
7. Edinburgh
8. Hope Reservoir Gifford.

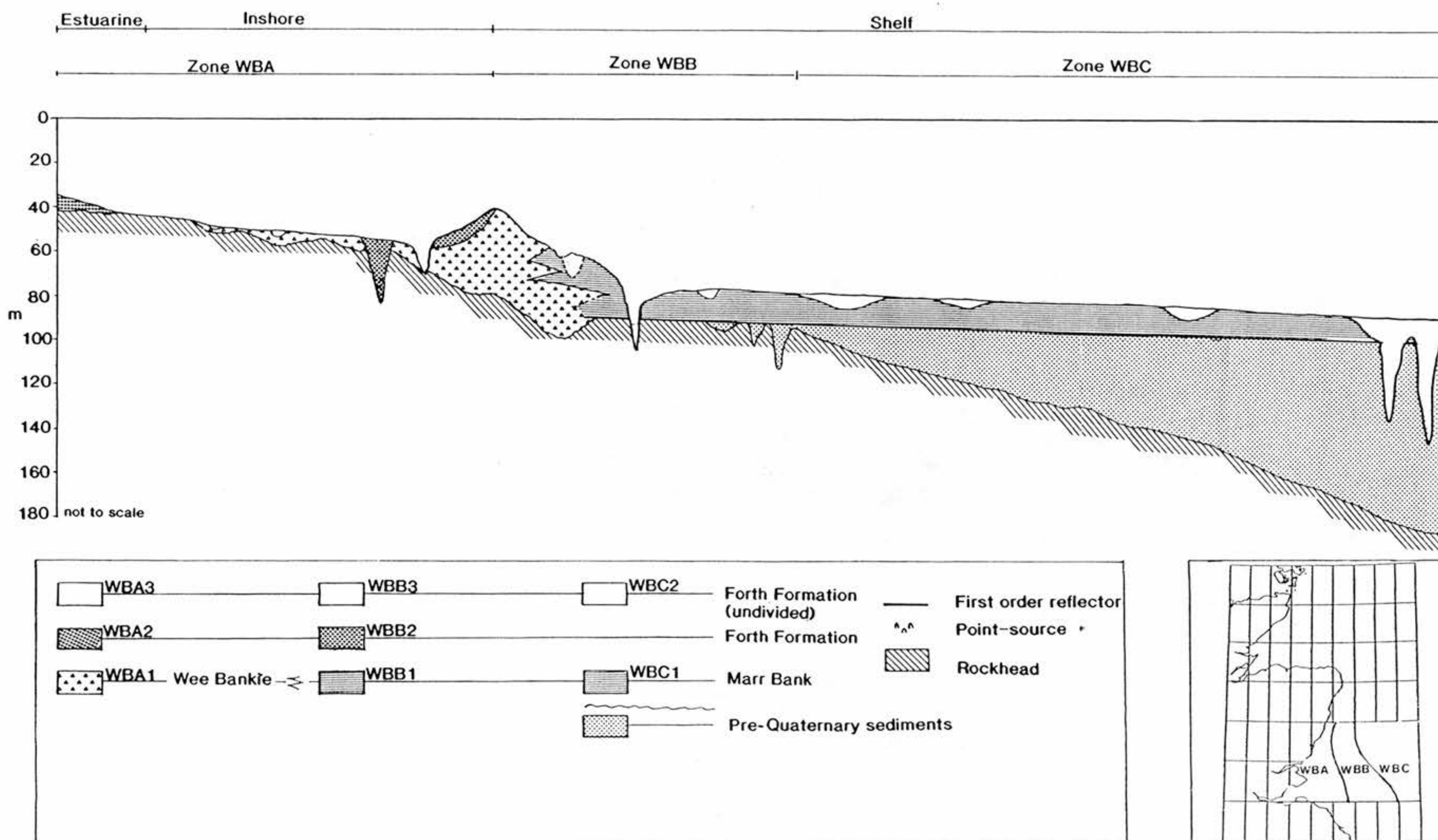
FIGURE 3.1 a) Seismic track chart and b) borehole and vibrocore locations.



a Wee Bankie (GEOTEAM)
b Southern Trench
c Beatrice

• Vibrocore
+ Borehole
• Dating site
O Sampled

FIGURE 3.2 Composite seismic profile for Wee Bankie, with a map showing the locations of zones WBA-WBC. Note the geometry of the first order reflector, units WBA1 and WBB1, and the seabed and rockhead morphologies.



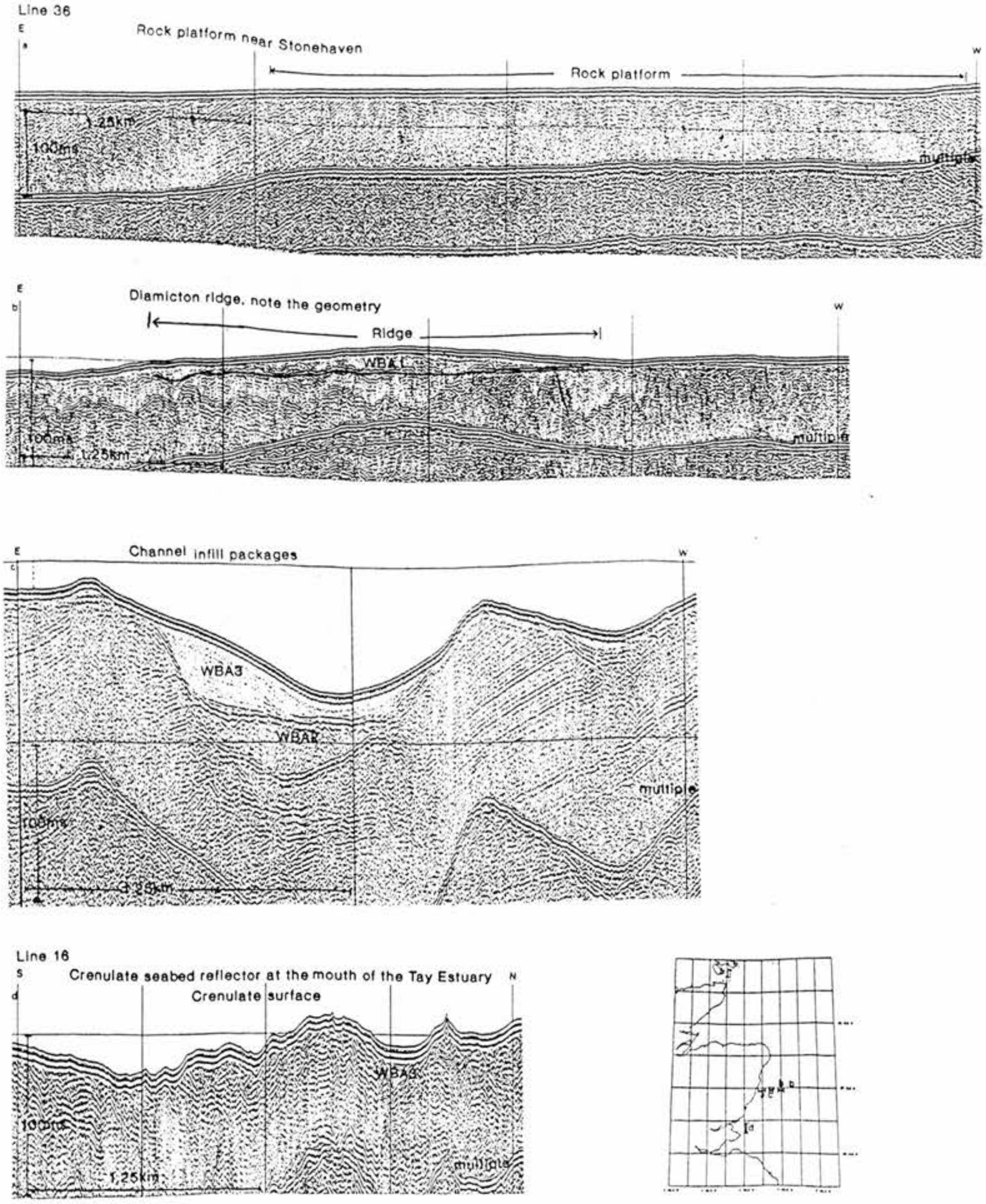
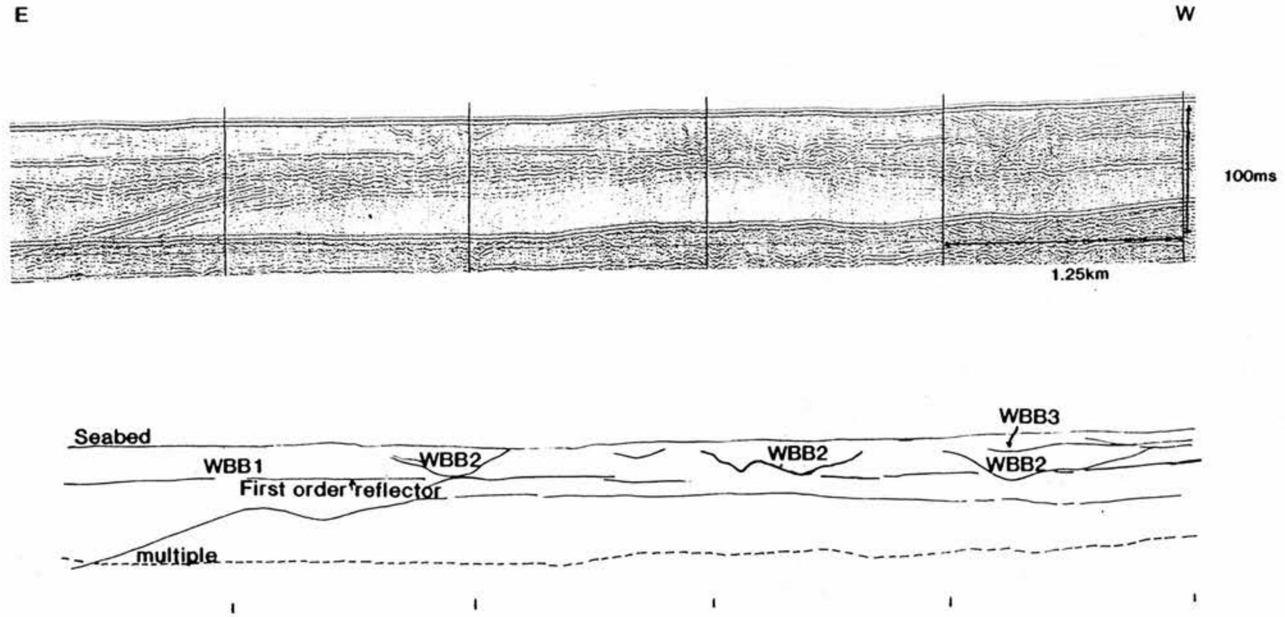


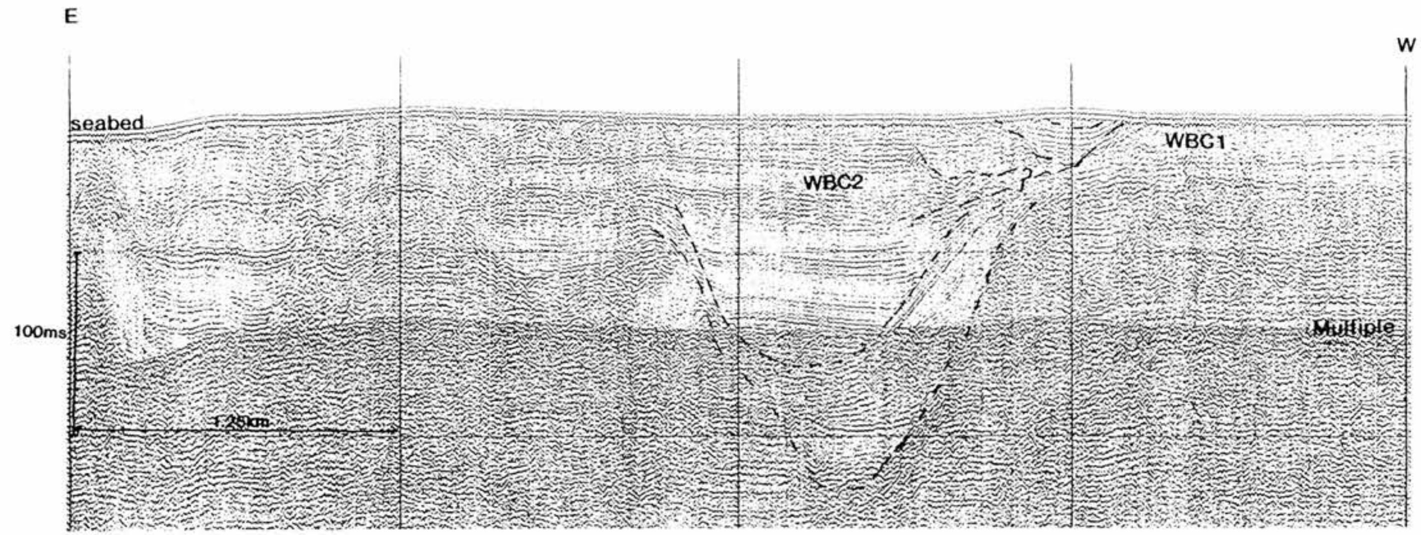
FIGURE 3.3 Seismic facies unit responses in zone WBA. Note the chaotic response of unit WBA1, and the different responses of units WBA2 and WBA3, infilling depressions and channels eroded in WBA1.

(R.E. insert; see plate 2i)

FIGURE 3.4 Seismic facies unit responses in zone WBB. Note the well-bedded response of unit WBB1, and the rockhead structure.



The insert shows the location of the section



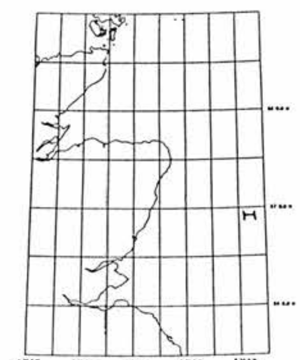


FIGURE 3.5 Section of project 80/03 Line 36, showing the multiple channel infill in zone WBC within the ice distal glaciomarine unit WBC1. The insert shows the position of the section.

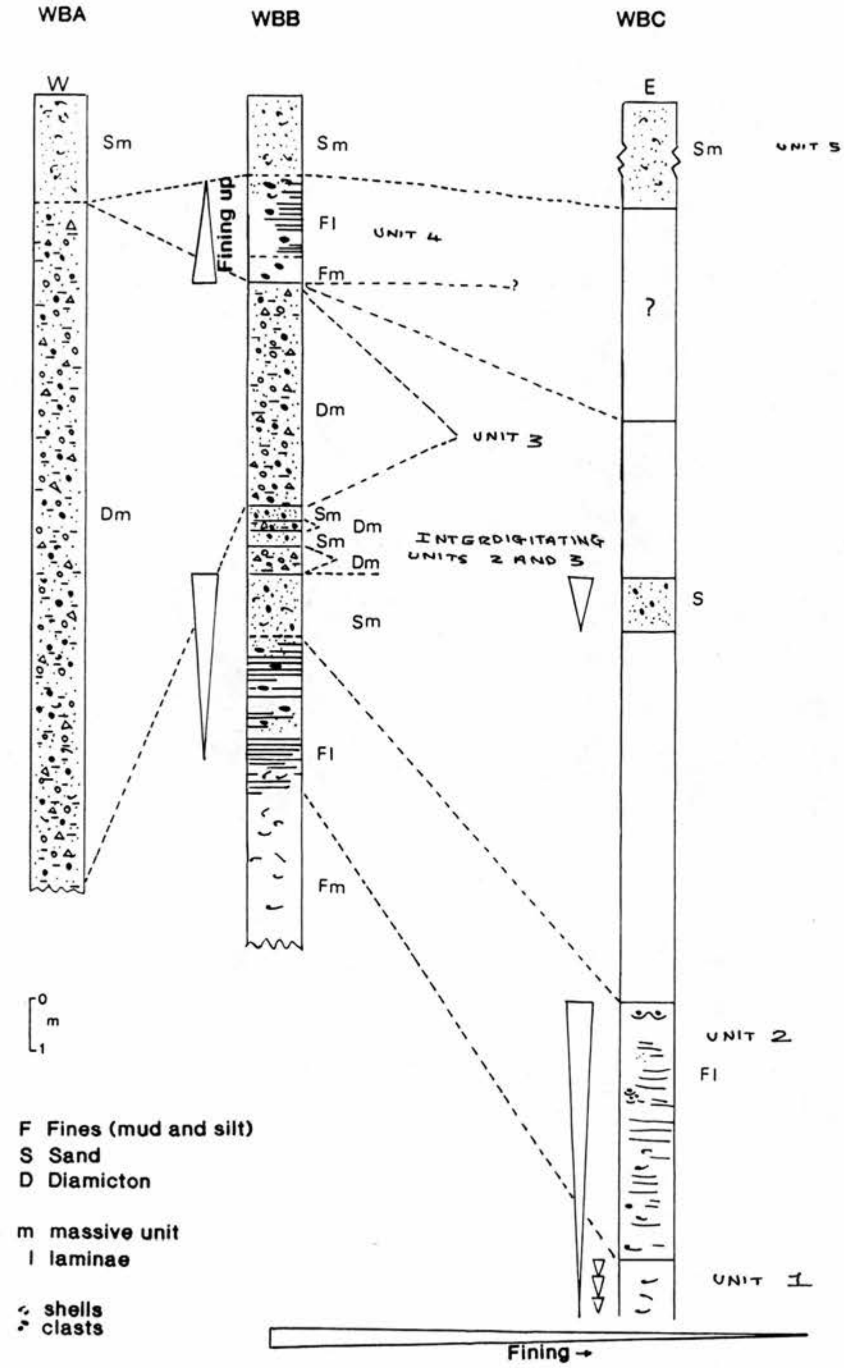


FIGURE 3.6 Composite logs of the sedimentary succession in the Wee Bankie area.

FIGURE 3.7 Summary diagram of the sedimentary facies units in the Wee Bankie area. This shows the particle size analysis results, and the acoustic responses of the units

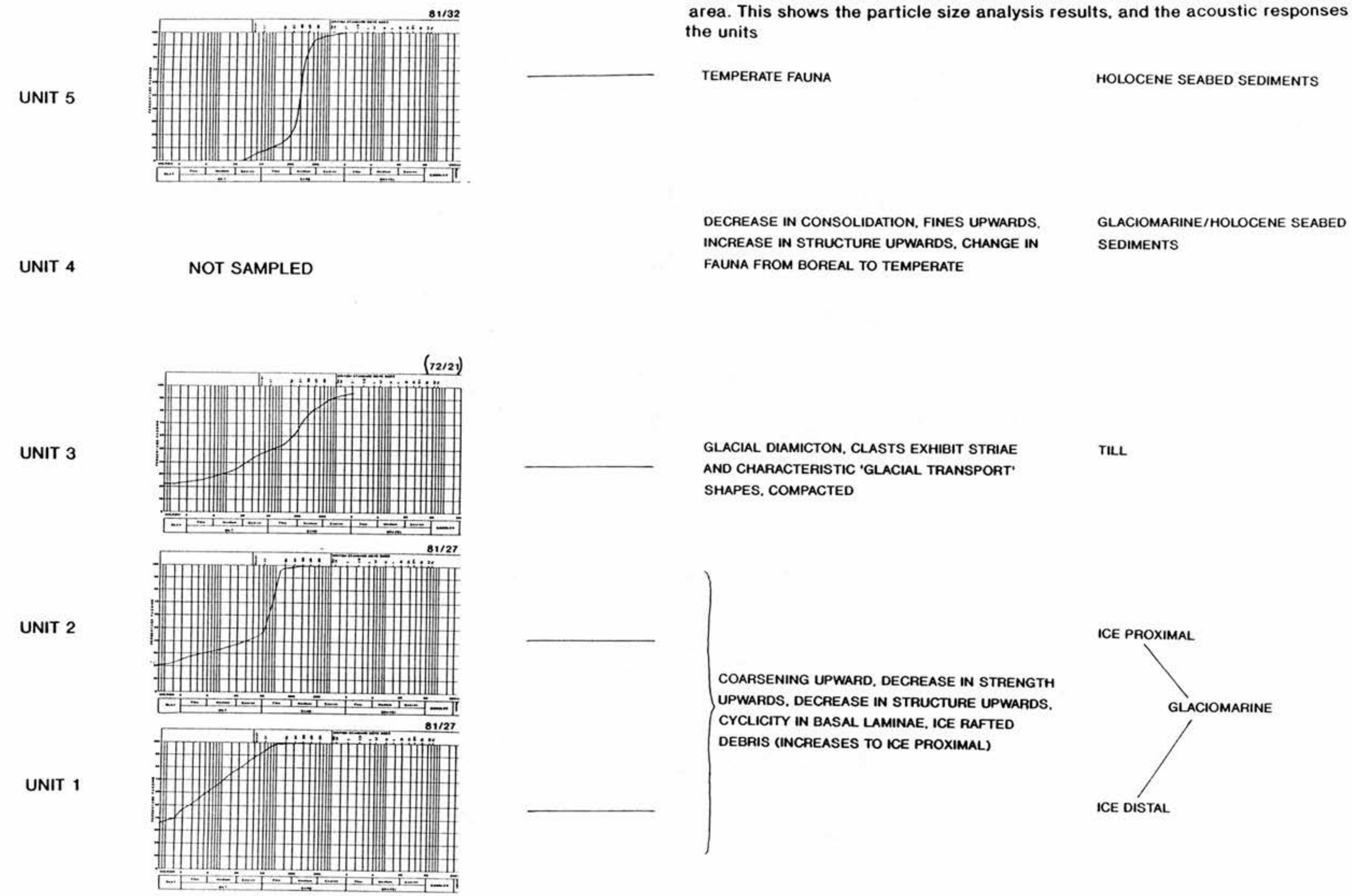
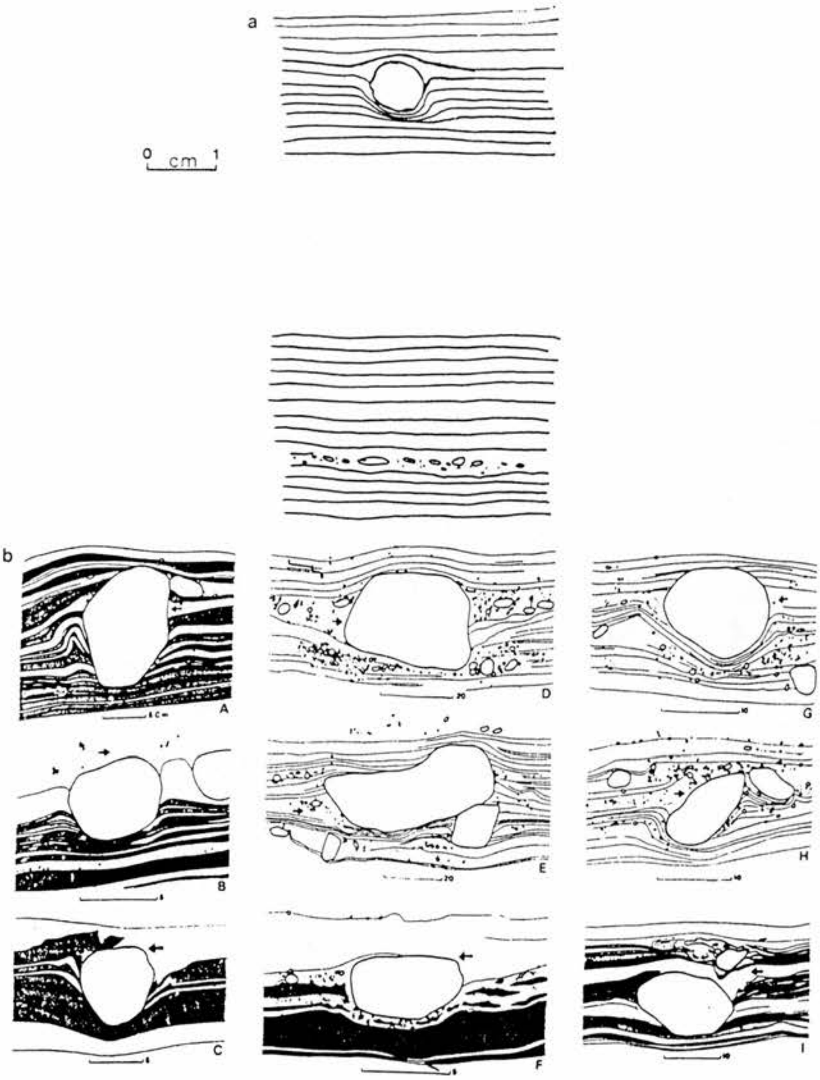


FIGURE 3.8 Provenance diagrams - see enclosure



Dropstone structures. Arrows indicate point in sequence when clast dropped. White: fine to coarse sand. Stipple: silt and clay.

FIGURE 3.9 Illustrations of dropstone structures within glaciomarine sediments from a) the recovered cores and b) onshore sites (after Thomas 1984).

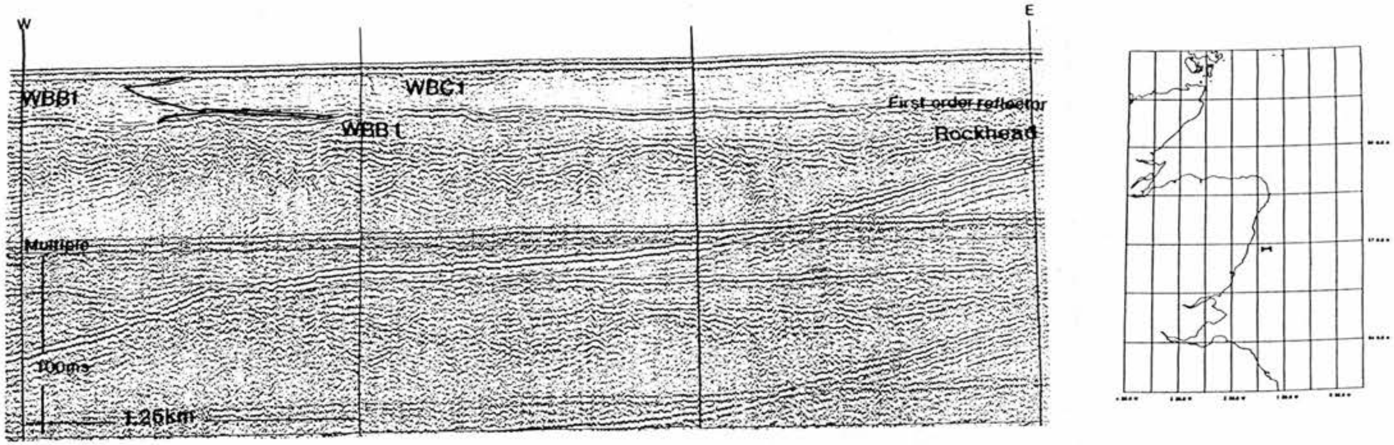
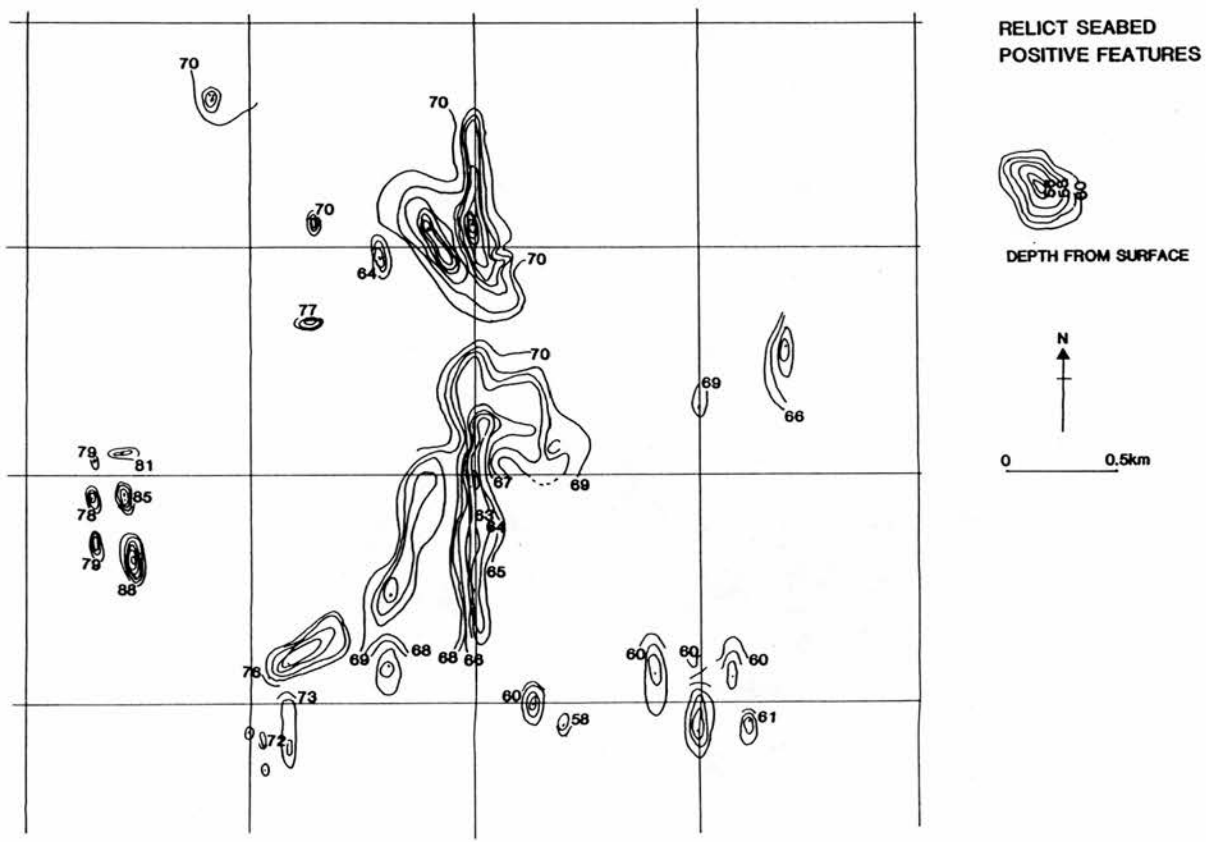


FIGURE 3.10 Seismic profile showing interdigitating seismic facies units, taken from Line 36, project 80/03. Insert shows location.

FIGURE 3.11 Map of the seabed topography of the Wee Bankie (GEOTEAM) site.



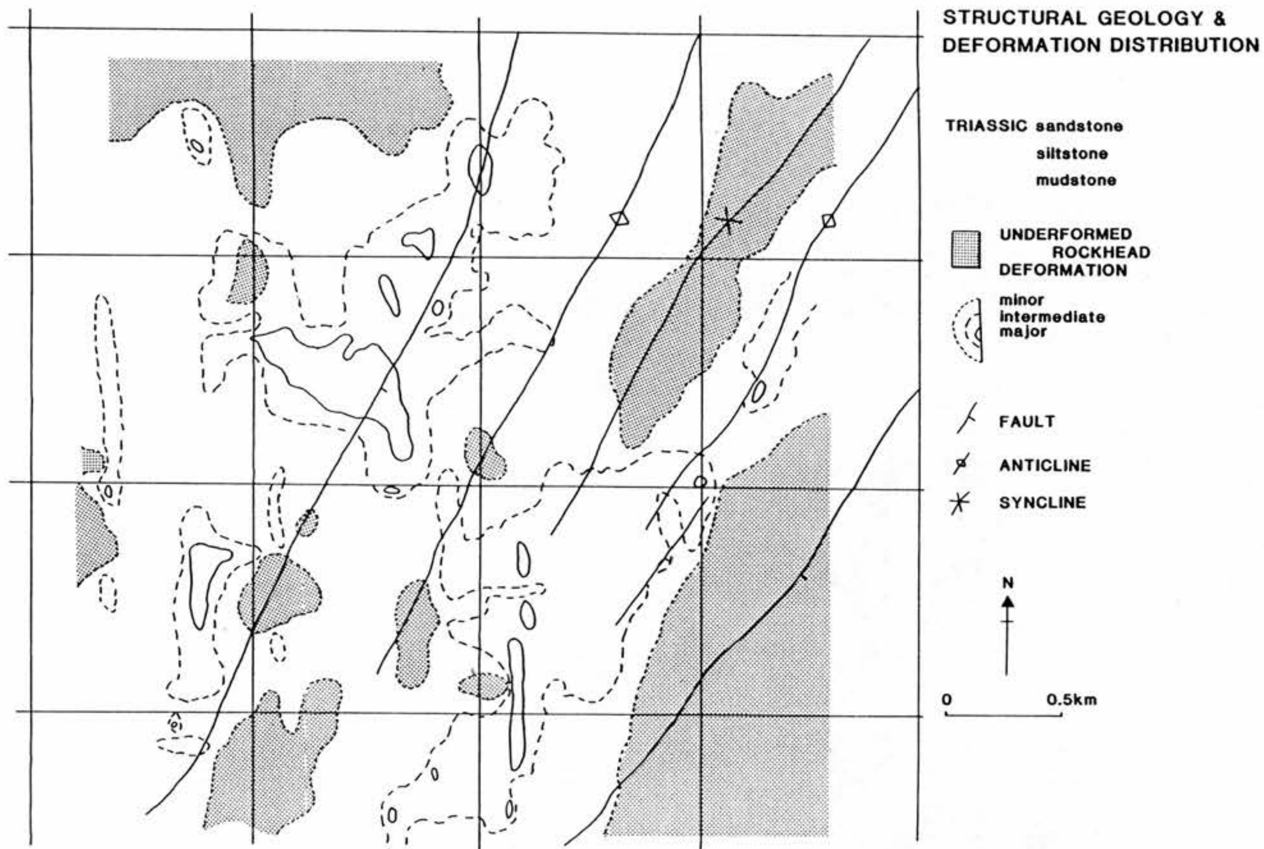


FIGURE 3.12 Map of the rockhead deformation. Note the relationship between structure and the areas of deformation.

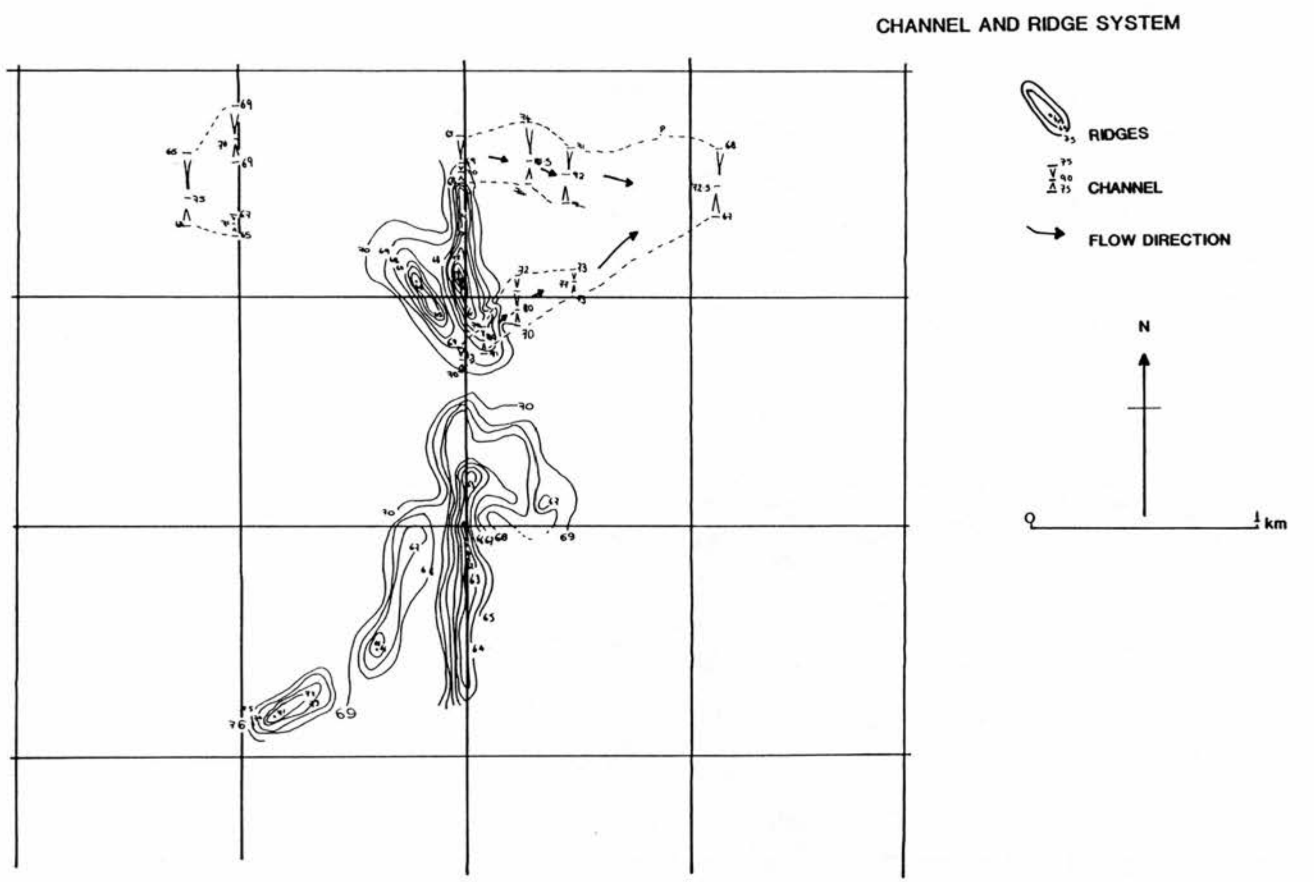


FIGURE 3.13 Illustration of the channel and ridge morphology.

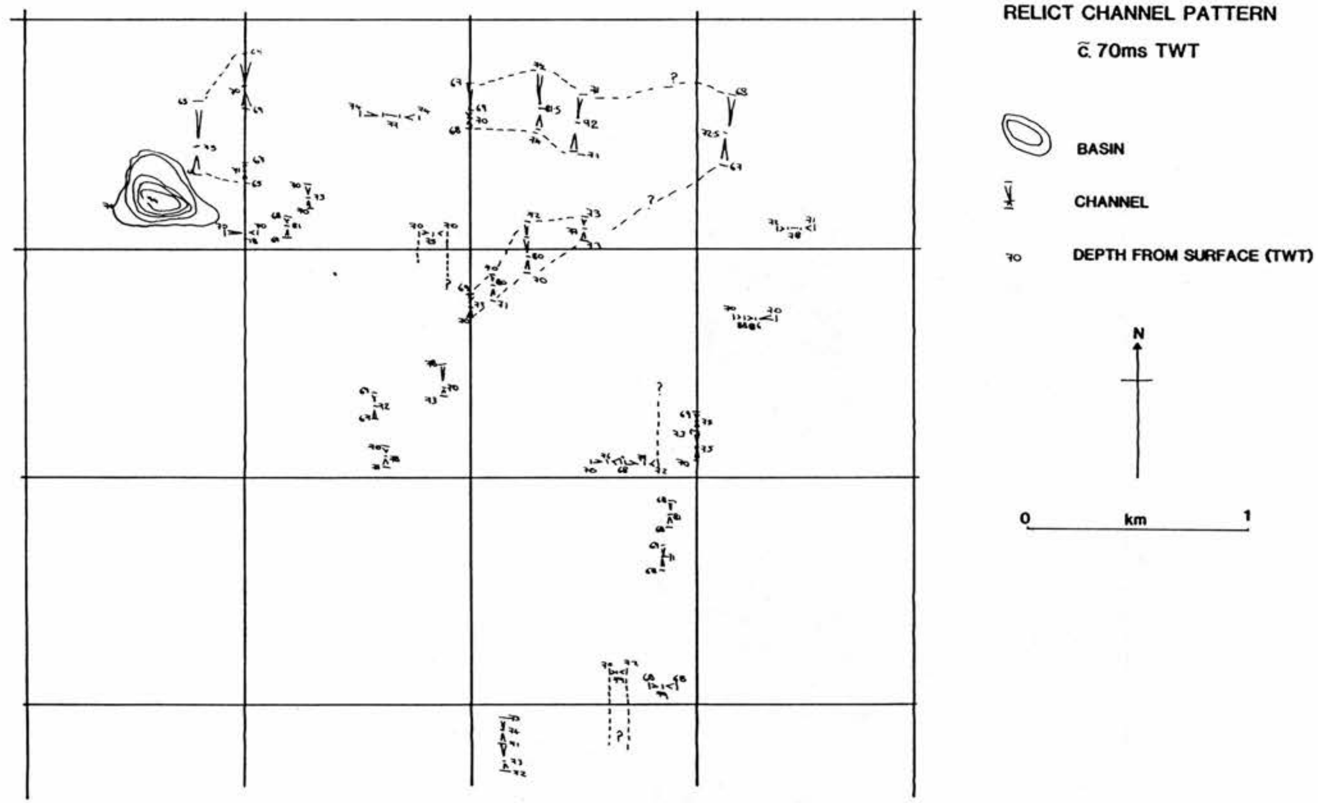


FIGURE 3.14 Map of the channels at c.70ms depth, buried within the sediment. Note the uneven base suggesting flow under hydrostatic pressure and confluent pattern beyond the ridges.

FIGURE 3.15 North to south, and east to west profiles across the detailed site showing the seismic facies units and their lateral contacts, as well as the seabed surface and rockhead topography.

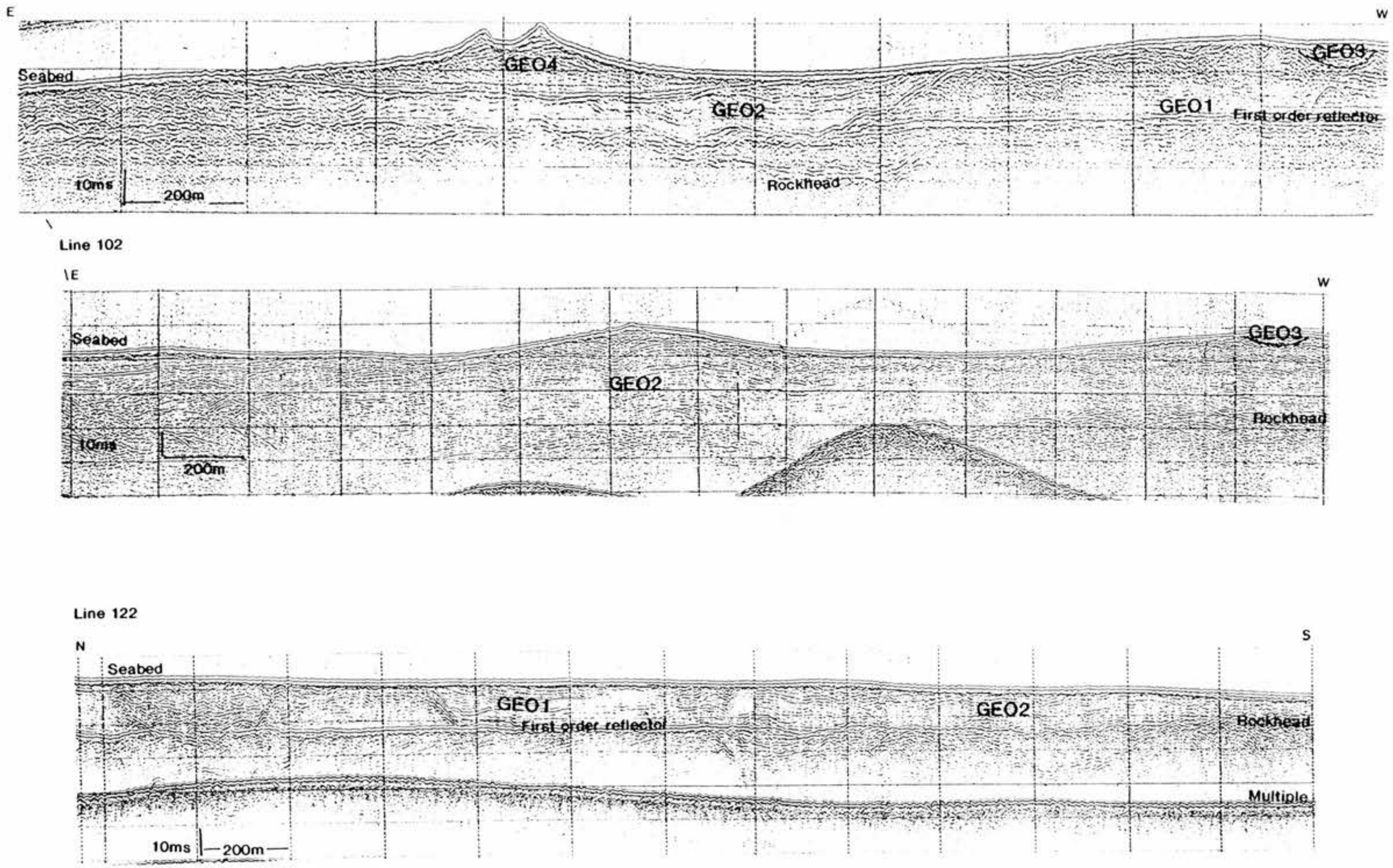
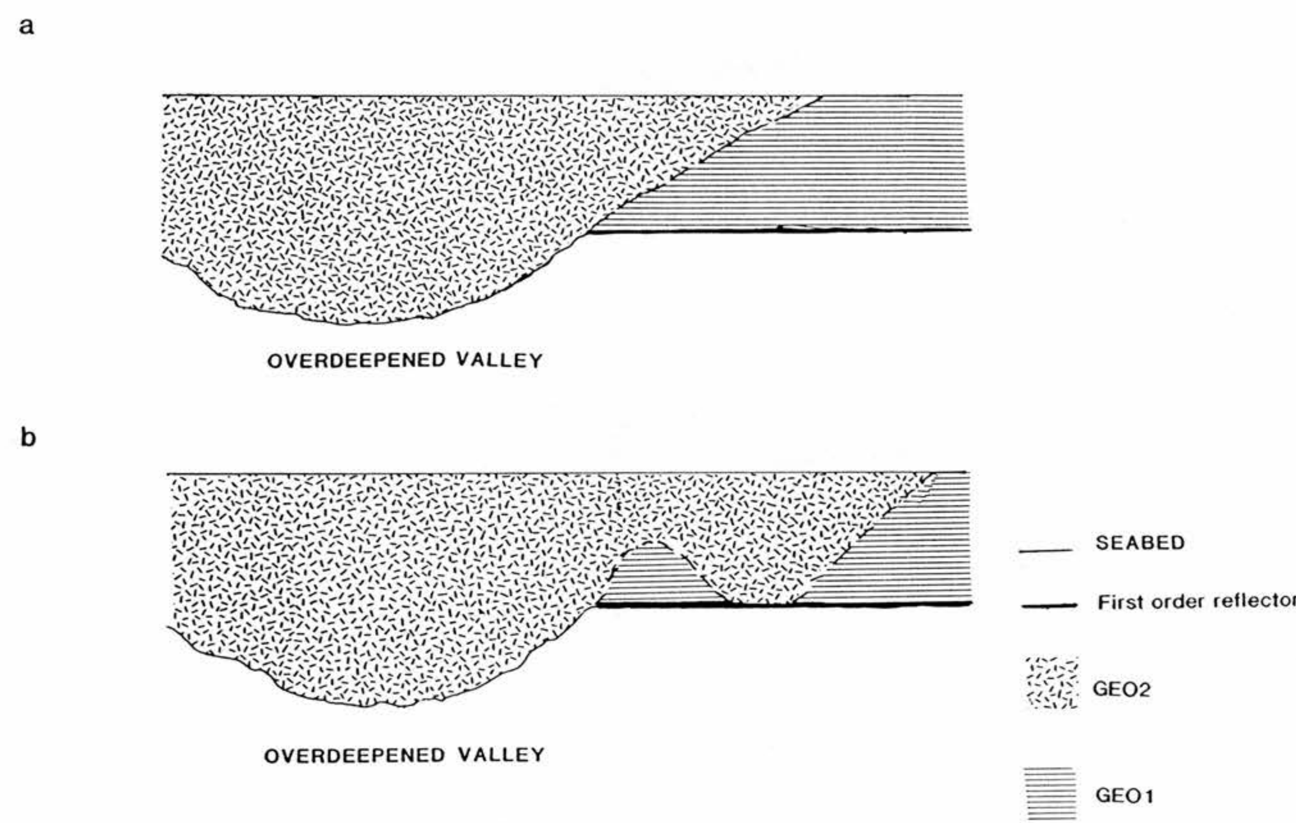


FIGURE 3.16 Schematic sections of the boundaries between the glaciomarine (GEO1) and the diamicton (GEO2) seismic facies units



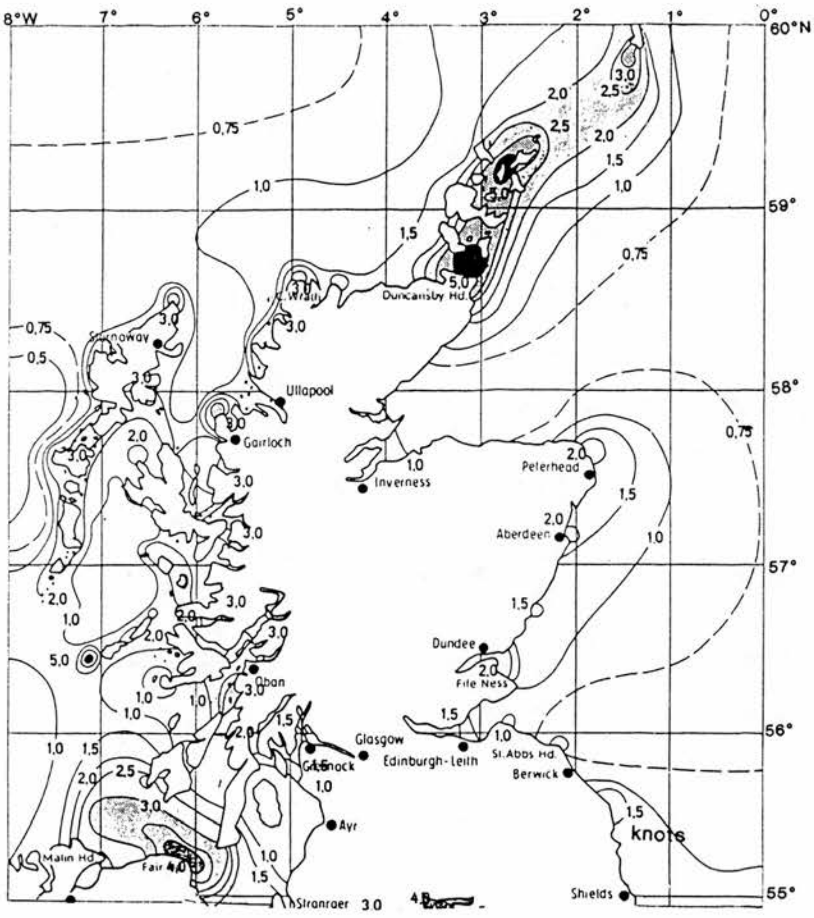


FIGURE 3.17 Map indicating the present day maximum spring currents (after Sager and Sammler 1968).

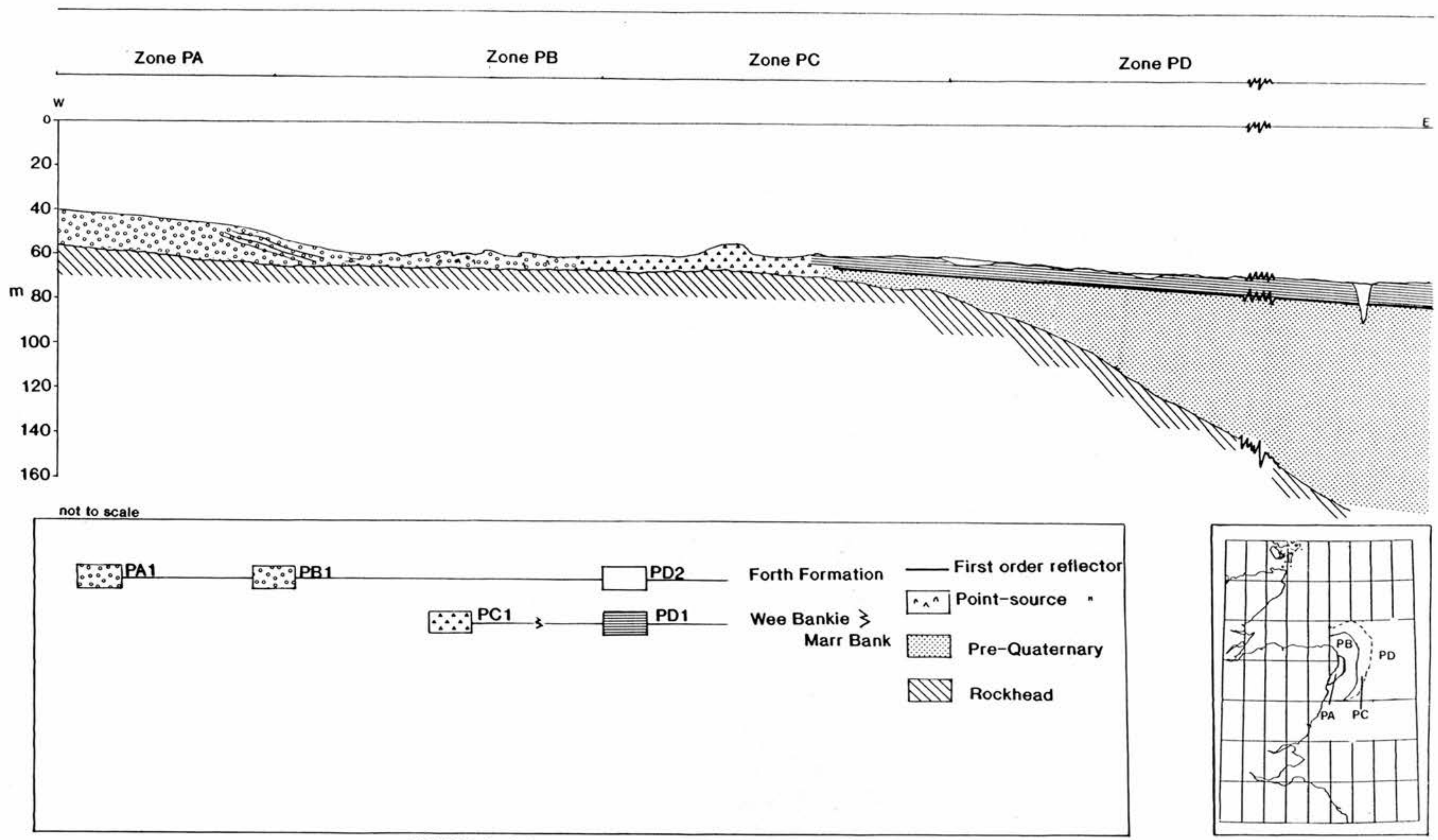
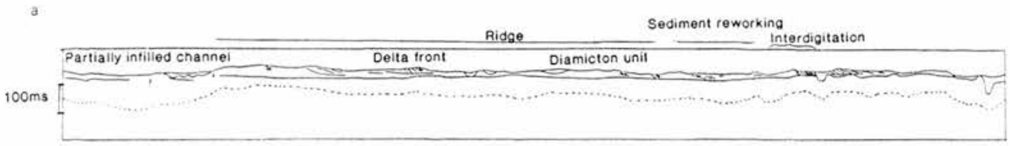
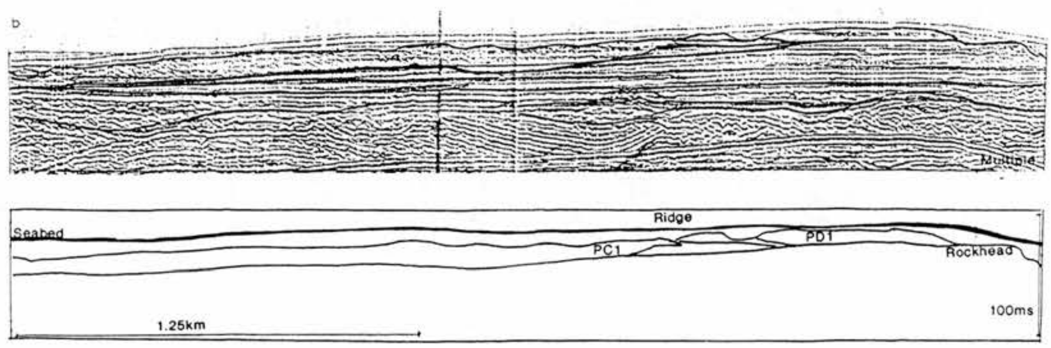


FIGURE 3.18 Composite seismic profile for the Peterhead area, with an insert showing the spatial distribution of the zones.

FIGURE 3.19 Examples of seismic profiles which occur in the Peterhead area. Inset shows the location of the lines.



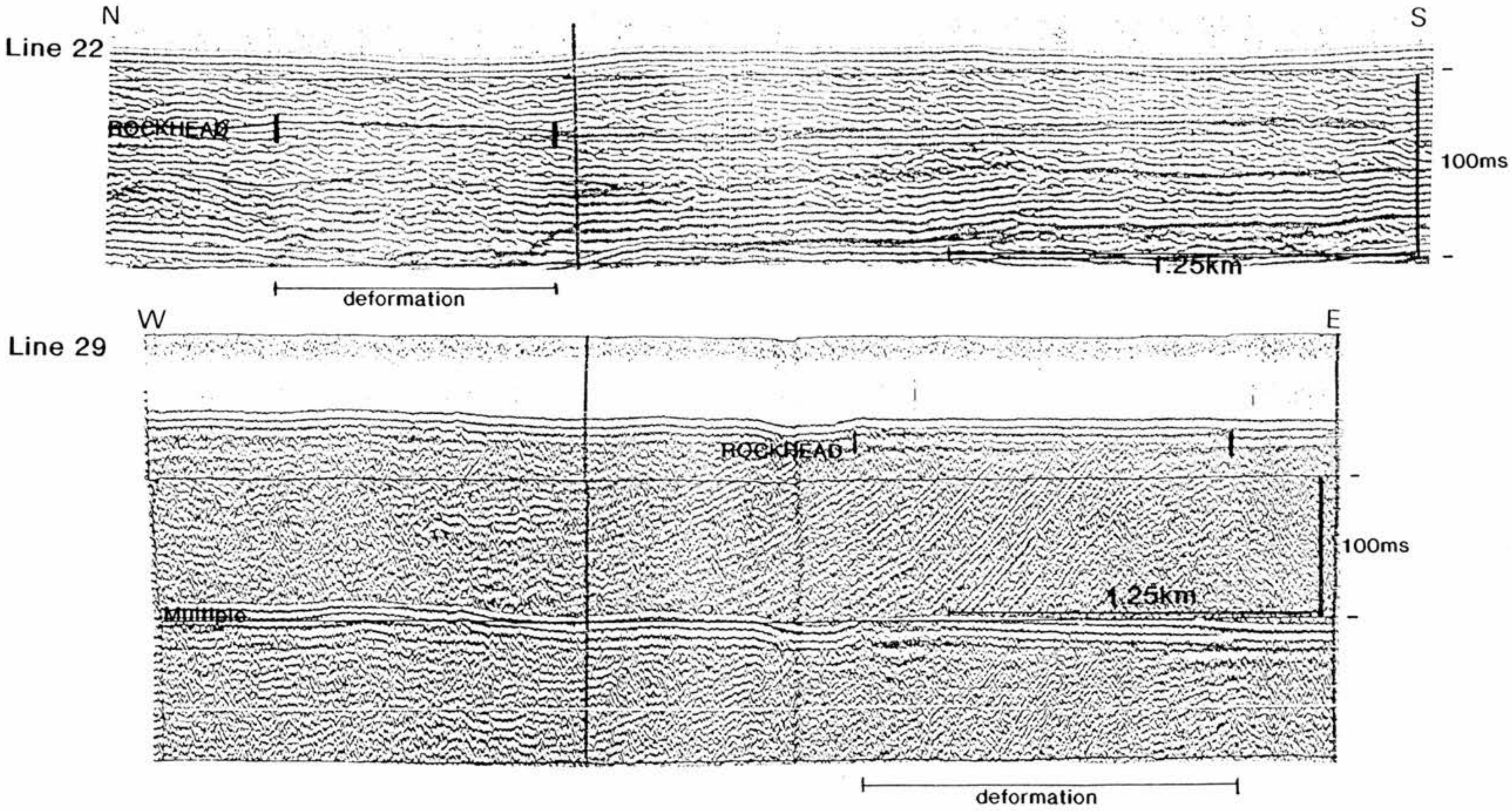
a) This line illustrates the north to south lateral continuations of the composite profile, and an area of interdigitating units in the south.



b) This shows the ridge in the northwest, the possible deformation of the rockhead

c) This contains a ridge with some internal structure, and some seabed sediment transport features.

FIGURE 3.20



The seismic sections show deformation of the rockhead and disturbance of the rockhead reflector

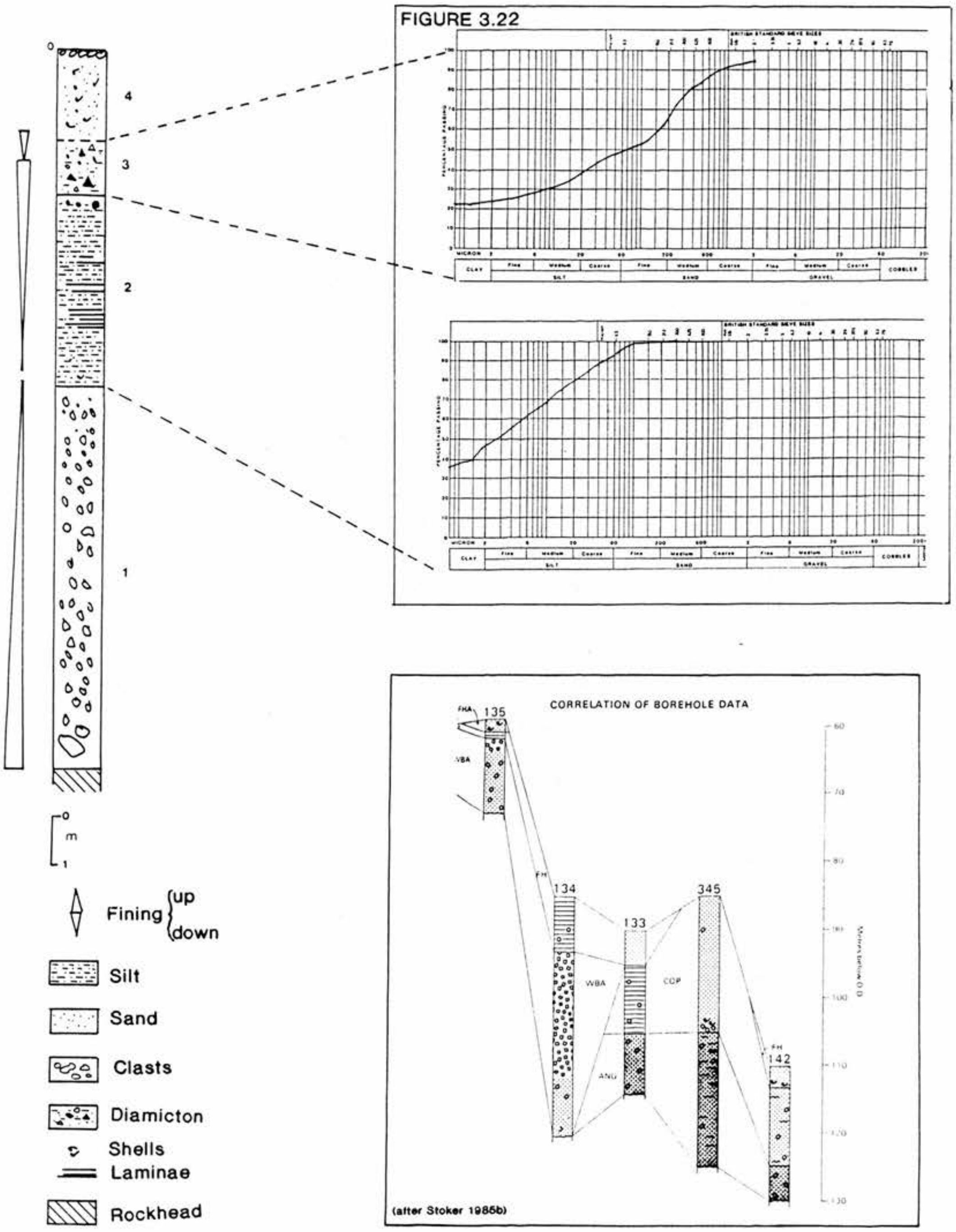


FIGURE 3.21 Incorporating FIGURE 3.22. Peterhead (West) Composite borehole with PSA results from 72/21

Note that the eastern composite borehole is the same as for the Wee Bankie area (FIGURE 3.6).

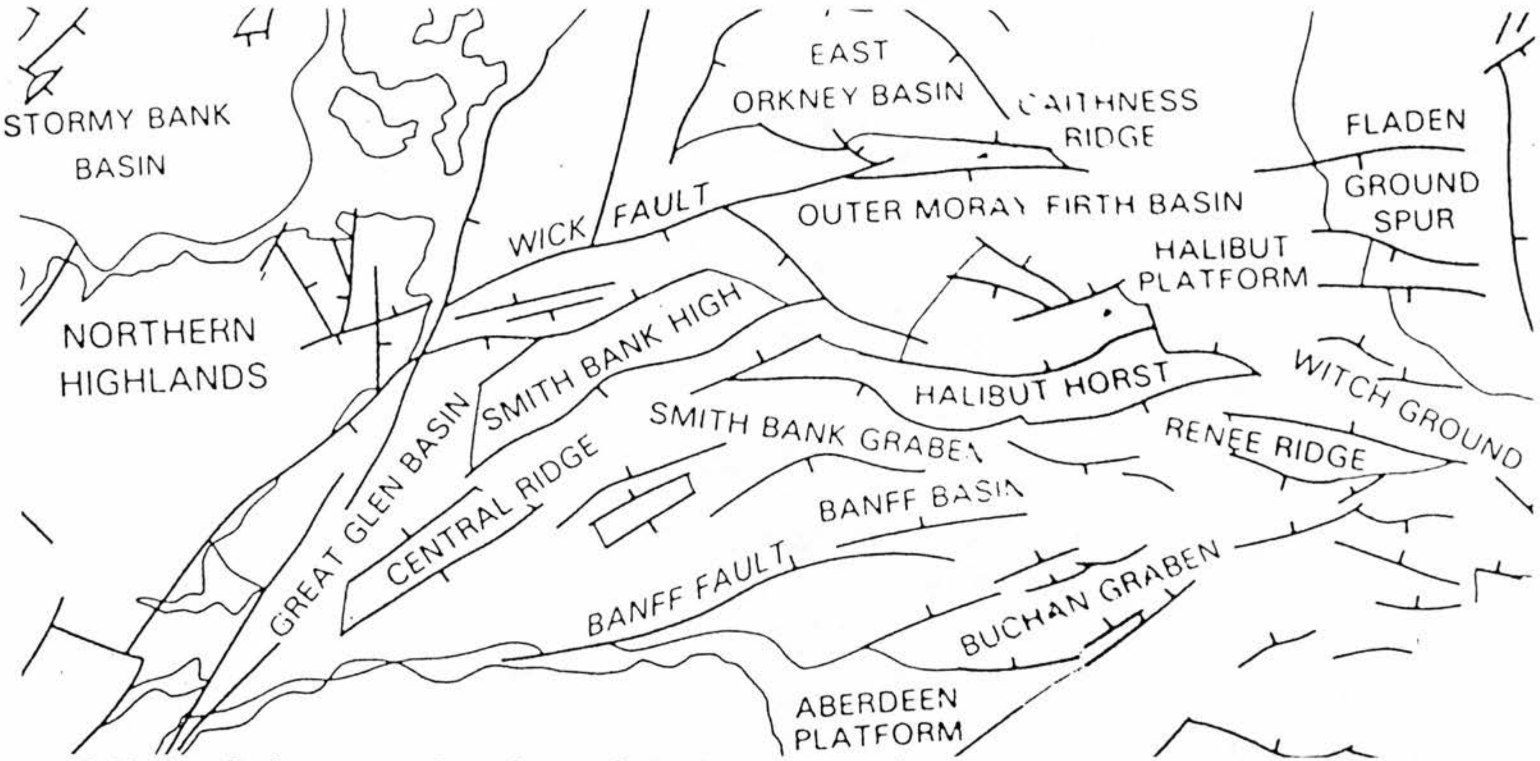
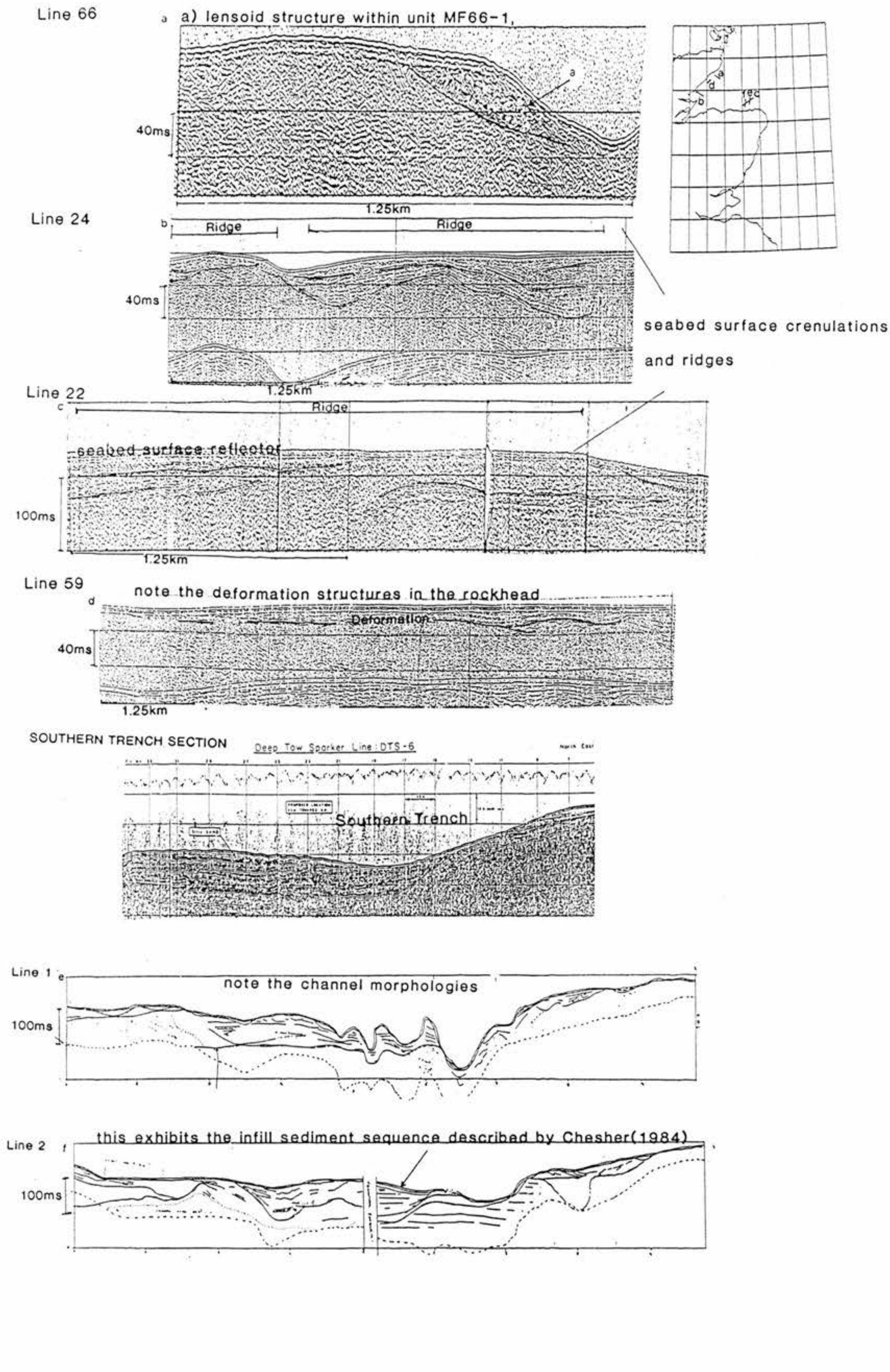


FIGURE 3.23 Detailed structural geology of the Moray Firth (after PESGB 1990).

0 km 50

FIGURE 3.24 Seismic profiles across the Moray Firth



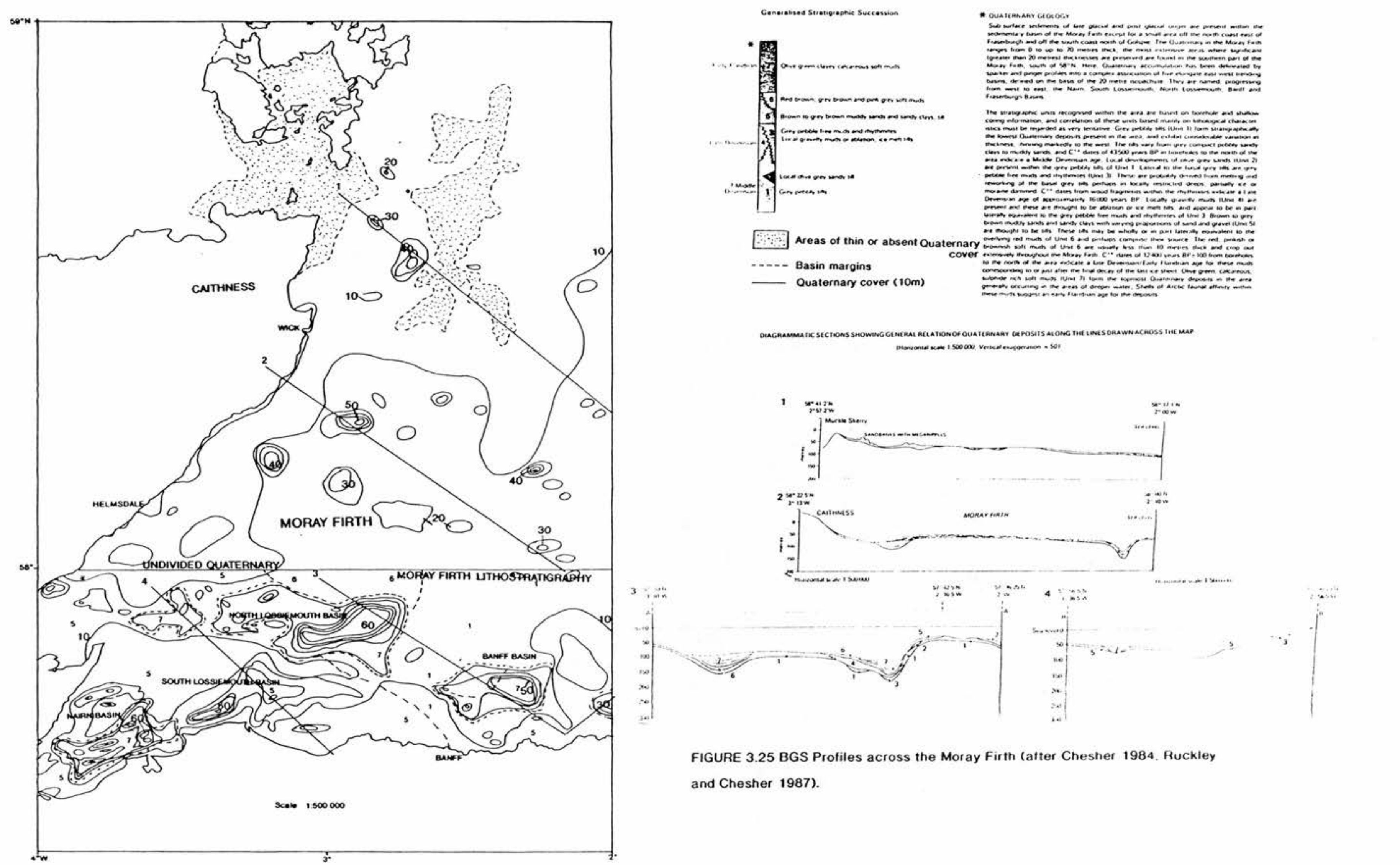


FIGURE 3.25 BGS Profiles across the Moray Firth (after Chesher 1984, Ruckley and Chesher 1987).

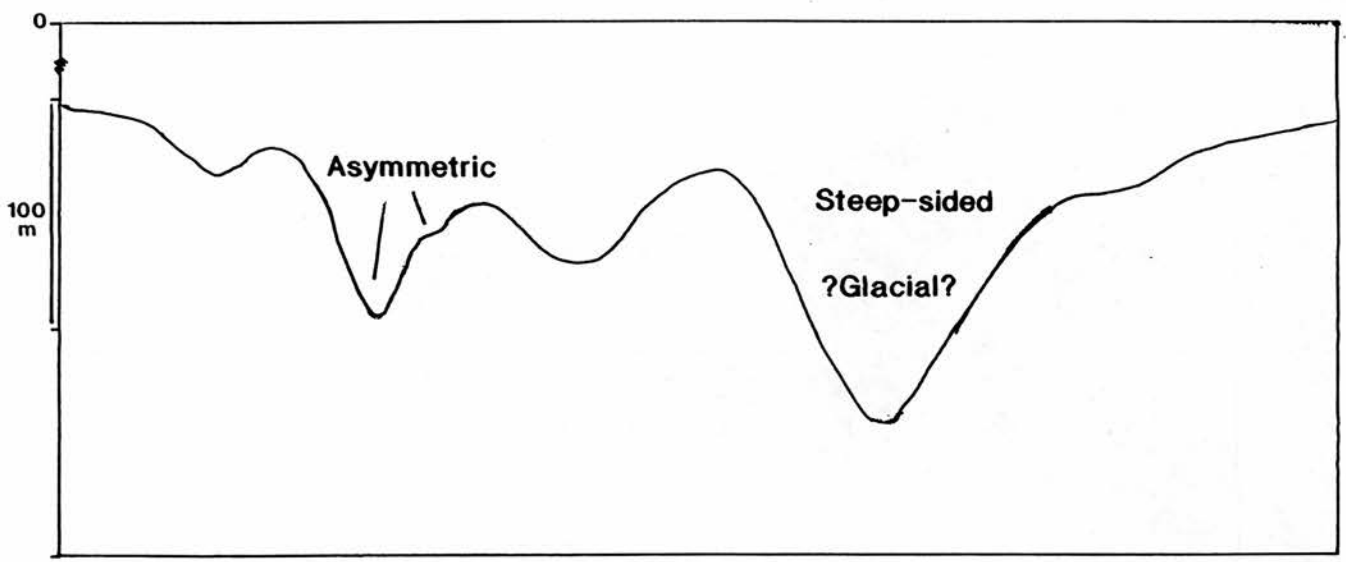


FIGURE 3.26 Topographical section across the incised channels; note the channel morphologies.

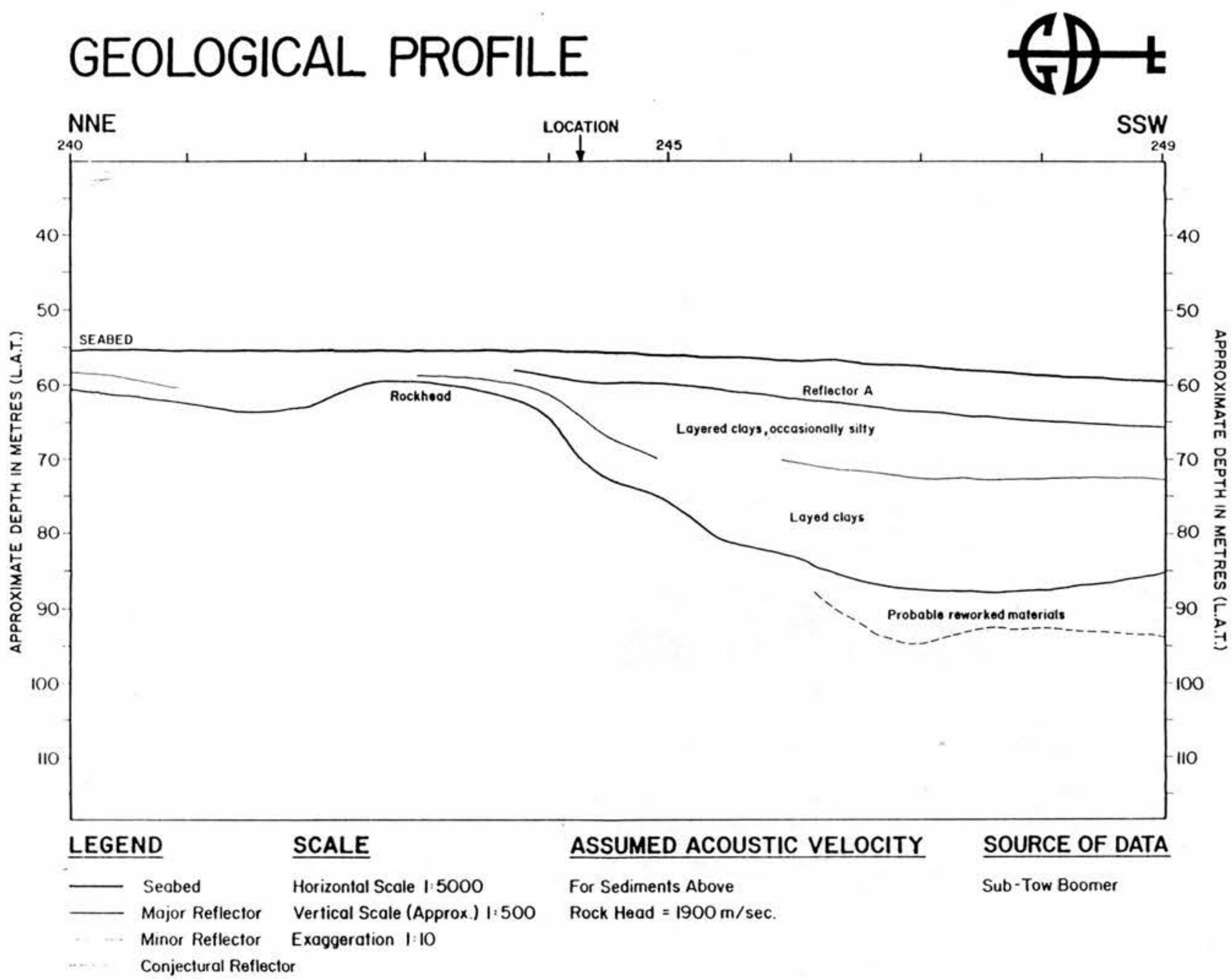


FIGURE 3.27 Profile across the Beatrice site showing the seismic facies units and the sedimentary succession (after FUGRO-CESCO BV 1977).

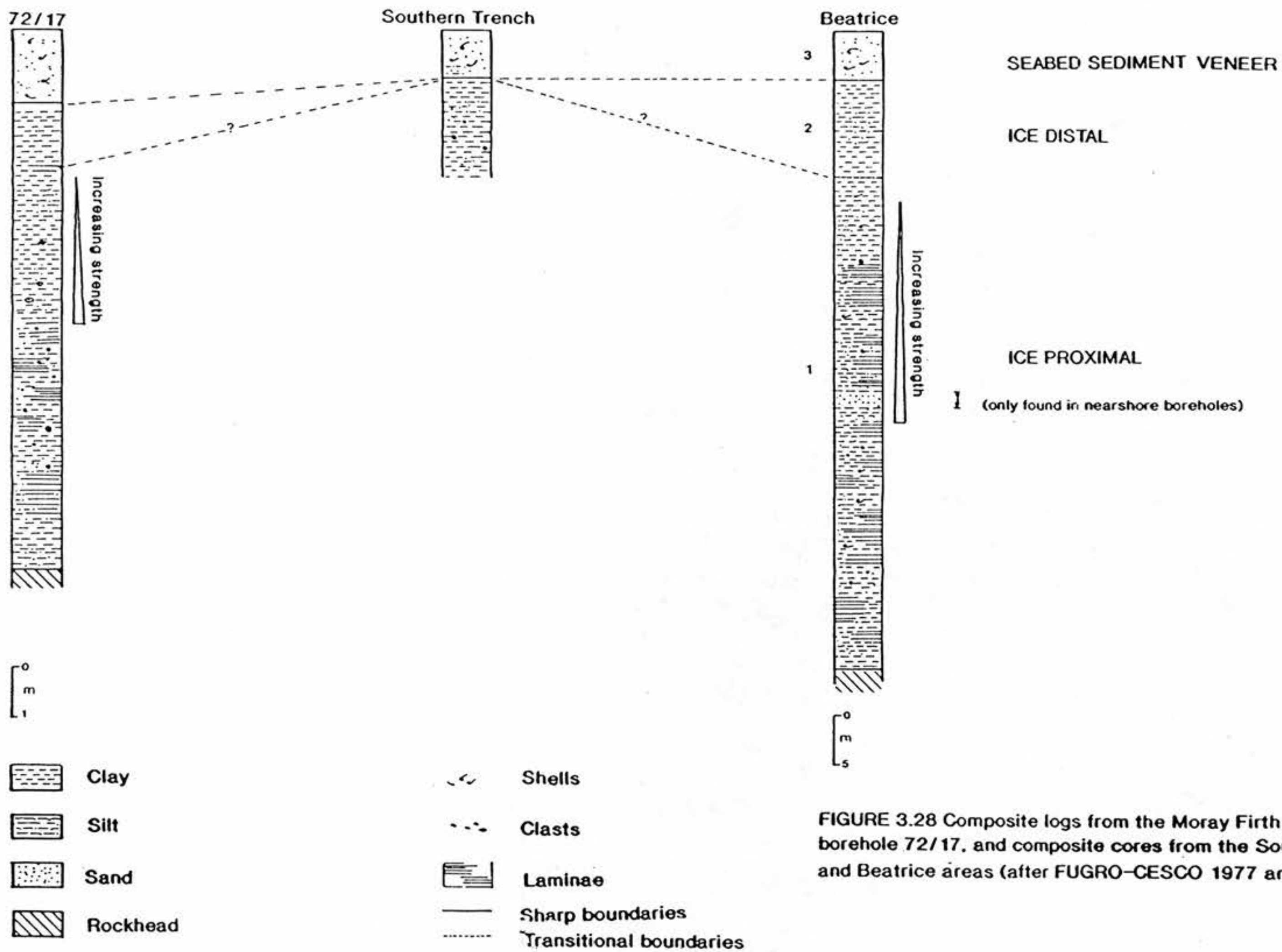


FIGURE 3.28 Composite logs from the Moray Firth including BGS borehole 72/17, and composite cores from the Southern Trench and Beatrice areas (after FUGRO-CESCO 1977 and RACAL 1988)

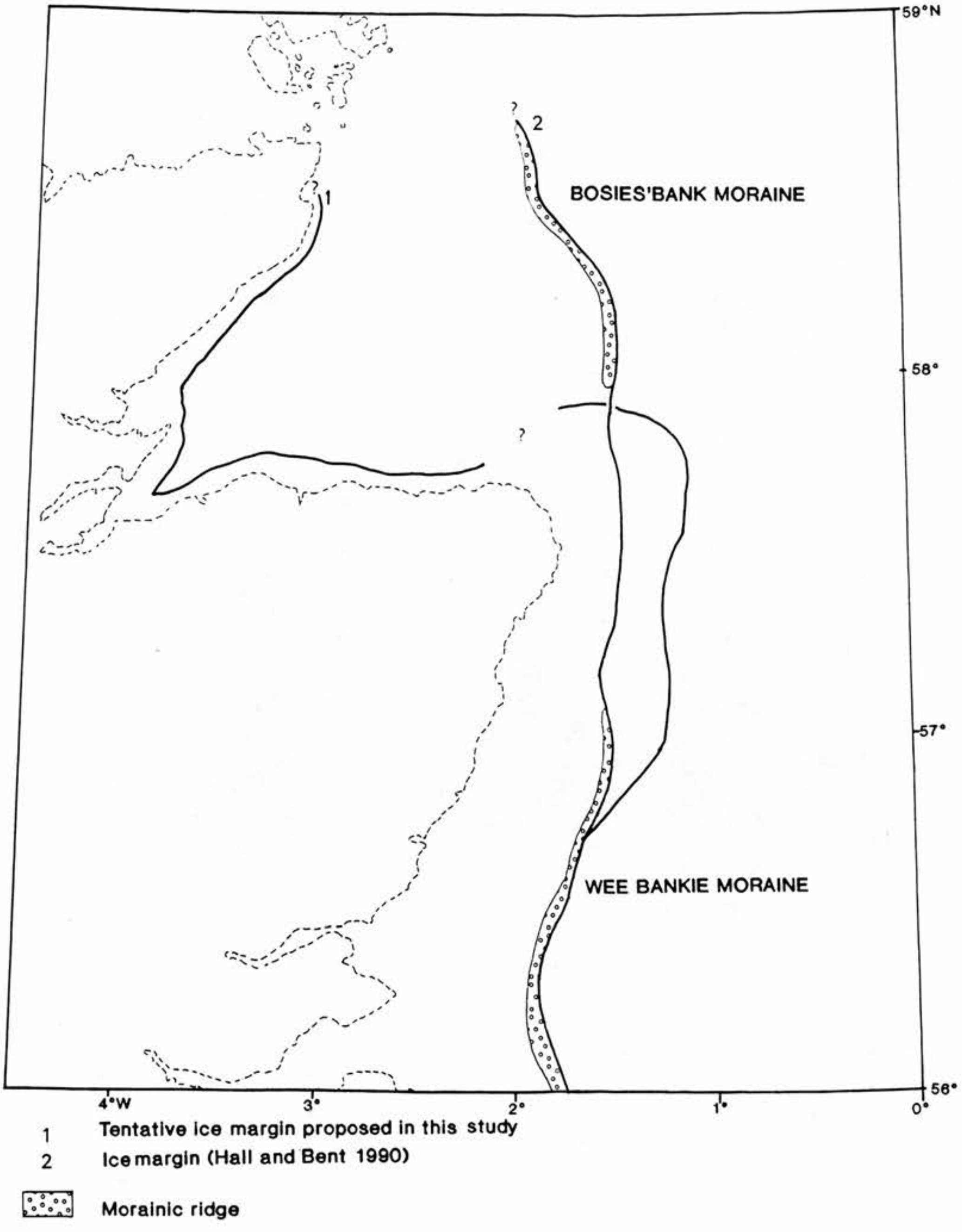
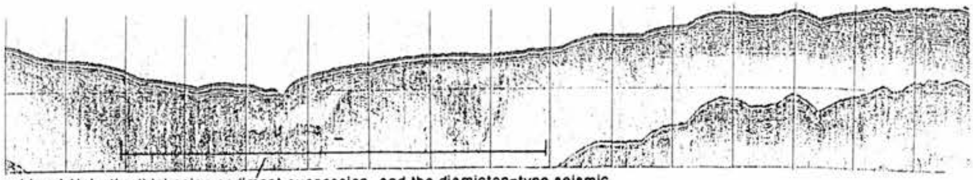
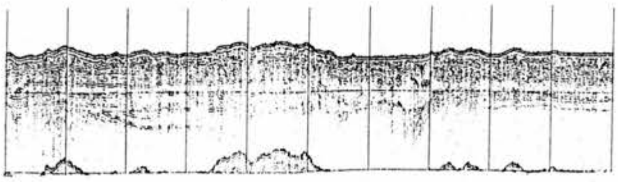


FIGURE 3.29 Map showing the location of the Bosies' Bank and Wee Bankie moraines.

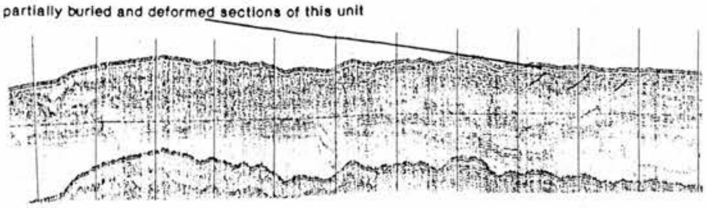
FIGURE 3.30 North to south and east to west trending seismic profiles from the Bosies' Bank moraine showing the morphology and seismic facies units present (compiled from Bent 1986).



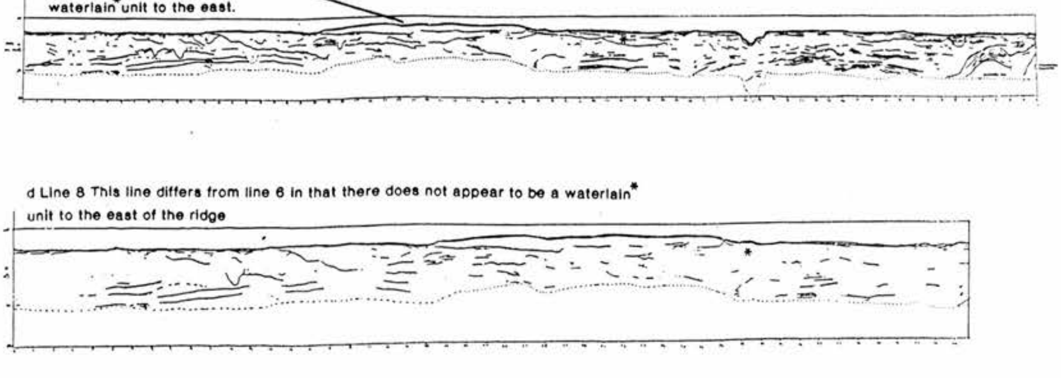
a Line 1 Note the thickening sediment succession and the diamicton-type seismic facies response within the infilled basin. Note the 'hummocky' surfaced unit occuring above the uneven rockhead with typical diamicton response



b Line 2 Note the more hummocky seabed surface than exhibited in line 1, and the partially buried and deformed sections of this unit



c Note the valley and the ridge interpreted by Bent as a moraine. Note the waterlain* unit to the east.

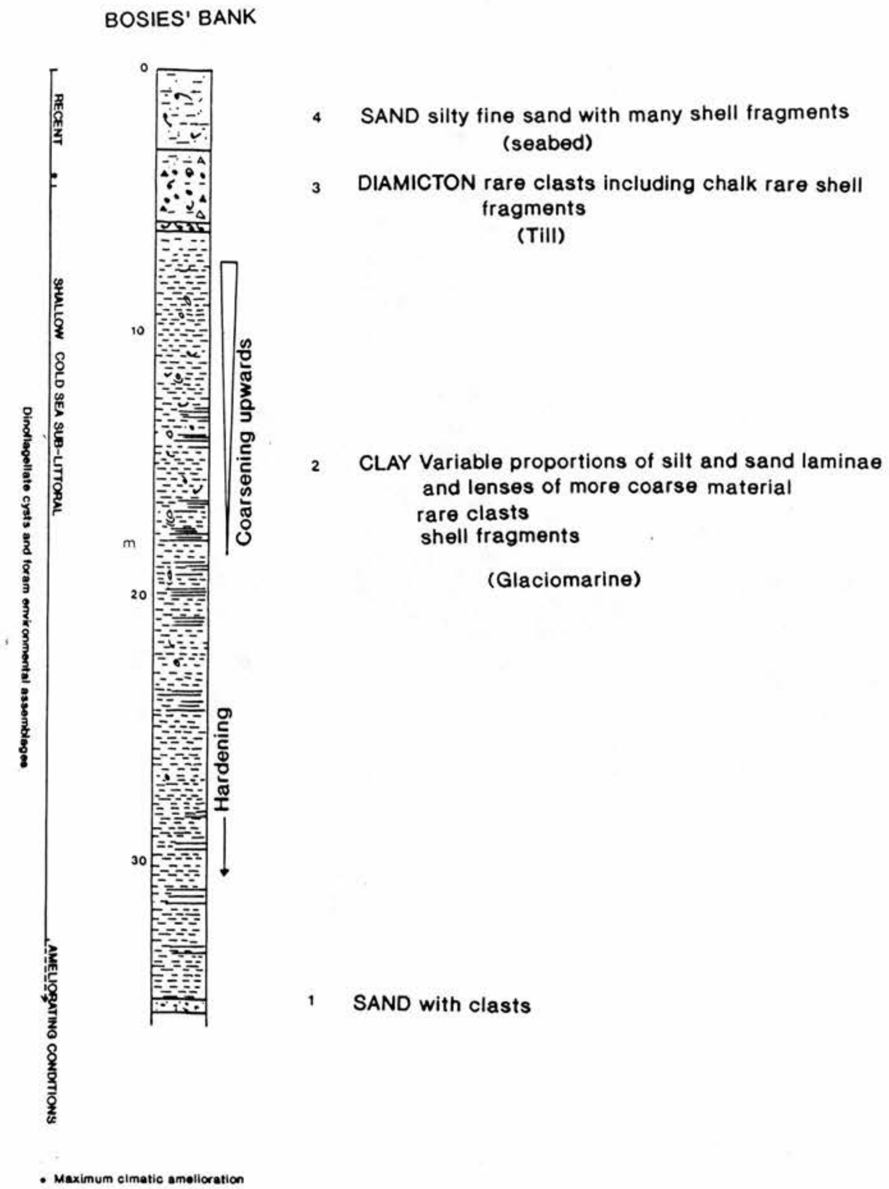


d Line 8 This line differs from line 6 in that there does not appear to be a waterlain* unit to the east of the ridge

Line locations

Isometric diagram, after Bent 1986.

FIGURE 3.31 Composite sedimentary log for the Bosies' Bank area (after Skinner and Bent 1988).



(after Bent 1986, Skinner and Bent 1988)

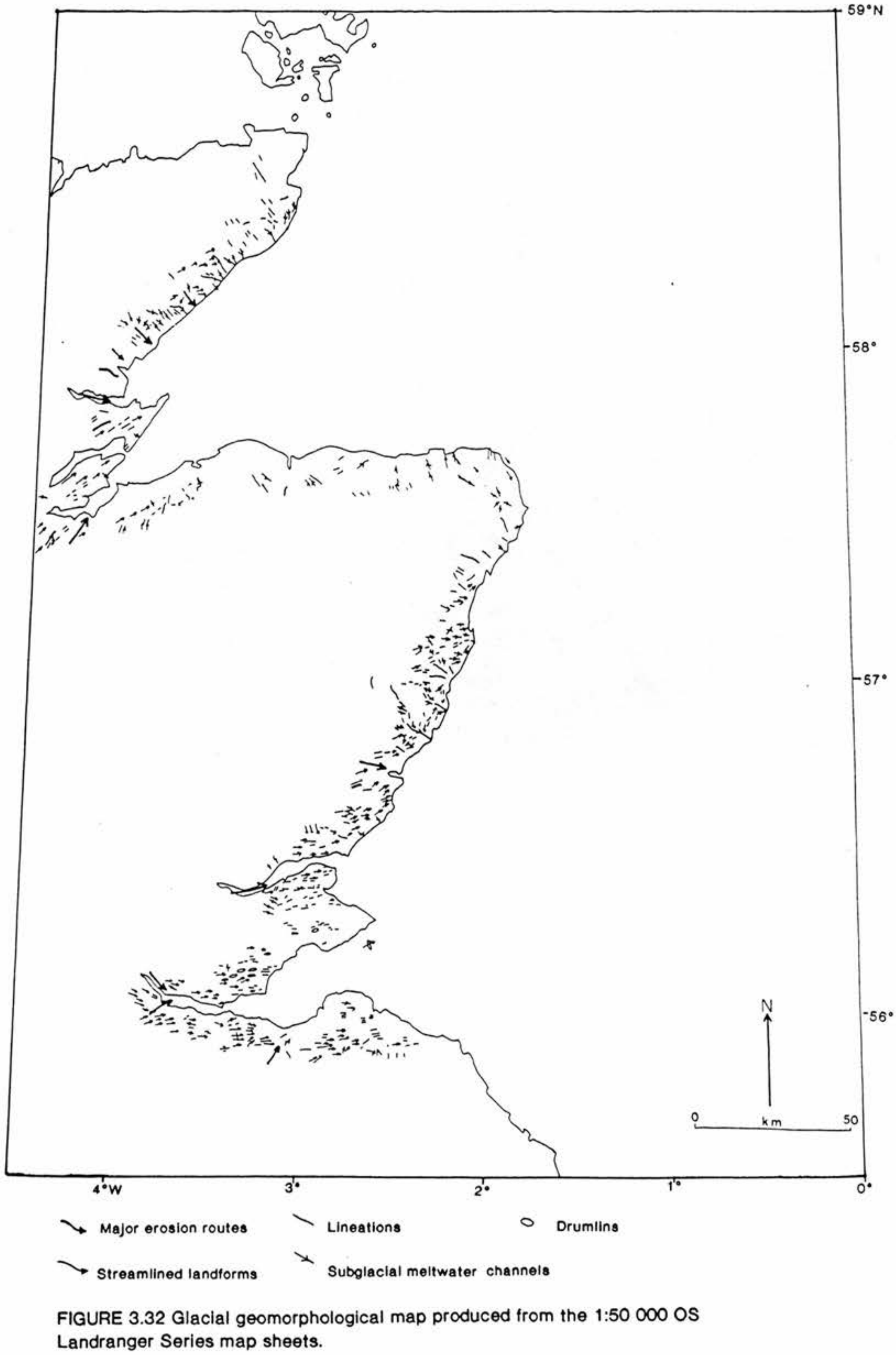


FIGURE 3.32 Glacial geomorphological map produced from the 1:50 000 OS Landranger Series map sheets.

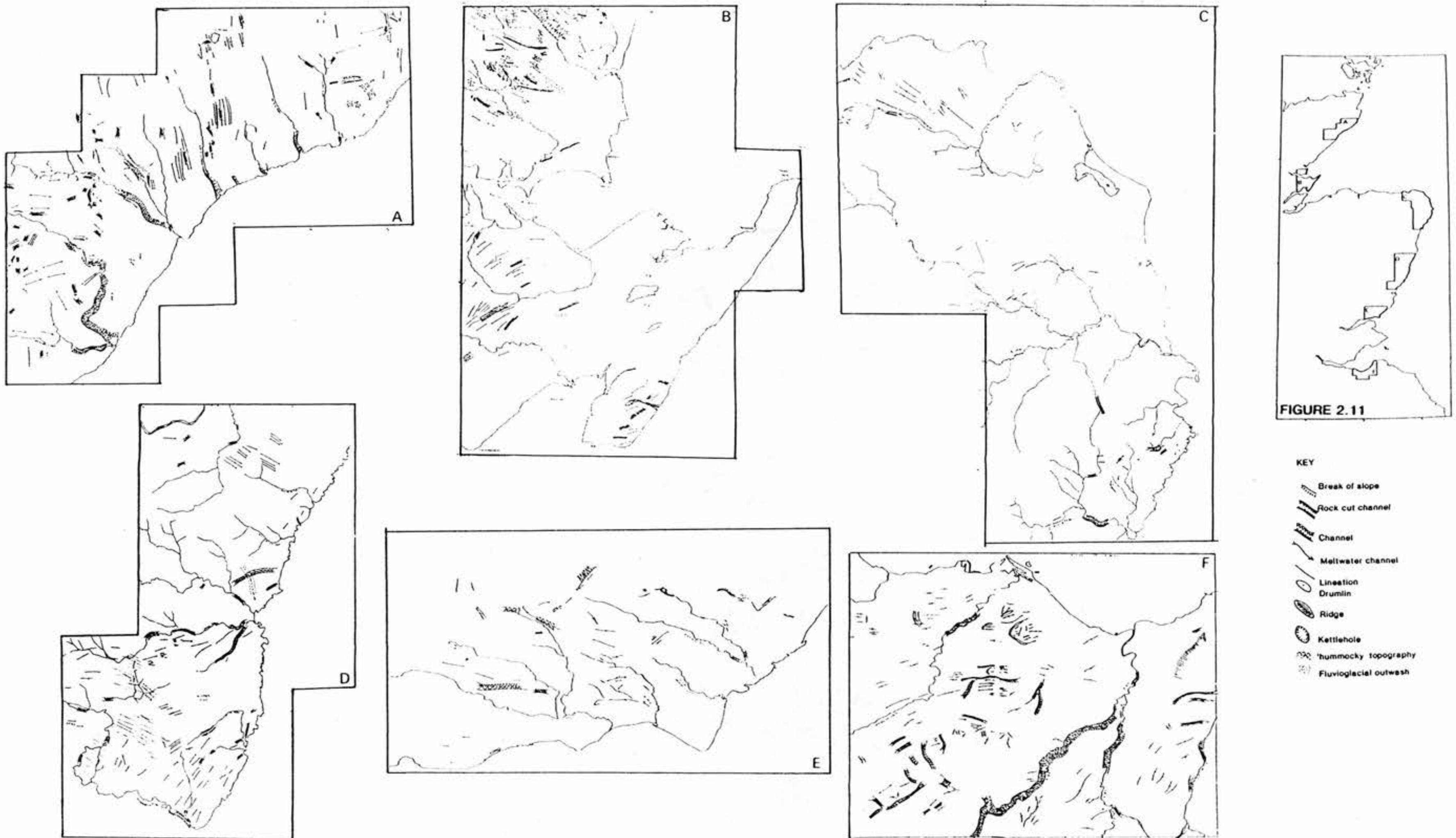


FIGURE 3.33 Glacial geomorphological maps of the 1:24 000 oblique aerial photographs (SDD 1989).

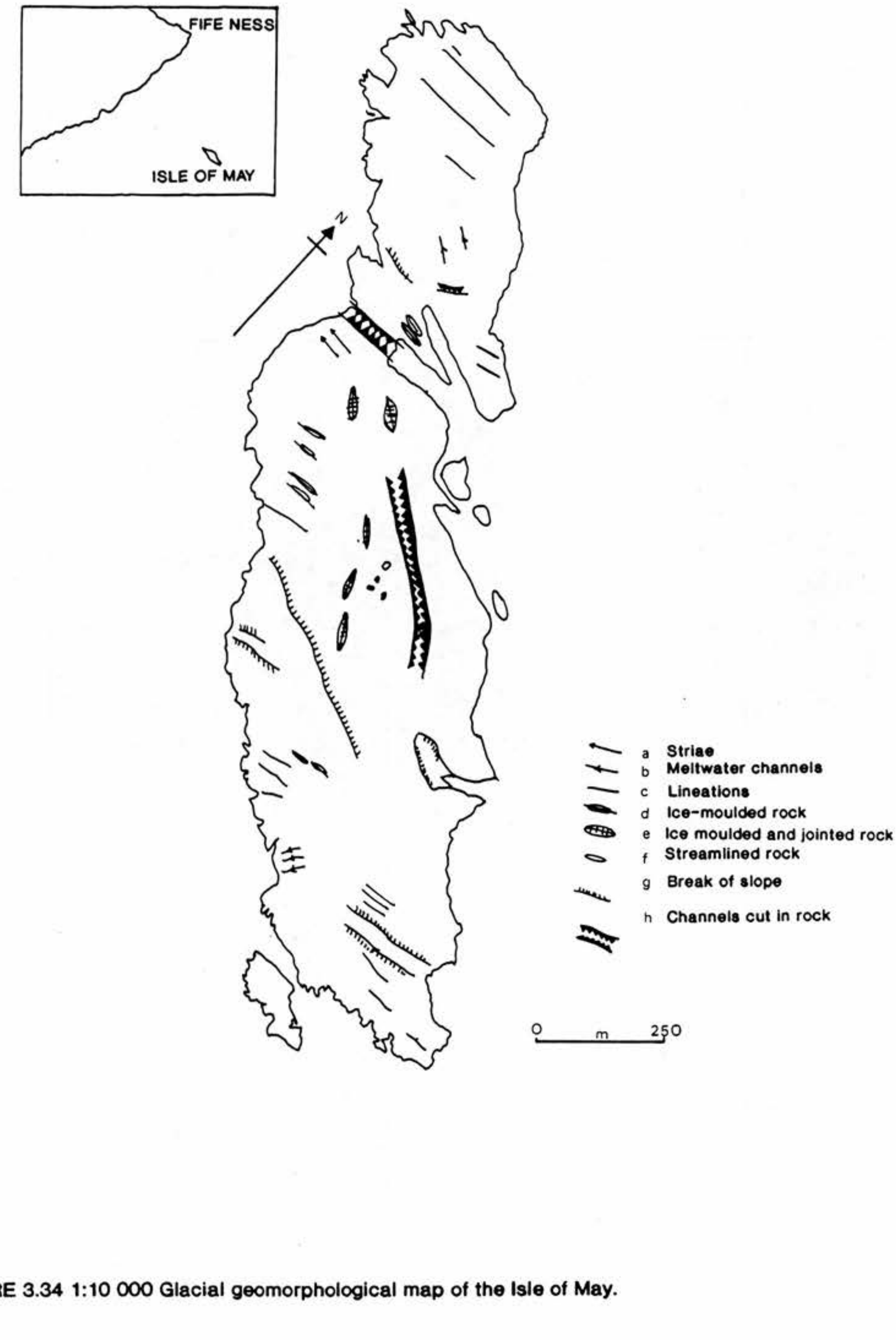


FIGURE 3.34 1:10 000 Glacial geomorphological map of the Isle of May.

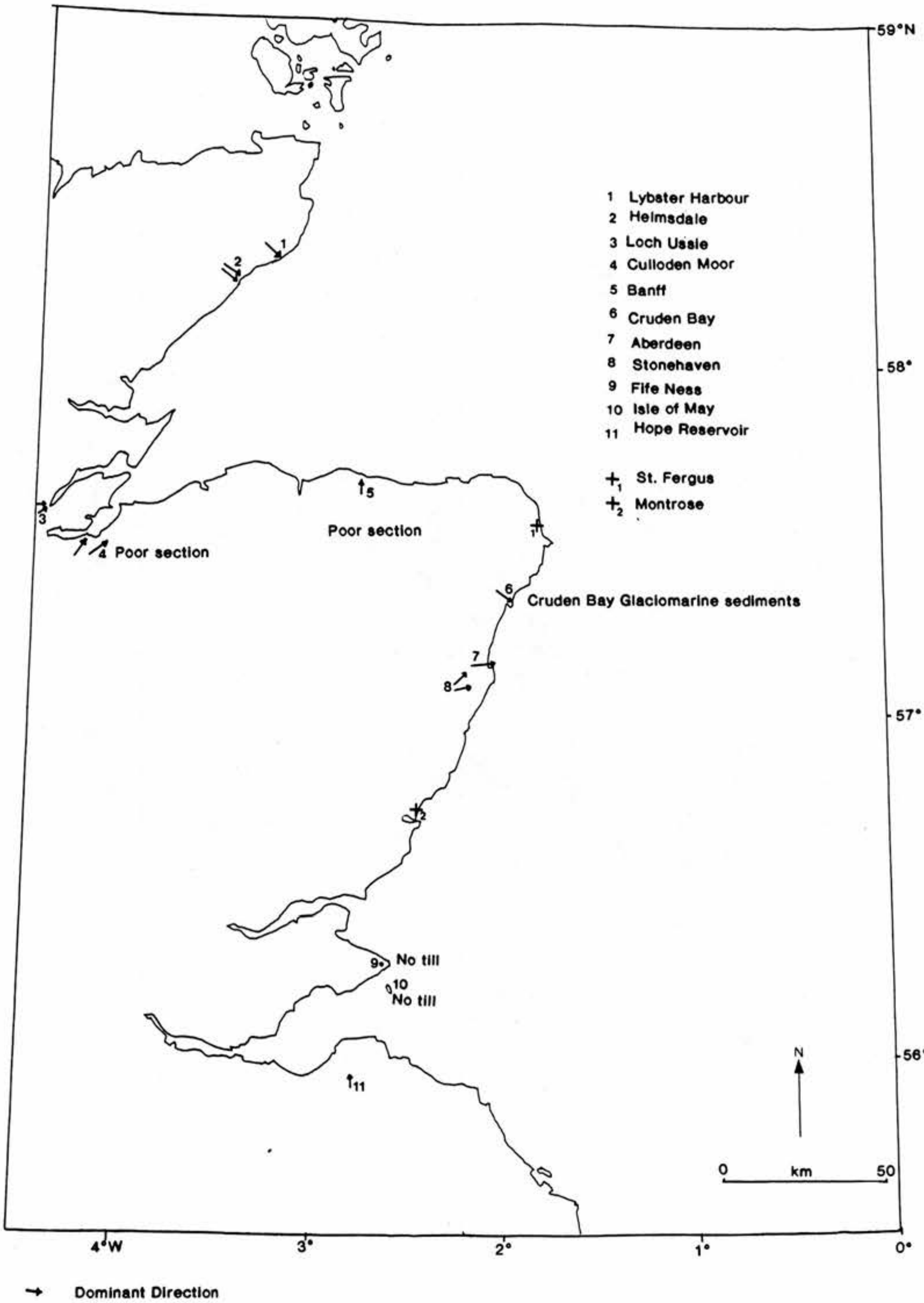


FIGURE 3.35 Map showing the onshore borehole and sediment section sites.

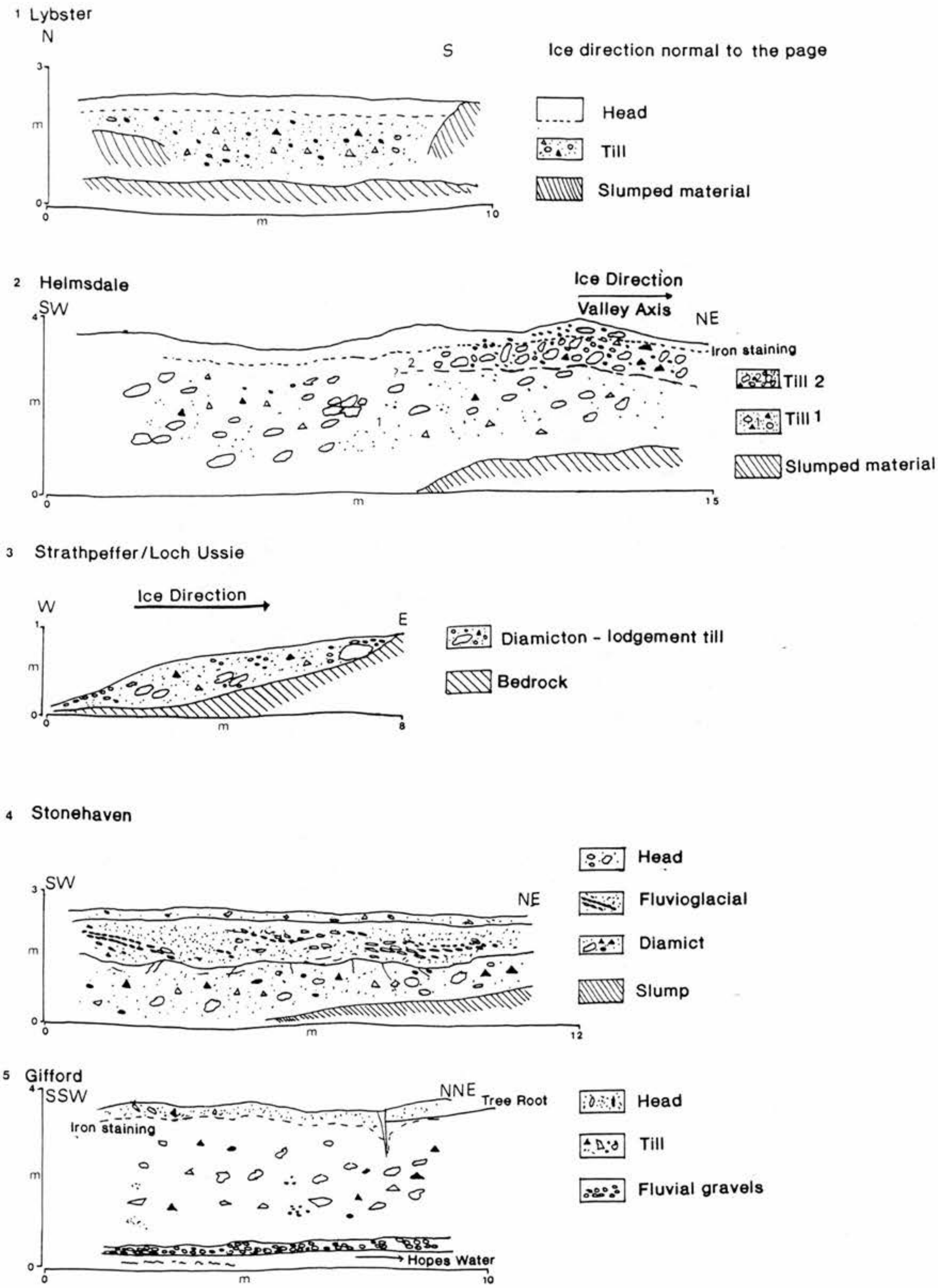


FIGURE 3.36 Field sketches of the onshore sections, illustrating the sediment successions at a) Lybster, b) Helmsdale, c) Strathpeffer, d) Stonehaven and e) Hope Reservoir, near Gifford.

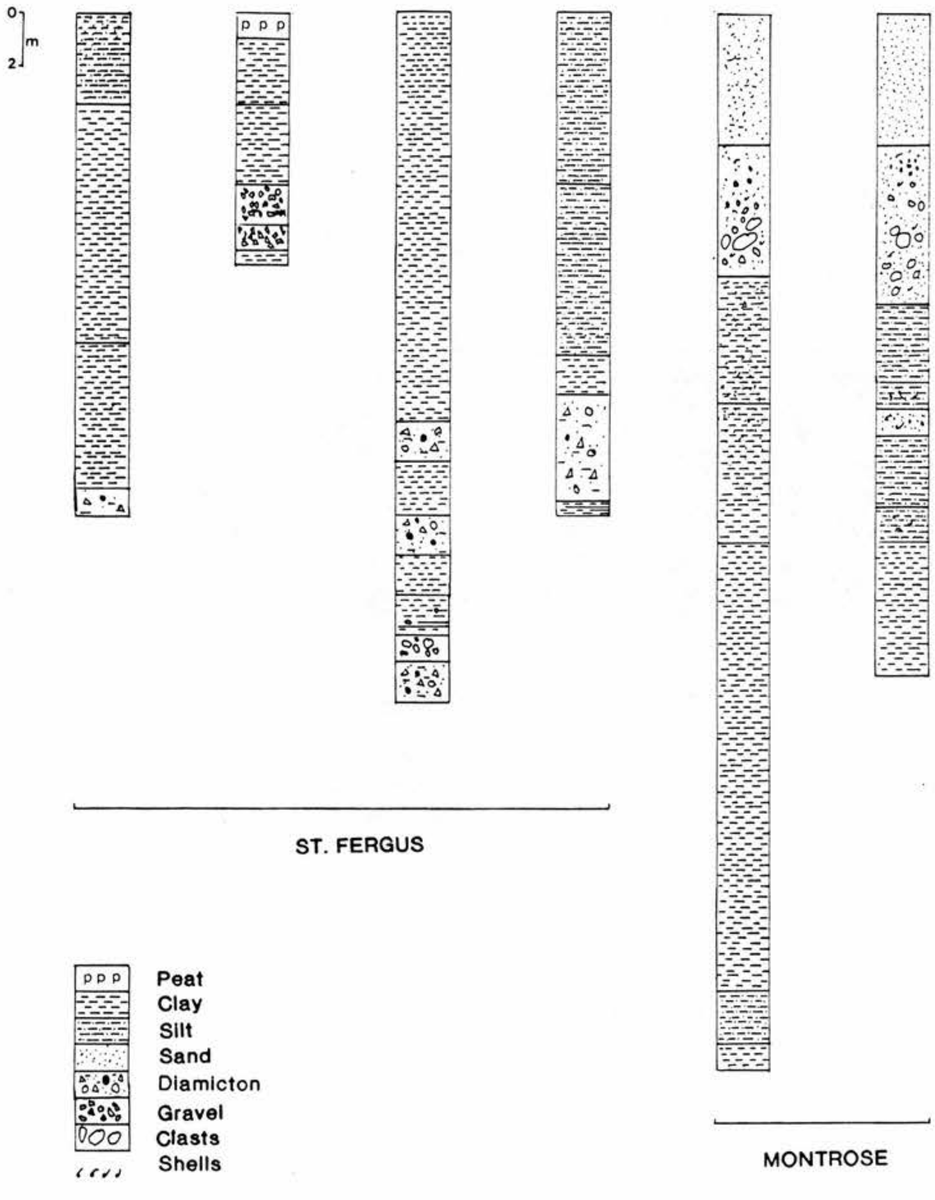
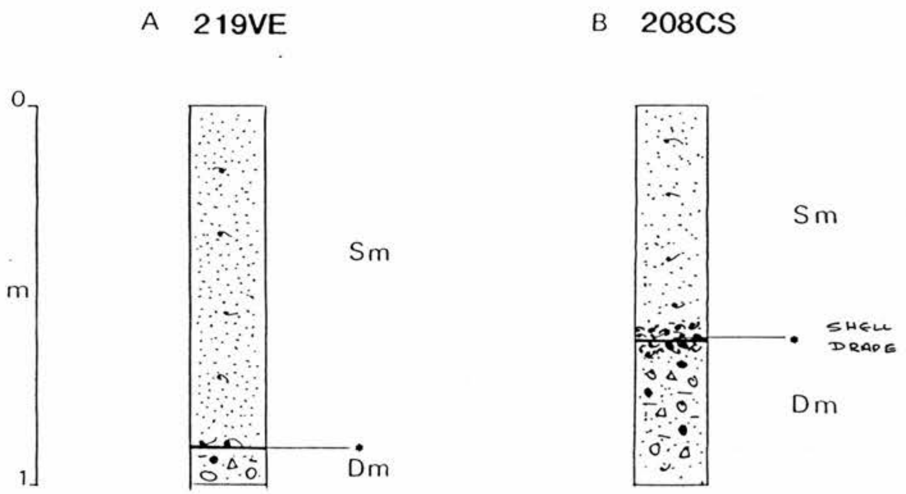
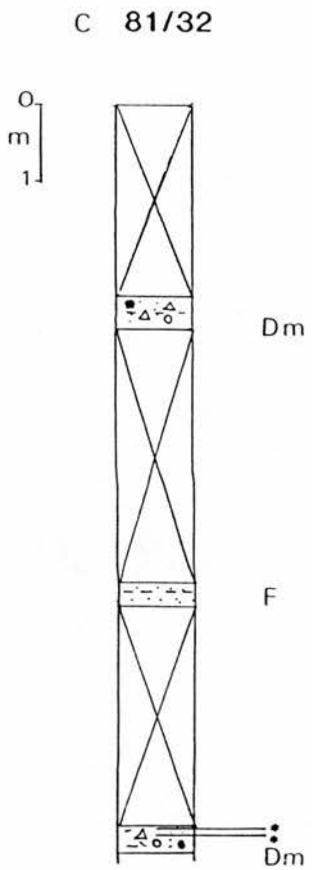
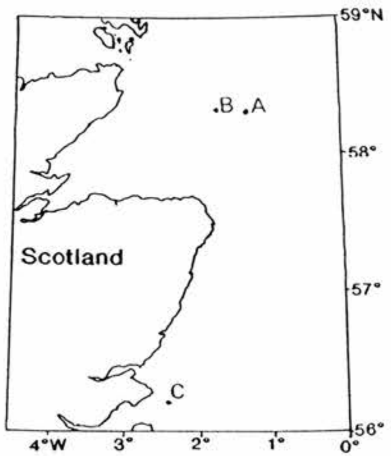


FIGURE 3.37 Logs of the boreholes at Montrose and St. Fergus. Note the presence of glaciomarine sediments in both areas, and more than one diamicton unit present in the succession at St. Fergus.

FIGURE 3.38 Logs showing the location of the amino acid racemisation sampling sites. Note the shell drape lying unconformably over the diamicton unit in core 208CS.







F Fines
S Sand
D Diamicton

m massive (structureless)
• Sampling point

Insert shows the position of the cores.

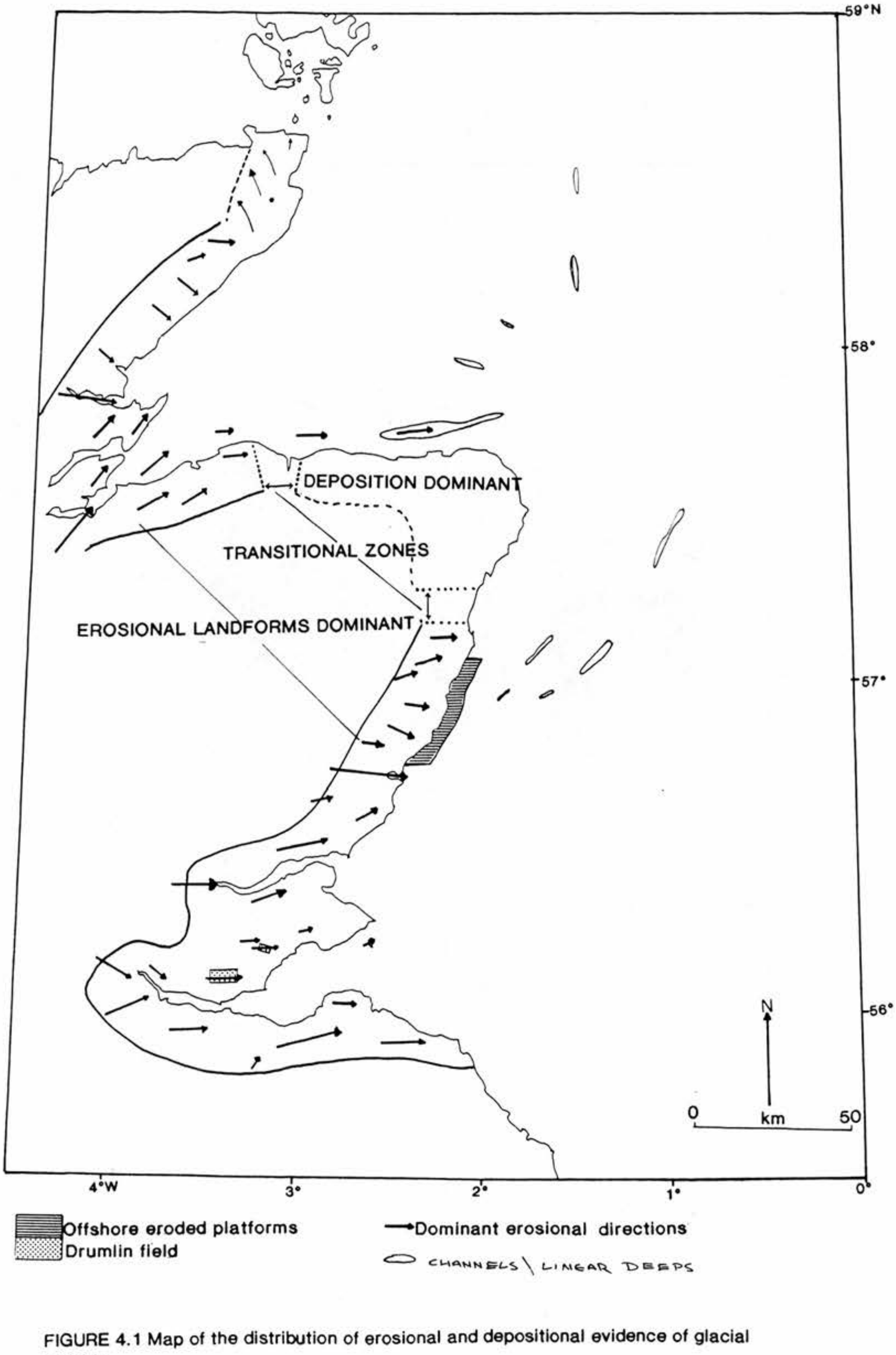


FIGURE 4.1 Map of the distribution of erosional and depositional evidence of glacial activity.

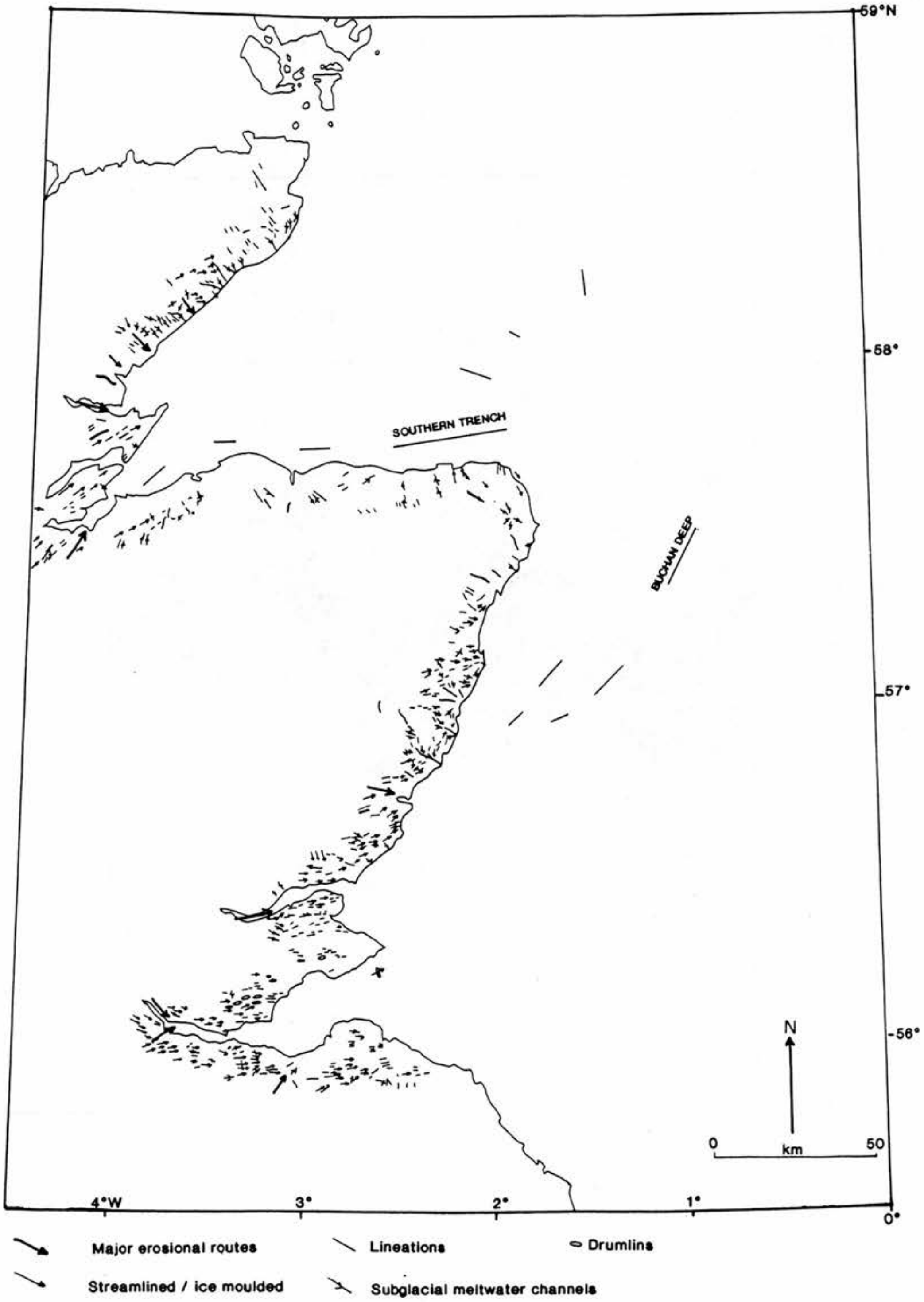


FIGURE 4.2 Map showing the distribution of the erosional landforms.

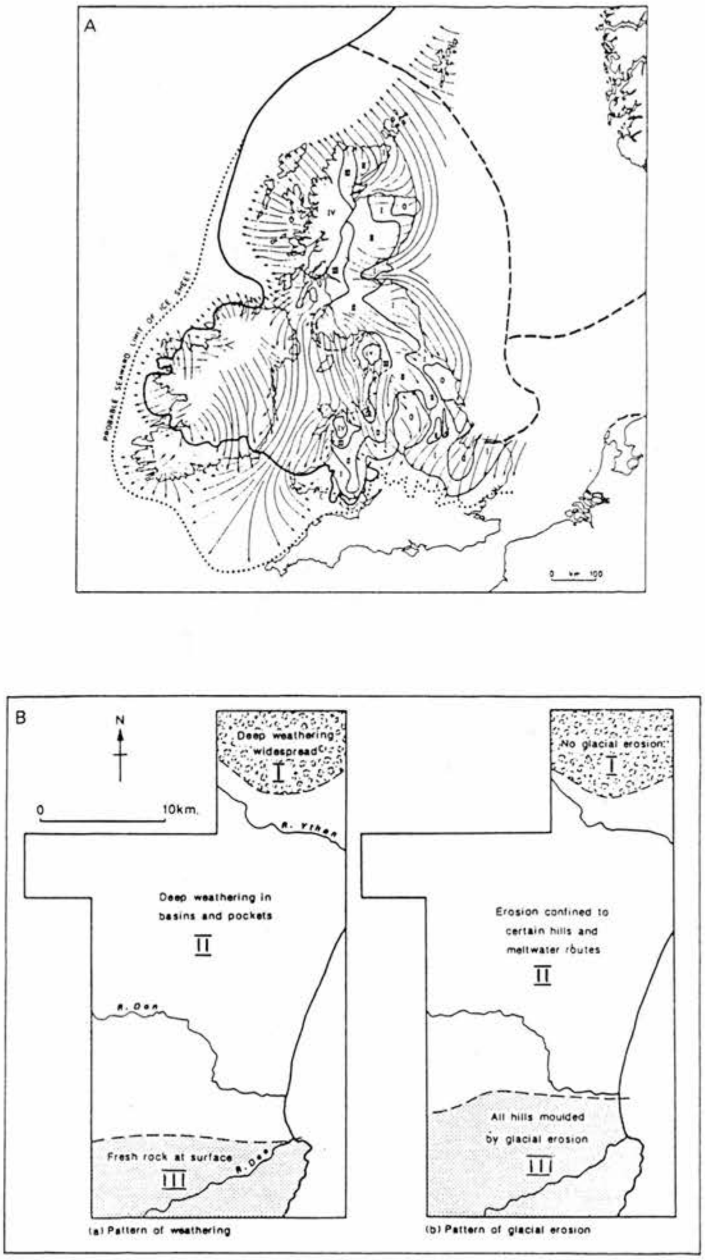


FIGURE 4.3 Map of the distribution of the regional erosional intensity (after Clayton 1974) and a local example of the difference in erosional intensity in the transitional zone to the north of Aberdeen (after Hall and Sugden 1987).

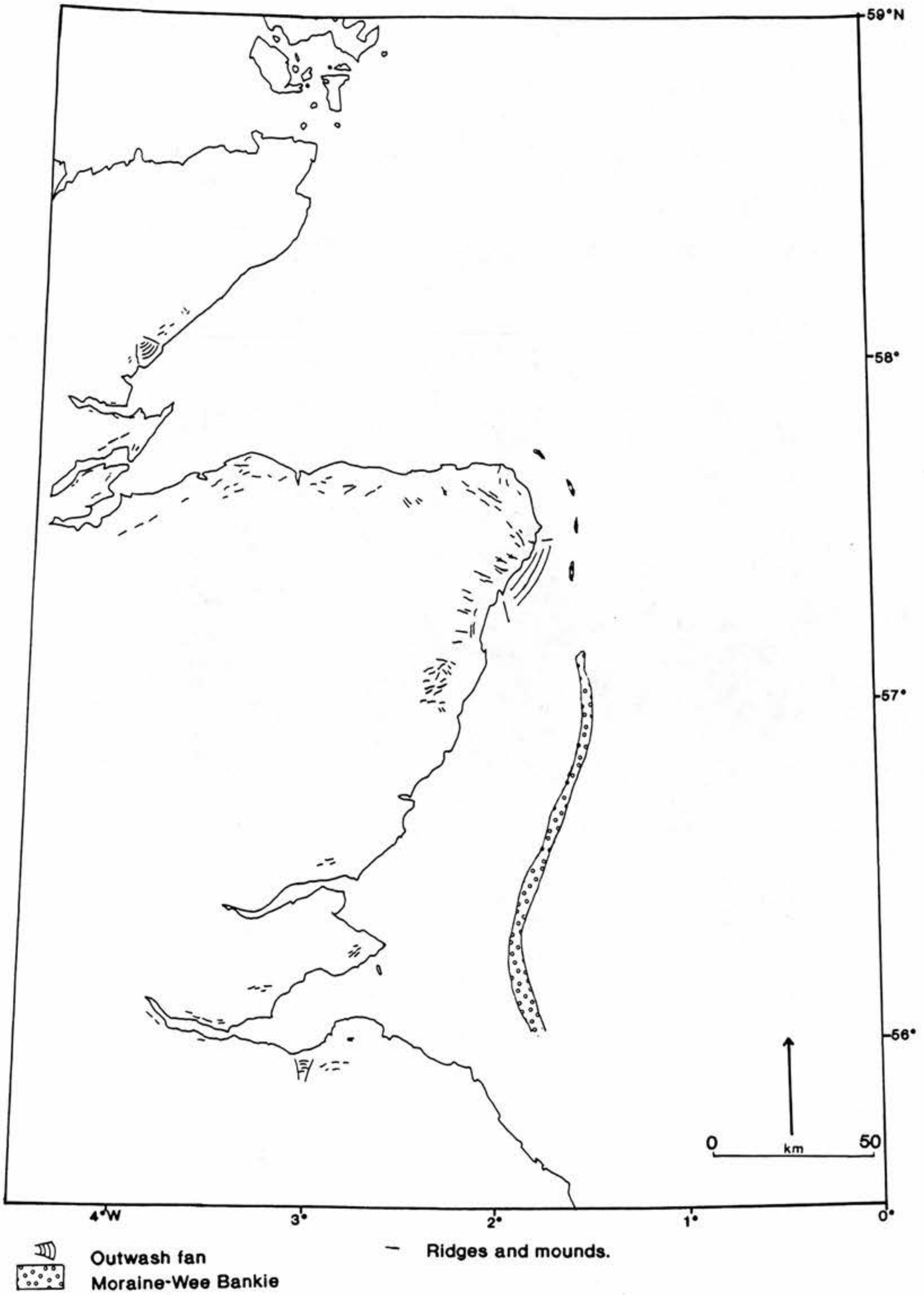


FIGURE 4.4 Map of the distribution of depositional evidence.

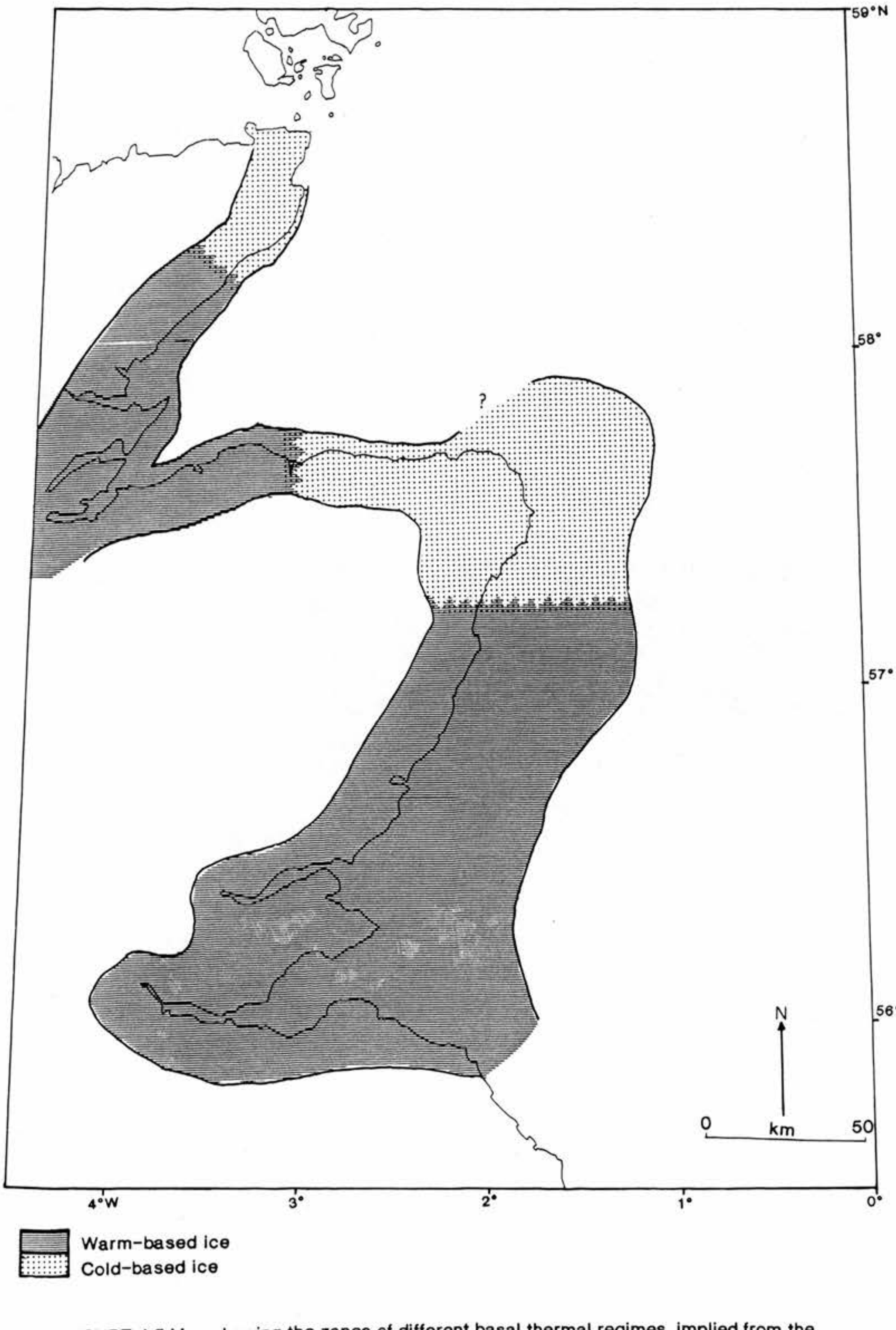


FIGURE 4.5 Map showing the zones of different basal thermal regimes, implied from the empirical evidence of erosional intensity.

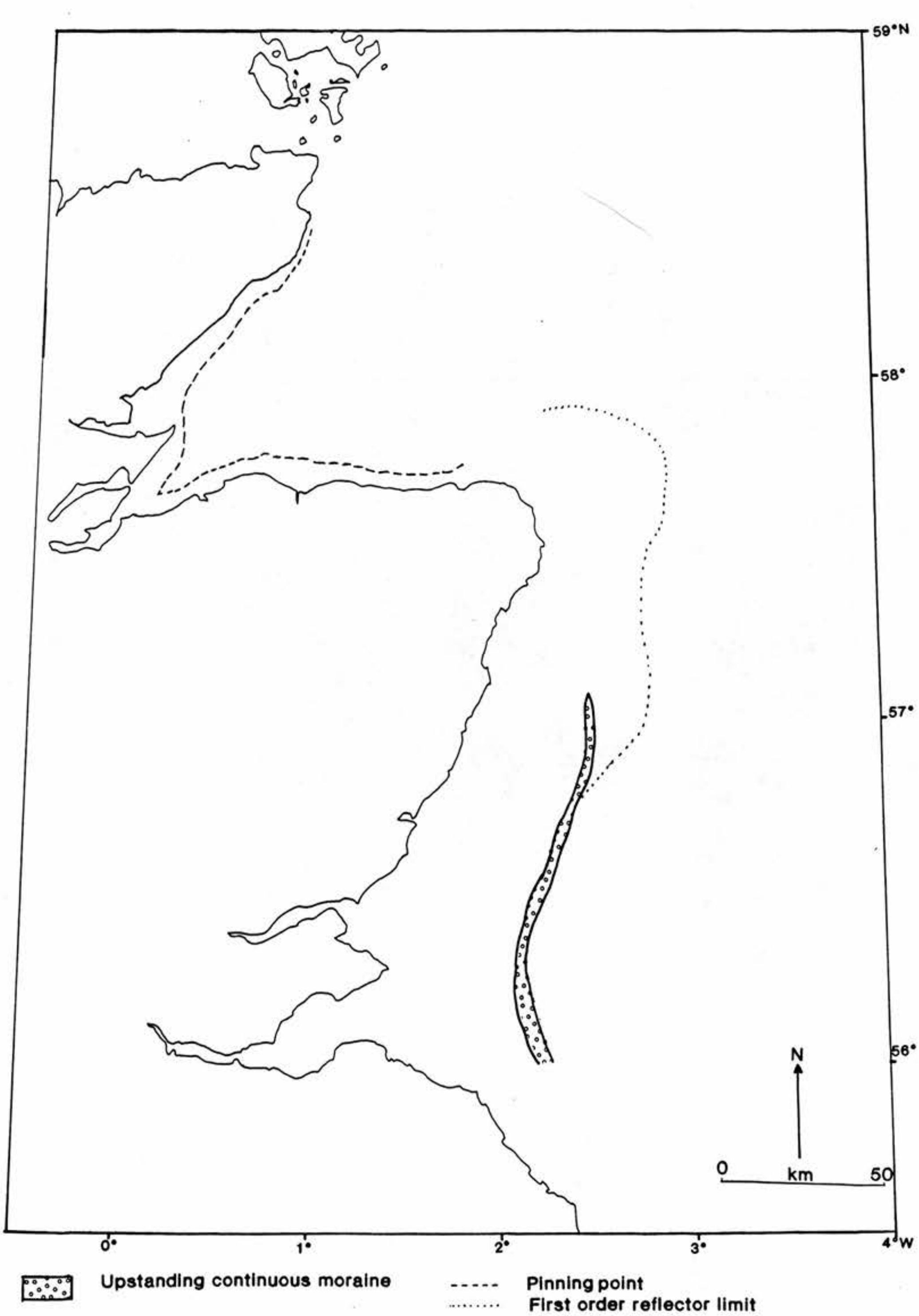


FIGURE 4.6 Map showing the location of the reconstructed ice margin.

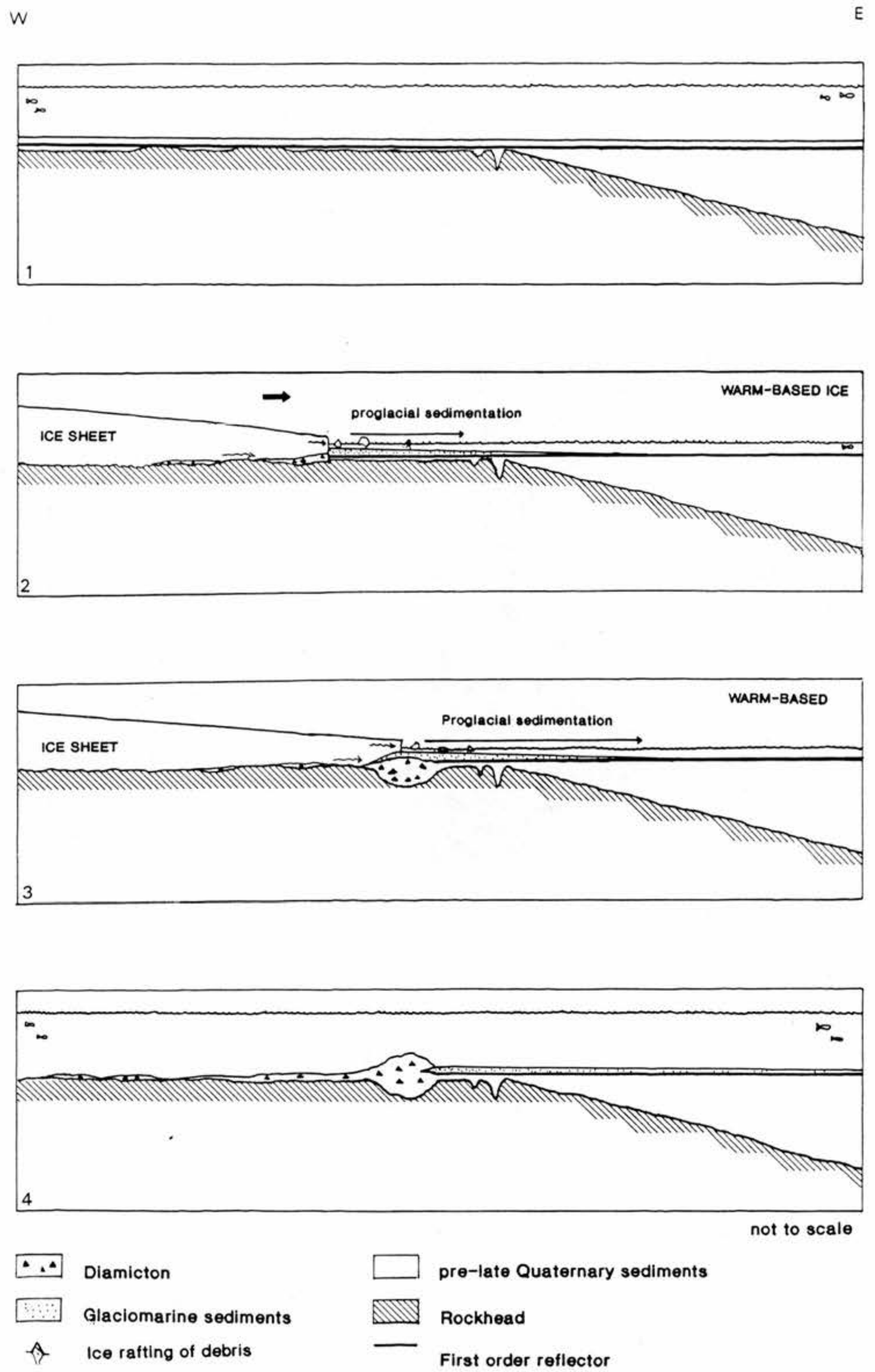


FIGURE 4.7 Model of the Wee Bankie ice margin. 1) Pre-late Quaternary sediment succession showing the lateral continuity of the first order reflector. 2) The ice sheet advances across the area in contact with the bed and destroying the first order reflector 3) Moraine accumulates at the margin with the ice decoupling with sea level variations 4) Present-day sediment succession showing the Wee Bankie moraine and the proglacial glaciomarine sediments. Note the extent of the first order reflector.

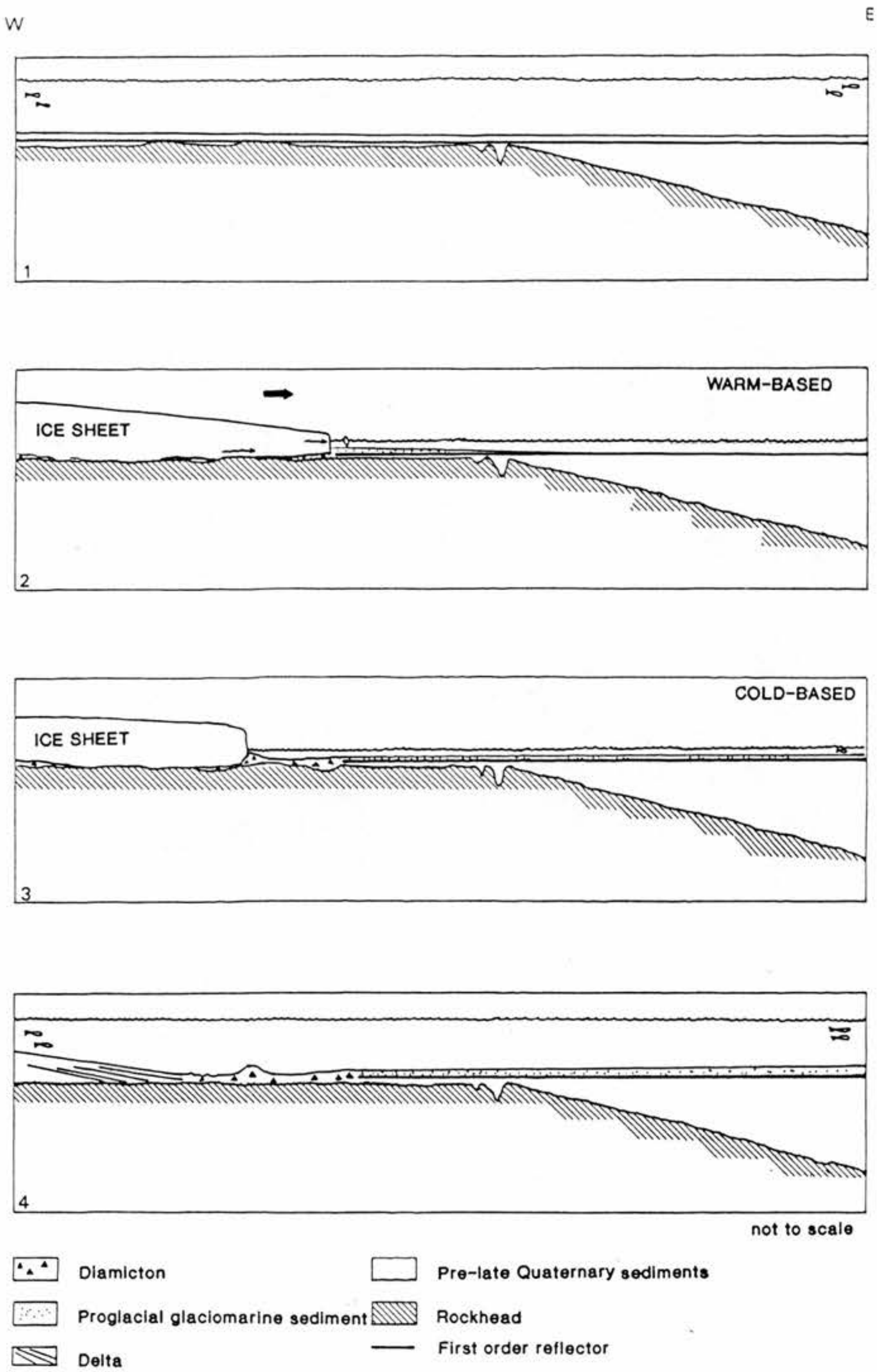


FIGURE 4.8 Schematic model of the Peterhead ice margin. 1) Pre-late Quaternary sediment succession, 2) Initial advance of ice to maximum position, note the destruction of the first order reflector as the ice advances, 3) Ice becomes cold-based and retreats from maximum position and small moraine accumulates, 4) Ice sheet withdraws from the area and the prograding delta was deposited.

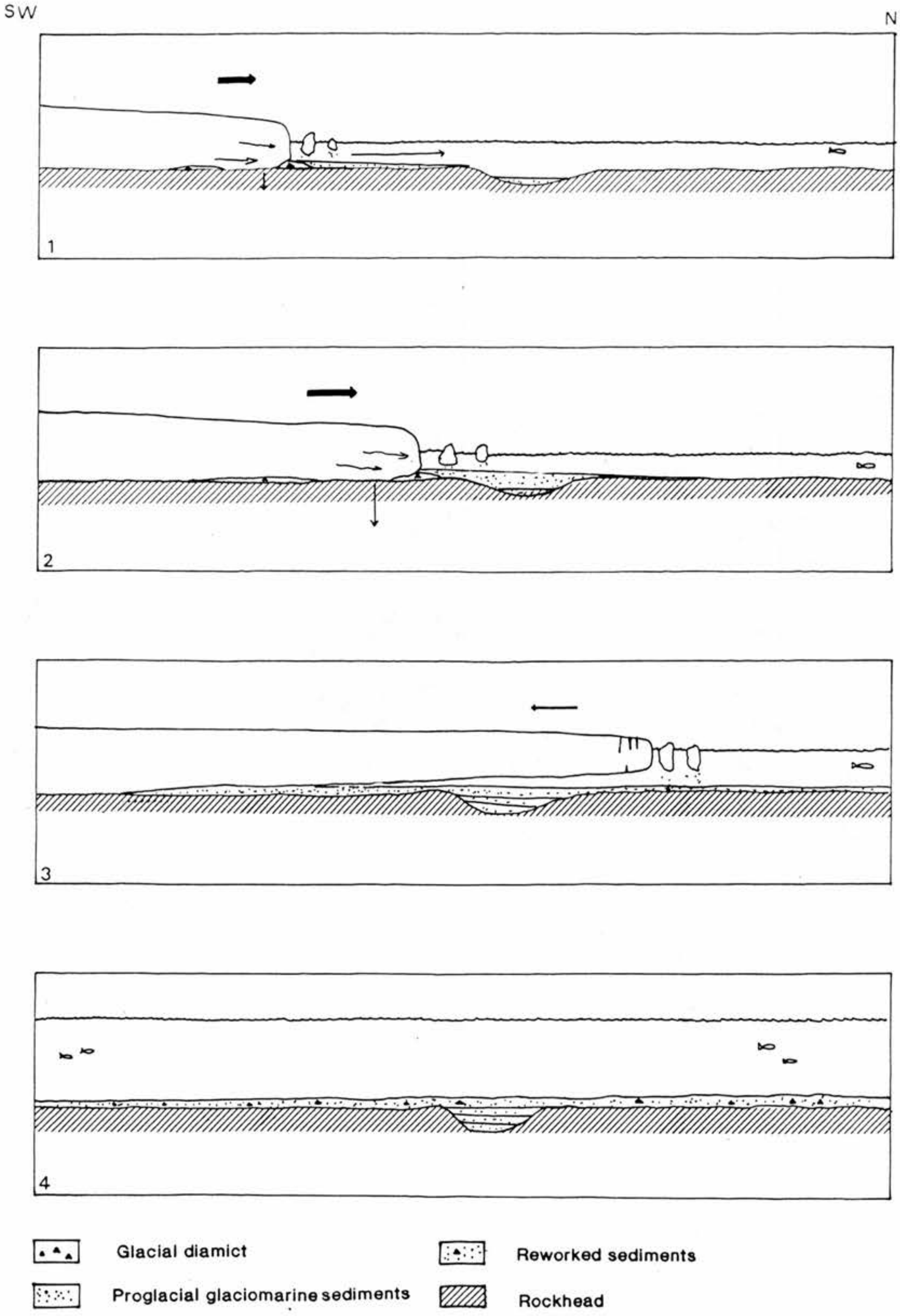


FIGURE 4.9 Model of the ice margin in the Moray Firth. 1) Ice advances into the Moray Firth in contact with the seabed, 2) the ice sheet advances further with increasing isostatic effects, 3) the ice floats off the bed as sealevel rises due to increased depression. Accelerated calving occurs at the margin and the ice sheet withdraws to (1). 4) Present-day sedimentary succession showing the reworked diamicton and the glaciomarine sediments preserved in the basins.

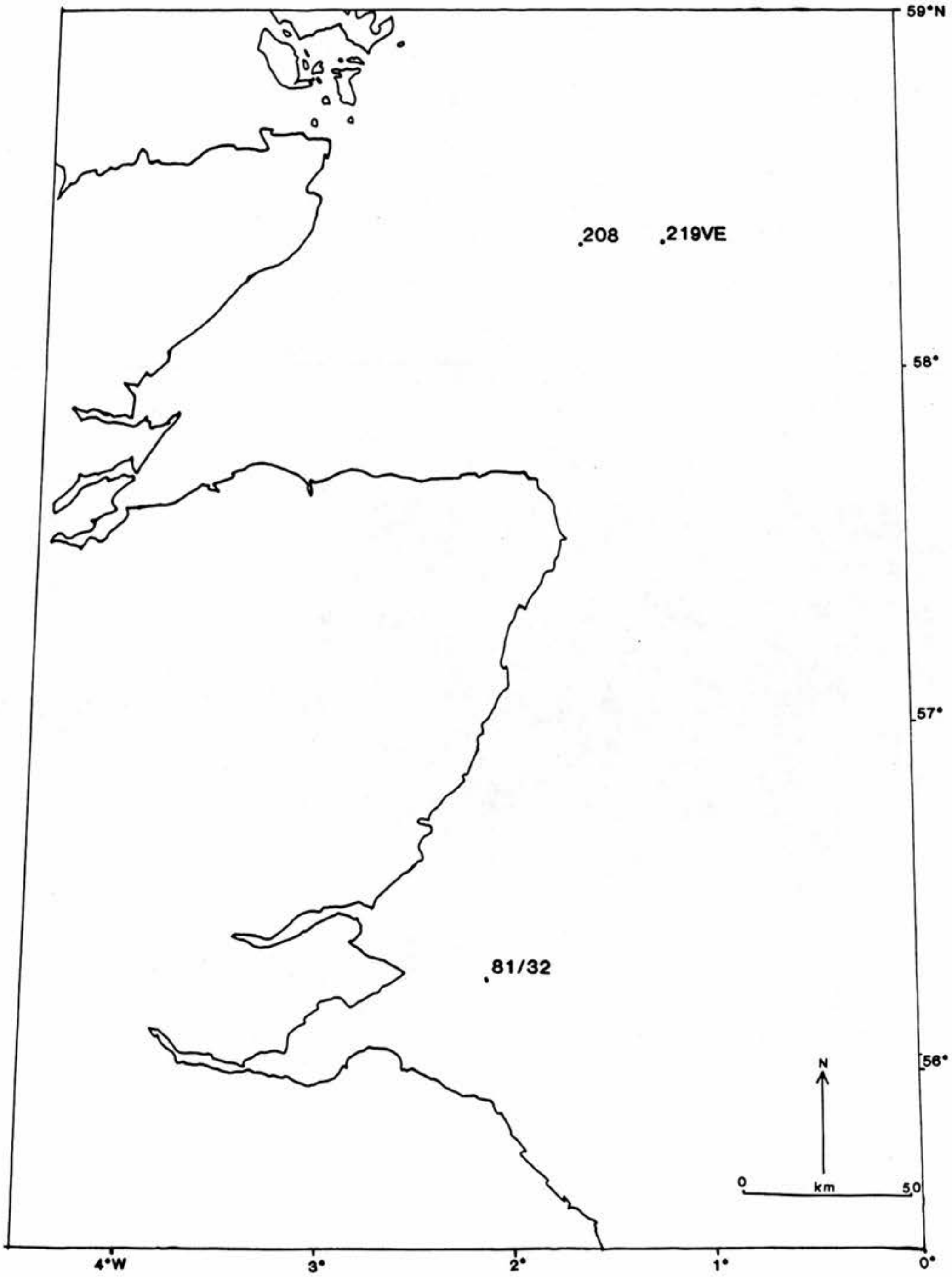


FIGURE 4.10 Map showing the locations of the amino acid cores

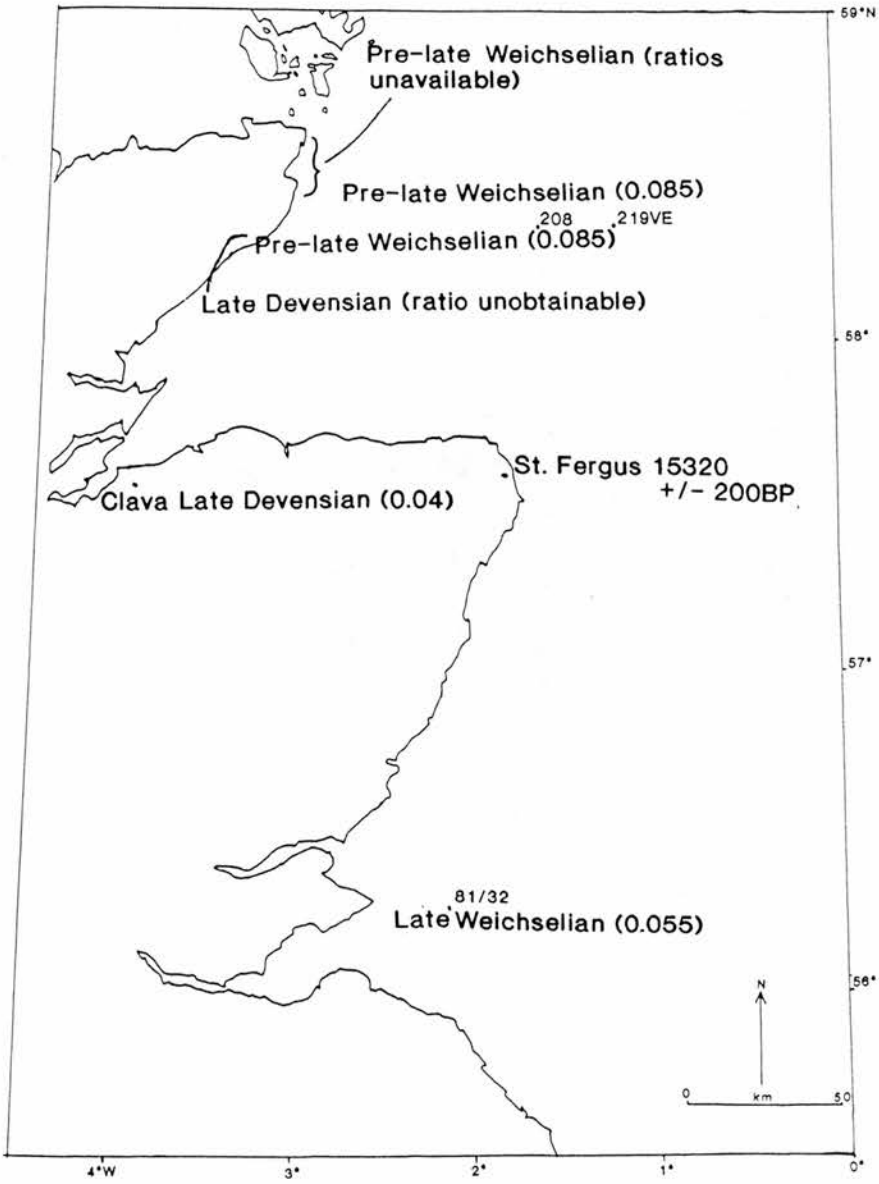


FIGURE 4.11 Map showing the location of the dated samples in the study area, DERIVED FROM MOLLUSCA AND FORAMINIFERAL MATERIAL.

(ratios indicate data derived from amino acid tests) Sources: Hall and Whittington 1989, Hall and Jarvis 1989, Auton *et al* 1990, Bowen *pers comm*, 1989, Hans Petter Sejrup *pers comm*, 1990.

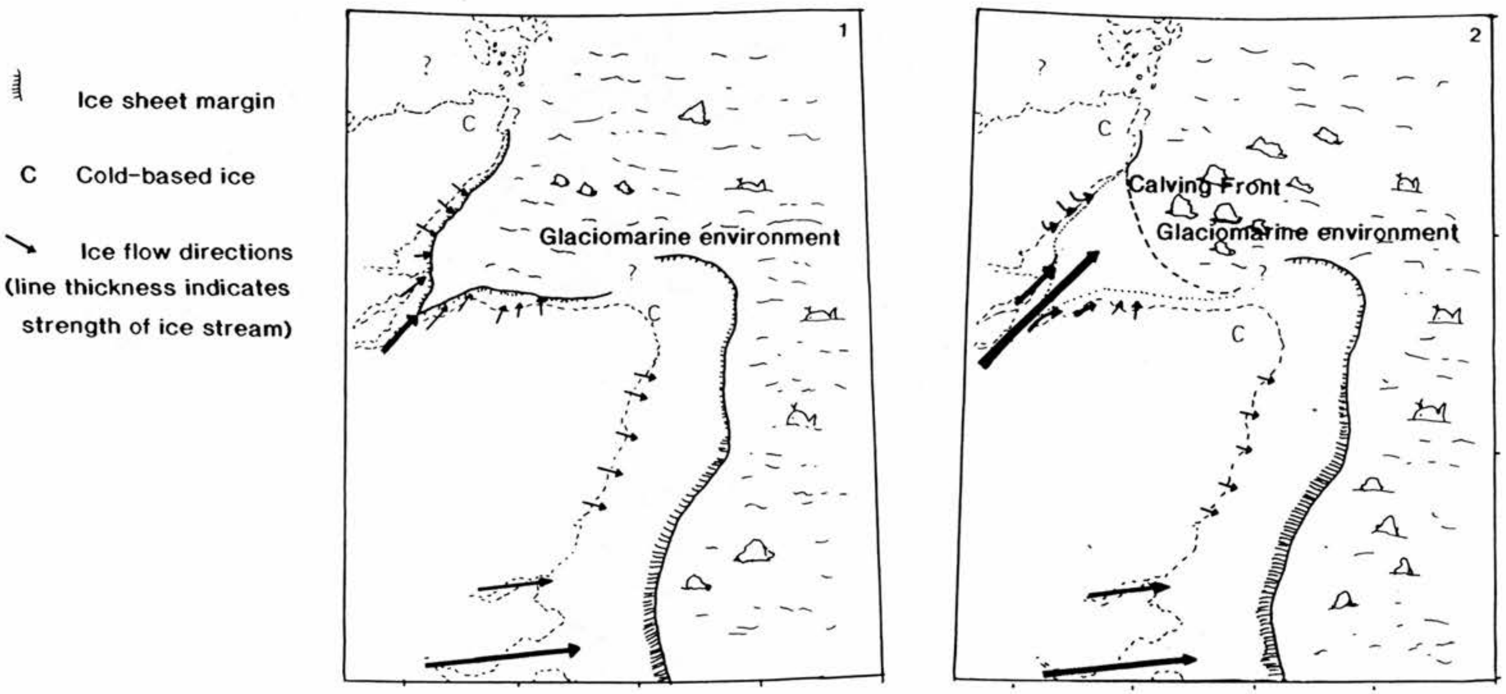
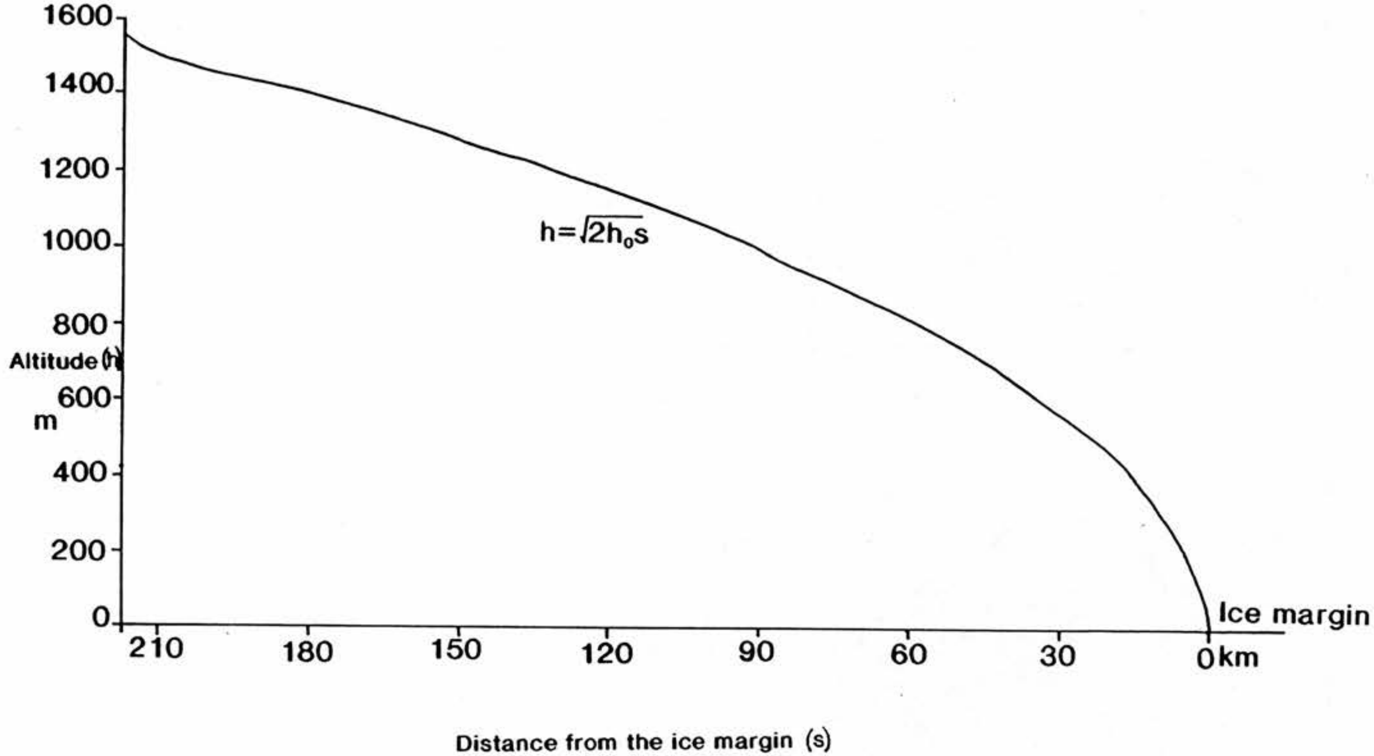
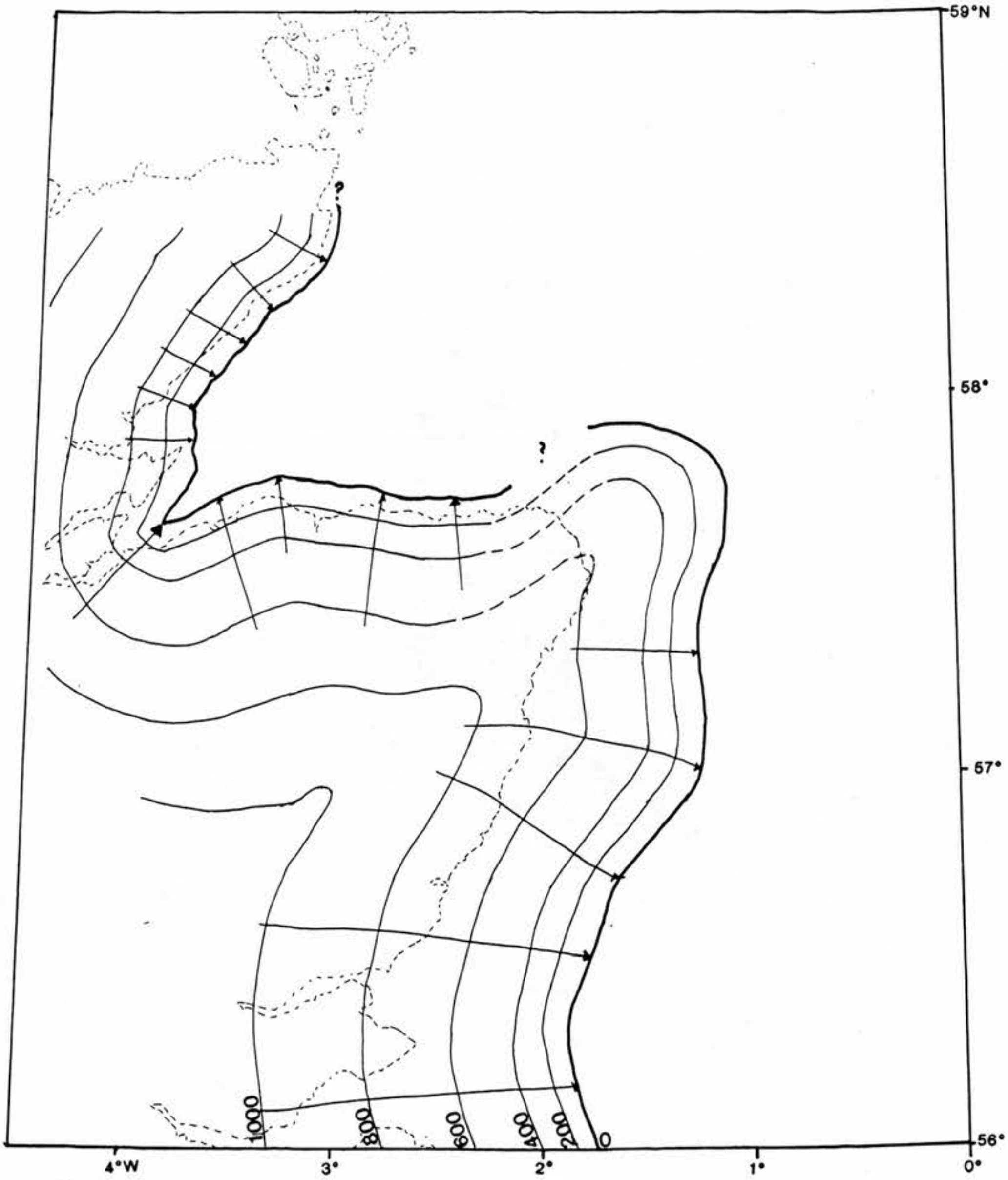


FIGURE 4.12 Reconstruction of the late Weichselian ice sheet margin in the North Sea illustrating the two stages in the cyclical development of the ice sheet in the Moray Firth. 1) Stage 1: Ice in contact with the seabed 2) Ice advances in contact with the seabed causing diversion of thé ice at the peripherary of the embayment.

FIGURE 5.1 Theoretical (Nye 1952) ice sheet profile for the eastern margin of the late Weichselian ice sheet in northern Britain.



Vertical Exaggeration X75



Ice margin, terminating in a glaciomarine environment

Profile contours 200m interval

Flow lines

FIGURE 5.2 Theoretical ice flow directions derived from the Nye profile, for the minimum reconstruction.

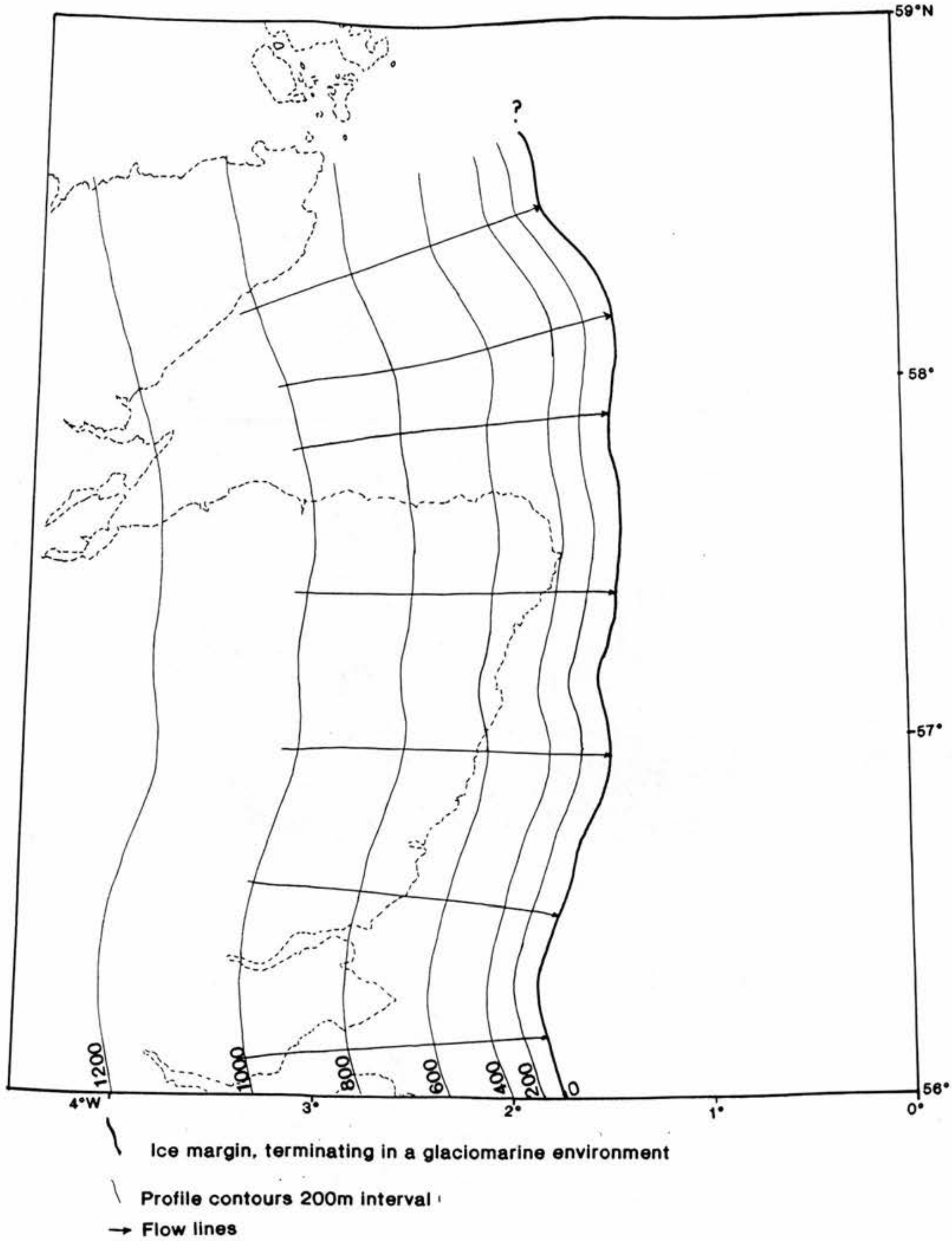


FIGURE 5.3 Theoretical ice flow directions derived from the Nye profile, for the maximum reconstruction.

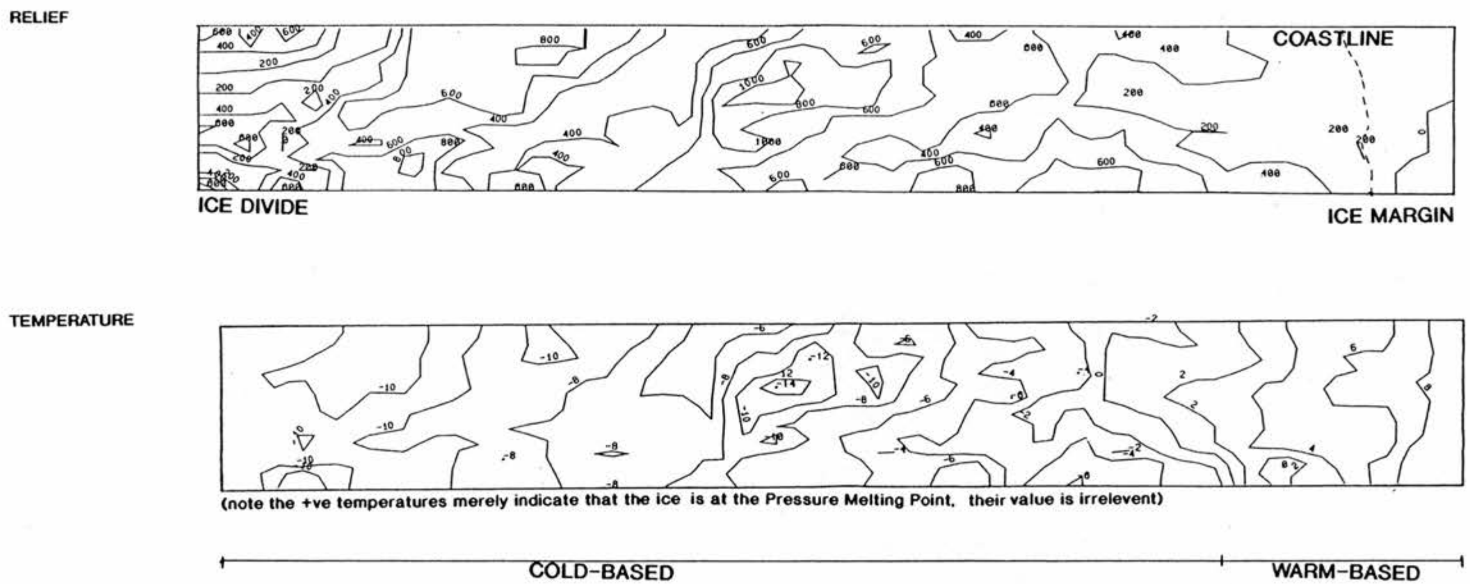
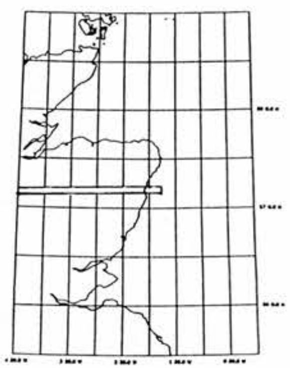


FIGURE 5.4 Basal thermal regime for a linear flow line from the ice divide to the margin of the late Weichselian ice sheet (after Glasser *pers comm*).



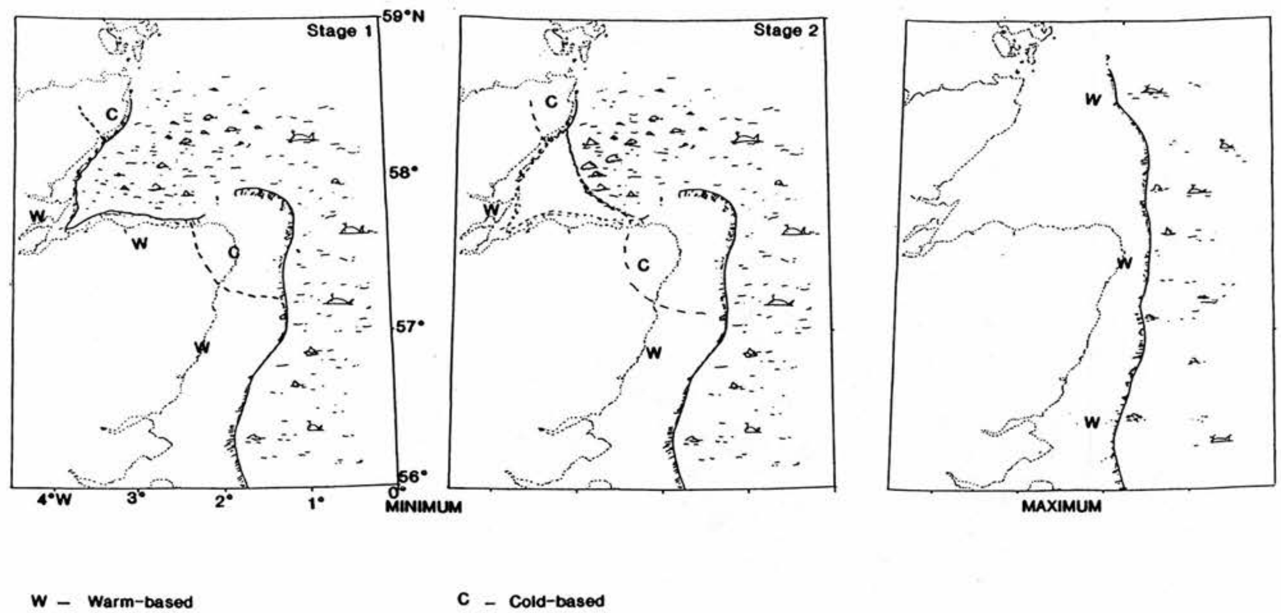


FIGURE 5.5 Theoretical basal thermal zones for warm- and cold-based ice for the maximum and minimum reconstructions of the ice sheet location.

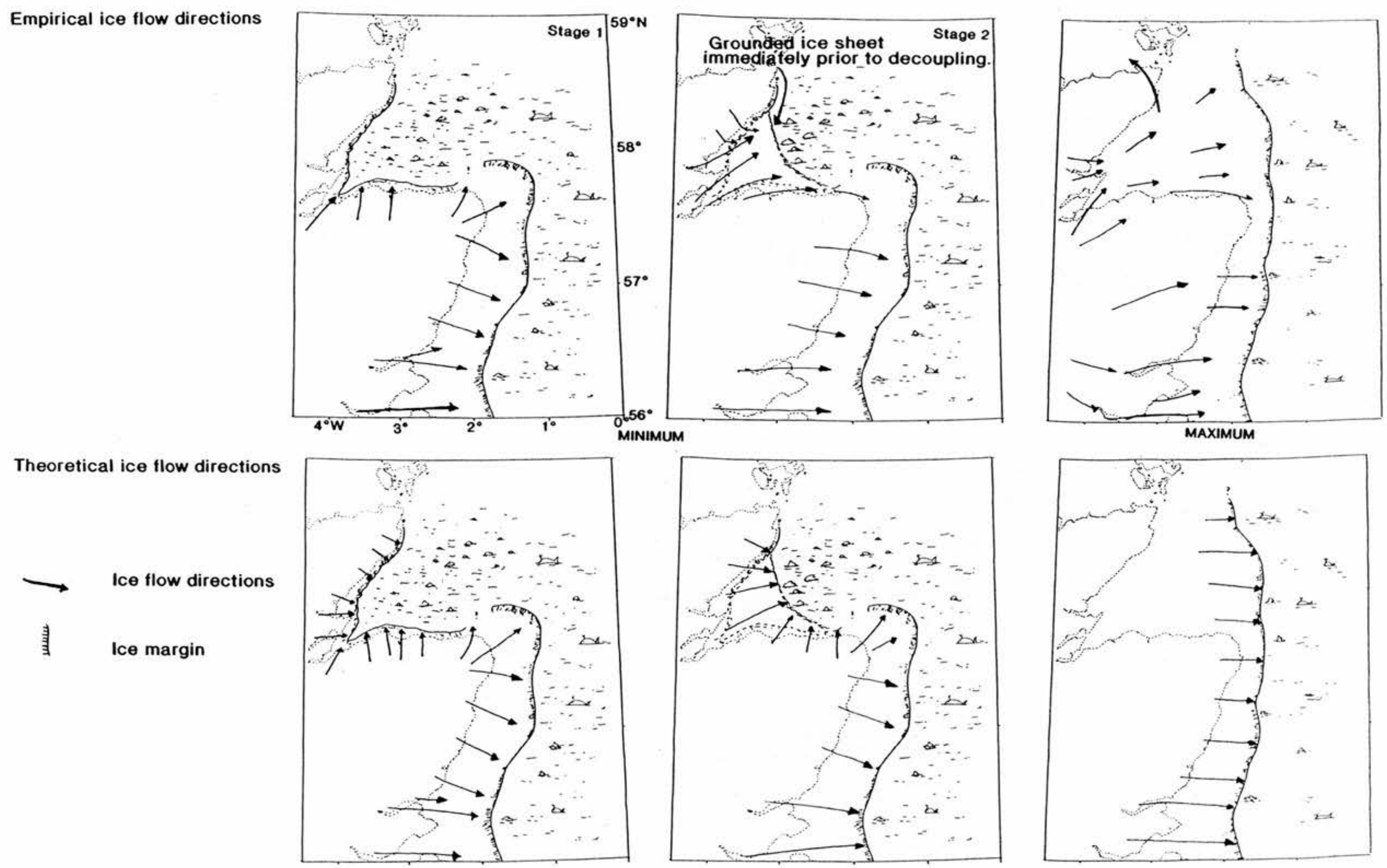


FIGURE 5.6 Empirical ice flow directions and predicted theoretical ice flow directions for the minimum and maximum ice margin reconstructions.

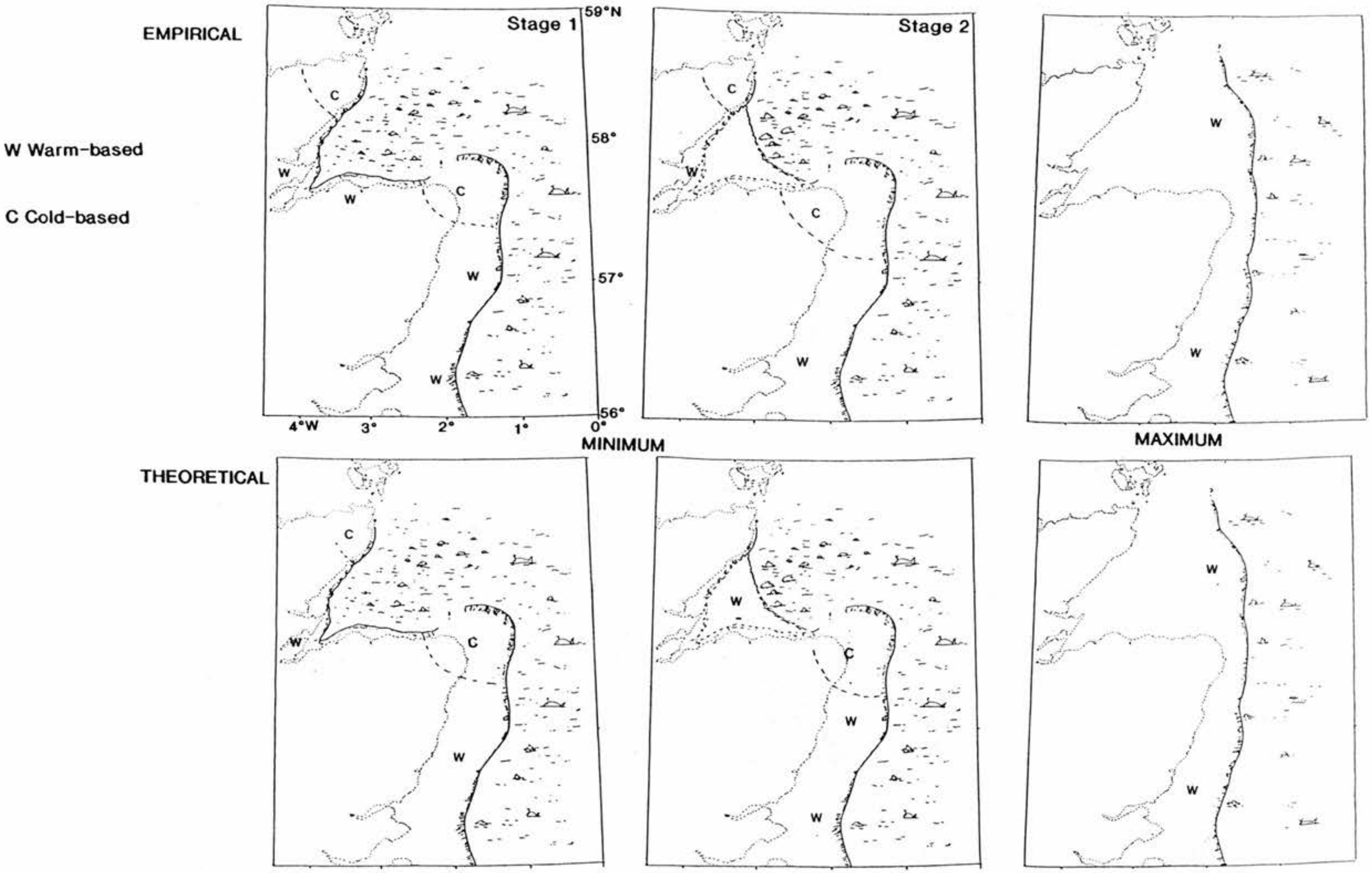


FIGURE 5.7 Empirically implied, and theoretically predicted warm- and cold-based ice sheet basal thermal regime zones, for the minimum and maximum ice margin reconstructions.

TABLES

(Volume II)

TABLE 1.1 Extensive ice sheet reconstructions

AUTHOR(S)	YEAR	MODEL/EQ^{ns}	IMPORTANT VARIABLES	ASSUMPTIONS	CONCLUSION
Boulton et al.	1977	Weertman(1961a.) Authors basal temperature regime	Derived climate parameters, Height - 1800m, t = 15ka Velocity, 150-500ms^{-1}	Steady state Margin stationary Mass balance = 0 Flow field/t = konstant	Coalescence $\bar{c}$ Norwegian ice. Concept of surging (NE - Humber lobe) Insufficient time for full icesheet developement.
————	1985	Deformable bed			deforming bed, incomplete cover
Andersen	1981	Empirical evidence (review) Chronology - C^{14} evidence			
Denton Hughes	1981	Climap inc: NYE (1975) Weertman (1957, '64a, '71) Paterson (1972)	Basal thermal conditions Basal shear stress Bed roughness Flow laws Basal sliding law.	Steady state Equilibrium achieved snow accumulation ≐ k Known isostatic depression Basal sliding dominant over melted bed Laminar flow dominant over frozen bed	Complete coverage - dome over GB & Norway saddle over North Sea Basin
Price	1983	Empirical evidence (Review)			Unknown eastern margin require alternate deflect cause before discounts extensive ice cover and Norwegian deflection of ice.
Flinn	1967	Offshore evidence (channels)			Extensive coverage

TABLE 1.2 Restricted ice extent reconstructions

AUTHOR	YEAR	EVIDENCE	COMMENTS
Jamieson	1865	Striae Glacial erratic trains Sedimentology Stratigraphy Glacial modification of the landscape	* Main / key reconstructions
Sissons	1967	As above + Radiometric dating	
Thomson & Eden	1977	Offshore - Seismic stratigraphy Sediment analysis Micropalaeontology Radiometric dates	BGS - offshore survey information
Clapperton	1977		Non-Ice-Free Buchan
Jansen	1976/79	BGS - offshore survey information Norwegian offshore survey information Position of "Tunnel Valleys"	Restricted Northern North Sea circulation subglacial water movement, drainage into glaciomarine/glaciolacustrine (brackish) water body Witch Ground Basin /Fladen Ground. (Note: Latter scenario is proposed for Weichselian maximum, but considered for 20,000 BP & earlier ⇒ late Weichselian/late Devensian).
Hall	1984	Weathering of deposits & amount of effective erosion age of sediments	Ice-Free Buchan
Sutherland	1984	Review of exisiting Literature	Ice Sheet only slight erosive effect on landscape; beware palimpsest.
Bent	1986		Bosies Bank moraine ⇒ northern continuation of Wee Bankie moraine.
Cameron et al.	1986	Re-interpretation/examination of offshore evidence	Marine embayment with thick sea ice cover
Bowen	1988	Biostatigraphic evidence (Amino Acid chronostatigraphy) $\delta O^{18}/O^{16}$ ratios (Shackleton & Opdyke, 1973) Geochronometric data - C14	"Shelly till" - northern Caithness - pre-late Weichselian/late devensian - ?warthe? advance - more extensive than late Devensian (limited to northern Britain).
Nesje & Sejrup	1988	Seismic stratigraphy (BGS + Norwegian Survey IKU) Deformable bed Glacio-isostatic modelling	Low angle, deforming bed Ice Sheets, restricted extent - Stagnated before reaching theoretical maximum
Wingfield	1990	Enclosed deeps Seismic stratigraphy	More extensive
Hall + Bent	1990	Seismic & sedimentary evidence Onshore geomorphology sedimentology & chronostratigraphic constaints	Complete ice coverage Links Wee Bankie Moraine to Outer Moray Firth Moraine Caithness sediments represent single, but dynamic glacial deposit - Late Devensian (Hall & Whittington 1989)
Ehlers	1990	Enclosed deeps Seismic stratigraphy	Much more extensive, - no evidence recorded in sediment because of erosion since marine transgression at end of extensive cover
Andrews et al	1990		Review

TABLE 1.3 Onshore late Weichselian facies units

TILL UNIT	CHARACTERISTICS	LOCATION (in conjunction with Fig. 1.6)
SHELLY	Diamict, often massive containing shells erratics and shell fragments derived from the Moray Firth Basin.	Caithness plain and coastal areas. Peach and Horne 1881
HIGHLAND	Diamict dominated by Dalradian and metamorphic clasts, often rounded, but showing glacial transportation and reworking	Found within and to the west of the Great Glen.
GREY SERIES	Diamict with high fines content especially silts. Clasts occuring within the diamicton are often derived from the Jurassic and Cretaceous sediments of the Moray Firth	Moray Buchan coast
RED SERIES	Characteristic red colouration derived from the Devonian source area. Include clasts from the Highland Boundary Fault	Occurs in Strathmore and extends north to Aberdeenshire
INLAND SERIES	Found in the upland areas and consists of coarse angular clasts within a coarse matrix.	Grampian area of the north-east of Scotland
LOCAL	a general term given to till derived from localised sediment sources.	

TABLE 1.4 Offshore BGS Quaternary sediment succession

AREA	FORMATION	LITHOLOGY	THICKNESS	DISTRIBUTION/GEOMETRY	MICROPALAEONTOLOGY	SEISMIC CHARACTER *	DATES	AGE
WEE BANKIE	Forth (FH)	Gravel-Clay	Vaiable (≤40m)	Sheet deposit Channel infill in Marr	marine arctic	St Andrews Mb:(b/p) structureless to strong & variable internal reflection pattern (Forth Estuary - prograding, sigmoid reflector.) (Tay - oblique progradational reflection pattern) Largo Bay Mb: (b/p) continuous, sub-parallel internal reflectors	Post 13,000BP	Holocene
	St Abbs (SBB)	Gravel-Clay	Variable (≤25m)	Inshore sheet deposit Channel infill	marine arctic	(b/p) structureless & opaque occasional faint discontinuous, sub-parallel internal reflectors	17,700-13000BP	Holocene/ Late Weichselian
	Wee Bankie (WBB)	Diamicton	15-50m	Sub-parallel hummocky deposit extending to 40km East of coastline		(S) structureless or dense texture with point source hyperbolic reflectors and short, strong uneven reflectors		Late Weichselian
	Marr Bank (MAR)	Sand-Silty Sand-Mud Fining eastward	15-20m	Sheet deposit, extends from eastern margin of Wee Bankie	Shallow glaciomarine becoming more brackish eastward	(S) Cross laminated, to parallel -bedded hummocky bedforms. Strong planar basal reflector (marine erosion surface)	21,700BP Lateral equivalent	Late Weichselian
PETERHEAD	Forth (undivided)	Sand-Mud	≤60m	Sheet & Channel infill	marine			Early Holocene/
	St Andrews Mb	Sands	1-25m	Prograding sheet deposit	fluviomarine	(S) Low angle, east-north-east prograding reflectors	10,000-7,000BP	
	Largo Bay Mb	Muds-Pebbly Muds	1-5m	Sheet deposit	boreal - glaciomarine	(b/p) Continuous sub-parallel internal reflectors	13,500-10,000BP	Late Weichselian
	Witch Ground (WGD)	Upward transition from Pebbly Muds to Fine Sands and Silts	≤15m	Basin deposit (north east only)	temperate marine	(b/p) parallel reflectors, lie concordantly on a highly irregular erosive base. Pockmarks in upper surface, and gas blanking	13,000-8,400BP Lateral equivalents in parts	Early Holocene/ Late Weichselian
	St Abbs	Pebbly Muds	≤5m	Veneer (south west only)	glacial	(b) structureless and opaque with unconformable base	18 000 - 13,500BP	Late Weichselian

AREA	FORMATION	LITHOLOGY	THICKNESS	DISTRIBUTION/GEOMETRY	MICROPALAEONTOLOGY	SEISMIC CHARACTER*	DATES	AGE
	Wee Bankie	Diamicton with thin layers of Sand & Sily Clay, and Coarse Sand & Gravel	0–30m	Hummocky, intermittent sheet deposit Absent north of 57°40'N & in East		(S) Occasional point source reflectors		Late Weichselian
	Marr Bank	Silty Sand–Silts	≤20m	Widespread in south west	Shallow, ice–distal glaciomarine	(S) as above	21,700BP	Late Weichselian
	Swatchway (SWAT)	Sands, Silts & Muds	10–15m	Common in north east depositional hollows	arctic	(S) Occasional sub–horizontal reflectors top – irregular micro–relief – iceberg scouring. 'Patchy' response	Lateral equivalent	Late Weichselian
	Coal Pit (COP)	Sand, Pebbly Muds & Sands	10–90m	Rare in south west	arctic marine	(S) Chaotic to sub–parallel reflectors, abundant planar and irregular discontinuity surfaces.		Weichselian
BOSIES BANK	Forth (undivided)	Sandy–Silty	5–10m ≤30m	Western part sheet. Deposit channel infill	subarctic–temperate ameliorating conditions	(S) accoustically opaque – well–bedded dependant on thickness	18,000–8,400BP	Early Holocene Late Weichselian
	Witch Ground	Silty Sands – Pebbly Silty Clays	≤20m ≤40m	Sheet subcrop in east Basin infill		(b/p) Closely spaced reflectors which sub–parallel the underlying topography. Pockmarks	Laterally equivalent (parts)	Holocene – Late weichselian
	Swatchway	Disturbed Silts & Muds	20m	Sheet outcrop in central & eastern parts of the area	ameliorating conditions	(S) sub–horizontal reflectors – patches with no reflectors and chaotic & accoustically opaque, in places		Late Weichselian
	Coal Pit	Massive Diamicton Sands Pebbly Muds Pebbly Sands	Variable – upper reworked area only	Sub crops whole area with some topographic highs		(S) Chaotic to sub–parallel reflectors with abundant discontinuity	(Reworking of older sediment during Weichselian)	Weichselian – Late Saalian

AREA	UNIT	LITHOLOGY	THICKNESS	DISTRIBUTION/GEOMETRY	MICROPALAEONTOLOGY	SEISMIC CHARACTER	DATES		AGE
MORAY FIRTH	7	Muds	0–40m	Basin infill	arctic				Early Holocene
(based on lithological data only)	6	Muds	11–10m	Sheet deposit basin infill	sub–arctic		12,400±100	Lateral Equivalent	Early Holocene/ Late Weichselian
	5	Massive Diamicton	0–30m	Sheet deposit in east				Lateral Equivalent	Early Holocene/ Late Weichselian
	4	Gravelly Muds	0–30m	Localised basin infill	sub–boreal		14,000BP	Partially lateral equivalent	Late Weichselian
	3	Pebble–free Muds & Rhythmites	0–10m	Localised basin infill	sub–boreal		16,000BP	Partially lateral equivalent	Late Weichselian
	2	Sands	5–10m	Localised basin infill					Middle Weichselian
	1	Pebbly Diamicton	0–35m	Sheet deposit			?43,500BP		Middle Weichselian

* Seismic Source p – pinger b – boomer s – sparker

Compiled from BGS 1:250,000 Quaternary Sheets Tay–Forth (Stoker, 1985a)
Marr Bank (Stoker, 1985b)
Peterhead (Stoker, 1987)
Buchan (Chesher, 1984)
Caithness (Ruckley & Chesher, 1987)
Bosies Bank (Bent & Skinner, 1988)

References Holmes 1977
Thomson & Eden 1977
Stoker et al 1985

TABLE 2.1 Velocities through different media

Compressional Wave Velocities (V_P) in Rocks[a]

Rock type	$V_P (m/s)$	Rock type	$V_P (m/s)$
Air	330	Anhydrite	3500–5500
Water	1400–1500	Rock salt	4000–5500
Ice	3000–4000	Granites and gneisses	5000–6200
Alluvium, sand	300–1700	Basalt	5500–6300
Glacial moraine	1500–2600	Gabbro	6400–6800
Sandstones	2000–4500	Dunite	7500–8100
Slates and shales	2400–5000	Peridotite	7800–8400
Limestones and dolomites	3400–6000		

[a]For a more extensive compilation of compressional and shear wave velocity data the reader may refer to Press (1966).

(from Sharma 1986, table 2.1 pp 19)

TABLE 2.2 Seismic acquisition, cruises and lines

SECTOR	SURVEYS/PROJECTS	LINES
WEE BANKIE	80/03	4 7 12 16 27 30 34 36
PETERHEAD	70/03	2 5 6 12 13 14 15 17 66
	72/04	2 5 11 21 22 23 27 28 29
	80/03	15
MORAY FIRTH	70/03	2 4 5 6 11 12 13 15 17 19 21 22 23 24 26 27 29 31 36 42 59 61 62 63 65 66 68
	72/15	1 AND 2
BOSIES'BANK	79/15	1 2 4 6 8 10 12 13 19

(SURVEYS: YEAR/PROJECT, if a line overlaps areas it is listed in both).

TABLE 2.3 Sediment sampling points, locations of boreholes and vibrocores

Vibrocores

Wee Bankie

100	56	46.84'N	1	38.13'W
152	56	43.73'N	1	43.10'W
160	56	48.02'N	1	40.31'W
95	56	55.75'N	1	38.03'W
301	56	55.30'N	1	39.00'W
48	56	31.68'N	1	56.01'W
63	56	41.68'N	1	41.18'W
199	56	07.39'N	1	55.68'W

Peterhead

167	56	47.13'N	1	27.66'W

Moray Firth

VC1A	557195 E	6407135 N
VC2	551280 E	6402425 N
VC3A	551336 E	6402415 N
VC4	551322 E	6402433 N
VC5	551302 E	6402370 N
GCD1	557077 E	6406248 N
GCD2	557083 E	6407075 N

Beatrice

VC1	515777 E	6438150 N
VC2	515875 E	6437563 N
VC3	515740 E	6437234 N
VC4	515914 E	6437289 N
VC5	515872 E	6436994 N

Bosies Bank

207	58	29.50'N	1	20.20'W
208	58	21.50'N	1	40.00'W
242	58	21.30'N	1	14.10'W
219	58	02.47'N	1	44.30'W
260	58	17.00'N	1	34.50'W
261	58	17.80'N	1	41.70'W
239	58	10.50'N	1	03.00'W
258	58	10.10'N	1	22.10'W
335	58	05.56'N	1	20.54'W
337	58	05.55'N	1	18.24'W
360	58	35.93'N	1	25.75'W

Boreholes

Wee Bankie

72/21	57	13.640'N	1	53.950'W
72/31	57	31.450'N	1	32.830'W
72/20	56	06.790'N	1	51.780'W
73/23	56	06.810'N	1	57.810'W
73/17	56	03.500'N	1	37.550'W
73/22	56	46.300'N	1	35.500'W
74/7	56	58.500'N	1	08.000'W
81/27	56	32.708'N	0	23.990'W
81/28	56	14.678'N	2	09.110'W
81/32	56	14.590'N	2	10.640'W
81/33	56	54.153'N	1	59.509'W
81/36	56	07.751'N	0	56.887'W
81/40	58	08.500'N	0	44.000'W

Peterhead

72/30	57	46.95'N	1	46.00'W
81/31	56	54.13'N	2	00.19'W

Moray Firth

72/17	57	44.25'N	2	01.90'W
71/23	57	43.83'N	2	15.81'W
71/17	58	05.36'N	3	22.47'W
71/25	58	00.80'N	3	18.50'W
71/27	57	55.77'N	3	29.69'W

Beatrice

B1	58	06'	30.000"N	3	06'	02.700"W
B2	58	08'	54.200"N	3	01'	11.410"W
B3	58	06'	30.245"N	3	06'	00.442"W
B4	58	06'	29.146"N	3	06'	04.775"W
B5	58	06'	27.559"N	3	06'	09.701"W
B6	58	08'	12.779"N	3	02'	03.345"W
B7	58	08'	11.025"N	3	02'	08.076"W
B8	58	08'	09.550"N	3	02'	12.550"W
B12	58	07'	30.559"N	3	02'	58.184"W
B13	58	07'	37.329"N	3	02'	54.567"W

Bosies bank

81/19	58	56.725'N	0	59.404'W
81/26	58	08.339'N	0	10.628'W

TABLE 3.1 Summary of Wee Bankie data correlations

LOCATION	SEISMIC FACIES UNIT	GEOMETRY	INTERNAL RESPONSE	ENERGY	LITHOFACIES	PROCESS	INTERPRETATION	BGS CORRELATION
ZONE A	WBA3	fill	low amplitude continuous	uniform low	silts/clays	suspension	marine/estuarine	St.Abbs Formation
	WBA2	fill and sheet	variable amplitude chaotic	variable energy	sand-dominated	prograding/ suspension	marine/estuarine	Forth Formation
	WBA1	sheet	point-source reflectors variable amplitude chaotic	high	diamicton	glacial deposition	glacigenic diamicton	Wee Bankie Formation
ZONE B	WBB3	fill	variable amplitude	variable	sand-dominated	high energy	marine / estuarine-distal	Forth Formation
	WBB2	fill	low amplitude continuous	uniform low	silts and clay	suspension	marine	Forth Formation
	WBB1	sheet	medium amplitude continuous	variable low	sands silts clays	suspension/ ice rafting	glaciomarine	Marr Bank Formation
ZONE C	WBC2	channel fill	low amplitude continuous	variable	sands	deposition	marine	Forth Formation
	WBC1	sheet	medium amplitude continuous	low	silts/clays dropstones	suspension/ ice rafting	glaciomarine	Marr Bank Formation

TABLE 3.2 Seismic and sediment correlations

LITHOFACIES UNITS	SEISMIC FACIES UNIT				BGS FORMATIONS
5	WBA3	WBB3			Holocene sands St Abbs Formation
4	WBA2	WBB2	WBC2		Forth Formation (undivided)
3	WBA1				Wee Bankie Formation
2		WBB1		ice proximal	Marr Bank Formation
1			WBC1	ice distal	Marr Bank Formation

TABLE 3.3 Peterhead seismic facies units correlations

LITHOFACIES UNIT	SEISMIC FACIES UNIT	BGS FORMATION	INTERPRETATION
4	PA1 — PB1	St Andrews Bay Member	Delta
4	PD2	Forth Formation (undivided)	Seabed sand
3	PC1	Wee Bankie	Glacigenic diamict (Till?)
2	PD1	Marr Bank	Ice proximal glaciomarine
1			?Rockhead/fluvial/weathered or eroded marl

TABLE 3.4 Moray Firth correlations

SEISMIC FACIES UNIT			LITHOSTRATIGRAPHY	INTERPRETATION
MF66-1	MF24-4	MF22-2	7	Diamicton
	MF24-3	MF22-1	6	
	MF24-2		5	basin infill
	MF24-1		4	basin diamicton
			3	
			2	
			1	

TABLE 3.5 Bosies' Bank correlations

BGS FORMATION	AGE	INTERPRETATION
Forth	late Weichselian–early Holocene	Glaciomarine/marine/fluvial
Witch Ground	late Weichselian–Holocene	Glaciomarine–temperate marine
Swatchway	late–Weichselian	Glacimarine (with reworked Coal Pit Formation)
Coal Pit	late Saalian–Weichselian	Pebbly glaciomarine sediments

TABLE 3.6 Altitudes of highest points within 10km of the coastline

LOCATION	ORDNANCE SURVEY REFERENCE	GLACIAL MODIFICATION	ALTITUDE (m)
Dunnet Hill	ND 192 737	Striae	121
Scaraben	ND 066 268	Striae	626
Bin of Cullen	NJ 480 643	Glacial moulding	320
North Sutor	NH 828 714	Glacial moulding	203
Meikle Carewe Hill	NO 827 920	Glacial moulding	266
Montrose	NO 630 524	Glacial moulding	132
Dundee	NO 490 350	Glacial moulding	250
Linlithgow	NT 989 744	Ice scoured bedrock	271
Traprain Law	NT 193 611	Glacial moulding	221
Scald Law	NT 583 747	Glacial erosion	579

TABLE 3.7 Amino acid racemisation dating ratios

LOCATION	CORE	DEPTH (m)	SPECIES	HYD RATIO	RELATIVE AGE
Bosies' Bank	208CS	.61	*Macoma cal.*	.085	mid Weichselian
			Arctica isl.	.037	Holocene
Bosies' Bank	219VE	0.90	*Macoma cal.* } *Macoma cal.* }	.085	mid Weichselian
Wee Bankie	81/32	9.55	*Macoma?*	.055	late Weichselian
		9.65	*Macoma bal.*	.1	mid Weichselian
ONSHORE	NK 108 465	8.00	*Arctica*	.568	pre-Cromerian

mid Weichselian >40 000 ka

Correlation of oxygen-isotope stages, D/L sea-level events and glaciations, based on model I assumptions

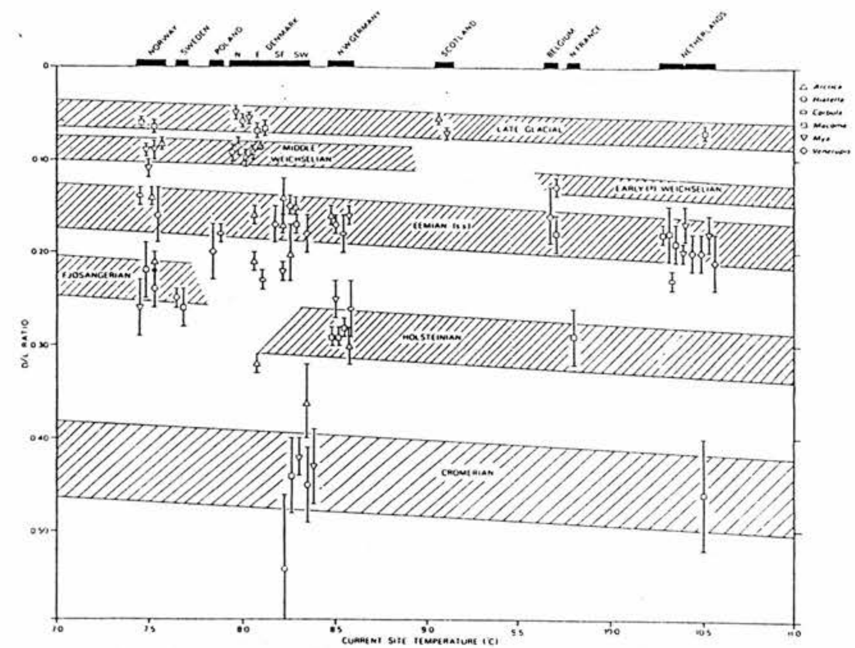
age*	stage	D/L sea-level event *Macoma–Arctica* (*Littorina*)	geochronology ka BP	glaciation
		8 0.05	11	G Loch Lomond
	2			
		7 0.07	17	F late Devensian late Weichselian
24				
	3	6 0.085		
59				E in Scotland, Ulster and Ireland
	4			
71				
	5			
122				
	5e	5 0.16 (0.11)	122	
128				D 'Warthe'
	6			
186				
	7	4 0.2 (0.16)	191	
245				C 'Drenthe'? Paviland
	8			
303			300 348	
	9	3 0.29 (0.22)		
339				
	10			
362			371	
	11	2 0.37 (0.26)		
423				B 'Elster' (Anglian, 'Irish Sea')
	12			
478				
	13	1 0.46		
524				A 'Elster' ('Elster I'?)
	14			
565				

* SPECMAP age (Imbrie *et al.* 1984).

(Bowen and Sykes 1988)

TABLE 3.8 Aminostratigraphy for north-west Europe

Both aminostratigraphies are presented to allow comparisons between them and to show the range of ratios obtained from different areas



Mean D/L ratios and one standard deviation for six of the dominant taxa in the moderate-rate group plotted against site temperatures for all sites with current mean annual temperatures between 7 and 11°C. (Data are from Table 7 except late glacial ratios which are from Miller, 1985.) Hatured envelopes define aminozones separating high-sea-level events across this region. The slope of the aminozones is due to the thermal gradient. More rapid epimerization in the warmer sites has produced higher D/L ratios in equivalent time periods than in cooler sites. In this alternative the Fjøsangerian is considered to be from a pre-Eemian (intra-Saalian or Holsteinian) interglacial and the Eemian (*sensu stricto*) group is correlated with the interglacial beds at Bø. Two *Corbula* from Strandegaard and a single individual of *Mya* from Ristinge are the only known Eemian measurements to fall outside the boundaries: they are considered aberrant data.

(Miller and Mangerud 1985)

Mean D/L ratios in shells from high sea-level events in NW Europe (Denmark, NW Germany, Netherlands) with postulated correlations to the deep-sea oxygen-isotope stratigraphy and limiting absolute age estimates.

Relative age	Mean D/L ratio: Moderate-rate	Mean D/L ratio: Slow-rate	Suggested correlation	Limiting absolute age
Modern	0.013 ± 0.002	0.013 ± 0.002	Modern	0
Late Weichselian	0.060 ± 0.010	about 0.04	1/2 boundary	10 to 12 ka
Middle Weichselian	0.090 ± 0.010	—	3	> 40 ka
Early Weichselian	0.12 ± 0.01	—	5a/c	70 to 100 ka
Eemian	0.18 ± 0.02	0.11 ± 0.01	5e	125 ka
Holsteinian	0.29 ± 0.02	0.22 ± 0.03	7 (or 9)	240 (or 330 ka)
Pre-Elsterian	0.46 ± 0.04	—	> 11 < 19	400 to 700 ka

TABLE 4.1 Glaciomarine ice margin models

a) Powell and Molnia (1989)

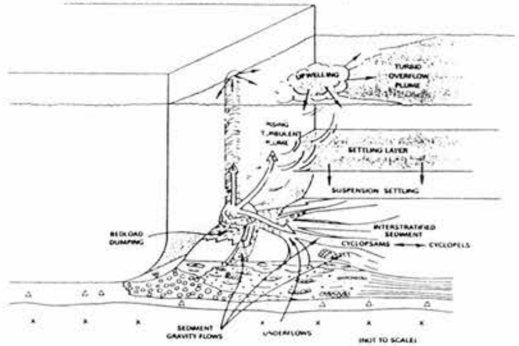


Fig 7. Processes and lithofacies associations of submarine outwash produced from subglacial discharges at tidewater fronts of temperate glaciers.

b) and c) Powell (1981)

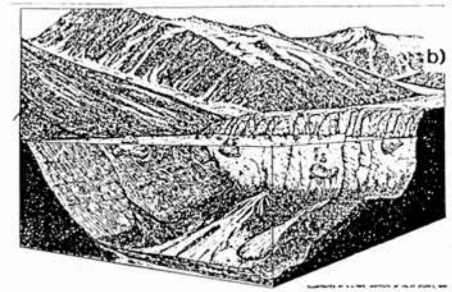


Fig.2. Slowly retreating tidewater glacier actively calving in shallow water. Sediment facies shown are Facies Association II.

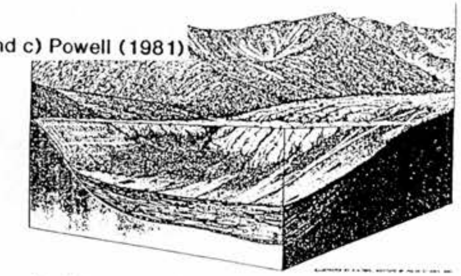


Fig.3. Slowly retreating tidewater glacier rarely calving in shallow water. Sediment facies shown are Facies Association III.

d) Powell (1981)

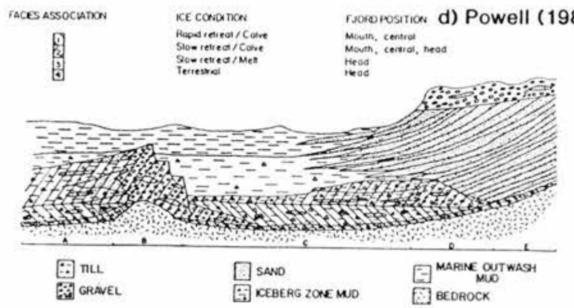
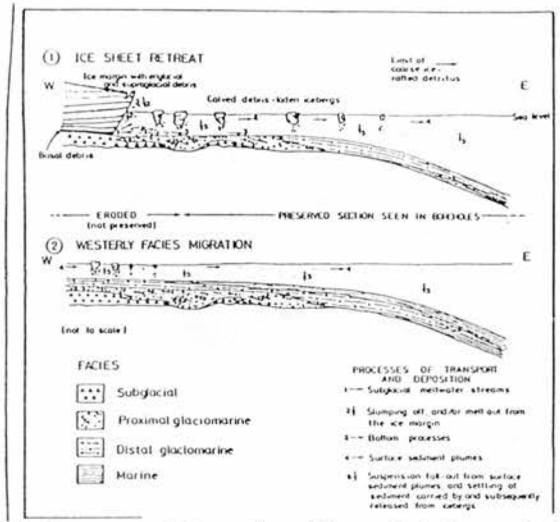


Fig.5. Hypothetical section of glacimarine sediment showing general sedimentary facies and facies associations.

e) Bent (1986)



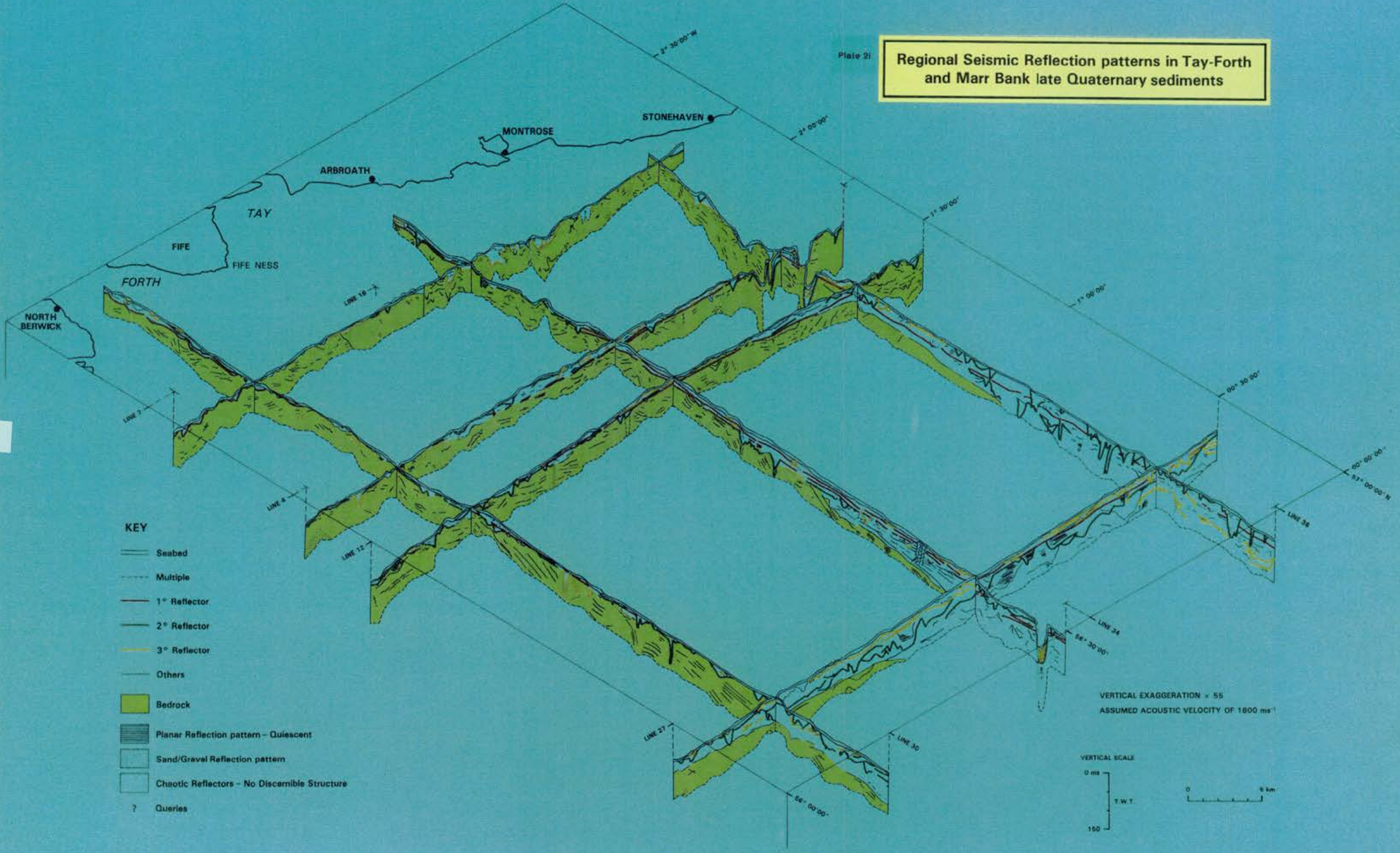
The schematic diagrams illustrate the different ice margin models proposed which are thought to apply to the project area.

PLATES

(Volume II)

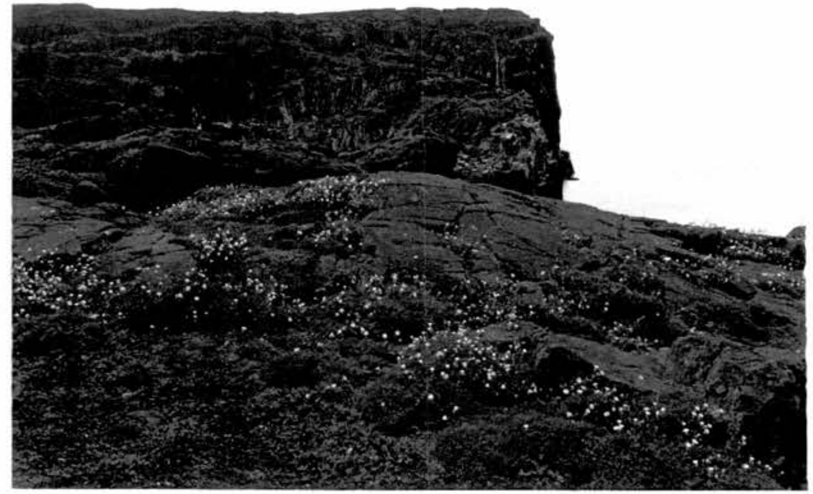
Plate 2i

Regional Seismic Reflection patterns in Tay-Forth and Marr Bank late Quaternary sediments



a

b



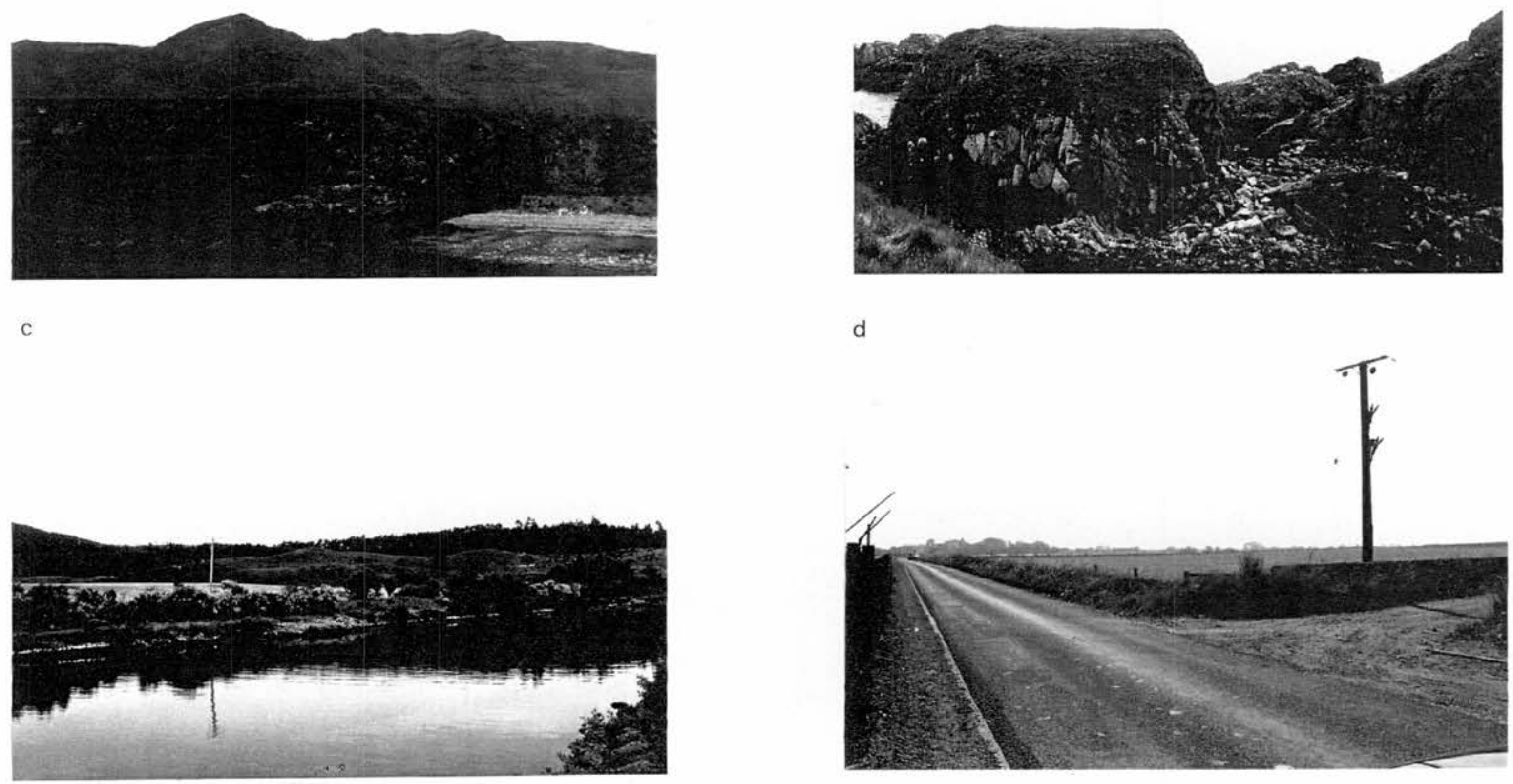
c

d

2ii Photographs of erosional landforms; a) meltwater channel, Isle of May, b) ice moulded bedrock, Isle of May, c) roche moutonnee Blackford Hill, Edinburgh and d) glacial trough Salisbury Crags, Edinburgh.

a

b



c

d

2iii Photographs of depositional landforms; a) and b) till drapes at the coast at Lybster and Cruden Bay, c) esker near Inverness and d) the featureless landscape at Fife Ness illustrating the effects of farming on landforms.

APPENDIX 1

APPENDIX 1

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APPENDIX 1

PARTICLE SIZE ANALYSER

The Sedigraph 5000ET particle size analyser is designed to compute Stokes' Law of Sedimentation and thus indicate the particle diameter. The limits placed on the diameter are +/- 1% if the system is maintained as instructed (MICROMERITICS, 1984).

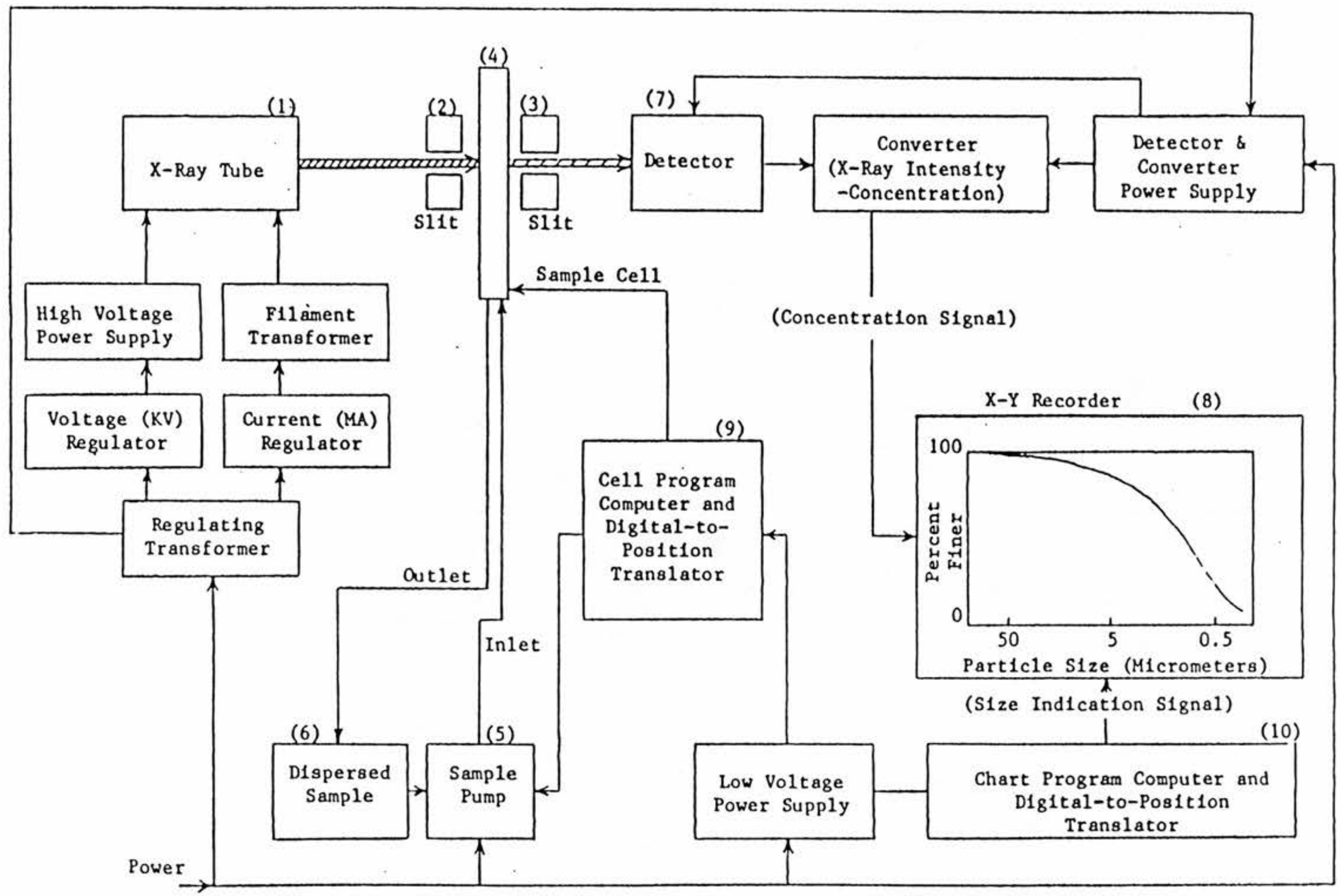
The system has been compared with a laser particle size analyser, the MALVERN 3600. The laser system exploits the differential diffraction of a low intensity laser beam by different particles in suspension (Casewell 1988). It is designed primarily as a quality control system and was unsuitable for the analysis of the mixed sediment samples examined in this study. It was unable to reproduce meaningful results and there was considerable internal disagreement in the results over time; a sample could be analysed on a time-series and the results were not reproducible. The correct result could not be identified within the time-series analyses; in tests with known controls the time taken to achieve the results was not constant. It was not possible to set up the system in such a way that it could be confidently stated that the results obtained would compare with those obtained by manual methods of sedimentation complying with British Standards BS3406 parts 1 and 2.

The SediGraph has been extensively tested in comparison with British Standard (BS3406 part 2) procedures and compares more favourably with the results than the laser system. A difference between the methods exist but it can be qualified in terms of the relative difference between the results (Stein, 1985). The sedigraph can deal with a range of samples between 100µm and 0.1µm and provides replicable results with small samples (1gram). A standardised sample analysis procedure ensures that the system is set up for the optimum results for the size range analysed.

Each sample is wet seived, and the <63µm fraction is retained. Excess water drawn off and the sample is freeze dried. A 1 gram sample is then passed through the sedigraph, and a graph of % sediment passing is constructed, as illustrated in Appendix 3.

The advantage with mechanical methods is the speed of analysis compared with conventional manual methods, especially when a large number of samples are analysed, given that the deviation from the British Standard method can be qualified.

Figure A1.1 shows the functional diagram of the instrument, and A1.2 the condensed procedure.



A1.1 Schematic diagram of the Sedigraph 5000 instrument

(Micrometrics 1984).

ABBREVIATED STEP-BY-STEP PROCEDURE

These condensed instructions are intended as a ready reference for operators who have gained familiarity with the SediGraph 5000ET by operating it under the guidance of someone from Micromeritics or another person with experience. A beginning operator will find them deficient. Any operator should refer to the more detailed instructions which follow when learning the operation and whenever questions arise.

1. The MASTER switch is ordinarily left ON except when the instrument is not to be used for an extended period. If it is OFF, turn it and the RECORDER switch to ON and put the X-RAY key switch to the X-RAY ON position. Allow at least one hour for the X-ray tube to achieve stable output.

2. Prepare the sample.

3. Calculate the appropriate rate and establish the largest particle size requirement.

4. Enter the sample description and other pertinent information on a clean sheet of graph paper and install this sheet on the recorder platen.

*4a. Set the CYCLE switch according to the option desired and the graph paper installed in step 4.

5. Move the RUN switch to RESET and then return it to its center OFF position.

6. Turn the 100 PERCENT knob fully clockwise.

7. Using the DIAMETER SET pushbutton, set the starting diameter at near the desired value, but stopping short of the precise value.

8. Check the recorder reference baseline (zero percent on the graph paper) using the ZERO knob and the ZERO pushbutton.

— — — — — —

*This step is applicable only to instruments having the multi-cycle recorder option which permits a choice of one-, two-, or three-cycle data presentation, i.e., equivalent spherical diameters from 100 to 10, 100 to 1, or 100 to 0.1 um.

9. Flush and fill the cell with pure, particle-free liquid and set the recorder baseline to 0% on the graph paper using the 0 PERCENT knob¹.

10. Check that the INTENSITY meter reading is betwen 40 and 50 uA for water. Somewhat less is satisfactory for other solvents.

11. Transfer the dispersed sample into the sample cell.

12. Adjust the recorder to 100% on the graph using the 100 PERCENT knob. Do <u>NOT</u> use a 100 PERCENT knob scale reading of less than 500. This would indicate that the sample concentration is too high and should be diluted for a more correct measurement.

13. Set the exact starting diameter.

14. Set the thumbwheels so that they indicate the proper rate as calculated in step 3.

15. Remove the cell, inspect for bubbles, and replace.

16. Position the tubing so it cannot drag on the sample container during cell descent. Close the compartment door.

17. Recheck the starting diameter, check that the recorder pen is set to the desired percentage (either 0 or 100% as described in step 12), and recheck the rate setting.

18. Start the analysis by switching the RUN switch to ON.

19. After the analysis is completed, reset the instrument by switching the RUN switch to RESET. This step is necessary even though the instrument has been through the automatic reset cycle.

20. Clean and flush the cell, leaving it filled with clean liquid.

21. Proceed to the next analysis or shut down the instrument.

¹When instrument is programmed to present results as cumulative mass percent <u>coarser</u>, the 100% mark is used as baseline with pure, particle-free liquid and the 0% line is adjusted when cell is filled with sample.

A1.2 Condensed operational instructions for the Sedigraph 5000 particle size analyser.

APPENDIX 2

APPENDIX 2

Contents

APPENDIX 2

DATING TECHNIQUES

Appendix 2 is concerned with the dating techniques considered in this project. It is split into two parts; the first part examines several techniques, whilst the second part is a report on amino acid racemisation.

Three techniques are considered, thermoluminescence dating, radiocarbon dating and amino acid racemisation. The latter is explained in detail in the second part of this appendix, and is not considered further in this section.

Thermoluminescence Dating

Thermoluminescence dating (TL) is a technique based on the amount of light energy emitted by non-metaliferous substances, when exposed to heat. The amount of energy emitted is related to the amount of ionising radiation that has been absorbed by the sample since it was last exposed to heat or ultraviolet radiation. Heat and exposure to ultraviolet radiation release ionising radiation from the sample. The technique, when applied to sediments, relates the amount of light energy emitted, to the amount of time taken for that quantity of ionising radiation to be absorbed by a buried sample.

Ionising radiation is emitted by radioactive impurities within the sample, and from radioactive sources which occur naturally within the environment; U, Th, K^{40} and cosmic radiation. The ability of the sediment to absorb the ionising radiation is dependent on the sediment, as is the rate at which the light is emitted on heating. This can be determined by standardised procedures on the sediment with known irradiation doses and known release conditions.

Given that the absorption and emission properties of the sample are known, and the natural dose rate of the burial medium can be measured, it is possible to calculate the length of time since the sample was last exposed to heat or ultraviolet exposure. In the case of sediments, this is usually equivalent to the length of time since burial, hence it is possible to produce a date for the burial of the sediment. The techniques used to produce the age are explained in Aitken (1985).

The technique, although simple in theory, contains several assumptions, which lead to many problems in interpreting the results, as outlined below.

Problems

1. It is assumed that at the time of burial that the level of ionising energy present within the sediment is zero, or some constant which can be quantified. This is not always the case, it is possible that a sediment may have been exposed for short periods of time during or after burial.

2. It is assumed that the burial history and conditions are known for the sediment. Where the environmental conditions change this creates problems because the ionising emission rate will not be constant. Particular environmental conditions which have significant reduction effects are the moisture content and the transport of material through the sediment column. The packing of the sediment, and the compression of the sediment due to the addition of overburden, creates differences in the received doses of environmental radiation. Some of the decay series (Table 1) are gaseous, hence sediments with large pore spaces will lose radioactive gases to the environment, such as Radon and Thoron, and thus reduce the environmental dose. The burial temperature may also fluctuate through time, and this will reduce the likely thermoluminescence levels measured, due to premature ejection of electrons during burial.

3. Spurious thermoluminescence is the term given to luminescence derived from other sources on heating, these are outlined in table 2.

4. The techniques used to derive the TL measurements also include problems which can create errors within the final results; these are explained within Aitken (1985).

Two core samples were selected to evaluate the applicability of this technique as a means of dating sedimentary samples (Boreholes 81/32 and 81/33). One sample was a till, the other an ice-proximal glaciomarine sediment. Results were obtained for both samples after an extensive six week testing programme. However the results were not meaningful, and it was concluded that the technique was not applicable to the sediments available for dating. Subsequent to this study it is now accepted that the application of this technique to till does not produce meaningful results (Gemmell 1988).

Radiocarbon Dating

Radiocarbon dating is a radiometric technique applied to organic material using ^{14}C. It is a useful technique applicable to the late Quaternary, with good resolution to 40ka BP. Libby (1955) established that there was a relationship between the amount of ^{14}C in an organic sample, and the length of time since death. Using this relationship it is possible to establish the age of any organic sample, as outlined in Lowe and Walker (1984). However, there are problems which affect the accuracy of the results, the most pertinent of which, are as follows;

1. It is assumed that there are no variations within the natural level of ^{14}C in the environment. This is not the case and it is necessary to make corrections in order to counteract these variable effects (Damon *et al.* 1978).

2. It is assumed that the ^{14}C levels are spatially uniform, however this is not the case, and spatial variation has been shown to occur (Harkness and Burleigh 1974). This probably varies through time too, and creates errors within the results.

3. Fractionation of isotopes occurs naturally, and ^{14}C is no exception. Temperature changes, biological processes and absorption by water, all affect the ratios of the diffrent isotopes of carbon, as well as the method of extracting samples in

the laboratory (Harkness 1979). This creates problems in the results, some of which cannot be quantified, and therefore increase the error.

4. Contamination of samples by addition of other sources of ^{14}C is a serious problem which occurs where mixing of deposits takes place, either by mechanical action, or water carrying material.

5. Anthropogenic processes can alter the natural ^{14}C levels, for example the emission of carbon as a by-product of combustion, and the change in the carbon flux as the result of the 'Global warming'. This creates problems in that it is difficult to gauge the magnitude of the effects on the carbon cycle, and the temporal variations.

6. Sample size proved to be a problem, with none of the material collected being of sufficient size to produce a suite of meaningful results. Recently an alternative method has become available which requires only 5mg of sample. However, it is difficult to obtain *accelerator mass spectrometer* analyses, hence this was not a viable alternate technique.

A2 Table 1

a

Radioactive Decay Schemes of Potassium and Rubidium[a]

Potassium-40 (natural abundance 0.0117%)		Rubidium-87 (natural abundance 27.8%)
potassium-40 (half-life: 1.25×10^9 years)		rubidium-87 (half-life: 48×10^9 years)
↓ 10.5%	↘ 89.5%	↓
γ(1.46 MeV)	β(1.36 MeV)	β(0.274 MeV)
argon-40 (stable)	calcium-40 (stable)	strontium-87 (stable)

[a] The value quoted for beta decay is the maximum energy of the beta particle spectrum. The average values are 0.583 MeV and 0.104 MeV for potassium and rubidium, respectively. The gamma emission is accompanied by electron capture.

b

Radioactive Decay Schemes of Thorium and Uranium

Thorium series		Uranium/radium series		Uranium actinium series (natural abundance 0.72%)	
Nuclide	Half-life	Nuclide	Half-life	Nuclide	Half-life
thorium-232	14.0×10^9 yr	uranium-238	4.47×10^9 yr	uranium-235	0.704×10^9 y
↓ 1α					
radium-228	6.7 yr	↓ 1α, 2β		↓ 1α, 1β	
↓ 1α, 2β		uranium-234	245×10^3 yr	protactinium-231	32.8×10^3 y
		↓ 1α			
		thorium-230 (ionium)	75×10^3 yr	↓ 2α, 1β	
		↓ 1α			
radium-224	3.6 d	radium-226	1600 yr	radium-223	11.4 d
↓ 1α		↓ 1α		↓ 1α	
radon-220 (thoron)	55 sec	radon-222	3.82 d	radon-219 (actinon)	4.0 sec
↓ 1α		↓ 3α, 2β		↓ 1α	
polonium-216	0.16 sec			polonium-215	1.8×10^{-3} se
↓ 2α, 2β		lead-210	22 yr	↓ 2α, 2β	
		↓ 2β			
		polonium-210	138 d		
		↓ 1α			
lead-208	stable	lead-206	stable	lead-207	stable

(after Aitken 1985)

A2 TABLE 2 Spurious thermoluminescence sources

Sources of Spurious Thermoluminescence (non-radiation induced)

TYPE	SOURCE	EFFECTS ON RESULT
PIEZO-THERMOLUMINESCENCE	PRESSURE	+/-
TRIBO-THERMOLUMINESCENCE	FRICTION	+/-
PHOTO-LUMINESCENCE	LIGHT	+/-
CHEMITHERMOLUMINESCENCE	CHEMICAL CHANGE/PHASE TRANSFORMATION	+/-

AMINO ACID RACEMIZATION DATING TECHNIQUE

This report arises from a visit to the University of Bergen from the 19th-29th of February 1988 to attend an intensive course on Amino Acid Dating led by Dr. Hans Petter Sejrup. "Hands on" experience was gained by analysing material from two boreholes, BH81/32 and BH81/33. This enabled an evaluation of the technique, results and problems with regard to using this method as a means of dating Quaternary sediments. It was thought that the use of Amino Acid Ratios found in molluscs and foraminifera would provide a cheap, efficient means of creating a relative chronostratigraphy for a large number of samples.

THEORY

The basis of Amino Acid Dating is the rate at which amino acids within organisms racemize after death. The most common types of samples analysed are carbonate molluscs, especially gastropods and bivalves, and foraminifera. However other materials have been used; wood, bone and soils but these suffer from greater assumptions than carbonate fossils concerning both their internal structure and environmental interactions.
Amino Acids form the basis of all living materials in that they are the constituents of proteins either as chains or sheets linked by peptide bonds (Fig 1). Twenty six Amino Acids occur naturally, of which twenty are common. When an organism dies diagenesis of the proteins occurs:

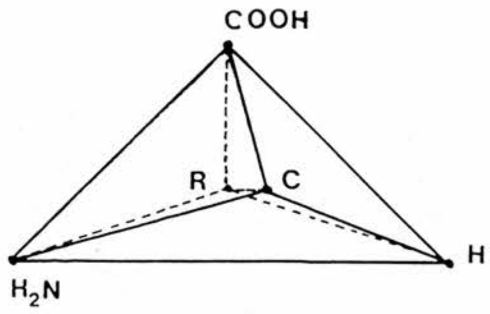
1. Hydrolysis of peptide bonds(reverse of construction)
2. Decomposition of Amino Acids (Unstable A.A. evolve to stable A.A. by unique pathway).
3. Racemization (Epimerization).

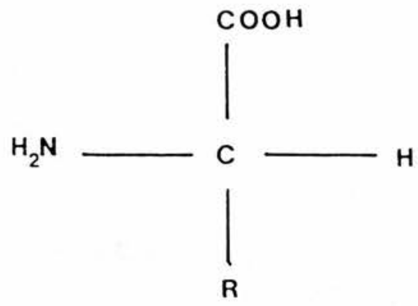
RACEMIZATION

Racemization is the mechanism whereby the structure of the Amino Acid changes without altering the chemical composition. Simply, this entails rotation about a central carbon atom; chiralism. In this way it is possible for an Amino Acid to occur in more than one structural form known as isomerism. Where the forms are left and right versions of each other they are known as enantiomers e.g. alanine. The number of enantiomers is directly related to the number of chiral carbons; $E=2^n$, where n= no. of chiral carbons. Where more than one chiral carbon exists diastereoisomers are formed and the process is known as epimerisation e.g. Isoleucine (fig. 2). Epimerisation creates slight chemical differences in the Amino Acids, however the main distinguishing property of the D and L forms is the affects they have on plane and polarised light. The L form of the Amino Acid is found within the proteinaceous matrix of the mollusc. On death this slowly epimerizes/racemises to the D form at a specific species dependent and temperature dependent rate through time.

CHEMICAL STRUCTURES

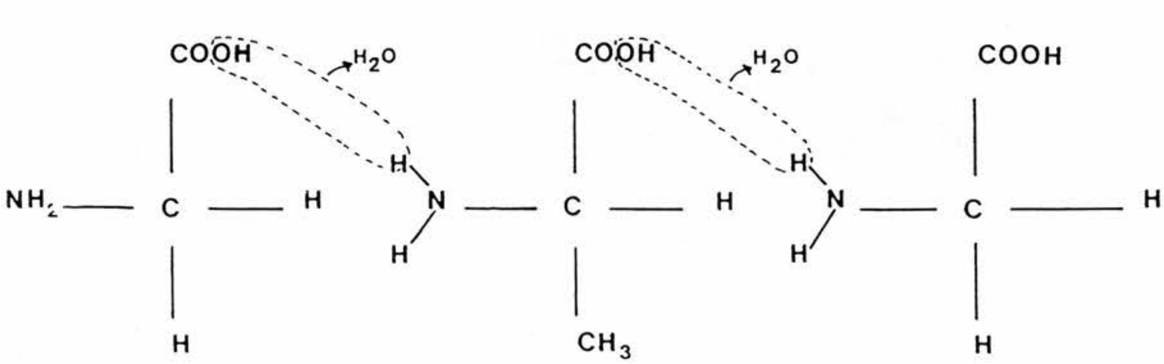
AMINO ACID





COOH	Carboxyl Group
H_2N	Amine Group
R	Carbon Chain
H	Hydrogen
C	Carbon

PEPTIDE BONDS



GLY   ALA   GLY

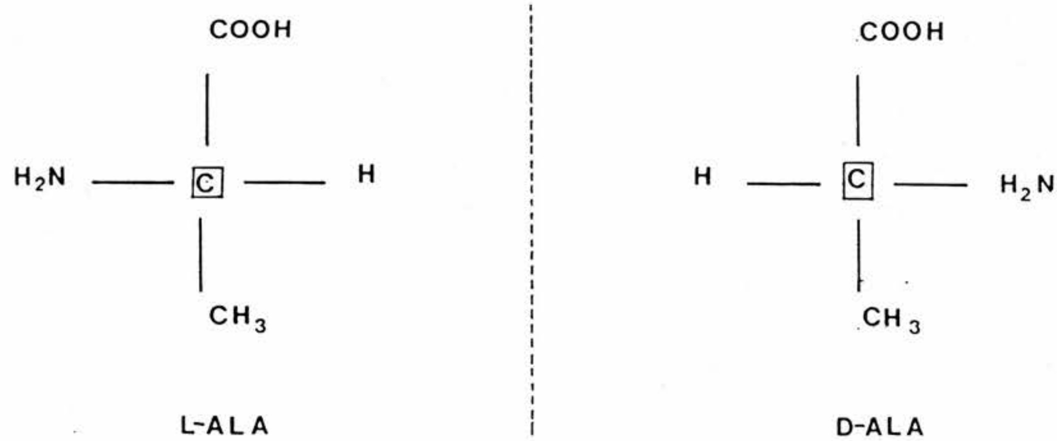
H_2N - Terminal   COOH - Terminal

(HYDROLYSIS = Reverse Reaction)

RACEMIZATION

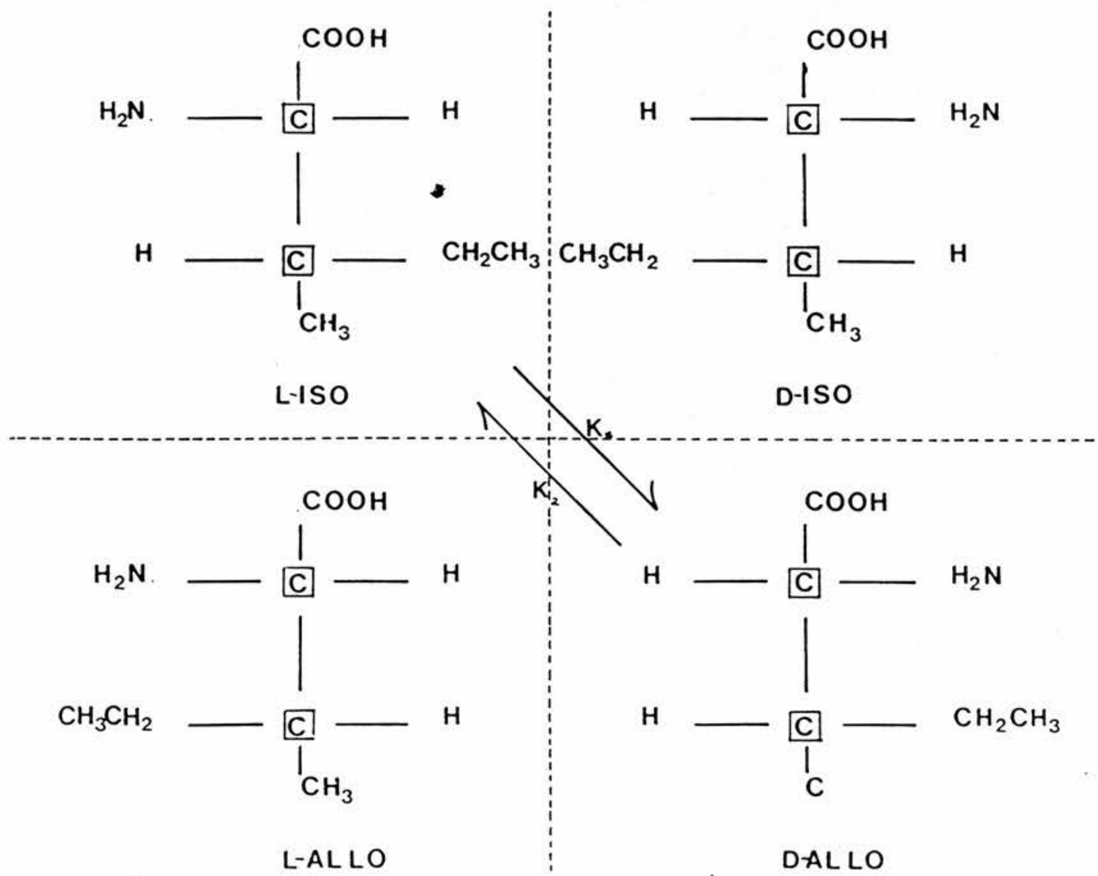
Fig 2

Alanine



EPIMERIZATION

Isoleucine



C Chiral Carbon

K Reaction Rate

The ratio between the two forms gives an indication of the length of time elapsed since death of the organism. The reaction is reversible so a limit is placed on the possible age when equilibrium is reached, for Isoleucine the ratio AIle/Ile = 1.3-1.4 indicates a sample at equilibrium.

RATE OF RACEMIZATION

Work concerning the kinetics of racemization (epimerization) has shown that the reaction rate is not constant, but depends (in addition to temperature) upon the state of the Amino Acid (Kriausakul & Mitterer 1978). Amino Acids are found in two states; Free and Bound, (either as terminal or internal members of peptide chains).
Kriausakul and Mitterer have shown that for Isoleucine the rate is dependent upon the position in the peptide chain, the nature of adjacent Amino Acids and the stability of the peptide bonds. The relative rate is:

NH -terminal>COOH-terminal>>interior>Free Amino Acid.

As hydrolysis of the original high molecular weight polypeptides to Free Amino Acids proceeds there is a reduction in the initial rate leading to the characteristic double sectioned rate curve, thus explaining the deviation from first order kinetics at this point. It follows that as the sample becomes older and the rate slows that there will be a reduction in the resolution of the derived age. Initially hydrolysis andepimerization (racemization) rates are both species dependent, however once 50% of the bound Isoleucine has been hydrolysed (AIle/Ile=0.5) there is an agreement in epimerization rates between species as epimerization of Free Amino Acids dominates. (Muller, 1984).

It is known that epimerization (racemization) is temperature and time dependent in addition to beingspecies dependent, therefore to use ratios for either dating or paleothermometry calibrationis required. This is done by consideringthe kinetics of the system:

HYDROLYSIS

$$\underset{\text{HYD}}{A} \longrightarrow \underset{\text{FREE}}{B} \qquad \ln \frac{a-x}{a} = -kt$$

where

a = Amount of A at time t=0
x = Amount of B created
k = Reaction Rate
t = Time

RACEMIZATION

$$L\ \text{form} \underset{k_2}{\overset{k_1}{\rightleftharpoons}} D\ \text{form} \qquad k_1 = \text{Forward Reaction Rate} \quad k_2 = \text{Reverse Reaction Rate}$$

At Equilibrium $\frac{k_1}{k_2} = K, \quad K' = 1/K.$

$$\Rightarrow \quad \frac{-d[L]}{dt} = k_1[L] - k_2[D]$$

$$\Rightarrow \quad \ln\left(\frac{1+D/L}{1-K'D/L}\right) = (1+K')k_1 t + C \qquad k_1 = k_2,\ K=1$$

$$\Rightarrow \quad \ln\left(\frac{1+D/L}{1-D/L}\right) = -2kt + C$$

Degree of Racemization at t=0 for a fixed temperature

$$C = \ln\left(\frac{1+D/L}{1-D/L}\right)$$

EPIMERIZATION

$$\text{Ile} \underset{k}{\overset{k}{\rightleftharpoons}} \text{AIle} \qquad k_1 \neq k_2$$

Given $K = 1.3$, then $K' = 0.77$

then

$$\ln\left(\frac{1+D/L}{1-0.77D/L}\right) = (1+0.77)k_1 t + C$$

This is temperature dependent..
The temperature dependence of the rate constant can be expressed in the form of the Arrhenius equation:

$$k_1 = Ae^{-E_a/RT}$$

where

A= entropy factor
E_a= activation energy
R= gas constant
T= temperature(K)

Take the natural logs

$$\ln k = \ln A - E_a/RT$$

To determine A and E a plot of $\ln k_1$ vs 1/T is made for each genus of mollusc. Theslopeisequal to $-E_a/R$,the y intercept is lnA. In practice values of $\ln k_1$ are determined by studying molluscs at different temperatures in the lab. Holocene examples of known diagenetic temperatures which can be reconstructed are also incorporated into the curve. Given the curve and the results of the D and L analysis from the sample it is possible to derive an age for the sample. Combining the above equations it is also possible to derive the palaeothermometry:

AGE

$$t=\{\ln((1+[D]/[L])/(1-K'[D]/[L])-\ln((1+[D]/[L])/(1-K'[D]/[L]))\}/(1+K')Ae^{-E_a/RT}$$

TEMPERATURE

$$T=-E_a/\{R(\ln[\ln((1+[D]/[L])/(1-K'[D]/[L])-\ln((1+[D]/[L])/(1-K'[D]/[L])_0)/At(1+K')]\}.$$

[D] Concentration of Alloisoleucine
[L] Concentration of Isoleucine

Note: although it is assumed that A and E_a are constants this is not always the case and can lead to further errors. It is also better if the temperature T is known rather than assumed as this gives greater resolution.

METHOD

Two methods are available for the analysis of Amino Acids in samples; High Pressure Liquid Chromatography (H.P.L.C.) and Gas Liquid Chromatography (G.L.C.). H.P.L.C. is based on the ionic structure of the different Amino Acids whereas G.L.C. is based on there volatilities. Bergen favour the former which is detailed below.

H.P.L.C.

H.P.L.C. is a two phase process utilising the different ionic behaviour and exchange capacity of the Amino Acids, and is very sensitive (to 1×10^{-12}g). It differentiates between the enantiomers and diastereoisomers of isoleucine, amongst others.
The machine consists of three buffers, sample injector, separating column, fluorescing solution, photomultiplier and counter.

PHASE ONE

Three buffers of differing pH (3.12,3.86,and 10.5) are introduced into the sample. These manipulate the acid / base properties of the Amino Acids such that there is enhanced ionic exchange.

The amino acids are released from the exchange sites which then become neutral. The active sites are the amineand carboxyl groups and depending upon the net charge different amino acids are released as the buffered solution changes. Therefore the fractionation of the amino acid is dictated by its isoelectric point with the lowest released first (table 1).

PHASE TWO-QUANTIFICATION

An artificial fluorescent inducing agent O-phthalaldehyde (OPA) was added after fractionation in order to assess the amount of each A.A. released. The fluoresence on heating was detected using a photomultiplier and counter. The results were displayed on a chromatogram and digitised printout (fig 3).
In order to quantify the concentrations an internal standard was introduced during preparation (Norleucine). This allowed comparative quantification by the Relative Molar Response method. The area under the peak is proportional to the concentration, therefore the exact quantity can be derived.

ASSUMPTIONS

These are primarily;
1) The fossil materials have a generically specific A.A. signature that does not change through time. This enables the identification of shell fragments from their A.A. signature, as shown by Andrews et al. 1985.
2) During preservation there is no diagenetic change of the A.A. signature except that due to racemization / epimerization.
3) There has been no phyllogenetic change through time.

PROBLEMS

These are summarised below:

CONTAMINATION

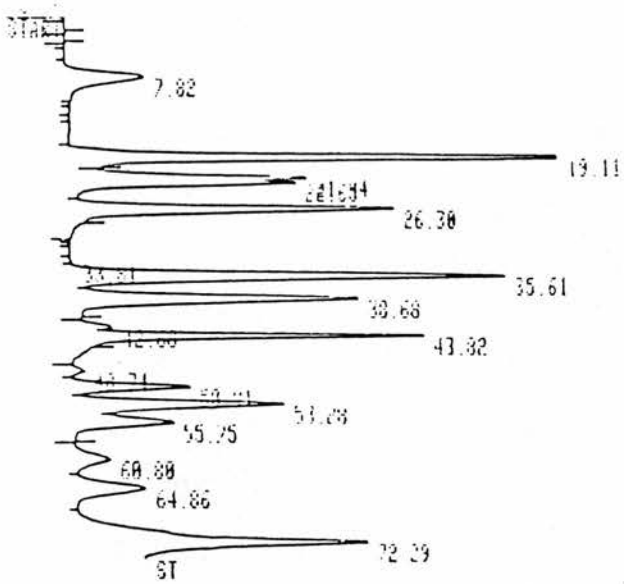
If samples come into contact with other organic matter contamination occurrs. This can be reduced by incorporating clean techniques into the preparation of samples. It is also possible to assess if contamination has occurred by examining the chromatogram, which should conform to a 'type' pattern for that species. If this is not the case contamination has occurred. Glycine and Serine are the main contaminants, therefore by considering the TRE and SER peaks (which are usually equal) it is possible to tell the degree

TABLE 1 AMINO ACID RELEASE SERIES

ABREVIATION	NAME	ISOELECTRIC POINT (pI)	
ASP	Aspartic Acid	2.98	FIRST
TRE	Threonine	↓	↓
SER	Serine		
GLU	Glutamic Acid		
GLY	Glycine		
ALA	Alanine		
VAL	Valine		
MET	Methionine		
Alle/Ile	Alloisoleucine/Isoleucine		
Iso	Isoleucine		
LEU	Leucine	6.04	
IST	Standard	↓	
TYR	Tyrosine		↓

EXAMPLE OF PRINTOUT

FIG. 3



RUN # 250 FEB/25/88 21:36:40

AREA%

RT	AREA	TYPE	AR/HT	AREA%
7.82	8876700	PV	1.925	3.832
19.11	3.5060E+07	PB	0.770	15.137
21.94	9857500	BV	0.777	4.256
22.65	9759700	D VP	0.797	4.214
26.30	2.0010E+07	PB	1.063	8.639
33.81	48753	PV	0.471	0.021
35.61	2.9302E+07	VV	1.133	12.651
38.68	2.0946E+07	VB	1.250	9.043
42.68	1334200	PV	0.817	0.576
43.82	1.5654E+07	VB	0.774	6.758
48.74	602430	BP	0.868	0.260
50.91	7020500	PV	1.012	3.031
53.28	1.5491E+07	VV	1.237	6.688
55.75	8454500	VB	1.439	3.650
60.80	3678400	BV	1.789	1.588
64.86	7394600	VV	1.794	3.193
72.29	3.8134E+07	I VH	2.195	16.464

TOTAL AREA= 2.3162E+08
MUL FACTOR= 1.0000E+00

of contamination, i.e. SER>>TRE. This also leads to an increase in ISO, therefore the D/L ratio is lowered causing an underestimation of age.

TEMPERATURE HISTORY

The Effective Diagenetic Temperature (EDT) is a function of the mean air temperature since burial T, the amplitude of fluctuation of the absolute temperatures through time, and the burial history of the sample, due to the differing temperaturesfound at the surface andvarying depths. Note that ocean temperatures may have only varied by $2C^{0}$, whereas the land temperatures may have been more extreme. How effectively can the palaeotemperatures be reconstructed?

INTRASHELL VARIATION IN MOLLUSCS

Intra shell variations in structure of molluscs can significantly affect the A.A. values obtained. The shell is formed by the layered secretion of calcite onto a proteinaceous matrix. Although the calcite surface acts as a buffer between the matrix and environment, if this is broken it is possible to lose proteins and therefore A.A.. It was thought that this loss (leaching) was primarily from the end of the layers, but unpublished work in Bergen suggests it is due to changes within the microstructure of the calcite and can occur anywhere. Samplesfrom the hingedarea of the bivalve are best as it is here that the structure is most dense and potential for leaching lowest.
Little information is available about the rates of loss of A.A. but forams arethe most retentive. Againthisis dependent on the environment.

INCORPORATION OF ENVIRONMENTAL AMINO ACIDS

If leaching occurs, is it then possible to incorporate FREE A.A. or polypeptides from the environment into the mollusc ? Miller & Hare (1980) have shown that although FREE A.A. may interchange without altering the ratios, polypeptides and proteins are too large to reenter the structure from the environment.

SEDIMENTARY ENVIRONMENT

Is the fossil in situ? This requires a careful examination of the site of the fossil and the fossil itself. It is not possible for a fossil which became extinct in the Tertiary to exist in situ in Quaternary deposits! It is also likely that fragmented shells in a clay rich matrix have been reworked.

DIFFERING RATES OF EPIMERIZATION / RACEMIZATION

As shown above, rates of epimerization / racemization are a function of the proportion of the A.A. in protein (medium), small chain (fast) and FREE (slow) states. Though it is possible to make corrections for this using first and second order kinetics, it remains a problem, compounded by that of a realistic reconstruction of burial history. (McCoy, 1987).

INTERLAB/SYSTEMS COMPARISON

Wehmiller, 1984, hasconsidered this problem,and though finding good intralab reproducability on standards of A.A., interlab comparisonsof the same standards gave up to 25% differences. As aresult of this study it is now common practice for standards and blanks to be run with every batch of samples to allow for standardisation.

APPLICATIONS

MAIN:

1. Relative chronostratigraphy (with calibration, relative dating)
2. Resolution of mixed population of sample, given curves of known monopopulation (Muller, 1984)
3. Aid to radiocarbon dating-resolve limits of age

OTHERS:

1. Absolute chronology, requires calibration; resolution in young and old samples is poor.
2. Calculations of palaeotemperatures
3. Determination of species
4. Phyllogenetic Tracing [Surely this is not feasible because one of the bases of A.A. Dating is that there has been no such change in phylla through time ?]

SAMPLE PREPARATION

Two samples BH 81/32 (9.65m) and BH 81/33 (12.3m) were prepared for A.A. treatment of both molluscan and foraminiferal materials as follows:

MOLLUSCS

1. Identify mollusc
2. Fill out form, assign BAL no. and register
3. Clean shell with fine brush to remove sediment particles, place in ultrasonic bath, if necessary.
4. Break shell into fragments of ~ 100mg
5. Use Rubber Gloves For Rest Of Procedure
6. Rinse fragments in distilled water
7. Place in clean labelled test tube
8. Add 0.33ml/100mg shell of 2N HCL to dissolve 1/3rd of the surface layer.Leave for 1 hour at room temperature.
9. Remove solution, wash; twice with distilled water, twice with double distilled water.
10. Dry on sterile paper
11. Crush shell and weigh out two 25mg (+/-0.1mg) samples into test tubes, one labelled 'FREE', the other 'HYD'.
12. Add internal standard in solution with 7N HCl:-
    v=0.02ml Int. Std.xM(mg) Shell
13. FREE Samples:-
    Evaporate off the Int. Std. at 60^{0}C, under Nitrogen
14. HYD Samples:-
    Pyrolise for 22hrs at 110 ^{0}C in sealed vials containing Nitrogen.Ensure seal is tight. Cool ,then evaporate as above.
15. Add 0.1N HCl to the samples v=M/25 ml
16. Inject into H.P.L.C.and run. Run must include lab standard and blank in order to assess noise etc.

FORAMINIFERAL PREPARATION

1. Sieve sample using 1mm, 250µm and 63µm sieves. Dry.
2. Use residue from 250µm sieve. Examine under microscpe to identify and isolate forams.
3. Depending on the forams present up to 100 samples must be isolated.
4. Place samples in microreaction glass.
5. Wash with pure distilled water using pippette, place in ultra sound bath for 5 minutes. Repeat twice. Then wash and ultrasound for 1 minute three times.
6. Evaporate off water at 40^{0}C.
7. Add 7ml 7N HCl+Norleucine.
8. Flush vial with Nitrogen ,seal at 110^{0}C for 22hrs.
9. Evaporate in a vacuum.
10. Rehydrate with 100ml pH2 (0.1N HCl) solution.
11. Inject into H.P.L.C. as in molluscan example.

PROBLEMS ENCOUNTERED

Foraminiferal analysis of the samples was not possible because insufficient examples were found:

BH	FORAMS	SPECIES
81/33	0	0
81/32	2	Oolina sp
		Elphidium sp

The fragments of useable molluscs in BH 81/33 were less numerous than was at first thought, the other fragments being mussels and barnacles. It was decided to run the fragments remaining even though they could not be identified byphysical features alone. It was hoped to use the method of Andrews et al. in order to identify them.

RESULTS

BH 81/33
Unfortunately it was not possible to identify the genera of the samples from this borehole, due in part to contamination and the lack of matching ratios to those of Andrews et al. The results obtained are shown in table 2.

BH 81/32
The molluscs were identified as Macoma balthica, a species common in inshore/estuarine waters and which has been used extensively for A.A. work in the Quaternary.
The results obtained are shown in table 2.
The results were decided to be best used as ratios rather than as absolute dates after consideration of the problems associated with absolute dates.
The ratios obtained were compared to those shown in work of Mangerund and Miller (1985) which deals with European Marine Deposits and a general A.A.chronostratigraphy for the area. BH 81/32 lies outwith the core study area of the work, however they have extrapolated their results beyond this and I feel this can accommodate this site, because it probably hada similar post depositionaltemperature history.The above work would suggest that the material was of Eemian age. Stratigraphically the sediment in which it was foundcorresponds to the Wee Bankies Formation (Stoker et al 1985). This is thought to represent the terminal moraine ofthe Late Devensian Ice Sheet in Eastern Scotland and as suchis much younger than the interglacial. This suggests that the material was reworked into the till as it overran the existing sediments. This does not mean that the material underlying the ice sheet was Eemian, reworking of previously reworked sediment containing the shells could have occurred. The presence of forams with iron staining,quartz growths and broken sections would support this. It was

TABLE 2 RESULTS AIle/Ile

BH	BAL	HYD1	HYD2	FREE1	FREE2
81/32	1453a	.1	.27		
	1453b	.094		.224	.339
81/33	1452a	.482	.024	.183	
	1452b	.496	.495	.341	
	1452c	.130	.129	.236	

unlikely that the fragments were in situ and a wealth of evidence supporting the younger age produced by theBGS in their Offshore Program exists.
The molluscs were contained within a sandy unit within the diamicton. This suggests the incorporation of coarser material into the till at that point. The sand (250µm-63µm) was predominantly composed of well rounded quartz crystals and well rounded fragments of igneous and metamorphic material. When this is compared with the same fraction in BH 81/33 there is a marked difference between the rounding, the latter being much more angular and having a bimodal distribution, withan entirely quartz finesubsample. This suggests the incorporation of beach or shallow marine sand into the till of BH 81/32 and could explain the lack of reworked forams by washing out of finer material during incorporation. I would expect that as the molluscs were preserved in very good condition that forams would also be preserved as reworking could not have been destructive.
If washingoutwas the method of removal why is there sucha high (23%?) amount of material <63µm, unless this has been washed into the sample site?

CONCLUSION

From the above results it is to be concluded that the Late Devensian till contains a proportion of reworked material from the Eemian interstadial. It is likely thatthesame conclusion could be drawn from BH 81/33 if the molluscan material could be identified. The results are replicable and of high resolution and may be useful in the future.

APPLICABILITY TO PROJECT

From the above results, an appreciation of the theory and the problems associated with this technique, it may not be as useful as first thought if it is used in isolaton. Ratios can only provide a relative age (the resolution for absolute ages for young samples being poor)which can be open to question due to the errors shown above.The problem also arises as to whether the fossil is in situ, although careful logging can reduce this, but it will indicate the likely age of the material if this is of use. If absolute dates are required Accelerator dates would produce better results, although A.A. ratios would indicate whether it was an in situ source.Again this technique has problems.
Given that amino and lithostratigraphies exist for the area it may be possible using A.A. ratios to combine these and so give a relative age to the areas lying to the North and West of the Wee Bankies Project Area.
Only two samples were run in this trial and perhaps more should be undertaken at a later date on samples specially

chosen on samples more suited to this technique.The availability of material, ease of sample preparation and speed of this technique make it ideal for this type of study, as does the use of ratios which can be correlated on a regional scale. I think that further tests should be done later this year for further evaluations.

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APPENDIX 3

APPENDIX 3

Contents

APPENDIX 3

RAW DATA

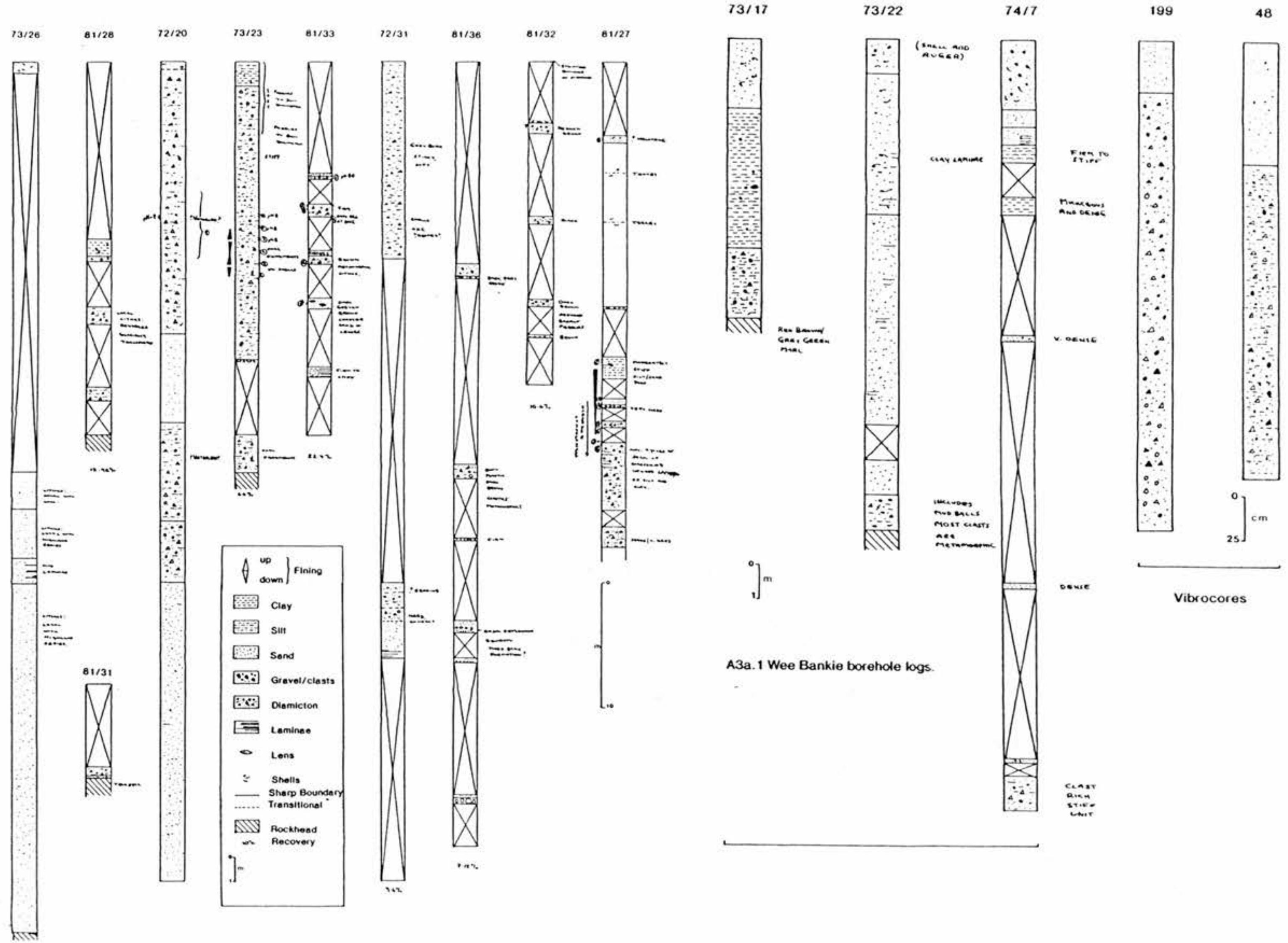
This appendix contains the raw data from which the composite diagrams have been prepared. It also contains the raw data used for checking the aerial photograph exercise, and an example of the onshore fabric analysis work. The data is split up into two parts; a) offshore, and b) onshore.

OFFSHORE

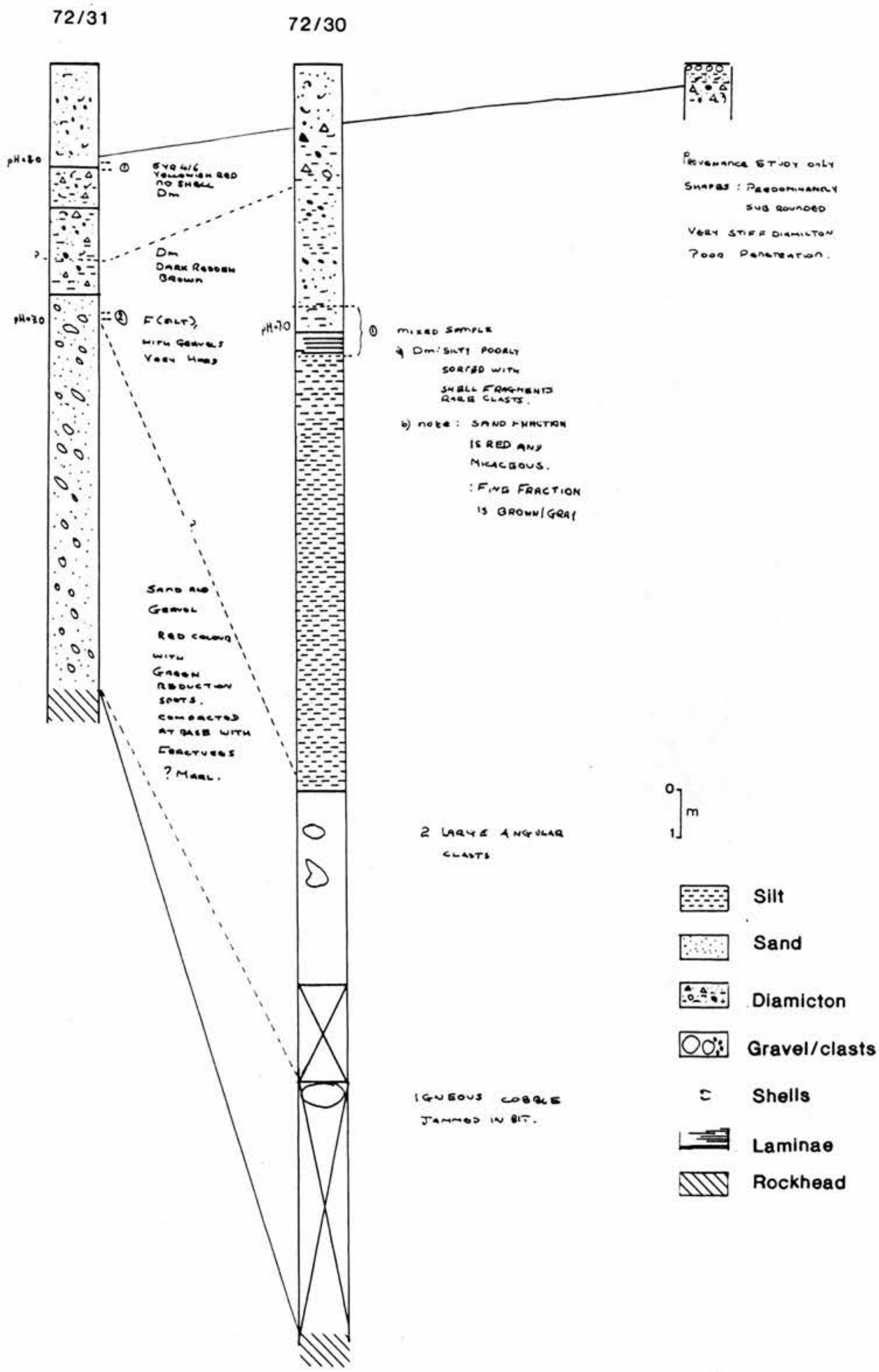
The offshore raw data is presented as a series of figures and plates listed below:

FIGURE	CAPTION
A3a.1	Wee Bankie core logs
A3a.2	Peterhead core logs
A3a.3	Moray Firth core logs
A3a.4	Bosies' Bank core logs.

PLATE	
Ai	Examples of sediments: diamicton and glaciomarine sediments
Aii	Examples of clasts indicating the shapes and surface morphologies

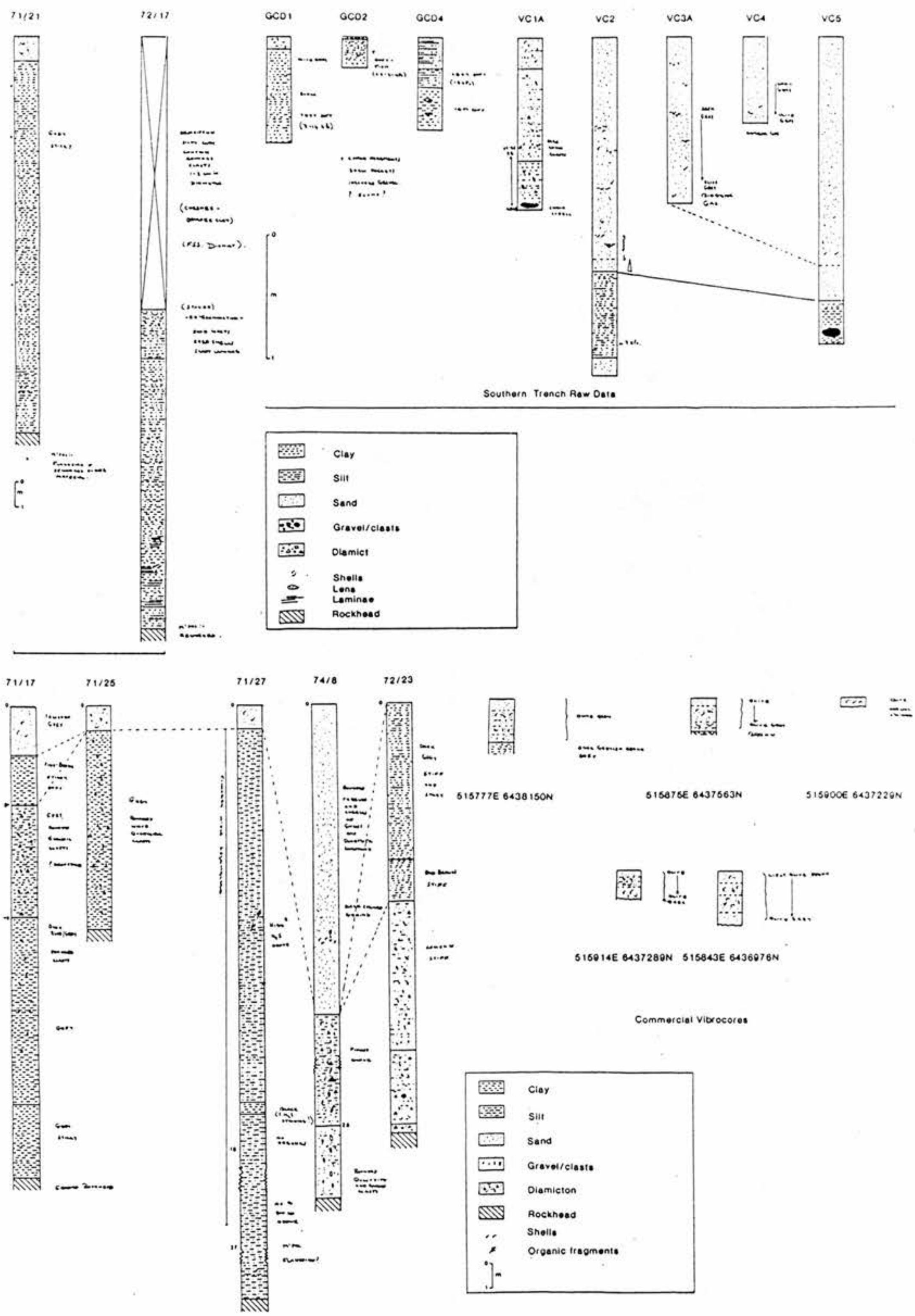


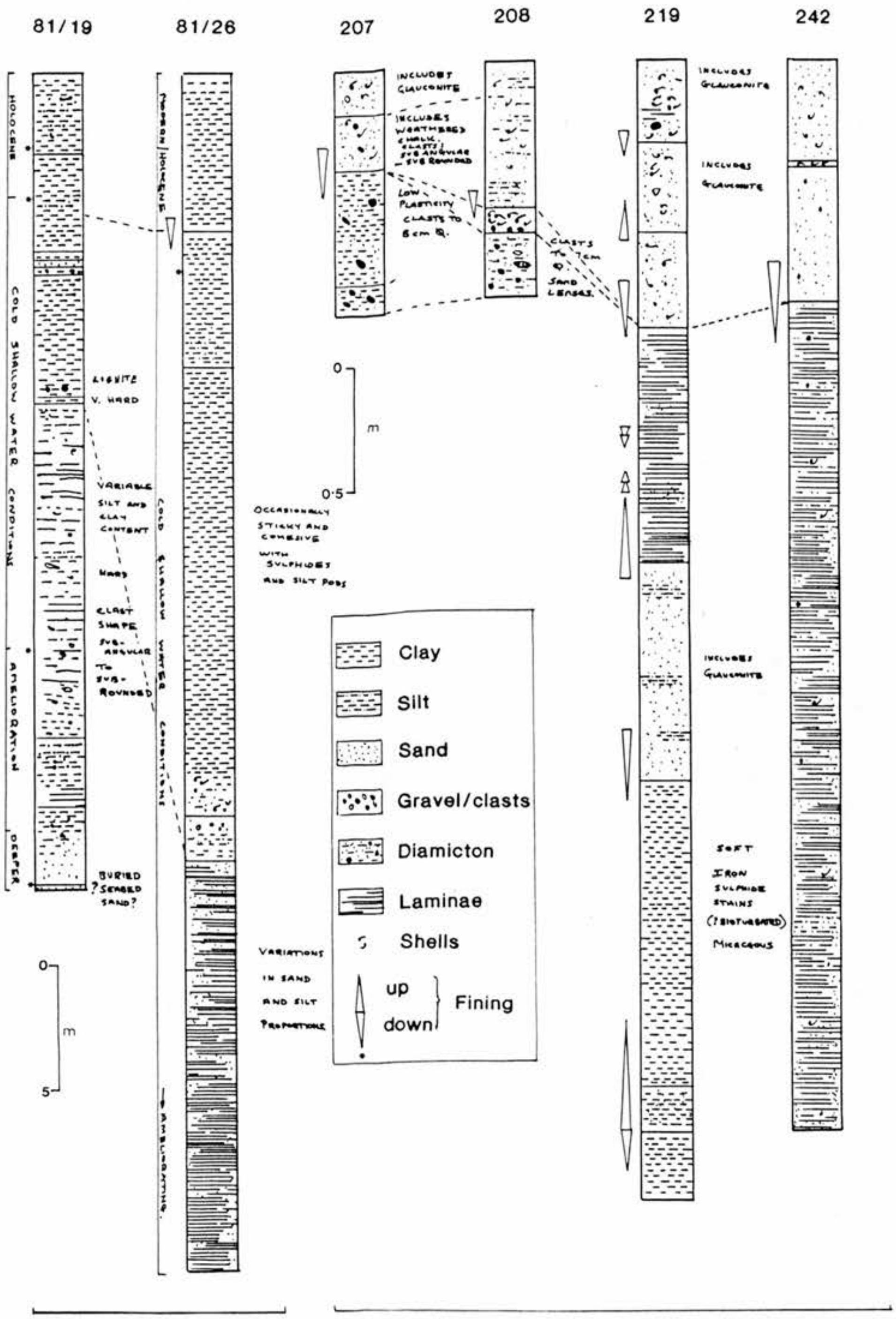
A3a.1 Wee Bankie borehole logs.



A3a.2 Peterhead borehole logs.

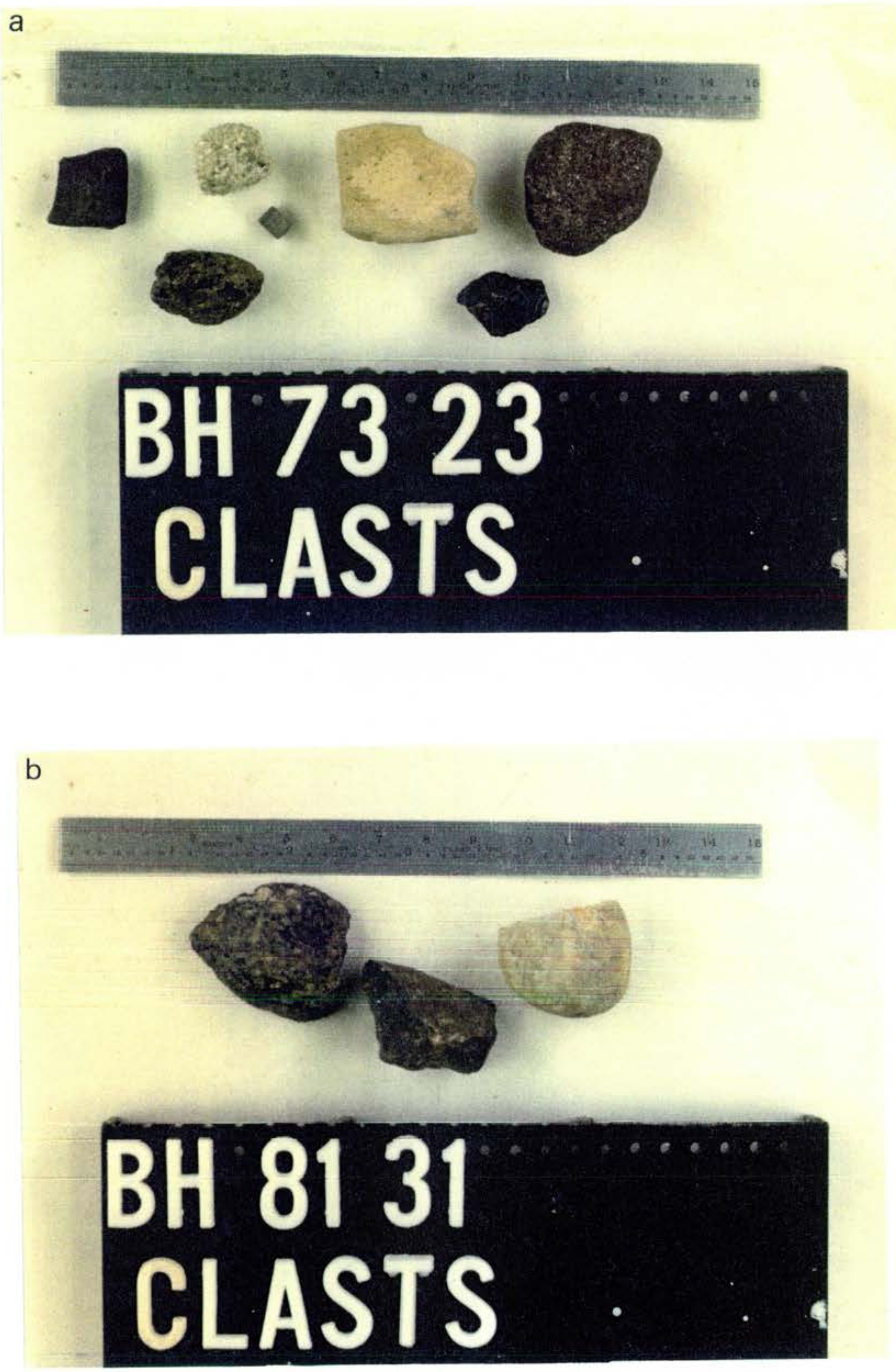
A3a.3 Moray Firth borehole logs.





A3a.4 Bosies' Bank borehole logs.

Ai Examples of a) glaciomarine sediments and b) diamicton.



Aii Examples of clast shapes and morphology, a) glacially transported clasts and b) reworked clasts

ONSHORE

AERIAL PHOTOGRAPH - GROUND TRUTHING

Method: Geomorphological maps of eight sites was drawn using 1:10 000 scale aerial photographs. Features of glacigenic origins were drawn on, both erosional and depositional. The sites were visited in turn and surveyed by field observations concentrating on the features marked on the map. Amendments and additions were also made as were some measurements to see if the detailed information matched the information carried on the aerial photographs.

SITE SUMMARIES

1. HELMSDALE (Fig. A3b.1)

Five important conclusions can be drawn from the survey:

a) Strong west-northwest to east-southeast trends exist in the lineations, ice scoured bedrock and roche mouttonees also follow this trend.

b) Localised meltwater channels indicating more topographically constrained conditions (restricted glacier activity rather than ice sheet) exist perpendicular to the main valley sides and the bedrock scours.

c) Interesting height variation between ice scoured and unmodified rock, ice scoured material exists above 200m.

d) Change in dominant direction towards the coast, however, the main trend is west-northwest to east-southeast throughout the area.

e) Small glacial deposits occur in the Strath of Kildonon, on the valley floor and as terraces along the valley side.

2. STRATHPEFFER / DINGWALL (Fig. A3b.2)

Evidence of differing effects and possibly rates of ice movement in the area is illustrated by different intensities of ice moulding and erosion, as well as different directions of glacial erosion. Main stream of ice flowed along Strath Peffer, existing next to an area of little movement in basin with small loch. The result is two conflicting sets of glacial features reflecting a sluggish ice component in the basin environment and a main area of ice movement. Suggest that the features within the basin are later than the those originating in the more dominant ice flow area to the N. Suggest the ice direction at the maximum would again be an onshore - offshore movement as indicated by the rock scouring on the tops of the higher ground to the east of the small basin. It is suggested that that these relate to more active ice conditions preceding the stagnation and depositional period in the basin. Note the ridge which was incorrectly identified on the aerial photographs!

3. BANFF (Fig. A3b.3)

Area of deposition rather than erosion, except the meltwater channel in the R. Deveron which would suggest an onshore - offshore direction of ice movement. There are several depositionary features which suggest an alternate direction of meltwater flow at odds with the general trend. Much evidence has been destroyed as a result of anthropogenic activity within the area, both in urbanisation and extensive agriculture and forestry which obscure the features or remove them entirely from the landscape. It is necessary to set up selection criteria in order to overcome this problem. This entails examination of the feature and a judgement as to whether it has been so affected that it no longer gives meaningful information r.e. direction. The survey carried out from the aerial photographs is of greater value in this area than examination of the evidence in the field. This is because the gross morphology of features is apparent on the photographs, whereas in the field the features are obscured.

The main area of conflicting direction is in the coastal strip.

4. STONEHAVEN (Fig. A3b.4)

This site was chosen to tie in with the presence of the Highland boundary fault and the supposed deflection of ice. It indicated that the area was dominated by depositional landforms, which form a complex pattern indicative of several ice movement directions, and downwasting of stagnant ice *in situ*. The complexity of the pattern, and lack of good sediment sections made it difficult to interpret the ice movements in the area, and to relate specific landforms to the late Weichselian maximum.

5. MONTROSE (Fig. A3b.5)

Most features in this area relate to the presence of the Basin and the affects that this has had on the local geomorphological processes; there is lots of evidence of the infill of the basin in recent times.

The lack of any high ground in the coastal area makes it very difficult to find ant traces which indicate erosional activity associated with the last substantial ice cover and hence makes it difficult to place a relative chronology on the features. It would be interesting to establish the structure of the basin itself, and the sedimentary succession preserved within it. Anthropogenic modification masks any important geomorphic indicators of ice movement, that may exist.

This area ties in with the onshore boreholes taken near the shore.

6. FIFE NESS (Fig. A3b.6)

Not very fruitful! Totally reworked by man with any remnants subdued to such a degree that it is impossible to infer anything of use about the ice movements. Note the raised beach features.

7. EDINBURGH (Fig. A3b.7)

This area exhibits excellent examples of ice moulded and streamlined landforms. All of the hills are aligned in a west to east direction, with the exception of a dike, which exhibits west to east modification on its surface. Depositional landforms are not as common, however series of meltwater channel networks show there was a subglacial fluvioglacial system associated with basal erosion.

8. HOPE RESERVOIR (Fig. A3b.8)

Two main conclusions can be drawn from this the most inland site investigated:

a) Direction of ice in uplands is different to that shown by the depositional features in the area.
b) Possible to work out a chronology on the erosional vs. depositional features as a result of their relative positions.
This site provides a general overview of the glacigenic evidence available to the south of the Firth of Forth, away from the main ice stream.

From the comparisons between the geomorphological maps drawn in the laboratory, and the field checking of the data it is suggested that the aerial photographs have been interpreted to an acceptable standard, and that this is a viable technique with which to map the regional trends. However, it must be stated that errors can be made in interpretations, for example, the Strathpeffer 'esker'/rock ridge!

Care must be taken when analysing the aerial photographs in the lower areas, especially those areas near settlements, and in intensive agricultural locations, that the features mapped are real, rather than artifacts of anthropogenic behaviour. The sites most suited to aerial photography surveys are in areas of high ground, away from settlements, and where erosional and depositional landforms have not been altered.

KEY TO ONSHORE GEOMORPHOLOGICAL MAPS

Break of slope

Rock cut channel

Channel

Meltwater channel

Lineation

Drumlin

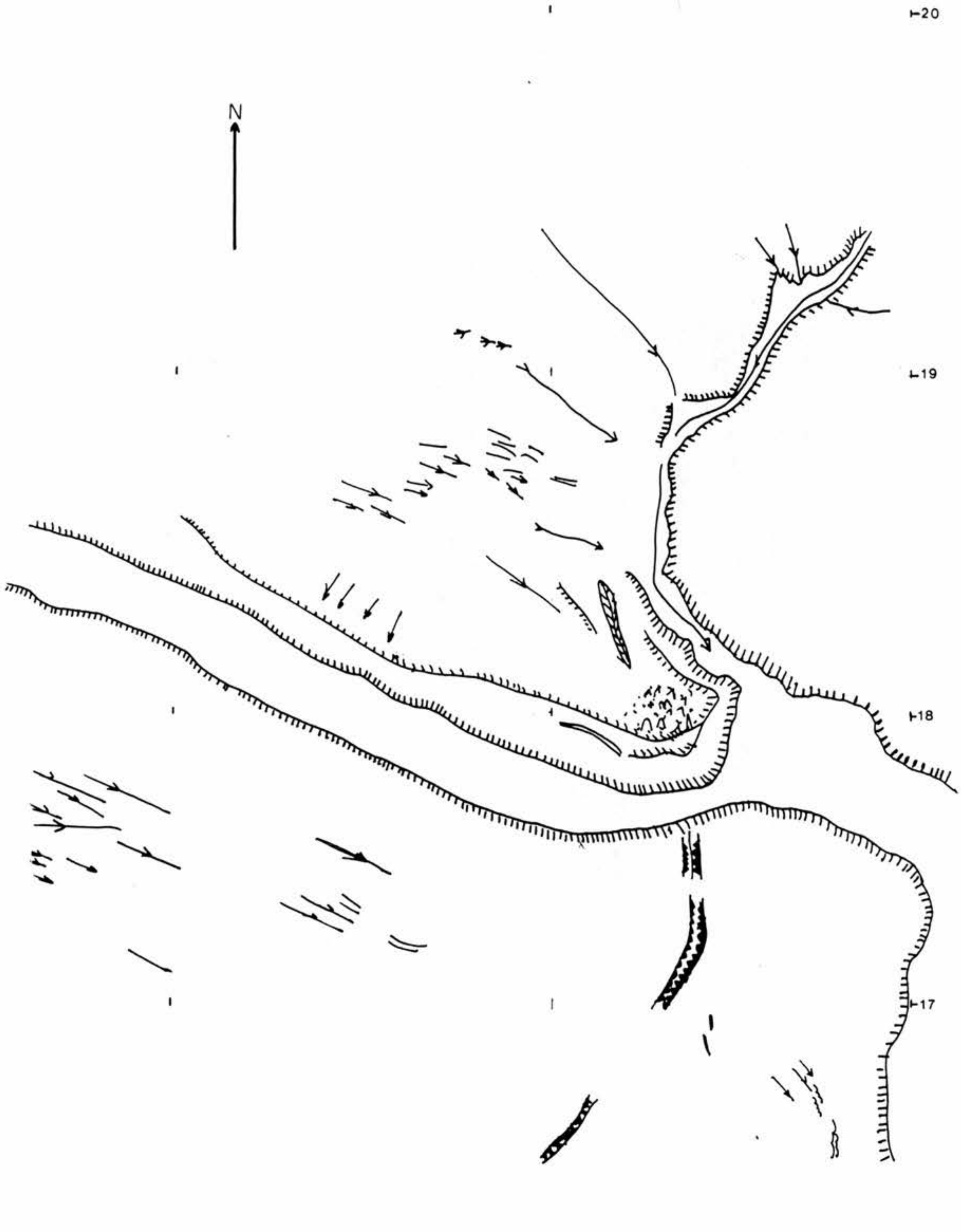
Ridge

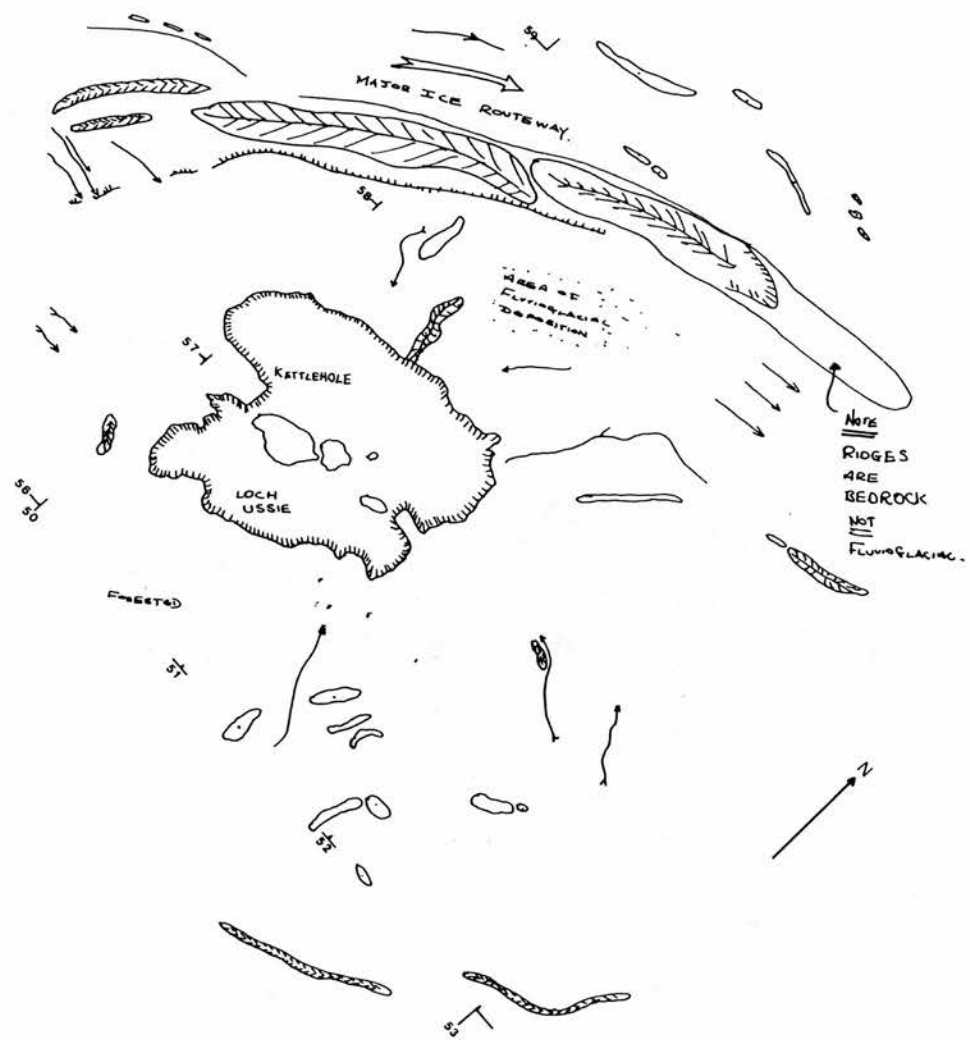
Kettlehole

'hummocky' topography

Fluvioglacial outwash

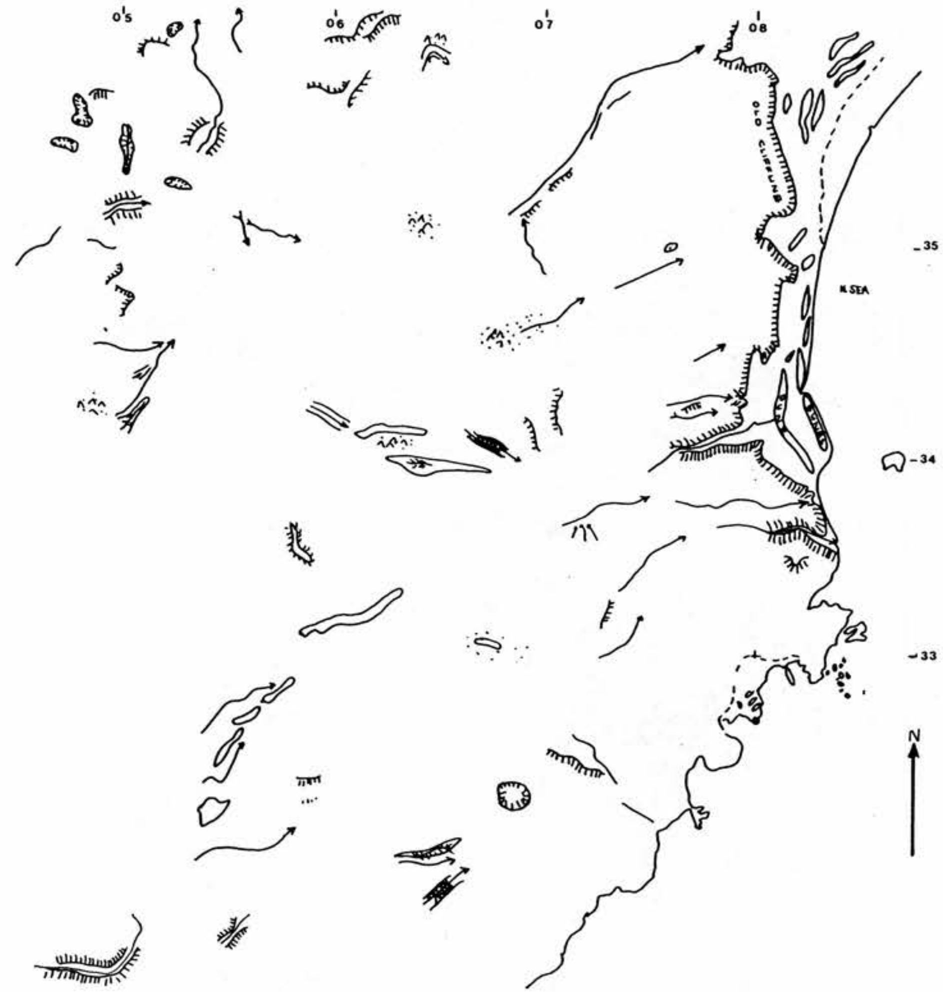
A3b.1 Field geomorphological map of the Helmsdale area, note the lineations within the landscape, and the valley floor landforms.



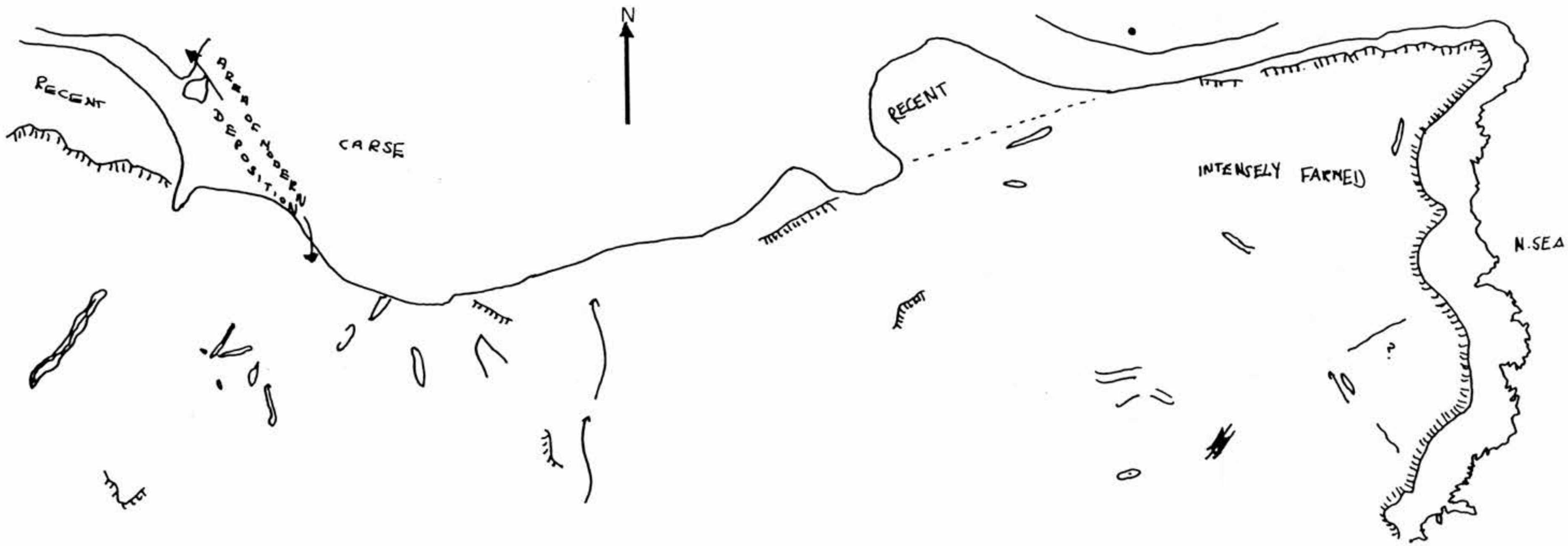


A3b.2 Field geomorphological map of Strathpeffer and Dingwall, near Loch Ussie. Note the two groups of glacial indicators and the ridge incorrectly identified as an esker!

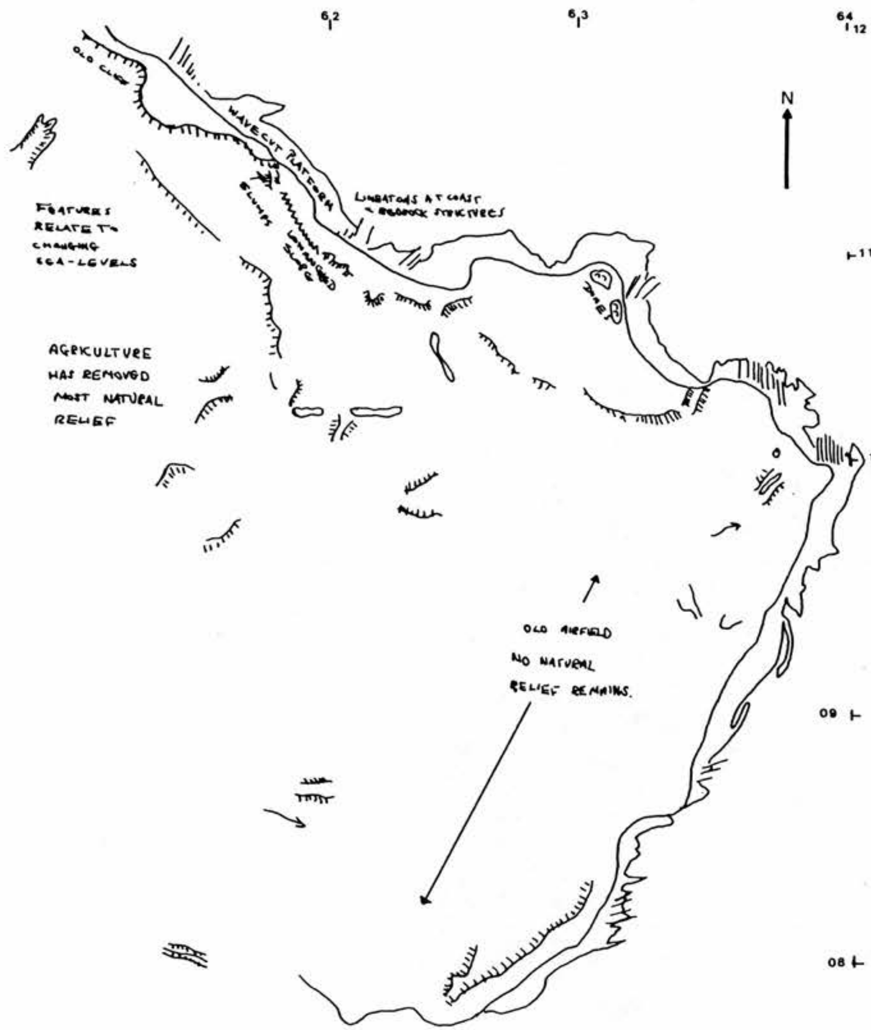
A3b.3 **Field geomorphological map of the landforms near Banff. Note the dominance of depositional glacial landforms, with the meltwater channel occupied by the River Deveron the only erosional feature of note.**



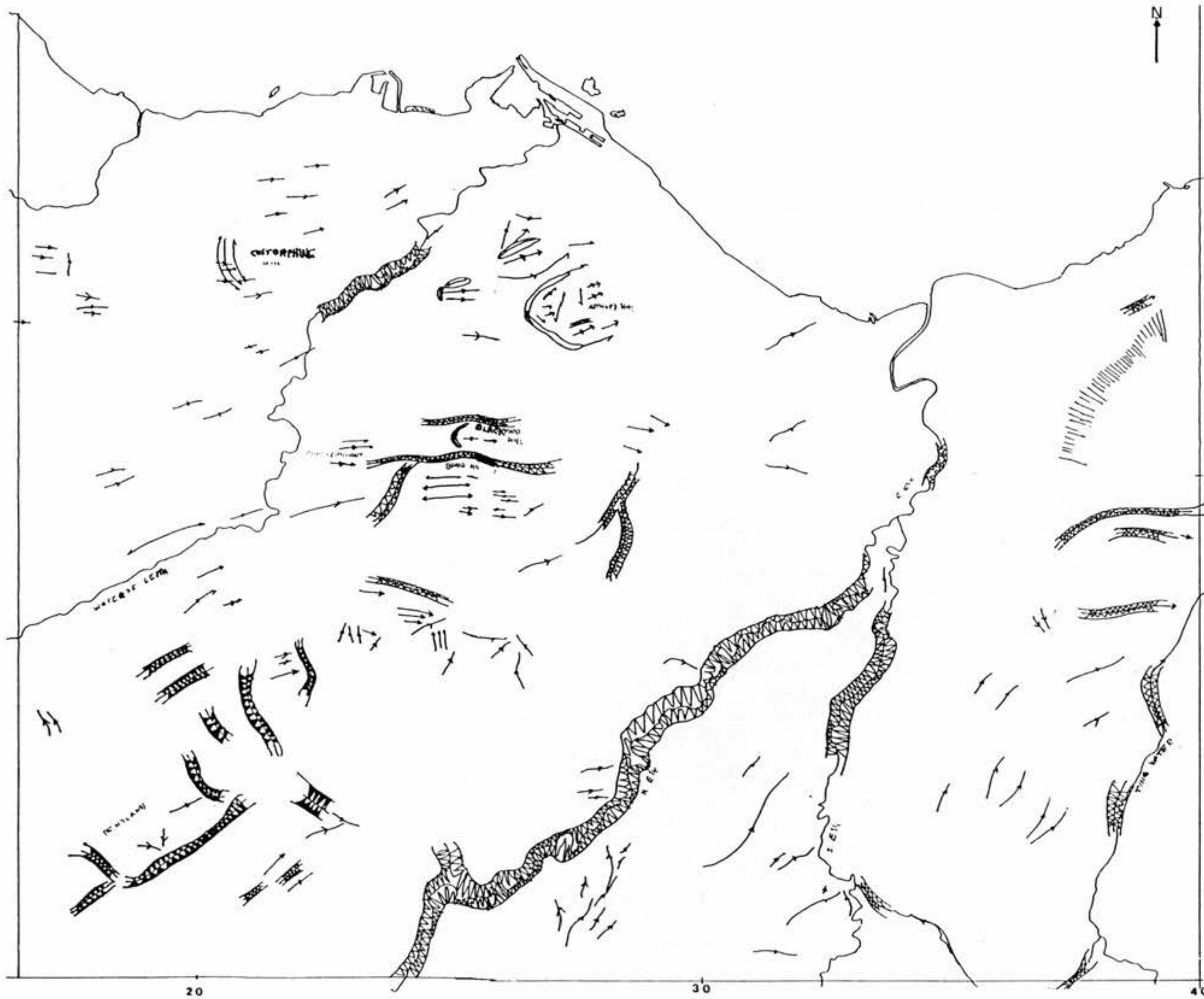
A3b.4 Field glacial geomorphology map of the area near Stonehaven. Note the complex pattern of depositional landforms.



A3b.5 Glacial geomorphology map of the area near Montrose, note the lack of erosional evidence, and the effects of anthropogenic alteration of the landscape.



A3b.6 Glacial geomorphological map of Fife Ness indicating the total lack of glacial erosion and the destruction of any depositional landforms. The only noteworthy feature is the raised beach.



A3b.7 Glacial geomorphological map of Edinburgh. Note the west to east trend in the landforms, and the complex subglacial network of meltwater channels.

A3b.8 Map of the site at Gifford, showing the dominance of small features related to local ice movement only.

APPENDIX 4

APPENDIX 4

Contents

An Evaluation of Seismic and Borehole Data available from Onshore and Offshore Site Investigations of Relict Glaciated Areas.

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ABSTRACT Using late Quaternary ice marginal sites from the North Sea and Iceland a comparison of the sedimentary information available from subaerial and submarine site investigations was made. This was with regard to palaeo-environmental reconstructions of ice marginal sedimentation processes. A detailed high resolution seismic survey in the North Sea was compared to a similar subaerial site in Iceland. Submarine cores were compared with logged sections available from cliffs. These comparisons highlighted the differences in resolution of the structural information available and also the problems of applying existing models of glacimarine sedimentation to offshore sites. This has raised questions concerning the accuracy of reconstructing palaeo-environments and processes in offshore sites presently under investigation. The implications of this for engineering projects in offshore areas requiring very precise site information about relict glaciated areas are significant.

INTRODUCTION

Offshore sediments are investigated by continuous seismic profiling and borehole studies. Both methods yield an oversimplified interpretation of the sediments involved due to the technical limitations of the systems. Current models of glacimarine environments cannot be applied to the collected data because the models require greater resolution and better quality of information than that presently available.

In order to evaluate the importance of this limited data recovery, comparisons between the information obtained from seismic and borehole investigations of offshore sediments are made with information obtained from conventional mapping of onshore analogues. The onshore data is from a site in the central North Sea basin, 40km E of Montrose. This includes late Weichselian ice marginal glacimarine sediments as deduced from a closely spaced (120m interval) Huntec Deep Tow Sparker seismic survey (DTS) (ANON 1984,Stewart 1988). The onshore analogues consist of a 5km long isostatically uplifted glacimarine and diamicton sequence and a similarly raised glacimarine fan deposit. These are located in the lower Borgarfjordur region of W Iceland, 15 and 5km from Borgarnes, respectively. The sediments are late Weichselian and have been deposited from a fluctuating ice margin which ended in a shallow body of water in the Borgarfjordur. The sequences have been described in detail using conventional mapping and sedimentary analyses techniques (Ingolfsson 1987). In addition a borehole from the UK NW Shelf is used to illustrate the losses associated with coring glacimarine sediment successions (Stoker 1988).

Seismic Evaluation

One of the main problems associated with interpreting seismic data is establishing the extent to which the seismic line is a realistic representation of the sediment body being examined. In order to demonstrate this an hypothetical seismic line of the section has been constructed (Fig. 1). This shows the predicted acoustic response of the section to a seismic survey across it using the DTS system. The model is compared with the information from conventional field mapping of the section. This provides a direct measure of the minimum information lost by the seismic interpreter and provides an indication of the likely loss which can be expected at similar sites. The line was synthesized using Ingolfssons' mapped section, sedimentary descriptions (including geotechnical data where available) and data collected in the field by the author. The latter relates especially to the nature of the unit boundaries; sharp or gradational, internal lithofacies variation; homogenous or heterogenous, the dimensions of the smaller diagnostic features for example dropstones, and the nature of the fault and thrust structures in the section; size and complexity. This information has been used to predict the acoustic response of the section to a sparker seismic survey. The descriptions of the sediments and the variability within the lithofacies have allowed the use of 'type' acoustic response for this system to be used, for example diamicton produces an acoustically chaotic response (Stoker & Bent 1985, Syvitski & Praeg, 1989). The presence or absence of reflectors has been determined on the basis of lithological and geotechnical changes at the boundaries of the units and within the areas of glacitectonic deformation. The size of dropstones has determined whether they will give a point source response (hyperbolae) or whether they will be below the resolution of the seismics, this also applies to other small and indistinct features. One of the main geotechnical properties which determines the acoustic response of the unit boundaries and hence the presence, or not, of reflectors, is the density of the adjacent sediments. This was obtained from the sediment descriptions and field examinations.

The hypothetical seismic line was compared with the field mapped section. The areas where the response recorded on the seismic section does not match that shown on the mapped section have been classed as areas of information loss. This has been quantified as a percentage loss of the total area of the section; the 'Areal Loss'. In addition the losses due to the affects of the vertical and horizontal (scale dependent) resolution of the DTS system (5m minimum), the 2D nature of the line and its intersection with the sediment body and the structures within it, must be recognized; hence the 'areal loss' is the minimum loss. Figure 1 illustrates the method for part of the line. The affect of the loss of the main reflector on the information and the interpretation for this section is substantial. This is due to a gradational boundary between the units which cannot produce an associated high amplitude acoustic signal. This and the poor resolution lead to the loss of the thrust structures.

Borehole Evaluation

The main problem of using borehole information from widely spaced cores is the extrapolation of the inferred depositional environments over large areas. To simulate the problems associated with this approach to environmental problems the ice proximal glacimarine fan complex (Ingolfsson 1987) was logged at 50m intervals along its 350m coastal exposure. This shows the lateral and vertical changes which are characteristic of ice proximal glacimarine deposits (Fig. 2a). An idealized section of borehole dimensions has also been logged from this section (Fig. 2b). This illustrates the detail of the sediments which are available in onshore sites, as well as the scale of some of the diagnostic indicators required for current models of glacimarine sedimentation (Powell 1981,1983, Orheim & Elverhoi 1981). It also illustrates a facies type commonly washed out of boreholes during coring and sediment extraction. Figure 2c shows a real example which illustrates how partial recovery can leave a very unrepresentative sample of the sediment with only diamicton recovered, and interpretation therefore severely restricted.

RESULTS

The results derived from the seismic and borehole studies indicate that the information losses associated with these techniques are significant. The calculated information loss for the whole of the constructed seismic line gives a minimum (areal) loss of 13.5%. Added to this are the variable losses associated with the problems of resolution, 2D interpretation of features, intersection between the line and the sediment, and the subsequent effects of the oversimplified interpretation. The borehole study shows a direct loss inversely proportional to percentage of the core recovered (in this case 70%). Added to this is loss of information associated with simplification of the interpretation of the sequence as a whole because of uncertainty as to the nature of the missing material. If the missing sediment has a structure as complex as that shown in Fig. 2b, then this is a much greater loss than if it were a massive sand unit which had been washed out. The logged sections in Fig. 2a illustrate the complexity and rapidity of change associated with the depositionary sequence in this environment over a very short distance (50m). They highlight the dangers of palaeo-environmental reconstructions between widely spaced borehole sites. The main sources of information have been isolated and are discussed below.

DISCUSSION

HUNTEC DTS VS. LOGGED SECTIONS

There are five major problems of extracting data from seismic sections as opposed to logged onshore sections. These are resolution, scale, acoustic response, distortion and dimensional.

1. Huntec DTS has a vertical resolution of 5m, below which it is impossible to discern detailed structural information within the sediments unless this results in point source responses, for example. Many diagnostic indicators of the glacimarine environments are much smaller than 5m.

2. Vertical and horizontal distances on seismic lines are measured by different methods at different scales, resulting in omissions, vertical exaggeration and distortion of structures in the sediment body. Again this makes detection and interpretation of key features difficult.

3. Different sediments transmit the energy of the sparker system at different velocities. This is the basis of the distinction between the different sediment units. However the relative transmission lag (or lead) which develops within the body of sediments becomes a factor of the way the energy is transmitted through the deeper sediments. This leads to distortion of subsequent acoustic responses e.g. laterally continuous planar reflectors can become uneven and discontinuous.

4. The acoustic response (or signature) of adjacent units may be insufficient to register as distinct signals on the seismic line, resulting in oversimplification as no differentiation between the units would be recorded.

5. There is a variable loss of information in the seismic line in two dimensions. When a three dimensional reconstruction is attempted the loss from using only two dimensional sources and interpolating between lines causes the net loss to increase. The loss is directly proportional to the line spacing, as is the ability to quantify the loss of information.

BOREHOLE VS.LOGGED SECTION

There are four major problem areas in dealing with boreholes as opposed to logged sections; point sampling and extrapolation, identification of reflectors, recovery problems and corelation between boreholes.

1. A borehole represents linear vertical sampling at a point on the seabed, of the sediment which can, theoretically, be tied into a seismic line to give lithological control over the sediments and acoustic responses at that point. However the horizontal resolution of the seismics limits the accuracy of correlation to >10m in this study. Examination of contemporary subaerial ice marginal environments show they are complex with major changes in process and composition within a 10m interval. The acoustic response associated with this rapid rate of change is a chaotic structureless signal. Is it therefore wise to assume that, although the sediment type is similar (glacial diamict) the structures and processes found in the chaotic area are uniform ?

Obviously this assumption can apply to the whole range of sedimentary environments offshore. This can be alleviated with logs of the natural gamma emissions of the sediments down the borehole as different sediments emit gamma radiation at different rates, indicating the lithological changes through the borehole. This is especially important where the sediment type is difficult to recover.

2. When the core is recovered from the borehole it is subject to mechanical disturbance and deformation. Evidence of boundaries and breaks in sedimentation is destroyed and the correlation with the implied acoustic response is impossible. Removal of confining stress can create unloading structures, and distort bedding structures. The coring process also creates pseudo-bedding and smear surfaces.

3. 100% recovery is rare in boreholes; accurate interpretation of a sequence is marred by gaps in the sequence, uncertainty as to the exact location of the material in the sediment sequence and also uncertainty about the missing material, as illustrated in Figs 2b and 2c. This makes environmental reconstructions from boreholes alone very difficult.

4. Correlations can only be made between boreholes in close proximity which contain some obvious stratigraphic marker. Obviously correlation over large areas, using results for anything more than a simplified regional overview, is hazardous!

CONCLUSION

The results show that information collected using seismic and borehole techniques offshore for the analysis of ice marginal sediments is limited in quantity and quality when compared to conventional mapping of similar sites onshore. When applied to offshore surveys of the sediments in the Central North Sea basin, both at a regional scale and a detailed local scale, they show that unless there is a detailed site investigation involving blanket seismic coverage and a dense array of boreholes, it is difficult to establish the three dimensional picture of the palaeo-environment given the degree of variabilty within this type of site. However there can be advantages if there is a closely spaced net of seismic lines in an area, as this can provide more information than is often available for an onshore site with a restricted number of unrelated sections. However even given ideal circumstances it is doubtful whether current information retrieval systems can return the quality of data required to test models of glacimarine environments which place considerable emphasis on some of the smaller features e.g. dropstones and rhythmites (Powell 1981,1983, Orheim & Elverhoi 1981). There are implications for industrial and research applications involving offshore sites of this kind. The information obtained from a site may be unrepresentative, thus requiring large financial inputs to constrain data already collected and to avoid hazards which were not recorded initially. However, if the problems can be recognised and quantified for the different environments the potential of current systems for collecting data from other inaccessible sites is enormous. Data collected by bodies such as The British Geological Survey using these techniques has enabled maps of the offshore areas to be made which demonstrates the usefulness of this approach to exploring the offshore environment. The author considers that the findings for this sedimentary environment are likely to be applicable to other offshore deposits resulting from other sedimentary regimes.

ACKNOWLEDGEMENTS. I wish to thank O. Ingolfsson for the use of his mapped section and also BP and GEOTEAM, and the British Geological Survey for access to data from the North Sea. I acknowledge and thank NERC for funding the fieldwork in Iceland as part of my studies. This paper is published with the permission of the Director, British Geological Survey (NERC).

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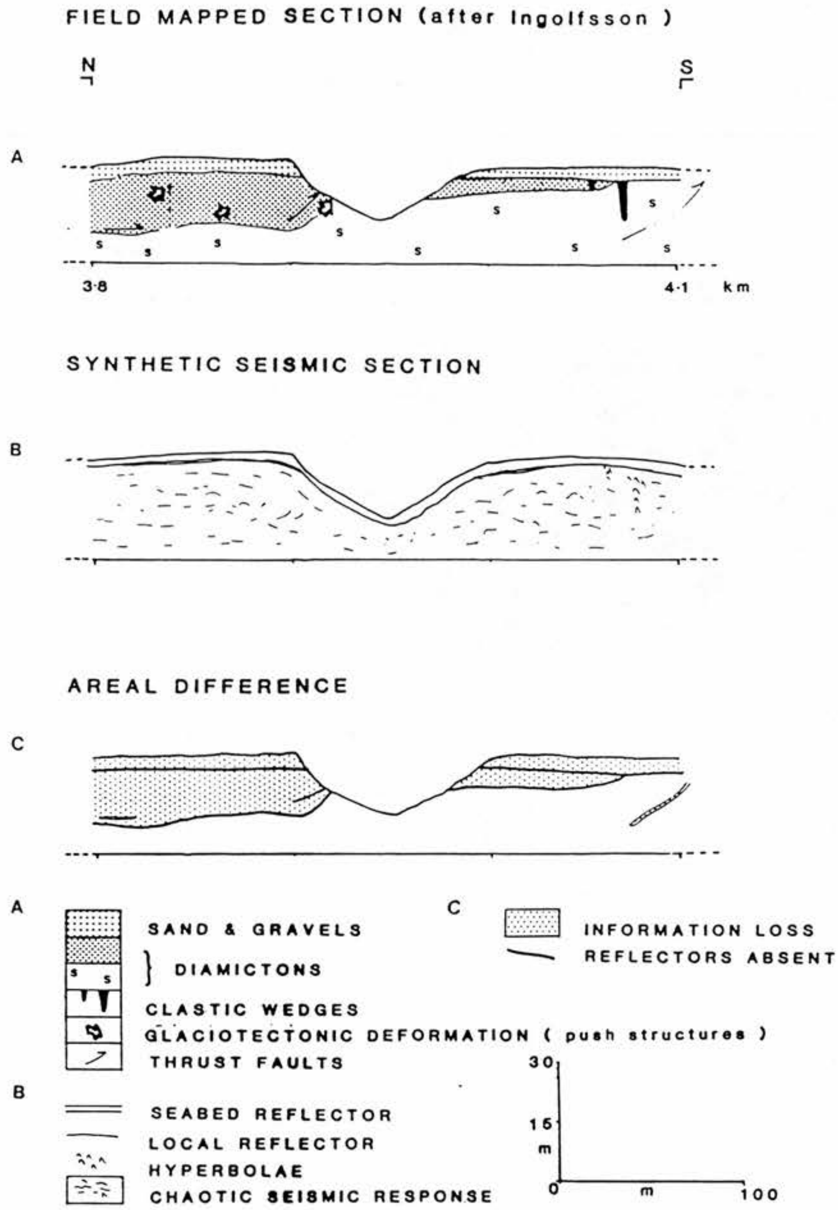

Fig. 1. Extracts from the raised glacimarine section, W Iceland, showing the field mapped section, the hypothetical synthetic seismic line and the section showing the resultant loss of information for this extract.

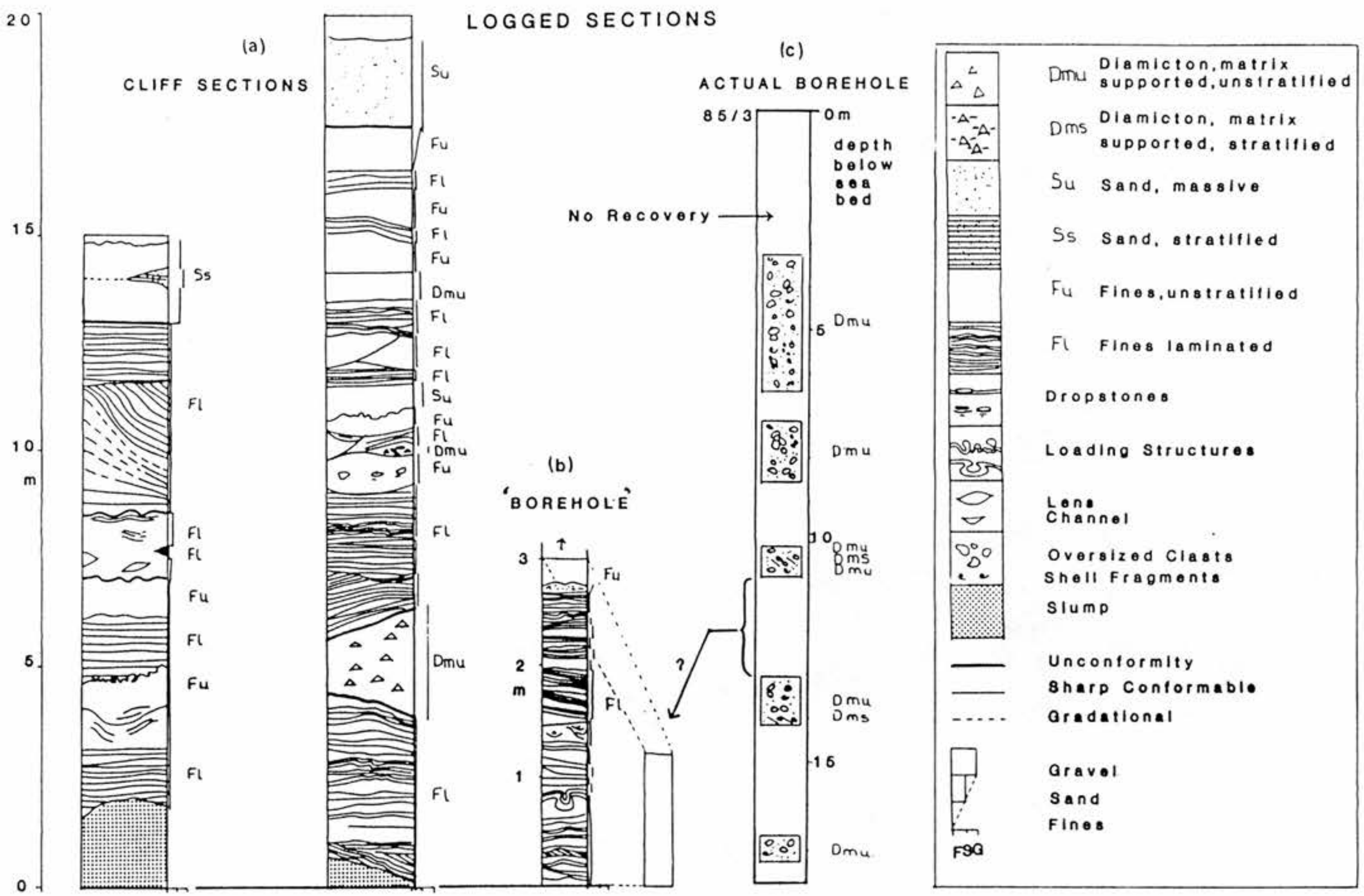

Fig. 2. Examples of some of the logged fan deposit including the 'imaginary' borehole section from the fan and the real borehole. (a) shows the detail and variability within 50m of the cliff section, (b) indicates the fine detail available with 100% recovery of fines, which are often lost in the extraction process and are missing from actual boreholes as shown in (c). The loss of this material is crucial in reconstructing palaeo-environments.

Geo-Marine Letters (1990) 10:151–156

Geo-Marine Letters

Problems Associated with Seismic Facies Analysis of Diamicton-Dominated, Shelf Glacigenic Sequences

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Abstract

Diamicton-dominated shelf glacigenic sequences are characterized on high-resolution seismic records by a structureless to chaotic acoustic texture, often with abundant hyperbolic (point-source) reflections. Existing depositional models, based primarily on seismic data, have been constructed on the basis that this acoustic signature is indicative of subglacial till. However, borehole data from the UK continental shelf indicate that glaciomarine facies are also present. Thus, while this acoustic character may be indicative of diamicton lithofacies, it should not be taken as a predictive genetic indicator of a specific depositional process.

Introduction

High-resolution seismic profiles (sparker, boomer) have shown that glacially-modified continental shelves are generally characterized by regionally extensive, subhorizontal, sheet-like depositional sequences (King and Fader 1986, Praeg and others 1986, King and others 1987, Stoker 1988, in press a, Josenhans and Fader 1989, Vorren and others 1989). These form stratigraphic units composed of genetically related strata bounded at their top and base by unconformities or their correlative conformities (Mitchum and others 1977). Diamicton-dominated sequences are defined as stratigraphic units composed of beds comprising a poorly sorted and unlithified admixture of clasts and matrix regardless of depositional environment (Frakes 1978, Eyles and others 1983). Such sequences may range in thickness from several meters to several tens of meters.

While the geometry of diamicton-dominated sequences can be established from seismic profiles, the environmental setting and lithofacies of these sequences are not easily inferred from seismic reflection records due to their predominantly homogeneous acoustic texture. Existing sedimentary models have been constructed, based primarily on seismic facies analysis, proposing monospecific depositional processes for their formation e.g., subglacial deposition (King and Fader 1986, King and others 1987).

In this paper, we present a summary of the seismic characteristics of diamicton-dominated sequences, using examples from the northern United Kingdom (UK) continental shelf (Fig. 1). These are taken from 1Kilojoule sparker and Huntec deep-tow boomer profiles. In addition, we summarize lithological data derived from numerous boreholes which have penetrated these sequences. In depositional models developed to date, lithological information has mostly come from short piston cores and grab samples (King and Fader 1986, Praeg and others 1986, King and others 1987) which only sample the top few meters of these sequences. Our data indicate that, despite the overall acoustic homogeneity of these sequences, a variety of sedimentary processes may contribute to their formation.

Characteristics of Diamicton-Dominated Glacigenic Sequences: Examples from the UK Continental Shelf

The diamicton-dominated sequences are described in terms of their seismic and lithological characteristics. The descriptions are based on information obtained during the regional mapping program of the northern UK continental shelf by the British Geo-

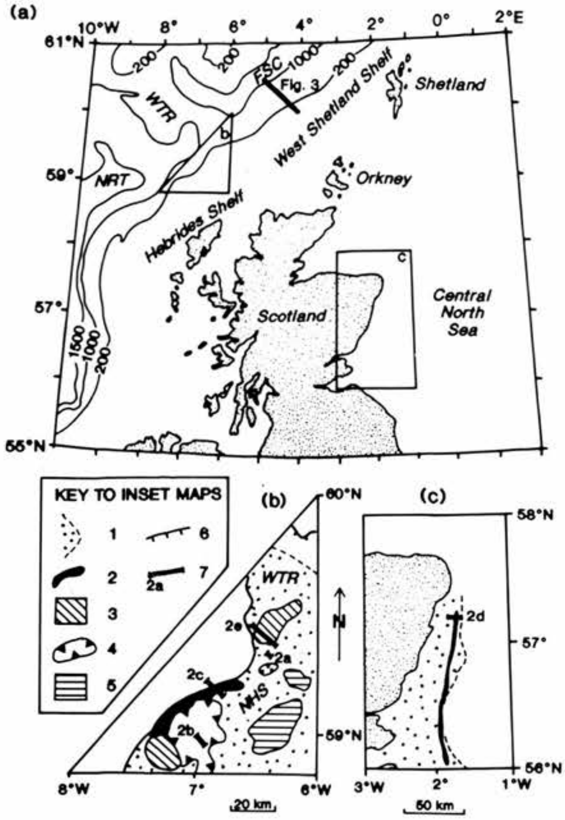


Figure 1. Map 1 northern United Kingdom continental shelf showing: a) location of study areas; b) enlargement of northern Hebrides Shelf; c) enlargement of central North Sea. Abbreviations: WTR, Wyville-Thomson Ridge; NHS, northern Hebrides Shelf; NRT, northern Rockall Trough; FSC, Faeroe-Shetland Channel. Key to inset maps: 1. Extent of diamicton-dominated sequence; 2. Major depositional ridges; 3. Wedge-shaped deposits; 4. Overdeepened basins; 5. Rock outcrop; 6. Shelfbreak; 7. Location of seismic profiles in Fig. 2. Bathymetric contours in meters. Geoseismic profile illustrated in Fig. 3 is located in Fig. 1a.

logical Survey (BGS), with examples from the central North Sea and the northern part of the Hebrides Shelf (Fig. 1). The sequence in the central North Sea is late Weichselian in age (Holmes 1977, Thomson and Eden 1977, Stoker and others 1985); the age of the northern Hebrides Shelf sequence is uncertain, although regional seismostratigraphic relations suggest that it predates the late Weichselian (Stoker 1988).

Seismic Characteristics

The glacigenic sequences form extensive sheet-like units (Figs. 1b, 1c, 2a) which range regionally from <5 m to locally in excess of 30 m thick. The top of the sequences occurs mainly at or near the sea bed, although where discrete areas of the shelf have bee glacially overdeepened (Fig. 1b) the sequence gen erally drapes the irregular basin floor, and is burie beneath basin-fill deposits (Fig. 2b). Their upper sur face is generally smooth although locally irregula microrelief may be due to iceberg scouring. The bas of the sequences is planar to irregular, and uncon formably overlies predominantly non-glacigeni Pleistocene and older strata.

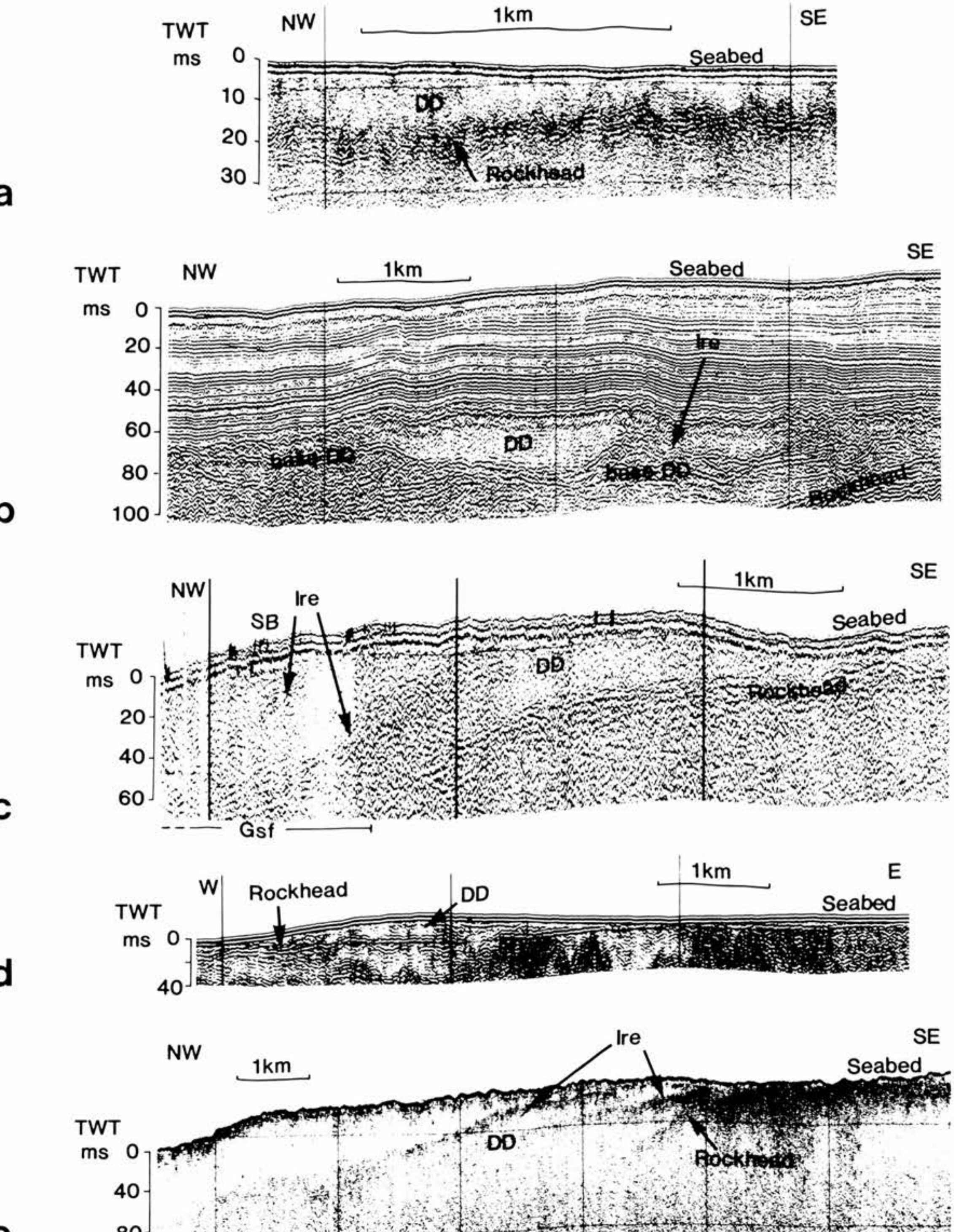
The sheet-like form of the sequences may be lo cally modified and thickened by distinct mounde accumulations, which often form prominent ridge on the sea bed. On the northern Hebrides Shelf, distinct ridge, 20–30 m high, up to 4.5 km wide an laterally traceable for 70 km, occurs at the shelf-edg (Fig. 1b, 2c). On the northwest margin of the ridge discrete slopeward-dipping reflectors, which form pa of a prograding, glacigenic slope-front sequenc (Stoker in press a), appear to 'root' into the ridg (Fig. 2c). This relationship has been interpreted a an interdigitating contact between the shelf and slope front glacigenic sequences (Stoker in press a).

In the central North Sea, an equally distinctiv ridge, 15–20 m high and up to 4 km wide, has bee traced for 130 km at the seaward edge of the glac genic sequence (Figs. 1c, 2d).

In both of these areas, the major ridge feature ha been interpreted as a submarine end-moraine (Holme 1977, Thomson and Eden 1977, Stoker and othe 1985, Stoker 1988), although the possibility of drowned, terrestrial end-moraine cannot be di counted. Smaller isolated ridges up to 20 m high, km wide and 10 km in length occur sporadically o the landward side of the end-moraine in both area documenting the retreat of the respective ice ma gins.

At the junction of the Hebrides Shelf and Wyville Thompson Ridge (Fig. 1b), the sheet-like depos passes laterally into a discrete wedge-shaped deposi up to 100 m thick, 10 km wide and at least 25 k long (Fig. 2e). Morphologically this deposit is simil to an ice-contact fan (Syvitski and Praeg 1989).

On sparker and boomer profiles, the diamicto dominated sequence is generally acoustically stru tureless to chaotic with occasional point-sourc hyperbolic reflections (Fig. 2). Sporadic mediu amplitude, discontinuous, undulatory reflectors a imaged in the basin floor deposit (Fig. 2b), whi internal, inclined low to medium amplitude reflecto that suggest both an aggradational and progrado tional development are associated with the shelf-edg ridge and wedge-shaped deposit (Figs. 2c, 2e). Thes latter two deposits offer little penetration to boome sources.



igure 2. Seismic characteristics of diamicton-dominated se-uences: a) sheet-like deposit (boomer) overlying rockhead (top f bedrock); b) basin-floor deposit (sparker) overlain by acous-cally well-layered basin-fill sediments; c) shelf-edge ridge (spar-er) with discrete internal reflectors associated with slope-front equence appearing to 'root' into the ridge; d) ridges (sparker) verlying rockhead; e) wedge-shaped deposit with prograding in-ernal reflectors (sparker). Abbreviations: DD, diamicton-dominated unit; base DD, base of diamicton sequence where above rockhead; Ire, discrete reflectors within and/or interdigitating with diamicton sequence; TWT ms, two-way time in milliseconds; SB, shelfbreak; Gsf, part of prograding, glacigenic slope-front sequence. Profiles (a–c) and (e) from northern Hebrides Shelf, profile (d) from central North Sea. Rockhead in all profiles, and base of diamicton in 2b, have been established from boreholes and shallow cores. Profiles are located in Fig. 1b and 1c.

Lithological Characteristics

A total of 38 boreholes have been drilled into the glacigenic sequences in the central North Sea and on the northern Hebrides Shelf. Twenty-eight of these boreholes have totally penetrated the sequences, with continuously cored intervals ranging from <5 to 35 m thick, although core recovery is variable, ranging from 10–40%. The recovered sediments mainly consist of a range of diamicton lithofacies.

In the central North Sea, the bulk of the sequence, including the submarine end-moraine (Fig. 2d), consists of stiff, massive, dominantly matrix-supported diamicton with sporadic thin interbedded sand, pebbly sand and silty clay (Stoker and others 1985). The sequence contains no significant indigenous fauna or flora, and has been interpreted as predominantly subglacial in origin (Thomson and Eden 1977, Stoker and others 1985). However, an influx of microfauna towards the top of the sequence may be indicative of a late-stage glaciomarine component (Stoker and others 1985).

On the northern Hebrides Shelf, the diamicton fossil assemblage is composed of microfauna and flora indicative of a glaciomarine depositional environment (Stoker 1988, 1989). Massive to stratified, firm to stiff, matrix- to clast-supported ice-proximal glaciomarine sediments, deposited from subaqueous debris flows have been recovered from the sheet-like deposits (Figs. 2a, 2b) (Stoker 1989), as well as the wedge-shaped, ice-contact fan (Fig. 2e) (Stoker 1988). Massive, poorly sorted, mass-flow sands, up to several meters thick, are occasionally interbedded with the debris flows. Massive, matrix-supported dropstone diamictons, which are a mix of suspension and ice-rafted sediment (Powell 1984), are increasingly abundant in the upper part of the sequence, particularly the shelf-edge submarine end-moraine (Fig. 2c) and the ice-contact fan (Fig. 2e) (Stoker 1988, 1989). Unfortunately, the lower part of the end-moraine has not been cored and a subglacial component cannot be discounted.

Discussion

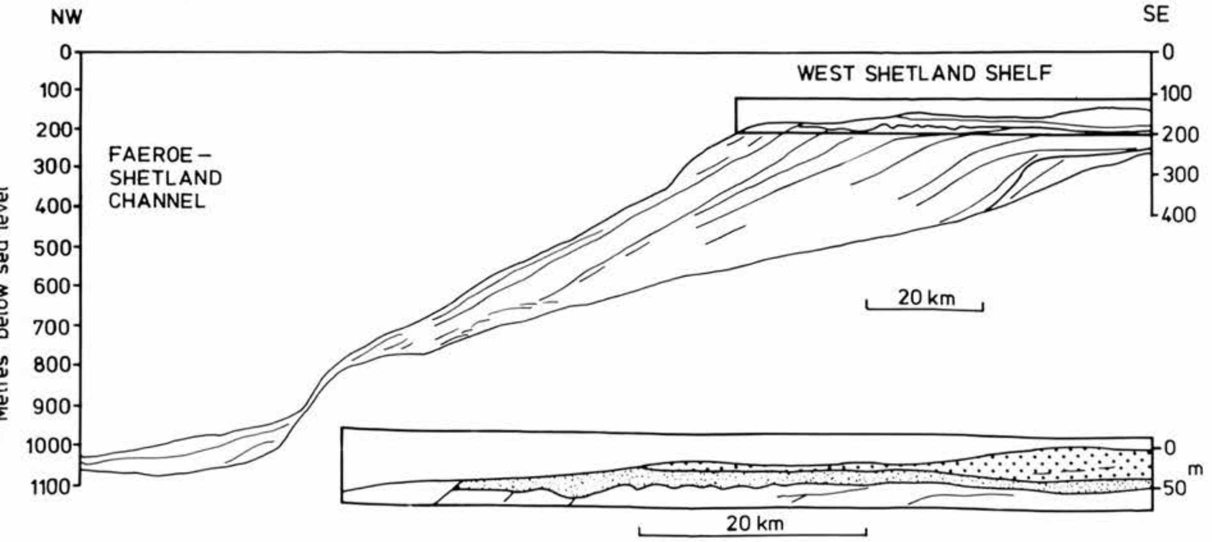
The complexity of the glacial system, in general, is such that the coarse resolving power of the seismic method may lead to oversimplistic interpretation of glaciated shelves. For example, in studies on the Scotian, Baffin and mid-Norwegian shelves seismic sequences characterized by a "uniform dense pattern of incoherent reflections"—essentially chaotic—have been interpreted as being diagnostic of glacial till with the implicit assumption of subglacial deposition (King and Fader 1986, King and others 1987, Josen hans and Fader 1989).

However, diamictons, regardless of origin, contai many point sources, such as are obtained from boul ders, which reflect the acoustic energy of the sparke or boomer in a disorganized manner. This woul produce a sequence with high internal backscatter thus creating a uniformally chaotic seismic texture Moreover, the penetration of sound through the se quence would be limited. The higher the clast con tent, the greater the effect.

In order for seismic reflection systems to imag any intra-sequence boundaries there must be a acoustic impedance across the boundary great enoug to produce a reflection. In shelf sequences charac terized by an overall lithological similarity, individua beds are unlikely to be imaged (Stewart 1989). Whil lithological uniformity is applicable to till or multipl till sequences, it should not be regarded as exclusiv to such sequences. Ice-keel turbate (sediment re worked by icebergs) is acousticaly and composition ally indistinguishable from a glacial till (Vorren an others 1983). Moreover, in proximal glaciomarin settings, diamictons often occur in stacked associa tions with only thin sandy or silty interbeds (Ingolfs son 1987, Stoker 1988) which are often of insufficien thickness (<0.5 m) and lateral continuity to produc coherent reflections on sparker or boomer profiles If bed thickness increases, however, reflections ma be generated; the discontinuous, irregular reflection towards the base of the basin floor deposit (Fig. 2b correlate with mass-flow sands several meters thic (Stoker 1989).

Where internal reflections are present they ma give some idea of facies. A series of inclined reflec tors may represent outwash sands and gravels (Old ale 1985). Alternatively, such a pattern may also rep resent glaciotectonic faults or slip planes. Possibl ice-pushed sediments described from the souther North Sea and the Gulf of Maine, contain steepl dipping to contorted internal reflection patterns (La ban and others 1984, Oldale 1985). For the souther North Sea, an onshore analogue may be the glaci otectonized deposits at Cromer, East Anglia (UK) where large chalk rafts, 10 m thick and many ten of meters in length, have been incorporated into th glacial sequence over a distance of several hundre meters (Eyles and others 1989). Such bedrock inclu sions may provide adequate impedance contrasts t be recorded on seismic profiles, although even o this scale they may only appear as short discontin uous reflectors on a seismic profile with a horizonta scale of 1:100,000.

Obviously, the external geometry of the sequenc is an important aid to seismic facies analysis, e.g.



'igure 3. Geoseismic profile of Plio-Pleistocene succession on the West Shetland Shelf, showing the development of a multiple stratiform liamicton succession on a passive subsiding margin. Inset shows detail of stratiform succession: buried unit (light stipple) with no liagnostic surface morphology, overlain by moulded seabed unit (heavy stipple). Profile is located in Fig. 1a.

he ridge and wedge-shaped deposits of this study. However, in multiple stratiform diamicton seıuences, which characterize subsiding, passive coninental margins (Vorren and others 1989, Stoker in press b), any diagnostic surface morphology, origiıally associated with a presently buried sequence, nay have been eroded away by the overlying unit eaving a uniform, sheet-like deposit (Fig. 3). In this etting, seismic facies analysis, alone, is unlikely to esolve the problems of environmental interpretation ınd lithofacies of the buried sequences.

In addition to the problems inherent in seismic nterpretation, the analysis of borehole data may also e subjective. The poor recovery encountered in the lrilling of diamicton sequences precludes detailed ɔaleo-environmental interpretation, as diagnostic riteria such as bed contacts and fine scale sedimenary structures are rarely preserved (Stewart 1989). Moreover, borehole data or any other kind of core lata, only provide point-source information. In a lacial sequence characterized by rapid lateral facies hanges such information remains site specific, and s not necessarily regionally applicable. In a modern helf setting, the spatial separation between boreoles generally precludes reliable correlation within diamicton succession.

Conclusions

On high-resolution seismic records, diamicton-domıated shelf glacigenic sequences are characterized y a structureless to chaotic acoustic texture often with abundant hyperbolic reflections. Borehole data indicate that while this seismic pattern may be diagnostic of diamicton facies, it does not necessarily imply a subglacial origin. Diamicton occurring in a glacial environment can be derived from a variety of processes active throughout this environment. Thus, in conclusion, our data suggest that extreme caution be exercised in the seismic interpretation of shelf glacigenic sequences.

Acknowledgments

Prof. D. Sugden, Drs. D. Evans and C. D. R. Evans and Mr. D. Long critically read an early draft of the manuscript. One of us (FSS) acknowledges the receipt of a NERC Case studentship (Ref. no. GT4/87/GS/128). This paper is published with the permission of the Director, British Geological Survey (NERC).

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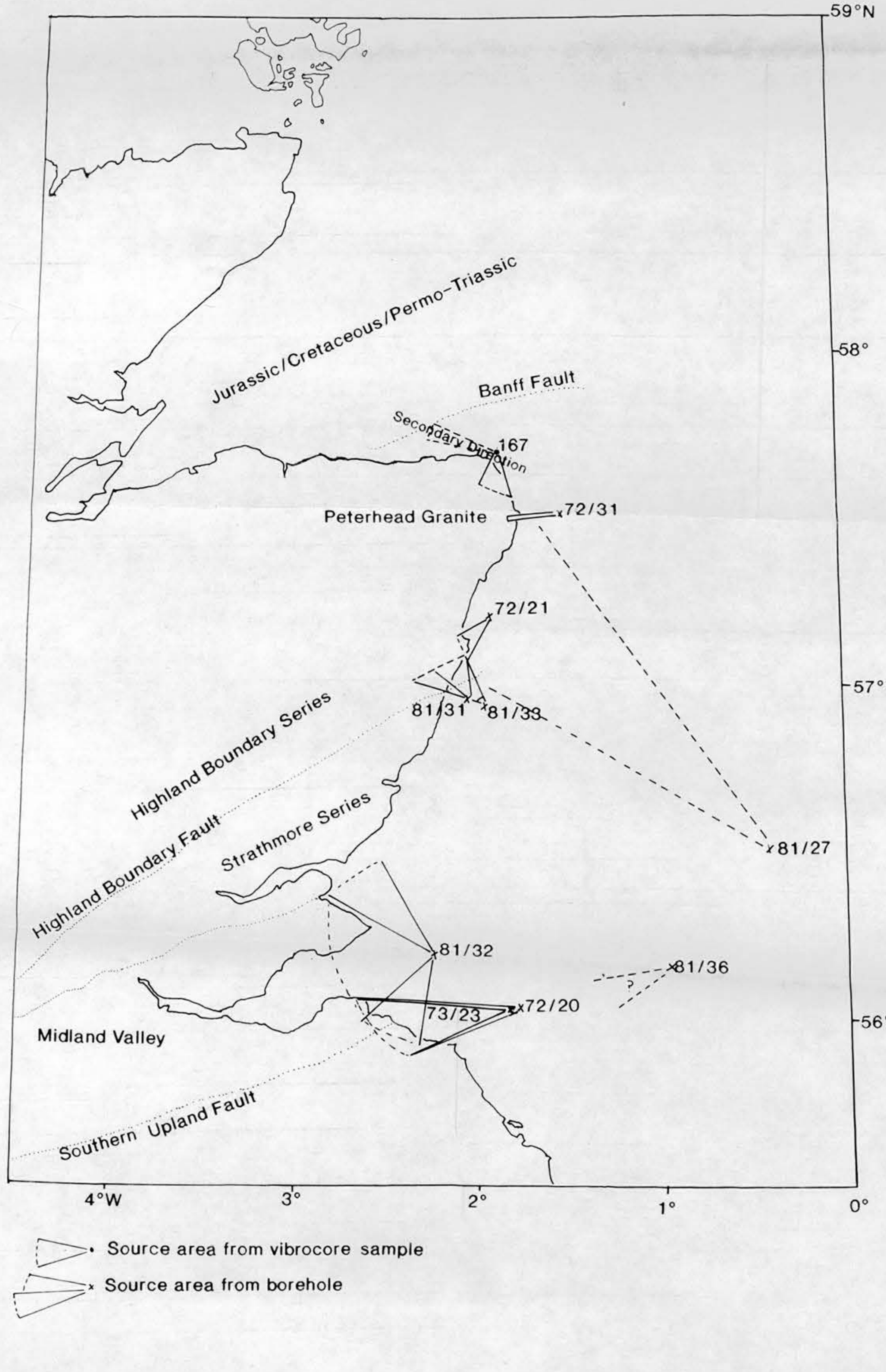
Manuscript received 10 October 1989; revision received 17 April 1990.

FIGURE 3.8a Provenance map for the >10mm clasts



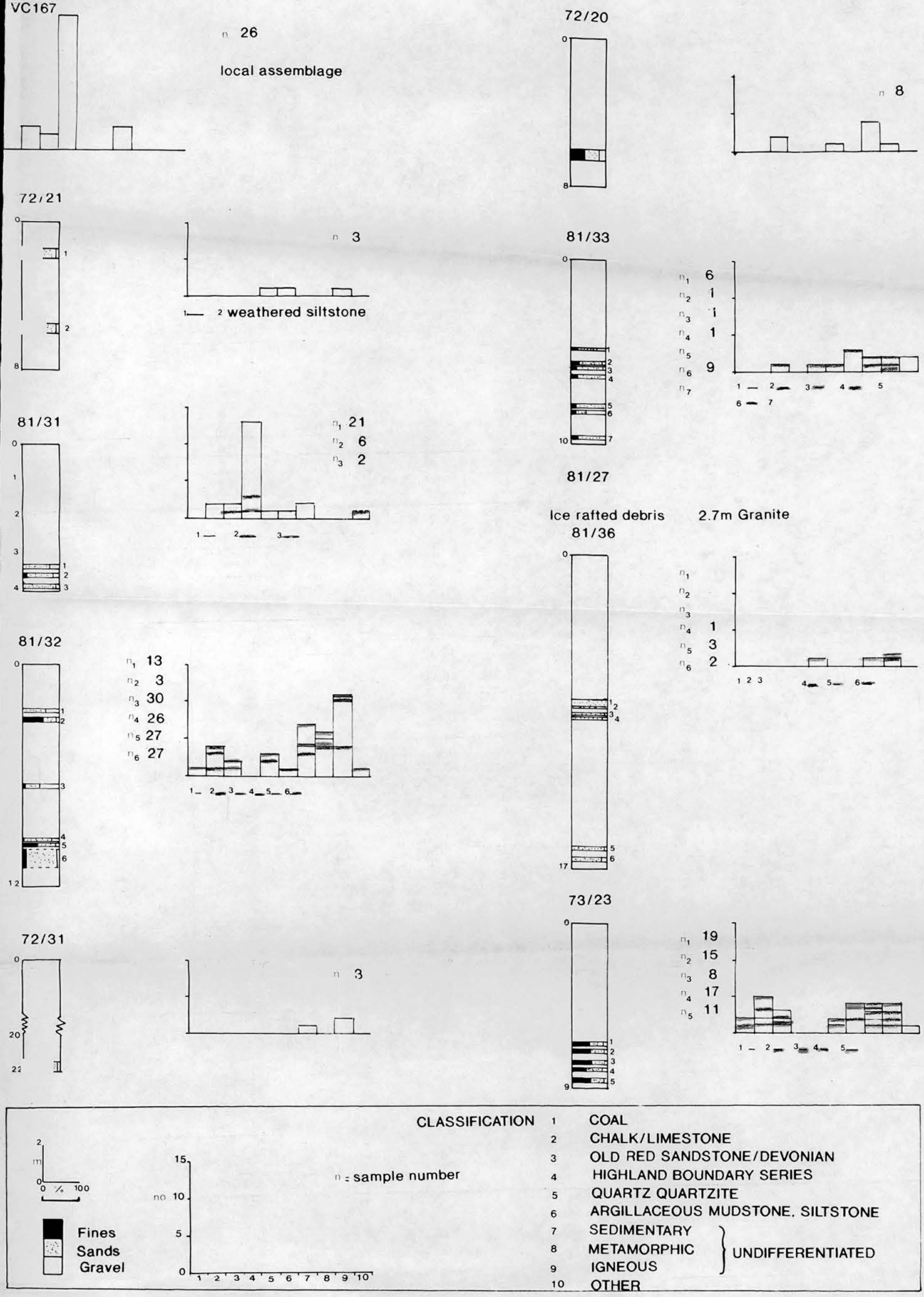
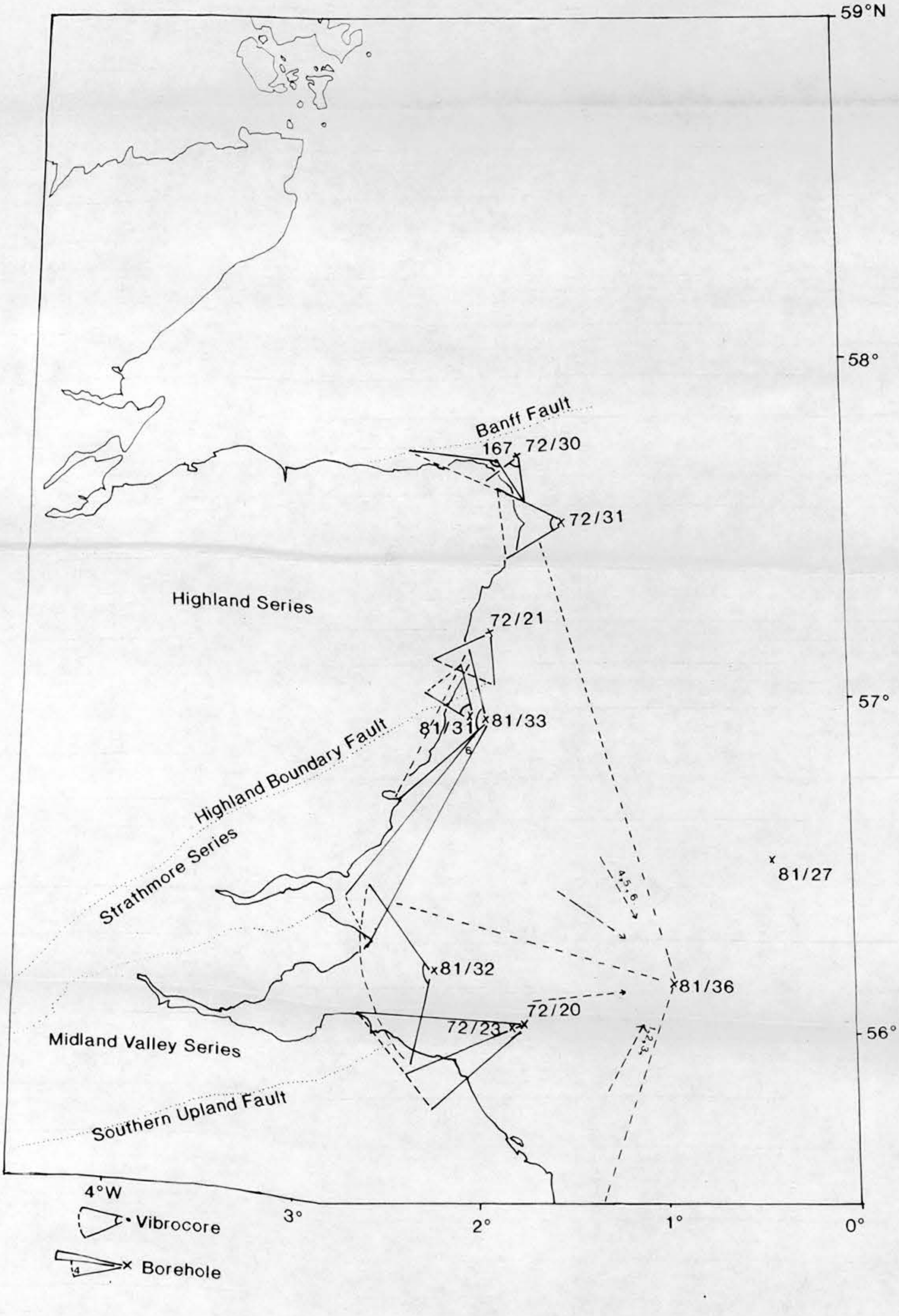

VC167
n 26
local assemblage
72/20
n 8
72/21
n 3
1— 2 weathered siltstone
81/33
n_1 6
n_2 1
n_3 1
n_4 1
n_5
n_6 9
n_7
81/31
n_1 21
n_2 6
n_3 2
81/27
Ice rafted debris 2.7m Granite
81/36
n_1
n_2
n_3
n_4 1
n_5 3
n_6 2
81/32
n_1 13
n_2 3
n_3 30
n_4 26
n_5 27
n_6 27
73/23
n_1 19
n_2 15
n_3 8
n_4 17
n_5 11
72/31
n 3
m
%
Fines
Sands
Gravel
no
n = sample number
CLASSIFICATION
1 COAL
2 CHALK/LIMESTONE
3 OLD RED SANDSTONE/DEVONIAN
4 HIGHLAND BOUNDARY SERIES
5 QUARTZ QUARTZITE
6 ARGILLACEOUS MUDSTONE, SILTSTONE
7 SEDIMENTARY
8 METAMORPHIC
9 IGNEOUS
UNDIFFERENTIATED
10 OTHER

FIGURE 3.8b Provenance map for the 3-5mm clasts (Ehlers 1978)



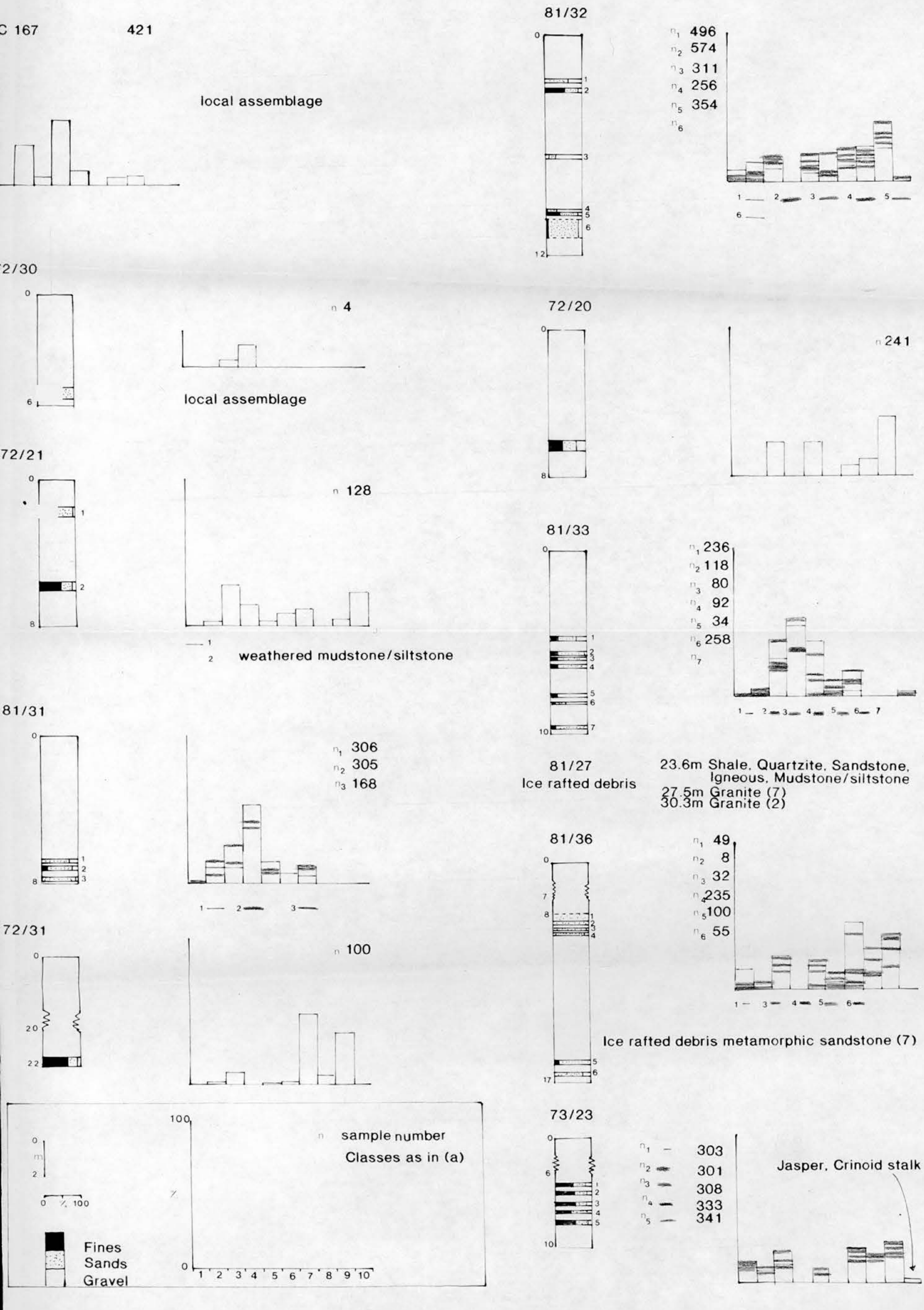
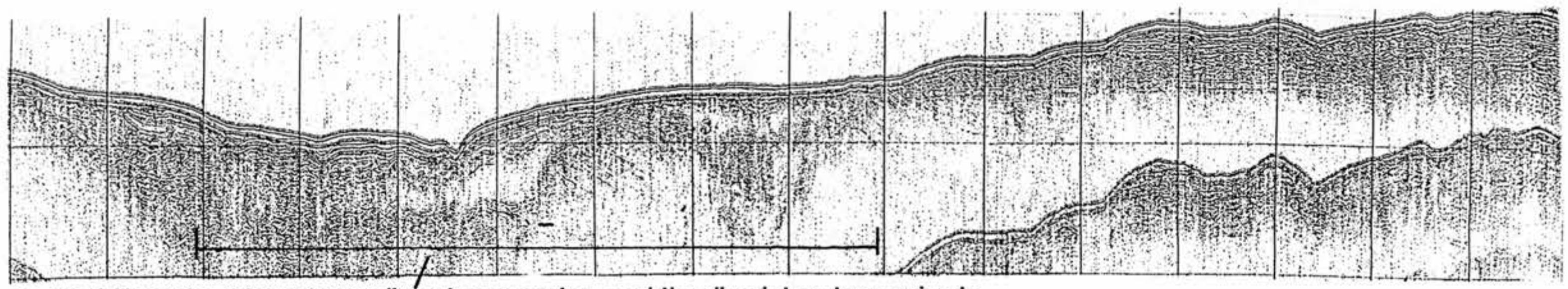
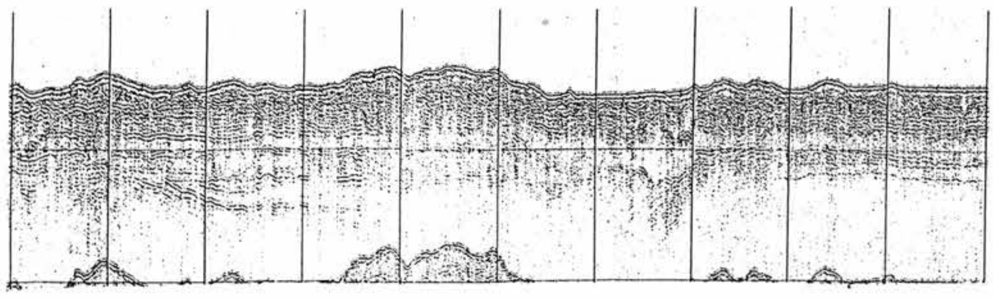

C 167
421
local assemblage
81/32
n1 496
n2 574
n3 311
n4 256
n5 354
n6
72/30
n 4
local assemblage
72/20
n 241
72/21
n 128
weathered mudstone/siltstone
81/33
n1 236
n2 118
n3 80
n4 92
n5 34
n6 258
n7
81/31
n1 306
n2 305
n3 168
81/27
Ice rafted debris
23.6m Shale, Quartzite, Sandstone, Igneous, Mudstone/siltstone
27.5m Granite (7)
30.3m Granite (2)
81/36
n1 49
n2 8
n3 32
n4 235
n5 100
n6 55
72/31
n 100
Ice rafted debris metamorphic sandstone (7)
n sample number
Classes as in (a)
m
%
Fines
Sands
Gravel
73/23
n1 303
n2 301
n3 308
n4 333
n5 341
Jasper, Crinoid stalk

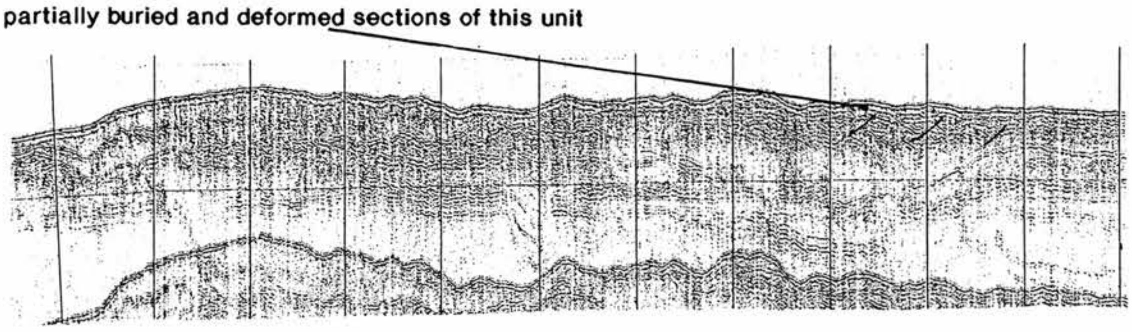
FIGURE 3.30* North to south and east to west trending seismic profiles from the Bosies' Bank moraine showing the morphology and seismic facies units present (compiled from Bent 1986).



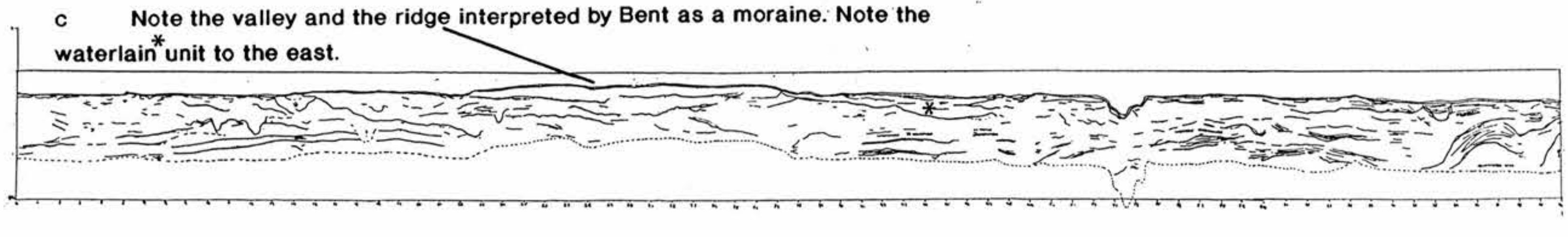
a Line 1 Note the thickening sediment succession and the diamicton-type seismic facies response within the infilled basin. Note the 'hummocky' surfaced unit occuring above the uneven rockhead with typical diamicton response



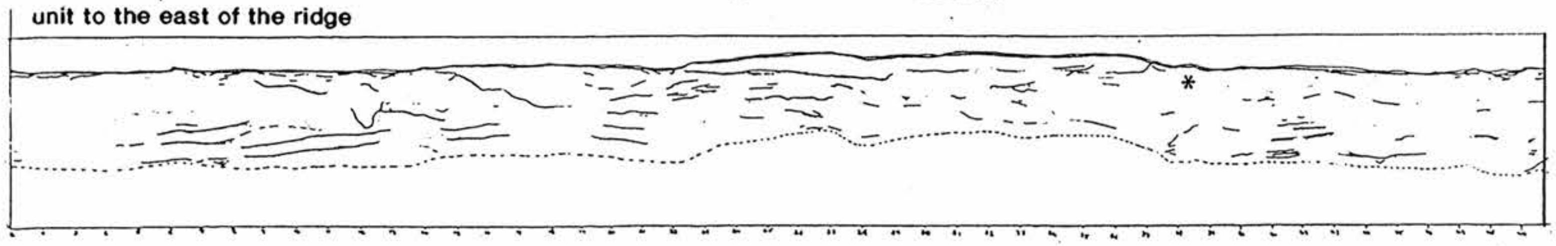
b Line 2 Note the more hummocky seabed surface than exhibited in line 1, and the partially buried and deformed sections of this unit



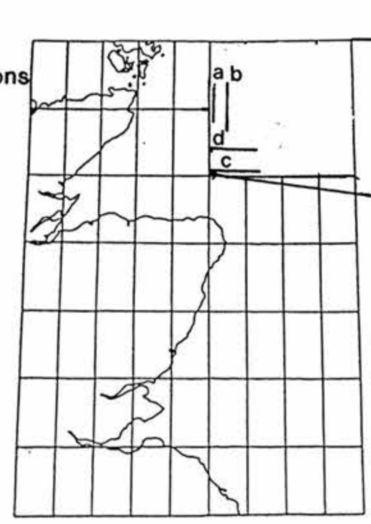
c Note the valley and the ridge interpreted by Bent as a moraine. Note the waterlain* unit to the east.

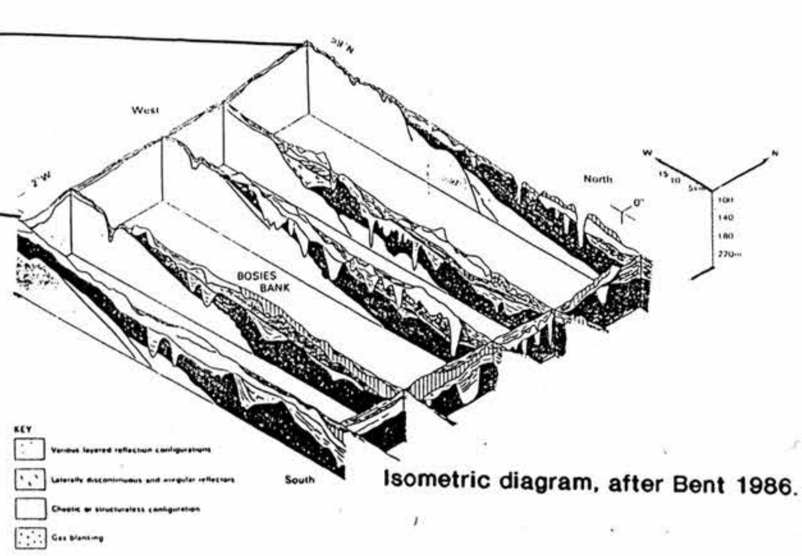


d Line 8 This line differs from line 6 in that there does not appear to be a waterlain* unit to the east of the ridge



Line locations





Isometric diagram, after Bent 1986.

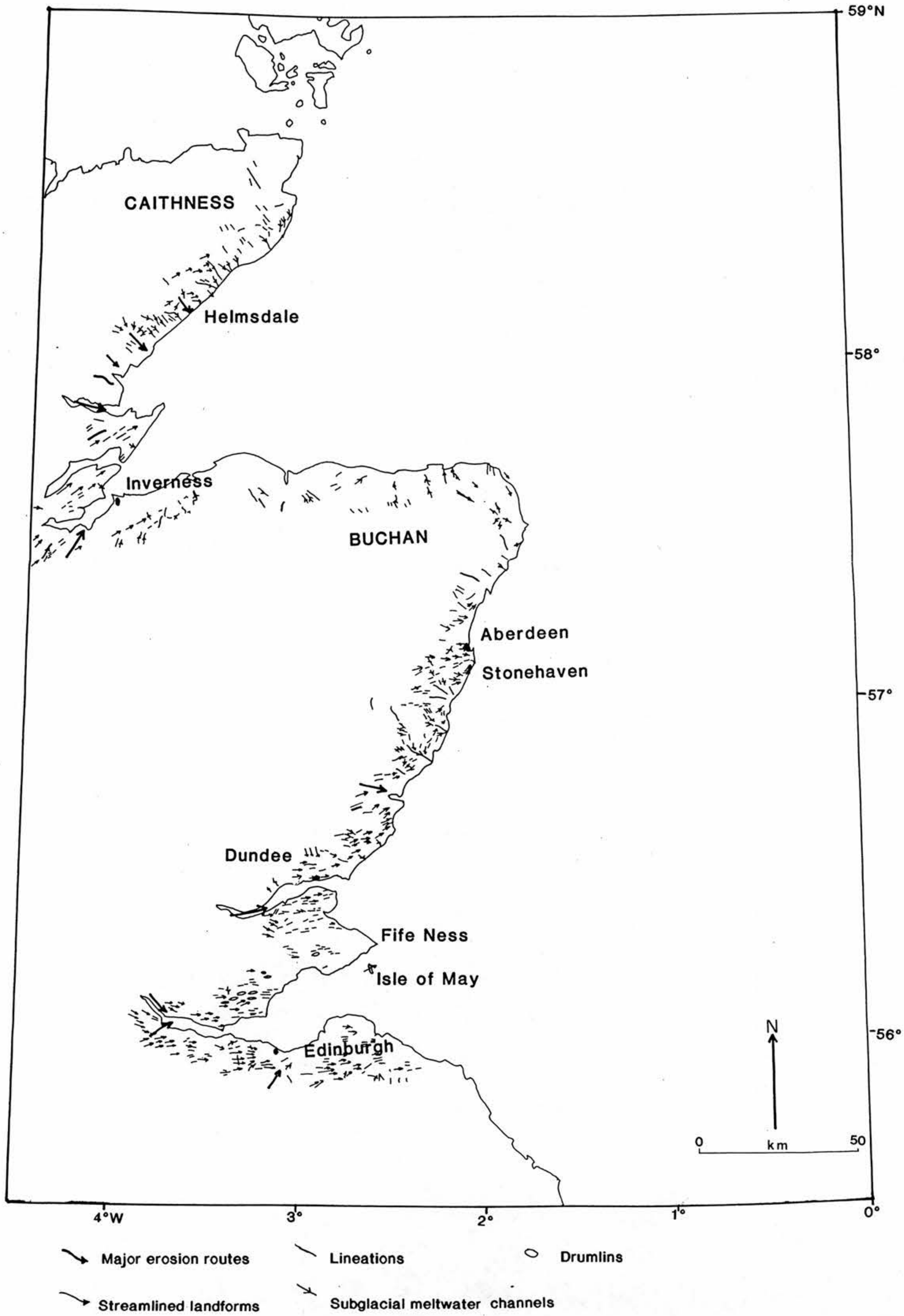
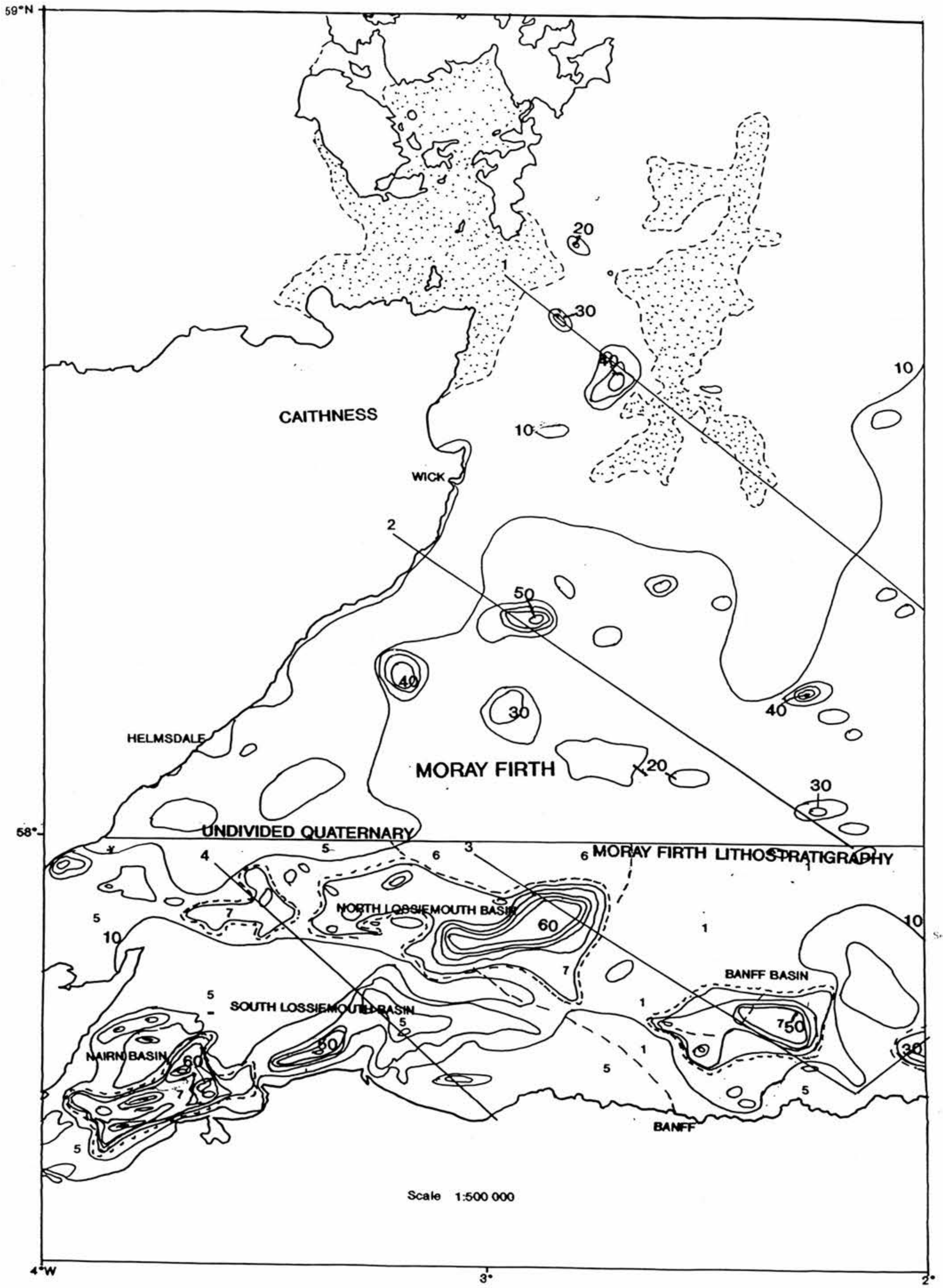
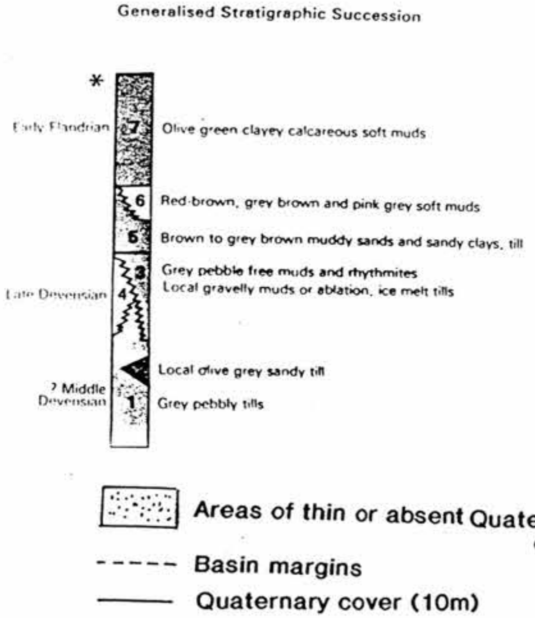


FIGURE 3.32*Glacial geomorphological map produced from the 1:50 000 OS Landranger Series map sheets.





* QUATERNARY GEOLOGY

Sub-surface sediments of late glacial and post glacial origin are present within the sedimentary basin of the Moray Firth except for a *small area off the north coast east of* Fraserburgh and off the south coast north of Golspie. The Quaternary in the Moray Firth ranges from 0 to up to 70 metres thick; the most extensive areas where significant (greater than 20 metres) thicknesses are preserved are found in the southern part of the Moray Firth, south of 58°N. Here, Quaternary accumulation has been delineated by sparker and pinger profiles into a complex association of five elongate east-west trending basins, defined on the basis of the 20 metre isopachyte. They are named, progressing from west to east, the Nairn, South Lossiemouth, North Lossiemouth, Banff and Fraserburgh Basins.

The stratigraphic units recognised within the area are based on borehole and shallow coring information, and correlation of these units based mainly on lithological characteristics must be regarded as very tentative. Grey pebbly tills (Unit 1) form stratigraphically the lowest Quaternary deposits present in the area, and exhibit considerable variation in thickness, thinning markedly to the west. The tills vary from grey compact pebbly sandy clays to muddy sands, and C^{14} dates of 43500 years BP in boreholes to the north of the area indicate a Middle Devensian age. Local developments of olive grey sands (Unit 2) are present within the grey pebbly tills of Unit 1. Lateral to the basal grey tills are grey pebble free muds and rhythmites (Unit 3). These are probably derived from melting and reworking of the basal grey tills perhaps in locally restricted deeps, partially ice or moraine dammed. C^{14} dates from wood fragments within the rhythmites indicate a Late Devensian age of approximately 16000 years BP. Locally gravelly muds (Unit 4) are present and these are thought to be ablation or ice melt tills, and appear to be in part laterally equivalent to the grey pebble free muds and rhythmites of Unit 3. Brown to grey-brown muddy sands and sandy clays with varying proportions of sand and gravel (Unit 5) are thought to be tills. These tills may be wholly or in part laterally equivalent to the overlying red muds *of Unit 6* and perhaps comprise their source. The red, pinkish or brownish soft muds of Unit 6 are usually less than 10 metres thick and crop out *extensively throughout the Moray Firth.* C^{14} dates of 12400 years BP ± 100 from boreholes to the north of the area *indicate a* late Devensian/Early Flandrian age for these muds corresponding to or just after the final decay of the last ice sheet. Olive green, calcareous, sulphide rich soft muds (Unit 7) form the topmost Quaternary deposits in the area generally occurring in the areas of deeper water. Shells of Arctic faunal affinity within these muds suggest an early Flandrian age for the deposits.

DIAGRAMMATIC SECTIONS SHOWING GENERAL RELATION OF QUATERNARY DEPOSITS ALONG THE LINES DRAWN ACROSS THE MAP

(Horizontal scale 1:500 000; Vertical exaggeration × 50)

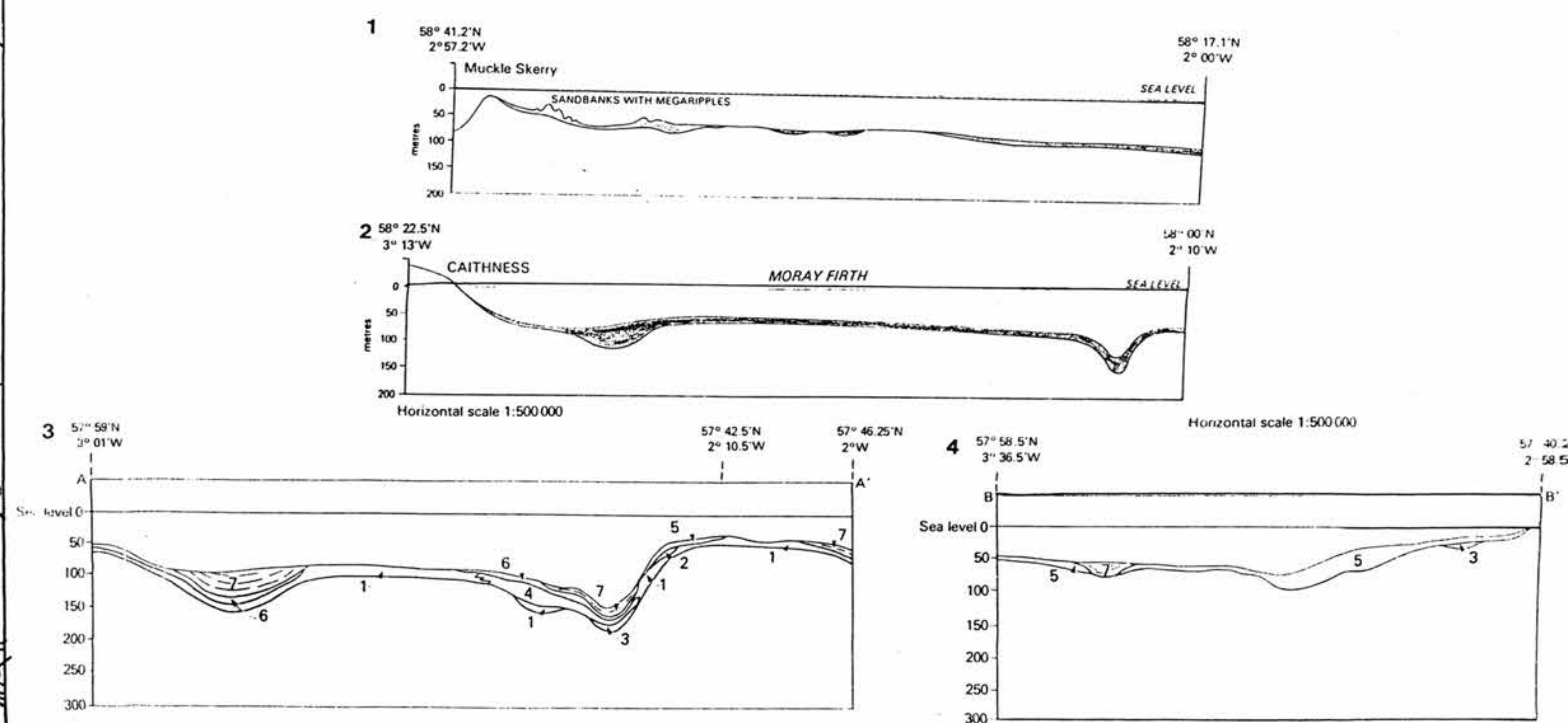
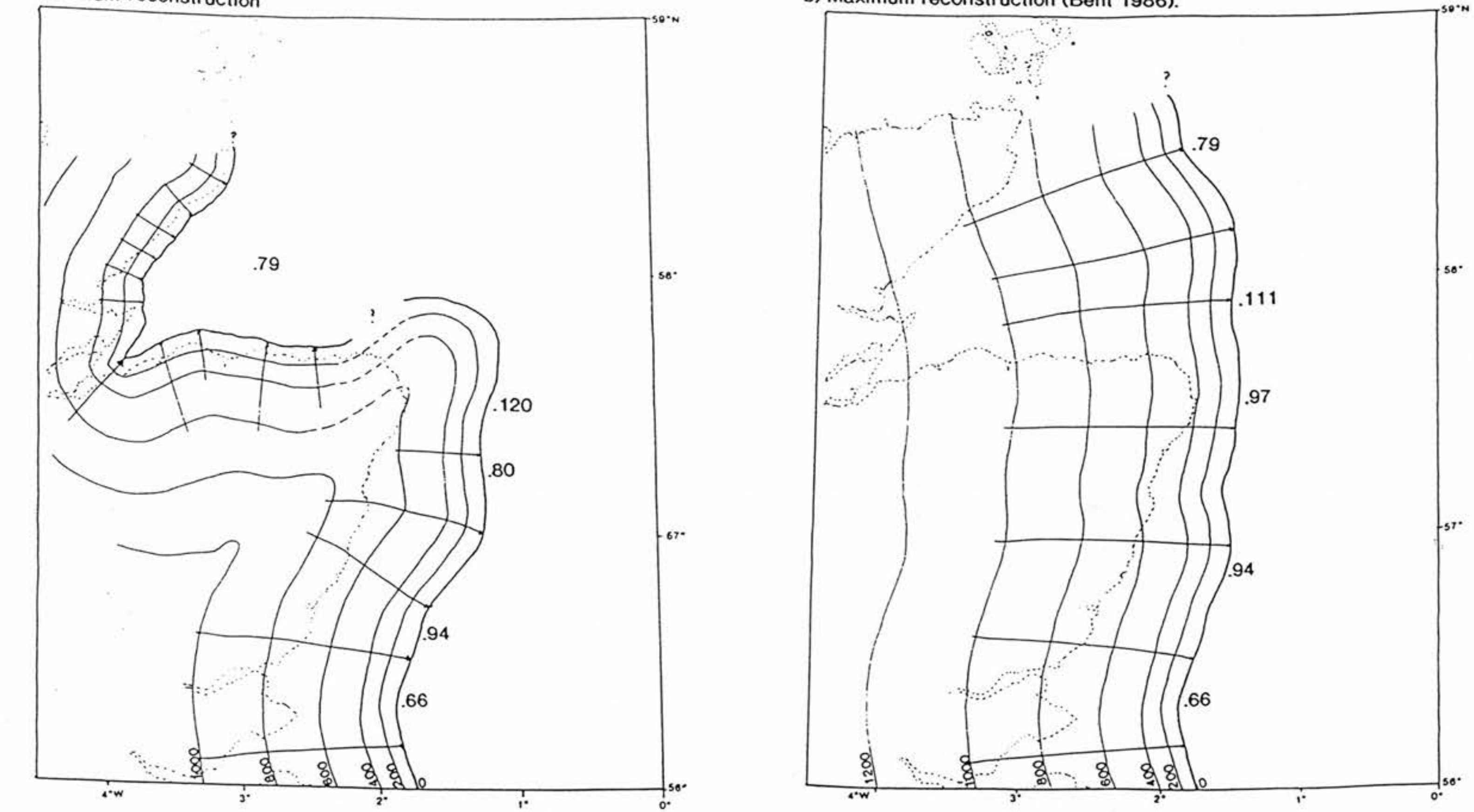


FIGURE 3.25* BGS Profiles across the Moray Firth (after Chesher 1984, Ruckley and Chesher 1987).

a). Minimum reconstruction

b) Maximum reconstruction (Bent 1986).



.60 depths in metres below sea level

600 height of ice in metres

FIGURE 3.39 Water depths at the ice margin calculated from the glacio-isostatic depression caused by the thickness of ice at the centre of the ice sheet (Nye 1952) and relative eustatic sea level (Fairbanks 1989).