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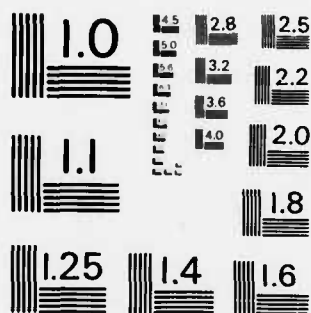   W RITCHIE JUL 83 DAJA45-83-M-0210

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NORTHEAST SCOTLAND
COASTAL FIELD GUIDE AND
GEOGRAPHICAL ESSAYS

FRONT   COVER

N.A.S.A. Landsat scene 221/20 of
North East Scotland on 30th May, 1982.
Colour composite of spectral wavebands
500-600 nm (green), 600-700 nm (red) and
800-1100 nm (reflected infrared).

Prepared and printed by the UK National
Remote Sensing Centre, Royal Aircraft
Establishment, Farnborough

(Approximate scale 1:370,000)

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Department of Geography
University of Aberdeen
July 1983

Edited by W. Ritchie

PREFACE AND ACKNOWLEDGEMENTS

The visit of the International Geographical Union Coastal Commission to the University of Aberdeen in July 1983 offers an opportunity to produce this combined volume of site descriptions of those coastal areas in north Scotland that will be visited during the field visit and a series of essays by former research students, past and present staff of the Department of Geography and other invited contributors. These essays are derived from research that has been undertaken since the early 1970's and includes much original work hitherto unpublished.

The typing and reproduction of the volume was done by the secretarial and technical staff of the Department of Geography, University of Aberdeen and special mention should be made of Miss L. A. Croucher, Miss L. Coutts, Mrs. C. Dalgarno, Mr. J. Doverty, Mr. R. Gard, Mr. J. Livingston and Miss L. Urquhart. I would also like to thank Dr. J. S. Smith and Mr. R. Wright for their help in the editorial and compilation processes. Most of the costs of producing this volume were provided for by the Research Office of the U.S. Army in Europe and particular thanks are recorded to Mr. W. Grabau for his assistance. The Countryside Commission for Scotland kindly gave permission to reproduce text and figures that had been published previously in several 'Beach Survey Reports'. I am grateful to the U.K. National Remote Sensing Centre (RAE Farnborough) for providing the cover photograph and some of the illustrations in Part 2 of this volume. The NCC (Geological Conservation Review Unit) also gave permission to use some of the material used in the Spey Bay site description.

To the authors of the various sections of the report I give my warm thanks for providing stimulating material in good time to produce what I hope is a useful addition to the geographical literature relating to coastal studies in Scotland.

William Ritchie

June 1983

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PART ONE
FIELD GUIDE

1. GENERAL CHARACTERISTICS OF NORTHEAST COAST

The coastline of Northeast Scotland in plan is determined by faults
running close inshore to both North Sea and Moray Firth coasts. Along
the northern margin, an east-west trending system of faults can be
identified by steep gravity gradients north of Fraserburgh. This line
also coincides with the orientation of a prominent bathymetric deep
(Cheshire, 1977). Off the east coast, recent geological work by the
Institute of Geological Science has confirmed the pioneer Quaternary
work of Jamieson which indicated that relatively recent geological strata
of Permo-Triassic age lie close inshore. For both north and east coasts,
the detail of the coastal plan, within which the soft coastal elements
have accumulated, is governed by the varying lithologies of the solid
geology along the land margin. Three broad sub-divisions can be
identified where differences of lithology and orientation have created
distinctive coastal scenery.

(a) The Highland schists of the Banffshire coast.

(b) The granites, gneisses and schists of the east coast of Aberdeenshire,
     to the north of the Highland Boundary Fault.

(c) The younger sedimentaries downfaulted south of the Highland Boundary
     Fault, the outliers at Pennan, together with the downwarped sedimen-
     tary formations of the Moray Firth basin, west of Spey Bay.

The Banffshire coast consists of a generally high rocky coastline with
small bays orientated in sympathy with the rapidly changing geological
succession of the Highland schists. Units are small and generally
separated from each other by rock cliff headlands and deep water. The
bayhead orientation is continued inland by strike-stream valleys, often
markedly overfit in relation to current fluvial activities, and the
fluvial input, with the exception of the Deveron, is generally small.
The coastal scenery is bedrock-dominated and rapidly changing in
character along the geological succession.

On the east Aberdeenshire coast, the role of the underlying bedrock,
although by no means uniform, is subordinate to Pleistocene and post-
Pleistocene events. With the notable exception of the granite coast-
line north of Collieston (especially at Buchan Ness), and the intricate
cliff coast between Girdleness and Stonehaven, the character of the coast
is of extensive arcuate dune-backed embayments, hinged on low bedrock
outcrops and lag glacial deposits. Fluvial inputs while locally
significant, are not impressive in their supply of beach material.

West of Spey and south of Stonehaven, the younger sedimentary rocks
form substantial lengths of high cliff coast, with variation in
character according to lithology. Particularly impressive are
the conglomerate sea cliffs at Fowl's Heugh, just south of Dunnottar.
On the north coast Permian sandstones form a very distinctive series
of low sea cliffs between Covesea and Burghead, but west of this
point, and between Lossiemouth and Portgordon, the coastline is
dominated by major strandplains of late- and post-glacial age, again,
as in the case of the east Aberdeenshire coast, supported by bedrock
outcrops.

In relation to the soft coastal elements solid geology forms a varied
platform on which beaches and landward blown sand deposits have

accumulated. But over more than 80% of the sandy beaches, bedrock
geology forms a minor element in their evolutionary history and present
characteristics. Exceptions occur on the Banffshire, Kincardineshire and
Moray coasts, where the beaches are set in small bayhead situations
resting on rock platforms. Here the beach arc and its landward landform
characteristics are closely governed by the geological framework within
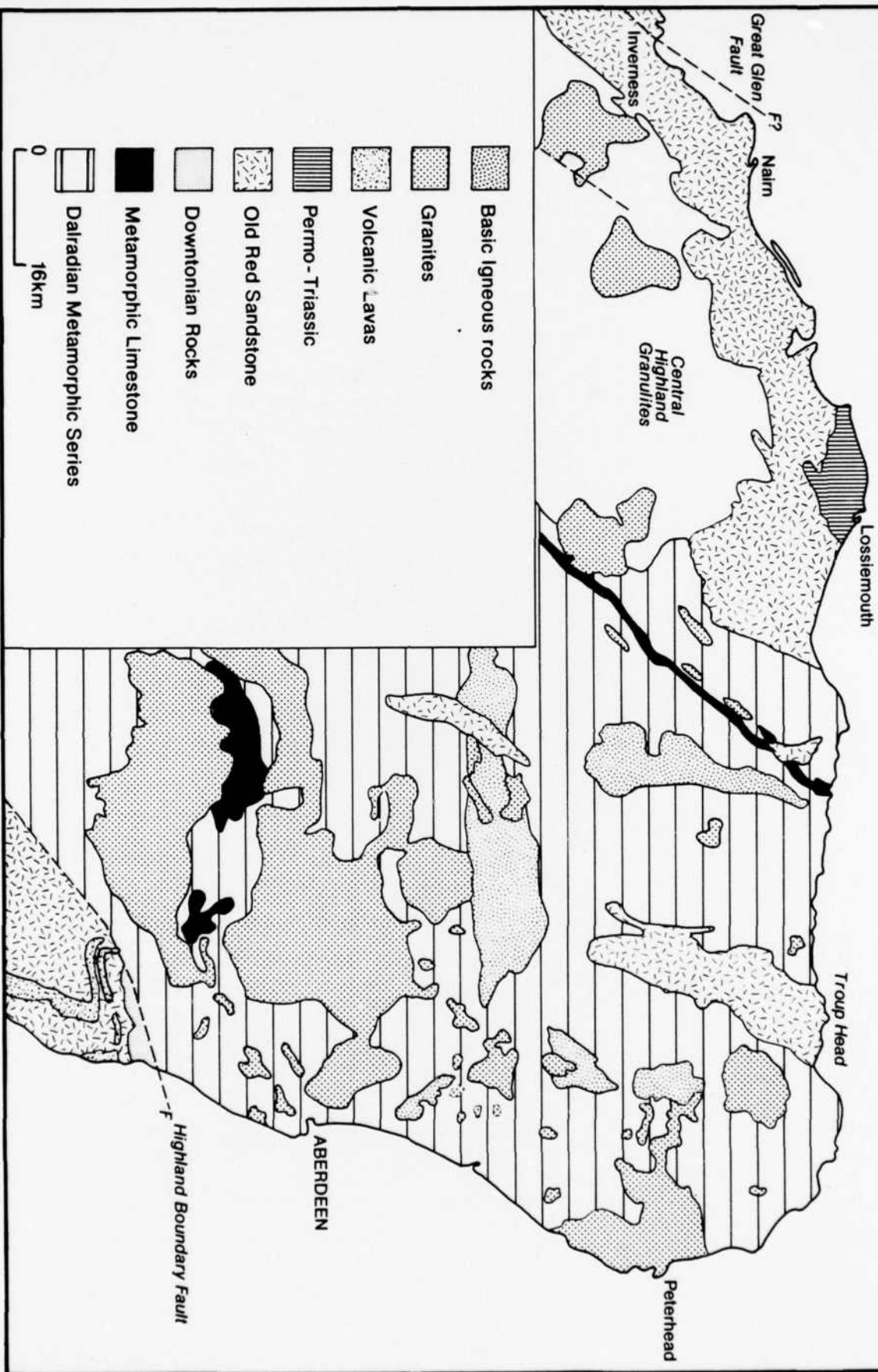which it is lodged.

The events of recurrent glaciation during the Pleistocene are much more
pertinent to the soft coast geomorphology of Northeast Scotland. The
glacial history of Northeast Scotland (Synge, 1956) involved successive
advances of ice both from the Moray Firth basin and from the Deeside-
Donside area. In Banffshire, the cliffs are capped by till and by the
enigmatic coastal gravels, both of which contain material of Cretaceous
origin derived from offshore. On the east coast of Aberdeenshire and
Kincardine a red till derived from Strathmore and from offlying submarine
sandstone outcrops forms a prominent capping to the sea cliffs, as at
Dennottar and Hackley Head. At several points both on the east and north
coasts, ancient elements of the preglacial coastline are plugged with
glacial till even in relatively high energy situations, testifying to
the relatively slow evolution of the pre-Pleistocene bedrock coastal
landforms (Walton, 1959). Examples of till-plugged sea stacks occur at
Covesea and immediately south of the Bay of Nigg. Impressive sections
of superimposed coastal tills occur at the Bay of Nigg.

As the ice melted, large quantities of fluvioglacial materials were
released into the coastal zone, the materials being transported down
preglacial river valleys as in the case of the Spey and Findhorn, or
more directly released from impressive meltwater channels as in the
Pennan-Troup Head area. The high-cliff coast near New Aberdour is
dissected by deeply incised coastal ravines which are partly of meltwater
origin. In situations where ice-fronts rested near to the present
coastline, as occurred between Aberdeen City and the Ythan, and at the
Binn Hill just west of the Spey, sorted materials were released to be
later incorporated into recent coastal strandplains. Large quantities
of material travelled down the Spey and Findhorn which acted as major
late-glacial spillways, as attested by the huge lateral fluvioglacial
terraces of their lower and middle valley sections.

Land-sea relationships changed as a result of the interplay of isostatic
rebound of the land and eustatic change in sea level. The result was to
cause shoreline displacement, initially rapid and latterly slowing down.
Where unconsolidated materials were subject to wave action, strandplains
were formed representing the land-sea relationship at that time, and
subsequent land rebound raised these to form the late-glacial shorelines
which fringe the interior edges of the major coastal embayments. On
occasion, the late-glacial sea overtopped the bedrock cliffs, and
resorted the coastal gravels mentioned earlier to form beach gravels
as at Portknockie. Marine clays were deposited in sheltered coastal
situations as at Cruden Bay and Tipperty, often associated with a cold
water fauna. After this phase of relatively high sea level, it is
evident that sea level dropped to a level below that of the present time,
resulting in river and estuarine rejuvenation. As climate ameliorated,
vegetation spread into the emerging coastal zone.

Later in response to the warming world climate, sea levels rose rapidly,
and the coastal zone was inundated by a major marine transgression (the
Flandrian transgression) which caused a landwards migration of the shore-
line, leading to the burial of peats and their capping with marine

Solid Geology

Basic Igneous rocks

Granites

Volcanic Lavas

Permo-Triassic

Old Red Sandstone

Downtonian Rocks

Metamorphic Limestone

Dalradian Metamorphic Series

0   16km

Great Glen F? Fault

Nairn

Inverness

Central Highland Granulites

Lossiemouth

Troup Head

Peterhead

ABERDEEN

Highland Boundary Fault

F

F

Relief

Legend:
- 0 - 122m
- 122 - 244m
- 244 - 427m
- > 427 m

Scale: 0 ___ 16km

Labels: Nairn, LAICH O'MORAY, Lossiemouth, R. Nairn, R. Findhorn, R. Lossie, R. Spey, R. Deveron, BUCHAN, Mormond Hill, R. Ugie, Peterhead, R. Ythan, Bennachie, R. Don, R. Dee, R. Cowie, Bervie Water, ABERDEEN

deposits. The highest point of the postglacial transgression is marked sea cliff at about 6 m O.D. which can be traced almost continuously from Strathbeg in the north to Aberdeen City in the south. It also formed the well-defined inland margin of the Moray strandplains as at the Binn Hill. Final land emergence caused a second seaward shoreline displacement, during which vast quantities of sands and gravels were made available for shoreline regularisation. Successive shingle bars hinged on till or isolated bedrock headlands mark the progress of this final period of shoreline displacement. In areas where substantial coastal embayments existed, as in the Moray coast or the east coast of Aberdeenshire, regularisation involved the construction of wide strandplains on which blown sand accumulated. On occasion blown sand deposits extended landward of the marine limit forming a veneer on till and fluvioglacial landforms. In response to dominant wind and wave activity, shingle spits were built, deflecting the Ythan to the south on the east coast, and the Spey and Lossie to the west on the north coast. The smooth arcuate nature of the coastal plan between Aberdeen and Collieston, between Buchanhaven and Inzie Head, and between Spey Bay and Lossiemouth represent a final shoreline equilibrium form achieved through the recycling of sediment by wave and current. West of Burghead, active shoreline progradation continues through the building westwards of spits and bars. Much of the material is derived from the recycling of existing forelands as in Burghead Bay, resulting in problems of coastal edge erosion, as waves and currents sweep the material westwards into the Inner Moray Firth.

In the case of the smaller bayhead beaches, the processes of change are less dramatic, as a balance appears to exist between material supplied from cliff and offshore sources, and that lost from the beach by downcombing during heavy swell. On the Banffshire coast, where each unit is separated from its neighbour by cliff coasts and stretches of deep water, each beach unit functions separately, but in the Inner Moray Firth, where large units are linked in long coastal sweeps, coastal edge erosion is associated with deflation of the exposed dune faces. Backshore erosion at Burghead Bay has in the past revealed exposures of the peat which formed during the shoreline regression phase preceding the Flandrian (Steers, 1937).

On top of the shingle forelands where the constituent material reflects the formerly abundant supply of fluvial and fluvial-glacial materials, sand deflated from the drying upper beaches has accumulated as dune systems. These vary locally in their form and complexity. The relatively simple successive foredunes of Strathbeg, St. Fergus and Lossie form massive ridges separated by slacks. At the Sands of Forvie, and to a lesser extent Culbin, the forms are much more complex, including parabolic dunes whose current activity and pattern of evolution makes them of great physiographic interest. Here the older late- and post-glacial landform elements are largely buried by a blown sand landscape carrying evidence of sequent occupance (Kirk, 1955). In both Culbin and Forvie, the story of prehistoric and historic sand-blow cannot be separated from the activities of man (Ross, 1975). Historical and neo-historical sand-blow at Culbin resulted in 20th century afforestation of the dunes, but at Forvie, the dunes continue to evolve naturally.

The very large beach units and their backing forelands described above contrast in size with the small bayhead units set within a rock-girt coastline. Here the beaches rest on rock platforms and are generally backed by settlements nestling on the post-glacial ledges, at the base of a marked sea cliff, generally of bedrock, capped with till, and

overlain by thin and often discontinuous blown sand deposits. The blown sand landforms are small by comparison with the North Sea coast beaches, and are generally inactive, partially masked and modified from their original characteristics by anthropic influences.

Almost all the beach and dune areas are man-modified. The most common use is agriculture but some very extensive areas are afforested. Some small bay units are dominated by harbours and fishing villages. Many links areas are golf courses. Nature conservation is also well represented as at Culbin and Forvie. In spite of the economic significance of North Sea oil and gas developments the visible impact of these activities is remarkably small, consisting of two main areas, the St. Fergus Gas Terminal north of Peterhead and the oil platform fabrication yard at Ardeseir. Otherwise the evidence of North Sea Oil is in the harbours and urban areas.

1 (a)   BALMEDIE

Although the area is, for convenience, described as Balmedie, it
includes Eigie Links to the south and Pettens Links to the north. The
area popularly known as Balmedie is named after the village and on
Ordnance Survey maps the dunes and links are called Drumside.

As shown Balmedie has the advantage of a good quality surfaced road
leading to large car parking areas with services and other facilities.
Nearby is the growing village of Balmedie with shops and a hotel. This
area is the most important beach and dune recreational area north of
Aberdeen which is 11 km away by road to the south.

The Balmedie dune and links areas correspond to the section of the
coastal plain where the old cliffline retreats furthest inland and is
replaced by a broad, low raised beach surface only a few metres above
present sea level.

The ease of access which concentrates hundreds of visitors to a specific
entry point and which has a clear environmental impact on the dune
system is epitomised by the aerial photograph which, although taken in
1972, clearly illustrates the radial path system on the most popular
part of the dune system. Since this photograph was taken the parking area
has been enlarged and additional parking areas south of the one shown have
been developed. The total capacity is now of the order of 500 cars.
These new car parks have allowed other points of access to be used and has
thus spread pedestrian impact more widely.

Five streams reach the beach zone in the Balmedie area. The Millden is
the largest and has the greatest catchment area. The Kepplestone Burn
(also called the Eigie Burn) immediately to the north is the next largest.
The succeeding stream is much smaller and reaches the beach beside the
Kepplestone Burn. Further north the Blairton Burn separates Drumside
Links from Pettens Links where there is also a small stream course.
There are other minor streams, ditches and drains in the general area and
some of them end in low wet or marshy hollows in the links and do not
break through to the beach. Nevertheless, as a consequence of the amount
of drainage water, the links areas can be very wet in winter with pools
of standing water in some dune slacks and in many places the ground
remains wet for much of the summer. All these streams contain water
derived from field drains and are probably rich in nutrients. The
amount of water entering the beach zone directly or by seepage has some
morphological effects on the beach and foredune zones. It should also
be noted that all these stream courses have a history of migration at
the point where they leave the dune zone and cross the beach. Over
the last ten years studies of aerial photographs show that such
changes in position can be quite appreciable.

In anticipation of the increase in population at Balmedie a new sewer
outfall pipe was laid in 1974 through the links and dune zones and
passes under the beach near the outlet of the Kepplestone Burn before
terminating several hundred metres offshore.

The intertidal beach ranges from 120 to 190 m wide and has a complex,
dynamic morphology, best described as a series of sand bars and tidal
pools. Towards low water mark the beach has a scalloped shape with
detached and partially detached bars up to 100 m long lying along the
breaker zone. Deeper pools run into the beach. Near mid-tide level
there is another more varied series of sand bars with channels or
lows running obliquely between them. These bars also retain pools of

water which parallel the shoreline. These longitudinal pools are most conspicuous where they are fed by stream water discharge. At times an almost continuous pool can link all the stream outlets along the beach at a level just below that of high water mark. The intertidal beach is therefore undulating and wet. In those few places where there are no bars, sand banks, tidal pools or stream courses, the beach is low and flat. Above high water mark there is an abrupt steepening of the beach profile (5 to 7°) to a high sand platform which rests against the base of the foredune. In winter it is not unusual for this higher sand reserve to be removed and the tide reaches to the base of the dunes.
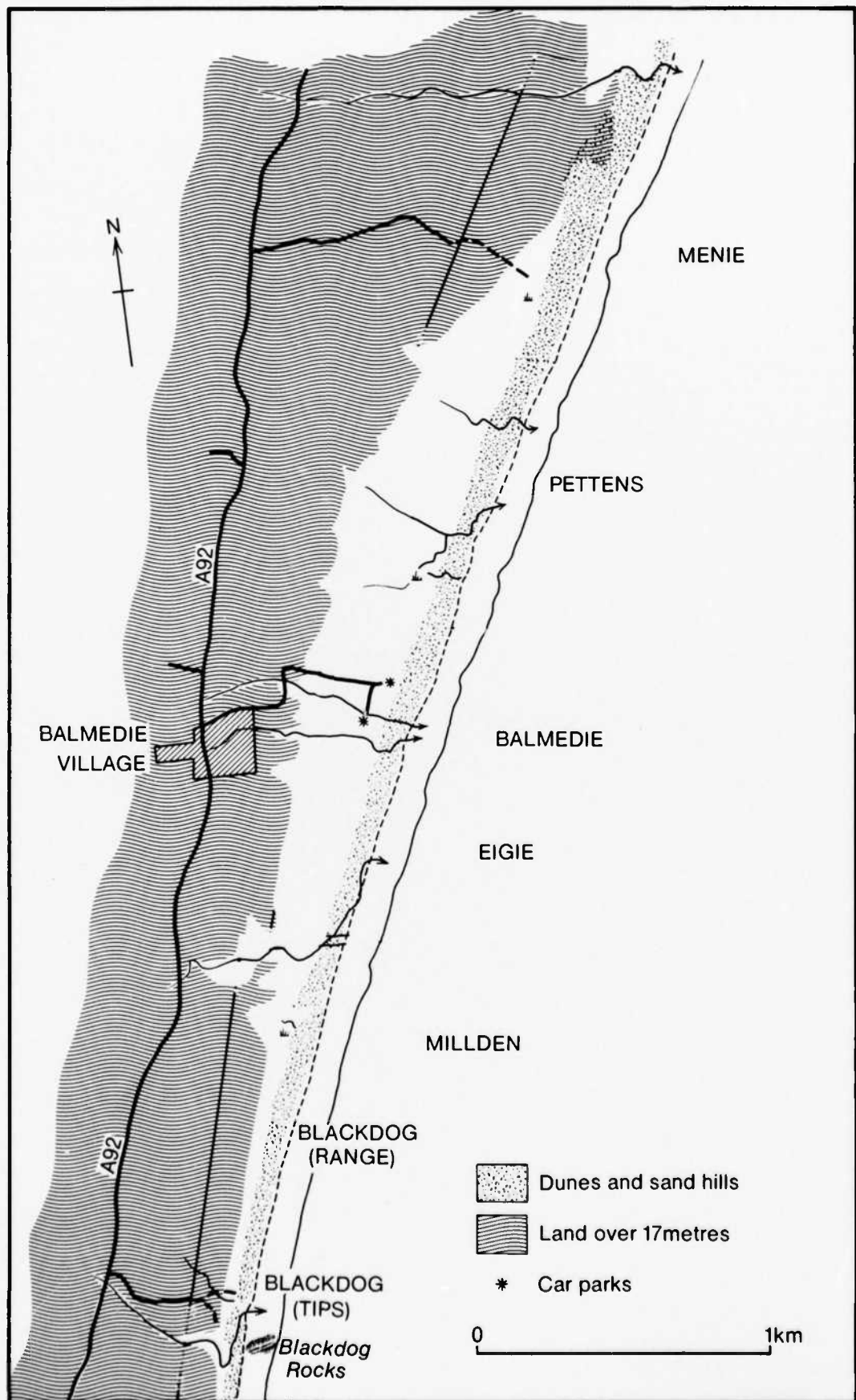
Below low water mark there is evidence to indicate that a further series of sub-parallel sand bars, separated by deeper hollows are found offshore.

In the south, the foredune ridge forms the eastern boundary to the Millden Burn which flows for almost 500 m parallel to the beach before turning sharply east at the base of an undercut, high sandcliff to meander across the beach to the sea. This dune ridge has an asymmetric profile with a steep, formerly undercut, seawards face. Recently there has been accretion at the base of the slope and a low parallel foredune has formed on the original slope. Considerable quantities of sand have blown onto and over this dune ridge and there is vigorous Marram cover. Beside the Millden Burn there is also a steep bank which has been produced by stream action.

On the west side of the burn and especially where it nears the beach there is severe undercutting to produce bare sand-cliffs which are, in places, up to 14 m high and lead into three relatively large blow-out features. The stream has shifted south recently and sand has filled its old course which is in process of colonisation by pioneer species.

Further inland the dune backslope becomes hummocky and merges into broken lines of old sand hummocks and ridges. The impression gained is that of an amorphous field of low sandhills and broken ridges which are separated by low hollows and flats. There is, however, an impression of parallelism in these fields of hummocks. Near the outlet of the Millden Burn the dune zone becomes much higher (over 15 m O.D.) and the sandhills are deeply dissected by active blowouts with steep undercut sides. The excavated sand has spread inland onto the lower links surface. Further north the same high series of sandhills form the coastline where it is again undercut by storm waves during high tides. This high sandhill zone is broken by a very large blow-out complex (about 250 m north of the Millden Burn). This is a major erosional feature which has been reduced to the base level of the water table. The sides of this blow-out are over 20 m high, steep and being actively undercut. Pinnacles and ridges of Marram-covered surfaces remain to give a highly dissected appearance to the local topography. The sandhill complex is higher on the north side from which it slopes steeply towards a further complex of dunes and sand ridges south of the Kepplestone Burn. The main blow-out has received some remedial work in the form of replanting and sand-fence construction. In spite of this, the bare sands drifts steadily northwards down onto the lower backslope of the main dune zone.

North of this major blow-out there is a broad, crescentic arc of high sandhills which fall steeply to another curved hollow, part of which reaches down to the water table and forms a marshy pool of standing water, especially in winter. This high sandhill complex rises to more than 25 m O.D. and is being dissected by wind erosion on its south side.

MENIE

PETTENS

BALMEDIE

EIGIE

MILLDEN

BALMEDIE
VILLAGE

A92

A92

BLACKDOG
(RANGE)

BLACKDOG
(TIPS)

Blackdog
Rocks

Dunes and sand hills

Land over 17metres

*   Car parks

0   1km

Aerial photograph of central Balmedie.

BALMEDIE
Recreational Provisions

GRAZING LAND

Pay Box (20p charge)

Car Park
(Landscaped)

Access Point

■ Toilet block

Low

Low

B

B

Low

*

FARMLAND

G

Low

Grass

Car Park

17

Separate

Bays

R.A.

Sand Beach

H.W.M.

L.W.M.

Sand Beach

N

• Pill Box	⁄⁄ Bridge	····· Tank blocks
▲ Summits >15m	✳ Lifeguard station	Main bare sand areas
Road	**B** Barbecue pit	Disturbed ground
Track	**G** Broken gun emplacement	Planted trees
····· Footpath	**R.A.** Restored area	Picnic tables
Boardwalk	–·– Boundary of recreation area	0 200 m

The north side is very steep (over 20°) and is a partially stabilised depositional slope.

Along this section of coastline, i.e. between the Millden and Kepplestone Burns, the coastal edge is at first a steep sand-cliff which was cut by a recent northwards extension of the Millden Burn. The stream has shifted southwards and sand has accumulated over the former outlet area. Vegetation has colonised this higher beach surface and the sand-cliff shows signs of natural restabilisation. Between this old sand-cliff and the entrance to the main blow-out complex (which is a bare sand ridge and is not reduced to beach level) the coastal edge is steep and shows signs of undercutting. About 50 m north of the blowout there is a dune ridge which extends north to the combined outlets of the Kepplestone and Balmedie Burns. There is a high (8 m), broad, accreting ridge with a steep seawards face. Vigorous stands of Marram and Sea Lyme grasses testify to recent and continuing sand accretion. The backslope of this ridge runs into older dune and sandhill surfaces which have been severely eroded where there were large concrete gun emplacements (these were reduced to rubble and broken slabs by Army demolition teams in 1974). Inland from the gun emplacement area there is a prominent residual sandhill which slopes steeply in a talus-like ramp of sand into the meandering course of the Eigie Burn. This general area has been greatly affected by human usage over a long period of time.

The Eigie Burn has steep banks where it cuts through the inner dune backslope and zone of hummocky links. Nearer the sea there is a broad marshy floodplain which might be underlain by peaty marsh deposits.

North of the Eigie Burn there is a mature sandhill area with distinctive stabilised hollows. These are likely to have been old blow-out depressions.

The Balmedie Burn flows through a shallow basin-shaped area which has been modified as a result of stream straightening and the restoration works associated with the laying of a sewage/drainage pipe through this zone to the beach. Before these changes this was also a marshy area, especially north of the stream course.

North of this stream is the area of maximum recreational pressure. This is a hilly area with numerous bifurcating footpaths. Perhaps surprisingly there is little erosion associated with these bare sand footpaths. Larger erosion hollows tend to occur on the northeast side of this sandhill complex. In the centre and south there are distinctive, deep hollows which are mature, fully stabilised large-scale blow-out features. The north and east-facing limit to this high sandhill zone is a steep escarpment which is completely bare of protective vegetation over much of its length. Although steep and bare there is little sign of active erosion here and towards the sea there are signs of recolonisation and some rounded young sand dunes have developed on the floor of the main deflation surface.

The coastal edge immediately north of the stream outlet is steep, and in places, undercut. Nevertheless, undercutting has not been a problem in recent years as the beach seems to be sufficiently thick and wide to offer some protection to the frontal dune slope.

The coastal edge which lies to the east of the massive deflation surface consists of eroded fragments of the original dune line. Active dissection has produced steep relief forms which have been accentuated by

redeposition onto the residual vegetated surfaces. Further north the
dune line remains intact but is under active wind erosion from the
landwards side.

In the extreme north of the area dissected ridges curve landwards and
form the margin of another high relatively stable sandhill complex.
On the seawards margin there is a zone of accretion and a high, stable
dune ridge has formed over older, more irregular, sand ridge morphology.
This dune has a characteristic concave profile with the lower segment
being produced by recent sand accumulation.

One of the most impressive landform features at Balmedie is the great
convex ridge of totally bare sand with its associated deflation
surfaces to the south and its encroaching, mobile steep-fronted sand
slopes to the north. This massive sand wave is almost 500 m from south
to north and over 200 m wide. This area at Balmedie is the first of
three similar extensive sand waves which are found south of the Ythan
estuary and an even larger series of similar surfaces are found in the
Sands of Forvie. To describe this sand wave feature as an erosional
area is an oversimplification. Certainly there is active erosion and
sand transport from the south where deflation has reached down to the
base level of the water table. On the margins to east, west and north,
dunes and older sandhills are being attacked by various forms of wind
erosion at a variety of scales of activity. For most of the surface,
however, the main process consists of mega-ripples of sand shifting
across a broad convex dome which is based on a former area of high sand-
hills such as remain in existence further south. These sand layers move
with the play of the wind but there is a net northwards migration and
the limit of advance is marked by an abrupt steepening of the encroach-
ing sand front. Blown sand is also carried landwards over the zone of
hillocks and for a considerable distance onto a low undulating links
surface nearby. It is not unusual to visit Balmedie (and the areas
further north) and see clouds of sand reaching 10 to 20 m into the air
and being carried for a considerable distance inland. Such deflation
can occur in any season but seems to require winds greater than 30 to 40
knots and dry conditions to produce such spectacular movement.

The development and rate of expansion of this and similar sand waves
would require considerable research work but it is likely that its
origin is due to the expansion of a major blow-out complex on the
south-facing flank of a zone of higher sandhills or ridges which expands
northwards and, possibly, coalesces with other erosion features to such
a degree that the original protective vegetation is almost completely
destroyed. After a certain stage the process might be self-accelerating
in so far as pronounced wind channelling could be produced as a result
of deep topographical dissection.

Inland from the broad range of coastal dunes and sandhills there is
normally a low area (4 m O.D.) which extends for several hundred
metres landwards to the limit of blown sand. The limit is invariably
in an area of agricultural fields and is difficult to define. In
some fields old, flattened dune and sandhill topography can be dis-
cerned. These mature surfaces might be ancient landforms related
to a different coastline position. Elsewhere, the links are
smooth or gently undulating. There are also marshy depressions and
some permanent pools of standing water. The stream courses are
often artificially straightened and the old courses can just be seen
as sinuous damp depressions. Between the various types of links
surfaces there is normally a zone of mature hillocks or low

North car parking area at Balmedie.

Example of wooden slat pathway at Balmedie.

discontinuous sandhills. These hillock areas appear to have random topographic patterns but it is possible to see suggestions of a south to north orientation; a direction which is often picked-out by relatively straight, but discontinuous, depressions.

Field boundaries, drainage, cultivation and grazing has altered the surface forms of the extensive links surfaces at Balmedie but enough remains to suggest that the natural morphology is far from uniform and probably represents a complex history of development.

On the whole the vegetation of Balmedie and adjacent areas is similar to that of most of the dune coastline between Aberdeen and the Sands of Forvie. The dunes are covered in the usual Marram-dominated association, ranging from early to late stages of fixation and complexity. Several of the newer coastal dunes sections have an admixture of Sea Lyme Grass. Where there has been recent erosion Marram tussocks are revitalised, but other subsidiary species tend to be eliminated. Associated with the combination of heavy pedestrian use and a range of natural depositional and erosional processes is a wide range in ground cover species.

The most distinctive vegetation change is between the areas of long dune grasses (*ammophiletum*) and the short dune grasses and shrubs such as Gorse and Broom, of the links. Grazing (including rabbits) is a factor in modifying vegetation associations but the stability of the landform, its height and slope, and, most significantly, the depth to water, are the dominant environmental controls.

In the wetter areas, but also in some of the drier links and backslope areas, there is a considerable variety and richness in floristic composition. Near the stream courses, especially the Millden Burn, there are considerable numbers of plants, ranging from rushes to mosses.

The vegetation and to a lesser extent animal life at Balmedie is described in considerable detail in the 'Ecological Survey of the River Don to River Ythan Report' to the Grampian Regional Council. In this report, the south part of the area is considered to be of most interest and variety. Further north trampling is considered to be responsible for reducing the variety of species. The same report also quotes Leney (1974) who studied the effects of trampling and other activities on vegetation in the Balmedie area and concluded that Marram and other dune species are sensitive to even light trampling pressures. At certain moderate degrees of trampling a few species may be promoted, i.e. *Poa pratensis, Festuca Rubra,* and in damp areas *Agrostis stolonifera, Carex arenaria, Carex nigra, Juncus squarosis* (Grampian Regional Report, 1977, p. 49).

Although grazing, burning, drainage and trampling are important controls on the patterns of vegetation at Balmedie, it is nevertheless necessary to state that large areas remain relatively unaffected by direct anthropic modification and retain a remarkably natural appearance, in spite of the thousands of visitors who come to the area each year. This observation might be related to the resilience of the vegetation types but it is also related to the pattern of recreational and other activities and the way in which much of these pressures pass <u>through</u> the links and dunes areas or take place on a variety of bare sand surfaces and leave such transit surfaces more or less unchanged. On the whole, natural forces still account for more physiographic change at Balmedie than those changes which are induced by man.

Four main types of geomorphological processes can be seen at Balmedie.
The beach zone is the most dynamic zone with considerable variations
in offshore-onshore rates of sand movement. In general the backshore
builds-up in summer and the base of the dune cliff is masked by a ramp-
like slope of wind-blown sand. In storms this reserve of sand tends to
be removed. Similarly, in winter, the beach is lower and flatter due
to the greater proportion of destructive, back-combing waves. Longi-
tudinal movements are equally important with the net longshore drift
appearing to be north-going. Bars, lagoons, troughs and berms drift
along the coast at variable rates. With prolonged northerly winds
the process may reverse and the beach changes accordingly. Some lagoons
and pools are more permanent, especially those related to the stream
outlets. Nevertheless, these outlets also change their position and
their courses across the intertidal beach are obviously diverted or
changed in response to the interaction of freshwater flow, wave and
tidal action. These changes in beach morphology are complex and little
can be said that would aid the prediction of likely alterations in short
or long time scales. Moreover, Balmedie beach is not a closed system
with clear boundaries; it is a small part of the greater beach system
of Aberdeen Bay - a 24 km arcuate beach between Rockend at Forvie and
Girdleness at the mouth of the Dee in Aberdeen - and sensitive to the
more general changes that occur within this wider system.

Associated with beach changes (which, in turn, reflect changes in wave
action, tidal levels and sand supply) are the processes of erosion and
accretion along the coastal edge. Dune cliffing and undercutting are
normal occurrences where all the streams break through the dunes to
reach the beach. Elsewhere erosion is due to wave action when the sea is
raised by tides and storm conditions. Undercutting and slumping produce
the characteristic steep seawards profile which leads upwards to a
relatively sharp crest corresponding to the plane of weakness down
which blocks and sections of the dune front slide to the beach. From
time to time, sections of these sand-cliffs stabilise or even acquire
a low parallel accretionary ridge at their base, thereby producing the
concave, 'step-like' profile which is presently found at the south end
(Pettens) of the area. There are also sections of more permanent
accretion particularly near the Kepplestone and Balmedie Burn outlets.
On the whole, observations seem to suggest that there is some accretion
of sand on most backshore and frontal dune areas. This current build-up
of sand has reduced dune-face angles, increased stability, invigorated
dune vegetation and generally disguised some of the earlier erosional
features.

Related to the supply of sand from the beach is the second zone of
activity, the crest of the coastal foredunes. Three areas are presently
characterised by accretion. These include the finger-like dune ridge on
the south side of the outlets of the Millden and Kepplestone Burns.
Blown sand has spilled across to the backslope zone in both these areas
and strong Marram and Sea Lyme tussocks produced rapid and effective
consolidation. A similar accretion occurs along the coast on the
extreme north part of the area of study. Sand accretion has also
taken place on the seawards side of almost all the blow-out features.
These zones may or may not be vegetated. The deposition tends to take
the form of a broad ridge lying transverse to the entrance of the blow-
out where it breaches the coastal foredunes ridge. Further inland the
morphology tends to consist of amorphous sand hillocks which are
partially vegetated by young Marram plants. Both these depositional
landforms represent natural methods of stabilising erosional features

and emphasise the cyclical nature of many geomorphic processes in coastal dunes.

To the landwards of all the active blow-out and deflation zones there are extensive areas where sand spills onto older mature surfaces. Where the blow-outs are linear, e.g. on the south part of the area, the redepositional zones tend to be hummocky and steep. Where the deflation surface is more extensive, e.g. in the north, redeposition consists of extensive sheets of sand which can be carried relatively far inland. Local wind flow patterns control the shape and volume of redeposition as does the slope and configuration of the reception surface. The time and rate of sand spread determines whether or not the pre-existing vegetation can survive. In general, Marram can stand several centimetres of burial; short grass sward cannot. Activity is not confined to the inner margin of blow-outs; the edges, especially those on the north and east-facing flanks, are actively undercut and retreating. Spectacular, high slopes of sand are produced especially in the southern groups of blow-outs. Very high sandhills are found where local redeposition associated with such erosion is adding to an already high sandhill surface. In the north in the deflation sand wave areas, erosional activity has produced highly dissected, residual-type landforms on all sides except the south.

The remaining area of major sand movement occurs on the larger deflation and blow-out surfaces where waves and mega-ripples of sand migrate with prevailing wind conditions. At the leading edge of the main (north) deflation area, sand cascades forward in a steep slope on both the north and northwest margins. A similar but smaller migrating slope of bare spilling sand is found on the south side of the Kepplestone Burn near the old gun emplacements. In this location the sand is removed by the stream and transported back to the beach zone.

The remaining zones of activity are related to the streams themselves. Downcutting is limited by gradient controls and most of the lower courses are at altitudes of the order of 3 m O.D.; only a little higher than spring tide levels. Moreover, part of their courses is underlain by peaty layers and (it is suspected) by shingle spreads. Erosional activity is directed laterally, and is most obvious at the stream out- lets. Nevertheless, the steep slopes and incised courses of the streams as they cross the hillock and dune zones should be noted. Much of the stream load is deposited in the distinctive flat marshy tracts which are found in all the stream courses where they cross obliquely through the main coastal dune system. These marshy flats are depositional zones for entrained sand and finer sediments. There is also organic deposition provided by decaying vegetation remains. A further factor influencing deposition on these low marshy tracts is the observation that tidewater penetrates occasionally quite far back up the stream courses.

1 (b)   THE SANDS OF FORVIE

The Sands of Forvie is a triangular area of extensive complex dune
systems. It forms the northern part of Aberdeen Bay and lies north and
east of the River Ythan. On a broad scale it is possible to distinguish
two landform tracts; North Forvie where the sand surfaces lie on top of
an increasingly high rock plateau (which reaches the sea at Rockend)
which is, in turn, covered by various thicknesses of glacial deposits,
and South Forvie which is a narrower peninsula of sand resting on raised
beach terraces and buried ridges of glacial origin. The south extremity
of South Forvie is a dynamic spit and bar formation where the River
Ythan meets the North Sea.

In the N.C.C. Review (1977) the Sands of Forvie are summarised as
follows:

> *"Dunes (810 ha). These form the fifth largest and
> least man-disturbed of the large sand-dune systems in
> Britain. Lime deficient and locally highly mobile
> dunes are developed as river-mouth spits and there are
> open coast dunes to the south. There is an extensive
> development of slack communities, especially a Salix
> repens-Erica tetralix-Empetrum nigrum type, and dune
> dwarf-shrub-lichen heaths .... This site is also
> regarded as an important northern example of lowland
> acidic heath. The bryophyte flora is rich and there
> is a strong representation of northern species ....
> There are moderate colonies of breeding terns,
> including Sandwich terns, and the biggest colony of
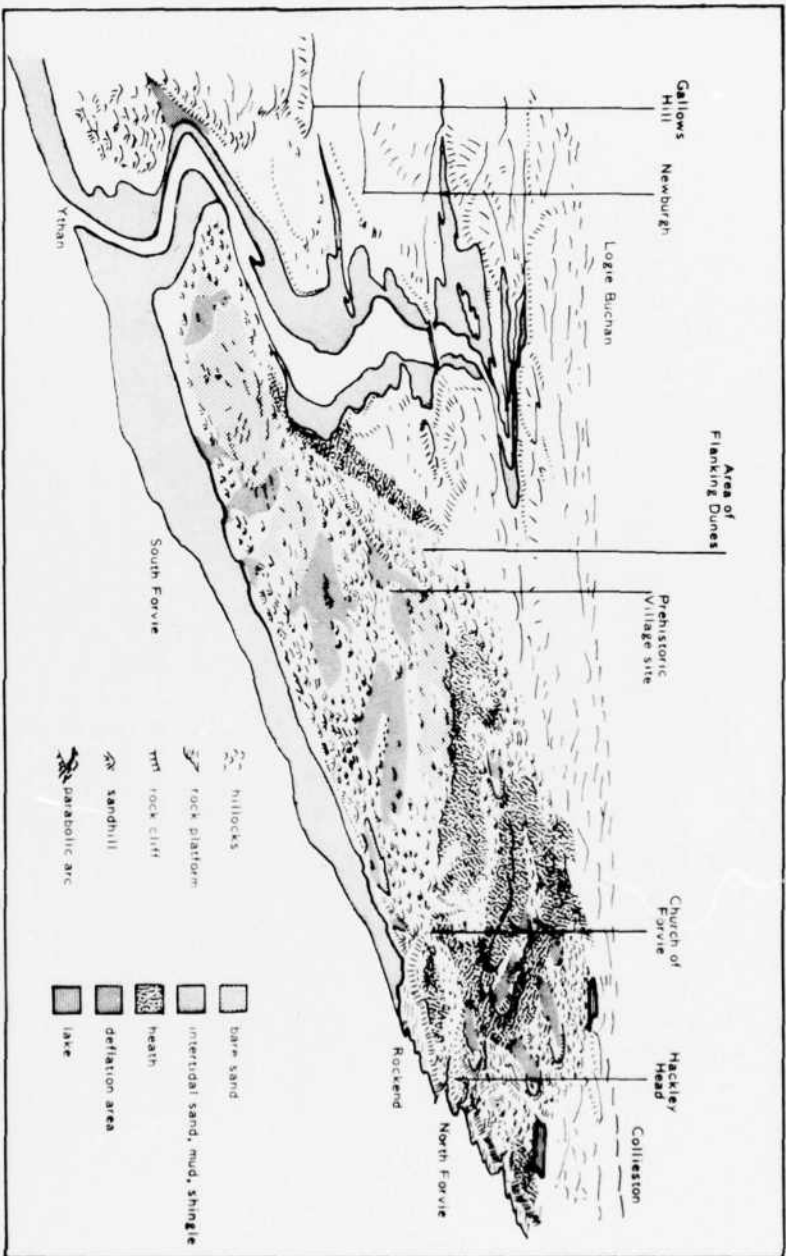> eiders (2,000 pairs) in Britain."*

The estuarine flats, marsh and cliffs of North Forvie are also described
in the same report as being of biological interest and value.

There is an extensive literature on the scientific study of parts of the
National Nature Reserve. The majority of these studies are ecological
and are also related to the Ythan estuary which is an integral and
vital part of the nature reserve area. There is also considerable
ongoing research in the estuary and adjacent sand dune systems. Since
its establishment in 1959, the area has been managed for conservational
purposes but a degree of recreational use is also present. Moreover,
the reserve is leased from Slains Estate who retain and use sporting
rights across the land. There is also considerable archaeological and
historical interest in the area.

To avoid the problem of presenting excessive detail a considerable
degree of generalisation has been made and this is summarised in the
accompanying figure which presents the main elements of the Forvie
landscape. South Forvie is a sand peninsula which derives its sand
supply from the beach and to a greater degree from the sand bar and
spit at the mouth of the Ythan. After the maximum extent of the last
major post-glacial transgression, which is usually referred to as the
Flandrian, around 7,000 years ago, sea level fell and sand, derived
from glacial and fluvioglacial deposits, was carried inland where
it accumulated over the raised beaches and estuarine terraces, and
across the pre-existing ridges and hills of glacial and fluvio-
glacial origin. The Ythan was the landward limit of sand encroach-
ment and probably provided a mechanism whereby sand carried westwards
across the peninsula was returned to the nearshore zone and recirculated

Sands of Forvie, Ythan, Foveran and Newburgh in 1946.

Gallows Hill

Newburgh

Logie Buchan

Ythan

Area of
Flanking Dunes

Prehistoric
Village site

South Forvie

Church of
Forvie

Hackley
Head

Collieston

Rockend

North Forvie

hillocks
rock platform
rock cliff
sandhill
parabolic arc

bare sand
intertidal sand, mud, shingle
heath
deflation area
lake

onto the beach and dune areas; a process which still continues. A vast
sand dune complex developed by an early date and the form of this
surface was to a large extent controlled by the shape of the underlying
non-sand landforms which appear to consist of curved glacial ridges
separated by broad depressions, with a broad band of low raised beach
surfaces running south from Rockend around the point of the peninsula
and reappearing as estuarine terraces on the side of the Ythan estuary.
These terraces occur at 3 to 6 m O.D. but there may also be a higher,
older terrace between 10 to 12 m O.D. These early dune and sandhill forms
would appear to have been in existence and locally stabilised probably
by 2000 B.C. or even earlier. Subsequent development must be partly
conjectural but it appears to consist of two main lines of movement.
The coastal dune ridge retained its position but suffered a degree of
wind erosion and redeposition with a tendency to produce secondary
forms at an oblique angle to the alignment of the beach. Secondly, the
central part of the interior was subject to considerable deflation with
a generally south to north trend. This created the so-called sand waves
and deflation areas which are clearly illustrated on the accompanying
block diagram. This sequence of plain and ridge forms consists of a low
deflation plain on the south side, a curved, high series of marginal
sandhills to the north and lines of residual dunes and active erosional
escarpments to the west and east. The east margin coalesces into the
coastal dune ridge to produce variable coastal edge morphology, i.e.
where the high sand arcs meet the coast high nodal sandhill areas are
formed. The exceptional feature of South Forvie is the great dome of
bare sand at the south end of the peninsula which is a north-encroaching
sand wave, and is continually nourished from the wide intertidal zone at
the mouth of the Ythan estuary.

Turning to North Forvie it is necessary to envisage that excess sand from
the peninsula to the south advanced northwards onto the sloping rock
platform, possibly in historical time (e.g. the Church of Forvie is
recorded as being inundated by sand in 1413). On this higher plateau,
detached from its primary beach and spit sources, the sand spread north-
wards either as discrete masses which followed separate routes to form
detached waves and sandhill complexes, or, the spread of sand was a more
continuous process and a more extensive former cover was broken into
the series of parabolic dune areas, groups of sandhills and active sand
escarpments which characterise the topography of North Forvie. There
is a contrast between the broad curves of South Forvie and the narrower,
more varied series of dune ridges of North Forvie. Moreover in South
Forvie the intervening areas are low, deflation plains but in North
Forvie, the areas between the sand dune arcs consist of sloping heath
surfaces and broad rock-controlled ridge forms with only a thin veneer
of blown sand.

In summary, North Forvie consists of sand ridges, parabolic dunes, groups
of sandhills and hillocks resting on red glacial till and separated by
broad heath-covered surfaces all of which rest on sloping metamorphic bed-
rock. With the exception of the cliff-girt Hackley Bay, North Forvie has
a rock cliff coastline. South Forvie consists of various dynamic sand
dune and hill forms with deflation and erosional surfaces of various
ages resting on fluvioglacial or glacial ridges or low raised beach/
estuarine terraces. South Forvie has an active sand beach and spit
coastline.

The balance of field and historical evidence (e.g. Landsberg, 1955;
Esler, 1976) indicates a generally northwards movement of sand which
may at times show a preference to diverge to the northwest or north-
east depending on the direction of dominant wind influences during

the specific formative period. As a final point it is also useful to reiterate that the Sands of Forvie are the northernmost part of Aberdeen Bay which is more than 20 km long. Along the length of this bay the dunes and links become broader and more massive northwards, and consistently reveal a tendency for sand to have a net northwards movement. With the added supply of the Ythan catchment it is not surprising that the most extensive dune and sandhill area should be found in the extreme north part of the Aberdeen Bay system and that it should encroach beyond its northern boundary of the rock headland and plateau of Rockend/ Hackley Head to reach a limit at Cotehill Loch which is 3.0 km north of the nearest source beach.

Except where the Ythan estuary is the landward boundary, the Sands of Forvie blend into rolling fluvioglacial topography which becomes generally higher northwards. An interesting boundary area is found on the northwest side of South Forvie where the dunes slope relatively steeply onto a low terrace which was a former elongated extension of the estuary during the Flandrian marine transgression. A similar terrace forms the banks of much of the remainder of the Ythan estuary downstream from the Bridge of Logie Buchan and underlies Newburgh village and links.
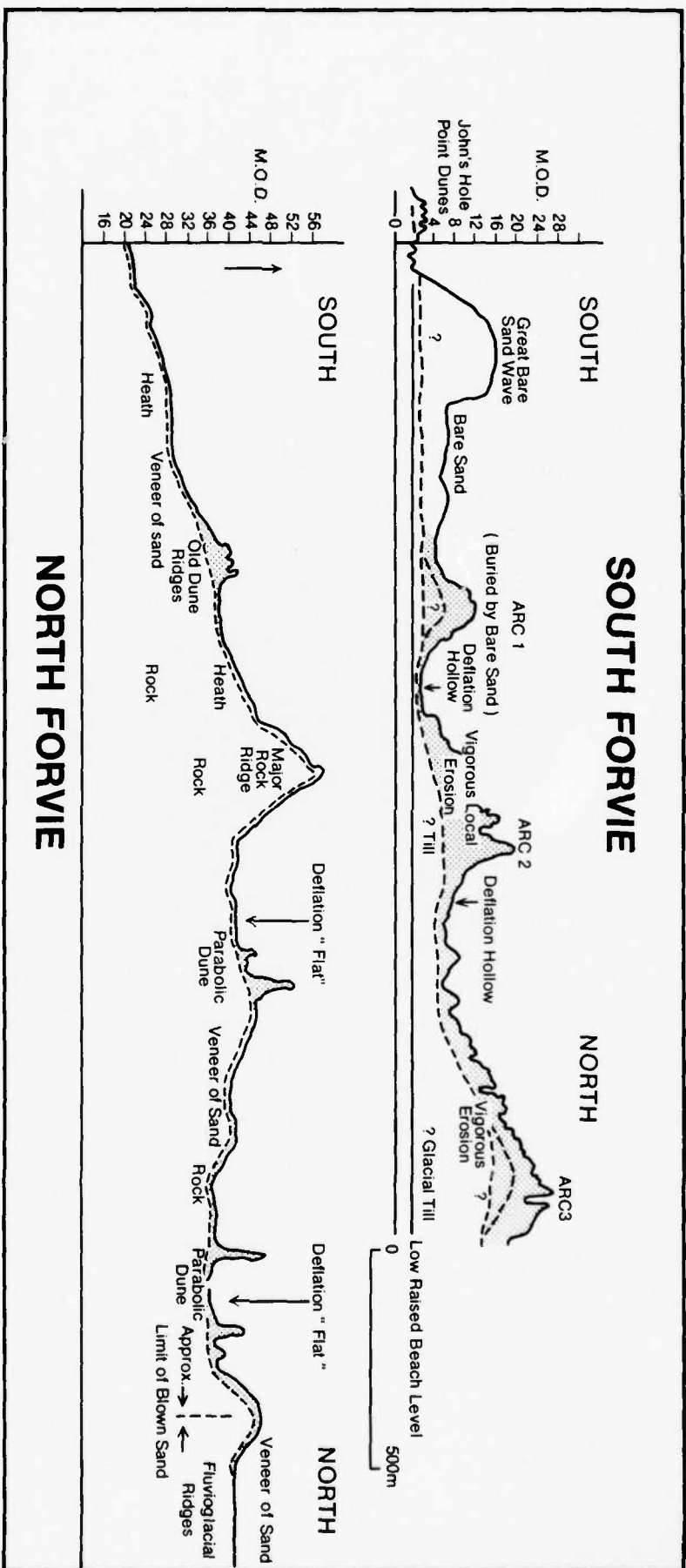
The mouth of the Ythan is a dynamic zone where tidal, wave and fluvial forms combine to form shifting sand bars in the intertidal and subtidal zone. A full account of the coastal processes operating in the zone cannot be given here. It is sufficient to stress the variability of this zone, the rapidity of sedimentary processes, the relatively high velocities achieved by coastal and fluvial currents and the crucial role that this wide sand area plays in the evolution of the dune systems of South Forvie.

Further north the beach becomes relatively narrow and high tides frequently reach the base of the coastal dunes. Beach bars and troughs suggest a north-going longshore current but from time to time this must be reversed as the spit at the mouth of the Ythan often points strongly southwards. The beach has a series of rip-current sections and also a further line of sand bars below low water mark. At Rockend there are patches of shingle and the beach terminates among a low, irregular series of rock platforms and reefs.

Further north there is an attractive cliff-girt enclosed bay, Hackley Bay, with a wide sand beach. The beach has a high tide radius of c. 350 m and the beach is over 200 m wide. Rock platforms, rock cliffs and spreads of shingle and cobbles mark the two extremities of the beach area. The backshore area has a storm beach of rounded shingle and cobbles which leads to a narrow platform backed by stabilised scree and fan deposits at the base of the steep rock and glacial till cliffs (see later section). The beach has a very low gradient and little sand is exposed during high tides.

North of Hackley Bay there are some patches of sand, shingle and cobbles within the irregular series of reefs and skerries which characterise the rock platform at the base of the North Forvie cliffs.

Four main types of coastal edge can be recognised at the Sands of Forvie; (1) the estuarine shore, (2) the open coastal dunes, (3) small cliff-foot platforms (e.g. Hackley Bay), and (4) the 3 km stretch of cliffs between Rockend and Collieston harbour.

SOUTH FORVIE

SOUTH

NORTH

M.O.D.

28
24
20
16
12
8
4
0

John's Hole
Point Dunes

Great Bare
Sand Wave

Bare Sand

ARC 1
(Buried by Bare Sand)

Deflation
Hollow

Vigorous Local
Erosion

? Till

ARC 2

Deflation Hollow

Vigorous
Erosion

? Glacial Till

ARC3

Low Raised Beach Level

0   500m

NORTH FORVIE

SOUTH

NORTH

M.O.D.

56
52
48
44
40
36
32
28
24
20
16

Heath

Veneer of sand

Old Dune
Ridges

Heath

Rock

Major
Rock
Ridge

Deflation " Flat "

Parabolic
Dune

Veneer of Sand

Rock

Deflation " Flat "

Parabolic
Dune

Approx.
Limit of Blown Sand

Veneer of Sand

Fluvioglacial
Ridges

The section of the estuarine shore which abuts on the Sands of Forvie
is a relatively short section, stretching just over 2 km north of
the river outlet. In the south the tidal sand beach known as Red
Inches curves into the bare sand surface of the South Forvie peninsula.
Sand banks slope down to this estuarine beach and blown sand often
spills across this slope. Towards the south, near an area known as
John's Hole Point, there is normally a low sand cliff where flood and
ebb currents run against the bank. About a kilometre north of John's
Hole Point the estuarine banks are composed of silt, mud and sand
with a superficial veneer of gravel. There are also mussel beds. Here
the bank is a low, water-washed terrace rarely more than a metre high.
The bank is normally cut into raised estuarine deposits with a variable
thin cover of blown sand. Occasionally a pure yellow (glacial?) clay is
found near the base of these under-cut banks.

In general the coastal edge of the dunes of South Forvie is character-
ised by erosion in the form of undercut sand cliffs. There are several
blow-outs which tend to a V-shape and some areas, especially in the
south, have been reduced to remnant dune segments and pinnacles and
there is little barrier between the backshore and inland sand areas.
There are high sand cliffs where the great curved sand arcs meet the
coast. One section near Rockend, for example, is almost 20 m high and
is a very prominent coastline feature. The coastal dune ridge is
normally lower and 10 m O.D. would be a maximum height. Associated with
the high degree of linear and blow-out erosion forms, there is consider-
able crest and backslope redeposition and vigorous vegetational growth.

At Hackley Bay and in a few sections further north there are narrow
cliff-foot terraces a few metres above high tide level and usually less
than 30 m wide. Little blown sand has accumulated on these coastal
fringes since the sands of Hackley Bay are normally wet throughout the
tidal cycle. There is also a stream and general groundwater seepage onto
these cliff-foot terraces and backshore areas; a feature which further
reduces the possibility of sand blowing. These terraces are backing screes
and detrital fans are vegetated and stable with a tendency to marshiness.

The cliffs range from a few metres in height at Rockend to more than
40 m O.D. at the north end of the Reserve. Developed on an irregular
sloping plateau of ancient andusite schists with a steeply tilted
foliation, they have a rugged, indented appearance. Stacks, caves,
skerries and reefs as well as geos and other inlets are common. The
cliffs are steep, but are often composed of two slope elements; a
steep basal rock section and an upper slope developed in red boulder
clay. The upper overburden of glacial deposits becomes increasingly
thick northwards and is always the greater part of the cliff profile north
of Hackley Head. Towards the north end of Forvie only the base of the
cliff is composed of rock and the upper section although remaining steep
(30° or more) is developed on these superficial deposits. The upper section
is usually vegetated and there is sometimes a veneer of blown sand. Some
slumping has taken place and it is difficult to determine the exact
relationship between the rock basement and the glacial overburden.
The cliffs are stable and geomorphologically relatively inactive. Wave
action is dissipated on the reefs and rock platform and rarely reaches
the base of the cliffline.

The general pattern of dunes and sandhills is as shown in the attached
figure   which is a simplified reduction of the 1:7,500 scale
published geomorphological map (Wright and Ritchie, 1975).

In the extreme south of South Forvie there is a group of dissected,
hummocky dunes rising to 8 m O.D.   There may be residual dunes from
a more complete cover.   They are, however, covered in vigorous Marram
tussocks and receive substantial amounts of blown sand from the wide
beach to the south.   (These dunes and adjacent gravel spreads are one
of the main resting and roosting areas for birds, especially terns.)
Other dune fragments are found to the northwest, east and north of
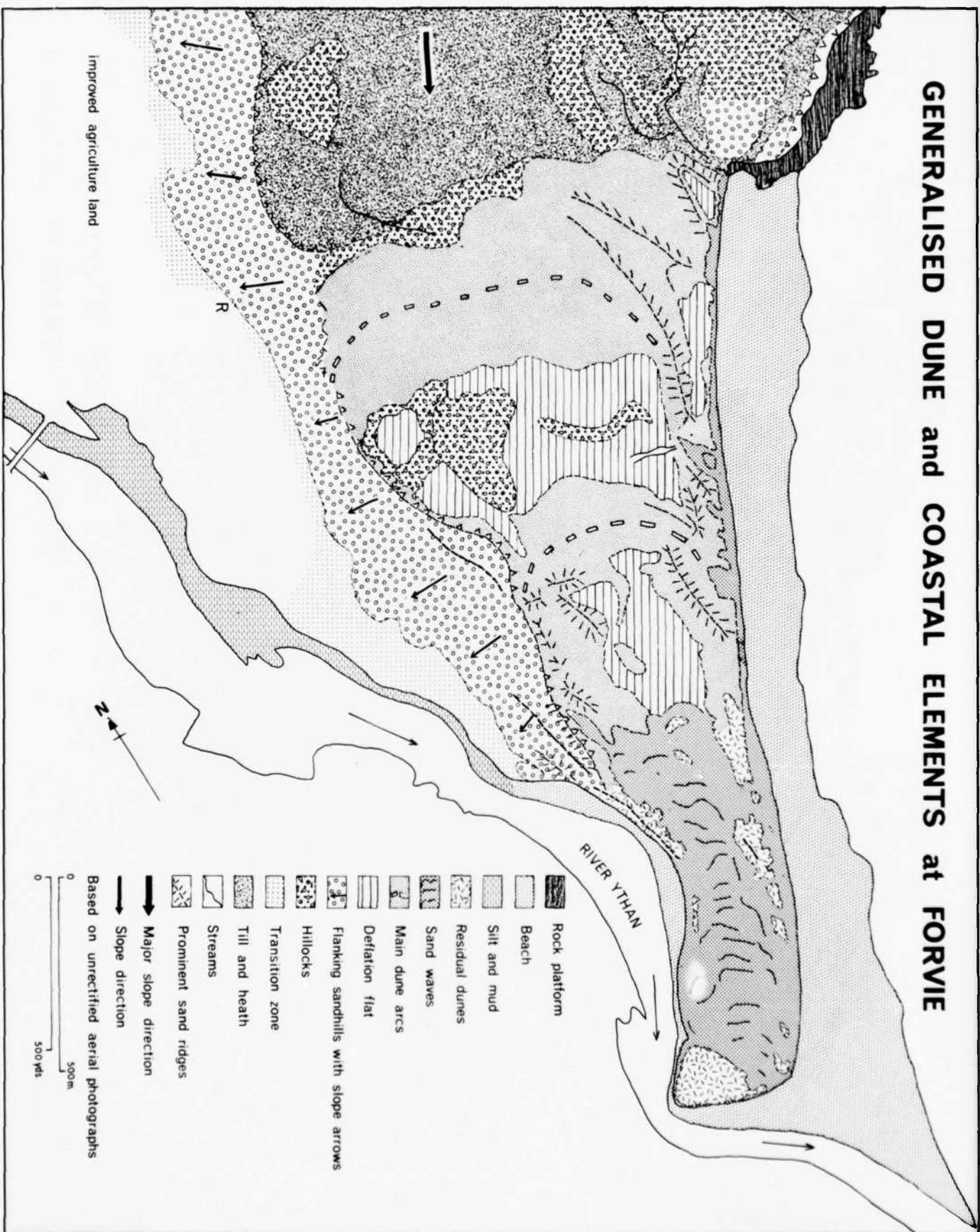this massive bare sand area.

Similar dunes form a broken line along the south part of the peninsula,
with crestline altitudes between 5 and 9 m O.D. Further north the coastal
dune ridge is continuous and has an average height of 10 to 12 m.   The
coastal dune system is interrupted by several V-shaped blowouts at
various stages of development.   Where the two main arcuate sand ridges
meet the coastal dunes, high, conical sandhills rise to over 20 m O.D.
and the dune relief patterns become increasingly complex northwards.
Older sloping surfaces and hollows are interspersed among the dune
ridges.

The two main arcuate sand ridges are massive features, in the south 500 m
wide and in the north about 1,500 m.   The north to south widths of these
ridges are both more than 200 m but the surface forms may be subdivided
into various ridge and deflation surfaces.   In general, however, the
south-facing slope is often at a stage of severe deflation and has been
reduced to a base level of an old soil horizon or the underlying glacial
till basement.   This is particularly true of the west side of the ridges.
There are also deep linear blow-out depressions and V-shaped hollows at
various degrees of activity.   Associated with wind erosion are redeposi-
tional forms of which the northwest side of the north ridge provides a
good example of a mass of bare sand spilling northwards as a steep,
partially vegetated talus slope.   The main crests of the south ridge reach
over 20 m O.D. whereas the north ridge can exceed 35 m O.D.   The dis-
tinctive rise and fall of the sand ridges over intervening hollows are
shown in the accompanying long profile.

Some auguring has been attempted in both of these massive sand ridge
areas and glacial till has been detected beneath the surface on the
west side.   A second profile summarises some of these field observations.
This figure also shows in more detail the raised estuarine terraces on
the west side of the peninsula.   Glacial till boulders and smaller
stones also outcrop on the surface of some deflation areas.

The remaining large area of dunes in South Forvie is the east-facing
escarpment and dune ridge which forms the west boundary of the sand
peninsula.   This escarpment can be traced continuously as a sinuous
line from almost the south tip of the peninsula across the depression
axis (which is used by the path to Forvie Church) and into North Forvie.
In North Forvie the ridge is less continuous and is only a conspicuous
landscape feature where it merges into the parabolic dune complexes
(see below).   For most of its length this escarpment has a steep and
frequently actively eroding east-facing slope. Numerous erosion
features break into the dune ridge and the crest is often a zone of
considerable redeposition.   The escarpment tends to reach higher absolute
altitudes northwards, e.g. it is 10 m O.D. in the south but almost 32 m
O.D. near the junction with the boundary path (i.e. between South and
North Forvie).   The backslope has a straight or concave slope and is

GENERALISED DUNE and COASTAL ELEMENTS at FORVIE

RIVER YTHAN

improved agriculture land

R

N

Rock platform
Beach
Silt and mud
Residual dunes
Sand waves
Main dune arcs
Deflation flat
Flanking sandhills with slope arrows
Hillocks
Transition zone
Till and heath
Streams
Prominent sand ridges

Major slope direction
Slope direction
Based on unrectified aerial photographs

0   500m
0   500 yds

completely stable. The backslope merges into a transitional zone of tussocky dune pasture and raised shoreline terraces.

The remaining group of dunes and ridges within South Forvie consist of minor residual features of low relief amplitude. There are also oblique ridges and hummocky forms are particularly common on the west side of the coastal dune ridge but there is a conspicuous area of rounded hillocks on the west side of the dune backslope which leads down to the Ythan estuarine terraces.

A different type of sand dune morphology is found in North Forvie. These are described as parabolic dunes by Landsberg (1955). A detached group of parabolic forms is found in the northwest of the area, and a massive west-facing group is found north of Hackley Bay. Another group occurs north of this and extends as an irregular escarpment as far as the west side of Sand Loch in the extreme north of the reserve. The remaining parabolic arc is found in the centre of the north plateau. A similar series of ridges and escarpments from the northern limit of the Sands of Forvie near Cotehill Loch - a distance almost 6 km north of the mouth of the Ythan. These dune arcs face south, southwest and west and consist of several intersecting parabolic sections with trailing 'arms' of lower dune segments. Field mapping indicates that there is consider-able variation in geomorphological activity and some parts of the ridges are stable. Insufficient evidence is available however to indicate how these dunes and sandhills migrate over pre-existing heath and similar surfaces.

Other forms of sand deposition occur in North Forvie. The most common consists of a 'field' of hummocky dunes and low, rounded sandhills. The best example of this surface is found in the area north of the ruins of Forvie Church. Residual dune areas are also found especially south of the parabolic arc systems. The northwest and west margin of North Forvie is a series of dune ridges and hillocks which sometimes merge into undulating, less conspicuous, mature blown sand surfaces.

Because the dunes and sandhills lie on a plateau of rock which is covered by a variable capping of red clay till and has an altitude ranging from 20 m in the south to 35 m O.D. in the north, summit altitudes are remarkably high. Most ridges exceed 45 m O.D. and several crests exceed 50 m O.D.

The highest altitude in North Forvie is not a sandhill however, but is a broad rock which dominates the landscape of North Forvie and stretches for more than 1.5 km northwestwards from a point c. 300 m northwest of Hackley Bay. A trigonometric pillar marks the crest of this ridge and has an altitude of 57.2 m O.D.

Between the lines of dunes and the major sand arcs there are distinctive flat or gently sloping surfaces. In South Forvie, these would appear to be deflation plains which were produced as the sand dunes migrated in a generally northwards direction. Some of these plains reach the base level of wind erosion which is the water table and are therefore marshy. Many low areas flood in winter. In other areas the base level is raised beach gravel layers and in a few areas, especially further inland, the glacial till basement is exposed (e.g. near the 'prehistoric village site'). In the south of the peninsula one of these deflation plains is in process of disappearing beneath the leading edge of the broad, advancing sand wave.

In North Forvie similar flat, marshy deflation plains are produced in
'front' of all the parabolic dune systems. The processes of retreat
creates a plane surface at or just above the water table which, in turn,
overlies the glacial till surface. This can be seen particularly
clearly in the parabolic arcs due north of Hackley Bay. Similar forms
at various stages of activity are found at the north limit of the reserve
where there is a complex pattern of curved hollows, marshes and low
residual sand ridges.

In North Forvie the greatest area is occupied by sloping expanses of
heath with a distinctive Heather/Crowberry vegetation, often associated
with a considerable cover of Lichens and Mosses. This acid heath has
developed on the glacial deposits and has been influenced by drainage,
altitude and exposure. In many areas, however, the surface layer is
composed of a thin veneer of blown sand. Occasionally thicker sand
layers (more than 1 m) are found, and it would not be true to describe
the heath areas as 'non-sand' areas. There is considerable complexity
in the vegetation cover (Landsberg, 1955; Burnett, 1964; Wright and
Ritchie, 1975) and in some areas this can be related to cultivation
within the historical period. Patterns of rigs can still be seen on the
ground and in aerial photographs and these patterns can also be seen in
South Forvie on the terraces near the estuary.

Several streams drain the area and there are more than a dozen separate
systems of drainage ditches, some of which peter out into vague
depressions and seasonal marshes. This waterlogging promotes acidity
and is a major factor in explaining the vegetation pattern. There are
several pools and small lochs. All these features reflect the broad
relief patterns created by bedrock and glacial deposits. Of particular
importance and topographical significance is the large valley of the Burn
of Sanyne and its associated tributaries. This valley forms the boundary
between North and South Forvie and reaches the coast 100 m west of
Rockend below the plateau upon which the ruins of Forvie Church are
found. This major depression is used by the footpath from the main gate
to Forvie which leads eastwards to Forvie Church and down to the beach.
It is thought that this valley might correspond to the south boundary
of the basement rock surface, but no proof of this is available so far.
In the extreme north the underlying landforms are kames and eskers of
a fluvioglacial origin and Sand Loch and Cotehill Loch are probably
flooded kettle-hole depressions into which blown sand has drifted since
at least the 18th century.

A variety of other landform elements can be recognised - stream margins,
loch depressions, marginal sand spreads, residual ridges and hummocks,
and fields of small dune and sandhill forms. In relation to the great
extent of the Sands of Forvie, however, these forms must be considered
too small to merit detailed description.

Vegetation has been a subject of considerable research effort at Forvie
and there are several ongoing projects. Landsberg's thesis (1955) is
primarily a vegetation study. A detailed map was prepared by the
Departments of Botany and Geography at Aberdeen University in 1972
using 1967 aerial photographs (Wright and Ritchie, 1975). More than
twenty distinctive associations were recognised in this study but for
cartographic reasons these were reduced to eight main types. These
groups can be further rationalised into four categories, viz. - bare
sand , Ammophila dominant, heath (Heather and Crowberry dominant) and
dune pasture (mainly Festuca, Poa, Agrostis); and these types have
a close association with the distribution of landforms and their

degree of mobility. The N.C.C. Warden in his 16th Annual Progress
Report (1977) notes that seventeen unrecorded species of fungi from the
reserve were added to existing lists to bring the total to 60. He also
completed a survey of vascular plants to bring the present total to 267
species. It is also interesting to note that in the same report a start
was made to record marine algae and other lifeforms on the rocky shore
of North Forvie, thereby adding another dimension to the scientific
interest in the area.

Zoological research is equally significant. Although famous for its
bird life, especially ducks (particularly nesting eiders) and seabirds
(especially nesting terns), several studies have been completed and are
underway on invertebrates, lepidoptera and terrestrial molluscs. Some
of this research interest lies mainly in the Ythan estuary but it is
impossible to consider the dune system and the estuary as separate
environments; there being too much interdependance and ecological
linkages between the two areas. In 1977 along the Warden notes fourteen
major zoological research activities in the Sands of Forvie that are
currently active. They range from the study of foxes to fulmars and
from brown trout to moths.

Since the excavation of the prehistoric village site by Kirk (1955),
Forvie has been recognised as being of considerable archaeological
importance. Stone circles, spreads of flint flakes and other finds
have all been recorded, and a number of sites are currently under
investigation.

Some historical research in documented records relating to the old
parish of Forvie was used by Landsberg (1955) to attempt a reconstruction
of sand movements. A field of research remains in the distribution and
nature of the old cultivation rigs which are scattered over North Forvie.

Several physical geographical studies have also been completed (e.g.
Walton, 1966; Esler, 1976; Stove, 1978) and other projects are under
way, particularly these relating to dynamic aspects of geomorphological
development at the mouth of the estuary, on the rates of movement and
short-term changes in specific dune ridge areas, and salt-marsh micro-
form studies.

1 (c)   RATTRAY HEAD

Rattray Head is a double peninsula that forms the transition between the
east-facing beach and dune system of Rattray Bay and the northeast-
facing Strathbeg Bay to the north. No clear-cut division exists between
the Rattray and Strathbeg systems and the boundaries shown on the accompany-
ing figure are somewhat arbitrary. The focus of the area is never-
theless clear and consists of the road leading past the lighthouse
shore station houses to the car parking area and, further, to the track
leading to the point on the beach opposite the important lighthouse of
Rattray Head which lies some 250 m offshore on a small rock outcrop called
'The Ron'.

Rattray Head has a complex offshore configuration which consists of a
series of low intertidal rock platforms which are partially covered by
sand banks. There are also low, wave-washed ridges of boulders and
shingle which have been derived from a former cover of boulder clay. To
the south and north this variable, shallow offshore configuration of
reefs, banks, pools and platforms gives way to a sand bed, although
occasional outcrops of boulder clay can be seen beneath the sand cover
after particular storm and wave conditions.

Associated with this variable seabed configuration are complex patterns
of wave action and the planimetric outline of the beach low water mark
consists of a series of points and inlets corresponding to complex
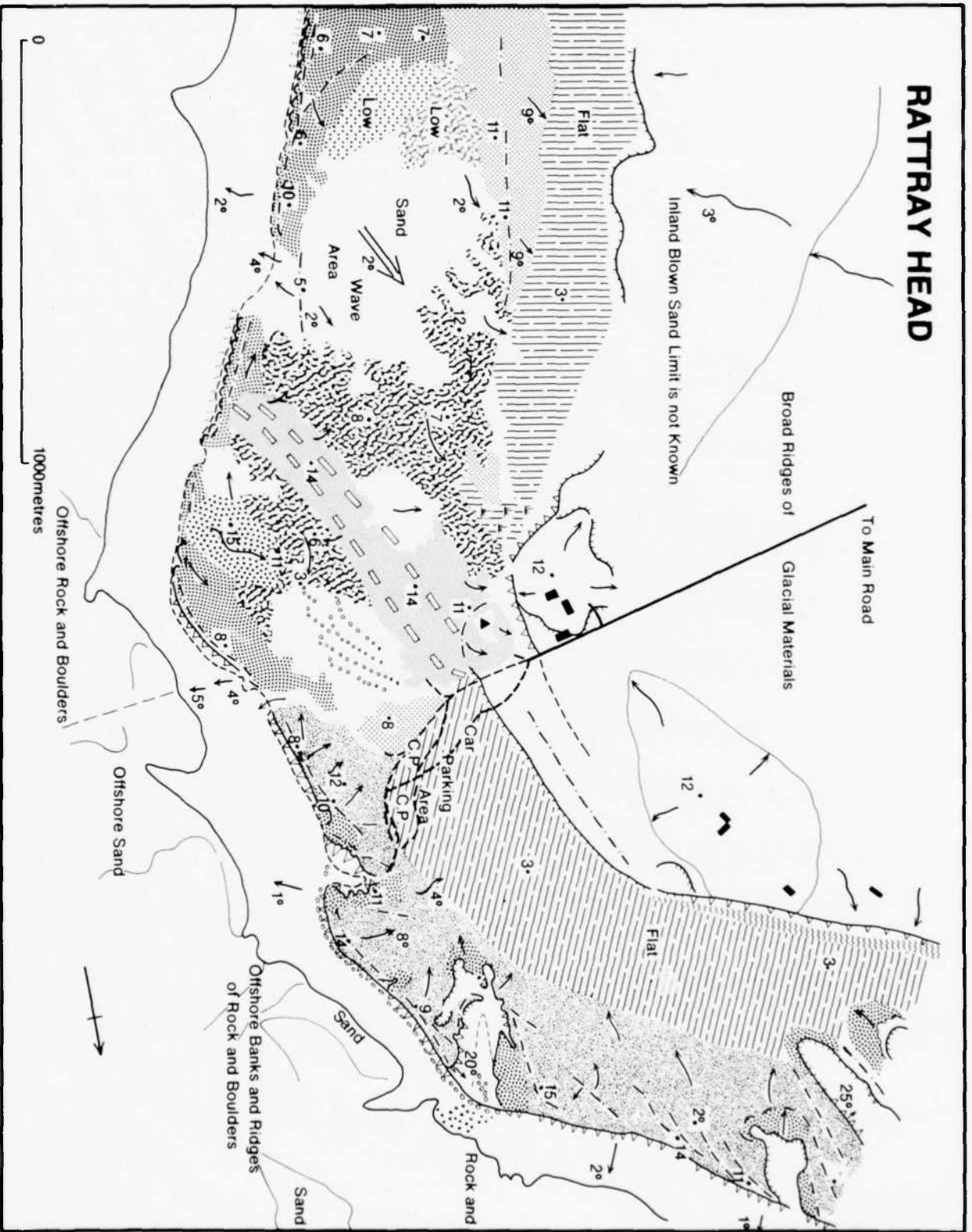refraction and reflection wave patterns.

The intertidal beach varies greatly in slope and general morphology.
There are also variations in composition with gravel and broken shell
layers being common. The mobility of the beach may also expose buried
materials. North of the main promontory area, beach cobbles outcrop at
the base of the retreating dune cliff. These and other exposures within
the dune system indicate that the dunes rest on an extensive series of
shingle and cobble bar and spit formations which are probably of a
similar age and origin to those found further north at Strathbeg.

The main contrast in the nature of the coastal edge is the prevalence
of active erosion in the centre and north of the area. High, actively
retreating sand-cliffs are associated with this north area whereas the
coastline south of the headland is lower, more rounded and has consider-
able banks of accreting sand above high water mark at the toe of the
frontal dune ridge. In the centre and north of the area active blow-out
corridors break through the high dune ridge and there is active
redeposition on the sides and inner margin of these deflation features.
Large bare sand features are also found south of the headland but these
tend to consist of mounds of fresh, accumulating sand, moving in from
the beach and linking-up landwards with the extensive deflation surfaces
further inland.

The coastal edge is characteristically high and normally sharp-crested.
Redeposition is active and there is considerable variation in the
stability and cover of vegetation in different parts of the main
coastal ridge.

North of the car parking area the dunes are a continuation of the Strathbeg
system to the north and are massive features, rising to over 15 m O.D.
A single dune ridge rises abruptly from the flat, low (c. 3 m O.D.) links
surface to the landwards and contrasts sharply (especially in the north

RATTRAY HEAD

Inland Blown Sand Limit is not Known

Broad Ridges of Glacial Materials

To Main Road

Flat

Flat

Low Sand

Low Sand

Wave Area

Car Parking

C.P. Area

C.P.

Offshore Rock and Boulders

Offshore Sand

Sand

Sand

Offshore Banks and Ridges of Rock and Boulders

Rock and

0

1000metres

where extensive blow-outs have developed) with the maturity of the inland plain. Blow-outs and ridge crests tend to be orientated in a north to south direction whereas the coastline has a general northwest to southeast orientation.

Opposite the lighthouse the topography is more complex and has been affected by tracks to and through the dune area. South of the car parking area there is a complex series of deflation surfaces (down to a basement shingle platform), small redepositional hillocks, older sandhills and several types of curved dune ridge systems. Further south there is an extensive sand wave area of bare sand which is developing in a northwesterly direction. Smaller deflation surfaces are also found and are associated with various types of redepositional features. A broad, high ridge of more continuous dunes sweeps southeast across the system from the lighthouse keeper's houses to the coast. In the landward extremity of this ridge is an exposure of glacial till and this dune ridge may be partly based on a ridge of glacial deposits.

In the extreme south of the area the dunes are part of the double line of dunes which stretch southwards for more than 3 km towards St. Fergus.

Inland, the inner dune and sandhill surfaces spill onto a narrow links depression which has been described as a winter loch since it is under water for most of the winter. Inland from this low-altitude, wet depression is a low terrace which forms the margin of the broad, high ridges of glacial material. These massive inland ridges are partially covered in blown sand and it is difficult to define the boundary of sand penetration. Old clifflines at other breaks of slope on this ridge have been described as corresponding to higher sea levels and the area is an important location for studying changing sea levels and coastal configurations in the northeast of Scotland.

There would appear to be nothing of particular interest in this area and the vegetation is typical of the areas to the north and south. The main association is Marram Grass with a wide range of vigour and age. A few Sea Lyme plants are found on the north side of the headland. Associated with human activities near the car parking area are stands of Fireweed, and Thistles and Ragwort are common plants on the dune back-slope and links areas.
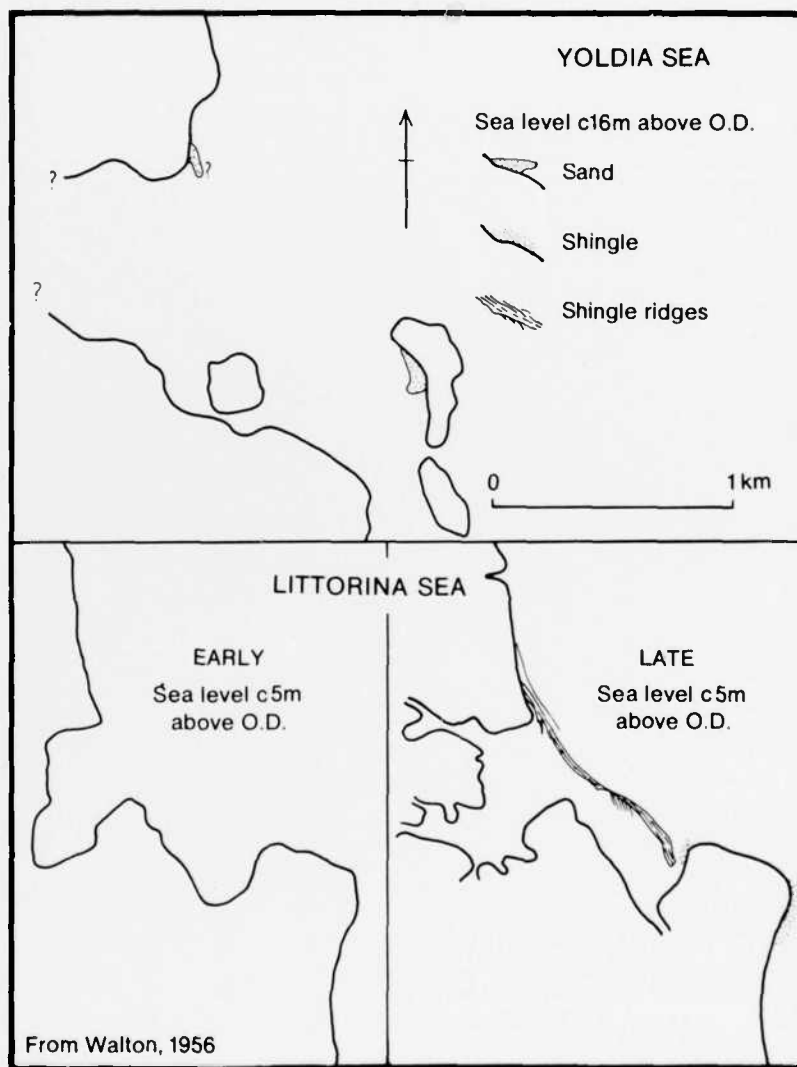
There is also a rabbit problem and this added to grazing increases the tendency of many areas to suffer active erosional damage.

1 (d)   STRATHBEG

Strathbeg dune system lies between St. Combs and Rattray Head. The
coastline faces northeast and runs parallel to the long axis of the Loch
of Strathbeg, a unique sand dune loch which is of considerable extent but
shallow depth and which forms the landwards limit of the extensive dune
and links system. As described by Walton (1956) the loch and the
associated dunes were formed by the progressive enclosure of a former
sea inlet. The main mechanism was the series of shingle bars which
grew from St. Combs southwards. These bars are still prominent landform
features and may be traced throughout the area. In the south, for
example, they form the southeast margin of the loch and re-curves at the
distal end of the bar run into the loch. The evolution of the area is
nevertheless a complex sequence and the reader is referred to Walton
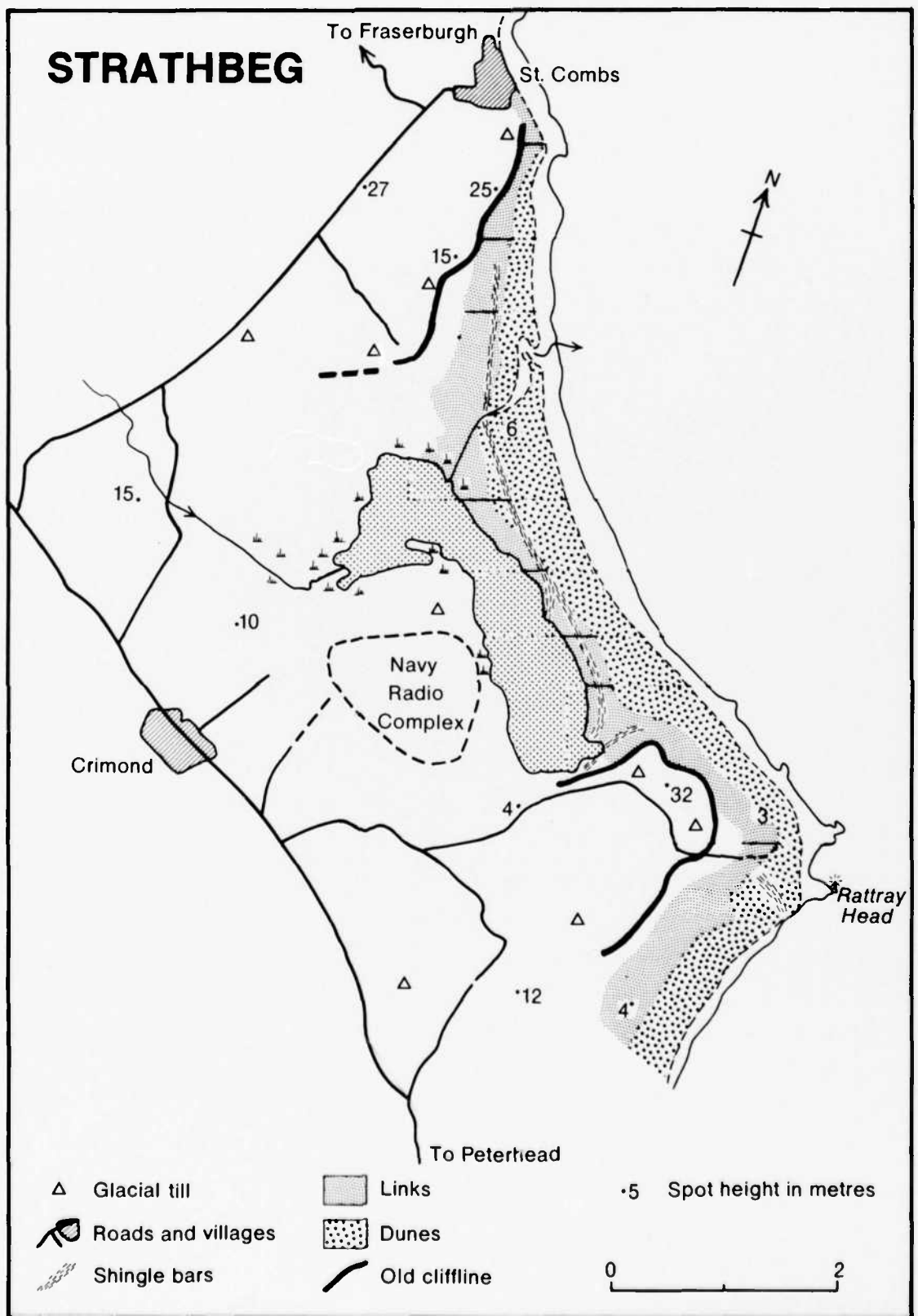(1956) for further details, including the role of sea level changes in
the area.

The loch is a focus for a considerable part of the drainage system in
this part of northeast Scotland and has a high nutrient level (Forteath,
1977). It is also a most extensive water body and attractive to thousands
of birds of numerous species, especially migrant geese. Indeed it is
claimed that it is the largest *"paramaritime body of water in Britain"*
(N.C.C. Review, 1977). As such it is a wildlife reserve of national
importance; a status recognised by its designation as a Grade I S.S.S.I.
by the N.C.C. and an internationally known bird reserve by the R.S.P.B.
For a succinct description of the botanical and ornithological importance
of Strathbeg, including the dunes, the reader should consult the article
in Nature (1973) by Bourne, Gimingham, Morgan and Britton. The S.S.S.I.
and R.S.P.B. reserves are not precisely the same areas but, in effect,
all the dunes, links and loch areas may be considered as nature reserve
areas. To the west of the loch is the Ministry of Defence Radio Complex
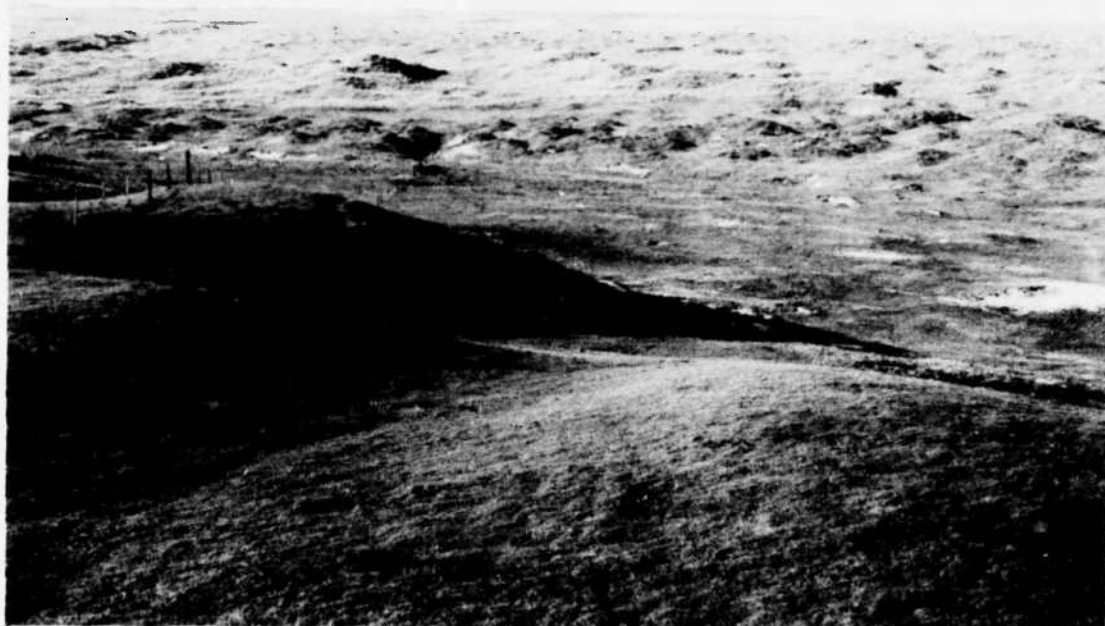which occupies the site of an old airfield.

The beach is relatively narrow - normally less than 90 m with a slightly
steeper backshore zone. At the north and south ends the smooth arcuate
form is broken by minor beach arcs which correspond to more extensive
intertidal rock platforms and reefs. In the north-centre the beach is
much wider and there is an extensive intertidal lagoon which corresponds
to the outlet course of the only stream draining the loch. This stream
is an artificial cut of considerable age (i.e. at least 200 years since
it is shown on the Roy map of c. 1746). This outlet cut has sometimes
been used to regulate the general level of the loch. Elsewhere the beach
has a regular profile but is also characterised, especially in the south,
by a series of berm ridges and sub-parallel beach depressions. Offshore
there are clear indications of complex sand bars, lying 'en echelon' just
below low water mark. The offshore zone near Rattray Head is particularly
complex with sand bars, rock reefs, boulder and shingle platforms and
other shallow coastal forms lying near the beach zone. Most observations
suggest that the beach is highly dynamic and that the general drift of
sediment is variable. It is also a beach with strong evidence of
accretion on the backshore zone. This process which is intimately
linked to the progradational evolution of the parallel dune ridges
which consolidated the shingle-bar enclosure of the loch in post-
glacial and later times. Accretion appears to have continued into the
20th century and field examination shows it to be continuing south of
the outlet cut.

Suggested Evolution of the Coast in the Rattray Area

From Walton, 1956

STRATHBEG

To Fraserburgh
St. Combs
·27   25·
15·
·6
15.
·10
Navy
Radio
Complex
Crimond
·4   ·32   3
·12   ·4
Rattray
Head

To Peterhead

△ Glacial till   Links   ·5 Spot height in metres

Roads and villages   Dunes

Shingle bars   Old cliffline

0   2

General view of south links and hillocks.

Southeast corner of Loch of Strathbeg.

STRATHBEG (Centre)
(Partly Schematic)

Cross section

N

Tidal slack

Loch of Strathbeg

Old Cliffline 5-9m high

Shingle

Coastal dune ridge

Dune slacks

Area of parallel dune ridges

Smooth links /machair plain

800 metres

S.W.
Old Airfield

Glacial Till

Water Level 2m. O.D.

Bed of Loch is Mostly Sand

? Glacial & marine sediments

Sand

Shingle

?Rock Head?

3
7
O.D.
7m

1600m
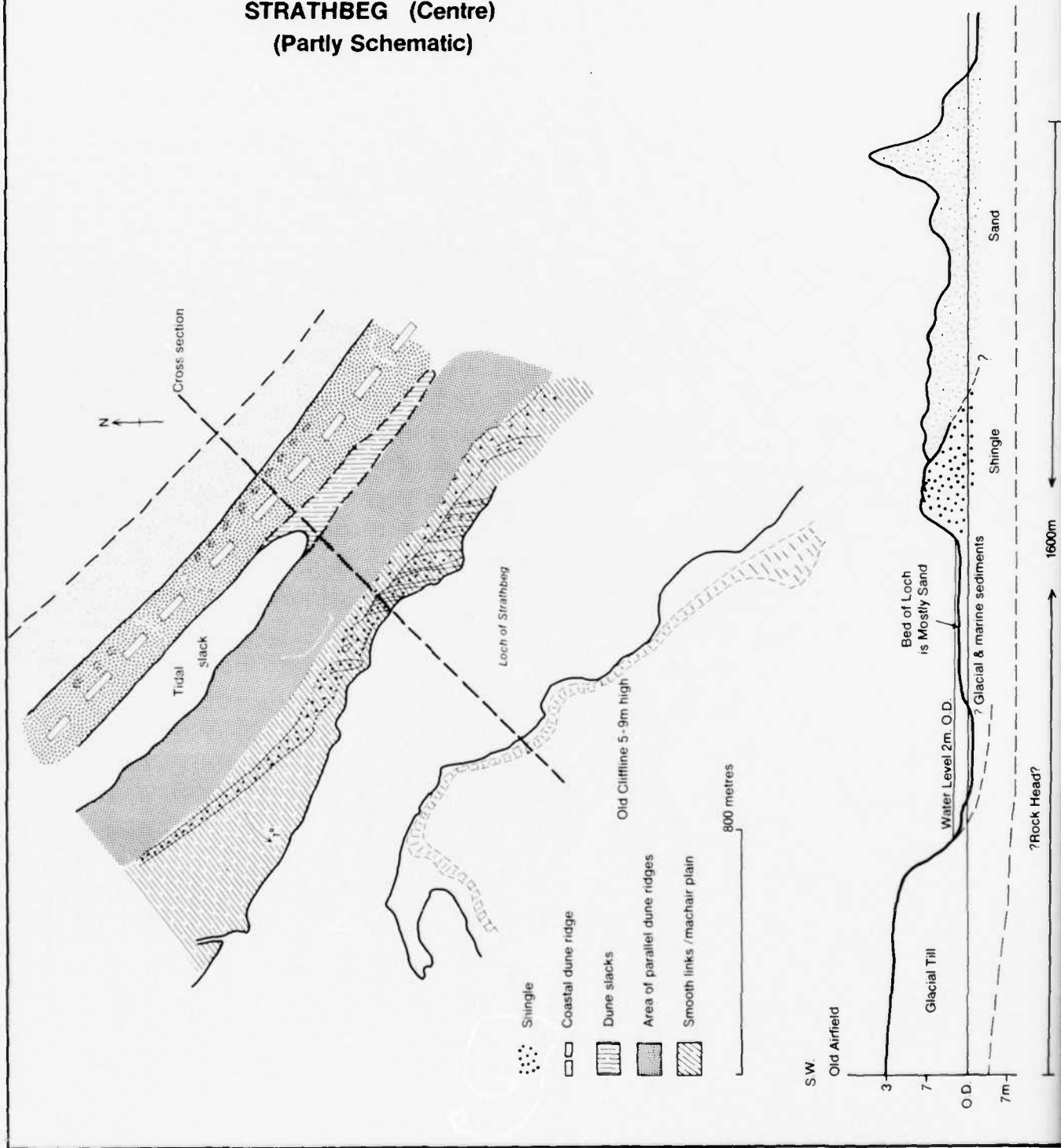
The availability of sand in the backshore area has allowed a new fore-
dune to develop at the base of the main dune ridge. This ridge has a
distinctive concave profile with the central axis being bare, accumulated,
sand mounds. To the seawards the new ridge is consolidated by vigorous
Marram and Sea Lyme tussocks but other pioneer species are also present.
There is, for example, a rich platform of luxuriant Sea Rocket at the
extreme south end of the beach near Rattray Head.

In the north end of the bay the coastal edge is a steep, active sand-
cliff, 4 to 7 m high. The coastal edge becomes lower and more 'neutral'
towards the area of the outlet lagoon and ultimately consists of low
progradational ridges and mounds which are part of the spit-like feature
which is growing southwards across the intertidal outlet lagoon area.
South of the outlet there is a short sand-cliff section which changes
to the 'normal' compound, accretionary profile.

The coastal edge is usually 6 to 9 m high and has a 12 to 15° slope.
In the south, however, the edge is broken by several major south to
north orientated blow-out corridors. Here the order of relief is much
greater and remnant dune ridge sections near the coast often rise to
20 or even 30 m above sea level.

From north to south there is considerable variation in the morphology
and development of the extensive series of dune forms found at
Strathbeg.

North Strathbeg has an exceptional coastal sand-cliff which is under-
going active erosion. Inland there are multiple parallel dune ridges
with 2 to 5 m. of relief and summit altitudes ranging from 5 to 10 m.
O.D. To the north of these mature sand ridges is a higher, more
irregular hummocky area which is succeeded northwards by a higher
coastal section. This is, in turn, succeeded by a low machair-like
coastal platform, some 3 to 5 m. above beach level and formed over
a raised beach terrace. An incised small stream forms the junction
between the (higher) dune and (lower) coastal sand platform.

Further south the coastal dune ridge is truncated by a series of oblique
dune ridges. These are lower, more recent features and are associated
with arcuate accretional ridges. This younger system clearly diverges
from the older, parallel dune ridges which are found further inland.
Very young embryo and pioneer sand hummocks indicate the continuing
southwards movement of this spur of sand dunes which enclose the north
part of the tidal lagoon associated with the outlet of the drainage
cuts from the Loch of Strathbeg.

South of the gap created by the drainage outlet there is a massive
asymmetric dune ridge rising to over 8 m. O.D. This ridge was mapped
by Walton in the 1950's and he recorded that it was only in process
of formation at that time (Walton and Ritchie, 1978). Like the dune
ridges to the north there are few bare sand or erosion features
associated with these dunes. Further south the dune ridge is growing in
height and width and many of the bare sand features are not produced
by erosion but are simply excess accumulation on the dune crest and
slopes.

This dune ridge and associated secondary features provides the sea-
wards boundary to the long narrow tidal lagoon and sandy saltmarsh
area. The parallelism of the Strathbeg dune morphology is illustrated
by the accompanying schematic figure; a parallelism which reveals the

continuing accretional history of the system since its post-glacial origin with the enclosure of the loch by the shingle ridges of the Back Bar. There are, in fact, eighteen separate dune crests between the beach and the loch margin.

Further south the main coastal dune ridge retains the massive characteristics which are described above. At a point approximately level with the south end of the loch there is a marked change in morphology. A series of large blow-outs and deflation surfaces cut deeply into the dune system. High residual hills and sand ridges create a spectacular, active, coastal landscape. The erosion hollows are not recent and can be clearly seen in aerial photographs dating from the 1940's. There is also considerable field evidence of recolonisation and re-deposition on the blow-out floors and especially across the breaches in the main coastal dune ridge. There are, nevertheless, very spectacular, large-scale erosion features which allow deflation processes to cross through the dune system completely and reach the margin of the low links surface to the south and west. Very high ridges and active sand escarpments form the margins of these blowout corridors. Some of the highest sandhill altitudes (over 35 m. O.D.) in Northeast Scotland are found in this general area.

In general, the main coastal dune ridge is succeeded inland by multiple ridges of increasingly mature lines of dunes. In the north and centre these ridges are particularly clear. Towards the south the pattern is more diffuse and the lines of dunes splay-out and become increasingly broken. On the ground the dunes break-up into fields of low sandhills and hillocks and it is only on aerial photographs that one can differen-tiate the broad grouping of features which suggest that the parallel ridge systems end some distance short of the south end of the loch and there is a lower plain and hummocky zone between these parallel dune ridges and the high glacial and fluvioglacial plateau. It is possible that this low area may represent the old gap or inlet which was used as an access to the sea from the tidal loch of Strathbeg when Rattray was still an important trading port in the late 17th century (for a description of the decline of the seaport of Rattray which once flourished on what is now the south shore of the Loch of Strathbeg the reader should consult Walton, 1956).

The lines of parallel dunes are particularly well developed near and over the old raised shingle bar which runs the entire length of the east side of the loch and, indeed, is the reason for the formation of the loch in historical time. These dunes and the series of shingle bars are extremely prominent features especially near and south of the outlet drainage cut. Between the parallel lines of dunes, especially the inner, higher ridge systems, there are linear hollows and in the centre of the area distinctive grassy flats and dune slacks. Nearer the backslope of the present coastal dune ridge the morphology is more complex, and consists of an extensive series of large hummocky sandhills.

To understand the evolution of all the different dune elements and their relationships to the loch, the shingle bars and the coastline would require a major research project, nevertheless it is important to state that the morphology of the dunes suggests a parallel progradational development of dune ridges on a wide beach which was banked against the original, older shingle bar and spit structures; a process that appears to be continuing.

Links and machair-like, short grass surfaces exist in several types of localities. They exist as narrow elongate depressions between dune ridges. The east shore of the loch has a smooth, short-grass sward developed, in the main, on the flatter landward slope of the shingle ridge system. In the north and south extremities of the area a more extensive level links surface, only 3 or 4 m. above sea level separates the hillocks and dune ridges from the old post-glacial cliffline which forms a distinctive, abrupt boundary to the main Strathbeg dune system. This old cliffline also forms the south, west and north margins of the Loch of Strathbeg and is a very clear topographical feature. Most of these flat areas flood in winter and represent the gap between the south limit of the shingle and dune ridges and the high plateau surmounted by the coastguard station. It is probably the remnant of the former opening between the loch of Strathbeg and the sea.

Near the outlet cut and elsewhere along the sides of the loch there are more extensive marshy areas where the surface is lower and the drainage inefficient. Nevertheless, in these localities the basic soil substrate is sand (as is the bed of the loch) of a probable wind-blown origin.

The influence of wind-blown sand decreases sharply westwards but it is difficult to define an exact boundary due to agricultural, drainage and other land improvements and modifications.

In the north and south ends of the Strathbeg area there are high sand surfaces, possibly of an ancient origin, on top of the high inland plateaux of glacial till. Although old surfaces, at altitudes greater than 20 m O.D. and often used for improved grazings, it is possible to detect old ridge and depression forms. In the south the surface is quite hummocky and in the 1940's, and more recently, was subjected to considerable active erosional activity. Remnants of this activity can still be seen in places. Blown-sand also masks the slope of the old post-glacial cliff but the cover is variable and sometimes completely absent.

Geomorphological activity occurs in several zones and some have already been described in the preceding sections. Nevertheless, it is possible to highlight the main zones of current activity - the beach, the dune face, some coastal blow-outs and a few erosional points further inland. There is also stream and tidal action in the extensive tidal pool area. Dune face erosion is largely confined to the north end of the beach but there is also a very active zone of wave undercutting and sand slumping in the extreme south where high sand-cliffs are produced. Elsewhere the coastal edge tends to be in process of aggradation, and this generalisation includes the entrances to the most northerly of the major blow-out corridors. On the coastal and inland dune surfaces wind erosion is of a very low order of magnitude and the system can therefore be described as essentially stable; the exception being the major deflation areas in the south of the area.

Geomorphological activity associated with the loch and its associated drainage outlet is almost entirely depositional. Stream-carried silts and muds as well as organic matter are accumulating on the loch bed (Stove and Durno, 1978). There is little evidence of much wind-blown sedimentation associated with present processes.

1 (e)   CULLEN LINKS

(view from Hotel at NJ 500 672)

Cullen is an exposed open bay facing north-west between the headlands of
Scar Nose and Logie Head. The basement quartzites which form the main
setting of the bay are capped on the north-west headland by Old Red
Sandstone conglomerates and breccias. The beach and landward links are
backed by an impressive degraded raised cliffline cut into the conglo-
merates, with the imposing backdrop continued eastwards by a massive
embankment and railway works. Raised sea stacks of Old Red Sandstone
protrude through the golf links, while smaller quartzite residual stacks
diversify the shore platform within the intertidal zone.

Two relatively straight beach sand arcs are hinged to, and rest on top
of a quartzite intertidal platform. The upper beach consists of a
fringing cobble and shingle beach, largely of quartzites, some of which
are originally derived from weathering out and recycling of the conglo-
merate outcrops. The coastal edge takes the form of a backshore ridge
highest in the east, where it has been much modified by tipping and
human interference including rudimentary coastal defence works,
declining in height westwards. At the western end, the upper beach
passes almost imperceptibly to grassed links. Undercutting of the coastal
edge to the west of the man-made defences reveals interbedded sand and
cobble layers. Where the original form of the coastal edge ridge remains,
the feature can be interpreted as a massive dune-capped storm beach,
convex in cross-profile, with a low 10 degree slope towards the golf
links which extend inland to the colluvium apron of the degraded cliffs.

The character of this coastal ridge changes just east of the massive trans-
verse basal breccia sea stack which protrudes into the beach and acts, with
its associated intertidal platform, as a middle hinge point to the twin
arcs of Cullen Bay. Immediately west of this stack, the coastal edge is
heavily undercut, and fronted for a short distance by tilted concrete
blocks. The height of the coastal edge, which is still considerably
altered by tipping, declines sharply to a height of about 2 metres at the
ditch outlet. The coastal ridge carries scattered Ammophila communities
in a dominantly herb association. There is a single clump of Elymus
at the coastal edge. From the ditch outflow westwards, (deflected in that
direction), the coastal edge takes the form of a low grassed shingle
ridge. Despite the grassed nature of the shingle rim, fresh cobbles are
thrown over 15 metres inland of the coastal edge. The western end of the
beach arc rests on a mica-schist and quartzite intertidal platform complex,
with pseudo-strike running approximately normal to the shore. The 70
degree rock cliff backing the platform is capped by till, and at one
site, by rolled gravels.

Cullen Links are almost exclusively utilised by golfing activities with
the result that the raised bar complex sitting on the rock platform has
been much modified by green and fairway construction. The links extend
from the crest of the coastal ridge, firstly in a landward slope of about
6 degrees (essentially the landward slope of the blown sand-capped bar),
and thence in a series of swales and ridges to the till-capped old cliff-
line. The relict stacks protrude through the links and are mesa-like in
form, with characteristic vertical face and lower depositional apron.
Certain of the stacks near the base of the relict sea cliff are plugged
to it by till, indicating a pre-glacial origin for at least parts of the
Cullen embayment marine features.

Cullen Links is arguably the most attractive coastal prospect in scenic terms of the southern Moray Firth coast. The attractiveness of the view is compounded by the railway viaducts and settlement geography which form a framework to the great arcuate sweep of the bay. The view has a semi-wild yet pleasingly tidy appearance. Although vehicular access is only possible at the eastern end, both the beach and the slopes of the degraded cliffs are utilised as recreational walks. Casual walking along the links is possible along tracks and paths during periods of low golfing activity.

1 (f)   LOSSIEMOUTH (East)

- en passant (NJ 238 706)

Viewed from Lossiemouth, this beach forms only a part of a continuous
unconsolidated coastline extending in a gentle seawards-concave arc from
Lossiemouth to Speymouth. The predominantly sandy beach and landward
yellow dune systems which are so apparent at the western end are pro-
gressively replaced eastwards by a shingle foreshore, backed by old
shingle bars mantled with a very thin blown sand mantle. The current
shoreline represents the latest stage in a progressive infill of a large
coastal embayment through the construction of spits extending westwards,
successively displacing the mouth of the river Lossie towards the pre-
glacial rock headland of sandstone on which Lossiemouth stands. This
headland has provided a measure of permanance in an otherwise changing
late and post-glacial shoreline, and plays a major role in the nature of
the present beach complex. Inland lies a raised strandplain of post-
glacial age whose successive shorelines are still clearly displayed
within the Forestry Commission plantations. As the strandplain extended
with shoreline regression, the stratigraphical evidence suggests that the
quantities of sand available on the beach for dune formation have not always
been constant, and the morphological evidence suggests that rather more
has accumulated in the most recent phases of the strandplain evolution.
This may reflect the recent near-stable land-sea relationship, and
reduced rates of shoreline migration.

The complex falls into three parts. The most westerly portion of the
complex is the most dynamic portion and is characterised by marked
seasonal change with redistribution of sediment from the outer to the
inner shoreline. Within this generally changing situation, the dune
remnants and their assymmetric cross-profile are indicators of a
generally retrograding dune edge, with spring tides overtopping the
beach bar (underlain by shingle) and creating temporary sand splays into
the Lossie. The central portion, in the mid-distance, in total contrast,
is characterised by an accreting coastal edge, with a succession of
foredune ridges running inland to now-forested old grey dunes. This
'making' central portion passes eastwards in turn, to a neutral long
straight foredune edge, which, at the easternmost end, passes inland
and is protected by a series of recent shingle bars, as a degraded
old grey dune system. Thus the dynamic distal portion in the foreground
with its signs of summer human trampling contrasts with the more stable
proximal end of the complex in the distance, although there are signs
that stability at the eastern end is a fairly recent situation.

1 (f)   CLASHACH COVE

(Moray.   NJ 159 702)

The general setting of Clashach Cove is extremely dramatic by comparison
with most other beaches on the southern limb of the Moray Firth.   'En
petit', it invites comparison with the small Banffshore cliff-foot
beaches like New Aberdour (NK 888 646).   The beach lies at the base of
30 m high sandstone cliffs, portions of which are vertical, even
overhanging.   The approach is through wild golf links encumbered with
much gorse.   The descent to the beach is made through one of a number
of deeply incised paths cut into the weathered sandstones which form a
localised pocket within the sedimentaries into which sub-aerial and marine
processes have cut deeply to produce the cove.   The term 'cove' is unusual,
indeed, unique by North-East Scottish standards, but this Southern England
term justly describes the pocket-bay character of the beach.   Both the
view and the descent into Clashach Cove are truly breathtaking.

The cove re-entrant is less than 0'1 km long.   The lower sand and upper
fringing cohble beach sits on an intertidal rock platform, hinged to east
and west on active sub-vertical sea cliffs.   The cobble beach is composed
principally of highly flattened metamorphics which have in places accumu-
lated on top and around locally wave-quarried sandstone blocks.   Small
nodules of black flint occur within the beach cobbles.   The local Permian
sandstones dip landwards at a low angle giving characteristic near-scarp
faces to the upper cliff faces.   The abrasion platform upon which the
beach complex sits only appears at either flank.   Several platform levels
are represented, the upper ones of which are relict, including the spur
to the west which is capped by residual blown sand resting on a high
level salt weathered rock platform with lichened alveoles.   Below a
presently active salt weathering platform with active alveoles, is being
quarried away by the action of waves operating within the intertidal band.
The higher relict platform, which is approximately 3 metres above current
storm wave levels, seems to correlate with raised caves within the cove-
re-entrant, the entrances to which are partly masked by a blown sand
apron.   Although the platforms in detail are clearly structurally
controlled, they exhibit fascinating forms of biochemical and biological
weathering within the spray zone, and are an indication of a fairly
recent change in the land-sea relationship.   Similar 'two-storied platforms'
occur within Old Red Sandstone sedimentaries on the Pennan-New Aberdour
rocky coasts of Banffshire.

The coastal edge is generally protected by cobbles and shingle, although
towards the west, backshore cuttings reveal storm beach material capped
with the blown sand apron which has in the past accumulated against the
relict cliffline of the cove re-entrant.   On the eastern headland, the
cliff is bevelled with a thin till capping, and there is a small fault
within the sedimentaries.   The exposed cliff faces have a basal wave-cut
visor reminiscent of Majorca cliffs, and the structural lines within the
sandstones reveal its aeolian origins.

Although the cove has no dunes or links in the classic sense, sand derived
both from the weathering of the Permian and Triassic sedimentaries
together with offshore and longshore sand sources have in the past been
blown landward to accumulate as an irregular apron against the inner
slopes of the re-entrant.   The originally cliff-cut origin of the inland
cove slopes is shown by the line of slightly raised caves, partly buried
by a combination of blown sand and colluvium.   The incised nature of the
access paths from the clifftop which apart from trampling activities also

undergo intermittent rilling, are an indication of the easily weathered nature of parts of the local sandstones, and may suggest that debris aprons exist beneath the blown sand mantle. Late-glacial marine gravels also cap portions of the clifftop, and these in turn, carry thin and discontinuous spreads of blown sand now under golf links. At NJ 175 707 to the east, the Sculptor's Cave which has been recently re-excavated contains a series of occupation deposits from later Bronze Age onwards together with Pictish carvings. It is possible that some of the sealed Clashach caves might also contain archaeological deposits.

1 (h)   WHITENESS HEAD

(NH 820 578)

This shingle spit complex lies 6 kilometres west of Nairn and five kilo-
metres east of the major change in coastal plan caused by the wave-
reworked end moraine of Ardersier-Chanonry Ness. Landward of the spit
extends an area of lagoon, tidal flats and salt marsh, backed in turn, by
the low post-glacial raised beach of sand and shingle, with prominent
old sea cliff below the farm of Hilton of Delnies (entry point NH 843 562).
The oil platform production yard of McDermotts occupies a partially
reclaimed site of over 300 acres, occupying portions of a formerly more
extensive salt marsh. Sand periodically removed from a dredged channel
fronting the wharf has been settled out in extensive lagoons, a process
which was also adopted to reclaim the construction site. The spit takes
the form of a series of recurved shingle bars, up to 5 metres O.D.,
prograding in a westerly direction, and with successive storm ridges
thrown up. A thin blown sand cover overlies parts of the complex,
notably at the distal end where Ammophila and Elymus dunes currently
forming. Severe coastal edge erosion is taking place at the proximal
eastern end where only a single partly truncated shingle ridge prevents
frequent overtopping during spring tides, and flooding of the inland
marshes.

The spit is presently extending down-drift at rates of about 17 yards per
year. Such a figure was estimated by Ogilvie in the 1920's, and was
confirmed by comparison of aerial photographs in the years 1946 and 1967.
In 1870, the spit head lay close to the easternmost Salmon bothy. This
fairly rapid westerly growth of the shingle bars has however apparently
been at the expense of the distal portion at the aptly-named Gut where the
innermost and hence the oldest of the present spit bars is currently being
eroded. Successively younger albeit historical ridges are presently being
eroded at their eastern ends, with wave-transported materials being
moved along the beach westwards to form the evolving and building distal
portion of the complex. In a sense, Whiteness Head is evolving at its
own expense, and duplicates a feature of many beaches on the southern
limb of the Moray Firth which are apparently characterised by accretion
at their western ends and backshore erosion at their eastern ends. It
may be suggested that the distal portion of Whiteness Head represented an
advanced stage of the sediment redistribution which finally severed The
Bar (NH 920 600) from the mainland.

The main plant communities of the older eastern shingle ridges are Gorse
and Heather (including Calluna hirsute, unique to the Moray Firth coasts).
Westwards, with dune forms appearing, Ammophila becomes dominant, while
the embryonic dunes at the distal end of the spit carry Elymus sp.
Ultimately, the westerly carry of material downdrift will create a flying
bar of Whiteness Head.

1 (i)   SPEY BAY

Spey Bay extends for a distance of about 16 km between the supporting
rock headlands at Lossiemouth on the west and Portgordon on the east.
The bay faces slightly east of north, and is remarkably straight. The
only major interruption is the complex deltaic outlet of the River
Spey, some 5 km west of Portgordon. The general location of Spey Bay
and its main topographic features are shown in Figure 1. On this figure
attention is drawn to Binn Hill and the associated high ground to the
south and southwest – areas that are composed of extensive glacial and
fluvio-glacial deposits. Glaciation, deglaciation and sea level changes
are the essential ingredients of the physiographic evolution of the
general coastal area of Spey Bay and, although this description is solely
concerned with the active shingle beach, it is necessary to give a brief
description of the evolution of this coastal lowland area since both the
supply of littoral sediments as well as some aspects of coastal morphology
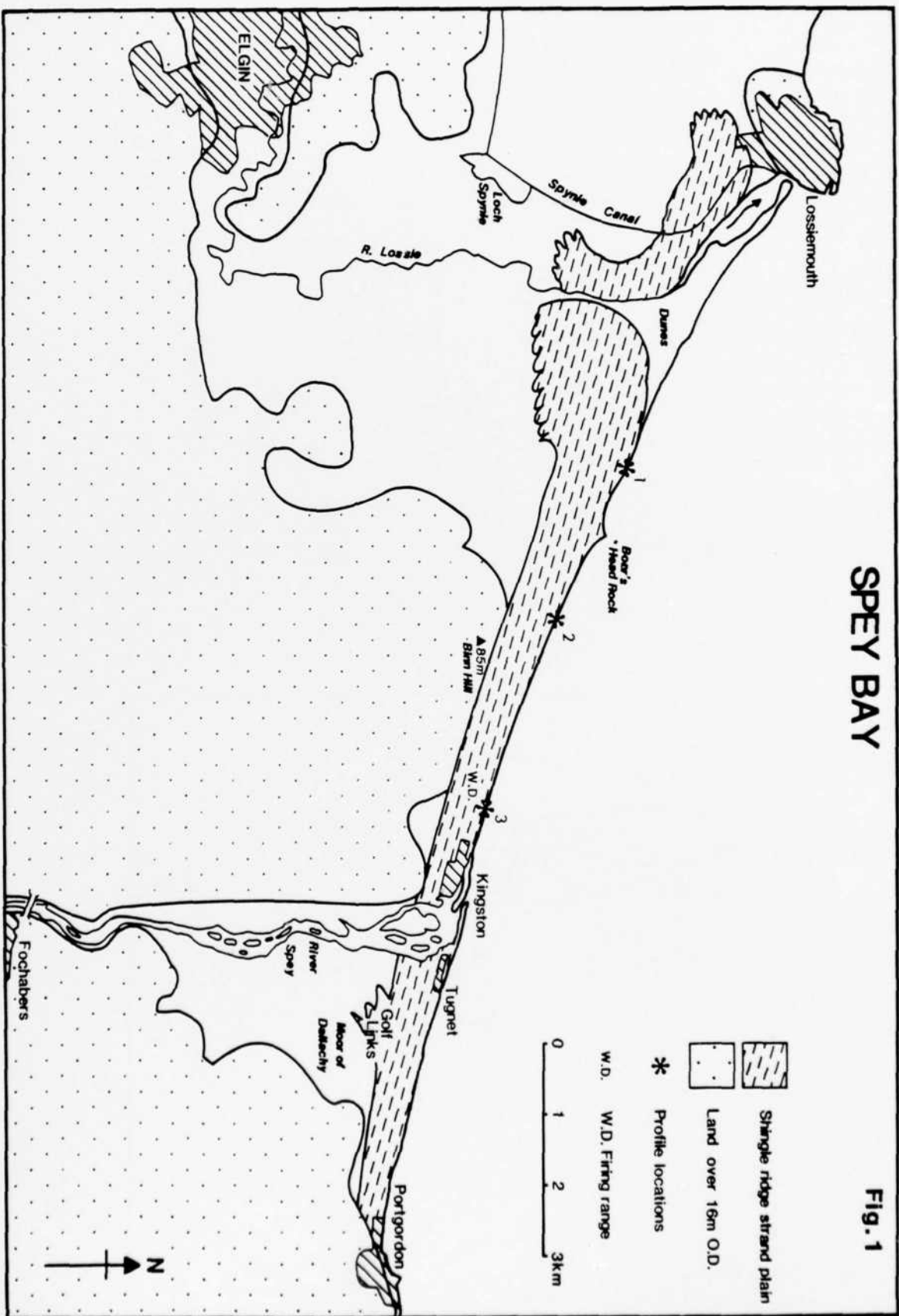are related directly to these more ancient forms and processes.

In 1923, A. G. Ogilvie produced a detailed description of the Moray Firth
Coast. This study remains the only geomorphological work of note and the
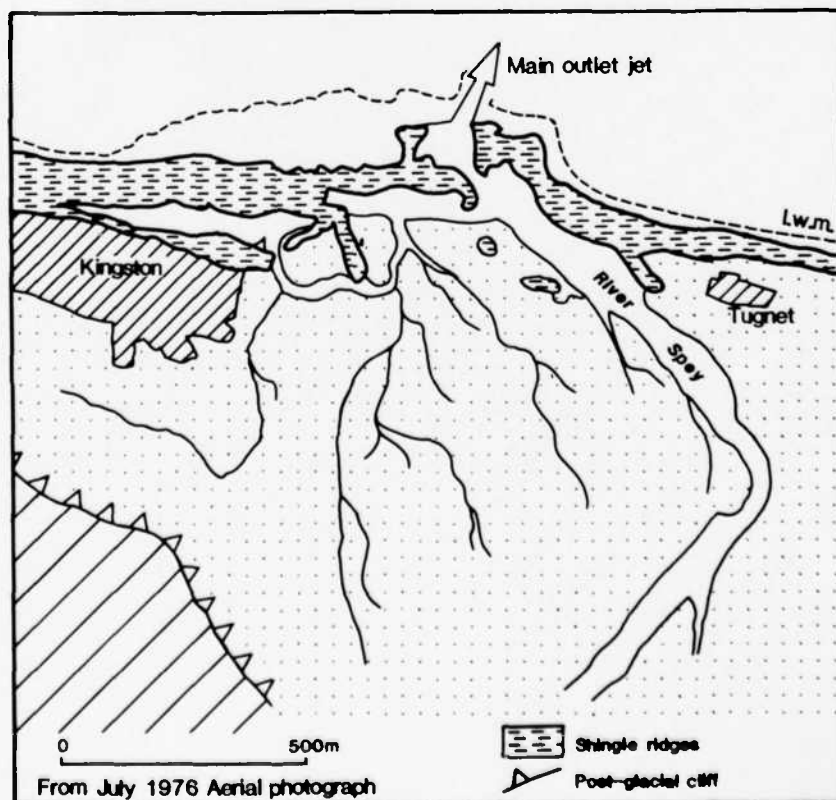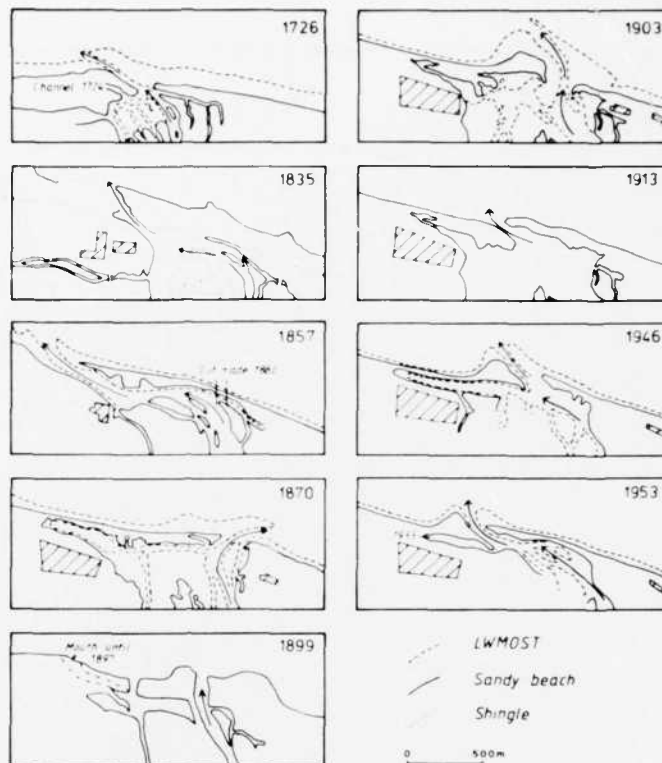following account is derived almost entirely from his paper.

Essentially the Spey Bay coastal plain may be divided into two compartments.
First, there is the area between Binn Hill (Figure 1) and the rock pro-
montory upon which Lossiemouth stands. This area is an extensive lowland
basin centered on Loch Spynie and drained by the River Lossie. The
southern and eastern rim (including the Binn Hill complex) consists of
irregular deposits of glacial and fluvioglacial origin that were deposited
during the movements of an extensive ice sheet which moved eastwards,
parallel to the coastline, along the Moray Firth coastal plain. This
higher ground and the coastal sandstone ridge which terminates at
Lossiemouth were never submerged by the higher late- and post-glacial
seas that flooded the interior basins. Progressively the strait between
Binn Hill and Lossiemouth was closed by the accretion that accompanied
successive relative falls in sea level and, at each stage, by the
accretion of marine structures growing westwards from the direction of
Binn Hill. The details of the closure of this coastal section are
extremely complex and are summarised in Figure 1. This shows the
numerous raised shingle bars with their various recurves in the vicinity
of the Lossie outlet. As shown in the central part of Figure 1 these
parallel shingle bars, each representing a former position of the
coast, form a wide corrugated apron up to 800 m wide to the seawards of
Binn Hill where at least eight to twelve major shingle ridge systems
with intervening linear depressions can be identified. These ridges
continue eastwards to the Spey outlet and provide some if not most of
the material for reworking by present day shoreline processes. Similar
ridges continue east of the Spey as far as the eastern limit of the bay
at Port Gordon.

The second compartment is the lower valley and outlet of the Spey. The
boundaries to the west and east are again higher areas of glacial and
fluvio-glacial deposits which have distinctive breaks of slope
associated with higher sea levels. This area is a triangular fluvial
area formed from a series of gravel and shingle estuarine and
deltaic terraces (which are also associated with various higher sea
levels). The present river cuts a braided channel through these
terraces and floodplains before crossing the coastal shingle ridges
through a complex of channels, bars and inlets.

SPEY BAY

Fig. 1

1726   1903
1835   1913
1857   1946
1870   1953
1899

LWMOST

Sandy beach

Shingle

0   500m

Main outlet jet

Lw.m.

Kingston

Tugnet

River Spey

0   500m

From July 1976 Aerial photograph

Shingle ridges

Post-glacial cliff

The form of the present coastline of Spey Bay is thus part of a long sequence of events whereby a series of shingle ridges has sealed-off and regularised complex areas of glacial and fluvio-glacial deposits, raised beaches, fluvio-glacial and recent river terraces and residual pockets of low lying marshy ground.

For convenience the modern shingle coastline is divided into four sections; the area east of the Spey outlet to Portgordon, the mouth of the river and the area between the river and an area approximately 2 km west of Boar's Head Rock where the shingle beach gives way to sand. The fourth area consists of a sand beach, spit and dunes and extends west from this transition zone to Lossiemouth. This last area of sand beach and high dunes is not included in this report which is solely concerned with coastal shingle formations.

The mouth of the Spey is a complex, shifting area with a recorded history of violent and dramatic change. These changes have been analysed by Grove (1955) on the basis of cartographic records and the oral evidence of local residents. The origin of these variations is partly a result of the steep lower course of the river channel below Fochabers, coupled with its large seasonal variations in discharge. The lower valley is characterised by braided channels where it crosses its own gravel terraces and old raised deltaic deposits. Grove (1955) shows various positions of the mouth (Figure 2) and describes how Garmouth and Kingston (Figure 1) were important shipbuilding centres until 1875 when the shifting waterway finally became too expensive to train and preserve. Grove also describes the great spate of 1829 when the river rose 13 ft 9 inches above the ordinary level at Kingston and a breach 400 yards wide was made in the shingle ridge at the mouth of the river. River deflection as a result of variations in flow and the offsetting effect of coastal processes continue to produce relatively frequent but in recent times small scale changes in channel and outlet geometry. The inset on Figure 2 shows a sketch of the outlet area made from 1976 aerial photographs. Notable features are the multiple active channels, the old main channel north of Kingston Village, the distinctive outward curvature of the modern delta, numerous "islands" and the westwards orientation of the outlet which is deflected almost parallel to the coast by a relatively short shingle spit. The coastal shingle spit and the shingle ridge to the west of the outlet are relatively high (4-5 m) but the other terraces and depositional bars inland of the coastline are lower and subjected to inundation at high river stages. The entire area is composed of gravel and shingle. No direct evidence is available to prove that the Spey continues to feed sediment, especially gravels, into the coastal sediment budget. Nevertheless the channel pattern, bank morphology and history of dramatic flooding along with the evidence of changing outlet positions might suggest that the Spey continues to carry a substantial load of gravel and shingle to the coast with these materials being derived from the erosion of its own earlier fluvial and deltaic deposits.

The coastline west of the Spey contains the finest active shingle ridges in Scotland. These steep shingle beach ridges extend 8 km west of the present mouth of the river and taper-out some 2.5 km west of Boar's Head Rock (Figure 1). According to Grove (1955) much of this westward growth has been within the last century i.e "while the river mouth has repeatedly altered its position, the most recent shingle bank on the west side appears to have grown steadily along the beach towards Lossiemouth over a distance of one and a half miles since 1870".
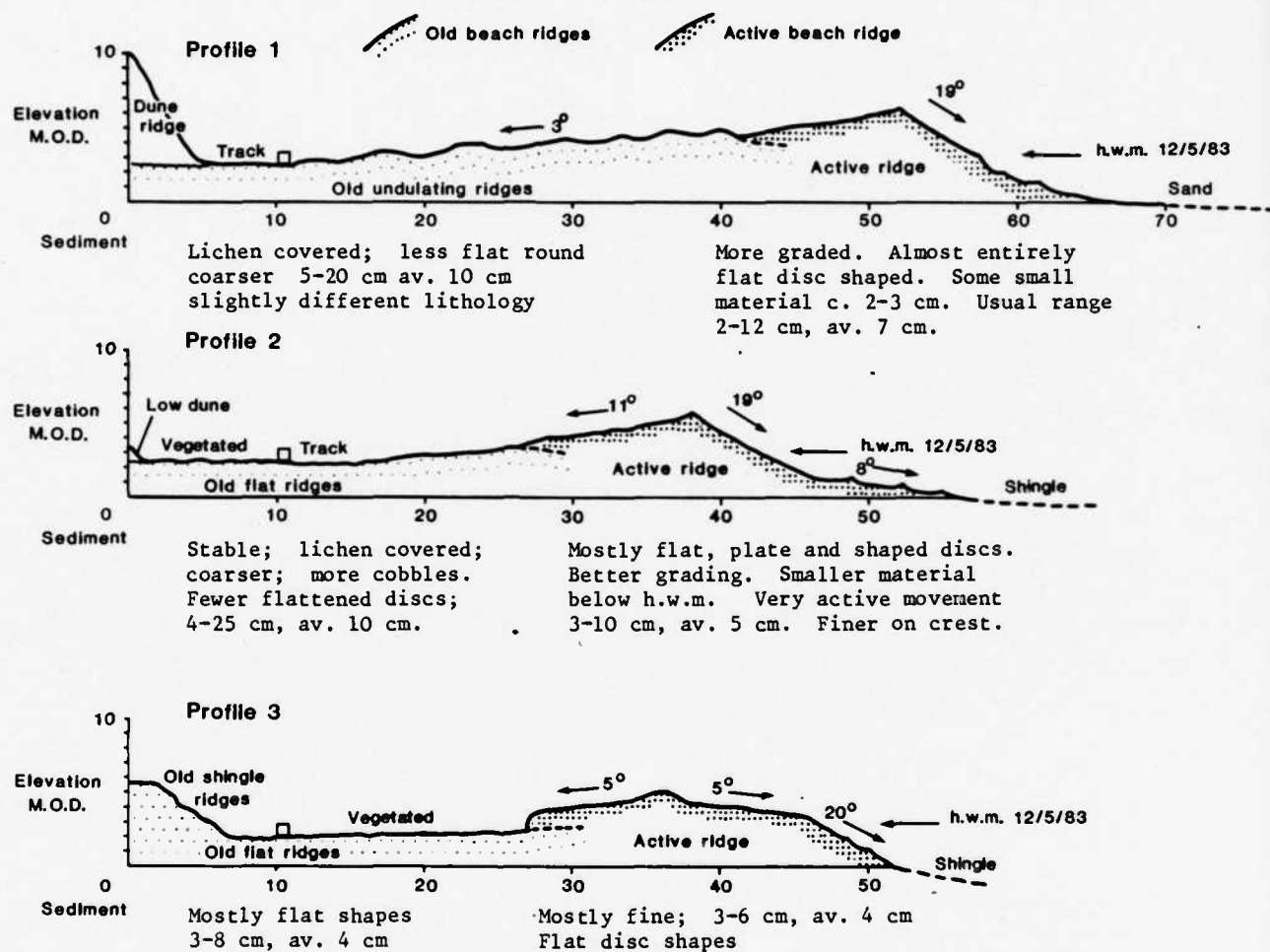
Beach face slope angles, the size and spacing of ephemeral features such as cusps, the degree of sorting and crest elevations alter in response to offshore-onshore and longshore processes which vary with wave and tidal conditions. There is also evidence that from time to time exceptionally high water levels during storm conditions carry shingle and cobbles over the crest which has an estimated average height of 4 to 5 m above mean tide level. There are also more regular changes in crest width and backslope form. The composition and size of shingle shows systematic variations on the beach face slope with finer well-sorted shingle occurring in the intertidal position whereas large calibre, more mixed shingle is found at and above high water mark. Most of the shingle has the typical flat disc or blade shapes of coastal materials. There appear to be some changes in size and possible composition as one proceeds westwards but a massive, systematic sampling and measurement programme would be required before these textural changes could be proved statistically. Nevertheless some notes on size and composition have been added to the surveyed profiles (Figure 3).

The width, thickness and height of the ridge varies considerably along the length of the bay. Heights are lower near Kingston and highest near Boar's Head Rock (Figure 1). A more significant change is seen in the area between Kingston and the W.D. Firing Range (Figure 1) where, in addition to clear evidence of storm wave overtopping, the active shingle ridge is extending over the track. This encroachment is relatively recent i.e. within the last decade, and suggests that there may be a degree of coastline retreat so that the active storm shingle ridge is overlapping onto the older shingle ridges. If this is true then it would support the assertion that the present massive shingle coastal forms are being reworked from the older ridge systems.

Rather than describe the various morphological and textural changes that are found along this 8 km long active shingle storm beach ridge three representative annotated surveyed profiles are shown in Figure 3. These profiles extend landwards to the first raised shingle ridge which begins the massive sequence of parallel ancient shorelines against which the present shoreline is placed. That the seawards face of these shingle formations are active features is not in doubt, nor is the fact that long-shore processes are extending the shingle features westwards. Between Boar's Head Rock and the distal end of the shingle storm beach the lower and middle beach sections are of sand with distinctive west-pointing inter-tidal ridges. A close examination of the orientations of the present and most recent crests of the shingle ridge and storm beaches adjacent to the present coastline also show a distinct series of gentle landward curves. It is this juxtaposition of the present active coastal zone with the ancient more massive but genetically similar coastal landforms that poses the fundamental question of Spey Bay - whether or not the present beach ridge is another shingle beach ridge that continues the pattern of progradational ridges or, as is more likely, it is largely a product of the reworking of the front of one of the ridges of the raised shingle foreland?

The coastline between the low rock platform at Port Gordon and the well developed shingle storm ridge which continues as a spit across the mouth of the Spey contains a great variety of coastal forms. In some respects it could be described as a transitional coastline between the non-descript mixed beach sediments at Port Gordon and the 5 m high shingle ridge near the mouth of the Spey. Inland the well-developed parallel shingle bars which continue the pattern found west of the river outlet, give way to level raised beach surfaces and former river terraces. Curved beach ridges of shingle are also found near the fossil cliffline which runs diagonally from Port Gordon to Fochabers (Figure 1). This triangular area of terraces, low ridges and marshy plains has not been

FIG.3   TYPE PROFILES WEST OF SPEY (For locations see fig.1)

Profile 1

Old beach ridges   Active beach ridge

Elevation M.O.D.

Dune ridge

Track

Old undulating ridges

Active ridge

h.w.m. 12/5/83

Sand

Lichen covered; less flat round coarser 5-20 cm av. 10 cm slightly different lithology

More graded. Almost entirely flat disc shaped. Some small material c. 2-3 cm. Usual range 2-12 cm, av. 7 cm.

Profile 2

Elevation M.O.D.

Low dune

Vegetated   Track

Old flat ridges

Active ridge

h.w.m. 12/5/83

Shingle

Stable; lichen covered; coarser; more cobbles. Fewer flattened discs; 4-25 cm, av. 10 cm.

Mostly flat, plate and shaped discs. Better grading. Smaller material below h.w.m. Very active movement 3-10 cm, av. 5 cm. Finer on crest.

Profile 3

Elevation M.O.D.

Old shingle ridges

Vegetated

Old flat ridges

Active ridge

h.w.m. 12/5/83

Shingle

Mostly flat shapes 3-8 cm, av. 4 cm

Mostly fine; 3-6 cm, av. 4 cm Flat disc shapes

Notes: Rounded cobbles up to 25 cm are found in most surfaces, especially landward of active crest. Lithology is varied but there is large proportions of Old Red Sandstone materials as well as grey and white metamorphic rocks. Almost all the material is well-rounded disc or blade shaped with a greater proportion of flat shapes being found on (seawards) active beach face.

studied in detail and Ogilvie (1923) does little more than describe this area near the coast as a "Strand plain of shingle bars at 25 ft" with the area further inland being "Delta of the Spey; built behind the barrier and redissected by the river" (p. 379).

The active shingle ridge begins as a relatively low angle feature at Port Gordon (where there has also been indiscriminate rubble tipping) and is fronted by the wide intertidal beach of Tannachy Sands. The ridge becomes increasingly well defined and steepens westwards until at a point some 2 km east of the river outlet the lower sand beach disappears. The active shingle ridge is then equal in height and form to the analagous ridges west of the Spey outlet. Like the ridges to the west.the present storm ridge is constructed against an older series of parallel ridges. The village of Tugnet (Figure 1) and Spey Bay Golf Course are sited on this broad ridge system. The number, width and total dimensions of these eastern beach ridges are less than those west of the outlet. This probably reflects the fact that throughout the long period of their development the fluvial (and fluvio-glacial) sediment input from the Spey was largely carried westwards. Nevertheless substantial proportions of the supply must have moved eastwards during periods of incident waves from the west and northwest. The narrowing of the shingle ridges eastwards from Tugnet, the increasing dominance of non-shingle sediments (including mud, sand and lag boulders) and the more variable beach forms eastwards seem to indicate that the general vicinity of the Spey outlet was the main source of sediments. There is little evidence that much material was derived from the till cliffs and raised beach platforms at Port Gordon.

The shingle features of Spey Bay provide a 13 km stretch of unrivalled physiographic interest. The massive scale of development and the evidence of short and medium scale dynamic coastal processes are almost unique around the Scottish coastline. The complex delta and associated coastal forms are added features of geomorphological interest. Although the purpose of this report is to describe the present coastline it would be a serious omission not to record the importance of the juxtaposition of these contemporary shingle features against the magnificent strandplain of gravel and shingle ridges which is undoubtedly part of one of the most important coastal physiographic sites in the British Isles.

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2. GENERAL CHARACTERISTICS OF NORTHWEST SUTHERLAND COAST

The area to be visited lies to the west of the Moine thrust plane. The coastal landforms lie within rocks of Torridonian, Lewisian and Cambrian age - the beaches, dune and machair being set within a basically fyord and cliffy coastline. The coastal diversity reflects the differing resistances of the geological outcrops, on both macro- and micro-scale, with faults, joint planes, the juxtaposition of Torridonian against Lewisian forming the ledges or embayments against, or on top of which, the soft coastal elements have accumulated. As the bedrock is the original source of sand and shingle, it is notable that while the gneisses are generally resistant to current processes, the softer sandstones and gritstones yield readily to weathering processes, and are the major original suppliers of the coastal sediments. A limited amount of solutional activity occurs where Durness limestones outcrop on the coast.

The regional landforms, although dominated by structural elements, are characterised by major planation surfaces, above which rise residual peaks of Torridonian sandstone, on occasion capped by Cambrian quartzites. Into these planation surfaces, the drainage patterns have been incised to create major arteries of meltwater dispersal which carried sands and gravels to the coast and beyond during deglaciation. On occasion, ice-contact fluvio-glacial landforms have subsequently formed resting places for the accumulation of dune and machair complexes in the lower and outer portion of drowned inlets. Changing land-sea relationships have created a complex of raised and submarine shorelines most clearly displayed to the east of the Moine thrust where ice-fronts lay close to the coastline. In the extreme north-west, the generally drift-free nature of the terrain makes it extremely difficult to identify raised shorelines.

The climatic inputs in terms of wind speeds and directions reveal that winds blow most frequently from the south-west quarter in both summer and winter, although the increasing frequency of easterly winds is a feature of the summer months. Clearly no single direction controls directions of wave and wind activities on the coastline, and this is reflected in the detailed characteristics of machair distribution and landforms. Thus beaches and aeolian landforms will be highly dynamic in response to short term weather patterns, and erosion of dunes and machair may proceed from any direction, although local topography will also be a control factor. Assuming that high magnitude events are most important, then high wind velocities for the north coast reveal a concentration along the sectors NW to NNE and SE to SSW. Overall, by comparison with areas further south, the coastline of NW Sutherland is an area receiving a high energy input for both marine and aeolian processes.

As far as the inshore environment is concerned, admiralty charts reveal the existence of unconsolidated deposits offshore, in particular an abundance of sand and shellsand, a mirror-image of the coastal shell-sand beaches. By comparison with the relatively bleak interior, the blown sand landforms at the coast carry soils which are usually freely drained and base-rich in character. These have been utilised since prehistoric times for agriculture. The coastal pattern of settlement was compounded in the early 19th century by the displacement of much of the inland population onto the coast with the introduction of commercial sheep farming into Sutherland and the later development of deer forests. These 'clearances' were often accompanied by resettlement schemes with the aim of developing a dual crofting-fishing economy. There followed a period of increasing population, land hunger and rural poverty which culminated

in the establishment of the Crofters Holding Act of 1886 which had the
result of virtually fossilising a pattern of very small croft units and
areas of common grazing strung out along the coastal embayments. Thus
most of the coast, apart from areas between Cape Wrath and Durness,
lies under crofting tenure. A very small proportion of the croft land
may be under cultivation, but the major proportion is given over to
grass, while on the common grazing, which frequently lies on the machair
landforms, the land use is grazing, controlled by committees whose duty
is to prevent overgrazing and misuse. Such grazing may have a detri-
mental effect not only on the vegetation and hence on the carrying capacity,
but may also result in soil erosion through a diminishment of the binding
and protective functions of the machair sward. In addition, rabbit popula-
tions are on occasion extremely high. Pressure on these limited resources
is in some cases increased by caravanning and camping, leading to over-
exploitation of the resource. The machair areas remain valuable agricul-
tural resources, but in at least some areas, erosion rates seem to have
increased. In recent times a situation which is a matter of some concern
both to the crofters and to the Countryside Commission for Scotland. The
most seriously damaged beaches at Achmelvich and Clachtoll have been the
subject of fairly successful machair and dune rehabilitation projects,
and hopefully such projects may be extended once their success becomes
apparent.

In conclusion, it is worth noting, as will be apparent in Sandwood, that
sand movement is a natural and long-established process of the Sutherland
coastal environment. Indeed, the erosion of dunes is the natural process
in the evolution of mature machair topography. As will be seen at Oldshore
Beg, the critical area is the machair, where increasing deflation rates
may strip off mature swards and soils which have taken centuries to
develop.

2 (a)   SANDWOOD LOCH AND ADJOINING COASTLINES

(NC 194 640 to 225 655)

Sandwood Bay lies at the western end of a glacially modified valley
developed along the junction between Torridonian grits to the south and
Lewisian gneisses to the north-west. The beach, dune and machair system
occupy the lower portion of Strath Shinary, perched on a discontinuous
rock bar, parts of which outcrop as skerries through the inland dune
landforms. The structural evolution of the Sandwood embayment replicates
the scenery of West Sutherland in a small scale, in that the relatively
easily weathered Torridonian Sandstones and gritstones have weathered
south-eastwards as a massive structural scarp, exposing the Lewisian
basement, and leaving behind minor Torridonian residuals. The 100
metre Torridonian cliffs of the southern headland are characterised by
cliff cambering near their edge, forming small reverse slopes and
incipient groups, while their faces are crumbling to form screes and
blockfalls. Similar block screes now covered by blown sand also occur
on the inland structural faces. The Torridonian cliffs thus provide and
have provided abundant materials to the inshore zone, parts of which have
fed the massive cobble spits which initially closed the seaward end of
Strath Shinary. The scale of the cobble spits and their constituent
materials can be seen at the northern end of Sandwood beach where the
loch drainage flows over into the sea. The coarse and reddish nature
of the dune sands also suggests a derivation from this Torridonian
material.

In contrast, the Lewisian cliffs which form the northern headland to the
bay are generally resistant to wave processes and weathering, except
where fracturing or minor lines of lithological weakness can be exploited.
These bold convex Lewisian cliffs show little material at the cliff
foot, other than that derived from re-worked glacial deposits. Within
this outstanding scenic albeit remote geological framework, wind and
wave activities have built the largest beach and dune system in West
Sutherland. The two-mile long beach experiences relatively rapid
changes in outline and profile, and there is constant interaction between
wave activity and the loch drainage. In a sense, it is naturally dynamic
and unstable. Apart from the main dune building area around and on top
of the Lewisian bedrock knolls, blown sand has created machair high on
the Lewisian ridge to the north, and infilled parts of the loch basin.
Blown sand also extends in a southerly direction along the sides of the
loch and into the col through which the main access path passes. In the
south-west, several large blow-outs have linked together, their location
suggesting the topographic effect of the Torridonian scarp in funnelling
wind. The dominance of Ammophila in the foredune system is an indicator
of the variable and continuing activity of sand blow, and this plant
dominance even extends into the blown sand apron cloaking the Torridonian
screes. In addition, varying loch levels and local wave action within
the loch are currently cliffing both dune and machair landforms. Such
sand recycling and blow-out activity has clearly operated over centuries,
and indeed, the landforms of the whole area are a complex of old and new
cycles of activity and partial consolidation. On the norther Lewisian
ridge, machair intermingles with scree and bare rock, the former carrying
a typical machair-heath plant assemblage. Erosion scar development is
related to sheep and rabbit grazing and in some instances, rilling has
developed. Because of the high energy nature of the Sandwood environment
and the thinness of the machair cover, these tend to extend fairly rapidly.

Because of its isolation, human impact at present is minimal. A clachan
formerly existed at Sandwood, surviving today in the form of field
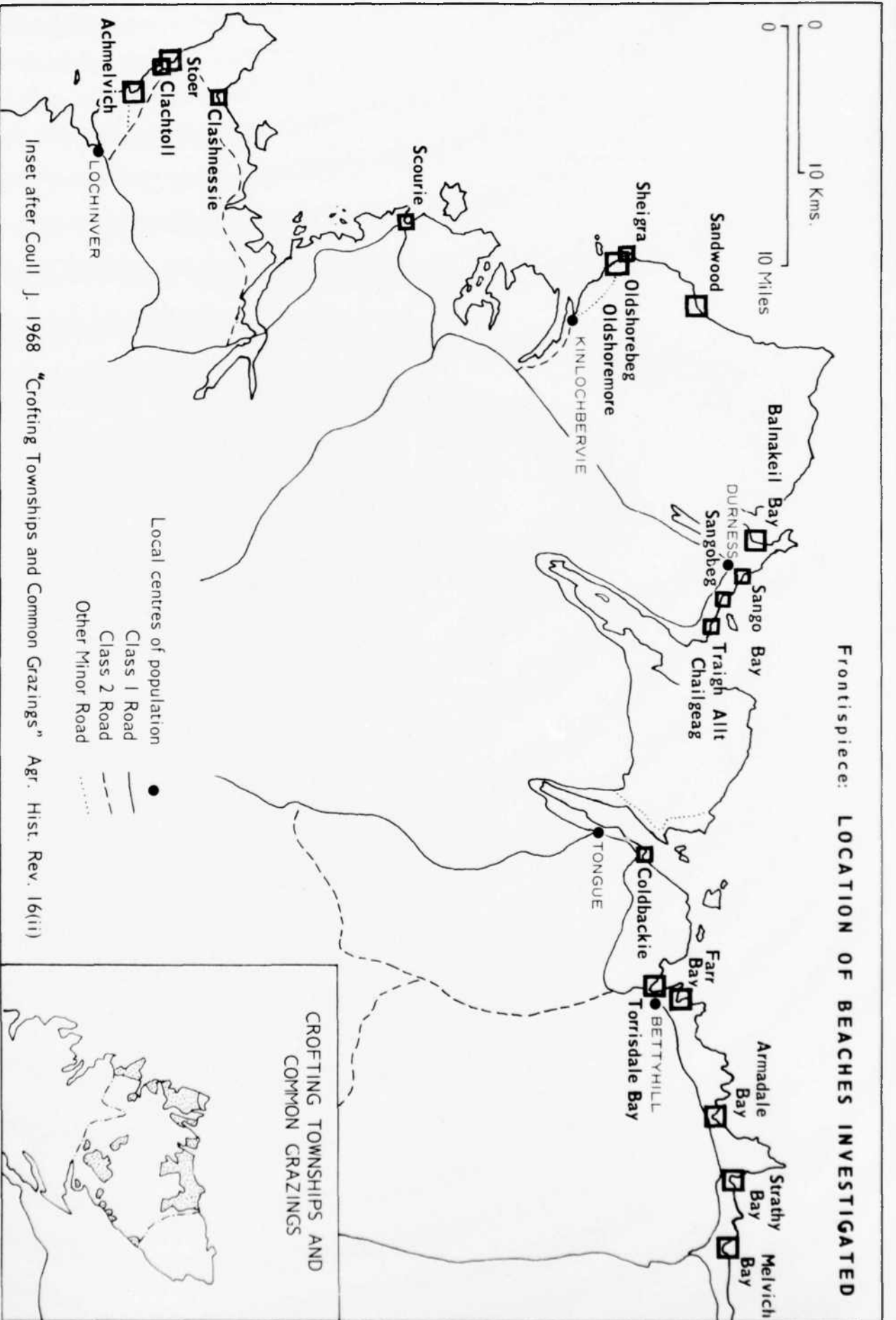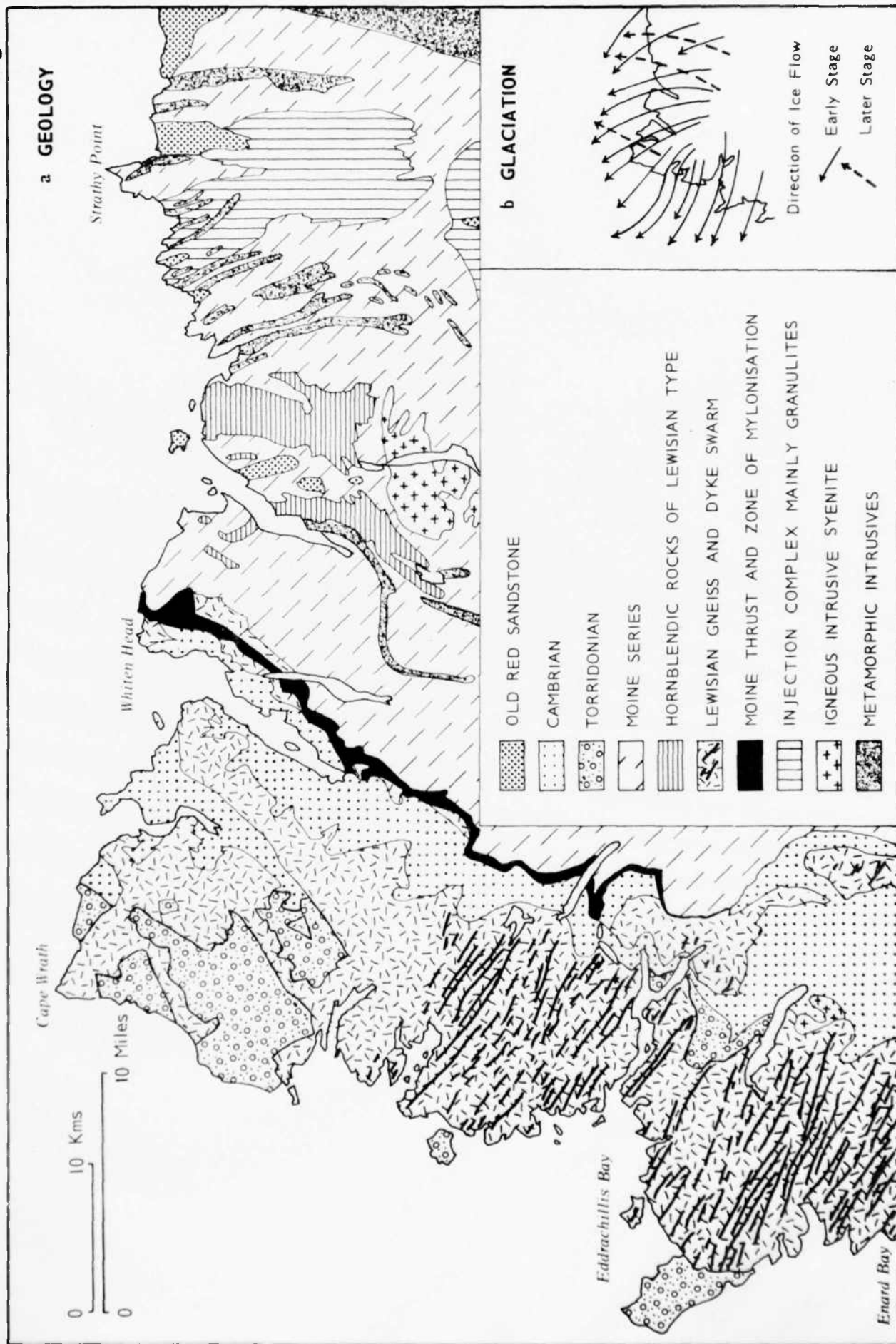
Frontispiece: LOCATION OF BEACHES INVESTIGATED

Balnakeil Bay

DURNESS

Sangobeg
Sango Bay

Traigh Allt Chailgeag

Sheigra

Oldshorebeg
Oldshoremore

KINLOCHBERVIE

Sandwood

Scourie

Coldbackie

TONGUE

Farr Bay

Torrisdale Bay

BETTYHILL

Armadale Bay

Strathy Bay

Melvich Bay

Clashnessie

Stoer

Clachtoll

Achmelvich

LOCHINVER

Local centres of population

Class 1 Road
Class 2 Road
Other Minor Road

Inset after Coull J. 1968 "Crofting Townships and Common Grazings" Agr. Hist. Rev. 16(ii)

CROFTING TOWNSHIPS AND COMMON GRAZINGS

0

0

10 Kms.

10 Miles

Fig. 1

a GEOLOGY

b GLACIATION

OLD RED SANDSTONE

CAMBRIAN

TORRIDONIAN

MOINE SERIES

HORNBLENDIC ROCKS OF LEWISIAN TYPE

LEWISIAN GNEISS AND DYKE SWARM

MOINE THRUST AND ZONE OF MYLONISATION

INJECTION COMPLEX MAINLY GRANULITES

IGNEOUS INTRUSIVE SYENITE

METAMORPHIC INTRUSIVES

Direction of Ice Flow

Early Stage

Later Stage

Cape Wrath

Whiten Head

Strathy Point

Eddrachillis Bay

Enard Bay

10 Kms

10 Miles

Sandwood Bay from the south illustrating the highly active nature of the aeoilan landforms.

The coastal edge at Sandwood looking southwards towards the Torridonian cliffs which are the ultimate source of much of the beach and dune sand.

The loch inland of the dune-capped cobble bar at Sandwood Bay.

Typical machair deflation scars at Oldshore Beg, Sutherland.

boundaries, house and hut foundations, and lazy beds. There is also
evidence for sheals. Today the area is lightly stocked with sheep and
common grazing by several crofting townships, and rabbit populations
are low. Although human impact was certainly greater in the past, it
has never been a major influence in landform evolution. Rather the
complex can be regarded as naturally unstable and dynamic, and a useful
baseline against which to view other North-West Highland beach complexes
with higher intensities of grazing and recreational uses.

2 (b)   OLDSHORE BEG

(NC 190 590 - access via Droman pier (NC 185 594))

The beach and landward valley has developed in a south-west trending
depression in the Lewisian gneiss basement. The depression is character-
istically assymmetric, with the south-eastern margin rather steeper,
probably a result of fault control. The beach is protected to the west
by the offlying island of Eilean an Roin Mor, a continuation of the
ridge form of the headland. The ten fathom line lies some three quarters
of a mile offshore. The rock ridges forming the margins of the depression
are markedly ice-scoured and plucked, generally devoid of till cover or
weathered material, but are diversified by numerous glacial perched
blocks. By comparison with Sandwood, the beach is well sheltered, apart
from the open south-west quarter. The distribution of blown sand deposits
inland appears to confirm that winds between south and south-west are
dominant in its evolution. Although some Lewisian cliffing has taken
place in fault-weakened segments, generally the sources of beach material
must be sought offshore. The relatively sheltered beach is backed by
a generally stable low dune front, with high proportions of shell sand.
A very limited amount of dune and machair sand is re-cycled back to the
beach by stream activity.

Both the frontal dune ridge and low angle machair are generally stable.
In contrast to the stability of this flattish machair, the thinner
sloping machair on the northern ridge appears to be very susceptible to
deflation, and numerous scars, several quite large, have developed, some
of which may be termed 'blow-outs'. The latter have a crescentic shape,
the concave eroding face facing south-west and the prevailing wind.
These blow-outs seem to have originated at the change in slope angle
between the thin sloping machair and the flat machair, and to have
subsequently spread onto the latter. A second type is rather more
linear in plan, and is best developed to the west of the western headland
ridge crest. These 'blow-outs' are orientated parallel to the prevailing
wind and roughly parallel to the ridge orientation. At their leeward
ends, they on occasion open out to present a face at right angles to wind
direction, although they are more frequently linked at their windward
ends to present a crenulate front edge. A third type of linear plan
is orientated at right angles to wind direction, but is mainly confined
to the ridge crests. The overall distribution of machair to the west
of the stream implies the dominance of winds from the southern quarter
in capacity of sand transportation, while, of course, the ridge itself
offers some protection from the west.

The vegetation pattern is typically simple. The open marram community
of the front part of the dune ridge gives way landwards to machair turf,
while along the stream sides, freshwater marsh communities exist in the
poorly drained hollows. On the headlands, salt spray must be an impor-
tant factor in the vegetation. The major part of the machair area is
common grazing with animals on the ground for most of the year. On the
north-west headland, small field systems and house foundations attest
to the considerably higher population which the townships carried in
the late 18th and early 19th century, when parts of the machair were
successfully cultivated. Today while sheep rubbing will aggravate machair
erosion scars, in many cases, the original causal factor seems to be
rabbit burrowing. As the rabbit is essentially an introduced species
albeit historically, and rabbit populations can, and should, be controlled
in a manner akin to grazing control, the machair deflation here at Oldshore
Beg can be regarded as a result of undermanagement of the resource.

3.   GENERAL CHARACTERISTICS OF EASTER ROSS COAST

Easter Ross carries a relatively short stretch of sandy coastline in
comparison with East Sutherland, and also in comparison with its total
length.   The most extensive beaches occur within the Lower Dornoch Firth
where coastal progradation has formed extensive forelands and strand-
plains, often fringed by sandy beaches and capped by dunes.   Changing
land-sea relationships in the past have resulted in much of the blown
sand accumulations occurring on raised sand or shingle bars, frequently
backed by old clifflines.   Rosemarkie, Cromarty, Nigg and Portmahomack
are all beaches fringing late and post-glacial forelands of varying size
and complexity.   Other beaches backed by restricted dune or machair systems
occur in cliff-foot situations, as at Balintore and Wilkhaven.   The
development of a wide dune complex has been restricted by the presence
of an old cliffline behind, together with the prevailing offshore winds.
Only where sand blow can occur along the coast have high dunes been
formed in such cliff-foot situations.   In such narrow dune systems, plant
communities originally dominated by Marram are eventually replaced by
other species colonising down from the cliff behind.   The originally
subdued system thus becomes increasingly less dune-like.   In plan, the
beaches tend to be straight or slightly convex-seawards, and there are
few of the bayhead beaches, which are a common feature of other parts
of the Highlands of Scotland.

Where the offshore zone is shallow, as in the Lower Dornoch Firth,
changing land-sea relationships have provided sufficient material to
construct highly complex strandplains on a scale unusual in a Highland
context.   These occur in the relatively exposed lower firths.   The
inner parts of the firths are dominated by estuarine processes, creating
marshes and extensive sandflats as at Nigg Bay, in the Cromarty Firth.
On the outer coast, however, the size of the Morrich More strandplain is
an indication of the availability of both sand and shingle in the past,
and of sand at the present time.   As a general rule, sand appears to be
freely available to the strandplain beaches at present, while the smaller
cuspate foreland beaches have very limited offshore supplies.   Streams
and cliff erosion play a very minor role in the evolution of beach and
dune systems in Easter Ross.

The east coast situation, together with landward shelter often provided
by cliffs, has resulted in subdued dune topography and stable situations.
Most dune systems are completely stable, although some are separated
from the beach by low coastal edge erosion scarps.   Supply is thus
effectively cut off from beach to dune.   In such circumstances, marram is
progressively replaced by herbs and grasses.   In general the rate of
coastal edge retreat is minimal, in part due to the shingle substrate
on which many dunes have accumulated, and which forms backshore pro-
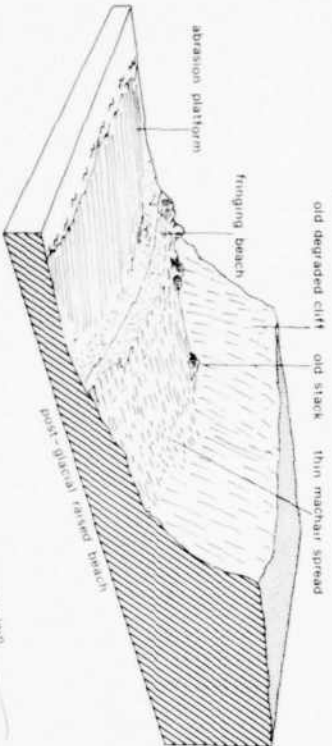tection to the coastal edge.

Many dune and links complexes back onto agricultural land and have been
partly improved agriculturally from their landward margin.   The division
between low dune, links and partly improved grazing is often very indeter-
minate and marked only by a fenceline.   Other beaches are backed directly
by roads and small settlements.   Almost all the beaches could be termed
low energy beaches in that the distribution and amount of beach materials
changes little from year to year.

Only in the case of Morrich More is coastal accretion rapid.   The areas
of blown sand deposits and the amplitude of the dunes are small in
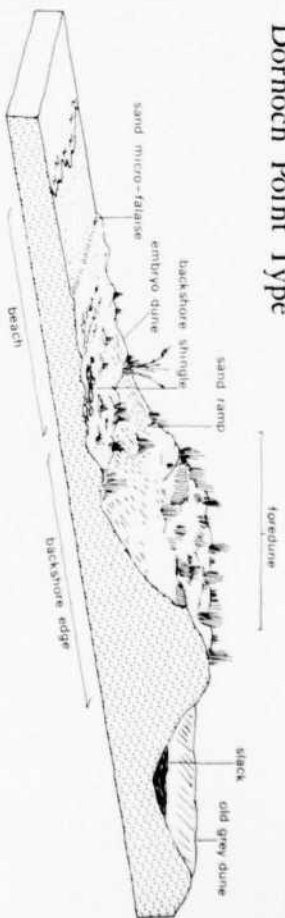comparison with the Western and Northern Highlands.   Organised recreation

tends to be confined to the smaller and less distinguished beaches beside villages like Balintore, Rosemarkie and Portmahomack, which carry 50% of the beach-back caravan capacity of Easter Ross.
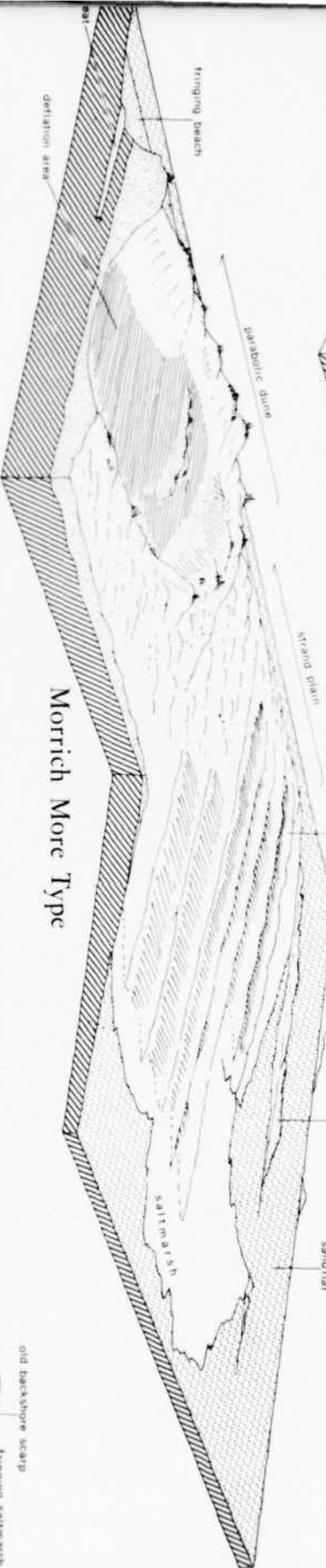
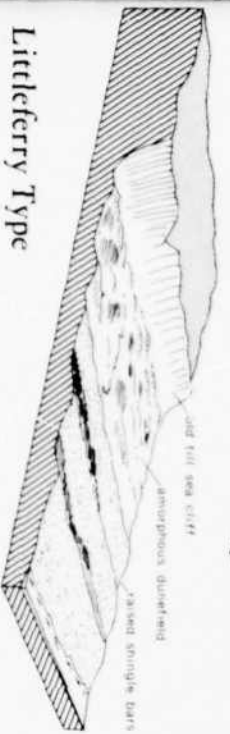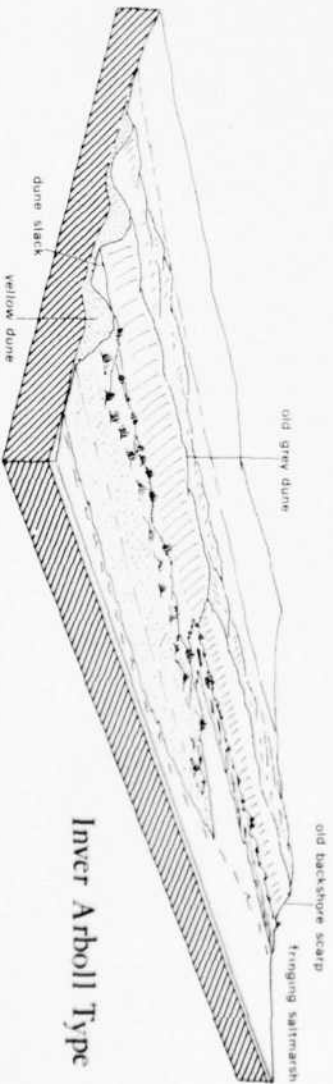# COASTAL NOMENCLATURE

Wilkhaven Type

old degraded cliff
old stack
thin machair spread
fringing beach
abrasion platform
fringing beach
post-glacial raised beach

Dornoch Point Type

foredune
sand micro-falaise
backshore shingle
embryo dune
sand ramp
beach
backshore edge
slack
old grey dune

Morrich More Type

parabolic dune
strand plain
damp slack
dune capped
offshore bar
saltmarsh
sandflat

Littleferry Type

fringing beach
deflation area
peat
old till sea cliff
amorphous dunefield
raised shingle bars

Inver Arboll Type

dune slack
yellow dune
old grey dune
old backshore scarp
fringing saltmarsh

5

3 (a)   THE MORRICH MORE

(military activities permitting)

The Morrich is a low-lying parallelogram of post-glacial and recent sand
ridges resulting from long term progradation north-eastwards from the
prominent post-glacial cliffline. It occupies a substantial proportion
of the southern shore of the lower Dornoch Firth and extends from Tain
to Inver. Genetically, the Morrich is a 6 km broad strandplain fronted
seawards on its north-eastern margin by dune-capped offshore bars which
are separated from the main strandplain by sandflats. The offshore bars
are actively accreting. The total package thus represents a long period
of continued accretion within the last seven thousand years (since the
Flandrian transgression which cut the landward cliffline). It consists
of alternating slacks and sand ridges orientated at right angles to the
maximum seaward fetch. The ridge system is truncated on its north-
western flank by backshore erosion, contrasting with continuing sandflat
and offshore bar accretion on its north-eastern shore. It contains a
range of flora from intertidal sandflat species through to Juniper-
Calluna association on the oldest landward ridges, and is backed landwards
by reclaimed agricultural land. The strandplain is grazed by letting
to neighbouring farms, and a large part is utilised as a bombing range
by military aircraft based at Lossiemouth. An area of blow-out and
parabolic dunes to the east of Tain Golf Course has been partially
reafforested.

Although the strandplain is almost entirely built of sand, traditional
beaches (defined as freely drained sand thrown up by waves with a notable
seaward gradient) are very restricted in size and distribution. The
major components are intertidal sandflats (1000 hectares) and alternating
ridges and slacks, largely colonised with vegetation. The type of
vegetation association at any point varies with salinity, periods of
submergence (or emergence), age of the ridges, and altitude. The major
beach units occur in the north-east shores in the form of elongated off-
shore islands capped with rapidly accreting yellow dunes. Small sand
bars also occur on top of the more recent saltings, where spring tide
wave action and currents have disturbed the pioneer Puccinellia cover,
and resorted the sand substrate into ephemeral sand bars, even embryonic
dunes. A very narrow fringing beach along the western margin of the
strandplain extends from Tain to Rubh'na h Innse Moire. It is less
than 6 metres broad and is composed predominantly of shell fragments
washed out of the backshore face of post-glacial-recent deposits. The
shell content is locally as high as 90%. The beach is fronted by
sandflats 1200 metres broad with minimal seaward gradient, but the
surface is patterned by mega-ridges and runnels running sub-parallel to
the high water mark. Erosion along this western shore is traceable in
historical documents and maps and has been responsible for the clear
truncation of the Morrich ridge system. The rate of backshore erosion
is least where peat outcrops on or at the back of the beach. The peat
pre-dates the Flandrian transgression and probably underlies much of the
ridge and slack system. Small areas of coastal machair occur north-
east of the parabolic dune system. The machair is generally relict
in the sense that it is effectively cut off from beach supplies by a
low coastal edge.

The outer islands on the north-east shore consist of sand beaches
elongated from north-west to south-east, separated from the main unit
by sandflats and fringing salt marsh. The sandflats do not dry out
entirely at low tide, and their surface is colonised by a microscopic

green algae, which in conjunction with the wetness, precludes sand blow.
These are thus highly stable in their natural state. The offshore islands,
particularly the Innis More, are nourished by sand thrown up by waves into
bar form. As the bar emerges and extends laterally, increased area
permits possibilities for drying, favours sandblow, and accumulation
around shore wrack is replaced by small Elymus dunes two to three metres
high. In the field, the succession of progradation is represented by
concentric patterns of dune ridges surrounding the island. The outer
dune island of Innis More thus may form a model of the way in which the
strandplain has formed. However, the Innis More dunes are higher and
more continuous than on any older sand ridge within the system, perhaps
representing a longer period of shoreline stability than has occurred
during any previous phase in its formation. As the rate of land uplift
has decreased, the distance between individual ridges ie shoreline
positions - has increased, and this may explain the greater height and
size of the ridges nearer the outer coast, and their considerably wider
spacing.

The most striking feature of the eastern margin of the Morrich are the
exceptionally high parabolic dunes which have a relief amplitude in
excess of 14 metres. The dunes, almost entirely clothed in Marram on
their ridge tops, run in a series orientated north-eastwards, and sub-
parallel to the western edge of the Morrich. As the dunes have travelled
eastwards, they have left behind deflation areas scoured almost to the
water table, and revealing old soil surfaces. The most easterly dunes
are still partly mobile with sand faces spilling forward, but the major
part of the system has been stabilised, partly by a decrease in sand
supply caused by their own forward movement, and assisted by afforestation.
The technique of afforestation is substantially similar to that used in
the Culbin Sands of Moray, with brushwood laid on the steep faces and
railway sleepers across the major sand blow corridors.

The vegetation pattern of the Morrich is dominated by the ridge-slack
pattern. The total flora number over 200 flowering species. The
following summary generalises the main characteristics in terms of
process and succession. The extensive expanse of tidal sandflat fringing
the strandplain provides surfaces which vary in stability according to
currents and silt content. The western sandflat from Tain to Innis More
carries extensive Enteramorpha and Zostera growth, particularly on the
megaripple lows. Between Innis More and the mainland, microscopic green
algae (Lyngbya sp) occurs, stabilising the surface which can be traversed
by Land Rovers collecting off target bombs. To the east where the
influence of the Inver channel is felt, Ruppia occurs, with Salicornia
in limited areas of mud accretion. The dune vegetation on the offshore
islands starts off with Elymus arenarius and Agropyron junceiforme, with
Ammophila arenaria taking over when dunes reach two to three metres in
height and becoming dominant. Certain land species like Tansy and Thistle
which add variety to the islands are brought in by gull or tide. These
island carry heavy gull populations, and terns and whimbrel nest here.
The seaward salting on the north-eastern shore is unusual in terms of the
amount of free sand locally available on its surface. While Puccinellia
maritima is dominant and forms the main pioneer species, Plantago and
Armeria are also present. The surface is hummocky and is activated
periodically by wave activity. Further inland within the same association/
landform, the dune species like Agropyron come in again and small dunes
form. The low ridges hacking the saltings appear to develop from initial
Ammophila - clad bars, followed by Carex arenaria and Festuca rubra.
Subsequently, the variables of moisture and leaching rates supervene,
the ground cover being completed by mosses and dune pasture species.

MORRICH MORE

GENERALISED VEGETATION (after P.A.S. Rae, 1972)

Slack–Carex with Armeria-Glaux replacing nearer sea

Intertidal beach and sandflat
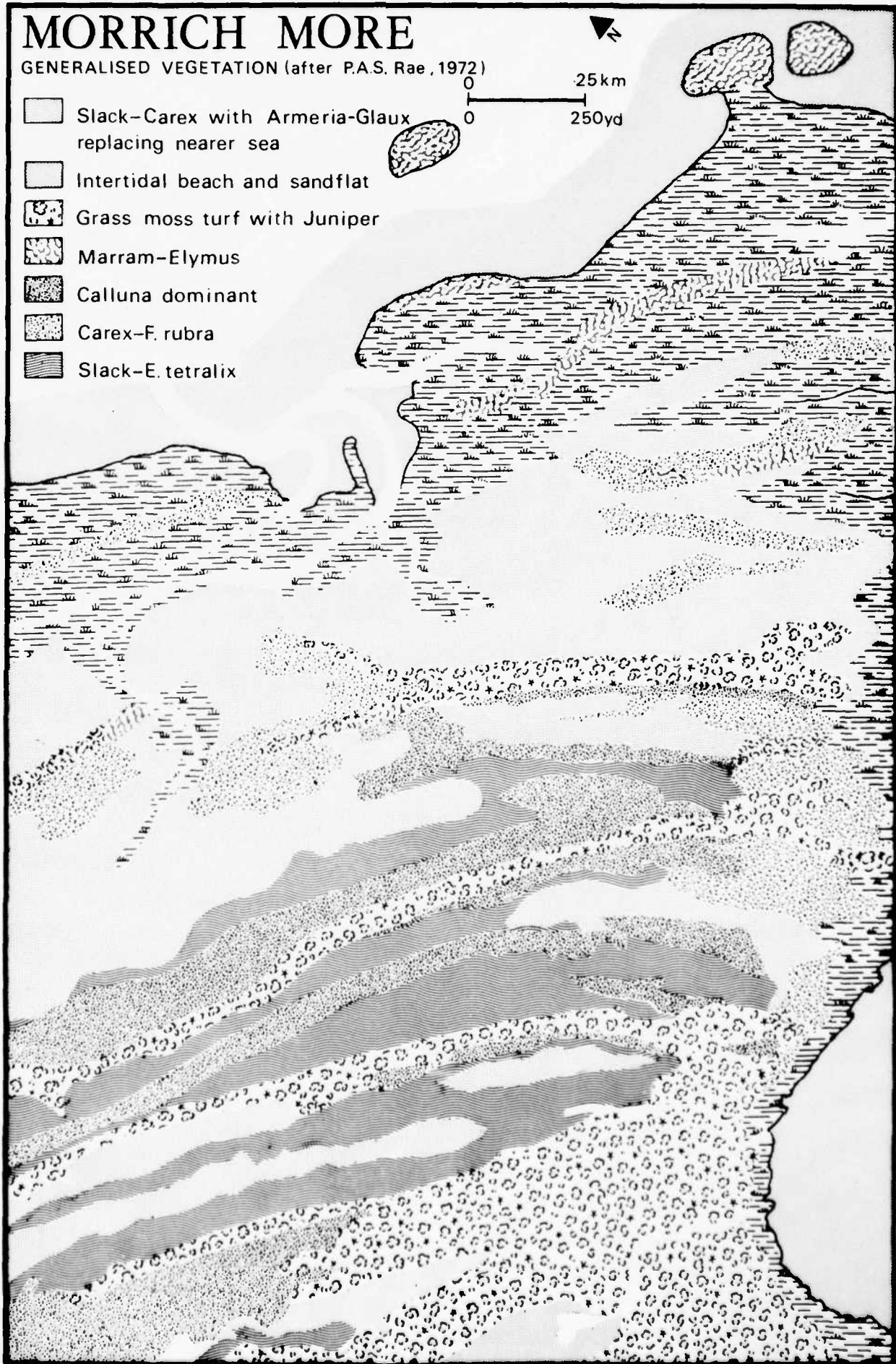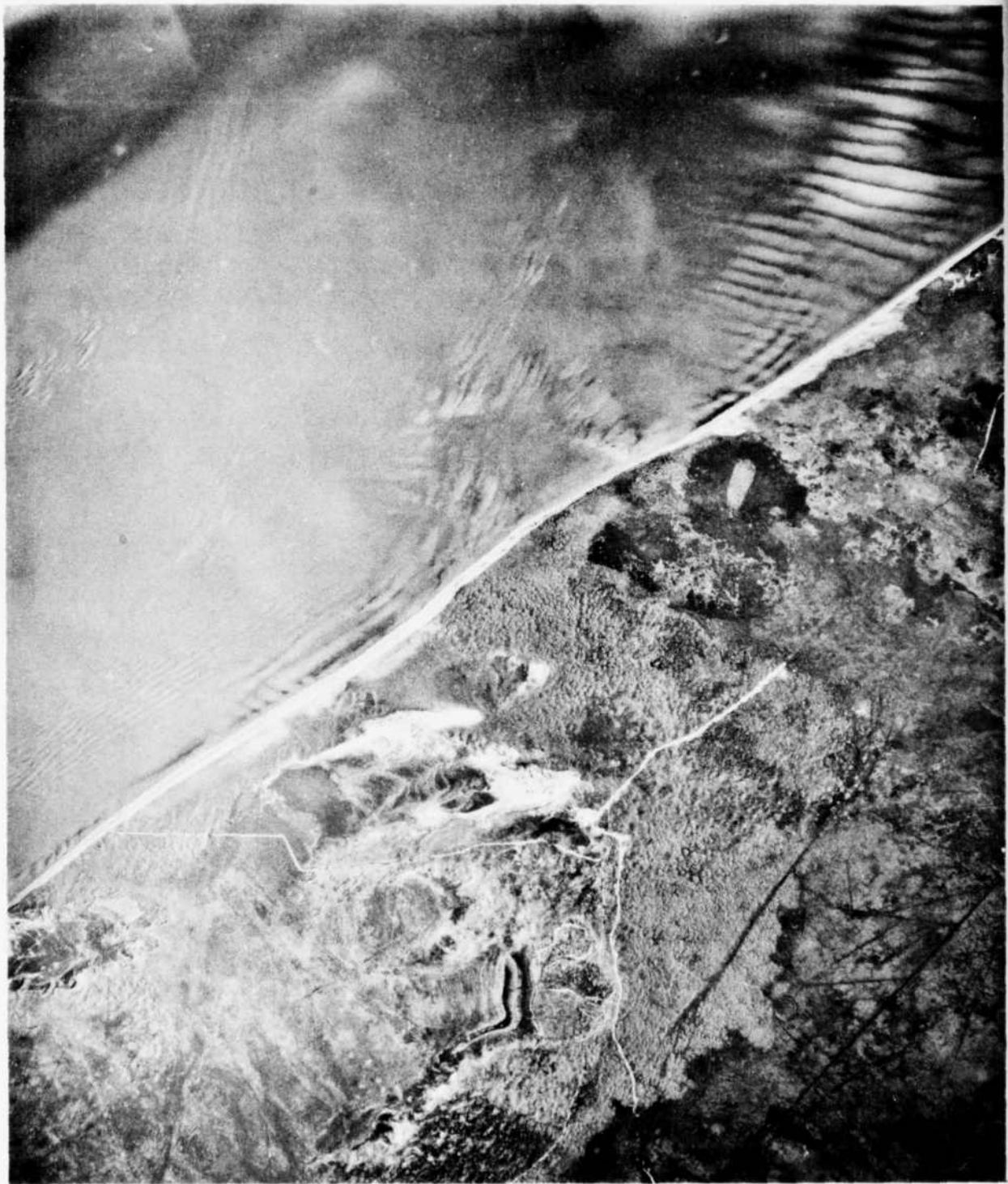
Grass moss turf with Juniper

Marram–Elymus

Calluna dominant

Carex–F. rubra

Slack–E. tetralix

0 ____ 25km

0 ____ 250yd

The Morrich More - an aerial view of the most active parabolic dunes
near the western shore. Note narrow fringing beach and extensive
sandflat.

The Morrich More – the complexity of the ridge and slack sequence is
apparent together with the prograding nature of the dune islands.
Aerial Survey, 1966.

The Worrich More - Marram stabilising white sand surfaces.

The Worrich More - Elymus dunes at the western end of Innis More.

As distance from the outer coast and possibilities of salt spray or sub-mergence recede, so the ridge cover progressively changes into a turf grassland with a Juniper upper storey over Festuca ovina. Thymus and Trifolium repens. Progressively a heathland type of vegetation becomes dominant, with Calluna, Agrostis and Juncus squarrosus. The Calluna vulgaris is the variant hirsute, and on occasion, Erica tetralix can be picked out. Clearly the immense variation here makes generalisation dangerous, particularly as the rate of moisture replenishment and of leaching are governed in part by water table fluctuations, in turn controlled by complex networks of creeks and virtually imperceptible gradients.

The slacks which separate the ridges are equally complex, species fading out and shading in with no demonstrable relationship to topography, distance from sea. Once deserted with shoreline progradation, slacks have been infilled with variable quantities of blown sand. Today, the slacks carry a low turf with occasional tussocks often containing species also found on the intervening ridges. Characteristic of the seaward slacks are Carex, Festuca rubra, Euphrasia sp and Armeria, while in the older inland ones, the appearance of the slack surface is characteristi-cally more hummocky with Erica tetralix, Salix repens, Carex, Potentilla and Juniper. Empetrum and Juncus balticus also are present.

In between some of the ridges, standing water occurs in the form of elongated lochans of which Loch nan Tunnag and Loch na Muic are the most permanent. These are very lime-rich, and carry thriving colonies of Chara and of Potamogeton sp. Their bottoms are floored by clay over sand. In the oldest zone of all near the Range Control Station, is an association of low Juniper scrub with much lichen and Ulex europaeus, a rather rare association in Scottish dune systems. The Nature Conservancy Council regard the Morrich as 'one of the most interesting dune systems in Europe and of international importance'.

3 (b)   THE BALNAGOWAN AND ANKERVILLE SALT MARSHES

Nigg Bay, Cromarty Firth

Nigg Bay is the major intertidal embayment within the Cromarty Firth.
The Bay has a drying area of 8 km^2 and is the one of a number of shelf
embayments fringing the 10 fathom ice-scoured channel of the Firth.
Within the bay, fringing salt marshes pass into inter-tidal sandflats,
the latter carrying substantial populations of Zostera sp. The sediments
beneath the marshes consist of sand and gravel infill, with the upper
parts, interspersed layers of shell and peat. From plant remains
found near the base of the marsh silts identified as Larix (Larch) species,
this tree only being introduced into Rossshire around two hundred years
ago, portions of the present residual marsh can not be older than this.

All the Nigg marshes have the common characteristics of a sand and gravel
substrate and a frontal micro-falaise, the latter often fringed by a
narrow and lower secondary marsh. The marshes are at an advanced stage
of frontal erosion by high tide wave action, and dissection by creeks and
sub-surface water and sediment dispersal. The present marshes are thus
only a part of a once much more extensive salting, parts of which have
been eroded away, and parts of which now lie landward of the dyke, reclaimed
into agriculture. The tidal range at spring tides is around 3.5 metres,
but on the marsh itself, submergence only occurs intermittently, although
such tidal processes are believed to have considerable roles in pan and
creek formation. Vegetation transects indicate that there is considerable
overlap of species between the secondary and the upper marsh, although
there are notable changes in frequency. Drainage and marsh micro-
topography are important selecting factors, but generally species variety
increases inland from the marsh micro-falaise.

The marshes here seem to exhibit a wide variety of pan forms, some of
which do not appear to have been fully described in the marsh literature.
From the days of Yapp's pioneer studies of Dovey marshes, it has generally
been accepted that pans do not originate de novo on existing marsh turf.
Yapp distinguishes between

   (i)   primary pans and channels which originate contemporaneously
          with the accreting intertidal area - these thus represent
          areas of the original intertidal floor which have never been
          vegetated, due either to the presence of standing water or
          the action of running water.

   (ii)   secondary pans and channels which are formed in the secondary
          marsh, and hence the product of random turf-fall from the
          erosion of the marsh micro-falaise.

   (iii) channel pans which result from the roofing over of existing
          channels by lateral sedimentation of the channel walls and
          the intertwining of vegetation across the narrowing channel.
          The end result of this would be to convert a tidal creek into
          a series of channel pans, the drainage continuing through a
          subterranean channel.

   (iv)   residual pans which Yapp describes as secondary information,
          being created by the partial plant colonisation of larger
          pans.

However examination both of the literature and of the pan and creek forms on the Cromarty Firth marshes (and other sites in North Britain) fails to demonstrate how it can be certain that channel pans, for example, result from infill and vegetal colonisation, rather than from the collapse and/or subsidence of subterranean drainage systems. Examination of the marsh forms here while confirming Yapp's classic theories, also suggests that pans distributed in a linear or dentritic pattern are, in many cases, linked to each other by pipe systems - sub-surface passageways through which water and sediment are dispersed during the ebbing of spring tides (which totally submerge the marsh and create a form of hydraulic gradient). In many cases, pans are topographically linked to each other and to creek systems by linear surface depressions - marking local collapse along the alignment of underground pipes. Sagging interpan divides also exist. Such dispersal of water and sediment not only accounts for pan and creek forms which do not easily fit into the Yapp model, (notably sinkholes and surface sags), but also accounts for the problem of sediment dispersal from expanding pans (his crenulate variety), at least when they are linked to pipe systems. In addition, pipe systems also help to explain the apparently random pattern of empty and water-filled pans following a period of tidal submergence.

In order to achieve sub-surface flow below marshes, it is necessary to have a sufficient hydraulic gradient (reasonable tidal range), appropriate marsh sedimentary characteristics, a retrograding micro-falaise, and arguably, a recent change in the land-sea relationship, which it may be suggested, is here producing what is essentially marsh rejuvenation.

3 (c)   SUMMARY OF FLANDRIAN SEA-LEVEL CHANGES

IN THE INNER MORAY FIRTH

1. Introduction

Little or no previous work has been published for the Moray Firth area
explicitly dealing with sea-level change during the Flandrian Age. This
is extremely surprising because it is now sixty years since Ogilvie (1923)
stated that the area "contains some of the finest and most complex
examples of raised beach at several levels" (p 377).

Ogilvie's impressive and detailed monograph is, however, primarily a
morphological study concerned with the changing shape of the coast between
Golspie and Port Gordon. It contains a fine description of the great
variety of beach form encountered in the Moray Firth area including
the high fault-controlled cliffs on the south-east coast of the Black
Isle, the flat carselands of the Beauly Firth and the desolate (now
afforested) sand and shingle foreland of the Culbin Sands. It is
perhaps indicative of the quality of Ogilvie's work, coupled to the
lack of research since that comparatively recent publications use
his work extensively (Sissons 1967, 1976, Steers 1973). However the work
contains little reference to stratigraphy and offers only the broadest
time control.

Evidence for Flandrian sea-level change is often implicit in the
published literature and there is no synthesis available. A brief
summary of the disparate pieces of information follows.

At a number of sites around the shores of the Moray Firth thin layers of
peat are found beneath later marine deposits or below present MHWS.
Wallace (1883, 1896) records local memory of an extensive peat bed
covering the floor of Burghead Bay; the rights of turbary were the
subject of a law suit in 1787. The peat layer was formerly more exten-
sive than the present sporadic occurrences, though at one site (0.6 m
O.D.) c. 50 cm of compact woody peat was observed to overlie blue-grey
silty sand containing abundant shell fragments.

Eyles et al (1946) provide information of a buried peat layer in the
Spynie depression. A brick-clay pit, worked until 1939 near Loch
Spynie, c. 5 km north of Elgin contained a peat layer 38 cm thick,
570 cm from the surface overlain by a shell bed and blown sand and
underlain by c. 45 cm of light blue clay and over 600 cm of dark clay.
Near to Beauly, on Barnyards Farm they also make reference to a trial
pit excavated for brick clay where a thin peat layer, 0.3 m thick was
noted to underlie 2.3 m of brown and grey clay. Further observations
of peat layers underlying later marine deposits are recorded by Smith
and Mather (1973) on the Morrich More, J. S. Smith (1968) at Delny and
the Geological Survey near Lower Kincraig.

Some morphological forms have also been used as evidence for a lower
sea-level, J. S. Smith (1963) calls attention to the well developed
gullies between Cromarty and Jemimaville on the southern shore of the
Cromarty Firth. The gullies are sharply incised into higher, earlier
beach deposits and are graded to a level below that of the Flandrian
raised beaches. There are no debris cones at or below the junction with
the lower raised beach which would tend to indicate they are older forms.
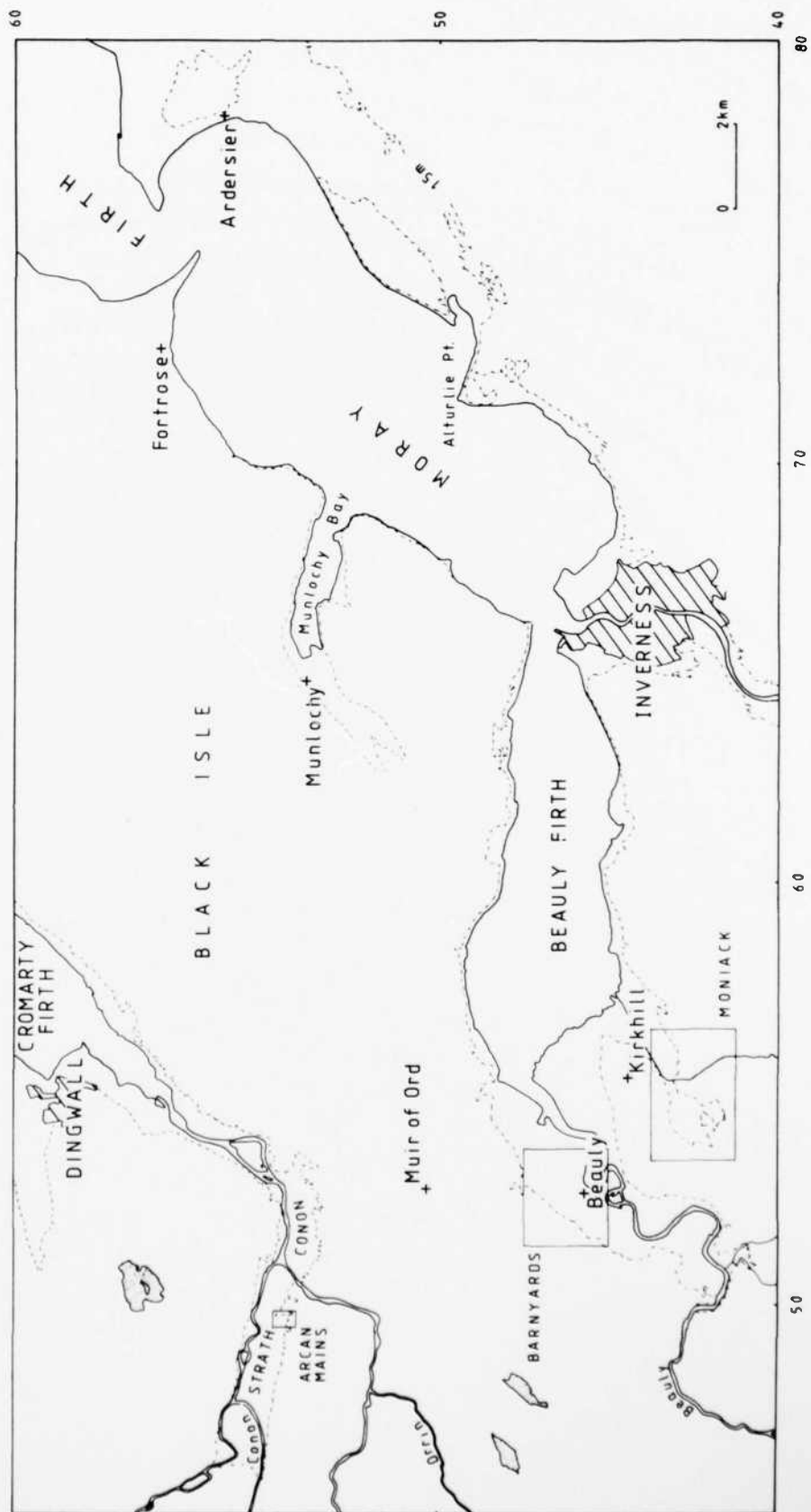Smith (1963) favoured an early Atlantic age c. 5,000 B.P. Sissons et al

FIG. 1

Maximum altitude of Flandrian marine deposition — at Moniack

at Barnyards

HAT
M′ | MHWS
| MHWN
| MTL

POSITIVE TENDENCIES
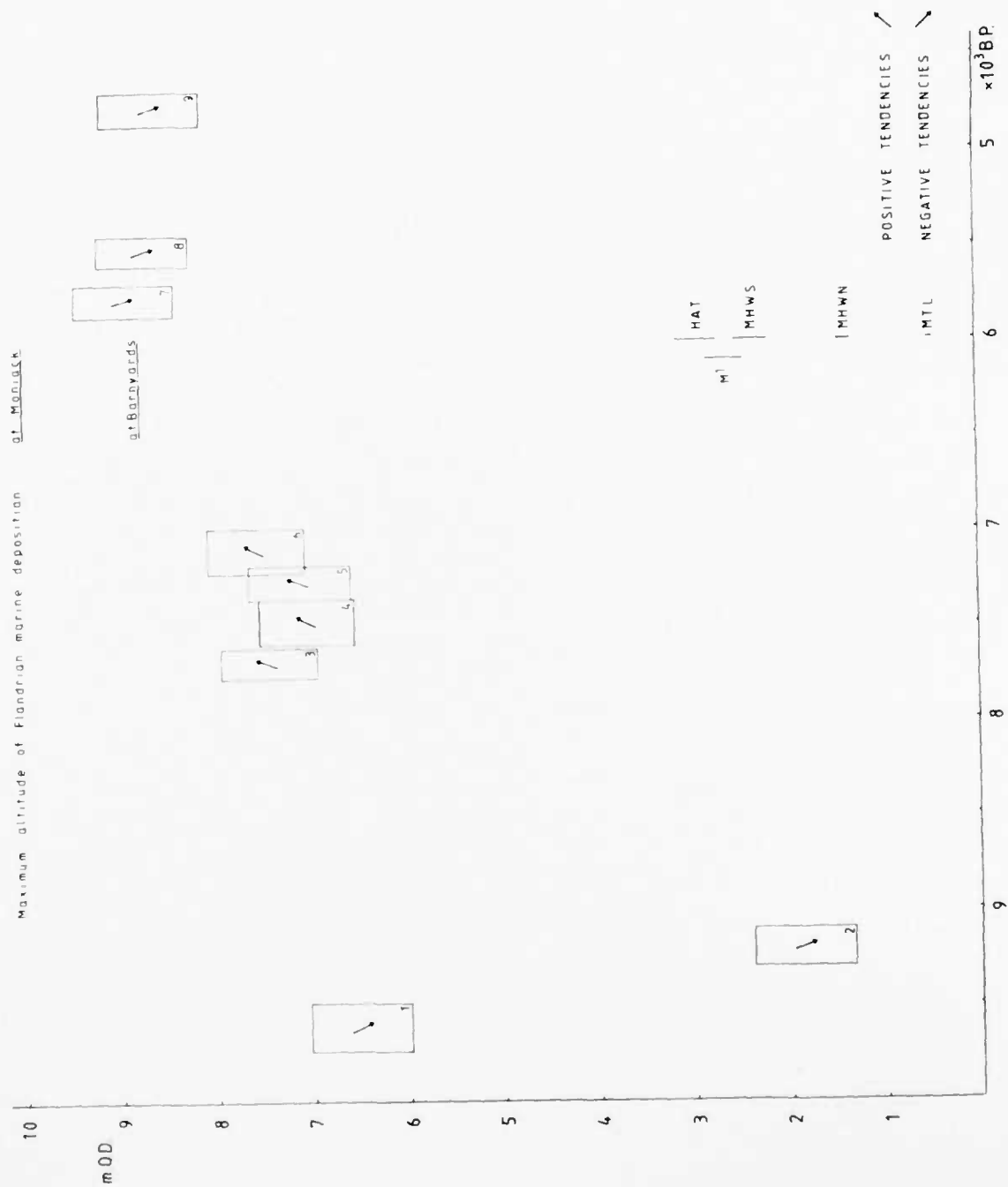NEGATIVE TENDENCIES

×10³BP.

mOD

FIG. 2

(1965) criticized the paper and described similar forms in the Forth and Tay area that are older and were in existence at least 8,000 to 8,500 BP.

The only detailed stratigraphic record with independent age corroboration pertaining to Flandrian sea-level change is that given by Peacock et al (1980) for the Cromarty Firth borehold C2. Using all borehole data three informal lithologic units have been described: from the base up, the Findon beds, Ardullie beds span the transition from Late Devensian to Flandrian. There are three radiocarbon dates from the lower Cromarty beds, SRR1068, 8748 ± 80 B.P. dating plant debris and two dates on shells, SRR1069 at 7326 ± 360 B.P. and SRR 1070 at 8156 ± 150 B.P. All dates have been normalized with respect to the P.D.B. standard. The lower Cromarty beds therefore probably accumulated during the early Flandrian.

If the marine shell dates are to be questioned then the lower Cromarty beds accumulated c. 8750 B.P. at the time of the relative low sea-level recorded in the Forth. The lower Cromarty beds have a high proportion of very shallow water species and the stratigraphy contains possible channel lag deposits. If the age quoted above is correct, an altitude of -6 m O.D. for the contemporary sea-level is reasonable (Peacock et al 1980).

If the plant debris date is to be questioned and shell dates accepted then the lower Cromarty beds accumulated between 8,000 B.P. and 6,500 B.P. at the time of the rise in sea-level to the Flandrian maximum in the Forth. The shallow water fauna could then be explained through downward translocation of shallow water and intertidal species. The fauna of the Upper Cromarty Beds indicate deposition in deeper water which may relate to the culmination of the Flandrian rise in sea-level and subsequent events.

Flandrian raised beaches have been described by the field officers of the Geological Survey (Horne and Hinxman 1914, Peach 1912, Read et al 1925, Read et al 1926) by Ogilvie (1923) and Steers (1937) though accurate height measurements and overall synthesis are lacking. Smith (1966) notes two Flandrian raised beaches, the higher one rises from 8.22 m at Kessock to 9.14 m at Tarradale, a gradient of c. 0.09 m/km. The lower beach is at 3.9 m O.D. but accurate height determination was impossible due to disturbance by road building.

In conclusion the fragmentary data suggest a relatively low sea-level during the early Flandrian - perhaps lower than -6 m O.D. at c. 8750 B.P. - followed by a rise to produce the well developed raised beach at c. 9-10 m O.D. in the inner firths and by intermittent fall to the present level.

2. A Flandrian Sea-Level 'Curve' for the Inner Moray Firth

Nine new radiocarbon dates from three sites at Barnyards (NH 5247),
Moniack (NH 5443), and Arcan Mains (NH 4954) (Fig. 1) provide a preliminary
time control for sea-level change during the early and mid-Flandrian. The
approach used in 'curve' construction (Fig. 2) is essentially a site-based
one and relies on lithostratigraphic and biostratigraphic evidence to
argue for direction in sea-level movement with height determinations and
radiocarbon dates allowing index points to be located with respect to the
ordinates of age and altitude. The 'curve' is depicted as a series of
error boxes and represents the approximate course of MHWS between c. 9600
and c. 5500 B.P. Details of stratigraphy, environmental evidence and inter-
pretation in terms of sea-level movement are given in Haggart (1982).

The altitudinal error boxes include consideration of sampling error and
the indicative range of each dated index point (after Shennan 1980). No
attempt is made to correct for consolidation of sediments or changes in
palaeotidal range. The age error box is representative of a range of 16
about the mean of each radiocarbon date. Further details are given in
Table 1.

TABLE 1

Index Point	Altitude (m)	Mean Age B.P.	Site
1	5.98 - 7.03	9610	Barnyards
2	1.33 - 2.38	9200	Barnyards
3	6.93 - 7.94	7700	Arcan
4	6.52 - 7.53	7430	Moniack
5	6.57 - 7.62	7270	Moniack
6	7.05 - 8.06	7100	Moniack
7	8.15 - 9.20	5510	Barnyards
8	8.39 - 9.44	5575	Arcan
9	8.10 - 9.15	4760	Moniack

The course of MHWS is suggested to have fallen from between 5.98 - 7.03 m
at 9610 B.P. to 1.33 - 7.38 m at 9200 B.P., both dates coming from the
regressive overlap of the lower peat at Barnyards. Although the dates
are not significantly different at the 95% level it is assumed an age
difference of c. 400 years exists between these two points based on
pollen data. This gives a maximum rate of fall of 3.17 m/100 yrs and
a minimum rate of 0.56 m/100 yrs.

The minimum altitude of the early Flandrian fall in sea-level is not known
but Peacock et al (1980) suggest a figure of -6 m O.D. based on marine
faunal studies of the Cromarty C2 borehole. Their ^{14}C date from derived
plant debris at 8748 ± 100 B.P. could give a broad estimate of the age
for this minimum. Morphological evidence for an early Flandrian low sea-
level includes the impressive incised gullies between Jemimaville and
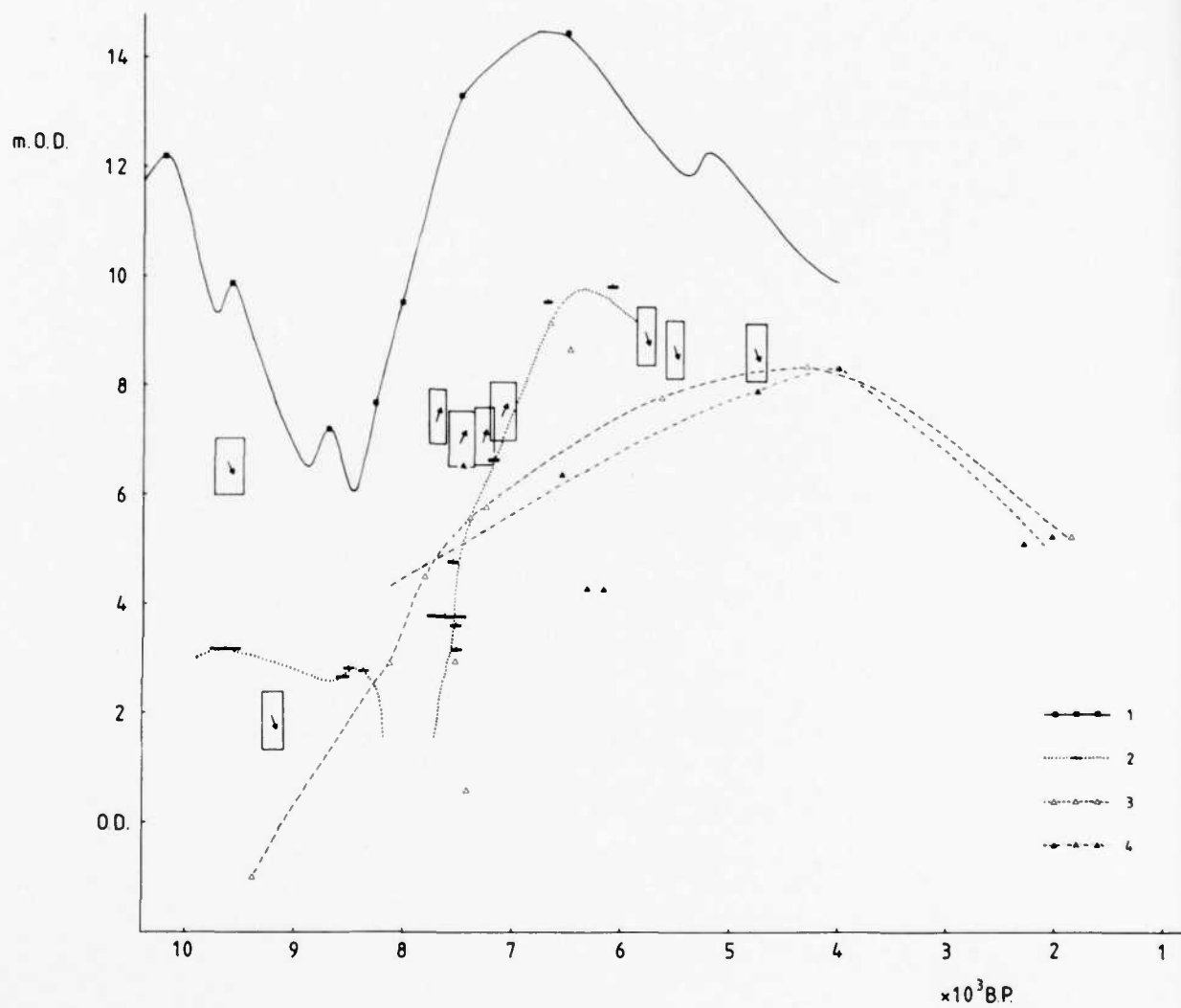Cromarty, mentioned above.

FIG.3

Because of a lack of data points no reliable conclusions can be made concerning the initiation of the following rise in sea-level nor of the rates of rise involved. As an initial estimate, based on pollen and diatom evidence from Barnyards, sea-level was probably rising by c. 8200 BP.

Index point 3 from Arcan Mains is considered to represent a rise in watertable prior to the arrival of marine conditions at the site and its age of 7700 BP may be slightly early for the initiation of marine conditions. Index points 4 and 5 from Moniack lie either side of a grey micaceous silty sand layer. Both are shown as indicating positive tendencies since there is insufficient evidence as yet to interpret the regressive overlap of the thin peat layer above the sand as a fall in sea-level. The sand layer may represent a storm surge deposit.

The culmination of the Flandrian rise is suggested to have taken place at c. 9 m, the altitudinal limit of the Flandrian marine sediments at Barnyards, at c. 6100 - 6400 BP. The altitude may in fact be a little higher since colluvial deposition precluded the confident identification of the limit. The altitude at Moniack, some 1 m higher is taken to represent local enhancement of the altitude of MHWS through the constructed nature of the site.

The final fall in sea-level is registered at Arcan Mains (index point 7) and Barnyards (index point 8) at 5775 BP, 8.39 - 9.44 m and 5510 BP, 8.15 - 9.20 m OD. The Moniack index point (9) is thought to reflect local conditions caused by the renewed activity of the Moniack alluvial fan and may reflect a delay in peat growth. Further research is needed to clarify this problem.

Figure 3 attempts to compare several recently published sea-level curves for a different areas of Scotland with the inner Moray Firth curve. A similar curve appears in Jardine (1982) though in this paper all curves including those from Jardine (1975) are plotted with respect to original index point altitude and age.

Full analysis of similarities and differences will be published elsewhere. Of note however is the agreement in overall shape of all curves save those from south-west Scotland. With such a small data base for the inner Moray Firth curve it would be injudicious to undertake explanation with too much certainty. Refinement of the scheme including greater time control on the initiation of the main Flandrian rise in sea-level and its culmination is required before statements on the synchroneity or diachroneity of shorelines or movements in sea-level are made.

PART 1   SECTION 3

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PART TWO
COASTAL ESSAYS

PART TWO   COASTAL   ESSAYS

PAPERS GIVEN BY GUEST LECTURERS

1.   # CONTEMPORARY MORPHOLOGY OF THE
       # FACE OF THE FOREDUNES AT FORVIE

The morphological characteristics of the summits and the seaward face of
the foredunes at Forvie are typical of coastal foredunes which have
experienced an apparent phase of net sand loss. When the supply of sand
to a beach is reduced, the natural maintenance of any dunes which might lie
to landward of that beach is prohibited. As a consequence erosion features
tend to predominate. At Forvie there are many examples of dune blowouts,
and dunes which have been greatly reduced in stature. The reasons for this
situation will be discussed below. The foredunes at Forvie show a great
degree of variation in height. Despite this there is generally a continuous
ridge of foredunes except at those points where blowouts have developed.
Hummocky foredune features are found mainly in the southern extremities of
Forvie where the erosion of the foredunes has reached a more advanced stage.

The Forvie foredunes range in height from 3.5 metres to 20.9 metres above
sea level. The lowest heights occur at places where blowouts are well
developed while the greatest dune heights are found in the more northerly
parts of the dunes where there is an element of protection from the sea and
wind due to the higher ground and rocky cliffs of Rockend to the north. The
height of the foredune ridge foot at the seaward edge varies from 0.25 metres
to 1.65 metres above mean high water. Again, the higher values are found on
those dunes to the north although some exceptions are found where there is a
lower dune with correspondingly low vegetation cover. In these instances,
seaward movement of sand by offshore winds may cause the dune foot height to
be raised. The width of the beach lying between the dune foot and the mean
high water level ranges from 17 metres to 55 metres with the protected northern
dunes possessing the widest beaches. The vegetation cover of the foredune
face varies between nil and 65%. A complete vegetation cover on the dune face
is virtually impossible to attain as a small scree of mobile sand is normally
to be found at the foot of coastal foredunes.

The morphology of the face of the foredunes is best described in terms of
shape of profile, including concavity and slope. Dune face profile is
either angular or smooth and rounded. An angular profile results from
severe aeolian erosion at a point of weakness in the vegetation cover or from
wave attack on the seaward edge. A smooth profile results from prolonged
sand deposition and movement. It may be vegetated now, or lack of a vegetative
cover on a dry sand surface which allows large amounts of sand movement. The
Forvie foredunes possess examples of the four typical foredune profile shapes.
These are:

a)   straight seaward face comprised of almost sheer cliffs which extend
     from the dune summit to the dune foot or having a very low flat profile.

b)   vertical or near vertical cliffs of lesser extent, may be vegetated,
     and having large screes of loose sand at the base,

c)   smooth vegetated dunes having profiles closely resembling a normal curve,

d)   low rounded profiles comprised of loose windblown sand with an unvegetated
     or poorly vegetated surface.

The 33 dune segments sampled on Forvie (Fig. 1) are categorised according to the face profile shape as follows:-

```
Dune Segment - 1 - b   7 - a  13 - d  19 - c  25 - d  31 - c
                2 - c   8 - a  14 - b  20 - c  26 - a  32 - c
                3 - c   9 - b  15 - b  21 - c  27 - c  33 - c
                4 - c  10 - b  16 - b  22 - c  28 - c
                5 - b  11 - b  17 - b  23 - a  29 - d
                6 - a  12 - b  18 - d  24 - d  30 - d
```

Dune face morphology may be quantitatively described through the measurement of variables relating to the curvature of the dune face and the angle of slope of the dune face.   Curvature is measured by using a curvature index.   This index is derived by drawing a chord line across the curve of the dune face, finding the midpoint of this chord and subtending a line perpendicular from the midpoint to the surface of the dune.   The chordlength is then divided by the length of the perpendicular line to produce the index value.   In this way a dune face which has a very concave profile will have a relatively low value on the curvature index, while a straight profile will yield a higher value.   Values for the sampled dune faces at Forvie range from 8.2 to 159.0, indicating that a full range of dune face profiles exists at Forvie.

Skewness of the dune face concavity can also be measured to give a further indication of the profile shape.   This is done by measuring the area enclosed by the dune face and chord above the midpoint of the chord and expressing this value as a percentage of the total area enclosed by the chord and dune face.   For the Forvie dunes this variable ranges in value from 31% (which indicates a marked lower profile concavity) to 68% which indicates that the dune face concavity is strongly skewed in the upper part of the dune.   Dunes having a value of more than 50% skewness tend to be those of the "b" category above, i.e. those in which the profile shape consists of a short near vertical cliff which has a scree of loose sand at its base, and to a lesser extent, "c" profiles.

A general appraisal of the dune faces along the Forvie coastline indicates that the dunes are in various stages of erosion due to a lack of adequate sand supply and dominance of sand removal over sand supply.   The morphology of the dune faces shows that erosion due to wave attack and aeolian activities has reduced the vegetation cover of the foredunes, steepened the seaward faces of the dunes, produced blowout features and widespread sand movements through exacerbation of weaknesses by wind action.

Factors Affecting the Development of Dune Face Characteristics

Dune face characteristics, along with the character of the dune as a whole, are the net result of the movement of sand.   This movement includes both the addition and removal of sand from the dune face. The movement of sand particles relates to the mechanics of sand movement while the patterns of this movements relate closely to the actual dune face morphology.   The mechanics and patterns of sand movement are not mutually independent in this regard, however, but act in conjunction to produce the physical appearance of the dunes.   Both the mechanism and the pattern are determined by external factors which initiate movement and determine the rates thereof.
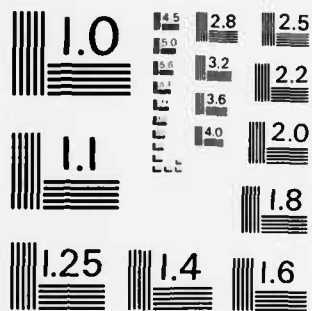
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

Mechanisms of Sand Movement

a. Under aeolian action - sand particles can be translocated by
several means resulting, either directly or indirectly, from
the effect of wind action.   These means are:- first, suspension -
whereby only the smallest of grains are carried in the moving
air;   second, saltation - the bouncing of grains along the sand
surface which accounts for most of the sand movement;   third -
creep - the tumbling and rolling of grains along the sand surface;
fourth - flow - whereby sand moves en masse down a dune face and,
fifth, slumping - the sudden downslope movement of blocks of sand,
often partly consolidated by vegetation.   Bagnold (1941) gives a
detailed description of these modes of sand movement.

b. Wave induced sand movement - this plays a most important role in
the development of dune face characteristics.   It is the means
whereby most of the sand enters the system.   The waves provide
the mechanism for the movement of sand from the offshore zone
to the beach.   From there the sand particles are moved into
the foredune zone by aeolian processes.

Wave induced movement of sand on the foredune face occurs only
during periods of storm surges, at times of exceptionally high
tides, or a combination of the two.   Under these circumstances
waves may reach the dune foot and subject the dune face to direct
wave attack.   In crossing a beach wave energy is expended and if
the wave reaches the foredune any remaining energy is expended on
the dune foot and face.   Sand is removed and cliffing on the
seaward face will result.   Material eroded from the dune in this
way is removed to the immediate offshore zone and is lost, perhaps
only temporarily from the dune system.

Sand Movement and Dune Face Characteristics

Once sand movement has been initiated the areal patterns of sand
movement, in conjunction with the mode of sand movement, will
produce the morphological character peculiar to the dune involved.
The variability and complexity displayed amongst dunes and dune
faces is a function of the different rates, time scales and
locations of sand moving processes.   These, in turn, are affected
by a wide range of variables which will now be discussed.

a) Total Topographic Situation - The location of dunes in relation
to the surrounding topography has a profound influence on the
workings of the system.   For example, a dune system located on
an exposed open coastline will experience a wider range of marine
and climatic influences than will a bayhead beach guarded by high
peninsulas.   The former experiences multidirectional winds while
the latter has a dominant wind direction due to the funnelling
effects of the surrounding peninsulas.   The actual effect of
topography may be slight, but may on occasions be sufficiently
strong to render insignificant the other processes acting upon it.
The Sands of Forvie occupy an exposed position for which the wind
regime exhibits a strong multidirectional element.

b) Sand Supply - The maintenance of coastal foredunes depends upon
the addition of a suitable amount of material to the system.
Without an adequate sediment supply dune construction and main-
tenance cannot be initiated or sustained even if all other relevant
factors are favourable.   Dune growth and/or a widening of the

Rockend

SANDS
OF
FORVIE

River Ythan

NORTH
SEA

N

⊐6 Sampled foredune
segments
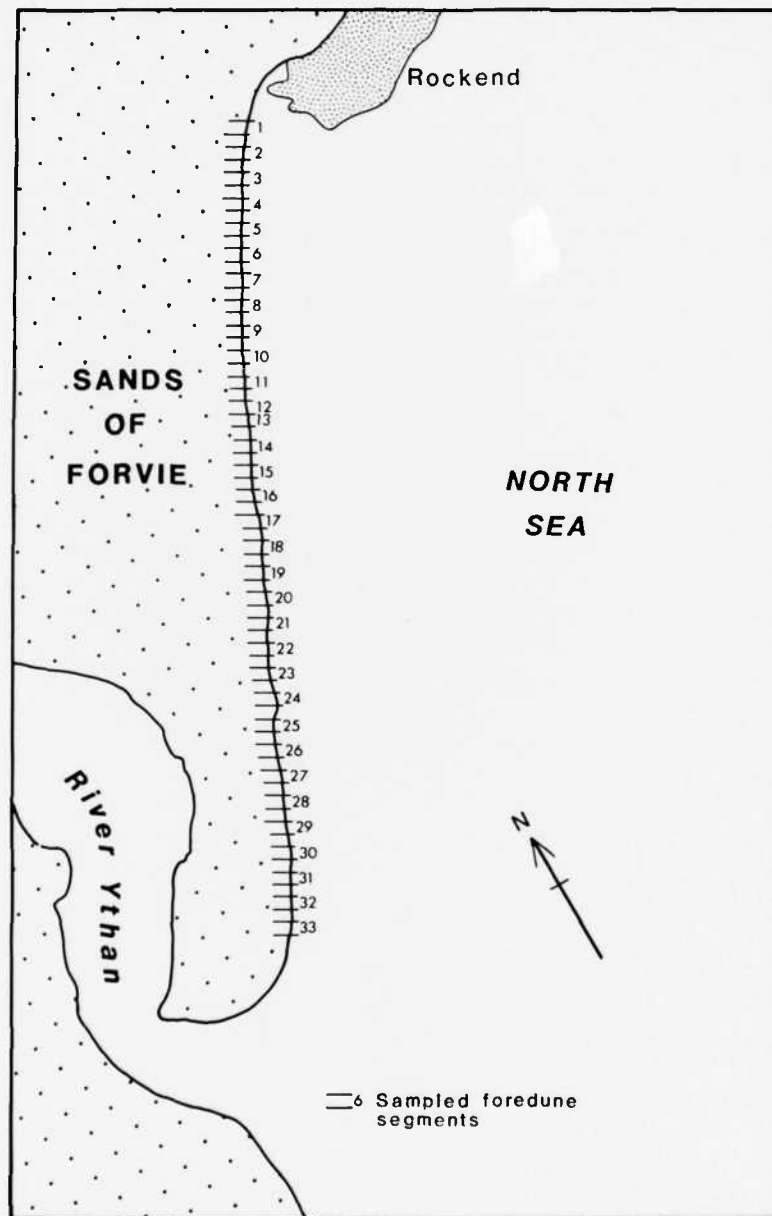
associated beach is evidence of net sand gain while erosion of
the dune and, particularly, the foredune face is evidence of a
net sand loss.   In the latter case narrow beaches, retreating
foredunes and undercutting of the dune face are common character-
istics.

At the present time the Forvie dunes are displaying evidence
of an excess of movement of material outward from the system.
There is no construction of a new foredune ridge after wave
cutting of the foredunes.   The evidence suggests that both
wave and aeolian actions are responsible for the sand loss.
This deficit in the sand budget may be a result from an increase
in the operating intensity of transporting agents, however, the
most probable solution centres on the depletion or exhaustion
of the glacially derived offshore reserves of sand material
combined with the recent rise in world sea levels.

c) Sand Characteristics - The characteristics of the sand grains of
which the dunes are comprised will have some effect on sand
moving processes.   Bagnold (1941), Hsu (1974) and others have
shown that sand grain size will affect the rate of transport
under the influence of wind action.   For example, there is a
direct relationship between grain size and threshold wind velocity,
such that the larger the grain size the greater is the wind
velocity required to commence sand movement.

Grain size will also affect the angle of rest attained by
unvegetated dune faces.   Where vegetation is absent and the
sand surface is dry, larger grain sizes are usually associated
with relatively steeper slopes.   This influences down slope sand
movement such as sand flow because larger sand grain sizes and
steeper slopes present a more stable sand surface in which dis-
lodgement of grains by wind and impact is rendered more difficult.

Analysis of sand particle sizes along the foredunes of the South
Forvie peninsula indicates that grain size does increase from
north to south.   This increase is not statistically significant,
however, and would have little effect on the variation of sand
moving processes in this particular area.

Moisture content of dune sand will account in part for
variations in the operation of sand moving processes.   The
amount of water contained in dune sands may be affected by
the organic content of the sand since this material assists in
the retention of water.   Most coastal foredunes are "yellow"
dunes with relatively low organic content and this means that
their moisture content, particularly close to the surface, will be
somewhat reduced in comparison with older "grey" dunes possessing
a well developed humic layer and a correspondingly greater capacity
to absorb and retain moisture.   The moisture content of dune face
sand may also be increased through salt spray settling on the dune
surface, especially during periods of strong onshore winds.

As the moisture content of the dune sand increases so does the
critical shear velocity value, that is, the minimum velocity
required for the commencement of aeolian sand movement.   This
is due to a subsequent increase in the cohesiveness of the dune
sand.   Belly (1964) found that for sands having a moisture
content of 0.1% the shear velocity was about 34.5 cm/sec, while
for sands with 3.0% water content the shear velocity was 58

cm/sec.   In addition, wet sands present a relatively smooth
surface at the sand/air interface as the interstices between
the sand grains take up water.   As a consequence of this
smoother surface sand movement potential is reduced.

d)   Climate - All elements of climate have some effect on coastal
dune form, either directly or indirectly.   They operate in
conjunction with each other and with other non-climatic variables
to influence sand moving mechanisms.and patterns.

Wind is the most important instigator of sand movement on coastal
dunes and the wind regime of an area will often yield clues as
to the formation of and morphological characteristics exhibited
by present day dunes.   Effective wind direction and strength
control the areal development, maintenance and erosion of dunes.
Dune face characteristics are determined mainly by onshore winds
due to the protection from offshore winds afforded by dunes to
landward and vegetation.   Also to be considered are rainfall
amounts and patterns, dew, fog, sunshine hours (insolation),
evaporation rates and relative humidity which are highly
influential in the control of sand moisture content and its
movement potential.

On the Sands of Forvie sand movement by aeolian means tends to
occur at a relatively constant rate throughout the year.   While
the sand tends to be dry during the months from May to September
wind speeds are typically lower than for the months October to
April when the sand is normally wetter.

e)   Marine Factors - Major changes induced by the sea at the land/sea
interface are usually associated with the seasonal changes in
beach profile in response to seasonal changes in wave energies.
Only under exceptional circumstances do waves have a direct
effect on the foredunes themselves, for example, at times of
higher sea levels.   Variations in sea level can take place on
a variety of time scales.   Those which occur over short time
spans have greatest effect on the coastal foredunes as they
occur more locally and too rapidly to allow satisfactory process
compensation.   Long term changes in sea level tend to be more
concerned with general coastal development and occur at a rate
slow enough to prevent any striking changes in foredune morphology
from being patently obvious within a short period of time.

Short term variations in sea level may be caused by abnormally
high or "king" tides, storm surges and tsunami.   Under these
conditions waves may reach the dune foot where remaining energy
is expended on the foredunes causing the seaward face to erode
and large amounts of sand to be moved offshore.   Sand movement
down to dune face is primarily by slumping as cliffing and under-
cutting occur.   Morphologically, once the high water level has
abated a new dune foot is established on a level slightly lower
than the highest attained sea level.   The foredune profile then
reveals a steep, straight cliffed face which is now more
susceptible to aeolian erosion.   As the newly exposed sand face
dries out, abrasion and winnowing by wind action will exacerbate
the erosion achieved by the abnormally high water levels.
Vegetation affords little effective protection against the forces
of a storm surge, tsunami or "king" tide as the erosive power of
waves is much greater than that of winds.

f) Vegetation - Many of the morphological characteristics of coastal
    foredunes result from the presence of vegetation, and its
    distribution, density, height and type. The influence of plants
    usually arises from their collective role as a community; it is
    only in the initial phase of dune development that individual effects
    of plants are most clearly evidenced. For a coastal foredune face
    to be stable it requires as complete a vegetation cover as possible.
    Complete (100%) vegetation cover is rare on a dune face due to the
    common presence of a zone of loose blown sand at the dune foot,
    however at least 80% of the dune face should be vegetated if
    stability is to be achieved. Typical well vegetated dune faces
    present a regular shape whereas faces with broken vegetation cover
    tend to show evidence of scalloping due to the aeolian induced
    removal of sand from the exposed surface. The presence of
    vegetation causes a reduction in the wind speed at the sand surface
    thereby protecting the dune from aeolian processes. At the same
    time the plant root systems tend to bind the sand together further
    reducing the ability of other processes to cause the sand to be
    moved. The funnelling effect of clumps of vegetation on air
    passing over a dune increases wind velocities in the natural
    "channels" between the vegetation. Erosion potentials are in
    turn, increased due to the increase in velocities. As a consequence,
    erosion corridors may develop through the foredune ridge with
    associated characteristics of sand cliffs, steep sided, smooth
    surfaced corridors extending from the beach to the swale immediately
    inland. The ultimate product of this situation is a dune blow-
    out of which good examples are found on the South Forvie dunes.

g) Induced Biotic Influence - The biotic influences are significant
    in that they may well occur at times when the existing natural
    environmental conditions would otherwise ensure prevailing
    morphological stability. The most latent effects of biotic
    influences on the dune face are those which result from negative
    impacts, and these impacts are usually related to the destruction
    of the vegetation cover. Changes may result from both human and
    natural factors, for example, grazing by rabbits, fire, grazing
    by introduced species such as cattle, or trampling by humans.

    On the dune face itself one of the more damaging activities relates
    to human usage. Children and adults alike delight in running
    and sliding down steep dune faces, in particular those which have
    little or no vegetation cover. This results in greatly increased
    erosion and downslope movement of sand and can, in a relatively
    short period of time, cause considerable alterations to the morphology
    of the dune face. In more recent years the growth in popularity
    of machines such as beach buggies and trail bikes has introduced a
    new and more severe factor in the development of dune face morphology.

    Other naturally induced biotic changes may result from the destruction
    of vegetation by sand blasting under aeolian influence or from the
    effects of salt spray on non-tolerant species. Whatever the cause,
    however, the morphological character of a coastal dune face will
    be indirectly affected by these induced biotic changes. At the
    same time, it is worth noting that changes of a positive nature
    (that is, involving the addition of an element to the landscape) may
    also give rise to changes in the dune face morphology. An example
    of this is found wherever artificial vegetation plantings have been
    made in order to reduce the amount of sand movement in a dune system
    or part thereof.

h)   Morphological and Small-scale Topographic Characteristics -

Variables such as the height of the dune foot above mean high water
level and the distance of the dune foot from that level will affect
the dune face morphology.   They are related to the accessibility
of the foredune to marine erosion in such a way that the greater
the values for the two the less likely is marine erosion of the dune
face to occur.   On the South Forvie foredunes the narrowest parts
of the beach possess evidence of wave attack at the foot of the
corresponding dune.   In general, wider beaches are associated with
dunes for which the dune foot is relatively higher above mean high
water.   Hence, on the narrower beach sections on South Forvie the
foot of the dunes tends also to be lower.

Summary

When the processes of sand movement, the factors affecting the rate of
sand movement and its pattern of operation, and the formal character-
istics of the dune which result are considered within the context of
a systems framework, the complexity of the form/process relationship
can be fully appreciated.   The close relationship between factors
influencing process characteristics involves an intricate system of
linkages which leads through to the end point - the dune, its form
and its stability status. The process/response system involves a
series of negative and positive factors working in opposition to each
other; in the coastal dune context examples are vegetation versus wind
velocity or beach width versus wave energy.   If the balance should
tip in favour of the negative factors then erosion conditions will
prevail and the dune form will gradually assume characteristics
pertinent to that status.   Should the positive factors have a net
advantage then the foredunes will display characteristics of stability
or even accretionary growth with consequent seaward advance of the dune
face.   In any event the major guide to the prevailing status of the
foredune is the condition and morphology of the dune face and this is
determined by the above mentioned factors acting in close relationship.

The Concept of Dune Face Stability

The Oxford Dictionary states that for an object to be stable it must be:-
1. firm, not likely to give way; 2. stationary, keeping in one place,
not fluctuating;   3. able to maintain place of position, presenting
resistance to dislodgement; 4. strong, capable of endurance.   From
the same source, stability is defined as:- 1. the power or remaining
erect, fixity of position in space; 2. permanence of arrangement, the
power of resisting change of structure.

The stability of sand dunes may be seen within the context of these
definitions.   Dune face stability must also be considered in this
way.   Both embody the consideration of two critical aspects of the
dunes, namely, the permanence of position and shape of the dunes, and
the sand movement characteristics of the dunes.   Where permanence
of location and morphology are threatened or absent the dunes lack
stability.   Consequently, stable dunes may be defined as those "which
are stationary in space and resisting translocation, which will main-
tain their morphological character and structure, and which experience
no net sand loss or gain".   In other words, for dunes to be stable all
movement of sand must be precluded for it is only then that form and

position will be maintained. Stability of the dune face presumes a preservation of prevailing morphological characteristics such as shape and slope in the absence of sand movement. These stability requirements are best found in those dunes which possess complete or almost complete vegetation cover of relatively high density and having no erosion surfaces.

An unstable dune is not necessarily one which is eroding, nor is an unstable dune face necessarily one which is retreating. A dune which is growing in size or an accreting foredune where new foredunes are being formed on the beach and the dune system is prograding towards the sea may also be considered unstable structures. As the incipient dune is gradually colonised by vegetation the vegetation may provide only a small percentage area cover of low density. Hence, sand movements will take place and the dune face will not be fixed in position or have a permanence of arrangement as demanded by the definition of stability. In other words, there are two types of dune instability - instability associated with erosion and instability associated with accretion. In addition there are varying degrees of instability ranging from slight instability through to high or severe instability.

Dune Face Stability - Its Value as an Indicator of the Development of Dune Systems

Dune face stability is an important concept in the study of the development of coastal dune systems. A study of dune stability per se is closely related to dune development processes and a study of the one almost necessarily involves consideration of the other. Erosion of dune systems may occur across the entire range of the systems from the dune face to a good distance inland from the beach, however, it is what is happening at the dune face at a given point in time which decides whether a dune system is expanding or retreating. Thus, by ascertaining the contemporary stability status of the dune face some idea can be obtained as to the developmental phase the dune system is experiencing at that time.

In this way, if the dune face is stable then the dune system is in a state of equilibrium at the seaward edge; it is neither accreting nor retreating. On the other hand, an unstable dune face shows that the dune system is undergoing changes in either morphology or position in space, or both. A study of the factors which affect the stability of the dune face necessarily involves a study of those factors which control the development of the dune system as a whole.

At the present time the foredune ridge at South Forvie shows evidence of severe seaward face erosion with blowouts, overwash plains and large areas of unvegetated sand being a common occurrence. A study conducted by Esler (1976) revealed that only a small proportion of the foredune face at South Forvie is stable, while a greater proportion of the dune face has a high level of instability. The present stage of development of the South Forvie dune system is therefore one of general retreat or erosion of the dune system. It is unclear at this stage whether this situation is of a long- or short-term nature. The most plausible explanation of the current status, that is, exhaustion or near exhaustion of the glacially derived offshore sand reserves which supply the system, tends to suggest that the trend is of a long-term nature

and that the period of growth of the dune system is over.

What is important, however, is that the foredune ridge marks the seaward boundary of a coastal dune system and that it is on the seaward face of the foredune ridge that evidence of retreat or advance of the system will first occur. The contemporary stability of the dune face will therefore enable a ready assessment to be made of the contemporary stage of development of the coastal dune system.

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ABERDEEN BEACH AND DONMOUTH SPIT -
COASTAL DYNAMICS ON AN URBAN SHORELINE

2.

The Context

Aberdeen beach comprises one of the larger beach systems of Eastern
Scotland. Between the outlets of the Dee River in the south and the Don
River in the north, it is slightly less than 4 kilometres long and
faces almost exactly due east (Figure 1). It is the southern part of a
larger beach system which extends from the rock headland of Girdleness
and the contiguous mouth of the River Dee (which now forms the entrance
to Aberdeen harbour) (see figure), northwards to Rockend in the Sands of
Forvie Nature Reserve, a distance of more than 22 kilometres.

Aberdeen beach provides a case-study of coastline changes related
primarily to civil engineering works of several types and ages.
Historical evidence (Ritchie and Buchan, 1978) from several sources may
be used to identify the more significant changes, which have their
origin in the building (in the period 1775 to 1815) of the stone piers
of harbour in the sand banks and channels of the Dee Estuary. Quay
construction and reclamation followed, e.g. in 1829 the Dee was
diverted to create new docks, until the modern situation as shown in
Figure 1 was reached.

The process of coastline adaption and protection developed progressively
northwards from the harbour area in the form of beach groynes and back-
shore stabilisation measures. Such forms of permanent protection date
primarily from the mid-twentieth century onwards, culminating in the
mid-1960s in the construction of an esplanade, sea revetment, and a
complete suite of beach groynes. Prior to the imposition of such
measures, Aberdeen beach was wider and thicker than it is now and the
backshore limit comprised a line of massive marram vegetated sand
dunes (12-14 m O.D.). This backshore dune-line was broken by blowouts
with tracks and footpaths reaching across the links to the beach zone.
From the end of the nineteenth century, there is evidence of consider-
able population pressure (primarily commercial and recreational) on
dune and beach areas (Ritchie and Buchan, 1978). The other major
coastal change for which evidence exists is the progressive drainage
of the inland links (raised shoreline and fluvioglacial deposits (Murdoch,
1975), where streams and lochans which generally drained northwards into
the Don estuary were filled or diverted. Increasingly, the links and
the dunes were modified to become the focus for recreation and amenity
for holidaymakers and city-dwellers.

Throughout this historical period of development and change, the outlet
of the River Don remained, as it does to this day, largely free from
direct human interference (Buchan and Ritchie, 1979). Indeed, in the
present situation with the beach confined by groyne and concrete
revetment, the Donmouth spit, in spite of its complex interrelationship
with the rest of the beach system, exhibits the natural unfettered
mobility and dynamism which is an essential feature of natural sand
beach systems. The scale and nature of this dynamic change is
illustrated in Photo-Plate 1, where a suite of photographs
demonstrate the river-outlet configuration for specific dates within
the last 30 years.

However, such historical evidence is essentially static and, while
pointing to the scale of inherent dynamism in the natural coastal

Table 2: Cross-Sectional Area and Volume Changes,
Aberdeen Beach Profiles, 1973-74

Profile Locations	Cross-Sectional Area m^2 Volume m^3	Jan-May 1973	June-Sept 1973	Oct-Jan 1973 1974	Feb-June 1974
Profile VII	Cut m.^{2} Fill m.^{2} Volume m.^{3}	– 90.75 +90.75	2.34 4.50 +2.16	63.25 9.00 -54.25	13.95 4.92 -9.03
Profile VI	Cut m.^{2} Fill m.^{2} Volume m.^{3}	– 42.50 +42.50	26.60 6.68 -19.92	27.10 0.93 -26.17	18.00 – -18.00
Profile V	Cut m.^{2} Fill m.^{2} Volume m.^{3}	8.19 1.07 -7.12	0.41 8.25 +7.84	20.53 0.62 -19.91	– 21.24 +21.24
Profile IV	Cut m.^{2} Fill m.^{2} Volume m.^{3}	0.59 12.31 +11.72	6.63 13.60 +6.97	32.00 7.49 -24.51	5.87 1.57 -4.30
Profile III	Cut m.^{2} Fill m.^{2} Volume m.^{3}	3.05 2.81 -0.24	1.50 6.90 +5.40	33.59 – -33.59	– 11.83 +11.83
Profile II	Cut m.^{2} Fill m.^{2} Volume m.^{3}	4.08 8.19 +4.11	– – –	10.33 0.16 -10.17	5.11 0.43 -4.68

(The Volume changes refer to the residual of loss (–) and gain (+)
of material on each profile. It should be noted that these volumes
refer only to the measured profiles.)
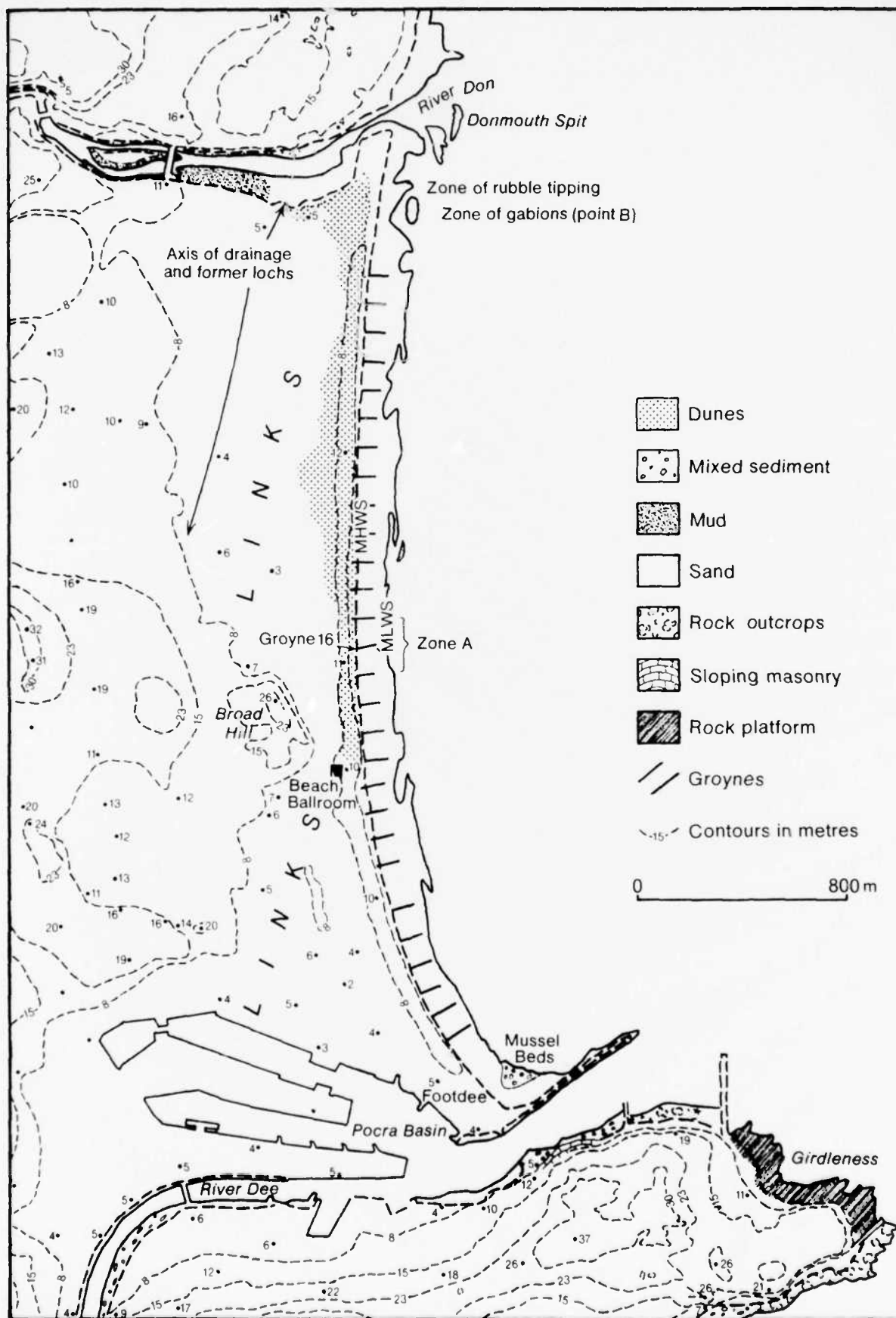
FIG. 1
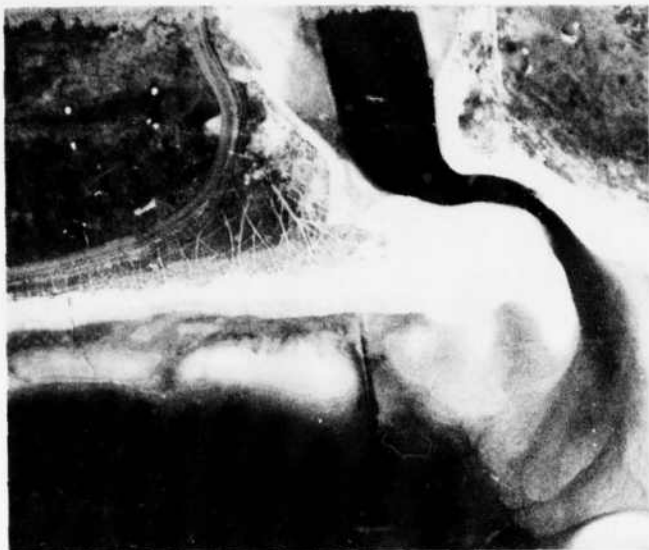
1953

1960
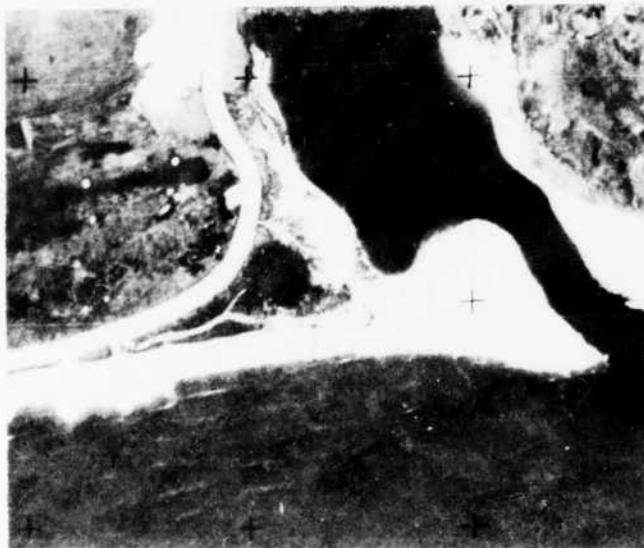
1966

1969

1973

1974

Aerial view of the Don estuary and mouth taken in May 1977. The shape of the spit and asymmetry of the river mouth can be seen. In the foreground, the disturbed wave-refraction pattern is associated with a complex series of shifting nearshore sandbars and banks and various flood and ebb tide channels. On the right, erosion of the dunes of the north bank of the river may be clearly seen.

(Photograph by D. Robertson)

system, does not allow anything other than glimpses of formal change in the environment. The study of detailed change, the reasons for such change, the interrelationship between constrained and unconstrained sections of the system, the processes of change – all require measurement and observation in the short-term, the results of which may be used to interpret observed long-term changes in the system and to postulate causal factors: in the example of Aberdeen beach, these are wave climate, river flow, tidal change and climatic variation.

Beach and Bay Planimetry

As shown on Figure 1, the rock headland of Girdleness at the south end of the bay is a dominant feature of the entire bay planimetry. Yasso (1964) identified beach planimetry of a similar nature as a common occurrence and applied the term "headland-bay" beach to "a beach lying in the lee of a headland subject to a predominant direction of wave attack. Such beaches characteristically have a seaward-concave plan shape resulting from erosion caused by refraction, diffraction and reflection of waves into the shadow zone behind the headland". Yasso's subsequent analysis showed this shape to approximate closely to the logarithmic-spiral model and this has since been corroborated by Silvester (1970) and Silvester and Ho (1972).

The distinctive shape of these headland-bay beaches, such as Aberdeen, is their particular orientation to the oblique resultant wave energy vector, so that the orthogonal of this vector will be nearly normal to the straight section of the log-spiral model, while the upcoast curve is within the wave shadow of the headland.

Analysis by Buchan (1976) of the relationship of Aberdeen beach to the logarithmic spiral model shows that the planimetry of the beach approximates to the log spiral shape, with its customary elements of a downcoast straight section and a curved upcoast section in the lee of the Girdleness headland. The planimetry is, however, insufficiently developed to attain a high statistical fit to the spiral model as it exhibits a mean error of fit of some 1.6 metres for the 40 points used to test the model.

In the fully developed model (Silvester and Ho, 1972), the beach attains this shape by natural erosion and littoral sand transport, so that an equilibrium condition will be reached. In this theoretical condition little or no net longshore transport occurs due to the incoming waves being refracted and diffracted into the wave shadow of the headland to break simultaneously. At the same time, the downcoast tangential section of the model is approached by the predominant wave trains at a normal angle to the beach, and no littoral drift is generated.

The importance of this concept cannot be overstated in the context of Aberdeen beach, as it is possible that it is the failure of the beach to attain its natural equilibrium plan shape that lies at the heart of an energy continuum flowing between the beach and the Don outlet sand spit, and the consequent erosion and river-mouth problems which were experienced.

The present beach plan may be considered as being at an advanced stage in the evolution of the equilibrium log spiral shape. The historical erosion of the foredunes and the undercutting of the promenade road which necessitated the construction of the present beach defences, can be considered to be an integral step in the spiral's evolution, particularly

with regard to the concave curved upcoast section, i.e. in the direct shadow of the headland. It was in this area that we have seen that sea defences were first erected last century to prevent erosion and flooding of Footdee (Figure 1) (Ritchie and Buchan, 1978). These defences have prevented further backshore erosion but have also irrefutably halted the beach's progression to its natural plan shape. As a result, the diffracted and refracted waves do not break parallel with the shoreline in this area, but at varying angles.

Downcoast, i.e. further north, the tangential section of the model shape has also been stabilised, and because the upcoast curve has been prevented from evolving, the downcoast area will never lie normal, i.e. at a perpendicular, to the predominant line of wave attack from the south east (Pallett, 1964; Buchan, 1976).

The conclusion can therefore be drawn that the optimum equilibrium log spiral between beach plan form and breaking wave crests cannot be achieved due to the beach stabilisation measures. The result in a certain element of obliqueness in the incident wave angle all along the beach, and in an accompanying quantity of longshore transport along the beach, which in turn will feed the Donmouth spit and exacerbate the problem of river-bank erosion caused by river-mouth asymmetry. Herein lies the essence of the relationship between beach and sandspit. It should be noted that although the logarithmic spiral model is used to assist the geomorphological study of Aberdeen Bay, the axiomatic condition that the beach should be in the line of a predominant direction of wave attack is not always present. Strong wave action strikes the beach from the north east and east and brings about substantial short-term changes as, for example, in January 1978, when the Donmouth spit was almost removed in one severe gale which coincided with an extremely high tide. Nevertheless, on the longer time scale an analysis of all available wind and wave data (Buchan, 1976) has shown that dominant direction of wave approach is from the southeast quadrant.

The direct nature of the feeder beach/spit relationship, the role of wave incidence angle in that relationship, the range of marine and beach processes operating within the bay system - these have previously only been inferred from somewhat fragmentary and conceptual evidence. Evidence is however available of a short-term, quantifiable nature (Buchan, 1976) which reveals more precise areal and volumetric changes in form and materials in response to the bay's energy climate.

Beach and Spit Changes - The Short Term

Along the beach, a series of seven profiles were levelled seasonally during 1973 and 1974. Their location is shown in Figure 1. Three sets were profile pairs, I/II, III/IV, V/VI   taken within the groyne fields at the points considered to be most sensitive to change; i.e. the outer extremities of the upcoast spiral curve and the downcoast tangential, and the central fulcrum of the beach. A further profile, VII, was located beyond the groyne field, on the "free" beach, between the northernmost groyne and the sandspit, in order to monitor the degree of change of the unprotected and unsheltered beach.

Net computations of change over an eighteen month uninterrupted period indicate an overall loss of volume from the beach, increasing from north to south, with the maximum net loss in the southern half of the beach (Figure). During the period of the surveys, the free end of the beach registered a net gain in volume (Table 2). Such net computations

naturally disguise considerable short-term seasonal variation in the profile shape and volume; variation which is entirely predictable in terms of the energy climate measured within the same period. The overall conclusions drawn over this period require care in their interpretation since more profiles surveyed at short-time intervals would be required to increase the accuracy of the calculations. It was completely impracticable to do this within the terms of this short-term process study and the validity of the conclusions rests heavily on accepting the representative nature of the carefully selected profile locations.

Beach profile gradients (defined as elevation upon distance from dune/ seawall base to the mean sealevel intercept) were also averaged for each profile, and are tabulated below. These gradients were supplemented by monthly beach slope measurements by Abney level.

TABLE 1

Profile	VII	VI	V	IV	III	II
	0.043	0.034	0.034	0.042	0.036	0.033

The trend illustrated is for an uneven increase in slope from south to north, a trend which, in spite of the low number of data, yielded a product-moment correlation of 0.65, significant at 98%.

Analysis of beach sediment samples (taken at mid-tide reference level in 18 sites (Bascom, 1951)) also indicates a similar trend. The mean particle diameter increases from south to north, from fine sand (2.4 phi (0.189 mm)) in the south end of the bay to coarse sand (0.2 phi (0.87 mm)) on the beach north of Donmouth. The trend of increasing sediment size from south to north along the bay was tested by product-moment correlation and yielded a coefficient of 0.931, significant at the 0.1% level of probability.

The Donmouth sandspit was subject over the same time period to detailed tacheometric surveys. These suggested the existence of a general state of dynamic equilibrium and a trend to cyclical changes in the form and materials of the spit. The cycle of change in the volume of the sandspit had three basic components:

1) an overall growth through spring and summer into autumn;

2) drastic reduction in October to January - by a factor of 0.6%;

3) a growth through late winter and spring to a summer peak. The winter reduction accounts also for over 63% of the measured deviation from the computed trend.

Commensurate with a growth in volume is a trend for decrease in overall length, while the converse also prevails. The maximum length measured was 440-450 metres, when the volume was also at a minimum. As growth

in volume occurred, this generally took the form of an increase in spit height and a decrease in spit length. Thus a simple but fundamental characteristic of the spit is established.   Table 3 summarises this fundamental and quantifies the nature and scale of change.

The close and direct relationship between spit volume and height and the close inverse relationship of length to the above parameters are directly explicable in terms of the processes operating upon them. Volume and height tend to be at their maximum in summer when wave activity is generally "constructive", i.e. low waves of medium to long length, and when tide levels are at their most stable. As a result of this low energy marine environment, waves are refracted round the distal end of the spit, carrying material which is deposited on the landward side of the form thus reducing the overall spit-length but generally building up the well-known "hooking" characteristic of free-forming spits. At the same time, the general constructive nature of the waves moves material alongshore and onshore in the form of small inshore bars which consolidate on the seaward slope of the spit. The stable tide levels, high tide being in the range of 1.5 to 2 metres O.D. on the actual spit, allow waves to deposit material on the spit crest. The combination of such constructive action produces a stable, high, recurved spit form. In addition, in summer months, river discharge is generally at its lowest and is therefore incapable of eroding the spit as it seeks to extend across the river-mouth.

Table 5:   Donmouth Spit Parameters

Month	Net change in the calendar month			
	Volume (1000 m.^{3})	Height (m.)	Length (to 0.0 m.)	Movement (m.) Landward + ve Seaward - ve
March '73	64.88	2.88	323	-
April	-	2.44	317	+19.75
May	55.75	2.87	295	+34.75
June	58.13	2.98	297	-20.29
July	61.64	3.26	306	+4.3
August	61.65	3.04	312	+3.75
September	62.40	2.77	312	+22.58
October	61.87	2.77	326	+1.83
December	52.41	2.99	336	+12.08
January '74	24.23	(2.87)	146.5	+12.37
February	40.11	1.24	440	-98.5
March	49.83	1.71	450	+63.8
April	50.86	2.13	460	-18.0
May	52.88	2.41	389	+14.25
June	54.6	2.46	329	+16.5

The converse, of spit length at its maximum in the winter months, with volume and height at a minimum, may be explained in terms of the overall energy increase of the process environment during such months. Predominant among the process variables is the river discharge which is at its maximum and is capable of eroding the recurved distal end, or, as happened on at least one occasion, of breaching the form and carrying the whole spit seawards, depositing it further offshore. Simultaneously wave length and energy levels, both onshore and longshore, are increased (Figure 3) and tidal levels often are considerably higher than predicted. Such marine factors resulted in significant overwashing of the spit by waves and tides and spit material being deposited in the river only to be transported seaward. Thus the spit volume and height are reduced, and the overall length is decreased initially. Subsequent increase in length occurs as material is carried back landwards to the spit at low tide level. The cyclical process of formation then recommences.

Horizontal movement of the spit crest illustrates a predominantly landward trend, interrupted by both minor and major reversals, occurring largely in the same winter period, and also in later summer where, after summer quiescence, movement suddenly increases from 3.75 m to 22.58 m at a rate of 0.65 m per day. Crest movements also appear to be related to tidal conditions, and the height on the spit where swash forces can reach.

The actual form of the spit as indicated by its length and shape has considerable variation (Figure 4). The recurved form, created by material being carried along the foreshore of the spit by obliquely incident waves and currents (Evans, 1942, Yasso, 1964), is dominant through the summer periods, while during late autumn and winter the spit has a straight non-recurved form or a concave seawards form which is probably caused by the increasing meandering and flow of the River Don in flood stage eroding and pushing the whole spit seaward.

The composition of the spit materials also varies considerably. Reflecting the interaction of the four formative processes - river flow, tidal movements, wave and wind action - the materials of the spit may be considered in four principal groupings:

1) sediments of the spit foreshore - coarse, poorly sorted (in comparison to the other groupings), negatively skewed,

2) sediments of spit crest and lagoon - fine, less skewed,

3) sediments of the back of the spit - intermediate, widely mixed;

4) shingle of the spit surface - mean roundness of 540 (Cailleux roundness index).

This breakdown of sediment characteristics is evidence of the range of processes and process environments found in the spit complex - marine, aeolian, high and low energy expenditure.

Sediment was also collected in the vertical through the spit, and displays characteristics similar to surface samples - coarse sand, ill-sorted and with high negative skewness values. This analysis further corroborated an important feature of the spit - it is a free formation, not founded on any fossil base. It is therefore a dynamic feature, free to change and find its own equilibrium with the ever-changing process/energy environment. Compare this with the constraints imposed upon the beach's movement and adjustment.
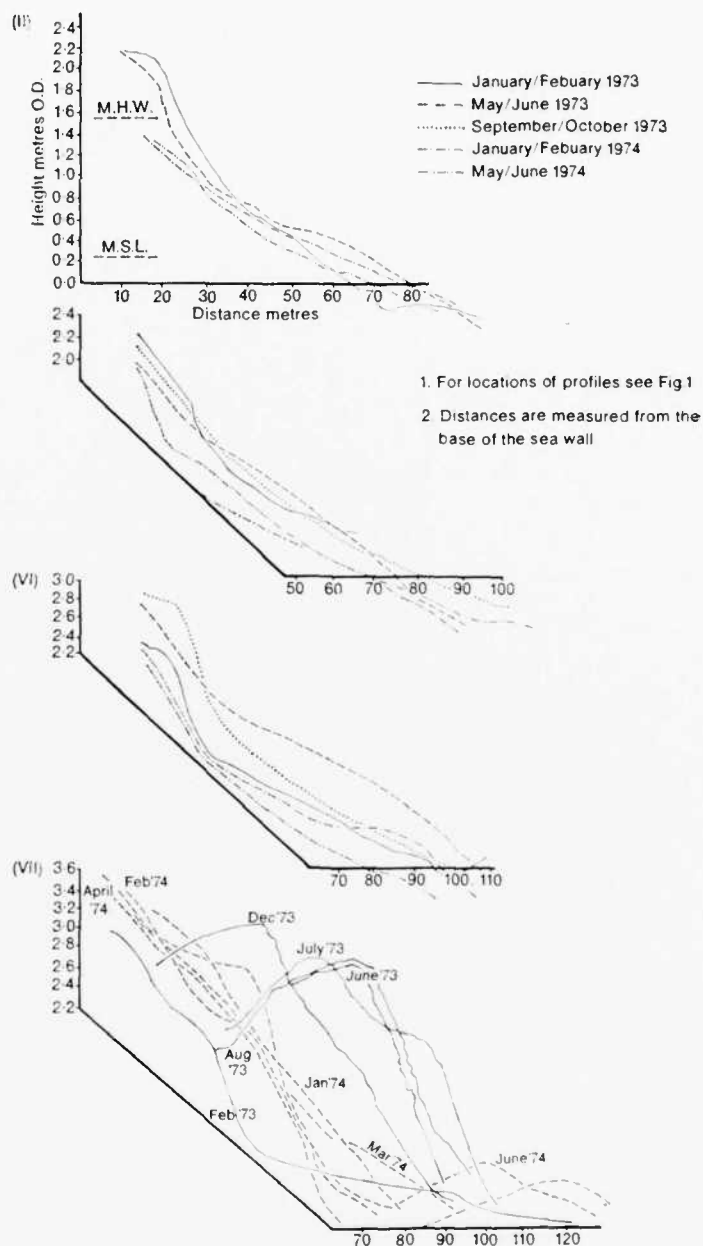
Selected beach profile surveys showing changes in beach gradients and depth.

FIG. 2

The Energy Environment and its Role in the Relationship

The major spatial trends in morphological and sedimentological variation which have been described as occurring in Aberdeen Bay, suggest, when considered in terms of a dynamic marine environment, the existence of a south to north energy gradient in the nearshore wave climate. This hypothesis can only be proved valid by a study of the Energy environment within the bay. The wave climate of Aberdeen Bay is dominated by three principal modal classes of wave height and wave period distributions:

Mode A: 0.75 - 1 metre height at 4 - 5 seconds period

Mode B: 1.75 - 2 metres height at 6 - 7 seconds period

Mode C: 2.5 - 3 metres height at 8 - 9 seconds period

The ordering of the three modal classes reflects their decreasing frequency of occurrence and conversely their increasing scale of energy content.

The modal classes and wave distribution were derived from weather data by hindcasting techniques and by direct measurement and observation. Wave approach angle was observed to be predominantly from vectors between 110° and 160°. These findings are in agreement with published wave climate records for the North Sea.

In order more directly to relate spatio-temporal variations in the energy climate to similar variations in the morphological and sedimentological environments, the wave climate as described above was analysed by computer using a modified wave-climate program (Dobson, 1967, Coleman and Wright, 1971). This modification utilised digitised bay bathymetry via magnetic tape and wave hindcast and wave observations as input data.

The results of this computer analysis are summarised in Figure 3. This illustrates wave energy components, both onshore and longshore, at four selected locations within Aberdeen Bay, corresponding to the physical components of the Bay's planimetry as described earlier. A number of significant characteristics can be identified:

a) The effects of wave attenuation upon deep-water wave energy as it enters shallow water. The magnitude of this attenuation is such that energy levels within the waves are reduced by more than 50% from their deep water levels. The attenuation is the result of friction with the shallowing submarine profile and in transporting sediment both along the bed and in suspension.

b) The spatial variation longitudinally within the bay is such that wave energy at the north end of the beach, i.e. on the downcoast tangent of the spiral, is of the order of 50% greater than that of the south end, the upcoast curve, in the spiral terminology.

c) Temporal variations in the wave energy climate correspond with seasonal variations in the weather climate, and are consequently readily predictable. Wave energy therefore peaks principally in the late winter months of January to March, and conversely attains its minimum values in middle summer.

d) Temporal variations in longshore energy coincide largely with those in onshore energy, although in comparison to onshore levels, longshore energy is less well developed. What is important to note,

however, is that during periods of significant wave energy incidence, tne longshore component at the north end of the bay may be as much as 300-400% greater than energy in the southern half.

e)   This spatial variation in longshore energy within the bay is further emphasised by analysis of the angle of incidence of diffracted breaking waves in the bay. Previous research (Sonu et al, 1968; Zencovich, 1967) has shown that longshore energy and currents are primarily dependent on the angle of incidence. Tnis being the case, it is evident that longshore energies and direction of flow in the north half of the bay are radically different from those in the south end – mean angle in the northern half was between 155° and 170°, i.e. consistently south of east, while in rhe southern half, mean angle lay between 70° and 90°. These latter angles would in fact create a reverse flow of north to south in the southern half, as opposed to a south to north in tbe northern half. These computer generated angles were corroborated by regular theodolite measurements from the esplanade. However the overall resultant vector of annual deep water wave energy is 32°45' south of east, with some 92% of incident wave energy having a southerly orientation and significant longshore element.

Statistical testing of the relationship between beach form and sedimentary characteristics and tne process environment yielded a number of correlations significant at the 1% and 0.1% levels:-

   Longshore Distribution of Total Wave Energy/Distance
   Wave Energy Distribution/Offshore Gradients
   Wave Energy Distribution/Offshore Mean Particle Size
   Wave Energy Distribution/Beach Mean Particle Size

Multiple Regression analysis of the process variables and morphology/ material trends isolated the incident angle of the breaking wave as the primary variable explaining, on average, some 85% of measured variance in morphology/material change, with onshore energy lateral gradient the secondary variable (Buchan, 1976). In addition, statistical correlation tests of the relationship between form and sediment characteristics with increasing distance in a northerly direction along the beach yielded the following probability results:-

1)   Beach Profile Gradient   -0.6 - 1.0% significance

2)   Beach Mean Sediment Grain   -0.931 - 0.1% significance
     Size (phi)

3)   Beach Sediment Sorting (phi)   +0.826 - 0.1% significance

4)   Beach Sediment $CaCo_3$ Content   -0.936 - 0.1% significance
     (%)

5)   Nearshore Beach Profile   -0.615 - 5.0% significance
     Gradient

6)   Offshore Submarine Profile   -0.866 - 0.1% significance
     Gradient

7)   Offshore Mean Sediment Grain   -0.861 - 0.1% significance
     Size (phi)
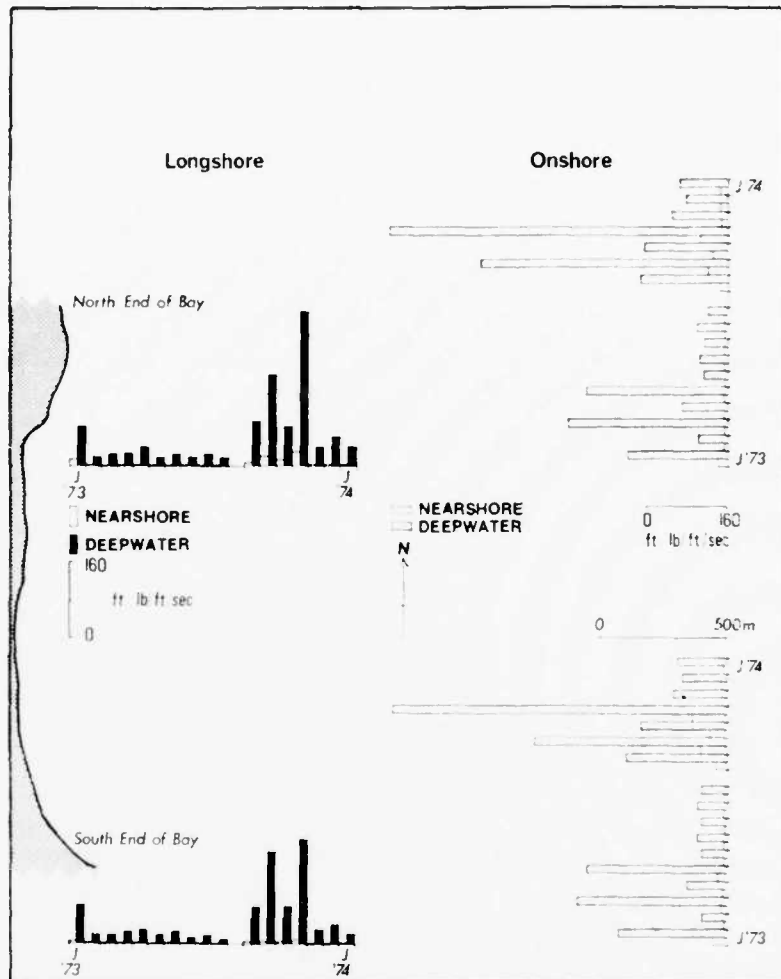
Monthly calculations of onshore and longshore energy. Nearshore and Deep
Water at South and North ends of Aberdeen Bay, January 1973 to June 1974.
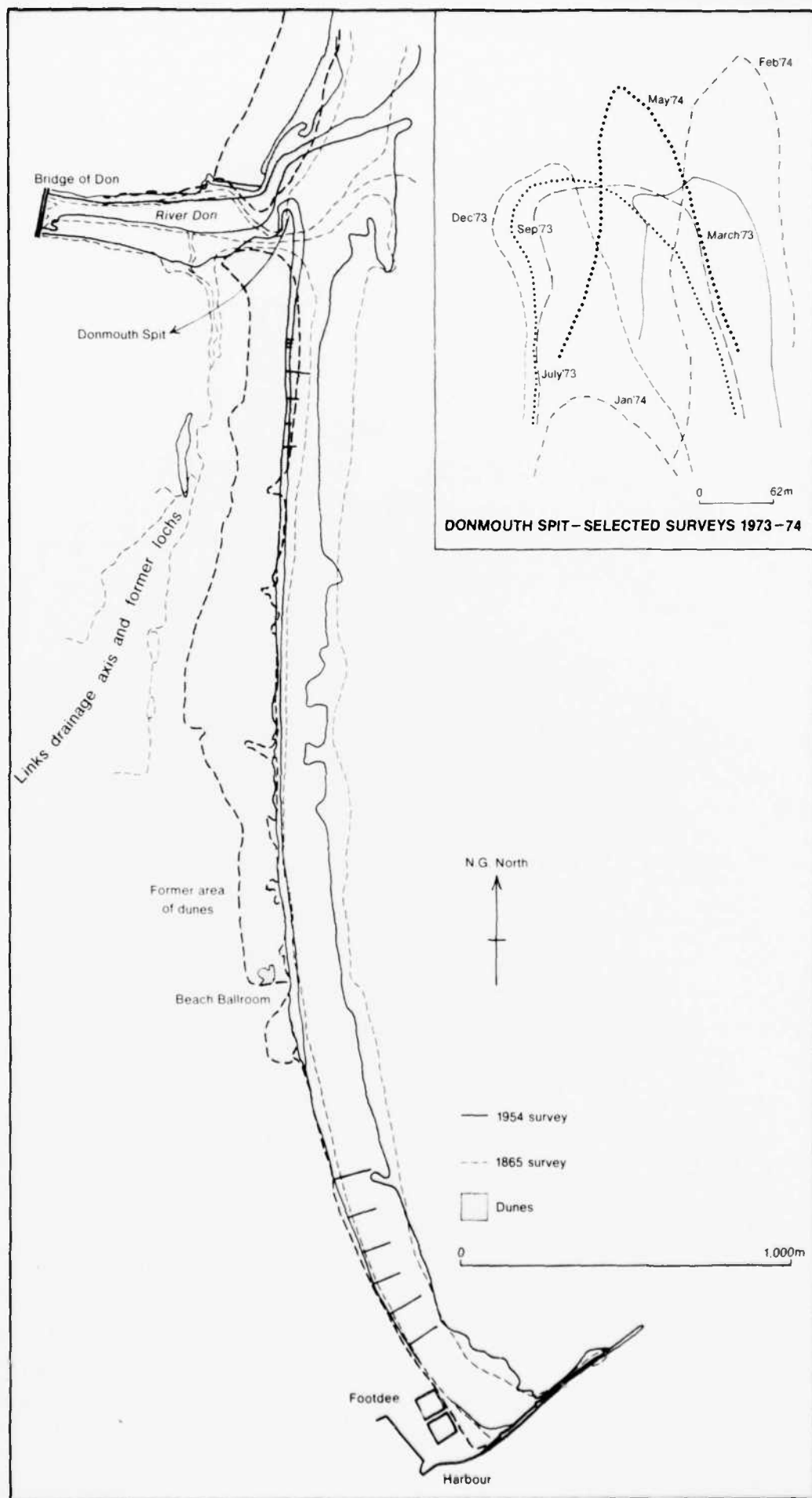
FIG. 3

DONMOUTH SPIT — SELECTED SURVEYS 1973–74

Bridge of Don

River Don

Donmouth Spit

Links drainage axis and former lochs

Former area of dunes

Beach Ballroom

Footdee

Harbour

N.G. North

Feb'74

May'74

Dec'73

Sep'73

March'73

July'73

Jan'74

0   62m

———— 1954 survey

------- 1865 survey

☐ Dunes

0   1,000m

FIG. 4

8) Offshore Sediment Sorting (phi) +0.732 - 0.1% significance

9) Offshore Sediment $CaCo_3$ Content
   (%)   -0.852 - 0.1% significance

Such evidence in total therefore allows the acceptance of a distinct
resultant lateral energy continuum existing in Aberdeen Bay, flowing
from south to north. It allows the acceptance of the "null-point"
hypothesis of sediment sorting by shoaling waves (Zenovich, 1967) and
the "profile of equilibrium" concept of beach form and grain size
(Zencovich, 1967, Wright, 1970). These suggest that spatial variation
in sediment particle size and in morphological slope are predictable
in terms of the energy environment - increasing with an increase in
energy and, the converse, decreasing with decreasing energy.

The direct morphological consequence of this lateral energy flow within
the bay is the sandspit formed in the southern edge of the Don outlet.
Growth of the spit occurs from the addition of drift material and from
the onshore movement of migratory nearshore bars. Evans (1942), in
his classic paper, concludes that "spits increase in length above the
water only when the waves and shore drift move from the direction of
their land connection" (p. 863), and that hooking of the spit distal
termini is "a normal accompaniment of spit-building usually as a result
of wave refraction" (p. 869) round the distal terminus.

The ability of a river-mouth spit to grow is however limited by the
river-flow, and therefore the spatio-temporal variations in form and
material of this type of free spit are explicable in terms of a
dynamic balance between fluvial and marine processes (Kidson, 1963;
Clifton et al., 1972; Buchan, 1976).

River Discharge Variations

Analysis of river flow records of the Don at Parkhill gauging station,
8 miles above the mouth, points to a "simple" regime (Ward, 1967), of
the oceanic rainfall type, typical of the oceanic area of Europe where
rainfall is fairly evenly distributed throughout the year but with a
definite winter maximum and where evapotranspiration during the summer
months results in low run-off during this season, in contrast to high
run-off values during the winter months.

During 1973-4, mean river discharge reached minima of 5.89 cumecs during
September 1973 and 6.26 cumecs in August 1973, while maximum flows were
41.9 cumecs in January 1974 and 31.3 cumecs in December 1973. Prior to
the maximum in January, discharge builds from October at 11.3 cumecs,
through November at 12.6 to December and January peaks before falling
through 25.9 cumecs in February, 25 cumecs in March, 12.6 in April to
11.27 cumecs in May. After May discharge falls to a single figure.

A minor peak of 14.9 cumecs occurred in May 1973, disturbing the orderly
pattern.

Disguised within these monthly averages, is a great variation in daily
flow. A daily maximum in 1973-4 of 120 cumecs was recorded and a
minimum of 4.7 cumecs, in January 1974 and July 1973 respectively.

The Donmouth Spit and its Process Environment

It has thus far been established that the necessary engineering activities undertaken by the appropriate authorities to stabilise Aberdeen Beach have had a radical influence upon the evolving planimetry of the beach. This has resulted in the establishment of a resultant flow of marine energy and materials north along the beach, which in turn explains much of the observed and previously described changes in the characteristics of both the beach and the Donmouth sandspit. This is not to diminish the importance of the onshore element of wave energy, acting normal to the shoreline, in influencing both beach and spit.

These elements of the marine process environment, longshore and onshore, however, provide only one half of the explanation of the changes in the sandspit as described in this paper. A controlling mechanism over sand-spit growth and movement exists in the form of the scale of river discharge from the Don, such that under conditions of low discharge, as would be expected during summer months, the spit, as has been demonstrated, is at its maximum. During this period, marine forces provide the dominant energy input. The converse of course is expected when, during the wetter months of September to March, an increase in river discharge introduces disequilibrium to the system and erodes the spit distal end. Fluvial factors are then in relative ascendancy.

The importance of marine/fluvial balance of processes in the Donmouth can be most clearly illustrated by the results of multiple regression analysis of the various morphological/sedimentary/process variables. In terms of spit height and spit volume, two closely interrelated variables, it was found that river discharge explained 60% of temporal variation in height and 79.5% of spit volume. Significant also as secondary agents were both onshore and longshore wave power; these adding sediments to the form by swash run-up and lateral drift. The contribution of tide levels (Springs range 3.6 m, but attaining 4.5 m with onshore wind set-up) in controlling the height of wave action upon the spit should also be noted.

It has been shown from previous research (Evans, 1942; Wright, 1970) that lateral or longshore drift and wave refraction are primary elements in shaping the evolution of a sandspit and the degree of recurvature of the form.

Two main process variables could therefore be expected to show through in the regression analysis as explaining spit recurvature - longshore energy flow and onshore energy or wave power - under conditions of marine ascendancy. The longshore elements of wave power, wind power and breaking wave angle, explained 36% of variation, while onshore wave power, when refracted round the distal end of the spit, added an additional 6% of explanation. The overall extent of equilibrium and stability, as attested by the degree of recurvature, is however heavily dependent upon fluvial discharge. When discharge increases, distal end recurvature is reduced by erosion and any material being added by marine longshore and onshore processes is carried into an essentially fluvial dominated environment where currents are excessively high and prohibit any sedimentation.

The overall length of the spit, in view of previous trends, would normally be expected to increase primarily by addition of sediments from both onshore and longshore components, which can give rise to long-shore currents flowing in the surf zone at Aberdeen Bay of up to 1.o m/sec.

(Buchan, 1976). The spit length, however, would be <u>controlled</u> (as with volume, height and recurvature) by the fluvial discharge of the Don, when greatly increased by high stage conditions and when a more powerful process than marine agents.

The ability of the spit accumulation form to translate landwards or seawards under wave action is a characteristic previously noted by Yasso (1964). Of the process variables, onshore wave power explains most significantly the variance in spit translation, some 45% with longshore components and river discharge also of some importance. Two major trends or characteristics of the Donmouth spit and the Donmouth plani- metry are therefore identifiable. Firstly, all elements of the spit, volume, length, height, recurvature and translation, are explicable in terms of marine origin and marine dominated growth. Secondly, the discharge of the River Don exercises control upon the spit's dimensions, the degree of control varying with the level of discharge.

There is, therefore, a state of balance between the marine and fluvial process environments in the Donmouth whereby the marine dominated origins and growth of the sandspit are in effect controlled by the influence of the river during increased or flood stage when rivermouth currents are of a velocity sufficient to erode and restrict spit development across the river mouth. The varying contributions of marine and fluvial processes within this condition of balance are well illustrated in Photo-Plate 1, which reflects a series of single instances over a 30-year period of this equilibrium condition. In the extreme case, at times of flood stage of the Don, clear breaching of the spit (as in 1976) is the obvious mani- festation of the power of the river to overwhelm normal coastal processes.

Conclusion

Aberdeen beach provides a case-study of a dynamic evolving shoreline which has been progressively influenced and, indeed, restricted in its inherent flexibility by man's engineering activities. It also provides an example of how the economic role of a coastline can dictate a degree of inter- ference with normal physical coastal processes in that two of the primary energy and sediment input sources, the rivers Dee and Don, have been altered, both physically and biologically, in response to port and industrial development in the historical period. It can be argued that man's response to these economic motives has caused the loss of much of the natural sand beach through his building of harbour piers and esplanade revetment walls. The deflection of the Don rivermouth northwards and the related coastal erosion on the northern edge of the estuary can then be interpreted and indeed shown as a direct consequence of these man-induced changes in the local coastal system. It is true that the coastline has now found a stable condition and has, with the exception of short-term fluctuations which at the time may appear quite dramatic, attained an overall state of dynamic equilibrium. The Donmouth spit, while owing its origins to a man-induced longshore energy flow, is free from direct human interference and provides the only example in the system of a completely natural and freely evolving coastal form where marine and other physical processes can be studied.

This case-study does however illustrate the problem in coastal geomorphology of a relative lack of basic raw data pertaining to coastal environment near a developed and economically important shoreline. This lack of knowledge underlines the difficult, costly exercise that is involved in obtaining essential information of such apparently simple factors as sand

supply or wave climate. Conversely, the careful observation and measurement of forms and materials are shown to have some value in reflecting the resultant or net effect of dynamic changes engendered by complex and interacting process variables.

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3. <u>WATER MASS MIXING IN THE ESTUARY</u>
    <u>OF THE RIVER DON AND ITS ASSOCIATED</u>
    <u>COASTAL WATERS</u>

1. Introduction

The River Don discharges into the North Sea through a small estuary on
the northern outskirts of the City of Aberdeen. Although a clean river
over most of its length, the Don suffers rapid deterioration of its
biological status over the last 10 km of its course; the synergistic
effects of paper mill and sewage discharge depressing the quality of
the river waters below "a consistently acceptable level" (NERPB, 1980).
This paper describes the findings of a project initiated to examine
the way in which these waters are mixed with those of Aberdeen Bay, the
receiving coastal water body.

In recent years an extensive amount of research has been devoted to study-
ing the processes active within estuaries and the part that they play in
mixing fluvial discharge with coastal waters. However, in many cases it
is apparent that the volume of fluvial discharge entering the estuarine
system is large enough relative to the volume of saltwater exchanged
over the tidal cycle, such that fresh and saltwater are not completely
mixed within the estuary. Consequently, fresh or brackish waters may
spread seawards from the mouth of the estuary, mixing being completed by
processes active within the coastal waters. The methodology and object-
ives of this project, therefore, evolved from a recognition of the
necessity to treat estuarine and associated coastal waters as one mixing
system, the "River Discharge Dispersion System". Recognition of this
need is particularly important in the case of rivers such as the Don,
when it may be necessary to assess the aerial impact of any effluent
or waste carried within the river waters.

The results summarised in this paper are based on the analysis of exten-
sive boat borne surveys of salinity, temperature and currents within the
Don Estuary and Aberdeen Bay, supplemented by data obtained through air-
borne photographic surveys. The results and analysis are presented in
detail in Grant (1982).

2. The Physical Environment

The River Don has a perennial discharge regime, demonstrating the "simple"
flow pattern of Ward (1975), with a basic seasonal fluctuation. Mean
flows are high from December to March and low from June to September.
The 11 year mean flow of the Don (1970-80) was 20.34 cumecs, with a
minimum measured daily mean of 2.55 cumecs (August 1976) and a maximum
of 347 cumecs (October 1976) during that period.

The Don has a very small estuary, the main part extending 1.3 km seawards
from the Brig 'o' Balgownie (Fig. 1), covering an area of approximately
0.17 km^2. Within this section the mean water depth is about 1 metre
at low water and 4 metres at high water. Above the Brig the Don is
confined within a narrow gorge. Although estuarine, in that tidal
influence on water levels extends up to 0.8 km upstream of the Brig,
saline penetration of this gorge section is minimal. Water levels within
the estuary, and the upstream advance of saline waters, are also
affected by the presence of two weirs. The principal weir lies at the

head of the island beneath the Brig (see Fig. 1) while the second, of lesser importance to water mass mixing, lies within the gorge section, some 400 metres upstream of the Brig.

In Aberdeen Bay, the mouth of the estuary breaches 24 km of continuous sandy beach (see Fig. 2). The beach was formerly backed by a natural dune ridge over its entire length, but south ⸳ ⸳ the river is now almost entirely backed by a sea wall and esplanade. The mouth of the estuary, as a consequence of the soft sediments into which it is cut, has, through-out history, exhibited a continual conflict between fluvial and marine processes, resulting in a cycle of continuous change. During quiescent months an extensive spit/spit-bar complex develops, with subsequent destruction during periods of high fluvial or marine activity (see Buchan, this volume; Grant, 1982)

3. The River Discharge Dispersion System

3.1 Introduction

The estuary of the River Don experiences a saline penetration every 12 hours 25 minutes (approximately) with the passing of semi-diurnal high tides. During this penetration the water column within the estuary shows a high level of stratification arising out of the density difference attributable to the salinity difference between river water (0 ^{o}/oo salinity) and sea water (34 ^{o}/oo). Consequently, the saline waters form a distinct wedge, passing upstream at depth beneath seaward flowing fresh-water. The estuary, therefore, exhibits the characteristics of a salt wedge estuary, at high water, as defined by the classificatory scheme of Hansen and Rattray (1966) (See Grant, 1982). Following the passing of high water the saline wedge withdraws, and by low water saline waters have been completely flushed from the estuary, except where retained in the depths of potholes (see Fig. 1).

Under mean conditions, although tidal influence may affect water levels within the gorge section above the Brig 'o' Balgownie, at high water saline penetration was found to extend only as far as the Brig, where the more dense saline waters were observed to "spill" into the deeps of the gorge beyond. Particularly high tides may result in the salt wedge extending well into the gorge section, but only as far as the weir 400 m upstream.

Mixing of salt and freshwater within the estuary, and also the coastal waters, was observed to be achieved principally via two processes, advective and non-advective mixing. Acvective mixing (entrainment) involves a net flux of mass as well as salt. Where two water bodies are passing one another and one has a greater level of turbulence, entrainment acts at the inter-face, the more turbulent body "dragging" the less turbulent water mass into it. Since it involves a one way transfer of mass, therefore, entrainment contributes to the net circulation patterns within the estuary.

Non-advective mixing (turbulent diffusion) involves a net flux of salt but not mass, mass being transferred equally between the two water bodies involved. Both advective and non-advective mixing may be active at any one time, although advective mixing becomes relatively more important where one water body is more turbulent than the other.

Within the Don Estuary the relative importance of the two processes was found to vary with time, in respect of the tidal cycle, and with location.
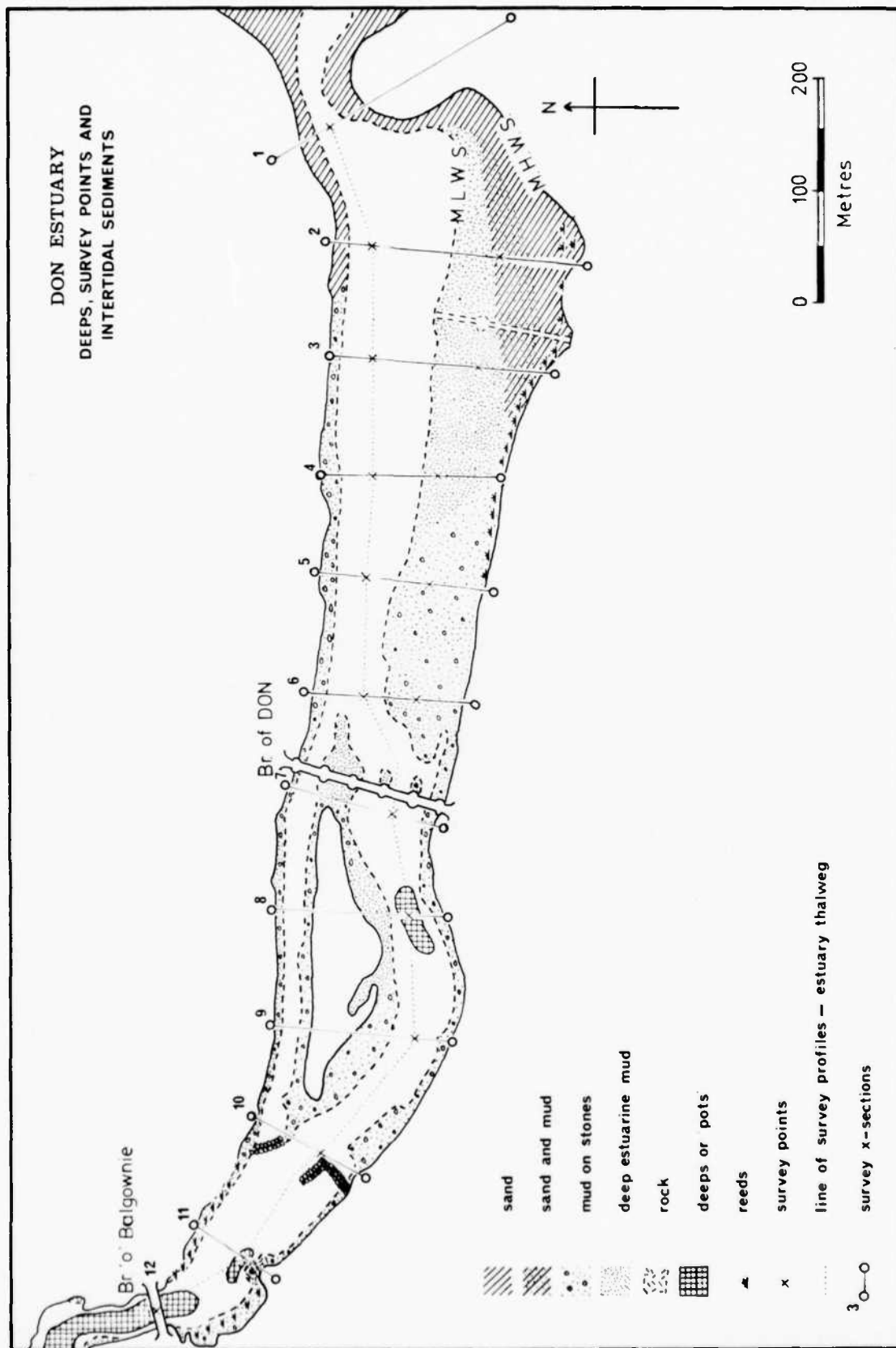
DON ESTUARY

DEEPS, SURVEY POINTS AND
INTERTIDAL SEDIMENTS

sand

sand and mud

mud on stones

deep estuarine mud

rock

deeps or pots

reeds

survey points

line of survey profiles — estuary thalweg

survey x-sections

Metres

Fig. 1
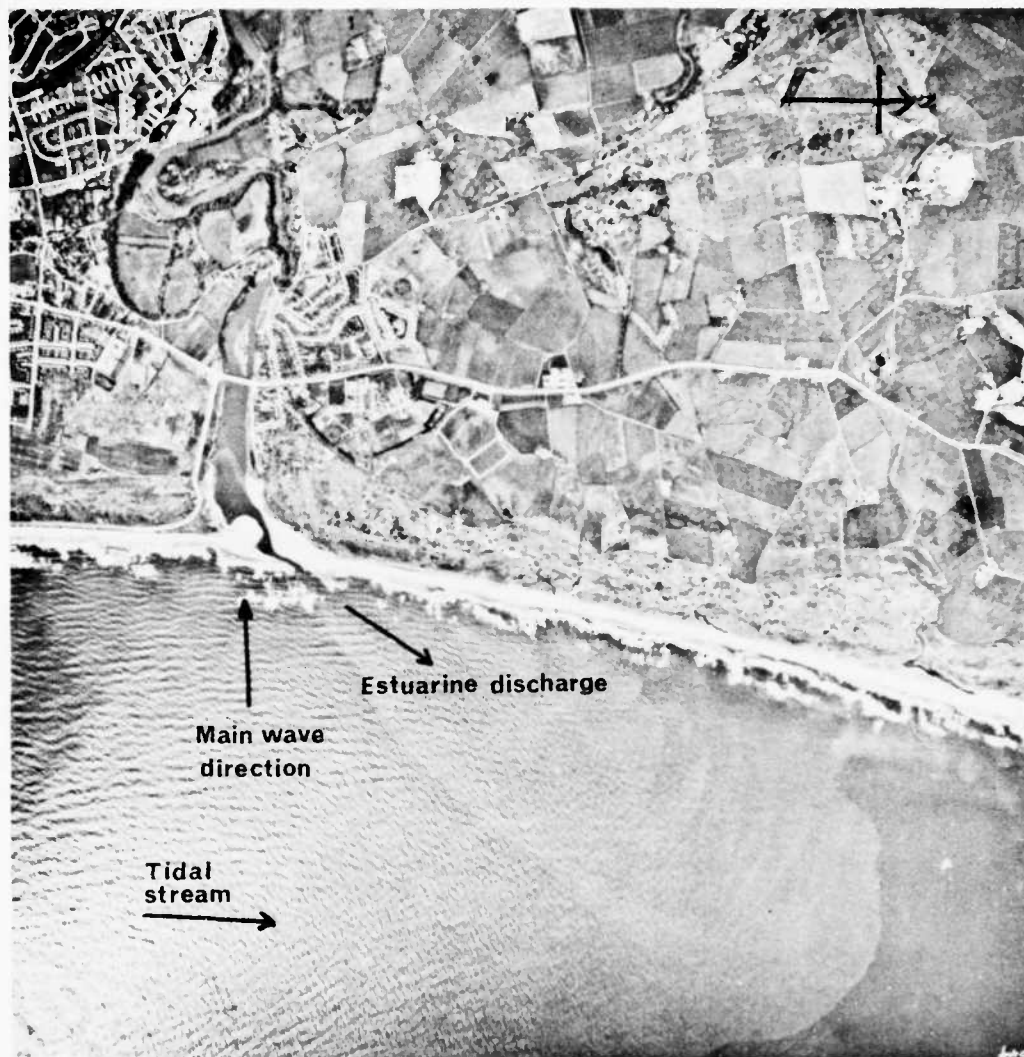
Estuarine discharge

Main wave
direction

Tidal
stream

FIG. 2

However, the strong density stratification within the estuary over much
of the tidal cycle, and the total expulsion of saline waters during the
ebbing tide, ensure that most mixing of the Don discharge with coastal
waters actually takes place seawards of the estuary mouth. Throughout
the survey period, under mean fluvial and tidal conditions, fresh or
brackish water was found to pass seawards through the estuary mouth at
all states of the tide. The low density of this discharge enabled it
to form a thin, highly buoyant surface layer (the plume) within Aberdeen
Bay. The buoyancy of this plume persisted throughout the year despite
the large variation in the relative temperatures of river and sea
water.

Surveys demonstrated that as soon as the less dense estuarine discharge
passes beyond the confining banks of the estuary mouth, they undergo
a rapid lateral expansion and vertical thinning in response to the buoyant
superelevation that they experience. This results in a rapid spread
and sharp deceleration of the outflow as it comes under the influence
of the coastal tidal stream. Although the initial direction of the out-
flow is determined by the intertidal geometry of the estuary mouth (which
demonstrates considerable variation), as it passes seaward the coastal
tidal stream gains quick ascendancy and becomes the principal determinant
as to the direction of spread of the buoyant plume. The tidal stream in
Aberdeen Bay flows northwards during the ebb tide and southwards during
the flood.

The extent to which the buoyant plume flows offshore before experiencing
the deflection attributable to the tidal stream is a resultant of the
relative strengths of the estuarine outflow and the tidal stream. As
the relative strength of the tidal stream increases (as towards spring
tides and low fluvial discharges), then longshore deflection of the plume
becomes sharper.

As the buoyant discharge leaves the estuary mouth mixing is initially
very rapid, both advective and non-advective processes being active.
Turbulence levels are very high at this point as a result of the buoyancy
induced spread of the effluent, inertia, resulting in a large transfer
of kinetic energy to turbulent energy as the discharge decelerates
sharply, and nearshore breaker activity. Inertia induced turbulence is
particularly marked during the ebb tidal discharge phase, and at all times
during high fluvial discharges. The zone of intense mixing activity was
found to extend from 400 to 800 metres offshore. Within this zone the
salinity field demonstrated a distinct central axis to the plume, with
a longitudinal increase in surface salinity with distance from the
estuary mouth, and a lateral increase to both sides.

Beyond this zone of intense mixing plume waters were found to extend
for many kilometres to the north or south from the estuary mouth. They
formed a thin brackish surface layer, never greater than 0.5 m in
depth, of salinity 25%/oo to 34 %/oo, and preserved a clear identity when
wind, wave and tidal activity were capable only of producing weak
mixing. A high suspended sediment load within the fluvial discharge
often results in the plume being clearly visible from the air (see
Fig. 2).

As these brackish waters spread, variations in the vertical salinity
profile, suggest that two way diffusive mixing with the ambient coastal
waters beneath is active. This results in a regular rise in salinity
of the surface waters with distance from the estuary mouth. The
distance over which plume waters maintain their distinct identity is

determined by the rate of this diffusive mixing process, and the rate
of the longshore tidal stream. Admiralty tide tables indicate mean
coastal tidal streams for this area of 0.46 ms^{-1} and 0.23 ms^{-1} during
spring and neap tidal cycles respectively, while float surveys showed
streams in excess of 0.70 ms^{-1}. Such figures would allow plume waters
to complete a traverse of 5 to 11 km during one half tidal cycle.
Normally, however, the diffusive mixing processes preclude the plume
waters maintaining their distinct identity over such distances.

During surveys it was apparent that wind induced surface currents could
enhance or restrict the offshore spread of plume waters when blowing
in an offshore or onshore direction. When blowing in a longshore direction
winds were also seen to promote or restrict the tidal stream in the
immediate surface layers. Observations made during surveys demonstra-
ted that the plume was, in fact, likely to behave in a similar manner to
an oil slick, in that a "wind push" factor results in the inducement of
a surface current speed of 3.3% of wind speed, acting in the direction
of the wind. During the period over which the surveys were carried out
70.65% of all winds experienced had the capability of producing surface
currents of 0.08 - 0.25 ms^{-1}, 56% of these winds having some onshore
component. However, high energy wave activity, resulting in the rapid
mixing of discharge as it leaves the estuary mouth, precludes the form-
ation of a buoyant plume. Published evidence suggests, therefore, that
where windspeeds exceed 20 knots, then wave action becomes of primary
importance to plume mixing (see Reed's Nautical Almanac, 1981, p. 811).
Field evidence suggests that in Aberdeen Bay, wave induced turbulence
may, in fact, become important at wind speeds considerably lower than
this.

When formed, the buoyant plume was usually marked by a sharp thermo-
haline front along its up-current edge. The front was found to be a
zone of strong surface convergence, where the flow of the plume waters
as they spread is in direct opposition to the coastal tidal stream (see
Figs. 5-8). Convergence at the front results in intense surface
activity, cabelling, and the concentration of foam, debris and suspended
sediments carried within the estuarine discharge. Consequently, the
front is clearly visible from the air (Fig. 3) and from a boat, and is
shown to be sinuous in plan. The high suspended sediment load within
the estuarine discharge also frequently results in a sharp colour change
across the front. Measurements demonstrate a strong schooling of
isohalines towards the front from the plume side, salinity increasing
sharply towards that of the ambient coastal waters.

Mixing at the plume front would appear to be principally by entrainment
of the brackish waters down and back under themselves with the flow of
the coastal waters (see Fig. 4). The maintenance of the identities of
the water masses on both sides of the front clearly indicate that
there is no horizontal mixing across it.

The front was observed to persist until a switch in the tidal stream
resulted in the abandonment and subsequent dissipation of the particular
plume. The frontal system is maintained by the continuous supply of
fresh or brackish waters to the plume and, consequently, collapses as
soon as that supply is cut off. A frontal system was rarely observed
at the distal end of the plume, since at this point the buoyant surface
layer is moving with the flow of the ambient waters gradually mixing with
them. Eventually the horizontal homogeneity of the buoyant surface
layer is broken down.

Front

FIG. 3

N

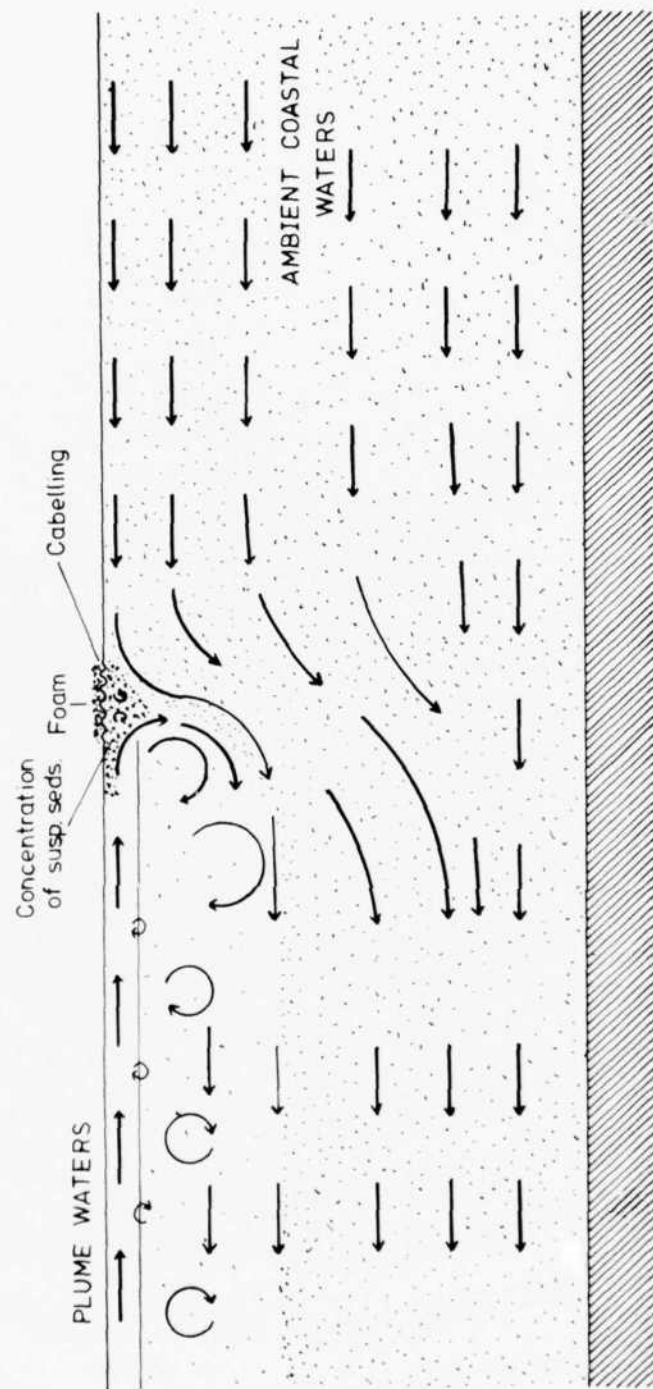River mouth

CIRCULATION AT PLUME FRONT
(relative to front)
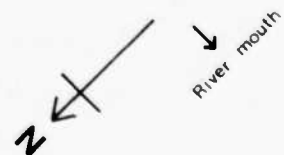
Fig.4

3.2

Since the above discussion has shown the pattern of mixing and disperal within the River Don discharge dispersion system to be strongly related to the tidal cycle, a summary of events with respect to that cycle is presented below.

3.2.1 Flood Tide (see Fig. 5)

As sea level rises saltwater enters the estuary at depth. The saline waters advance rapidly within the estuary and the seaward flow of fresh water at the surface is severely restricted. Nevertheless, under mean conditions a layer of freshwater continues to flow seawards throughout the flooding tide, allowing the formation of a distinct southward directed plume in Aberdeen Bay.

Extreme conditions may result in there being no saline penetration of the estuary, or there being a penetration as far as the weir in the gorge 1600 m from the estuary mouth. The extent of the saline penetration, and, consequently, the pattern of mixing within the estuary, is a resultant of the relationship between fluvial discharge and tidal height. These two factors form a dynamic balance controlling the rate and volume of influx of saline waters to the estuary. Individually the two parameters offer little explanation for the variance in the extent of penetration; however, an index derived using both parameters demonstrated an explanation of 96% of variation.

The length of the saline penetration was found to be directly proportional to the height of high water (H) and inversely proportional to river stage (S) as representative of discharge. Field evidence led to the derivation of an empirical relationship:

$$L_{max} = -1342 \cdot 0 + 2114 \cdot 7 \ln \left(\frac{H}{S} \right) \tag{1}$$

(with 95% conf. limits of $\pm$ 189.18 m)
where L_{max} = length of saline penetration (metres)

  H = Height of high water (metres)

  S = River stage, Parkhill - 10 km upstream (metres)

From this relationship, under mean conditions (R. flow = 20.34 cumecs) it can be shown that the expected saline penetrations for MHWS (4.3 m), MHW (3.85 m) and MHWN (3.4 m) are 1345 metres, 1111 metres and 848 metres respectively (ie spilling into the gorge above the Brig 'o' Balgownie, just short of the Brig, and reaching the weir at the head of the island (Fig. 1)). At extremely high river flows saline penetration of the estuary is prevented: >50 cumecs, >65.2 cumecs and >83.3 cumecs for MHWS, MHW and MHWN respectively. Throughout the survey period the percentage exceedance of these flow levels by daily means was 9%, 4.4% and 1.5% respectively.

Conversely, it was shown that during periods of extreme low river discharge, a high tidal influx was likely to prevent the seaward flow of freshwater altogether, thus preventing the formation of a plume offshore. Analysis suggested that for MHWS, MHW and MHWN, this was likely to occur when river discharge drops below 13.4 cumecs, 7.8 cumecs and 3.7 cumecs respectively. Field observations supported these figures. Under these conditions were also experienced the maximum saline penetrations of the estuary, with stratification showing some loss of strength as a

result of the cessation of the seaward flow of freshwater.

During the flood tide, under mean conditions, the water column in the estuary consists of three layers: about 1 metre of freshwater flowing seawards, beneath which lies about half a metre of mixed waters flowing upstream with the saline waters over which they lie. The freshwater layer was observed to maintain $0\%o$ salinity until passing seawards of the estuary mouth. The saline waters, however, demonstrated a reduction in salinity in an upstream direction, indicating a level of advection of freshwater down. This evidence, and the fact that the mixed waters are moving in an upstream direction, suggests that, during the flooding tide, mixing in the Don Estuary is principally by entrainment of the freshwater down into the saline layers. This is converse to Pritchard's (1955) classic model for mixing in a salt-wedge estuary – where saltwater is entrained upwards from a 'static wedge' into the seaward flowing freshwater. However, in assuming a 'static salt-wedge, Pritchard's model does not allow for the rapid advance and retreat of saline waters with the passing of the tidal cycle, that a small estuary, such as the Don experiences. Where two fluids are flowing past one another, entrainment acts to transfer mass towards the more turbulent layer. During the flooding tide in the Don, the rapid advance of saline waters passing beneath a restricted, slow moving fresh water layer, ensures a higher level of turbulence within the saline waters – with resultant entrainment down into them.

As the saline waters lose momentum and turbulent energy in an upstream direction, then advective transfer of mass may reverse. Consequently, towards the toe of the salt-wedge saline waters may be entrained upwards into the overlying freshwater layer.

During situations where freshwater flow through the estuary mouth is prevented by the flooding tide, then a convergent front, similar to that found at the plume margin, may form at the mouth. Freshwaters, entrained downwards at the interface, then flow back upstream with the rapidly advancing saline waters.

Under most conditions, however, a layer of freshwater continues to flow seawards to form a plume. The reduced momentum of this surface layer, added to the high stratification within the estuary mouth during the flooding tide, ensures that buoyancy spread forces dominate plume behaviour as it leaves the confines of the estuary mouth. On leaving the mouth the plume waters demonstrate a rapid rise in salinity as a result of mixing, surface salinity usually achieving $25\%o$ within 400 metres. As a result of the restricted estuarine discharge during the flood tide, the plume area is small, and the coastal tidal stream gains quick ascendancy over the discharge causing a rapid southerly deflection of the plume waters. Under mean conditions brackish waters were identifiable up to 2 km south of the river mouth, up to 4 km during conditions of extreme calm.

3.2.2 High Water (see Fig. 6)

Tidal influx to the estuary is at a maximum from HW – 3 hours to HW – 1 hour. After this period, as the force of the tidal influx slackens and the driving force for salt-wedge advance is cut-off, the turbulence within the saline layer decreases. At the same time, no longer retarded, the freshwater flow seawards accelerates, with an accompanying increase in turbulence within this layer. Consequently, the advective transfer of mass reverses, entrainment now acting to transfer saline

Sketch Diagram: River Don Discharge Dispersion System.
FLOOD TIDE

R. Mouth

0‰

Flow with Ambient Waters

c. 32‰

Tidal Rise

L (max.) Turbulent mixing at toe of s.wedge

Saline intrusion advancing and expanding rapidly.

Entrainment of F.W. down

Rapid buoyant spread.

Zone of intense vert. mix. turb. diff. + entr. up

Continued mixing by turbulent diffusion dependent on marine conds.
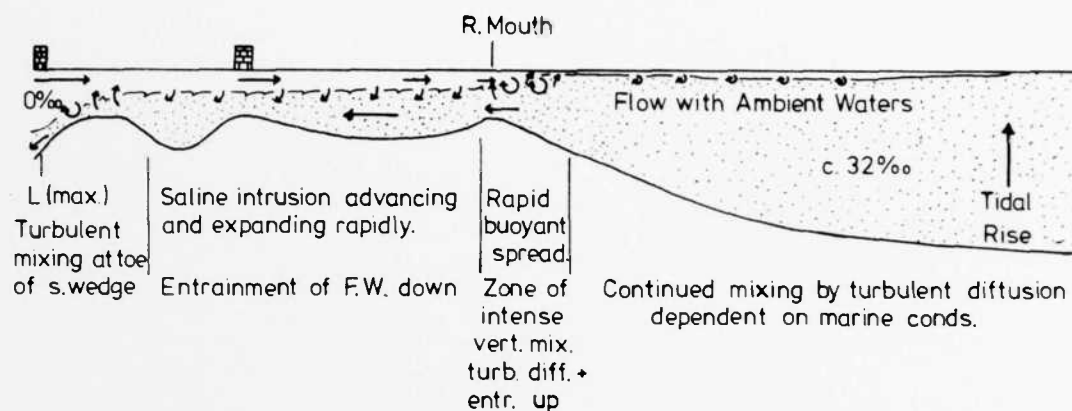
Events within the estuary are determined by the inputs from both ends of the system, the relationship between river stage and tidal height. Rapid, high tidal rise; against low river flow results in a cessation of freshwater flow seawards of the river mouth.

Wind induced currents may oppose or promote plume spread.

→ Z

S. Wedge advancing

rapid buoyant expansion and seaward deceleration

Salinity increasing with continuous mixing

Buoyant Plume

convergent front

Extreme wave conditions preclude plume formation.

Tidal Stream
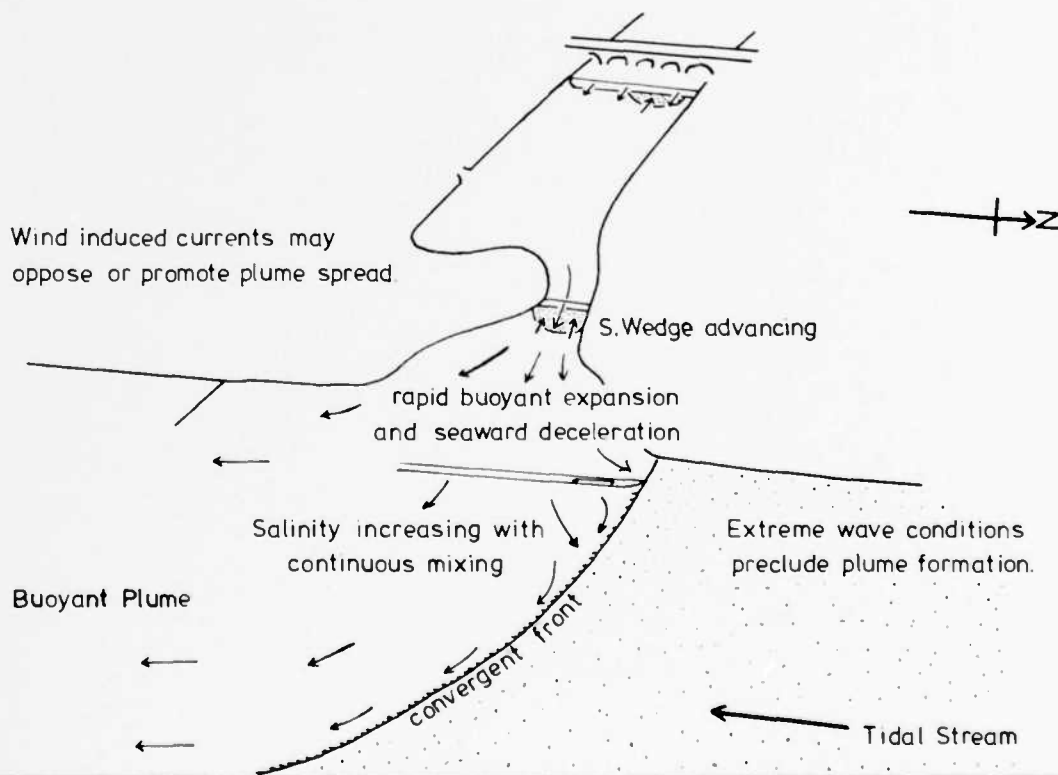
Fig.5

Sketch Diagram: River Don Discharge Dispersion System.
HIGH WATER

R.Mouth

0‰

c. 32‰

'Arrested' Wedge
Accelerating F.W. flow over
stagnant wedge → mixing by
entrainment of S.W. upwards

Rapid
buoyant
spread
intense
vert. mix.
entr. + turb.

mixing by turbulent diffusion

Accelerating seaward
surface flow of F.W.

→ z

rapid buoyant expansion
and seaward deceleration
intense vert. mixing

Slackening tidal stream
increased F.W. discharge –
–plume front pushes north before
dispersal on tidal switch

Plume at max. southerly
extent (1 –2 km.)

Tidal Stream
slackening before switch

Fig. 6

waters upwards into the seaward flowing freshwater. The direction of flow within the mixed layers also reverses during this period, now moving seawards with the freshwater.

At high water, therefore, for that instant when the salt-wedge is static, neither advancing nor retreating, the Don Estuary conforms to Pritchard's (op cit) classic pattern of a salt wedge estuary-freshwater flowing seawards over an "arrested" salt-wedge entrains saline waters upwards across the interface. However, the salt-wedge immediately starts to retreat following the passing of high water.

Offshore, the flood tide plume reaches its maximum southerly extent at high water, before tidal switch causes its abandonment and the commencement of the formation of a new plume in a northerly direction.

3.2 3 Ebb Tide (see Fig. 7)

As the tidal level in the coastal waters falls saline waters rapidly retreat from within the estuary. Flow at all depths of the estuarine water column is seawards. The increasing hydraulic gradient resulting from the fall in water level at the estuary mouth, coupled with the accelerating flow, produces a high level of turbulence. Consequently, turbulent diffusion becomes active in mixing fresh and saltwater. During this turbulent phase of the tidal cycle mixing is at a maximum within the estuary, and diffusion, acting against the density gradient within the water column, results in a breakdown of stratification. A further consequence of the high vertical salt flux is the fact that surface waters passing through the estuary mouth during the ebbing tide show a slight rise in salinity, reaching levels of 2-5 ⁰/oo. Eventually the water column becomes completely mixed with a resulting horizontal salt flux seawards at all depths. Tidal reversal, therefore, results in a reversal of both net horizontal and net vertical salt flux within the estuary.

During the ebb, the waters held within the estuary by the flood tide are released, producing a greatly enhanced discharge. Coupled with the cessation of stratified flow at the estuary mouth this results in the discharge emitting from the Don Estuary approximating, initially, towards a "turbulent jet" flow (see Kashiwamura and Yoshida, 1967). A high level of inertia induced turbulence causes rapid mixing of this jet, until, a short distance offshore, seawater intrudes beneath the advancing waters and buoyancy spread supercedes. Mixing by entrainment and turbulent diffusion continues to cause a rapid increase in salinity of the buoyant discharge for some distance offshore, before flow within the surface layers becomes uniform with that of the ambient coastal waters. The zone of initial mixing extends 600 to 800 metres seawards from the estuary mouth, beyond which the brackish waters move northwards with the tidal stream; mixing slowly with coastal waters as a result of turbulent diffusion induced by coastal currents and wave activity. The aerial extent of the discharge plume emitted by the Don is at a maximum during the ebbing tide as a result of the enhanced discharge. Under mean conditions plume waters were identifiable up to 6 km northwards, covering an area of 5 to 6 km^2. Under conditions of high discharge and low wave activity these figures may be much greater, plume waters being identifiable up to 10 km northwards.

3.2.4 Low Water (see Fig. 8)

By low water saline waters are almost totally flushed from the estuary,
except where retained in deeps. The last remnants of the saline influx
are flushed from the estuary several hours before the incessant tidal
cycle brings another influx. At low water flow within the estuary is
fully turbulent, currents at all depths achieving maximum seawards
values in excess of 1.00 ms^{-1}. Discharge from the estuary mouth, there-
fore, tends towards a fully turbulent jet, passing seawards for up to
800 metres before deceleration allows buoyancy to supercede. Inertia
induced turbulent mixing seawards of the outlet is, therefore, at a
minimum during this phase of the tidal cycle. The plume is also at
its maximum extent, before tidal switch at low water results in the
abandonment and dispersal of that plume, and the commencement of a
flood tide plume towards the south.

4. Conclusion

From the above discussion it is clear that mixing processes within the
estuary, and hence the presence of a buoyant surface discharge seawards
from the estuary mouth, are governed by the following factors: The
density difference between salt and freshwater and the resultant
stratification; Freshwater volume flux, and; Saltwater volume flux
within the estuary.

Seaward of the estuary mouth the principal determinants of plume behaviour
were: Tidal stream; Wind induced currents; Wind and wave induced
turbulence, and; Inertia induced turbulence and buoyant spread. At all
stages of the tide the area and extent of the plume depends on these factors,
the combined effects of which determine the distance over which discharge
may maintain its distinct identity.

Sketch Diagram: River Don Discharge Dispersion System
EBB TIDE

R. Mouth

Accelerating seaward flow and
increasing hydraulic gradient –
→ high level of turbulent mixing.
Saltwater retreating from estuary

Rapid
decel.
increasing
level of inertia
induced turbulence

c. 32‰

Falling
Tide

Buoyant expansion.
mixing by turbulent diffusion
due to marine processes

Increasing estuarine
discharge

rapid deceleration,
intense vert. mixing

buoyant spread

z

Plume spread northwards.
continuous vertical mixing
with ambient waters.

Tidal Stream.

Fig.7

Sketch Diagram: River Don Discharge Dispersion System
LOW WATER

0-2‰

c. 32‰

Max. hydraulic gradient. Saline waters totally flushed from estuary. Fully turbulent flow of F.W. seawards.

Zone of intense inertia induced turbulence -vert. mixing. Following sharp decel.- buoyant spread.

Buoyant expansion, spread with tidal stream mixing by turbulent diff.
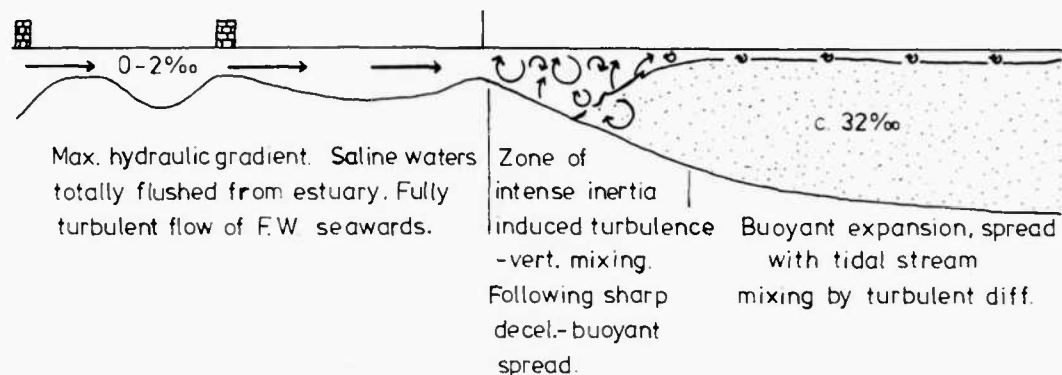
For any given fluvial and marine conds. the plume is at its max. extent at L.W..

The actual extent of plume spread depends on the F.W. input, tidal stream and rate of mixing beyond the initial zone (which depends on marine conds.).

→z

intense turbulence and vert. mixing

buoyant spread.

Plume waters spread north 5-6km. before continued diff. renders them indistinguishable.

Tidal stream slackening
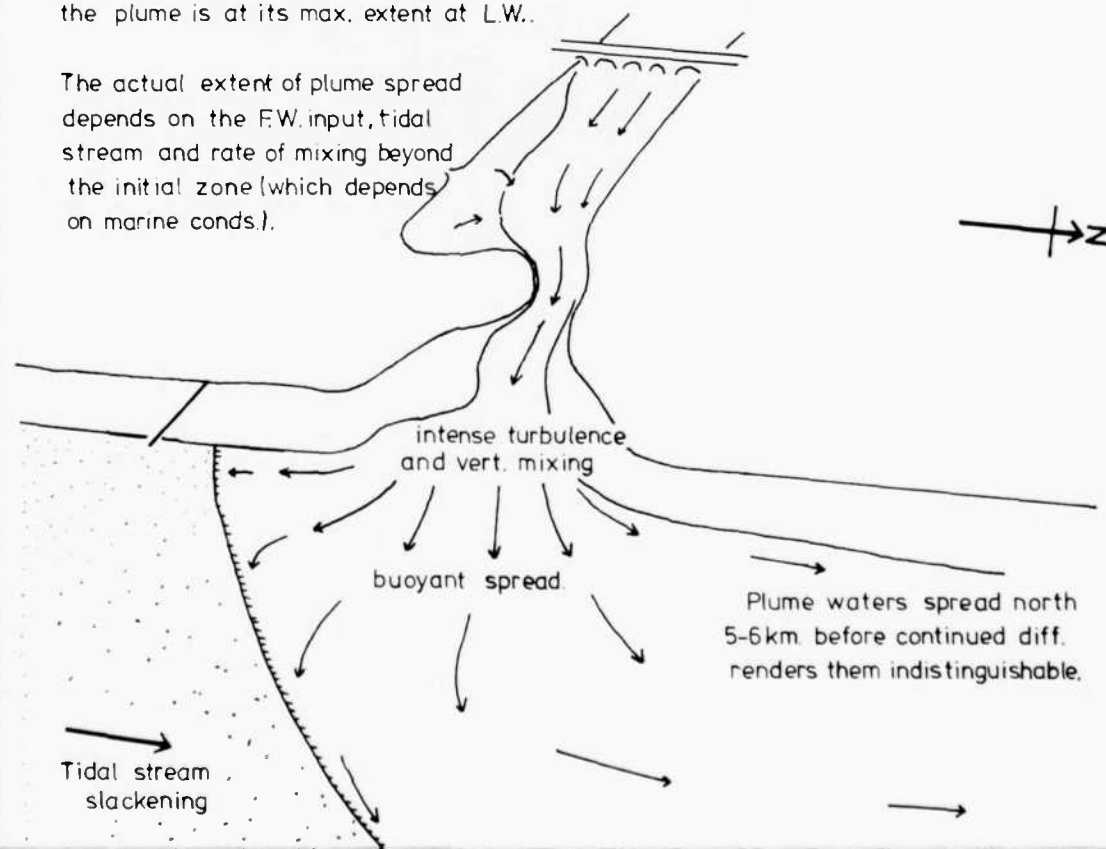
Fig.8

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COASTAL LAND USE IN NORTH EAST SCOTLAND

1. Introduction

The land use of the coastal zone of North East Scotland varies in response to many factors, both physical and human. The purpose of this paper is to describe and analyse the land use of the coastline in an attempt to explain the distribution of land uses and to outline the recent changes and conflicts in land use that have occurred.

In many ways north east Scotland is a transition area between highland and lowland Scotland, with a corresponding variation in landforms and land uses. The area bears witness to the differing geomorphological effects of glaciation and periglaciation, and together with the varied geology gives north east Scotland even more of the appearance of a highland/lowland transition area. It is not the purpose of this paper to delve deeply into the geology and physiography of north east Scotland, as this has been more than adequately covered elsewhere in the literature; but the physical background of the area will be outlined to provide a physiographic framework in which the patterns of land use can best be understood and explained.

In the first part of the paper the physiographic background will be outlined, and the area of north east Scotland will be put in its wider context. Secondly the land use history of north east Scotland will be outlined briefly and this will be followed by an account of the present distribution and extent of land uses along the coastline of north east Scotland. Finally recent changes in land uses and conflicts in land use will be described.

2. The Physiographic Background

The present distribution of coastal types and features along the 350 kms section of coast from Aberdeen to Inverness reflects the patterns of the underlying geology of the area and the action upon this of the past and present geomorphic processes.

Whilst geology and structure are important in the understanding of the distribution of coastal types, the coastline of north east Scotland has been influenced to a very great extent by the effects of glaciation and periglaciation. The Beaches Survey of north east Scotland identifies 3 lithological units along this coastline:

a. Highland schists of Banff

b. Granites, gneisses + schists of the East Coast north of Highland boundary fault

c. Younger sedimentaries and the downwarped formations of the Moray Firth west of Spey Bay.

The influence of this underlying geology on the present day scenery is controlled by the extent to which these areas have been modified by glaciation, in particular by deglaciation and the deposition of outwash material. In Banffshire the coastal morphology is controlled by the varying lithologies of the rock strata, whereas on the Aberdeenshire coast the landforms are controlled more by the glacial deposits. As one approaches the Moray Firth the coastline becomes softer, the high cliff coast of the sedimentary rocks of Banffshire and Moray give way to the sand shingle coast west of Burghead.

Along its length, the coastline of north east Scotland reflects the varied action of geomorphological processes of erosion as along the Banffshire coast; of deposition and re-working of glacial deposits as at the mouth of the Spey; and of sand deposition and movement as at the sands of Forvie and Culbin. These processes and the varied geology have given the north east coast a very varied coastal land-scape. The coastline between Aberdeen and Inverness is approximately 350 kms in length and Table 1 shows a breakdown of coastal types along this coast.

Table 1

Length of Coastal Types

Cliffed Coast	84 kms
Sand coast	165 "
Rocky coast	12 "
Intertidal flats	51 "
Protected coast	21 "
Docks etc.	13 "

These figures were derived from a survey using colour aerial photographs carried out by the Department of Geography at the University of Edinburgh, and show clearly how the coastline is dominated by soft shoreline features. This is of importance when one looks at the influence of coastal topography on land use and development. Nowhere else along the east coast of Scotland is the dominance of sand beaches quite so marked. This is borne out by Figures 2 and 3. Figure 2 shows the percentage composition of coastal types in 13 geographic units along the east coast of Scotland. In each section the length of coast is calculated and the percentage of that figure occupied by each coastal type is plotted. Figure 3 shows for each of the 13 sections of coast the percentage of the whole coast of east Scotland occupied by the coastal type in that section of coast.

Figure 2 illustrates clearly the variation between the harder coasts of Caithness and the Borders and those of the firths and estuaries. Excluding the softer depositional coasts of the estuarine areas, the north east coast of Scotland has a greater length of soft coast-line than elsewhere. This is more clearly shown in Figure 3 where the dominance of the beach component in north east Scotland can be seen. This is of significance for land use in terms of the potential for development which will be outlined in section 4.

3. Land Use History

The first chapter in the development of North East Scotland began about 4000 BC when mesolithic hunters and squatters came into the Moray Firth area. The first farmers were however the neolithic people. Settlement was concentrated along the coastal strip and in particular around the shores of the Moray Firth. The area of north east Scotland has witnessed a progressive increase and improvement in the area of agricultural land in response to the development and expansion of settlement along the coastline.

The rate of change was slow until quite recently and most develop-ments and improvements have taken place in the last 3-400 years. Settlement was initially concentrated along the coastline where small fishing ports and trading ports became established in the 17-18th centuries, such as Findhorn, Burghead and Lossiemouth.

The settlement of the more inland parts received a major setback in the form of the Highland clearances which resulted in an even more pronounced coastal distribution of settlement. This event led in part to the development of herring fishing and distilling as 2 major sources of activity in north east Scotland. Many ports developed as centres of herring fishing in the 19th century. This concentration of population put further pressures on the agricultural system and gradually led to further improvements in agriculture and a large increase in the area of land under cultivation. Agriculture up to this time had been slow to develop owing to the inhospitable terrain in land of the fertile coastal plains of the Moray firth. Glaciation had left a legacy in north east Scotland of a barren area of muir and moss, heavily furrowed by glacial erosion and outwash deposits. This has resulted in a relatively chaotic drainage pattern which further added to the difficulties facing agricultural improvement.

The incentive provided by the growth of coastal settlements led to a vast improvement in agriculture. In the 18-19th centuries land was levelled, mosses were drained and miles of ditches were dug, such that after many years of labour much of Buchan was brought under the plough. The effects of glaciation could also be found in the great variety of soil types found over north east Scotland. Many areas proved difficult to cultivate and required constant attention to maintain their fertility while areas like the Laich of Moray had for a long time been fertile and easier to cultivate, so much so that this area had become known as the granary of Scotland and Portgordon had developed into a grain exporting port for the inland grain growing areas.

While agricultural development and improvement continued along the coastal plains and inland the fortunes of coastal settlements fluctuated. Herring fishing reached a peak in the late 19th century since when many small harbours suffered a decline. This was a result of the decline in herring fishing and a centralisation of fish marketing in the larger ports of Peterhead, Fraserburgh and Aberdeen. Some ports became more industrialised e.g. boat building at Aberdeen and Buckie.

The 20th century saw a continued concentration of population in the coastal settlements, a trend which was reinforced by the growth of tourism which was oriented towards the coast. Several towns and ports became centres for tourism e.g. Nairn, Findhorn while smaller ports became valued for their picturesque settings. This has to a certain extent offset the decline in fortunes of several coastal settlements.

Another major development in the 20th century was the growth of afforestation. Afforestation of inland areas had first begun in the mid 18th century and developed into a flourishing trade. Kingston at the mouth of the Spey had developed a small ship building industry in the late 18th century using timber floated down the Spey. The 20th century saw large areas towards Inverness afforested, e.g. Culbin sands which were planted in response to the need to control the sand dunes which had engulfed many hectares of farmland.

4. Present Distribution of Coastal Land Uses

Table 2 shows a summary of coastal land uses along the north east coast of Scotland, while Table 3 presents a more detailed breakdown for the whole coastline of Highland Scotland.

Percentage of total length in each section   *Fig.2(i)*

(Total section length)

Borders Coast   Forth   East Fife
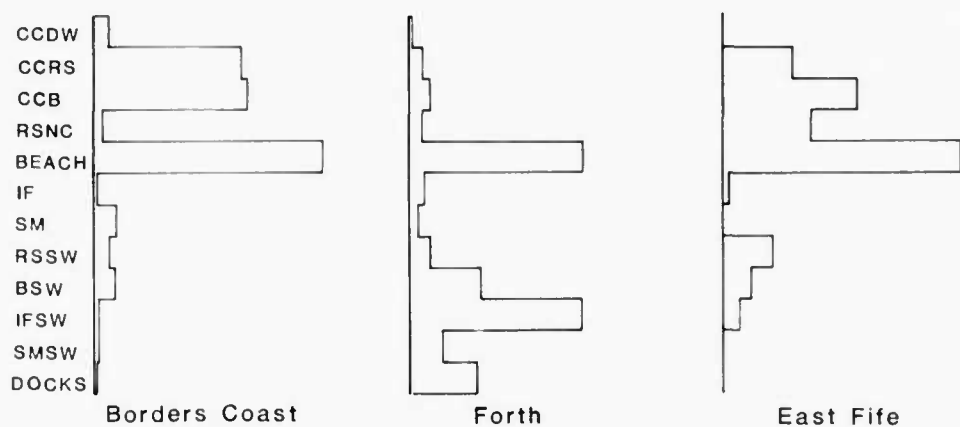
Key to abbreviations on following page

Tay   Dundee–Fraserburgh   Fraserburgh–Inverness

Moray Firth   E.Black Isle   Cromarty Firth

Fig.2(ii)

Cromarty-Tarbat Ness   Dornoch Firth   East Caithness

North Coast
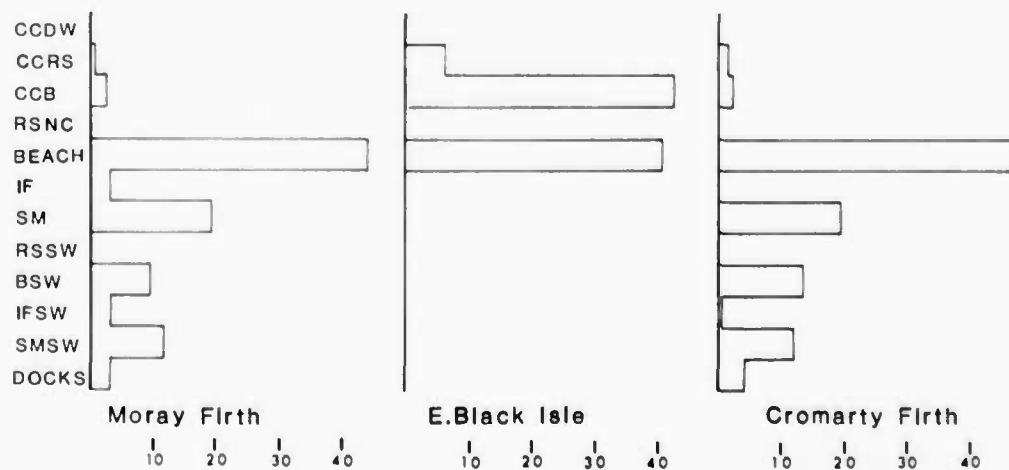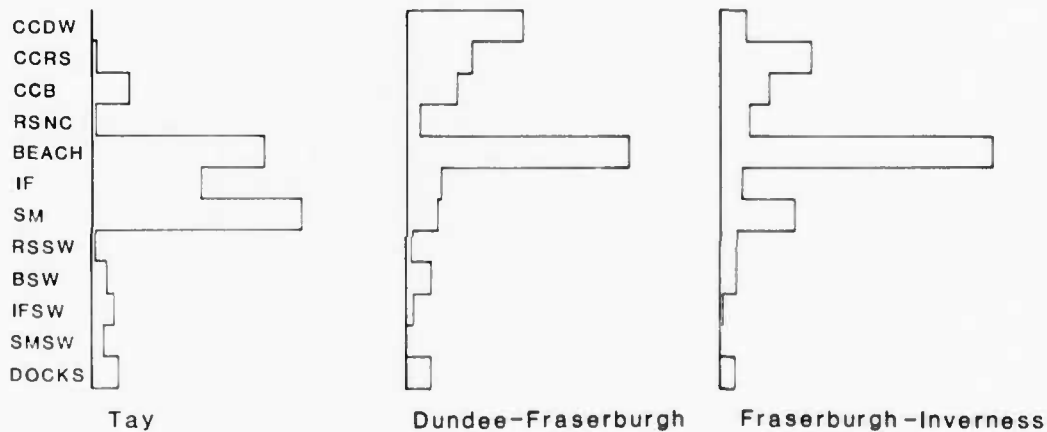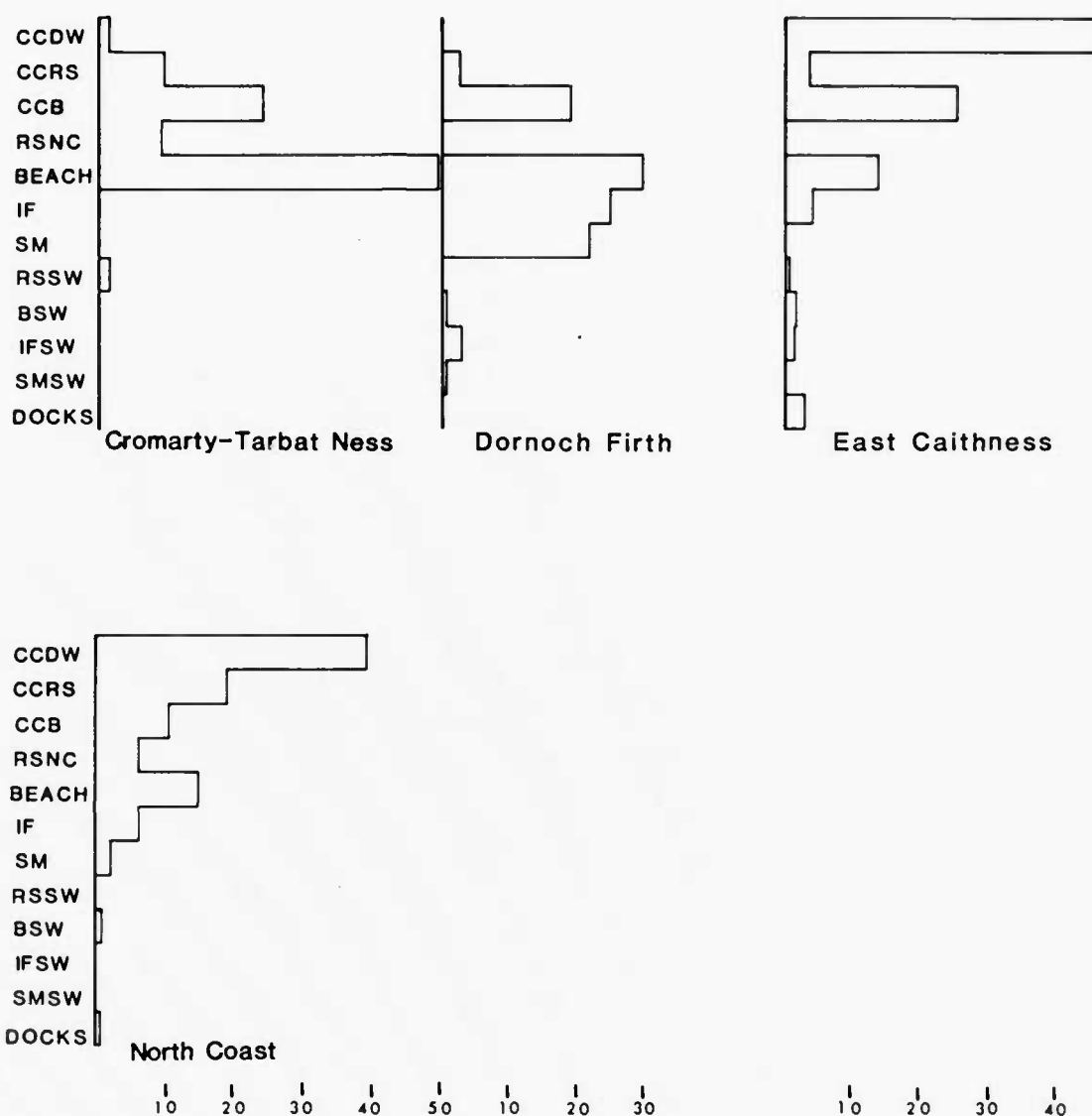
CCDW	Cliff Coast : Deep water	SM	Salt Marsh
CCRS	Cliff Coast : Rocky shore	RSSW	Rocky shore : Seawall
CCB	Cliff Coast : Beach	BSW	Beach : Seawall
RSNC	Rocky shore : No cliff	IFSW	Intertidal Flat : Seawall
IF	Intertidal Flat	SMSW	Salt Marsh : Seawall

Percentage of total length of each type for each section

Fig.3
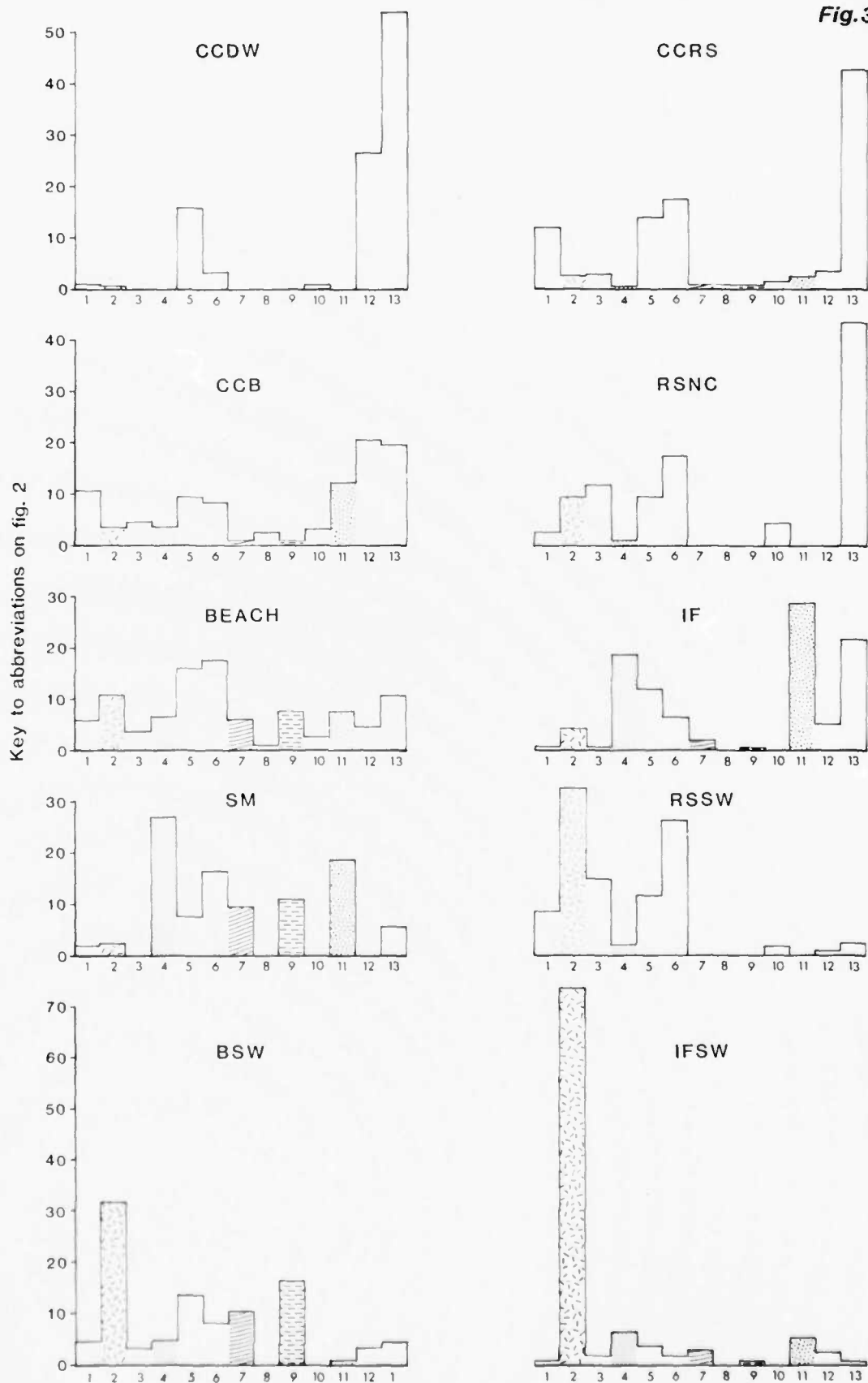
Table 2

Coastal Land Use in North East Scotland

Agriculture	177.5 kms	50.6%
Forestry	39.3 "	11.2%
Recreation	38.7 "	11.0%
Residential	39.8 "	11.4%
Industrial	32.7 "	9.3%
Moorland	22.2 "	6.3%
		100.0
Nature Conservation	122.3 "	34.8%

Table 2 illustrates the dominance of agricultural land use along the north east coast of Scotland. The remaining land uses would appear to be of equal importance but examination of Table 3 shows that these other land uses are not evenly distributed along the coastline.

Agriculture dominates the coastline north of Aberdeen and along the Banff-Buchan coast. This reflects the large tracts of dunes and links which are used for sheep and cattle grazing. Elsewhere, where the coastal plain is more even arable cultivation occurs. On the higher cliffed parts of the coastline grazing with some cultivation of oats, barley and potatoes are the main types of agriculture. Further west into Moray and Nairn agriculture becomes less dominant along the coast, although inland parts of Morary are extremely fertile.

Forestry is completely absent along the east coast of the region but becomes locally very important along the western part of the Moray Firth coastline. While large inland areas of north east Scotland have been afforested in the 20th century relatively few areas of the coast-line have been affected. The main areas of planting have been the Culbin forest, Roseisle west of Burghead and east of Lossiemouth. The Culbin forest, now covering approximately 3100 ha was planted to stabilise the large dune area that became mobile in the 17th century and which had engulfed neighbouring agricultural land. At its peak the bare sand extended to over 3800 ha, most of which has now been planted. This represents an interesting example of the relationship between land use and the underlying physiography, although in the case of the Culbin forest the land use was a direct response to a geomorphological process which was threatening agricultural land.

Recreation has developed as a major land use along the north east coast of Scotland, particularly in the 20th century. This has occurred along the soft sandy coastlines on the east coast and along the western coast of the Moray Firth in Nairn. Recreational developments have taken two forms: firstly the use of the links areas for golf courses. As the Beaches survey for north east Scotland notes, between Fraserburgh and Aberdeen 20% of the coastal dunes are occupied by 8 major golfing areas, while most settlements along the western part of the Moray Firth coastline have their own golf courses. The second major recreational use of these areas is for informal recreation and caravan + camp sites. This has been especially marked in Nairn which has become a popular resort. Notwithstanding the large number of golf courses and caravan stances which can be found along this coastline many areas of sandy coastline still remain relatively inaccessible from main roads. Assess is only provided in a small number of locations; this is especially true of the coastline north of Aberdeen and around the Culbin area. As a result, where access is provided the level and intensity of use is very high, e.g. at Balmedie (North of Aberdeen) and at Nairn. This represents

one of the few conflicts of land use along the north east coast of
Scotland. The highly varied nature of the coastline has meant that
the differing land uses have all been able to find a location sutiable
for their particular requirements. Only rarely has there been compet-
ition for land between competing land uses.

Other smaller sandy beaches along the north coast are also used for
recreational purposes but not so extensively as the other areas
described above. Industrial and residential use of the coastline is
more restricted. Settlement has occurred all along the coastline of
north east Scotland and has grown up around small harbours, natural
or otherwise, where fishing and trading by sea were the original main
activities. As can be seen in Table 3 and Figure 4 the main con-
centration of residential and industrial use is along the east coast
and eastern part of the Moray firth coast. In this area are to be
found the major settlements of Aberdeen, Peterhead and Fraserburgh.
It is here that industry has developed and become concentrated.

The main industry has for a long time been fishing, to which most
coastal settlements owe their existence. The fishing industry,
while still important in many towns and settlements has become
concentrated at Aberdeen, Peterhead and Fraserburgh; where processing
industries and marine engineering have grown up as well. Aberdeen
and Buckie have for a long time been centres of shipbuilding and
general engineering. Quarrying is another activity that is important
in north east Scotland. This particular land use is restricted to
the Aberdeen area and to the area south of Peterhead at Longhaven,
where a large granite quarry has developed.

Conservation plays an important role in coastal land use in north
east Scotland by acting, in certain areas, as a constraint on land
use and development. Table 4 shows the area and length of coast
designated as SSSI's and NNR's. Several of the sites have been
designated for ornithological reasons to protect seabird colonies
along cliffed coast, and for geological reasons to preserve exposures
of certain geological formations exposed in the cliffs. In both
cases the designation only affects a narrow coastal strip and has not
led to a significant restriction on land use development. In the
case of areas of dunes and links that have been designated for
physiographic and or botanical reasons the restrictions on land use
are more significant. Several such areas have been designated, e.g.
Sands of Forvie, Foveran and Drum links and the Culbin sands area.
In most cases there are few problems for development due to the
general lack of access to the beach environment in such areas, a factor
which helps to protect the scientific interest of such sites.

The present extent of the various land uses described above is shown
in summary form in Figure 4, which shows the percentage composition
of coastal land use along the coastline of Highland Scotland. The
concentration of residential and industrial land uses along the north
east coast can be seen as well as the importance of recreation along
the east coast of Aberdeen and along the Moray firth at Nairn. The
Figure shows also the varying intensity of land use and the relatively
small extent of developed coast in the Highland parts of Caithness and
Sutherland compared with the more intensively used parts of north east
Scotland. The extent to which these various land uses have changed
and led to conflicts in north east Scotland will be outlined in the
following section.

Table 3

Coastal Land Use in Scotland (length in kms)

	Agric.	Forest	Rec'n	Resid	Ind.	Moor	MOD	Total
Aberdeen/Gordon	101.3		19.8	15.5	21.8	7.6		148.0
Banff-Buchan	43.3		8.2	16.6	7.9			70.5
Moray	29.5	34.5	6.0	6.3	3.1			83.2
Nairn	3.4	4.8	4.7	1.1		7.2		21.2
E.Inverness	36.5	1.4		4.5	5.3	4.0	4.2	56.0
E.Ross+Cromarty	182.4	10.9	6.1	18.7	4.3	15.0	0.3	237.8
E.Sutherland	47.8	22.2	9.5	4.2	0.1	15.8	0.3	100.0
Caithness	131.4	0.4	4.3	6.4	5.5	37.2		185.1
W.Sutherland	198.7	12.9	3.2	5.5	0.3	277.9		498.5
W.Ross+Cromarty	229.8	74.1	6.8	20.0	0.5	240.2	1.4	572.8
W.Inverness	76.3	63.3	5.0	12.1	5.0	161.2		322.9
Argyll	663.3	371.0	15.1	66.7	9.2	111.3	1.3	1237.8

Table 4

Nature Conservation: List of Designated Sites

	ha	kms
Culbin Sands - Findhorn Bay	5029	17
Masonhaugh Quarrie	25	1
Sands of Forvie	764	7
Collieston - Whinnyfold Coast	116	7.5
Foveran - Drum Links	310	4.5
Ythan Estuary	262	
Aberdour Coast	136	11
Bullers of Buchan - Longhaven	157	11
Cairnbulg - St Combs	80	6
Cullen Troup Head	60	46
Quarryhead - Fraserburgh	234	11

5   Recent Changes and Conflicts in Land Use

Recent changes in land use in North East Scotland have been
restricted to a very few areas.   Agricultural improvement and continued
afforestation have led to some changes in the landscape but have not
significantly affected the coastline of North East Scotland.

Recreational developments have continued to be concentrated in locations
where access to sandy beaches is provided, and the only change has been
one of the increased intensity of use with the increasing number of
visitors.   This has led to problems of erosion of fragile dune areas
as at Balmedie and Findhorn, where remedial measures have had to be
taken to prevent further erosion and damage.   The sea front at Aberdeen
has been considerably altered to protect the dunes and sand beach by
constructing groynes, sea walls and an access road for visitors.

The most significant change in land use has been brought about by the
impact of North Sea oil exploration.   Initially this provided a
stimulus to the existing major ports.   Aberdeen and Peterhead have
developed into major service bases for oil exploration and this has
led to quite marked changes in both harbours, with the construction
of new wharves and quays together with warehouses.   The soft coast-
lines of North East Scotland have proved to be highly suitable for the
landfall of oil and gas pipelines as at Cruden Bay and St Fergus
respectively.   In both cases however, development has gone ahead with
minimal damage to the fragile coastal environments, indeed at Cruden
Bay it is now hard to see where the pipeline came ashore owing to the
careful restoration works that were carried out.   At St Fergus a
large gas processing plant has been constructed on the land behind
the coastal dune system, and as a result the coastline itself has not
suffered any adverse effects.

Another major development has taken place at Whiteness Head, west of
Nairn, where an oil platform construction site has been developed.   This
was located on a soft coastline adjacent to the deeper waters of the Moray
Firth, and necessitated the excavation of the site and a considerable
modification to the shingle foreshore.   Dredging has also been necessary
to keep open the deep water access to the construction yard.   Although
such developments are on a large scale, and in the case of Whiteness
Head and St Fergus have led to significant alterations of the local
environment, there have been few major problems or conflicts as a result.
In both areas access to coastline was already restricted, so no major
recreational conflicts arose.   There has been a certain amount of farm-
land lost at St Fergus, but only at Whiteness Head has the coastline
itself been significantly altered.

It can be seen therefore that the rate and scale of development proposals
has increased considerably in recent years.   This has been particularly
marked along the coastline of Scotland as a whole.   This development has
included both industrial and recreational developments.   The resulting
planning problems caused by such large scale developments prompted the
Scottish Development Department to produce a document called the Coastal
Planning Guidelines.   In this document the SDD aimed to provide a frame-
work in which local Planning Authorities could make decisions as to the
location of large scale developments.   This was achieved by designating
preferred development zones, the policy being to encourage the location
of large scale development in such areas, thereby reducing potential
conflict along the coastline with other land uses and development proposals.

Fig.4

Coastal land use

Coastal components
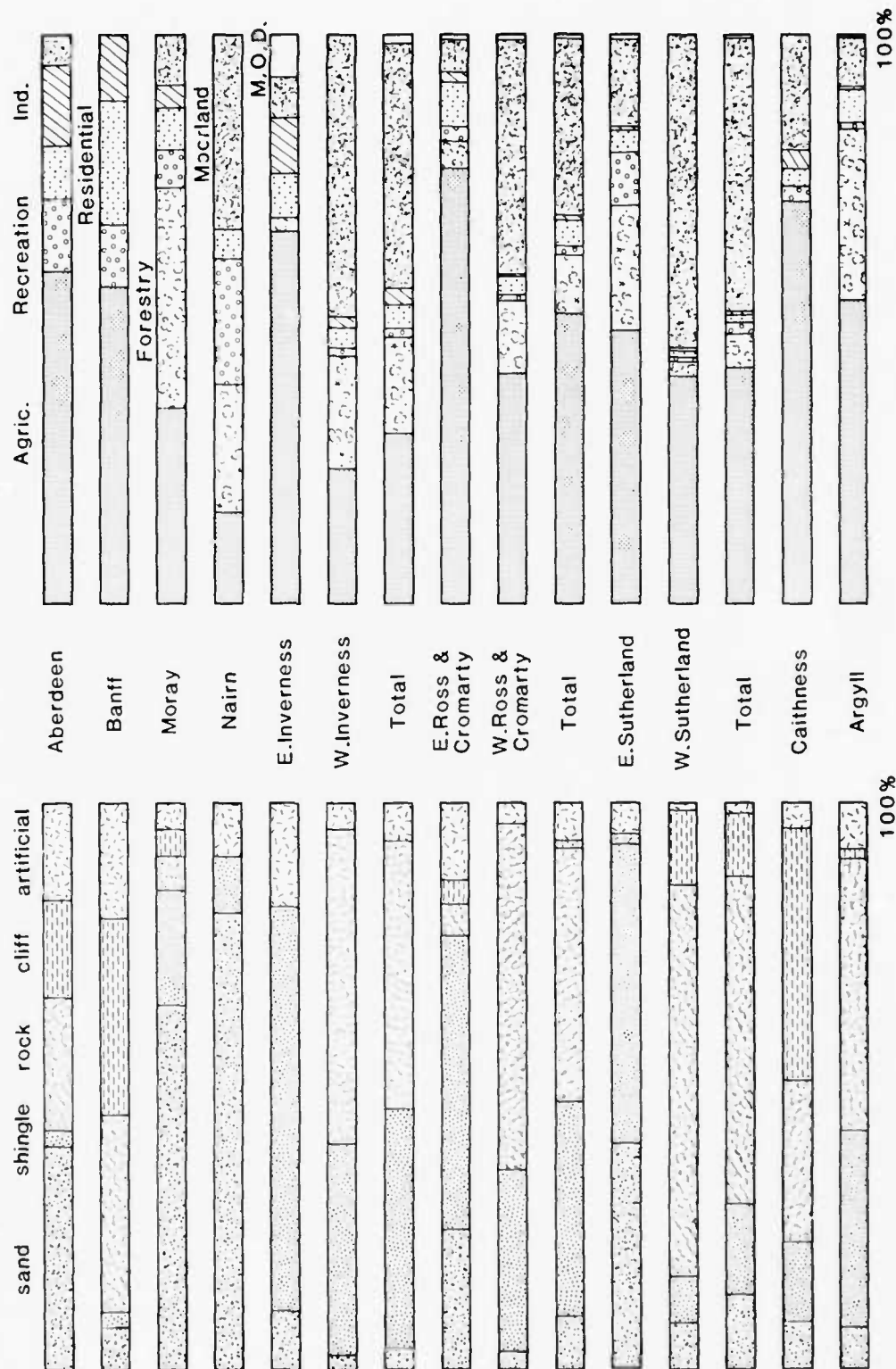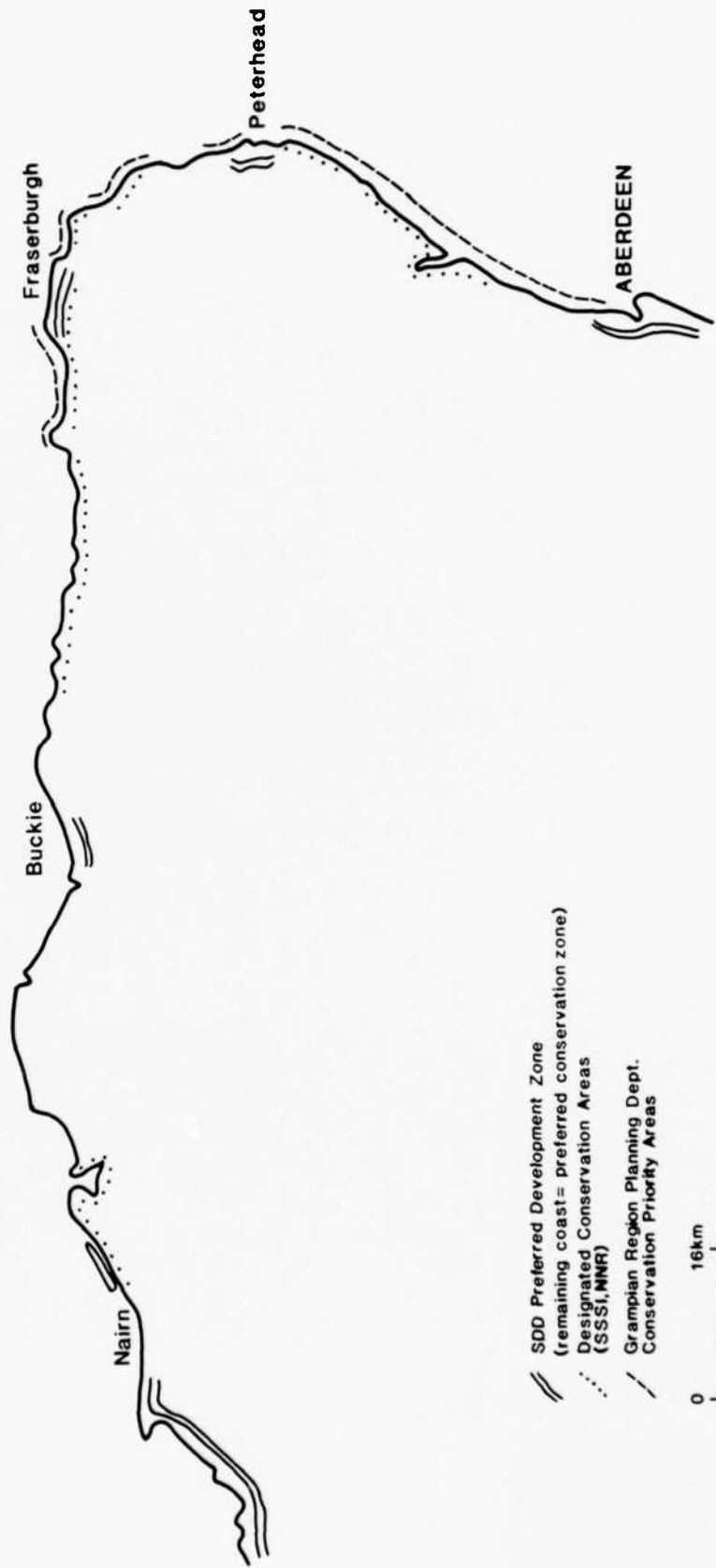
PLANNING AND CONSERVATION CONSTRAINTS IN N.E. SCOTLAND

Nairn

Buckie

Fraserburgh

Peterhead

ABERDEEN

Fig. 5.1

SDD Preferred Development Zone
(remaining coast= preferred conservation zone)

Designated Conservation Areas
(SSSI, NNR)

Grampian Region Planning Dept.
Conservation Priority Areas

0   16km

PLANNING AND CONSERVATION CONSTRAINTS IN N.E. SCOTLAND

Fig. 5.1

Nairn

Buckie

Fraserburgh

Peterhead

ABERDEEN

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0   16km
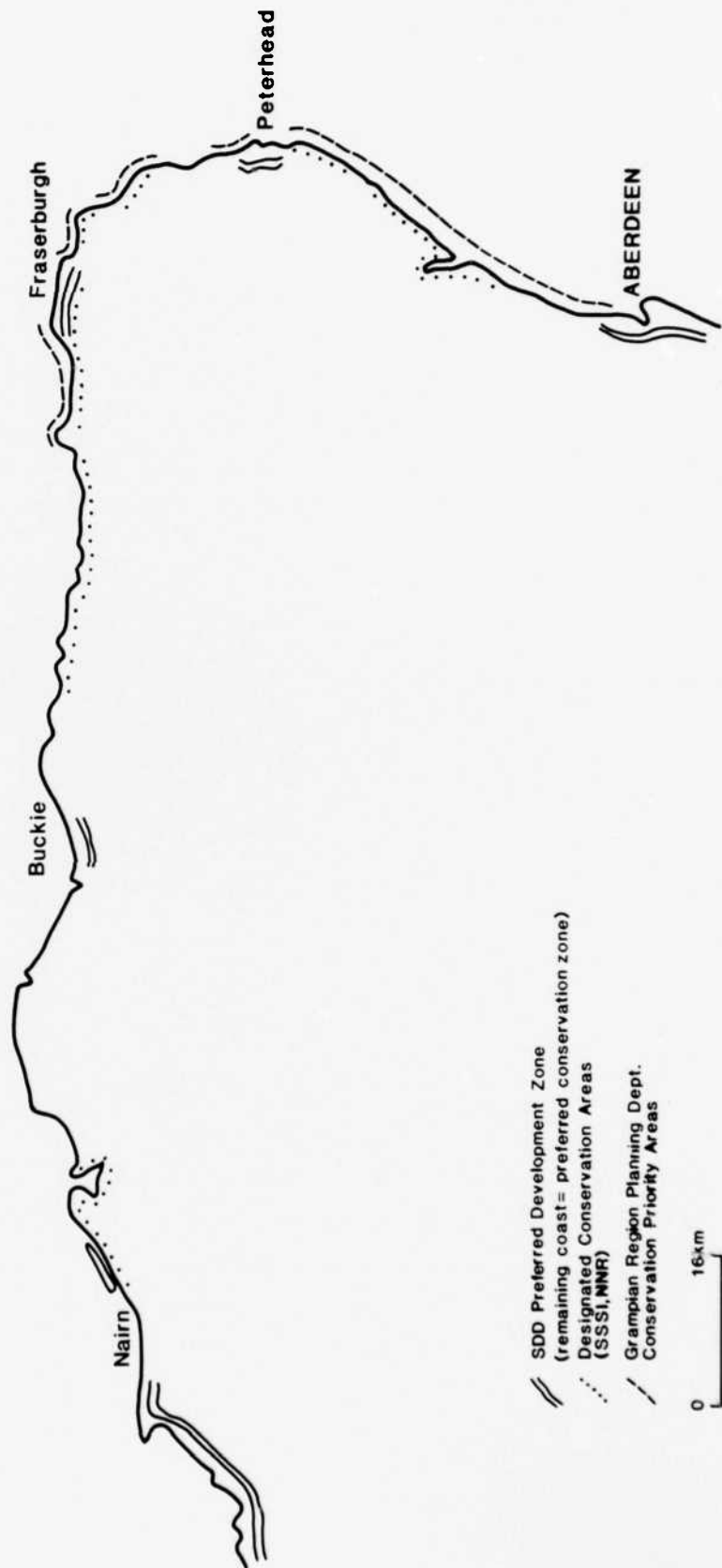
Figure 5.1 shows the location of these zones, together with the preferred conservation in North East Scotland. The report defined the zones of conservation and outlined the reasons for their importance, and this represented an important attempt to develop a national planning frame-work for the coastal zone to avoid conflicts in land use. Within this overall strategy, several local conservation plans have been drawn up, e.g. for the Aberdeenshire coast, and for specific areas such as Balmedie beach, where the emphasis is on the control of erosion through the control and management of public assess to the beach areas.

All such plans and policies aim to minimise land use conflicts by the allocations of scarce resources amongst competing demands; to a large extent however development is automatically constrained by the physiography of the coastline. Nowhere does this apply more than along the coastline of North East Scotland where the highly rocky coasts provide a natural hindrance to development. In contrast to this however on soft shorelines where access is easier the environment is more fragile and susceptible to damage and it is in these areas that the greatest problems and conflicts arise.

6. Summary

This paper has outlined the land use history of the North East coast of Scotland together with the physical background. Section four outlined the present distribution of land uses along the coastline, while section five described some of the conflicts involved and the ways in which planning authorities have attempted to minimise these conflicts. While certain large scale developments, mainly oil related, have adversely affected the coastal environment, these have been restricted to very small sections of the coastline. Large sections of the coastline (identified by SDD as preferred conservation zones) have remained relatively unaffected and undisturbed by these developments. As outlined above this is to a large extent the result of the physiography of the coastline exercising control over the location of development.

In conclusion, whilst development has caused problems and conflicts in some areas, by far the greatest part of the coastline remains unspoilt. It is to be hoped that planning policies allow this state of affairs to continue by only allowing suitable developments to proceed in the most environmentally appropriate locations, and by controlling access to the coastline along the sensitive soft shorelines.

5. <u>EVIDENCE FOR SEA LEVEL FLUCTUATIONS IN NORTH EAST SCOTLAND</u>

A REVIEW

Introduction

The present coastal morphology of north-east Scotland, with its alter-
nation of high and low coastal elements (Fig. 1), is a product of the
interaction between land and sea over a considerable period of time and
at a variety of altitudes within respect of Ordnance Datum (OD). Elements
of this coastline, particularly the low coasts so succinctly described
by Walton (1963, 25-27), are difficult to explain solely in terms of
present marine activity. Along much of the low coast the beach backs on-
to a strip of raised marine deposits lying only a few metres above sea
level and frequently terminated inland by a fossil cliff. In areas
where it is protected from the sea by a dune belt, as at St. Fergus north
of Peterhead, the raised beach may be up to 300 m in width (Fig. 2).

On the cliff coasts, the low-level raised beach is seen only in sheltered
localities such as the head of Stonehaven Bay (Bremner, 1925). It is
therefore the low coasts that preserve the best evidence of recent sea
level changes (eg. Smith, Cullingford and Seymour, 1982).

The cliff coasts (Fig. 1) yield relatively little information about
oscillations in the relative levels of land and sea. The hard rocks
from which the cliffs are carved react only slowly to the insistent
hammering of the sea. Short-lived episodes of sea level stability do
little to the surface of the cliff, and are often unrecognised and unremar-
ked when the cliffs are studied. Evidence for some episodes of sea level
fluctuation has been discovered in pockets of sediment preserved in the
'yawns' or narrow inlets cut into the cliffs. Fossil stacks related to
a sealevel other than the present one have been recorded on the coast
just south of Aberdeen and at Cullen (Walton, 1963; Synge, 1956, 1963;
Clapperton, 1977). Abrasion platforms related to ancient sea levels are
well developed near Gourdon and Johnshaven (Fig. 1), south of Aberdeen,
and at a number of locations on the Moray Firth coast east of the mouth
of the Spey. Fossil abrasion platforms have also been recorded from
higher levels, though as we shall see, their interpretation has been a
matter for contention. In many places though, the cliffs plunge straight
into the sea and platforms and other evidence of sea level change are
absent.

Many of the coastal features of north-east Scotland are composite, the
product of events spanning a considerable period and during which the
level of the sea will not have been constant. This has led to consider-
able difficulties in the dating and correlation of some of the landforms.

The influence of sea level changes on the present coastal morphology of
north-east Scotland is undeniable. What may be rather less obvious is
that the sea may in the past have attained levels which spread its
influence far from the present coastline. It is necessary to consider
inland as well as coastal sites if sea level changes and their influence
on the evolution of the coasts of north-east Scotland is to be understood.
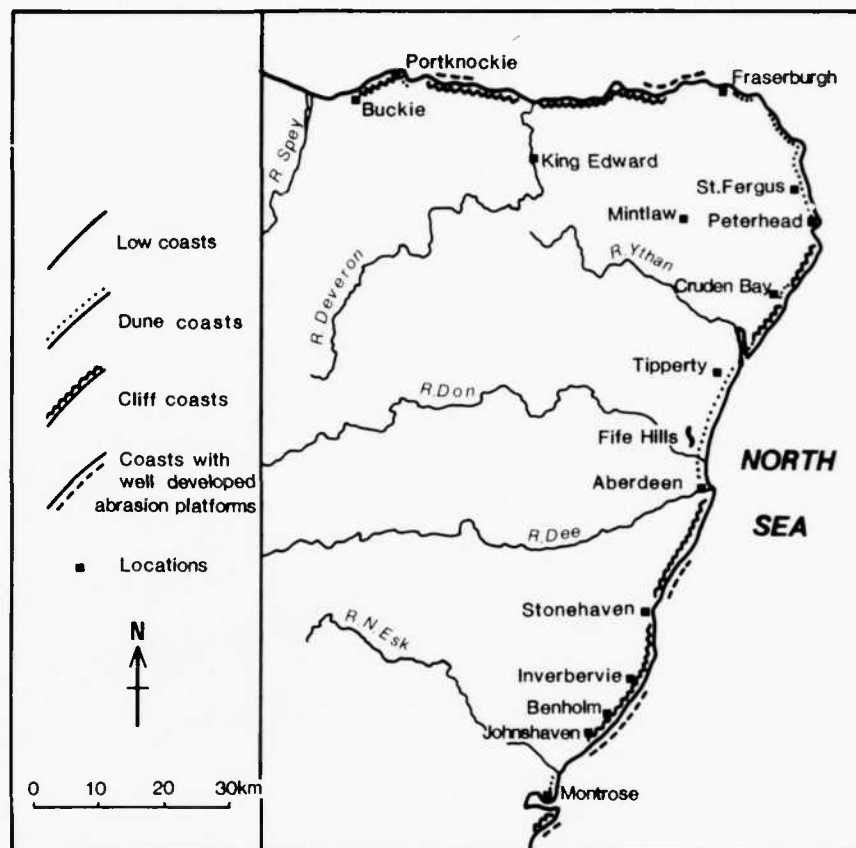
Figure 1   Distribution of coastal types in north-east Scotland.   Locations
            mentioned in the text are also indicated.

Causes of Sea Level Change

'Five factors affect sea level and its variations over time: (1) long
term tectonic changes, (2) glacial isostasy, (3) hydro-isostasy, (4)
geoidal changes, (5) glacio-eustatic movements in sea level due to
alternating glaciation and deglaciation' (Bowen, 1978; p. 158). All of
these factors will have been active during the evolution of the coastlands
of north-east Scotland.

Long-term tectonic factors include the opening of the Atlantic Ocean, and
the ongoing subsidence of the central North Sea basin (McCave, Caston and
Fannin, 1977; Eden, Holmes and Fannin, 1977). Holmes (1977) calculated
that some 160 m of subsidence has taken place during the last 50,000
years in one sector of the central North Sea. Crustal deformation on
such a scale must have influenced land/sea relationships on the coasts
bordering the North Sea, but the full implications have yet to be resolved.

Hydro-isostasy resulting from the flooding of the North Sea basin must
have affected land/sea level changes in the region. Certainly, if world
sea level c. 20,000 BP stood some 120 m below the present level, as claimed
by Fairbridge (1961), Shepard and Curry (1967) and Shackleton and Opdyke
(1973) among others, then much of the bed of the North Sea must have been
dry land at that time (Jansen, 1976; Sissons, 1981; Jardine, 1982),
although Holmes (1977) has expressed doubts on this matter. The flooding
of such an area during the late-Devensian and Flandrian rise in sea level
is estimated to have produced seabed depression of the order of 30 m
(Sissons, 1981).

Geoidal variations in sea level (Mörner, 1977) make it very difficult to
extrapolate eustatic sea level curves obtained from such areas as
Barbados (Fairbanks and Matthews, 1978) and Bermuda (Harmon, Schwarcz and
Ford, 1978) into the North Sea basin. Thus in the absence of other
evidence, sea levels predating the late-Devensian glaciation are identified
on a relative rather than an absolute stratigraphic and chronological basis.
The interaction of glacio-eustatic movements of sea level and glacial
isostatic movements of the land would produce complex land/sea relationships
even were the factors detailed above not also active. The north-east of
Scotland is somewhat remote from the main centre of glacial accumulation
in Scotland which lay 200 km to the south-west. Consequently the area
was ice-covered for shorter periods than regions to the south and west,
and was isostatically depressed to a lesser degree. Indeed some workers
consider the Buchan district of north-east Scotland to have escaped
glaciation during at least the Devensian (Charlesworth, 1956; Fitzpatrick,
1972; Synge, 1956, 1963, 1977), although Clapperton and Sugden (1977) refute
this idea.

There is less dispute about the glaciation of the coastal areas. Along
the North Sea coast from south of Aberdeen to Peterhead the glacial
deposits are predominantly red in colour. This Red Series (Jamieson,
1906) is associated with a northerly ice-flow emanating from the
Strathmore area (Fig. 3). Glentworth, Mitchell and Mitchell (1964)
demonstrated that this Strathmore ice did not flow directly along
the coast, but expanded onto the floor of the North Sea before being
diverted back to land.

Within the immediate environment of Aberdeen, Red Series deposits are
scarce, a circumstance interpreted by some as indicative of their
removal by a subsequent advance of a Dee Valley glacier (Jamieson,

1882a, 1906; Bremner, 1925; Synge, 1956, 1963). Alternatively, the situation is seen as the result of two separate ice-masses co-existing in the Aberdeen area, one of which was laden with Red Series sediments while the other held debris gleaned from inland (Simpson, 1948, 1955; Murdoch, 1975, 1977).

North of Peterhead and along the Moray Firth coast, the surface glacial deposits are what Jamieson (1882a) described as the Blue Clay, similar in character to the Red Series but held to be the product of ice from the Moray Firth lapping onto the coastal areas. Some of the stratigraphic relationships are complex, and both Jamieson (1906) and Bremner (1915) expressed doubts as to whether these deposits related to the last glaciation of the area. Synge (1956) introduced the concept of solifluction of the deposits to account for some of these anomalies, and the Blue Clay is now generally accepted as being the deposit of the last phase of glaciation to affect those coasts.

Holmes (1977, p. 23) believes '... that deglaciation of the sea adjacent to Scotland probably occurred more than 18,000 years ago.', though this important conclusion has been challenged by Sissons (1981) on the grounds that the inferences required to obtain such a date are unsafe. Equally uncertain is the suggestion by Synge (1977) that the area may not have become ice-free until 16,000-14,500 BP. It can only be said that the exact date for the deglaciation of north-east Scotland, and hence of the recommencement of shoreline development, has yet to be determined.

Simpson (1955) used evidence relating to the altitudes of the outflows from glacial meltwater channels in the coastal zone to postulate that the area between Peterhead and Fraserburgh was the first part of the coast to become ice-free. Ice-fronts then retreated in stages westwards into the Moray Firth and southwards along the coast towards Aberdeen and Stonehaven. Cullingford and Smith (1980) suggest that further south, in the Stonehaven-Montrose-Dundee area, shorelines developed in association with a westward-retreating ice-margin (Fig. 3).

Evidence for former sea levels

Erosion Surfaces and High-level Gravels

The landscape of north-east Scotland is dominated by erosion surfaces, of which the most extensive are the Buchan Surface at 100-130 m O.D. and a lower surface at 60-80 m O.D. fringing the coastlines between the Ythan estuary and Peterhead, and between Banff and Buckie. The surfaces are separated by 'steps' of steeper terrain. The association of flat surfaces backed by a steeper element has been likened by several workers to a marine abrasion platform and associated cliffline. This idea was used by Walton (1963) to suggest that all surfaces below 350 m were of marine origin, although he considered higher surfaces to be the work of subaerial processes operating with respect to various, but unknown, baselevels.

The marine planation hypothesis has tended to wither for the lack of corroborative evidence. The discovery by Godard (1965) of various weathering phenomena on erosion surfaces in north-west Scotland helped to develop the theory that the surfaces formed subaerially in a relatively warm, possibly savanna, climate. This is now generally accepted as the most probable mode of origin of these surfaces, although as recently as 1977 Clapperton stated that the Buchan surface probably originated as a surface of marine planation.

Surveyed Cross Section St. Fergus Near Pipelines

Sketch Block Diagram Near Pipeline Landfalls
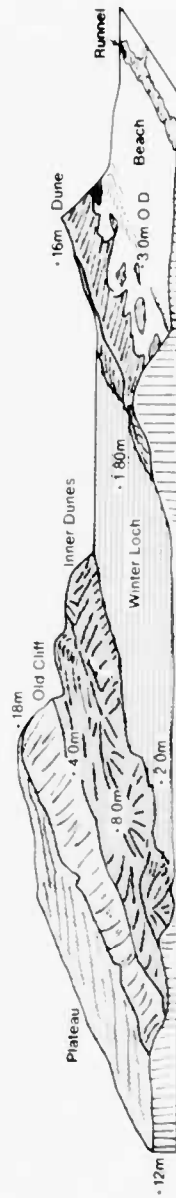
St. Fergus

Figure 2   Typical low dune coast topography, St. Fergus.

Plate 1   Low sandy coast north of St. Fergus.   Sand dunes are well-
developed in this part of the coast.

Plate 2   Soft dune-fringed coast near St. Fergus

The persistence of the concept of a marine origin for the Buchan surface
was due in no small part to its being the only surface for which suppose-
dly corroborative evidence was available. That evidence was the presence
of the so-called 'Pliocene' gravels of Buchan (Fig. 3), accumulations of
flint and quartzite gravels resting on the erosion surface. The highly
rounded nature of these cobbles persuaded many observers to conclude that
they were looking at a shingle deposit related to a sea level c. 130-
170 m OD (Ferguson, 1850, 1855; Jamieson, 1858, 1865, 1874, 1882a).
Because the gravels are overlain in some locations by material of
glacial derivation, they were believed to be preglacial in age, probably
Pliocene. Later Jamieson (1906) noted that the granite debris on which
much of the gravels rested was not itself water-rounded. He concluded
from this that the gravels had been shaped prior to deposition, and
suggested that they were glacially transported morainic debris.

Later work was again dominated by the rolled character of the clasts, and
the concept of a marine origin revived (Flett and Read, 1921; Synge,
1956). Recent detailed study of these deposits (Gemmell and Kesel, 1979,
1982; Kesel and Gemmell, 1981; McMillan and Merritt, 1980; Merritt and
McMillan, 1982; Hall, 1982) indicated that the gravels can be differentia-
ted into a western quartzite-dominated gravel of fluvial origin and an
eastern flint-dominated facies most probably of glacial and fluvioglacial
origin, though Merritt and McMillan disagree on this last point. The
use of the Buchan gravels as an indicator of a former high sea level must
now be regarded as extremely doubtful, and the existence of such a sea
level as unproven.

Abrasion platforms truncate sea cliffs at an altitude of c. 25 m OD in
the Stonehaven area (Bremner, 1925; Walton, 1963). The presence of till
on the surface of these platforms led to their being considered preglacial
in age. They must pre-date the late-Devensian glacial maximum, but their
precise age is not known.

Low rock platforms and cliff notches provide some evidence of former sea
levels, though the conclusions reached by Sissons (1982) in a study of
high-level rock platforms in western Scotland must call into question
any interpretation based on such features until more detailed research
has been conducted upon them.

In the absence of dateable material, the age of the various platforms and
notches around the coast of north-east Scotland remains a matter for conjec-
ture. Some of these features are composite in the sense that they have
been reshaped during temporally separate episodes of accordant sea level.
As Mitchell (1977, p. 173) has noted "... in each warm stage sea-level
returned to approximately the same level." Such coincidence of land/sea
levels is more likely during mild interglacial conditions than during and
immediately following glacial episodes, when glacio-isostatic and glacio-
eustatic fluctuations would be at their most dramatic.

At the Bridge of One Hair, south of Aberdeen, a till-capped fossil stack
is joined to the main cliff by a plug of red 'Strathmore' till which
rests on a rock base a short way above present sea level (Synge, 1956).
The stratigraphy suggests that the sea level at which cliff retreat
isolated the stack predates the last ice cover, though this conclusion
must be in doubt if the infill soliflucted from the surrounding cliffs.

High-level Marine Sediments

Synge (1956) published a map in which he shows marine deposits as being
located near Mintlaw, in central Buchan (Fig. 1), 10 km inland and at an
altitude of c. 30 m OD. No mention is made of this site in the accompany-
ing article, so it is not known what evidence led Synge to conclude that
the sea had reached this location. In 1976 excavation for the constru-
ction of a sewage treatment plant at Mintlaw allowed temporary exposures
in terraces on the north bank of the South Ugie river to be studied.
Sections revealed a 3 m thick succession of red, green and black clays
overlain by a coarse gravel, probably fluvioglacial. Study of the clays
revealed the presence of numerous palynmorphs, probably derived from
Mesozoic rocks outcropping in the Moray Firth (E. R. Connell, pers. comm.),
but no sign of marine organisms. The black clay layer contained enough
organic material for an infinite radiocarbon age to be determined.

The author and Dr. A. S. Murray recently attempted to date a sample of
the red clay from the site by means of thermoluminscence techniques. The
effort was not entirely successful, but indications were that the
sediment might be well over 100,000 years old. The evidence suggests that
if these are the deposits Synge mapped, then their marine origin must be
open to doubt.

High-level Shell Beds and Associated Deposits

The presence of shelly material in many of the superficial deposits of
north-east Scotland has long been considered evidence of past submergence
of the land, even though many of the shells are crushed and obviously
not in situ. In 1860, Jamieson published a study of water-worn and
rolled gravels in Scotland, in which he concluded that the majority of
gravels found at altitudes of up to 800 m OD had been produced by the
sea washing glacial deposits during a major cycle of submergence and
emergence. The extent of this submergence was more precisely defined
in later papers (Jamieson, 1882a, 1882b) as at least 160 m OD, the
altitude of the highest of the 'Pliocene' gravels of Buchan. Jamieson
recognised that shelly deposits were found only up to 70 m OD, and that
many deposits at the higher levels contained only crushed shells, and
were most probably of glacial origin. Only at low altitudes that were
shells found in growth position.

By 1906 Jamieson was arguing for a sealevel at around 100 m OD at the
time of deposition of the Red Series which he thought had been "...
brought to Aberdeenshire by a drift of ice from the south, at a time when
the coast was submerged beneath water ..." (p 21).

Bremner was less convinced of such a degree of submergence, and by 1917
was discussing raised beaches at altitudes up to c 30 m OD, without any
mention of a greater degree of submergence having occurred in the past.
The Red Series was now accepted as being of glacial origin.

Considerable discussion of past sea levels has been occasioned by the
presence of shell beds at altitudes considerably above the highest
recognisable beach form in three localities in north-east Scotland.
Studies of the deposit at Benholm, near Inverbervie (Fig. 1), reveal
a black shelly boulder-clay which appears to underly red 'Strathmore'
till. Lumps of the shelly clay form erratics within the red till
(Campbell, 1934) at altitudes up to c. 65 m OD.

Plate 3   Coast at Gardenstown, on the Moray Firth. Note the dissected
            cliff and the abrasion platform at around present sea level.

Plate 4   Wave at platform at around present sea level associated with
            a cliffed coastline near New Aberdour.

The shell bed at King Edward, near Banff (Fig. 1), is rather lower (c 50 m OD) then the Benholm site. The shells are found in a sequence of sands, gravels and clays. Jamieson (1906) studied the site and found "Arctic shells embedded in a fine bluish silt, apparently wnere the organisms had lived and died" (p. 33). Here again the shell-bearing strata lie beneath till, and so are considered to predate the last glacial episode.

At Gardenstown (Fig. 3) a mass of sand shot througu with seams of dark clay contains shells similar to tnose obtained from King Edward, but at altitudes of up to 90 m OD. This succession of sands and clays, known as the Coastal Deposits (Peacock, 1971), rests on a till base. Samples of the shells have been subjected to radiocarbon assay, but yield infinite dates. Peacock considered the shell-bearing strata to be part of a shelly till, probably pre-Devensian if the dating of the shells is accurate. The Coastal Deposits are believed to be fresh-water sediments, laid down in water-bodies trapped between the Moray Firth ice mass and the rising ground to the south. The shelly material is held to have washed or soliflucted into the Coastal Deposits from the underlying Banffshire shelly till, or else to be glacially transported 'rafts' of sediment. Peacock therefore believes "... there are no late-Glacial marine deposits with an arctic fauna above present-day sea level in Banffshire and North Aberdeenshire" (Peacock, 1971, p. 87).

When the descriptions of the three shell-bed sites are studied, it is clear that each of them might have been deposited by some agency other tnan direct marine sedimentation. This being so, they again can not be regarded as useful indices of past sea level fluctuation.

Such a conclusion is challenged by Sutherland (1981) who postulates that these and similar beds elsewhere in Scotland are indeed of marine origin lain down in depressed areas produced by crustal downwarping at the margin of an advancing Scottish ice mass, possibly c 75,000 yrs BP. Because of its position bordering the Atlantic and its heavy cyclonic precipitation, Sutherland believes that the Scottish ice mass accumulated more rapidly than its North American and Scandinavian counterparts. There would thus have been isostatic downwarping in Scotland at a time when glacio-eustatic sea level was relatively high. This would produce coastal and marine deposits which would subsequently be lifted to considerable altitudes by isostatic rebound. As the majority of any such deposits would have been over-ridden by ice and destroyed, this theory is very difficult to substantiate. Even if correct, it does not permit us to gain any real idea of the relative altitude of the contemporary sea level. The possibility must also remain that even if Sutherland's hypothesis is correct, the marine beds may not be in situ, but rafted to their present position by the advancing ice. Thus Sutherland's idea, while interesting, does little to elucidate sea level fluctuations in north-east Scotland.

The Red Clays

Within the range of sediments associated with the predominantly glacial or fluvioglacial Red Series are pockets of what have been described as laminated clays (Jamieson, 1906, Bremner, 1915), brickearths (Simpson, 1955) or brickclays (Synge, 1956). These fine-grained deposits infill valleys and hollows in the topography at altitudes generally below 60 m OD.

It is agreed by all who have studied these clays that they have accumulated in quiet water conditions, for they are fine-grained sediments which often display well-developed laminar structures. Simpson (1955) noted that the laminae were sometimes rather poorly defined, a condition which he attributed to flocculation of colloidal material in salt water. In this context it is worth noting that Murdoch (1977) divided the Red Clays into an upper and a lower series in the Aberdeen district. The lower series have yielded fish and duck skeletons, starfish remains and shells (Jamieson, 1882a). Similar organic remains have been obtained from low-level pits in the Red Clays elsewhere in north-east Scotland.

The low series sites, almost invariably found below 12-15 m OD, are usually considered to be of marine origin, largely on the basis of their fossil content, correlated by Peacock (1975) with the Errol beds of the Forth and Tay estuaries. If correct, this would mean that the lower Red Clays accumulated sometime between 15,000 BP and 13,000 BP.

Laminated clays with a marine fauna are also to be found in the Montrose basin (Synge, 1956). Here they are overlain by outwash gravels graded to a sea level of over 25 m (Cullingford and Smith, 1980), confirming that land ice was present at the time of their deposition.

The upper series of laminated clays and brickearths is exposed at a number of locations including the well-known sites of Tipperty and Cruden Bay (Fig 1). For much of his life, Jamieson held that these were marine deposits, but by 1906 held it possible that they had accumulated in water-bodies ponded against the western margin of the Strathmore ice sheet. Murdoch (1977) undertook detailed study of the Tipperty site, which lies at c 20 m OD, and concluded that the deposit was indeed the infill of a glacially-dammed lake. Simpson (1948) thought a similar clay deposit at Tullos on the southern outskirts of Aberdeen had accumulated in similar circumstances related to a lake-level of 20-25 m OD, whilst Bremner (1915) suggested that the brickclays of Cruden Bay formed in an ice-dammed lake at a level of c 30 m OD.

The correlation of the Cruden Bay site with those at Tipperty and Tullos is thrown into some doubt by Fitzpatrick (1975), who observed that the bedded sands and clays exposed in the brick-pit are overlain by a massive unbedded red material containing erratics and which he considers to be a till. If this material is not soliflucted, then it is possible that the underlying lacustrine sediments relate to an episode of ice-damming during glacial expansion rather than decay, and may therefore predate the Strathmore glaciation.

The laminated clays of the lower Red Series can be used to infer approximate positions of the margin of the downwasting Strathmore ice, at least to the point at which the sea was allowed access to the land. Just north of Aberdeen, this occurred sometime between 13,000 BP and 15,000 BP, with a relative sealevel in the region of 15 m OD.

Late-Devensian Raised Shoreline Terraces and Associated Deposits

The coastal strip of north-east Scotland is fringed by bands of marine deposits and associated benches and strandlines at a variety of altitudes. These raised shorelines are especially well developed between Montrose and Inverbervie, between Aberdeen and the Ythan estuary, between Peterhead and Fraserburgh, and west of Buckie. They are usually absent where the coast is cliffed.
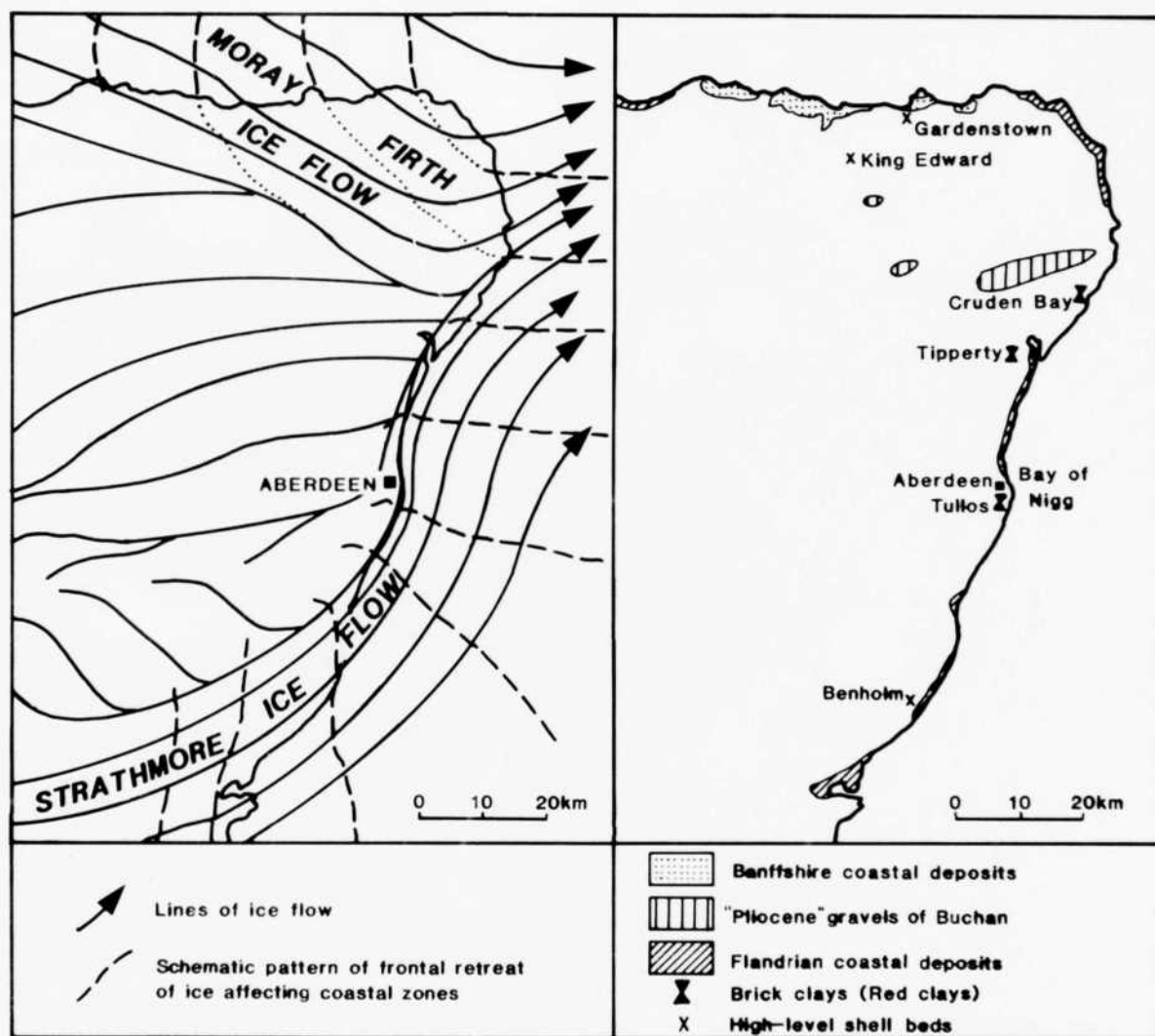
Figure 3   A   Schematic patterns of ice flow and decay, based largely on Simpson (1955), Clapperton and Sugden (1977) and Cullingford and Smith (1980).

              B   Distribution of important raised marine deposits and associated features. Data from Peacock (1971), Kesel and Gemmell (1981), Sutherland (1981), Murdoch (1977), Cullingford and Smith (1980), Smith, Cullingford and Seymour (1982) and Ritchie and Walton (1972).

No fewer than eight late-Devensian raised shorelines (dating most probably from the interval 17,000-13,000 BP) have been identified by the detailed studies of Cullingford and Smith (1980) in the area between Dundee and Stonehaven. The isobases for these shorelines run sub-parallel to the coast (NNE-SSW). From their association with outwash and other fluvioglacial landforms, the earliest of these shorelines are considered to have formed close to the retreating ice-margin. The fact that successively lower shorelines are less steeply inclined than those above suggests that their present elevation and altitude are substantially a product of glacio-isostatic effects related to a former Scottish ice mass. Cullingford and Smith identify shorelines at altitudes up to 35 m in the Stonehaven area, and as high as 38-39 m near Inverbervie. North of Stonehaven the cliffs prevent effective development and preservation of raised shorelines until Bay of Nigg, just south of Aberdeen. Here a noted section in the superficial deposits of the area (Jamieson, 1882a, 1906; Simpson, 1948, 1955; Synge, 1956, 1963; Chester, 1975) is capped at an altitude of 27 m OD by a sand and gravel series which Synge held to be a late-glacial beach deposit. It is more generally considered to be either 'morainic gravels' or a fluvioglacial deposit grading laterally into bedded sands and gravels which might mark a washing limit on the till cover of the hillside (Simpson, 1948, 1955), related to a sealevel c 30 m OD at the time that ice finally melted from the area.

Observers have described raised shorelines at 20-30 m OD north of Aberdeen. Sedimentary sequences in the Fife Hills, a fluvioglacial accumulation just north of the city (Fig. 1) led Synge (1963) to suggest that their formation might be related to a sealevel at 50 m OD, and certainly to show evidence of one at 25-30 m OD. Traces of lower shorelines (c 17 m OD) are also considered by Synge to exist around Bay of Nigg, and at the Fife Hills.

Further north, the estuary of the Ythan is flanked by terraces at altitudes between 27 m OD and 16 m OD which have been interpreted as raised shoreline remnants (Ritchie and Walton, 1972). As yet no detailed correlations have been made between these and the shorelines of the Aberdeen district.

Exposures in a pipeline trench near St. Fergus show that a break of slope at an altitude of 14-16 m OD is approximately coincident with a change from fluvioglacial to beach sediments (E. R. Connell, pers. comm.). This information supports the observations of Walton (1956) who believed that breaks of slope in this area at a similar altitude marked late-glacial sea levels. Boreholes in the vicinity of St. Fergus reveal that the surface of the associated terrace is cut in a blue clay, laminated in places and occasionally containing shells and pockets of peat. On this basis the clay can be considered a marine or lagoonal deposit, or possibly a reworked marine deposit, though this last option is unlikely.

The highly cliffed nature of much of the eastern Moray Firth coast precludes extensive development of raised beach terraces. Clapperton (1977) does however record that at Cullen '... a higher beach-like terrace is located at about 30 m above the relict cliffs' (p. 37), while small exposures of what appear to be beach gravels have been found on the clifftop at Portknockie (Fig. 1), at c 20 m OD.

More research is needed before the data culled from these spot locations can be integrated into a coherent story. The evidence indicates that high relative sea levels were present in north-east Scotland at the time of deglaciation. If Simpson's model is correct, and the area between Peterhead and Fraserburgh was the first part of the region to become ice-free, then the shorelines at 16 - 18 m at St. Fergus will be among the

oldest of the late-Glacial raised marine features, while the highest shoreline remnants along the coasts to south and west will be progressively younger. The oldest shorelines are confined to the extreme north-east, though later ones have a much more extensive distribution.

Post-Glacial (Flandrian) Raised Shoreline Forms

Barring the steepest cliffs, the coastline of north-east Scotland is fringed by a continuous ribbon of raised beach deposits backed by a fossil cliffline. The materials of which these low-level shorelines are composed include carse clays in the sheltered environments such as the Montrose basin, but more generally range from gravels to sands and silts.

Low-level raised shorelines are found at 6-7 m OD in the Aberdeen area (Synge, 1963; Ritchie, Smith and Rose, 1978), and northwards towards the Ythan. At St. Fergus, the late-Devensian blue clays have been eroded to form a fossil cliff against which sands and gravels interpreted as beach deposits have been banked to an altitude of c 2 m OD. Here no intermediate beach forms survive between those just described and the surface of the blue clay at c 10 m OD.

A few kilometres north in the Philorth valley near Fraserburgh (Fig. 1), Smith, Cullingford and Seymour (1982) have established details of the events associated with the formation of the Flandrian shoreline. To be strictly accurate, the sediments they investigated appeared to be of estuarine facies, so that their findings may not be strictly equivalent to those established for more open coasts, but they at least provide a basis for comparison. They consider a micaceous sandy silt layer to be the equivalent of the Flandrian carse clays found elsewhere in Scotland. This layer has a surface altitude of 1.2-2.3 m OD, very close to the altitude of the sand and gravel beach at St. Fergus with which it may possibly be correlated.

Radiocarbon dating of peats bracketing the micaceous sandy silt layer suggest that the marine incursion which deposited it was under way by 6300 + 60 BP, culminated sometime after 6095 + 75 BP, and that the sea had retreated from that level by 5700 + 90 BP (Smith, Cullingford and Seymour, 1982). A second estuarine deposit began to accumulate sometime after 4760 + 60 BP, at least part of which may be related to present sea level.

In the Montrose district the Flandrian transgression, here associated with a shoreline at 6-7 m OD, culminated between 6983 + 60 BP and 6704 + 55 BP (Smith et al, 1980). Although it is tempting on the basis of these dates, together with those from Philorth and from areas like the Forth and Tay valleys, to conclude that there is a tendency for the culmination of the transgression to be earlier nearer the centre of isostatic uplift, the culmination at Philorth is rather more recent than might have been anticipated. It is certainly younger than the age of c 7000 BP predicted by Donner (1970) for the culmination of the Flandrian transgression in marginal parts of the Scottish landmass. The altitude of the Main Postglacial Shoreline, which backs the carselands declines steadily northeastwards. In the Forth Valley it is found at heights c 15 m OD, in the Tay Valley at c 12 m OD, 7 m OD near Montrose and apparently at 2-3 m OD in the Fraserburgh/Peterhead district. There is an anomaly however in the shorelines at 5-7 m OD reported from the Ythan estuary and from the Aberdeen district (Ritchie and Walton, 1972; Stove, 1978), which are higher than might be anticipated on the basis of a steady
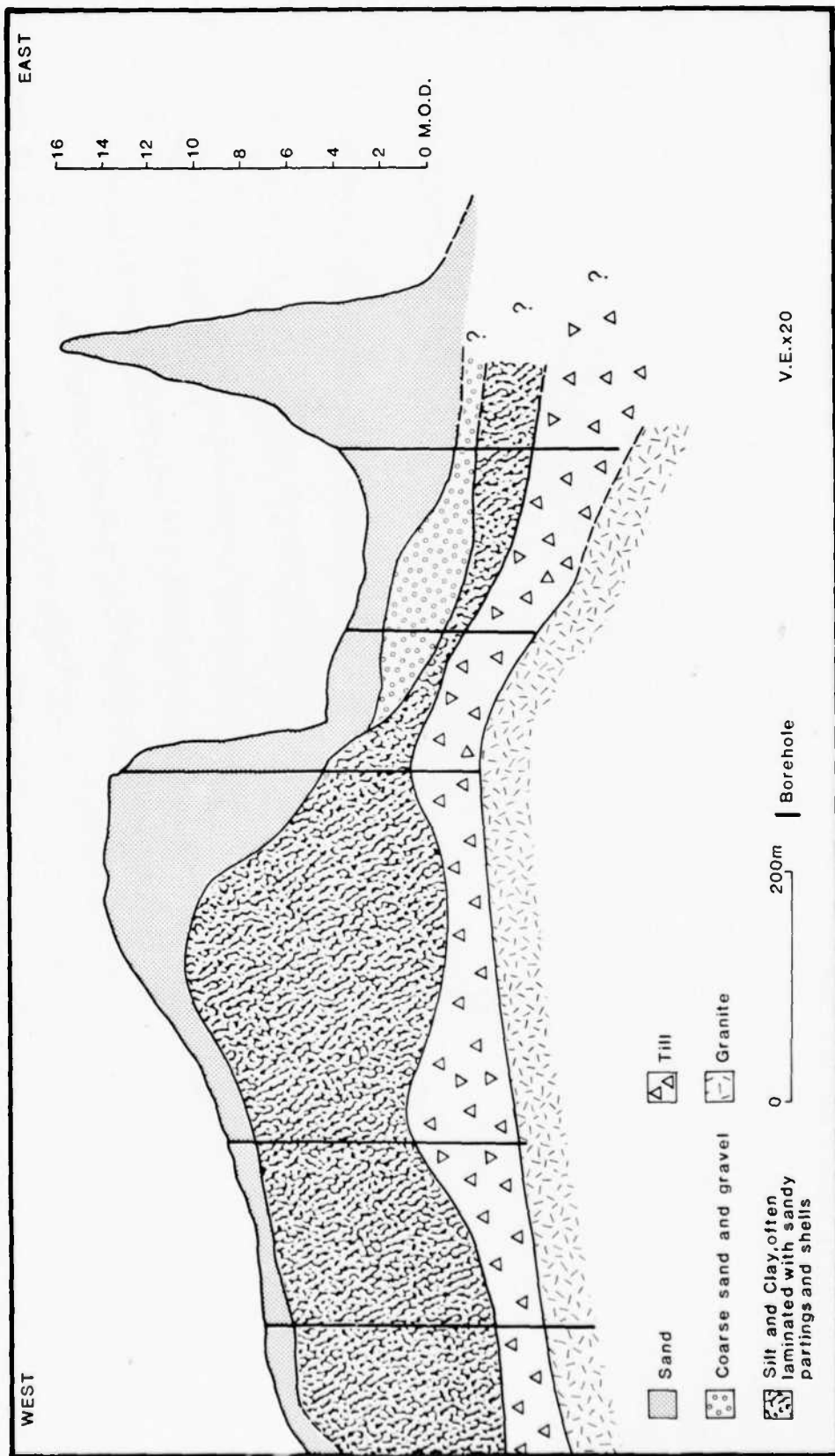
Figure 4   Stratigraphy related to sea level change at St. Fergus.

decline in shoreline altitude from the Forth Valley to Buchan. Either
there is a rather abrupt drop in the level of the shoreline somewhere
between the Ythan and Peterhead, or else the possibility has to be
admitted that the 5-7 m shoreline in the Aberdeen-Ythan area may not be
the Main Postglacial Shoreline. On balance, considering present evidence,
the latter seems the more likely explanation.

Evidence for Sea levels below Ordnance Datum

As discussed earlier, eustatic sea level has varied greatly throughout
the Quaternary, and may have lain between -110 m and -130 m as
recently as 15,000 BP. Under such circumstances, there should be some
evidence of low relative sea levels in north-east Scotland.

Organic remains have been found in several Quaternary formations in the
North Sea basin. Holmes (1977) records the presence of partially
lignitised wood within certain horizons underlying the North Sea, but
expresses doubts as to whether it is in situ. Sissons (1981) suggests
that the existence of a deltaic environment in the central North Sea at
a time when sea level was much lower than at present would account for
these and other organic remnants found in the area.

Peat and tree remains have been found in shallow waters just off the
present coast. Jamieson (1858) postulated the existence of a former
sea level lower than that of the present day on the basis of finds of
peat below sea level near Belhelvie, in Peterhead Bay, and in the Moray
Firth. Smith, Cullingford and Seymour (1982) suggest that prior to the
onset of the early Flandrian peat accumulation, sea level in the Philorth
Valley may have been as low as -1.37 m OD. At nearby St. Fergus, the presumed
Flandrian beach gravels rest on a surface cut into the raised blue clay
deposit (Fig. 4). This surface, interpreted as a wave-cut notch or
platform, has an altitude of c -2 m OD. Again, this can be regarded as an
approximate guide only, but supports the suggestion of an early Flandrian
sea level below OD.

There is good evidence for the existence in the region of valleys, now
buried, having been cut to levels well below present sea level. Synge
(1963) noted that the lower part of the valley of the Den Burn in Aberdeen
is infilled below 8 m OD with post-glacial estuarine deposits. He inter-
preted this as an indication that the valley continued beneath these
sediments, although no indication was given of the precise level to which
it was graded.

Examination of records of boreholes drilled in the vicinity of Bay of
Nigg confirms that a major channel, cut to a depth of at least - 30 m OD,
runs out to sea just north of the cliff section. Simpson (1948) suggested
that such a channel marked a former course of the River Dee.

A similar depth of channel has been discovered during seismic investi-
gations beneath the estuary of the River Ythan (Stove, 1978). In
both this and the Nigg situation, however, the possibility can not be
eliminated that what has been detected is a product of glacial over-
deepening rather than a reflection of a former sea level.

Problematic Evidence - the Basal Gravel from Bay of Nigg

Resting on bedrock at an altitude of 2 m - 5 m OD at the southern end of
the Bay of Nigg section is a bed of sand and gravel, the so-called Basal
Gravels. These sediments are roughly horizontally bedded though dis-
playing some flow structures suggesting derivation from inland (west).
The clasts are quite well rounded, and sometimes form lenses within the
sands. The Basal Gravels have been described by Synge (1963) as a beach
deposit, laid down at a time when sea level was close to its present
elevation. In contrast, Simpson (1948) considered them to be no more
than a layer of coarse sand and gravel, possibly derived from the till
deposits found to the west (inland). This conclusion was based on the
erratic content of the gravels, which was found to be broadly similar
to that of the till, save for the presence of an occasional erratic
Scandinavian origin (Bremner, 1931; Read et al., 1925) within the
gravels.

A recent re-examination of the Basal Gravels by the author tends to
reinforce Simpson's conclusions. Flow structures in the gravels are
commensurate with deposition from the west. Till clasts and armoured till
balls discovered within the Basal Gravels have a mineral composition very
similar to that of the overlying grey till (E. R. Connell, pers. comm.),
sufficiently so for them conceivably to have been derived from the same
source. It is concluded that the most likely origin of the gravels is
that they were deposited by fluvial or fluvioglacial agencies emanating
from the west, probably in front of the advancing margin of the ice body
which was to deposit the overlying till.

The Basal Gravels of the Bay of Nigg section are therefore not of marine
origin, and so can give little information about former sea level, save
that it was probably below 5 m OD at the time of their deposition.

Summary

Possible indicators of former sea levels have been described from a large
number of locations in north-east Scotland, and have been used to invoke
the former presence of a wide range of land/sea levels ranging from - 130
m OD to over 350 m OD. As has been demonstrated in this review, many of
the lines of evidence have been misinterpreted in the past, whilst other
sites provide inadequate proof of the existence of former sea levels.
Those lines of evidence which are acceptable proof of former sea levels
do not always allow those levels to be placed accurately within a chronology.
The most striking example of this is the abrasion platform developed at
or near present-day sea level and which may have formed in the course
of episodic erosion at a given elevation, rather than relating to a
single phase of landform development.

The relics of former sea levels which are regarded as acceptable evidence
of those levels fall naturally into two categories, erosional features
and depositional features. Erosional features include abrasion platforms
and cliff notches, found at various altitudes below 25 m OD. All that
can be said about the age of most of these is that they probably pre-date
the "Strathmore" glaciation.

The Basal Gravels at Bay of Nigg rest on a rock platform truncated to the
north by the buried valley cutting down to c - 30 m OD. The platform
must therefore pre-date the grey till which infills that channel. As
the grey till and the red "Strathmore" till are roughly contemporaneous,
the conclusion can be reached that low-level platforms are likely to

Plate 5   South shore of Loch of Strathbeg, near St. Fergus, with the
           fossil cliffline associated with the Flandrian shoreline
           deposits in the left foreground.

Plate 6   Low coast north of Rattray Head looking north towards the
           village of St. Combs. Here Flandrian coastal deposits are
           covered to some extent by coastal dunes.

predate the late-Devensian glacial episode.

Depositional shorelines record land/sea level fluctuations from the moment of deglaciation in the late-Devensian at which time a high relative sea level obtained. Isostatic uplift gradually raised the land and created sequences of raised beaches, well illustrated between Montrose and Stonehaven (Cullingford and Smith, 1980), or, as at St. Fergus, raised estuarine or lagoonal sediments. The likely pattern of sea level fluctuations since that time is exemplified in a sequence from St. Fergus (Fig. 4). Sea level dropped until it stood below its present level. During this fall the fossil cliff backing the Flandrian coastal sediments was cut. If Donner (1970) is correct, this minimum level should have been attained c 8800 BP. Subsequently sea level rose to levels of 2-7 m OD depending on location, reaching its maximum level c 6-7000 BP before dropping to the present level.

The extreme north-east of Scotland is highly marginal with respect to the main area of isostatic uplift. Smith, Cullingford and Seymour (1982) suggest that in the Philorth valley the present-day estuarine deposits mark the culmination of the Flandrian Transgression, a fact which can be related to the global eustatic rise of sea level being greater than the speed of the by now largely exhausted isostatic compensation in this region.

The fossil shorelines of north-east Scotland repay careful study, for they are the product of a most complex sequence of events. Within the region there is a transition from districts in which Flandrian deposits have been raised above sea level and preserved for all to see, to marginal areas in which the equivalent deposits are now buried beneath present-day accumulations. The north-east can truly be said to display a little of all the configurations of land/sea level changes in Scotland, a veritable museum of coastal evolutionary sequences.

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6.   RELATIONSHIPS BETWEEN ARCHAEOLOGICAL SITES AND

GEOMORPHOLOGY IN THE COASTAL ZONE OF NORTH-EAST SCOTLAND

In recent years, the use of archaeological data to provide at least a measure of chronological control in the study or coastal development and change has become well-established (Thompson, 1980). Clearly, such control is likely to be at its most delicate in areas where comparatively minor change is likely to have provoked a discernable human response: perhaps the classic European example of this phenomenon is to be seen in the construction and elaboration of the terp settlements in the areas marginal to the southern fringe of the North Sea as a response to the intermittent inundation of low-lying areas (Schmid, 1978, Louwe Kooijmans, 1980).

Opportunities for the kind of regional patterning of the archaeological record recognisable in the above case as a result of sequential transgressions are absent to a large extent from the archaeological database for North-East Scotland. Nevertheless, the sites of the coastal zone offer instances of a variety of types of interplay between geomorphological processes and previous human activity.

From the archaeological standpoint, the coastal zone may be considered to be of significance for two, distinctly different, reasons. These are first, site survival, and second, the contemporary resource base of the communities whose relict sites are recovered in these environments.

The primary consideration is undoubtedly the prosaic one of survival and detection. An archaeologist, viewing the present-day landscapes of North-East Scotland, would be inclined to divide them into zones of destruction and of survival (Stevenson, 1975). The former sectors are characterised by the more or less total destruction of archaeological monuments as surface features, and include much agricultural land as well as areas subsequently used for settlement and industry. The zones of survival, in contrast, as those which have witnessed much less human pressure and usually, although not invariably, exhibit much less 'change' in consequence. In this context, 'change' may be taken to represent that sub-set of human and environmental processes which are inimical to the survival and detection of archaeological sites.

In terms of the landforms of Grampian Region and adjacent areas, these zones of survival tend to occupy a comparatively narrow altitudinal band above the upper limit of present-day cultivation. In such areas, the vagaries of human choice, superimposed on questions of economic return, accessibility, changing technology, and other factors of that kind, as well as the potentially-discernable impacts of small-scale environmental changes, have played a major role in site formation and survival. Thus, in such parts of the landscape, traces of some past human activities can still be detected as surface features, although these may now be much reduced in scale.

Elsewhere, in the lowlands, patches of survival tend to be very restricted in extent and reflect either particular inhibiting factors, as for example in the case of the rugged land immediately bordering the middle course of the River Ythan (Shepherd and Ralston, 1981) or landowners' decisions - for example in the establishment of woodland shelter belts, which may contribute to the survival or archaeological monuments. Archaeological sites thus tend to survive on land which is perceived to

be 'marginal'.

The coastal zone conforms in part to this model, in offering 'zones of survival' in terms of recent land-use patterns, for example on some coastal promontories, now considered unsuitable for agriculture. Even here, however, the relationship is a dynamic one, and reclamation of coastal headlands for pasture may result in the attrition of the archaeological record: an example in the North-East is offered by Crathie Point, on the Banffshire coast, near Sandend.

However, the processes of geomorphology also give rise to other sets of circumstances in which archaeological traces may be preserved. Instances of both former marine caves and the extensive coastal strandplains are relevant to this part of the discussion. Examples of both will be considered in some detail infra. However, the dynamics of sand movement, which may provoke both the overwhelming of previous occupation surfaces (and hence their survival), as well as their subsequent exposure (thereby permitting archaeological examination) are perhaps the critical process in underscoring the importance of the coastal zone as of major archaeological significance in this part of Scotland. We may contrast the sheer scale of the emerged coastal strandplains as at Forvie, Strathbeg, and Culbin, with the submergence of equivalent areas further north in Scotland, near or beyond the zero-isobase.

Whilst it should be pointed out that coastal changes may contribute in other ways to the survival of archaeological material, either through subsequent submergence in periods of rising sea-level, or through the abandonment of sites which had been at least partly dependent on maritime factors through silting, there has been comparatively little exploitation of archaeology of this kind in Aberdeen's hinterland. In general, our area is perhaps less conducive to these varieties of research than other portions of maritime Scotland - more particularly in the estuarine carselands and in the firths of some of the major rivers, or along the machair coasts of some of the Hebridean islands. However, sites which have fallen into disuse as a result of coastal changes can certainly be recognised, and the abandoned medieval burgh of Rattray, near the Loch of Strathbeg, may be cited as an example. Elevated to Royal Burgh status in the middle of the sixteenth century, silting of the harbour provoked its demise within a century.

Archaeological site survival is, in sum, much conditioned by processes both human and natural in origin. Grossly to generalise, the cumulative effect of these is to favour the detection of stone-built monuments, and those which involved the quarrying of ditches, which have not silted up in the intervening period - human micro-geomorphology - on the upland moors. In the agricultural areas, stone-built structures again quantitatively dominate the record of upstanding monuments. For centuries, particularly in areas where agriculture has been hampered by a surfeit of surface stone, such monuments have simply not been worth removing, and we may surmise that the cumulative effect of this is that the surviving archaeology of these areas probably include a disproportionately large percentage of 'major' monuments, since minor ones are likely to have disappeared long ago into the miles of dry-stone dyking, which is a feature of many areas of the North-East, not to mention other types of construction.

In part, this imbalance in the agricultural areas may be rectified through aerial photography, particularly that undertaken in the summer months for cropmark sites - those showing as a result of localised stress in the crops during the growing season. The outcome of this kind of survey

tends to produce a bias contrary to that noted supra, in favour of sites the construction of which required either the digging of ditches or other disturbance of the sub-soil, for it is this very disturbance which provokes the differences in crop growth that are apparent from the air. Since, as a rule of thumb, most marks thus detectable which do not correspond simply to ditches for defence, delimitation or drainage, should indicate the former stances of upright timbers - ancient stone buildings rarely incorporate excavated foundations - it is possible to see how aerial photography offers a corrective to a view of the past conditioned largely by the examination of up-standing stone-built monuments. As will be mentioned subsequently, the bird's eye view also offers another interface with geomorphological research.

The key significance of the coastal zone in this regard is that it may conserve, comparatively accessibly, both stone-built structures and other more fragile traces, which in the majority of other environments previously discussed, would simply not have the opportunity to survive. Moreover, in areas of soft coastline, the effect of the deposition of a cover of blown sand over an archaeological site should be to preserve the structures and features much less selectively than in other circumstances. Further- more, old land surfaces incorporating archaeological remains, which have been overwhelmed by sand which has subsequently deflated, offer the possibility of the survival of a measure of vertical stratification in the enveloping deposits; thus offering scope for the discovery of the sequencing in the activities represented on site. It is however apparent that this need not necessarily be a straightforward task, as the winnowing of fine material may result in the marked enrichment of certain layers at the base of the series with heavier archaeological debris.

The second major aspect of the significance of the coastal zone for archaeological research derives from the relative environmental richness of that area in regional terms. In North-East Scotland, as in many other areas at comparable latitudes, this wealth has been of very considerable significance in the prehistoric settlement of the area. The fringe between land and sea offers a diversity of habitats for man, plants and animals: habitats which were all the more important in that, in eras when subsistence economies were much more prevalent, they offered a range of products which provided sustenance for both flora and fauna and hence for man himself through the leanest seasons of the year (Clarke, 1978, fig. 3). Since evidence from further south on the east coast of Scotland, particularly from Tentsmuir Sands near Saint Andrews, points to the settlement of that area by hunter-fisher-gatherers before 6,000 bc, (Coles, 1971) it is unlikely that the initial occupation of the North- East began much later than that.

For economies based on agriculture, which were ousting those that relied on the exploitation of the bounty of nature by 3,000 bc, the coastal zone must have remained a preferred habitat. Inferences in support of this assertion include the presence in some areas of lighter soils, easier to cultivate with the then-available technologies, the reliance of early farmers on exotic crops, brought from climatically more-favoured areas, and the suggestion that the post-glacial forest cover may have been less densely established in some coastal sectors.

Thus, in contrast to the upland zones of survival, which we may consider to have been marginal to a lesser or greater extent for agriculture even during periods when environmental circumstances were more favourable than present-day conditions, and to the present-day agricultural areas, with their generally more degraded monuments, the coastal zone - owing to the

complex interplay of past human activity and geomorphological change –
offers a suite of environments in which very remarkable preservation may
occur. The scale of the survival of archaeological features is at least
partially correlated with the magnitude of some kinds of geomorphological
processes, whereas, coversely, man-made features may contribute, albeit
on a much smaller scale, to the preservation of geomorphological units
which are otherwise either destroyed or inaccessible.

The geomorphological dimension – beyond that of chronological control
mentioned at the outset – arises when man, acting as a geomorphological
agent through his earthmoving activities, inadvertently protects or
seals deposits which may otherwise not survive. Conversely human
activity may contribute to accelerated geomorphological change, for
example through the processes of erosion. In this regard, an indication
of both the scale and the duration of past human activity may be of help
to the Quaternary geomorphologist.

In general, the archaeology of North-East Scotland has been less system-
atically exploited this century than that of certain other areas of the
British Isles, and to this rule the coastal zone is no exception. The
remainder of this paper will concentrate on providing evidence from
individual sites which have been the subject of at least partial
investigation, rather than attempting to give an overall view of the
survival or patterning of archaeological sites along the coast-line,
and their relationships with its varied geomorphology. An initial list
(Ralston and Shepherd, 1978) confirms that the majority of well-known
sites, recognised by structural, rather than artefactual remains, are
stone-built monuments on areas of rocky coastline. This is, however,
probably no more than an indication of the amount of prospection that
remains to be done. Whilst it is certainly premature to talk in terms
of the extraction of a general model of the relationships between
archaeological sites and their geomorphological settings on the basis
of the data presented here, it is to be hoped that some of the recurring
associations may be of assistance in detecting sites in other less fully
prospected sectors of the coastline of North-East Scotland, without
precluding the possibility of other kinds of sites, and other types of
setting, subsequently being discovered.

Areas of hard coastline

Numerically the most important group of sites to have been recognised in
these environments is a series of defended enclosures which profit from
the presence of either active or fossil marine cliffs to minimise the
extent to which man-made fortification was required. These are referred
to in the archaeological literature as 'promontory forts' and are
recognisable in the field through the presence of a bank-and-ditch, or
a wall – both of which features may be multiply present – drawn across
the landward margin of the site (Lamb, 1980). Of the North-East Scottish
examples which have been the subject of archaeological excavation, the
majority have provided evidence of extended periods of use (Ralston,
1980). Their floruit, not necessarily uninterrupted, appears to have
spanned the first millennia BC and AD: some show more recent use, often
in the form of medieval castles. Perhaps the classic, and certainly the
largest, examples in our area are the promontory of Burghead, discussed
below, and Dunnottar Castle on the coast of Kincardine, now occupied by
an impressive medieval stronghold (Simpson, 1968), but, accepting the
evidence of Dark Age annals, likely to have been the site of an
important fortification in more immediately post-Roman times (Alcock,
1981). It is however the smaller sites which have produced the best

evidence of longevity of use: Castle Point, Troup, near Pennan, with a variety of uses spanning the period from the middle of the first millennium bc (if not earlier) almost to the present-day, is perhaps the key site in this regard (Greig, 1970, 1971, 1972).

From the viewpoint of the geomorphologist, the potential significance of such sites is perhaps to be considered in terms of two by-products of the construction of man-made elements on them. The first of these is concerned with continuing rates of erosion and is, on presently available evidence, a potential rather than an actual source of data. Evidence from a number of these sites points to continuing coastal erosion having removed their seaward margins since their initial period of use. We may suggest that the exigencies of using such exposed locations for settlement, as was certainly the case at both Castle Point, and the Green Castle, Portknockie, indicates that some form of boundary - fence, wall, or whatever - must have been constructed on the seaward side of such sites. Recovery of the position, and an indication of the direction in which such a feature was oriented, might contribute to an indication of the scale of cliff retreat: however, to date, such features have not been recovered, although the wall at the seaward end of Burghead, discussed below, is unlikely to have been unique.

The second factor is of more general significance. The construction and subsequent decay of these monuments offers scope, sometimes inadvertently, for the preservation of environmental data which should be of assistance in the reconstruction of the coastal vegetation which was contemporary with these episodes in the utilisation or abandonment of these sites. However, it is evident that the interpretation of such data - since it potentially incorporates materials brought in by the early inhabitants from outwith the coastal zone, is perhaps less than straightforward. The archaeological record can provide surprising instances of the nature of man's use of the coastal zone, which give rise to the possibility that he may have played a more considerable role in shaping coastal modifications at an earlier date than is perhaps usually surmised.

As an isolated example of this, we may point to the evidence of cultivation, in the form of ardmarks cut into the upper surface of the aeolian sand, predating the construction of the defensive wall on the coastal promontory at Portknockie (D & ES, 1976-82). Stratigraphically, this evidence is unambiguous. If such a small area - the usable upper surface of this promontory (at about 23 m OD) measures 70 m by 15 m - had been pressed into cultivation in the early centuries AD, might it not be all the more likely that substantial portions of the coastal edge were in similar use at that time? And, given that the indications are that early cultivation methods were relatively inefficient and liable to provoke erosion, how significant might such activities have been in contributing to coastal change for at least the last two millennia?

The site of Burghead (ill 1) is probably the most informative of the coastal promontories as our evidence stands at present. The subject of intermittent archaeological excavation since the 1860s, and substantially destroyed by the construction of the fishing village and harbour of Burghead during the Victorian hey-day of that industry, the site has been described as a 'Pandora's box' by Small (1969).

The surviving remnant of the fort is dominated by portions of an enveloping defensive wall, now reduced to an irregularly preserved rampart. Unusually, as noted above, this occurs at the seaward end of the site, as well as edging the upper portion of the promontory and

the Lower Fort, on its NE margin, at about 8 m OD. Much of the interior of the latter part of the site has been artificially lowered, thereby probably destroying much of the occupation evidence, and the landward end of the site - once marked by an elaborate series of defences - has been built over.

Whilst we are fortunate to have an XVIIIth century plan of the site, prepared for General Roy (1793; reproduced by Small, 1969) which provides us with an indication of its configuration prior to the depredations attendant on the construction of the village, the archaeological evidence is inadequate for any attempt to obtain an impression of the rate of erosion of the sandstone and conglomerate cliffs at the seaward end. Contrastingly, in this portion of the site, continuing erosion recently permitted the re-examination of a brief suite of environmentally significant layers. These had previously been recorded by the various excavators of the site's defences, and had been noted stratigraphically to underlie these. They were recovered amongst tumble from the wall and cliff-fall materials (Edwards and Ralston, 1978).

Available radiocarbon dates indicate the construction, and perhaps also the refurbishment, of this wall in the first millennium ad, so that material stratified below it should be securely datable at latest to the initial centuries of that millennium. Two organic horizons predating the construction of the wall have been recorded. Established on sand, they are also separated by a thin layer of the same material. The upper organic horizon has produced a single radiocarbon date of 1690 +/- 40 bp (UB-2208), statistically indistinguishable from two dates obtained by Small for the construction of the wall.

Both organic horizons incorporate an admixture of sand and particulate charcoal, suggesting clearance of an already sand-covered site prior to the construction of the fort.

The pollen record from these two organic bands suggests an alteration in the environment during their accumulation. The pollen spectra from the lower band, considered in conjunction with the grey sand and iron pan which underlies this layer, suggests the former presence of an acid peaty soil which originally carried a dry-heath flora. The small percentage of woodland species represented, dominated by Corylus/Myrica, cannot safely be attributed to the site as long distance transport is distinctly possible. This horizon lacks an absolute date.

Contrastingly, the upper organic horizon, statistically contemporary with the building of the defensive wall in terms of the available radiocarbon dates, although clearly preceding this event stratigraphically, suggests rather different environmental conditions. The pollen record is dominated by grasses and Liguliflorae, suggesting less acidic conditions prevailing on site. This environmental change may be attributed to the arrival of fresh wind-blown sand, perhaps from a dune system or other sand source which had not suffered severe leaching (Edwards and Ralston, 1978). In any case, the evidence is eloquent of blown sand being deposited on the promontory in the early centuries ad. In contrast to Portknockie, there appears to be no direct evidence, either in the pollen record or from the archaeological work, of cultivation of the Burghead headland at this early stage.

Clearly, further work on old soil surfaces sealed by such archaeological monuments may be of considerable assistance in providing evidence of habitat and other environmental changes in the coastal zone. Unfortunately,

ill 1 : Promontory fort at Burghead, showing eroding New Red Sandstone
cliffs: in the background are the afforested Culbin Sands.
[photo : Aberdeen Archaeological Surveys, Crown Copyright Reserved].
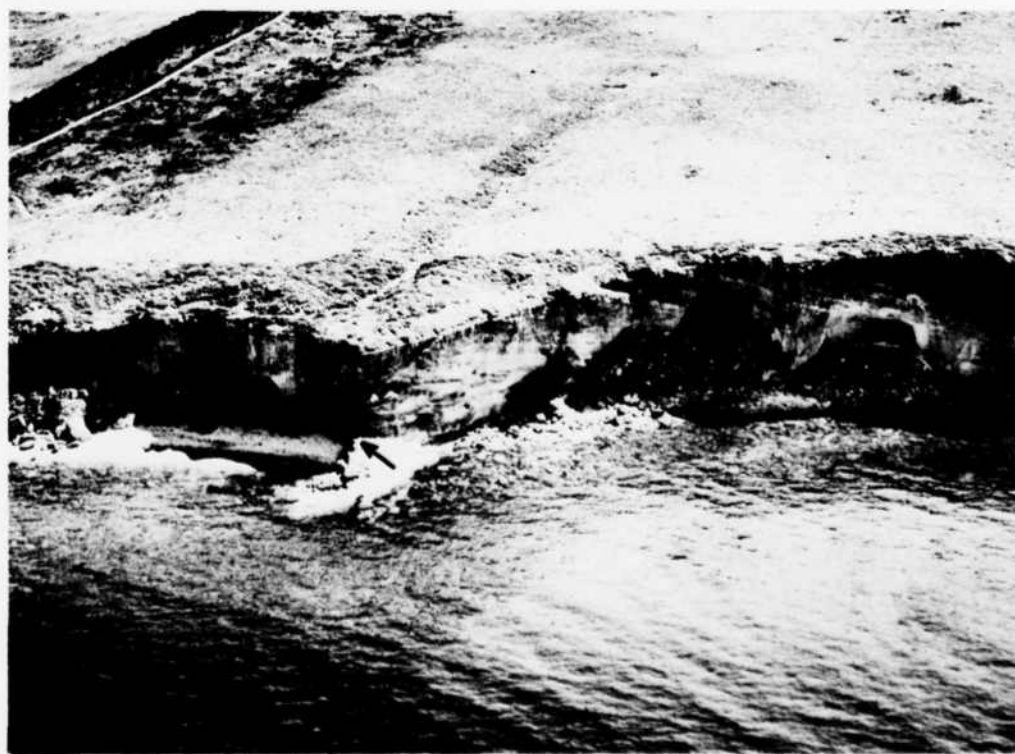
ill 2 : Sandstone cliffs at Covesea, Moray, showing caves related to
higher sea levels and recent cliff-fall material. The Sculptor's Cave is
arrowed.
[photo : Aberdeen Archaeological Surveys, Crown Copyright Reserved].

they are not always present, as the preparation of a level surface for construction may eliminate them.

In contrast to the comparatively long tradition of the examination of the coastal promontories of the North-East, the former use of caves for settlement and other purposes has only been systematically established for one site, the Sculptor's Cave at Covesea, again on the Moray Firth coast, (Benton, 1930: D & ES, 1979, 14) although other sites in its immediate vicinity have been noted to contain at least a small quantity of archaeological material (D & ES, 1969, 34). Cave sediments, whether human or geomorphological in origin, are perhaps rather a specialist field, marginal to our main concerns and governed by more local circumstances, but some account of the evidence from the Sculptor's Cave is appropriate.

The Sculptor's Cave (ill 2) is one of a series cut into the soft greyish-yellow sandstone cliffs to the east of Hopeman. Most appear to be related to sea-levels a little higher than at present. The cave is only accessible at low tide: otherwise entry can only be gained by climbing down the cliff. The Sculptor's Cave - the name is derived from the Pictish and later carvings incised into its walls - is distinguished by possessing two entrance passages, which give access to a substantial chamber. The overall length of the cave from the mouth to the back of the chamber is about 27 m by a maximum of 12 m wide (plan in Benton, 1930-1, 179).

Although carvings were noted in the cave in the nineteenth century, the recognition of archaeological deposits on the floor of the cave did not follow until Miss Benton began work at the site. Her excavations in the late 1920s were followed by a second series on behalf of the Scottish Development Department in 1979.

The lowermost stratification examined consisted of a raised beach deposit, located inside both entrances of the cave. The upper surface of this, at its interface with a suite of clay deposits, was marked by the presence of a few bird bones and some fragments of charcoal, considered by the recent excavators potentially to betoken very early human occupation on the beach outside the cave. The sand and clay laminae which overlay the raised beach deposit appear to have preceded all other recognisable human use of the cave. Up to 1.3 m in thickness, these layers have been attributed to ponding within the cave, and presumably represent at least in part, material eroded from its walls. In addition, the apparent longevity of this process suggests the presence of a shingle bar or other obstruction at the mouth of the cave which prevented the egress of water.

In the eastern entrance, the baulk left by Miss Benton was found to contain a basal archaeological layer, incorporating human and animal bones, marine mollusca, charcoal spreads and artefactual debris attributable to the Late Bronze Age - around 700 BC. This layer was stratified below a further band of clayey material, about 15 cm thick, which in turn was sealed by lenses of sand and midden deposit. Towards the mouth of the entrance, glacial till had been redeposited over these layers by human agency, apparently in an effort to raise the level of the floor of the entrance passage. Although varying in detail, the stratigraphic sequence within the western entrance consisted in the main of similar elements, suggesting that the stratification had been built up through both natural and anthropic processes.

In general the archaeological evidence is indicative of use of the cave
during the Late Bronze Age and in the third and fourth centuries AD: the
Pictish and other carvings suggest recourse to the cave at a later date.
Unfortunately, the comparative paucity of more recent artefactual material,
combined with disturbance to the stratification means that a direct
archaeological contribution to the elucidation of the cave environment
in more recent times is not feasible. It is to be hoped that the
possible earliest occupation may be fixed by radiocarbon dating.

Areas of soft coastline

Whilst it would be possible to consider the recovery of geomorphological
information from archaeological sites in areas of hard coastline almost
as an accidental by-product of the archaeological investigation of sites –
although they may offer the geomorphologist the opportunity to examine
in plan what he may normally only see in section – the relationship
between the two subject areas is much more intimately connected in areas
of soft coastline. The Sands of Forvie, at the estuary of the Ythan, offer
a clear example of this inter-relationship. Indeed, the factor of
geomorphological change has made this area, along with many others on
the Scottish coastline from Luce Sands in the South West to Freswick
Links in Caithness, the subject of repeated antiquarian and archaeological
interest since the XIXth century. Whilst most recent work has been done
on the Atlantic and Northern coasts and islands of Scotland (papers in
Burgess and Miket, 1976: Crawford, 1978: Crawford and Switsur, 1977:
Mercer, J, 1979: Ritchie, 1979: Evans, 1979: Mercer, R, 1981:
Shepherd, 1980), a certain amount of attention has been devoted to the
east coast from Caithness south (Batey, 1982).

Forvie's only rival in the North-East as a storehouse of archaeological
information on the coastal zone is Culbin Sands on the Moray Firth coast,
but the stabilisation of this latter area by afforestation (ill 1) means
that the detection and examination of features in this extensive area is
now hampered by the established conifers (Coles and Taylor, 1970).
Fragments of the same kinds of systems to be discussed in relation to
Forvie have been noted elsewhere amongst the dune systems fringing
Aberdeen Bay, but have not been the subject of long-term study. It should
be made clear however that, despite the apparent richness of the archae-
ological environment of Forvie, this dune system is unlikely to be unique
on the eastern seaboard of our area.

The best summary account of the archaeology of Forvie as revealed up
to and including the post-war years is that of Kirk (1953). This
details some of the work then in progress. More recent examination of
the area recommenced in 1976, and revealed the extent to which the
visible archaeology of Forvie has changed since the mid-1950s. Areas
which at that stage were in an advanced stage of deflation have now
been in part vegetated, in part recovered by dunes, whereas other sectors
have blown clear in the intervening period.

For ease of presentation, the archaeological evidence from this
extensive area of sand-dunes and related features may be presented as
four separate components. All are of different date, and all, as they
are presently visible, are fragments of more extensive systems.

(a)   Forvie church and the medieval village of Forvie: these features
are located on the W side of the present-day fringe of dunes at the
back of the beach, on the NE side of Oldkirk burn. Only the church,

cleared of sand, is presently visible, though a row of buildings edging
the break-of-slope above the burn also appears to have been examined
by Kirk (D & ES, 1955, 1957, 1960). These monuments should represent
the remains of the village of Forvie, perhaps established with the church
in the XIIth century, but deserted in favour of Newburgh, in the face
of encroaching sand, apparently in the fifteenth century (Kirk, 1953,
151). Possibilities of earlier, later prehistoric, occupation of this
area (D & ES, 1955, 4) do not seem to have been substantiated by later
work (D & ES, 1960, 2).

(b)   Areas of prehistoric occupation, comprising burial monuments,
settlement sites, flint scatters, and traces of agricultural plots.
These have been identified in a number of localities within the dune
system, as a result of blow-outs. These areas, all located to the south
of the Waterside-Rockend track, are presently the most subject to change,
and will be discussed in detail below. Two areas have been the subject
of excavations this century.

(c)   A series of shell-middens, located on raised beach deposits flank-
ing the Ythan estuary on its E side, opposite Udny Links. These are now
largely grass-covered, although one is being eroded on its seaward edge.
Examination here, and in rabbit-burrows and the scrapings made by nesting
fulmars elsewhere, suggests that tne principal visible components of these
middens are mussel shells and fragments of shattered stone. However,
detailed examination of comparable middens elsewhere, revealing the
presence of, for example, quantities of fish bone (Mellars, 1978a)
suggests that such superficial impressions are likely to give inaccurate
assessments of the food debris incorporated in the middens. These middens
at Forvie are most likely to date to the late mesolithic period, at the
earliest, and some may be considerably more recent, given the historically-
documented collection of shellfish from this area until the XIXth century.
The middens appear in the main to post-date the most recent marine trans-
gression locally, although Kirk noted that at least some of the midden
material appears to be interstratified with raised beach deposits (D &
ES, 1955, 2). Nineteenth century records note the recovery of iron, as
well as stone tools, bone, and charcoal from a cutting in a midden, so
that there remains the possibility of using these features in the closer
dating of minor marine fluctuations in the estuary of the Ythan. These
features are located between about 2 and 7 m OD.

(d)   Areas of rig-and-furrow cultivation, restricted to the sector N of
the Waterside - Rockend path, and illustrating the continued process of
agricultural retreat in the face of northward-moving sand. The principal
areas of rig-and-furrow have been mapped by Wright and Ritchie (1975).
Many of these are visible on tne ground, as the plateau of North Forvie
lacks the overall cover of deep sand which prevails further south.
Some of these areas may have been those on which abatements of rents
were granted in 1759 (Kirk, 1953, 152): interestingly, neither of the
maps prepared by General Roy or by Robertson (1822) show rig in this
area, although that can not be taken as conclusive evidence for its
abandonment by the early nineteenth century. Detailed examination of
the configuration of the rigs might indicate something of their period
of use.

Whilst all these areas have potential for elucidating and dating the
extension of the dune system of Forvie, or for dating sea-level changes,
recent work has been focussed exclusively on the areas referred to supra
as '(b)'. These are presently the areas of most dynamic change, to
the extent that members of the archaeological team who worked on the

area in the 1950s were disorientated by the degree of change when revisiting the area in 1980.

Evidence of previous human occupation has been recovered from the interior of South Forvie since the middle of last century, only however in areas where deflation has revealed the underlying old ground surface. At this level, traces of stone-built structures, midden deposits, and scatters of artefactual debris (usually dominated by imported flint) have been recovered. The two principal blow-outs which have been examined since the last war lie on either side of a transversal dune ridge, now much reduced, in the central portion of the present National Nature Reserve. The area is conveniently located in Fig 5.14.2 of Ritchie et al, 1978. For convenience, the southern portion, examined by Kirk, will be referred to as Area I, and the northern, examined by the present author, as Area II.

The features identified in Area I occur in the main on a raised beach deposit at about 55 ft (c 19 m) OD (Kirk, 1953, 55-6). In all, some 17 circular stone-walled structures were mapped in this area (D & ES, 1960) spread out along about 300 m, and various other features, including middens, were identified. Various of the features were excavated (D & ES, 1955-60; and Kirk, 1953, 158 ff). In sum, this work suggests occupation of Area I from the Late Neolithic/Early Bronze Age – although this date can only be arrived at typologically – until the early centuries AD. Oak timber from the post-hole of one stone-built structure has produced a C14 date of c 652 bc (Q-761), and it is possible that this represents the main settlement period, with typologically-later artefacts being subsequently deposited on this horizon through the winnowing action of the wind removing an upper undulating vegetated surface, which seems initially to have masked the stone features and the middens, but which had been substantially eroded by the early 1950s (Kirk, 1953, 156). Subsequent surface finds from this area include a bronze Romano-British brooch.

Area II, at the time of writing the subject of continuing erosion, is centered about 200 m N of Area I: the collapse of the dune on the eastern margin of the site to reveal a substantial arc of stones indicates that the site extends eastwards from the 3500 sq m considered here. It shares with area I the characteristics of a surface scatter of flint debris, and the presence of stone-built monuments, first noted during deflation in the mid-1960s, but lacks any surface indications of midden.

Area II appears to consist of an enlarged cauldron blow-out, which has deflated as far as a thin soil horizon developed on the underlying red till, which tilts gently westward from a maximum altitude of about 24 m OD. Geomorphologically, there is little exceptional in the configuration of this site: it consists of a rounded glacial, possibly rock-cored ridge, on which sand had subsequently accumulated (ill 3).

Two elements of the site appear worthy of especial consideration from the geomorphological point of view. First, the spread of stones over the deflation surface to the west of the cairns was noted to consist of a curious admixture of bare areas and others, including the convex slope at the western margin of the site, on which a variety of stones has accumulated. Their occurrence on the surface might be presumed to be the result of some winnowing or washing process whereby the finer materials have been removed – and sheet flooding was observed over this surface, during the course of the excavation – but excavation confirms that at least part of this pattern is to be attributed to human endeavour.
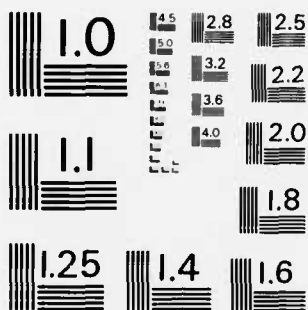
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

ill 3 : Excavations in an area of deflation on the Sands of Forvie :
examination of a Bronze Age cairn and sampling of the adjacent old land
surface.
[photo : Aberdeen Archaeological Surveys, Crown Coryright Reserved].

ill 4 : Sands of Forvie, Aberdeenshire : sample excavation of ard-marked
surface. The marks appear lighter than the midden surface (foreground),
but darker than the sand. Scale 6x5cm.
[photo : Ian Ralston, Crown Copyright Reserved].

Examination of a sample of metre-square excavation areas illustrates that
those in the 'bare areas' frequently exhibited the traces of ard-marking -
the scratches formed by a primitive form of plough - whereas those in the
vicinity of the stone scatters normally showed no signs of previous
cultivation in the upper surface of the subjacent till. At a restricted
number of points, the identification of pebble and beaten-earth floors
offered confirmation that some of these scatters of stones appeared to
represent structures in the final stages of attrition - structures which
would stand little chance of survival or recognition in other environments.

The immediate vicinity of one of the burial cairns at the eastern margin
of the site was examined in rather more detail. This indicated that,
contrary to the indications at the outset, this monument, built of sub-
stantial glacial erratics presumably gathered locally, was not set into
the underlying till, but was rather established on a pre-existing midden,
which occupied a hollow in the upper surface of the till. This midden,
since its formation must pre-date the construction of the cairn, probably
in the centuries around 1,000 BC (radiocarbon confirmation is awaited),
is of considerable significance.

The limited sampling that has been possible in this midden, a major
component of which consists of organically-stained sand, suggests that
it incorporates a considerable series of episodes in its build-up.
These may be enumerated briefly. Initially, features appear to have been
dug into the subjacent red till: thereafter traces of both stone-built
structures and an episode or episodes of ploughing are indicated during
its accumulation. All the evidence points to the continued use of the
site over a number of centuries prior to the construction of the kerb-cairn
and at a period when sand was already being blown on to the site. Although
wet-sieving failed to produce indications, in the form of carbonised
grains, of the crops which were being grown, it appears likely that this
area was less acidic than it is presently. The most obvious evidence for
sand in this area by the second millennium BC (Ritchie et al, 1978, 196)
is offered by the illustration of ard-marks cut through the periphery
of the midden and adjacent sand (ill 4), combined with the evidence for
other episodes of ploughing, stratified below the cairn for example. The
evidence recorded archaeologically here offers one indication of the
continuing human use of this area in the face of sand accumulation, and
suggests that its overwhelming was not altogether sudden.

At the beginning of the excavation in 1977, traces of a later standstill
phase could be seen in the form of a vegetated surface, dominated by
burnt heather roots, which appears to have covered the cairns. The
antiquity of this upper horizon may not be very great: whilst Area II
was apparently enveloped in about 10 m of sand in the 1950s, it appears
possible that some stone-robbing from the cairn may have been the result
of Victorian interest. However, in the absence of clear stratigraphic
indications, these more recent alterations can only be speculative.
However, the evidence from Area II seems incontrovertibly to suggest
that sand was present in later prehistory. The date of the final
abandonment of this site is difficult to establish: the early centuries
AD may be advanced on the basis of a rotary quernstone found as a
surface find, but again this may have been redeposited from a higher
level.   ⁓

Whilst we have concentrated here on Forvie, other sites, more summarily
known, may yield similar sequences. Menie and Foveran are examples.

Aerial Photography

As a final example of the inter-relationship between archaeological sites
and geomorphological features, we may consider an area from a little
further S, on the margins of the Lunan Bay in the N part of Angus
district. Here, we are firmly in the zone of destruction (ill 5),
with an absence of sites - apart from the masonry fortification known
as the Red Castle - known as surface monuments. However, the free-
draining raised beach deposits which occupy the landward margin of the
present coastal zone, now extensively used as cereal-growing arable,
are one of the most-favoured areas for the development of archaeological
cropmarks in Scotland (RCAHMS, 1978).

In some cases, as in this illustration of the fields to the NE of Red
Castle Farm, it is comparatively straightforward to distinguish between
the broad and sinuous marks of geomorphological origin and the bulk of
the rather more recessive marks that can be attributed to archaeological
sites, but in other cases the division between 'man' and 'not-man' is
much less clear-cut. An instance of this overlap is offered by patterned
ground, resulting from ice-wedge cast networks, noted for example in low-
lying arable ground on the northern margin of the Montrose Basin during
archaeological air photography (Gemmell and Ralston, forthcoming). In
some cases, it is difficult to distinguish between the traces of such
systems formed in periglacial conditions and those of the ditched
boundaries of early field systems.

Thus, even in a comparatively understudied area such as North-East
Scotland undoubtedly is from the archaeological point of view, the inter-
relationships between archaeological sites and geomorphology can be seen
to embrace a number of different aspects. These include the mutual
preservation and detection of sites or deposits of interest, for
archaeology more especially by the processes of sand movement, for
geomorphology through the recognition of potentially-significant relict
deposits on archaeological sites. Cropmark aerial photography represents
a particular case where features of interest to both disciplines are
liable to appear under similar conditions, although this is by no means
restricted to the coastal zone.

Furthermore, archaeology has the potential to provide markers, both
chronological and environmental, at least for the last eight or so
millennia, which may be of interest to the Quaternary geomorphologist.
In addition, recognition of the scale of previous human impacts by
archaeology stresses the degree to which many parts of the coastal
zone have been subjected to long-term human pressures. In the final
analysis, too, much of the field stage of archaeology, and perhaps
particularly of excavation, consists in essence of 'human geomorphology',
of distinguishing between the effects of man and his constructions and
those of geomorphological processes in shaping small-scale landscape
features. The actual processes of digging and recording an archaeological
site, perhaps particularly in the coastal zone, have little to do with
history, but much with geomorphology.

ill 5 : Cropmarks of archaeological and geomorphological origin in raised
beach deposits, Lunan Bay, Angus.
[photo : Aberdeen Archaeological Surveys, Crown Copyright Reserved].

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ACKNOWLEDGEMENTS

7.   <u>ASPECTS OF COASTAL TERRAIN AND ESTUARINE</u>

<u>HYDROGRAPHY IN NORTH-EAST SCOTLAND</u>

<u>INTERPRETED FROM SEQUENTIAL LANDSAT DATA</u>

<u>Background</u>

In July, 1972, the first experimental land applications satellite (LANDSAT) of
the US National Aeronautics and Space Administration (NASA) was launched. The
orbital altitude was about 915 km and the orbit was near-circumpolar and sun-
synchronous, passing over the same ground area every 18 days at about 10.30 am
local time. Further satellites, with similar orbital characteristics, were
launched in 1975 (LANDSAT 2), 1978 (LANDSAT 3) and 1982 (LANDSAT 4). In each
case the principal sensor on board was a multispectral scanner system (MSS),
sensitive to reflectances from the earth's surface in the following wavebands
of the electromagnetic spectrum:

> Band 4, 500-600 nm (green visible)
> Band 5, 600-700 nm (red visible)
> Band 6, 700-800 nm (reflected infrared)
> Band 7, 800-1100 nm (reflected infrared)

The ground reflectance values received at the satellite are transmitted to a
ground receiving station where they are recorded in analogue form on magnetic
tape. The smallest ground area which records as a separate reflectance value
on the signal tape is determined by the instantaneous-field-of-view (IFOV) of
the satellite and for the standard LANDSAT MSS this is about 79 m square.
LANDSAT 4 has an additional MSS, the Thematic Mapper (TM), which operates in 7
bands of the visible and infrared parts of the spectrum with an IFOV of about
30 m. However, TM data is not yet available for this study area.

The magnetic tape of the analogue signal is processed to produce a digital
computer compatible tape (CCT) and also a master negative from which photo-
graphic products of the MSS spectral bands can be produced. The CCT has the
advantages of retaining the detailed information for every 79 m ground cell
and of being amenable to rapid and varied manipulation on a digital image
analysis system. The signal data for each ground resolution element (or IFOV)
can also be displayed as a separate picture element (pixel) on the image
display.

Products (both optical and digital) from the LANDSAT experimental satellites
are available in this country from the UK National Remote Sensing Centre (NRSC)
at the Royal Aircraft Establishment, Farnborough. Facilities for the analysis of
LANDSAT data are also available to users including advanced digital image
analysis systems, such as the Plessey IDP 3000 and the GEMS system (which was
used on this project).

Note: This paper should be read along with Plates 1 and 2 which are inserted
        in the pocket inside the back cover.

Introduction

The Ythan estuary is some 20 km north of the city of Aberdeen on the northern limit of the larger scale feature of Aberdeen Bay. The estuary is the largest natural inlet between Montrose basin, 80 km to the south, and the Moray Firth, 150 km to the north and west. This fact established the estuary as a significant element in the development of a prosperous local economy in the days when sea transport was relatively more important than it is today (Walton, 1966). Tidal influence extends up river as far as Ellon, about 10 km from the mouth and the considerable width of the estuary, especially at high tide when it extends to almost 700 m at its widest point, was conducive to the early development of maritime trade, although a hazardous sand.bar close to the river mouth necessitated the use of a local pilot to negotiate a safe passage into the estuary.

Between the estuary and the sea lies a triangular shaped peninsula, the Sands of Forvie, and along the seaward edge, at about 3 km north of the river mouth, the soft, sandy coastline which commences at Aberdeen gives way to a cliff coastline of mainly metamorphic rocks.

Ritchie and Walton (1972) identify three geomorphological problems associated with the Forvie peninsula:

      (i)   glaciation and de-glaciation,
     (ii)   late- and post-glacial sea levels, and
   (iii)   the spread of coastal sand landwards in the form of
                dune arcs and sandhills.

Evidence for (i) and (ii) is rather subtle and requires detailed ground inspection to unravel. However, (iii) is still happening today under present processes and it may be possible to monitor by remote sensing methods.

Since the last glaciation it is believed that blown sand accumulated on the emergent beach and shingle surfaces of the seaward edge of Forvie. Under wind action, dunes and sand hills have migrated inland, generally from south-east to north-west. Influenced by the underlying pre-sand topography, South Forvie developed into a series of deflation plains and arcuate sand hills, with many individual parabolic and V-shaped blowouts. From south to north 8 major deflation surfaces have been identified with associated re-depositional sand hills and retreating windward escarpments of bare sand (Ritchie and Walton, 1972). On North Forvie the dune systems are essentially stabilised by vegetation (Fig. 1) whereas on South Forvie the systems are still relatively mobile.

The Ythan estuary and Forvie Sands together form a National Nature Reserve. This status was first established in 1959 when Forvie was leased by the Nature Conservancy Council from the local Slains estate. Scientific interest in the estuary and the sands, and in the wildlife which inhabit them, is long established. Researchers from Aberdeen University have been studying eiders, shell duck and terns, in some cases for more than twenty years. Research has also been carried out on various aspects of vegetation, landforms and the hydrodynamics of the estuary and river mouth (Wright and Ritchie, 1975; Stove, 1978 and Weatherill, 1980). It was the existence of this vast fund of knowledge and expertise, including a series of large scale maps of topography, landforms and vegetation which prompted the selection of this area as being suitable for an experiment involving multi-temporal LANDSAT image analysis.

Image processing experiments conducted at RAE Farnborough

At the UK National Remote Sensing Centre an archive exists of all the best LANDSAT scenes acquired over each path and row in the UK since the launch of the first NASA Earth resource satellite, LANDSAT 1, on 22nd July, 1972. Considering the research interests in Aberdeen with reference to the Ythan Estuary and the Sands of Forvie, a library search was initiated for all the best images of this area, together with ancillary terrain, hydrographic and hydrological data. The results of this search revealed that the best historical images of this area held at the National Centre in digital form included scenes of 11th March, 1973 (Plate 1a), 4th July, 1977 (Plate 2a), and 12th July, 1979 (Plate 2b). In addition to the above scenes, four further images of the area were acquired during 1982 as part of the AGRISPINE programme, an experiment in the rapid dissemination of remotely sensed data for time-dependent applications. Those images included scenes of 24th April, 12th May, 30th May and 3rd October, 1982, respectively. The first three of the AGRISPINE scenes are unique in that they represent the first case of three consecutive images acquired during this experiment in 1982 with cloud-free conditions. Plate 1b is a composite of a single band (Band 7) from the three consecutive dates, illustrating temporal change by colour tones.

(The objectives of the AGRISPINE experiment were to demonstrate an operational use of the satellite communications link, to investigate the utility of LANDSAT Data for a variety of time-dependent applications, and to construct a prototype rapid delivery network for remotely sensed data from future satellite systems planned such as LANDSAT D, SPOT, or ERS-1.)

Bearing in mind the objectives of the AGRISPINE experiment, a series of image processing experiments were conducted at the National Centre to test whether short term changes in coastal terrain and estuarine hydromorphology could be detected (over three consecutive 18-day cycles) and, in a similar manner, to compare the longer term changes between the 1973/1977/1982 scenes (Plate 1d) and the 1977/1979/1982 scenes (Plates 1c and 2d).

The digital image processing experiments employed a GEMS image display system, originally developed by the Computer Aided Design Centre with special image processing software developed by the National Centre at RAE Farnborough for remote sensing. This system includes four image memory planes holding 512 x 512 8-bit picture elements (pixels) and four 1-bit overlay planes. The GEMS system has a high resolution colour monitor with a zoom and pan facility; the zoom can be appreciated if the scale of Plates 1a and 1b is compared with the scale of plates 1c and 1d. The image processing tasks were performed by software on the host computer (a PRIME 750) and these tasks fell into three distinct operations:

1. rectifying each image set to the National Grid so that multi-temporal bands could be precisely overlaid for change detection;

2. optimising the most suitable enhancement technique for the interpretation of terrain and coastal features; and

3. superimposing the multi-date images of similar bands for change detection, display of additional information and evaluation of the shorter and longer term changes.

An extract covering the Ythan Estuary and Sands of Forvie was selected from each of the six LANDSAT scenes mentioned above. In each case, an area slightly larger than this extract was rectified to the National Grid, using the library of ground control points held at the National Centre and then resampled to 50 metre pixel size. The study extract measured 148 by 198 pixels, or 7.4 km by 9.9 km, the top left hand corner of each scene (Plates 1 and 2) starting on Eastings 398050 and Northings 829950.

The second main image processing task required careful selection of the most appropriate enhancement technique from the range of processes available on the GEMS contrast stretching menu. All the automated techniques were tried for each scene and whilst a two-step linear stretch of the input reflectance data and a gaussian stretch showed interesting effects, it was found that manual stretches of the individual bands (Band 4 on the blue gun of the TV display, Band 5 on the green gun and Band 7 on the red gun) gave the most suitable enhancement of terrain and coastal features for interpretation. A certain amount of radiometric balancing had to be done because it is always difficult to get the optimum stretch over land and over water at the same time, this being critical when the land/water interface and sea bed in the nearshore zone is of major interest (Plates 2a, b, and c).

The final image processing method employed for interpretation, and in particular for change detection, was overlaying the same spectral bands from each scene on the three TV guns thus creating a false colour composite image (Plates 1b, 1c, 1d and Plate 2d) in each case quite different from the normal stretched false colour composites (Plates 1a, 2a, 2b and 2c). For example, Plate 1b represents a multi-temporal false colour composite picture produced by superimposing on the TV display the Band 7 infrared images from 24th April, 1982 (transmitted through the blue gun), 12th May, 1982 (transmitted through the green gun) and 30th May, 1982 (transmitted through the red gun). This additive colour technique helps to define change and aids the interpretation of terrain features. In general, if little change in terrain reflectances has occurred over the three sequential 18-day LANDSAT passes then the blue, green and red additive process produces white light on the colour display if the surfaces are highly reflective, and dark grey or black if the surfaces have a low reflectance.

White or near white tones or dark grey or black tones on Plate 1b thus indicate little or no change in ground conditions. Yellow tones, which result through differing tonal states transmitted through the green and red guns, indicate that change in ground conditions has occurred over some areas on 12th May and 30th May. This feature is related to a change in crop growth, as would be expected at this stage in the growing season. Green tones indicate ground features which are strongly reflecting on the 12th May, whereas blue features (in this case mainly small clouds) indicate features which are strongly reflecting on the 24th April. The pronounced orange tones on a number of agricultural fields on Plate 1b indicate stronger reflectances coming through the red television gun (ie the 30th May scene) than through the green television gun (the 12th May scene). Since this LANDSAT band is the strongest chlorophyll absorption band, it is natural to assume that there has been much more greenery from crop growth present in the 30th May scene.

This final image processing experiment was particularly concerned with detection of change with time and its subsequent measurement. Three

multi-temporal change cases were considered:

1. short-term changes over three consecutive LANDSAT passes (Plate 1b)

2. medium-term changes defined here as from 1977 to 1979 to 1982 (Plates 1c and 2d), and

3. longer-term changes defined here as from 1973 to 1977 to 1982 (Plate 1d)

In each case, the measurement of change, particularly in coastal forms as discussed in a following section, was made by the pixel count facility on the GEMS image processing system. Using this facility, the feature was zoomed usually to the maximum setting, 8 times, as opposed to the 2 times zoom displayed in Plates 1a and 1b. The zoom facility on the GEMS is achieved by pixel duplication such that if a pixel count is made while in the 8 times zoom mode, then the total number of pixels counted must be divided by 8 and multiplied by 50 metres to give the true linear distance in metres. For example, if a simple measurement is made of the change detected on the 12th May, 1982 Image, Band 5, associated with the spit/bar complex at the mouth of the Ythan Estuary, then the mean north-south distance in pixels from the foredune limit to the bar is 90 pixels at 8 times zoom. This translates to a rectified linear north-south distance of (90/8) x 50 metres equal to 562.5 metres. If the same features are measured on Figure 4 for the 1967 position of the tip of the spit (white tip) then this distance from the foredunes is 620 metres. On the same figure if the 1974 position of the tip of the spit is measured from the southern extremity of the foredunes then this measurement is 500 metres.

Interpretation of LANDSAT imagery of Sands of Forvie and adjacent agricultural land

Preliminary considerations

The Sands of Forvie occupy a peninsular area of some 10 km^2, bounded to the east by the North Sea and to the west by the Ythan estuary and the A975 road to Cruden Bay and Peterhead. From the northern limit, approximately along a line between Cotehill Loch and Sand Loch (Fig. 1), the peninsula narrows southwards to the bare sand area of South Forvie at the mouth of the river Ythan.

At a general level, there is a simple two-fold division of the peninsula into North Forvie and South Forvie, each with distinctive morphological and vegetation characteristics. Detailed mapping of vegetation and land forms has been carried out using 1:7500 scale aerial photography, dated 1967, and the resulting maps may be used as a base-line against which subsequent imagery may be compared (Wright and Ritchie, 1975).

The basic differentiation of the image on LANDSAT is due to differences in land cover, since the sensors are effectively recording the differing levels of reflectance of electromagnetic energy from the ground surface. In a non-urbanised area this is more or less synonymous with recording differences in the vegetation cover.

Except in the case of high latitude areas, where images from two adjacent orbits may overlap by more than 60 per cent, LANDSAT does not provide

basic stereoscopic coverage. Even where an overlap and stereo-base are
provided by imagery from two adjacent orbits, the altitude of 915 km is
such that a poor base/height ratio of less than 1:10 obtains, and so
relief perception using overlapping images is rather weak. The ground
relief must, therefore, be of the order of thousands of metres for an
appreciation of landforms based on their three-dimensional morphology.
The relief variation within the Sands of Forvie (several tens of metres)
although it may be appreciable on large-scale stereoscopic aerial photography
is virtually undetectable on overlapping LANDSAT scenes from adjacent orbits.
The three-dimensional form of the ground must, therefore, be inferred from
some other indicator. The major features of geomorphology on the Sands
of Forvie may be deduced from the gross vegetation patterns which are
provided by the surface reflectance values on LANDSAT imagery.

An accurate record of the landforms and vegetation of the Sands of Forvie
is provided by the maps prepared from 1:7500 scale and aerial photography
of 1967 (Wright and Ritchie, 1975). Although there have been changes in
detail since then, the major elements of geomorphology and vegetation are
essentially the same now as then.

At a general level there is a close correspondence between the major land-
form systems and the main vegetation communities on the Sands of Forvie.
For example, on the map showing the major elements of vegetation (Fig. 1)
the dune grasses (1) and other dry grassland (2) are more or less coincident
with the major dune arcs or sand hills, and the large areas of calluna
heath (3), which predominate in North Forvie, correspond in the main to
the smooth or gently undulating plateau surfaces formed of drift, till or
rock. The bare sand areas (6) are evident, even without stereo viewing,
and are indicative of forms such as blowouts, beach areas above HWM and
sand waves on the dune areas. The principal vegetation communities may
therefore be detected using LANDSAT and these, in turn, are surrogates for
the major landform elements.

At the micro level, changes in landforms and vegetation take place on the
Sands of Forvie at a measurable rate. However, at the macro level represented
by LANDSAT imagery changes are much less likely to register since the
area, whilst dynamic, is only noticeably so over a much longer time scale.
The change which is most likely to be recorded on LANDSAT imagery is if there
is a significant alteration in the area of bare sand since that has an
abnormally high reflectance and will register a perceptible change if the
area is altered, either by erosion or by accumulation of blown sand.
Changes in the vegetation cover will only be noticeable if they produce a
significant alteration in the colour, and hence the reflectance, of the
vegetation. Major changes in vegetation cover are likely to take place
rather slowly, in response to some other physical changes in the environment
which sustains the plant cover. However, periodic or seasonal differences
in the vegetation may be noted at the gross scale as, for example, due to
different rates of growth in different years, perhaps indicative of changes
in the ground water conditions. Thus the effects of an excessively wet
spring may be noticeable in the vegetation pattern on LANDSAT summer imagery.

Detailed interpretation of major terrain features

The major terrain features of the Sands of Forvie area, as indicated in the preceding section, are:

> (a)   the undulating plateau surface of North Forvie;
> (b)   the dune arcs and dune slack areas;
> (c)   the bare sand areas.

Since they are also apparent on the imagery, the following terrain features have also been considered briefly:

> (d)   cropland
> (e)   woodland and water

The processed LANDSAT images are given in the eight extracts on Plates 1 and 2. The interpretations have been conducted on the basis of the major features indicated above, considering their appearance on the various single-date false-colour composites (FCC) and multi-date (or multi-temporal) LANDSAT images.

(a)   Undulating plateau surface of North Forvie

The limit of the calluna vegetation (3) is a fairly reliable marker for this extensive feature. The 1973 FCC scene (Plate 1a) delimits the area quite clearly in dark brown, and it is also clear on the 1977 (Plate 2a) and 1982 (Plate 2c) scenes, although ill-defined on the 1979 FCC (Plate 2b). In terms of reflectance the overall appearance of the dry calluna heathland is consistently dark, despite changes observable on the ground at micro-scale during the growing season. Consequently the multi-temporal images of Plates 1b, 1c and 2d depict a stable appearance of the calluna areas. The dark rendition of this feature on Plate 1d (Band 7) is particularly successful since it is clearly discriminated from certain features on the nearby agricultural land which on Plate 1a (1973 FCC) have a similar dark brown appearance on the image but which are depicted in the quite different colours of the cropland on Plate 1d.

(b)   Dune arcs and dune slack areas

A series of sub-parallel arcs of sand hills, resulting from seven or eight migratory waves of wind blown sand, rest on the undulating plateau surface of North Forvie and on what is believed to be a basement of glacial moraines, till and bedrock underlying South Forvie. In plan view the dune arcs bend towards the north, in North Forvie, and four successive waves are clearly visible on the FCC of 1977 (Plate 2a) and some are also apparent on the other images of Plate 2, if less clearly. The dune arcs are picked out largely as a result of the high reflectance of the bare sand exposed on the dune crests and the light toned marram grass (ammophila) on the flanks of the dunes contrasting with the generally darker appearance of the moister dune slack areas and the dark surroundings of the calluna heathland.

The dune arcs are less clearly visible on the March 1973 FCC (Plate 1a) since presumably the reflectance contrasts mentioned above for July images are more subdued in the wetter ground conditions likely to prevail in March.

The single year multi-temporal image (Plate 1b) and the band 4 and band 7 multi-year images (Plates 1c and 1d) all give unsatisfactory depictions of the dune arc systems, indicating that there has been relatively little detectable change in the locations of the dune arcs on this scale of imagery.

On Plates 2a and 2b a circular dark patch is apparent in the south of the area designated North Forvie. This is believed to be due to a damp depression in the undulating plateau at the western end of the large area of lichen dominant vegetation in the central part of the peninsula (4 in Fig. 1). This seems to be a persistent feature since it is also apparent on the multi-year composites, especially Plates 1c and 2d.

In the coastal dune belt at Foveran, to the south of the Ythan mouth, a clear example of change-detection is apparent in the dune slack area on the 1982 multi-date composite (Plate 1b). During the winter and early spring this area is very wet, usually with a winter loch evident. The reflectance would, therefore, be low on the 24 March image of band 7, which activates the blue colour on the composite. The other two dates (in May) would be during a drier period when the dune vegetation would be more highly reflective, and result in a higher proportion of green and red in the final image. This combination results in a yellow appearance for the large dune slack area in Plate 1b.

(c) Bare sand areas

The most distinctive reflecting surfaces on the Forvie peninsula are sand areas which are devoid of vegetation. This includes most of the sand hills, deflation areas, blowouts and coastal dunes of South Forvie, although three significant extensive areas of bare sand are evident in North Forvie (Plate 2d). When it is dry, bare sand has a stable and high reflectance value throughout the visible spectrum. Therefore on the single-date FCCs (Plates 1a, 2a, 2b and 2c) and on the multi-date composites of visible wavebands (band 4, Plate 1c and band 5, Plate 2d) the bare sand areas are highly distinctive. The band 7 multi-date composites (Plates 1b and 1d) do not display the same clear identification of bare sand areas since the reflectance signature is less distinct in the reflective infrared.

Although the single-date colour composites (Plates 1a, 2a, 2b and 2c) depict the bare sand areas clearly, there are some highly reflective targets on adjacent agricultural land which could be mistaken for bare sand on the July images (Plates 2a and 2b) but which are not evident earlier in the year (March for Plate 1a and May for Plate 2c). Knowledge of the local crop calendar might explain this aspect. By far the clearest portrayal of bare sand areas is given on the band 5 (Red visible radiation) composite of three different years (Plate 2d). The white appearance of only the bare sand areas in Plate 2d testifies to the unvarying signature of this stable reflector.

Band 5 multi-date composite, is therefore, an almost certain means of isolating, without ambiguity, the bare sand areas in the scene.

The two major bare sand areas in South Forvie run approximately south-north and east-west, connected by a short stretch of the coastal dune belt (Plates 1a, 1c, 2a, 2b, 2c and 2d). On the landward side of this connecting strip of coastal dunes is a large deflation area which is extensively covered by forms of lusher vegetation, including willow trees, as a result of the higher water table. This area, predominantly of wet grassland (5 in Fig. 1) is noticeable as a light brown or dark yellow patch in Plates 1a, 2a, 2b, 2c and 2d, but is not striking in Plate 1b since the cover, and hence the reflectance, had not changed significantly between March and May.

(d) Cropland

The adjacent agricultural land is partly in semi-permanent pasture and partly in rotation crops. This division is best represented in Plate 2c (12 May, 1982) where the high infrared reflectance of the pasture produces an orange/red colouring whereas the crop fields, being at an early growth stage, are dominated by the low reflectance from the soil, resulting in a blue-green colour. This distinction is not clear in Plates 2a and 2b, both of which are dated July when the reflectance from the crop fields will be dominated by the crop itself, producing a high infrared reflectance and making such fields virtually indistinguishable from pasture fields.

The multi-temporal images (Plates 1b, 1c, 1d and 2d) are particularly effective for the identification of fields of maturing crops, on a short-term basis, or changes in the crop rotation over a longer period. On Plate 1b (Band 7 of 24 March, 12 May and 30 May on blue, green and red, respectively) the fields which have been highly reflective in the infrared on all three dates (pasture) appear almost white, whereas fields which were bare soil in March and early May (hence little or no infrared reflectance) but had a significant crop growth towards the end of May have registered in a reddish-orange colour. The colour mosaic of cyan, green, yellow, blue, white and magenta displayed on the agricultural area of Plate 1d may be similarly interpreted in terms of relative presence or absence of a crop in particular years. By combining band 7 images from several years, and from several stages within the growing season, it should be possible, aided by knowledge of the crop rotation and of crop phenology, to identify particular types of crop.

(e) Woodland and Water

On single-date multispectral composites (Plates 1a, 2a, 2b and 2c) woodland is particularly difficult to distinguish from the dry calluna heath areas of North Forvie, since both have an overall dark brown colouring. Separation is best on the 12 May, 1982 image (Plate 2c) where two small brown patches are detectable on either side of the large bend in the river Ythan, in the top-left of the image. These same two areas, which are predominantly evergreens, register as dark brown images on Plate 1b (1982, 24 April, 12 May and 30 May), but another wooded area (brown colour at left-centre of Plate 2c) shows on Plate 1b as a lighter yellow-brown. This indicates that this area is probably mainly deciduous woodland, since the leafless trees in March (blue component) would contribute a lower response than the trees in full leaf in May (green and red components) resulting in a lighter yellow-brown depiction of deciduous woodland. The combined use of Plates 1b and 2c would therefore permit separation of evergreen and deciduous woodland.

Water areas are generally the most easily identified terrain features on
LANDSAT imagery. The reflectance is consistently low in all bands,
particularly in band 7 where most of the incident infrared radiation is
absorbed by the water. Consequently, the landward water features (such
as Cotehill Loch and Sand Loch, Fig. 1) are consistently easily
identified on the single-date multispectral images (Plates 1a, 2a, 2b and
2c). On the multi-date composites they are poorly identified on band 4
(Plate 1c) and on band 5 (Plate 2d) but are readily distinguished on
the multi-date infrared composites of band 7 (Plates 1b and 1d). There
has been no appreciable change in the water levels, but if such changes
were significant then a multi-date composite of band 7 would reveal
the changes as colour bands around the edge of the water body.

The Estuary and Inshore Zone

Previous research work (Stove, 1978) has demonstrated that the Ythan
Estuary can be classified as a shallow (Figs. 3 and 5), partially-mixed
estuary, which is almost closed by a mobile spit/bar complex at the mouth.
It has also been demonstrated that the estuary currently experiences
marked longitudinal and lateral advection of marine and aeolian based
sediment, so that the main channel and inter-tidal areas are presently in
a state of active sediment accumulation. Further research on river mouth
dynamics (Weatherill, 1980) has indicated that in comparison to many
other mid-latitude, medium sized estuaries, and particularly the Don mouth
at the southern end of Aberdeen Bay, the Ythan inlet exhibits a low order
of magnitude of inlet dynamics. This latter research has emphasised
that the most notable morphological changes affecting the Ythan inlet
over both the long and the short time-scales involve infrequent fluctuations
in the alignment of the main (ebb) channel between two extreme positions –
namely orientated to the north (Plate 1a) or to the south (Plate 2c).
Previous research (Stove, 1978) has demonstrated the substantial changes
in the outlet channel over the longer timescale (1967 to 1974) as can be
seen in the maps produced to illustrate erosion and deposition (Figs. 4
and 6). The later work (Weatherill, 1980) illustrates the considerable
short-term mobility of the distal end of the main channel with lateral
shifts of the channel thalweg location by up to 200 metres over the period
from June 1977 to September 1978 (compared with about 600 metres over the
long term).

The survey work of Stove (during 1973 and 1974) and Weatherill (during 1977
and 1978) has produced a valuable data base of short and long term changes
in estuarine and littoral forms, backed up by considerable measurements of
marine, tidal and fluvial processes. This background information provided
the main incentive to look at multi-temporal change in the LANDSAT scenes
to test whether the same broad trends detected by Stove and Weatherill
from aerial photography and hydrographic surveys could be seen in the
satellite images.

Interpretation of LANDSAT images over the Main Channel

The Ythan Estuary is a bar-built estuary with a maximum tidal intrusion
length of just over 10 km. The estuary has a high water area of about
$2\frac{1}{2}$ km^2 and a river catchment of over 680 km^2. Stove has demonstrated
that the area bounded by the mean low water mark which delimits the main
estuarine channel, in 1974 is only 56% of the same area in 1967. In the

Lower Ythan Estuary (Fig. 4) the main channel area in 1974 is 69% of the same area in 1967. In the Middle Ythan Estuary (Fig. 6), the main channel area has been even more reduced by sedimentation in 1974 to only 46% of the 1967 main channel area.

Before LANDSAT images from the short and long term situations can be compared for the detection of change in channel conditions, it is important to establish (a) the time and state of the tide at LANDSAT overpass and (b) the mean river flow at time of overpass. These two conditions can certainly influence the interpretation of true morphological change in channel forms. The first good LANDSAT image of the Ythan Estuary was obtained on 11th March, 1973 and this image is unique because sea truth information was being collected at time of overpass, which occurred during a hydrographic tidal cycle survey.

At this time a catamarran was moored in the main channel at Station C (Fig. 3) taking hydro-oceanographic measurements every twenty minutes for the 12 hours 25 minute tidal cycle duration. At time of LANDSAT overpass, the water depth in the main channel at Station C was about 0.5 metres, with a seawards ebb flow current of 0.1 ms^{-1}, flowing at 209°T. The flow at this stage was virtually laminar in the main channel, with a mean salinity of 18.00^{o}/oo and a mean temperature of 3.6^{o}C. Suspended sediment concentration in the water at this time (from a depth-integrated sample) was 48 mg/l.

At the mouth of the estuary, seawater level at time of LANDSAT overpass was approximately -1.0 m below Mean Sea Level (Ordnance Datum Newlyn). The tidal state was a Neap, just over 1 hour before low water, with a limited range of 2.7 metres. This low water condition came 6 minutes before predicted LW, but was 24 cm lower than predicted. The mean gauged freshwater inflow to the estuary was 2.551 cumecs.

In contrast to the large amount of sea-truth information available for the 1973 image pass (Plate 1a), only river inflows and tidal information are available for the other five scenes. However, surveys by Weatherill conducted between June 1977 and June 1978 help to delineate trends in the change of the main channel at the mouth and this information was used to compare channel changes between the 1977 (Plate 2a) and 1979 (Plate 2b) images. Weatherill's research proved that maximum change in thalweg location occurred between June 1977, when the channel was orientated to the north at the mouth, and June 1978, when it was orientated to the south. From a fixed reference position at the mouth, this represented a lateral shift of 177.5 metres. Along the same reference axis, channel changes were measured from the overlaid multi-temporal LANDSAT (Plate 2d), and the channel change between the 1977 and 1979 images measured 32 pixels, or 200 metres. The general trend of change in channel mouth as measured from the overlaid LANDSAT images is in broad agreement with Weatherill's findings, although he did not have any survey information for the 1979 date. The magnitude of change (i.e. 200 m) is also in general agreement with the scale of events which occurred between 1977 and 1978.

The 4th July, 1977 image (Plate 2a) represents a spring tide condition scanned about one hour after low water, with a tidal range of some 4.1 metres for the day and a mean river inflow of 3.3 cumecs. For comparison, the 12th July, 1979 scene (Plate 2b) was scanned during a spring tidal

condition about 1½ hours after low water, with a similar tidal range of 4.1
metres, but a lower mean river inflow of 2.7 cumecs. The AGRISPINE images
overlaid in Plate 1b represent spring, neap and spring tides, respectively.
The 24 April scene transmitted through the blue gun represents a water level
of 2.50 metres above Chart Datum, 3½ hours after LW, with a higher river
inflow of 3.99 cumecs. The 12 May scene (Plate 2c), transmitted through the
green gun, was imaged about one hour after low water with a water level
recorded of 1.51 metres above chart datum and a river inflow of 3.2 cumecs.
In contrast, the 30 May scene, overlaid on the red gun in Plate 2b,
represents a tidal state some 3½ hours before LW, with a water level of 2.18
metres above chart Datum Aberdeen and a tidal inflow of 2.9 cumecs.

Interpretation of change in Estuarine Inter-Tidal areas

The research work and maps produced by Stove (Figs. 4 and 6) testify to the
changes in the inter-tidal areas of the Lower and Middle Estuary between
1967 and 1974, illustrating areas of net erosion and deposition. This work
demonstrated that the main sediment deposition in the main channel was due
to inter-tidal accretion by lateral banks rather than the accumulation of
medial banks in the main channel. It was also clear that the net inter-tidal
deposition on the left bank of the estuary compared with the net total inter-
tidal deposition, is significantly greater than the equivalent right bank
sedimentation. This conclusion holds for the Lower (Fig. 4) and Middle
(Fig. 6) Ythan Estuary. The 1967 to 1974 change measured indicated that the
net depositional area for the Lower Ythan Estuary was some 57% for the left
bank area, compared with 43% for the right bank area. For the Middle Ythan
Estuary, the same ratios were 61% and 39%, respectively.

Using the GEMS pixel count facility change in inter-tidal areas was measured
and most change was detected from the overlaid band 5 (Plate 2d) and band 4
(Plate 1c) scenes. The overlaid band 7 scenes (Plate 1d) was mainly useful
in detecting the maximum wetted area on the inter-tidal regions. Using the
band 4 and band 5 overlays (1977/1979/1982) it was found that most change
in the inter-tidal areas occurred on the left bank just north of Hydrographic
Station C (Fig. 4). This area of deposition on the left bank from 1977 to
1982 represented an additional 22 pixels, or 137.5 metres. A similar inter-
tidal change could be measured in the Middle Estuary at Station E (Fig. 6)
from the 1977 to 1982 overlays and this represented an extension of the left
bank inter-tidal area by some 16 pixels, or 100 metres. It is interesting
to note that the same general trends of left bank change in the inter-tidal
areas can be detected from the LANDSAT overlays, although the accuracy of the
pixel areas cannot compare with the photogrammetric and hydrographic techniques
employed by Stove in his earlier work.

Interpretation of change in Littoral and
Inshore areas off the Ythan Mouth

The first detailed inshore hydrographic mapping work off the Ythan was
completed by Stove during 1973 and 1974 and this resulted in a map showing
the generalised isobaths at 1 metre intervals down to -20 m Ordnance Datum
Newlyn (Fig. 2). This base map and the later profiles and river mouth
configurations plotted by Weatherill during 1977 and 1978 were used to test
for similar trends showing up in the overlaid LANDSAT scenes.

Weatherill demonstrated from his 1977 and 1978 surveys that there was a strong positive relationship between the growth of the northern entrance shoal to the Ythan mouth and deflection of the channel southwards. If the 1977 (Plate 2a) and 1979 (Plate 2b) false colour composites are compared side by side this trend in the river mouth change from 1977 to 1979 with a related growth in the northern entrance shoal can be observed and measured. The LW scene of the 12 May, 1982 (Plate 2c) indicates a further extension of the spit southwards, but this time the southern entrance shoal can be detected on the imagery and appears to be growing. This could well mean that the channel is on the point of swinging northwards again, having adjusted to its maximum southerly extension. The location of the southern entrance shoal was measured at 700 metres from the edge of the foredunes on the 12 May, 1982 scene. Comparing the four images on Plate 2, some seabed penetration is evident, especially on the 12 May, 1979 imagery to a maximum distance of about 1200 metres offshore. This distance represents a seabed elevation of about -7 to -8 metres ODN (Fig. 2) which equates with the lower limit of the Main inshore asymmetrical bar at its trough in the idealised nearshore profile drawn by Weatherill.

CONCLUSIONS

Single-date multispectral false-colour composite (FCC) images of Landsat are successful for depicting the major landform and vegetation elements on the Sands of Forvie, particularly on summer scenes where the contrast between dry sand on dune crests and the moister patches in dune slack areas is accentuated. The short-term multi-temporal composite, represented by the AGRISPINE image, is not generally useful for change-detection of landforms and vegetation since the time span is too short to produce detectable changes.

An exception is the excellent depiction of certain areas of dune slack which are wet in spring and dry out in the summer months. The multi-temporal images of different years are similarly restricted in change-detection capability except where significant differences occur in the water table conditions from one date to another.

Areas of bare sand are generally very clearly depicted on all scenes and particularly with band 5 multi-temporal imagery spread over several years. Water features can be seen to best effect on band 7 imagery and multi-temporal band 7 composites should depict changes in water level where they exist. Woodland areas can be differentiated from other dark surfaces if multi-temporal imagery is used, and if this imagery covers several seasons then a deciduous/evergreen division of woodland is feasible.

If multi-temporal images of band 7 covering different stages in the growth cycle of crops are combined then a definitive crop classification becomes possible. If images of band 7 of different years are combined then it may be possible to identify the crop rotation.

Interpretation of the short-term sequential LANDSAT scenes acquired during the AGRISPINE project has demonstrated that tidal water levels can be detected and equated with both tidal states and freshwater inflow conditions. Lateral shifts in the main ebb channel of the order of 100 metres at the outlet can be detected, particularly on the band 4 AGRISPINE scenes, while the band 7 AGRISPINE composite image (Plate 1b) determines the maximum estuarine and littoral wetted surfaces.

Over the longer time scale from 1977 to 1979 lateral shifts in the main outlet
channel of the order of 200 metres have been measured and this equates well
with previous research work conducted during 1977 and 1978. Over the longer
time scale from 1973 to 1982 lateral shifts in the main outlet channel of up to
600 metres again compares well with previous evidence of change from 1967 to 1974.
Similarly in the estuarine area proper, change in the inter-tidal areas reflects
earlier conclusions that sedimentation still tends to be more prominent on the
left bank areas than the right bank in both the lower and middle estuary.

Finally, in the littoral and inshore zone the northern entrance shoal at the
Ythan mouth can be detected and measured from the 1977 and 1979 images in
particular. The AGRISPINE scenes, particularly the low water image of 12 May,
have added new evidence of the growth of the southern entrance shoal which
suggests that the main outflow channel is on the point of swinging north again.
Seabed detection is also possible in the inshore zone down to about -8 metres
ODN which correlates with the lower limit and trough of the main inshore
asymmetrical bar, some 1200 metres offshore.

It is clear that the multi-temporal study of the LANDSAT scenes has given
a new perspective to the estuarine and littoral hydrography of the Ythan
area. If further image contrast stretches are produced in the sea only, then
the suspended sediment plume coming out of the Ythan can be detected on most
of the scenes. It is however vitally important to take into consideration
tidal states and river inflow conditions before accurate channel change and
computation of erosion and deposition can be made using LANDSAT imagery.

Overall, therefore, the dynamics of the landforms and vegetation are much
slower acting and the effects less evident at the macro-scale than in the
estuarine and coastal environment, where the effects of fluvial and tidal
processes can be much more dramatic on a short time-scale. Such processes
are also acting on an environment with elements of contrasting reflectance,
thus almost ensuring detection of the changes taking place.

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SANDS OF FORVIE
Major elements of vegetation

COTEHILL LOCH

SAND LOCH

N

1 ▨ Dune grasses, esp. Ammophila arenaria

2 ▤ Grassland (Carex arenaria, Nardus stricta)
Dune Pasture (Festuca, Poa, Agrostis)

3 ⠿ Calluna heath with grasses and mosses

4 ▨ Lichens, esp. Empetrum nigrum and
Cladonia sylvatica

5 ▨ Wet Grassland (Agrostis with scattered
Juncus effusus)

6 ☐ Bare Sand

0   500   1000m

Fig. 1

LOWER YTHAN AND
INSHORE
BATHYMETRY

Isobath interval 1 m
Datum ODN

0 metres 500

Fig.2

826000

400000

LOWER YTHAN
ESTUARY
1974
Hydromorphology

100 0 100 200 300 metres

Channel base reduced to metres O.D.N.

Fig.3

LOWER YTHAN
ESTUARY
From 1967-1974
Erosion & Deposition

100   0   100   200   300 metres

Fig.4

MIDDLE YTHAN
ESTUARY
1974
Hydromorphology

100 0 100 200 300 metres

Fig.5

MIDDLE YTHAN
ESTUARY
From 1967-1974
Erosion & Deposition

100   0   100   200   300 metres

Fig.6

PIPELINE LANDFALLS IN NORTHEAST SCOTLAND

A SUMMARY

Introduction

Six major pipeline landfalls occur in mainland Northeast Scotland. Five oil and natural gas pipelines come ashore within a distance of 35 km to the north of Aberdeen, and a sixth is at an advanced planning stage. Further north, across the Moray Firth, a smaller oil pipeline from the Beatrice field lands near Balintore in Easter Ross. The oldest line is the pipeline carrying oil from the Forties field. It makes its landfall at Cruden Bay (Photograph 1) and the oil is pumped southwards to the long-established refinery at Grangemouth. The twin natural gas lines from the Frigg field (which includes reserves in the Norwegian sector of the North Sea) lands at St. Fergus north of Peterhead where British Gas have their massive receiving station which was built on a green field site (Photograph 2) and from which several pipeline systems continue southwards to carry natural gas into the UK gas grid. Contiguous with the British Gas terminal at St. Fergus is the Shell receiving terminal for natural gas from the Brent Field. Natural gas from this area is transferred to the contiguous British Gas terminal but ethane is carried southwards in a separate pipeline, presently (summer 1983) under construction. This pipeline terminates at Mossmoran in Fife where a major new industrial area has been constructed. A smaller diameter gasline from the Fulmar field is also planned to land at St. Fergus and the gas will feed into the existing Shell terminal. The projected date for construction work for this pipeline is 1984. All these pipelines are large diameter sea bed pipelines which have been constructed at great cost to carry hydrocarbons from large offshore reservoirs to the nearest suitable point of mainline UK north of Aberdeen.

The oil pipelines from the Beatrice field is a smaller undertaking with a shroter subsea section is relatively shallow water. The pipeline is 16 inches in diameter and made a landfall at Shandwick on the Tarbert peninsula in 1978. From the landfall a buried landline carries the crude oil to the refinery at Nigg Bay at a site contiguous with the oil platform fabrication yard.

All these pipelines and their locations are shown in Figure 1. The offshore route of the Fulmar pipeline is conjectural but at some point offshore or onshore it has to cross the Forties, the Frigg and Brent pipelines. The following tabulation summarises some of the technical data relating to each pipeline landfall.

PIPELAND LANDFALLS - SUMMARY

PIPELINE	LOCATION	CONTENT	LANDFALL DIAMETER	BEACH BURIAL	OFFSHORE LENGTH	METHOD AND DATE OF PLANNING	OPERATOR	USE
BEATRICE	SHANDWICK	OIL	16"	3.8 m	67 km	FROM Laybarge and pulled by winches onshore through beach and dunes SUMMER 1979	Britoil	To Nigg Oil Terminal
FORTIES	CRUDEN BAY	OIL	32"	>2-3 m	167 km	ditto SUMMER 1973	B.P. Ltd.	To Grangemouth Refinery
FRIGG (2 pipe-lines)	ST. FERGUS	NAT. GAS	32"	>2-3 m	c.360 km	ditto SUMMER 1975	TOTAL (UK) LTD.	To British Gas St. Fergus Terminal
FLAGS (BRENT FIELD)	ST. FERGUS	NAT. GAS	32"	>2-3 m	>400 km	ditto SUMMER 1976	SHELL (UK) LTD.	To British Gas St. Fergus Terminal and Mossmoran (Fife)
FULMAR	ST. FERGUS	NAT. GAS	-	STILL	BEING	DESIGNED -	SHELL (UK) LTD.	

Fig.1

LOCATION OF PIPELINES

Land pipelines (generalised locations)

Sea pipelines

(Projected)

Sea route

Wick

Beatrice Field

1 oil line

Shandwick
Nigg Bay
export by sea

Inverness

St.Fergus Terminal

To National Gas Grid
and one NGL line
to Mossmoran

Peterhead

Cruden Bay

From Brent – 1 gas line

From Frigg Field – 2 gas lines

From Fulmar – 1 gas line

From Forties and Brae Fields
1 oil line

To Grangemouth

ABERDEEN

N

100km

Photograph 1. The Forties pipeling landfall site at an early stage of construction. Cruden Bay.

Photograph 2. The British Gas/Total (U.K.) Ltd. Terminal at St. Fergus. Construction had not yet started on the Shell Terminal to the north of the main site.

Photograph 3.   A winter photograph of the coastal dune ridge at
St. Fergus shows both the height and the vigour of
erosion on the dune face.

Photograph 4.   For four months or so each year the low area, the winter
loch, inland from the main dune ridge floods.
St. Fergus.

ENVIRONMENTAL SITUATION

Environmental aspects of the coastal landfalls in all three locations
(i.e. Shandwick, St. Fergus and Cruden Bay) were assessed by various
forms of environmental impact procedures.   At a general level, the
landfalls are all similar;   the approach is across a low gradient, sand
covered seabed, and the landfall is through a beach and dune trench.
Thereafter the pipelines continues as buried land lines to a nearby
terminal treatment area.   The exception to this is the Forties pipe-
line which passes through a small pumping and surge tank facility,
located near the coast, before continuing for over 200 km, southwards to
the long-established petro-chemical and refining complex at Grangemouth
on the Firth of Forth.

In detail the topography and environmental conditions at the three land-
fall areas are quite different.   Cruden Bay is a sheltered location at
the corner of a sediment filled bayhead.   The coastal dunes are low and
the area was rough grazing and had little ecological value.   The main
problem was the proximity of a championship golf course beside the pipe-
line landfall.   St. Fergus is a much more difficult situation.   The
coastline is more exposed and has relatively high but variable wave
energy inputs.   The dunes are up to 14 m high compared with 3 m at
Cruden Bay.   The dunes are also eroding (Photograph 3).   Inland from
the dunes there is a long flat-floored dune slack which floods with
fresh water during the winter and is important   for plants and bird
life (Photograph 4).   This area is bounded to the landwards by a zone
of older lower sand dunes and the post-glacial cliffline which is formed
in late glacial or glacial clay deposits.   Geomorphological processes,
existing landform characteristics and environmental sensitivity renders
St. Fergus a much more demanding location for the technical design of
the landfall and subsequent restoration and management.   The landfall
at Shandwick near Balintore occupies a section of the only sand filled
embayment in the largely cliff-grit eastern coastline of the Tarbat Ness
peninsula.   Unlike the other landfalls the pipeline landfall is adjacent
to a small village.   The landfall is at the south end of the beach near
a sandstone rock platform.   The coastal edge is low (about 2 m) and
takes the form of a sloping sand platform rather than recognisable dune
formations.   The blown sand rests on a series of shingle bars which are
part of the raised beach deposits which characterise this section of the
Tarbat Ness coastline.   The blown sand system extends from the coastal
edge inland at a gradient of 5 to 10 degrees in the form of a continuously
vegetated foredune ridge with traces of older parallel ridges but most of
the area had been severely modified by levelling for housing and gardens
etc.   At the landfall site the ridge system was almost featureless and
little more than a stable irregular sloping sand surface which impinged
on the foot of the old cliff line some 100 to 150 m inland.   There were
no areas of ecological importance and the coastline, although open, is
a relatively low energy environment.   The coastline has been described
elsewhere as "degraded" due to natural wave undercutting, trampling and
some tipping of rubble etc. on the backshore.   Some of the pressure on
the coastline derives from its popularity as a holiday area, particularly
for caravanning.   There is a caravan site near the landfall area.

A comparison of the three landfall sites can be obtained from comparing
Figures 2, 3 and 4 which show the morphological characteristics of the
three areas along with the approximate pipeline locations.   Whilst the
similarity of the three sites is apparent the more open and complex

situation at St. Fergus can be appreciated readily - and, since this is
the focus of landfalls for several natural gas pipelines the added
complexity of pre-existing pipelines both nearshore and onshore and
the presence   of previously restored and landscaped ground give added
complexity to the environmental assessment and management problems.

Acknowledgement

The author would like to thank Mr. N. Rose Britoil (Aberdeen) for
information relating to the Beatrice Field and pipeline.

CRUDEN BAY

Village

Cruden Bay Village

·33

Chalets
and Caravans

Golf Club

Undulating

Golf Course

·12

·10

·10

Port Errol

General area
of recreational uses

·34

·10

·9

RED TILL

30·

Golf Course

38·

Steep post-glacial cliff with variable sand
cover,cut in red till clay till

Steep often undercut dune face

Cobble and shingle beach

Footbridge

Dunes with main crest lines

Undulating links

River and raised shoreline terrace

0   500m

DEVELOPED ON

LAND

17·

·4

7

AGRICULTURAL

Golf
Course

·6

Pipeline Landfall

·4

19

·20

·46

Whinnyfold Village

Rattray Bay

? Old sand dunes

16

25

Rattray Head

20

N

15

7

4

14

18

15

Old cliff line in glacial deposits

Degraded lower terrace

Prograding dune line

Q   **Quarry**

Low undulating links

Undifferentiated dunes

Slacks/Winter loch (2-4m O.D.)

Undifferentiated raised beach areas usually < 8m O.D.

Remaining areas are plateaux of glacial material usually >10m O.D.

Q

9

Shell

Pipelines

Total

St. Fergus

British

Gas Terminal

15

8

Blackwater

0   1000m

12

3

.4

14

St. Fergus Village

Scotstown Head

.2

Q

14

9.

22

BALINTORE

Balintore

C.S.

Approximate landfall
of Beatrice pipeline

N

0   455m

0   500yd

Contours in feet

TEXT OF LECTURES BY
VISITING SPEAKERS
RELATING TO THE COASTLINES OF
NORWAY AND DENMARK

THE LANDFALL OF THE STATPIPE'S PIPELINE AT KALSTØ,

THE ISLAND OF KARMØY, WESTERN NORWAY

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Introduction

The Statpipe gas-gathering pipeline will make its landfall at Kalstø in Western Norway through a rocky, high energy coastline. The nature of the landfall contrasts with most other North Sea landfall sites which are usually through beaches and dunes. The Statpipe is organized as a partnership of Statoil (The Norwegian State Owned Oil Company) (60%), Elf Aquitaine Norge A/S (10%), Norsk Hydro Produksjon a.s. (8%), Mobil Development Norway A/S (7%), Esso Exploration and Production Norway A/S (5%), A/S Norske Shell (5%), Total Marine Norsk a.s. (3%) and Saga Petroleum a.s. (2%) (Statoil informasjonsavdeling 1983). Statoil is the operator. The decision to build the Statpipe System was taken by the Norwegian Parliament on the 10th of June 1981.

The pipelines

The pipeline of Statpipe will transport gas from the Statfjord- and the Gullfaks-fields through a 30 inch pipeline to the Kårstø Gas Terminal, Fig. 1, a distance of approximately 300 km. This pipeline has to cross the 300 metres deep Norwegian Trench. It will be the first time a pipeline has been laid at such great depth. Technical problems in the 1970s made the Trench a hinderance of such magnitude that the gas from the Frigg-field had to be taken ashore at St. Fergus in Scotland (Ritchie 1980). The pipeline of Statpipe will have its landfall at Kalstø on the Island of Karmøy in Western Norway, Fig. 2. From Kalstø it will cross over to the Kårstø Gas Terminal via trenches and tunnels as shown in Fig. 3.

The gas arriving at the Kårstø Gas Terminal will be a rich gas. At the Terminal the natural gas liquid will be split into its component parts: propane, butane and natural gasoline which are to be shiped out. The natural gas compounded by methane and ethane, will be transported by another new pipeline to buyers on the European continent. This 28 inch pipeline will follow the same trenches and tunnels back to the Kalstø landfall. Here the pipeline will enter the sea, cross the Norwegian Trench, and on the way to the Ekofisk-field pick up the pipeline from the Heimdal-field, Fig. 1. From the Ekofisk-field the natural gas will run through the existing Norpipe's pipeline to Emden in West-Germany. The pipeline of Statpipe is supposed to be operative from the 1st of January 1986. At that time the production at the Ekofisk-field will decline and the Norpipe's pipeline can offer transport to the gas from the northern fields.

. The physical setting

The site of the importing and exporting pipelines at Kalstø on the island
of Karmøy provides an interesting example of an approach to and landfall
on a rock platform coastal environment.   The island of Karmøy and the
Kårstø area are parts of the Norwegian strandflat.   The strandflat
(Klemsdal, 1982) has an undulating, rugged topography where small, low and
rocky knobs and knolls are raised above smaller or larger depressions and
valleys.   Where this rugged topography declines towards the sea it makes
a very uneven coastline with bays and headlands, inlets and promontories
and a lot of minor islands and skerries, Fig. 2.   Offshore the same
topography continues, the depths on the sea chart tells this clearly,
Fig. 2.   Relatively near to the shore there are depths of 40 and 60
metres, Fig. 2.   The shore-zone is composed mainly of a very gently
sloping ice-smoothed rocky shore, some shorter stretches of more steeply
sloping ice-smoothed rocky shore and some smaller parts with stoney beaches,
Fig. 4.   The two small islands to the right on the photograph, to the south-
southwest of the landfall, will protect the landfall from some of the waves
from that direction.   This rugged topography, both on land and under water,
with a rocky shore and few skerries provides the physical setting of the
landfall, Fig. 4.

The dynamical setting

The dynamical situation at the landfall site is a composite of the offshore
topography, and the wave climate as decided by   fetch, direction of the
waves, wave height and period and duration of waves above certain heights.

The fetch within the sector from south-southwest to north-northwest is decided
by islands along the coast of the island of Karmøy, Fig. 3, where it is 370
km or more, reaching from Scotland and the Shetland islands.   The island of
Utsira and two minor groups of smaller islands and skerries probably have
little effect on the approaching waves.

The frequency distribution of wind directions at Utsira, Fig. 3, (Håland 1978),
illustrates a common but unexpected situation: the many observations of winds
blowing parallel to the coast.   Winds blowing parallel to the coast are
rather common along long parts of the coast of Norway.   Little analysis of
the wind directions has been made during stormy days.   From the cyclonic
passages over Southern Norway during late autumn and winter the expected wind
direction during storms would most probably be from northwest and southwest.
The wind-rose diagram from Utsira, Fig. 3, indicates those directions as well.
Storm waves approaching from the southwest and northwest pass over a sub-
marine relief similar to the strandflat, varying in depth between 80 and
120 metres.   The depth is reduced to 30-40 metres 500 metres off the coast
at the landfall.   This means that the offshore topography does not reduce
the incident wave energy until the waves are close to the shore.   Measure-
ments of wave direction, height and period have only been made occasionally
over the last 2 or 3 years at Utsira, 15 km west of the landfall, Fig. 3.
The wave height, however, has been observed visually and the wind force and
direction have been measured for many years at the meteorological station at
Utsira.   Values of significant wave height computed from the visual
observations is shown through model-computing by Håland and Småland (1980)
to be representative.   The frequency distribution of significant wave
height, valid for a point 20 nautical miles off the coast of Utsira is as
follows:-
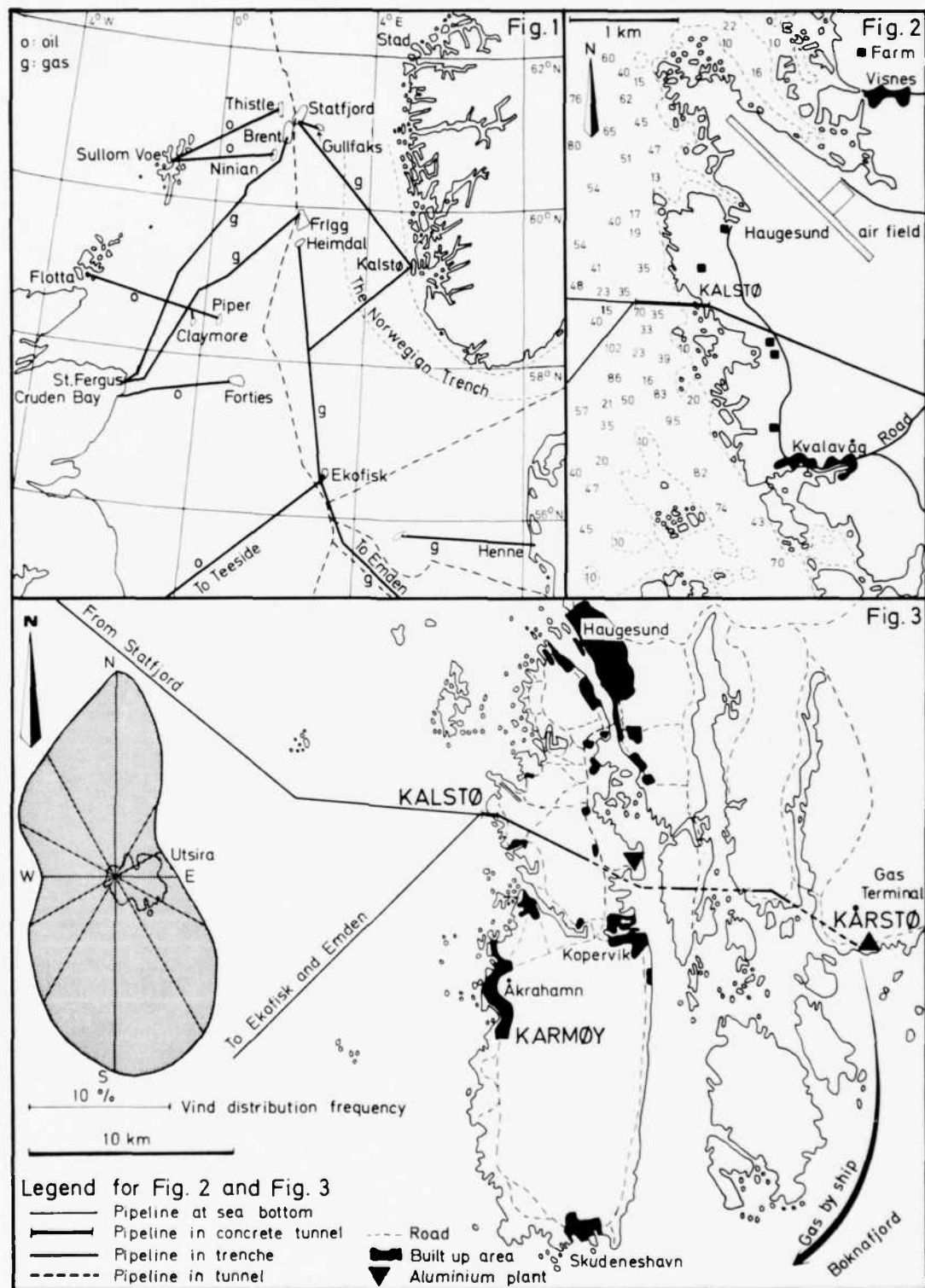
Fig. 1   Oil-and gas- fields and pipelines in the northern parts
         of the North Sea.

Fig. 2   The landfall at Kalstø on the island of Karmøy.
         The figure builds on the topographic map in the series
         M711, no 1113 I Haugesund, 1:50 000 from the Norwegian
         Geographical Survey and the depths are from the sea chart
         no. 18 from the Norwegian Hydrographical Survey.

Fig. 3   The location of the islands of Karmøy and Utsira, the
         landfall at Kalstø and the Gas Terminal at Kårstø.

Fig. 4   The physical setting of the landfall at the beginning
of the construction works.   Photo taken the 27th of
May 1982 by Statoil.   Source: Statoil.

67% are 2.4 metres and less;   24% are between 2.5 and 3.9 metres;
9% are between 4.0 and 8.9 metres and 0.16% are 9 metres and more.   As
many as 1/3 of the significant wave heights are 2.5 metres and higher
and 1/10 are above 4 metres, see Fig. 5.   The significant wave height
computed for each month (Håland & Småland 1980) gives that the period
October – February has the largest waves, Fig. 5.   The hundred year
wave for Utsira, calculated from statistics by the Bumbel distribution,
based on a time series of 25 years turns out to be 30 metres – 10%
(Håland 1978).

The highest and most powerful waves are developed under storm conditions.
The frequencies of wind velocity for Utsira are:

     73% below 7 m/sec Beaufort: 0-4 (moderate breeze or less)
     22% between 8 and 13 m/sec   5+6 (fresh and strong breeze)
      5% between 14 and 20 m/sec   7+8 (near gale and gale)
    0.3% above 21 m/sec   ≧ (severe storm or stronger)

The frequency distribution indicates that there are relatively large
periods of strong winds.   These result in the number of stormy days per
year at Utsira, varying from 1 day both in 1927 and 1928 to 42 days in
1938, and with a mean of 14.7 stormy days per year (Håland & Småland 1980).
The record goes back to 1920.

The maximum significant wave height for the annual extreme storm from
1948/49 to 1976/77 varies between 5.7 metres in 1969 to 13 metres in
1959, with a mean of 9.5 metres.   This means that during strong storms
with wind-pressure raising sea level by up to 1.5 metres, waves may easily
attack the shore-zone up to 5 and 6 metres above normal sea level.   The
mean tidal range in the landfall area is only 0.6 metres, and is, on this
rocky shoreline, of little importance.

The large number of high significant waves, the high value of significant
wave height during the extreme storm of the year, the great number of
stormy days and the offshore conditons, all indicate a strong wave climate
at Utsira and the landfall.   In fact, compared with other stations along
the coast, it is the strongest one along the southwestern coast of Norway.
Only in the Stad area (Fig. 1) it becomes somewhat stronger.

The landfall at Kalstø

The Kårstø area was early pointed out as the site for the Gas Terminal
and then Kalstø was the most natural place for the landfall along the
western coast of the island of Karmøy.   There was 4 alternatives to take
the pipeline ashore at Kalstø:

1. The pipeline placed on a concrete foundation on the sea bottom,
2. Through a tunnel from land, ending offshore,
3. Through a trench blasted in the sea bottom, and
4. Through a prefabricated concrete tunnel, placed on pre-cast
    foundations on the sea bed.

The last method was chosen, because it would give a straight and relatively

easy way to pull the pipelines ashore and provide very good protection from wave attack. The construction work started at the landfall early in 1982 and was finished in late autumn the same year (pers. comm. W. Olsen, Statoil informasjonsavdeling 1983). Fig. 4 and 6.

The concrete tunnel has an inner cross section of 5 by 3 metres. The outer measures of the concrete tube is 6 by 4 metres, except for one section which crosses over a small valley in the sea bottom and therefore measures 6 by 5 metres (Statoil informasjonsavdeling 1983). The concrete tunnel is 670 metres long. It was built as prefabricated sections, between 80 and 140 metres long, which were put in place in September 1982, Fig. 7 and 8. The section at the water-line, however, was poured on the site as were the foundation blocks for the concrete tunnel on the sea bed. The sections were filled with water and placed on the foundations. The pipelines were pulled through the concrete tunnel in April 1983 (pers. comm. W. Olsen, Statoil informasjonsavdeling 1983).

The concrete tunnel ends in approximately 70 metres of water on a sandy sea bed. In a 200 m. wide zone near the coast, extending to a depth of 30 m, the sea bed consists of stones. Strong wave activity has removed all the loose material except for stones. Between this zone of stones and the sandy bottom at the end of the concrete tunnel the sea bottom has the same rugged topography as on land, i.e. rocky knobs and knolls with loose material in between in the depressions (pers. comm. H. Lavik, Statoil informasjonsavdeling 1983).

Environmental aspects

The landfall area is shown on the air photograph which was taken on the 14th of May 1982, Fig. 9. The two main features that have an impact on the environment are the stone quarry (100 metres from the shore) and the landfall: the concrete tunnel with a breakwater on each side. In addition a new road about 450 metres long has been built. The quarry is triangular with 150 metres long sides and has a low rock wall at one side. The quarry provided the material for the road, the landing site and the breakwaters.

In a country with numerous rocky road cuttings and a large number of stone quarries with rock walls, the resulting aesthetic impact of the quarry did not raise any particular issues during the discussion of conservation or restoration of landscape and environment. Quarries are normally left as they are when they are closed down. Some regulations have been established during the last few years concerning what to do when a quarry is closed down. At Kalstø a part of the quarry will be used for engineering work entailed in the commissioning of the pipeline, another part will be kept open as a quarry for future needs and the rest will be cleaned up and restored. A landscape architect firm has got the responsibility to restore the landfall area and along the trench between Kalstø and Kårstø, although the actual restoration plans are not yet available (pers. comm. H. Lavik, Statoil informasjonsavdeling 1983). Some steep slopes will probably be levelled and soil left-over from the trench or from one of the many bogs in the island of Karmøy will be used to cover some of these excavations. The landward part of
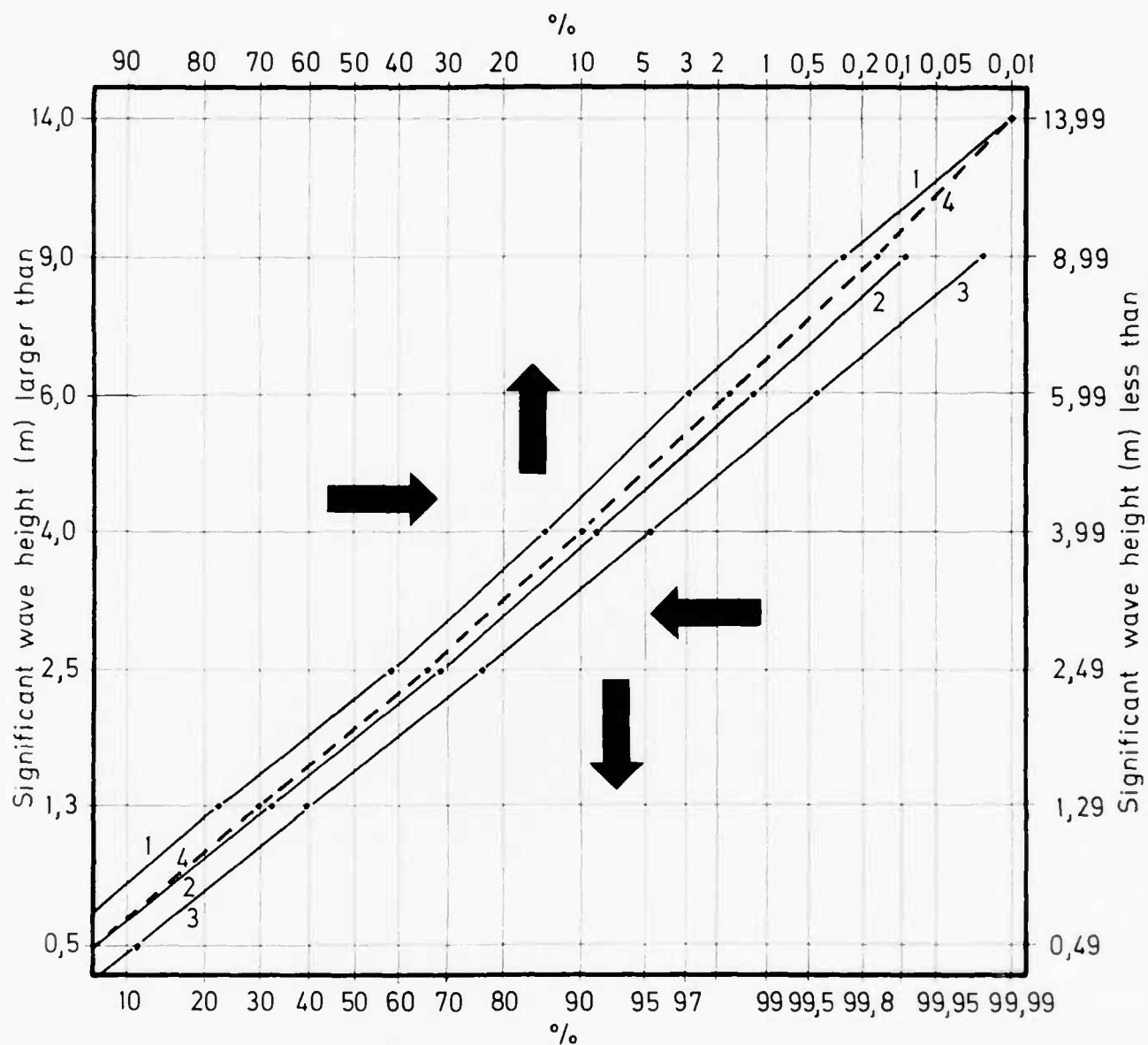
Fig. 5 The probability diagram of significant wave heights at
Utsira. 1: October - February, 2: March, April and
September, 3: May - August and 4: mean of the year.
Source: Håland & Småland 1980.
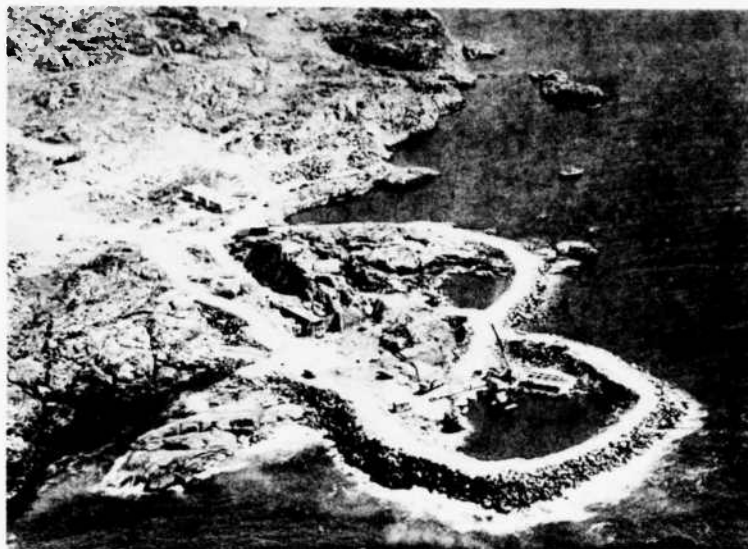
Fig. 6   The construction of the landfall during the summer
         1982.   Source: Statoil, 1982.   Karstø, informasjon om
         Statpipe.   Årgang 1, no. 2.

Fig. 7   The concrete tunnel.   Source: Statoil informasjonsavdeling,
         1983.   Statpipe.   The brochure.

Fig. 10   The landfall and the concrete tunnel the 1st of October
         1982.   Source: Statoil informasjonavdeling, 1983.
         Statpipe.

The Kalstø Landfall
The island of Karmøy

From To Ekofisk and Emden
Statfjord and Gullfaks
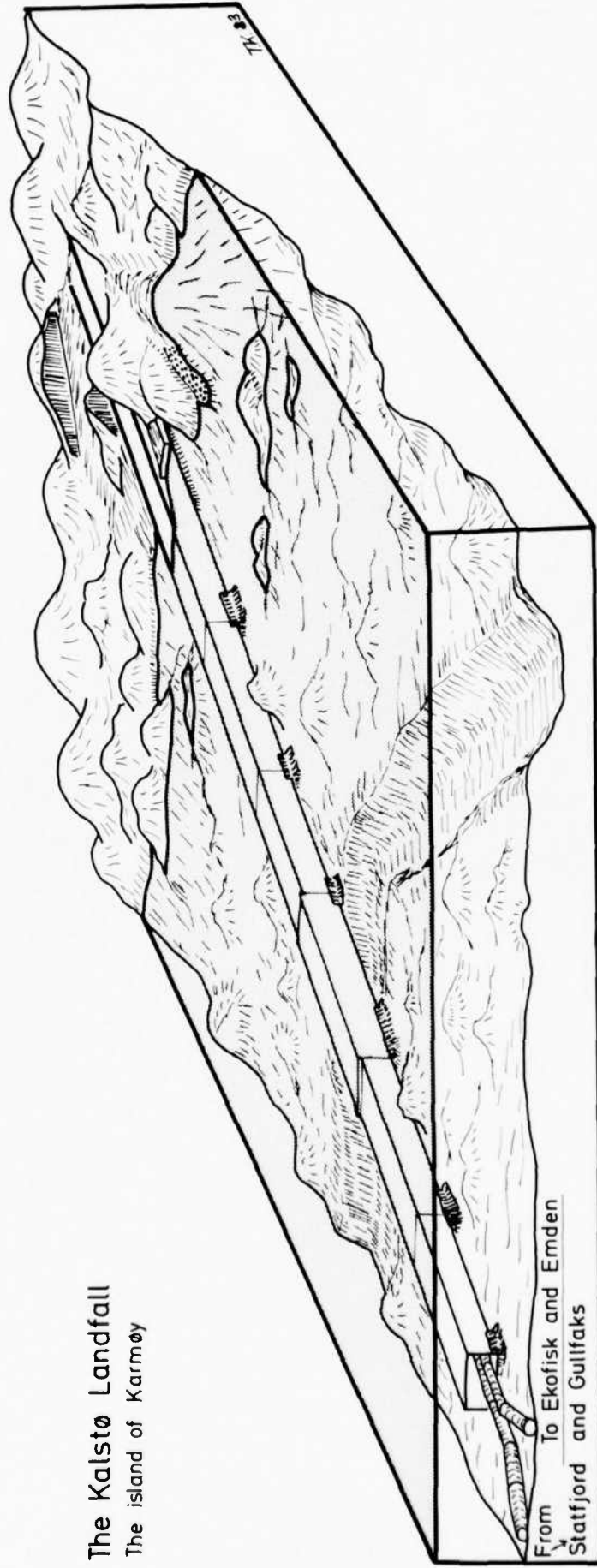
Fig. 8 Sketch illustrating the landfall and the concrete tunnel.

Fig. 9   Air photo of the landfall area, 14th of May 1982.
Photo: Fjellanger Widerøe.

200 m

the concrete tunnel where the landfall goes through a rock knoll will be treated in the same way.

The work on the trench was not started when the air photograph was taken, but from the air photograph (Fig. 9) it is obvious that the trench through such terrain will have a significant affect on the landscape, but, in time, it is likely that revegetation will occur and the impact will be minimal.

The breakwaters were removed at the end of September 1982, although a short breakwater was left on the southern side to protect against waves from that direction. At the landfall the concrete tunnel will emerge gently from the sea, Fig. 10, and gradually, over a length of 100 metres, enter into the trench. The landfall, which is only 30 metres wide and between 120 and 140 metres long, occupies only a small area. Ultimately the appearance of the area will include the stone quarry, the concrete tunnel, the levelled surface along it and the short breakwater to the south, Fig. 10.

On the whole the landfall and the quarry affects only a small part of the coast. In the landfall area there are 5 small farms, of which one is disused and the other 4 run on marginal basis, some few scattered houses and the small village of Kvalavåg, Fig. 2. The Haugesund air field is 1.5 km to the north and northeast, Fig. 2. The people living in the area have a small harbour at Kvalavåg, behind a mole, focusing the use of the coast at this point. The northernmost of the farms has two boat-houses with landing stages. The recreational use of this coastal stretch is also minimal. This outer unprotected coast is avoided by sailors and boatsmen, who prefer to go through the sound east of the island of Karmøy. Fishing from small boats and from the rocky shore and strolling along the shore are the only use of this part of the coast.

The concentration of people on the island of Karmøy is found further to the south on the west coast i.e. at Veavågen and Åkrahamn, at the southern-most point at Skudeneshavn and along the eastern coast at Kopervik, Fig. 3. The similar coast with the same type of shores and even a sandy beach at Åkrahamn with easy access offer the people good opportunities to use the coast of the island elsewhere than in the landfall area. As the landfall area has a remote situation on the island very few go there for fishing and strolling. Thus the landfall will have little influence on the coastal environment and its use.

The landfalls of Scotland at Cruden Bay and St. Fergus are both on a sandy beach coast. In Denmark the landfall at Henne strand will also be through a sand beach. The landfall in West-Germany at Emden is through a salt marsh area. Ritchie (1980) described and discussed the Scottish landfalls and their environmental aspects. The restoration of the dune- and inland forms and vegetation have been most successful at Cruden Bay and St. Fergus, even though the vegetation in parts of St. Fergus has not yet regained its original appearance. On a salt marsh or a sandy beach coast the possibilities of restoration appear to be better than on a rocky coast although the landfalls associated with Sullom Voe in Shetland are now relatively difficult to detect.

Along the Norwegian coast there is bound to be some visible effects of a pipeline landfall. The engineering solution of the concrete tunnel appears to combine easy pipe-pulling with minimal alteration of the

shore-zone. The tunnel also provides for strong protection against wave attack on the landfall. The relatively small area involved, the minor changes to the landforms and the relatively minor amount of new constructions do not affect the landscape much – and the planned restoration is likely to reduce the visual impact further. Compared with the airfield or the aluminium plant at Kopervik and the Gas Terminal at Kårstø the actual landfall site, like those in Scotland, is on a quite different scale which when set against the wider coastal settings might even be described as negligible.

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ARTIFICIAL STRUCTURES ON A NORTH SEA COAST

THE BARRIER COAST AT TORSMINDE, DENMARK

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Introduction

Danish coasts facing the North Sea are dominated by sandy beaches
suspended between resistant projections such as moraine cliffs, reefs
of boulders and limestone promontories.   Several embayments, open
to the North Sea, have existed between Horns Rev (rev = reef) and Lodbjerg
(Fig. 1).   Owing to plentiful amounts of loose sediments, coastal
processes formed large offshore bars.   The bars developed into barriers
which closed the embayments.

Ringkøbing Fjord (fjord = embayment in this part of Denmark) and
Nissum Fjord are now connected with the North Sea by controlled channels
allowing the fresh water from the rivers to stream into the sea without
hindrance.   The barriers west of Limfjorden were rather stable in
position if not in existence.   From time to time the North Sea broke
through, during storms. and, after the storms possible gaps soon silted
up leaving the barrier unbroken.   The present outlet is kept artificially
open partly because of the trade in Limfjorden and partly to secure the
existence of the fishing port Thyborön.   Some small embayments were once
situated between the great embayments.   They are now more or less re-
claimed and have been changed to farming land.   They have no direct
connection to the North Sea and can hardly be recognized as old parts
of the sea.

Normally the name barrier, in Danish 'tange' appears in the plural form.
Two barriers exist west of Limfjorden but west of the other embayments
one barrier only stretches from north to south.   The plural form is
probably used because this part of Denmark was rather unpopulated.   The
farmers living north and south of the embayments must therefore have
regarded the barriers as a kind of no man's land.   Further, the barriers
were often penetrated by the sea and for this reason a barrier was a
rather uncertain connection between regions.   The name of the barrier
west of Nissum Fjord is Bøvling Klit (klit = dune or dune ridge).
Specifically, this name is connected with the northern part of the barrier.
To the south the eastern part of the barrier has the name Fjand Grönne
(grönne = the green).   The official name of the barriers is now
Torsmindetangerne, the Danish definite, plural form: The barriers of
Torsminde.   The last part of the name, 'minde', means mouth or gap.

Wind conditions and water level variations

The most frequent winds effecting the coast at Torsminde come from the
northwest.   The wind statistics are based on rather primitive recordings
from 1931-60.   In this period 18% of all winds came from the northwest.

On average winds from this direction occurred more than 1.5% of the year
for wind forces above 7.   During 18% of the year, wind effecting this
coast, exceeded wind force 5;   during 10% force 6 and during 4.4% force 7.
The resultant direction for wind forces above 6 lies within the sector
$287-293^{o}$, for all wind forces the resultant direction is 274°;   both under
the assumption that to construct resultant directions is a valid technique.

The water level variations depend on tide, wind set-up and runup of waves.
The tidal range at Torsminde is small, 0.6 m, but the effect of wind set-
up is rather great.   The total effect of tide and wind-set-up has been
estimated to have the following values: a water level of 2.8 m will occur
once every 25 years;   a water level of 3 m once every 50 years;   of 3.2 m
once in 100 years and 3.4 m once in 200 years.   The highest water level
during the periods 1938-44 and 1956-77 (3 m above Ordnance Datum) was
recorded in January 1976 at wind force 9-10.   The share of the runup of
waves is depending on the slope and varies with time and location.   Wave
recording has not been carried out at Torsminde, but at Hvide Sande 41 km
further to the south.   The order of wave heights can be illustrated by
the recordings from 20th January 1976, when the maximum height was 9.9 m
and the average height 2.9 m for a recorder situated in a water depth of
18 m.

Landscape

The barriers west of Nissum Fjord rest on postglacial, marine deposits
down to 10 m below surface followed by glacial deposits down to 20-40 m
below surface.   The barriers were probably built up during the Litorina
period by materials eroded in the moraine cliffs at Bovbjerg (Fig. 1)
north of the region.   Later on the barriers were covered with dunes.
To a high degree the dunes are now removed, again by wave action and wind
erosion.   For a long period the dune ridges were the most important
protection against flooding of the low lying areas east of barrier.
Originally the shallow embayment Nissum Fjord had an area of 77 km^2 with
an average depth of approximately 2 m.   The catchment area is 1700 km^2,
from which the fresh water normally ran to the North Sea through temporary
channels in the barrier.   Sometimes the channels silted-up and the meadows
around the embayment were flooded by inwater until the water level was so
high that the barrier could be penetrated again.   From time to time the
North Sea penetrated the barrier and the meadows were flooded with salt
water, but as soon as the level was normal in the North Sea the drainage
of the embayment and its surroundings were satisfactory.   The only,
almost permanent outlet is situated at Torsminde and was regularly open
in 1741-1804.   Since 1804 a channel has been kept by occasional dredging.

Historical development

About 1840 efforts were made to drain the entire embayment for land
reclamation purposes and for maintenance of a permanent outlet.   Sluices
were constructed in 1860, renewed in 1863-65 and at last in 1868-70 the
construction was stable enough.   This sluice was situated north of the
old outlet at Torsminde (Fig. 3) and is now a part of the present sluice.
At the same time as the construction of the first sluice, the old outlet
was closed with a dike and several small dikes were constructed along
the coast to prevent flooding of the barrier.   The reclamation works
started in the southeastern corner of the embayment.   Here a part of the
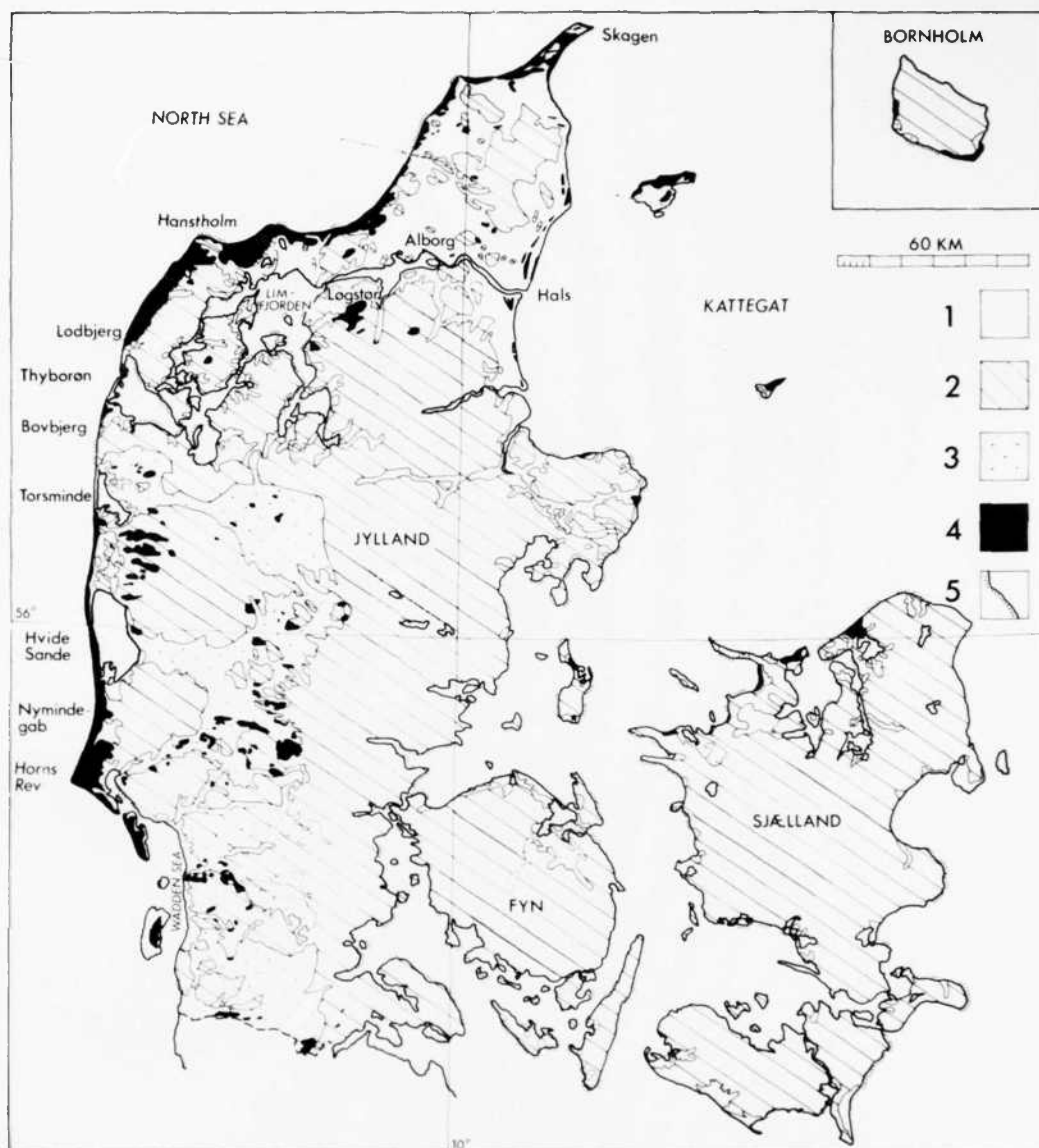
Fig. 1. Locational map of Denmark with a simplified view of the
surface deposits. 1, lifted sea floor and, along the coasts of
the Wadden Sea, salt marsh. 2, moraine deposits. 3, fluvial
deposits. 4, blown sand. 5, coastal cliffs.
The great embayments separated from the North Sea by barriers
are the western part of Limfjorden (Nissum Bredning) with the
outlet at Thyborøn, Nissum Fjord with the outlet at Torsminde
and Ringkøbing Fjord with the outlet at Hvide Sande. Nymindegab
was the old outlet.
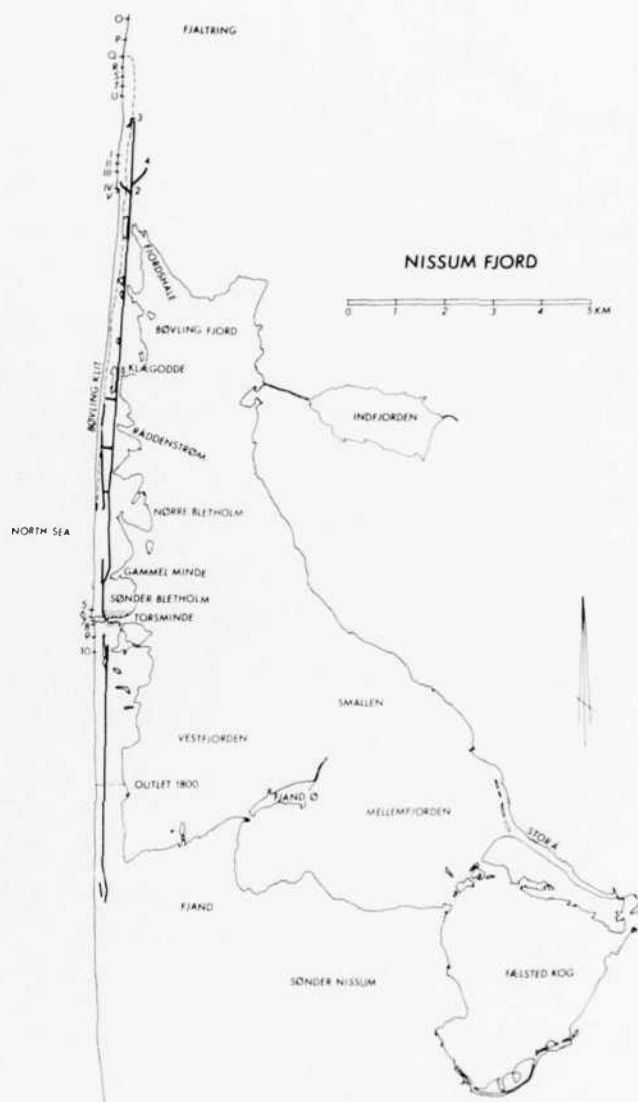
Fig. 2. Nissum Fjord. The map shows the shoreline from the ordnance map 1:50.000, revised in 1958. The shoreline from 1978 has been indicated with a hatched line. The dike between the points 1-2 was constructed in 1941-49 and extended to point 3 in 1952. In 1974 the section 2-3 had to be replaced by the section 2-4, owing to the coastal erosion. The groynes R-U and I-V have completely disappeared. The jetties supporting the outlet are seen at 6 and 7 respectively. 5 and 8-10 are groynes. Several old gaps can be seen in the barrier. The village of Torsminde is indicated with a hatched area. Faelsted Kog (kog - polder) was completely reclaimed but later abandoned. The next area to be reclaimed was Mellemfjorden. Remains of dikes can still be seen.
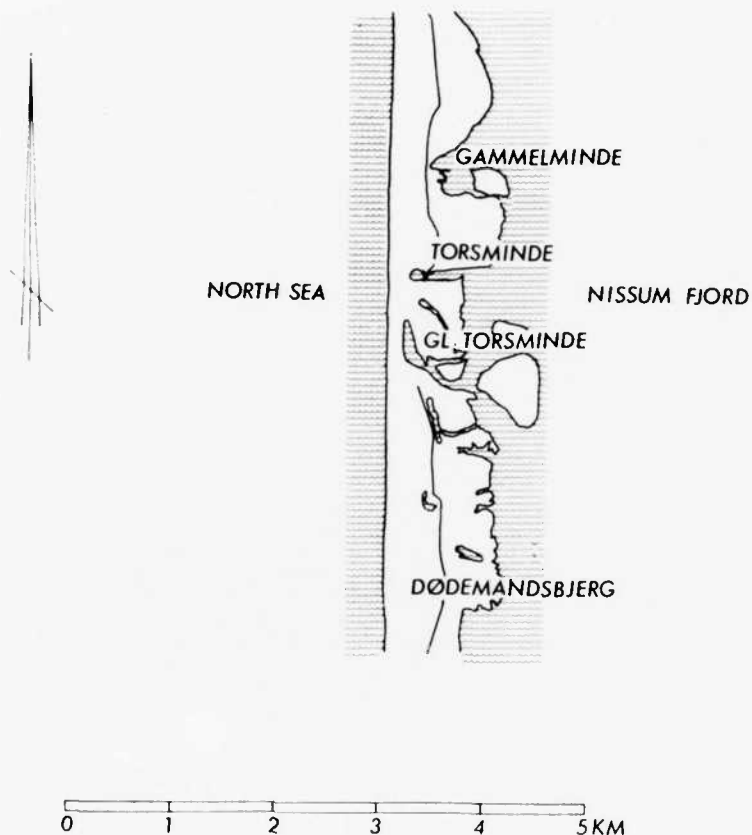
Fig. 3. *Torsminde according to the ordnance map 1:40.000 revised in 1917. At this time a proper outlet did not exist at all. The excess of fresh water from the rivers simply had to find its way across the barrier at gl. Torsminde (gl. = gamle = old). The only indication of the outlet is the lack of the road (the thick line). At this time the sluice constructed 1868-70 was temporarily abandoned (1889-1931). Dødemandsbjerg ("death man's hill") is a burial place for seamen. Drowned persons were normally buried on local graveyards. In case of long distance to a church the funeral very often took place in the dunes, then named Dødemandsbjerg.*

embayment was pumped and changed to farming land, Felsted Kog (kog = polder). However, the polder had to be given up after some years owing to the sandy soils being unsuitable for farming and because the dikes were far too weak. The only importance of these land reclamation works was the controlled outlet preventing floodings of the meadows along the embayment. At last all reclamation works were stopped and the old outlet was re-opened. Thus the sluice constructed in 1868-70 remained isolated and useless during the period 1889-1932 (Fig. 3) when a new outlet was excavated.

Harbours

Formerly it was impossible to find any beach landing sheltered against winds from western directions between Horns Rev and Skagen. Thus a need for harbours existed, especially for emergencies. For obvious reasons the outlets from the embayments were utilized as harbours, in particular if the Department of Hydraulic Engineering (the Danish name for this Department is now Kystinspektoratet, 'the inspectorate of coasts') started coastal protection works introducing facilities such as small provisional piers and jetties. The fishermen's use of the outlets at Thyborön, Torsminde and Nymindegab, the old outlet from Ringköbing Fjord (Fig. 1), called for further facilities because many fishermen moved to these places attracted by the better possibilities compared to the normal beach landings. Used to small boats and small catches the fishermen soon experienced the advantages of sheltered landings, in particular because they now could use larger vessels. Thus the mere existence of a shelter created a demand for harbours, again attracting more people and soon local fishermen's villages grew up. In this way the authorities were almost forced to construct permanent harbours in spite of increasing problems concerning the outlets as weak points on a very weak shoreline.

If the fishermen were reluctant to leave their sheltered, but unstable landings in the outlet, then the farmers were more reluctant to accept floodings of their fields and meadows around the embayment again. Consequently the sluice had to be re-established. The original sluice was extended and a ship lock constructed in 1931 (Fig. 4). Then a canal was excavated and the old outlet, Gl. Torsminde (Fig. 10) was closed for ever. To prevent the new outlet from silting up owing to the sediment transport along the coast, jetties on both sides of the outlet were established (Fig. 5-8).

On the Danish west coast any unprotected outlet drain must be regarded as temporary. From time to time the water will break through at weak points in the barrier because of the high water level either in the North Sea owing to storms, or in the embayment owing to fresh water input. Regardless of the cause most breaches soon silt up, just leaving characteristic patterns in the meadows (Fig. 5). Dredging can stabilize an outlet with regard to time but not to position. The only solution is a channel stabilized with parallel works and jetties stretching to an acceptable depth in the sea and finally a sluice to control the amounts of water passing the channel. After these measures were carried out at Torsminde it was necessary to construct a groyne north of the northern jetty (Fig. 6, 5) in an attempt to reduce the transport of sediments that were entering the dredged channel. A great problem is the formation of bars at the entrance to the channel because such shallowing-up is very dangerous to boats entering the harbour.

Obviously the constructions have caused increased erosion south of the outlet (Fig. 5, 7 and 8). Small groynes were constructed here, but they did not solve the problem. On the contrary, they contributed to an increased erosion on the very weak part of the barrier south of Torsminde. On the other hand it was absolutely necessary to prevent too much erosion of the shoreline immediately to the south of the outlet to protect the village and the harbour (Fig. 5) even at the expense of the stability of the coast further to the south. The bar at the entrance to the channel is also a delicate problem. At times the depth over the bar is so shallow that it is possible to cross the channel in long rubber boots. An extension of the jetties further to the west will lead to increased erosion owing to the creation of eddies at the terminal point of jetties. The only solution seems to be frequent dredging in the outlet and beach nourishment compensating for the erosion south of the jetties.

The sea water at Torsminde is clean and the place is an excellent position for a fishing harbour. However, the entrance to the embayment offered very little room for fishing vessels. Further the lock only allows very small boats into the embayment because the lock has the shape of a tube, closed upwards (Fig. 4). In 1967 a new fishing harbour was constructed just south of the sluice and with the entrance in the channel (Fig. 5).

Since it was vital for one fishing industry the basin had to be excavated in the very weak barrier in spite of the risk to the coast. Just a narrow rim of sand protects the harbour against the North Sea (Fig. 5 and 9). Thus the problems with regard to the protection of the shoreline remain the same, or they may even have increased. The worst problem of all is that the erosion of the barrier appears to be unstoppable in spite of the great efforts carried out by the Kystinspektoratet.

Shoreline development

The development along the North Sea coast here is closely connected with the corresponding development of neighbouring shorelines to the north and to the south of Nissum Fjord. The moraine cliff at Bovbjerg (Fig. 2) is a kind of a fixed point in the coastal protection. To protect the barriers west of Limfjorden the construction of groynes had to be started in 1876 north of Bovbjerg. Immediately the shoreline south of the groyne system was eroded owing to the southerly sediment movement. As time went on the groyne protection system had to be extended still further to the south until the constructions had to be stopped near the northern part of the barrier west of Nissum Fjord. If not, the erosional area would have moved to the barrier shore.

The west coast facing the North Sea, and in particular the barriers, have been carefully observed by Kystinspektoratet since 1899 by means of soundings along fixed lines at right angles to the shoreline and at intervals of 600-1000 m. The soundings have been carried out several times every year, up to 12 times in one year. In spite of the many observations it is still difficult to estimate the size of the sediment transport. However, the resulting transport has been calculated at approximately 500.000 m^3/year along the barrier west of Nissum Fjord.

*Fig. 4. The sluice at Torsminde with all valves open, seen from
the southern jetty in 1983. The sluice was constructed in 1868-
70 and controlled the outlet until 1889. Then it remained abondoned
and isolated until 1931 in which year the sluice was extended with
two sluice valves and a shiplock and re-opened. The gantry crane
to the right lifts the lock gate, on the photography hanging halfway
in the water. The entrance to the present fishing port is to the
far right.*
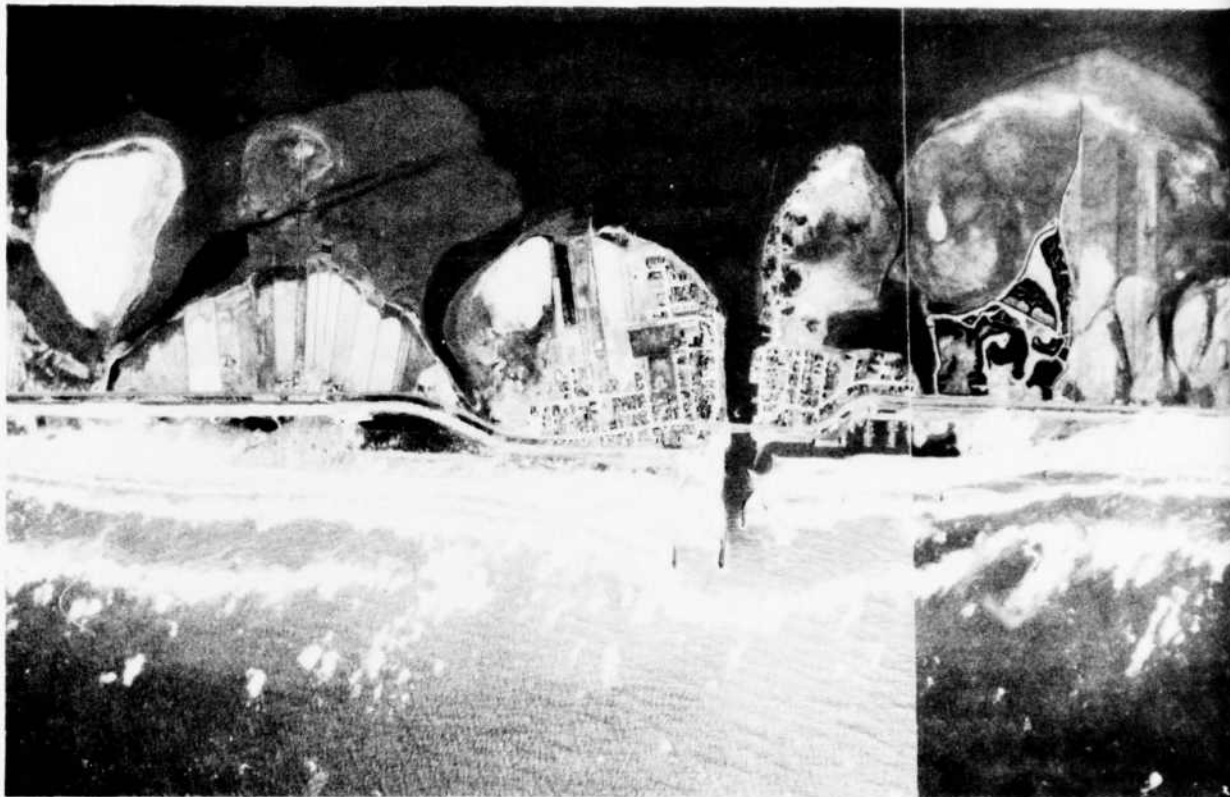
Fig. 5.   Aerial photography approx. 1:25.000 of the Torsminde
region.   The village is situated on both sides of the channel
east of the sluice.   The old outlet, closed in 1931, is seen
south of the village.   The fishing port is situated west of the
dike, to the south of the outlet.   In the meadows east of the
dike several old breaches can be traced.   The surf lines indicate
the position of offshore bars.   In the southern part of the
photograph blown sand has covered the dike and the road east of
the dike, but the dike itself is unbroken.   The photograph was
taken in April 1982.   Aerial photograph: Geodaetisk Institut
(D 8201 H, no. 219 and D 8210 J no. 156, 1982).   Reproduced by
permission of Geodaetisk Institut (A 368/83). Copyright.

Fig. 6.   The outlet to the North Sea from Nissum Fjord seen from
the south in April 1983.   The short jetties flanking the outlet
are seen in the central part of the photograph.   In the far
background the groyne north of the outlet (5, Fig. 2) can be seen.
The surface in the foreground has been built up artificially.   The
tube was placed in connection with experimental works on nourishing
the beach south of the outlet with sand, dredged in the fishing port.
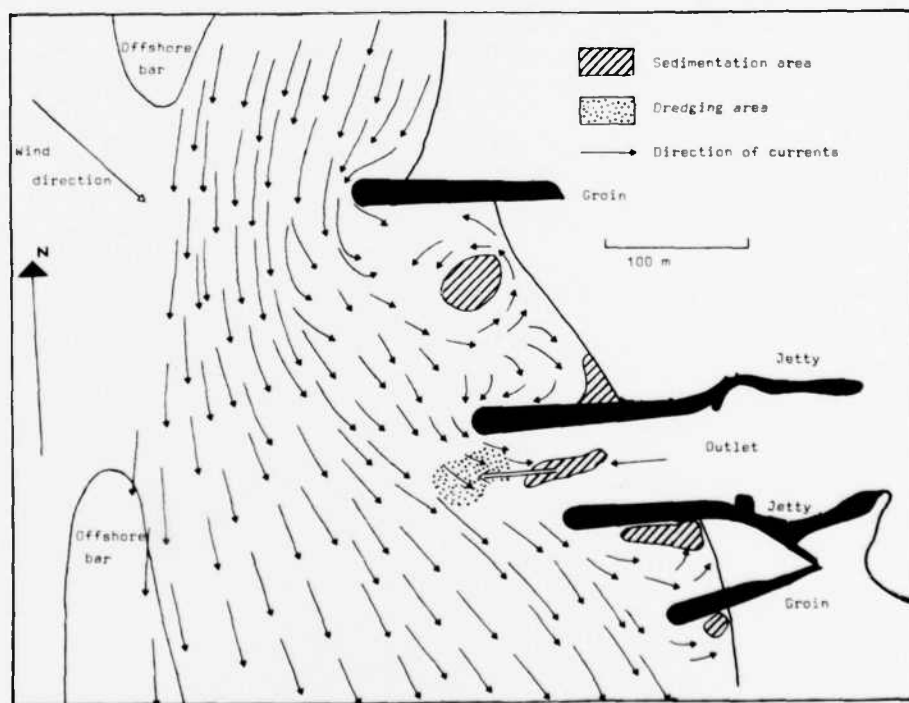
Fig. 7.   Sediment transport during wind from northwest.
Groynes and jetties are black.   The sediments deposited in the
outlet are transported towards the sea owing to the water
streaming out from the embayment.   Model experiments have been
done, but it is difficult to find a solution considering the
navigational conditions as well as protection of the barrier to
the south of the outlet.   A navigable channel calls for an
extension of the jetties and they have been extended to the west
in consequence of the experiments.   However, the best solution
seen from a coastal protectional point of view would have been a
removal of the projections into the sea.   Kystinspektoratet (1978).

Fig. 8.   The coast south of the outlet at Torsminde seen from
the southern jetty in April 1983.   The coastal cliff has been
supplied with gravel, but in the background the eroded cliff can
still be seen.   The groynes (Fig. 2, 8 and 9) are constructed
1939-45 in an attempt to prevent erosion south of the outlet.
It is clearly seen that the groynes did not work.   The beach- and
cliff nourishment is very expensive, but the harbour basin is
situated just 150 m east of the cliff (Fig. 5).   The material
for beach nourishment here has been excavated north of the northern
jetty, thus reducing the transport of sediment ending up in the
outlet.

Fig. 9.   The harbour basin in Torsminde seen from the south in
April 1983.   The beach facing the North Sea is less than 150 m
to the left.   During easterly storms only the tall poles are
above the sea level.

On the whole the beach is receding but with large variations in rate.
Normally the construction of groynes will stop the recession of the
coastline proper.   However, the consequence is a steeper profile because
the sea floor outside the groynes is still eroded, but along the barrier
coast the slope is rather stable.

Based on the observations mentioned above Kystinspektoratet estimated in
1978 the development of the barrier shoreline as follows:

The shoreline at:	Expected velocity of recession m/year	m^3/year/m shoreline
Bovbjerg	0-0.6	0-10
Fjaltring	10.7	182
Opposite Fjordshale	5.7	97
North of Torsminde	2.1	36
South of Torsminde	3.9	66
Opposite Fjand	3.9	66
South of Fjand	2.9	49

The right column shows the average volume of sand removed from the coast.
Along the entire shoreline mentioned above the net erosion is 650.000 m^3
each year.   The proportions of the eroded sediments that are either
transported to the sea or are transported southwards along the coast are
not known.

As soon as a part of the shoreline was protected by groynes the erosional
area moved to the lee side of the groyne system.   Groyne K, 2 km north
of Fjaltring (Fig. 2) was constructed in 1937 as the last one in the system
which was started north of Bovbjerg in 1909.   There was a gap between
groyne H and the groyne systems further to the south, Q - U, constructed
in 1934-36 and I - V, constructed in 1931-32 (Fig. 2).   Very soon the
erosion south of groyne K increased to 10 m/year.   The strong erosion
on the lee side of the groynes continued between K and Q, between U and
I and south of V.   The shoreline receded to such a degree that the groynes
south of Q had to be abandoned in 1951.   In 1963 the gap between the
groynes K and Q was closed with a new groyne system.   Then the erosional
area moved to the shoreline between the groynes O and Q, in particular
south of groyne Q (Fig. 11).   Lee-side erosion of groynes has been
investigated by Bruun (1953) who paid special interest to groyne systems
between Bovbjerg and Torsminde.

Kystinspektoratet could not take the responsibility for moving the
erosional area further to the south by extending the groyne systems
southwards.   The groynes north of M are now maintained fully, while the
groynes O - Q have been shortened and groyne Q has been cut off to a lower
height in an attempt to create a smoother   transition to the unprotected
coast to the south.   The shortening of the groynes was essential, because
the distance between the westernmost point of groyne Q and the coast had
increased to such a size that the sediments were transported directly south-
wards across the bay formed by the coastal protection pattern thus
depriving the beach of sediments.   South of the groyne

systems the shoreline is still very vulnerable.   In 1974 a new dike
east of the old dike (Fig. 2) had to be constructed and, in fact, some
farming land was given up.   As it appears from Fig. 11 the coast at
groyne Q is still heavily eroded and new measures are taken to protect
the shoreline.   Boulders of a very high density basalt are imported
from Norway.   They are placed on the beach as artificial reefs
(Figs. 11 and 12).   Further, a nourishment of the beach with 200.000 m^3
of sand pumped to the shallow water in the shape of an offshore bar
was started in May 1983.   It is anticipated that further sediment
transport southwards along the beach can be done by the waves.

Many efforts have been done to maintain the fishing port and the
barriers.   A breakthrough from the North Sea would be a disaster
to the village, to the harbour, to the farming land near the embayment
and finally to the increasing number of holiday houses;   all activities
of great importance to the local economy.

Tourist activities are of growing significance in the local economy.
During the summer many people are attracted by the sandy beaches and
the dunes facing the North Sea.   Investments in tourist activities in
this region depend very much on the stability of the barrier.   Never-
the-less the tourists, in general, have very little understanding of
the local conditions and the menace from the North Sea.   In fact the
tourists themselves are rather a threat to the measures taken to protect
the shoreline and the dunes.   At the southern part of the barrier at
Fjand Grønne a recessed dike has been constructed a short distance to
the east of an old dike (Fig. 2).   Some few holiday cottages are situated
in the area between the dikes (Figs. 14 and 15).   Because of the holiday
cottages the old dike is still maintained.   Nevertheless the dike is
looked upon as a sort of a quarry, accessible to everybody who needs
gravel for repairing a road or for constructional purposes.   In case
of a breakthrough in the old dike the owners of the holiday cottages
would claim damages from the government.

The great problem in the efforts of keeping the barrier is the loose
sediments and the constantly changing environment.   The only tools
for resisting erosion are groynes, jetties, lateral constructions and
beach nourishment.   The last method is a very expensive countermeasure,
even if it is effective.   The maintenance of the shoreline has to be
continued incessantly because the shoreline and the dikes cannot resist
erosion, especially during high water levels in the North Sea.   In
spite of the beach nourishment the dikes have to be reconstructed
regularly (Figs. 11, 12 and 13).   In a not too distant future a new
dike east of the present must be constructed.   In that case it is
difficult to see how it shall be possible to keep Torsminde village
and fishing port in existence because they will form a projection out
of the future shoreline alignment.   Originally the dikes were estimated
to resist flooding at a realistic high water level once every 150-200
years.   Now the estimate is once every 10-150 years, depending on the
height of the beach and the width of the barrier.

The last problem to be mentioned here is expense.   At 1977 price levels
the expenses were estimated as follows, (in Danish crowns).

Fig. 10.   The old outlet, Torsmindestrømmen (strøm = stream),
closed in 1931.   The photograph was taken in April 1983 from
northeast from the dike.   The road behind the dike is seen in
the foreground.   The houses are situated very close to the water
level in the embayment.

Fig. 11.   Groyne Q in the background opposite the houses seen
from the south in April 1983.   The small embayment, eroded on
the lee side of the groyne, is clearly seen.   On the beach heaps
of basalt boulders have been placed and small tombolos connecting
the cliff with the artificial reefs have been created.   The surface
in the foreground with the eroded side, facing west, is an artificial
coastal cliff built in attempt to protect farming land and houses
opposite point 3, Fig. 2.

Fig. 12.   The dike with the road to the left north of Torsminde
photographed towards south in April 1983.   The dike is under re-
construction.   Heaps of building materials are seen on the beach.
The dark spots to the far right are artificial boulder reefs.   The
dike is planted with Marram Grass to prevent aeolean sand transport.

Fig. 13.   Constructional works on the northern part of the barrier
seen from the south in April 1983.   The dike has newly been re-
established and planted with Marram Grass, but the foot of the dike
has recently been strongly eroded.   A wall, supporting the foot of
the dike, is under construction.   Such measures have to be carried
out along a shoreline of 18 km.   See also Fig. 12.   In the far
background the groyne O can be seen.
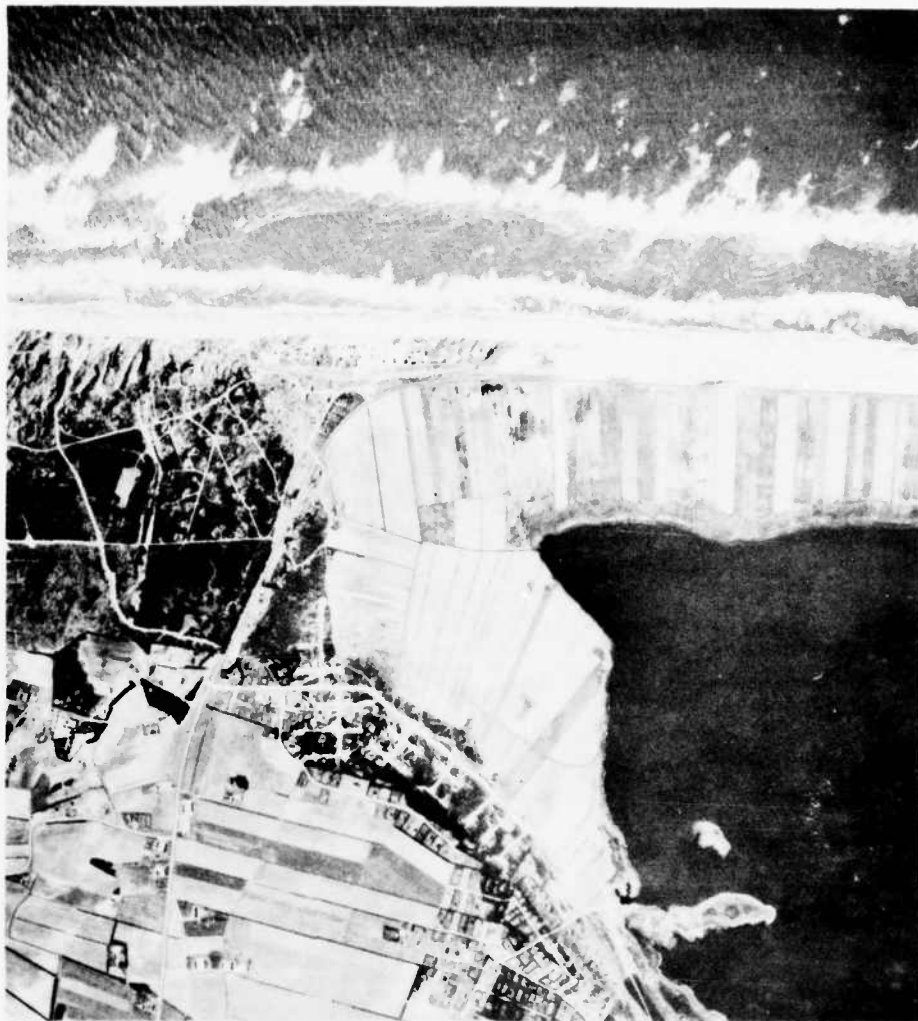
Fig. 14. Aerial Photography of Nissum Fjord near Fjand (Fig. 2)
in April 1983. The regular field pattern indicate the meadows
along the embayment. The road and the present dike are situated
immediately west of the fields. In the northern part of the
photograph only sand can be seen. The striations are wind
fences (Fig. 15) the dunes are regularly planted with Marram
Grass to prevent wind erosion (Figs. 12, 13 and 15). The holiday
cottage area between the old and the new dike is situated at the
bend of the road. In some places blown sand has covered the dike
and the road. It is impossible to see any difference in the sand
surface on the aerial photograph, but in fact no damage can be
seen in the landscape. Aerial photography: Feodaetisk Institut
(D 8201 K, no. 151, 1982. Reproduced by permission of Geodaetisk
Institut A 368/83). Copyright.

Fig. 15.   The holiday cottages area in April 1983 seen from the
north, west of the old dike (Fig. 14).   The recessed dike cannot
be seen.   The westernmost row of houses is very close to the newly
re-established dike.   The marks from the machines can still be
seen.   The two wind fences consist of brushwood.   To the left of
the wind fences rows of Marram Grass are planted directly in the
sand, the most frequent way of stopping sand movements in the dunes.

	Millions of Danish crowns	
	Maintainance	Initial expenditure
Normal maintainance of existing conditions	1.0	
Shortsighted protection (Appr. 10 years)	5.5	2.4
Longsighted protection (25 - 40 years)	22.7	3.0
Total protection (at least 100 years)	38.4	10.4

It has to be mentioned that this coast is just a small part of the Danish west coast which calls for expensive measures to protect lives and properties.

Postscript

The problems concerning the existence of the barrier and the fishing port are of great importance to local people, of some importance to Danish authorities but, seen globally, just a very local case. For that reason very little has been written dealing with this interesting case of coastal geomorphology. Further the greater part of the literature is in Danish. The most important papers are the commissional reports and the main report was carried out by Kystinspektoratet.

Acknowledgements

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<u>KEY TO **LANDSAT** IMAGE PLATES TO</u>

<u>ACCOMPANY PAPER BY **ODELL**, **STOVE** AND **WRIGHT**</u>

PLATE 1a   Multispectral (MSS 4, 5 and 7), manually stretched false-colour
            composite (FCC) image from LANDSAT 1, acquired on 11 March, 1973,
            at 10.30 GMT (Approx. scale 1:70,000).

PLATE 1b   Multi-temporal FCC (stretched) of three band 7 images from LANDSAT 3
            scenes acquired on 24 April, 12 May and 30 May, 1982, during the
            AGRISPINE Project. Each scene (normally acquired at 10.30 GMT) was
            subsequently transmitted to the ground receiving station at
            Kiruna (Sweden) where system corrections were applied before 12.00
            GMT, and then each scene was transmitted back into space to be
            relayed by the OTS telecommunications satellite to another
            receiving station at the National Remote Sensing Centre. The time
            slot for this relay was 12.30 to 13.00 GMT on the same day.
            (Aprox. scale 1:70,000)

PLATE 1c   Multi-temporal FCC of three band 4 images, acquired by LANDSAT 2
            on 4 July, 1977 and 12 July, 1979 and LANDSAT 3 on 12 May, 1982.
            (Approx. scale 1:140,000)

PLATE 1d   Multi-temporal FCC of three band 7 images acquired by LANDSAT 1 on
            11 March, 1973, LANDSAT 2 on 4 July, 1977 and LANDSAT 3 on 12 May, 1982.
            (Approx. scale 1:140,000)

PLATE 2a   Multispectral (MSS 4, 5 and 7) manually stretch FCC image from
            LANDSAT 2, acquired on 4 July, 1977.
            (Approx. scale 1:100,000)

PLATE 2b   Multispectral (MSS 4, 5 and 7), manually stretched FCC image from
            LANDSAT 2, acquired on 12 July, 1979 (<u>Note</u>: an extra stretch has
            been applied in the sea to enhance the sea bed in the in-shore
            zone and this has consequently degraded some of the terrain features).
            (Approx. scale 1:100,000)

PLATE 2c   Multispectral (MSS 4, 5 and 7), manually stretched FCC image from
            LANDSAT 3, acquired on 12 May, 1982.
            (Approx. scale 1:100,000)

PLATE 2d   Multi-temporal FCC of three band 5 images, acquired by LANDSAT 2 on
            4 July, 1977, and 12 July, 1979 and LANDSAT 3 on 12 May, 1982.
            (Approx. scale 1:100,000)

GEOMORPHOLOGICAL SYMBOLS

ASSOCIATED WITH ROCK SURFACES

▶ Major steep slope

◁ Steep slope or cliff with lower part in bare rock

▬ ▬ Ridge crest

+ + Rock exposure

Ⓣ Torridonian rock

Ⓛ Lewisian rock

ASSOCIATED WITH SAND SURFACES

≡ Smooth vegetated sand surface (indicates main slope of ground)

≋ Undulating vegetated sand surface (includes machair, dunes and sandhills)

⫶⫶ Transition zone

∇ ∇ Dune edge (growing)

∇ ∇ Dune edge (eroding)

☀ Sand hill

▭ Bare sand

⊂ Blowout or other erosion scar

▭▭ Ridge crest (in sand)

▷ Major slope (in sand)

◁ Rock slope partly covered by blown sand

⌐ ⌐ Solifluction terracettes

℧ Slump

▬ Terrace edge

ϟ Flat surface

⫶⫶ Sand and scree fan

Selected contour lines in feet

Planimetry of geomorphological maps compiled from Ordnance Survey 1:10,500 plans

ASSOCIATED WITH SURFACES SUBJECT TO GLACIAL AND FLUVIO GLACIAL ACTION

▯ Erratic

△ Till

← — Axis of meltwater channel

▦ Outwash sands, gravel and shingle

ASSOCIATED WITH SURFACES SUBJECT TO MARINE ACTION

▼▼▼ Live cliff

▼▼ Dead cliff

▱ Abrasion platform

▭ Beach sand

▦ Shingle

▦ Cobbles

ᴑᴑᴑᴑᴑ Shingle cobble ridge

▬ Low and High Water spring tide marks

⌒ Cave

GENERAL

⋏ Marsh

⋏ Saltmarsh

⇌ Bridge

▭ Pier

▬⋯ Track / Road

·₂₉ Spot height (in feet)

↘ Slope gradient

▯ ▫ Buildings

↜ Stream or drainage ditch

↯ Waterfall

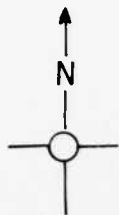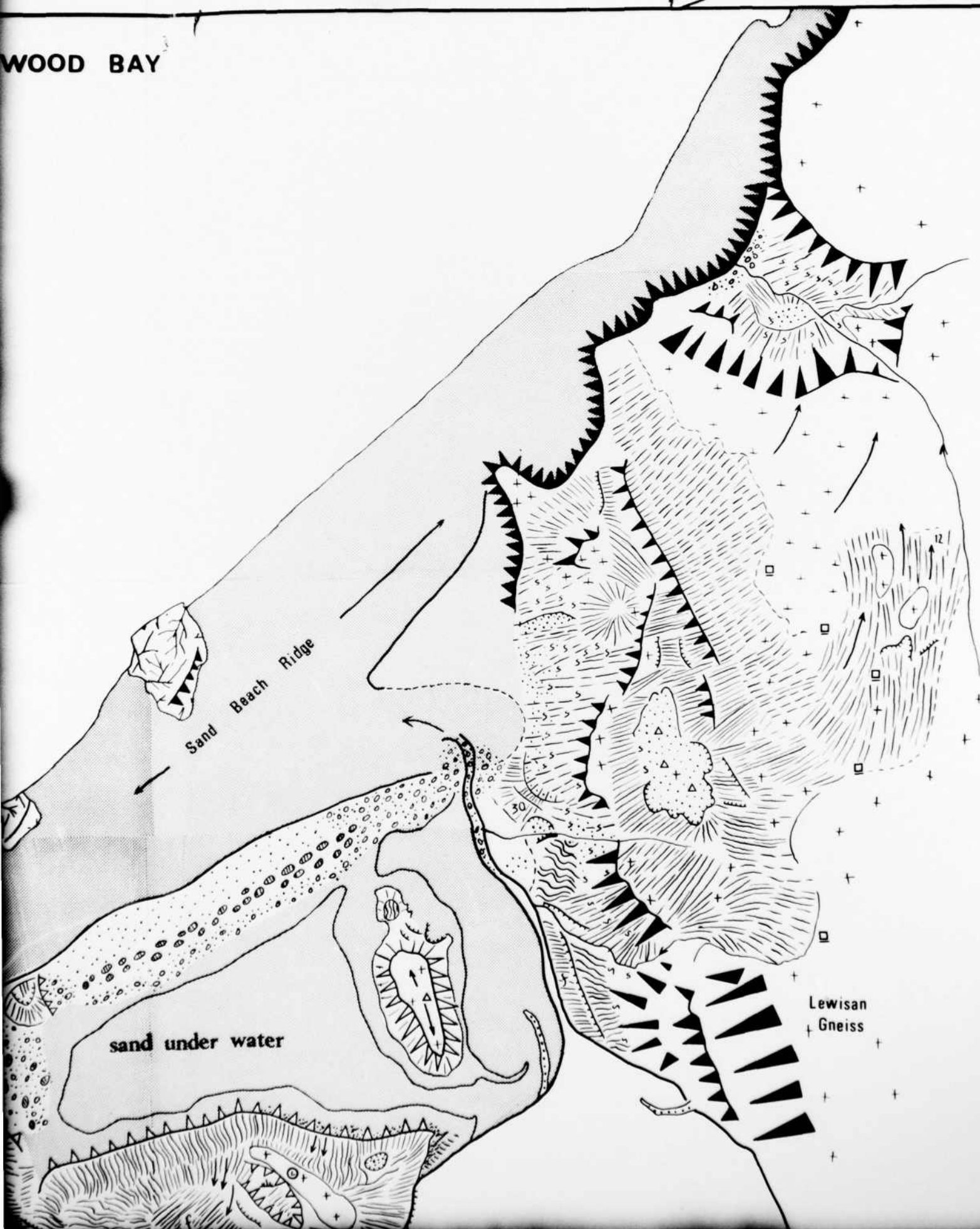⊗ ∪ Archaeological sites
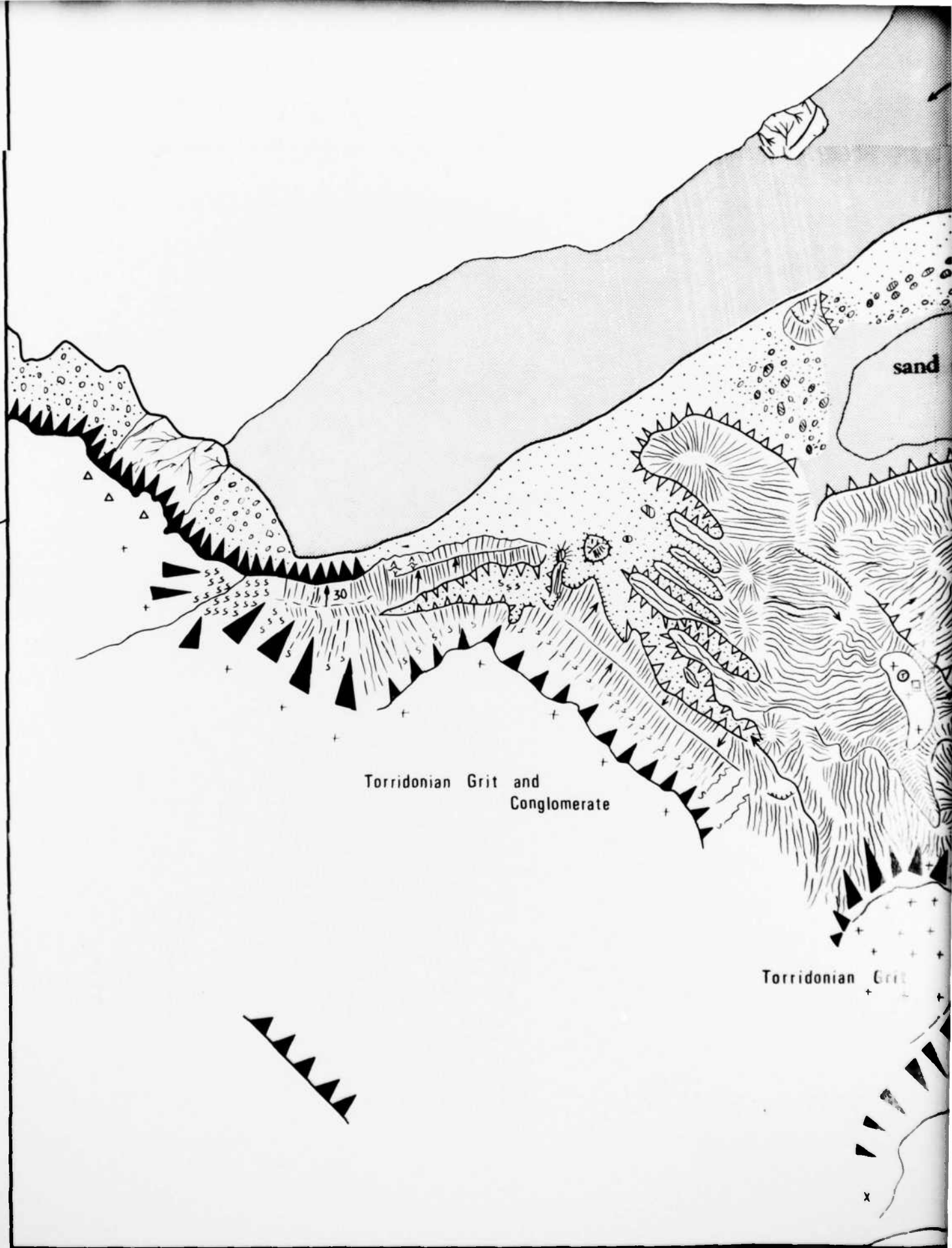
Plate 1a

Plate 1b
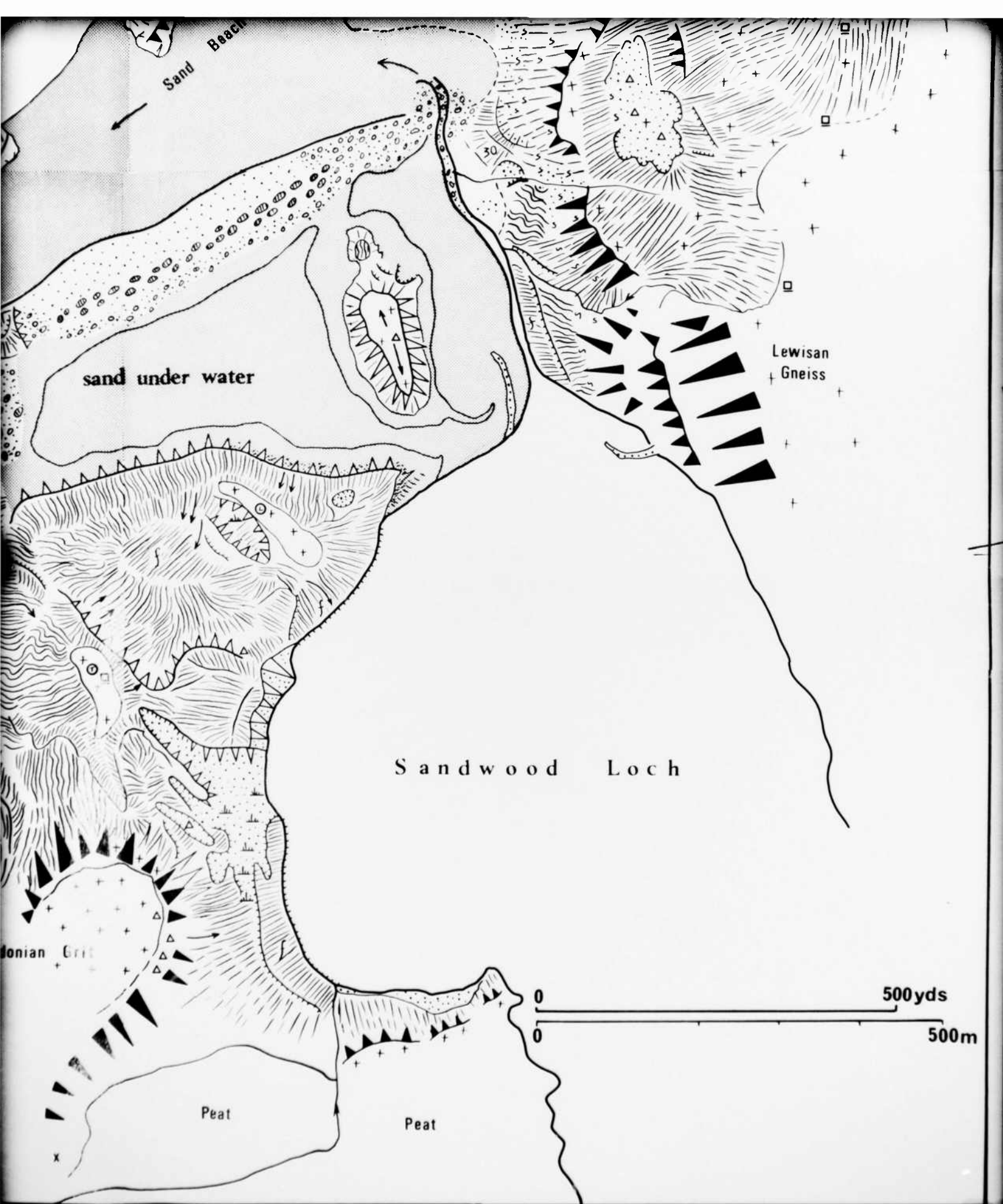
Plate 1c

Plate 1d

N

SANDWOOD BAY

sand u

Sand Beach Ridge

sand under water

30

12

Lewisan
Gneiss

sand

Torridonian Grit and
Conglomerate

Torridonian Grit

Sand Beach

sand under water

Lewisan
Gneiss

30

Sandwood   Loch

Caledonian Grit

Peat

Peat

0   500 yds
0   500 m