WEATHERING AND LANDFORM EVOLUTION IN NORTH-EAST SCOTLAND

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Weathering and Landform Evolution in North-East Scotland.

by

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SUMMARY

Weathered rock has been located at over 450 sites in north-east Scotland. Depths of weathering locally exceed 30m but the weathering front is often highly irregular. The incidence of weathering is spatially variable and weathering zones are identified which reflect the influence of geology, fracturing, slopes and patterns of glacial erosion.

Two weathering types, grusses and clayey grusses, are recognised after examination of granulometry, geochemistry and clay mineralogy. The grusses have low clay contents, high proportions of little-altered felspar and biotite, modest soluble base losses and heterogeneous clay mineral assemblages. The grusses are equivalent to the 'sandy weathering type' of Bakker (1967) and were formed mainly under the temperate environments of the late Pliocene and the early Pleistocene. The clayey grusses have elevated clay contents, high proportions of detrital quartz, high soluble base losses, kaolinite-illite bi-mineralic assemblages and may be rubefied. The clayey grusses formed under warmer environments than at present, probably in the Miocene.

The Buchan Gravels consist of two formations of separate age. The Windyhills Formation comprises fluvial gravels of Middle to Late Pliocene age. The Buchan Ridge Formation includes glacially-disturbed masses of fluviatile deposits of Late Miocene to Early Pliocene age.

The denudational history of the region is reconstructed using evidence from morphology, weathering types, and onshore and offshore

geology. In the Late Cretaceous, transgression into the Buchan area left a cover of Greensand and Chalk. In the Palaeocene, the eastern Grampians were uplifted and tilted but the eastern lowlands were simultaneously downwarped towards the outer Moray Firth. Western areas subsided after the Early Eocene, the Chalk was exposed and the Mid-Palaeogene etchplain developed under tropical environments. Differential movements recurred at the Oligo-Miocene boundary, with uplift and tilting west of the Bennachie-Fare Fracture and initiation of basin development. Further etching in the warm and stable Middle Miocene period led to the establishment of the main erosion surfaces. The Eastern Grampian Surface (450 - 750m) is an etchsurface produced by lowering of the Mid-Palaeogene etchplain. The Marginal Surface (280 - 370m) is derived from a Miocene etchplain that was raised and tilted gently eastwards in the late Neogene. Fragments of this surface are associated with clayey grusses and the Buchan Ridge gravels in central Buchan and the Buchan Surface (60 - 140m) has developed by lowering of this relief in the Pliocene. Drainage incision in the early Pleistocene led to development of younger forms along valleys. Repeated glaciation failed to greatly modify pre-existing relief.

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"It seems, indeed, not a little curious, that notwithstanding the amount of geological knowledge diffused through this country regarding the origins of the various systems and formations which lie beneath the surface, so much ignorance and uncertainty should exist with respect to the origin of the surface itself."

Sir Archibald Geikie,

"The Scenery of Scotland
Viewed in Connexion with
its Physical Geology"

London and Cambridge 1865.

To my wife.

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CHAPTER 1 Research Problems and Aims

1.1 Opportunities for study of relief development

Research into the preglacial origins of the relief of the Scottish Highlands has been seriously neglected in recent years. The last major studies were completed over 15 years ago (Linton 1951; Godard 1965; George 1966) and little new material has appeared (Sissons 1976). This lack of interest in long-term relief development stems partly from the belief that correlative deposits have been largely swept away by the Pleistocene glaciations (Sissons 1976). However the scarcity of recent studies also reflects the reaction against denudation chronology in British geomorphology and the dominance of short-term process studies (Dury 1983). Research into aspects of pre-Quaternary geomorphology has continued uninterrupted in Europe (Bakker and Levelt 1964; Gjessing 1967; Godard 1971; 1972; 1978; Birkenhauer 1972; Touraine 1972; Klein 1974; Peulvast 1978; Budel 1979; 1982; Lidmar-Bergstrom 1982) but it has been left mainly to French workers to pursue similar studies in the British Isles (Godard 1965; Reffay 1966; Battiau-Queney 1978; Reffay et al 1982). This lack of involvement by British workers in wider problems of relief development has recently been criticised (Thomas 1978) and the present project forms part of a minor resurgence of interest in the evolution of the British landscape (Davies and Stephens 1978; Mitchell 1980; Isaac 1981; Jones 1981).

Previous work indicates that north-east Scotland offers considerable scope for research into problems of weathering and landform development. Repeated glaciation has apparently failed to greatly modify the preglacial relief (Linton 1959; 1963; Clayton 1974; Clapperton and Sugden 1977). Deeply weathered rocks occur widely (Fitzpatrick 1963; Peacock and Michie 1975) which are generally considered to be pre- or inter-glacial in age (Linton 1951; 1955; Fitzpatrick 1963; Basham 1974; Wilson and Tait 1977). Gravel deposits of possible Pliocene age and containing Cretaceous flints are found at a number of sites in Buchan (Flett and Read 1921). Offshore lie two major sedimentary basins, the North Sea and Moray Firth Basins, whose Mesozoic and Cenozoic histories are increasingly well known (Woodland 1975; Illing and Hobson 1981; McQuillin et al 1982). The weathering covers and sediments onshore and the stratigraphic record offshore provide a potential correlative framework for relief development which is unparalleled in the Scottish Highlands. Yet apart from the single study of Walton (1963), the geomorphic evolution of the region has received little attention. This study was prompted by the need for a detailed examination of the links between weathered rocks, sediments and morphology and attempts to identify the main stages in the evolution of the relief of north-east Scotland.

1.2 Previous investigations of weathered rock in the region and some outstanding questions

It is now 20 years since the publication of the first detailed survey of weathered rock in north-east Scotland (Fitzpatrick 1963). The presence of rotten rock had long been known and was perhaps first noted by Wilson (1882) who described partially-kaolinised quartz schists and decomposed knotted schists and granites in the short Memoir for the Fraserburgh district. However this and other early

Aberdeenshire Memoirs (Wilson 1886; Wilson and Hinxman 1890; Hinxman 1896) seem to have regarded the weathering as a post-glacial phenomenon of no great significance. That the depths of weathering might be too great for formation in the post-glacial period seems to have been considered first by Barrow et al (1913). These authors described schists and granites on the Gaick Plateau decomposed to depths of more than 10m and suggested a preglacial origin. Debate about the significance of the weathered rock then lapsed until after the Second World War when sewer excavations in Aberdeen revealed deeply weathered granites beneath till which were variously interpreted as products of preglacial (Bailey 1950), interglacial (Phemister and Simpson 1949) and post-glacial (Carruthers 1950) alteration. In a series of papers on Scottish landforms, Linton (1950; 1951; 1955) made frequent references to weathered rock which he regarded as preglacial or interglacial in age.

Most of the modern information about weathered rock in the region has come from studies by soil scientists based at the Macaulay Institute and the University of Aberdeen. Early investigations into the mineralogy of weathered granites around Aberdeen were made by Milne (1952). Little mention of weathered rock is found in the Soil Survey Memoirs (Glentworth 1954; Glentworth and Muir 1963) but sites discovered during field-mapping formed the basis for the major study of Fitzpatrick (1963). This work marked a significant advance by the presentation of a map of the distribution of weathering sites and of a summary diagram illustrating the principal characteristics of the weathering profiles and their overlying deposits. After comparisons with local tills and the Buchan Gravels and deposits in numerous other areas, Fitzpatrick concluded that the weathering was of preglacial origin.

Recent studies have concentrated on the mineralogical transformations involved in weathering. The work of Wilson and co-workers (Wilson 1966a and b; 1967; 1970; Wilson and Tait 1977; Wilson et al 1971; 1981) has added greatly to knowledge of the clay mineralogy of soils. Basham (1968; 1974) provides an important survey of the mineralogy of weathered gabbros on the Insch and Boganclogh intrusions and Koppi (1977) gives detailed analyses of two quartz-mica schist weathering profiles. The geochemistry of the weathered Peterhead granite is discussed by Moore and Gribble (1980).

The majority of these studies refer to saprolites (the term used to describe weathered rock in situ) or soils derived from basic rocks (Wilson 1966a and b; 1967; 1970; Basham 1968; 1974). Yet alteration affects a wide variety of other rock types (Fitzpatrick 1963) whose weathering products are largely unknown. Moreover there are doubts as to whether the low degree of alteration shown by the basic saprolites is typical, for there are a number of descriptions of more highly altered materials (Wilson 1882; Milne 1904; Fitzpatrick 1963; Koppi 1977; Wilson et al 1981). Finally, although recent opinion has favoured a pre- or inter-glacial age for the weathering (Bain 1977; Wilson and Tait 1977; Koppi and Fitzpatrick 1980), no conclusive evidence has been produced and the possibility that weathering profiles of more than one age may co-exist in the region seems not to have been considered.

The nature of regional weathering patterns remain little-understood. Although Fitzpatrick (1963) locates as many as 125 weathering sites and others are reported in the literature (in particular see Basham 1968; 1974; Peacock and Michie 1975; Chester 1978), it became clear at an early stage in field-mapping that previous surveys had been far from exhaustive and a total of over 500 sites were eventually identified. Moreover these studies had been able to give only isolated figures for depths of weathering (Basham 1968). A substantial number of borehole records have recently become available which allow much more detailed assessment of weathering patterns. Interpretations of the distribution of weathering in terms of geology (Fitzpatrick 1963; Chester 1978) and patterns of glacial erosion (Chester 1978) can now be re-examined and wider links between weathering and landform development can be established.

1.3 Previous geomorphological investigations and outstanding problems

Early studies of the shaping of the regional relief tended to be concerned largely with drainage evolution (Hinxman 1901; 1907; Bremner 1912; 1921; 1942). Although some perceptive descriptions of relief were given (Bremner 1919), heavy emphasis was placed on exhumation from beneath the Old Red Sandstone (Hinxman and Wilson 1902; Barrow et al 1912; Bremner 1942) and on modification by glacial erosion (Wilson and Hinxman 1890; Bremner 1912; 1921). A significant pre-war study was that of Fleet (1938), who identified stepped erosion surfaces throughout the Grampian Highlands. His observations have been largely accepted by later writers (Linton 1951; Walton 1963; Sissons 1967; 1976).

In discussing the evolution of the Scottish scenery, Linton (1951) made a number of important observations on the relief in north-East Scotland. The structurally-discordant drainage network in the region was considered to reflect superimposition from a former Cretaceous cover. The sub-Cenomanian surface was thought to be preserved on the Cairngorm Summits but Linton also stated that the Chalk persisted in the Tertiary "near the eastern coastline where it had not been raised significantly above base-level" (p.69) and thereby implied substantial differential earth movements. The Grampian Main and Lower Surfaces of Fleet (1938) were referred to phases of planation under humid tropical environments in the early Tertiary. In the lowlands, Linton recognised a further erosion surface planed across complex geology which gave way inland to a series of major basins.

Although the preglacial relief of the Cairngorms has been described in some detail (Linton 1950; Sugden 1968), the only account dealing specifically with eastern areas is that of Walton (1963). Inselberg and pediment forms developed under warm and seasonally arid climates were identified on the high-level surfaces of the eastern Grampians (see also Fitzpatrick 1969; 1972). However the series of erosional levels recognised below 350m were interpreted as marine erosion surfaces due to their disregard for geological variations and to the association of the major lowland surface, the Buchan Platform, with an inner cliff and gravel deposits of supposed marine origin (Flett and Read 1921). Walton also notes a wide variety of preglacial landforms in the lowlands including residual hills, basins, valley benches, wind gaps and tors.

Apart from general descriptions (Fitzpatrick 1969; 1972; Clapperton and Sugden 1963), there has been no recent work dealing with the preglacial relief of north-east Scotland. However detailed studies in other parts of the Highlands (Godard 1965; George 1966) have challenged earlier models of relief development and have direct significance to the present study. The concept advanced by Linton (1951) of an Upper Cretaceous transgression across the whole of the Highlands is now rejected and emphasis is placed instead on the importance of uplift and deformation in the early Tertiary (Godard 1965; George 1966). However whilst there is agreement that no element of the end-Cretaceous relief survived the Palaeogene earth movements, the later history of the Highlands remains controversial. Godard (1965) considers that the highest fragmented levels in the northern Highlands are representatives of a phase of planation which commenced immediately after the cessation of magmatic activity and that lower surfaces reflect episodes of subaerial levelling. However, George (1966), claims that "the whole of Highland Scotland is in its present geomorphic frame Neogene in origin" (p. 33) and that the Hebridean landscape reflects the pulsed emergence of wave-cut benches. An attempt to link these contrasting hypotheses is made by Sissons (1967; 1976) who proposes that marine and subaerial planation surfaces formed contemporaneously whilst close to base-level continued to evolve after uplift by scarp retreat. A variation on this theme has been recently suggested by Lidmar-Bergstrom (1982) in which older surfaces are worn back and lowered to produce new levels. However whilst these new theories have potential value, the fundamental questions of the starting point for relief development in the Highlands and of the nature of the processes which fashioned the relief have yet to be resolved.

Whilst previous studies of landform development in north-east Scotland have contributed to the understanding of the main characteristics of the preglacial relief, the origins and age of this relief are uncertain. The reality of the various morphological levels remains to be demonstrated and structural relationships have received only cursory examination. Exhumation of relief from beneath Devonian and Cretaceous covers has been widely proposed (Wilson 1886; Wilson and Hinxman 1902; Barrow et al 1912; Bremner 1942; Linton 1951; Johnstone 1966), but no maps showing the former extent or configuration of the sediments have been presented and the nature of the exhumed relief is in doubt. The geomorphic significance of the Buchan Gravels (Flett and Read 1921) has also yet to be established, for despite much recent attention (Koppi and Fitzpatrick 1980; McMillan and Merritt 1980; Kesel and Gemmell 1981), there is no agreement as to the origins of these deposits or of the Chalk flints included in them.

There has been little attempt to integrate weathering and morphology and lowland erosion surfaces have been attributed to marine planation despite the presence of deep weathering covers (Walton 1963). In Europe, investigations of the characteristics and palaeo-environmental significance of weathering covers are part of the mainstream of geomorphic research (Alexandre 1958; Bakker and Levelt 1964; Esteouelle-Choux 1967; Godard 1971; 1972; 1978; Birkenhauer 1972; Bibus 1973; Kiselev 1975; Coincon et al 1976; Lidmar-Bergstrom 1982) but this approach has had only limited application in the British Isles (Godard et al 1961; Eden and Green 1971; Hodgson et al 1974; Battiau-Queney 1978; Isaac 1981). The saprolites in north-east Scotland have considerable correlative potential and can supply information on the age and mode of origin of both erosion surfaces and their constituent landforms.

Regional and local models of relief development are in urgent need of review in the light of the recent explosion in information on offshore geology (Pegrum et al 1975; Woodland 1975; Evans et al 1981; Illing and Hobson 1981). The continuous Cenozoic record in the North Sea Basin and the interrupted sequenceselsewhere around the Scottish shelf can provide an invaluable tectonic and palaeoclimatic framework in which to consider the evolution of the Highland relief. This framework will require substantial revision as new data becomes available, but already evidence of regionally-correlated unconformities and transgressions (Morner 1980; Evans et al 1981; Ziegler 1981; 1982) and changes in rates and styles of sedimentation (Clarke 1973; Morton 1979; Sutter 1980; Knox et al 1981; Ziegler 1982) can be related to alternating phases of tectonic stability and uplift. Variations in marine temperatures through the Tertiary are increasingly well-known (Savin et al 1975; Buchardt 1978; Backmann 1979) and these palaeo-environmental trends have major significance for morphogenic processes (Lidmar-Bergstrom 1982). Of particular relevance to the present study are recent analyses of mineralogical variations in North Sea (Karllson et al 1979; Berstad and Dypvik 1982) and North Atlantic (Chamley 1979; Debrabant et al 1979) Cenozoic sediments. This work provides the first opportunity to correlate the clay mineralogy of terrestrial weathering covers in Scotland with dated marine sequences. By combining evidence found in offshore sediments on tectonic and climatic environments, rates of denudation and styles of weathering, it is possible to make detailed inferences about the dominant morphogenic conditions on adjacent land areas (Chamley 1979). The enforced reliance on morphological evidence to identify phases of planation in the crystalline terrain of the Highlands can now be relaxed and the possibility is raised that the age of bedrock surfaces can be established from the offshore record.

1.4 Study area

The main study area lies north of the River Dee and east of a line running southwards from Cullen on the Moray Firth coast through Huntly and to Aboyne. This area was chosen for a number of reasons:-

(i) Earlier surveys had shown that weathered rock occurs extensively in this region but becomes less frequent further west (Fitzpatrick 1963; Basham 1968; 1974; Peacock and Michie 1975; Chester 1978).

(ii) Detailed borehole information is available for areas W and NW of Aberdeen, eastern Buchan and the Huntly district but is sparse elsewhere.

(iii) The study area includes all known outcrops of the Buchan Gravels.

(iv) The geology of the region is generally well-known. Although the Memoirs of the Geological Survey are now rather dated, the efforts of H.H. Read have ensured that north-east Scotland has become a classic area for the study of metamorphism. Much recent work is available, often in unpublished theses (see Chapter 2).

Some attention has also been given to the elevated plateau areas east of the Cairngorm Massif to allow landform development in the lowlands to be placed in a wider context.

1.5 Research aims and methods

The study has 5 main aims:-

(i) to establish the distribution, principal characteristics and age of the weathered rock.

(ii) to examine the origins of the Buchan Gravels and their flints.

(iii) to identify the preglacial form of the region and to relate morphology to geology and structure, former sedimentary covers and weathering patterns.

(iv) to review recent studies of offshore geology in order to identify the main tectonic and palaeoclimatic events in the Tertiary evolution of the Scottish Highlands.

(v) to combine evidence from morphology, weathering covers, the Buchan Gravels and offshore sediments to establish a regional denudation chronology.

Weathering patterns have been established by a literature search for weathering sites, by field-mapping and by collation of borehole records. Three main characteristics of the weathered rocks have been examined, granulometry, geochemistry and clay mineralogy. Samples were taken from a large number of separate sites in a wide variety of rock types. Two weathering types are identified whose age is established by reference to saprolites of known age elsewhere and to the offshore record. Recent work on the Buchan Gravels is reviewed (Koppi and Fitzpatrick 1980; McMillan and Merritt 1980; Kesel and Gemmell 1981) and new analyses are presented in order to compare the mineralogy of these deposits and the subjacent weathered bedrock with that of surrounding saprolites. The origins of the flints are discussed. Morphological levels recognised by earlier workers are re-examined and 3 main erosion surfaces are identified on the basis of hysometric and geomorphic evidence. The origins of a variety of preglacial meso-scale landforms are discussed with particular reference to weathering patterns. A model of landscape evolution in the lowlands is developed and the relief is dated using evidence from the weathering types and the Buchan Gravels. The development of the main erosion surfaces is considered in the light of evidence for late Tertiary differential tectonic movements and the surfaces are correlated with phases of regional base-levelling identified from the offshore record. Finally, patterns and depths of glacial erosion are assessed using evidence from the distribution of weathering, the degree of modification of preglacial forms, till composition and glacial landforms.

PART I Regional Background

CHAPTER 2 Physiography and Geology

2.1 Introduction

The study area forms the southeastern corner of a regional structural unit, the Grampian High (Ziegler 1982). This crystalline block is bordered to the north and west by the Mesozoic sedimentary basins of the North Sea and the Moray Firth and to the south by the Old Red Sandstone basin of Strathmore. The area is underlain by a complex series of Precambrian to Dalradian metamorphic rocks intruded by Caledonian granites and basics. The only sedimentary rocks of any importance are the numerous outliers of Old Red Sandstone.

The regional physiography is characterised by stepped plateaux developed indiscriminately across varied geology. Rocks which are associated with mountainous terrain in much of the Highlands form extensive lowlands in north-east Scotland (Linton 1951; Sissons 1976), a contrast which has yet to be satisfactorily explained. The lowland plain rises from remarkably linear coastlines and dominates the relief of Buchan and the Skene depression (Figs. 2.1.i and ii). The detailed relief of the lowlands shows much diversity but at the regional scale the lowland plain is interrupted only occasionally by isolated hill masses. Inland the lowlands interdigitate with higher plateaux along the Insch depression and the Dee valley and the upper relief is further fragmented by a number of major basins. Along the Moray Firth coast, the lowlands are more restricted and are backed by tabular hills and plateaux lying between 280 and 390m. However, further south the ground rises sharply from the lowlands to more elevated tablelands surmounted, in turn, by isolated summits standing above 800m. This highland plateaux extends from the Highland Line, overlooking Strathmore, to the foot of the Cairngorm Massif, which forms rolling landscapes culminating

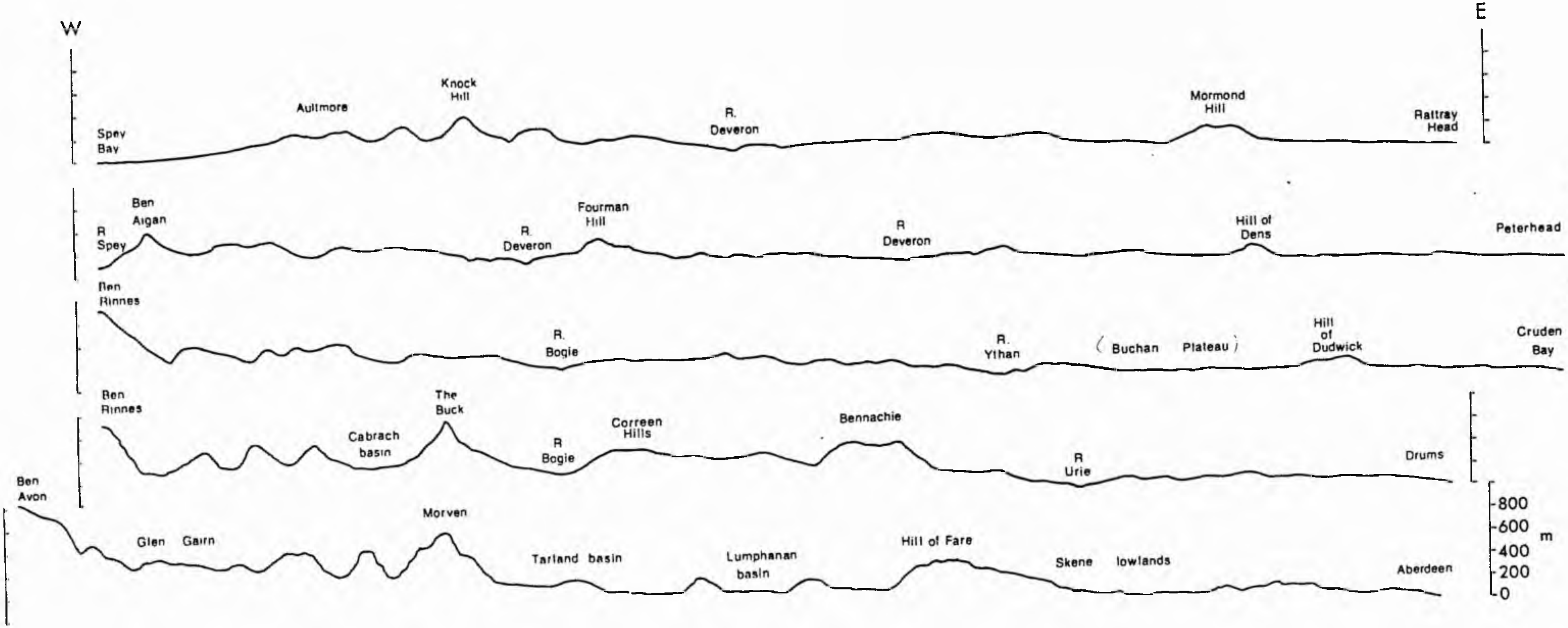


Fig. 2.1.i. Topographic profiles across north-east Scotland.

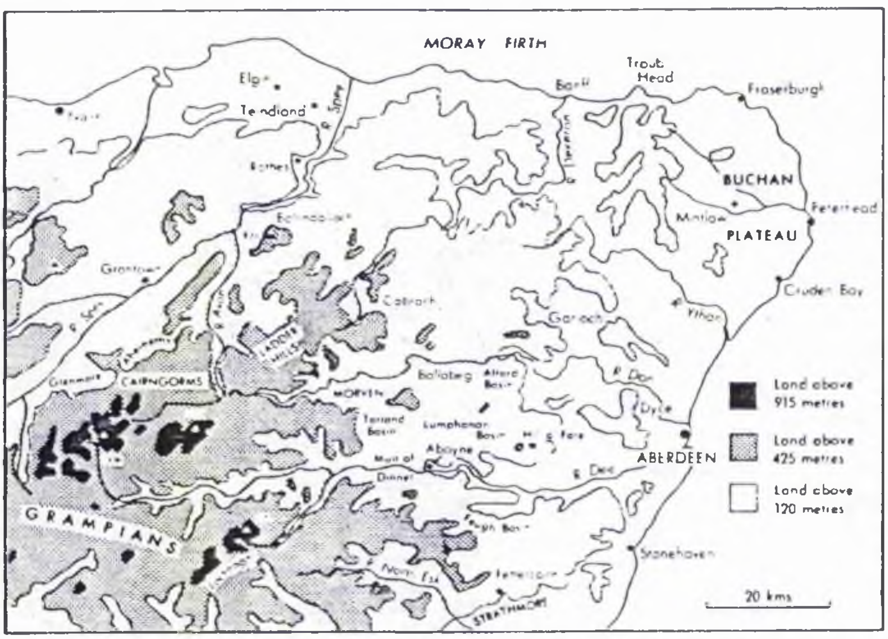


Fig. 2.1.ii. General relief features.
(Fig. 3 of Clapperton and Sugden 1977).

in Ben Macdui at 1311m. The regional drainage is dominated by a series of rivers flowing W-E across the Caledonian structural trend.

2.2 Morphological Regions

A number of morphological regions can be recognised in the study area Fig. 2.2.i. :-

A. Mounth Plateau

The Mounth Plateau is a broad surface of low relief developed mainly in granites extending eastwards from the Lochnagar Massif almost to the North Sea coast. Bounded to the south by the Highland Boundary Fault and to the north by the Dee valley, the Mounth Plateau is surmounted by a small number of isolated hills, of which Morven (871m) and Mount Keen (939m) are the most notable examples. The wide surfaces between Glens Muick and Clova lie at between 700 and 800m a.s.l. but elevations decline eastwards and the Plateau becomes increasingly dissected.

B. Dee Valley

The Dee valley is a major topographic corridor running from the heart of the Cairngorm Mountains to the North Sea Coast. East of Ballater, the Dee flows through a series of constricted and open reaches as the river encounters rocks of variable resistance.

C. Grampian Foothills

The Ladder Hills and the ridges and hills of the Blackwater

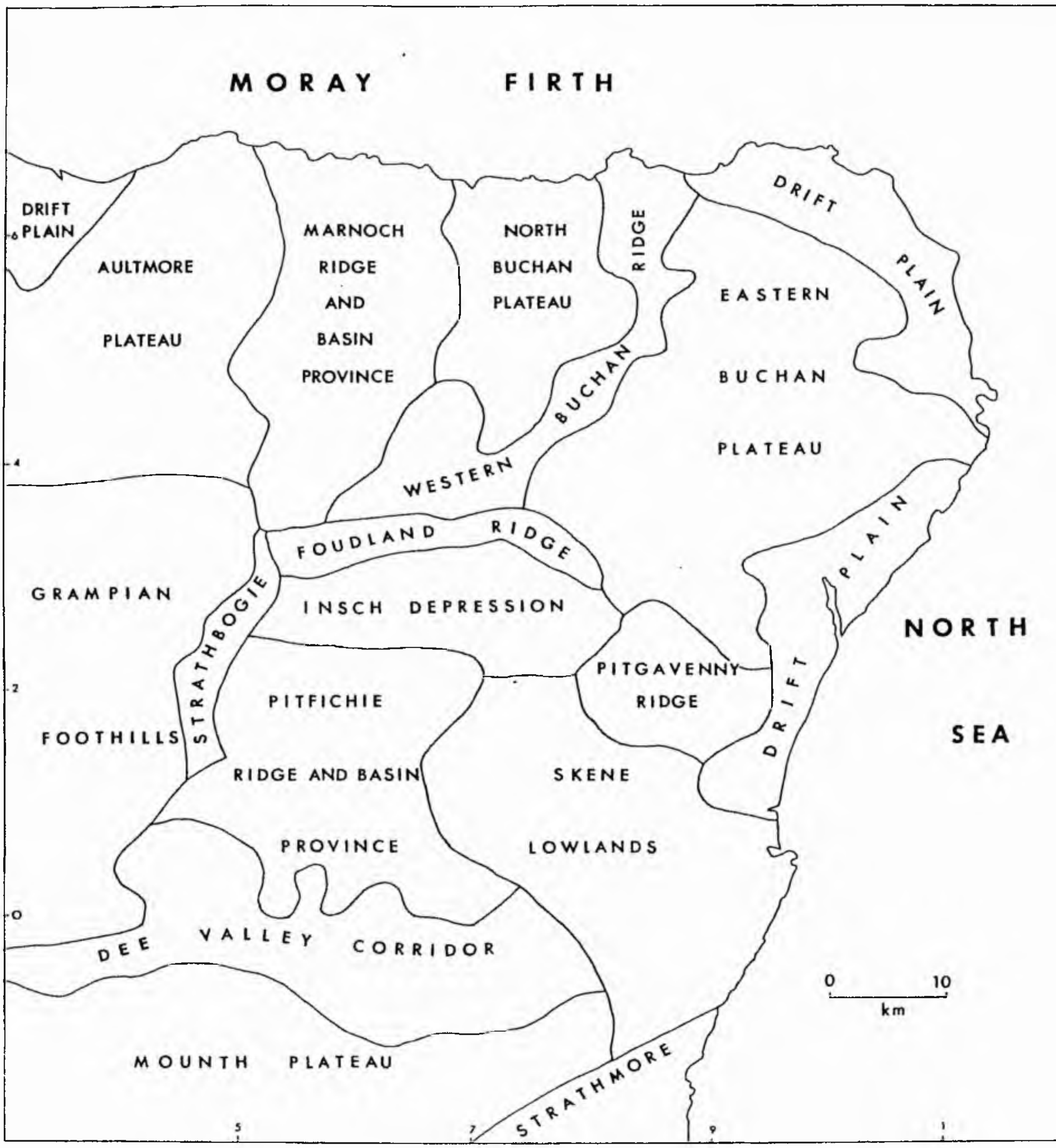


Fig. 2.2.i. Morphological Regions.

and Clashindarroch Forests are a northern extension of the Grampian Mountains. These hills carry the headwaters of the Livet, Fiddich, Deveron and Buchat and exploitation of strong Caledonian structural trends has created a series of SW-NE trending valleys and ridges. Broad summit surfaces of gentle relief survive in the main watershed area, east of the isolated hill of The Buck (721m).

D. Pitfichie Forest Ridge and Basin Province

This part of central Aberdeenshire is an area of strongly compartmented relief. Resistant leucogranites and andalusite schists form the upstanding masses of Bennachie (528m), Hill of Fare (471m), Pressendye (619m) and the Correen Hills (487m). Zones of weaker rocks have been exploited by differential erosion to create a number of basinal landforms, including the impressive Howe of Alford. The Don has cut deep gorges through the resistant ridges and the trellissed nature of the tributary drainage indicates the local importance of N-S and E-W structures.

E. Skene Lowlands

The Pitfichie Ridge and Basin Province is bounded to the east by a number of major scarps which present an abrupt hill-front to the Skene Lowlands. The lowlands are developed mainly in granitic rocks and glacial erosion has picked out transecting structural trends to create a distinctive geometric topography. Relief is locally high and the area includes numerous isolated hills and hill masses, including the prominent residuals of Tyrebagger Hill (250m) and Brimmond Hill (266m). Rectilinear basin forms of varied dimensions are the main elements of negative relief.

F. Insch Depression and Strathbogie Corridor

The gabbroic rocks of the Insch and Boganclogh Masses form a major linear depression extending into the Grampian Foothills. The depression extends over 40km eastwards from the Cabrach and contains an assemblage of smaller topographic features including stepped levels, basins and tors. The Strathbogie Corridor provides the only major break in the ridges enclosing the Insch Depression and follows an important line of weakness occupied by the Rhynie Old Red Sandstone basin.

G. Pitgavenny Ridge

North of the Don, a broad ridge extends southeastwards from Pitgavenny Hill (236m) and is gradually dissected into a number of isolated hills towards the coast. The dislocation of the ridge has been caused partly by the opening-out of basin-like tributary valleys towards the heads of the drainage networks. These distinctive 'basined valleys' are a characteristic feature of the lower Don valley.

H. Coastal Drift Plains

In coastal areas between Aberdeen and Cruden Bay and between Peterhead and Rosehearty the bedrock topography is masked by thick accumulations of glacial, fluvioglacial and glaciolacustrine deposits. The main topographic features in the generally subdued relief of the drift belts are of depositional origin.

I. Foudland Ridge

The Insch Depression is enclosed to the north by the Foudland Ridge, extending from Tap o'Noth (563m) and Hill of Foudland (467m) to the east of Core Hill (245m). The Ridge is developed in slates and pelitic schists and forms a major topographic and drainage divide.

J. Eastern Buchan Plateau

This Plateau is an extensive surface of low relief formed in a wide variety of igneous and metamorphic rocks and lying at elevations of between 60 and 150m. Quartzitic rocks commonly form ridges and hills rising above the general level but the only conspicuous relief form in the area is the quartzite mass of Mormond Hill (234m). The topography is gently rolling with few sharp breaks of slope and the steepest slopes are provided by the dense networks of small meltwater channels. Shallow basins are set into the plateau at Maud and New Pitsligo. This region contains the majority of outcrops of the so-called Pliocene gravels (Flett and Read 1921).

K. Northern Buchan Plateau

This is a more restricted area of similar characteristics and elevation to Eastern Buchan. Subdued topography developed across Old Red Sandstone and slate slopes towards the lower Deveron and is finely dissected by meltwater channels. Small patches of Pliocene(?) gravels occur around Turriff.

L. Western Buchan Ridge

The Western Buchan Ridge rises above the plateaux of Eastern and Northern Buchan but exhibits comparable broad, gently-undulating surfaces. The Ridge is best developed on the Old Red Sandstone and slate and forms a tract of ground extending from the summit surfaces around Windyheads Hill (231m) and the more isolated flat-topped hills around Monquhitter to terminate at an elevation of around 200m against the Foudland Ridge. The headwaters of the Ythan occupy shallow, open valleys around Wells of Ythan but the main drainage routes elsewhere are incised well below the Ridge.

M. Marnoch Ridge and Basin Province

Differential erosion has exploited sharp contrasts in resistance between adjacent members of the Dalradian succession in this part of Banffshire to create a series of SW-NE trending ridges with intervening basins and corridors. The ridge crests lie between 220 and 310m a.s.l. and are surmounted by the conical inselberg of Knock Hill (430m), whilst the floors of the corridors are found between 100 and 150m a.s.l. The ridges are formed mainly, but not exclusively, of quartzite and the local Younger Basic intrusions are generally associated with negative relief. However, certain topographic lineaments, while following the Caledonian trend, do not correspond with lithologic boundaries but with the alignment of major fracture zones. It is significant that the middle Deveron largely ignores the dominant structural trend and cuts through the resistant ridges.

N. Aultmore Plateau

East of the Spey, a number of tabular hills are developed across the Old Red Sandstone and Dalradian flags and quartzites and collectively form the Aultmore Plateau at elevations of between 180 and 265m. Dissection increases southwards across Strath Isla and the planar summits are replaced by a shallow depression centred on the Daugh of Cairnbarrow and circled by low hills rising to 417m.

The characteristics of these morphological regions are discussed further in Part III.

2.3 Geology

North-east Scotland is an area of complex geology containing rocks of Precambrian to Permo-Triassic age (Map 1 in folder). Moinian and Dalradian metamorphics are intruded by large areas of Caledonian granitic and basic igneous rocks. The only important sedimentary rocks in the region belong to the Old Red Sandstone sequence. In situ Mesozoic and Cenozoic rocks are absent, although Mesozoic sediments fill the adjacent Moray Firth Basin.

2.3.1 Moinian

Moinian rocks are confined to areas west of Ben Rinnes and Strath Avon, outside the main study area. The rocks belong to the Grampian Division and consist mainly of quartzo-felspathic granulites. The relationships between the Moinian and Dalradian metamorphic in the area between Grantown and Tomintoul are described by McIntyre (1952).

2.3.2 Dalradian Metamorphics

The metamorphic rocks of the Dalradian are the most extensive rocks of the region. The coast of Banffshire cuts across the Dalradian strike and affords excellent continuous sections, although exposure inland is often poor. As a result of this fine coastal exposure and of the succession of eminent Scottish geologists who have worked in the area north-east Scotland has become a classic region for the study of rock metamorphism.

It is largely through the lifelong efforts of H.H. Read that the area has become so well known. Read first gained detailed experience of the geology of north-east Scotland during his mapping of Sheets 86 and 96 (Banff and Huntly) for the Geological Survey of Scotland. In the Memoir (Read 1923), he advanced a correlative stratigraphy of the Dalradian succession in Banffshire which formed the basis for much of his later work (Read 1935, 1952, 1955, 1956). Read proposed that the Dalradian metamorphics of the Banff and Huntly districts could be divided into two major units, the Banff Series and the Keith Series, separated by a plane of discontinuity known as the Boyne Line. The rocks of the lower Keith Series had suffered more intense metamorphism (Barrovian-type) than those of the upper Banff Series (Buchan-type). The Keith Series comprises schists, gneisses and granulites, with staurolite, kyanite, sillimanite and cordierite as typical minerals. The Banff Series, however, rarely pass beyond a phyllitic stage and are characterised by a lower grade andalusite and cordierite mineral assemblage with subsidiary sillimanite, staurolite and garnet. Read (1955) suggested that the Banff Series formed a tectonic sheet on the Keith

Series, the two being separated by the major slide of the Boyne Line. The Keith Series is arranged in a huge recumbent anticline, the Banff Nappe, closing to the south-east and with its upper limb broken by the dislocation of the Boyne Line. The core of the Nappe is largely composed of the basement of the Banff Series, the Cowhythe, Donside and Ellon migmatitic gneisses. The Nappe is modified by two massive secondary folds, the Buchan Anticline in the east and the Turriff Syncline or Boyndie Synform (Sutton and Watson 1955) towards the west.

The characteristics of the main litho-stratigraphic groups identified within the Banffshire succession by Read (1955) are outlined in Table 2.3.i, together with some of his other regional correlations (Read 1955; Read and Farquhar 1956). Many of the Dalradian groups are composed of a variety of different rocks, a result of original sharp sedimentary contrasts. Even the more homogeneous groups, such as the Mormond Hill, Durn Hill and Cullen Quartzites show high internal variability in their colours, textures and felspar contents. Consequently the geology changes rapidly along the Dalradian strike in many areas. The sole exception to this general variability is the Macduff Group, whose slates maintain a persistent uniformity over their wide area of outcrop.

Later work has shown that the Dalradian structures of north-east Scotland are more complex than either Read (1955, 1956) or Sutton and Watson (1955) envisaged. Johnson (1962) has shown that at least four phases of deformation occurred, namely:-

<table>
<tr><th></th><th>BANFFSHIRE</th><th>FRASERBURGH</th><th>COLLIESTON</th><th>FORMARTINE</th></tr>
<tr><td rowspan="4">UPPER DALRADIAN (BANFF DIVISION)</td><td colspan="2">MACDUFF GROUP
Slate, greywacke and grit</td><td rowspan="3">COLLIESTON BEDS
Grits, grey-wackes and pelites</td><td rowspan="3">FYVIE SCHISTS
Andalusite schists with quartzites</td></tr>
<tr><td>BOYNDIE BAY GROUP</td><td>ROSEHEARTY BEDS</td></tr>
<tr><td colspan="2">Andalusite schist and pebbly grits</td></tr>
<tr><td>WHITEHILLS GROUP</td><td>KINNEARDS HEAD GROUP</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Rapid alternations of grits, pelites and limestones</td><td></td><td></td></tr>
<tr><td></td><td rowspan="2">BOYNE LIMESTONE
Limestone and mica schist</td><td colspan="2">unconformity</td><td></td></tr>
<tr><td></td><td colspan="2">MORMOND HILL QUARTZITE
Quartzite and mica schist</td><td></td></tr>
<tr><td>BOYNE LINE</td><td colspan="4">unconformity</td></tr>
<tr><td rowspan="10">LOWER DALRADIAN (KEITH DIVISION)</td><td>COWHYTHE GNEISS</td><td>INZIE HEAD GNEISS</td><td>ELLON SERIES</td><td>DONSIDE GNEISS</td></tr>
<tr><td colspan="4">Predominantly biotite gneisses</td></tr>
<tr><td>PORTSOY GROUP
Mica schist</td><td colspan="3"></td></tr>
<tr><td>DURN HILL QUARTZITE</td><td colspan="3"></td></tr>
<tr><td>SANDEND GROUP
Limestone, schists</td><td colspan="3"></td></tr>
<tr><td>GARRON POINT GROUP
Mica schist</td><td colspan="3"></td></tr>
<tr><td>CRATHIE POINT GROUP
Calc-biotite flags</td><td colspan="3"></td></tr>
<tr><td>FINDLATER FLAGS
Mica flags</td><td colspan="3"></td></tr>
<tr><td>WEST SANDS GROUP
Mica schist</td><td colspan="3"></td></tr>
<tr><td>CULLEN QUARTZITE</td><td colspan="3"></td></tr>
</table>

Table 2.3.i. Main lithostratigraphic groups in the Dalradian succession after Read (1955) and Read and Farquhar(1956).

Note : Gneisses immediately below the Boyne Line are regarded as allochtonous elements of Precambrian basement by Sturt et al (1977).

F_1 nappe formation

F_2 minor structures of the lower Dalradian

F_3 major monoclines

F_4 late stage brittle movements

More recently Ashworth (1975) has re-examined the sillimanite zones of the Huntly-Portsoy area and concluded that the sillimanite-bearing rocks from an aureole about the Younger Basic intrusion and that Read's Cowhythe Gneiss does not represent a single litho-stratigraphic unit. Ashworth has also cast doubt on the reality of the Boyne Line as a tectonic slide. The evidence for the Line may be better accounted for by a combination of rapid sedimentary facies variation (Fettes 1970), a coincidence with the eastern edge of the thermal aureole of the Younger Basics and the existence of a local shear zone on the coast.

Recent dates for the Inzie Head Gneiss (691$\pm$39Ma) and the Ellon Gneiss (724$\pm$120Ma) have cast further doubt on the status of the Banff Nappe. The migmatitic gneisses, formerly placed in the core of the Nappe (Read 1955), are now regarded as allochthonous elements of Precambrian basement within the Dalradian (Sturt et al 1977).

2.3.3 Older Igneous Rocks

Prior to the earth movements responsible for the structure and disposition of the Dalradian rocks of north-east Scotland, a varied series of igneous rocks was intruded (Read 1923). These rocks are of limited extent, being largely confined to the Portsoy area, to a SW-NE trending belt to the north of Huntly and to the Morvern-Cabrach district. The rocks are predominantly basic with lesser ultrabasic and acid components. The Older Igneous Rocks commonly show signs of later metamorphism, with shearing, crushing and amphibolitisation being widespread. This evidence of cataclasis is in marked contrast to the Younger Igneous Rocks, where original structures are largely unmodified. Recent radiometric ages for the Portsoy and Windyhills granites of 669$\pm$Ma show that they were intruded well before the main Dalradian metamorphic events (Pankhurst 1974).

Younger Basics

There are at least eight major basic igneous masses in north-east Scotland:-
the Insch-Boganclogh, Huntly, Knock, Portsoy, Haddo, Arnage, Maud and Belhelvie masses.
The unpublished work of Henry (1938) shows that at least part of the Morvern-Cabrach mass belongs to the Younger Basic suite (see also Allan 1970). Several minor basic bodies also occur (Stewart 1970, Wilson 1970). These masses are of considerable size and cover a total area of 430km^2. They form part of a large sill-like sheet intruded into the Dalradian metasediments towards the end of the orogenic movements (McGregor and Wilson 1967; Fettes 1968). Though each mass possesses its own distinctive characteristics, the high degree of similarity between the masses leaves little doubt that they form a single province.

The rocks of the Huntly Mass, recently subdivided into three separate bodies, are mainly layered cumulates and xenolithic rocks (Munro 1970). The Insch Mass comprises various types of gabbro together with peridotite, troctolite, norite, quartz-diorite, syenite and granite, forming part of a differentiation sequence ranging through ferrogabbros and syenogabbros to syenites (Read, Sadashivaiah and Haq 1961). The other masses show similar basic and ultrabasic types, though with a tendency towards the development of quartz-norites in the Morvern-Cabrach, Arnage and Haddo Masses (Stewart 1970). The Maud intrusion is unusual in that it seems to be composed largely of norites (Smith 1933). Several masses are intruded by more acid rocks.

In several localities the original gabbroic magma has absorbed, either partially or completely, material of sedimentary origin to produce what Read (1923) has termed the "contaminated igneous rocks". These rocks vary from highly contaminated norites to mainly sedimentary types, such as garnet, cordierite-potash felspar rocks. In places the contaminated rocks are crowded with xenoliths of imperfectly-digested country rocks, giving them a highly distinctive appearance. The contaminated rocks of the Haddo and Arnage Masses are part of the roofs of those intrusions (Read and Farquhar 1952; Stewart and Johnson 1960) but those of the Huntly Mass are not confined to that position (Read 1923).

Radiometric dating shows that the Younger Basic Rocks were intruded prior to the F_3 folding responsible for the Boyndie syncline and the Buchan anticline (Brown et al 1965; Pankhurst 1970). Several masses show steeply inclined banding and considerable folding and faulting probably took place during the F_3 event (Stewart and Johnson 1960), although Munro (1970) suggests that the abrupt termination of deformation in the Portsoy, Insch and Belhelvie Masses may well be due to later post-ORS faulting. Shear belts occur within certain intrusions, and the south-western margin of the Insch and Boganclogh Mass shows major dislocation (Read 1956; Blyth 1969). Contact metamorphism is often limited, especially where contaminated rocks do not intervene between the basic intrusions and the country rocks (Smith 1933; Munro 1970). Distinct aureoles do appear in the Macduff slates to the north of the Insch Mass and in the gneisses around the Haddo House intrusion (Gribble 1966). Elsewhere the aureoles were either not developed or are absent due to faulting, as along the southern boundary of the Insch and Boganclogh Mass (Read 1956; Blyth 1969).

2.3.4 Younger Granites

Apart from a few restricted occurrences of granites within the Older Igneous Rocks, the granites of north-east Scotland all belong to the group of intrusions known as the Younger Granites. These granites are of similar age to the Younger Basics, although their episodes of emplacement may span most of the period between the close of the main Dalradian folding and metamorphic events and the deposition of the Middle Old Red Sandstone. Radiometric dating divides the granites into two groups; a late-kinematic suite and a post-kinematic suite (Pankhurst 1973; Burswill et al 1975).
The late-kinematic suite is by far the smaller group and includes the Aberchirder, Longmanhill and Strichen granites and the Kennethmont granite-diorite series, all intruded about 460my (Pankhurst 1974).
The post-kinematic suite comprises the granite masses of the Cairngorms, Aberdeen and Peterhead which give radiometric ages of about 420my (Bell 1968). This places the granite intrusions as slightly later than the Younger Basics, dated at around 490my (Pankhurst 1970).

A. The Hill of Fare complex

This great mass of granite stretches along the north side of the Dee from Aberdeen to the Hill of Fare and Bennachie. The Hill of Fare Complex is a discontinuous intrusion of irregular outline which varies widely in its internal composition. Bissett (1932) recognises the following divisions:-

Red Granite	Later Caledonian
Grey Granite Transition Granite Porphyritic Granite Diorite	Earlier Caledonian

Recent work by Walsworth-Bell (1974) has largely confirmed Bisset's divisions, although all of these granites are now regarded as being of similar age (Bell 1968). Walsworth-Bell has identified 7 units within the Hill of Fare Complex which are combined into 5 groups.

Group 1: The Sundayswells and Gask Diorites

Group 2: Two-mica granites occurring around Kemnay and in the area to the north and west of Aberdeen.

Group 3: Tillyfourie and Correnie Granites. The Tillyfourie granite is a medium-grained, foliated biotite-hornblende granodiorite to diorite, whilst the Correnie granite is a small lens of pink biotite granite.

Group 4: This group roughly corresponds to Bisset's (1932) Porphyritic Granites within the Skene Complex. Walsworth-Bell (1974) classifies them as granodiorites, often containing phenocrysts of orthoclase felspar and with some hornblende.

Group 5: The Red Granites of the Hill of Fare and Bennachie. The greater part of these masses is composed of acid and coarse-grained granites with abundant pink felspars, much quartz and scanty biotite.

To these groups can be added the granites of the Alford district, which are medium-grained, grey, occasionally hornblendic granites, with minor pink biotite-bearing varieties.

B. The granites of Cromar

A band of granitic rocks, from 3 to 6km in breadth, extends west from Lumphanan, through the Howe of Cromar to terminate around Ballater. The Cromar granites are similar in composition to the Red Granites of the Hill of Fare and Bennachie, though medium-grained two-mica granites are also found (Anderson 1939). In the Tarland basin Read (1927) recognises two main types, the Coull granite, akin to the Red Granites, and the Tomnaverie granite, which is a grey medium-grained biotite granite.

C. The Kennethmont granite-diorite series

Granitic rocks are locally developed at the western end of the Insch basic intrusion. They comprise pink granites similar to the Red Granites and a varied suite of dioritic rocks (Sadashivaiah 1954; Burswill et al 1975).

D. The Auchedly granite

This small poorly-exposed intrusion lies at the south-east corner of the Haddo House basic mass. It is largely composed of fine-grained grey granite, containing quartz, orthoclase, plagioclase and biotite.

E. The Peterhead granite

Buchan (1934) has divided the Peterhead granites into two main types. Type A is a coarse, pink, non-porphyritic granite, composed essentially of orthoclase and quartz, with some biotite. Type B is finer grained than Type A and slightly more siliceous, with little or no biotite. Other minor varieties also appear. A grey plagioclase-bearing granodiorite outcrops along the South Ugie Water between Longside and Old Deer and more basic types are found to the north of the Moss of Cruden. Diorites were formerly quarried for ornamental stone at Rora.

F. New Pitsligo granite

The prominent type within this mass is a medium-grained, grey granite with large porphyritic crystals of orthoclase. The other essential minerals are quartz, partially-altered plagioclase and biotite (Anderson 1939). Coarser-grained pink varieties occur around the western margins of the intrusion.

G. Longmanhill granite

This minor intrusion is composed of a coarse grey, often porphyritic granite composed of abundant oligoclase and microline, with quartz, orthoclase and biotite (Read 1923).

H. Aberchirder granite

The coarse grey Aberchirder granite consists of plentiful microline, quartz, orthoclase, oligoclase and partly chloritised biotite.

2.3.5 The Old Red Sandstone

This formation reaches its fullest development just offshore where a band of Old Red Sandstone from 5 to 10km wide hugs the entire coastline from Buckie to Aberdeen (Map 1 in folder). Tiny outliers of these offshore sediments are found close to the shore along the Banffshire coast (Read 1923) and patches occur at Cruden Bay (Wilson 1886) and beneath Aberdeen city. The largest accumulations on land are found in a series of down-faulted basins:- the Turriff, Deskford, Rhynie, Cabrach and Tomintoul outliers. Bremner (1942) also mentions a small outlier in the basin of the Feugh, a south bank tributary of the Dee.

Several of these sedimentary basins have been denuded to the point that virtually only the basal conglomerates are represented within them. At Tomintoul 160m of conglomerates rest on a highly uneven floor. The conglomerate is a "coarse tumultuous assemblage of large well-rounded and occasionally sub-angular blocks of crystalline quartzite of local origin, set in a finer conglomeratic matrix, also chiefly composed of quartzite" (Hinxman 1896 p. 29). The close correspondence between the lithologic character of the conglomerates and the rocks on which they lie is repeated in the Deskford valley, along the sliver of O.R.S. that extends northwards from Gartly and in the western portions of the Turriff outlier. Only in the Rhynie and Turriff basins are there any important accumulations of rocks other than conglomerates. The Turriff outlier consists of two divisions (Geikie 1878):- (i) the Lower or Crovie Group of conglomerate followed by sandstones, flags, shales and marls, and sandstone once again; and (ii) the Upper or Findon Group consisting chiefly of conglomerates. At Rhynie the succession is as follows:- basal slatey or quartzitic conglomerate overlain by calcareous shales, shales and sandstones, volcanics, conglomerate and sandstone, and, finally, flags, shales and sandstones (Wilson and Hinxman 1890; Read 1923). Minor andesites also occur in the Cabrach outlier.

Not all the basins are down-faulted. The Deskford and Tomintoul O.R.S. conglomerates appear to be ancient valley fills, little complicated by faulting (Geikie 1878; Read 1923). The western margins of the other three main outliers are all fault-bounded. Geophysical surveys have shown that concealed N-S faults continue beneath the Turriff basin (Ashcroft and Wilson 1976), as speculated by Read (1923). The same faulting along 020^{o} defines the western edges of the Rhynie and Cabrach Old Red Sandstones and the margins of the Bennachie granite mass, and represents the re-activation of Dalradian structures (Ashcroft and Wilson 1976). Faulting along 070^{o} in the Turriff basin parallels the trend of the Permo-Carboniferous dykes of north-east Scotland (Bisset 1932) and the faults along the south side of the Moray Firth basin (I.G.S. 1976). A third fault orientation along 325^{o}, not recognised elsewhere, completes the rectilinear form of the Turriff outlier.

2.3.6 Permo-Carboniferous Rocks

The sole representatives of formations of this age in this part of Scotland are a number of WSW-ENE trending quartz-dolerite dykes. The dykes are of interest in that one of them is continuous for some 80km (Read and Haq 1965), indicating that there has been no major transverse faulting across the line of the dyke since emplacement in the Permo-Carboniferous.

2.3.7 The sediments of the inner Moray Firth Basin

Underlying the Moray Firth is a deep Mesozoic basin downwarped within the larger Old Red Sandstone Orcadian Basin. The absence of Carboniferous rocks indicates that the basin was initiated in the Permian (Chesher and Bacon 1975). The Mesozoic succession youngs eastwards with several minor unconformities intervening. Triassic sandstones rest directly on the Old Red and are themselves covered by a thick column of Jurassic rocks. The Lower, Middle and early Upper Jurassic sediments are shallow water sandstones, shales and siltstones, with deeper water black shales appearing in the Upper Jurassic (Kent 1975). Similar sediments continue into the Lower Cretaceous, where shales, siltstones and glauconitic and calcareous sandstones are represented. The Upper Cretaceous is confined to the eastern end of the Firth and is composed of chalk and marl resting unconformably on Lower Cretaceous. No Tertiary rocks are known from the inner part of the Moray Firth Basin but thick accumulations of Palaeocene sands occur further east (Morton 1979; Knox et al 1981; Rochow 1981).

2.4 Structure and Lineaments

2.4.1 Description of lineaments

In order to identify the main structural features of the region, the 1:50 000 Ordnance Survey maps were analysed for lineaments using a technique based on that of Lidmar-Bergstrom (1982). Each grid square was scrutinised for straight, parallel and closely-spaced contour lines signifying topographic lineations. The orientation of all lineations over 1km in length was then used to construct directional rose diagrams for separate areas (Fig. 2.4.i).

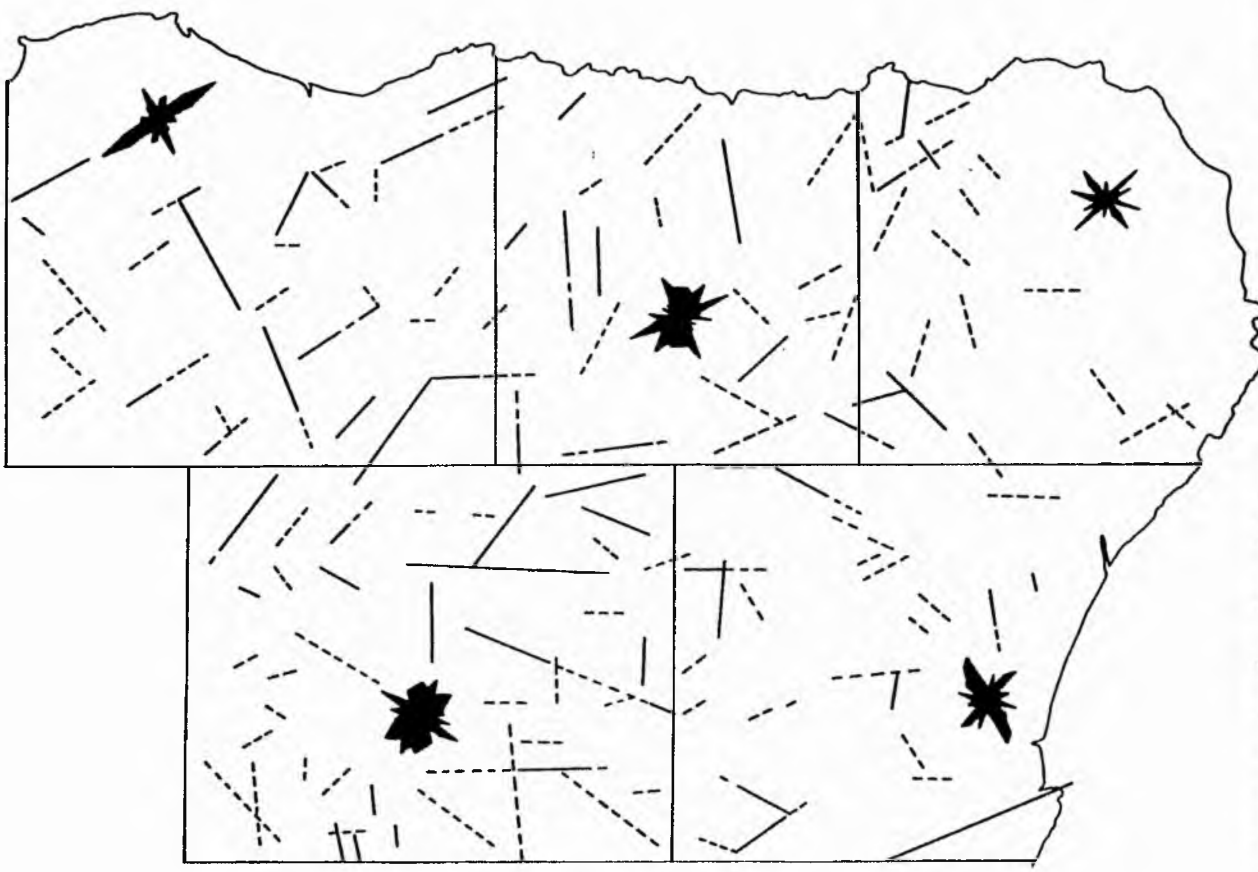


Fig. 2.4.i. Main Topographic Lineaments.

Two directions dominate the regional pattern of lineaments, 055° and 155°, with lesser maxima around 010°, 090° and 125°. The strength of the individual lineaments varies in individual areas. Lineations along 050° and 155° dominate Sheet 28 (Elgin) but strongly modal directions are less obvious on Sheet 29 (Banff). The lower relief of Sheets 30 (Peterhead) and 38 (Aberdeen) makes the identification of lineaments more difficult but both these eastern areas are dominated by 055° and 130° trends. These lineaments are a reflection of the main structural features of the region.

2.4.2 Structural Framework

North-east Scotland lies at the eastern end of the Grampian High, a major basement horst bounded to the north by the Great Glen Fault and to the south by the Highland Boundary Fault. Fractures along the Spey and Dee valleys break up the Grampian High into discrete tectonic blocks, the Monadhliath, Cairngorm and Mounth Blocks, and the serrated hill-front presented to the east by Bennachie and Hill of Fare suggests the existence of a fourth tectonic sub-unit, the Formartine Block (Fig. 2.4.ii). The remarkably straight coastlines of the region are of tectonic origin and follow the boundary between the Grampian High and the adjacent Moray Firth and North Sea Mesozoic sedimentary basins. However the onlap of Old Red Sandstone on to the edges of the basement indicates the presence of tectonic border zones, rather than sharp hinge-lines, between these major structural elements.

The more detailed structural patterns in the study area can be identified by combining available geological information (Fig. 2.4.iii)

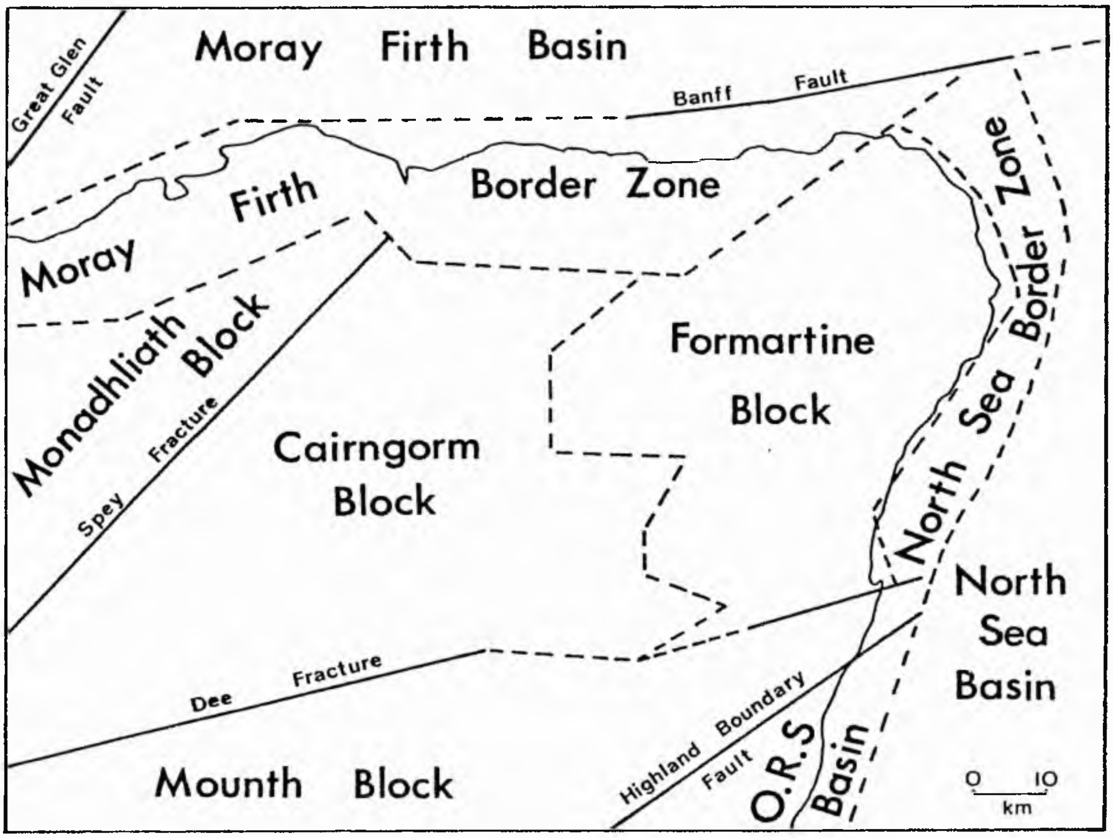


Fig. 2.4.ii. Main structural features.

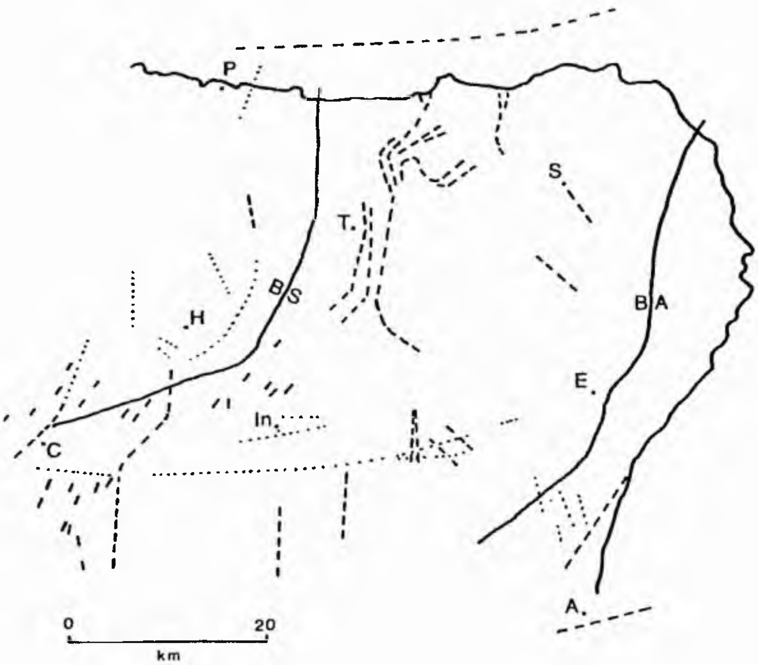


Fig. 2.4.iii. Fracture patterns, after Ashcroft and Munro(1978).

- - - fracture ...... shear - cleavage trends

BS Boyndie Syncline BA Buchan Anticline

A Aberdeen C Cabrach E Ellon H Huntly

In Insch P Portsoy S Strichen T Turriff

with that provided by analysis of the main topographic lineaments. The prominent directional component, 055^{o}, corresponds with the trend of the Dalradian strike and related post- Old Red Sandstone faulting. Fracturing along 055^{o} controls much of the drainage of Banffshire, including parts of the Findhorn, Spey, Isla and Fiddich. The upper Deveron also follows a major tectonic shear along this orientation between the Cabrach basin and Haugh of Glass (Fettes 1968). Post- O.R.S. faulting has, in certain cases, followed these earlier structures (Ashcroft and Munro 1978) and has itself contributed to the SW-NE grain of the relief. Faulting along 040^{o} defines the western margins of the Cabrach and Rhynie O.R.S. outliers. Further south the influence of 055^{o} fracturing is reduced but is still apparent in the orientation of valleys on The Mounth.

Moving east from the Spey the Dalradian strike moves towards 040^{o} but there is doubt as to whether fractures along 020^{o}, which are a prominent feature in the deep structure of the Turriff O.R.S. basin (Ashcroft and Wilson 1976), can belong to this group. N-S lineaments occur further west, bounding the gneissose ridge of Craigbourach Moss and the Aberchirder corridor, and transect 055^{o} lineaments. Moreover 055^{o} lineaments persist further south, notably controlling the alignment of the lower Dee valley, and co-exist with N-S elements such as those which form the eastern and western edges of the Bennachie granite mass (Ashcroft and Wilson 1976). There are grounds, therefore, for believing that the 010^{o} and 055^{o} maxima in the lineament pattern relate to separate axes of fracture.

Fractures along the Dalradian strike in Banffshire are complimented by a further group along 155^{o}. The Rothes fault is the major fracture of the 155° group but forms only one of several valleys transverse to the main SW-NE trend. East of the Spey this fracture group turns towards 125°. This trend is well expressed in the topography of the Fyvie area and the major shear in the Dalradian followed by the Ythan, south of Gight (Farquhar 1950) probably belongs to this group.

Transecting 055° and 155° fractures form a number of small horsts with steep scarps facing the Moray Firth. The horsts, such as Aultmore, Bin of Cullen and Troup Hill, mark a tectonic border zone along the edge of the Dalradian basement.

A lesser structure along 090° is not emphasised in the lineament pattern. Faulting along 070° is important in the Moray Firth basin (Chesher and Bacon 1975) and the structure re-appears further south in the Insch basic mass (Read 1956). The persistence of E-W links in the drainage network probably reflects this structure.

One of the most important groups of local structures are the shear zones associated with the Younger Basic masses. Shears define the southern and eastern margins of the Insch Mass (Read 1956; Ashcroft and Munro 1978). Near Huntly, the hill mass of The Bin is an upstanding block of unsheared basic rocks bounded by other basic rocks which shearing has rendered highly susceptible to weathering and erosion (Munro 1970; Ashworth 1975), a very similar arrangement to that found at Barra Hill, east of Oldmeldrum (Ashcroft and Munro 1978). Shearing also affects the Arnage and Belhelvie basic masses (Ashcroft and Boyd 1976).

The age of many structures is problematical. Fractures along

055^{o} and 010^{o} cut Old Red rocks but probably represent re-activised Dalradian structures (Ashcroft and Munro 1978). An extension of the Rothes fault, part of the 155^{o} group, appears to displace Lower Jurassic north of Elgin (Map 1 in folder). E-W fractures are associated with Permo-Triassic dykes and downfault Upper Cretaceous in the Moray Firth (Chesher and Bacon 1975). Movement along the Highland Boundary Fault also affects Upper Cretaceous rocks in the North Sea (Heybroek et al 1967). All indications are of repeated re-activation of ancient structures throughout the Mesozoic.

There is no reason to suppose that tectonic activity ceased in the region at the end of the Cretaceous. The outer Moray Firth Basin saw massive accumulation of clastics during the Palaeocene (Morton 1979) and subsidence of the North Sea Basin has continued into the Pleistocene (Clarke 1973). On the west coast of Scotland, Neogene movement along the Great Glen Fault has displaced Eocene dyke swarms (Holgate 1969) and downfaulted upper Oligocene sediments by 500m (Smythe and Kenolty 1975) and some of this activity was felt further east along the Fault (Threlfall 1981).

The succession of stepped erosion surfaces in north-east Scotland is itself testimony to phases of Tertiary uplift (Fitzpatrick 1969). Morphological evidence presented later (see Part 3) suggests that styles of uplift were variable and that uplift was accompanied by differential movements. Movements continued into the Pleistocene along the Southern Uplands Fault (Lumsden and Davies 1965) and Late Glacial and Holocene differential movements in response to glacio-isostatic recovery have been recently demonstrated by Sissons and Cornish (1982). Records of minor earthquakes along the Great Glen Fault and the Highland Boundary Fault (Anderson and Owen 1968) indicate that neotectonic activity in Scotland may be far more important than is generally realised.

2.5 Summary

The general physiography of the region is outlined and a number of morphological regions are identified. The complex basement geology is described along with the characteristics of Devonian sediments on land and Mesozoic sediments beneath the Moray Firth. The main structural trends are reviewed.

CHAPTER 3 Regional Tectonic, Palaeoclimatic and Geomorphic Framework

3.1 Introduction

The reconstruction of the main events in the shaping of the Scottish landsurface is a difficult and sometimes speculative task. The Scottish basement block has been a positive relief element throughout the Tertiary (Ziegler 1982). As a consequence, the stratigraphic record of this period is almost wholly to be found offshore in the North Sea basin and along the edge of the continental shelf. The basement block has been an area of erosion and uplift where ephemeral sediments have been rapidly and effectively denuded before consolidation. Almost all remaining fragments of Tertiary terrigenous deposits were swept away by the successive glaciations of the Pleistocene. The lack of correlative deposits onshore and the yet limited knowledge of the relevant offshore stratigraphy creates severe difficulties for any investigation of the development of the Scottish relief through the Tertiary. The gap in the Scottish geological record in the Neogene means that all evidence of the events that fashioned the relief during that period must come from the examination of Neogene erosional landforms. Yet these palaeoforms can supply no precise information as to their age; only a relative age can be established by reference to their present position in the landscape. Further evidence of their antiquity can only be gained by interpreting the various types of palaeoforms as climatogenetic landforms (Budel 1980), developed in response to distinct sets of former climatic conditions. The recognition of climatogenetic landforms is problematic as the influences of structure, climatic variation, polycyclic landform development and other factors serve to obscure any original genetic links between morphology and climate. Nevertheless useful comments can be made on the relationship between certain major landforms and former climates by careful observations of palaeoforms and their relation to geology and structure (Godard 1965).

This chapter aims to identify the main tectonic and palaeoclimatic events affecting the Scottish Highlands through the Tertiary. These events provide a framework in which to consider the long-term geomorphic evolution of the Highlands and a background against which to examine the particular problems of relief generation in north-east Scotland.

3.2. Tertiary Tectonic Events

During the Late Cretaceous and Tertiary, the Highland Block was located between two active centres:- the expanding North Atlantic Basin and the subsiding North Sea Basin. Movement of the Highland Block has been governed by the pattern of tectonic activity in these neighbouring centres.

3.2.1 Activity in the North Atlantic Basin

Opening of the North Atlantic commenced in the Late Cretaceous (Stride et al 1969) and was accompanied by regional magmatic activity. Igneous centres developed along the length of the western margin of the Highland Block in response to crustal separation (Fig. 3.2.i), extending from Antrim in the south, through the Hebridean Province, the Rockall and Faroe Plateaux to an isolated centre north of Shetland (Chalmers and Western 1979). The timing of activity

Fig. 3.2.i. Cretaceous and Tertiary rocks in the Scottish area,

after Evans et al(1981).

Light stipple - Cretaceous Heavy stipple - Oligocene
Dashed shading - Palaeogene intrusives

differed between individual centres (Fitch et al 1978). Localised magmatism occurred as early as 80Ma on the Rockall Bank (Roberts et al 1974). In Hebridean Scotland, the three main phases of volcanism, igneous intrusion and dyke injection were completed within the period of 65 to 59Ma with minor intermittent activity finally ceasing around 50Ma (Evans et al 1973). The main regional event in the North Atlantic occurred between 56 and 53Ma, with injection of the Cleveland Dyke, intrusion of the Rockall granite and massive extrusions of basalts in the Faroes and Greenland (Fitch et al 1978). The magmatic activity around western Scotland spans the period between 80 and 50Ma during which the Highland Block must have suffered repeated tectonism.

3.2.2 Activity in the North Sea Basin

Gentle regional uplift at the end of the Cretaceous brought an end to marine carbonate sedimentation in most of the North Sea basin, although formation of chalks continued into the Danian in the major grabens (Pegrum et al 1975). The style of deposition changed abruptly in the early Palaeocene in the outer Moray Firth area, with the accumulation of large volumes of sands in coalescing submarine fans (Ziegler 1982). Rates of subsidence accelerated sharply (Sutter 1980) and rapid infilling of the Palaeocene basins culminated in the establishment of deltaic conditions in the earliest Eocene (Knox et al 1981; Rochow 1981).

Sedimentation of coarse clastics largely ceased after the Early Eocene in the central North Sea. Infilling of the Central Graben continued, although subsidence temporarily slowed (Sutter 1980) and rates of sedimentation in the Forties Field fell to less than a third of those in the Palaeocene (Walmsley 1975). Around the margins of the North Sea Basin, the Eocene was a period of widespread transgression (Owen 1978; Ziegler 1982).

In the Central Graben, later Tertiary sediments consist largely of muds and silts and fine-grained marine sedimentation was maintained into the Early Pleistocene (Caston 1977). However rates of subsidence accelerated in the Neogene, with half the total subsidence in the Tertiary taking place after the Middle Miocene (Clarke 1973). To the north, the Viking Graben continued to receive sands from the Shetland Platform in the Middle Oligocene and in the Neogene (Ziegler 1982) and further instability of the Scottish source area is indicated.

3.2.3 Movement of the Scottish Block

The initial phases of rifting and magmatism in the North Atlantic area produced uplift of the Scottish basement, with widespread erosion in the North Sea basin (Sutter 1980) and stripping of Cretaceous rocks from many parts of the Hebridean Province (George 1966).

Uplift was renewed and intensified after the Danian in the North Sea and throughout the Scottish area. Rapid denudation of the raised and tilted Orkney-Shetland Platform produced a massive influx of terrigenous sands into the northern North Sea. Other parts of the Highland Block were also uplifted at this time, with differential movements between the Orkney-Shetland Platform and the rest of the Scottish mass (Knox et al 1981). The position of ash markers towards the top of the Palaeocene sequence in the North Sea shows that the main phase of volcanism in the Hebridean Province occurred after substantial uplift had already taken place (Rochow 1981). The magmatic activity in the west occupied a period of only about 6Ma (Evans et al 1973) and involved further uplift, widespread dislocation and arching of cover rocks (George 1966). Enormous numbers of minor dykes and sills were forcibly intruded into the country rocks, causing sub-parallel fracturing over wide areas (Watson 1977).

The main axis of Palaeocene uplift lay to the west and north and the Highland Block was tilted towards the North Sea Basin (Ziegler 1981). Tilting was probably also accompanied by down-warping towards the rapidly-subsiding basins in the outer Moray Firth and local differential movements also occurred (Knox et al 1981). High relief was maintained by repeated uplift in the west until the cessation of magmatic activity in the Early Eocene. Intermittent movements continued, with dislocation of dyke swarms along the Great Glen Fault (Holgate 1969) and assymetric uplift in the inner Moray Firth area (Threlfall 1981).

The change to fine-grained sedimentation in the North Sea Basin after the Early Eocene indicates subsidence of the Orkney-Shetland and Highland source areas (Ziegler 1981). The Middle and Late Eocene depositional hiatus in the Rockall Trough is also a result of subsidence (Roberts 1976) and the submergence of the Minch at this time is shown by the occurrence of Middle Eocene marine sediments overlying Palaeocene lacustrine silts in a small basin preserved against the Minch Fault (Inst. Geol. Sci. 1982). Regional subsidence can be inferred, although the bulk of the Highlands must have remained a positive area.

Uplift was resumed in western Scotland in the Oligocene. The Canna Basin contains about 1km of lacustrine sediments resting on downwarped lavas whose uppermost layers contain lignites dated as Late Oligocene (Evans et al 1979). About 500m of marine sediments of similar age are downfaulted by the Great Glen Fault against the Blackstones Bank intrusion (Smythe and Kenolty 1975) and a thin Oligocene conglomerate overlies Eocene marine silts in the Minch (Inst. Geol. Sci. 1982). The extent of this tectonic activity is unclear, although the presence of Oligocene marine sands east of Shetland (Evans et al 1981; Ziegler 1982) indicates that deformation was not confined to the Hebridean area.

Morner (1980) identifies a phase of regional tectonic activity around the North Atlantic at the Oligocene-Miocene boundary at 22m.y., with uplift of Fennoscandia and subsidence of the Iceland-Faroe Ridge. Around Scotland, post-Oligocene unconformities occur in the Sea of the Hebrides, along the western edge of the Orkney-Shetland Platform (Ridd 1981) and in parts of the central North Sea (Sutter 1980). In the Sule Sgeir Basin, earliest Miocene lignitic and kaolinitic clays rest on weathered Lewisian and demonstrate temporary emergence. Local and regional evidence suggests uplift of the western and northern edge of the Highland Block at this time, although the amount of movement must have been modest for there was no interruption of fine-grained sedimentation in the Central Graben of the North Sea (Pegrum et al 1975).

The Highlands appear to have subsided again after the early Miocene for the terrigenous sediments of the Sule Sgeir Basin are overlain by later Miocene marine sands. Evidence for subsequent Neogene tectonic events is limited but there are a number of pointers to continued movement. Firstly, the progressive onlap of marine Neogene sediments west of Scotland (Stride et al 1969) and the accelerating subsidence in the central North Sea (Clarke 1973) suggests further tilting and uplift. Secondly, the succession of erosion surfaces identified at different levels in the Scottish Highlands (Fleet 1938; Linton 1951; Godard 1965; George 1966) indicates pulsed uplift in the late Tertiary. Finally, uplift and warping occurred throughout the Neogene in southern Britain (George 1974), with uplift of the southern Pennines by around 500m since the Miocene (Walsh et al 1972) and events of similar magnitude probably affected the Scottish area.

3.2.4 Summary of tectonic events

The Highland Block was affected by episodic tectonic movements throughout the Tertiary. The main phase of uplift in the Middle Palaeocene to Early Eocene was terminated by subsidence in response to lithospheric cooling (Ziegler 1981). Tectonic activity recommenced during the Oligocene and further uplift occurred in the early Miocene. Events thereafter are more obscure, although pulsed uplift probably continued through the Neogene and, perhaps, into the Pleistocene in response to denudational unloading. The Highland Block was tilted towards the North Sea Basin in the Palaeocene (Ziegler 1981) and again in the later Tertiary (Stride et al 1969). The hinge line of tilt was probably located along the earlier, Mesozoic structures which define the western limits of the North Sea and Moray Firth Basins. The magnitude of local differential movements of structural elements within the Highland Block remains largely unknown.

3.3 Tertiary Palaeoclimates and Weathering

3.3.1 Introduction

The main course of global palaeotemperatures through the Tertiary has become much clearer over the past decade. In the northern Hemisphere warm forest floras dating from the early Tertiary are found at high latitudes, including northern Alaska, Greenland and Spitzbergen. Wolfe (1971) has shown that tropical rain forest extended as far north as Alaska prior to the Oligocene. The Eocene was a period of extraordinary warmth, with latosols developing throughout western Europe (Millot 1970) and around a widening North Atlantic (Nilsen and Kerr 1978). A sharp drop in marine temperatures occurred in the Early Oligocene (Savin et al 1975; Haq et al 1977; Buchardt 1978) at the same time as the first major expansion of Antarctic sea ice (Kennett 1977). A more gradual decline then set in, reaching a temperature minimum in the Late Oligocene. Temperatures then slowly rose again until the Middle Miocene (Haq et al 1977), when low and high latitude temperatures diverge, with rapid and persistent cooling at high latitudes (Savin et al 1975) and with a dramatic expansion of the Antarctic ice sheet beyond its present volume (Kennett 1977). In NW Europe, conditions remained warm temperate to subtropical until the late Miocene, after which periodic cool phases progressively reduced the warmer floristic elements (van der Hammen et al 1971). Related marine cooling in the earliest Pliocene is recorded in the Hatton-Rockall Basin (Poore and Berggren 1975). A brief temperature maximum occurs in the Middle Pliocene (Buchardt 1978) but thereafter the picture is one of increasingly rapid fluctuations of climate, with the stades gradually becoming more severe until the onset of continental glaciation in the Pleistocene.

Reconstruction of the Tertiary climates of Scotland relies heavily on inferences from known trends in other areas. Organic deposits are largely absent from the Scottish mainland, except for the sub- and inter-basaltic floras of Mull and Ardnamurchan (Simpson 1961) and the pollen of the Canna Basin (Evans et al 1979). The lack of organic remains has forced a heavy reliance on patterns of palaeo-environmental change interpreted from flora preserved in more southerly and more continental locations in western and central Europe. The extrapolation of these reconstructions to Britain must include a recognition of the possible cooling and maritime influence of the North Atlantic.

3.3.2 Palaeogene Climates and Weathering Types

It is reasonably certain that Palaeogene temperatures were high in all but the northernmost latitudes. Eocene fossils of thermophilous species such as alligators and turtles have been found on Ellesmere Island in the Canadian Arctic (Dawson et al 1976). Buchardt's (1978) work in the southern North Sea region indicates warming throughout the Palaeocene with temperatures close to those of the present humid tropics in the Eocene (Fig. 3.3.i). In southern England, the London Clay flora of Early Eocene age is generally taken to represent a true Tropical Rain Forest vegetation (Chandler 1964). However Daley (1972) has suggested instead that the flora is indicative of a climatic type not found at present; seasonal, frostless, with abundant rainfall but with lower temperatures than those necessary for the establishment of Tropical Rain Forest today.

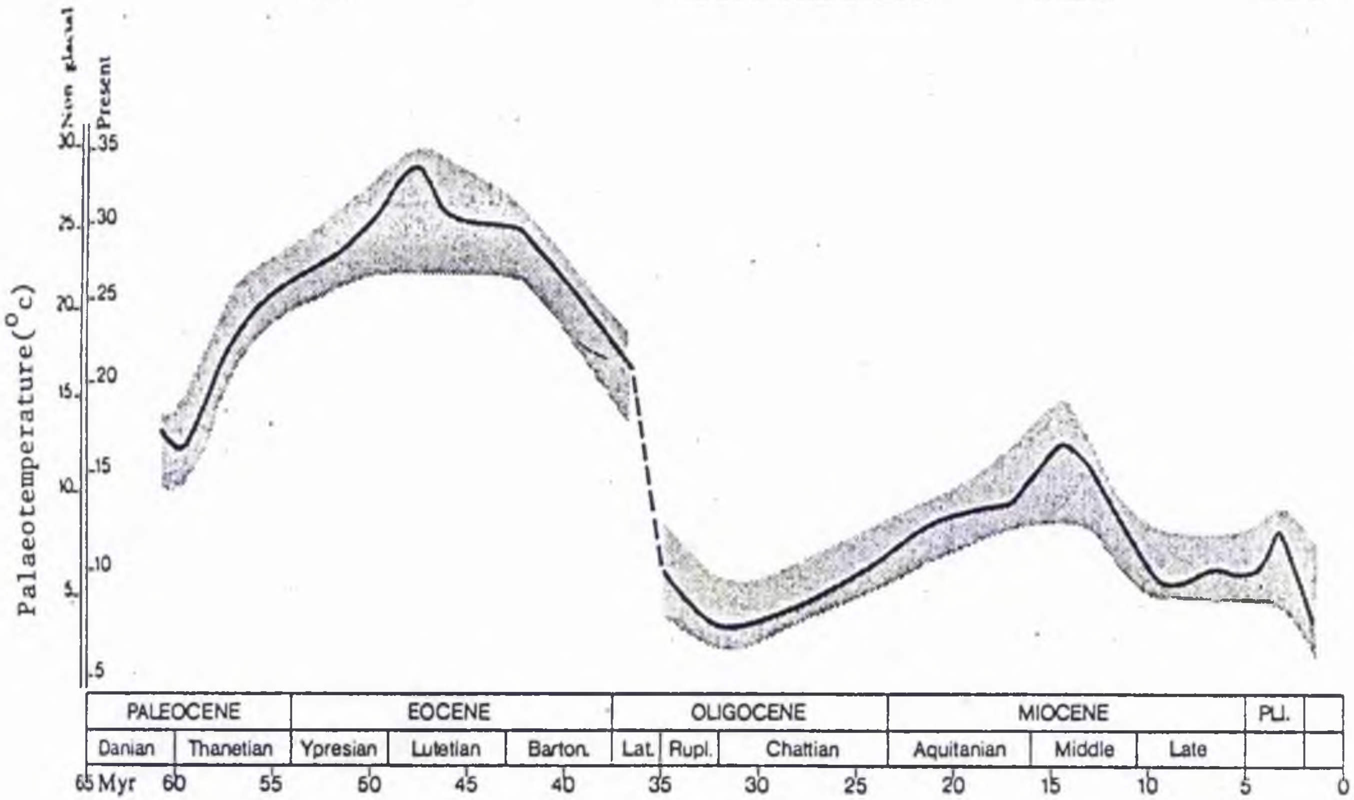


Fig. 3.3.i. Isotopic bottom temperatures in the North Sea during the Tertiary. Fig. 2 of Buchardt(1978).

Palaeocene climates were certainly hot and humid enough, and sufficiently stable, to allow deep, intensely-weathered soils to develop. Laterites belonging to this period are well-represented in western Europe (Millot 1970). The Palaeocene sands of the North Sea contain fragments of granite, basalt and metamorphic rocks (Sutter 1980) but this immaturity is a reflection of high rates of denudation, rather than cool climates. Palaeocene and Early Eocene inter-basaltic latosols are known from Antrim, the Faroes, western Greenland, Baffin Island and the Iceland-Faroe Ridge (Nilsen and Kerr 1978), though their Scottish counterparts in Skye, Mull and Ardnamurchan are thin and less well-developed (Godard et al 1961; Bain et al 1980). Regoliths were predominantly siallitic, with kandite clays dominating Palaeocene weathering profiles in SW England (Isaac 1981), Eocene saprolites in Brittany (Esteouelle-Choux 1967) and Eocene gravels in Devon (Hamblin 1973a). Dry phases in this long Palaeogene period of hot and humid climate were less important in southern Britain than in the Paris Basin (Daley 1972). The dominant geomorphological processes may have closely paralleled those presently operating in the humid tropics (Thomas 1978), but with levelling of the Scottish area being controlled by tectonic, rather than bioclimatic rhythms.

The short but sharp deterioration of climate at the Eocene/Oligocene boundary (Haq et al 1977; Kennett 1977) must have initiated important morphogenetic changes, with stripping of deep Eocene saprolites from many areas. On the shelves of the southern North Sea bottom temperatures dropped by an estimated 12^{o}c between 36 and 38Ma to reach a minimum of 7 to 8^{o}c in the mid-Oligocene

(Buchardt 1978). On land important floral extinctions took place (Wolfe 1971), though in Britain conditions remained warm and frost-free (Wilkinson et al 1980). The Oligocene basins of western Britain record an initial phase of stripping, with vigorous clastic transport, succeeded by much calmer clay-silt lacustrine and paludal sedimentation (O'Sullivan 1979; Wilkinson et al 1980). Weathering conditions were sufficiently intense to produce a predominantly kaolinitic clay mineral assemblage from diverse rock types, though illite is an important component of the Devon basins (Bristow 1968) and in the Mochras borehole (O'Sullivan 1979). Also a significant proportion of a chlorite-vermiculite intergrade appears in the Ballynakilly borehole in the Lough Neagh Clays (Bain et al 1976). Deep saprolites must have developed in the surrounding areas and contributed a steady supply of clayey alteration products to the basins. Fining-upwards sequences in the Mochras borehole (O'Sullivan 1979) and the Petrockstow basin (Freshney 1970) indicate that sand-sized material was introduced into the basins by flood events, but the far greater thicknesses of clays and silts were sedimented almost continuously, apart from brief interludes of vegetation growth and seat earth formation (O'Sullivan 1979).

The Late Oligocene sediments of the Canna Basin contain much higher proportions of coarse clastics (Evans et al 1979), indicating rather different depositional environments. The presence of pebbles of basic rocks, in particular, suggests fairly rapid denudation of recently-elevated source areas.

3.3.3 Neogene Climates and Weathering Types

Conditions in the North Sea appear to have warmed again from the Upper Oligocene onwards to reach a peak in the Middle Miocene (Buchardt 1978). Miocene shelf sea sediments in the Forties Field (Sudijono 1975), in the English Channel (Jenkins 1977) and in Denmark (Rasmussen 1966; Spjeldnaes 1975) all indicate bottom conditions similar to those off the Southwest Iberian Peninsula today. The flora of the pocket deposits of the Brassington Formation of Derbyshire suggests that the deposits are late Miocene to early Pliocene in age and that warm frost-free oceanic conditions prevailed during that period (Boulter 1971). Yet the pollen of cool phases in the early Pliocene (Susterian) of the Netherlands is dominated by pine, pointing to cool-temperate or boreal environments. This is in clear contrast to the warm temperate to subtropical flora of the Miocene in the same area (van der Hammen et al 1971), and perhaps indicates that the Brassington Formation should be assigned wholly to the Miocene.

Miocene climates in NW Europe continued to favour deep rock decomposition. In Denmark, the heavy minerals of fluvial, estuarine and littoral Miocene sands are depleted and strongly altered (Friis 1974; 1976). Further south, the Miocene and Early Pliocene sands of the Ardennes foreland are also deeply weathered, with silicification of the surface layers (van der Broek and van der Waals 1967; De Jong and van der Waals 1971). In Scotland, the early Miocene terrigenous sediments of the Rona Basin are predominantly kaolinitic (Evans et al 1981) and deep alteration of rocks to clayey saprolites probably continued at least until the middle Miocene.

Marine temperatures dropped sharply in the Late Miocene in the southern North Sea (Buchardt 1978) and in the earliest Pliocene in the Rockall-Hatton Basin (Poore and Berggren 1975). Cooling and the increasing periodicity of the climate favoured the stripping of older regoliths and the development of less mature saprolites. Important changes in clay mineralogy occur in North Sea sediments after the Middle Miocene, with the appearance of chlorite and amphibole, increasing illite and felspar contents and corresponding reductions in kaolinite and smectite contents (Karllson et al 1979; Berstad et al 1982). In Brittany, Early Pliocene felspathic terrigenous sands mark a break from the clayey sedimentation characteristic of the earlier Tertiary (Durand 1960). These changes in sediment mineralogy reflect a major transformation in styles of weathering in NW Europe in the Late Miocene and Early Pliocene, when earlier mature, clayey alterites were replaced by sandy saprolites containing substantial amounts of detrital felspar and biotite (Bakker 1967; Esteouelle-Choux 1967; Lidmar-Bergstrom 1982).

The increasing complexity of Pliocene climates was due to repeated oscillations of ever shorter duration which culminated in the rapid Late Pleistocene stadial and interstadial alternations. The Early and Middle Pliocene climate of the Netherlands was oceanic and temperate, apart from periodic cool phases (van der Hammen et al 1971). Progressive cooling set in again after a Middle Pliocene temperature high (Buchardt 1978) but conditions were still mild enough to support mixed-oak forest in the Netherlands and East Anglia during the Upper Pliocene (Zagwijn 1960; West 1980).

Continental glaciation began in the Northern Hemisphere at around 2.5Ma (Backmann 1979), although most of Europe remained unglaciated until as late as 0.6Ma (van der Hammen et al 1971; Bowen 1978). In western Europe, the Early Pleistocene was a period of frequent cold-temperate cycles, but with the cold phases being less severe than those of the later Pleistocene. Each stadial was accompanied by subarctic to boreal vegetation, with loess accumulation on cold steppes further east in central Europe (Butzer 1976). In the latter part of the Pleistocene, the duration of interglacial phases was further reduced, with temperate forest replacing herb vegetation for periods of, at most, a few tens of thousands of years (West 1980).

3.4 Geomorphic Development of the Highlands through the Tertiary

3.4.1 The sub-Cenomanian surface and the extent of the Cretaceous transgression

The extraordinary extent of the Late Cretaceous marine transgression in many parts of Europe (Ziegler 1981) has encouraged speculation that most or all of Scotland might have had its own Chalk cover. Linton (1951), following on from Bremner (1942), developed the idea that a sub-Cenomanian peneplain acted as a master surface for the later evolution of the Scottish scenery. The main drainage lines were thought to have been initiated on this peneplain after uplift, with remnants of the original master surface preserved as the highest summit surfaces of the Western Highlands and the Cairngorms.

The concept of a sub-Cenomanian master surface has been severely criticised (Godard 1965; George 1966; Sissons 1976), not least because of the lack of evidence that the Scottish landmass was ever submerged during the Cretaceous. Remnants of Cretaceous rocks on land appear only as scattered fragments dotted around the Inner Hebrides and as inclusions within Tertiary vents on Arran (George 1966). Of these sediments only the thin Chalk beds were laid down in the open sea and earlier Cenomanian sands were deposited in shallow water adjacent to an upstanding landsurface composed of Moinian and granitic rocks (Humphries 1961). The Cretaceous is absent from the northern parts of the Sea of the Hebrides and from most of the North Scottish Shelf (Evans et al 1981 and Fig. 3.2.i). The confinement of thin Cretaceous beds to outliers in western Scotland offers little support for the former existence of a continuous cover of Cretaceous over Scotland (George 1966). Moreover, pre-basaltic Palaeocene sands in the North Sea Basin contain much material derived from crystalline and Old Red sedimentary rocks (Morton 1979; Sutter 1980), indicating that the Orkney-Shetland Platform and Highland source areas were free of extensive covers of Cretaceous or earlier Mesozoic sediments in the Middle Palaeocene.

It is now generally accepted that the Scottish landmass remained an area of positive relief throughout the Cretaceous (Owen 1978; Ziegler 1981), apart from localised submergence of the Hebridean area. However it is probable that the Cretaceous also overstepped on to basement in areas bordering the Moray Firth (Wilson 1886). Cretaceous rocks outcrop extensively beneath the Moray Firth (Chesher and Bacon 1975) and the purity of the Chalk in this area signifies that neighbouring crystalline and Mesozoic sedimentary rocks were unable to supply detritus in the late Cretaceous. The proximity of the Chalk to Dalradian basement in the eastern part of the Moray Firth and the presence of clasts of Cretaceous flint and silicified greensand in the Pliocene (?) Gravels of Buchan (Flett and Read 1921) both indicate that the margins of the Moray Firth Basin were periodically submerged during the Cretaceous.

3.4.2 The Scottish landsurface in the Late Cretaceous

Although the concept of a sub-Cenomanian surface must now be abandoned, the recognition that the Scottish area remained a positive element throughout the Cretaceous focusses attention on the likelihood of regional subaerial planation during this long period. Extensive levelling of relief occurred in North America (Blank 1978) and many parts of north-west Europe (Lidmar-Bergstrom 1982) during the Cretaceous. Planation of the quiescent Scottish landsurface under the tropical climates of the Cretaceous must also be a strong possibility (Linton 1951) and the lithology of the Moray Firth and Hebridean Chalks suggests that the Scottish Block had been reduced close to base level by the Late Cretaceous. The limited development of Chalk in the west may also reflect the beginnings of regional tilt towards the North Sea.

3.4.3 The disruption of the Cretaceous relief

The onset of the first magmatic activity in western Scotland at around 80Ma (Fitch et al 1978) began the disruption of a levelled Scottish landmass. In western Scotland, the later Palaeogene earth movements destroyed all traces of the Cretaceous relief (Godard 1965; George 1966). In many areas, Cretaceous rocks were already missing before the extrusion of the first basalts (George 1966) and the lavas were laid down on an irregular surface (Godard 1965). This sub-basaltic surface was then itself further dislocated and modified during the uplift and faulting associated with the emplacement of the igneous masses (George 1966).

The depth of subsequent denudation of the Hebridean Province requires that even the highest erosion surfaces in western Scotland post-date the Palaeocene to Early Eocene magmatic phase. Deep-seated plutons are now exposed at the surface and dominate the scenery of the Inner Hebrides. On Skye, at least one kilometre of cover rocks must be missing and erosion has provided 600m of vertical section through the Red Cuillin granites (Stewart 1965). The entire original thicknesses of lavas have been stripped from parts of Skye, Rhum and Mull (George 1966). However much of this denudation took place during the magmatic phase. On Mull, some 2km of lavas were removed between 56 and 58mA (Curry et al 1978). The Rhum granophyre was exposed soon after emplacement at around 58mA and supplied pebbles to prebasaltic conglomerates on Canna (Emeleus 1973). On Rhum itself, the lavas infill valleys on the granophyre surface and as the intrusion retains fragments of its Lewisian roof, it can be demonstrated that post-Palaeocene erosion has achieved no more than removal of the basalt pile (Dunham and Emeleus 1967). Further demonstration that many intrusions were unroofed early in the Tertiary is given by the overstep of Oligocene sediments on to the exposed and submerged Blackstones Bank igneous centre, emplaced around 57mA (Curry et al 1978). Very high rates of denudation are implied, possibly reaching 1000B on Mull and Rhum.

The magnitude of denudation in other parts of Scotland after the Palaeocene is less certain. Late Palaeocene and Early Eocene dykes are found at elevations of 900m in the Western Highlands and 600m in the Southern Uplands (Sissons 1976) and imply surface lowering by at least several hundred metres in these areas. The volume of material supplied by the raised Orkney-Shetland Platform to the Palaeocene basins in the North Sea also indicates destruction of all pre-existing relief forms in this area (Rochow 1981). However it is possible that the magnitude of Palaeocene uplift and subsequent denudation was considerably less in other areas away from the main axis of movement. Due to tilting of the Highland Block towards the North Sea, the scale of uplift will have declined eastwards. It remains feasible that eastern areas of elevated and levelled relief, such as the Cairngorm summits, have survived from the Palaeogene. Another possible area of more limited Tertiary erosion is the Outer Isles Platform. The vesicularity of the Eocene dykes along the eastern coasts of the Outer Hebrides may show that the maximum thickness of cover rocks at the time of injection was no more than 1km, allowing speculation that the highest peaks of Harris are close to the level of the pre-basaltic landsurface (Watson 1977).

3.4.4 Relief development and Erosion Surfaces

Due to the poverty of the post-Eocene geological record, the geomorphologist is thrown back upon the evidence of palaeoforms in order to piece together the erosional history of the later Tertiary. In Scotland planation surfaces, inselbergs, basins, major breaks of slope and the chief lineaments of the drainage net have all been interpreted as preglacially-formed elements of the relief. Of these forms, the planation surfaces have received by far the most attention. Yet whilst it is obvious that, regionally, the Scottish relief is composed of series of stepped erosional levels there exists little agreement as to the inter-regional correlations of such levels and to their possible modes of origin.

There are only a few studies dealing with the erosion surfaces of Highland Scotland. The early work of Peach and Horne (1930) split the relief into three broad bands: (i) the High Plateau between 600 and 900m; (ii) the Intermediate Plateau with an upper limit at about 300m; (iii) and the Continental Shelf. The height limits of Peach and Horne are so vague as to render their scheme of little practical use. The work of Fleet (1938) in the Grampian Mountains is often referred to yet was based solely on cartographic analyses. Fleet recognised four erosional levels and produced a map showing their extent. The Grampian Summits formed a group of residuals standing above a break of slope between 760 and 880m. Below this altitude three surfaces were recognised, viz:- (i) the Grampian Main Surface, from 700 to 900m, an extensive surface truncating a wide variety of rocks and bounded by clear breaks of slope; (ii) the Grampian Lower Surface from 400 to 600m, fringing the Grampian Main Surface and (iii) the Grampian Valley Benches from 200 to 300m, comprising restricted areas of low relief confined to the Loch Ness district, the Rannoch basin and the Highland border in the extreme south-east. Fleet's work has provided a useful breakdown of the relief of the Grampians but there remains a need for a more field-oriented study.

On Arran and over large areas of Hebridean Scotland, George (1966) has identified surfaces of limited vertical range at 970, 730 and 490m. The horizontality and general indifference to geological structure lead George to identify these flats as marine erosion surfaces. Similar interpretations have been advanced for surfaces in southern and central Scotland (see Sissons 1976) and Walton (1963) regarded all surfaces below 350m in north-east Scotland as of marine origin. There are several strong objections to the hypothesis that many Scottish surfaces are the product ot marine erosion. Firstly, King (1963) has demonstrated that marine abrasion platforms cannot be widened beyond about 1300m unless sea level is gently rising. The formation of extensive marine surfaces would thus require that gradual sea level change had kept pace with marine erosion over long periods. The continuance of such conditions over the time spans necessary to allow the formation of surfaces across most of Scotland is unlikely and some other mode of planation is almost certainly involved. A second objection to marine erosion as an important agent of planation is that many surface fragments are found in locations where it is difficult or impossible to envisage effective wave attack, such as along narrow straths or within partially enclosed basins. Thirdly, unless it is postulated that there has been massive episodic subsidence of the Scottish landmass, the identification of horizontal high level marine surfaces requires pulsed uplift accompanied by only insignificant warping and a very low degree of post-formational modification. Neither condition is likely to have been satisfied (Sissons 1976). Finally, it is clear that close examination of many of these surfaces reveals a strong relationship between surface form and the underlying structure and geology, underlining the important role of differential weathering in their formation (Godard 1965; 1969). In the absence of Tertiary marine deposits it is probably wise to look for alternative models of subaerial planation to account for the erosion surfaces of Scotland.

The work of Linton (1950; 1951) provided important contributions to the study of the Scottish scenery. Linton (1951) placed earlier reconstructions of the Scottish relief (Hinxman 1901; Bremner 1919; 1942) within a geological framework in an effort to date phases of relief development. The importance of tectonic activity in the erosional history of the Scottish landsurface was recognised and Linton (1951) cited evidence for tilting of high level erosion surfaces in the Grampians. The variety of palaeoforms present in the scenery was acknowledged and the origins of certain of these landforms, notably basins and tors, was considered in detail.

The most detailed and careful work on Scottish erosion surfaces is that by Godard (1965), covering the whole of the country north of the Great Glen. Godard identifies three distinct surfaces across northern Scotland, plus a high level surface composed of summit heights and fragments. With the exception of the lowest Pliocene level, all the surfaces are warped to different degrees by later phases of uplift. Godard's Surface Superieure rises eastwards, from 700 to 750m on the isolated mountains of north-west Scotland to 900 to 950 on Ben Wyvis in Easter Ross. This is the opposite to what would be expected for an easterly tilt to the country during the Tertiary, which perhaps indicates that these widely scattered fragments belong to more than one level. The Surface Intermediaire lies between 375 and 500m and consists mainly of plateaux cut across diverse lithologies. The surface is preferentially developed on granitoids and other relatively easily weathered rocks and Godard suggests formation under a tropical climate with marked dry seasons. Bordering the Surface Intermediaire is the Surface Ecossaise, a surface of impressive extent lying at about 300m. The principal characteristics of this surface are a general indifference to geology, with low-angle slopes cut across rocks normally rather resistant to alteration, the presence of abrupt breaks of slope along the inner margins of the surface and the development of partially closed basins. Godard regards this as a surface of pediplanation, created under semi-arid climates. Whilst acknowledging the difficulty of appeal ing for arid environments in the Scottish Neogene, Godard feels that the morphological evidence is so strong as to demand the acceptance of the possibility that such conditions did prevail, perhaps in the late Miocene. The Surface Ecossaise was the last surface to penetrate to the interior of northern Scotland. It was succeeded by the Niveau Pliocene, a marginal level developed widely across coastal districts and along the major valleys. This level was formed late in the Tertiary and so remained little uplifted or deformed. Of great importance is the survival of palaeosols and saprolites on its surface. Red soils found preserved within limestone joints at Durness, Inchnadamph and Loch Kishorn were thought to resemble ferreto soils of Mediterranean type and presumed to be mid Pliocene in age (Godard et al 1961). The more widespread illitic saprolites were developed under somewhat cooler conditions, perhaps in the Villafranchian (Godard 1965). The Niveau Pliocene was a product of this low intensity weathering combined with periodic stripping under temperate or warm temperate environments.

The height ranges of the different surfaces identified by these various writers are presented in Fig. 3.4.i. In general, the correlations between the separate regions are not good, except for the equivalence of Godard's Surface Superieure (700-950m) and Surface Intermediaire (375-500m) with Fleet's Grampian Main (700-900) and Grampian Lower (400-600) surfaces. George's two upper levels fall close to the breaks of slope between the higher surfaces recognised by Godard and Fleet. At lower elevations Walton (1963) describes four platforms below 300m in north-east Scotland whereas, further north, Godard finds evidence for only two. This perhaps reflects the different levels of resolution of these two studies. All the investigations of the erosion surfaces of the Highlands use different techniques and Godard's is the only study to isolate flats induced by structural control. In view of these discrepancies it is not possible to decide whether the regional differences in elevation between the surfaces which have been identified are real or apparent.

3.5 Rates of denudation

Both Fleet (1938) and Godard (1965) recognise at least four phases of planation penetrating deep into the Highlands. The amount of denudation is impressive but opinions vary as to the time spans required for levelling. Godard (1965) considers that sculpting of the Highlands has occupied all of the post-Eocene period,

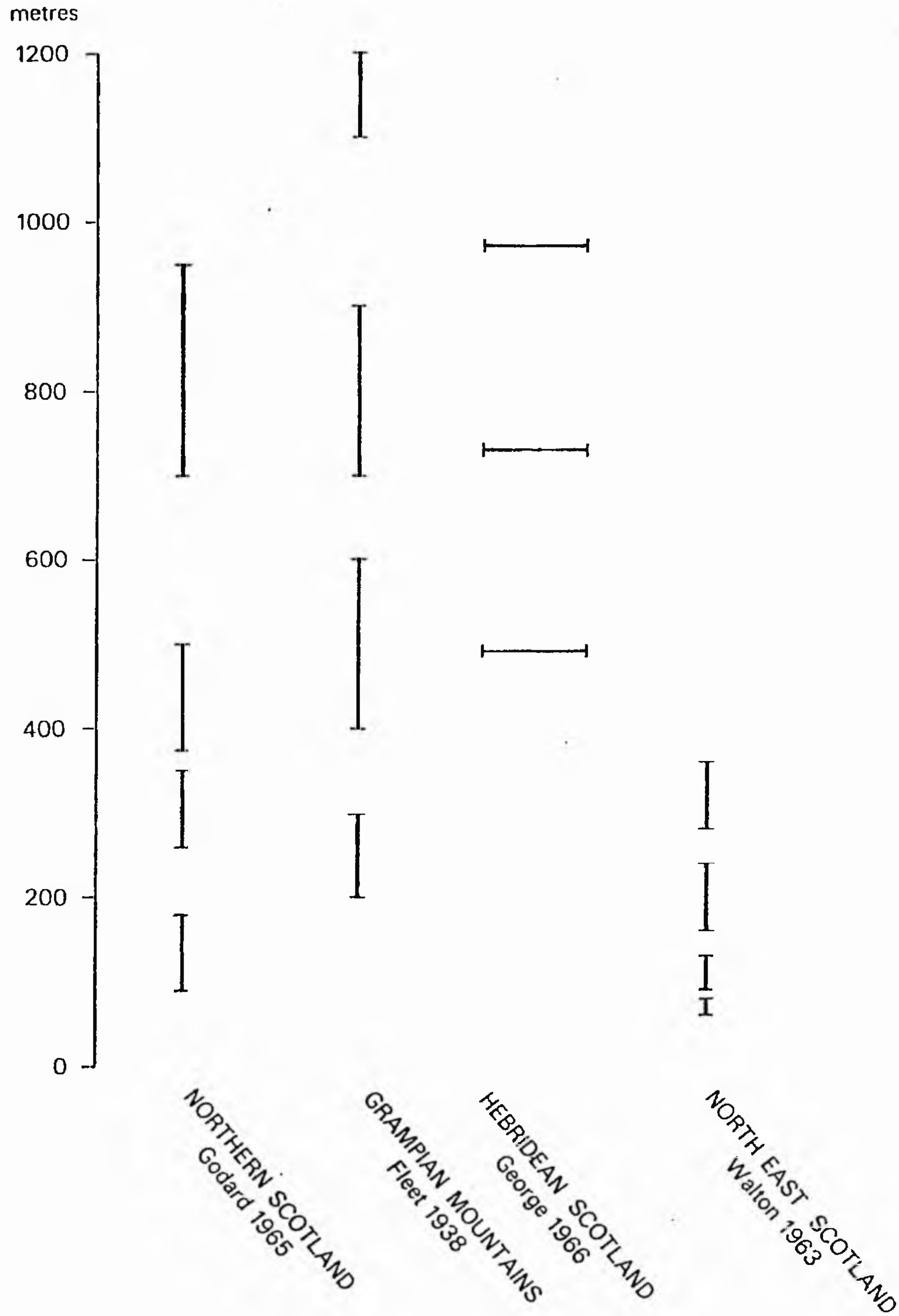


Fig. 3.4.i. Height ranges of Highland erosion surfaces.

with development of the summit relief soon after the end of magmatic activity in the Hebridean Province. In contrast, George (1966) regards the relief of the Western Highlands as wholly Neogene in origin. These divergent views reflect the lack of information about long-term rates of denudation from the Highlands.

Yet crude estimates of rates of denudation can now be derived from volumes of Cenozoic sediments in the central North Sea. These simple calculations require values for only a small number of parameters:- contributing area, sediment volumes and sediment porosity and carbonate content (Gilluly et al 1970; Matthews 1975; Laine 1980). Even though only approximate values can be supplied for the Highlands and the North Sea Basin, useful order of magnitude estimates can be obtained.

The contributing area for Tertiary sediments is taken to lie east of the axis of maximum uplift in the Palaeocene. This boundary is defined as running northwards from the Southern Uplands Fault through the igneous centres of Arran, Mull, Ardnamurchan and Skye. The line then follows the mountain front of the Northern Highlands, a re-activated sub-Mesozoic feature (Sissons 1976), and turns northeastwards at Cape Wrath to follow the faults bounding the western edge of the Orkney-Shetland Platform (Evans et al 1981) to terminate at latitude 61^{o}N. The eastern margin of the contributing area is taken as the edge of the Tertiary subcrop in the North Sea (Evans et al 1981).

The contributing area for Pleistocene sediments is rather smaller. North of the Southern Uplands Fault, the western margin follows the ice-shed of the last ice sheet (Sissons 1976) as far north as Loch Broom. The margin then turns northeastwards to pass along the watershed of the Northern Highlands and through the centre of the Orkney and Shetland Islands. The eastern margin is defined as a line running along the east coast of mainland Scotland, the Walls Boundary Fault and the east coast of the Shetlands.

The receiving area for Tertiary sediments in the North Sea is largely notional but taken as the area between latitudes 56^{o} and 61^{o}N, the edge of the Tertiary subcrop and the U.K.-Norway Median Line, which follows the axis of the Central Graben (Pegrum et al 1975). The corresponding area for Pleistocene sediments is extended to the eastern coast of the mainland. Isopachs are from Evans et al (1981). Based on thicknesses in the Forties and Montrose fields (Fowler 1975; Walmsley 1975), Palaeogene sediments are estimated to account for 43% of total Tertiary accumulations.

No figures are available for the porosity of complete Cenozoic sequences in the North Sea. However, Matthews (1975) and Laine (1980) give values of 60 and 51% for sediments of similar age off eastern North America and North Sea porosity is accordingly estimated to average 55%. Total carbonate and organic contents are estimated at 10% following Laine (1980).

The calculations are shown in Table 3.5.i. The volume of Palaeogene sediments in this part of the central North Sea indicates a loss of 301m of rock per unit area, a denudation rate of 7B (1 Bubnoff = 1m per million years). A figure of similar order is given by Knox (in discussion of Rochow 1981) who calculates that 200m of rock was eroded from the Orkney-Shetland and Platform to supply the Palaeocene-Early Eocene sands of the Outer Moray Firth Basin. However these estimates are undoubtedly far too low. Curry et al (1978) suggest that 2km of basalts were removed from Mull between 56 and 58Ma, indicating local rates of denudation of around 1000B. Only the coarse detritus from this massive Palaeocene denudation was lodged in the central North Sea and heavy minerals of Highland provenance were carried as far south as the Hampshire Basin (Morton 1982). The actual receiving area for Palaeogene detritus thus extended far beyond the western half of the central North Sea.

The estimate of Neogene erosion of 228m of rock, a rate of 14B, may be more reliable. Subsidence of the Central Graben accelerated during the Oligocene and through the Neogene (Clarke 1973; Sutter 1980) and less material was probably carried beyond the notional receiving area. However it is noteworthy that the estimate is still well below the rate of uplift of 66B given for the Miocene-Early Pliocene Brassington Formation of the southern Pennines (Walsh et al 1972).

Table 3.5.i Estimates of Tertiary and Pleistocene rates of denudation based on volumes of sediments in the central North Sea.

Tertiary	
Contributing area	129217km^2
Volume of wet sediment	168774km^3
Loss of wet sediment per unit area	1.306km
Take out pore space and carbonate content to give total depth of rock removed in Tertiary	529m
Estimated erosion in Palaeogene	301m
Estimated erosion in Neogene	228m

Table 3.5.i (contd)

Pleistocene	
Contributing area	$52334km^2$
Volume of wet sediment	$25260km^3$
Loss of wet sediment per unit area	483m
Take out pore space and carbonate content to give estimated depth of rock removed in Pleistocene	195m

Estimated Pleistocene erosion from the Highland source area of 195m of rock, a rate of 78B, is comparable to total Neogene erosion. The figure is also twice that given by Laine (1980) for Pleistocene erosion in eastern North America. The reliability of the estimate is in some doubt due to uncertainty about the size of the source area, the proportion of sediment transported beyond the notional receiving area, the amount of reworked Tertiary sediments and other factors. Nevertheless, if the order of magnitude is correct, the estimate implies deep Pleistocene erosion in parts of the Highlands and substantial mass transfer to the North Sea Basin.

At least 724m of rock, and probably considerably more, has been removed from this part of the Highlands since the start of the Cenozoic. The minimal estimate of 228m of Neogene erosion demonstrates that substantial remodelling of the relief occurred in the late Tertiary. Post-Oligocene uplift is implied and long-term isostatic movements in response to denudation must have continued into the Pleistocene. The scale of denudation supports George's (1966) contention that the summit relief of Hebridean Scotland is of Neogene age but the possibility remains that the elevated plateaux areas farther east and closer to the hinge-line of tilt are inherited from the Palaeogene.

3.6 Summary:

A framework for the geomorphic evolution of the Scottish Highlands through the Tertiary.

By bringing together evidence of the main tectonic and palaeo-climatic events, the nature of weathering covers, rates of denudation and regional morphology, it is possible to develop a model of the geomorphic evolution of the Highlands through the Tertiary (Table 3.6.i).

Upper Cretaceous

The Highland Block remained a positive area during the Upper Cretaceous and was extensively levelled. Transgression was restricted to marginal areas, with deposition of Chalk in the Minch and along the edges of the basement in the east. Tilting towards the North Sea may have already begun.

Palaeocene and Early Eocene

Regional magmatic activity began around 65mA and reached a climax around 59mA, with minor activity continuing until 50mA (Curry et al 1978). Magmatism was accompanied by major uplift and tilting of the Orkney-Shetland Platform and the Highland Block towards the North Sea. Substantial differential movements in the Hebridean Province (George 1966) were matched in the east (Knox et al 1981), with downfaulting of the Moray Firth Basin and downwarping of adjacent areas and movement of the Highland Boundary Fault.

Earlier subdued relief was destroyed almost throughout the Highlands. Massive denudation in the west lead to the unroofing of recently-emplaced intrusions and the Orkney-Shetland Platform was greatly

Age	Epoch	Tectonic events	Sea level changes	North Sea temps.	North Sea clays	Morphogenic events
0 – 2.5	PLEISTOCENE	Pulsed uplift and possible tilting	Glacio-eustatic oscillations			Regional glaciation
2.5 – 5	PLIOCENE L, E			cool / warmer / cool	Kaolin/Smectite decrease Illite/Chlorite increase	Denudation in W. Valley and basin deepening. Lowering of Miocene surfaces in E. Sandy regoliths.
5 – 10	MIOCENE L			cool min 9°c		
10 –	MIOCENE M	Stable		warm max 17°c	Kaolin increase	Levelling and basin development in Highlands. Kaolinitic regoliths.
	MIOCENE E	Subsidence in W.				
20		Regional uplift and tilting	Regression	fairly warm	High Smectite content	Denudation of W. Highlands and Shetland area.
	OLIGOCENE L, M	Local uplift in W. Highlands and Shetland area		cool min 7°c		
30 – 40	OLIGOCENE E; EOCENE L	Stable	Transgression	very warm max 27°c		Extensive levelling but hilly relief probably maintained in W. Highlands. Latosols develop.
40 – 50	EOCENE M, E	Subsidence of W. Highlands			Kaolin increase	
50 – 60	PALAEOCENE L, M, E	Major uplift and tilting of Highlands and Shetland Platform	Regression		Very high smectite content	Major denudation of mountainous terrain Exposure of newly-intruded plutons
70	L. CRET.	Stable but growing activity in W.	Transgression	cool min 12°c		Levelling in E. Hilly relief maintained in W.

Table 3.6.1. Summary of the Tertiary morphogenic history of the Scottish Highlands.

Tertiary time scale after Curry(1978). Sea level changes after Ziegler (1982). North Sea bottom temperatures after Buchardt(1978). North Sea clay minerals after Karllson et al(1979) lowered. The intensity of erosion declined eastwards towards the hinge line of tilt along the western edge of the North Sea Basin but probably remained substantial. Perhaps the only areas to escape deep erosion were those downwarped towards the Moray Firth.

Middle Eocene to Early Oligocene

The Highlands subsided after the Early Eocene and the sea re-occupied the Minch. The establishment of more stable tectonic conditions allowed extensive levelling of the relief under the prevailing humid tropical climates and, as a result, rates of sedimentation declined sharply in the North Sea. Widespread development of latosols can be inferred from the increase in kaolinite contents in North Sea sediments at this time (Karllson et al 1979) and from the composition of contemporaneous sediments and saprolites in other parts of north-west Europe (Lidmar-Bergstrom 1982). These biostatic environments (Erhart 1955) were interrupted by the abrupt climatic deterioration at the Eocene-Oligocene boundary and the resultant phase of stripping is marked by influxes of sand to the central North Sea (Berstad and Dypvik 1982).

Middle Oligocene to Early Miocene

Localised uplift began again in western Scotland and the Shetland area during the Oligocene and culminated in a phase of modest regional uplift and renewed tilting at the Oligocene-Miocene boundary. Oligocene deformation in the west caused substantial remodelling of the subdued Eocene relief and the Hebridean landscape is largely of Neogene origin (George 1966). However, the amount of uplift declined eastwards once again and the estimated magnitude of subsequent Neogene denudation does not preclude the possibility that the summit topography of the Cairngorms is inherited from the Palaeogene.

Middle Miocene

The phase of tectonism around 22mA was short-lived and the Highland Block had probably subsided by the Middle Miocene. After the Oligocene temperature low, conditions warmed to reach subtropical levels in the Middle Miocene (Buchardt 1978) and kaolinitic saprolites developed widely in north-west Europe, leading to a rise in kaolinite contents in North Sea sediments (Karllson et al 1979). The dominance of biostatic conditions, with tectonic stability and intense weathering, suggests that extensive levelling of the Scottish relief took place at this time.

Late Miocene and Pliocene

The increasing proportions of unstable minerals arriving in the North Sea Basin after the Middle Miocene reflect both renewed uplift and climatic change. Comparisons with southern Britain suggest that vertical movements of the order of several hundred metres occurred, although their geomorphic effects remain to be demonstrated. Episodic tectonism and the growing frequency of climatic oscillations reduced the time spans available for levelling and relief development became increasingly compartmented. The marked change in the characteristics of European weathering covers in the Late Miocene and Early Pliocene (Bakker 1967) must also have been reflected in Scotland and the sandy saprolites of northern and northeastern Scotland (Fitzpatrick 1963; Godard 1965; Basham 1974) probably belong to these latest phases of morphogenesis.

This sequence of regional events provides a framework in which to consider the long-term geomorphic evolution of north-east Scotland.

CHAPTER 4 Patterns of Ice Flow

4.1 Introduction

The stratigraphic record of Pleistocene events in north-east Scotland is extremely limited. Most tills are now generally assigned to the latest glaciation and deposits which definitely predate this phase are rare (Connell and Edwards 1981). Until recently, there was no wholly convincing evidence that the region had been glaciated on more than one occasion but it is known that ice sheets covered eastern Buchan during at least 3 separate periods (Connell et al 1982).

The inadequacy of the regional stratigraphy can be judged by comparisons with the more complete offshore and continental records (see Bowen 1978). Deep sea cores indicate that multiple cold phases of glacial intensity occurred in the Pleistocene (Shackleton and Opdyke 1977). In central Europe, loess sequences demonstrate at least 17 glaciations over the past 1.7mA (Fink and Kukla 1977). Continental glaciation began in the Northern Hemisphere at around 2.5mA (Backmann 1979) but the timing of the onset of regional glaciation in Scotland is unknown. Many parts of Highland Britain must have experienced many intervals of glacierisation and almost certainly north-east Scotland has been glaciated on far more than the 3 occasions for which there is stratigraphic evidence.

Even the available stratigraphic evidence presents many problems. Exposure is often poor and many tills are thin and contain high proportions of locally-derived material (Clapperton and Sugden 1977), hindering correlation of deposits between areas.

Periglacial disturbance of surface layers is widespread (Fitzpatrick 1975) and complicates fabric analyses. Moreover material suitable for absolute dating is rarely available and no satisfactory chronological framework exists in which to place stratigraphic sequences of deposits.

This review of the glacial stratigraphy of the region focusses on the reconstruction of former ice flow lines. Information on the pattern of ice flow is of great importance in discussions of the distribution and geomorphic setting of weathered rocks and in the assessment of the impact of glacial erosion on the preglacial relief.

4.2. Types of evidence

Many types of evidence have been used to establish sequences of glacial events in the region, including the distribution of erratics, striae, orientations of roche mountonées, drift stratigraphy, glaciological theory and depositional morphology. Early accounts record a wealth of stratigraphic detail, although the identification of new sources of indicator rocks has cast doubt on certain patterns of erratic movement (Clapperton and Sugden 1975). Subsequent studies have relied more heavily on morphological data, some of which is now regarded as being as of little value. The hummocky fluvioglacial deposits used by Synge (1956; 1963) and Charlesworth (1956) to delimit ice margins are no longer accepted as end-moraines (Clapperton and Sugden op cit.). The ice-marginal meltwater channels of Bremner (1934; 1938; 1943) have since been re-interpreted as sub-glacial in origin (Clapperton and Sugden 1975; 1977), an interpretation which may also be questioned. Recent studies have paid much more attention to stratigraphic evidence and earlier models of multiple glaciation have been replaced by others assigning complex depositional sequences to single glacial events.

4.3 The work of Jamieson

The sequence of glacial events proposed by Jamieson (1858; 1859a and b; 1865; 1906) was fairly simple. The oldest unit was the shelly indigo boulder clay of the Ellon district, thought to be derived from the Moray Firth. This till sheet was largely stripped by a later phase of ice movement which deposited locally-derived and shell-free tills over inland areas. Along a narrow coastal strip of eastern Aberdeenshire, Jamieson found that this Lower Grey Boulder Clay was overlain by the Red Clay Series, highly varied deposits characterised by their strong red coloration and the presence of Old Red erratics. Jamieson suggested that the Red Clay Series had been transported north from Strathmore by ice which was deflected onshore by a Scandinavian ice mass in the North Sea. In the Peterhead area the Red Clay Series was seen to mingle with another till unit, the Dark Blue Boulder Clay. This deposit belonged to a contemporaneous ice movement which carried large volumes of Mesozoic, mainly Jurassic, fine-grained sediments from the Moray Firth and left large erratics of these rocks throughout Buchan. Local ice was thought to have retreated far to the west during this incursion, although the Lower

Grey Boulder Clay was regarded as broadly similar in age to the coastal ice masses.

The final event involved the expansion of inland ice. A restricted glacier in the Dee valley reached the coast over a breadth of c. 8km, largely removing the Red Clay Series from the Aberdeen area. The Red Clay was also "much wasted" in the Ythan valley. Overlying sands and gravels were interpreted as moraines of the final ice lobes but Jamieson, in fact, described little that could be interpreted as till overlying the Red Clay Series.

The patterns of ice movement according to Jamieson are summarised in Fig. 4.3.i.

4.4 The work of Bremner

Bremner (1915; 1931; 1934; 1939; 1943) envisaged a series of 3 ice sheet glaciations, separated by interglacial periods (Fig. 4.4.i). The First Ice Sheet moved from the W and NW leaving in its track erratics from Sutherland, Ross and Cromarty and the Great Glen. Dark Blue shelly till was carried from the floor of the Moray Firth and deposited along the northern coast. Bremner (1943) claimed that ice of the First Glaciation coalesced with Scandinavian ice at the angle of Buchan. The combined ice mass then moved southwards leaving distinctive rhomb-porphyry and larvikite erratics (Read et al 1921; Bremner 1939). Peats formed on the deposits of the First Glaciation during a later interglacial.

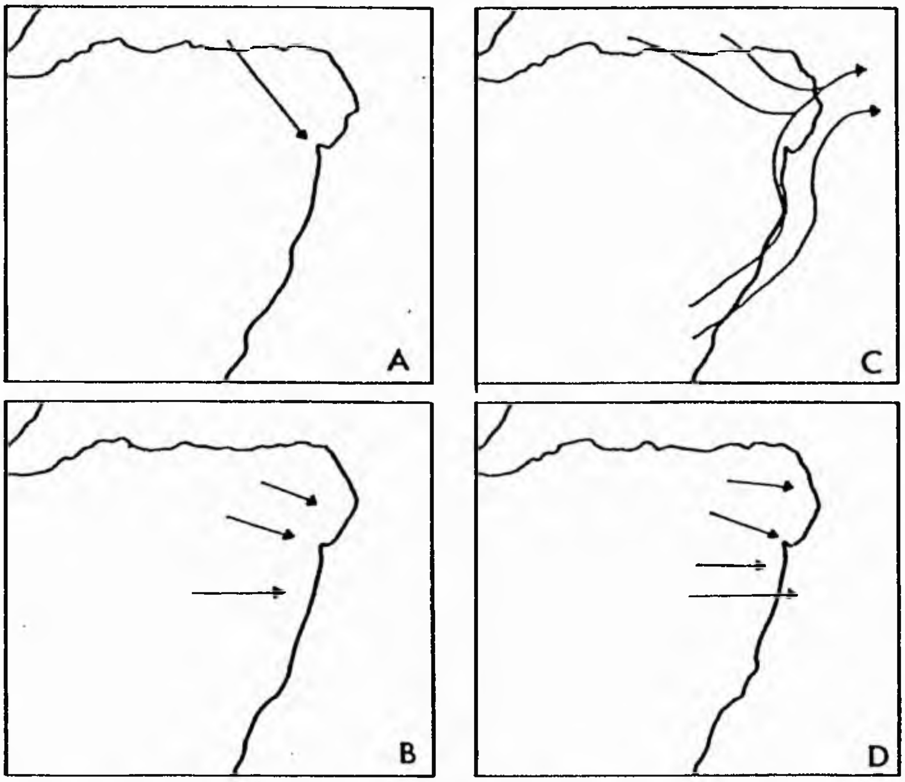


Fig. 4.3.i. Patterns of ice flow after Jamieson.

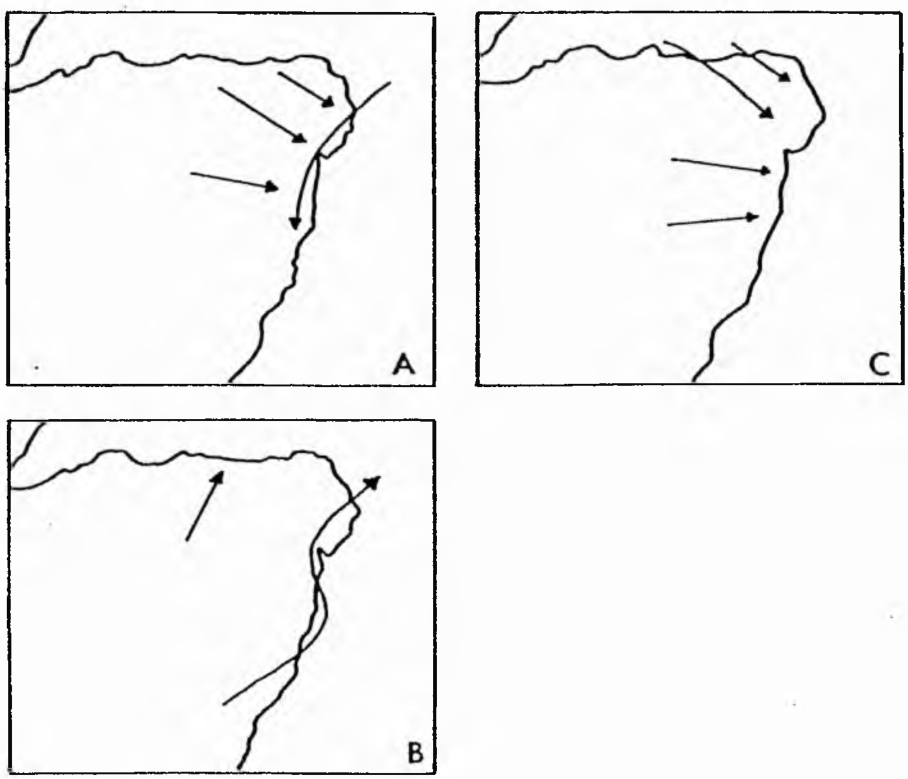


Fig. 4.4.i. Patterns of ice flow after Bremner.

The Second Ice Sheet traversed Buchan from the SW and S. Ice from Strathmore deposited red tills along the Aberdeenshire coast and during its retreat laminated clays were deposited in freshwater lakes ponded against the ice margin. Evidence of the directions of movement in many other areas was scant and Bremner relied heavily on the earlier evidence of Read (1923) for ice movement towards the NE in Banffshire.

Tills from the Third Ice Sheet were difficult to identify due to the reworking of earlier drifts. Sites at Rothes and south of Ellon showed locally derived tills overlying deposits referred to the first two glaciations but elsewhere patterns of ice flow were interpreted from the position of supposed ice-marginal meltwater channels and other morphological evidence.

4.5 Research in the post-war period

The work of Simpson (1948; 1955) was notable for its concern for stratigraphic detail. Simpson assembled evidence from the Aberdeen area to show that the deposits and meltwater channels attributed by Bremner (1938; 1943) to his Third Ice Sheet were produced during the wasting of co-existent coastal and inland ice masses. More generally, Simpson (1953) agreed with Jamieson (1865; 1906) that the dark shelly tills of the Moray Firth coast were contemporaneous with the red tills of eastern Aberdeenshire, an interpretation denied by Bremner (1943).

Synge (1956; 1963) recognised three separate glaciations in north-east Scotland and two readvance stages during the decay of the final ice sheet (Fig. 4.5.i). The earliest glaciation moved

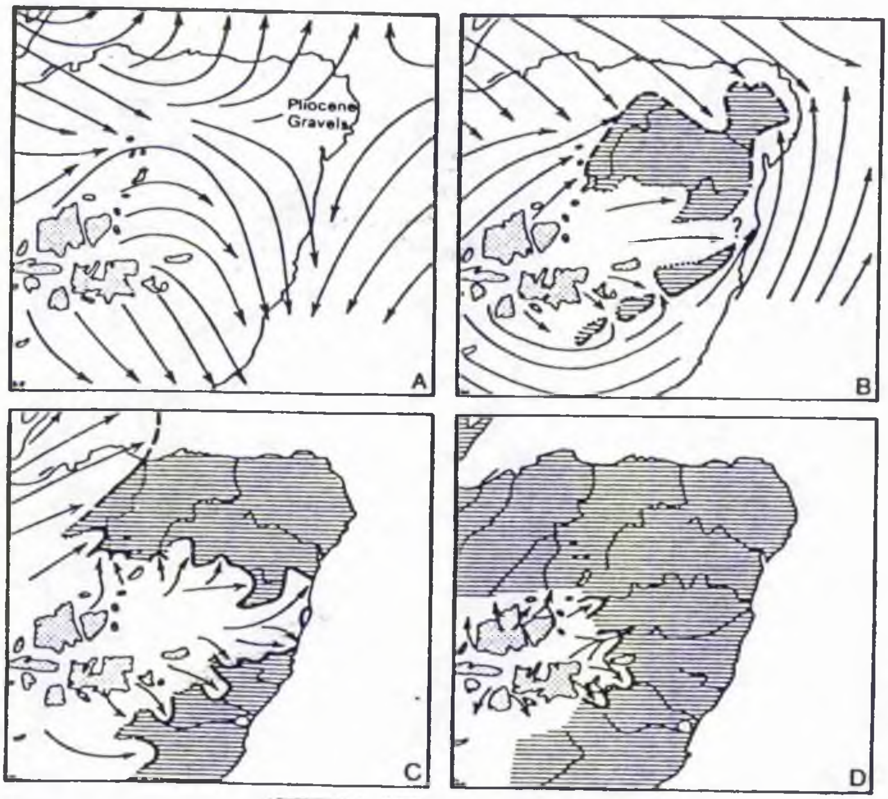


Fig. 4.5.i. Patterns of ice flow after Synge.
(Fig. 5 of Clapperton and Sugden 1977).

into the area from the east or north-east, leaving Scandinavian erratics close to the coast. There then followed a Greater Highland Glaciation in which Scottish ice was forced to bifurcate at the North Sea coast by the pressure of an offshore ice mass. Extensive bedrock weathering occurred in the succeeding inter-glacial period. During the final glaciation, Moray Firth and Strathmore ice streams flowed around an ice-free enclave in the Buchan area. This "moraineless" area contained weathered tills, saprolites and tors and widespread evidence of former periglacial conditions (Charlesworth 1955; Synge 1956; 1958; 1972; Galloway 1961). Decay of the Strathmore ice lobe was accompanied by the deposition of red clays under estuarine conditions. Two short cold intervals lead to a readvance of Grampian ice into the Aberdeen area and a final oscillation at the Dinnet limit.

4.6 Recent Research

The recognition that complex depositional sequences may result from rapidly varying processes and environments within single glacial events has lead to a partial rejection of earlier models of multiple glaciation. Recent work considers that most of the drift in the region belongs to the last glaciation (Murdoch 1975; Maclean 1977; Clapperton and Sugden 1975; 1977). However doubts still remain about the timing of the last glaciation and about the main directions of ice-flow (Sissons 1981).

4.6.1 Deposits of the last glaciation and ice-flow lines

The conclusion of Jamieson (1906) that the ice streams which deposited the dark grey shelly tills of the Moray Firth coast and the red tills of eastern Aberdeenshire were contemporaneous is founded on firm stratigraphic evidence. The surfaces of these till sheets are little weathered and must represent the latest glacial event. In the Aberdeen area, red tills inter-digitate with tills dominated by local crystalline rocks (Simpson 1955; Murdoch 1975; Maclean 1975; Clapperton and Sugden 1975; 1977). Further north, both red and dark grey shelly tills can be found in intimate association with tills derived from inland (McMillan and Aitken 1981; Hall and Connell 1982; Connell et al 1982). This stratigraphic evidence suggests that the inland, Moray Firth and Strathmore ice streams were confluent and contemporaneous.

Clapperton and Sugden (1975; 1977) have put forward a model of generalised ice flow for confluent inland, Moray Firth and Strathmore ice streams during the last glaciation (Fig. 4.6.i). The reconstruction relies heavily on the interpretation of the regional meltwater channel network in terms of superimposition from beneath active warm-based ice. This kind of interpretation encounters many difficulties for the network includes channels inherited from earlier episodes, structurally-aligned channels and channels formed by both gravity flow and hydrostatic flow. Channel orientation has often been influenced more by local topography than by regional ice sheet gradients, even where subglacial and englacial superimposition can be demonstrated. Without some kind of division of the channels into genetic types, their distribution can offer only limited guidance as to former directions of ice-flow. Nevertheless the continuity of channel development is powerful evidence in support of a full ice cover during the last glaciation

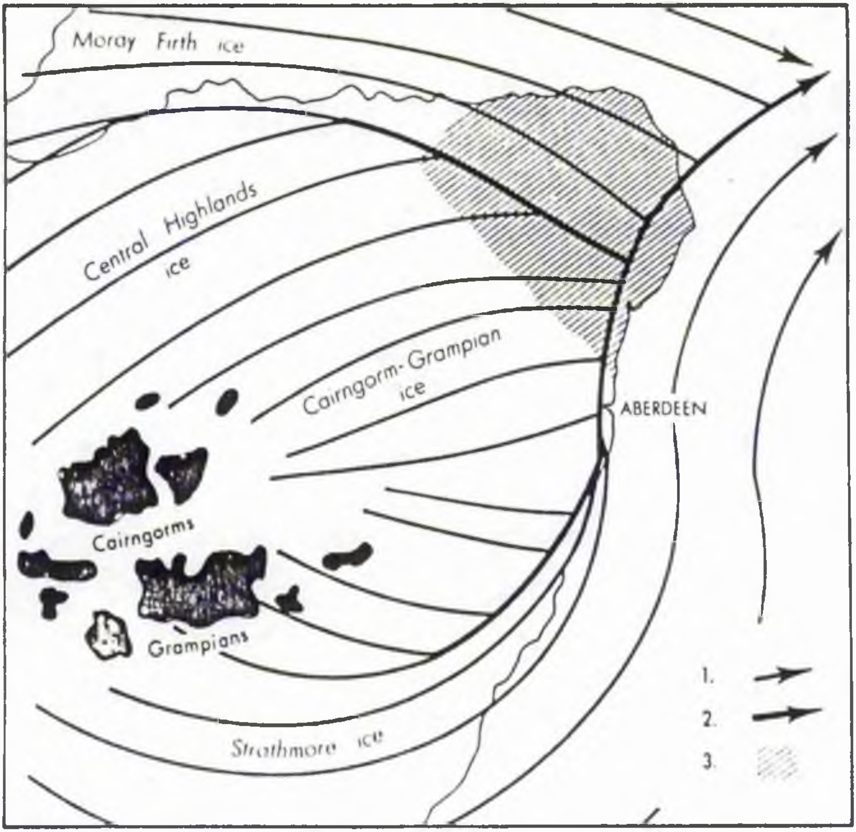


Fig. 4.6.i. Generalised flow lines for the Late Devensian ice sheet given by Clapperton and Sugden (1977 Fig. 6). 1. Flow lines. 2. Ice confluence zone of locally fluctuating flow strength and direction. 3. Buchan area peripheral to ice dispersal centres; a zone of low glacial erosion and deposition, exposed earlier than the Late-glacial to periglacial conditions.

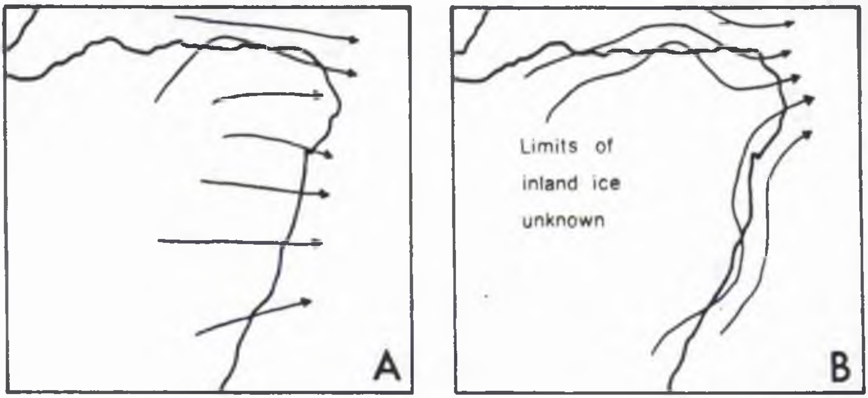


Fig. 4.6.ii. A two-phase model of ice flow for the last ice sheet.

and the pattern of movement put forward by Clapperton and Sugden (op cit) is in agreement with available stratigraphic evidence in most areas.

Yet this model involves a paradox. Along the North Sea coast the red and grey shelly tills form a continuous belt and no corridor can be identified through which inland ice reached the coast. For Strathmore and Moray Firth ice to be confluent in the Peterhead area inland ice cannot have been present at the coast.

Moreover the distribution of tills from the coastal ice streams also indicates that inland areas were ice-free during at least part of the last glaciation. Red tills and associated deposits extend into the valleys north of the Highland Boundary Fault (Synge 1956), into the Dee and Don valleys (Simpson 1955) and some 16km up the Ythan valley (Bremner 1915). Thick glaciolacustrine deposits infill the deep inner channel of the Ugie valley and as a result of ponding against a coastal ice mass (Merritt 1981). The manner in which the red till lobes into the main valleys and yet is absent from the low ridges south of Aberdeen and at Stirling Hill suggests the presence of a thin ice lobe whose movements were closely constrained by topography.

The isolated erratics of Mesozoic rocks which occur as far south as the South Ugie Water valley (Jamieson 1906; Read 1923; Merritt 1981) indicate that at some stage Moray Firth ice penetrated far into Buchan. Towards the end of the last glaciation the Moray Firth ice stream was unopposed by local ice and ice-dammed lakes developed along the Banffshire coast (Peacock 1971) and ice advanced up the Spey valley as far as Rothes (Jamieson 1906)

The distribution of the tills of the coastal ice streams suggests that the Clapperton and Sugden (op cit.) model of contemporaneous inland and coastal ice streams should be rejected in favour of a two-phase model similar to that originally proposed by Jamieson (1906).

During the first phase (Fig. 4.6.ii) the whole of north-east Scotland was ice-covered but Strathmore ice did not penetrate farther north than Stonehaven. Ice moving along the Dee valley and the Insch depression (Wilson and Hinxman 1890) crossed the coast between Aberdeen and the Ythan, leaving basic erratics at Nigg Bay (Simpson 1948). In Buchan the carry of erratics from the flint gravels at Whitestone Hill and the Maud norite indicates flow towards the north-east and east (Wilson 1886). The inland ice may have been confluent with Moray Firth ice along the valley of the North Ugie Water. West of the Deveron, ice flowed northeastwards across Banffshire to join with Moray Firth ice at the coast (Read 1923).

During the second phase, inland ice had retreated to an unknown position in the west. An attenuated ice lobe moved northwards from Strathmore and reached the Peterhead area. A more vigorous Moray Firth ice stream diverted inland ice eastwards in the lower Spey valley area (Read 1923) and pushed across northern parts of Buchan.

4.6.2 The timing of the last glaciation

A number of C14 dates from the Cairngorm Mountains demonstrate deglaciation before 13000 BP (Clapperton and Sugden 1977).

Deglaciation may have started as early as 18000 BP (Holmes 1977) but dates from Garral Hill (Galloway 1961a), Tarves (Clapperton and Sugden 1977) and Woodhead (Connell et al in prep.) only demonstrate deglaciation of lowland areas by 11500-12200 BP.

The timing of the onset of the last glaciation is problematic. The buried podzol at Teindland is dated at 28140^{+480}_{-450} (Fitzpatrick 1965). The date is minimal (Fitzpatrick 1965; Sissons 1981) but substantially correct (Edwards Pers. Comm.). The deposits overlying the palaeosol have been interpreted as till (Fitzpatrick 1965; Edwards et al 1976) or head (Romans 1977). A Betula-dominated peat, covered by head, at Crossbrae Farm, Delgaty, is dated, after alkali-pretreatment, at 22380 ± 250 BP (Connell et al in prep.). Both sites indicate that parts of north-east Scotland were ice-free for some period before 22000 BP but neither site proves that the region remained unglaciated in the Late Devensian. However in view of the extent of the Late Devensian glaciation in England (Bowen 1977), it must be considered highly probable that north-east Scotland was also glaciated during this period. The Wee Bankie moraine may represent the eastern limit of the Late Devensian ice front (Thomson and Eden 1977).

4.6.3 Events before the last glaciation

Deposits which definitely predate the last glaciation are rare (Connell and Edwards 1981). Foremost amongst them is the complex sequence at Kirkhill Quarry (Connell et al 1982) which demonstrates that this part of Buchan has been glaciated on at least two, and probably three occasions. The tills beneath the organic materials at Teindland and Crossbrae must also predate the Late Devensian. At Burn of Benholm, near Stonehaven, peat and masses of grey shelly till occur as erratics within red till (Connell and Edwards 1981). The peat has given an infinite C14 date (Donner 1979) indicating that the grey shelly till predates at least the last glaciation.

A number of other deposits have been referred to earlier glaciation but, in the absence of dateable materials, their ages are less certain. The indigo boulder clay of Jamieson (1906) has not been reobserved since the turn of the century. The base of the till sequence at Boyne Quarry, Portsoy, is weathered (Peacock 1966) but alteration does not affect the whole basal till unit and probably results from lateral groundwater movement. Hall and Connell (1982) mention pre-Late Devensian weathered tills from the Moreseat area and a glacial origin has been suggested for the highly altered Buchan Ridge Gravels Formation (Kesel and Gemmell 1981).

It may also be suggested that all tills composed mainly of Mesozoic rocks from the Moray Firth need not belong to the last glaciation. At Moreseat, dark grey clayey tills of Moray Firth affinities are found both at the surface (Hall and Connell 1982) and beneath thick deposits of sand (McMillan and Aitken 1981), whose surface layers include lenses of weathered till. At Oldmill, attenuated patches of dark grey till rest on deltaic sands and are covered by till of local origin. Tills derived from the Moray Firth are also buried by local tills further west at Boyne Quarry (Read 1923; Peacock 1966) and at Sandy Hill, Rothes

(Bremner 1938). It is possible that some of these, and other, dark grey tills were deposited before the last glaciation.

It should also be remembered that there is good geomorphic evidence for periods of local mountain glacierization in the Cairngorms. Many corries are far too large to have been formed by the modest Zone III glaciers. Moreover certain corries and troughs have been over-ridden during regional glaciation and must predate at least the last glaciation (Sugden 1968; 1969; Clapperton and Sugden 1977).

In view of the inefficacy of ice erosion in many parts of north-east Scotland (Clayton 1974), it is surprising that more deposits predating the last glaciation have not been reported. The problem is probably one of recognition. Unless successive ice sheets followed widely divergent paths, tills of different age will be of similar composition. Age-related differences, such as the degree of weathering, will be obscured by reworking, by periglacial activity and by the large amounts of pre-existing weathered material incorporated into the tills. Recognition of superimposed tills of similar composition but different age would require deep sections, which are rare, or detailed mineralogical work, which has yet to be attempted.

The ice flow lines of these earlier glaciations are unknown but the flow lines of the last glaciation can be used as a model for earlier ice sheets. The dominant controls over ice-movement will have been topography and climatic factors affecting ice-accumulation rates. Topography is essentially constant and will have tended to channel flow along similar routeways during successive glaciations.

Any differences in the pattern of ice-movement are thus largely products of climatic variations and the early wastage of inland ice during the last glaciation can be seen in terms of precipitation differences between its Cairngorm source area and the more westerly source areas of the coastal ice streams. These differences reflect a steep precipitation gradient across Scotland which is established at present and which operated during Loch Lomond Readvance times (Sissons 1976) and throughout the Pleistocene (Linton 1959). These precipitation contrasts will have tended to produce similar patterns of flow, especially as there is little reason to believe that earlier glaciations were much more extensive than the last. The proposed Late Devensian ice limit at the Wee Bankie moraine (Thomson and Eden 1977) lies between 40 and 60km from the coast of eastern Scotland. As till-like sediments are absent more than 50-100km offshore (Holmes 1977), it seems that earlier ice sheets had similar or lesser dimensions to the last.

4.7 Summary

A review of existing evidence suggests that the model of Late Devensian glaciation developed by Clapperton and Sugden (1975; 1977) requires modification. An alternative model is proposed, after Jamieson (1906), in which two phases of glaciation are identified, an early phase in which ice from inland crosses the North Sea coast and a late phase in which inland ice has retreated westwards and the coastal ice streams are confluent in the Peterhead area. Earlier glacial events are obscure but it is suggested that the pattern of flow in the last glaciation may be used as an analogue for earlier ice movements.

PART 2 Distribution, characteristics and age of the weathered rocks and the Buchan Gravels

CHAPTER 5 Distribution and Field Characteristics of the Weathered Rocks

5.1 Introduction

A major aim of the study was to provide a regional survey of the characteristics and distribution of rock weathering in north-east Scotland. Much new information has appeared since the earlier survey of Fitzpatrick (1963). In particular, a considerable number of borehole records are now available which provide detailed information on depths of weathering and on relationships between weathering, geology and landforms. The combined section and borehole data comprise over 450 separate occurrences of weathered bedrock and demonstrate the extraordinary potential for the study of weathering and landform evolution in the region.

5.2. Characteristics of Weathering Profiles in Sections

5.2.1 Types of exposure

Field mapping has involved the inspection of large numbers of permanent and temporary exposures of weathered rock (Fig. 5.2.i). The majority of sites from Fitzpatrick's (1963) survey have been visited and the author is indebted to Dr Fitzpatrick for access to his section index. In addition a systematic search was made of quarries and pits marked on the Provisional Editions of the 1:25 000 Ordnance Survey sheets for the area north of the Don and east of Keith.

Some 70 permanent exposures of weathered rock have been recorded, mainly from quarries and pits and only rarely from stream sections. Only a small number of quarries have been excavated wholly in weathered

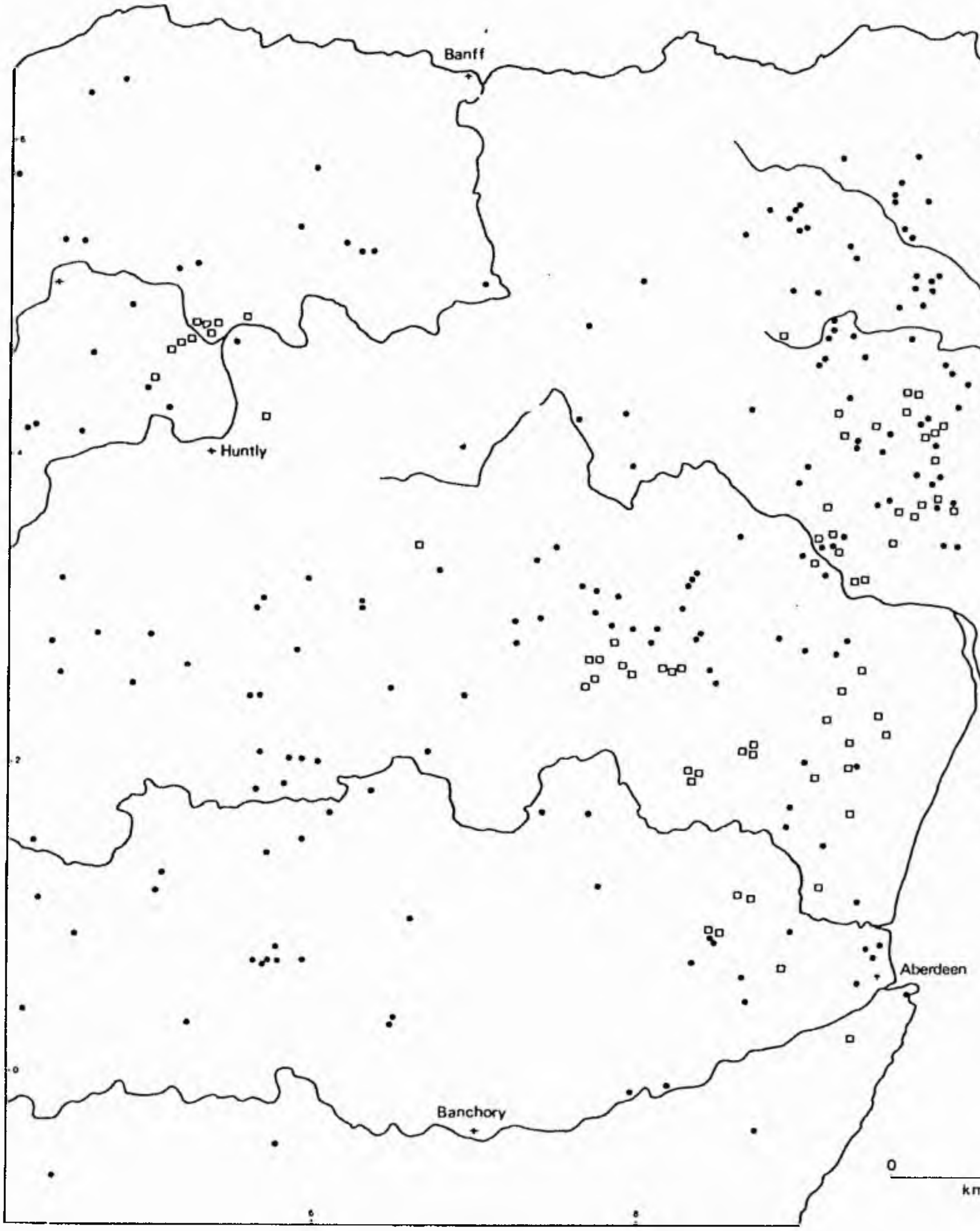


Fig. 5.2.i.
Weathered rock in
• exposures and
▫ boreholes

Note : Diagram includes virtually all of the sites recorded in the earlier survey of Fitzpatrick(1963). Additional sites to the W and S of the study area are given by Peacock and Michie(1975).

rock. However many quarries contain pockets or zones of weathering, often extending below the quarry floor. Quarry exposures do not provide a good guide to the distribution of weathered rock in many areas, as most quarries were opened up to provide hard rock for building or roadstone and are set into steep slopes to facilitate excavation.

About 100 temporary exposures were also observed. Most temporary exposures are shallow and weathered rock is often only encountered at the base of the section. As a result most sections in drainage ditches, construction sites and roadworks were not sampled in detail.

The development of the North Sea oil and gas fields has involved the construction of 4 pipelines across districts bordering the North Sea coast. Each pipeline makes landfall at St. Fergus and passes southeastwards across drift-covered country to the Ugie Water. Across the Ugie the pipelines diverge around the high ground of Moss of Cruden and Hill of Dudwick to meet again at the Ythan crossing around Ythanbank. The pipelines then continue southward, passing to the west of Aberdeen.

The pipeline trenches gave temporary and continuous sections to depths of c.2.4m. Bedrock, both hard and decomposed, was exposed in about 60% of the length of the trenches between the Ythan and the Ugie. The pipeline trenches north of the Ythan were painstakingly logged by Dr M. Munro, Department of Geology, University of Aberdeen, who has kindly made his field maps available. Mention of the pipeline sections south of the Ythan is made by Murdoch (1975).

5.2.2 Weathering profiles and superficial deposits in sections

The model of Fitzpatrick (1963) provides a good summary of the principal characteristics of the weathering profiles of north-east Scotland (Fig. 5.2.ii). All of the horizons are only rarely found together in a single section but each horizon is to be found in a large number of separate profiles. The characteristics of the horizons vary considerably and will be described briefly.

(A) Soils

Soils are only occasionally developed directly on weathered rock and often pedological features are confined to the overlying drift deposits. On free-draining sites, soils above 500m are podzolic in type and brown forest soils rarely extend above 300m (Glentworth 1954). At Mill Maud (elevation 300m), the bleached A horizon of the podzol overlies a red brown layer which probably represents the basal part of a brown forest palaeosol dating from the post-glacial climatic optimum.

At lower elevations soil type is dependent on parent material and drainage status, with brown forest soils associated with base-rich parent materials and podzols developed on acid materials (Glentworth 1954; Glentworth and Muir 1963).

The sedentary soils on the acid grusses at Blackrigg and Cairnlea and the basic gruss at Silverford are immature and may be classified as incipient podzols or humic soils.

(B) Tills

The tills incorporate various amounts of subjacent weathered rocks. In inland districts the tills are generally thin and sandy and are predominantly composed of local material (Read 1923;

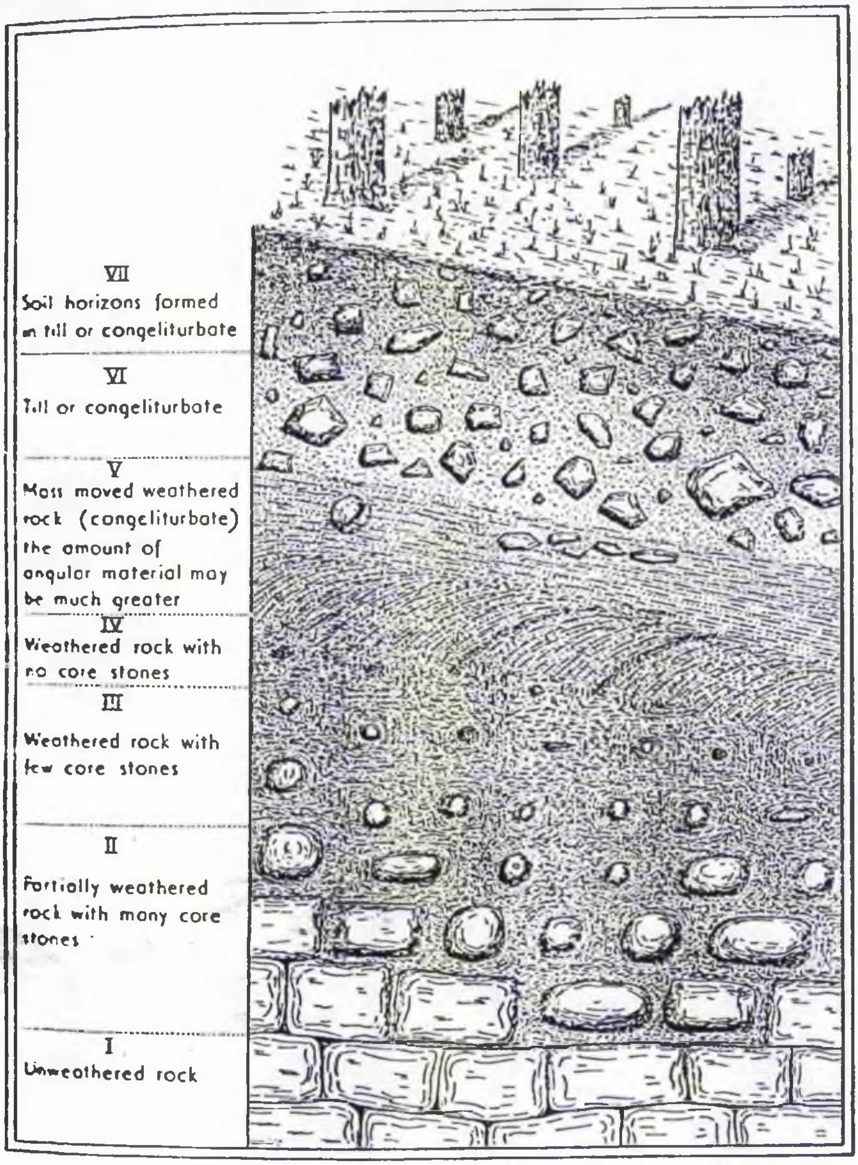


Fig. 5.2.ii. Fitzpatrick's(1963 Fig. 3) summary diagram of weathering profile characteristics.

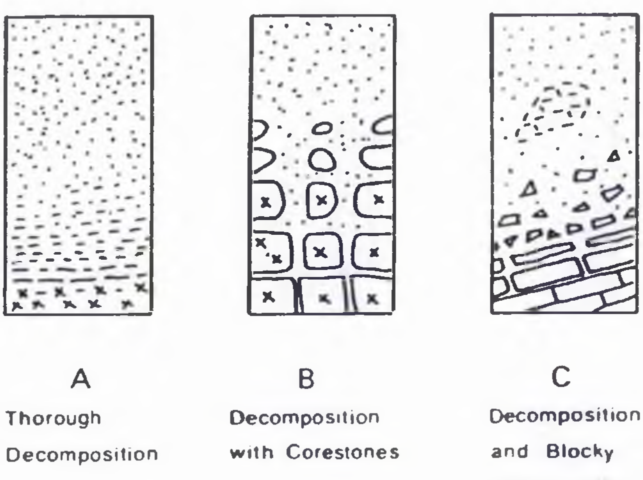


Fig. 5.2.iii. Types of Weathering Profile

Glentworth 1945; Dare-Edwards and Livesey 1976). Proportions of erratic clasts are modest and decrease downwards from the surface. On the northern slopes of the Moss of Cruden the colour of the tills varies with that of the underlying granite grusses, implying very local transport of material. The predominance of local rocks in the tills of inland areas probably indicates ice masses with very limited erosional and transportational capability (Whillans 1978).

In zones of more vigorous glacial activity, particularly many coastal areas, weathered rock is generally absent and, where present, commonly differs in both texture and colour from the overlying glacial deposits. Tills at weathering sites along the major valleys also usually contain larger numbers of erratic clasts.

(C) Congeliturbate and head

Evidence of periglacial disturbance of surface horizons is ubiquitous (Fitzpatrick 1958; 1963; 1975; Galloway 1961a, b and c). Outcropping bands of resistant rock are frequently shattered and feed stone-lines showing strong downslope fabrics. In many cases, mass movement has affected the upper layers of the saprolites to produce bedded gruss and downslope flaring of rock structures. Cryoturbation is common. Large frost cracks occur at Howe of Dens and the Sunnyside section shows fine examples of erected clasts. Evidence of former periglacial activity is seldom found more than 1.5m below the surface and soliflucted horizons are generally less than 2m thick, even at the foot of slopes.

(D) Weathered Rock

Three basic types of profile can be recognised in the weathered rocks (Fig. 5.2.iii). Type A profiles are characterised by thorough disaggregation, with a gradual downward increase in coherence towards hard rock. Type A profiles are commonly associated with coarse grained granites which show only weak tendencies towards corestone development (Plate 5.2.i). Such profiles also occur in a number of other homogeneous and closely fractured rock types.

Type B profiles resemble granite weathering profiles in many other parts of the world (Linton 1955; Ruxton and Berry 1961; Ollier 1967). The upper parts of the profiles are thoroughly decomposed, although structural details are preserved. The zone of thorough decomposition merges downwards into a zone of corestone development, where kernels of fresh rock are isolated by the penetration of alteration along joint planes. Type B profiles are found on most acid and basic igneous rocks. Corestone development is particularly impressive on the Boganclogh gabbroic mass (Plate 5.2.ii), where exhumed corestones litter the ground and form small tor groups. Glacially-transported corestones occur widely on the Knock, Huntly and Insch basic masses and east of the New Pitsligo granite.

Type C profiles are characteristic of weathered metamorphic rocks (Plate 5.2.iii). At the base of the profile the metasediments break up into angular blocks separated by thin seams of decomposed material. The blocks become progressively reduced in size up the profile and are surrounded by decomposed rock. The heterogeneity of many metamorphic rocks means that zones of blocky disintegration

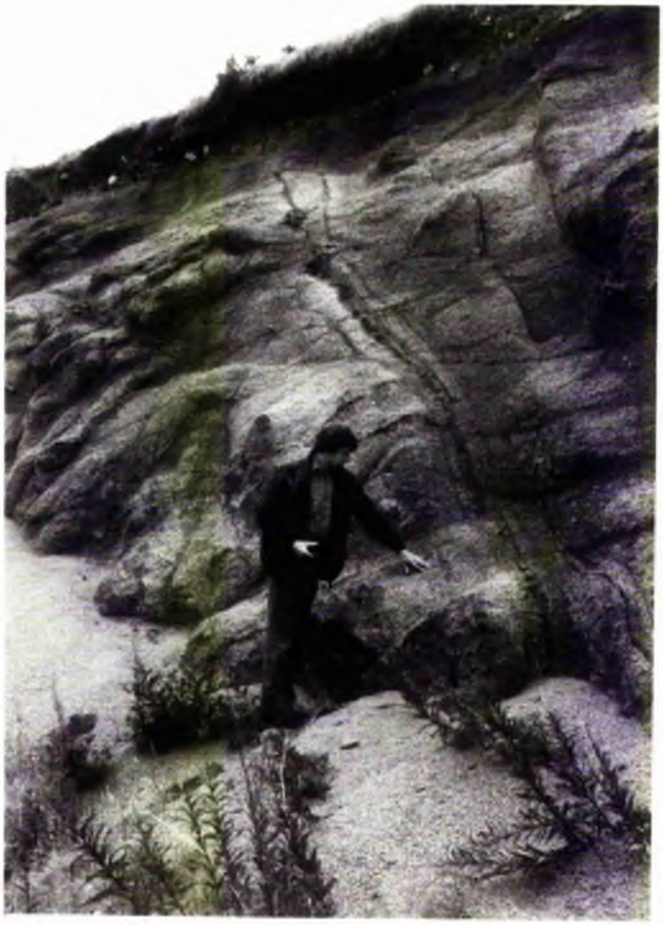


Plate 5.2.i.

Type A weathering profile.

Weathered granite, Hill of Longhaven.

Plate 5.2.ii. Type B weathering profile.

Weathered gabbro, Siverford, Cabrach.

Plate 5.2.iii

Type C weathering profile.

Weathered quartzite and quartz schist,

Whitestones Hill.

and isolated fragments persist even in the upper zones of deep profiles.

The sections represent profiles in various stages of preservation. Many profiles have been truncated and sections showing only a basal zone of corestone development are common. Elsewhere pockets of weathering have been protected from erosion by adjacent bands of hard rock. This situation occurs repeatedly in the granite quarries around New Pitsligo and is found in many other districts where the cover of weathered rock is discontinuous. Other profiles are more complete and several sections show 8m or more of weathering without sign of fresh rock. The colour of deep sections is uniform and textural changes take place gradually.

A characteristic of many sections, both deep and shallow, is an increase in the competence of the weathered rock with depth. Although fresh rock is not present in many shallow sections there is little doubt at most sites that alteration has penetrated downwards from the surface.

A number of other features of the sections may be noted. Several sections have evidence of translocation of fines. Clay coats are found along joint boundaries in the basal zones of granite weathering profiles and on the surface of blocks in weathered metasediments. Bleaching is also common along fracture planes or beside large tree roots.

Rubefaction, with hues equal to or greater than 5YR occurs in a variety of situations. Most frequent are rubefied granite grusses, such as those on the Peterhead and Mill Maud granites, whose coloration derives from the high iron content of the parent rock and from the presence of iron minerals, especially haematite, as late-stage alteration products. Less common are rubefied saprolites derived from rocks which show few signs of iron enrichment. Most notable is the Bennachie Car Park site, where translocation of iron has produced both reddened and bleached zones (Wilson et al 1981). Equally important however are the rubefied quartzitic saprolites found at Sunnyside and Drinnies Wood, where the coloration appears to result solely from subaerial weathering. Other weathered quartzitic rocks at Howe of Dens and Mormond Quarry show rubefied zones or veins but there is more doubt as to the origins of these iron minerals. Of note also are the reddened stringers lying above much more weakly-discoloured weathered quartz-mica schist at Howford, which are possibly remnants of an interglacial palaeosol. The mineralogy of these rubefied zones is examined in Chapter 8.

Staining of weathered rock by Mn or Mn-Fe oxides is widespread. This dark staining is particularly associated with saprolites derived from rocks rich in mafic minerals. The presence of MnO_2 has been interpreted as an indicator of present or former hydromorphic conditions in the weathering profile (Koppi 1977) and the significance of this and other hydromorphic minerals will be discussed in Chapter 8.

5.3 Characteristics of Weathering Profiles in Boreholes

5.3.1 Interpretation of Borehole Information

A substantial amount of borehole and trench information is available which provides detailed subsurface data for several areas. A total of at least 240 boreholes sunk in north-east

Scotland have encountered decomposed bedrock (Fig. 5.2.i). The borehole data is localised, being largely confined to the Huntly-Portsoy basic masses, the eastern end of the Insch basic mass and a belt some 5-10km inland from the coast between Peterhead and Aberdeen. These boreholes demonstrate deep alteration at many localities and confirm the presence of weathered rock in several poorly exposed districts.

The bedrock decomposition recorded from borehole logs cannot be automatically related to the degrees of weathering observed in section. Only rocks of Engineering Grades I or, perhaps, II (Dearman et al 1978) will yield diamond drill cores and all material of lesser strength is liable to be recorded as "weathered". This study has concentrated on weathered rocks of Grades IV and V and care is needed when comparing borehole and sectional information. However the bulk of the borehole logs record the competence of the bedrock under certain categories which help in the interpretation of the logs. Common descriptions include "weathered", "decomposed", "soft", "bands of hard and soft rock", "shattered rock" and "hard". For the purposes of this study only those parts of the boreholes recorded as "weathered" or "decomposed" are regarded as comparable to weathering in surface exposures.

The borehole records come from 3 sources:- (i) Department of Geology, University of Aberdeen, (ii) RioFinEx Ltd and (iii) Institute of Geological Sciences, Edinburgh.

The bulk of the records come from the Department of Geology, University of Aberdeen (UADG). The main aim of the UADG drilling programme has been to recover rock samples from areas where hard bedrock is not exposed due to drift cover or to deep weathering. UADG now have considerable experience of borehole logging in north-east Scotland and the accumulated records are a large and reliable data source. The RioFinEx boreholes were exploration holes sunk in a search for zones of mineralisation in the Knock and Arnage basic masses. There is evidence that many of these boreholes have been logged incorrectly, probably due to poor recovery in the upper sections of the holes. In the Arthrath area (Fig. 5.3.i), several RioFinEx boreholes record over 20m of drift. Drift cover in this elevated part of Buchan is seldom more than a few metres thick away from the valley floors. Moreover a number of these boreholes fall within areas mapped as "Bedrock at or near surface" by officers of the I.G.S. (Merritt 1981). Two UADG boreholes around Mains of Dudwick logged only 4m and 1m of drift and weathered bedrock is exposed at Sunnyside. It is considered that weathered rock has been logged incorrectly as drift in this area and Rice (1975) appears to reach a similar conclusion. Comparison of RioFinEx and UADG logs from the Knock basic mass, north of Huntly, suggests that the RioFinEx logs also exaggerate drift thicknesses for this area. The RioFinEx borehole records must be interpreted with care but are of considerable interest in that they indicate alteration to depths in excess of 20m at several localities.

The remainder of the borehole records originate from the I.G.S., Edinburgh. Only a few boreholes are on the regional file but recent Industrial Minerals Assessment Unit (IMAU) sand and gravel resource surveys (Merritt 1981; McMillan and Aitken 1981) have involved drilling in the Ellon and Peterhead areas. The IMAU boreholes

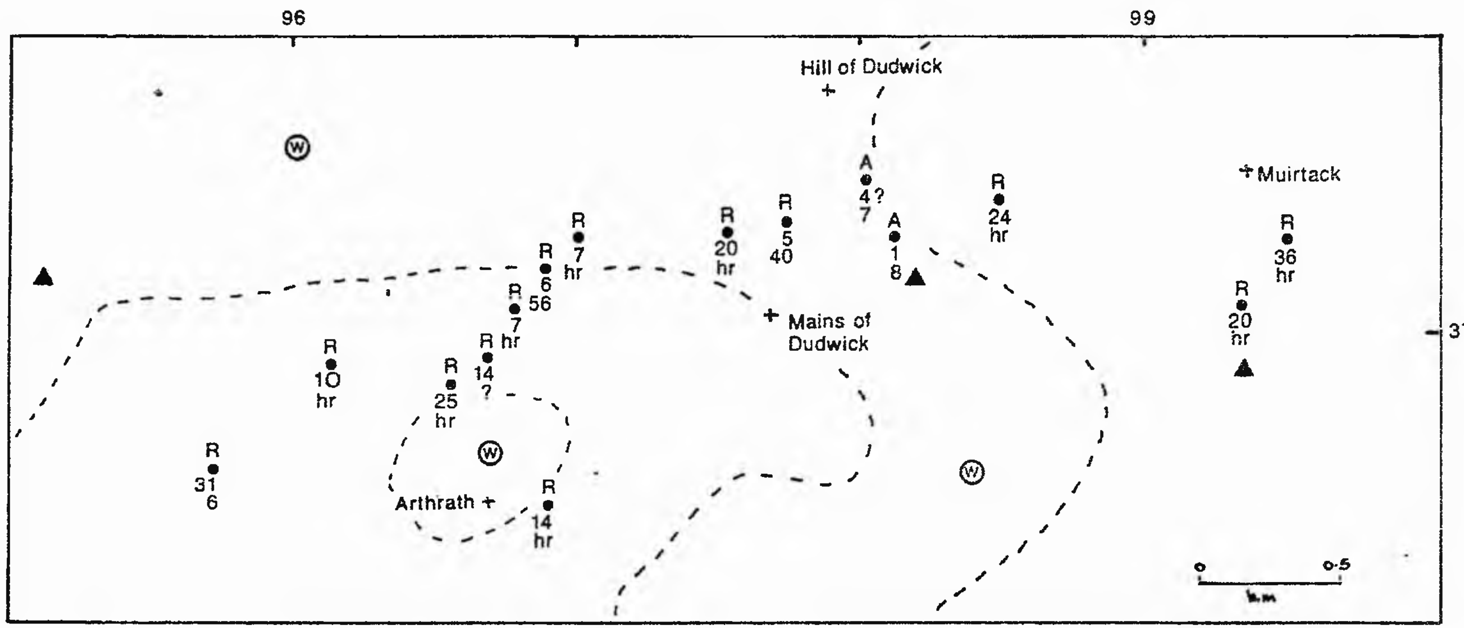


Fig. 5.3.i. Logged drift thicknesses in RioFinEx boreholes in the Arthrath area : drift or weathered rock?

R	RioFinEx bore
A	UADG bore
●	borehole location
24	logged drift thickness (m)
6	minimum saprolite thickness (m)
hr	hard rock
(W)	bedrock at or near surface (after Merritt 1981)
▲	saprolite exposure

penetrate only a few metres into the bedrock and provide no information on depths of alteration.

5.3.2 Depths of weathering

Weathering to depths of over 60m is recorded from north of Arthrath (Fig. 5.3.i) and in a fracture zone in the Peterhead granite (Edmonds and Graham 1977). Peacock and Michie (1975) also refer to leaching of Permo-Triassic sandstone to depths of more than 50m near Lossiemouth. These depths may not be exceptional, for few boreholes penetrate more than 20m below the surface and many provide only minimum depths of alteration. Continuous weathering covers to depths of at least 10m are found over much of central Buchan. Comparable thicknesses of saprolite occur in almost all areas where borehole information is available, although these depths tend to be more exceptional and relate to basins or shafts of weathering. The survival of depths of weathering of 20m or more in a variety of locations and on a number of different rock types and despite profile truncation indicates original weathering covers of considerable thickness.

These depths of weathering are well in excess of the 2-3m of growan reported from Dartmoor (Eden and Green 1971). Depths of sandy weathering in Central Europe commonly reach 6m (Bakker 1967), but pockets exceeding 30m are also known (Thomas 1976) and these depths are of the same order as those found in north-east Scotland. Only locally does the weathering reach depths reported from the hydrothermally-altered biotite granites in Wyoming (Eggler et al 1969) and from tropical alterites (Thomas 1966; 1976).

5.3.3 The transition to hard rock in boreholes

The borehole records reveal that the transition from wholly disaggregated to hard rock is highly variable in character.

Boreholes passing directly from weathered to fresh rock are common (31.5% of UADG boreholes), particularly where depths of weathering are relatively shallow. However in the majority of boreholes, the boundary between weathered and hard rock is ill-defined and thick transitional zones may intervene. The transition towards fresh rock may be gradational (21.0% of holes), especially within more homogeneous rocks, with a gradual downward increase in rock competence over several metres. More usually (47.5% of holes) hard rock is overlain by alternating bands of decomposed, semi-decomposed, weakened, shattered and hard rock. Such alternating sequences may persist for depths of 15m or more before true rockhead is reached.

The existence of thick transitional zones between thoroughly disaggregated and fresh rock is not a feature generally associated with deep weathering in tropical environments. Observations from many parts of the humid tropics have shown that the change from clayey alterite to fresh rock is often abrupt (Gilkes et al 1973; Eswaran and Bin 1978; Thomas 1974a and b), although this is by no means always the case (Thomas 1966; Dixon and Young 1981). The boundary has been termed the basal surface of weathering (Ruxton and Berry 1959) and the weathering front (Mabbutt 1961).

In north-east Scotland, these terms can only be applied to about a third of the boreholes, although it must be noted that the majority of boreholes have been drilled in basic and metamorphic rocks and a clearly-defined basal surface may be more typical of granitic saprolites. Elsewhere no sharp contact exists between decomposed and fresh rock. In some boreholes, the weathered rock grades into fresh rock over considerable depths and incipient alteration reduces the mechanical strength of the rock at depths well below the surficial decomposed zones (Table 5.3.i).

Table 5.3.i UADG Borehole Log. NJ 8400 2032

Depth (Feet)	Description
0 - 8	Fine clayey gravel
8 - 16	Weathered rock
16 - 36	Bands of hard and soft rock
	% recovery of diamond drill cores
36 - 40	37.5
40 - 43	11.1
43 - 44	75.0
44 - 54	6.7
54 - 57	33.0
57 - 61	75.0
61 - 65	25.0
65 - 83	100.0

Incipient chemical alteration in the transitional zone will prepare the way for later decomposition of the rock. In tropical weathering environments, the transitional zone appears to be frequently missing and the basal parts of the weathering profile are severely altered, perhaps due to enhanced lateral groundwater flow beneath impermeable clayey alterites.

The presence of transitional zones in the weathering profiles has some significance in any models of weathering and landform evolution in north-east Scotland. In the event of stripping of the overlying decomposed rocks, the materials of the transitional zone will present considerable resistance to further erosion. Where the transitional zone is gradational, the weakened rock preserves much of its coherence. Alternatively bands of hard rock will protect underlying zones of gruss. Yet the transitional zone is already in the early stages of chemical alteration and retains a reservoir of groundwater. Further alteration can be expected to produce rapid loss of competence. Saprolites may be quickly reproduced after phases of stripping and only severe or prolonged denudation will expose the fresh rocks beneath the resistant transitional zones.

5.3.4 Lateral variations in weathering depths

Many sections and boreholes indicate rapid lateral variations in weathering depths. In sections at Northseat, Cairngall, Kirkhill and Ythanbank, zones of weathering adjacent to fresh outcrops extend more than 15m below the surface. Very closely-spaced boreholes at Cuttlehill, near Ruthven, and at Lumphart, near Oldmeldrum (Fig. 5.3.ii), demonstrate variations in depth of greater than 20m over distances of less than 100m. Lateral depth variations of similar magnitude occur in the Knock basin.

These rather extreme variations in weathering depths are associated with highly fractured or hydrothermally altered rocks and with sequences of rocks of widely different resistance. Rocks of more homogeneous composition tend to show more gradual changes in weathering depths. The absence of fresh risers from many Type A profiles developed on coarse granites suggests that

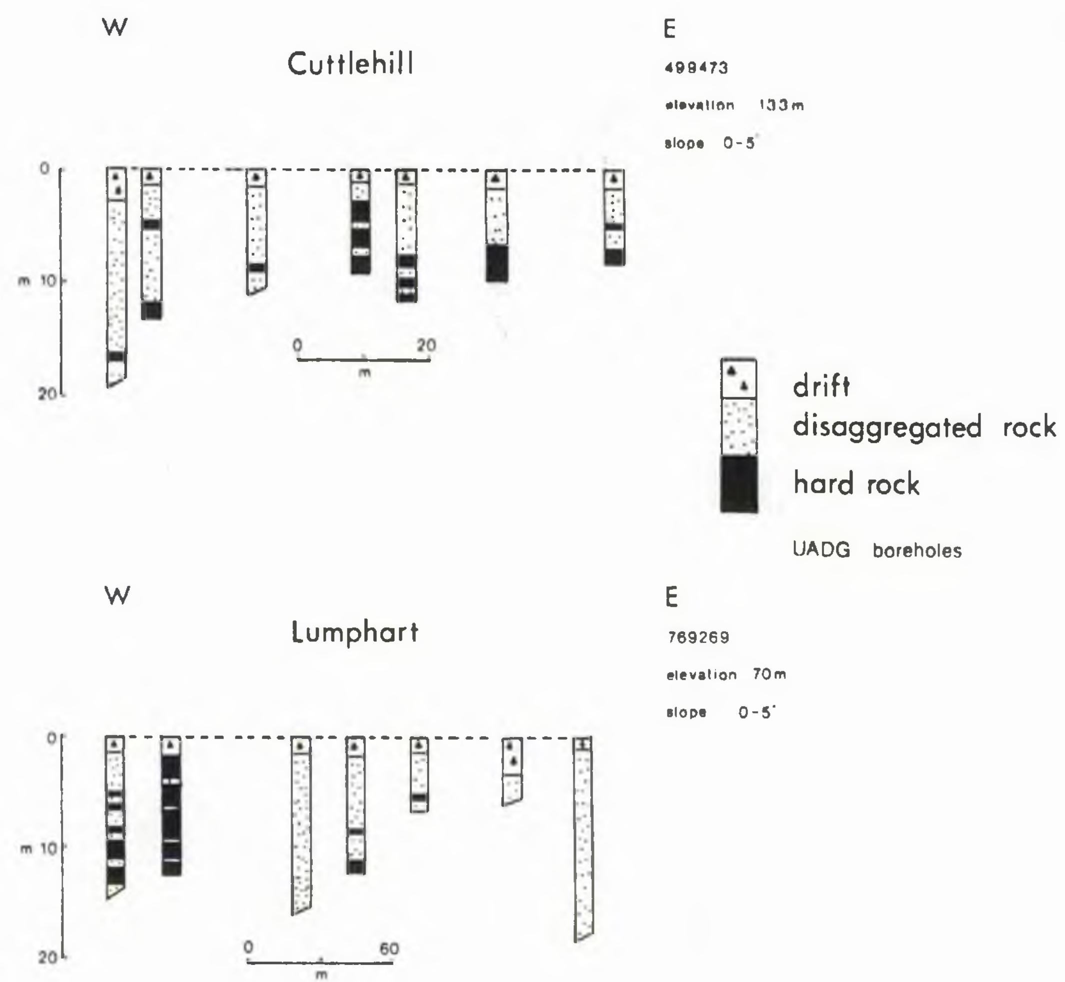


Fig. 5.3.ii. Variations in weathering depths in two closely-spaced borehole transects.

these saprolites grade into fresh rock along relatively level surfaces. At Home Farm, Kingseat, 15 UADG boreholes across a sequence of norites, picrites and granites showed depths of weathering of between 11 and 16m over a distance of 80m, a much lower magnitude of variation than in the borehole transects illustrated above. In general, however, lateral variations in weathering depths in excess of 5m can be expected over short distances in most areas.

The rapid lateral variations make it impossible to draw isoline maps of weathering depths, as Thomas (1966) has done for study areas in Nigeria.

5.3.4 Weathering and its relation to the water table

The logs of UADG boreholes record the level at which water first enters the borehole in any quantity. The level of the first sign of water will almost invariably lie below the level of the water table and boreholes left open overnight show a modest rise in water level. Nevertheless the level of the first sign of water will give a maximum depth for the level of the water table.

A few general points can be made about the relationship between the weathering profiles and the present water tables:-

i) In several holes where depths of weathering exceed 15m, water is not met for 10m or more from the surface. This situation is particularly common in the deeply weathered rocks of the Crichie- Skelmuir- Dudwick area, away from the valleys.

ii) Alteration often extends well below the first sign of water and, by implication, even further below the water table. Decomposition extends for at least 15m beneath the water table in one borehole and depths of sub-water table decomposition commonly exceed 6m.

iii) The first sign of water frequently coincides with the contact between weathered and hard rock, where this boundary is sharp.

These observations raise a number of interesting questions:-

i) The low water tables in several deep weathering profiles will create free-draining conditions in much of the profile. Free-drainage will favour the formation of clay minerals of the kaolinite and illite groups (Tardy et al 1973).

ii) The extension of decomposition well below the present water table demonstrated the effectiveness of alteration in the phreatic zone, especially as former water tables were probably located above present levels.

iii) Given the contrasts in permeability between the saprolite and the subjacent hard rock it is hardly surprising that the water table often coincides with the boundary between the two. However, the coincidence might be taken to imply that the water table controls the depth of penetration of weathering. In fact, the observation that elsewhere decomposition extends below the water table suggests that the opposite is the case; that the depth of weathering is an important factor in the location of the water table.

5.4 The local distribution of weathering

The availability of section and borehole information varies greatly between districts (Fig. 5.2.i). Exposure in coastal districts is generally good but the frequency of exposure declines inland and with increasing altitude. Borehole information is localised and largely confined to eastern Aberdeenshire and parts of the Insch, Huntly and Knock basic masses. In some districts, data points are sufficiently closely spaced to allow the factors controlling the local distribution of weathering to be identified. Elsewhere sections are few and widely scattered and, in the absence of boreholes, it is often difficult to establish the incidence of weathering in the district. Due to the variation in the availability of information, it is necessary to discuss each district separately before the regional distribution of weathering can be considered.

5.4.1 Fraserburgh-Peterhead coastal zone

The coastal zone south from Fraserburgh to St. Fergus and Peterhead is obscured by thick accumulations of fluvioglacial, glaciolacustrine and glacial sediments. No information is available as to the nature of the bedrock between Peterhead and Crimond but IMAU boreholes south of St. Fergus show weathered bedrock at a few localities beneath more than 10m of drift. Weathering also frequently occurs beneath thick glaciolacustrine sediments in the over-deepened valleys of the North and South Ugie Waters downstream of Strichen and Old Deer (McMillan and Aitken 1981).

5.4.2 Mormond Hill

The massive and generally pure quartzite of Mormond Hill is highly resistant to weathering and the Hill is probably a long-established inselberg. However Mormond Quarry, close to the contact with the New Pitsligo Granite, exposes numerous zones of kaolinised silicate rocks and temporary trenches on the western slopes of Waughton Hill revealed bleached quartzites with patches of highly altered silicate rocks.

5.4.3 The New Pitsligo basin, the valley of the North Ugie Water and the Forest of Deer

The floor of the New Pitsligo basin is hidden beneath peat but hard granite is exposed in the quarries at Lambhill and in the sides of the meltwater channel occupied by the headwaters of the North Ugie Water. Trenches south of the B9093 showed thin, blocky and almost wholly granitic tills resting on fresh bedrock. Granite gruss is seen at Blackrigg and there are other records of decomposed granite in the basin (Wilson 1886; Glentworth and Muir 1963; Moore and Gribble 1980). All the quarries in the western slopes of the basin have pockets or zones of grussification and the quarry set in the low hill at Craigculter shows a tor form in the process of exhumation. The biotite-rich and partially altered New Pitsligo Granite (Anderson 1939) is highly susceptible to grussification and the confinement of decomposed granite to pockets sheltered by adjacent fresh rock indicates significant glacial erosion. Glacial removal of gruss is supported by the scatter of corestones on the slopes of Mormond Hill.

The valley of the North Ugie Water contains several exposures of weathered quartz-mica schists. In addition, Milne (1904) records kaolinised bedrock and china clay along the south side of Mormond Hill. The source of this kaolin has not been located and it is unclear whether it is an alteration product of the quartzites or the quartz-mica schists. Further east, the drift thickens and hard rock is more widespread. Hydrothermally-altered quartz-porphyry and diorite is exposed at Kirkhill Quarry and grussified diorites occur around Rora Moss.

The quartzites of the Forest of Deer are more varied in composition than their equivalents at Mormond Hill and several old quarries between the racecourse and Drinnies Wood contain highly altered bands of quartz-feldspar-mica metasediments.

5.4.4 Eastern Buchan between the South Ugie Water and the Ythan

Eastern Buchan is an area of widespread deep weathering (Fig. 5.4.i, ii and iii). Hard rock exposures are numerous in the quartzites of the Hill of Dens but to the south around Crichie boreholes have proved deeply weathered metasediments, with weathering depths increasing downslope to reach 19m beneath the meltwater channel. South of Crichie is an area of deep and almost continuous weathering covers. Boreholes beneath Skelmuir Hill, Hill of Dudwick and further east around Bogengarrie commonly encounter weathering to depths of 10m and more and outcrops are confined to bands of pure quartzites. Around Arthrath, RioFinEx boreholes indicate weathering penetration to depths as great as 50m in a highly fractured and complex group of contaminated basic igneous rocks. It is significant that this area also contains outcrops of the kaolinitic Buchan Gravels at Whitestones Hill and Moss of Cruden.

Weathering depths decrease sharply away from this central area, although decomposed granites and metasediments remain common to the north and south of the Moss of Cruden ridge. Exposures of

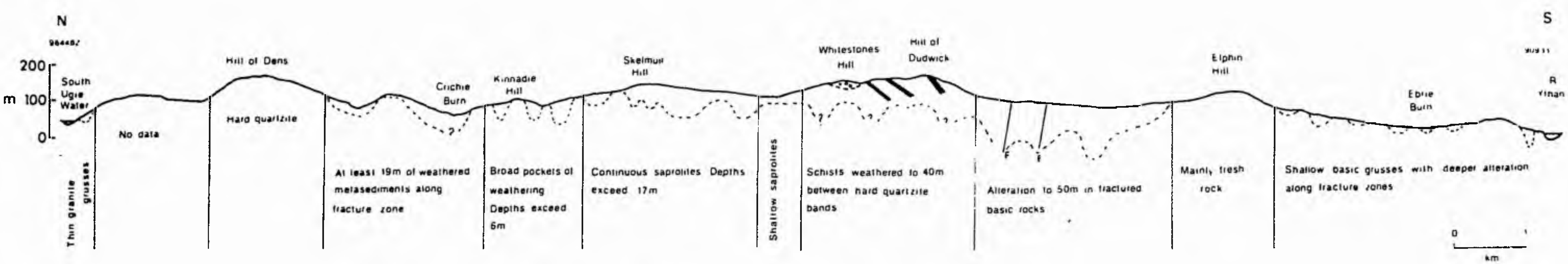


Fig 5.4.ii Weathering patterns across central Buchan

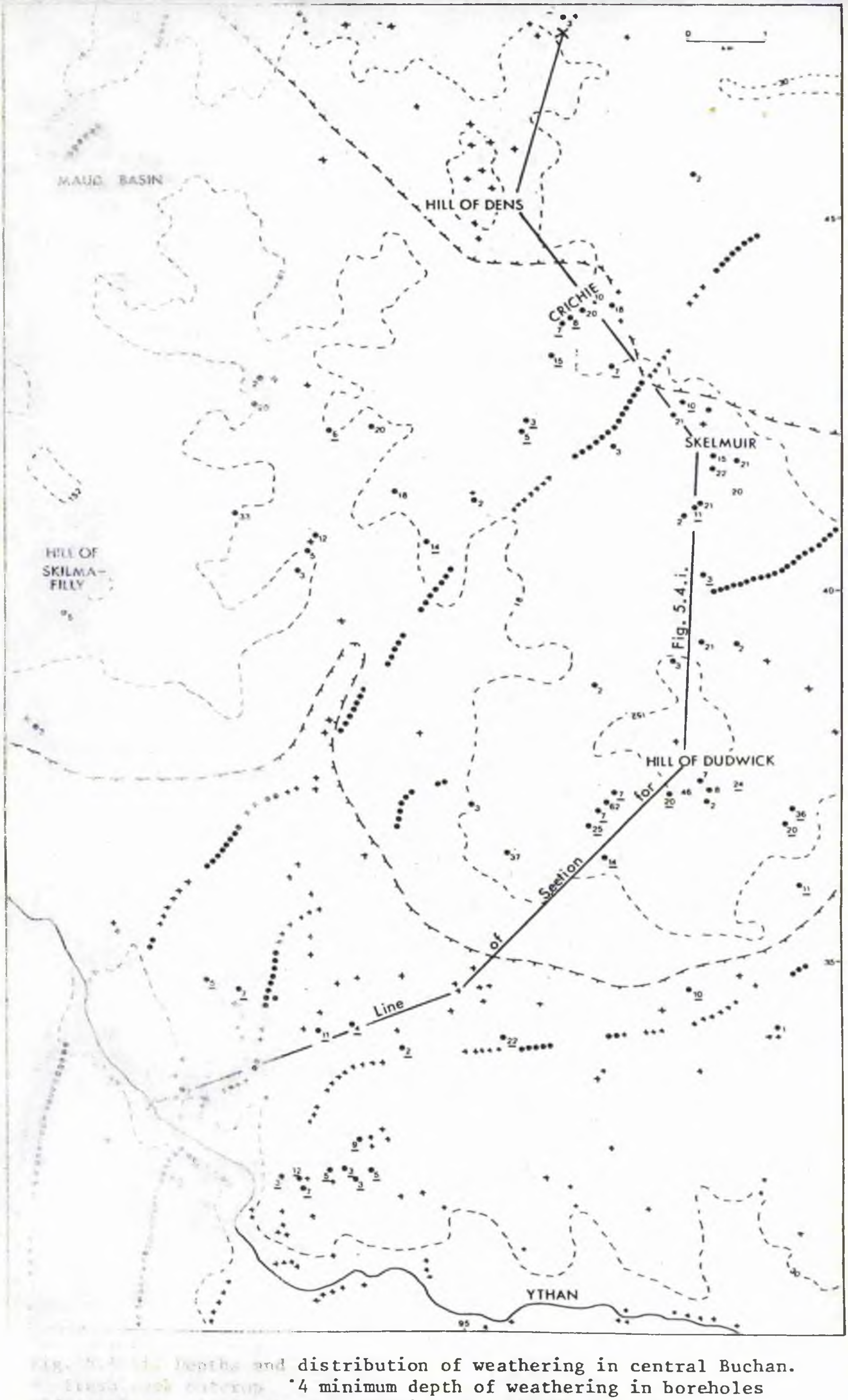


Fig. 5.4 i. Depths and distribution of weathering in central Buchan. + fresh rock outcrop ·4 minimum depth of weathering in boreholes and sections 4 depth of weathering above fresh rock. Pecked line delimits central area of continuous saprolites.

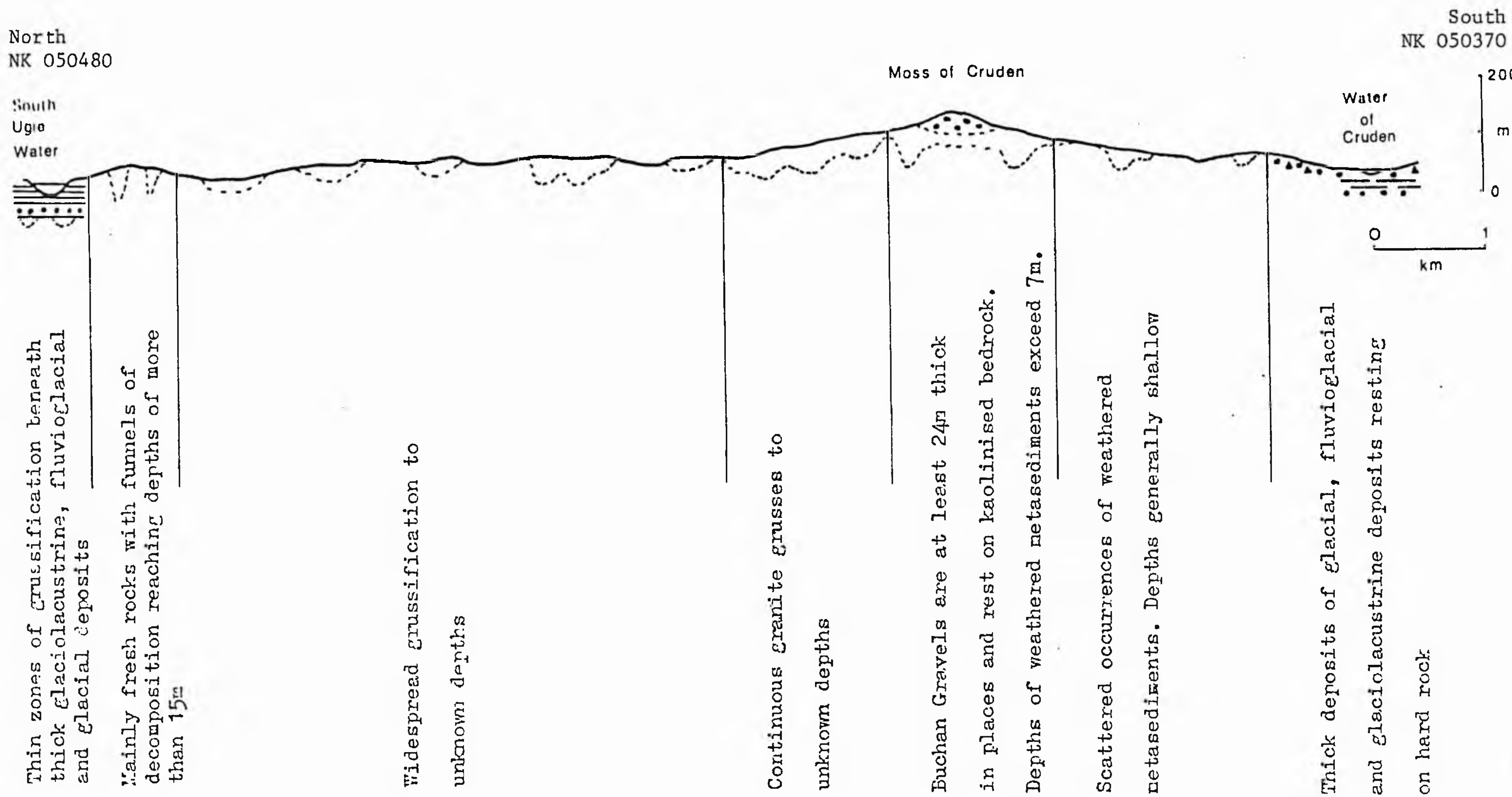


Fig. 5.4.iii. Weathering patterns across eastern Buchan.

Note : Weathering depths not to scale.

fresh rock become much more frequent to the north of Ellon and along the Ythan valley and most of the low hills in this area appear to be hard rock knobs rising above more weathered terrain. The norites of the Ebrie Burn valley are often decomposed, but probably not to any great depths. Deep zones of alteration are found around Ythanbank, often adjacent to hard rocks. The highly irregular rockhead contours here are a response to the dislocated nature of the local granites, metasediments and contaminated basic rocks which are sheared and fractured and may also have undergone some hydrothermal alteration.

Bedrock weathering is generally absent between Hatton and the coast. IMAU boreholes in this area (Merritt 1980; McMillan and Aitken 1981) record varying depths of glacial and fluvioglacial deposits resting on hard rock and the Red Till ice crossing this area must have completed the removal of all pre-existing weathered rock. In the Stirling Hill area to the north, the picture is rather different for grussified Peterhead granite is present at many localities and to considerable depths. Stirling Hill was also traversed by Red Till ice (Jamieson 1906) but the widespread preservation of grusses indicates a rapid northerly decline in its erosive power.

5.4.5 Western Buchan north of the Ythan

The western part of Buchan between Maud and Turriff is poorly exposed and virtually without borehole information. The norites of the Maud basin are decomposed at several sites and a single borehole at New Deer town recorded decomposition down to 35m. Sections near Auchnagatt show schists weathered to at least 13m and it is likely that the belt of country between Hill of Skilmafilly and New Deer is also deeply weathered. Further west, hardrock exposures become more numerous and the incidence of weathering probably decreases, although few sections are available.

In the Turriff Old Red Sandstone outlier, the basal conglomerates are weathered at a few sites and geophysical surveys indicate weak alteration down to 10m in places (Ashcroft Pers. Comm.). However, the numerous stone quarries and the prevalence of hard rock outcrops suggests that much of the Turriff outlier is unweathered.

The Macduff slates east of the Deveron are also largely unweathered, although Basham (1968) mentions 3m of rotted phyllite from near Turriff.

5.4.6 The coastlands between the Ythan and the Don

A narrow coastal belt between the Ythan and the Don is obscured by drift but available information indicates thick fluvioglacial and glacial deposits resting on hard rock. The belt lies within the Red Till zone (Murdoch 1975) and is continued northwards by the strip of significant glacial erosion between Hatton and the coast.

Further inland, weathering becomes common although the effects of glacial erosion are more apparent in this district than in most parts of the region (Murdoch 1975). Several of the hills, such as Beauty Hill and Overhill, are ice-roughened and most hills and steep slopes are free of weathering. Peat-filled rock basins are frequent but ice-scour has failed to remove numerous deep pockets of weathering. At Harestone Moss (Fig. 5.4.iv), up to 11m of weathered hornfels and picrite is found alongside ice-smoothed rock drumlins, almost certainly due to deep penetration of alteration along shear zones at the margin of Belhelvie basic mass (Ashcroft and Boyd 1976).

The valleys of the Tarty Burn, the Foveran Burn and most tributary streams have been scoured by meltwater to leave hard rock floors. In a few cases, however, deep weathering survives beneath the valley floors. The Rack Burn, west of Hill of Minnes, flows across a broad valley floor below which alteration extends to at least 18m. Shallower zones of decomposition also occur in the valley of the Blackdog Burn, NW of Potterton. The preservation of deep zones of alteration within the valleys suggests that many meltwater channels, now occupied by misfit streams, owe their alignment to pre-existing weathering patterns, which were, in turn, strongly influenced by the disposition of fracture zones.

Further west, the forms of glacial erosion become less marked. Weathering is still absent from most hill and ridge summits but is common in most of the basined valleys. The basined valley at Newmachar has been largely stripped of weathered material but the smaller feature to the north, at Straloch, retains up to 20m of weathered rock beneath its floor. At Straloch, boreholes indicate a gradual thickening of saprolite downslope from the surrounding interfluves but in the Blair basined valley the situation is more complex with weathered zones at least 11m deep occurring beneath bounding slopes of 6-8^{o} (see Section 12.4).

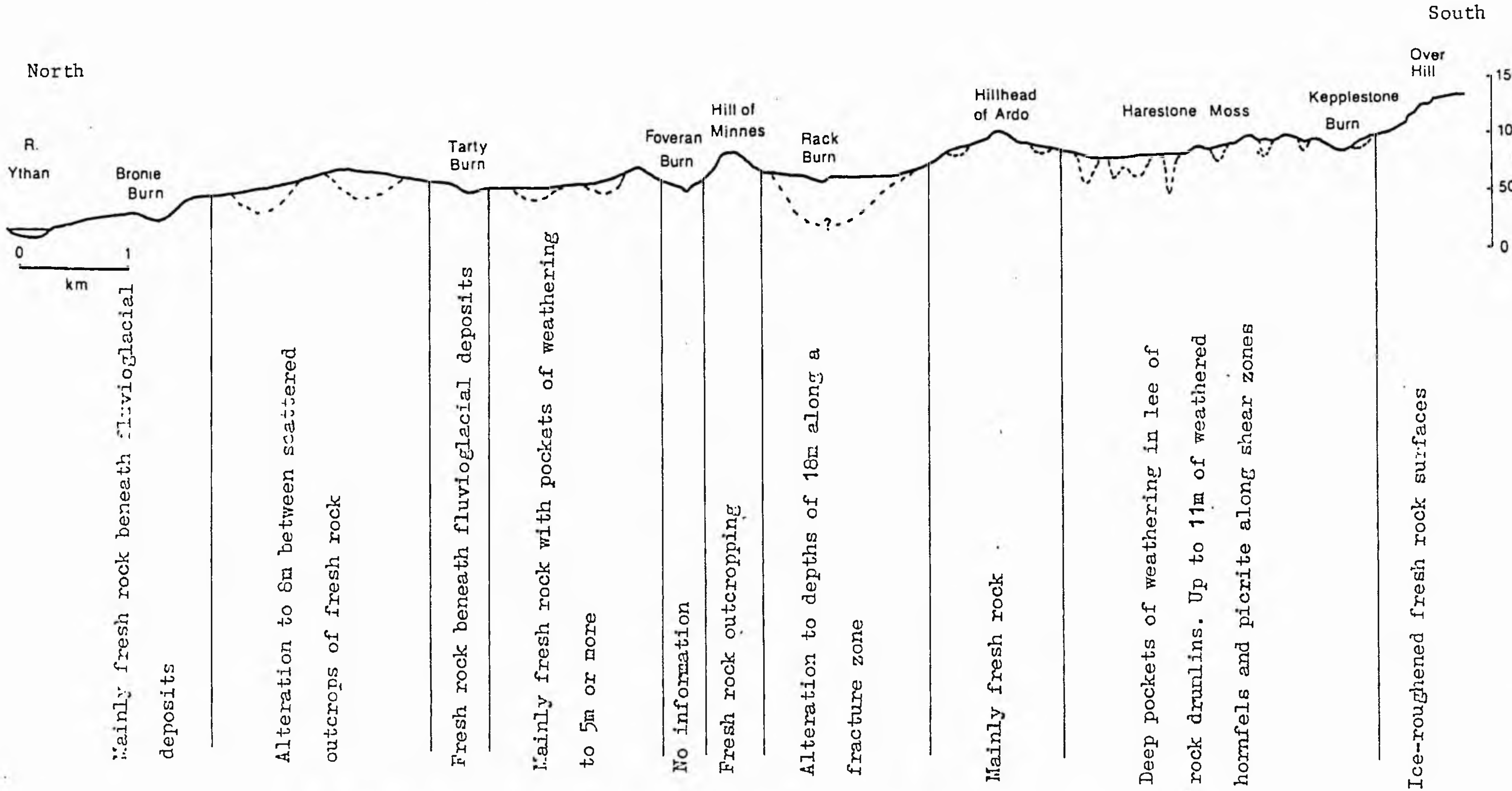


Fig. 5.4.iv. Weathering patterns south of the R. Ythan at Ardlethen.

Note : Weathering depths not to scale.

5.4.7 The Skene depression and Aberdeen City

Very little borehole information exists for the Skene depression. Hard rock is exposed on many of the hills to the north of the depression and quarries on the floor show only pockets of weathering. Nevertheless granite grusses have been noted at several sites around the Skene depression (Walsworth-Bell 1974; Chester 1978) and weathered granites are probably fairly widespread.

There are many records of weathered granites from beneath Aberdeen City (Phemister and Simpson 1949; Milne 1952; Higginbottom and Fookes 1970) and grusses are exposed at Nigg Bay (Synge 1956) and Bucksburn. The basal surface of weathering is highly irregular with bosses of hard granite rising out of the gruss (Higginbottom and Fookes 1970). Depths of 10m or more of granite gruss are known (Phemister and Simpson 1949; Higginbottom and Fookes 1970) and Basham (1968) mentions alteration of mica-schist down to 16m at Kincorth, south of the Dee. The widespread survival of grusses around Aberdeen is of considerable interest for the City is located in the zone of confluence of inland and Strathmore ice (Synge 1963), a location at which more efficient ice-scouring might be expected.

5.4.8 Banffshire north of the Deveron and the Isla

Much of that part of Banffshire north of the Deveron and Strathisla is free of weathered rock. On the Macduff Slates to the east hard rock is exposed on many of the hills and in the deeper valleys and only a single exposure of altered slate is known. Along the coast, north of Aultmore and Knock Hill, only rare pockets of weathering occur. Weathering is absent in most of the boreholes on the Portsoy basic mass and in view of the widespread decomposition of similar basic rocks elsewhere it seems that this portion of the Moray Firth coast has lost most of its weathering covers as a result of glacial erosion.

Inland weathering again becomes common on the lower ground between the hard and resistant ridges of Sillyearn Hill, Brown Hill and Black Law. In parts of the Aberchirder basin, notably around Auchintoul Moss, saprolites appear to be continuous. The Findlater Flags to the north of Keith are decomposed in several places (Fitzpatrick 1963). In the Knock depression, boreholes close to the Isla-Deveron confluence show deep decomposition of gabbroic rocks, often in close association with drift-covered hard rocks.

5.4.9 The Daugh of Invermarkie, Clashindarroch Forest and the Cabrach

Numerous exposures of weathered rocks occur around the Daugh of Invermarkie, south of Keith and the survival of saprolites on slopes as steep as 10^o indicates only modest glacial stripping. To the south, the high ground of Clashindarroch Forest is poorly exposed but Koppi (1978) has studied the weathering of a metasediment on the side of the Ealaiche Burn, at an elevation of 351m. Much of the drift in this area is little-travelled (Muir and Fraser 1940) and weathering may well be widespread, although the hills above the Deveron upstream of Haugh of Glass are ice-roughened.

The basic rocks of the Cabrach are extensively decomposed (Basham 1968). The small Kirkney basin, in particular, appears to be virtually unmodified by glacial erosion for sections show that the gabbroic grusses are almost drift-free and a number of small tors fringe the basin floor.

5.4.10 The Macduff Slates south of the Deveron

Exposure in this area is poor. Hard rocks outcrop extensively on the Hills of Foudland, although an isolated UADG borehole on the eastern flank of the Hill of Tillymorgan encountered 12m of weathered rock. Quarries northwards towards the Deveron generally show only fresh rock but there are also numerous indications that weathering is also present in this area. Alternating bands of weathered and fresh rock are exposed in deep sections at Nether Lenshie and Smiddyseat. Two short seismic lines at Bothwellseat and Heathfield proved 15m of 'drift' (Wilson 1970), which may include weathered rock. The subdued nature of the topography east of Wells of Ythan, and the rarity of fresh outcrops, are also suggestive of the weathered terrain further east.

Further west, RioFinEx boreholes indicate deep decomposition of basic rocks along the Drumblade Shear Zone (Ashworth 1975).

5.4.11 The Insch depression

Decomposed basic rocks are found over much of the Insch depression. Basham (1968) has shown that gabbroic grusses are present beneath thin drift in large numbers of soil pits on the floor of the depression. Sections expose weathered diorites, gabbros, epidiorites and serpentinites and hard rocks are largely confined to the sides of the main meltwater channels and to the belt of syenitic hills, west of Insch.

Detailed borehole information is available for the eastern margin of the Insch basic mass at Oldmeldrum. The rocks here are extensively sheared and fractured and weathering extends well below rockhead in many places. Weathered basic rocks remain on the floor of the Barra basined valley and decomposition to 6m or more is frequent on the gentle slopes of the northern margin. Hard rock outcrops extensively on Barra Hill but, in places, deep zones of alteration reach depths of more than 13m, despite slope gradients of 8-10^{o} (see Section 12.5).

5.4.12 Hill of Fare, Bennachie and the Correen Hills

The hill masses of Hill of Fare, Bennachie and the Correen Hills are largely free of drift and fresh rock outcrops extensively. Weathered granites are present at sites on the lower flanks of Bennachie and gruss-type material is found around the summit tors.

5.4.13 The Alford, Cushnie and Tarland basins

Weathering in the Alford basin is widespread and has affected the entire basin form. Granite grusses occur on the basin floor at Bandley (Clapperton and Sugden 1977), on the bounding slopes at Tulloch and Gallowhill and on the rim at Kingsford (see Section 12.6).

Hard rocks are more in evidence in the Cushnie basin but weathered schists occur around the basin margin. Numerous exposures around the foot of Mill Maud hill reveal decomposed granite to depths of more than 10m.

In the Tarland basin weathered rocks are confined to sheltered locations around the margins of the floor. The central metamorphic hills are ice-roughened and ice erosion in this basin has been relatively severe.

5.4.14 The Deeside valleys

Weathered granites are known from several of the valleys of southern Deeside. Grussification is widespread in Glen Dye (Reid 1979) and deep grusses are also present in Glen Cat and at Etnach in Glen Tanar (Milne 1952). The presence of weathered granites, together with V-shaped valley forms, suggests only minor glacial modification of these valleys.

5.4.15 Weathered rocks west of easting NJ 40

Although no systematic study has been made, it is evident that weathered rocks may be found at many points west of the study area (Fig. 5.4.v). In the Elgin area, the Old Red Sandstone is weathered to depths of 10m (Peacock and Michie 1975). Weathered biotite-hornblende schist (Wilson 1970) and Old Red Sandstone conglomerate (Wilson et al 1971) have been described from Nairnshire. Deeply weathered schists occur north of Tomintoul and around Tomnavoulin (Basham 1968). Granite grusses are found at several sites on the Cairngorm plateau (Linton 1950; 1951; 1955; Sugden 1968; Sissons 1976), notably around Cairn Lochan, and also in the corrie headwalls on Lochnagar. Of especial interest are the 10m or more of weathered granite on the Gaick Plateau (Barrow et al 1913) and the weathering associated with high-level basinal forms north of Balmoral (Crofts 1974) and above Loch Muick. These scattered records suggest that weathering may be more widespread at higher elevations than is generally realised, especially beneath the poorly-exposed, rolling plateau surfaces.

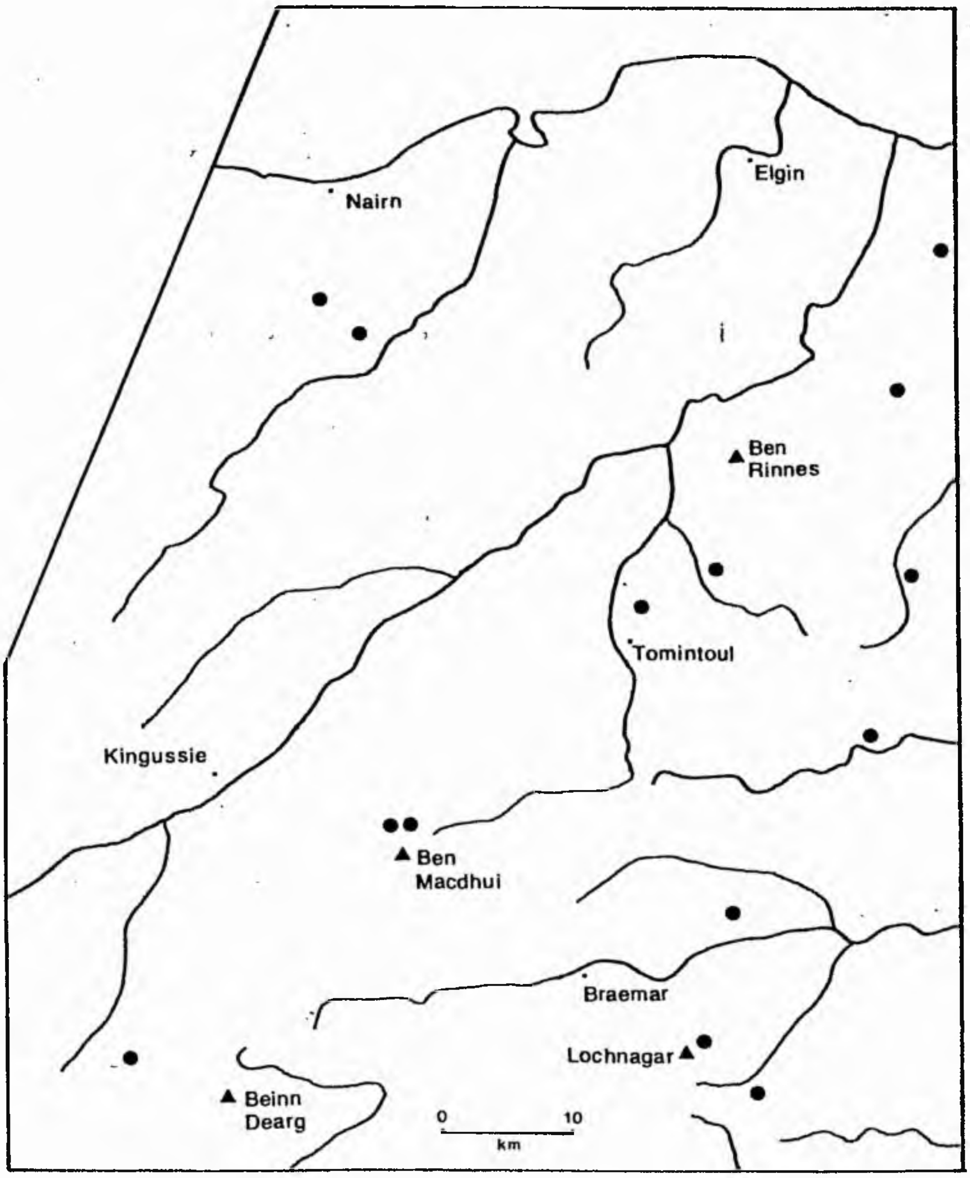


Fig. 5.4.v. Weathering sites west of Easting NJ 40

5.5 The regional distribution of weathering

5.5.1 Weathering zones

Using evidence from sections and boreholes and from the frequency of fresh outcrops, it is possible to divide the region into a number of weathering zones (Fig. 5.5.i):-

Zone 1: Areas of deep and continuous saprolites. Fresh outcrops are confined to highly resistant rocks, such as quartzites, and to the floors of the main valleys.

Zone 2: Areas of thinner and discontinuous saprolites with more frequent rock outcrops. Localised deep alteration is often present.

Zone 3: Saprolites are infrequent and largely confined to ice-lee locations. Weathering is generally absent from the main valleys and from interfluves and is common only within tributary valleys and basins.

Zone 4: Weathering confined to fracture zones with abundant fresh outcrops elsewhere. A distinction can be made between zones where weathering was probably extensive prior to glaciation (Zone 4a) and zones of resistant rocks and/or steep slopes where weathering was probably thinly or sporadically developed prior to glaciation.

The zones represent landscapes of differential erosion. Weathering covers, whose depths and distributions were products of geological and topographic variables, have been disrupted by erosional processes in the Pleistocene. The depth of erosion has been spatially variable and number of landscape types at different stages of denudation have been produced. The zonal scheme is directly comparable to the etchplain terminologies used by Finkl and Churchward (1973), and Thomas (1974a), although the environments

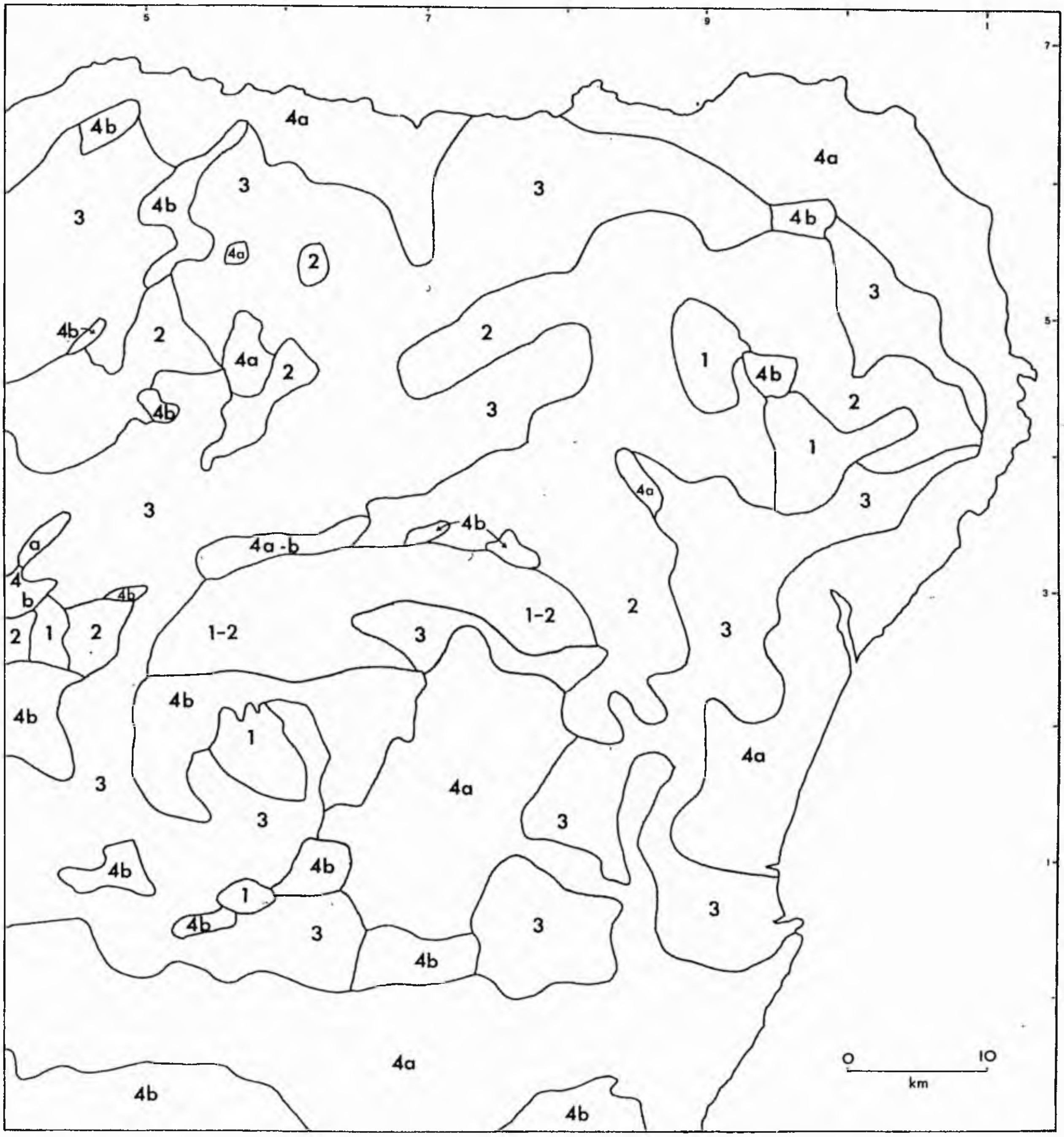


Fig. 5.5.i. Weathering zones. Key in text.

and time scales involved are rather different.

The recognition of these landscapes of differential erosion is of some geomorphic significance. Estimates can be made of depths of lowering of the landscapes using weathering patterns (Finkl 1979). Moreover the main palaeoforms can be observed at different stages of modification in a variety of landscapes and a picture of progressive change can be built up. Finally, once the geological and topographic factors influencing weathering patterns have been identified, it is possible to use the distribution of weathering as an indicator of regional patterns of glacial erosion.

5.5.2 Weathering and Elevation

The distribution of weathering in terms of elevation is also of interest (Fig. 5.5.ii). 57% of weathering sites are found at elevations of between 60 and 140m above sea level. These saprolites underlie a surface of low relief, termed the Buchan Platform by Walton (1963). The scarcity of saprolites below 70m reflects enhanced glacial erosion of coastal districts.

The decreasing frequency of weathering above 200m is partly a product of the increasing dissection of the relief towards the west. However saprolites remain uncommon even beneath the gentle relief of the high level erosion surfaces and differences in the intensity of erosion between highlands and lowland plateaux are indicated.

5.6 The influence of geology on the distribution of weathering

5.6.1 Effects of lithology

The distribution of weathering in north-east Scotland is greatly

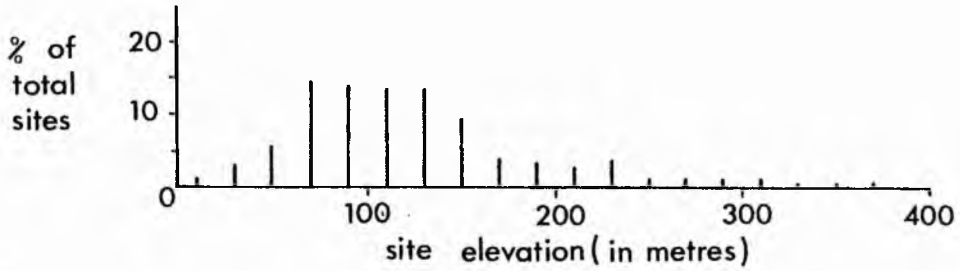


Fig. 5.5.ii. Distribution of weathering sites with altitude.

influenced by lithology and structure (Fitzpatrick 1963; Chester 1978). The incidence and depth of weathering varies with rock types and reflects different levels of rock resistance. The patterns of differential weathering revealed by the distribution of weathered rock often correspond with those deduced from the relationships between rocks and relief and provide a basis for models of weathering and landform evolution.

Granites and gabbros are the rock types most susceptible to decomposition (Table 5.6.i).

Table 5.6.i Percentages of sections in weathered rock for different lithologies

	A. % of total sections	B. % of total study area occupied by rock type	A/B
Granitic	42.3	17	2.49
Gabbroic	21.1	10	2.11
Quartzites and other metaseds	33.8	56	0.60
Macduff Slates	0.7	11	.06
Old Red Sandstone	2.1	6	.35

The Dalradian metasediments are also commonly weathered but the incidence of weathering varies both between and within Members of the Dalradian succession. The frequency of weathering in the quartzites reflects the lithological diversity of these rocks. In contrast, the homogeneous Macduff Slates are much more resistant to alteration.

More precise evidence of the differential resistance between rock types is provided by sections in which two or more rock types are exposed. Sections of this type occur in a variety of geological settings, notably at igneous and metamorphic contacts, in xenolithic rocks and where minor intrusive dykes and veins transect country rocks. These sections confirm the susceptibility of biotite granites, norites and gabbros to decomposition (Table 5.6.ii). Quartzites and quartz veins are invariably unaltered. Several types of metamorphic rocks are more stable than adjacent mafic igneous rocks.

The effects of differential resistance are also apparent in tills and fluvioglacial deposits of the last glaciation (Carruthers 1950; Peacock et al 1977) and in Old Red conglomerates. Biotite-bearing granites, gabbros and schists invariably form a large proportion of the decomposed clasts in these deposits.

Table 5.6.ii Differential weathering in sections

Location	Grid Ref.	Hard Rock Type	Weathered Rock Type
Aikey Fair Stance	NJ964478	Quartzite	Biotite granite
Auchintoul Moss	615535	Quartzite	Mica schist
Auchreddie (Farquhar 1950)	914351	Hornfelsed quartzitic metaseds.	Andalusite-cordierite schist
Banks Quarry (Smith 1933)	926478	Mica schist	Norite and biotite granite
Birness	991341	Hornblende schist	Sericite-chlorite schist
Blackpots	952413	Mica schist	Biotite granite
Bruxie	964493	Quartzite	Norite and crushed psammites
Fedderate	889505	Hornfelsed schists and quartzite	Hornblendic norite
Folla Rule	732322	Andalusite schist	Gabbro
Galla How	556181	Knotted schists	Biotite granite
Kingsford	566139	Quartz-biotite schist and micro-granite	Coarse two-mica granite
Northseat	930408	Quartzite and qtz psammite	Biotite-rich andalusite schist and felsite
Toddlehills	951371	Aplite	Mafic psammite

Mineralogy is a major determinant of the resistance of various rock types to chemical weathering. The role of biotite expansion in promoting rock decomposition is well documented (Wahrhaftig 1965; Duminovsky 1968; Isherwood and Street 1976; Bustin and Matthews 1979) and is perhaps the most important single factor determining the resistance of the rocks of north-east Scotland. In the granites, decomposition is almost always present in the biotite-rich varieties. Grusses are especially widespread on the granodiorites of the western part of the Peterhead mass and on the biotite-hornblende granites flooring the Alford basin. Decomposition affects all other important biotite-bearing intrusions:- the granites between Aberdeen and the Hill of Fare (Walsworth-Bell 1974), the Tomnaverie granite (Read 1927), the New Pitsligo granite and the Aberchirder granite. The Kennethmont, Torphins and Rora diorites also decompose readily.

On the Younger Basic rocks, weathering is extensive on the norites and biotite-bearing gabbros (Basham 1974).

In the metamorphic rocks the tendency for biotites to be concentrated along laminae in schists and within bands in gneisses undoubtedly facilitates alteration. Pipeline trenches show that weathering is widespread in the biotite-plagioclase Ellon Gneiss and weathering extends below 13m in biotite-rich andalusite schists at Northseat.

The importance of biotite in predisposing rocks to breakdown is due to the capacity of the mineral to absorb water and expand during alteration (Isherwood and Street 1976). Even modest alteration of biotite to hydrobiotite and vermiculite can cause major changes in volume and mineralogical changes of this type have been widely reported from the basic rocks of north-east Scotland (Wilson 1967; 1970; Basham 1974).

The quartz content of the rocks also has an important effect on rock resistance. Pure quartzites are inert to chemical alteration. Siliceous rocks such as the andalusite schists of the Coreen Hills and the leucogranites of Hill of Fare and Bennachie tend to show comparatively few signs of weathering. Exceptional in this respect are the quartzitic Members of the Dalradian, especially the Mormond Hill Quartzite. True quartzites form only a part of this Member and large areas of andalusite schist and quartz-feldspar psammite are extensively decomposed. In several sections even minor impurities in the Mormond Hill Quartzite have been exploited by weathering. Weathering in the Durn Hill and Cullen Quartzites is much less common, partly due to their more uniformly siliceous composition. Weathered quartzites are known from Hill of Maud (Peacock et al 1968) and The Balloch (Muir and Fraser 1940).

In standard weathering sequences of silicate minerals (Goldich 1938; Loughnan 1969), plagioclase feldspars are more readily altered than orthoclase feldspars. The effect of feldspar type on rock resistance is not generally obvious in north-east Scotland, although it is probably an element in the susceptibility to breakdown of plagioclase-rich rocks like the Ellon Gneiss and the New Pitsligo granite.

Grain size is a further factor influencing resistance through its effect on porosity. Pelitic and semi-pelitic metasediments, such as the Fyvie Schists and the Macduff Slates, are little weathered. In the Insch Mass, finer grained hypersthene gabbros are less frequently decomposed than neighbouring coarser textured variants (Basham 1974). Fine grained serpentinites and epidiorites are also less extensively decomposed than the gabbroic rocks. The influence of texture is less evident in the granites as fine grained varieties are rather uncommon. The effect of textural differences on granite weathering is best seen at Kingsford, where medium to coarse grained two-mica granite is thoroughly grussified whilst zones of microgranite have disintegrated to angular blocks which remain intact, even when bleached in the overlying podzol.

5.6.2 Effects of late-stage alteration

Late-stage alteration of the primary minerals may considerably reduce the resistance to alteration (Eggler et al 1969; Samuelsson 1973). Uralitisation in the Younger Basics often corresponds with zones of deep alteration, as in the Arnage Mass. Kaolinisation of plagioclase affects the New Pitsligo granite and the Cairngall microgranodiorite whilst chloritisation of biotite occurs widely, notably in the Aberchirder granite and the Kirkhill diorite. All these altered granitic rocks are extensively grussified, with funnels of decomposition penetrating more than 15m below rockhead in the Cairngall microgranodiorite.

5.6.3 Effects of Fracturing

Fracturing exerts a key influence over the distribution of deep zones of weathering. The increased porosity along fault lines and within shear belts (Niini 1968; Rolland 1975) has facilitated deep alteration along many of these structures. A number of major shears have been identified in the Dalradian (Farquhar 1950; Fettes 1968; Ashworth 1975) which coincide with topographic corridors and valleys. Alteration in the Drumblade Shear Zone extends to depths of 30m and linear zones of deep weathering beneath the valleys of the Crichie and Rack Burns suggest that many other lesser fracture zones await discovery. Shearing and dislocation is found in many of the Younger Basic masses (Ashcroft and Munro 1978). In the Huntly mass, deeply weathered shear belts along the Deveron valley and the Burn of Cairnie isolate the hills of The Bin and Ordiquhill. Shearing, fracturing and mylonitisation are responsible for the deep alteration of parts of the Arnage mass. Detailed subsurface information from the Oldmeldrum area at the eastern end of the Insch mafic intrusion demonstrates the close control of fault and shear zones on weathering depths and on local topography (see Section 12.5).

5.7 Summary

Weathered rocks have been found at over 450 locations in north-east Scotland. Depths of weathering commonly exceed 5m and locally extend below 30m. Lateral variations in saprolite depths are rapid and fresh outcrops may be found adjacent to deep pockets, basins and troughs of weathering. Many saprolite profiles have been truncated by glacial and periglacial erosion. Three basic profile types can be identified in which decomposition is either (i) thorough or (ii) accompanied by corestones or (iii) accompanied by blocky disintegration. Saprolites show little horizon development and competence increases gradually with depth. Many saprolites pass down into fresh rock through a thick transitional zone and a sharp basal surface of weathering (Ruxton and Berry 1959) is not typical. Many deep profiles are free-draining but decomposition may also extend well below the water-table.

After consideration of the distribution of weathering by districts, the region is divided into weathering zones. These zones represent landscapes of differential erosion and are discussed further in later sections on relief development and patterns of glacial erosion. The importance of such geological factors as mineralogy, late-stage alteration and fracturing in controlling the distribution of weathering is emphasised.

CHAPTER 6 Granulometry of the Weathered Rocks

6.1 Introduction

The weathering of crystalline rocks to produce saprolite involves the interaction of the twin processes of mechanical microdivision and mineralogical and chemical change (Millot 1970). The action of microdivision has two effects:- (i) the parent rock is broken down into its constituent primary minerals and into polymineralic aggregates of various sizes and (ii) the individual mineral crystals are divided along micro-fractures to produce smaller particles. The chemical evolution of the saprolite likewise produces two main effects:- (i) the reduction in size of the non-resistant primary mineral grains by etching and dissolution and (ii) the gradual replacement of these primary minerals by argillic alteration products. Microdivision and chemical alteration take place simultaneously though their relative importance varies with the stage of development of the saprolite. The initial disintegration of the parent rock is accompanied by rapid microdivision and only limited chemical change (Dejou and Pedro 1967). The rate of microdivision then starts to slow and chemical alteration becomes more important and eventually a point is reached where microdivision becomes controlled by the rate of penetration of alteration along mineral cleavages.

The nature of these changes is reflected in the granulometry of the saprolite. In medium and coarse-grained igneous and metamorphic rocks, microdivision leads to the progressive reduction of the coarse sand fractions of the saprolite and the accumulation of finely divided particles in the silt and very fine sand fractions. The products of chemical alteration, namely the clay minerals, are concentrated in the clay fractions. Secondary minerals are not confined to the clay fractions but in temperate environments the proportion of clay minerals in the silt fractions is generally low (Dejou et al 1967), unlike the more intensely weathered alterites of the tropics (Ruddock 1967; Eswaran, Stoops and Sys 1977). The granulometric changes accompanying the weathering of fine grained crystalline rocks have received little attention but it is possible that clay and silt-sized particles may be formed by both microdivision and alteration in pelitic saprolites.

The grain size distribution of a saprolite will thus provide a guide as to the stage of development of a saprolite (Millot 1970). The size of the clay fraction ($< 2\mu$) is an indicator of the degree of chemical alteration, at least at the more advanced stages of weathering (Wambeke 1962; Seddoh 1973) and saprolites with high clay contents can be expected to show marked depletion and replacement of the more weatherable primary minerals. Similarly the proportions of the coarse sand and silt fractions reflect the intensity of microdivision in a saprolite. Grain size analysis was employed here as one means of identifying different types of generations of weathering covers.

As the granulometric changes accompanying weathering can be expected to vary between rock types, the saprolites in this study have been split into 4 lithologic groups:- granitic, basic igneous, quartzitic metasedimentary and other metasedimentary. Comparison between rock types is then made in Section 6.8.

6.2 Methods

Particle size analysis followed the methods of the Soil Survey of England (Avery and Bascomb 1974). Due to the insignificant amounts of organic material in most subsurface samples, prior treatment with H_2O_2 was usually unnecessary.

Particle size descriptions follow the Wentworth Scale.

6.3 Granitic Saprolites

6.3.1 Variations within sections

Four sections were chosen to investigate the internal variations within a section:- Hill of Longhaven, Cairngall Quarry, Bennachie Car Park and Mill Maud.

(a) Hill of Longhaven

The grain size distribution for a single vertical section in the coarse grained disaggregated granite at Hill of Longhaven is shown in Table 6.3.i. The uppermost sample from directly below the till is depleted in coarse sand and enriched in fines relative to the other samples, probably as a result of incipient pedogenesis. Samples taken from the joints show slight losses in coarse sand and enrichment in silt relative to material taken from the adjacent disaggregated core blocks, possibly as a result of slightly faster rates of groundwater percolation down the vertical joint planes.

(b) Cairngall Quarry

The grain size characteristics for two vertical sections in this highly altered microgranodiorite are given in Table 6.3.ii. The size of the clay fractions varies considerably within both

Table 6.3.i . Hill of Longhaven- granulometry

Depth	CS	FS	Fines	Clay
0.5	75.1	10.7	14.2	1.2
1m joint	92.9	3.3	3.8	0.1
1m core	95.6	4.1	0.3	tr
3m joint	96.9	1.7	1.4	0.2
3m core	98.5	0.7	0.8	tr
5m joint	89.9	4.2	6.0	0.2

Sample Locations

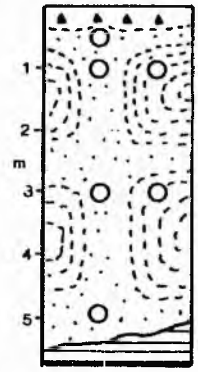
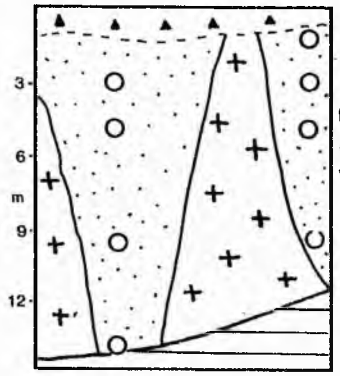


Table 6.3.ii . Cairngall Quarry- Granulometry

Profile	Depth(m)	CS	FS	Fines	Clay
1	3.0	65.6	8.4	26.0	6.4
	5.0	67.1	6.8	25.1	6.5
	10.0	73.5	6.0	20.5	7.9
	15.0	70.9	13.6	15.4	3.3
2	1.0	67.7	16.8	15.6	5.3
	3.0	75.4	9.2	15.4	6.1
	5.0	62.4	11.8	25.8	11.7
	10.0	74.2	10.8	15.0	7.0



Abbreviations

Symbol	Description	Diameter(μm)
G	Gravel	>2000
CS	Coarse Sand	250–2000
FS	Fine Sand	63–250
F	Fines	<63
S	Silt	2–63
C	Clay	<2

sections. Neither profile shows any systematic vertical variation.

(c) Bennachie Car Park

Fig. 6.3.ia illustrates the grain size changes down a single vertical profile from the Bennachie Car Park exposure, with sampling at 10cm intervals. The cryoturbated till, bedded gruss and weathered granite represent 3 separate granulometric populations. The cryoturbated till contains many basic igneous clasts derived from the adjacent Insch gabbroic mass. The bedded gruss differs markedly from the underlying in situ weathered granite with lower silt and clay contents and more coarse sand-sized material. The bedded gruss also contains conspicuous amounts of fresh pink feldspar which is absent from the underlying weathered rock. It seems that the bedded gruss has not been derived directly from the subjacent clayey weathered granite but has been transported from a rather less intensely weathered granite upslope. The weathered granite in this profile is vertically homogeneous in grain size, although the base of the profile is not seen. However the profile is not typical of the exposure as a whole as 8 samples taken elsewhere showed lower clay and silt contents.

(d) Mill Maud

A single vertical profile from the deep section at Mill Maud shows only minor changes in granulometry with depth (Fig. 6.3.ib). Samples from the base of the exposure are slightly coarser and contain fewer fines than samples closely to the surface. The granulometry suggests only a modest downward decrease in the degree of alteration in 7.5m of section.

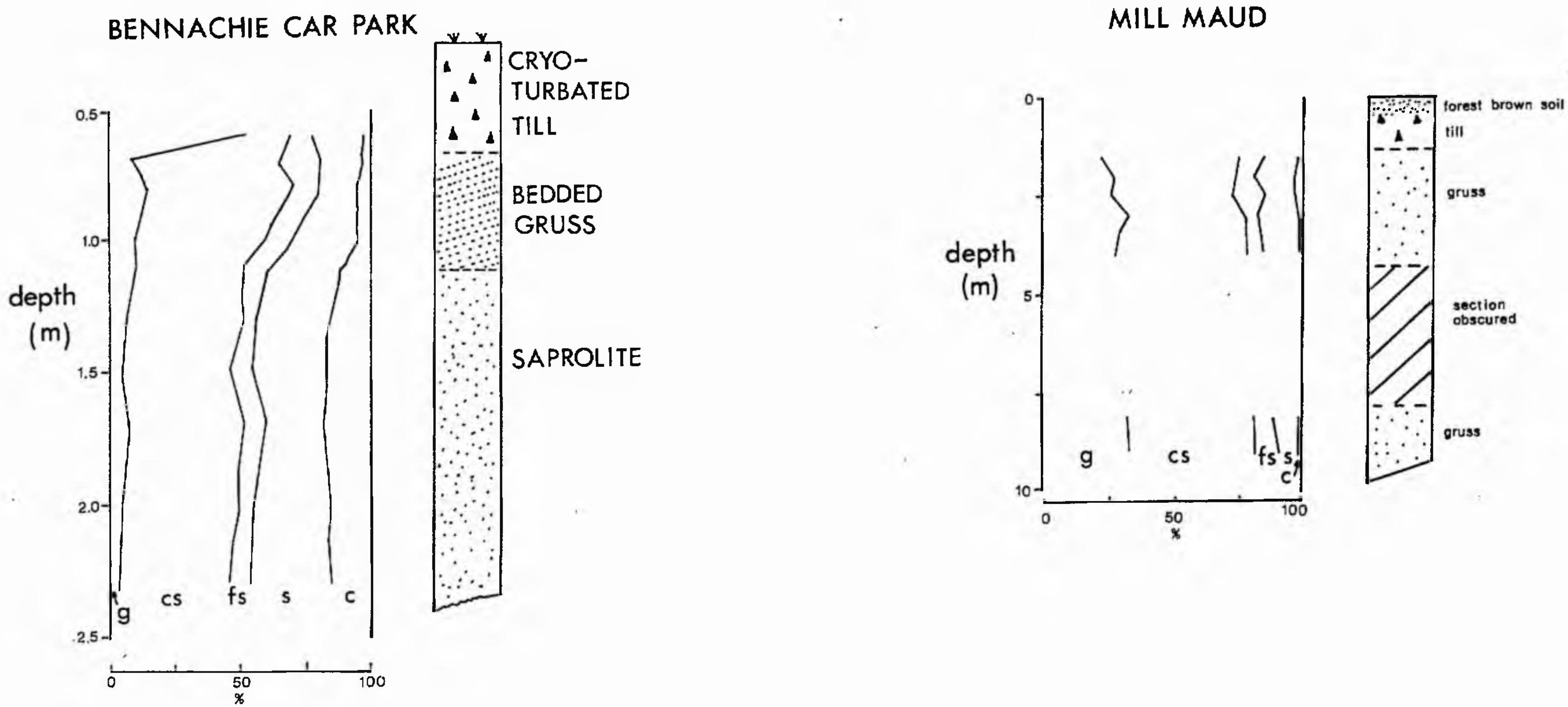


Fig. 6.3.i. Vertical variations in granulometry in two granite weathering profiles.

6.3.2 Variations between sections

The grain size characteristics of samples taken from 33 separate exposures of weathered granites are summarised in Fig. 6.3.ii. The sites show a wide granulometric range. Median grain sizes range from over 2000u to less than 50u and clays make up from 0.1 to 24% of total sample weights.

The weathered granites form a granulometric continuum which may be divided into certain types following the descriptive terminology of Flageollet (1977):-

Granular grusses (arènes grossière) are most commonly developed on coarse grained granites. Median grain sizes are above 1000u and development of fines is limited. Clay contents are always low and are barely traceable in some samples.

Grusses (arènes) have median grain sizes below 1000u. Fines contents vary between 10 and 30% and clay contents between 1 and 7%.

Clayey grusses (arènes argileuses) are represented by only four sites in the study area; Bennachie Car Park, Cairngall, Cruden Moss 5 and QX115. Grain size distributions are bi-modal. The primary mode remains in the coarse sand fraction and is largely provided by a residue of resistant quartz grains. Fines contents are elevated and create a secondary mode. Clay contents are above 6% and reach 44%.

Grain size curves representative of these granulometric types are shown in Fig. 6.3.iii.

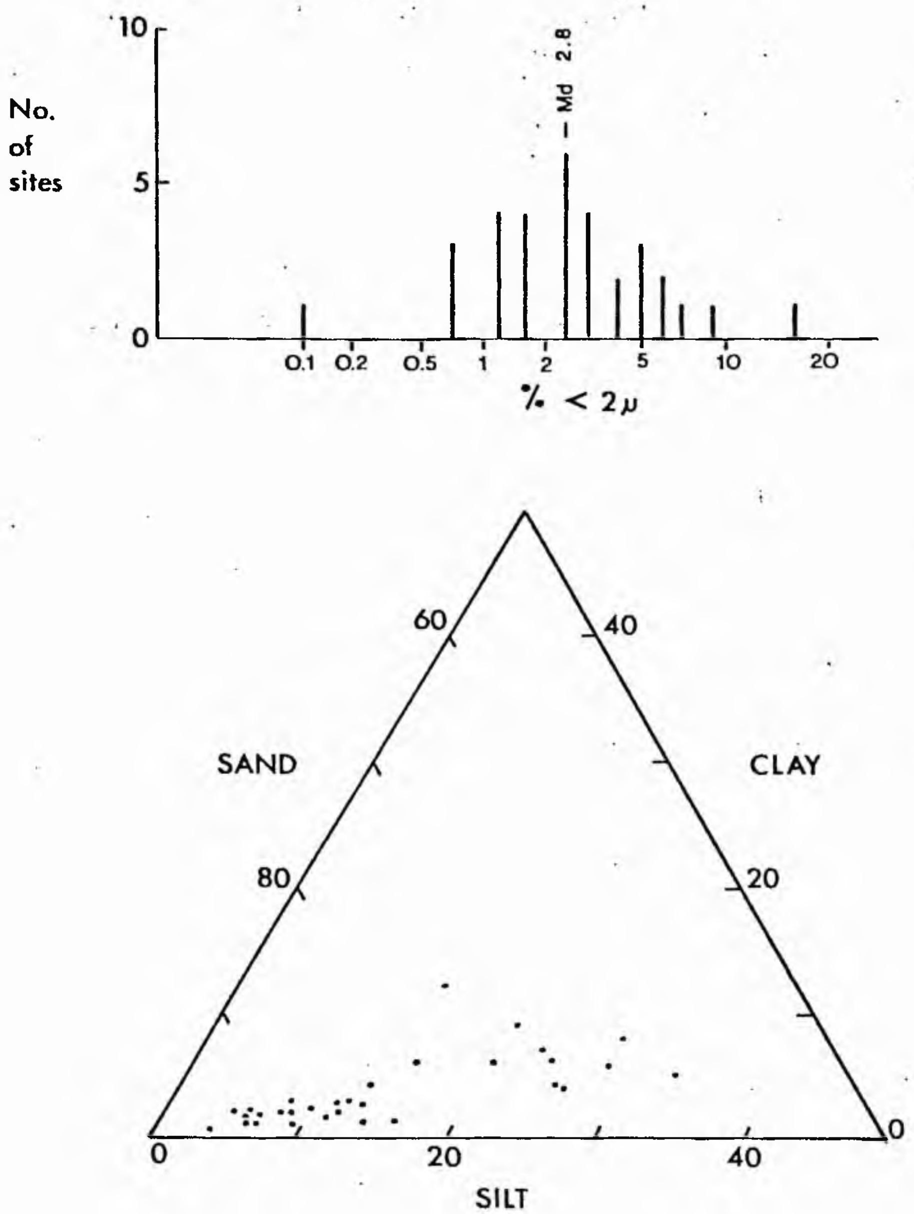


Fig. 6.3.ii GRANULOMETRY OF THE WEATHERED GRANITES

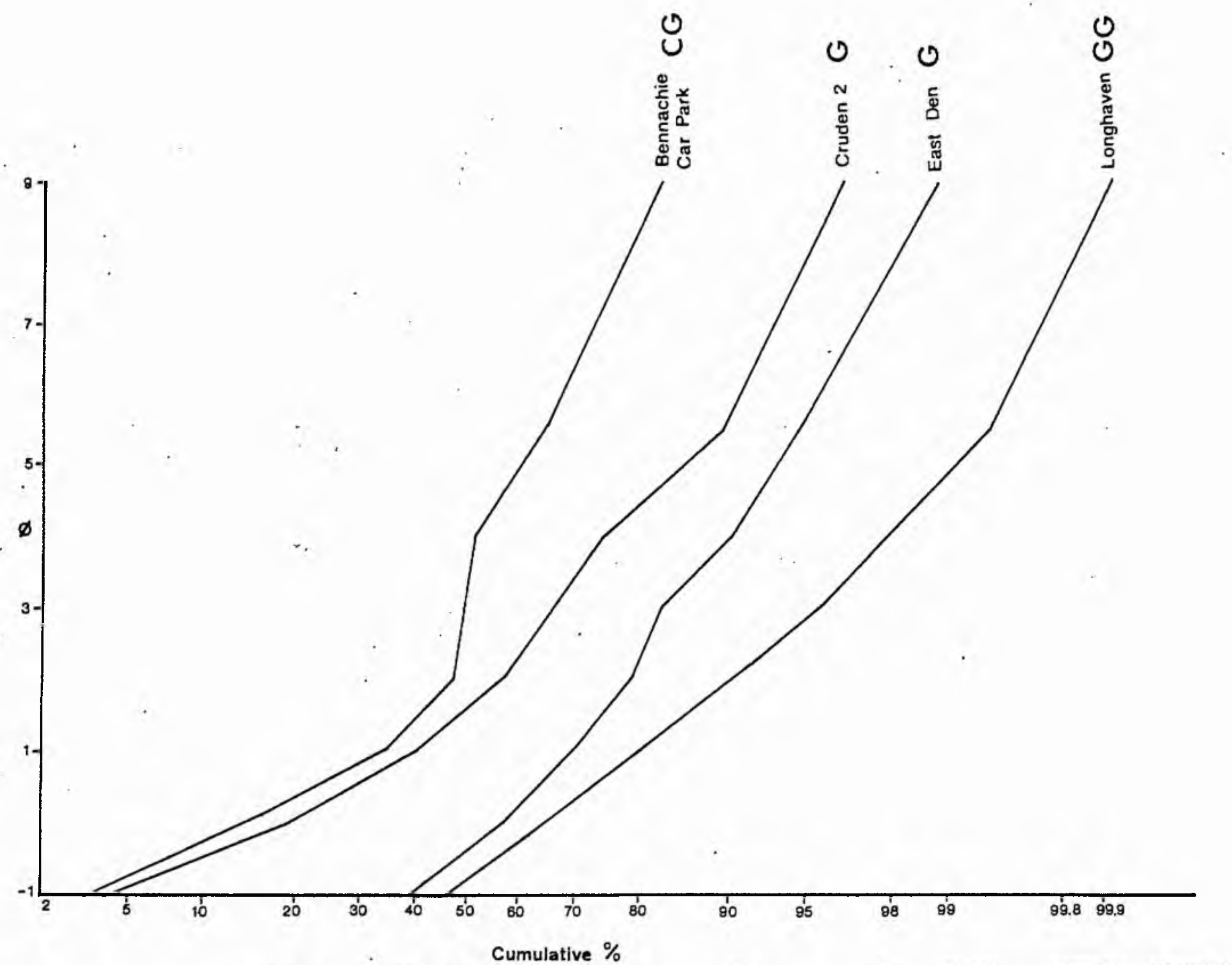


Fig. 6.3.iii. Grain size curves for granulometric types : granitic saprolites.

GG granular gruss G gruss CG clayey gruss

6.3.3 Variation of granulometry with granitic type

Table 6.3.iii shows that the granulometry of the granitic saprolites is related to the initial dimensions of the minerals in the fresh granite, at least in the earlier stages of development. Median grain sizes of the grusses increase with the coarseness of the parent granite, whilst the proportions of fines and fine sand show a corresponding decrease. As the size of the clay fractions increases, the differences between the median grain sizes of fine, medium and coarse grained granitic saprolites become less apparent.

Flageollet (1977) has reported similar relationships between gruss granulometry and the texture of the parent granites.

Table 6.3.iii Variation of granulometry with granitic type

Site	Depth(m)	Rock Type	CS	FS	Fines	Clay	Md
Redhouse	2.0	Fine grained biotite granite	64.6	20.7	14.6	3.6	445
Aikey Fair Stance	2.0	Medium grained biotite granite	65.9	18.6	15.4	0.5	451
Aberchirder	1.5	Medium to coarse grained biotite granite	84.7	18.1	7.0	1.9	1285
East Den	2.5	Coarse grained granite	78.5	11.1	10.4	1.2	1380
Glen Cat	4.0	Coarse grained biotite granite	82.6	9.1	8.3	2.2	1506

6.4 Basic Igneous saprolites

6.4.1 Variation in a section

The grain size variation in a single vertical section in weathered gabbro at Whitehills is shown in Fig. 6.4.i. The saprolite shows little variation in grain size with depth.

6.4.2 Variations between sections

The 15 sample sites are from medium to coarse grained basic rocks, mainly gabbros and norites (Fig. 6.4.ii). With one exception, the basic saprolites may be classed with the granites as granular grusses and grusses. Silt contents reach 20% but the majority of samples are below 10%. The median clay content (0.7%) is below that of the weathered granites (2.8%) and at several sites clay fractions are insignificant. Typical grain size curves are shown in Fig. 6.4.iii.

The weathered diorite at Gaval is quite distinct from the rest of the sites and may be classed as a clayey gruss.

6.5 Quartzitic metasedimentary saprolites

A total of 9 profiles in weathered quartzites and quartz schists were selected for particle size analysis. Of these, 6 are from the Mormond Hill group and the other 3 sites are from the Cullen and Durn Hill groups and a quartz schist at Balchimmy. In several cases, weathering is largely confined to zones of quartz-felspar-mica schist surrounded by bands or bosses of more pure and unweathered quartzites.

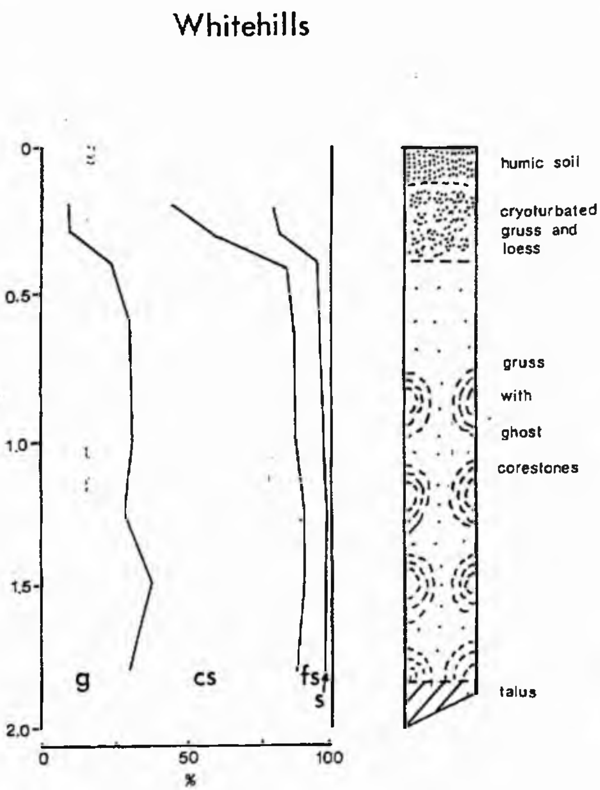


Fig. 6.4.i. Vertical variation in granulometry in a gabbroic weathering profile at Whitehills, Cabrach.

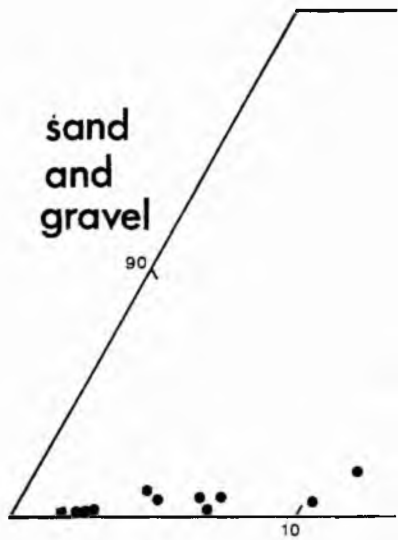
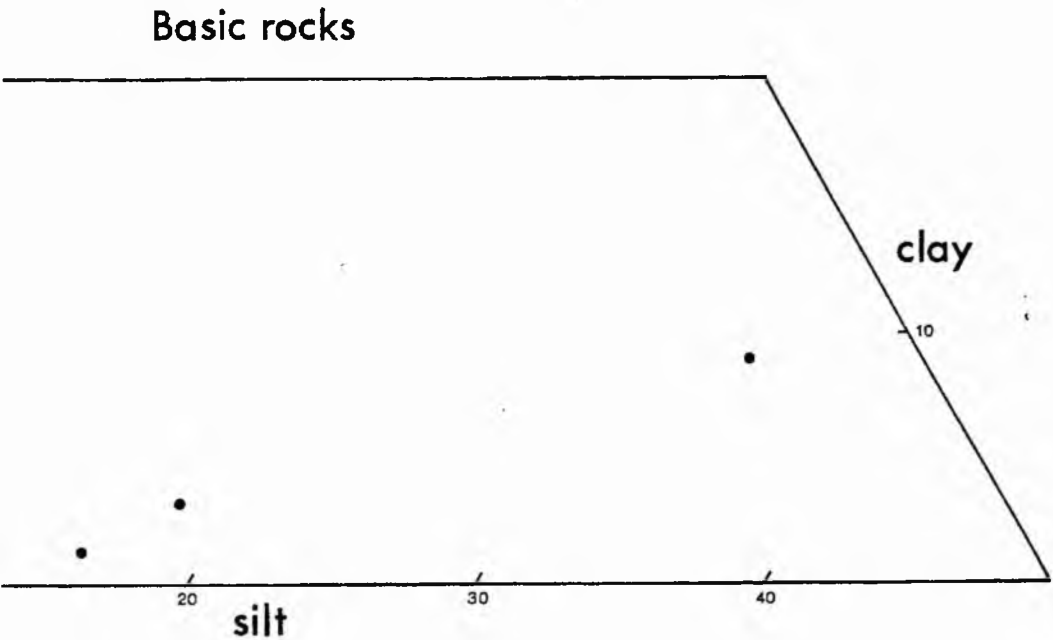


Fig. 6.4.ii.



Granulometry of the weathered basic rocks.

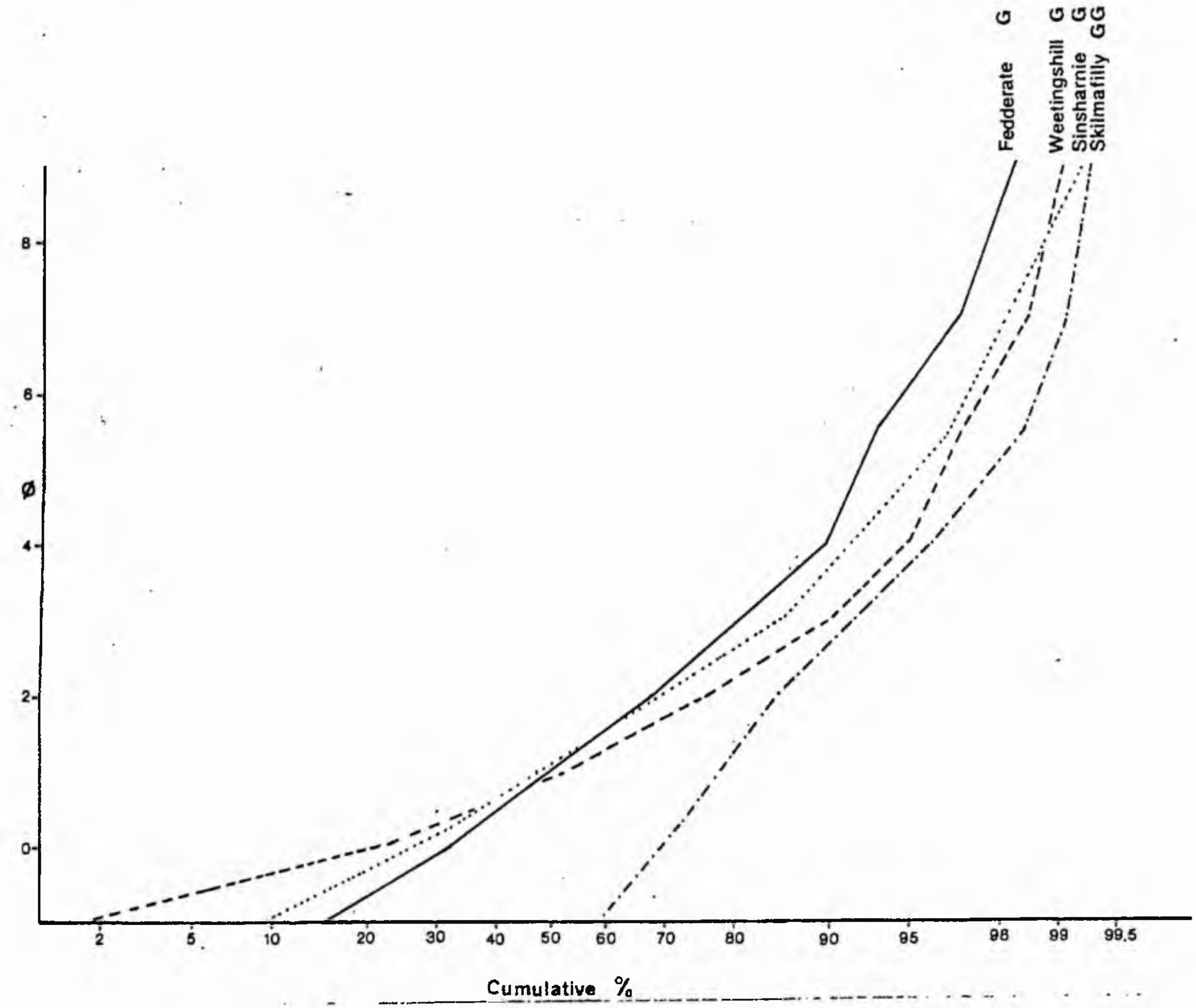


Fig. 6.4.iii. Grain size curves for granulometric types : basic igneous saprolites.

6.5.1 Variation within sections

The sections at Howe of Dens and Sunnyside were chosen to investigate the internal variations in grain size distribution in weathered quartzitic metasediments. Both sections possess heterogeneous lithology and include pure granoblastic quartzites, sugarey quartz metapsammites with minor feldspar and quartz schists with various amounts of feldspar, muscovite and niotite.

The weathering of these different rock types produces striking contrasts in grain size (Table 6.5.i; Fig. 6.5.i). Quartzites with a high degree of purity remain massive. Quartzites with small amounts of feldspar are often decomposed. The resultant saprolite has a high proportion of coarse quartz sand, giving median grain sizes greater than 400u, and clay fractions between 1 and 8%, depending on the original feldspar content (Howe of Dens S1S2; S1S3; S2 0.8; S3Z4: Sunnyside 3). Quartz schists with greater proportions of weatherable minerals give saprolites with higher clay and fines contents but the primary mode remains in the coarse sand size range. Bands of finer grained schistose rocks are often so highly altered that it is difficult to identify the original primary mineralogy. Such bands have very low median grain sizes, sometimes within the coarse silt range, and clay contents are as high as 30% (Howe of Dens S2m; S3Z1; S3Z2; S3Z3; S4 1.7: Sunnyside 4; 5; 6). The range of variation in these sections of heterogeneous lithology makes it impossible to give representative figures for the sections as a whole.

6.5.2 Variation between sections

Certain of the sections in weathered quartzitic rocks show

Table 6.5.i Howe of Dens - Granulometry

Sample	Rock Type	CS	FS	Fines	Clay	Md
S1S2	Quartzite with feldspar and minor muscovite	57.7	7.0	35.3	7.6	435
S1S3	Ditto	62.3	9.0	28.7	5.7	552
S1S4	Ditto	59.1	8.8	32.1	13.4	251
S2 0.8	Quartzite with minor feldspar	82.7	4.7	17.5	3.6	906
S2M	Schist. Quartz, feldspar, biotite and muscovite	45.6	16.1	38.5	5.8	194
S3Z1	Schist. Quartz, feldspar and biotite	35.9	16.4	47.7	6.3	82
S3Z2	Ditto	18.8	23.3	57.8	8.8	53
S3Z3	Feldspathic quartzite	35.8	14.4	49.8	13.7	62
S3Z4	Quartzite with minor feldspar and muscovite	70.5	6.9	22.6	4.8	901
S3B	Schist. Quartz, feldspar and biotite	68.5	10.8	20.7	6.4	756
S4 1.7	Schist. Quartz, feldspar and minor biotite	23.6	15.5	60.9	24.7	45
S4 2.3	Ditto	66.0	5.3	28.6	7.6	769

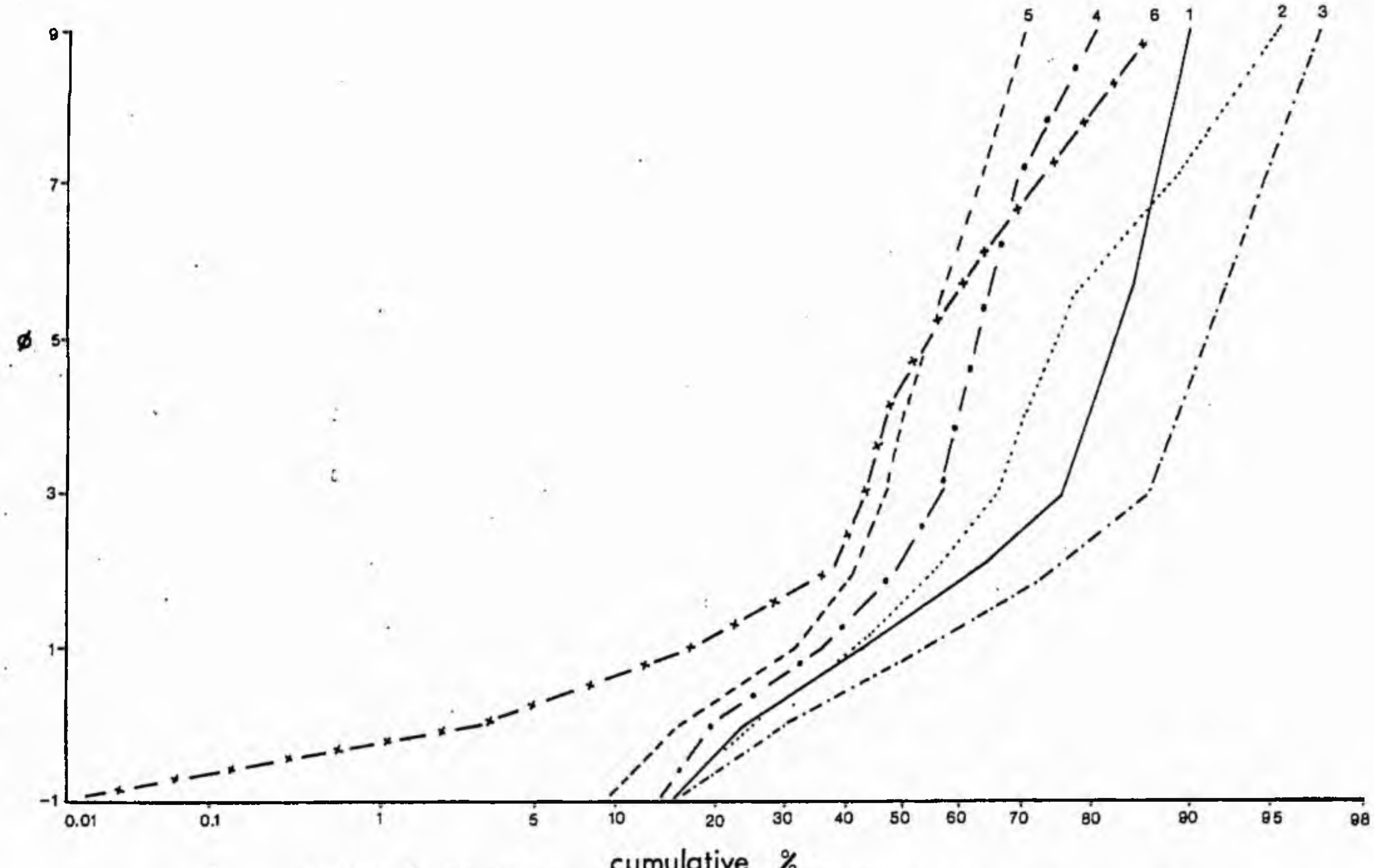


Fig. 6.5.i. Lateral variations in granulometry in a weathered quartzitic metasediment at Sunnyside, Dudwick. Samples taken from depths of between 1 and 2m over a distance of 30m.

much less internal variation in lithology and can be compared with each other. Grain size curves for 4 such profiles are given in Fig. 6.5.ii. The important differences in granulometry between the profiles are due largely to contrasting lithologies. The Mormond Quarry and Whitestones parent rocks originally contained higher feldspar contents and greater proportions of coarse quartz grains than the finer grained Rannas and Cairnbarrow quartzites. The low fines contents of the weathered Rannas and Cairnbarrow quartzites are a direct result of their originally low contents of unresistant primary minerals.

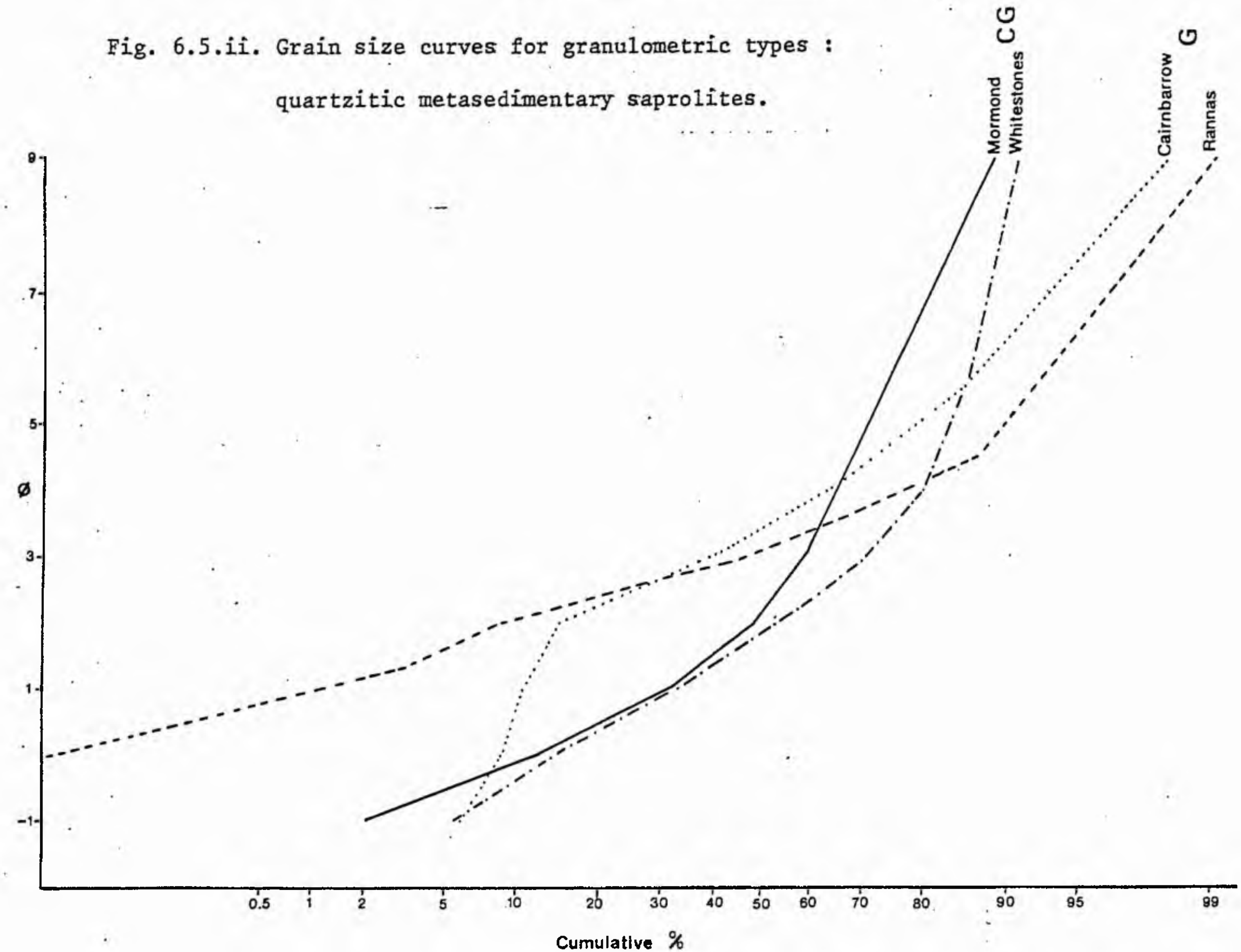
The dependence of the granulometry of the quartzitic saprolites on the content of non-quartz minerals creates problems in interpretation. The granulometric evolution of the saprolite will effectively cease, once the alteration of all available primary minerals is completed. In rocks predominantly composed of quartz, thorough alteration of other minerals can be achieved fairly quickly. Continued weathering may lead to Si mobilisation or to further changes in clay mineralogy but these changes will have little effect on the granulometry of the saprolite. Granulometry therefore offers a poor guide to the degree of evolution of quartzose saprolites.

6.6 Other metasedimentary saprolites

6.6.1 Variation within a section

The deep section in weathered biotite metapsammite at Northseat shows only modest vertical changes in granulometry (Fig. 6.6.i). The content of fines decreases downwards but the gradual coarsening with depth is interrupted by bands of blocky disintegration.

Fig. 6.5.ii. Grain size curves for granulometric types : quartzitic metasedimentary saprolites.



NORTHSEAT

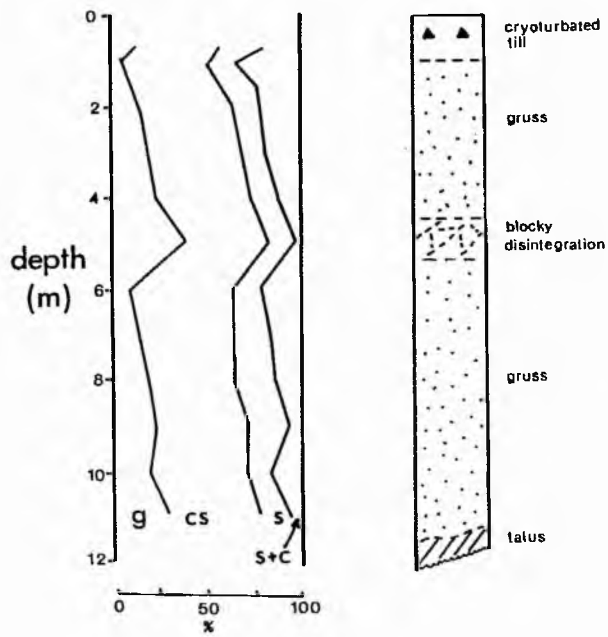


Fig. 6.6.i. Vertical variations in granulometry in a weathered biotite metapsammite at Northseat, Auchnagatt.

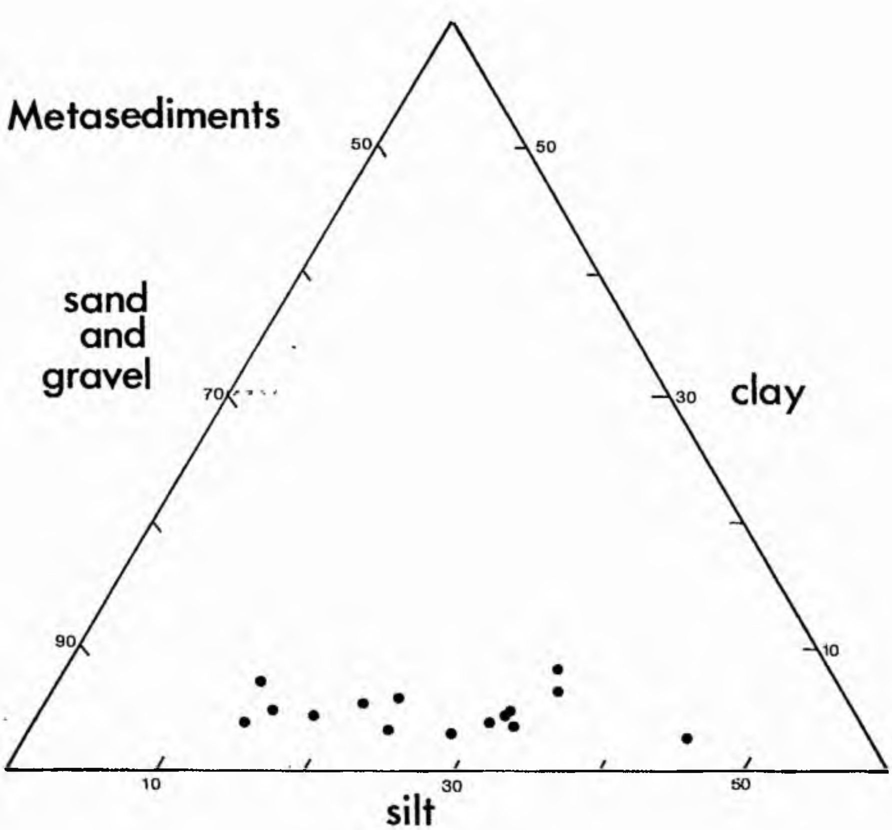


Fig. 6.6.ii. Granulometry of the weathered metasediments.
Note : Weathered metasediments below the Buchan Gravels are not plotted.

6.6.2 Variation between sections

A total of 16 sections in saprolites derived from other Dalradian metasediments were sampled for particle size analysis. The sections represent a wide range of predominantly fine to medium grained rock types (Table 6.6.i), yet the grain size distributions of the saprolites indicate a broad similarity in both the manner and stage of decomposition (Figs. 6.6.ii and iii).

The proportions of silt generally lie between 15 and 35% (Md 27.4%) whilst the clay contents range from 2.4 to 8.2% (Md 4.5%). The size of the sand fractions are more variable with several saprolites having predominant fine sand fractions (Boyne, Cairnhill and Montgrew). The median grain sizes of 10 of the 16 samples fall within the fine sand size range.

The samples of weathered schists and gneisses form beneath the Buchan Gravels at Moss of Cruden and Windyhills possess distinctive granulometries and are dominated by fines.

A notable characteristic of the weathered metasediments is that, unlike certain granitic and basic igneous saprolites, there are no samples which have very low fines and clay contents. In less thoroughly decomposed samples, such as Howford 1, Ythanbank and Bonnykelly, pebble and cobble sized fragments remain intact yet fines and clay contents already exceed 20% and 3% respectively. The transition from coherent rock to thoroughly decomposed saprolite can be observed in parts of the Howford and Northseat sections. The rock at the base of the profiles or within resistant bands is broken into angular blocks and alteration of the blocks is underway. The rock is discoloured by Fe and Mn staining, the

Table 6.6.i Weathered Metasediments - Granulometry

Site	Rock Type	CS	FS	Fines	Clay	Md
Auchintoul Moss	Quartz- mica schist	44.8	35.2	20.0	2.1	221
Boyne Quarry	Calc schist	20.3	40.3	36.1	4.8	101
Bonnykelly	Biotite meta-psammite	42.1	21.8	36.1	3.8	170
Bruxie	Quartz- mica schist	20.2	32.7	47.1	2.4	72
Cairnhill	Mica schist	32.3	40.3	27.4	3.5	122
Forglen	Macduff Slate	49.0	16.6	34.4	3.9	218
Hillfoot	Quartz- mica schist	45.1	19.2	35.6	4.1	197
Howford 1.3m	Quartz- mica schist	36.9	21.8	41.3	8.2	94
Kinmuck	Sericite- Chlorite schistose meta-pelite	63.5	16.3	20.2	7.1	481
Montgrew	Findlater Flags	27.5	45.2	27.2	5.8	155
Northseat	Biotite meta-psammite	62.7	14.5	22.8	4.5	603
Oldmeldrum	Mafic metapsammite	62.0	22.0	16.0	4.0	381
Toddlehills	Metapsammite	52.1	21.4	26.5	5.3	279
Wardhead	Quartz- mica schist	24.0	34.6	40.4	6.3	115
Ythanbank	Mafic metapsammite	31.1	37.6	31.3	3.0	108
Beneath the Buchan Gravels						
QX48	Pelitic schist	5.2	5.2	89.5	6.1	35
QX49	Pelitic schist	2.7	26.7	70.6	7.4	44
QX50	Knotted pelitic schist	3.1	3.2	94.7	22.2	26
PX61	Biotite gneiss	37.7	18.3	44.0	24.2	212

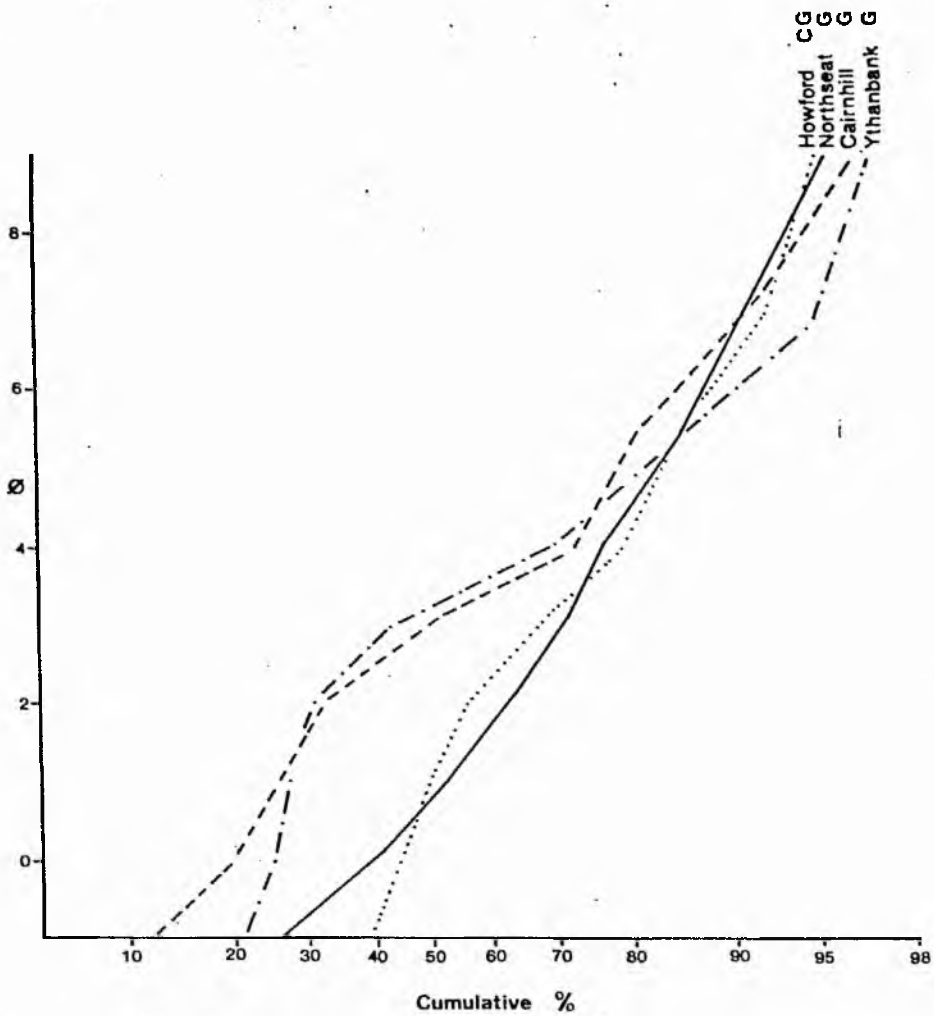


Fig. 6.6.iii. Grain size curves for granulometric types : other metasedimentary saprolites.

biotites often appear dulled or rusty and the larger feldspar grains may be soft under a penknife. Yet the blocks remain coherent and can only be broken by hand along the foliation planes with difficulty.

Further up the profile the rock fragments become smaller and more rounded and will crumble easily in the hand. Surrounding these isolated, coherent fragments is a matrix of predominantly sandy decomposed rock, usually including an important fines content. Small, crumbly rock fragments persist even at the top of the Howford weathering profile within a matrix of clayey sandy silt.

6.7 Granulometric variation in weathering profiles

6.7.1 Soils and saprolites

At a few sites, thin soils are found developed directly on weathered bedrock. Striking differences are apparent between the granulometry of the soils and the saprolitic parent material (Table 6.7.i).

Table 6.7.i Granulometry of soils and saprolites

Site	Rock Type	Soil			Gruss		
		CS	FS	Fines	CS	FS	Fines
Longhaven	Granite	75.1	10.7	14.2	96.9	1.7	1.4
Blackrigg	Granite	70.7	10.0	19.3	79.0	8.3	12.7
Silverford	Gabbro	44.7	31.5	23.8	66.1	27.2	6.7

The soils are immature and can be classified as incipient podzols or humic soils. In comparison with the subjacent grusses, the soils are greatly enriched in fines and deficient in coarse sand. Similar contrasts between soils and saprolitic parent materials have been noted by Dejou and Pedro (1967) and Eden and Green (1971). The relatively advanced alteration in the soils can be attributed to the action of organic acids in promoting mineral breakdown (Dejou and Pedro 1967).

6.7.2 Vertical variation

A number of deep sections in weathered rock show only modest changes in granulometry over considerable depths. Saprolites developed on a number of rock types have this characteristic but it is best displayed in the granitic granular grusses at Mill Maud, Glen Cat and Hill of Longhaven. Similar profiles are represented in boreholes which record gradational changes from decomposed to hard rock.

Other profiles have more complex granulometries. In many igneous rocks, evidence of vertical change is obscured by horizontal variations caused by corestone development. In weathered metasediments, granulometric variation is often a result of rapid changes in rock type within a section. Nevertheless samples from similar locations, such as joint planes, or from similar rock types at different depths in a section often have comparable granulometries. Good examples of similar particle size distributions at different depths can be found in the complex weathered metasediments at Oldmeldrum and Ythanbank. Such profiles correspond with the thick alterations of fresh and weathered rock encountered in many boreholes.

Vertical uniformity in grain size characteristics has been reported from deep sandy saprolites in several other parts of the world (Lumb 1962; Dixon and Young 1981; Eggler et al 1969). The modest changes in granulometry with depth found in the saprolites of north-east Scotland imply that any material removed from the profile by glacial erosion was similar to that now surviving in the truncated profiles. However it remains possible that a thin layer of more highly weathered material has been removed from the profiles (Basham 1974), although no remnant of such a surface layer has been observed.

6.7.3 Horizontal variations

Many sections show considerable internal variation in grain size characteristics. In extreme cases, such as the Howe of Dens and Daugh of Cairnbarrow sections, it becomes difficult to give figures which typify the granulometry of the whole section. Often this variability is a result of abrupt changes in the texture and mineralogy of the parent rock. However significant horizontal variation in grain size characteristics also occurs in saprolites derived from homogeneous rocks.

The amount of lateral variation in granite grusses can be considerable:-

Section	No. of samples	Md Range
Bennachie C.P.	13	96-550
Cruden Moss	10	351-521
Braeside	6	191-386

Other homogeneous rock types have not been sampled for lateral variation in grain size characteristics but observations suggest that many sections possess marked internal variability. Similar findings have been reported from decomposed granites in Hong Kong, where horizontal variation in grain size parameters is of the same order as vertical variation (Lumb 1962).

The scale of the variation makes it unlikely that single samples will provide a wholly accurate representation of the granulometry of a section. Nevertheless, single samples do give an adequate indication of the grain size distribution of grusses. Analyses of fines contents of paired samples from each of 15 sections in granitic and gabbroic grusses showed average differences of only 1.8% between the two values. Variations of this order will not affect the classification of grusses by grain size.

The problem becomes more acute in saprolites with higher fines content:-

Section	% Fines Range
Howe of Dens	17.2 - 60.9
Mormond Quarry	18.5 - 52.1
Sunnyside	11.3 - 53.8
Bennachie Car Park	15.5 - 47.0

Multiple samples are required to characterise the granulometry of such varied sections.

6.8 Granulometry and Rock Type

The granulometry of the saprolites varies with rock types. The granitic, basic and metasedimentary saprolites form separate granulometric populations (Fig. 6.8.i) with contrasting fines and clay contents:-

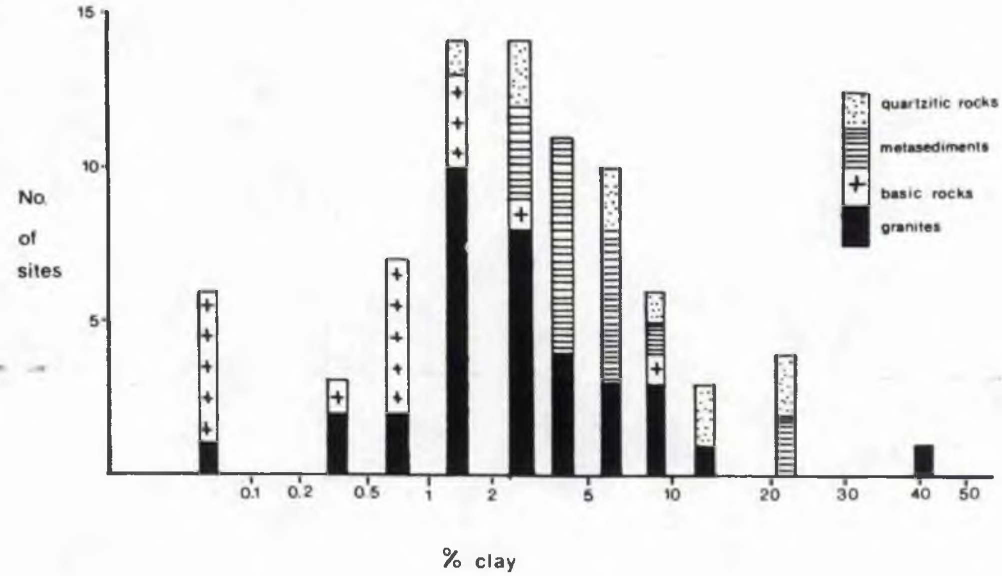


Fig. 6.8.i. Clay contents of weathered rocks and lithology.

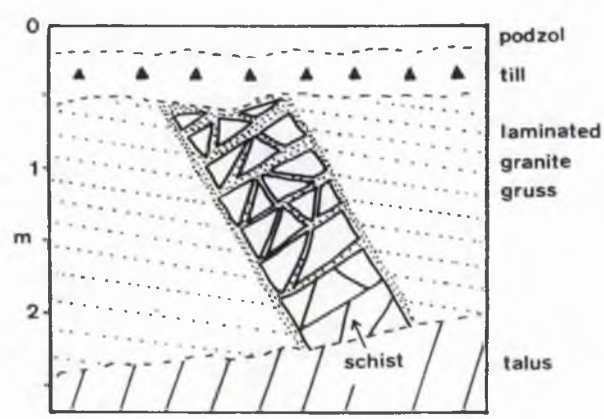


Fig. 6.8.ii. Contrasting styles of disaggregation of granite and schist at Kingsford, Howe of Alford.

	Median contents (%)	
	Fines	Clay
Metasediments	27.4	4.5
Granites	14.4	2.8
Basics	6.7	0.7

Distinct styles of disaggregation are indicated and the resultant saprolites possess different mechanical properties. The weathered quartzitic rocks represent a special case where granulometry is greatly influenced by the amount of weatherable minerals in the parent rock.

The initial disintegration of granitic and gabbroic rocks produces a polymineralic granular gruss. In the Insch gabbros, this process has been termed "granular disintegration" (Basham 1974) and the term is equally well applied to many granites in the early stages of decomposition. Yet whilst the style of initial disintegration is similar in both acid and basic igneous rocks, it is clear that the basic granular grusses have significantly lower fines contents.

The reason for this contrast probably lies in the differing stabilities of primary minerals in the two rock types at the early stages of alteration. In granites, plagioclase is generally the first mineral to be affected (Goldich 1938; Milne 1952), whereas, in gabbroic rocks, plagioclase is initially stable and biotite is the most altered mineral (Wilson 1967; Basham 1974). As plagioclase is more abundant in granites than biotite is in gabbro, equivalent chemical alteration will produce higher fines contents in the granitic granular grusses.

The initial disintegration of metasediments is distinct in style from that of igneous rocks. The metasediments first break up into angular blocks. Alteration then penetrates along the fractures and produces thin seams of decomposition containing significant fines fractions. These different styles of disintegration are well illustrated at Kingsford, where a band of fine grained quartz mica schist cuts medium to coarse grained two-mica granite (Fig. 6.8.ii). The schist has undergone "blocky disintegration" (Basham 1974) and decomposition is confined to the fracture planes and along the contact. Disintegration of the granite has been thorough and few large fragments remain. The seams of decomposed schist have much higher contents of fine sand and fines than the adjacent granite granular gruss:-

	G	CS	FS	F
Schist	54.7	16.1	14.0	15.2
Granite	75.6	19.5	2.4	2.5

These differences in granulometry between igneous and metamorphic rocks are also clear in comparisons between sections (Fig. 6.8.i).

These differences are partly a result of textural contrasts between the parent rocks. The granitic and gabbroic rocks are largely medium to coarse grained and contain only modest amounts of silt-sized primary minerals. The metasediments are predominantly pelitic and the original sediments must often have contained large proportions of fine particles. Due to their generally finer texture, disaggregation of the metasediments will tend to produce saprolites with lower median grain sizes and higher fines contents.

However the grain size characteristics also reflect the contrasts between the granular disintegration typical of the granitic and gabbroic rocks and the blocky disintegration typical of the metasediments. In igneous rocks affected by granular disintegration, limited chemical alteration is sufficient to promote thorough rock breakdown (Isherwood and Street 1976). Indeed, in certain cases it appears that the disintegration may be purely mechanical in nature. The granulometry of the Hill of Longhaven section, with very low fines contents and almost insignificant amounts of clay, indicates an extremely limited degree of chemical alteration. The degree of alteration seems insufficient to have produced the thorough disintegration of more than 6m of granite. Other granitic and gabbroic granular grusses contain small clay contents and are in the first stages of alteration. However disaggregation extends down to at least 10m in section and vertical gradients in alteration are only weakly developed. In these cases, chemical alteration seems to be superimposed on or subordinate to mechanical disintegration of the rock. Other writers (Duffaut 1957; Dejou and Pedro 1967; Folk and Patton 1982) have also argued for the initial mechanical breakdown of granites into gruss.

The style of initial disintegration is probably dependent on the way in which residual stresses are released from the rocks. In the finer grained metasedimentary rocks, residual stress is largely relieved by the fracturing involved in blocky disintegration. Alteration then acts on fragmented rocks which are effectively destressed. In contrast, igneous rocks may retain considerable levels of stress even after jointing (Friedmann 1972). Modest expansion of minerals on alteration (Isherwood and Street 1976; Bustin and Matthews 1979) releases inter-granular stresses and propogates microcracks through the rock (Bisdom 1967), thereby causing disintegration. In igneous rocks with high levels of residual stress, particularly coarse grained varieties, this microfissuration may be triggered off by denudational unloading (Folk and Patton 1981) before chemical alteration has begun.

With increasing alteration, the granulometric differences between rock types become less clear, although the metasediments continue to have relatively high fines contents. In the most granulometrically-evolved samples, those from beneath the Buchan Gravels, grain size characteristics are dependent on the content and texture of quartz particles in the parent rock. Pelitic schists at Windyhills are reduced to their constituent silt-sized particles. At Moss of Cruden, the gneissic and dioritic weathered bedrock is bi-modal, with a primary mode given by fines neoformed from the non-resistant primary minerals and a secondary mode representing the residual sand-sized quartz.

6.9 Granulometric Types

Although rock type has had a major influence on the granulometry of the saprolites, much of the variation within the main lithologic groups cannot be explained by differences in texture and mineralogy. The range of variation within lithologies is great. The granite grusses have fines contents between 0.8 and 75% and fines dominate several samples from the quartzites and from beneath the Buchan Gravels. Clay contents show similar wide variation, ranging from trace amounts to more than 40%. These variations reflect differences in the stage or degree of weathering.

The size of the clay fraction is of special importance as an indicator of the degrees of chemical alteration (Wambeke 1962; Seddoh 1973), as it is largely composed of the products of alteration, the clay minerals. With progressive alteration the fines content will rise with a corresponding decrease in the median grain size. As granulometry is linked to alteration, the grain size characteristics can be used to identify different types of weathering covers.

However the samples form a continuum of granulometric characteristics. Due to the continuous nature of the weathering process and to the fact that the profiles are in varying stages of truncation, no clear breaks can be identified in the aggregated grain size data (Fig. 6.8.i). Yet the range of granulometry is so great as to indicate wide differences in the degree of alteration of the samples. It is therefore necessary to use rather arbitrary and descriptive groupings in order to compare granulometry with other indicators of alteration.

Established French terminology (Flageollet 1977) is readily applicable to the granitic and basic saprolites and to most quartzites. However allowance must be made for the finer texture and higher fines contents of metasedimentary saprolites at equivalent stages of alteration. Moreover certain saprolites have considerably higher clay and fines contents than the granitic and gabbroic clayey grusses and must be allocated to a fourth group, termed clayey alterites.

The granulometric types are defined as follows:-

Type 1 Granular Grusses

This type includes coarse grusses with median grain sizes above 1000u, fines contents of less than 15% and low clay contents. The non- quartzitic metasediments are not represented in this type.

Type 2 Grusses

Median grain sizes are reduced below 1000u and fines contents are increased to between 15 and 25%. Comparable weathering in the metasediments produces finer grusses with median grain sizes below 500u and fines contents between 20 and 35%. Clay fractions are below 6% in all rock types.

Type 3 Clayey Grusses

In the weathered granites and quartzites median grain sizes are below 1000u and fines contents are above 25%. In the metasediments median grain sizes are below 500u and fines contents are above 35%. Clay contents are elevated but remain below 10%.

Type 4 Clayey Alterites

In clayey alterites the sand mode is no longer dominant. Median grain sizes are below 250u, fines contents are above 35% and clay contents are substantial, in excess of 10%.

The grouping of the sampled sections according to granulometric type is presented in Appendix 1.

6.10 Comparison with other areas

Studies of the weathering of granites in other areas and under different environments allow comparisons to be made with the granite grusses of north-east Scotland. Unfortunately the weathering of other rock types has received little attention and only indirect comparisons can be made.

Type 1 granulometries have been described from various parts of France (Dejou and Pedro 1967; Seddoh 1973; Flageollet 1977) and are recognised in classifications of weathered rocks for engineering purposes (Dearman et al 1978). Type 1 granulometries are characteristic of initial disaggregation at the base of profiles (Millot 1964; Seddoh 1973; Dearman et al 1978) or of rocks in the early stages of chemical alteration (Dejou and Pedro 1967; Flageollet 1977).

Type 2 grusses correspond with the sandy deep weathering type identified in many parts of Europe by Bakker (1967). The clay contents are similar to those of granite grusses in the Sudeten Mountains (Jahn 1974), the Karkonosze (Borkowcka and Czerwinsky 1973), Limousin (Flageollet 1977), the Massif Central (Collier 1961) and Dartmoor (Eden and Green 1971). These grusses are generally held to be a product of temperate weathering environments (Bakker 1967; Tardy et al 1973; Eden and Green 1971; Furtado 1974).

The small number of Type 3 clayey grusses represent a more advanced stage of alteration. Clay contents are similar to those of rubified grusses in Limousin (Flageollet 1977) and the Morvan (Seddoh 1973) but fall short of those in Mediterranean (Nettleton et al 1970; Penven 1980; Dixon and Young 1981) and sub-tropical (Eden 1971) environments.

The Type 4 clayey alterites are comparable in granulometry with older alterites in the Morvan (Seddoh 1973), the Ardennes

(Alexandre 1958) and Belgium (Gullentops 1954).

6.11 Summary

Analysis of samples from 78 separate exposures shows a wide range of granulometric characteristics. Within profiles, granulometry shows only modest changes with depth. Between profiles, granulometry varies according to rock type and reflects different degrees of chemical alteration. At the initial stages of weathering, the granitic, basic and metasedimentary saprolites form distinct granulometric populations. These populations partly reflect the different textures and mineralogies of the parent rocks. However sharp contrasts in the styles of initial breakdown between the granular disintegration typical of the granitic and basic igneous rocks and the blocky disintegration typical of the metasediments also strongly influence grain size characteristics. The samples form a granulometric continuum spanning saprolites at widely different stages of alteration. The samples can be grouped into four granulometric types on the basis of French terminology.

CHAPTER 7 Major Oxide Contents of the Weathered Rocks

7.1 Introduction

The geochemistry of selected sites has been investigated using major oxide analysis. Evaluation of the amount of chemical change between the parent rock and its saprolite allows the degree of alteration to be established (Brock 1943; Ruxton 1968). Estimates may also be made of the rate of alteration of different primary minerals (de la Roche et al 1966; Dejou et al 1974). In this study, major oxide analysis was used primarily to investigate the degree of chemical alteration in certain typical saprolites, in order to see whether differences in granulometry and clay mineralogy are also reflected in the geochemistry.

A major constraint on this type of analysis is that fresh rock is available for comparison with the saprolite samples. In many exposures, this constraint is not satisfied. Only rarely can a complete transition from weathered to fresh rock be observed in sections. Moreover, although bands of hard rock occur commonly in profiles, close examination will often show that these bands are mineralogically distinct from the parent rocks of the adjacent saprolites. These problems are particularly acute in metamorphic saprolites, where rock composition is often highly variable.

7.2 Methods

The major oxide contents of the samples were analysed using well-established techniques, including atomic absorption spectrophotometry and visible spectrophotometry. Contents of Na, K, Ti and P were determined by the $HF/HClO_4$ method of decomposition

(Shapiro 1975). Al, Fe, Mn, Mg and Ca were determined by the $LiBO_2$ fusion technique (van Loon and Parissis 1969). Si was determined by spectrophotometry after NaOH fusion in nickel crucibles (Shapiro 1975). These methods are described collectively by Batchelor (1980).

7.3 Granite saprolites

The vertical changes in geochemistry in the Cairngall, Longhaven and Mill Maud sections are often irregular (Fig. 7.3.i). The Cairngall clayey gruss is the most highly altered rock and shows the greatest internal consistency, although total Fe oxide contents are erratic. The geochemistry of the Longhaven and Mill Maud sections is more varied, probably as a result of internal variations in the composition of the parent rock. However the irregularity must also be a product of different degrees of alteration, for the relatively large losses of soluble bases at 0.5 and 5m in the Longhaven section correspond with granulometric differences, with higher fines and clay contents in these samples. The geochemistry of the Longhaven and Mill Maud sections indicates no simple relationship between major oxides and depth, in contrast to the profile examined by Moore and Gribble (1980) at Stirling Hill Quarry, Peterhead.

These vertical changes and the differences in geochemistry between grusses and parent rocks in other sections (Table 7.3.i) demonstrate important differences in mobility between the major oxides. SiO_2, Al_2O_3 and K_2O are stable in the less altered profiles. Total Fe oxide contents are variable, due to movement of Fe within the profiles. MgO is depleted and Na_2O and CaO show major losses. H_2O+ content is considerably increased.

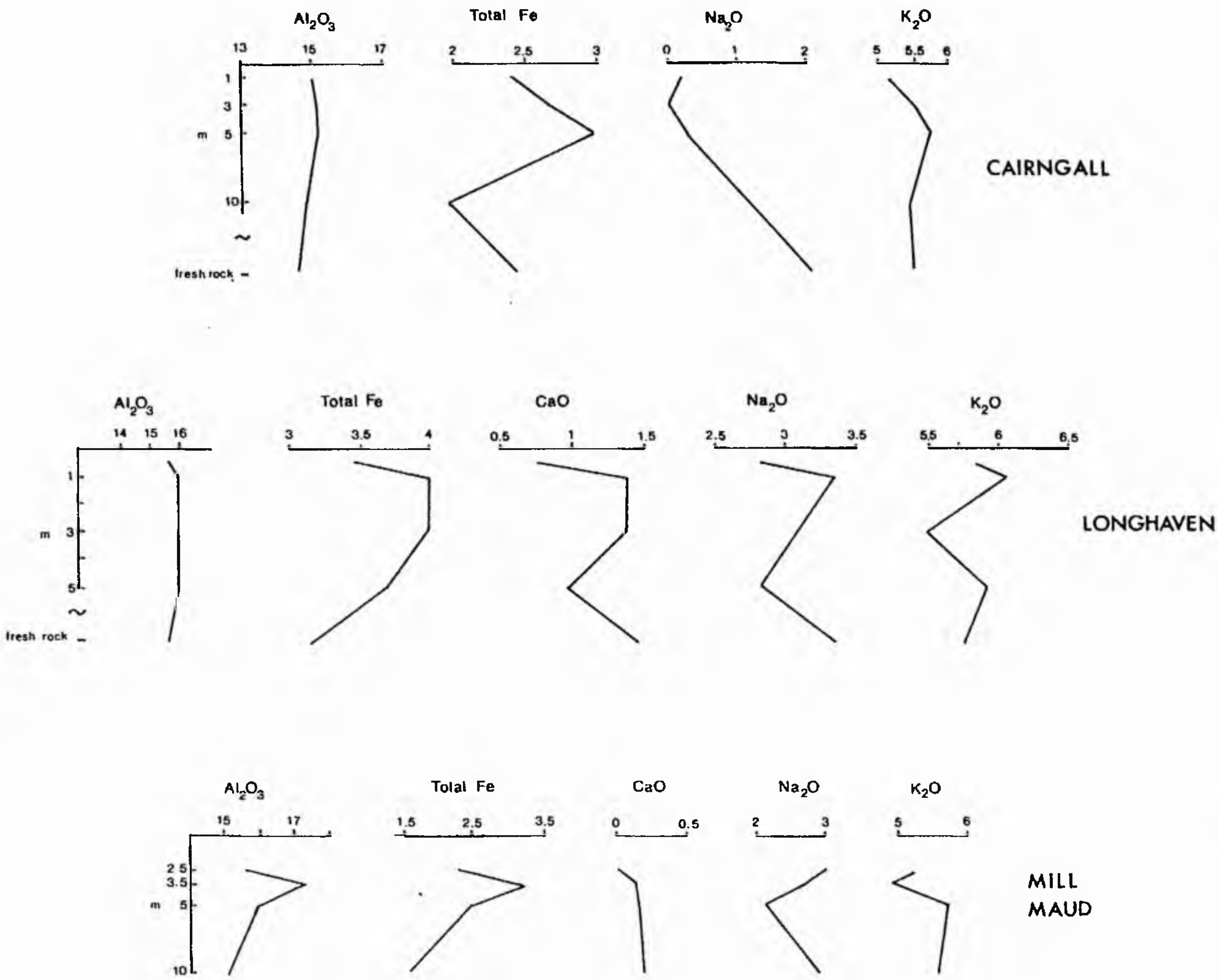


Fig. 7.3.i. Vertical variations in major oxide percentages in 3 granite weathering profiles

Table 7.3.i Major oxides for granite grusses and parent rocks

Section	Depth (m)	SiO_2	TiO_2	Al_2O_3	Total Fe	MnO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	Total
Bennachie C. P.	1.5*	78.01	NT	13.73	1.90	ND	0.11	.07	.14	3.0	.01	2.82	99.77
	2.0	80.79	NT	13.95	0.90	.06	0.17	.07	.13	3.0	.08	1.37	100.70
	2.5	78.04	NT	14.16	0.30	.02	0.09	.05	.10	2.7	.12	3.33	98.91
Coull Granite (Read 1927)		67.9	NT	15.0	2.29	NT	1.44	2.82	4.33	3.04	NT	NT	-
Blackrigg	1.2	71.56	.50	14.9	3.71	NT	.44	.12	1.58	4.65	NT	1.2	98.65
	Hard Rock	69.88	.54	14.6	3.60	NT	.75	1.48	2.75	5.0	NT	0.2	98.8
Cairnlea	1.2	70.58	.42	15.08	3.43	NT	.36	.08	1.13	5.3	NT	3.4	99.78
	Hard Rock	70.98	.45	14.06	3.61	NT	.39	1.05	2.83	4.82	NT	0.8	98.98
Cruden 4	1.5	69.55	.59	16.78	4.33	.03	.53	.37	1.81	3.56	.20	2.46	100.22
Cruden 5	1.5	74.5	.51	19.20	1.02	.02	.59	.41	.20	1.13	.21	1.77	99.54
Mormond N.S.	1.1	76.08	.30	14.70	1.10	ND	.51	.20	1.22	2.71	.20	3.28	100.30
QX115 (beneath Moss of Cruden flint gravels)	24	49.7	3.6	25.20	7.42	.09	.49	.49	.05	.45	.06	13.14	100.69

GG- Granular Gruss * Rubefied zone ND- Not detected NT- Not treated

G - Gruss

CG- Clayey Gruss

CA- Clayey Alterite

Ordering the major oxides by decreasing mobility establishes the following sequence:-

$$Al_2O_3,\ SiO_2,\ K_2O < MgO < Na_2O < CaO$$

This alteration sequence is similar to those of a number of other studies of granite grusses (Collier 1951; de la Roche et al 1966; Dejou 1967).

The degree of alteration varies markedly between the sections. Average losses of the more mobile bases, CaO, Na_2O and MgO, show pronounced differences (Table 7.3.ii).

Table 7.3.ii Average % loss of CaO, Na_2O and MgO between parent rock and saprolite

Longhaven (GG)	Cairnlea (G)	Blackrigg (GG)	Cairngall (CG)	Bennachie Car Park (CG)
5.9	53.4	58.6	70.5	95.4

The granular gruss at Longhaven is at an early stage of chemical alteration, well below that shown by other grusses in the Peterhead granite (Moore and Gribble 1980). The saprolites at Blackrigg and Cairnlea are more highly altered, with losses of more than 90% of CaO and about 50% of Na_2O. However losses of MgO are still low and levels of Al_2O_3 show only slight increases. Levels of Na_2O and MgO also remain high in the Cruden and Mormond North Side grusses.

In the Cairngall profile, losses of Na_2O and MgO are high, CaO is totally depleted, K_2O is slightly reduced and Al_2O_3 content is increased. The Bennachie clayey gruss is highly altered. Although no mineralogically similar fresh rock exists in this section, the figures may be compared with those for another Red Granite (Bisset 1932), the Coull granite (Read 1927). Losses of soluble bases are very high. Total Fe is seriously depleted in parts of the section and concentrated within rubefied zones. Levels of K_2O remain high, however, as a result of the continued presence of K-felspars in the weathered granite (Wilson et al 1981). The geochemistry of the QX115 sample from beneath the Buchan Ridge gravels suggests that the parent rock was dioritic in composition, with relatively high contents of soluble bases. These bases have been substantially depleted by alteration, although levels of CaO and MgO remain significant.

7.4 Basic igneous saprolites

Two sections in basic igneous saprolites were investigated, Fedderate and Silverford. The parent rock for the gruss at Fedderate is norite (Smith 1933), although the comparative fresh rock sample from a hard rock band in the section is nearer a diorite in composition. The parent rock at Silverford is a gabbro.

Chemical alteration is modest in both profiles (Table 7.4.i). Average percentage base losses are 19.0% in the Silverford granular gruss and 31.1% in the Fedderate gruss. SiO_2 is depleted whilst Al_2O_3 shows a slight gain. K_2O is stable. Levels of MgO, CaO and Na_2O are all significantly reduced. The following sequence in order of decreasing stability is indicated:-

$$K_2O < SiO_2, Al_2O_3 < MgO < CaO, Na_2O$$

Table 7.4.i Major oxides for basic igneous grusses and parent rocks

Section	Granulometric Type	Depth (m)	SiO_2	TiO_2	Al_2O_3	Total Fe	MnO_2	MgO	CaO	Na_2O	K_2O	P_3O_5	H_2O^+	Total
Fedderate	G	1.0	50.31	1.82	20.28	12.51	.18	4.52	4.66	1.59	.55	.63	4.69	101.74
		Hard Rock	58.75	1.71	17.83	5.71	.19	5.30	8.0	2.52	.55	.46	.59	101.63
Norite	Smith(1933)		47.50	3.73	19.56	9.74	.62	5.67	8.76	3.35	.46	.07	.49	100.39
Silverford	GG	0.7	50.0	.92	16.76	9.94	NT	6.60	8.44	1.98	.56	NT	4.2	99.41
		Hard Rock	51.32	1.44	15.93	10.25	NT	7.31	11.04	2.60	.57	NT	-1.2*	99.26

* Fe oxidisation

7.5 Quartzitic metasedimentary saprolites

The geochemistry of the weathered quartzitic metasediments is complex. Only certain sections or parts of sections can be classified on the basis of their chemical composition as quartzites sensu stricto (Table 7.5.i) and several samples differ greatly from the figures for a typical Mormond Hill Quartzite given by Gribble (1965). The high values of residual total Fe oxides, MgO and TiO_2 in certain samples from Howe of Dens and White Cow Wood suggest that the parent rock contained important amounts of mafic minerals.

Assessment of the degree of chemical alteration of the quartzitic metasediments is made difficult by the common heterogeneity of the rocks and by the absence of fresh rock, apart from pure quartzites, from the sections.

In all samples levels of CaO and Na_2O are low and H_2O^+ contents are high. Comparison with the Type Quartzite at Ardlethen indicates important losses in total Fe oxides, K_2O and MgO and attendant gains in Al_2O_3. In saprolites with residual SiO_2 contents below 70%, the contents of total Fe and MgO can be relatively high. This may perhaps imply a lesser degree of alteration than in the more quartzose saprolites. However quartzitic and quartz-feldspar-biotite saprolites are juxtaposed in the Howe of Dens section, demonstrating that differences in total Fe and MgO content are largely due to original variations in the parent rocks.

7.6 Other metasedimentary saprolites

The samples of weathered metasediments are amongst the most highly altered saprolites formed on these rocks. The weathered pelitic schists (QX48, QX50) from beneath the Windyhills gravels

Table 7.5.i Major oxides for weathered quartzitic metasediments

Section	Granulometric Type	Depth (m)	SiO_2	TiO_2	Al_2O_3	Total Fe	MnO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	Total
Howe of Dens														
S3 B	CA	1.5	64.4	.99	17.4	6.76	.02	1.27	.07	.03	2.8	.09	5.5	99.33
S3Z3	CG	1.3	85.8	.16	8.7	1.10	ND	.19	.06	.05	1.58	.04	2.8	100.48
S3Z4	CG	1.5	73.5	.07	16.7	.94	.01	.14	.07	.05	2.80	.05	4.96	99.29
S4	CA	1.7	55.4	1.38	24.7	5.62	.02	1.05	.07	.02	2.44	.06	9.0	99.76
Whitestones	CG	1.0	89.3	NT	7.46	1.1	ND	.13	.07	.14	.57	.03	1.16	99.96
		1.5	89.5	NT	8.04	.20	ND	.13	.10	.11	.18	.19	1.94	100.39
		2.0	90.77	NT	5.23	1.31	ND	.13	.07	.10	.53	ND	.66	98.90
		2.5	85.2	NT	10.87	.70	ND	.18	.10	.14	1.31	.43	1.57	100.57
Drinnies Wood	CA	2.0	68.3	.82	19.5	2.89	ND	.44	.72	.14	1.48	.91	5.23	100.43
Sunnyside	CG	0.7	92.06	.20	5.49	.51	ND	.15	.07	.10	.63	.16	.83	100.21
Mormond Quarry	CG	1.4	73.75	.17	19.3	1.29	ND	.24	.07	.15	1.24	.02	3.72	99.90
Mormond Hill Quartzite Ardlethen (Gribble 1965)			81.38	.79	7.8	2.67	.02	.44	.29	.79	4.47	.04	.64	99.33

Table 7.6.i Major oxides for other weathered metasediments

Site	Granulometric Type	SiO_2	TiO_2	Al_2O_3	Total Fe	MnO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	Total
Howford	CG	56.1	.69	21.3	8.41	.24	1.23	.23	.18	3.84	.13	8.14	100.49
PX61	CA	74.6	.41	16.62	2.41	.02	.77	.19	.12	1.35	.08	3.83	100.40
QX48	CA	65.2	NT	24.65	3.20	.01	.69	.16	.46	1.95	.05	2.62	98.99
QX50	CA	68.7	NT	22.68	4.46	.01	.18	.10	.55	.72	.16	3.63	101.19
Fyvie Schist at Woodhead		NT	NT	12.18	3.18	.02	1.08	.36	2.81	1.88	NT	NT	-
Fyvie Schist at Gight (Gribble 1965)		60.36	1.18	19.18	6.96	.12	2.51	1.54	2.41	3.08	.16	2.31	99.89
Weathered qtz-schist clasts, Buchan Ridge Gravels, Whitestones Hill. (Koppi 1977)		82.7	NT	11.7	.44	NT	ND	ND	NT	NT	NT	NT	-
		86.9	NT	8.9	.45	NT	.03	ND	NT	NT	NT	NT	-
		79.8	NT	13.4	.57	NT	.05	.12	NT	NT	NT	NT	-

may be compared with nearby outcrops (Table 7.6.i). The alterites show heavy losses in MgO, CaO and Na_2O and significant enrichment in Al_2O_3. No comparable fresh rocks are available for the Howford quartz-mica schist and PX61 biotite gneiss saprolite samples. However levels of CaO and Na_2O have clearly been substantially reduced, although MgO remains significant due to the presence of residual biotite.

7.7 Discussion

Consideration of the levels of chemical change revealed by losses of the more soluble bases, MgO, CaO and Na_2O, indicates different degrees of alteration. The sampled granite saprolites show a sequence of progressive alteration, ranging from the slightly altered Longhaven granular gruss to the advanced alteration found in the Bennachie clayey gruss. Differences in the composition of parent rocks make comparisons between rock types hazardous. However the sampled saprolites may be tentatively grouped on the basis of the thoroughness of removal of the soluble bases (Table 7.7.i).

The Group 1 saprolites show only slight base losses and are in the early stages of alteration. Group 2 saprolites are largely depleted of CaO but Na_2O and MgO contents remain high and the total level of chemical alteration is modest. Group 3 includes samples with SiO_2 contents below 70% whose parent rocks originally contained relatively high levels of basic oxides. Oxide losses have been substantial but levels of MgO often remain significant due to the presence of little-altered biotite. Group 4 saprolites are highly altered and basic oxides are largely depleted.

Table 7.7.i Weathering groups based on losses of soluble bases and their relation to granulometric types

	Granites	Basics	Quartzites	Metasediments
Group 1 (Slight losses)	Longhaven (GG)	Silverford (GG)		
Group 2 (Major losses of CaO, modest losses of Na_2O and MgO)	Blackrigg (GG) Cairnlea (G) Cruden 4 (G) Cruden 5 (CG) Mill Maud (GG) Mormond N. S. (GG)	Fedderate (G)		
Group 3 (Major losses but MgO remains significant)	Cairngall (CG) QX115 (CA)		Drinnies Wood (CA) Howe of Dens S3b, S4 (CA)	Howford (CG) PX61 (CA) QX48 (CA) QX50 (CA)
Group 4 (Severe losses)	Bennachie Car Park (CG)		Howe of Dens S3Z3, S3Z4 (CG) Mormond Quarry (CG) Sunnyside (CG) Whitestones (CG)	

Comparison with published figures for other areas shows that the moderate levels of chemical change in the Group 1 and 2 granitic saprolites are of similar magnitude to those of weathered granites in several parts of France (Collier 1951; de la Roche et al 1966; Dejou 1967).

The Group 3 and 4 saprolites represent a more advanced stage of chemical alteration. Unfortunately the lack of comparative fresh rocks for samples in these groups prevents assessment of the extent to which Si and Al have been mobilised. The intensity of alteration in these saprolites is less than that shown by kaolinised quartz schist cobbles in the Buchan Gravels at Whitestones Hill (Table 7.6.i.: see also Koppi 1977).

CHAPTER 8 Clay Mineralogy of the Weathered Rocks

8.1 Introduction

Clay minerals in weathered rocks may be either inherited from the parent rocks or neoformed from the primary minerals (Millot 1970). Inherited clay minerals include clays from rocks of sedimentary origin and clays resulting from the hypogene alteration of crystalline rocks. Neoformed clays are derived directly from the weathering of the primary minerals by meteroic waters close to the earth's surface.

The mineralogy of neoformed clays reflects the interaction of many factors, including lithology, drainage, topography, climate and time (Barshad 1959; 1966). Studies of the clay mineralogy of weathered rocks in relation to geomorphological problems generally attempt to isolate the factors of climate and time (Bakker 1967; Barrière 1971; Brewer and Walker 1969; Coinçon et al 1976; Godard 1972; Nieuwenhuis 1971; Seddoh 1973; Singer 1980; Tardy et al 1973). The effects of lithology are reduced by concentrating on weathering within single rock types and granites have received by far the most attention (Bakker 1967; Godard 1972; Nieuwenhuis 1971; Eden and Green 1971; Seddoh 1973). If the influence of rock type and other local factors can be successfully identified, then the effects of present and former climates on the clay mineralogy can be evaluated. Inferences may then be made about the age of the saprolites.

In this study clay mineralogy is used as an aid in the identification of weathering types, as an indicator of palaeoenvironments and as a means of dating weathering covers. A reconnaissance survey has been made of the clay mineralogy at

62 weathering sites. Attention has been concentrated on the alteration products of rocks other than basic igneous rocks, which have already received detailed attention elsewhere (Basham 1974; Wilson 1966; 1967; 1970). Only the gross mineralogy of the total clay fraction has been considered and no attempt has been made to follow the transformations of individual minerals during weathering. The total clay fraction will be composed mainly of the weathering products of the main non-resistant group of rock-forming minerals, the felspars, and clays neoformed from lesser constituents, notably biotite, will be under-emphasised.

8.2 Methods and Interpretation

8.2.1 Methods

Total clay fractions were separated from the weathered rocks by settling and decantation, after using Calgon as dispersant. The clays were flocculated with magnesium chloride and stored under water. In samples with low clay fractions it was often difficult to gather sufficient clay for analysis.

The clays were mounted as either oriented aggregates on glass slides or disoriented powders in metal holders.

All samples were run under 3 conditions:- (i) at room temperature and untreated, (ii) at room temperature after glycolation for 4 hours at 80^{o}c and (iii) at room temperature after roasting at 550^{o}c for 4 hours.

8.2.2 Identification of clay minerals

Identification of clay minerals is after Thorez (1975).

A. Kaolinite and halloysite

Kaolinite is identified by (001) and (002) reflections at 7.1A^o and 3.58A^o in untreated samples. The reflections are unaffected by glycolation but are destroyed by heating at 550^{o}c. In powder mounts of well-crystallised kaolinite, numerous secondary reflections can also be identified.

Halloysite is distinguished from kaolinite by the assymetry of the (001) and (002) peaks and by the increased intensity of the 4-4.4A^o band. Halloysite behaves similarly to kaolinite with glycolation and heating.

(B) Illite

Illite has characteristic reflections at (001) 10, (002) 5 and (003) 3.3. The reflections are unchanged by glycolation and heating.

(C) Smectite

In untreated samples the main (001) smectite peak is at 15.4A^o, with subsidiary peaks at (003) 5.1 and (005) 3.05. On glycolation, these reflections expand to (001) 17A^o, (003) 5.7 and (005) 3.4A^o and additional reflections appear at (002) 8.5 and (004) 4.2. On heating the even orders disappear and other reflections collapse to (001) 10A^o, (002) 5A^o and (003) 3.3A^o.

(D) Chlorite

Chlorite is identified in untreated samples by reflections at (001) 14A^o, (002) 7A^o, (003) 4.7A^o and (004) 3.5A^o. The reflections are unaffected by glycolation. Even orders disappear on heating.

Chlorite is distinguished from kaolinite in oriented mounts by the persistence of the (001) 14A° and (003) 4.7A° reflections after heating. Further distinction is possible in disoriented powder mounts by examination of lesser reflections.

Chlorite is distinguished from vermiculite by the persistence of the (001) 14A° peak after heating.

(E) Vermiculite

Vermicultie has a single (001) reflection at 14A°, which is unaffected by glycolation but which collapses to 10A° on heating.

(F) Gibbsite

Gibbsite possesses a characteristic pair of peaks in untreated samples at (001) 4.85 and (002) 4.37A°. Where gibbsite is present in small quantities, only the stronger (001) peak can be identified. The reflections are unaffected by glycolation but destroyed by heating.

(G) Iron minerals

3 types of iron minerals have been identified:- goethite, haematite and lepidocrocite.

Goethite is identified by reflections at (001) 4.20 and (002) 2.68A°.

Haematite is identified by the (001) reflection at 2.69A°.

Several samples show a minor reflection between 6.2 and 6.4A°. This reflection is interpreted as that of lepidocrocite (Peacock 1942; Brown 1953) with a (001) spacing at 6.25A°.

Samples from weathered rocks with low clay contents often give poor traces. This is due to the presence of amorphous material, including poorly-crystallised silicate clays, iron and manganese hydrous oxides and organic complexes.

Although the basic treatments serve to differentiate the main clay-mineral groups, it is often difficult to distinguish between types of expanding mineral, especially where intergrades are present.

8.3 Granite saprolites

8.3.1 Clay mineral assemblages

The weathered granites are dominated by clay minerals of the illite and kandite groups. Chlorite is a common accessory mineral. Vermiculite is poorly represented but is known to be an alteration product of biotite (Milne 1952). Expanding minerals are important in the less acid granite varieties. Gibbsite occurs in small quantities at several sites (Table 8.3.i).

The composition of the clay fraction is largely independent of the degree of weathering of the granites. Granular grusses are dominated by kaolinite and illite (Fig. 8.3.i). Halloysite is often present in important quantities and several samples contain gibbsite. These clays derive mainly from the alteration of plagioclase, the least resistant of the primary minerals. Biotites are discoloured but the nature of the alteration products cannot be established from analysis of the clay fraction alone. Several granular grusses contain inherited 2:1 clays.

The clay mineral assemblages in the grusses are more diverse (Fig. 8.3.ii). The dominant clays, kandites and illites, are neoformed from felspars. 14A^{o} minerals become important with increasing alteration of biotite (Milne 1952). Expanding minerals appear but gibbsite is usually absent.

Table 8.3.i Clay mineralogy of the weathered granites

	Granulometric Type	Kaolinite	Halloysite	Illite	Chlorite	Vermiculite	Smectite	Gibbsite	Mixed layers	Iron minerals	Remarks
ABERCHIRDER	GG	X		XX	X				X		Amorphous Fe-Mn Oxides
AIKEY BRAE	G		XXX	XX	tr						
AVOCHIE	GG	X		XX	X				X	X	Lepidocrocite
BENNACHIE C.P.	CG	XXX		XX						X	Haemitite-silicate mix
BLACKPOTS	GG		XX	XX			?				Amorphous Fe-Mn Oxides
BRAESIDE	G		XX	XX	X						
CAIRNGALL	CG	XXX		XX		tr					
CAIRNLEA	G		XXX								
CAIRN LOCHAN	CG	XXX		X	X	tr					
CAIRN O'MOUNT	GG	XX		XXX				X		tr	
COIRE RAIBERT	GG	XX		X				XXX		X	Haematite
CRUDEN MOSS	G	XX		X		tr	X				Amorphous Fe-Mn Oxides
CRUDEN 2	G	XX	X	XX		tr					
CRUDEN 3	G	XX		XX		X	X				
EAST DEN	GG	XX		XX	tr			tr			
GLEN CAT	GG	X	tr	X	X		X	tr			
HILL OF DENS	G	XX		XX	?	?		tr			
KINGSFORD	GG	X	X	X					X		
LAIRIG	GG		X	XX	X			XX			
LONGHAVEN	GG	X	X	XX	X						
MILL MAUD	GG	XX		XX	X						
MORMOND N.S.	GG	X		X				XXX		?	
PX48	G	X		XXX		X				X	Lepidocrocite
QX115	CA	XXX		X							
REDHOUSE	G	XX		XX		X		tr		tr	Lepidocrocite/ MnO_2
TULLOCH	GG		XX	XX							

XXX - Dominant XX - Strong X - Present tr - Trace ? - Uncertain identification

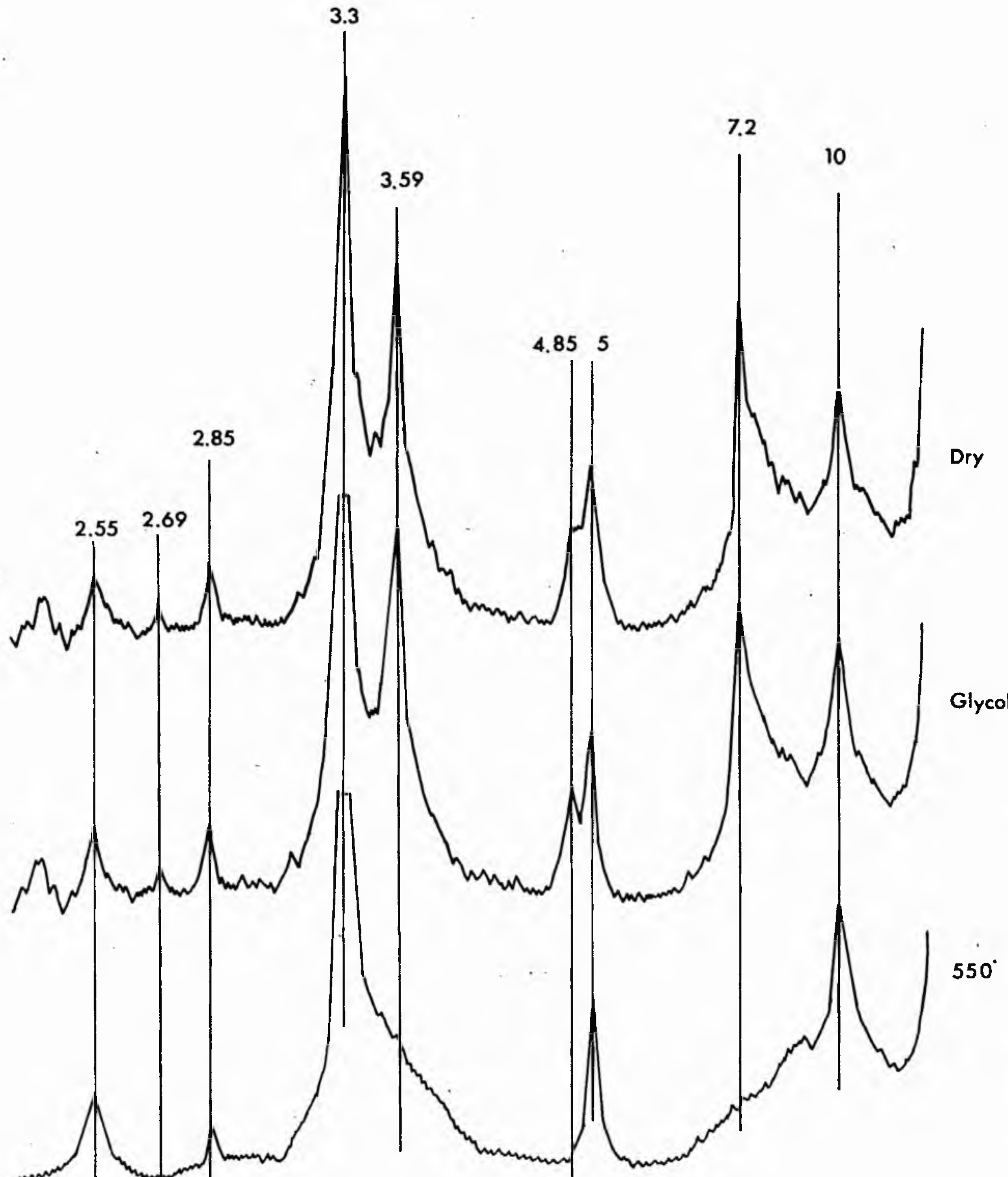


Fig. 8.3.i.a. Cairn o'Mount

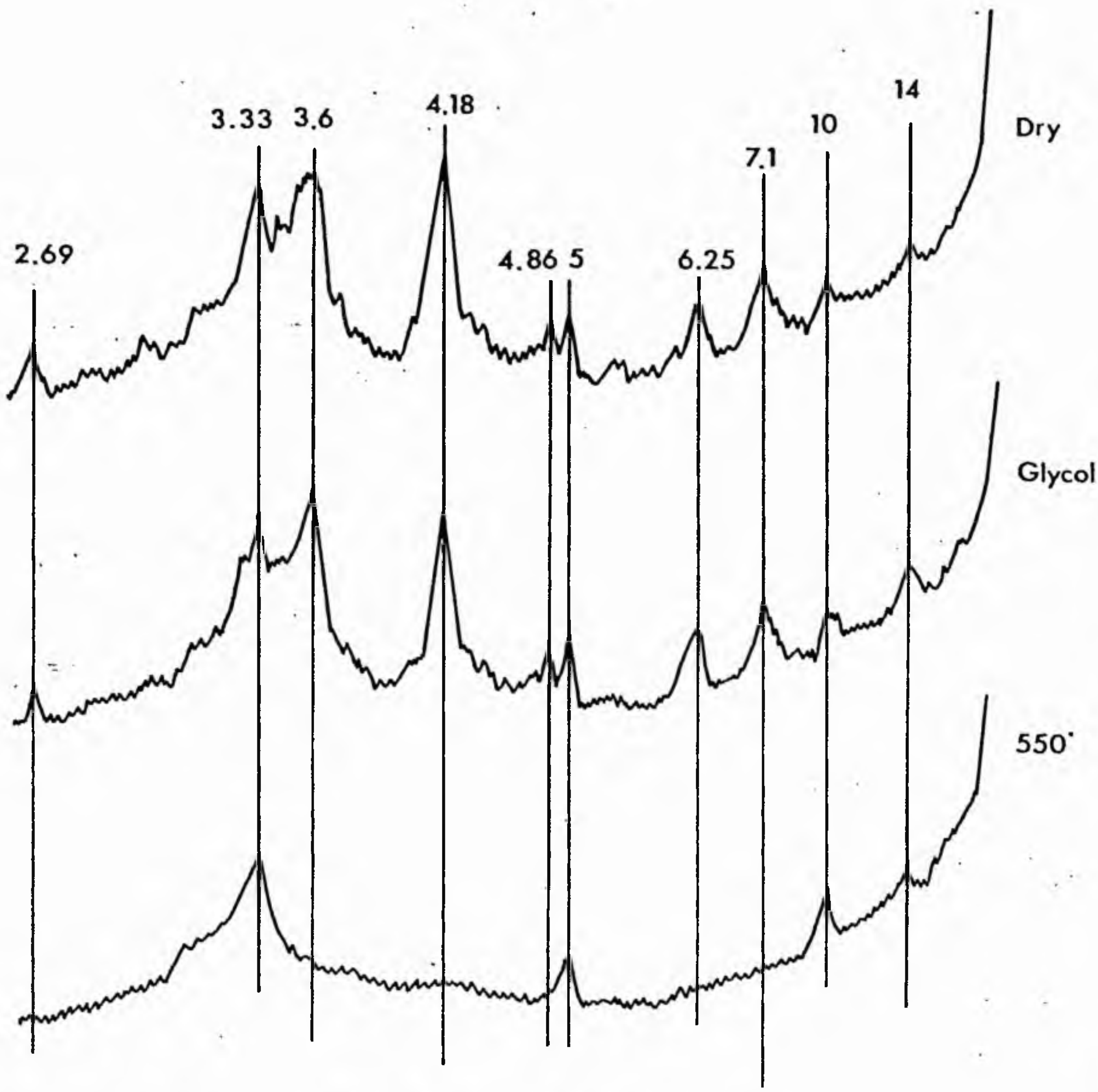


Fig. 8.3.i.b. East Den

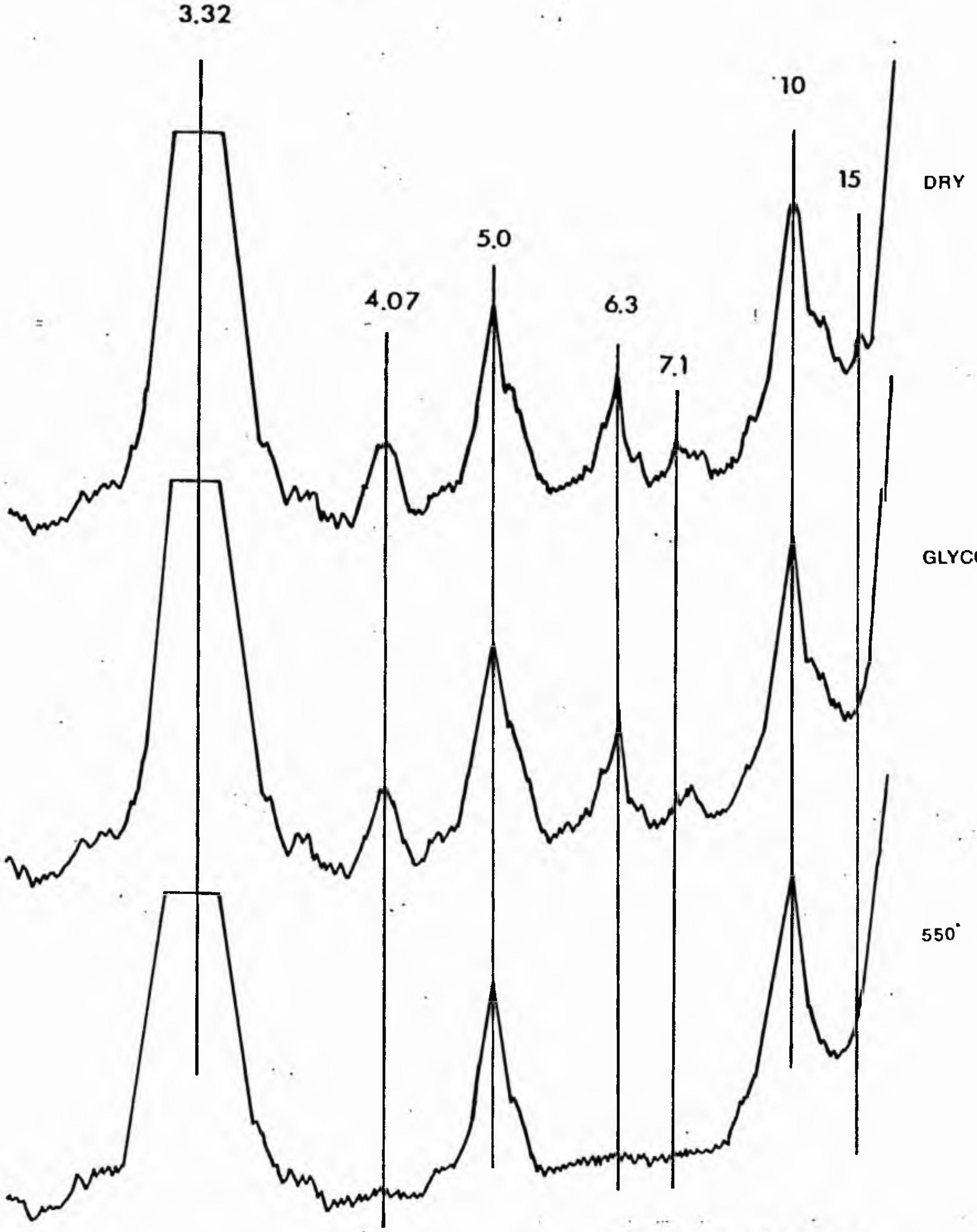


Fig. 8.3.ii. PX 48

The clayey grusses are dominated by kaolinite with subordinate illite. At Bennachie Car Park, K-felspars are altered to kaolinite and the strongly-corroded biotites may also be partially kaolinised (Fig. 8.3.iiia). The rubefied zones contain an interstratified haematite-silicate clay mineral (Wilson et al 1981). The main source of kaolinite at Cairngall is plagioclase (Fig. 8.3.iiib). Biotites are dulled but not greatly altered. The dioritic alterite beneath the Moss of Cruden gravels is also dominated by kaolinite (Fig. 8.3.iv).

The presence of kaolinite and halloysite in the granite granular grusses implies that conditions of free drainage are established in the early stages of gruss development. Before disaggregation groundwater movement will be weak and high concentrations of basic ions will favour the development of 2:1 minerals (Millot 1970). As free percolation develops, the initial alteration products will be transformed to kaolinites. However in certain cases kaolinite forms directly from felspar without any intervening stages. The tiny clay fraction of the Longhaven granular gruss contains a large proportion of disordered kaolinite (Fig. 8.3.v.), which can only be an initial alteration product.

8.3.2 The status of gibbsite

Gibbsite is present in small amounts in numerous granular grusses and is occasionally dominant (Fig. 8.3.vi.). Gibbsite also occurs in weathered granites and gneisses in Glen Dye (Reid 1979).

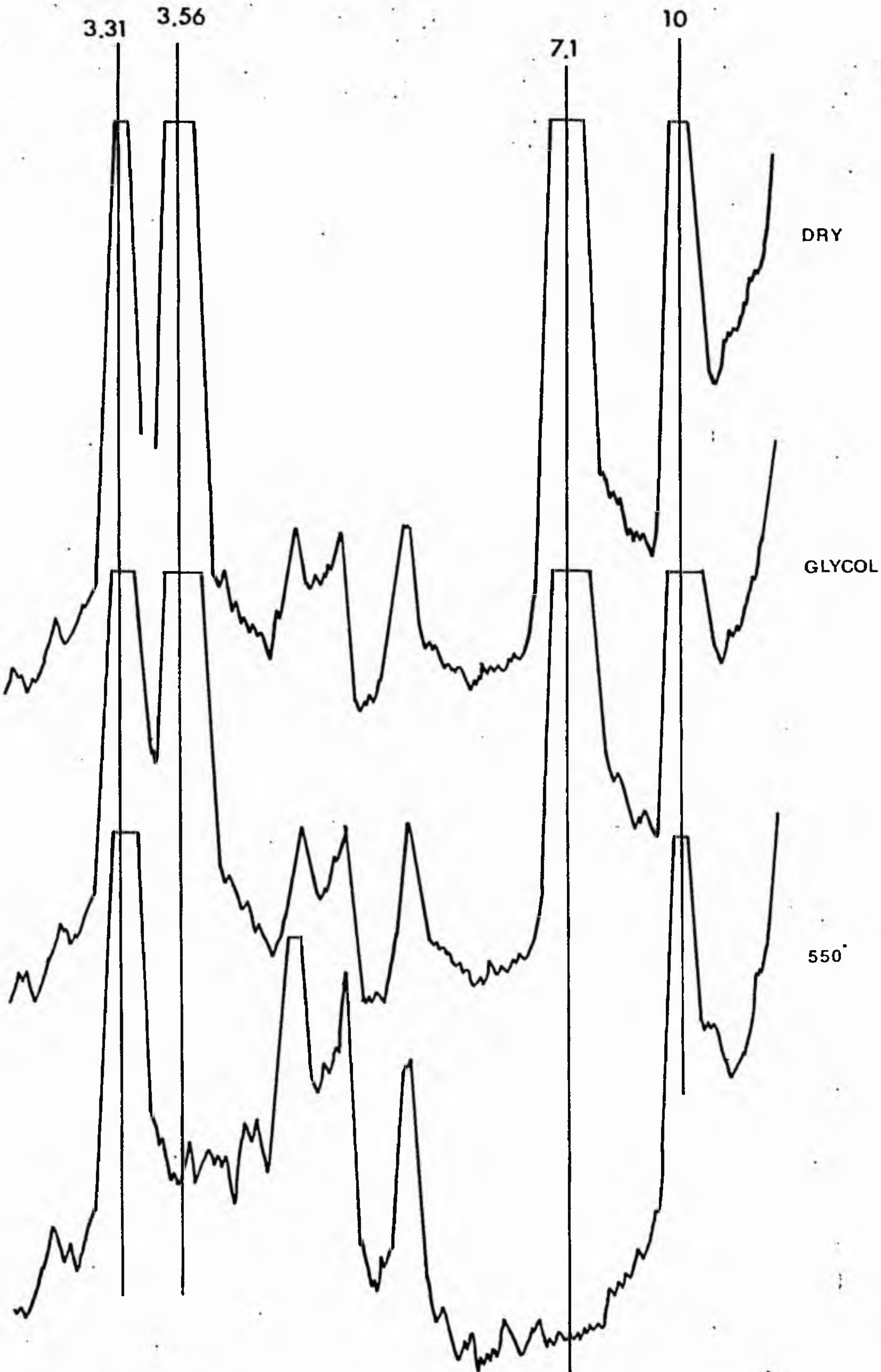


Fig. 8.3.iii.a. Bennachie Car Park

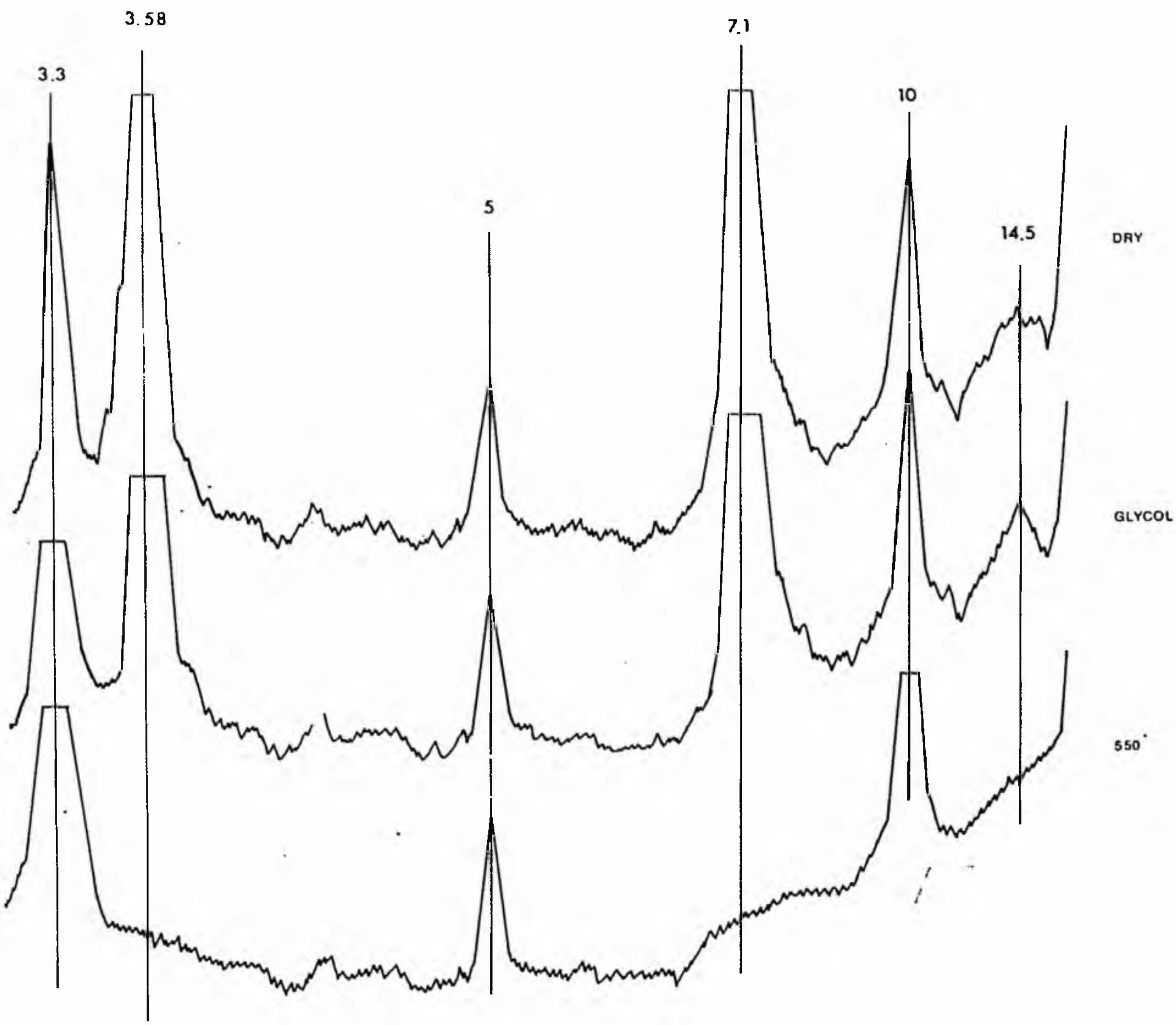


Fig. 8.3.iii.b. Cairngall

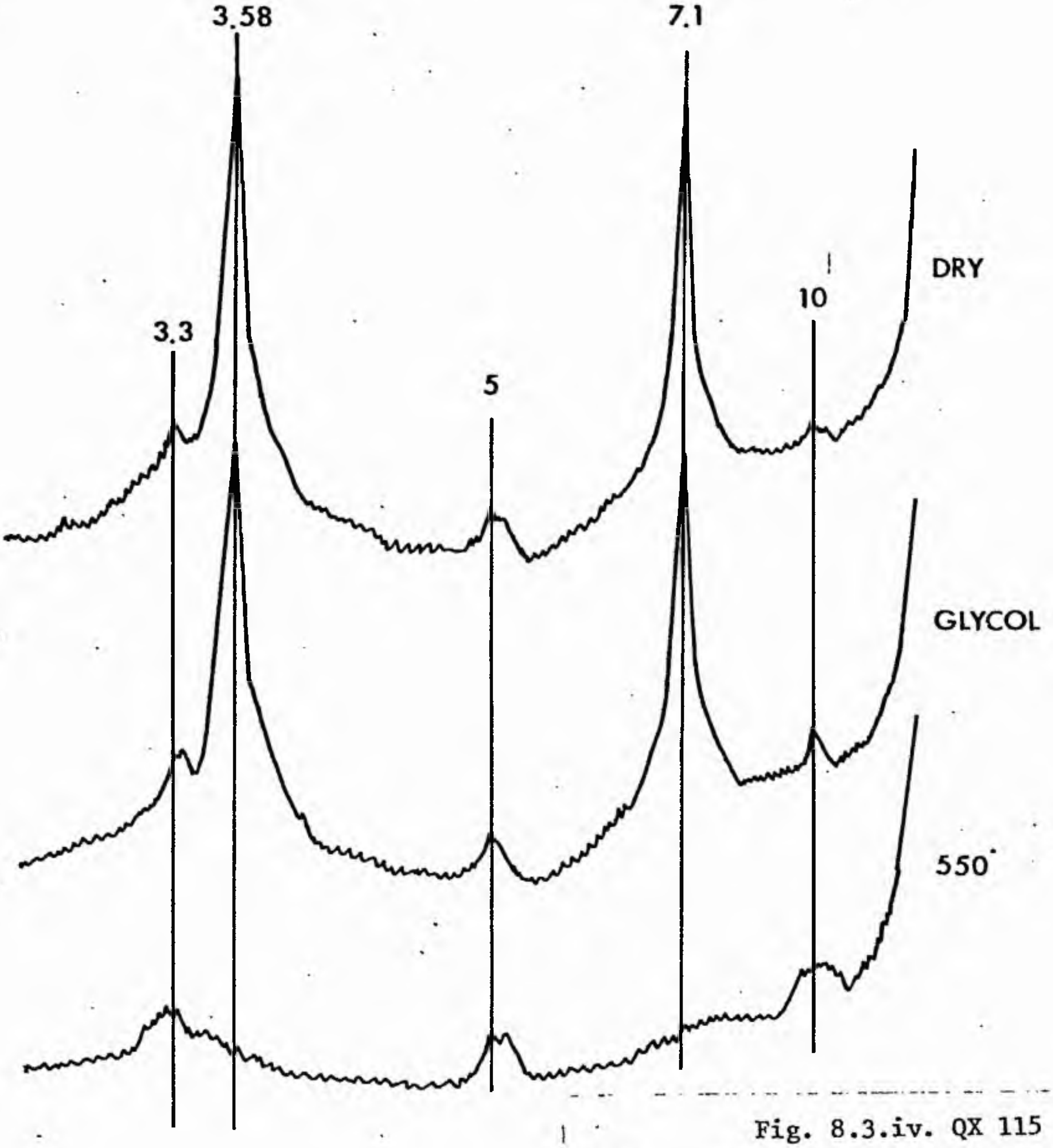


Fig. 8.3.iv. QX 115

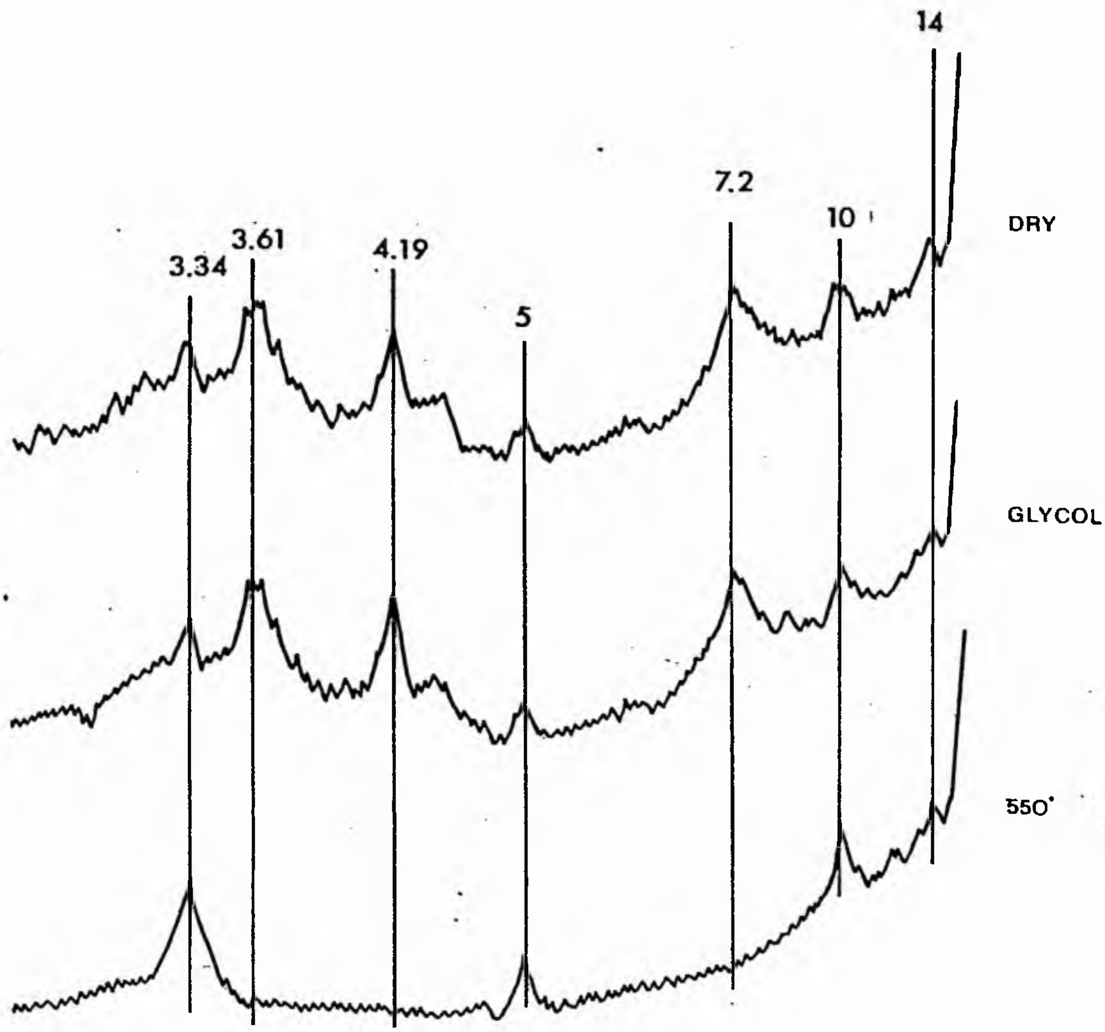


Fig. 8.3.v. Longhaven

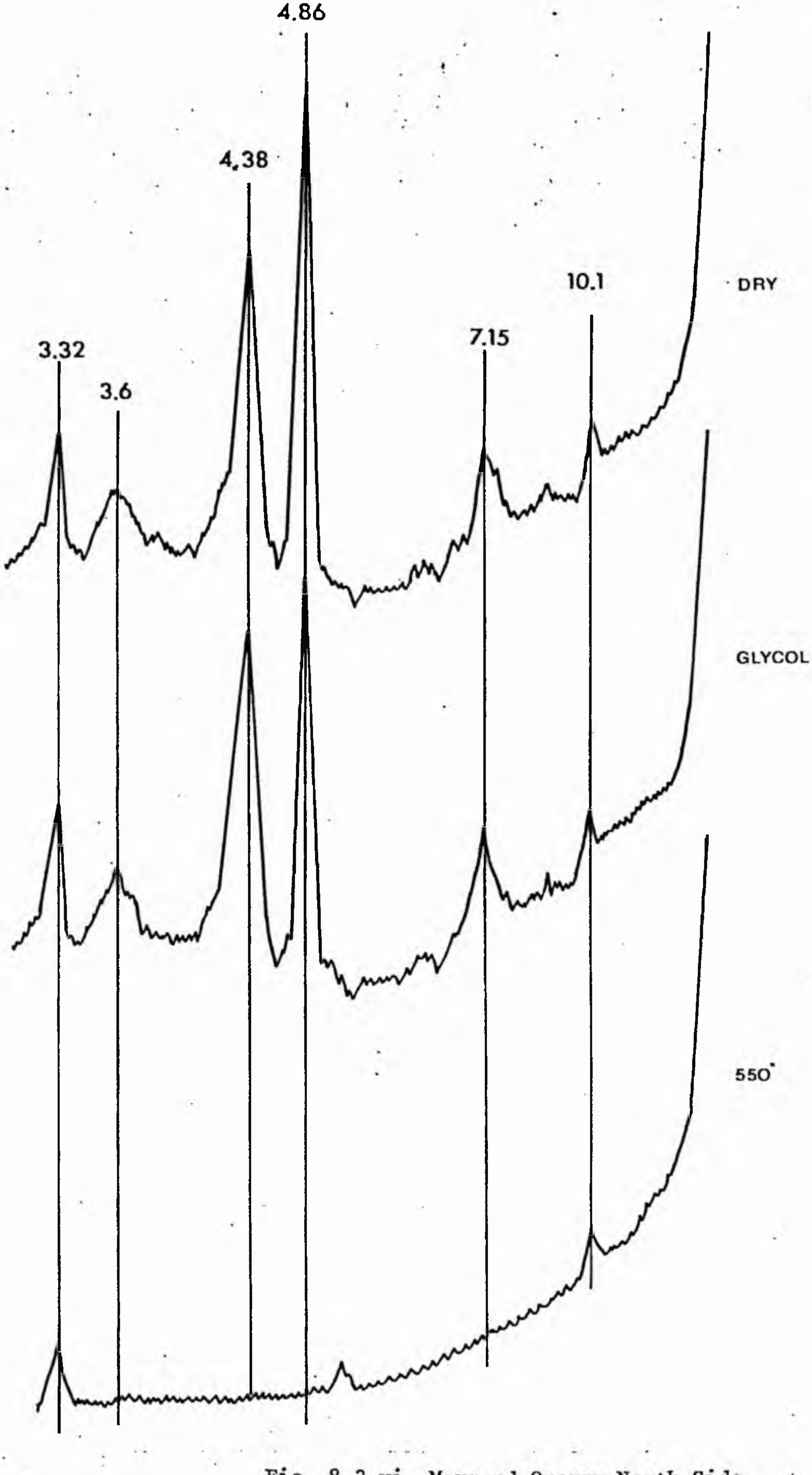


Fig. 8.3.vi. Mormond Quarry North Side

A growing number of studies have recorded gibbsite as a component of granite grusses and their soils (Dejou et al 1967; 1968; Erhart 1968; Green and Eden 1971; Cate and McCracken 1972; Pedro et al 1975; Torrent and Benayas 1977; Wilke and Schwertmann 1977). In north-east Scotland, gibbsite is pseudomorphed after plagioclase, a transformation found elsewhere (Maurel 1968; Pedro et al 1975).

Gibbsite will only form when silica concentrations in solution are low and when drainage is good (Pedro and Delmas 1971; Gardner 1972). In grusses, these conditions are satisfied in two situations:-

(i) in the initial alteration of granite at the surface, around corestones and at the base of profiles (Watson 1962; Godard 1971).

In the early stages of alteration, groundwater will be weak in silica. Gibbsite may appear and persist until such time as increasing silica concentrations suppress its formation and begin its silicification into kaolinite (Bonifas 1959). The proportion of gibbsite decreases up weathering profiles in grusses and drops dramatically in the soil zone (Wilson 1969; Tardy 1969; Green and Eden 1971; Cate and McCracken 1972; Wilke and Schwertmann 1977) as a result of the increasing silica concentrations (Bonifas 1959) and the action of organic agents (Bloomfield 1953).

(ii) in the alteration of leucogranites (Pedro et al 1975). The low quantities of plagioclase and ferro-magnesian minerals will yield only weakly siliceous solutions and encourage gibbsite formation.

The gibbsite in the granular grusses is an initial weathering product and its general absence from the more altered grusses is due to silicification.

Gibbsite may be presently forming in the alpine environments of the Cairngorms (c.f. Reynolds 1971). Surficially decomposed granite from beneath a snow patch on the plateau slopes, above the Lairig Ghru is dominated by gibbsite (Fig. 8.3.vii.).

8.3.3 Effects of lithological variation

The influence of the primary mineralogy of the granites on the alteration products is strong. Leucogranites such as the Hill of Fare and Peterhead granites produce bi-mineralic kandite-illite suites with restricted development of other minerals. Granites of intermediate composition contain more diverse mineralogies and 14A^{o} and smectite minerals become important in diorites (Fig. 8.3.viii.).

8.3.4 Inherited clays

Certain clays are inherited from late-stage alteration of the granites. Plagioclase within the Strichen granite is partially kaolinised (Anderson 1939). Chloritisation of biotite affects the granites at Aberchirder and Braeside and chlorite veins cut the granites at Longhaven and Redhouse. In addition several granites contain haematitic iron minerals which have been re-mobilised during weathering.

8.3.5 Variations with depth

The deeper profiles show little change in clay mineral type with depth (Fig. 8.3.ix). The most significant change is the increased disorder of kaolinite at the base of the sections.

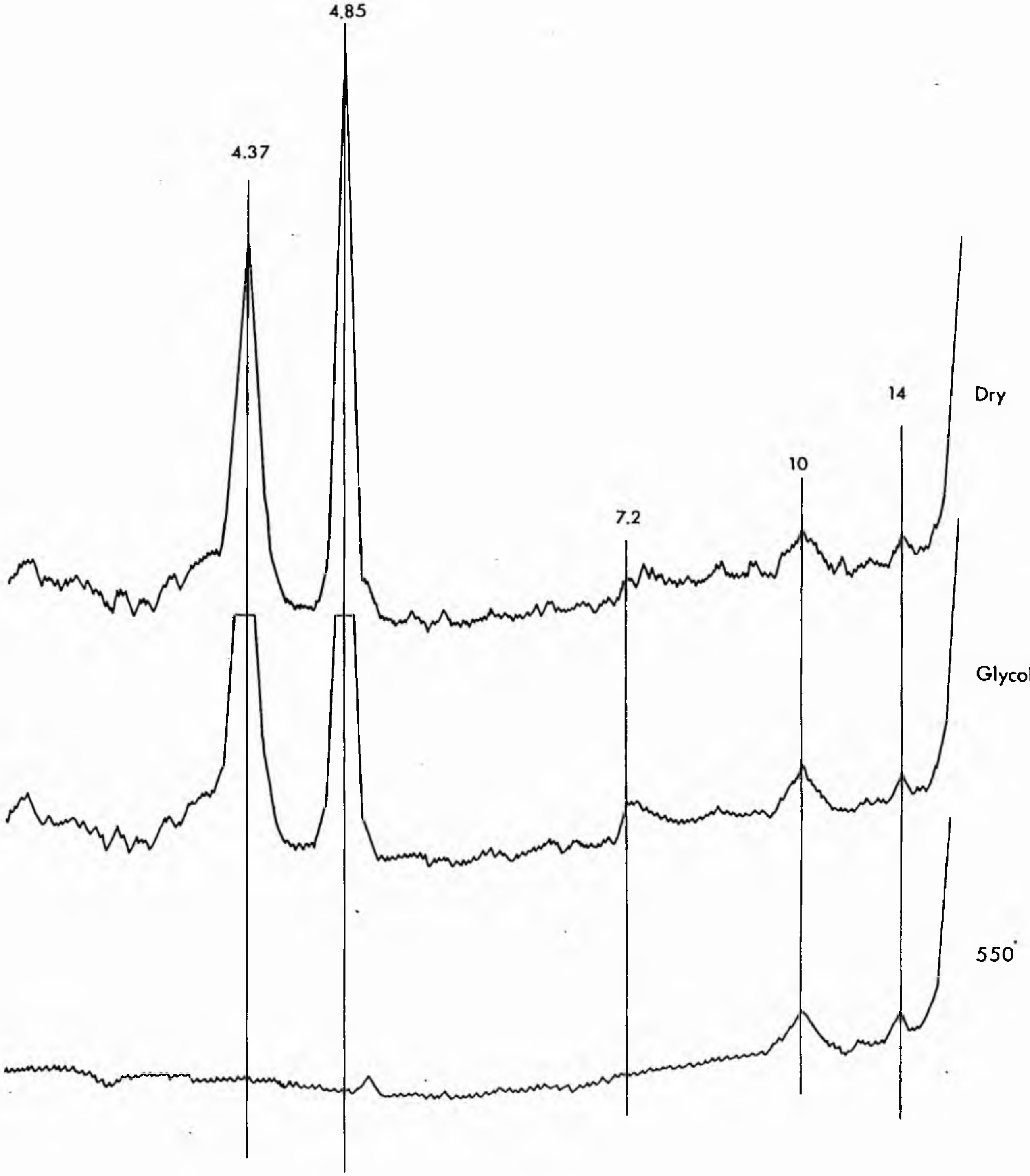


Fig. 8.3.vii. Lairig
Sample of surficially-weathered granite beneath a receding snow patch on the western slopes of Cairn Lochan, overlooking the Lairig Ghru.

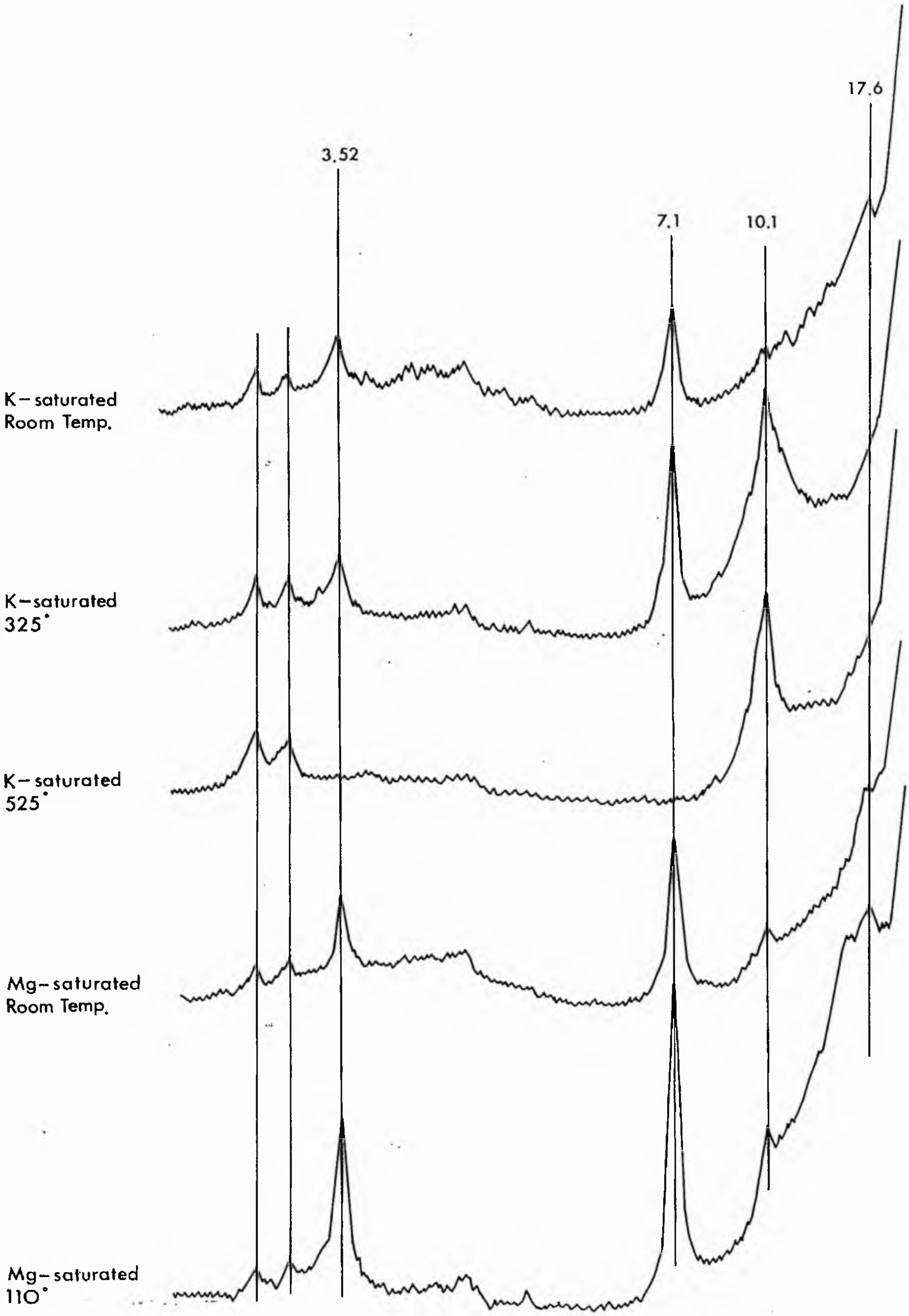


Fig. 8.3.viii. Cruden Moss

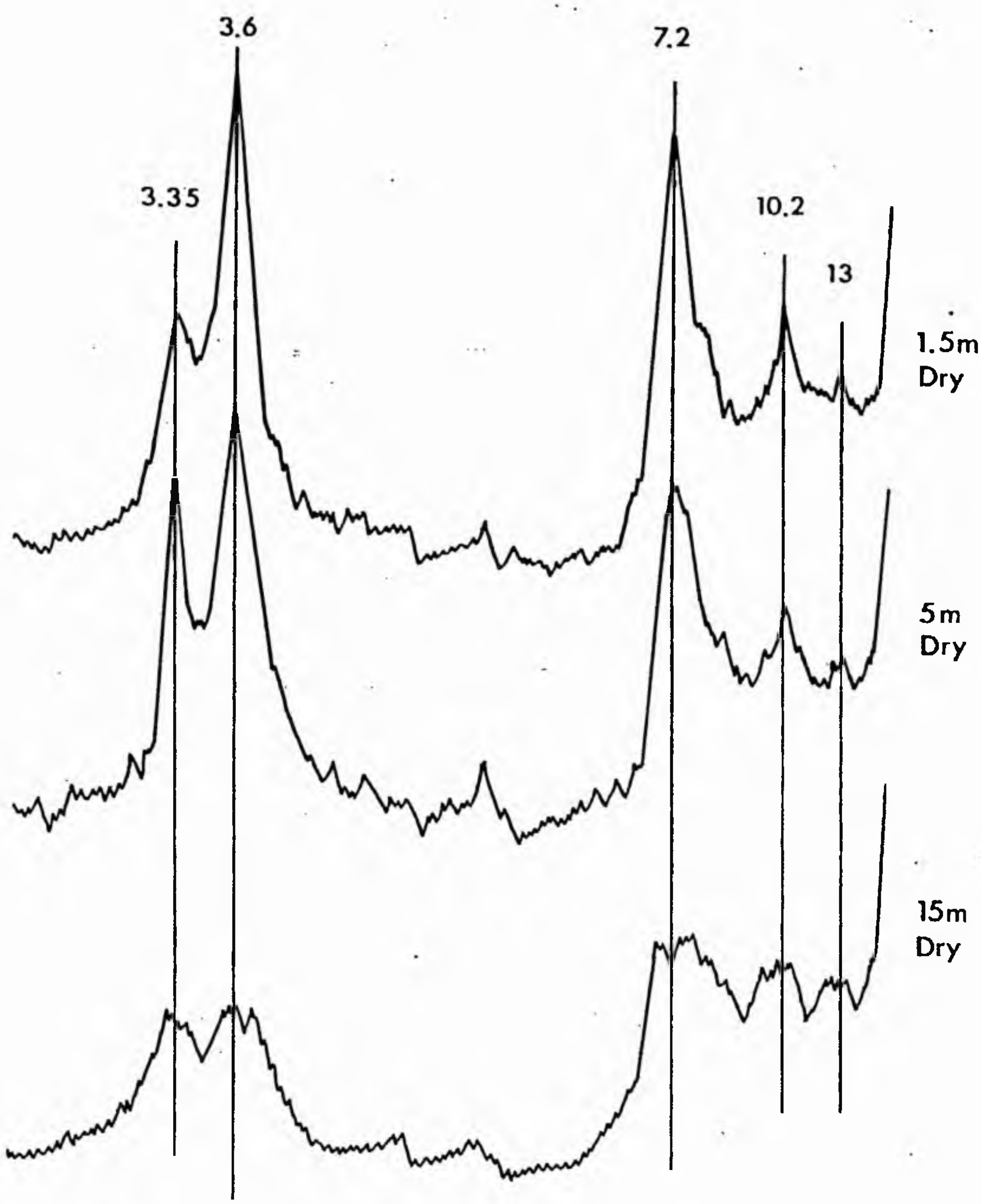


Fig. 8.3.ix. Mill Maud.
Variations in mineralogy
with depth.

8.4 Basic igneous rocks

8.4.1 Clay mineral assemblages

Most of the weathered basic rocks examined are of gabbroic composition and alteration has generally progressed little beyond the granular gruss stage. At this early stage of alteration, the clay fractions are dominated by illite, vermiculite and intergrades. Increasing alteration leads to the appearance of kandite, chlorite and smectite clays (Table 8.4.i).

The methods used in this study have been unsuited to the analysis of clay minerals of the basic granular grusses. Fortunately the clay mineralogy of gabbroic granular grusses and grusses and their soils has been studied in detail by Wilson (1966; 1967; 1970) and Basham (1974). In the grusses of the Insch and Morvern-Cabrach basic masses, biotite is the most altered mineral, pyroxene is slightly affected and plagioclase is largely unaltered. The clay fractions consist of hydrous mica-amorphous iron oxide assemblages with minor kaolinite and gibbsite (Basham 1974). The general order of primary mineral stability in soils derived from quartz gabbros is similar to that of the grusses:-

Quartz < Amphibole < Plagioclase < Biotite

(Wilson 1967)

Biotite in soils alters to complex 14A^{o} aluminous vermiculite-chlorite clays with minor kaolinite and chlorite (Wilson 1966).

Examination of granular grusses from other basic intrusions indicates a slightly higher degree of alteration. Grusses around the Kirkney basin contain poorly ordered illite-vermiculite clays.

BRUXIE	G	XX		XX		?	X			X
FEDDERATE	G	X		X				XXX		X
FORESTRY HUT	G	X		X	X	?			?	X
GAVAL	CG		XX	XX		X				
HUNTLY BRIDGE	G	X		X	X			tr	XX	
KIRKHILL	G	tr		X	XX	?			?	
KNOCKESPOCH	G	?		X	X		XXX			
SILVERFORD	GG			X		X				X
SKILMAFILLY	GG		X	X	X	?	X			X

Table 8.4.i Clay mineralogy of the weathered Basic Rocks

Granulometric Type	Kaolinite	Halloysite	Illite	Chlorite	Vermiculite	Smectite	Gibbsite	Mixed layers	Amorphous Fe-Mn Oxides

The norite granular gruss at Fedderate on the Maud mass is dominated by gibbsite, with minor illite and kaolinite. The basic xenolithic rock at Skilmafilly in the Arnage mass contains a varied assemblage of halloysite, illite, chlorite, smectite and some mixed layers (Fig. 8.4.i). In all cases, the grusses are heavily iron-stained.

With further alteration, the clays become better ordered and kaolinite and chlorite clays become more important. The fine grained, pale basic rock at Huntly Bridge has produced a diverse clay suite in which 12-14A^o mixed layer minerals are important (Fig. 8.4.ii). Norites along the contact of the Maud mass with the Forest of Deer quartzites contain considerable amounts of kandite (Fig. 8.4.iii) and may have been affected by the proximity of acid groundwaters. The Kirkhill diorite is dominated by chlorite (Fig. 8.4.iv) derived largely from late-stage alteration of biotite.

The fine grained ultrabasic rock at Knockespoch (epidiorite ?) has a distinctive mineralogy (Fig. 8.4.v). Smectite is dominant with substantial amounts of chlorite, probably including antigorite varieties.

Only a single clayey gruss is known formed from the weathering of basic rocks and as this rock occurs as a band amid the highly acid environment of the Forest of Deer quartzites, its clay mineralogy may not be typical of severely altered basics. Halloysite and illite clays are dominant with some vermiculite (Fig. 8.4.vi).

The presence of kaolinite and gibbsite in the gabbroic granular

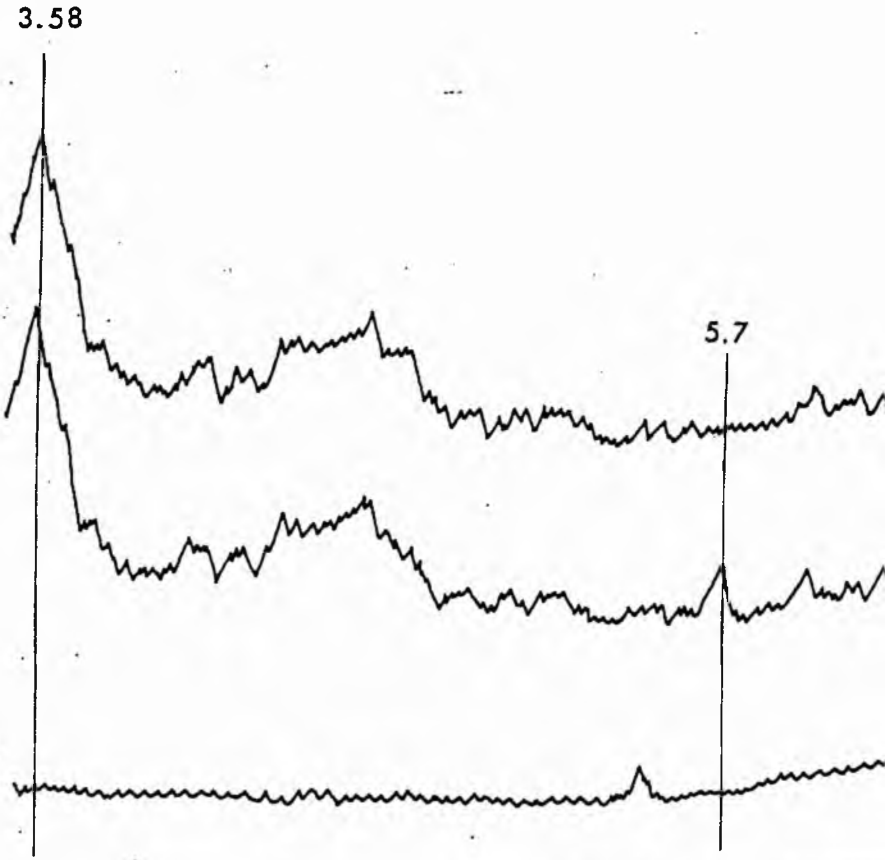
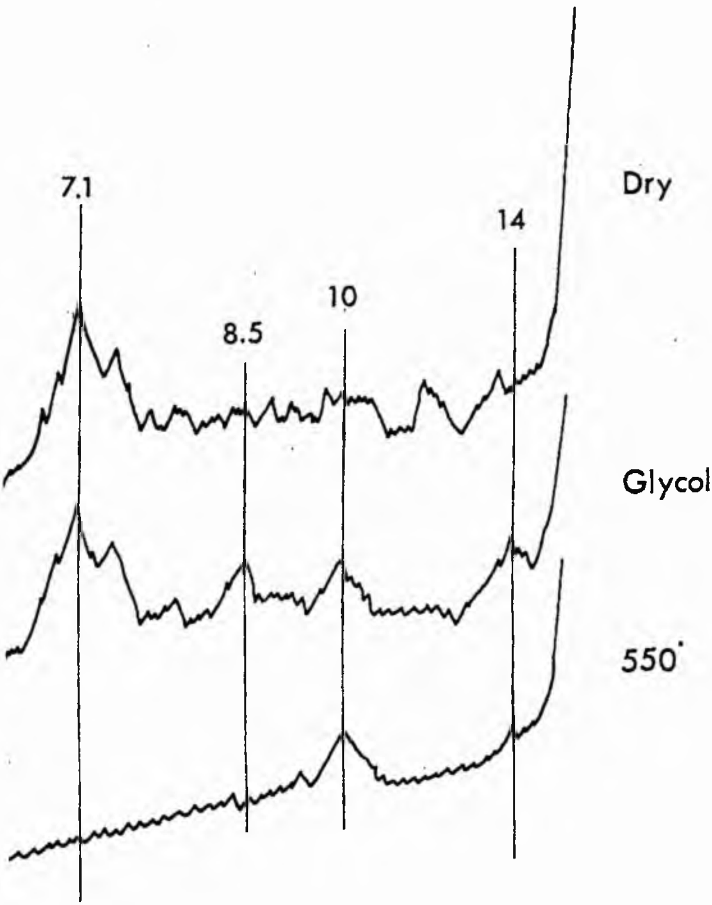


Fig. 8.4.i. Skilmafilly


7.1
8.5
10
14
Dry
Glycol
550°

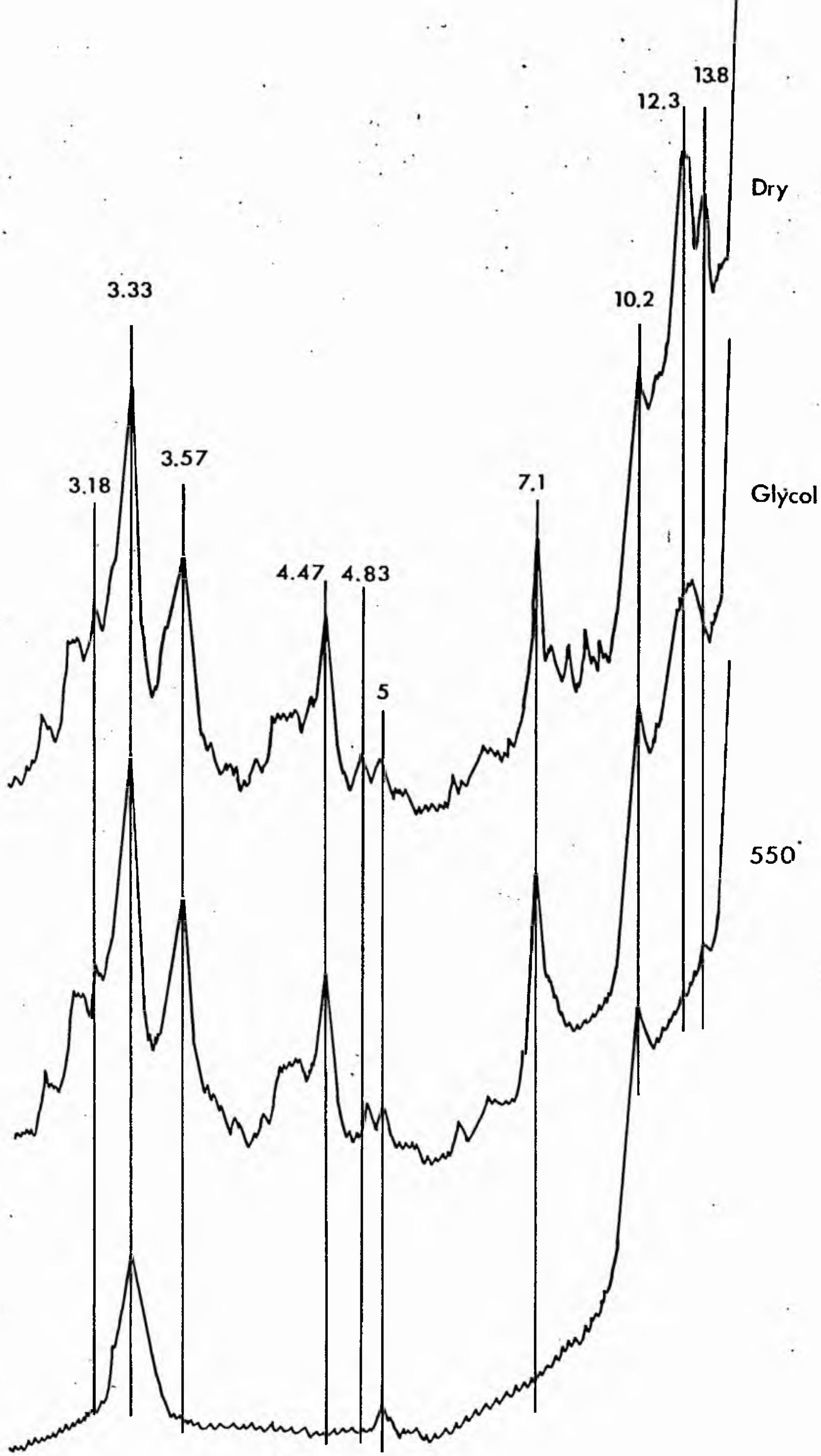


Fig. 8.4.ii. Huntly Bridge

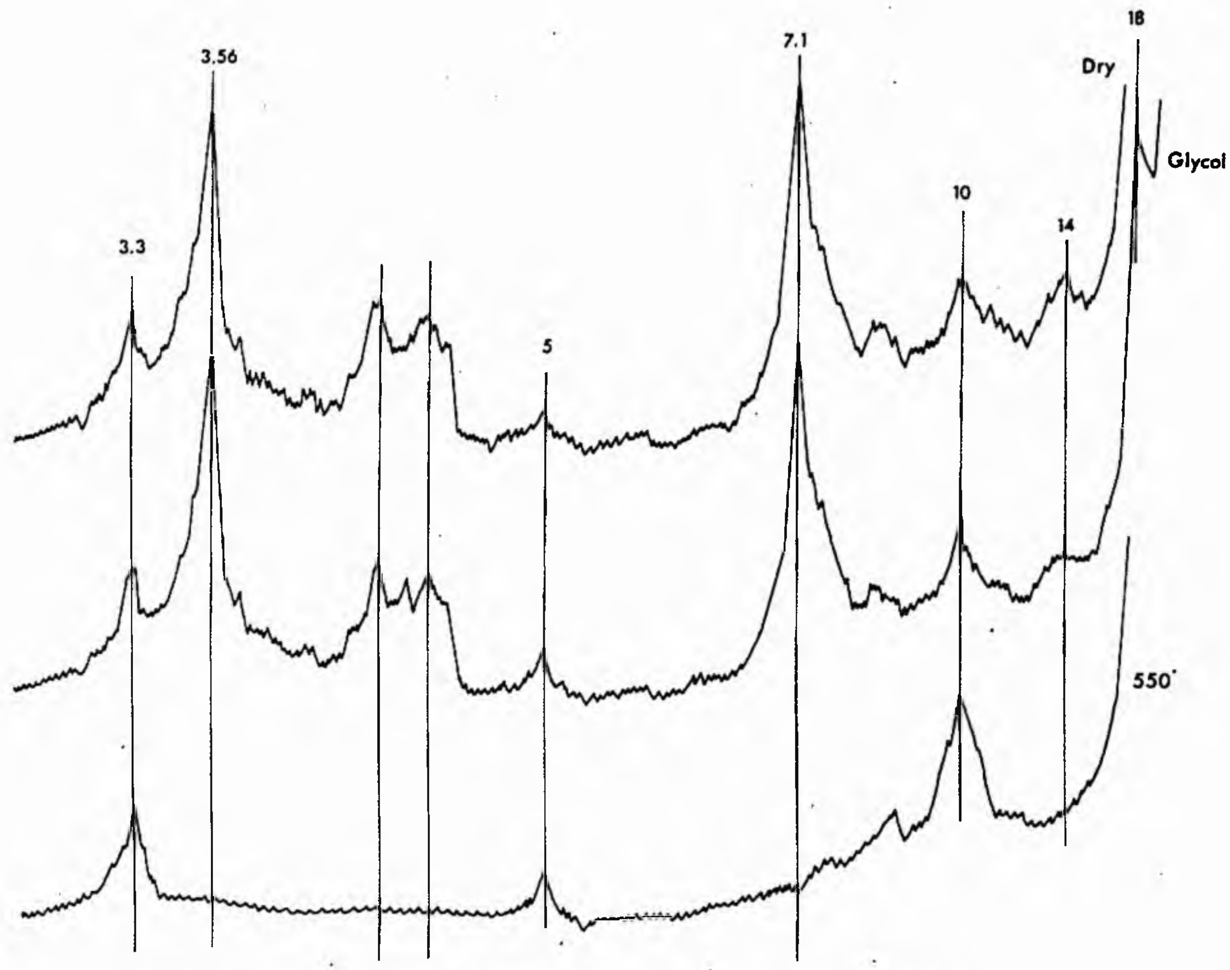


Fig. 8.4.iii. Bruxie

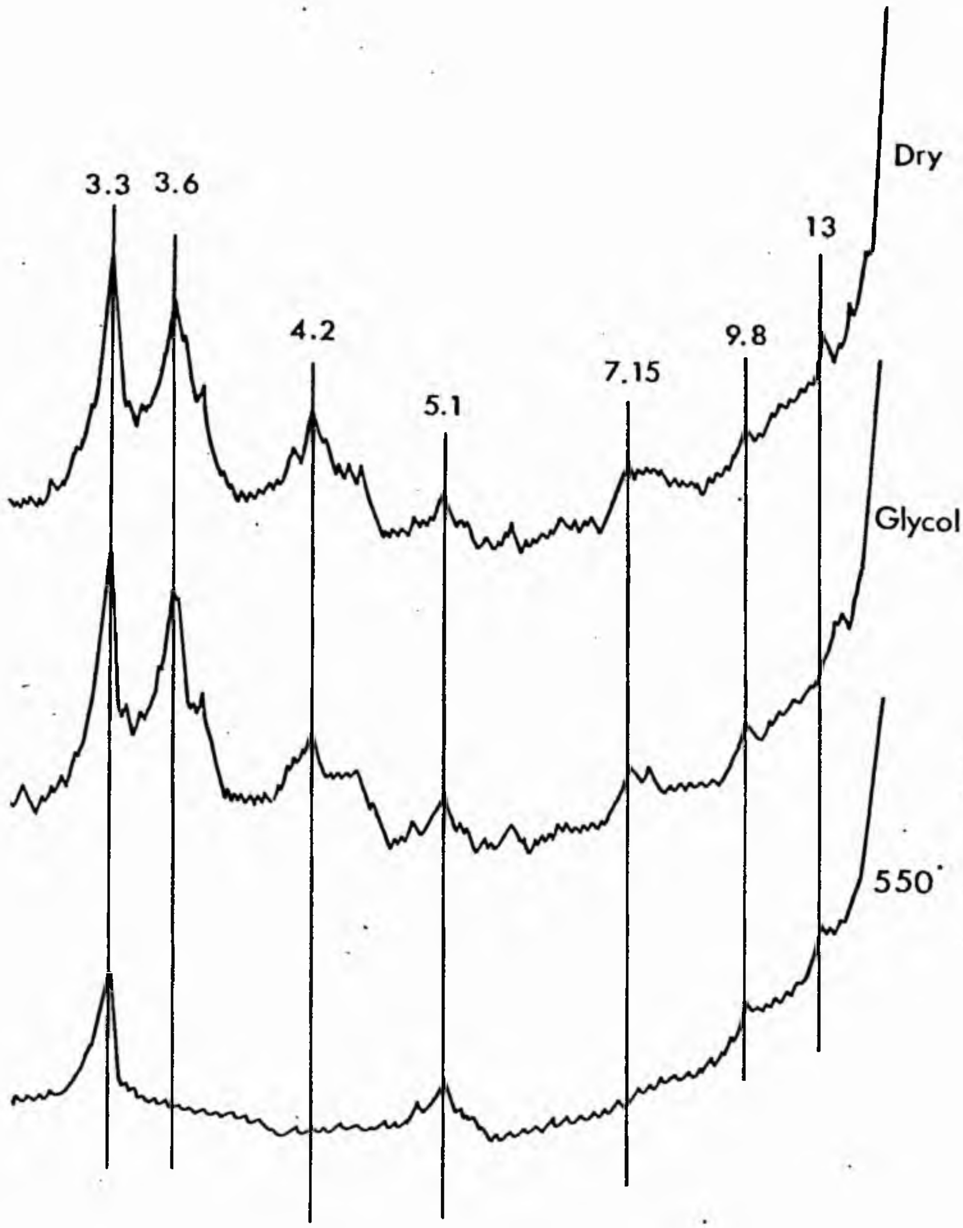


Fig. 8.4.iv. Kirkhill

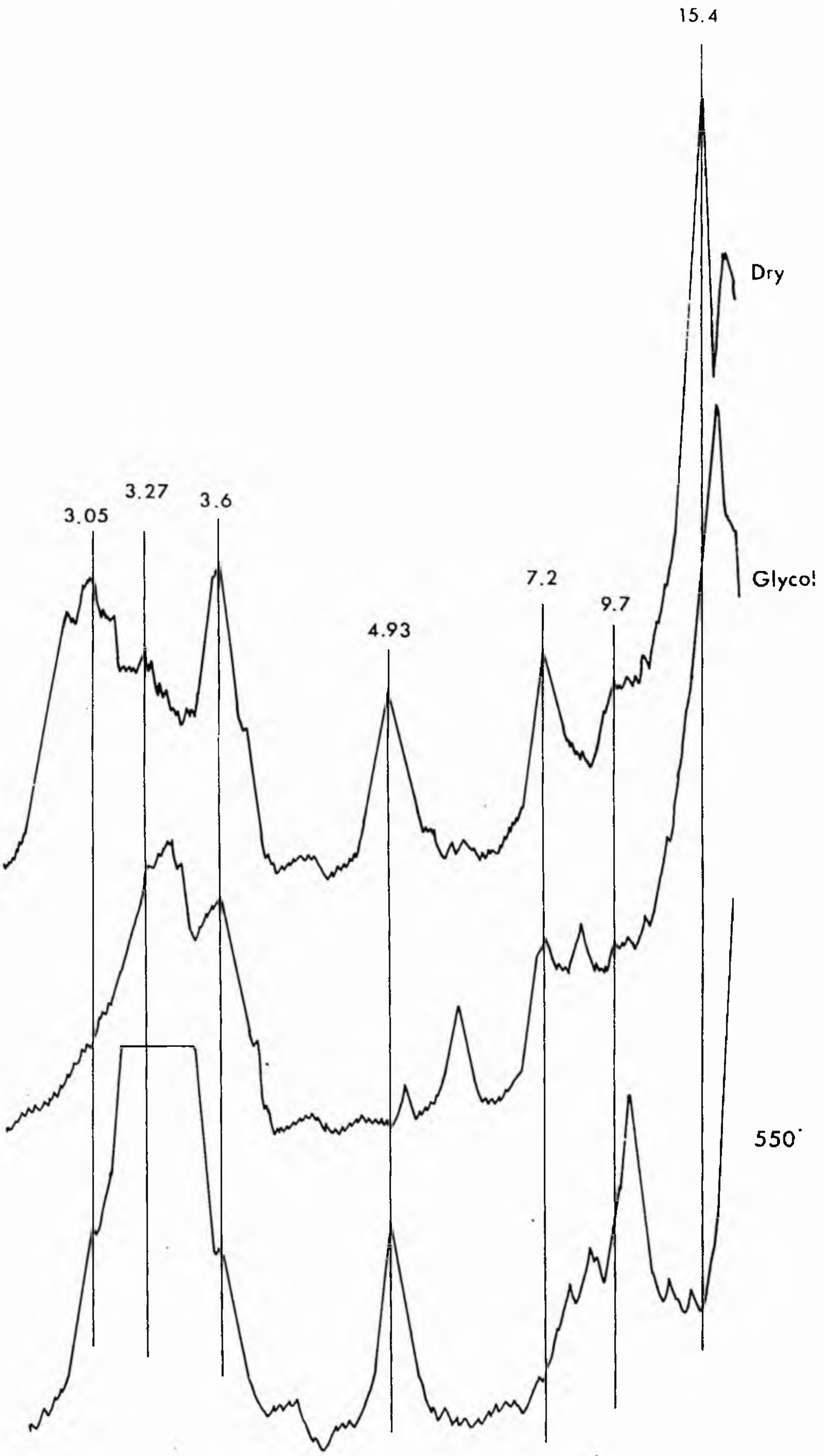


Fig. 8.4.v. Knockespoch

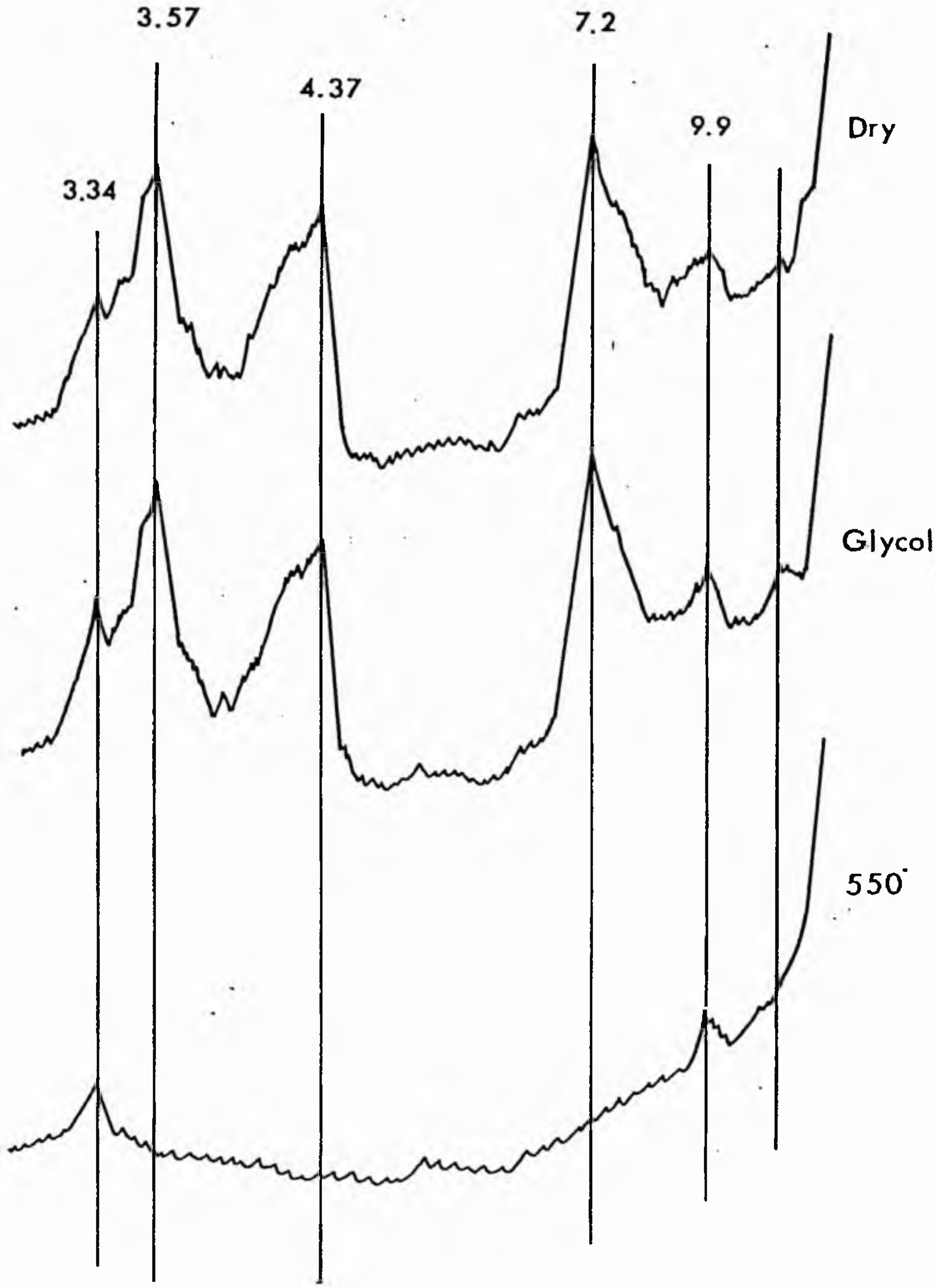


Fig. 8.4.vi. Gaval

grusses is a response to the free drainage of these saprolites. The persistence and increase in kandite contents in the more highly altered basic rocks suggests that the grusses are evolving towards kandite-illite-vermiculite assemblages, rather than smectite-vermiculite types.

8.5 Quartzitic metasedimentary saprolites

8.5.1 Clay mineral assemblages

The weathered quartzites are dominated by kaolinite, with substantial amounts of illite. Other clay minerals are present in only small amounts, if at all (Table 8.5.i). The clay mineralogy of the quartzites is the most uniform of the major rock types.

Although most samples are from highly altered rocks, the Fetterangus and Rannas samples provide evidence for the earlier stages of alteration in quartzitic rocks (Fig. 8.5.i). Kaolinite and illite are already dominant but the samples also include small amounts of vermiculite and traces of gibbsite. Gibbsite is also dominant in the Mormond North Side weathered granite, found within the Mormond Hill quartzites (Fig. 8.3.vi). It is likely that in quartzitic rocks containing plagioclase, gibbsite can appear as an early weathering product. Formation will be encouraged by the low silica concentrations in the initial stages of weathering, as in leucogranites (Pedro et al 1975). However, this gibbsite stage is not always present, as friable rock at the base of the Whitestones profile contains only kaolinite and illite.

Table 8.5.i Clay mineralogy of the weathered quartzitic metasediments

	Granulometric Type	Kaolinite	Halloysite	Illite	Chlorite	Vermiculite	Smectite	Gibbsite	Mixed layers	Iron minerals	Remarks
BALCHIMMY	G		X	XX		X					
CAIRNBARROW	G	X		X			XXX				
DRINNIES WOOD	CA	XXX		X						tr	Goethite
FETTERANGUS	G	XX		XX		X		tr		?	Lepidocrocite (?)
HOWE OF DENS S205	G	XXX		X							
S2 M	CG	XXX		X		X				X	Goethite
S3Z4	G	XXX		X							
S3 B	CA	XXX		X		X				X	Goethite
MORMOND QUARRY	CG	XXX		X							Quartz
MORMOND TRENCH	CG	XXX		X							
MORMOND IRON OXIDE	CG									XX	Haematite and quartz
RANNAS	G	XXX		X	?	tr		?			
RANNAS RED	G	XXX		XX	?	tr		?		X	Haematite
SUNNYSIDE	G	XXX		XX		?					
SUNNYSIDE RED	CG	XX		XX						X	Haematite
WHITESTONES	CG	XXX		X							Quartz (?)
WHITESTONES DITCH	CG		XXX	X							

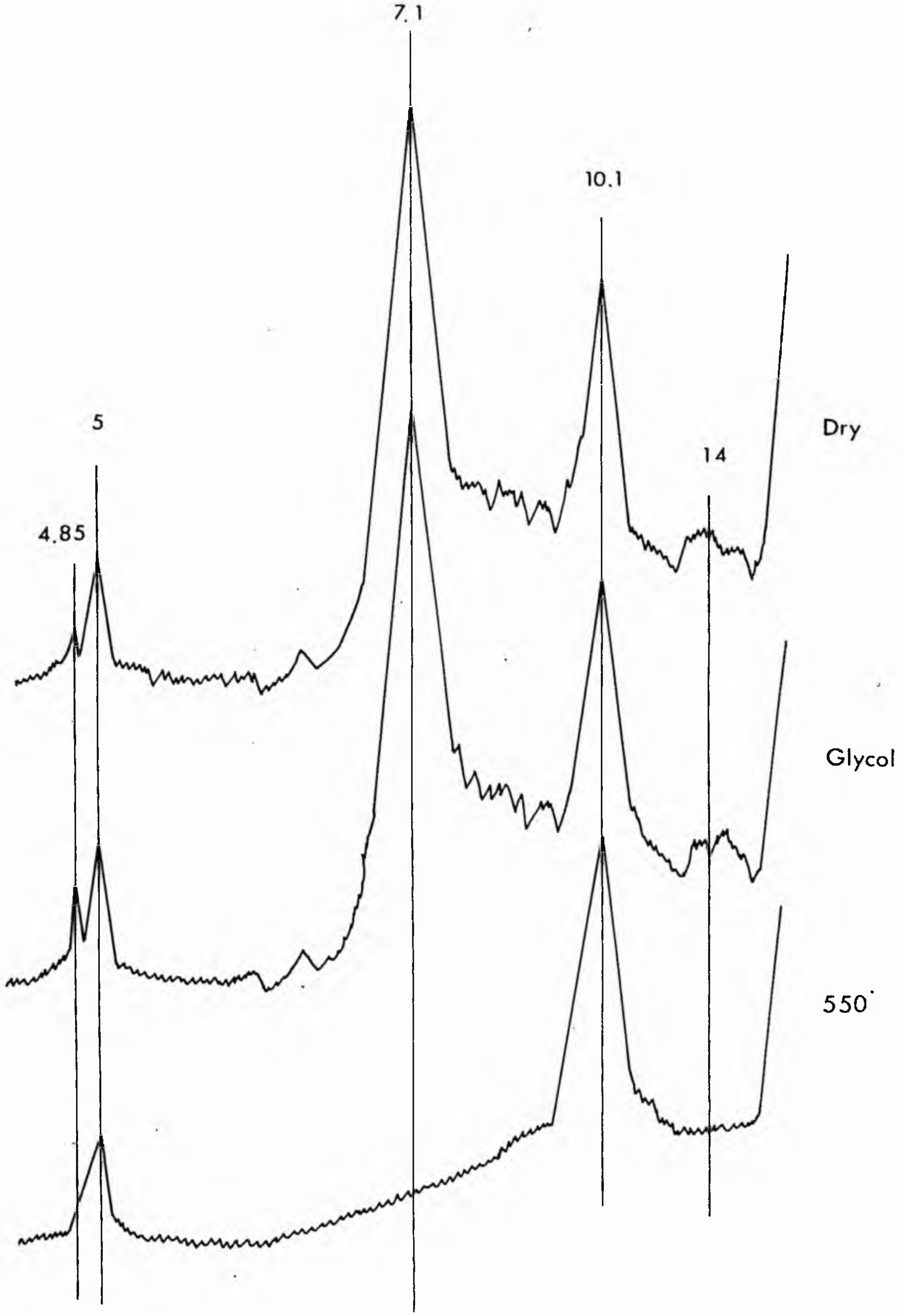


Fig. 8.5.i. Fetterangus

Other moderately altered quartzite grusses include the Balchimmy and Cairnbarrow profiles. The Cairnbarrow material is remarkable in its dominant smectite component (Fig. 8.5.ii). Smectite formation is prevented by rapid leaching and high silica concentrations (Millot 1970; Barhisel and Rich 1967) and its association with the alteration of a quartzitic rock is unusual. The smectite is probably a secondary mineral deposited by hydrothermal activity.

The highly altered clayey grusses are dominated by kaolinite, with varying amounts of illite and traces of quartz (Fig. 8.5.iii). The dominant clay mineralogy remains constant even in samples from sites of complex lithology such as Howe of Dens (Table 8.5.i) and Sunnyside, although vermiculite and goethite appear in small amounts in the bands of weathered quartz-felspar-mica schist (Fig. 8.5.iv).

In powder mounts, the kaolinite is often well-ordered (Fig. 8.5.v). However there are signs that halloysite varieties may form under poor drainage conditions (Whitestones ditch) or where bands of basic rocks are included in the quartzites (Gaval, see Fig. 8.4.vi).

8.5.2 Iron minerals

A number of samples contain small amounts of goethite and haematite. At Howe of Dens and Rannas, haematite occurs as a secondary mineral in the parent rock and its presence as a clay mineral may be due simply to remobilisation. At Mormond Quarry, haematite is found as a coating along fracture planes in the quartzite and as discrete, thin red lines along presumed former

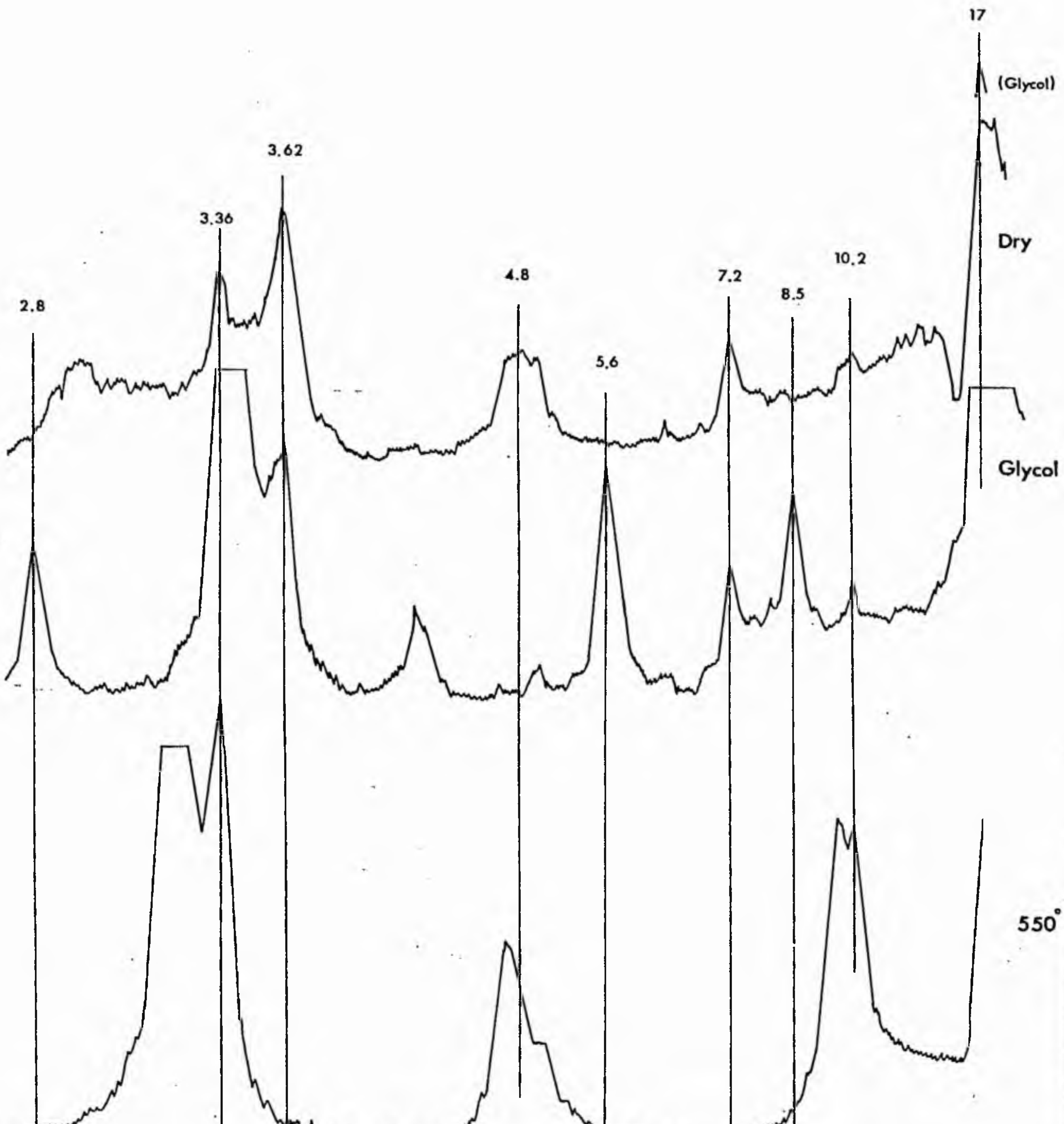


Fig. 8.5.ii. Daugh of Cairnbarrow

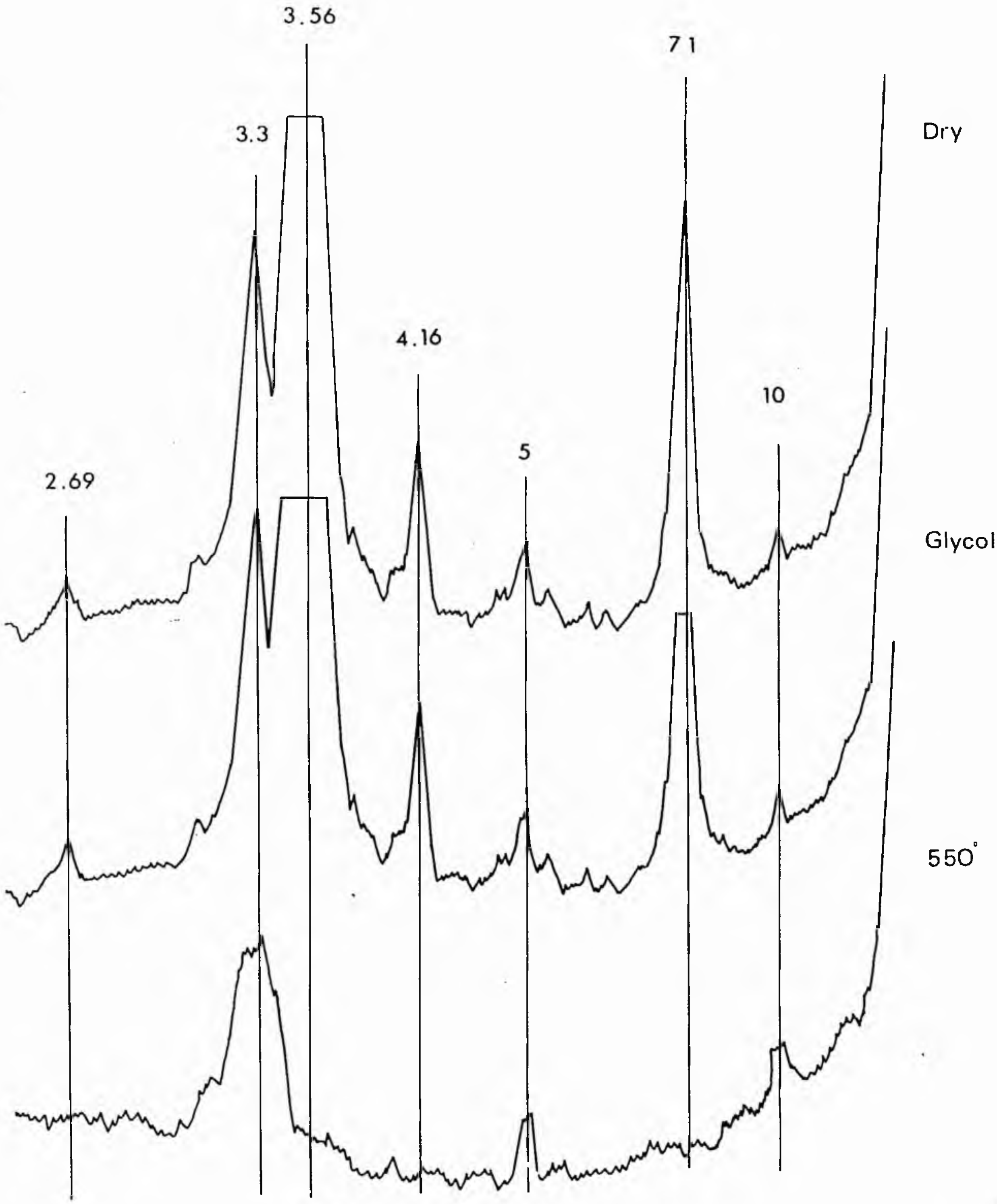


Fig. 8.5.iii.b. Drinnies Wood

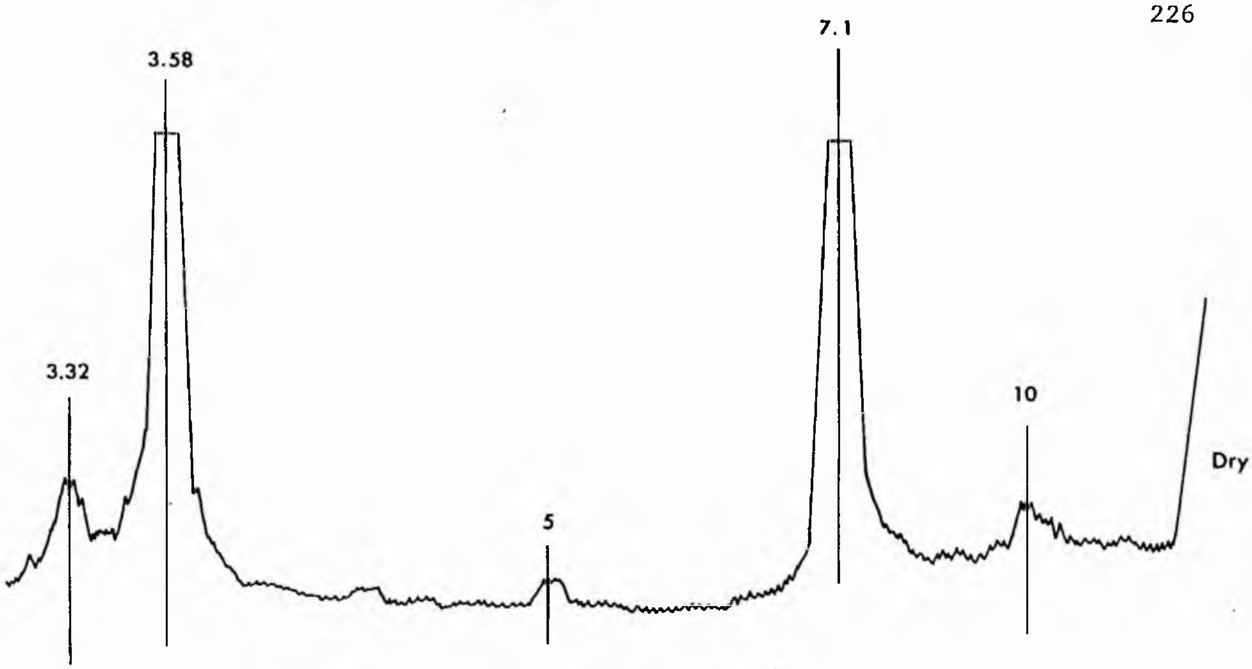


Fig. 8.5.iii.a. Mormond Quarry

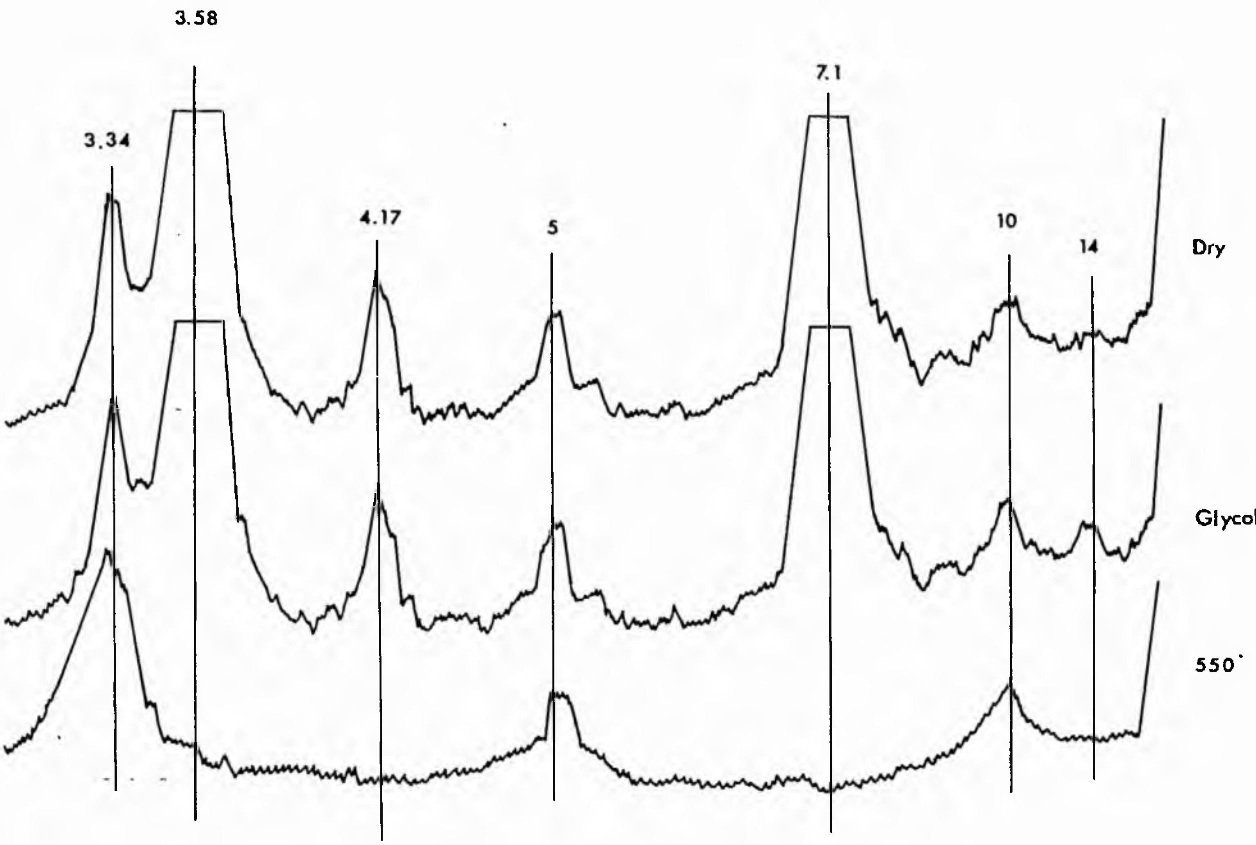


Fig. 8.5.iv. Howe of Dens S3b

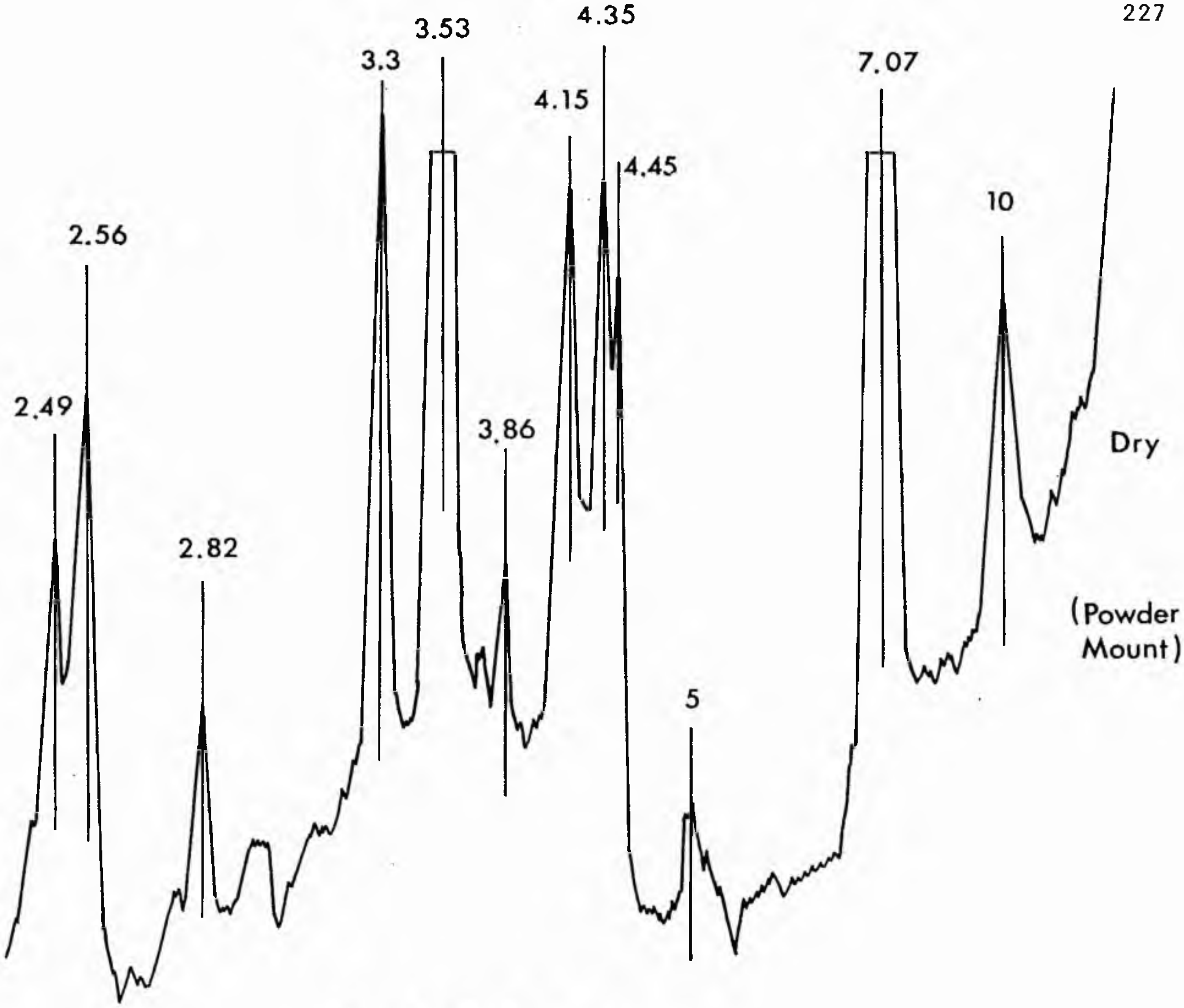


Fig. 8.5.v. Mormond Trench

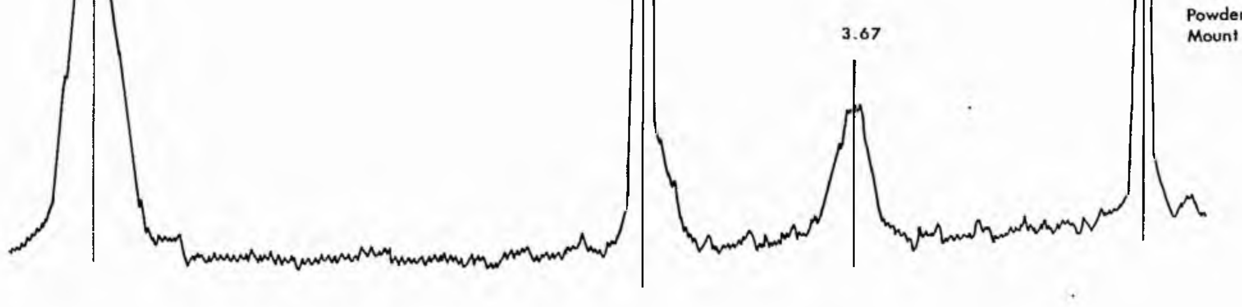


Fig. 8.5.vi. Mormond Quarry - iron oxide coating

fracture planes in kaolinised zones (Fig. 8.5.vi). The haematite predates kaolinisation of the felspathic zones as it is not disseminated through the kaolinised rock. The haematite may be a product of minor iron enrichment of the quartzite at a late stage of or even after crystallisation or of downward translocation of iron minerals from earlier weathering profiles.

The sections at Sunnyside (Fig.8.5.vii), Howe of Dens and Drinnies Wood (Fig. 8.5.iiib), contain zones of rubefaction where the iron minerals are undoubtedly products of neoformation. The presence of residual rubefied biotites in some Howe of Dens samples and at Drinnies Wood suggest that goethite and haematite may be neoformed after biotite.

8.5.3 Alteration of felspar

Due to the low amounts of minerals other than felspar and quartz in most of the quartzitic rocks, it is possible to identify the course of felspar alteration with progressive weathering.

	Alteration Products		
	Granular Gruss	Gruss	Clayey Gruss
Ca-felspar	Gibbsite Kaolinite Illite (?)	Kaolinite	Kaolinite
K-felspar	Illite	Kaolinite Illite	Kaolinite Illite

8.6 Other metasedimentary saprolites

8.6.1 Clay mineral assemblages

The weathered metasediments contain a highly varied suite of clay minerals (Table 8.6.i). Kandite and illite clays are

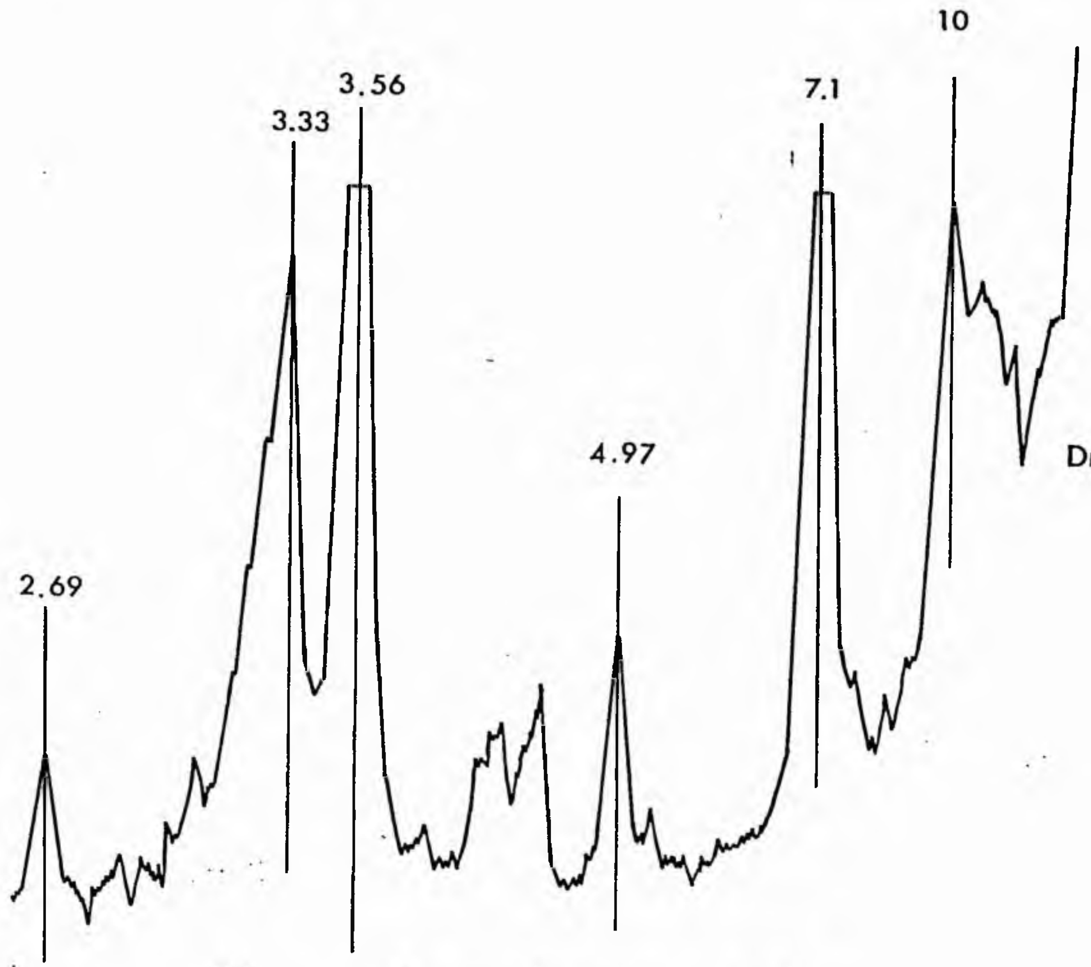


Fig. 8.5.vii. Sunnyside - rubefied zone

Table 8.6.i Clay mineralogy of other weathered metasediments

	Granulometric Type	Kaolinite	Halloysite	Illite	Chlorite	Vermiculate	Smectite	Gibbsite	Mixed Layers	Iron Minerals	Remarks
AUCHINTOUL	G	tr		X		XX	?				
BONNYKELLY	G	XXX		XX		X		tr	?		
BOYNE QUARRY	G	X		XX		?	XXX		X		
CAIRNHILL	G		X	X	X		XX		X		
CLAMANDWELLS	CG		XXX	XX		?				?	Geothite (?)
HILLFOOT	G	XX		XX							Amorphous Fe-Mn Oxides
HOWFORD	CG	XX	X	XX		tr					Amorphous Fe-Mn Oxides
KINMUCK	G	?		X	XX		?		XX		Swelling Chlorite
MONTGREW	G	XXX		X		tr					Amorphous Fe-Mn Oxides
NORTHSEAT	G		XX	XX		?	tr		?	tr	Lepidocrocite/ MnO_2
OLDMELDRUM	G		X	X		X	XX				Amorphous Fe-Mn Oxides
PX53	G	tr		XXX			X		?		Amorphous Fe-Mn Oxides
PX54	G	X	X	XXX			X			X	Lepidocrocite/ MnO_2
PX61	CA	XXX		tr							
PX69	G	XX		XX		X					Amorphous Fe-Mn Oxides
QX48	CA	XXX		X	X						
QX50	CA	XXX		X	tr						
YTHANBANK	G		X	X	?	?	XX		?		

important but large amounts of vermiculite and smectite may be present. Gibbsite is absent. By far the most important factor controlling the clay mineralogy of the weathered metamorphics is the composition of the parent rock.

Weathered quartz-mica schists are dominated clays of the kaolinite, halloysite and illite groups. Vermiculite is neoformed after biotite (Koppi 1977). Expanding clays are absent. The typical clay mineralogy is established in the less altered schist grusses (Fig. 8.6.i) and is reinforced by increasing alteration (Fig. 8.6.ii). The altered schist bands in the quartzites may represent the final stage of weathering reached in quartz-schists in this area, with reduction to bi-mineralic kaolinite-illite assemblages. The dominance of kandite-illite clays is due to the high silica contents of the quartz-mica schists and the type of alteration is comparable to that of the acid granites and quartzitic rocks.

In metamorphic rocks with high contents of ferro-magnesian minerals, kandite minerals become less important (Fig. 8.6.iii). Illite remains prominent but smectites may be dominant. Vermiculite may be neoformed after biotite.

Altered metalimestones and calc-schists are dominated by smectites and include mixed layer minerals (Fig. 8.6.iv). Smectite and chlorite are partly inherited from the parent rocks (Wilson et al 1968) but the low silica contents of the rocks will also favour smectite formation.

The weathered metamorphic rocks beneath the Buchan Gravels have distinctive assemblages. The pelitic alterites at Windyhills

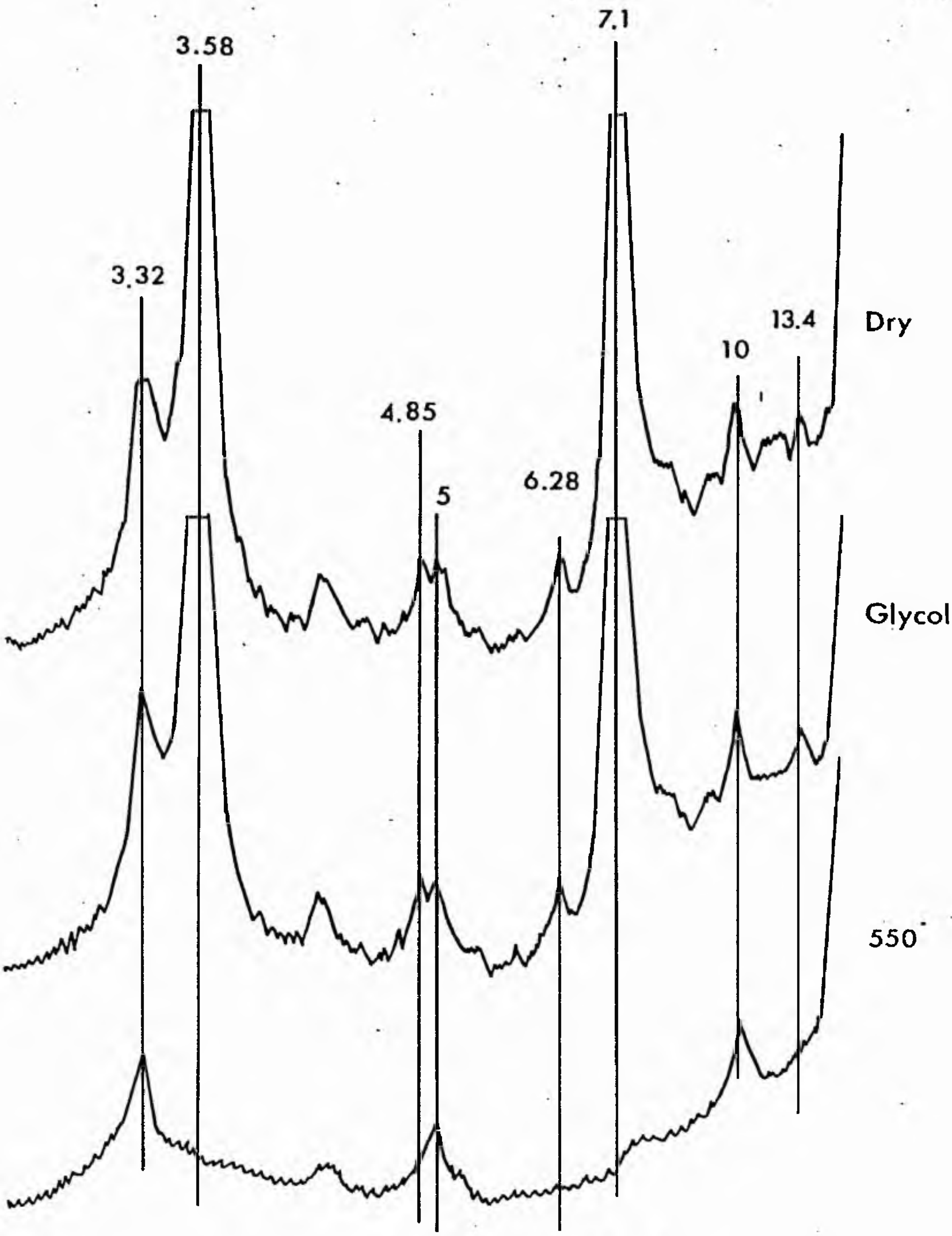


Fig. 8.6.i. Bonnykelly

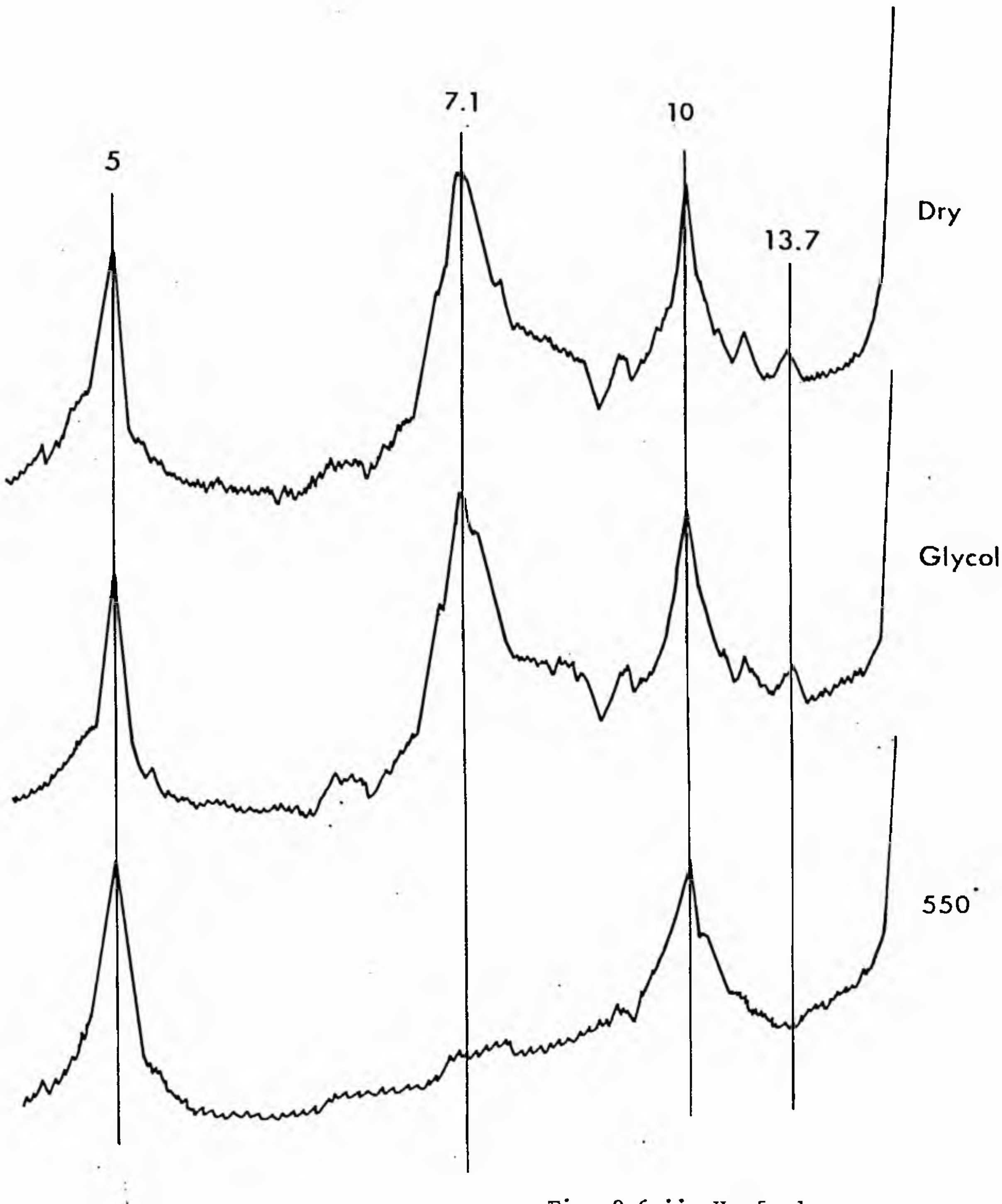


Fig. 8.6.ii. Howford

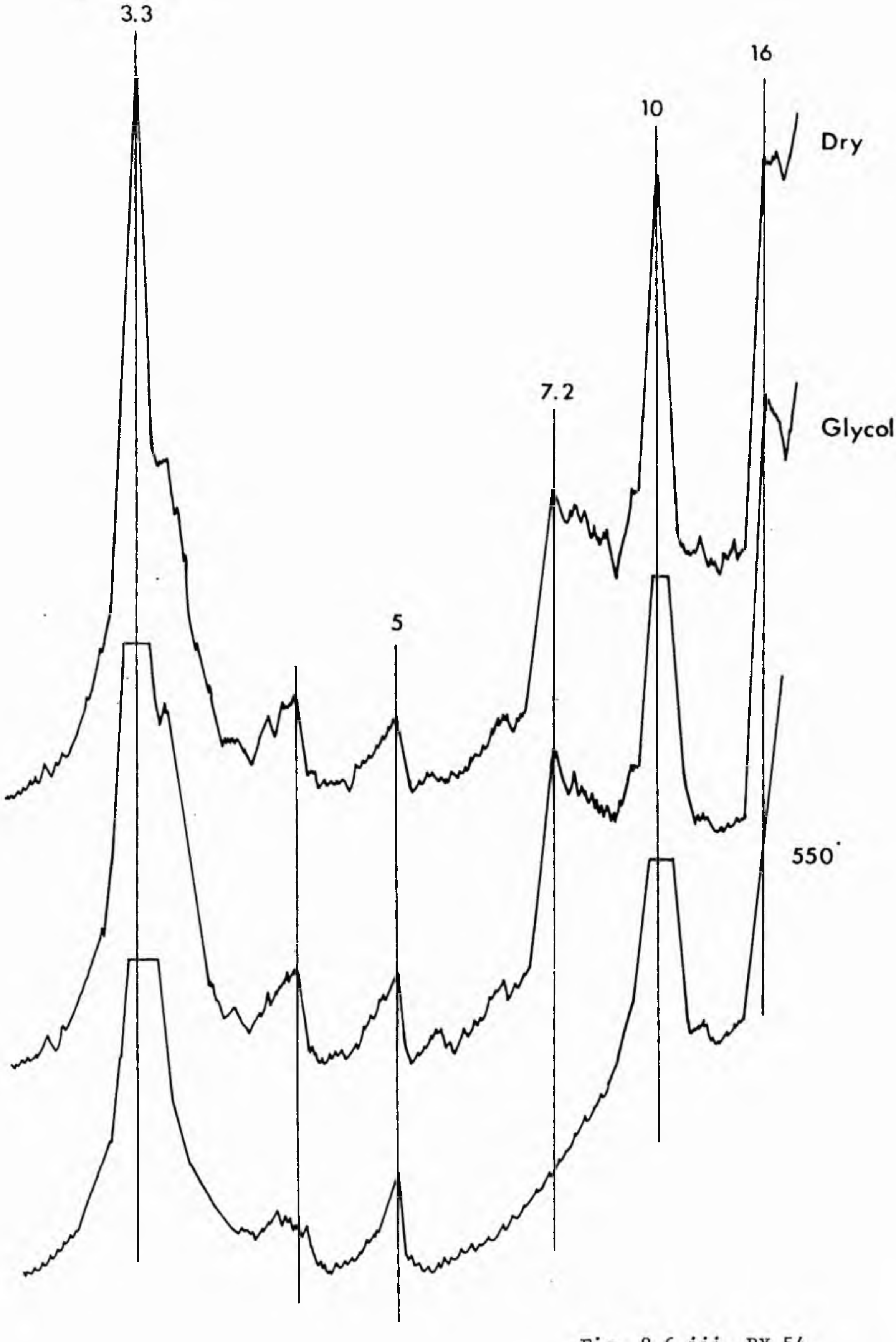


Fig. 8.6.iii. PX 54

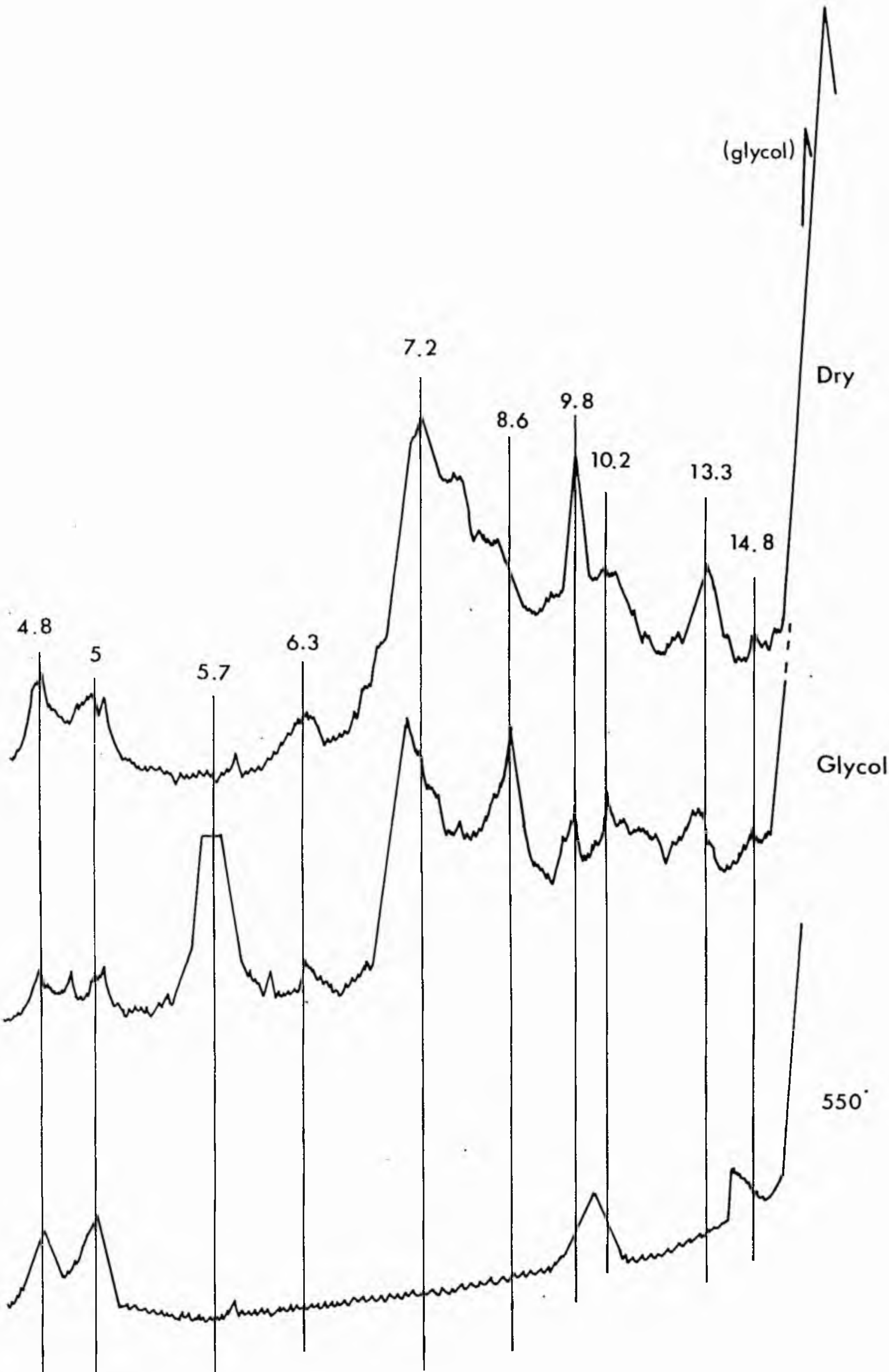


Fig. 8.6.iv. Cairnhill

are dominated by poorly-ordered kaolinites, with some illite and chlorite (Fig. 8.6.v). The weathered gneiss at Moss of Cruden is largely kaolinitic. The clay mineralogy of these alterites corresponds closely with that of altered clasts in the overlying deposits (Koppi and Fitzpatrick 1980) and with that of the matrix clays (see Chapter 10).

There is little systematic change in mineralogy with depth in the Northseat profile (Fig. 8.6.vi.).

8.7 Effects of rock type on the genesis of kandite clays

The weathered rocks contain various types of kandite clays. The varieties were investigated by slow scans of disoriented powder mounts over the 19.5-22^{o} range. This range contains the 3 peaks used in the calculation of the Hinckley (1954) crystallinity index for well-ordered kaolinites. Few of the kaolins are sufficiently ordered to allow crystallinity values to be calculated but the scan range can be compared visually with standard patterns for more disordered kandite varieties (Dimanche et al 1974). Illite, quartz and goethite all have reflections in the scan range and interfere with the kaolin reflections.

In weathered rocks of basic or intermediate composition, kandite clays are not generally dominant and disordered, halloysitic varieties predominate. Initially high concentrations of basic cations probably favour halloysite formation and dioritic arenes in Limousin are dominated by metahalloysite (Dejou et al 1972).

The kaolinites in the granite grusses are b-axis disordered to highly disordered (Fig. 8.7.i). The highly altered leucogranite

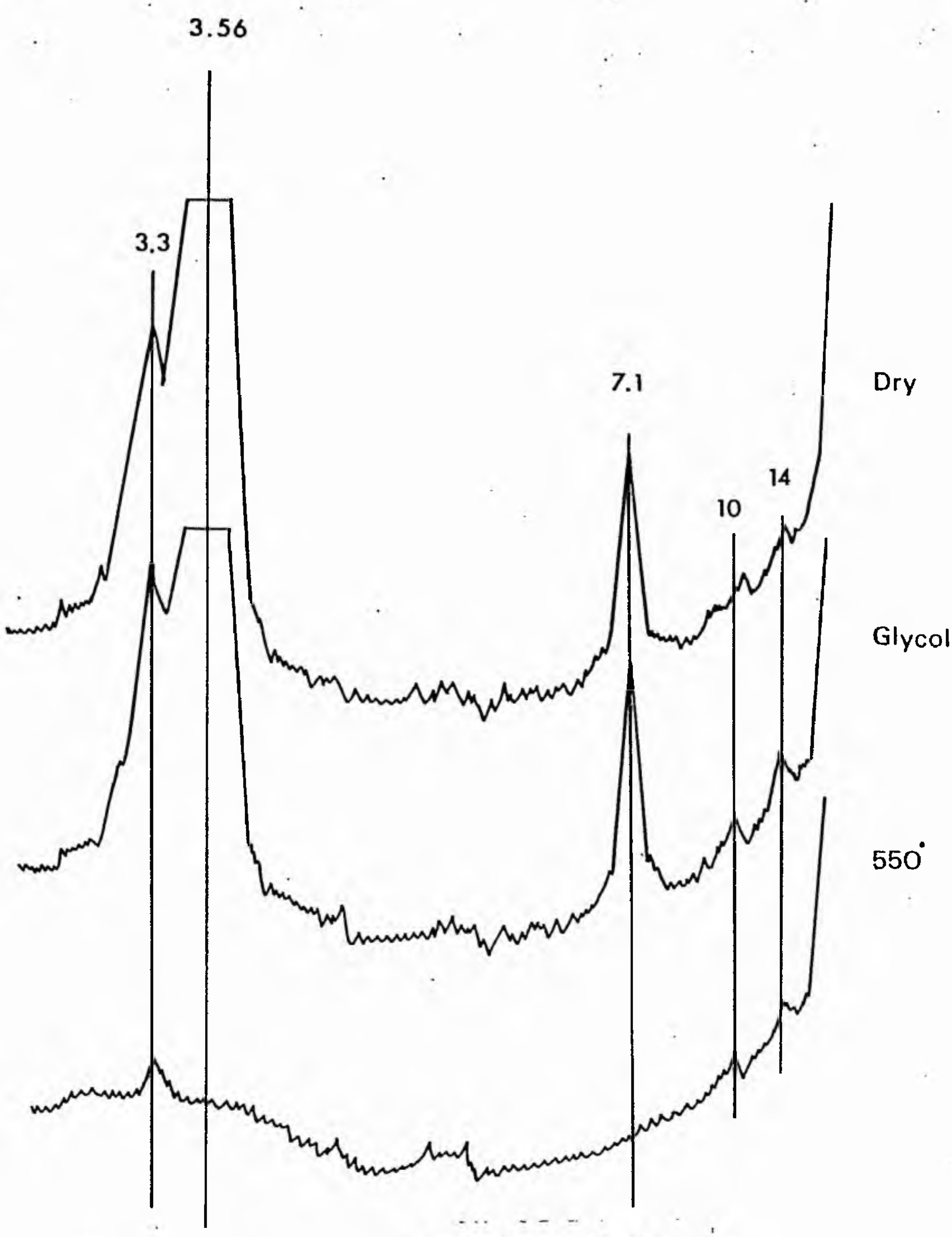


Fig. 8.6.v. QX 48

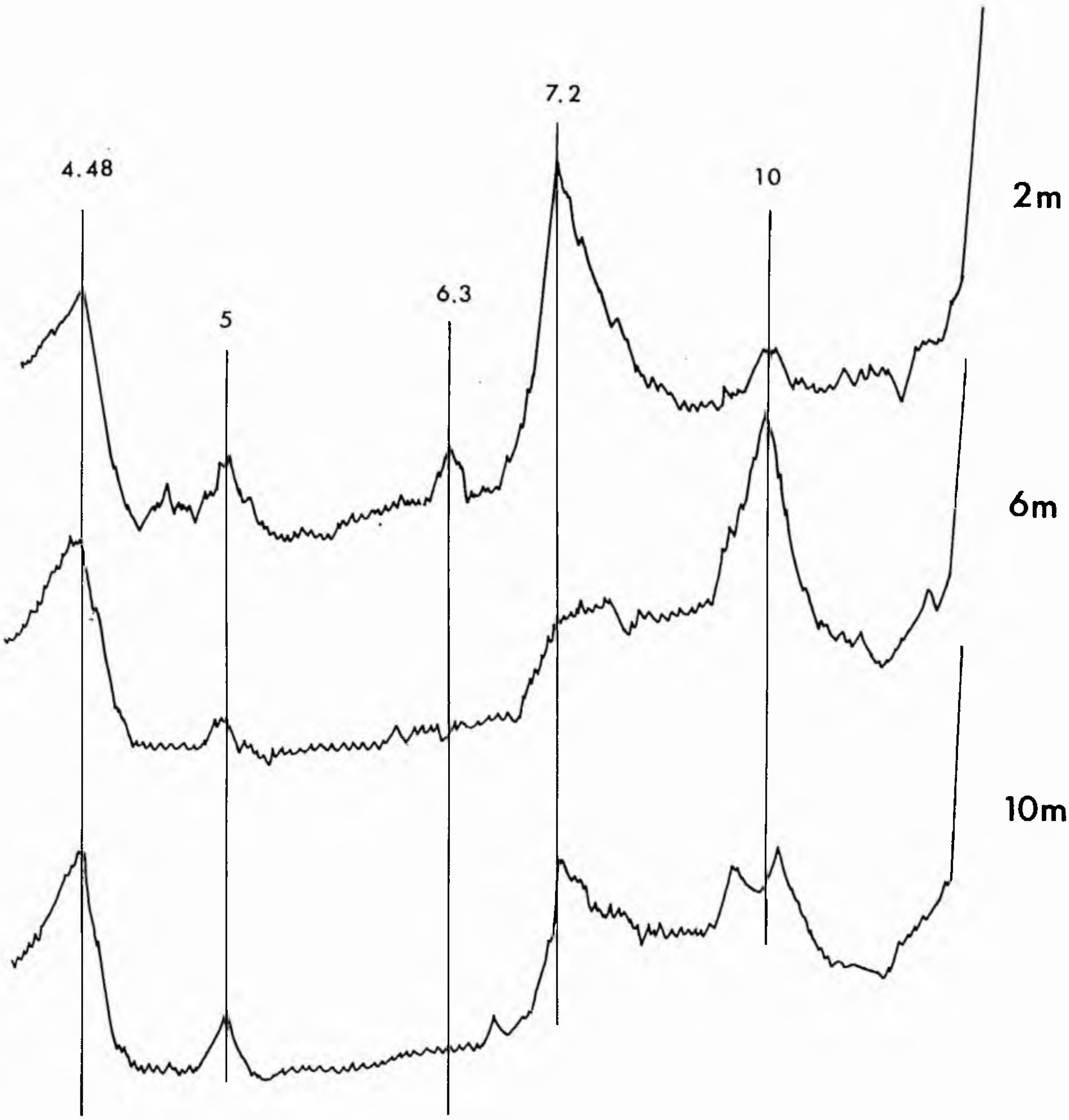


Fig. 8.6.vi. Northseat.
Variations in mineralogy
with depth.

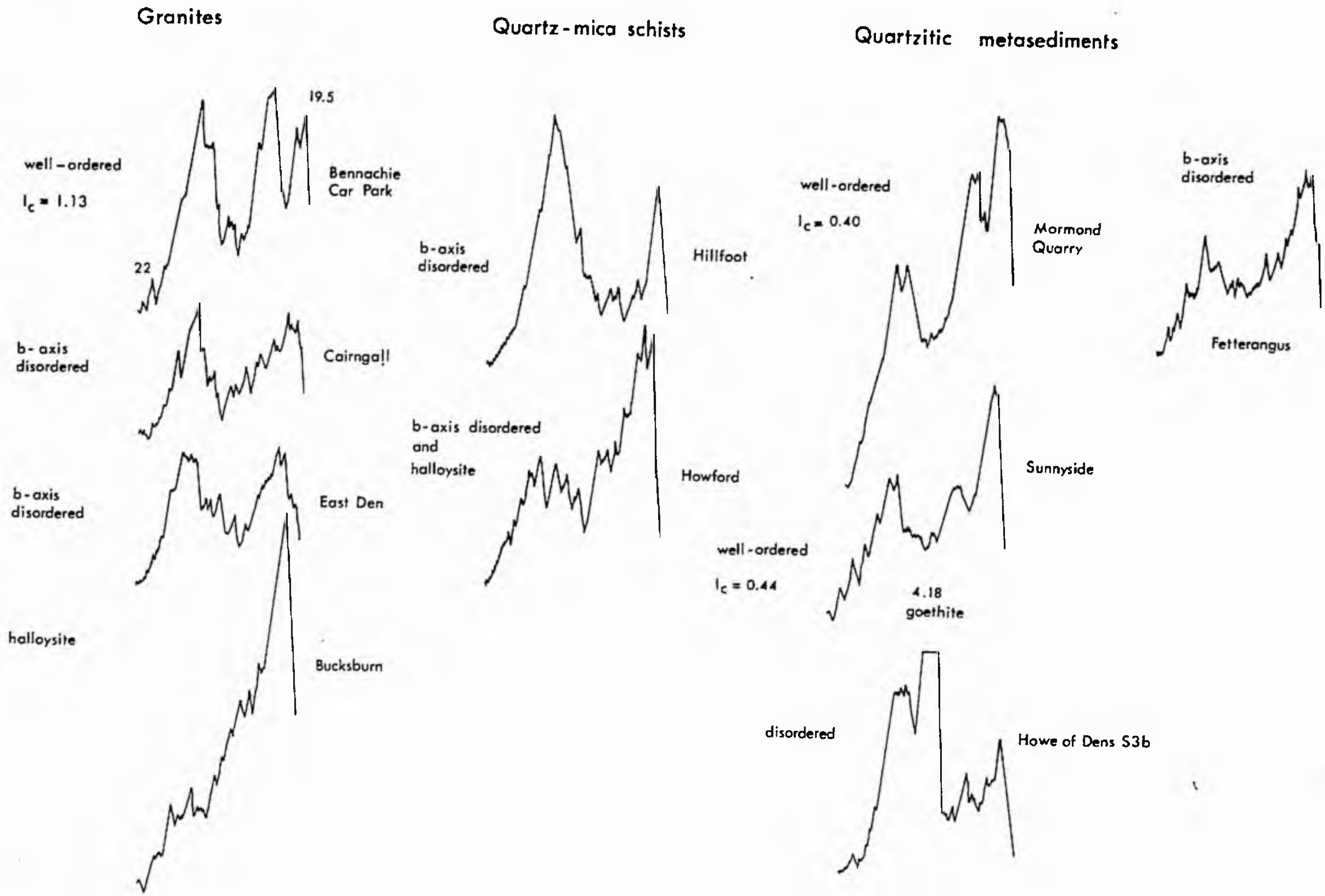


Fig. 8.7.i. Kaolin Crystallinity - Effects of Rock Type

I_c - Crystallinity Index (Hinckley 1954) at Bennachie C. P. is unusual in its degree of ordering.

The weathered quartz-mica schists contain b-axis disordered kaolinites and mixtures of b-axis disordered and halloysite types.

The kaolinites within the weathered quartzitic rocks are b-axis disordered to well ordered. Well-ordered varieties are characteristic of the less contaminated quartzites and kaolins within quartz-felspar-biotite schists at Howe of Dens and Drinnies Wood are less ordered. Kaolins in the less altered grusses at Fetterangus and Rannas are b-axis disordered. Drainage may affect kaolinite crystallinity as quartz-felspar psammites at Whitestones contain distinct kandite types under different drainage conditions (Fig. 8.7.ii).

The analyses indicate that kaolinite ordering is related to the acidity of the parent rocks and to drainage and that ordering improves with increasing alteration.

The relationships between the saprolite kaolinite types and the matrix kaolins of the Buchan Gravels are discussed in Chapter 10.

8.8 Influence of rock type drainage and climate on the genesis of clay minerals

The saprolites of north-east Scotland contain varied assemblages of clay minerals which demonstrate differences in both the type and degree (Pedro et al 1975) of alteration between sites. The type of alteration is greatly influenced by the composition of the parent rock and topographic control over drainage is locally important. The effects of climate on clay mineral type are obscured by these factors and allow only generalised comments to be made about palaeoenvironments.

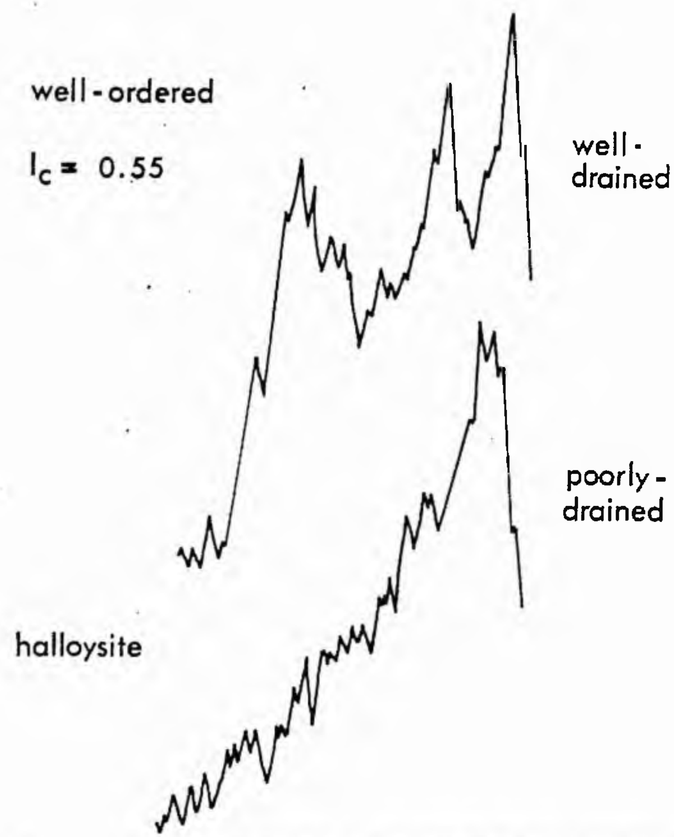


Fig. 8.7.ii. Kaolinite crystallinity at Whitestones.
Effects of drainage.

8.8.1 Rock type

The type of alteration is related to the amounts of silica in the parent rocks. In acid rocks, such as leucogranites, quartz schists and quartzites, stable clays appear at an early stage of alteration and bi-mineralic kandite-illite suites are quickly established. Rocks of intermediate composition produce more varied assemblages in which illites are often dominant and with important amounts of poorly ordered kaolinite and halloysite. Less stable 14A^{o} minerals and intergrades are common but smectite is usually absent or present in only small quantities. In the basic granular grusses, alteration is mainly restricted to the biotites, with transformation to hydrous mica clays. With increasing alteration, 14A^{o} clays and intergrades become significant but there is no clear trend towards smectite-dominated suites, as might be expected. Smectites are generally only dominant in ultrabasic rocks and where the mineral is inherited from the parent rock.

The importance of the mineralogical composition of the parent rock in determining clay mineral types is well illustrated by the case of gibbsite. Gibbsite appears as an early weathering product in acid igneous and metamorphic rocks and basic igneous rocks but usually not in rocks of intermediate composition. Formation of gibbsite is inhibited by high concentrations of silica in ground-water (Pedro and Delmas 1971) and the initial weathering of both acid and basic provides chemical environments suitable for gibbsite formation. In acid rocks, the low proportions of silicate and ferro-magnesian minerals will yield only modest amounts of silica to solution (Pedro et al 1975). The solubility of silica increases towards high pH's and aluminous hydroxides are left as residues from the desilicification of plagioclase in basic rocks (Wilson 1969).

The stability of the primary minerals varies with rock type. Biotites are less stable than plagioclase in the gabbros (Wilson 1967; Basham 1974) but in many granites these stabilities are reversed (see also Collier 1961; Harriss and Adams 1966). Biotite is also moderately stable in acid weathering environments as altered biotite-bearing rocks found within the quartzites, beneath the Buchan Gravels and as clasts within the Buchan Gravels (Koppi 1977) contain pleochroic biotite residues.

The influence of rock type over clay mineralogy is well documented (Seddoh 1973; Dejou et al 1974; Fritz and Tardy 1976). At the initial stages of rock alteration, exogenic factors have little effect (Dennen and Anderson 1962). The formation of alteration products is governed by local small-scale equilibria (Meunier and Velde 1979) and different clay minerals can form around individual primary minerals in response to micro-variations in crystal structure and to slight differences in the ionic composition of the groundwater solutions (Seddoh and Pedro 1975). With progressive grussification, the groundwater solutions become more homogeneous and dominant clay mineral types are established. Exogenic factors are increasingly important but the overall dominance of lithology is illustrated by the way in which weathered clasts of different rock types in boulder conglomerates contain distinct clay mineral assemblages (Table 8.8.i., see also Wilson et al 1971).

Table 8.8.i Total mineralogy of different rock types in a weathered boulder conglomerate, Virginia (from Barnhisel and Rich 1967)

Rock Type	%2u	Mont	Kaol	Qtz	Mica	Felspar
Pegmatite	2	tr	5	40	5	50
Granite	6	tr	30	40	20	10
Gneiss	18	5	50	45	1	1
Gabbro	25	70	20	10	tr	0
Gabbro	37	80	10	10	0	0

With continued alteration,the control of lithology will be reduced but it remains a significant influence on clay mineralogy even in clayey alterites in humid tropical environments (Blot et al 1976; Clemency 1976).

8.8.2 Drainage

Drainage influences clay mineralogy through its control over the rate of alteration of the primary minerals and its effect on the compositions of the groundwater solutions. In general terms, poor drainage will allow build up of basic cations in the saprolites and favour smectite formation. Good drainage encourages evacuation of basic cations and leads to kaolinite (Tardy et al 1973) and gibbsite (Gardner 1972) formation. Ideally, drainage differences lead to a weathering catena, with kaolinite-dominated saprolites in well-drained locations leading downslope to smectite-dominated saprolites in topographic lows (Tardy et al 1973). In practice, the situation is complicated by the fact that kaolinite may form and persist in environments with quite high concentrations of basic ions (Fritz and Tardy 1976; Koppi 1977).

Grusses offer a highly porous medium to the movement of groundwater and the early appearance of kandites and gibbsite in the granular grusses is a product of their free drainage. Drainage is rarely impeded in the sampled sections and the general scarcity of smectite is partly a result of this free drainage. Smectite does occur in borehole samples (PX 53, PX 54) of weathered gneisses from beneath fluvioglacial deposits in the Ugie valley and may be a more important mineral in the substantial depths of weathered rock known to exist beneath the water table in many areas.

There is evidence at many sites that drainage has changed over time. Lepidocrocite is present in several samples and this mineral is generally regarded as an indicator of hydromorphic conditions (Brown 1953; Schwertmann and Taylor 1977; Felix-Henningsen and Urban 1982). Staining of saprolites by hydrous ferro-manganese oxides is widespread and hydrous manganese oxides are commonly associated with waterlogged conditions (Koppi 1977). There are problems in using manganese minerals as evidence of present or former waterlogging, as these minerals are most commonly found in weathered biotite-rich rocks and may form continuously as biotite is altered. However manganese minerals are prominent in a number of Late Devensian fluvioglacial and glacial deposits (Tillybrex, East Pitscow and Upper Mill, Hatton) and these minerals have clearly been highly mobile and are concentrated in topographic locations with poor drainage. It can be expected that manganese ions derived from the alteration of biotite in free-draining locations will be quickly removed. The high concentrations of MnO_2 at Howford (0.24%) and the association of manganese minerals with lepidocrocite at Northseat, Redhouse and PX 48 suggest that manganese minerals do denote poor drainage.

Certain profiles contain lepidocrocite and/or manganese minerals, yet occupy free-draining positions in the present landscape. Most noteworthy are the Howford, Northseat and Redhouse sites which occur beneath steep valley sides, well above local water tables. Poor drainage conditions can only have prevailed at these sites before incision of the valleys and the presence of hydromorphic minerals is strong evidence for the relict nature of these saprolites.

8.8.3 Climatic Factors

The clay minerals of gruss weathering covers provide only indirect clues about climatic environments. In the early stages of weathering, the nature of the alteration products is largely determined by the composition of the parent rocks. Clay minerals in more mature grusses offer some guide to gross climatic characteristics (Borras et al 1975) but the effects of climate remain masked by local lithological and drainage controls. In addition, clay minerals are insensitive to climatic or environmental change (Singer 1980).

Climate can be split into two basic components, temperature and precipitation. Temperature has little effect on the nature of dissolution reactions (Pickering 1962) or the order of appearance of alteration products (Fritz and Tardy 1976). However temperature does govern the rate of alteration and, according to van t'Hoff's Rule, the speed of a chemical reaction will increase two or three times for each $10^{o}c$ rise in temperature. Experimental studies have shown that relatively small quantities of secondary minerals are formed at low temperatures (Fritz and Tardy 1976). Temperature will thus control the degree, rather than the type of alteration (Pedro et al 1975).

Temperature may be a factor in the genesis of iron minerals. In southern Europe red, kaolinitic ferreto palaeosols are confined to pre-Riss warm interglacial phases (Rutten 1963; Federoff 1965; Paepe 1968; Barriere 1971). In New Zealand, rubefaction of mature kaolinite-illite granite grusses requires warmer climates than at present (Te Punga 1964). The temperature threshold is uncertain but advanced rubefaction may require mean annual temperatures above 15^{o}c (Te Punga 1964; Pedro 1968; Thomas 1974b).

Precipitation will affect both the type and degree of alteration through its control over the rate of groundwater movement. High throughflow will hasten the removal of basic cations and lead to the more rapid development of siallitic saprolites. Low rainfall or the existence of a marked dry season will both reduce the rate of alteration and encourage formation of 2:1 minerals. Bisiallitic saprolites predominate under such conditions (Pacquet 1970) and may persist through periods of higher precipitation, as the base-rich secondary minerals will act as a buffer against the effects of higher throughflow.

8.9 Holocene clay mineral genesis in the soils of north-east Scotland

In attempting to establish the palaeoenvironmental significance of the saprolite clays, it is useful to consider Holocene clay mineral development in soils. In any comparison between saprolite and soil clays, it must be remembered that the actions of organic acids in soils greatly accelerates mineral breakdown (Ong et al 1970). Over similar time spans, soil clays will reach a more advanced stage of evolution. Nevertheless the soil clays do provide a good indication of the types of mineral transformation that have occurred under Holocene humid temperate climates.

Holocene soil development has acted on parent materials containing high proportions of clays inherited from pre-Devensian regoliths (Glentworth 1954; Glentworth and Muir 1963; Fitzpatrick 1963; Wilson and Tait 1977). Moreover the soils also contain relict, partially-altered primary minerals and separation of the inherited and Holocene elements in clay transformation is difficult (Mitchell 1963).

Alteration of primary and inherited secondary minerals has not advanced far in the Holocene. In granite tills, biotite is altered to trioctahedral illite and vermiculite and plagioclase are altered to dioctahedral illite (Mitchell 1963). These transformations are similar to those found in Norwegian podzols developed on granitic parent materials (Gjems 1967). Gabbroic soils contain similar alteration products to the underlying grusses (Wilson 1966; 1967; Basham 1974) and kaolinite may be actively forming in basic soils (Glentworth 1954). Halloysite clays are stable in soils (Wilson and Tait 1977). Chlorites are also little affected (Bain 1977), except in the A-horizons of podzolic soils (Stevens and Wilson 1970). Illites show limited transformation to hydrobiotite in Norwegian podzols (Kapoor 1972). The general trend of Holocene alteration is for transformation of the least stable minerals to aluminous 2:1 minerals (Gjems 1967). The types of transformation in the soils are broadly similar to those found in the less altered saprolites.

8.10 Clay mineralogy of saprolites in other humid temperate areas

8.10.1 Granites

Millot (1970) regards illite as the characteristic mineral of granite grusses and the "sandy weathering type" (Bakker 1967) in central Europe is dominated by kaolinite and illite clays. Plagioclase and biotite are the least stable primary minerals under temperate climates (Collier 1961). Plagioclase is considered to alter to kaolinite and montmorillonite, according to drainage conditions, and biotite to vermiculite (Tardy et al 1973).

General statements of this type ignore the variety of clay minerals within and between granite provinces. In south-west England, gibbsite is an initial alteration product in the Dartmoor granite (Green and Eden 1971) but illite and illite-vermiculite intergrades are dominant in two-mica granites in Cornwall (Butler 1953). In the Vosges, illite, smectite and vermiculite clays are all locally dominant but kandites are only of subsidiary importance (Tardy and Gac 1968). Stable illite-kaolinite suites are characteristic of rubefied grusses in Brittany (Esteouelle-Choux 1967; Meunier and Velde 1979) and in Valsesia, Italy (Giuseppetti et al 1963). Mature clayey grusses in the Harz Mountains contain kaolinite-gibbsite assemblages (Bakker 1967).

In the Massif Central, gruss types can be identified on the basis of distinctive clay mineral assemblages (Nieuwenhuis 1971;

Godard 1972; Seddoh 1973; Flageollet 1977). The grusses are associated with different topographic levels and represent an age sequence. Immature grusses in the valleys contain high smectite and vermiculite contents (Godard 1972). Other young arènes are dominated by kaolinite, with substantial amounts of illite, montmorillonite, vermiculite, halloysite and interstratified clays (Collier 1961). On the low plateaux of the Margeride, the arènes are predominantly smectitic, with occasional kandite dominance, and reflect the seasonality of precipitation in this area. At higher levels, deep, disconnected pockets show strong kaolinite dominance. The most highly altered saprolites are found on the high plateaux of northern Limousin. Rubefaction is widespread, kaolinite is dominant and large clay fractions contain up to 20% gibbsite (Godard 1972; Seddoh 1973).

Bakker (1967) claims that the "sandy weathering type" relates to climates "intermediate between those of the Gulf-state climate near the palm boundary (Cfa-climates) and the Mediterranean Cs-climate". In fact, the climatic significance of the clay minerals within many granite saprolites is uncertain. Clays cannot simply be related to Holocene climates, as many profiles are truncated and must predate this period (Seddoh 1973; Flageollet 1977; Meunier and Velde 1979). Even immature grusses must have experienced wide climatic fluctuations through the later part of the Pleistocene. Older saprolites are rubefied and contain stable clay mineral suites. These characteristics may be products of warmer palaeoenvironments but the effect of climate cannot be separated from that of progressive alteration over long time periods.

8.10.2 Basic igneous rocks

Wilson (1967) notes that the grussification of granodiorite in the warmer and more humid climate of Japan (Kato 1964) gives similar alteration products of the gabbroic soils of north-east Scotland. However gibbsite and vermiculite have also been recorded from the alteration of chlorite, amphibole and felspar in metadiorite in an alpine environment (Reynolds 1971). The similarity of the clay assemblages in these three climatically-contrasting areas underlies the tight control of rock type over clay mineralogy in the initial stages of alteration.

In Cornwall, hornblende gabbros are dominated by kaolinite (Butler 1953). Gabbros in Quebec give smectitic clays, with minor 14A^{o} minerals, and olivine, pyroxene and plagioclase are altered to montmorillonite and illite (Clement and De Kimpe 1977).

Highly-altered diorites in Limousin, France, and Geronne, Spain, are dominated by halloysite and kaolinite (Dejou et al 1972; Borras et al 1975). Basic clayey alterites in Brittany are smectite-dominated (Esteouelle-Choux 1967).

8.10.3 Quartzitic rocks

There are few studies of the weathering of quartzitic rocks. Sub-Cretaceous quartzites in Minnesota contain well-crystallised kaolinite with minor illite (Austin 1970). Weathered Eocambrian sandstones in the Rondane Mountains, Norway, also contain kaolin (Gjems 1963).

8.10.4 Other metasediments

Weathered biotite gneisses in Cornwall contain illite and kaolinite, with some vermiculite (Butler 1953). Illite is the only recognised clay mineral in altered mica schist in Normarka (Butler 1954). Clayey weathered biotite-plagioclase gneisses in Georgia are dominated by kaolinite (Grant 1964).

8.11 Discussion: the palaeoclimatic significance of the clay minerals in north-east Scotland

Only general comments can be made about the palaeoclimatic significance of clay minerals in the saprolites. The effects of climate are obscured by the dominance of the factors of lithology and drainage. Moreover comparison with other areas is difficult for saprolites elsewhere are often relict and of uncertain age.

The clay mineralogy indicates differences in both type and degree and alteration in north-east Scotland. These differences are a function of both climate and age and the two factors cannot be separated.

Many granular grusses and grusses show only minor alteration of the primary minerals. The secondary mineral types are closely governed by lithology. The presence of kaolinite and gibbsite in the granular grusses reflects their free-draining character but also implies generally humid climatic conditions. The similarity of the mineral transformations in the basic grusses with those of Holocene soils is consistent with development under climates little different from those of the present.

The alteration of felspars to illite and kandites in the granite grusses goes beyond the Holocene transformation of plagioclase to dioctahedral illite in granitic soils (Mitchell

1963). The illite-kandite type of alteration in the granite grusses resembles most closely that of the youngest arenes in the Massif Central (Collier 1961) and corresponds well with the clay minerals in the relict and temperate "sandy weathering type" in central Europe (Bakker 1967). In contrast, grusses in the Vosges contain higher proportions of 2:1 minerals (Tardy and Gac 1968). The similarity of the clay mineralogy of the granite grusses in north-east Scotland with that of grusses found in more southerly latitudes in Europe suggests formation under warmer climates. However rubefaction is not a characteristic feature of the Scottish grusses and temperatures need not have been far above those of the present.

There are many indications that the grusses formed under humid conditions with precipitation evenly distributed throughout the year:-

(i) The alteration of basic grusses tends towards kandite-illite-vermiculite suites.

(ii) 1:1 clays dominate weathered rocks of acid and intermediate composition and smectite dominance is largely restricted to ultrabasic rocks.

(iii) Kandites may be dominant even in profiles where hydromorphic minerals indicate the former existence of poor drainage conditions.

The trend of Holocene transformations in soils is for development of aluminous 2:1 minerals. The predominance of 1:1 minerals in the grusses suggests formation under climates with higher precipitation than at present.

The clayey grusses are highly altered. Ca- and K-felspars are kaolinised and biotites are partially transformed to kaonite and goethite. Several profiles are rubefied. The degree of alteration of the clayey grusses is comparable with that of more mature grusses in Brittany and the Massif Central. The clayey grusses probably developed under humid conditions with temperatures warmer than at present.

8.12 Summary

The saprolites of north-east Scotland contain varied clay mineral assemblages which demonstrate significant differences in the type and degree of alteration between sites. Rock type is the most important factor influencing clay mineralogy, especially in the earlier stages of alteration. Acid rocks tend to give kandite-illite dominated alteration products. Saprolites of intermediate composition have more varied clay mineral suites, in which illite is often dominant. The majority of basic rocks are not highly altered and the dominant transformation in the gabbroic grusses is the alteration of biotite to hydrous mica clays. The acidity of the parent rock has a major influence on kaolinite crystallinity.

The free-draining conditions in the granular grusses promote kaolinite and gibbsite formation in the initial stages of alteration of both acid and basic igneous rocks. Poor drainage locally affects clay mineralogy and smectites may be important where weathering penetrates below the water table. A number of profiles containing hydromorphic iron and manganese minerals now occupy free-draining sites, suggesting major changes in drainage status since formation of the saprolites.

General inferences may be made about palaeo-environments by comparing the types of transformations found in north-east Scotland with those characteristic of Holocene soils developed on similar parent materials and with those of saprolites from other regions. The transformations found in the basic granular grusses indicate formation under humid conditions with temperatures similar to the present. The clay suites of the granite grusses are comparable to those found in French and Central European weathered granites and formation under slightly warmer conditions than the present is inferred. The mature kaolinite-illite assemblages typical of the clayey grusses indicate formation over long time periods and the presence of rubefaction may indicate warmer climates.

CHAPTER 9 Weathering types and age

9.1 Saprolite characteristics and degree of alteration

Investigation of three key parameters, particle size, geochemistry and clay mineralogy, shows that rock type is a major source of variation in saprolite characteristics. At the early stages of weathering, gabbroic granitic and fine- to medium-grained metasedimentary saprolites form distinct granulometric populations. These populations reflect not only differences in the mineralogy and texture of the parent rocks but also the contrasting styles of initial disintegration of igneous and metamorphic rocks. The geochemistry of the saprolites is also closely related to that of the parent rocks and mineralogical variation is the main cause of differences in major oxide levels within profiles. Finally, rock type is a major determinant.of the clay mineralogy of the saprolites, especially in the initial phases of alteration.

Within the main lithological groups, the saprolites show a wide range of characteristics which reflect important differences in the degree of alteration. Saprolite granulometry is a product of both mechanical micro-division and chemical alteration (Millot 1970), but the size of the clay fraction is a useful index of the degree of weathering (Wambeke 1962; Seddoh 1973). Determination of the amount of chemical change between the parent rock and its saprolite allows the degree of alteration to be established (Brock 1943; Ruxton 1967). Clay mineralogy is perhaps a less sensitive parameter as the clay minerals are, to some extent, independent of the degree of alteration. Nevertheless, sequences of progressive alteration can be established for individual minerals (Godard 1972; Seddoh 1973; Tardy et al 1973; Koppi 1977).

Comparison of these parameters suggests that they give a generally consistent estimate of the degree of saprolite alteration (Table 9.1.i). The size of the clay fraction correlates non-linearly with levels of soluble base losses (Fig. 9.1.i). In granitic saprolites, these parameters are also related to the felspar/quartz ratio (Table 9.1.i and Eden and Green 1971). Where figures for actual base losses are unobtainable, due to the absence of comparative fresh rock samples, groupings based on estimated base losses largely correspond with those based on granulometry (Table 9.1.i). The relationship between these granulometric and geochemical parameters and clay mineralogy is less straightforward and quartzitic saprolites, clays of the kandite and illite groups may be dominant in samples belonging to any of the granulometric and geochemical groups. The type of alteration is thus, to some extent, independent of the degree of alteration (Pédro et al 1975), with stable clays forming in the early stages of weathering in response to free drainage and acid parent materials. In basic saprolites, sequences of progressive alteration are more easily recognised, with a tendency towards kandite-illite-vermiculite dominance with increasing alteration. In the metasedimentary saprolites, such sequences are obscured by mineralogical variations. Despite these difficulties, however, a clear trend can be recognised towards the development of bi-mineralic kandite-illite suites in saprolites belonging to the more granulometrically- and geochemically- evolved groups.

The parameters of granulometry, geochemistry and clay mineralogy demonstrate significant differences in the degree of

Table 9.1.i Comparison of parameters indicating degree of saprolite alteration

	GRANITE				BASIC				METASEDS		QTZTE		
	L'haven	Cairnlea	Blackrigg	Cairngall	Bennachie C.P.	Silverford	Fedderate	Gaval	Auchintool	Howford	QX 50	Fetterangus	Mormond Q
Granulometric Group	GG	G	GG	CG	CG	GG	G	CG	G	CG	CA	G	CG
% < 2u	0.2	1.9	1.7	6.8	17	tr	1.8	9.0	2.1	8.2	22.2	5.1	12.0
% <63u	2.5	14.4	12.7	19.9	45	6.7	11.3	35.0	20.0	41.3	94.7	19.6	32
F/Q Ratio (Eden and Green 1971)	1.2	0.9	1.2	0.2	0.1	-	-	-	-	-	-	-	-
% soluble base losses	5.9	53.4	58.6	70.5	95.4	19.0	31.1	-	-	-	78.9	-	-
Base Loss Group	1	2	2	3	4	1	2	-	-	3	3	-	4
Rubefaction	-	-	-	-	X	-	-	-	-	-	-	-	X
Dominant clay minerals	I K C	K	-	K I	K I	I V	G K I	K I V	V I	K I	K I	K I V	K I

GG - Granular Gruss G - Gruss CG - Clayey Gruss CA - Clayey Alterite

I - Illite K - Kandite C - Chlorite V - Vermiculite G - Gibbsite

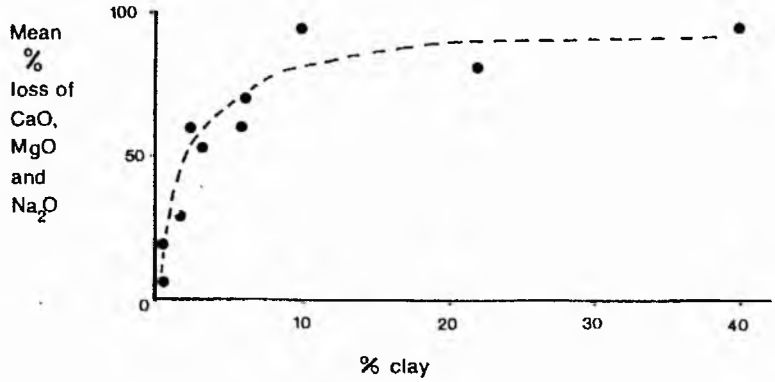


Fig. 9.1.i. Relationship between mean base losses and clay contents.

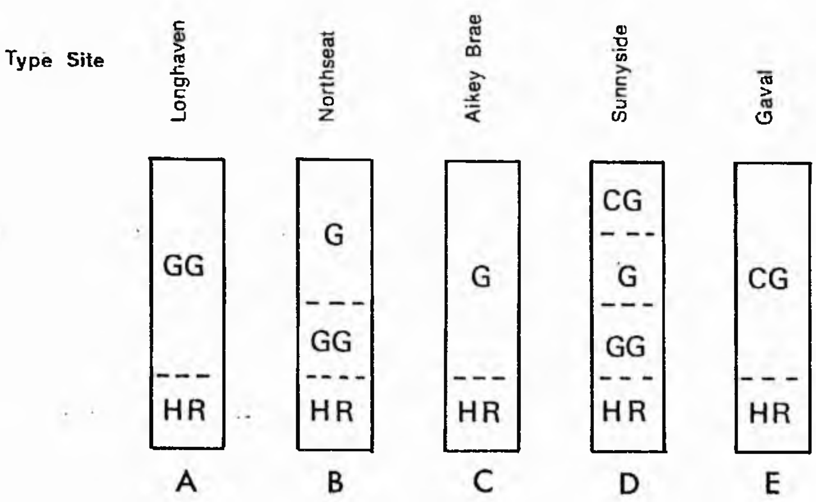


Fig. 9.4.i. Granulometric zones in weathering profiles.

weathering within the main lithologic groups. The range of variation is considerable and is of similar order to that reported by Bakker and Levelt (1964) from studies of weathering covers throughout central and western Europe. Bakker (1967) distinguishes two main weathering types of different age on granites in Europe on the basis of granulometry and clay mineralogy. The "clay weathering type" contains 15-30% clay of mixed illite-kaolinite composition. The "sandy weathering type" contains 2-7% clay of mainly kaolinite-illite types and would include many of the granite grusses of north-east Scotland. Other studies recognise similar distinctions (Esteouelle-Choux 1967; Tardy 1969; Millot 1970; Furtado 1974; Kiselev 1975). With detailed mineralogical work, it is possible to subdivide the "sandy weathering type" (Nieuwenhuis 1971; Godard 1972; Seddoh 1973; Flageollet 1977). However, before the degree of alteration can be related to the age of the Scottish saprolites, it is first necessary to consider other factors which influence the rate and intensity of alteration.

9.2 The contribution of hypogene alteration

Consideration of hypogene alteration is important in any discussion of the origin and age of decomposed rocks. Hypogene alteration can form secondary minerals which are indistinguishable from the products of supergene weathering (Konta 1969). Moreover even quite minor late-stage modification can substantially weaken the parent rock and prepare the way for subaerial alteration (Eggler et al 1969; Kennan 1973; Samuellson 1973). Saprolites developed from rocks modified by hypogene alteration will tend to be highly altered in comparison with saprolites derived from unaffected rocks. Unless the contribution of hypogene alteration is recognised, false conclusions may be drawn about the age and significance of the saprolites.

It has been suggested that the extraordinary development of decomposed rock in north-east Scotland is a result of regional hydrothermal activity (Peacock and Michie 1975). However decomposition affects metamorphic, igneous and dyke rocks of Moinian to Permian age and no single period of post-magmatic alteration can be recognised. Moreover decomposition occurs widely in the Devonian Old Red Sandstones and alteration is especially intense in the unconsolidated Buchan Gravels. There is also little doubt that decomposition generally extends downwards from the surface, for sections and boreholes show a decrease in the degree of rock weathering with depth.

Although most decomposition is of supergene origin, subaerial weathering has been superimposed on rocks weakened by post-magmatic alteration. Uralitisation affects a number of the Younger Basic intrusions (Ashcroft and Munro 1976). Certain granites also show signs of limited post-magmatic alteration, with chloritisation of biotite in the Aberchirder granite and the dioritic parts of the Peterhead granite, and with partial kaolinisation of plagioclase in the Strichen granite.

Evidence of hydrothermal alteration can be found at several sites. Veins of chlorite cut the granites at Redhouse and Longhaven and films of illite coat fracture surfaces in granite at Ballater (McKenzie et al 1949). The deep funnels of decomposition amid the fresh granodiorite at Cairngall Quarry follow zones in which plagioclase is partially kaolinised (Plate 9.2.i). Fragments from the lowest exposed parts of the funnels are silicified along fracture surfaces and alteration increases away from the fractures. Deep alteration of parts of the felsite dyke at Kirkhill (Plate 9.2.ii) probably dates from the time of injection, as the diorite country rocks have been chloritised in contact with the dyke. Hydrothermal alteration of dykes in the Peterhead granite has also been reported (Edmonds and Graham 1977).

There is little evidence of hydrothermal alteration at most sites. Many sections show decreasing alteration with depth and most deep boreholes eventually bottom on fresh rock. No phase of regional hydrothermal alteration is indicated and, apart from a few important exceptions, decomposition is a result of subaerial weathering.

9.3 Variations within weathering toposequences

Due to spatial variation in rates of groundwater flow, there will be differences in the type, degree and depth of alteration within weathering toposequences (Tardy et al 1973). In the study area, profile truncation creates major difficulties for any systematic study of toposequences and the level of variation in the degree of alteration is uncertain. However, closely-spaced samples from areas underlain by single rock types suggest that variation is limited. Weathered gabbros on the Insch and Boganclogh masses have consistently low clay contents and similar clay mineral assemblages (Basham 1974). The numerous exposures of weathered grey granite along the western edge of the New Pitsligo basin all fall into the granular gruss and gruss

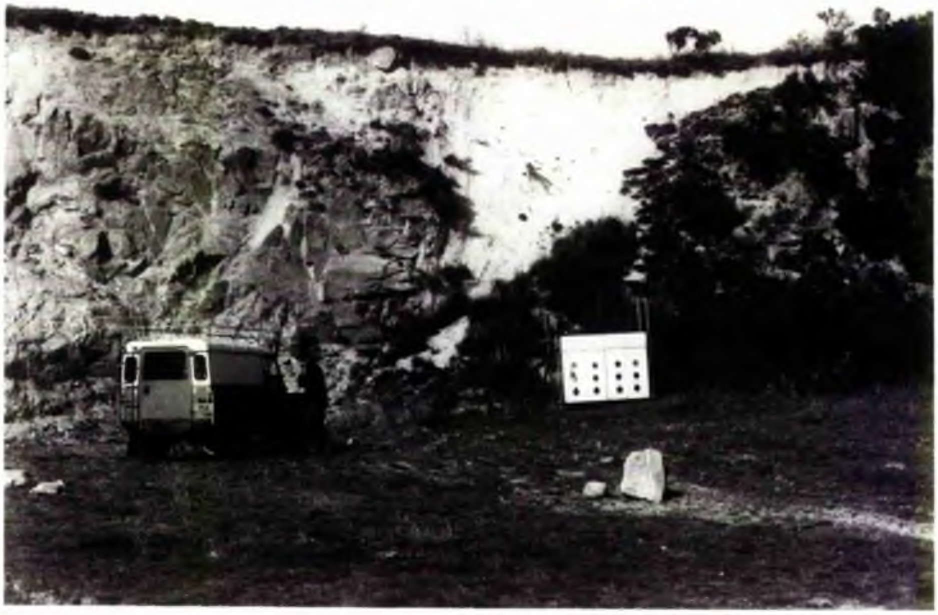


Plate 9.2.i. Hydrothermally-altered microgranodiorite at Cairngall. Supergene weathering has exploited zones in which hydrothermal activity has caused partial kaolinisation of felspars and silicification along joint planes.

Plate 9.2.ii. Hydrothermally-altered diorite in contact with a quartz-porphyry dyke, Kirkhill.

granulometric groups and kaolinite-illite clays are invariably dominant. These examples indicate that the variation in degree of alteration within toposequences is no greater than that found within individual profiles.

9.4 Zonation in weathering profiles

In warm environments, weathering profiles often exhibit characteristic zones or horizons, with varied mechanical properties (Ruxton and Berry 1957; 1961; Bayliss 1971; Thomas 1974a and b). Dissection of landscapes developed on such weathering covers exposes weathering zones at different stages of alteration (Ruxton and Berry 1957), but of common age. This kind of model of weathering and slope development has clear relevance to the problem of the age of the saprolites in north-east Scotland. In view of the widespread evidence for profile truncation in the area, it could be proposed that the observed differences in the degree of alteration between profiles are solely a result of differential stripping of zoned profiles. All remaining saprolites would then be of common age. The extent of zonation in the saprolites is thus crucial to questions of their relative age.

The saprolites generally show only gradual changes in granulometry and clay mineralogy with depth and zonation is not well developed. Moreover, it is clear that the depth of weathering is only loosely related to the degree of alteration, as deep profiles may be found in illite-altered saprolites, as at Longhaven. However, both deep sections and boreholes show that the degree of alteration often decreased with depth. By using granulometry as an indicator of alteration, it can be seen that the degree of alteration varies both between and within profiles (Fig. 9.4.i). Each granulometric group may rest directly on fresh rock (Profiles A, C and E) but profiles including all of the main granulometric groups can also be recognised in boreholes (Profile D). This complex picture reflects the existence of (i) profiles of different age and (ii) profiles of similar age at various stages of truncation.

Inferences about the relative age of the saprolites must be treated cautiously but the following conclusions appear valid:-

(i) Profiles of type D and E, which include zones of clayey gruss, are highly altered and are amongst the oldest group of saprolites.

(ii) Profiles of type A, B and C may be truncated basal portions of profiles of type D. However, a common age is only likely where profiles of type A, B and C occur in close proximity to profiles of type D.

(iii) Profiles of type B and C are younger than profiles of type D and E in areas where these latter profiles do not occur. The reasons for this conclusion are:-

(a) In most areas, there is no evidence from soil and drift mineralogy for the redistribution of highly kaolinitic surface horizons (Glentworth 1954; Glentworth and Muir 1963; Basham 1974).

(b) Boreholes in several areas show that profiles of type B and C reach depths of over 20m, indicating that phases of deep weathering have occurred since development of the clayey grusses.

(c) The clay mineralogy of most grusses indicates free-draining conditions during weathering and is not consistent with neoformation at the base of profiles.

(iv) Profiles of type A will generally be either:-

(a) the truncated basal parts of profiles of type B

or (b) relatively young profiles in the early stages of alteration.

Alternative (a) is supported by the existence in boreholes of thick transitional zones of similar characteristics to the granular grusses and lying beneath gruss-type material. Stripping of saprolites must have exposed these transition zones over wide areas.

Alternative (b) is supported by the existence of deep granular gruss profiles. The mineralogy of many of these deep granitic and gabbroic granular grusses again indicates free-drainage. Many of such granular grusses probably represent episodes of renewed weathering.

Recognition of the variety of profile development focusses attention on the continuity of the weathering process (Nikiforoff 1949). The older, clayey gruss profiles are of restricted distribution. In many areas, these relatively highly-altered profiles have been wholly or partially stripped. Renewed weathering has created deep, composite profiles, composed entirely of grusses and granular grusses. Finally, Pleistocene glacial and periglacial processes have truncated profiles of different age and exposed the basal parts of the profiles to further weathering.

9.5 Weathering types

The range of variation in the degree of alteration in the saprolites within the main lithologic groups indicates the existence of weathering types of different age. Profiles including clayey grusses can be regarded as relatively old. However the degree of alteration cannot be directly interpreted in terms of age in profiles composed of grusses and granular grusses, due to the presence of composite profiles and of profiles at different stages of truncation. Accordingly, a simple bi-partite division is proposed for the saprolites of north-east Scotland, with classification as either "gruss" or "clayey gruss" weathering types. The classification highlights the differences in relative age between the two weathering types. Moreover, the distinction is very similar to that made by Bakker (1967) between "sandy" and "clay" weathering types, a distinction which has been widely applied in Europe (Esteouelle-Choux 1967; Millot 1970; Kiselev 1975; Lidmar-Bergstom 1982).

9.5.1 Summary characteristics of the weathering types

(A) The "gruss" type

In the gruss type, clay fractions are below 7% and fines do not exceed 25%, except in fine-grained metasediments.

The degree of chemical alteration is modest and the grusses contain large amounts of little-weathered felspar and biotite. Losses of Ca and Na are high. Losses of Mg are modest and Si and Al show only slight changes.

Clay mineral assemblages are varied and rock type is a major influence. In acid rocks, the dominant mineral transformations are:-

Ca-felspar-	gibbsite and kaolinite
K-felspar-	illite
Biotite-	hydrobiotite and vermiculite

Granite grusses also contain significant amounts of 14A^{o} and intergrade minerals.

In the basic grusses, biotite alters to hydrobiotite and vermiculite and illite is the dominant alteration product of felspar. Halloysite, kaolinite, smectite, chlorite and intergrade minerals are all locally important.

The gruss type includes saprolites in the first stages of disintegration and alteration. Median grain sizes are high and clay contents are very low. Chemical alteration is weak and transformations of the primary minerals are limited. These saprolites are termed "granular grusses".

(B) The "clayey gruss" type

The clayey gruss type includes relatively few sites. The type includes the clayey gruss and clayey alterite granulometric groups (see Section 6 .9). Clay fractions are above 7% and occasionally exceed 20%. Fines contents are high, usually well above 30%.

The clayey grusses are highly altered. The detrital primary mineralogy is dominated by quartz, with minor K-felspar and biotite residues. Ca and Na are almost totally depleted and losses of Mg are heavy. Losses of Si are considerable and Al is enriched.

The clay mineral assemblages are dominated by kaolinite, with varying amounts of illite. The dominant mineral transformations are:-

Ca-felspar	Kaolinite
K-felspar	Illite and Kaolinite
Biotite	Vermiculite, Kaolinite and Goethite

A number of clayey grusses are rubefied due to the presence of haematite and goethite.

9.6 The age of the weathered rock: lines of evidence

Previous workers have suggested a variety of ages for the weathered rock in north-east Scotland from post-glacial (Wilson and Hinxman 1890; Carruthers 1950) to Neogene (Fitzpatrick 1963; Walsh et al 1972). The wide range of dates reflects the use of different types of evidence, the predominance of local studies and the difficulties involved in dating saprolites. However by employing the various lines of evidence supplied by deposits, the geomorphic relationships of the weathering, depths of alteration, clay mineralogy and comparisons with saprolites elsewhere, it is possible to arrive at firm estimates of the relative ages of the weathering types.

9.6.1 Evidence from deposits

Deposits provide evidence of the age of saprolites where weathering profiles are overlain by sediments (Bakker and Levelt 1964; Williams 1968; Austin 1970; Kalliokoski 1975), by their composition (Millot 1970; Rosenqvist 1975; O'Sullivan 1979) and by the type and degree of post-depositional alteration (Alimen and

and Caillere 1964; Icole 1970; Hubschmann 1975). Unfortunately, deposits offer little guide to the age of saprolites in north-east Scotland as few pre-Devensian deposits have been recognised in the region.

Glacial and fluvioglacial deposits of presumed Late Devensian age indicate that deep weathering predates the Late Devensian. Flandrian soils developed on these deposits contain much matrix material which is derived from older regoliths (Glentworth 1954; Glentworth and Muir 1963; Fitzpatrick 1963; Basham 1974; Wilson and Tait 1977). Beneath the soil layer, clasts are usually fresh. In certain cases, fresh clasts occur in till which are identical in composition to the parent rocks of the subjacent saprolites. Decomposition of bedrock in these cases must predate deposition of the till (Phemister and Simpson 1949). The discovery of rafts of weathered granite showing fold and drag structures within till on the lee side of Tyrebagger Hill (D.E. Sugden Pers. Comm. 1982) is further confirmation that the weathering occurred before the last glaciation.

Evidence from periglacial features supports a pre-Late Devensian age for the weathering. Weathered rock is incorporated into solifluction deposits and is penetrated by frost wedges. As some solifluction deposits have been dated as Late Glacial (Zone III), deep rock weathering must predate the Late Devensian.

In other parts of Scotland where glaciation has exposed the basal surface of weathering, Flandrian weathering has had little effect. Even in the acid environments beneath peat, bedrock is generally fresh (Godard 1965), although shallow decomposition can be found beneath seepage zones.

Flandrian rock weathering has been limited. However many free-draining deposits contain decomposed clasts in the surface layers (Carruthers 1950). Decomposition is restricted to the least resistant lithologies, often the biotite-bearing varieties, and development of fines is insignificant. The decomposition of clasts in the tills and fluvioglacial deposits suggests that shallow grussification of rocks of low resistance may have occurred in the Holocene.

Tills reliably dated as pre-Devensian are rare. The pre-Ipswichian weathered till at Kirkhill (Connell et al 1982) contains significant amounts of detrital kaolinite, probably derived from weathered acid igneous and metamorphic rocks to the west. Parts of the basal till at Boyne Quarry are weathered (Peacock 1966) and alteration extends for about 0.5m into bedrock. However weathering does not affect the whole basal till unit and probably results from lateral movement of groundwater along the till-bedrock interface.

Undated, but possibly preglacial, channel-fill deposits in the lower Spey valley contain illite and kaolinite (Aitken et al 1979). The clay mineralogy is consistent with derivation from moderately-altered acid saprolites.

The Buchan Gravels provide evidence of the relative ages of the two weathering types. The composition of the deposits suggests that the Buchan Gravels predate the gruss type but incorporate materials from the clayey gruss type.

Neogene marine sediments in the central North Sea basin are dominated by smectite clays. Proportions of kaolinite increase in the Middle Miocene. Kaolinite and smectite decrease and illite and chlorite increase in the Upper Miocene and reflect climatic cooling and higher rates of terrestrial erosion (Karllson et al 1979; Berstad and Dypvik 1982). The component of terrigenous clays from north-east Scotland within these marine sediments is unknown.

9.6.2 Geomorphological evidence

The landforms of the region provide the following information about the timing of weathering phases:-

(i) Landforms of glacial and fluvioglacial erosion have exploited pre-existing weathering patterns. Development of the weathering must predate at least the last glaciation.

(ii) Several weathering profiles contain mineralogical evidence of former waterlogged conditions. The sites are now free-draining and considerable landscape modification has occurred since waterlogged conditions prevailed at these sites. At the Howford site, formation of hydromorphic minerals must predate deep incision of the North Ugie Water. Hydromorphic minerals at Northseat must also have formed before incision of the local tributary drainage, for the section is now located on a small hill top 20-30m above the floors of the tributary valleys. In other parts of Europe, deep incision of the main drainage routes is interpreted as the cumulative effect of Pleistocene fluvial and fluvioglacial erosion (Godard 1965; Gjessing 1966; Budel 1979;

Lidmar-Bergstrom 1982). The deep drainage incision in north-east Scotland is probably also Pleistocene in age, indicating that deep weathering at these sites predates most, and probably all, the Pleistocene glaciations.

9.6.3 Depths of weathering and rates of alteration

Borehole evidence shows that decomposition commonly exceeds 10m in depth and may reach depths of 50m in fracture zones. Many thinner saprolites probably represent the truncated portions of previous deep profiles. As even deep sections show signs of profile truncation, it can be estimated that many profiles were at least 20m thick before erosion.

There are many indications that deepening and renewal of saprolites has been insignificant in the Flandrian. This leaves the possibilities that saprolites either developed in earlier interglacial periods or that development began before glaciation and continued through the Pleistocene.

The time spans available for weathering in the Pleistocene are uncertain. The onset of Northern Hemisphere glaciation is generally put at c. 2.5m.y. (Poore and Berggren 1975; Backmann 1979) but the first regional, low-level glaciation in Scotland may have been as late as 0.6m.y. (Bowen 1978). Only part of this period can have been available for weathering, as chemical weathering of bedrock beneath ice sheets is presumably insignificant. Moreover, alteration in cool interstadial episodes will have been considerably less than that in warmer interglacials, due to the effect of temperature on weathering rates. Bowen (1978) suggests that interglacial periods, with temperatures at least as high as the present (Suggate 1965), may occupy only about 10% of Pleistocene time, although warm and cold stages in the marine isotopic record are of approximately equal duration. If this estimate is correct, the total duration of interglacial periods is between 2.5×10^5 yr and 6×10^4 yr.

Rates of saprolite formation under humid temperate environments are also uncertain. There are indications that shallow disaggregation of granitic rocks may occur rapidly under certain stress conditions as overburden is removed (Duffaut 1957; Struillou 1965; Dejou and Pedro 1967; Folk and Patton 1982). Experimental work has confirmed the possibility of rapid disintegration but shown that chemical alteration takes place much more slowly (Pedro 1961).

Studies of contemporary chemical denudation suggest that saprolites may develop over relatively short time periods (Judson and Ritter 1964; Cleaves et al 1970; Cleaves et al 1974; Reid et al 1981). On the basis of river water geochemistry and known mass losses from granite grusses, Tardy (1969) estimated that 3×10^4 yr was required for the development of 1m of gruss.

However contemporary rates of chemical denudation in humid temperate areas cannot easily be related to long-term rates of chemical alteration in saprolites. Present denudation rates are inflated by the effects of human activity and are liable to be considerably higher than those of pre-Flandrian periods (Menard 1961; Thomas 1974a). Moreover contemporary chemical alteration often acts on regoliths containing high proportions of fresh rocks and minerals. Rates of weathering of fresh clasts decrease rapidly with time (Colman 1981) and rates of chemical alteration of immature regoliths may well be unrepresentative of the longer term evolution of deeper and more stable saprolites. (Thomas 1976). Finally, in many areas where the regolith has been renewed and reworked by glacial and periglacial activity, chemical alteration is concentrated in the soils and superficial deposits (Reid et al 1981). The contribution of bedrock alteration to the overall budget of chemical denudation will often be small. These factors indicate that Tardy's (1969) estimate of the rate of gruss development must be regarded as minimal for the study area.

The thickness of the saprolites of north-east Scotland suggests formation before the glacial Pleistocene. Alteration of bedrock in the Flandrian has been slight and a succession of interglacials of similar duration and climate would only create thin saprolites. Moreover, saprolites are most unlikely to have developed by increments, with thickening of saprolites by a metre or so with each successive interglacial. The glacial Pleistocene must have been a period of net thinning of saprolites, even in this region of limited glacial erosion. Certainly the last ice sheet must have eroded and reworked the top few metres of regolith to account for the absence of Ipswichian soils and pre-Ipswichian deposits from many areas.

9.6.4 Clay minerals, palaeoclimates and saprolites elsewhere

The clay mineralogy of the different types of saprolite gives some indications of the palaeoclimates prevailing during the periods of weathering. Comparison of evidence from the clay minerals with the Late Cenozoic climatic record indicates periods in which the weathering types may have formed.

The climatic events in north-west Europe during the Tertiary were summarised earlier (Chapter 3). Eocene climates were hot and humid but temperatures dropped sharply in the Early Oligocene. Temperatures then rose again to reach a peak in the Middle Miocene and marine temperatures were similar to those off the Iberian Peninsula today. Thereafter temperatures declined, except for a brief recovery in the Middle Pliocene (Buchardt 1978). Mixed-oak forests grew in the Netherlands in the Upper Pliocene (Zagwijn 1960) and in East Anglia in parts of the Lower Pleistocene (West 1980).

The effects of climatic change are reflected in Tertiary deposits throughout Europe. Deep lateritic profiles developed in France and Britain during the Eocene (Esteouelle-Choux 1967; Millot 1970; Bain et al 1981). The Oligocene basins in western Britain contain predominantly kaolinitic clays (Wilkinson et al 1980). Miocene deposits in Denmark and the Ardennes foreland are severely altered (De Jong and van der Waals 1971; Friis 1974; 1976) and Miocene lignitic clays north of Cape Wrath are kaolinitic (Evans et al 1981). After the middle Miocene temperature peak, the composition of sediments changes and greater proportions of less stable clay and primary minerals appear (Bakker 1967; Lidmar-Bergstrom 1982). In the North Sea, illite and chlorite contents increase from the Upper Miocene (Karllson et al 1979). In Brittany, the Pliocene marine sables rouges mark the first appearance of large amounts of detrital felspar and illite in the Tertiary sediments of the region (Durand 1960; Esteouelle-Choux 1967).

Grusses were probably widely established in higher latitudes before the Pleistocene. Arenes are overlain by Upper Villafranchian basalts in the Massif Central (Bakker 1967) and by deposits of the oldest glaciation in the Sudeten Mountains (Jahn 1974). In North America, most sediments and saprolites present on the shield areas before glaciation were probably immature. The earliest tills of continental glaciations (Nebraskan and Kansan) contain high percentages of relatively unstable heavy minerals, such as hornblende (Willman and Frye 1970; Gravenor 1975), suggesting stripping of arenaceous weathering covers.

The clay mineralogy of the gruss weathering type in north-east Scotland indicates formation under humid temperate environments. The development of many little-altered grusses occurred under climates little different from those of the present, indicating formation during the early Pleistocene and during interglacial periods (c.f. Piller 1951).

Other grusses show a somewhat higher, although still modest, degree of alteration and clay mineralogy suggests formation under slightly warmer conditions than at present. Temperate climates suitable for the development of gruss-type weathering covers prevailed during the late Neogene and at intervals during the early Pleistocene (Bakker and Levelt 1964), and grusses probably formed continuously during these periods.

The high kaolinite contents in the clayey grusses indicates prolonged alteration under humid climates and the associated rubefaction is suggestive of higher temperatures (Bullock et al 1973). In Europe, kaolinitic saprolites formed throughout most of the Tertiary until the start of the Pliocene (Bakker and Levelt 1964; Lidmar-Bergstrom 1982). Around the Scottish area, kaolinite contents remain high in offshore sediments until the Late Miocene (Karllson et al 1979; Evans et al 1981; Berstad and Dypvik 1982) but decline thereafter in response to the final establishment of temperate climatic conditions (Buchardt 1978). Sedimentological evidence therefore indicates that the clayey grusses are of Miocene or earlier age. However it is also possible that prolonged alteration under cooler climates may also produce advanced kaolinisation. In this respect, it is significant that rubefied and highly kaolinitic weathered granites on the plateaux of Limousin are now regarded as early Pleistocene (Seddoh 1973), rather than Oligocene (Nieuwenhuis 1971) in age. A Miocene age for the clayey grusses should be seen as tentative and continued formation in the Pliocene cannot be discounted on available evidence.

9.7 Summary: the age of the weathering types

There is abundant evidence to demonstrate that saprolite development has been extremely limited in the Flandrian. Only thin granular grusses can have developed on rocks of low resistance within the past 12 000 yrs.

Many grusses are in the early stages of alteration. Clay mineralogy is consistent with development during interglacial periods but deep granular grusses probably belong to the early Pleistocene. Regeneration of thin granular grusses may have occurred repeatedly in interglacial periods in areas stripped of earlier saprolites.

Deep disintegration of some coarse granites may have occurred within the glacial Pleistocene. The degree of chemical alteration at Longhaven is insufficient to account for the depth of disaggregation and some form of stress release must be involved. However it is significant that even here the disintegration predates at least the last glaciation, as shown by the festoons of gruss within the overlying till. Initial mechanical disintegration may have affected other igneous rocks but the evidence has been obscured by subsequent alteration. The combination of ice-sheet loading and unloading (Carlsson and Olsson 1982), removal of overburden and residual rock stresses may have caused spontaneous disintegration, but only in certain rocks under special stress conditions and only in areas where earlier saprolites had been completely stripped.

The bulk of the grusses predate regional glaciation. Grusses supplied clays to the oldest recognised till in the region. Flandrian and theoretical rates of saprolite development indicate that even the cumulative duration of interglacial periods was not sufficient to allow weathering to penetrate to observed depths. Mineralogical evidence indicates that many saprolites must predate incision of the drainage net in the glacial Pleistocene. However, in view of the relative rapidity of the grussification process (Tardy 1969; Thomas 1976), it is unlikely that the grusses are of any great age and formation during the late Pliocene and early Pleistocene is proposed.

The clayey grusses are more difficult to date. The relatively highly-altered saprolites developed before the grusses. Clay mineralogy suggests development under warm and humid climates and, in the absence of evidence for exhumation from beneath cover rocks, the clayey grusses are tentatively dated as Miocene to middle Pliocene in age.

CHAPTER 10 The Buchan Gravels

10.1 Introduction

The Buchan Gravels are a distinctive deposit of quartzite and flint gravels found on numerous hills and ridges north of the Ythan (Fig. 10.1.i). The deposits attracted much early attention due to the presence of Cretaceous flints within them (Christie 1831; Ferguson 1850; 1855; 1893; Salter 1857; Wilson 1886; Mitchell 1896; Jamieson 1865; 1906). The rounded nature of the cobbles lead Ferguson (1850; 1855) to conclude that the deposits were a beach gravel, an interpretation initially supported by Jamieson (1865). However, in his final paper, Jamieson (1906) stated that "The Chalk flints ... have ... been brought from the Moray Firth by ... glacial agency"(p. 29). After detailed re-examination of the deposits, Flett and Read (1921) rejected a glacial origin and contended instead that the gravels were relics of Pliocene marine gravels.

For many years, this view remained unchallenged in the literature. However, a number of recent studies have added much new information on the Buchan Gravels (Koppi and Fitzpatrick 1980; McMillan and Merritt 1980; Kesel and Gemmell 1981) and other interpretations have emerged which suggest that the Gravels include fluvial (McMillan and Merritt 1980; Kesel and Gemmell 1981), fluvioglacial (Kesel and Gemmell 1981) or glacial (Jamieson 1906; Kesel and Gemmell 1981) deposits. The Buchan Gravels are of key importance for any reconstruction of the geomorphological evolution of north-east Scotland.

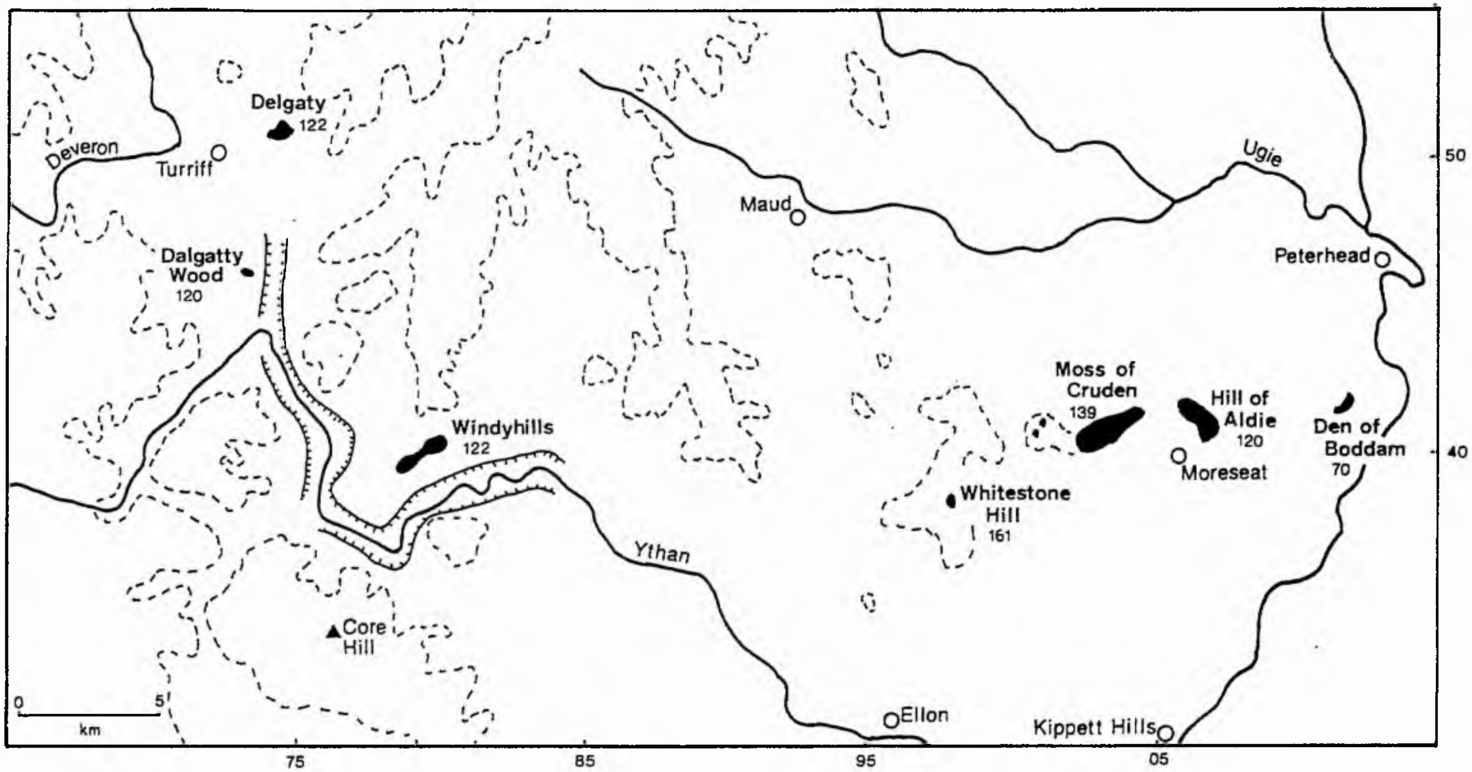


Fig. 10.1.i. Distribution of the Buchan Gravels.

10.2 Description

The Buchan Gravels Group can be divided on lithological grounds into the Windyhills metaquartzite-dominated and the Buchan Ridge flint-dominated Formation (McMillan and Merritt 1980). The Windyhills Formation includes the deposits at Windyhills, Delgaty and Dalgatty Wood; the Buchan Ridge Formation includes deposits at Whitestone Hill, Moss of Cruden, Hill of Aldie and Den of Boddam (Fig. 10.1.i).

10.2.1 The Windyhills Formation

The Windyhills Formation is best exposed at Windyhills where up to 15m of clast-supported silty sandy gravel, interbedded with white silty sand has been proved (McMillan and Merritt 1981). The gravel fraction is mainly composed of pebbles and cobbles of metaquartzite and vein quartz, together with friable quartz psammites, rare flints and cherts and a small proportion of highly weathered clasts. The sands are composed largely of quartz, with some muscovite. The dominant heavy mineral at Windyhills is an Fe-Ti mineral of ilmenite type (identification by H. Friis) which is visibly concentrated along laminae in the sandier units. Other minerals include common staurolite, andalusite, zircon and garnet with small amounts of kyanite and sillimanite (see also Kesel and Gemmell 1981). The sands and gravels are bound in places by white silt and clay, which is mainly composed of b-axis disordered kaolinite, with minor illite.

10.2.2 The Buchan Ridge Formation

The Buchan Ridge Formation is poorly exposed and much of the available information comes from recent shallow pits and boreholes. The gravels at Moss of Cruden and Hill of Aldie are at least 20m thick (Merritt 1981). The gravel fraction is composed of rounded pebbles, cobbles and boulders of flint, quartzite and vein quartz, together with kaolinised clasts. The sands are mainly quartz, with some flint grain. Heavy minerals include andalusite, garnet, zircon and staurolite (Kesel and Gemmell 1981). The matrix of the Formation is a white to yellow clay silt composed of well-ordered kaolinite with minor illite.

10.2.3 Overlying deposits

The Windyhills gravels are overlain by thin tills (Flett and Read 1921) and have been cryoturbated to a depth of at least 1m (Fitzpatrick 1975). Thick tills composed predominantly of subjacent material overlie the Moss of Cruden gravels (McMillan and Merritt 1980) and the presence of low solifluction lobes suggests that the deposits in this area have been significantly affected by periglacial mass movement. Observations made on the surface layers of the Buchan Ridge Formation (Kesel and Gemmell 1981) therefore may not be representative of the main body of the deposits (Merritt and McMillan 1982).

10.3 Post-depositional alteration and original composition

10.3.1 Post-depositional alteration

Post-depositional weathering of the Buchan Gravels has been severe. All clasts other than flints and pure quartzites are decomposed throughout the known depths of the Windyhills and Moss of Cruden deposits (McMillan and Merritt 1980). The non-resistant clasts are generally altered to white clayey silty sand. The dominant clay mineral is kaolinite: b-axis disordered at Windyhills and well-ordered at Whitestone Hill and Moss of Cruden. Quartz grains in the altered clasts show signs of solution and precipitation of silica, although alkali felspar and muscovite are often not highly altered (Koppi and Fitzpatrick 1980). The weathering of clasts in the Gravels bears many similarities in type and degree with that found in the quartzitic clayey grusses.

10.3.2 Weathering of the bedrock floor

The degree of weathering of the clasts decreases with depth (McMillan and Merritt 1980). Weathering extends into the underlying bedrock at Windyhills, where knotted pelitic schists are decomposed to a clayey silt, and at Moss of Cruden, where dioritic and gneissic rocks are decomposed to clayey sandy silts. Kaolinite is dominant at both locations, with disordered varieties at Windyhills and ordered varieties at Moss of Cruden, along with minor illite (Table 10.3.i).

Several metres of flint gravels cover granite grusses around the northern and western margins of the Moss of Cruden. The type of bedrock decomposition is quite distinct from that found in the deep boreholes (Table 10.3.i). These gravel bodies are thought to have been carried on to the grusses from the main outcrop by glacial and periglacial agencies.

Table 10.3.i Summary characteristics of weathered rock beneath the Buchan Gravels

	Rock Type	% Fines	% Clay	Md	Clay Minerals
A. Windyhills					
(i) QX 48	Pelitic schist	89.5	6.1	35	1.K 2.1 and C
(ii) QX 50	Knotted pelitic schist	94.7	22.2	26	1.K 2.1
B. Moss of Cruden					
(i) QX 115	Diorite	75.5	43.5	14	1.K 2.1
(ii) PX 61	Biotite gneiss	44.0	24.2	212	1.K
C. Gruss beneath flint till, Moss of Cruden					
(i)	Biotite granite	17.6	4.5	444	1.K and 1 2. M 3. H and V

Clay Minerals

K- Kaolinite I- Illite C- Chlorite M- Montmorillonite

H- Halloysite

V- Vermiculite

Md- Median Grain Size

The kaolinisation of the bedrock probably occurred after deposition. The local bedrock at Windyhills and Moss of Cruden supplied small numbers of clasts to the overlying gravels and cannot have been severely weathered at the time of deposition. Moreover, the clay mineralogy of the weathered bedrock at both sites corresponds with that of the matrix and with that of the weathered clasts in the overlying deposits, indicating that a single weathering profile extends through the gravels and into the bedrock. However, the gravels at Whitestone Hill are found in close association with very deep, and locally kaolinised saprolites and may have been laid down on a weathered floor.

Kaolinisation is unlikely to extend far into the bedrock. Boreholes record significant changes in the degree of weathering over depths of less than 2m (McMillan and Aitken 1981; Merritt 1981). Furthermore, trenches and exposures close to the margins of the gravel bodies have revealed only grussified or fresh bedrock. The intensity of alteration is probably a result of acidulated groundwater moving laterally along the gravel-bedrock interface.

10.3.3 Original Composition

The clasts within the Buchan Gravels consist mainly of stable quartzites, vein quartz and flint. Decomposed clasts account for less than 10% of the pebble and cobble fractions at most localities and of these a major proportion are quartz psammites and schists. Such "ghost" clasts retain their structure and form and have not been destroyed during weathering and provide a complete record of the original content of less resistant clasts. The sand fractions are overwhelmingly composed of quartz, with some flint and muscovite, although the rare presence of strongly corroded alkali feldspars suggests an originally more diverse sand mineralogy. However impregnated sections of closely-packed sands from Windyhills show few clay-infilled cavities indicative of the former presence of alterable minerals and the syn-depositional sand fraction was probably highly quartzose.

The kaolinitic clay and silt matrix may be partly a product of post-depositional alteration (Kesel and Gemmell 1981) but the fines are mainly of detrital origin. McMillan and Merritt (1980) point out that the thick beds of sandy and kaolinitic silt recorded from Windyhills, Cruden and Aldie cannot be of secondary origin. Moreover, although the degree of clast alteration decreases with depth at Windyhills and Moss of Cruden, the matrix clays remain homogeneous. At Windyhills, the matrix clay mineralogy of b-axis disordered kaolinite, with minor illite, is unchanged throughout the entire 15m of deposit. At Moss of Cruden, the crystallinity index values (Hinckley 1954) for well-ordered kaolinite matrix clays vary only between 0.84 and 1.20 in 23.5m of deposit. The uniformity of clay mineralogy over such depths and through beds with markedly different permeability demonstrates a mainly detrital origin for the kaolinite (Hall 1982). The degree of ordering of the matrix kaolin in the Buchan Ridge Gravels also argues against conversion from other clays (Hamblin 1973b).

These characteristics may be compared with those of weathered Tertiary felspathic sands in Dyfed. These lacustrine deposits include bands in which residual quartz grains are supported by the clayey alteration products of the felspars. Staining by Fe and Mn is extensive and the deposits rest on deeply weathered rock (Allen 1981). In contrast, the Buchan Gravels at deposition contained comparatively low proportions of weatherable material and were dominated by siliceous clasts, quartz sand and kaolinitic silt and clay. The high acidity and permeability of the Gravels will have facilitated the kaolinisation of unstable components (Koppi and Fitzpatrick 1980).

10.4 The geomorphic settings of the deposits

The individual deposits of the Windyhills Formation lie at accordant heights along a broad topographic corridor running between Turriff and Woodhead (Fig. 10.4.i). The courses of the lower Deveron and middle Ythan are deeply incised within this corridor and are connected by the Towie meltwater channel (Bremner 1934). The gravels rest on valley benches standing 60-70m above the floors of the inner gorges and must predate their incision.

The Buchan Ridge gravels rest on some of the highest hills and ridges in eastern Buchan (Fig. 10.4.i). The Whitestone Hill deposit stands well above the other localities, at the centre of an area of exceptionally deep weathering. Limited borehole information (McMillan and Aitken 1981; Merritt 1981) suggests that the Cruden and Aldie gravels infill a shallow depression running along the Moss of Cruden ridge. In marked contrast, the Denhead deposit partly infills a large meltwater channel and there is little doubt that it has been fluvioglacially, or more probably, glacially transported to its present location.

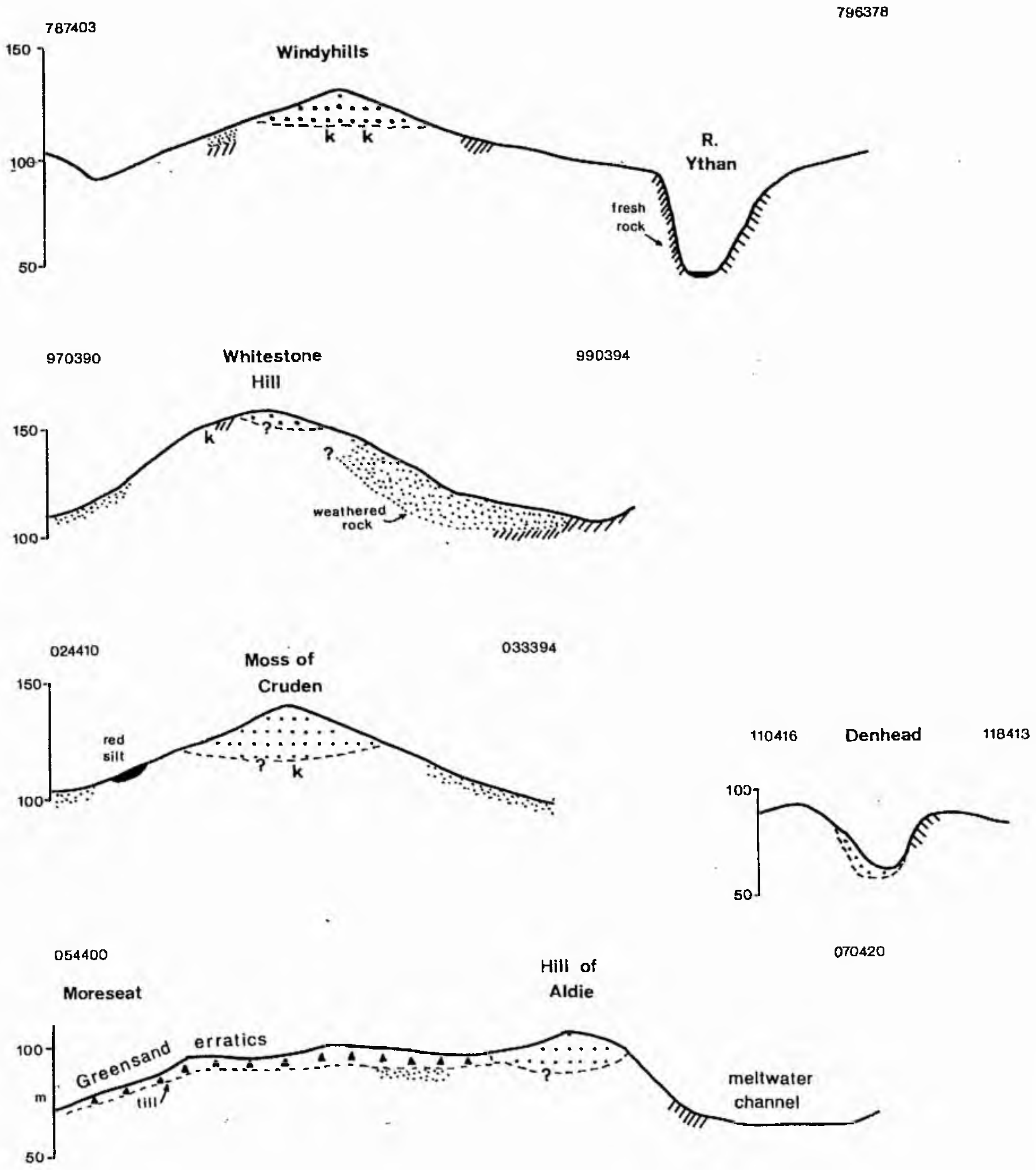


Fig. 10.4.i. Geomorphic settings of the Buchan Gravels

K kaolinised bedrock

The Buchan Gravels lie at elevations of between 70 and 160m in a variety of geomorphic settings. Deposition on an undeformed marine erosion surface (Flett and Read 1921) must therefore be ruled out. Moreover, the positions of all the deposits, apart from the Denhead gravels, demonstrates that substantial landscape modification has taken place since deposition. In particular, the locations of the Whitestones, Cruden and Aldie gravels indicate that topographic inversion has taken place since deposition, implying that these deposits are of considerable age.

10.5 The origin of the flint and chert

A major outstanding problem concerning the Buchan Gravels is the origin of the Cretaceous flints (Salter 1857) which dominate the gravel fractions of the Buchan Ridge Formation and occur rarely in the Windyhills Formation. An allied question concerns the Windyhills "cherts" mentioned by Flett and Read (1921). These are very rare porous siliceous clasts, identified as impure and fossiliferous chert nodules, possibly from the Cretaceous greensand (N. Trewin pers. comm.). All original calcareous material has been replaced by very fine grained secondary silica (Koppi and Fitzpatrick 1980).

The presence of Cretaceous flint and chert in the Buchan Gravels is of great interest for no Cretaceous rocks are known to outcrop in Scotland east of the Hebridean Province. Although fragments of greensand have been recovered from the surface layers of the Buchan Gravels at Aldie (Kesel and Gemmell 1981), from till exposed in a small gravel pit SE of Aldie (G.R. NK 054409) and from around

Moreseat (Ferguson 1855; Mitchell 1896; Jamieson et al 1897), there is no evidence that the greensand is in situ and the rocks are thought to be glacial erratics (Hall and Connell 1982).

In the absence of Cretaceous source rocks in north-east Scotland two suggestions have been made as to the origin of the flints:-

(i) glacial transport from Cretaceous outcrops offshore (Jamieson 1906; Kesel and Gemmell 1981; Gemmell and Kesel 1982).

(ii) derivation from a former Cretaceous cover (Judd 1873; Wilson 1886; Ferguson 1893; McMillan and Merritt 1980; Hall 1982).

The onshore transport of flints by ice is made plausible by the occurrence of individual flints (Kesel and Gemmell 1981) and erratic masses of Cretaceous rocks (Jamieson 1906; Cumming and Bate 1933; Hall and Connell 1982) in coastal districts north of the Ythan. However, although there is no doubt that Cretaceous material has been carried by ice from the Moray Firth and the North Sea, the flints in the Buchan Gravels are disseminated through the deposits and must have been reworked. The incorporation of flint into the deposits from an offshore source would require a complex and improbable series of events:-

(i) liberation of flint from Chalk on the sea bed.

(ii) concentration of flints, perhaps in beach gravels (Kesel and Gemmell 1981)

(iii) glacial transport of littoral deposits inland

(iv) incorporation of flint into the Buchan Gravels

A particular difficulty is that the glacial transport of flint and chert as far west as Windyhills would require ice moving from an unknown source to the NE to penetrate over 30km inland against ice streams moving eastwards from the Cairngorms and the Moray Firth. Moreover stage (iv) requires flints of marine and northerly or easterly origin to be mixed with materials of undoubted terrigenous and, probably, westerly (Kesel and Gemmell 1981) origin.

Derivation from a former Cretaceous cover is more feasible (Judd 1873; Wilson 1886; Ferguson 1893; McMillan and Merritt 1980; Hall 1982). Cretaceous rocks outcrop extensively in the Moray Firth (Chesher and Bacon 1975) and Chalk reaches to within 10km of the coast at Fraserburgh, where it is down-faulted against Permo-Trias (Fig. 1 in folder). Although there is little evidence for a continuous cover of Cretaceous rocks over Scotland at the beginning of the Tertiary (George 1966; Morton 1979), Upper Cretaceous rocks may well have overstepped onto basement in regions bordering the Moray Firth basin. Denudation of these rocks may have been completed early in the Tertiary but kaolinitic remanié deposits derived from the weathering of the Chalk (c.f. Hamblin 1973a) could have remained on the landsurface throughout the Tertiary and provided flint and chert clasts for later fluviatile sediments.

The former extent of the Cretaceous rocks is uncertain. The final phase of transport to Windyhills was from the west (Kesel and Gemmell 1981) but as flint and chert form only a very minor component of the Windyhills Formation, it can be suggested that the Chalk and Greensand parent rocks did not extend far to the west of these gravel localities. However the volume of flint within the

Buchan Ridge Formation implies denudation of considerable thicknesses of Chalk in more easterly areas. The base of the Upper Cretaceous must have stood above the highest flint gravel locality at c. 160m at Whitestone Hill but the links between the sub-Cenomanian surface and the present subdued relief are obscure. However the retention of flints on the landsurface throughout the Cenozoic indicates that the Buchan area has not been greatly uplifted since deposition of the Chalk.

It is worth emphasising the similarities between conditions in north-east Scotland and those in two other areas, south-west England and southern Sweden. In both areas, the Cretaceous sea transgressed across a weathered crystalline landsurface with deep zones of Mesozoic kaolinisation (Sheppard 1977; Lidmar-Bergstrom 1982). In south-west England, unroofing of the Dartmoor granite was completed in the Palaeocene (Groves 1931) and the massif supplied kaolin and flint to marginal tectonic basins in the Eocene and Miocene (Sheppard 1977). Outliers of Cretaceous rocks are found along the Swedish west coast (Lidmar-Bergstrom 1982) and the region supplied kaolinitic, terrigenous clastics to Upper Oligocene to Pliocene Danish deposits (Spjeldnaes 1975). In both south-west England and southern Sweden, it is the presence of residual flint which is the main evidence for the former existence of Cretaceous cover rocks.

10.6 The origin of the quartzites

A number of characteristics of the quartzite cobbles suggested to Flett and Read (1921) that the quartzites were not derived from the Dalradian rocks of north-east Scotland. However, mineralogical comparisons in thin section between cobbles from the Windyhills and Cruden gravels and the Banffshire quartzites has revealed many similarities (Kesel and Gemmell 1981). The Banffshire quartzites thus represent a likely source for the quartzite clasts in the Buchan Gravels. However, the possibility of recycling of Dalradian quartzites from the Old Red Sandstone should not be overlooked. The basal conglomerates of the middle Old Red Sandstone in Banffshire frequently contain high proportions of Dalradian quartzites (Read 1923; Peacock et al 1968). Derivation from Old Red conglomerates would help to explain the well-rounded nature of the quartzite cobbles and would remove the requirement for major denudation of the Banffshire quartzites in the period preceding deposition of the Buchan Gravels.

10.7 Quartz grain surface textures

The surface textures of quartz grains from different horizons at several Buchan Gravel localities were examined under the S.E.M. following procedures outlined by Krinsley and Doornkamp (1973). At least 50 grains of 1.0 to 0.0ϕ were examined for each sample and checks were made on grains in the 2.0 to 1.0 ϕ and 0.0 to -1.0 ϕ size ranges.

The Buchan Gravels contain two populations of quartz grains possessing distinct surface textures which roughly correspond to the shape groupings of sub-rounded to well-rounded and sub-angular to very angular. The angular group is predominant and the rounded grains rarely account for more than 10% of the total.

Certain textures are peculiar to the rounded group (Fig. 10.7.i). At low magnifications, occasional rounded grains show signs of deep

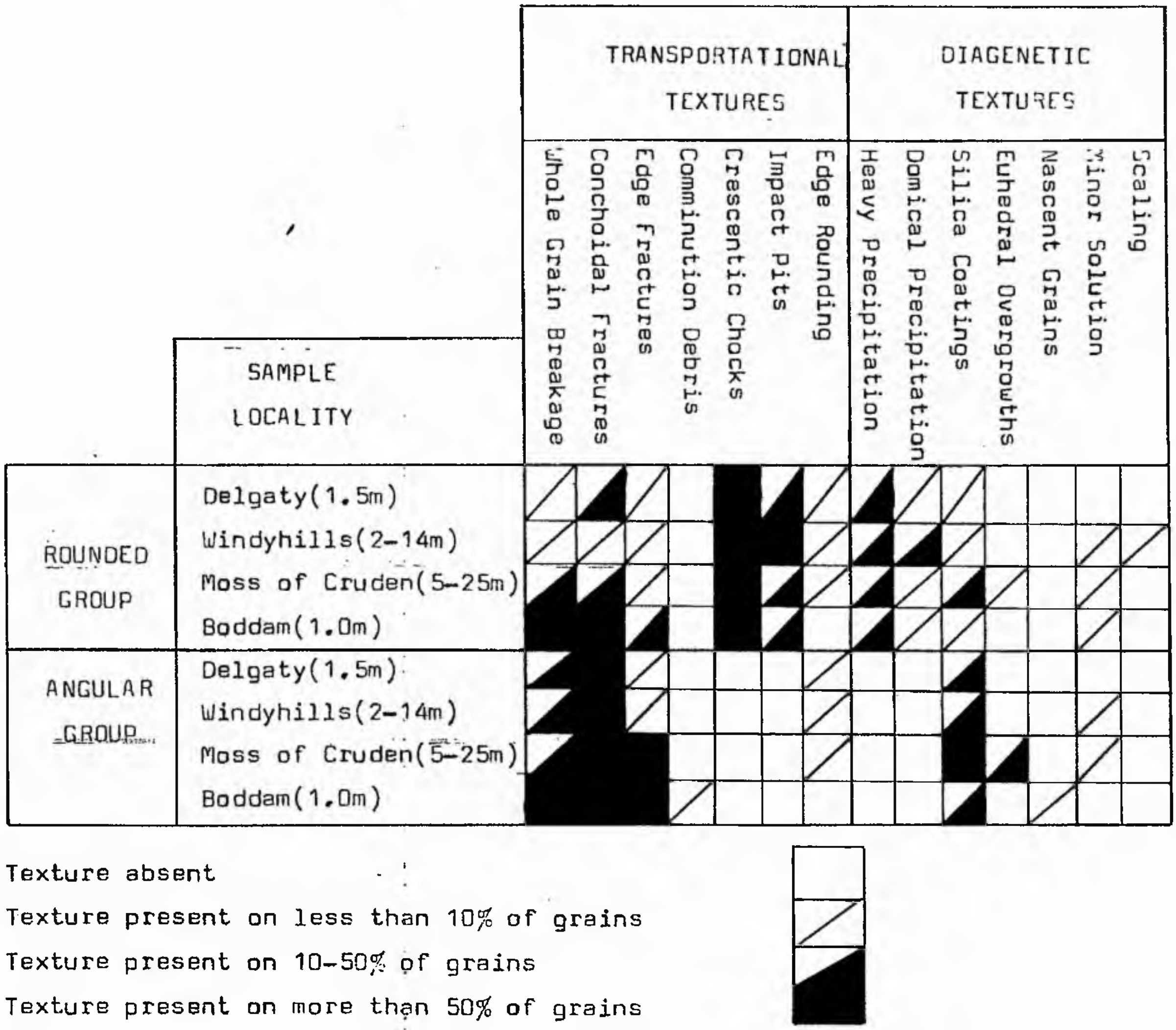


Fig. 10.7.i. Surface textures of quartz grains from the Buchan Gravels.

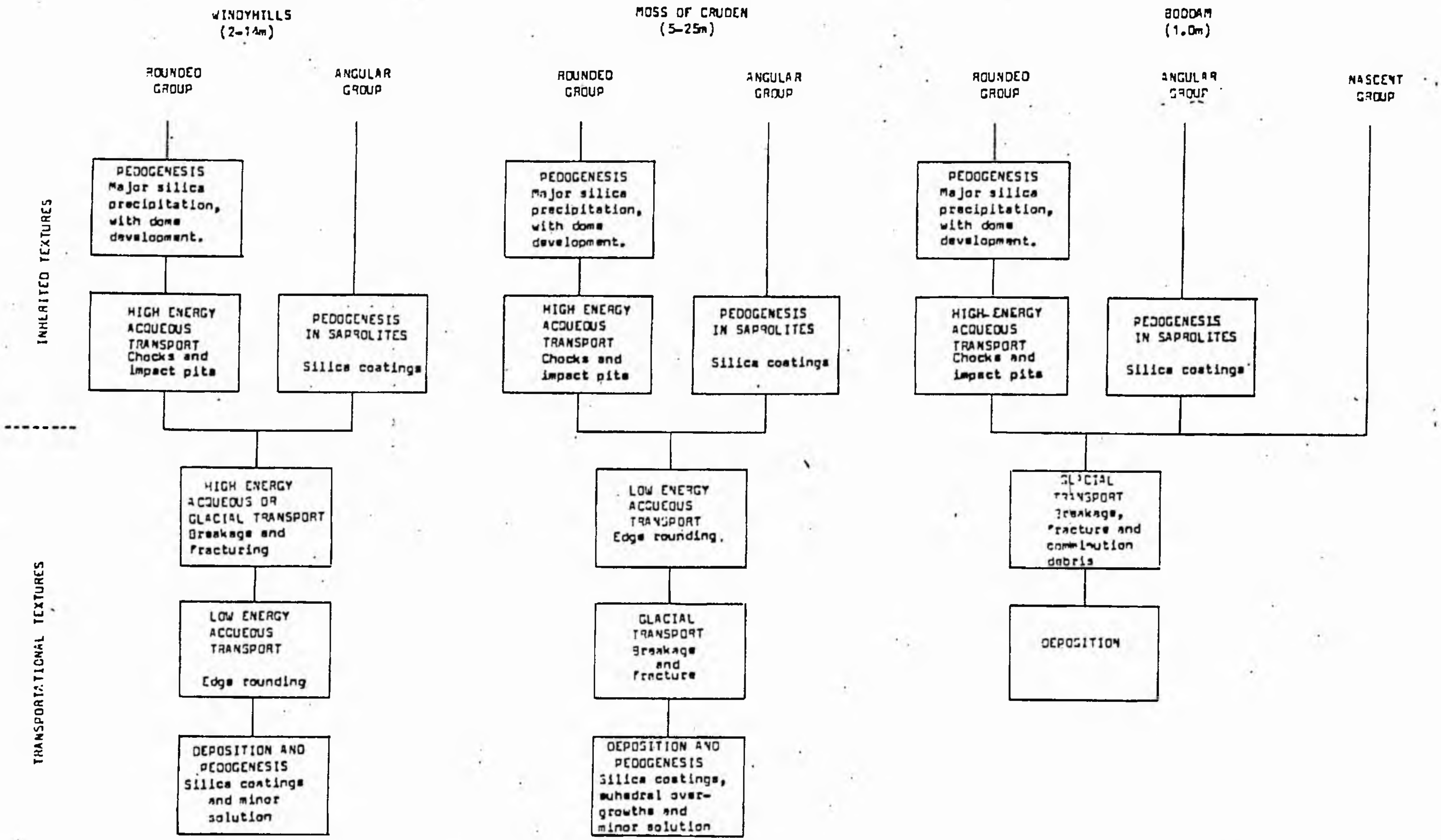


Fig. 10.7.11. Evolution of quartz surface textures in the Buchan Gravels.

corrosion and many have smooth precipitation surfaces with dome-like eminences (Plates 10.7.i-iii), indicating stabilisation in environments with high silica mobility (van der Waals 1967). These surfaces are indented by crescentic chocks and coalescing impact pits (Plate 10.7.iv) from a phase of high energy aqueous transport (Manker and Ponder 1978). In contrast, grains from the angular group have only thin silica coatings (Le Ribault 1971) similar to those observed on primary quartz from bedrock weathering profiles in north-east Scotland. Textural features indicate only low energy aqueous transport of the angular group.

Transportational textures common to both groups include evidence of breakage and fracturing. The breakage of mature, rounded quartz grains may be diagnostic of glacial environments (Kesel and Gemmell 1981) but fracture by cobble-to-cobble impacts during high energy aqueous transport is a further possibility (Harrell and Blatt 1978), especially where the numbers of broken rounded grains are small, as at Windyhills. Broken rounded grains are present throughout the known depths of the Windyhills and Cruden deposits and occur in great abundance in the Boddam samples (Plate 10.7.v). Angular grains also show widespread fracturing of pre-existing precipitation surfaces, possibly as a result of glacial transport, but fragmentation of first-cycle quartz grains is known to take place in other environments (Moss 1972; Brown 1973).

Many fracture surfaces on grains from Delgaty, Windyhills, Cruden and Aldie carry silica coatings and minor solutional features and some grains appear to have passed through more than one cycle of transport and stabilisation (Plate 10.7.vi). Silica precipitation has been particularly heavy below 5m at Moss of Cruden, with the development of euhedral quartz overgrowths (Waugh 1970; Pittman 1972; Whalley 1978).

Grains from depths of 1.5m at Cruden and 1.0m at Boddam have many fresh fracture surfaces (Plate 10.7.vii), with some adhering comminution debris. A number of fresh monocrystalline grains of granitic quartz have also been introduced into these surface horizons (Plate 10.7.viii).

The surface textures demonstrate a complex environmental history (Fig. 10.7.ii). Textures on the rounded group indicate inheritance from earlier sediments. Strong evidence for at least one phase of glacial transport exists for the Cruden, Aldie and Boddam deposits but textures from Windyhills are equivocal. The degree of post-depositional silica precipitation at Windyhills and Cruden suggests prolonged alteration but near surface samples from Cruden and Boddam have been glacially transported comparatively recently.

10.8 The origins of the Buchan Gravels

10.8.1 Comparisons between the Formations

Recent writers have emphasised that the two Formations comprising the Buchan Gravel Group are lithologically distinct and may be of different age and origin (McMillan and Merritt 1980; Kesel and Gemmell 1981). However it is worth recalling the similarities between the Windyhills and Buchan Ridge Formations.

The Buchan Gravel Group has been affected by severe post-

Plate 10.7.i

Plate 10.7.ii

Plate 10.7.iv

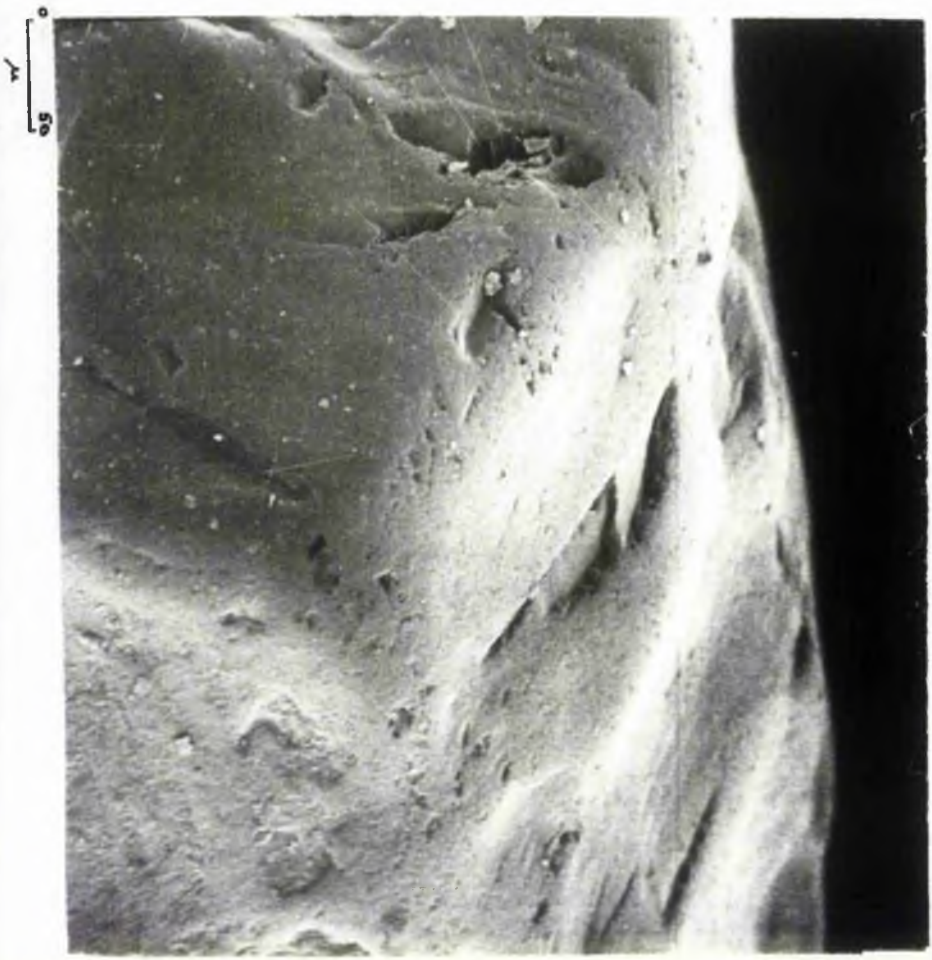


Plate 10.7.iii

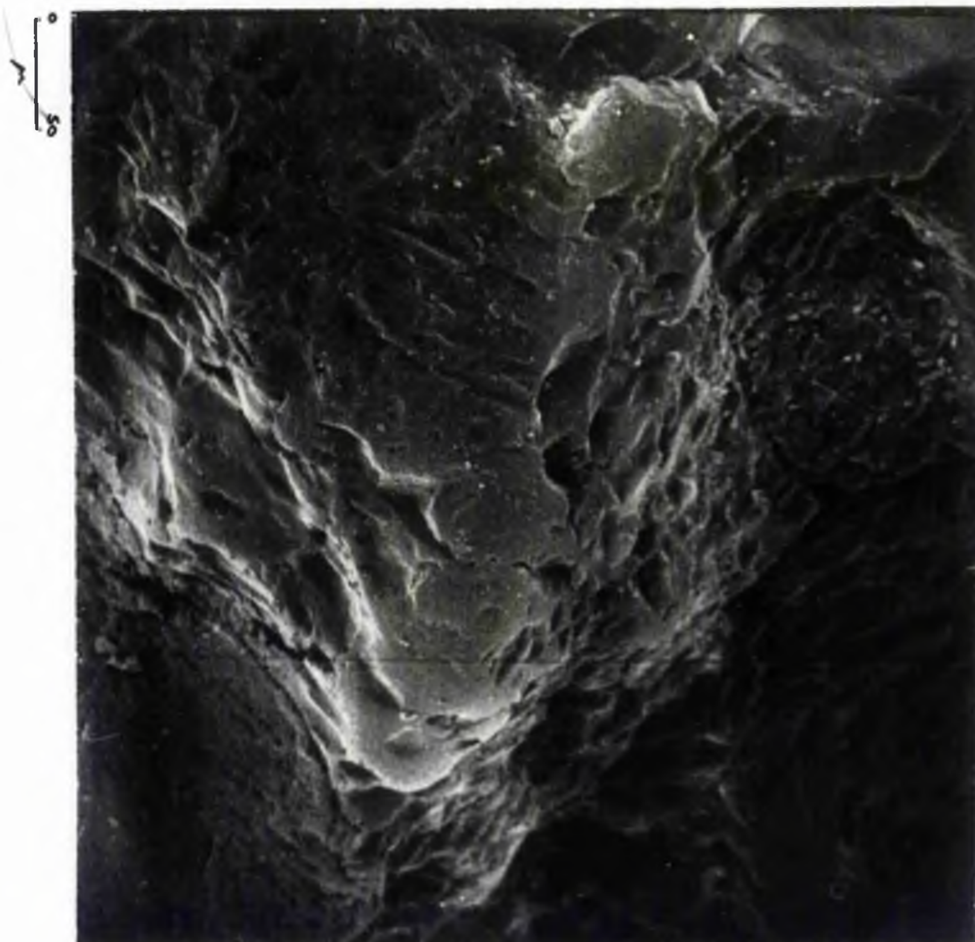


Plate 10.7.v

0 50
μm

Plate 10.7.vi

0 50
μm

Plate 10.7.vii

Plate 10.7.viii

TABLE 10.7.i Notes accompanying illustrations of quartz surface textures

Plate	Location	Depth	Group	Magnification	Main features
10.7.i	Windyhills	10 m	Rounded	100 x	Precipitation domes
10.7.ii	Windyhills	5 m	Rounded	30 x	Etching, breakage
10.7.iii	Moss of Cruden	5 m	Rounded	300 x	Etching
10.7.iv	Windyhills	10 m	Rounded	300 x	Smooth precipitation surfaces, with chocks and impact pits
10.7.v	Windyhills	10 m	Angular	300 x	Etching and breakage
10.7.vi	Windyhills	10 m	Angular	300 x	Breakage and chatter marks
10.7.vii	Boddam	1 m	Mixed	30 x	Breakage
10.7.viii	Boddam	1 m	Nascent	30 x	Fresh granitic quartz

depositional alteration. However it is clear that the original composition of the deposits was mainly siliceous, although minor non-resistant materials were also present. Sedimentary characteristics and quartz surface textures demonstrate phases of a queous transport and the calibre of the Gravels, with large boulders at Cruden (McMillan and Merritt 1980), indicates deposition under high energy environments.

The kaolinitic matrix of the gravels is of terrigenous origin (Millot 1970) and, together with the stable clast assemblages, indicates that the deposits were derived from a highly weathered source area. The ordered kaolinite in the flint gravels, the well-rounded quartzite clasts and the surface textures of the rounded quartz grains suggest reworking of earlier siliceous deposits. However, the presence of less resistant clasts indicates that stripping of the weathered landsurface and its associated deposits was at an advanced stage with non-stable materials entering the erosional system. The Buchan Gravels must represent a phase or phases of vigorous erosion in response to tectonic activity and/or climatic change.

The composition of the deposits suggests formation before the development of the gruss weathering covers in the region. Stripping of the grusses would produce arenaceous deposits with high contents of feldspar and biotite and diverse clay mineralogies. The Buchan Gravels do not appear to have originally contained large amounts of unstable minerals and must be related to earlier, more mature weathering covers (Hall 1982). The weathering type represented by the kaolinitic clayey grusses does provide a feasible source of the..

matrix clays and quartz sands. The Buchan Gravels are probably contemporaneous with the stripping of these older saprolites.

The original composition of the Buchan Gravels resembles that of many kaolinitic sands and gravels which occur throughout the Tertiary of northern Europe. These sediments are related to phases of warm and humid weathering environments which occurred repeatedly in the Tertiary (Buchardt 1978). Kaolin sands and gravels occur in the Eocene of south-west England (Hamblin 1973a), the Oligocene basins of western Britain (Edwards 1976; O'Sullivan 1979) and the Miocene and early Pliocene of southern Limburg (van der Broek and van der Waals 1967) and Denmark (Spjeldnaes 1975; Friis 1976). Progressive cooling of climate in the Pliocene lead increasingly to the formation of less stable deposits (Durand 1960; Bakker and Levelt 1964) but kaolin sands occur as late as the earliest Pleistocene in the Netherlands (Bijlsma 1981).

10.8.2 The origin of the Windyhills Formation

There is now general agreement about the origin of the Windyhills Formation (McMillan and Merritt 1980; Kesel and Gemmell 1981). Particle size characteristics and bedding structures indicate fluvial transport (Kesel and Gemmell 1981) and quartz surface textures are consistent with this interpretation. A number of features demonstrate a westerly provenance via a proto-Deveron-Ythan river system:-

(i) foresets and imbrication in the Windyhills deposit indicate transport from the west (Kesel and Gemmell 1981).

(ii) the quartzite cobbles are probably derived from the Banffshire quartzites (Kesel and Gemmell 1981), either directly or by recycling from Old Red conglomerates.

(iii) the most likely source for the ilmeno-rutile concentrations at Windyhills are the Younger Basic intrusions along the Deveron.

10.8.3 The origins of the Buchan Ridge Formation

The origins of the Buchan Ridge Formation are more controversial. Trenches have shown that, in places, the upper 5m of the deposit are matrix-supported. Furthermore, quartz grains from these surface layers show many signs of glacial transport (Kesel and Gemmell 1981). These upper horizons are undoubtedly tills.

Examination of borehole samples down to 24m from the Cruden-Aldie deposits shows that, even at depth, the deposits are, in places, matrix-supported. Moreover, splinters of flint and broken rounded quartz grains occur at intervals throughout the known depths of the deposits. Provided these characteristics are not drilling artefacts, it must be inferred that the whole of the Cruden-Aldie deposits have gone through a final phase of glacial transport. The Denhead gravel has also been glacially or, possibly, fluvio-glacially transported to its present location.

However, there are many reasons for doubting that the Buchan Ridge Formation is primarily of glacial origin (Kesel and Gemmell 1981). The highly siliceous composition of the gravels is quite unlike that of all other known glacial and fluvioglacial deposits in the region and is more akin to that of Tertiary gravels in other parts of Europe. Similarly, the degree of post-depositional alteration is far greater than that shown by the oldest known glacigenic sediment in north-east Scotland, the basal gravels at

Kirkhill (Connell et al 1982) and exceeds that shown by pre-Anglian glacifluvial gravels in East Anglia (Green et al 1980) and pre-Illinoian tills in the United States (Thorp et al 1951; Fitzpatrick 1963; Kays 1964; Willman and Frye 1970). Moreover, the deposition of the Buchan Gravels appears to predate the development of the gruss weathering type, which was earlier referred to the late Pliocene and early Pleistocene (see Chapter 9). A preglacial origin is further indicated by the amount of landscape modification which has occurred since deposition.

The composition of the Buchan Ridge Formation can be reconciled with the undoubted evidence for glacial transport by suggesting that the flint gravels are erratic masses of preglacial sediment. Questions then arise as to the origin and provenance of these parent sediments. Various authors have suggested that the Buchan Ridge Formation_may comprise beach gravels, either in situ (Flett and Read 1921; McMillan and Merritt 1980) or carried onshore by ice (Kesel and Gemmell 1981). However sedimentological and mineralogical evidence for a littoral origin is scant, particularly as diagnostic marine authigenic minerals are missing. The high content of detrital kaolinite suggests instead terrigenous deposition, and the quartzites indicate a westerly provenance. The presence of fluviatile sand beds in the Cruden gravels (Kesel and Gemmell 1981) and the similarities between the flint gravels and the fluviatile Windyhills Formation suggest that the Buchan Ridge Formation comprises glacial erratics of preglacial fluvial sediments.

These fluvial gravels cannot have been carried far from the sites where they were originally laid down. The Cruden gravels contain weathered clasts of biotite granite (Merritt 1981) and similar rocks occur only beneath and to the north of the deposit. Glacial activity may well have been largely confined to shearing and deformation and the Whitestone, Cruden and Aldie deposits may be virtually in situ.

10.9 The age of the Buchan Gravels

The Buchan Gravels are preglacial fluvial deposits, either in situ or locally transported as glacial erratics. The component Windyhills and Buchan Ridge Formations possess many similar characteristics, but differences in flint content, kaolinite crystallinity and geomorphic setting suggest that the Formations are of separate age (McMillan and Merritt 1980; Kesel and Gemmell 1981).

The flint and greensand clasts are evidence for Cretaceous marine transgression in north-east Scotland. How long these Cretaceous rocks survived on the land-surface is uncertain, but in the absence of any remnant of this cover, survival beyond the Palaeogene seems unlikely. Intense weathering under warm environments in the Palaeogene lead to the release of flints from the Chalk and Dalradian quartzites from the Old Red Sandstone. The silicification of greensand and the precipitation domes found on certain rounded quartz grains may date from this period.

Although these components may be inherited from periods of weathering in the Palaeogene, it is probable that the Buchan Gravels themselves are of Neogene age. The Gravels were deposited under high-energy fluvial environments and record a phase in which kaolinitic weathering covers were being stripped and replaced by less stable regoliths. In North Sea sediments, kaolinite contents decrease after the Middle Miocene (Karllson et al 1979) and stripping, in response to climatic cooling and pulsed uplift, was the dominant process thereafter in Highland Scotland (Table 3.6.i). In north-east Scotland, the late Neogene saw the stripping of the older clayey gruss weathering type and its gradual replacement by grusses in the late Pliocene and early Pleistocene. The Buchan Gravels probably belong to this long period of stripping in the Late Miocene and Pliocene.

The Windyhills Formation lies within the valley of a proto-Deveron-Ythan river. Post-depositional geomorphic change, although substantial, has not destroyed the valley form and the quartzite gravels need not long predate incision of the drainage in the Pleistocene. In contrast, no trace remains in the landscape of eastern Buchan of the rivers which carried the Buchan Ridge Formation. Since deposition, the flint gravels have been uplifted and a complete topographic inversion has taken place. The flint gravels now rest on some of the highest hills and ridges in the area, in close association with the remnants of the clayey gruss weathering type. The different geomorphic settings indicate that the Buchan Ridge Formation predates, by some considerable period, the deposition of the Windyhills Formation. On the basis of this geomorphic evidence, the Buchan Ridge and Windyhills Formations are tentatively dated as Late Miocene to Early Pliocene and Middle to Late Pliocene respectively.

10.10 Summary of the main events in the depositional history of the Buchan Gravels

The main geomorphic and geological events in the formation of the Buchan Gravels are summarised in Table 10.10.i. These events provide a useful framework in which to consider the geomorphic evolution of north-east Scotland.

Table 10.10.i Main Geomorphic Events in the Formation of the Buchan Gravels

Cretaceous	Marine transgression and deposition of Greensand and Chalk	
Palaeogene	Denudation of Cretaceous and O.R.S. sediments. Intense weathering under warm environments releases resistant flint, chert and quartzite clasts. Some evidence for major mobilisation of silica.	
Early to Middle Miocene	Continued deep weathering, with formation of highly kaolinitic saprolites.	
	ONSET OF LATE NEOGENE PHASES OF STRIPPING CLAYEY GRUSS DEVELOPMENT CONTINUES	
Late Miocene to Early Pliocene	Deposition of Buchan Gravels Formation.	
	STRIPPING OF CLAYEY GRUSSES NOW WELL-ADVANCED. GRADUAL REPLACEMENT BY LESS-MATURE GRUSSES	
Middle to Late Pliocene	Post-depositional alteration	Deposition of Windyhills Formation
Preglacial Pleistocene	Post-depositional alteration	Post-depositional alteration.
Glacial Pleistocene	Shearing, deformation and erosion of Whitestone, Cruden and Aldie gravels by ice, but little movement. Transport of erratics of flint gravel to Denhead.	Erosion and redistribution of surface layers by ice.

10.11 Other occurrences of kaolinitic deposits in north-east Scotland

10.11.1 Moss of Cruden

Temporary excavations on the northern slopes of the Moss of Cruden (NK 027404) exposed up to 2m of an unbedded, red, sandy clayey silt. The clay consists of poorly-ordered kaolinite, mica and the iron mineral, lepidocrocite (Peacock 1942). The silt and fine sand fraction consists of quartz, mica and kaolinite. Feldspar may be present as fine sand. The material contains only small amounts of soluble bases:-

SiO_2	TiO_2	Al_2O_3	Total Fe	MnO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	Total
69.0	NT	23.2	2.3	ND	.17	.10	.07	.17	NT	4.94	99.95

The field relations of the material are uncertain (Fig. 10.4.ii). Trenches downslope exposed thin till overlying granite gruss. The material must lie close to the northern limit of the Cruden flint gravel deposit. Red silt also occurs in till on Smallburn Hill (NK 018402).

No firm conclusions can be reached about the origin of this material on available evidence. The material is not a granite weathering product as it contains no coarse sand. The mineralogy and geochemistry indicate that the material is either highly weathered or derived from a highly weathered source and the presence of lepidocrocite in quantity signifies prolonged waterlogging (Schwertmann and Taylor 1977). The high iron content and the poor ordering of the kaolinite make it unlikely that the silt is related in age or origin to the adjacent Moss of Cruden flint gravels. The only similar deposits in north-east Scotland are the glaciolacustrine sediments associated with the red till sheet and silty beds within the Old Red Sandstone, but the Moss of Cruden silt is mineralogically distinct from both deposits (Glentworth et al 1964).

A sample of the silt is lodged with Dr M.J. Wilson at the Macaulay Institute.

10.11.2 Mormond Hill

Milne (1904) mentions occurrences of kaolin along the south side of Mormond Hill. The sites have not been relocated, but probably consist of zones of kaolinised bedrock.

10.11.3 Channel-fill deposits at Speymouth

A borehole survey of sand and gravel resources around Speymouth (Aitken et al 1979) has proved the existence of a deep rock-cut channel extending below O.D. The channel is filled with medium and fine grained greenish grey quartzose sands. Thin seams of pale greenish grey, sandy silty clay are also present, containing illite with kaolinite. The channel-fill deposits are covered by 20m or more of fluvioglacial and glacial deposits.

The channel is interpreted by Aitken et al (1979) as "an ancient, probably pre-glacial channel of the River Spey" (p. 6).

PART 3 Weathering and geomorphic evolution

CHAPTER 11 Exhumed and highland relief

11.1 Introduction

The nature and development of the preglacial relief of north-east Scotland has been investigated by a number of writers (Bremner 1919; 1942; Fleet 1938; Linton 1950; 1951; Walton 1963; Sugden 1968; Fitzpatrick 1969; 1972). The main aim of most of these studies has been the identification of erosion surfaces but a variety of major palaeoforms have also been noted including basins (Linton 1951; Walton 1963; Clapperton and Sugden 1977), inselbergs (Linton 1951), pediments (Walton 1963; Fitzpatrick 1969; 1972), ancient valley forms (Bremner 1919; 1942; Linton 1951; Sugden 1968) and tors (Linton 1950; 1955; Sugden 1968). Much of this work has been of a general and descriptive nature and there has been no detailed analysis of relief comparable to that of Godard (1965) north of the Great Glen.

There is broad agreement that a series of stepped erosion surfaces exists in north-east Scotland. Four separate surfaces have been identified above 300m (Fleet 1938; Linton 1951) and a further three surfaces are thought to occur in the lowlands (Walton 1963). However only Fleet (1938) has attempted any kind of morphometric analysis of relief and the reality of these morphological levels remains to be demonstrated. The relation of these surfaces to geology and structure has also been largely ignored. Further doubts exist as to the age and origins of these features. Several authors have proposed extensive exhumation of topography from beneath Palaeozoic and Mesozoic sedimentary covers

(Hinxman and Wilson 1902; Barrow et al 1912; Bremner 1942; Johnstone 1966). Others suggest that much of the present landsurface was fashioned in the Tertiary and erosion surfaces have been attributed to pedimentation under warm and arid environments (Walton 1963; Fitzpatrick 1969; 1972), planation under humid tropical environments (Linton 1951) and marine levelling (Walton 1963; Fitzpatrick 1969; 1972). These inferences about morphogenic processes are based almost wholly on morphological criteria and little effort has been made to relate evidence of deep weathering to relief development. This study aims to remove some of the uncertainty surrounding the long-term evolution of the relief in north-east Scotland by re-assessing the morphological evidence and by examining the links between weathering patterns and landform development. The information provided by the weathering types and by the Buchan Gravels about the age of the relief is then placed within the wider framework of regional morphogenesis established earlier (Chapter 3).

In the following chapters, a distinction is made between highland and lowland relief. Field work has concentrated on the lower ground which forms the bulk of the study area and work above 300m has been carried out largely on a reconnaissance basis. However although these differences in the resolution of study are important, the principal reason for the distinction lies in the distribution of weathering with elevation. Above 300m, there are only occasional occurrences of saprolite. The highland area consists mainly of rock-floored terrain and the relationships between the scattered saprolites and the evolution of macro-scale landforms are obscure. In contrast, there is detailed information on weathering patterns in a number of lowland areas and the links between weathering and landform development can be explored more fully. Yet although highland and lowland relief forms are initially treated separately and rather differently, no fundamental break in styles of relief generation with elevation is implied. The occasional relics of former weathering covers in the highlands show similar characteristics to the gruss weathering type identified in the lowlands. These common characteristics suggest that the latest phases of weathering and morphogenesis have involved comparable kinds of regolith at all elevations. Moreover there is no major difference in the types of landforms found in the highlands and lowlands and basins, for example, occur within an altitudinal range stretching from close to sea level in Buchan to above 900m in the Cairngorms. At the regional scale, the rock-floored highland surfaces can be seen as the stripped counterparts of the deeply weathered surfaces of the lowlands or, in other words, as high-level etchsurfaces and low-level etchplains (Thomas 1974a). In consequence, models of weathering and landform evolution developed in the lowlands can be usefully applied to more elevated terrain. The distinction between highland and lowland relief is therefore not of major significance for the processes of relief development and is employed for the purposes of description and discussion only.

Part III of this study is concerned with problems of weathering and geomorphic evolution. The remainder of the present Chapter seeks to establish the extent and nature of exhumed relief and to identify the main generations of relief in the highlands. Chapter 12 discusses the relations between weathering patterns and landform development in the lowlands and Chapter 13 goes on to examine the evolution of the lowland landscape. Chapter 14 aims to draw together evidence of highland and lowland relief development and to discuss the denudation chronology of the region.

11.2 Exhumed relief I : sub-Devonian

The numerous outliers of Old Red Sandstone in the region and their association with contemporary valley and basin forms have encouraged the view that the present topography is largely exhumed from beneath a former Devonian cover (Wilson and Hinxman 1890; Hinxman and Wilson 1902; Barrow et al 1912; Bremner 1942). However no detailed maps of exhumed relief have been published, in contrast with areas north of the Great Glen (Godard 1957; 1965; Williams 1969; Stewart 1972). In order to establish the extent and nature of the sub-Devonian topography, it is necessary to examine three questions:- (i) the original extent of the Devonian sediments, (ii) the nature of the topography beneath and around the remaining Devonian outliers and (iii) the importance of syn- and post-depositional faulting.

11.2.1 The original extent of the Devonian cover

The former extent of Devonian cover rocks may be gauged using two lines of evidence:- (i) the present distribution and dip of these rocks and (ii) the composition of the sediments.

Of the Devonian sediments, only the Middle Old Red Sandstone has any extensive development in the study area. The huge volumes of clastics in the Lower Old Red synclines of Strathmore indicate that the eastern Grampians was an area of high relief at this period. In the study area, Lower Old Red Sandstone is probably confined to residual pockets at the base of the Gamrie and Rhynie basins and these rocks were largely stripped before the unconformable deposition of the overlying sequences of Middle Old Red Sandstone (George 1965; House 1977). The Upper Old Red Sandstone is found only in areas east of the Spey but south of the Grampians considerable thicknesses of Upper Old Red Sandstone rest on folded and deeply denuded Lower Old Red rocks. Although little can be said of the former extent of Lower and Upper Old Red Sandstone in north-east Scotland, evidence from neighbouring areas suggests that any surviving exhumed relief would be highly accidented.

Middle Old Red Sandstones form a continuous belt just offshore and occur as widely scattered outliers on the Dalradian basement (Fig. 11.2.i). Apart from the main Turriff, Rhynie and Tomintoul outliers, there are several small occurrences, such as those in upper Strathisla (Wilson and Hinxman 1902) and the Feugh basin (Bremner 1942), which suggest that the Old Red Sandstone formerly covered areas well beyond its present outcrops (Sissons 1967).

Yet there are several reasons for rejecting Bremner's (1942) suggestion:-

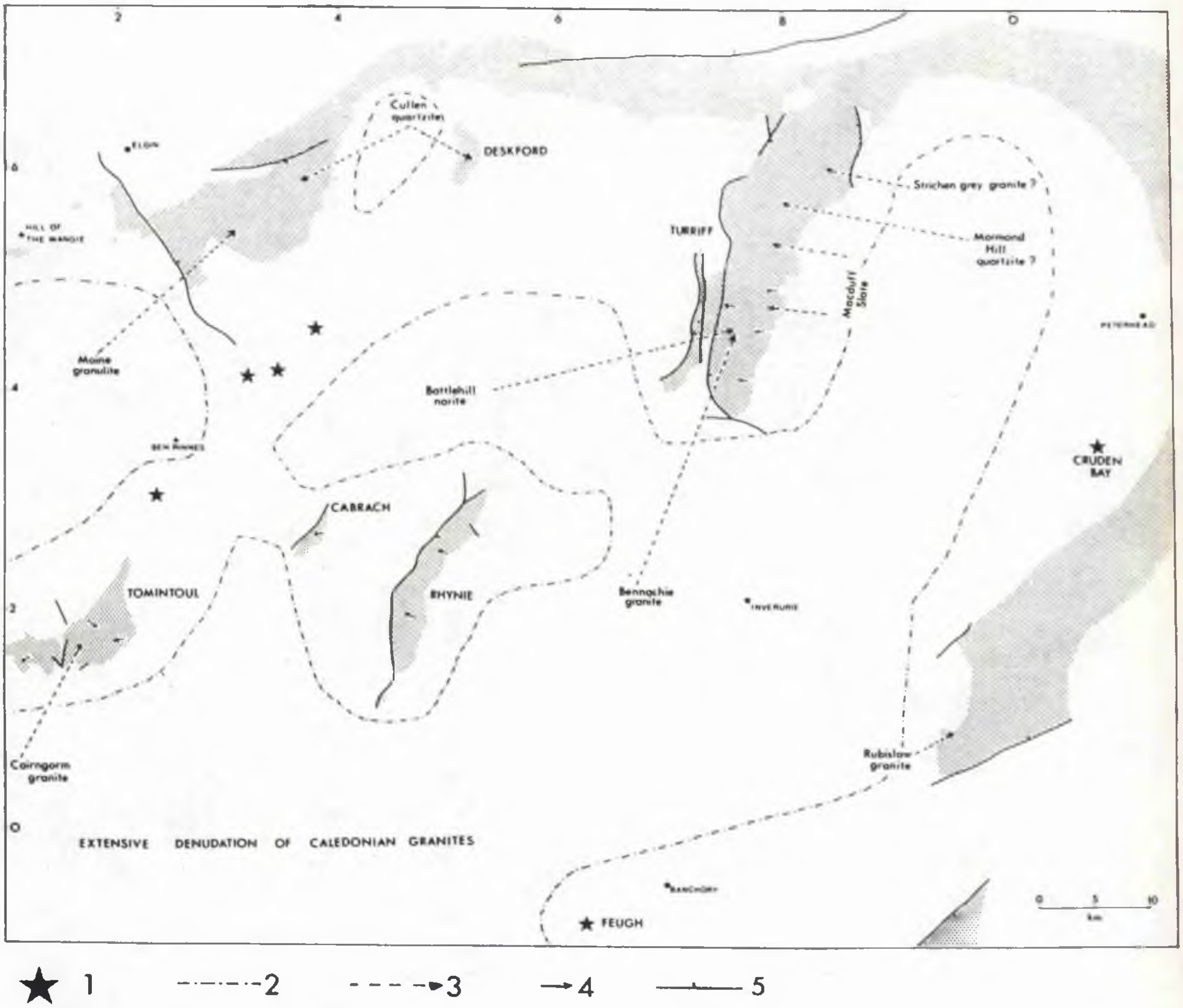


Fig. 11.2.i. Present and former distribution of the Old Red Sandstone.

1. Small outliers of Old Red Sandstone.
2. Approximate original limit of Old Red cover rocks.
3. Parent rocks of clasts in Old Red conglomerates.
4. Generalised dips of Old Red sediments.
5. Fault.

> "that nearly the whole of the area (north of the main axis of the Grampian Highlands) was buried in Old Red and later sediments." (p. 102).

In the Turriff outlier, dips increase from west to east, conforming with the basin shape in section and suggesting that the sediments did not extend far beyond its eastern limits. Dips in the Tomintoul outlier are variable and indicate infilling of a deep and partially enclosed basin. In contrast, the sandstones of the small Cabrach outlier are virtually flat-lying (Hinxman 1896) but rest in a topographic basin over 200m deep. The dips of these outliers suggests a pattern of deposition within isolated basins.

The basal conglomerates of all the Old Red outliers are dominated by clasts derived from the local basement (Wilson and Hinxman 1890; Hinxman and Wilson 1902; Read 1923; Peacock et al 1968). That the basement was not buried by later deposition is shown by the composition of conglomeratic bands higher in the sedimentary successions of the deeper outliers (Table 11.2.i). Clasts of local rocks remain dominant, confirming that areas of high basement relief bordered the basins.

11.2.2 The nature of the sub-Devonian topography

In several outliers, the Old Red deposits cover a highly irregular topography. The Deskford and Tomintoul conglomerates infill ancient valleys (Geikie 1879; Read 1923). In the Elgin district, conglomerates and breccias were deposited against steep hillsides marking the edge of the upstanding Moinian and Dalradian relief (Peacock et al 1968). The rapid thickening of Old Red sediments east of Aberdeen has also been interpreted as a result of deposition within intramontane basins (Duncan 1975). This varied topography was then dislocated by later fracturing to give a series of downfaulted basins.

A number of points may be made about the character of exhumed Middle Old Red topography in north-east Scotland:-

(i) It is unlikely that the Middle Old Red Sandstone ever formed a continuous cover. The region formed a piedmont zone between the positive axis of the Grampian granites and the main basin of deposition in Lake Orcady (Geikie 1879). Local relief was high and deposition was restricted to pre-existing zones of negative relief and fault-bounded basins. Any remnants of exhumed topography must be confined to limited areas around surviving outliers, away from known areas of positive Devonian relief (Fig. 11.2.i).

(ii) The irregularity of the sub- Middle Old Red topography and the importance of later fracturing preclude the existence of extensive exhumed surfaces of low relief, as claimed by Bremner (1942). Instead it seems that areas of accidented sub-Devonian topography have been planed by later, and probably Tertiary, morphogenesis, as in northern Scotland (Godard 1957; 1965).

(iii) Exhumed Devonian topography is a major element of the lower relief in areas bordering the lower Spey valley. Patches of Old Red occur in the Findhorn valley and along the structurally-aligned corridor followed by Glen Rinnes and upper Strathisla. These valley-fills leave little doubt that Devonian rivers had already exploited the prominent series of sub-parallel SW-NE fractures in this area and that the present drainage is largely superimposed (Hinxman and Wilson 1902; Sissons 1967).

Table 11.2.i Clasts identified from conglomeratic bands above the basal conglomerates in Lower and Middle Old Red Sandstone outliers.

Outlier	Formation or Location	Clast Lithology	Reference
Turriff	Bed 5, Findon Group	Slate Mica-schist Quartzite Grey/Pink granite Felsite Old Red Sandstone	Read (1923)
	Slack O'Causeway	Bennachie and Corrennie granite Huntly garnetiferous norite Inchbae foliated granite	Mackie (1923)
Rhynie	Tillybrachty Sandstone	Quartzite with knotted mica-schist granite, gneiss and felsite	Wilson and Hinxman (1890)
Aberdeen	Donmouth	Rubislaw granite	Mackie (1923)
Tomintoul	Strath Avon	Mainly quartzite with mica-schist and Cairngorm granite	Wilson and Hinxman (1890)
Elgin	Numerous localities	90% Cullen Quartzite with Moine granulites	Peacock et al (1968)

Moreover it is improbable that the Old Red was originally confined to the valleys and parts of the upper relief may well also be exhumed. A clear example of exhumation is provided by the schistose Hill of the Wangie, north of Dallas, where patches of sandstone and conglomerate surround the hill flanks (Hinxman and Wilson 1902). However the suggestion of Bremner (1942) that Ben Rinnes is an exhumed Devonian mountain must be rejected in view of the depth of burial required. The Hill of the Wangie has been planed during a much later erosional phase which created the extensive plateau surfaces north of Strath Spey and Glen Deveron. These planar surfaces contrast starkly with the irregular sub-Devonian relief of the Elgin district (Peacock et al 1968) and indicate that positive elements of the Devonian relief have been completely transformed by subsequent morphogenesis.

(iv) More localised exhumation of Devonian relief forms is found in several other areas. The Tomintoul and Cabrach basins are both in the process of re-excavation and the Feugh basin may be, in outline at least, a Devonian feature. The general form of the Insch depression may also be inherited, for basic clasts from the Insch and Boganclogh masses are apparently absent from the conglomerates of the Rhynie outlier (Wilson and Hinxman 1890), suggesting that the Old Red may have once extended over these rocks. Exhumed Devonian topography is therefore of only restricted importance in the study area. Tertiary morphogenesis has uncovered and modified an accidented Devonian topography. The principal exhumed forms are those of negative relief, notably valleys and depressions, and the extensive levelled areas surrounding several

Old Red outliers are of much later origin. Regional superimposition of drainage from an Old Red cover is unlikely (Bremner 1942), although superimposition is locally significant around the lower Spey valley (Hinxman and Wilson 1902).

11.2.3 Implications for post-Devonian geology and tectonics

The reconstruction of the Middle Old Red Sandstone topography and environments throws some light on the long-term structural evolution of the region. Rocks which formed upstanding relief in the Devonian, such as the Bennachie, Corrennie and Rinnes granites (Macie 1896; 1923), today once again form prominent hills. The unroofing of these intrusions is recorded in neighbouring Old Red Sandstone basins, yet the Bennachie granite is still capped by part of its former roof of cordierite gneiss on Cairn William (Wilson and Hinxman 1890). This mirrors the situation found in the Wicklow Mountains of Eire. Here the Caledonian Leinster granite batholith contributed material to Old Red sedimentary basins in Waterford and Kilkenny but retains parts of its schist roof. The limited denudation of these intrusions since the Devonian makes it unlikely that the granites remained as positive relief after the Devonian and re-activation by Tertiary uplift is implied (Davies and Stephens 1978).

Moreover there is no reason to suppose that the Middle Old Red Sandstone comprised especially thick accumulations of sediments, even in areas bordering the Moray Firth. The survival of restricted thicknesses of Old Red Sandstone in depressions in the Devonian topography, several of which are apparently uncomplicated by faulting, indicates only limited erosion since deposition. It must be concluded that these rocks have escaped denudation either by remaining close to or below base level since deposition or because of burial by later sediments or because some combination of these factors has operated.

11.3 Exhumed Relief II: Sub-Cretaceous

Post-Devonian sediments are absent from north-east Scotland, except for the patches of Permo-Trias around Lossiemouth. The evidence discussed above and the proximity of thick accumulations of Mesozoic sediments in the inner Moray Firth basin suggests periodic overstep on to the eastern edges of the Grampian Block (Johnstone 1966). However, in the absence of any in situ remnant of these Mesozoic rocks on the landsurface, nothing can be said of the nature of the sub-depositional relief.

Evidence for limited Cretaceous transgression into the region was presented earlier (Section 10.5). The former extent of the Cretaceous rocks is unknown but, given the confinement of rolled Chalk flints to the Buchan area, it is tempting to suggest that these Cretaceous residues have been lowered during denudation from a sub-Cretaceous surface that stood at no great height above the present subdued topography. However in the absence of any remanié deposits of the Chalk, it is not possible to define any close relationship between morphology and flint distribution, although such links have been amply demonstrated in southern Sweden (Lidmar-Bergstrom 1982).

The relief of north-east Scotland is thus in major part a product of Tertiary morphogenesis. Wide areas possess no sedimentary cover rocks and even where the Old Red Sandstone is present, the relief must be seen in terms of remodelling of ancient exhumed forms. The following sections will deal with the nature and origins of this Tertiary relief.

11.4 The nature of the highland relief

The relief forms at elevations above 300m fall into two broad categories:- the 'paleic' forms and the 'younger' forms (Gjessing 1967; Kaitenen 1969). The paleic relief comprises the smooth slopes of the wide upland surfaces and includes major palaeoforms, such as residual hills, basins and open valleys. The younger forms are sunk into this paleic relief and consist largely of deep and narrow valleys, often showing signs of intense glacial and fluvioglacial activity.

The paleic forms appear to have been little modified by glaciation. Landforms indicative of ice-scouring are only locally developed on the plateaux surfaces and the survival of such features as pockets of weathered rock (Barrow et al 1913), tors (Linton 1955; Sugden 1968) and integrated tributary drainage systems (Bremner 1919; Sugden 1968) would appear to preclude deep glacial erosion.

The paleic relief is developed largely across fresh rocks and, in the absence of any correlative deposits, the only available evidence of the processes responsible for relief generation comes from examination of the palaeoforms themselves. A common approach to the study of relief development in regions of Pleistocene glaciation is to define geological factors which will influence rock resistance and then to investigate to what extent palaeoforms have exploited these potential weaknesses. The level of geological control over morphology is then related to palaeoenvironments (Reffay 1966; Nonn 1969; Peulvast 1978; Battiau-Queney 1978). Godard (1965) applies this method to the Scottish relief to elucidate the morphogenetic origins of his four main surfaces.

This type of approach involves several assumptions:- (i) that the palaeoforms are climato-genetic features (Budel 1980) and products of identifiable climatic episodes, (ii) that the characteristics of the palaeoforms provide unambiguous comparison with similar landforms elsewhere whose mode of origin is known and (iii) that the palaeoforms have not been substantially modified since formation.

The problems of interpretation of this sort of evidence are formidable. It is becoming increasingly apparent that many erosion surfaces in middle and high latitudes are polycyclic in origin and have been affected by repeated climatic fluctuations (Rudberg 1965; Jones 1981; Lidmar-Bergstrom 1982). The likelihood of polygenetic origins undermines the frequent analogies made with models of tropical landform development (Godard 1965; Reffay 1966; Gjessing 1967; Kaitenen 1969; Budel 1977; 1978; 1980). Furthermore the mechanisms of relief development in low latitudes remain imperfectly understood, although the important effects of climatic change are increasingly recognised (Thomas 1974a).

Moreover insufficient attention has been given to the closeness or otherwise of the morphological links between the plateau surfaces and the original surfaces formed close to base level. Even if warping and dislocation during uplift can be discounted, it is inconceivable that the surfaces have not been lowered and remodelled, to some extent, by later morphogenesis (Sissons 1967; 1976). Sediment volumes in the North Sea Basin indicate that the Scottish Highlands as a whole have been lowered by a minimum of 724m in the Cenozoic. In north-east Scotland, original weathering covers have been stripped and replaced by later generations of regolith developed under different environments. The character of the most recent saprolites is shown by the patches of weathered granite found on the Cairngorm summit surface (see Section 8.3), which are directly comparable in granulometry and clay mineralogy with granite grusses found at lower altitudes. These latest weathering covers reach depths of over 10m on the Gaick Plateau (Barrow et al 1913) and must have been more widespread prior to glaciation. These high-level grusses imply that the plateau surfaces continued to evolve long after their initial uplift.

11.5 Recognition of different generations of highland relief

A number of writers have recognised stepped erosion surfaces above 300m in north-east Scotland (Bremner 1919; Fleet 1938; Linton 1950; 1951; Walton 1963; Sugden 1968; Fitzpatrick 1969; 1972). The surfaces recognised by Fleet (1938) are the most widely referred to, despite the fact that Fleet viewed his work as a reconnaissance study. No detailed analysis of the high-level topography is available and considerable doubt remains as to the number, elevation and form of the erosional levels.

The present study does not aim to provide detailed morphometric analysis as the bulk of the high-level surfaces lie west of the main study area. Nevertheless it is useful to consider these forms in relation to problems of long-term landform development in the region and to compare their characteristics with those of less-modified features found at lower levels.

The method for identification of high-level erosion surfaces is based on that of Macar (1938):-

For the area east of the Spey and north of Glen Clova, each kilometre grid square from the 1:50 000 First Series Ordnance Survey maps was examined visually for (a) tracts of low slope indicated by areas between consecutive contours of greater than $0.25km^2$ or (b) isolated summits. The elevations, to the nearest 10m, of tracts of low slope or isolated summits, where present, were then noted for each grid square. Adjoining grid squares with tracts of low slope with elevations within 30m or less of each other were grouped together as 'flats'.

The technique suffers from a degree of subjectivity and from inaccuracies in the contour information on the base maps. However the method is rapid and is sufficiently precise to identify basins and other relatively small erosional features, such as valley benches. The technique aims to include only information which is of value in surface reconstruction and is particularly useful in identifying core areas where surfaces have not been seriously disrupted. Outlying 'flats' and isolated summits can then be linked with these core areas to provide a picture of the extent and slope of the surfaces. The technique also serves to emphasise major breaks of slope between erosional levels. Field checks in the areas around Aultmore, the Clashindarroch Forest, Mount Keen and Lochnagar suggest that the technique is an accurate means of identifying areas of levelled relief.

The technique points to the existence of at least 4 regional erosion surfaces in north-east Scotland (Fig. 11.5.i):-
(i) the Summit Surfaces, (ii) the Avon-Clova Surface,
(iii) the Mounth Surface and (iv) the Marginal Surface. A similar number of surfaces were recognised by Fleet (1938) but only his upper and lower surfaces are strictly equivalent to the features recognised here.

11.6 The Summit Surfaces

The paleic topography of the Cairngorms has been described by Linton (1950) and Sugden (1968). The plateau surfaces possess considerable relief, with residual hills rising as much as 300m or even 400m above a break of slope at around 910m. The rolling slopes are conformable with well-developed pseudo-bedding and are surmounted by tors which have survived at least one glaciation (Sugden 1968). Of note also are the clearly-defined basins containing the Moine Mhor and the Moine Bhealaidh, the most elevated representatives of a suite of similar forms found throughout north-east Scotland.

In the Lochnagar and Glas Maol areas, the main summits rise from a local level at around 850m. More extensive surfaces occur at similar elevations on the Gaick Plateau and the Monadhliath and these fragments may be the remnants of a summit surface of low relief.

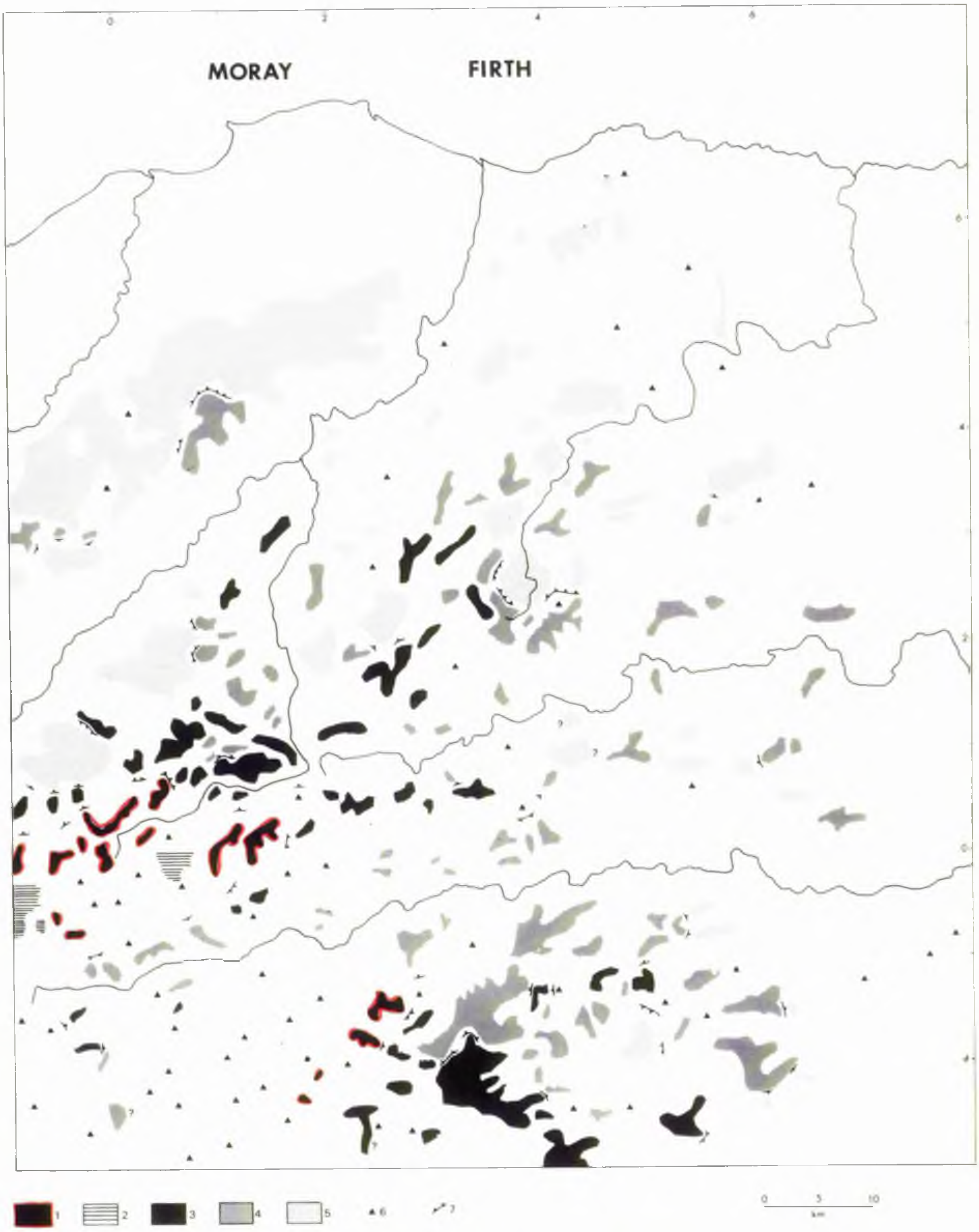


Fig. 11.5.i. Distribution of remnants of the main erosion surfaces.

1. Cairngorm Summit Surfaces 2. Basins of the Summit Surface
3. Avon-Clova Surface 4. Mounth Surface 5. Marginal Surface
6. Isolated summits 7. Major breaks of slope between surfaces

11.7 The reality of the Grampian Main Surface

Below the Grampian Summits, Fleet (1938) recognised a Grampian Main Surface at elevations of between 730m and 945m. The Main Surface was shown fringing the Cairngorm Massif and forming much of the high ground of the Hills of Cromdale, the Ladder Hills and plateau areas east of Lochnagar. The Surface was thought to reach its most extensive development in the broad tract between the Dee valley and the Atholl Basin.

There are a number of reasons for doubting the reality of the Grampian Main Surface. Firstly, there are few areas of levelled relief above 800m around the Cairngorm Massif. The Summit Surface around Cairn Gorm (1245m) is bounded to the NW by a sharp break of slope leading directly to a lower ring of hills at between 720 and 810m overlooking the Glen More Embayment (Linton 1950). Similarly the gentle surface of the Avon Embayment at between 680 and 780m is backed to the south by striking escarpments rising unbroken to the summits of Stob an t'Sluichd (1140m) and Ben Avon (1171m). To the SE the picture is less clear, for isolated summits such as Cullardoch (900m) and Carn na Drochaide (817m) fringe the main summit area, but in the upper Dee valley the bulk of Beinn Bhrotain (1157m) again drops dramatically to valley benches at around 610m (Fig. 1.7.i). The conclusion of Sugden (1968) that the Cairngorm Massif rises from a break of slope at around 760m must therefore be accepted.

A very similar situation occurs east of the Lochnagar Massif, where an abrupt hill-front faces the inner edge of the Mounth Plateau at around 730m. Moreover the topography east of Glas Maol is deeply dissected and this most extensive part of the Main Surface

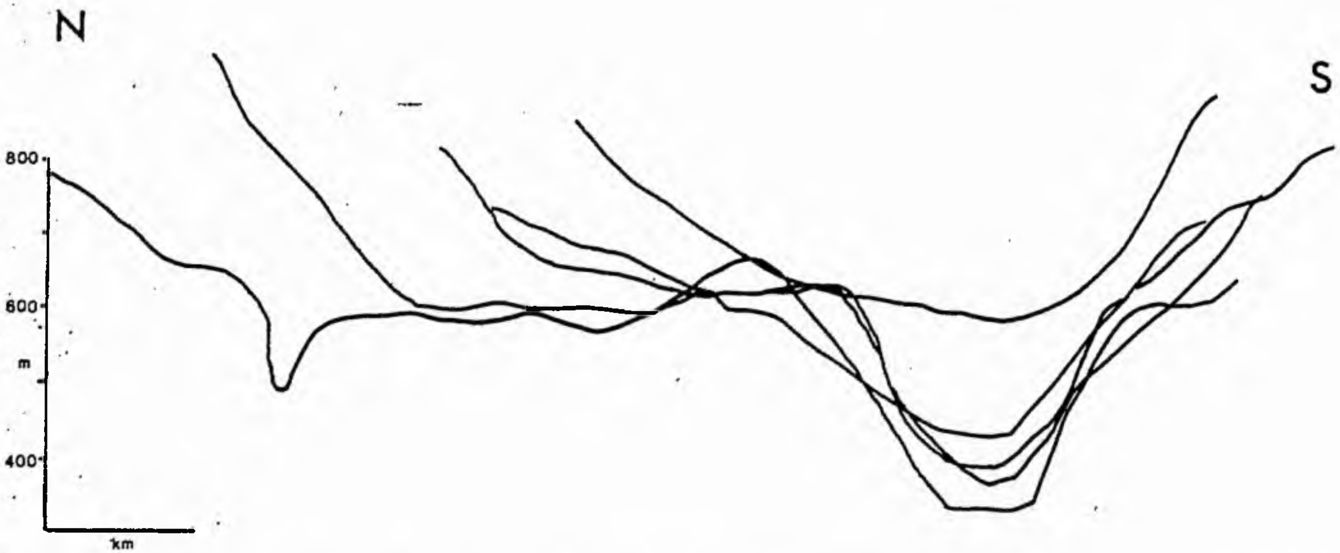


Fig. 11.7.i. Superimposed sections across the upper Dee and Geldie valleys.

is reconstructed almost entirely from isolated summits. In the absence of large areas of levelled relief covering the height range of 730-945m, it is necessary to reject the idea of a Grampian Main Surface in areas east of the Cairngorms.

11.8 The Avon-Clova, Mounth and Eastern Grampian Surfaces

The broadest surfaces of low relief bordering the Cairngorms are those of the Avon Embayment and the Mounth Plateau and it seems reasonable to begin the search for different generations of high-level surfaces in these core areas. Observations on characteristic relief forms may then be extended to districts with more disrupted relief.

11.8.1 Evidence for two surfaces on the high plateau of the Eastern Grampians

The Avon Embayment (Linton 1950) forms a shallow basin-like head to the former Don valley (Bremner 1921; 1942). The Embayment is backed by major scarps rising to the Cairngorm summits and is developed on the Cairngorm granite but extends on to Moine psammites (Fig. 11.8.i). The subdued topography of the Embayment floor lies between 680 and 780m, but along the Avon and Caiplich valleys, well-defined valley benches are sunk into this surface at heights of 640 to 680m. The present drainage of these rivers is incised deeply below these benches.

The Mounth Plateau, running eastwards from Lochnagar (1155m), is one of the most impressive areas of levelled relief in the whole of the Scottish Highlands (Plate 11.8.i). The remarkable preservation of the paleic relief can be judged from the reconstruction by Bremner

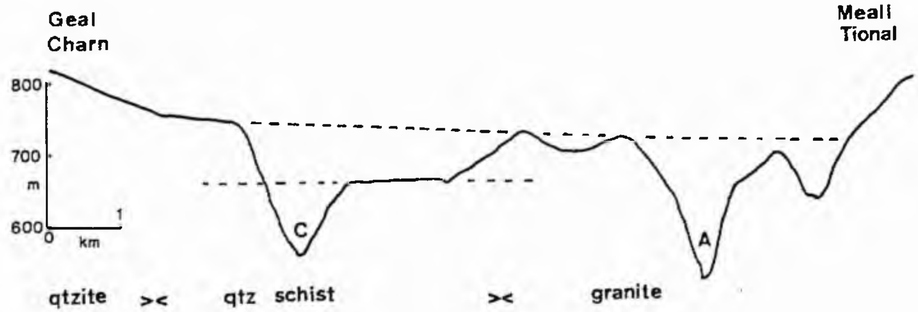


Fig. 11.8.i. Section across the Avon Embayment.

C Water of Caiplich A River Avon

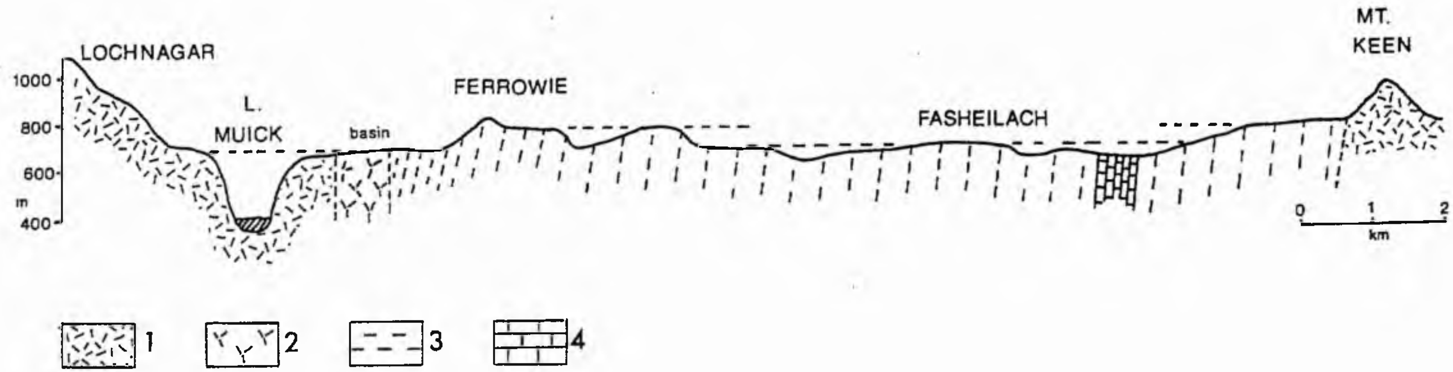


Fig. 11.8.ii. Section across the western Mounth.

1. Granite 2. Granodiorite
3. Quartz schist 4. Limestone

Upper level Avon-Clova Surface Lower level Mounth Surface

Plate 11.8.i. The Mounth plateau, looking west from the summit Of Mount Keen.

Plate 11.8.ii. Mount Keen from Glen Tanar.

(1919) of former tributary drainage networks in the area. This drainage originated in the hills lying above 900m to the east of Glas Maol and flowed NE before turning eastwards to follow structural trends along the broad and shallow valleys of the Waters of Mark, Lee and Unich. The glacial troughs of Glens Muick, Doll and Clova abruptly truncate these valleys and the divergence of ice-flow created by the troughs undoubtedly accounts for the insignificance of glacial erosion over much of the Mounth.

The relief of the Mounth can be resolved into two separate surfaces (Fig. 11.8.ii). The mass of Lochnagar drops to a bench at around 730m to the north of Loch Muick which can be traced eastwards around the foot of Broad Cairn and on to the string of low hills between 760 and 830m along the northern edge of Glen Clova. These hills are embayed by a shallow basin standing above and to the SE of Loch Muick and present a low escarpment to a planar surface which dips gently to the NE. The upper surface re-appears around Mount Keen (939m), where it forms a base for this residual hill (Plate 11.8.ii), but elsewhere it has been consumed by the lower level.

The twin surfaces of the Avon Embayment and the Mounth are here termed the Avon-Clova Surface and the Mounth Surface. Both Surfaces may be recognised in other areas but the relationships between them are clearest in these type areas. The interdigitation of the Surfaces and the limited height differences between them suggest a closely-related age and origin. The Mounth Surface appears to have developed out of the Avon-Clova Surface, which is now largely confined to fragments surrounding the Cairngorm Massif.

11.8.2 The Avon-Clova Surface

The Avon-Clova Surface shows only weak structural control. The backing scarp and floor of the Avon Embayment are both cut within the Cairngorm granite. Similarly the break of slope at the inner edge of the Mounth falls entirely within Oldershaw's (1974) A3 Adamellite (Fig. 11.8.ii), although its alignment follows the general trend of the Lochnagar Ring Complex. Although the break of slope at the western foot of Mount Keen lies along the contact between mica schists and the upstanding granite, the break occurs entirely within the granite on the other sides of the hill. Other outlying inselbergs such as Morven (871m), The Buck (721m) and Ben Rinnes (840m) were probably also isolated during formation of the Avon-Clova Surface. These hills are not associated with particularly resistant rocks and appear to be inselbergs of position rather than of resistance (Birot 1978). The case of Morven is particularly striking, for the hill and its base are formed of basic igneous rocks which elsewhere are almost invariably associated with negative relief.

11.8.3 The Mounth Surface

The much more extensive Mounth Surface is broadly equivalent to the Grampian Lower Surface of Fleet (1938). The upper limit of the Mounth Surface is at about 700m and the Surface slopes eastwards to fragments on the hills overlooking the Highland Boundary Fault and on Hill of Fare and Bennachie at between 450 and 500m, a gradient of c. 5m/km. Away from the Mounth, the

Surface is also well-developed to the south of Morven and in the basin-like valley of the Gairn. In the upper Feshie-Geldie Burn valley, which provided the headwaters of the Dee before glacial breaching and diversion (Bremner 1912; 1942; Linton 1949), there are a number of wide valley benches at around 600m backed by steep scarps (Fig. 11.7.i). Benches also occur in the upper Avon valley (formerly draining to the Don), in the Allt Garbh Buidhe valley (formerly part of the Tarf and draining to the Dee) and in the Quoich valley (Bremner 1919; 1942). These benches are the innermost representatives of the Mounth Surface and point to a major phase of valley widening.

North of the Don, the ridges of the Ladder Hills, the Blackwater Forest and the Buchat-Deveron interfluve carry extensive remnants of both the Avon-Clova and Mounth Surfaces. However the local relief is considerably in excess of that shown by these Surfaces in their core areas, partly due to the depth of valley incision and basin deepening which was well-advanced before glaciation.

The Mounth Surface is continued eastwards by the long resistant ridges of the Hills of Foudland, the Correen Hills and Bennachie, and Benaquhallie and the Hill of Fare. The hills of Bennachie, Cairn William and Fare terminate abruptly to the east in a series of major scarps which fall uninterrupted to the Skene lowlands.

As might be expected from its intimate association with the Avon-Clova Surface, the Mounth Surface shows only a weak regard for structure. On the Mounth itself, the Surface is developed predominantly in granite, but also cuts schists and quartzites. The plinth from which Morven rises is developed across both basic and acid igneous rocks but the Gairn basin is opened out wholly within granite. North of the Don, differential erosion has picked out certain less durable rocks, such as the granites of the Livet basin and the basic rocks of the Blackwater valley and the Cabrach basin, but the remnants of the Mounth Surface preserved on the intervening ridges are cut indiscriminately across quartzite, pelitic schist, granite and norite. Due to their position, the eastern outliers of the Surface are preserved only on resistant rocks, mainly leucogranites.

11.8.4 The composite form: the Eastern Grampian Surface

The Avon-Clova and Mounth Surfaces together represent a prolonged period when levelling penetrated deep inland to terminate in a mountain front against the Cairngorm Massif. An initial phase created extensive surfaces of moderate relief developed across rocks of variable resistance. Major basins were opened out in the granites of the Gairn and Avon valleys and along the western edge of the Cairngorms (Linton 1950) and a number of important inselbergs of position were isolated. This surface was then itself lowered and modified to produce the lower relief of the Mounth Surface. Surface extension appears to have taken place by basin development and valley widening towards the heads of the drainage networks. This later phase of levelling completely consumed the earlier surface in most areas, leaving substantial fragments only along the inner edge of the Mounth and in the Avon Embayment (Fig. 11.5.i).

This composite surface dominates the high-level relief east of the Cairngorms and represents a polycyclic erosion surface of regional extent: the Eastern Grampian Surface. The general disregard for geology, the abrupt backing scarps and the importance of inselbergs of position can be interpreted as climato-genetic features inherited from warm and periodically arid environments (Godard 1965; Birot 1978; Budel 1978). However as tropical climates did not prevail after the end of the Palaeogene in Scotland, this interpretation can only be accepted if some mechanism can be proposed to allow conservation of apparently ancient relief forms. This problem will be examined further in Chapter 14.

11.9 The Marginal Surface

The Mounth Surface represents the last period of levelling to penetrate deep inland and the dissected eastermost fragments of the Surface drop directly to the coastal lowlands without any significant intervening levels (Fig. 11.5.i). In the north, however, the Mounth Surface gives way to another extensive area of planed relief at elevations of between 280 and 370m, termed the Marginal Surface. This feature corresponds with the Grampian Valley Benches of Fleet (1938) and was described briefly by Walton (1963). The Marginal Surface consists of two main elements (Linton 1951):- (i) broad surfaces of low relief fringing the Moray Firth coast and (ii) a string of major basins and embayments stretching along the length of the Spey valley.

11.9.1 The coastal plateau

The Marginal Surface is best preserved on the hills S and SW of Elgin. In this area, the Surface forms a monotonous plateau rising to 370m and cut across Moine psammites. The plateau is surmounted by several low hills, such as Carn na Cailliche (404m) and by the prominent quartzite inselberg of the Knock of Braemoray (456m). In places, the plateau is backed by a weakly-developed scarp rising to residual hills of the Mounth Surface, as at the base of Carn Shalag (470m) and Carn na Loine (548m). Around Lochindorb, the Marginal Surface is so deeply embayed into this upper relief that it is almost coalescent with the most northerly of the Spey basins, the Carrbridge basin. To the north, parts of the plateau have been lowered to give the broad and shallow basins containing the Moss of Bednawinny and Dava Moor.

The Marginal Surface is continued eastwards across the Spey on the flags and quartzites of the tabular Hill of Aultmore at between 250 and 300m. Remnants also truncate the quartzite ridges of the Bin of Cullen (320m) and the Hill of Inverkindling (281m) and the gneissose Catstone Hill (259m) - Culvie Hill (264m) ridge. This characteristic bevelling of ridge and hill tops recurs much further east on Windyheads Hill (231m) and Hill of Fishrie (227m) and it is suggested that this small group of tabular hills south of Troup Head is the easternmost representative of the Marginal Surface. If correct, this means that the Surface drops from 360m to 220m in about 70km, a gradient of c. 2m/km.

In the lower Spey valley, the Marginal Surface is terminated by a series of SW-NE trending scarps whose position is unrelated to lithology (Fig. 11.9.i). The steep scarp south of Findochty shows particularly striking discordance, with both the Hill of Maud (270m) ridge and the low coastal platform formed in the Cullen Quartzite, but the pattern is repeated westwards across the Spey where several lower scarps fall entirely within the Moine psammites. The consistent trend suggests that these are fault scarps produced during uplift of the Marginal Surface in the border zone between the basement high and the Moray Firth Basin, an interpretation supported by the sub-parallel orientation of several known faults in the area.

Further inland, the prominent bench on the northern flank of the Hill of Foudland is also part of the Marginal Surface (Walton 1963). The bench is cut across steeply-dipping Macduff Slates (Fig. 11.9.ii) and the sharp break of slope to the rear is unrelated to lithology. However the reversal of dip across and the alignment of the deep Glens of Foudland meltwater channel indicates the presence of an important fracture. The wind gap north of the Hill of Tillymorgan suggests that the bench once carried the headwaters of the Ythan.

To the west, the relief of the Marginal Surface increases. Around the Daugh of Invermarkie, the Surface is represented by a shallow embayment between 290 and 320m developed across Older Basics, with quartzite ridges, such as the Hill of Talnamouth, rising to 380m. The narrow valley of the upper Deveron is flanked by a series of benches between 300 and 335m (Fig. 11.9.iii) and opens out into the Cabrach basin and the Black Hill degraded basin.

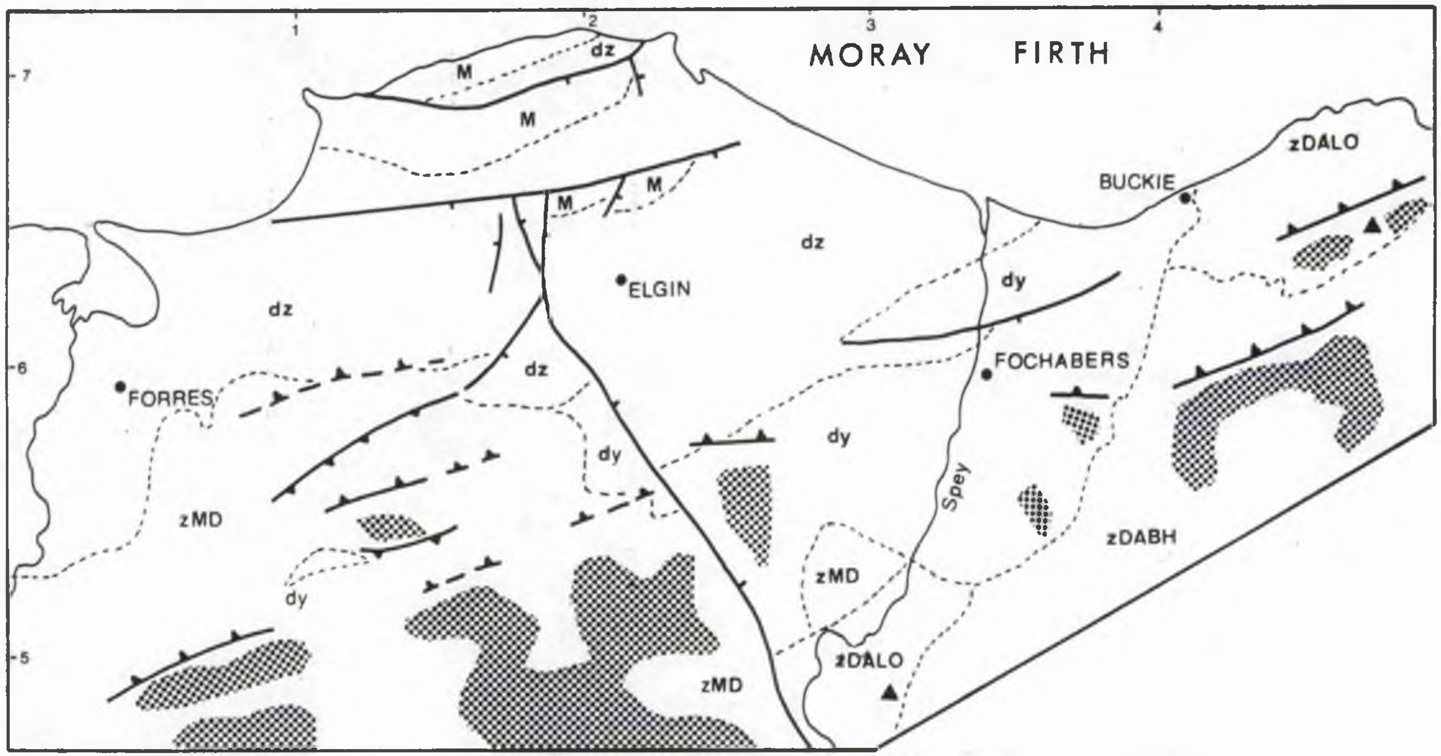


Fig. 11.9.i. Tectonic scarps in the Elgin district.

M Jurassic and Permo-Triassic sediments. dz Upper Old Red Sandstone
dy Middle Old Red Sandstone zDABH Dalradian schists, mainly flags
zDALO Dalradian quartzites zMD Moine granulites
Shaded areas Fragments of the Marginal Surface

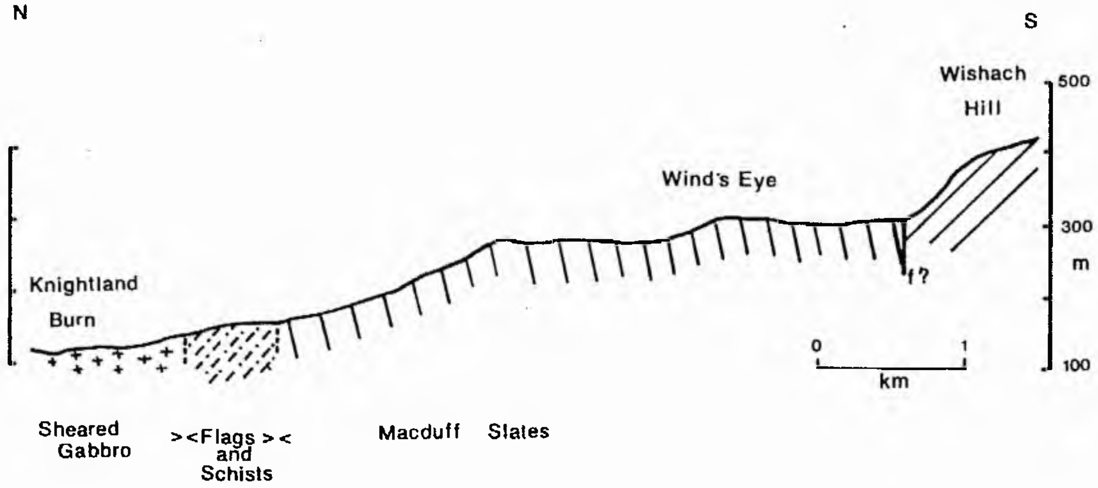


Fig. 11.9.ii. Section across the Marginal Surface at Wind's Eye.

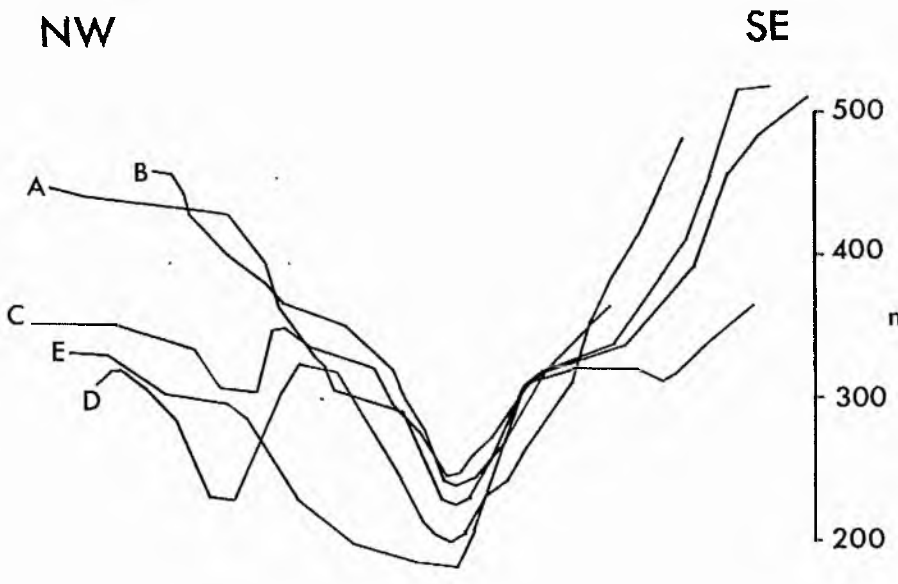


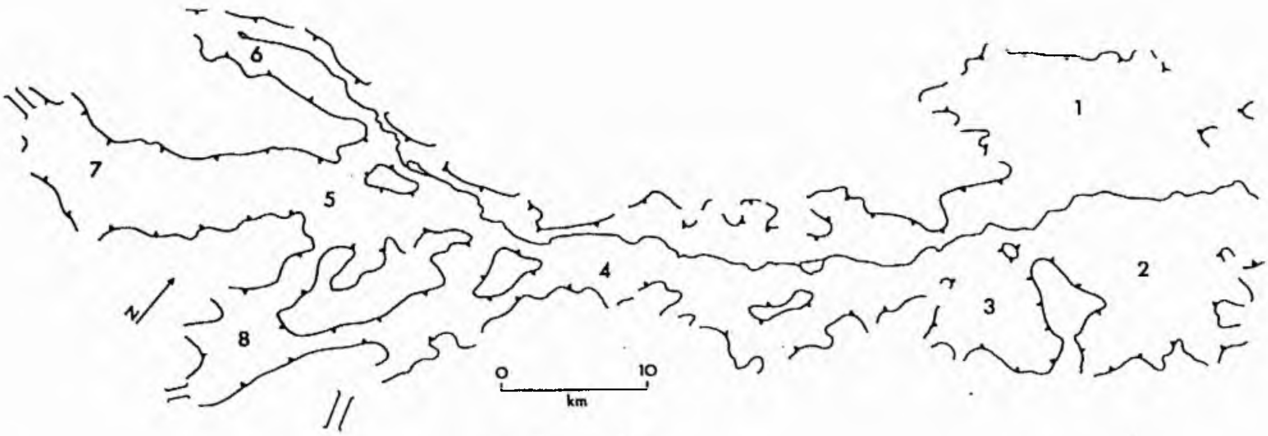
Fig. 11.9.iii. Superimposed profiles across the upper Deveron valley.

However the deep gorge at the exit of the Cabrach basin at Corinacy indicates a period of substantial lowering and the present floor post-dates the Marginal Surface.

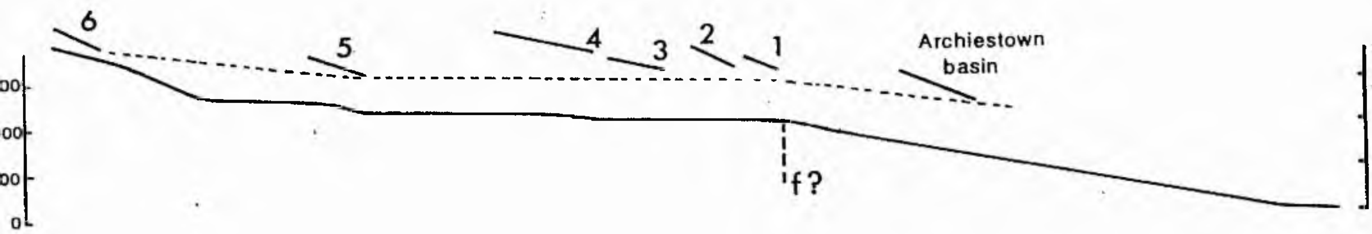
11.9.2 The inland basins

The Spey valley frequently opens out into broad embayments whose floors rise from c. 300m at Carrbridge to c. 410m at Loch Spey (Fig. 11.9.iv). The embayments lie upstream of the rejuvenated section of the lower Spey (Hinxman 1901) and demonstrate that the course of the middle and upper Spey was established prior to this period of levelling. Together with isolated basins at Tomintoul and in upper Glenlivet, these embayments form the second major element of the Marginal Surface.

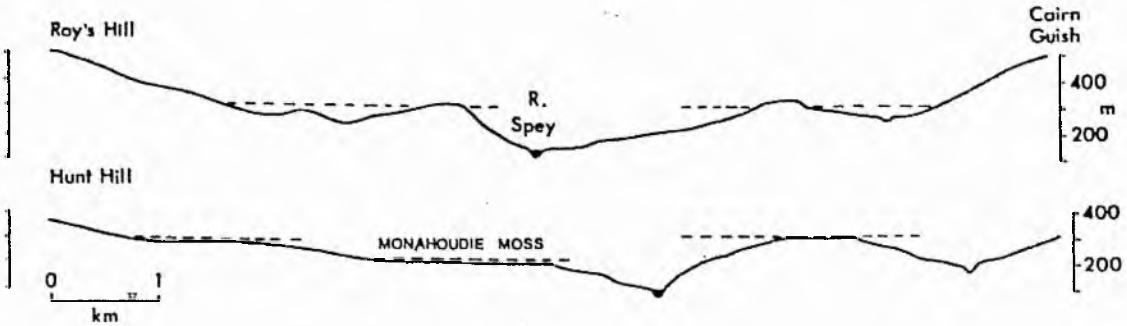
The most northerly embayment at Carrbridge gives way downstream to a dissected basin at c. 290m around Archiestown (Hinxman 1901). Upstream, the valley opens out into a series of ice-scoured embayments backed by bold scarps rising to the Cairngorm Massif. The Abernethy and Glenmore embayments are overlooked by semi-circles of isolated summits and the present floors have probably been fashioned from earlier and larger embayments (Linton 1950). Towards the headwaters, the degree of enclosure increases and the basins are set within hills rising above 1030m. The Alder and Spean basins lie alongside but well above major glacial troughs and must have been in existence well before glaciation. The proximity of these basins to the main watershed of the Highlands and to the mega-basins of Rannoch and Atholl indicate formation during a major phase of basin development reaching to the heart of the western Grampians.



a. Location



b. Elevations of embayment floors plotted against the long profile of the Spey



c. Sections across the lower Spey valley around Archiestown

Fig. 11.9.iv. Embayments of the Marginal Surface along the Spey valley.

1. Carrbridge 2. Abernethy 3. Glen More 4. Nuidhe Moss
5. Inverpattack 6. Loch Spey 7. Spean 8. Alder

The Marginal Surface is essentially a feature of the Moray Firth border and the valleys of the Spey and its major tributaries. East of Bennachie and Hill of Fare, the Mounth Surface drops directly to the Skene depression. Similarly, there is little sign of any erosional bench on the Highland Boundary Fault scarp above the Howe of the Mearns. In these southern areas, the only likely representatives of the Marginal Surface are the benches and degraded basin floors lying between 220 and 270m in the Dee, Don and North Esk valleys.

11.9.3 Structural Relationships

Both the coastal surfaces and the Spey embayments show only a weak regard for structure. South-west of Elgin, the Marginal Surface is developed in psammitic schists but to the east, fragments of the Surface are preserved on a variety of rocks, including Old Red Sandstone and Dalradian flags and quartzites. Further inland, the Foudland bench truncates steeply-dipping slates but remnants elsewhere are formed in less resistant biotite gneisses and Older Basics. The isolated basins of Cabrach and Tomintoul are partially-exhumed Devonian features but the embayments of the Spey are wholly Tertiary forms, with floors cut indiscriminately across Moine psammites and Caledonian granites.

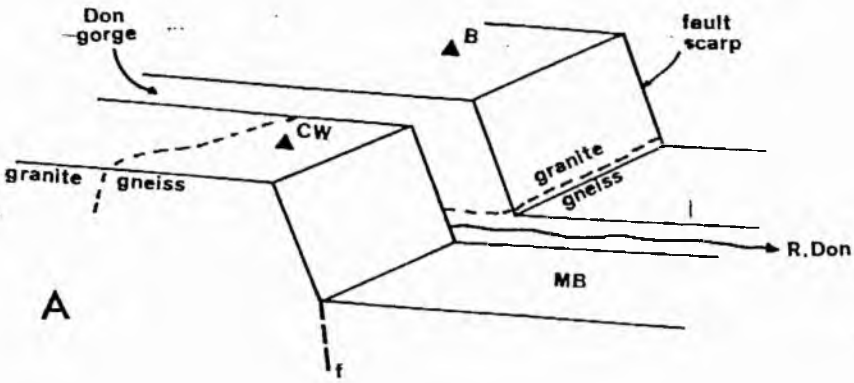
11.9.4 Possible modes of origin

The presence of a number of embayments along the inner edge of the coastal plateau suggests that the Marginal Surface was extended by basin development and widening. The importance of this process is well-illustrated in the Spey valley, although some of these embayments were probably opened out during formation of the Mounth Surface and subsequently lowered (Linton 1950). However the development of planar surfaces cut across quartzose rocks and the occasional occurrence of steep backing slopes against the Mounth Surface suggest that scarp retreat also had a prominent role in the formation of the Marginal Surface.

Although basin lowering was able to penetrate deep into the Grampians along the Spey valley, the more restricted extent of the Marginal Surface indicates formation within a considerably shorter period than its predecessor, the Mounth Surface. The Marginal Surface was apparently uplifted without significant deformation and tilted towards the east. Along the Moray Firth coast only narrow coastal platforms have developed since its formation, demonstrating that the Marginal Surface is of comparatively recent origin.

11.10 Tectonic origin for certain major scarps along the highland border

In a number of areas, the high-level relief is bounded by major scarps falling directly to the lowlands. The series of sub-parallel scarps along the edge of the Marginal Surface in the Elgin area have already been described but even more striking features occur to the south around the elevated plateau areas of Bennachie, Hill of Fare and the Mounth. At first glance, these scarps appear to be products of differential rock resistance but closer examination reveals significant discordance between geology and scarp alignment.



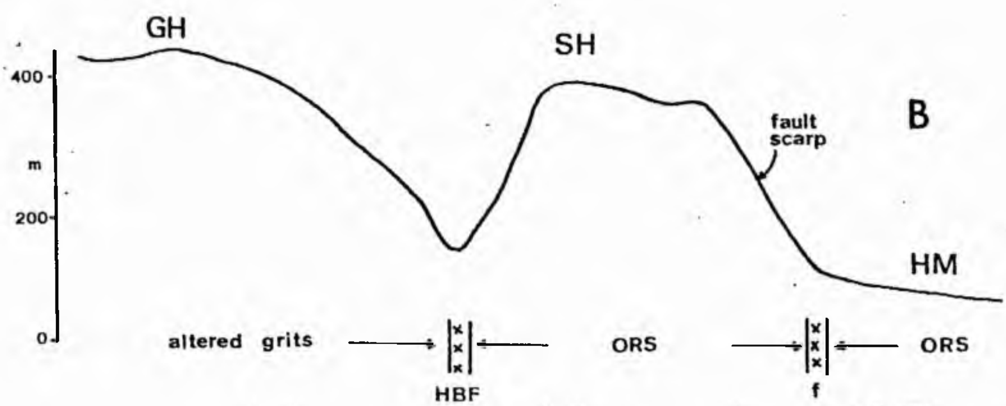


Fig. 11.10.i. Tectonic scarps A. Bennachie-Fare Fracture
B. Highland Boundary Fault

B. Bennachie CW. Cairn William MB. Monymusk Basin
GH. Goyle Hill SH Strathfinella Hill HM. Howe of the Mearns

The major scarp to the east of Bennachie (528m) and Cairn William (448m) illustrates this local discordance well (Fig. 11.10.i). North of the Don, the scarp can be seen as a resistant form dividing the upstanding relief of the Bennachie leucogranite from the cordierite gneiss and biotite granite forming the floor of the Monymusk basin. However this interpretation must be rejected, for around Cairn William the gneiss forms part of the plateau and the scarp slope as well as the basin floor. Similarly, although the steep scarps bounding the Hill of Fare can be related in general terms to the contact between acid granites and the biotite-bearing varieties of the Skene lowlands (Walsworth-Bell 1974), the acid granites also locally outcrop at the foot of the scarp, as around Tillybirloch (Wilson and Hinxman 1890). The Highland Line scarp overlooking Strathmore might also be regarded as a scarp of resistance separating the schists and granites of the Mounth from weaker Old Red sediments, yet the Old Red forms tabular hills rising to the general level of the backing plateau of the Mounth at several points between Stonehaven and Perth (Fig. 11.10.i).

In the Elgin area and along the Highland Line, the scarps run parallel to or are aligned along major faults. The Hill of Fare and Bennachie scarps follow no known faults but the dominance of the SW-NE and NW-SE lineations in the topography of these areas suggests strongly that important fractures are present. These scarps can thus be interpreted as fault-line scarps, although there are reasons for rejecting this view.

There is no geological evidence for post-Caledonian movement of the Bennachie-Fare fractures but the Highland Boundary Fault and at least some of the faults in the Elgin area were active throughout the Mesozoic. Movements cannot be assumed to have ceased simply because later rocks which might demonstrate movement are not preserved and, indeed, geomorphic evidence indicates comparatively recent activity:-

(i) These scarps are backed by extensive and relatively undissected plateaux belonging to the Mounth and Marginal Surfaces. The structural alignment of the scarps argues against significant retreat and these elevated tablelands cannot be regarded as remnants of the progressive encroachment of a later phase of planation. A model of cyclic erosion is not sustained and interpretation in terms of differential uplift seems more plausible.

(ii) The scarps cannot be seen as an expression of differential rock resistance. The Elgin scarps show gross discordance with geology and the other scarps display equally striking local discordance. This discordance is difficult to explain if these features are regarded as fault-line scarps aligned along ancient and dormant structures and marking the boundaries between geological provinces of different resistance. The presence of relatively weak sandstones and gneisses above the scarps is inconsistent with prolonged differential erosion and recent movements are implied.

(iii) Major uplift of the Bennachie-Fare massif relative to the Skene lowlands is suggested by the superimposed course of the Don. The Don flows through the plateau overlooking the Howe of Alford in a gorge some 300m deep. The gorge follows no known line of structural weakness and is cut through resistant andalusite schists and leucogranites. As there is no evidence of former cover rocks, superimposition during differential uplift seems likely.

(iv) Comparatively recent differential movements between the Moray Firth Basin and the surrounding basement were invoked by Hinxman (1907) to account for the marked steepening of gradient of the lower courses of the Beauly, Conon and Spey. This inferred style of movement is consistent with that proposed for the Elgin area.

(v) The pattern of movement is also consistent with that earlier in the Tertiary and in the Mesozoic and Palaeozoic. The occurrence of chalk flints was previously related to differential movements between the Cairngorm and Formartine structural blocks and the Bennachie-Fare Fractures probably represents an intervening fault zone which has been active since at least the Palaeocene. Uplift of the Bennachie granite in the Tertiary can be inferred from the continued presence of roof rocks on the intrusion despite exposure during the Devonian. In the longer term, the postulated differential movements between the rising basement of north-east Scotland and the subsiding sedimentary basins of the Moray Firth and Strathmore can be seen as the prolongation of styles of movement initiated in the Devonian and continued throughout the Mesozoic.

(vi) Neogene movements are supported by the continuance of tectonic activity into historical time. There are numerous historical records of movements of the Great Glen and Highland Boundary Faults. Perhaps the most dramatic event was the 1839 earthquake in the Comrie district, when movement of the Highland

Boundary Fault opened up a fissure 200m long and caused extensive damage to buildings (O'Dell and Walton 1962).

It is concluded that these scarps are of tectonic origin and reflect differential movements of considerable magnitude between structural units during uplift. Movement of the Highland Boundary Fault in the late Pliocene has been postulated by Fitzpatrick (1969; 1972) and substantial late Tertiary differential movement have been proposed in northern England (Trotter 1929; Versey 1935; Owen 1978). Tectonic scarps have also been recently described from Wales and relate to the deformation of a regional erosion surface in the Neogene (Battiau-Queney 1979). Comparisons may also be drawn with Brittany and southern Sweden, where Neogene horsts and grabens have been recognised in basement areas previously thought to be tectonically stable (Durand and Milon 1962; Gautier 1967; Lidmar-Bergstrom 1982). The limited dissection of the Mounth and Marginal Surfaces above the scarps suggests that faulting in north-east Scotland is also of late Tertiary age.

Although lesser movements away from the edges of the main structural blocks may have produced other unrecognised tectonic scarps, it should be emphasised that many scarps in the region are not of tectonic origin. The low scarp which backs the coastal plateau of the Marginal Surface is deeply embayed and this lower Surface has developed at the expense of its precursor, the Mounth Surface. Similarly the inselbergs of position which rise above the polycyclic Eastern Grampian Surface appear to be largely products of slope retreat. The scarps bounding the Cairngorm Massif may be partly tectonic in origin, for the Massif is rectilinear in outline and the scarps generally disregard the local geology. However whilst the positive relief of the Cairngorms may reflect some horst-like structure, this possible tectonic unit must have been dormant since extension of the Avon-Clova Surface along the major valleys and into the Cairngorm area. The highlands of north-east Scotland thus include major escarpments with origins in differential tectonic movements, differential erosion and scarp retreat and many scarps probably represent a combination of these factors.

11.11 The principal stages in the development of the highland relief

11.11.1 The geomorphic significance of differential tectonic movements

The recognition of substantial differential tectonic movements in north-east Scotland during the Tertiary has major geomorphic implications. The preservation of Chalk flints and unfaulted Old Red Sandstone outliers can be explained by the relative stability of the Formatine Block and the Moray Firth Border Zone compared with inland areas. It can also be suggested that the broad lowland plain on the Formartine Block and the elevated tablelands on the Cairngorm and Mounth Blocks are inherited from a single master surface which, prior to regional uplift and movement of the Bennachie-Fare Fracture, extended from the foot of the Cairngorm Massif to the North Sea coast. Both differential tectonics and regional tilting have tended to maintain eastern areas close to base level and the possibility is raised that the lowland relief contains elements of considerable antiquity. Differential movement also helps to explain why the Marginal Surface should be so extensive in the north and yet virtually absent south of the Insch depression. Finally, the identification of styles of tectonic movement allows reconstruction of the main stages in the development of the highland relief.

11.11.2 Evolution of the highland relief.

Much of the relief of north-east Scotland appears to have been inherited from a complex surface of low relief of regional extent. Uplift of this master surface took place on two stages and its later history has differed in northern and eastern areas. Along the Moray Firth coast, the master surface was raised initially to a position at least 200m above its original level. Development of the Marginal Surface took place during and after this primary phase of uplift by backwearing and lowering of the earlier surface. Further inland, the raised master surface was also lowered to form part of the Eastern Grampian Surface. A second phase of uplift then began and these surfaces were raised by a further 300m and tilted towards the east. Lowering of the highland relief continued and the Marginal Surface was disrupted along the Deveron by the eastward penetration of basin development.

South of the Insch depression, uplift of the master surface must have involved considerable differential movements for there is little sign that the Eastern Grampian Surface has been worn back to its present position overlooking the Skene lowlands. Instead it seems that initial uplift of the master surface saw movement and probably reactivation of the Bennachie-Fare Fracture, with areas west of the Fracture raised by at least 200m more than those to the east. This order of differential movement can be estimated from the existence of benches and degraded basin floors at between 220 and 280m in the Dee, Don and North Esk valleys. These scattered local flats now stand some 200m below the Eastern Grampian Surface and represent former valley and basin floors graded to an equivalent of the Marginal Surface in the Skene lowlands. This surface on the Formartine Block developed by lowering of the modestly uplifted master surface and failed to bevel the new fault-scarp. During the second phase of uplift, the surfaces on the Cairngorm and Mounth Blocks were raised by at least a further 200m to form the eastern portion of the Eastern Grampian Surface. However the latest floors of several basins along the Dee and Don valleys lie only about 100m below the earlier benches. Further differential movement across the Bennachie-Fare Fracture is indicated and the fault-scarp reached its present height of around 300m. The latest basin floors are now graded to the Buchan Surface in the Skene lowlands (Linton 1951; Walton 1963).

In outline, the evolution of the highland relief can be seen in terms of alternating phases of levelling and dissection, with reduction of relief during periods of relative tectonic stability and increased relief during periods of uplift. These alternating morphogenic environments can be matched with major intervals of biostasy and rhexistasy (Erhart 1955) inferred from the offshore stratigraphic record (Chapter 3). This type of correlation allows the timing of the main geomorphic and tectonic events in the shaping of the highland relief to be established. These problems of denudation chronology are examined in Chapter 14.

11.13 Summary

Exhumed relief is only of local importance in north-east Scotland. Sub-Devonian valleys and depressions occur widely but although there is evidence of periodic overstep of sediments on to the basement in the Mesozoic, no relief forms inherited from this period can be recognised. The stepped surfaces of low relief characteristic of the region are products of Tertiary morphogenesis.

Four high-level erosion surfaces are identified:- the Summit Surface, the Avon-Clova Surface, the Mounth Surface and the Marginal Surface. The Mounth Surface has been fashioned out of the slightly higher Avon-Clova Surface and together these features form the fundamental morphological level in the highlands: the Eastern Grampian Surface. To the north, this composite and polycyclic surface gives way to the broad coastal plateaux and major basins of the Marginal Surface at between 280 and 370m. These surfaces appear to have been uplifted without significant deformation and tilted towards the east. Uplift involved substantial differential movements between these raised areas and the adjoining structures of the Moray Firth Basin, the Formartine Block and the Strathmore Basin and prominent tectonic scarps mark the boundary between these uplifted and stable blocks. Finally, the principal stages in the development of the highland relief are identified.

CHAPTER 12 Weathering, slopes and landform development in the lowlands

12.1 Introduction

The landscape of north-east Scotland below an elevation of about 300m offers considerable scope for the study of the relationships between weathering and landform development. In many areas, glaciation has left intact parts of former weathering covers and information from boreholes and exposures allows the pattern and distribution of weathering to be established. Whilst the survival of saprolites demonstrates only modest modification of the preglacial relief, it is clear that the depth of glacial erosion has been spatially variable and palaeoforms can be recognised in various stages of degradation. These links between weathering and landform are examined, using a number of types of palaeoforms as case studies.

12.2 Some geomorphic implications of weathering profile characteristics

No single model typifies the weathering profiles and characteristics vary with rock type and structure. Three main types of profile have been recognised (Fig. 5.2.iii):-

(i) Profiles with thorough disaggregation

Transition from weathered to fresh rock occurs without significant corestone development. Typical of coarse-grained igneous rocks.

(ii) Profiles with corestones

Profiles exhibit the zonation described by Ruxton and Berry (1959), with a downward passage from completely grussified material to corestones and to fresh rock. Typical of fine- to medium-grained igneous rocks.

(iii) Profiles with blocky disintegration

Deep profiles retain bands or zones of blocky disintegration, even in the surface horizons. Typical of metamorphic rocks, particularly finer-grained varieties.

The nature of the transition from weathered to fresh rock varies in each of these profile types. Only in about one third of boreholes can a clear basal surface of weathering (Ruxton and Berry 1959) be identified and, more generally, disaggregated rock passes downwards into fresh rock either gradually or through alternating bands of weathered, weakened and fresh rock. This gradation takes place through a transition zone, which may reach a thickness of over 15m.

These characteristics are of some geomorphic importance. Most metamorphic and many igneous saprolites show only gradual changes with depth and regoliths with broadly similar properties can be maintained during landscape lowering. However profound stripping may produce striking differences in terrain. Bare rock landforms, such as tors, are only likely to emerge where a sharp basal surface of weathering exists (Thomas 1966). Exposure of thick transition zones will favour instead the development of smooth slopes. The tightly-interlocking structure of these partially-altered rocks will present considerable resistance to further stripping but competence is insufficient to support small, upstanding rock masses. Scale is a major consideration, however, for, whereas there is little sign of emergence of tor-like features in most metamorphic weathering profiles, larger dome-like features may occur. Such forms can be seen in the lower Ythan valley, where low gneissose hills rise out of surrounding saprolites.

The physical properties of the saprolites also have significance for geomorphic processes. Most grusses have little resistance to stripping, although granular grusses tend to be relatively more competent and will form steep faces in section. The development and preservation of sandy saprolites will be closely governed by thresholds presented by local slopes, by the disposition of rock barriers and by spatial and temporal patterns of regolith removal. Grusses may also reform comparatively quickly after phases of stripping (Tardy 1969; Thomas 1976), particularly where a reservoir of groundwater is retained within uneroded transition zones. Grussified landscapes are thus potentially highly dynamic.

A further consideration is that, whilst a relatively low degree of alteration is required to convert many granitic and gabbroic rocks to a granular sand, reduction of metamorphic rocks, especially finer-grained varieties, to a mechanically similar material involves more thorough alteration. This means that, at the initial stages of alteration, metamorphic saprolites will tend to be composed of coarser, and therefore more resistant material than corresponding igneous saprolites. These differences will be reduced with further weathering, when saprolite granulometry becomes increasingly dependent on the texture and mineralogy of the parent rock.

12.3 Weathering Patterns and Morphology

Occurrences of weathered rock are found throughout the lowlands of north-east Scotland, although the incidence of weathering varies greatly between areas (Figs. 5.2.i and 12.3.i). Depths of weathering in excess of 5m are common, and, although few deep borehole records are available, weathering is known to penetrate below 50m in a number of fracture zones. The frequency and depth of weathering indicate that many parts of the lowlands had saprolite covers at least 20m thick prior to glaciation.

At scales of less than 0.5km^2, depths of weathering can be highly variable and fresh outcrops may be found in sharp juxtaposition with deep pockets of weathering. Sections and boreholes show that the amplitude of the weathering front (Mabbutt 1961) may be greater than 20m within distances of 100m. Examples of more uniform weathering depths are not uncommon, but an accidented weathering front is the norm. Yet this highly irregular rockhead relief rarely finds expression in the surface topography, where smooth slopes cut bosses of fresh rock and pockets of weathering alike.

At broader scales, the amplitude of variation in weathering depths decreases and patterns of weathering become increasingly controlled by such factors as differential rock resistance, the disposition of major structures and topography. In Nigeria, Thomas (1966) identifies basins of weathering up to 50m deep and 250-1000m across bounded by domical risers. Comparable patterns of lesser amplitude can be discerned in the lower Ythan valley, where basins of weathering reaching depths of 10m are found adjacent to small hills rising to 25m above the general surface level. As

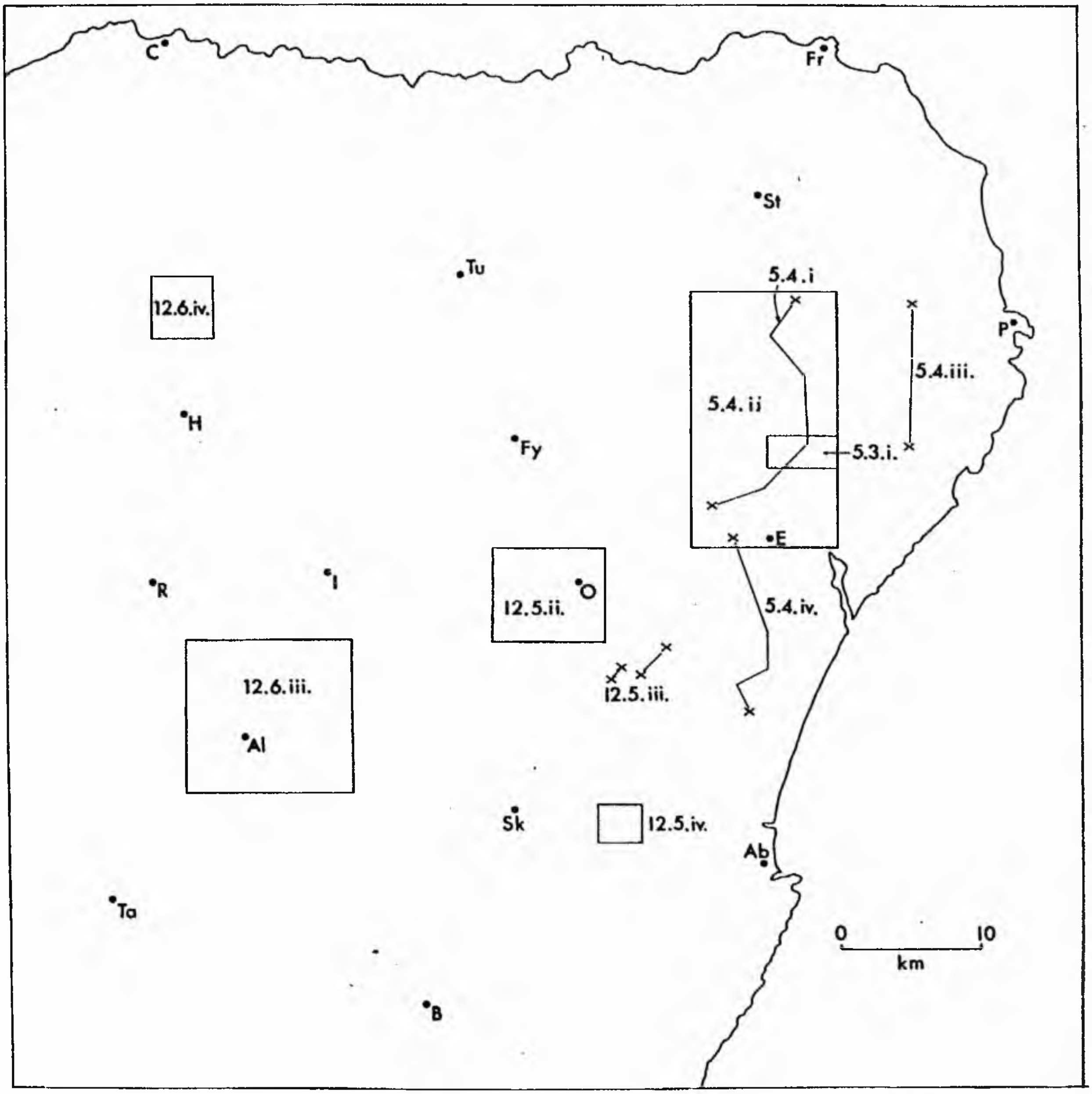


Fig. 12.3.i. Diagrams showing links between weathering patterns and morphology in the lowlands.

this area lies just to the south of the exceptionally deep saprolites around Arthrath (Fig. 5.4.i), the weathering front, prior to thinning of the saprolites, must have had a relief of at least 35m over distances of 0.5-2km. At Kinnadie Hill, to the north, the amplitude of the rockhead relief is around 25m/km and this order of variation may be typical of much of Buchan. Where the topography shows substantially greater relief than this, it is not likely to represent a simple basal surface of weathering exposed by glacial erosion.

Although the weathering front is perhaps characterised by successions of low risers and shallow depressions, a number of other significant features can be recognised. Of particular importance are linear zones of deep alteration following fracture belts. These weathering troughs occur at several scales, from features no more than 500m wide at Crichie and west of Hill of Minnes to troughs as much as 2.5km wide at Cairnie and along the Drumblade Shear Zone. Many narrow troughs of weathering have been exploited by meltwater channels but the common alignment of segments of the larger valleys with major fracture zones suggests that the main rivers became superimposed on weathering troughs prior to glaciation.

Another striking feature is the existence of scarp-foot weathering zones, similar to those described from warmer weathering environments (Wahrhaftig 1965; Bremmer 1975). These occur widely in the more compartmented relief of inland areas where the weathering troughs can be found at various stages of exploitation by the drainage (Fig. 12.3.ii). The alignment of the scarps can

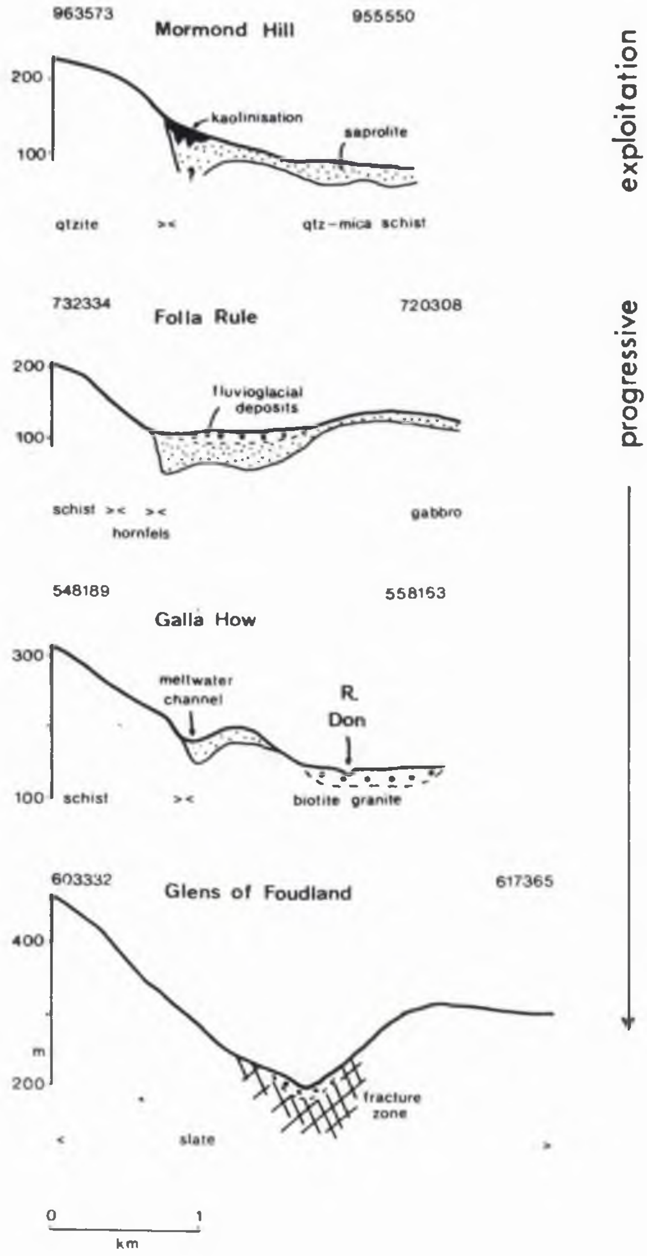


Fig. 12.3.ii. The scarp-foot weathering zone and its morphological expression.

generally be related to structure or lithological boundaries but differential weathering alone does not explain the decrease in weathering depths away from the scarp-foot zone. Rather it is the concentration and rapid throughput of groundwater at the base of the scarps that promotes deep decomposition (Bremmer 1975; Jahn 1980). The effects of moisture differentials are equally important for valley and basin development and these self-reinforcing links between groundwater movement, weathering and topography will be explored more fully later.

12.4 Weathering and slopes

12.4.1 Local relationships

Over distances of less than 0.5km, slope forms often show a striking disparity with weathering patterns. In many sections, smooth surface slopes are developed across materials at all stages of weathering. Bosses of fresh rock can be seen to have protected adjacent pockets of weathering from erosion but these risers commonly fail to have topographic expression. Numerous exposures of grussified granitic and gabbroic rocks display groups of corestones apparently in the process of exhumation, in identical settings to the classic example of an emergent tor at Two Bridges, Dartmoor (Linton 1955). Yet tors are largely absent from the lowlands, although many well-known examples occur on the summits of Bennachie, The Buck, Ben Rinnes and the Cairngorms (Linton 1955; Sugden 1969; Sugden and Clapperton 1977). The only recognised tors at lower levels occur in basic rocks at Carding Hill, Arnage and in the west around the Kirkney basin (Plate 12.4.i) and in Glenbuchat.

Plate 12.4.i. Tor group on the western margin of the Kirkney basin.

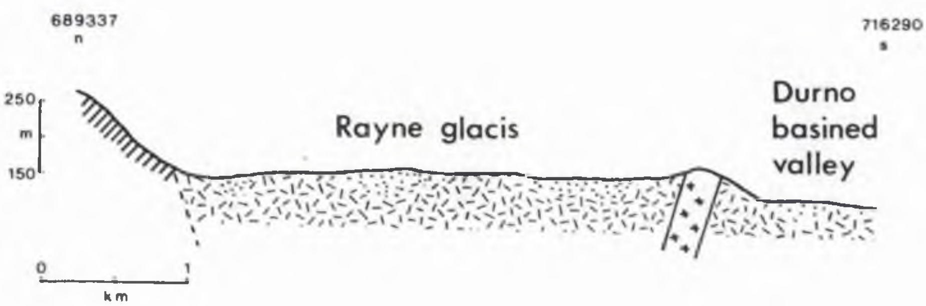


Fig. 12.4.ii. The Rayne 'glacis'

The location of this bench within the Insch depression is shown on Fig. 13.2.ii. The planar slope is developed across fresh and weathered gabbroic rocks and appears to owe its preservation to the protection afforded by the quartz-porphyry dyke. The backing slope follows the contact between the gabbros and the Fyvie Schists.

The general indifference of local slopes to a highly irregular basal surface probably reflects glacial and periglacial activity. Although glacial erosion has been ineffective in removing regolith in many areas, there are many signs that rock protruberances have been significantly modified by ice. In the Urie valley and to the west of Rhynie:-

> "the (boulder) clay is filled with huge rounded and subangular boulders of diorite and gabbro, some of which are as much as from 8 to 10 feet in length."
> (Wilson and Hinxman 1890 p. 32)

This description could be equally applied to most of the Insch, Huntly and Knock basic intrusions, where, in places, corestones are so numerous that farming was only possible after removal of the blocks to hugedykes forming the field boundaries. Elsewhere, corestones are more widely scattered, but surface litters of rounded blocks are to be found in a down-ice direction from all areas underlain by rocks which form corestones on weathering. The abundance of glacially-transported core blocks indicates the destruction of tor groups and some quarrying of grusses by ice. Comparable planing of upstanding rock forms is less easily demonstrated in weathered metamorphic terrain, but as only relatively large and unfractured whalebacks rise from surrounding grusses, it is reasonable to presume that all lesser protruberances have been removed by glacial erosion.

Periglacial activity appears to have been confined to the smoothing out of more detailed irregularities on the slopes and there are few signs of block-fields that might indicate destruction of large rock forms. Frost-shattering has been important in the reduction of narrow bands of chemically-resistant rocks and trains of shattered debris may often be seen extending downslope from fresh risers. However it is periglacial mass movement, aided by glacial deposition, that has provided a drape of superficial deposits over more variegated surfaces developed across fresh and weathered rocks. As these deposits are predominantly composed of material derived from the subjacent saprolites (Fitzpatrick 1963; Glentworth and Muir 1963; Wilson and Tait 1977), the smooth slopes developed across them are typical of those found in extra-glacial areas of extensively-weathered terrain (Ollier 1965; Nieuwenhuis 1971; Thomas 1976; Dixon and Young 1981). Although these superficial deposits are rarely more than 2m thick away from the coasts and valleys, they exert a disproportionate influence on the rolling landscapes of smooth hills and depressions characteristic of inland areas.

12.4.2 Profile truncation and slope development

The intensity of stripping has been spatially variable and the slopes can be described in terms of the depth of removal of regolith. This approach mirrors that of Ruxton and Berry (1957), who relate slopes in the humid tropical environment of Hong Kong to characteristic granite weathering zones. However the lack of consistently well-developed horizonation in north-east Scotland means that slopes can be described only by reference to depths of surviving saprolites and to the extent of fresh rock exposures.

Three main stages of regolith stripping and slope development can be recognised in areas of low initial relief (Fig. 12.4.i):-

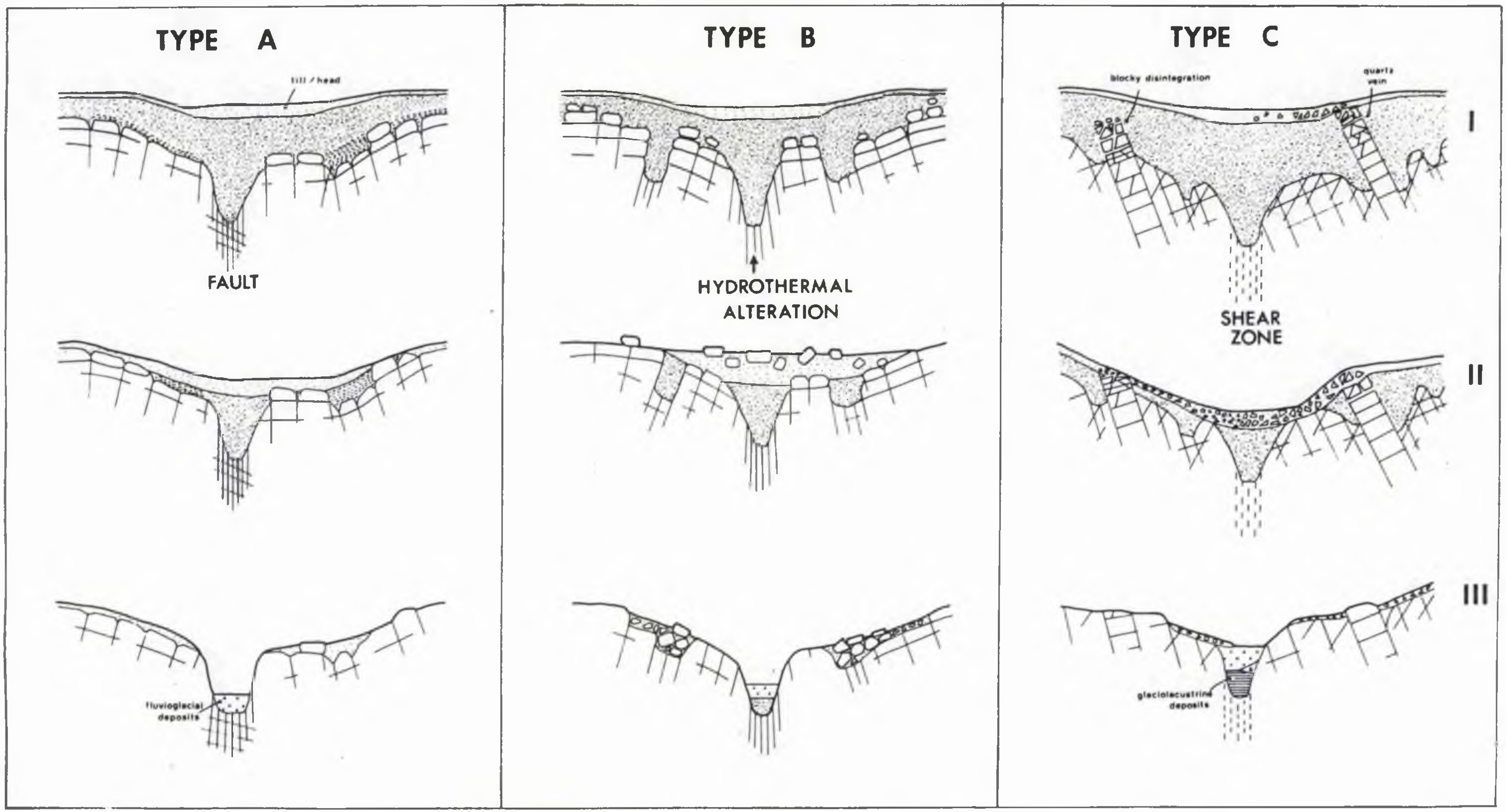


Fig. 12.4.i. Slope development and the progressive removal of weathering profiles of different types.
Type A thorough disaggregation Type B disaggregation with corestones
Type C disaggregation with blocky disintegration

<u>Stage A</u> Weathering covers are thinned but remain continuous and fresh outcrops are rare.

Slopes are developed across weathered rocks covered by thin layers of till and head. Slopes are gentle with few sharp breaks. The main relief is provided by small networks of meltwater channels, often cut entirely within fresh rock. This degree of saprolite preservation is found only in restricted areas, of which central Buchan is the most important.

At a few locations, planar, low angle slopes are found developed across thin superficial deposits resting on saprolite. Such slopes are generally elements of larger landforms and are well-displayed around Rayne (Fig. 12.4.ii), where they form a broad bench within the Insch depression, and at Auchintoul Moss, where planar slopes have been left perched by deep incision of the Deveron. In form, these slopes resemble 'glacis' (Mensching 1958) and comparable valley-side benches in Europe are related to dry phases in the late Pliocene and Early Pleistocene (Starkel 1964; Budel 1977). The origin of these glacis-type slopes in north-east Scotland is unclear, although slope development appears to predate drainage incision.

<u>Stage B</u> Weathering covers are substantially reduced and fresh risers are exposed.

Slopes are planed across irregular basal surfaces of weathering, where ribs of chemically-resistant rock have protected pockets of decomposition from erosion. Thin superficial deposits are predominantly composed of sandy residues from the saprolites mixed with fresh clasts supplied by the exposed risers. Low hills appear and are progressively emphasised by lowering of surrounding regoliths. Such slopes are common in marginal parts of Buchan and in the Knock depression.

Stage C Weathered rock is largely stripped.

Slopes are developed across fresh rocks and drift and remnants of former weathering profiles survive only in narrow fracture zones. Structural lineations are emphasised and bedrock may be locally polished, plucked and moulded by ice. Meltwater has cleaned out linear zones of alteration to create deep channels. The accidented bedrock surface often does not find topographic expression due to drapes of thick drifts. Slopes of this type are characteristic of the broken relief of the northern margin of the Skene depression and of the coastal belt between the Don and the Ythan.

In areas of greater relief, slopes developed across continuous weathering covers (Stage A) are rare. Summits and hillslopes generally carry only thin covers of regolith and the extent of stripping must be judged by the efficiency of removal of materials from topographic lows. Comparison with the stages outlined above centres on the degree of exploitation of the foot-slope weathering zone (Fig. 12.3.ii) and the level of exposure of the basal surface of weathering in valleys, basins and related forms.

12.4.3 Weathering, slopes and landscape types

The description of slopes in terms of the stage of lowering means that the regional weathering zones identified earlier (Fig. 5.5.i) may be seen as representing landscape types. Direct comparison may be made with the descriptive terminology of Thomas (1965; 1974a) in which landscapes are categorised by the degree of development or removal of regolith:-

A. Lateritised etchplains:- surfaces of low relief developed across thick and extensive latosols.

B. Dissected etchplains:- modified lateritised etchplains on which stream erosion has begun to strip away the weathering covers.

C. Partially stripped etchplains:- a further stage of modification at which rock outcrops appear in the form of tors and domes.

D. Dominantly stripped etchplains and etchsurfaces:- saprolite covers now substantially denuded. Where the exposed basal surface is markedly uneven, the terrain is termed an etchsurface rather than an etchplain.

E. Incised etchsurfaces:- the basal surface has not only been exposed but also modified by stream erosion.

F. Pedimented etchplains and etchsurfaces:- such terrains evolve from stages D and E after stream incision has ceased by slope retreat beneath shallow weathering profiles.

Although this scheme refers specifically to tropical areas, the general terminology is applicable to any terrain where present or former weathering covers have influenced morphology. Surfaces of subdued relief in north-east Scotland with continuous or frequent but fragmented saprolites may be described as etchplains or dissected

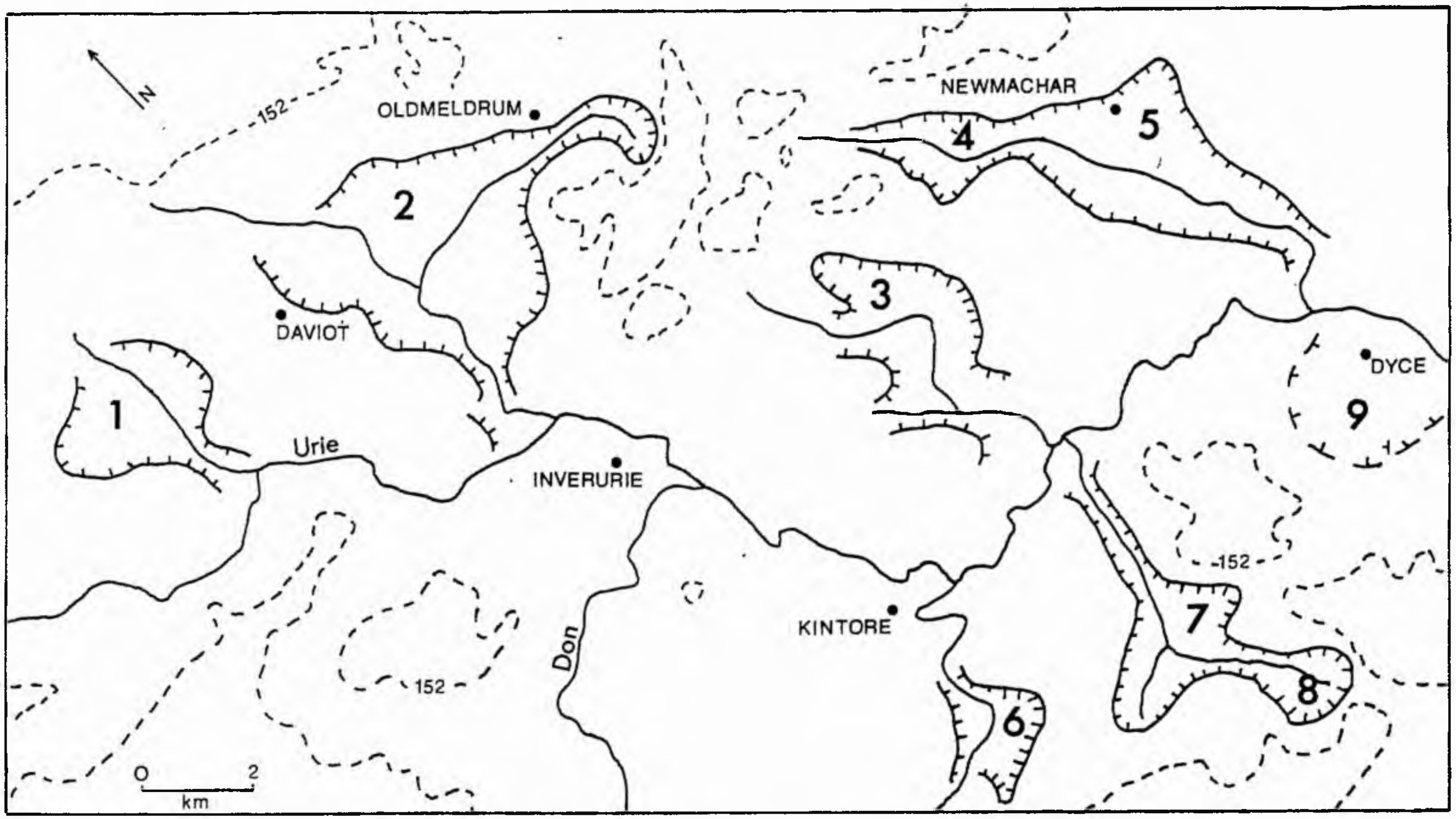


Fig. 12.5.i. Basined valleys along the lower Don.

1. Durno 2. Barra 3. Fintray 4. Straloch 5. Newmachar
6. Womblehill 7. Blackburn 8. Clinterty 9. Dyce Flat

etchplains. Conversely, areas where stripping has largely exposed the basal surface can be termed etchsurfaces and are broadly equivalent to the grundhockerrelief of Budel (1979). The application of this terminology allows local relationships between weathering and slopes to be placed in a wider framework of morphological development. These relationships will now be examined using case studies of basined valley, basin and valley formation.

12.5 Weathering and basined valley formation

Many of the tributary valleys draining into the lower reaches of the Don and Urie rivers occupy valley sections which are greatly widened relative to their length to give a number of shallow basinal forms (Fig. 12.5.i). These features are termed basined valleys and are part of a suite of basinal landforms that can be recognised at many scales throughout north-east Scotland.

12.5.1 Morphology

Basined valleys are small in area (1.5 - 15.7km^2) and restricted in length (1.3 - 5.6km). The shape of the floors of the basined valleys in plan can be approximated using morphometric indices developed to express drainage basin shape (Table 12.5.i), with low values for the circularity index, R_c, and the elongation index, E, and high values for the lemniscate index, K, representing marked elongation. In addition, the degree of enclosure, (E_x) of the basined valley floors is indicated by the proportion of the total floor perimeter backed by bounding slopes. These indices show that the floors are moderately rounded in plan ($\bar{R}_c$ = 0.59; $\bar{E}$ = 0.85) and well enclosed ($\bar{E}_x$ = 0.88).

The floors are flat to gently undulating and stand only 20 to 30m below the surrounding subdued topography, except where structurally-determined breaks of slope intervene. The margins of the basined valleys are usually marked by low scarps which die out towards the heads of the tributary drainage basins where the basins narrow to 1st and 2nd order valleys of normal dimensions. However where the basined valleys extend to the tips of the drainage network, the valley heads are steep, as with the eastern arm of the Barra basined valley and the small hollow south of Clinterty. The basined valleys are joined to the main valleys by short and incised valley sections.

12.5.2 Links with geology and weathering patterns

The influence of geology on the form of the basined valleys is generally not obvious. The Blackburn basined valley corresponds roughly with the limit of the Clinterty Granite (Walsworth-Bell 1974). Elsewhere geological information is limited but it is significant that in the sole case where the local geology is known in detail, that of the Barra basined valley, the control of structure can be seen to be paramount. Work by Ashcroft and Munro (1978) on the eastern part of the Insch basic intrusion has provided precise information on the structures beneath this basined valley (Fig. 12.5.ii). A zone of extensively sheared rocks forms the lowest part of the floor whilst the upstanding mass of Barra Hill is composed of dislocated but relatively unsheared basic cumulates. Deep grusses have formed along the fault and shear zones and have been exploited to produce the basined valley form. Deep grusses have also been proved in boreholes

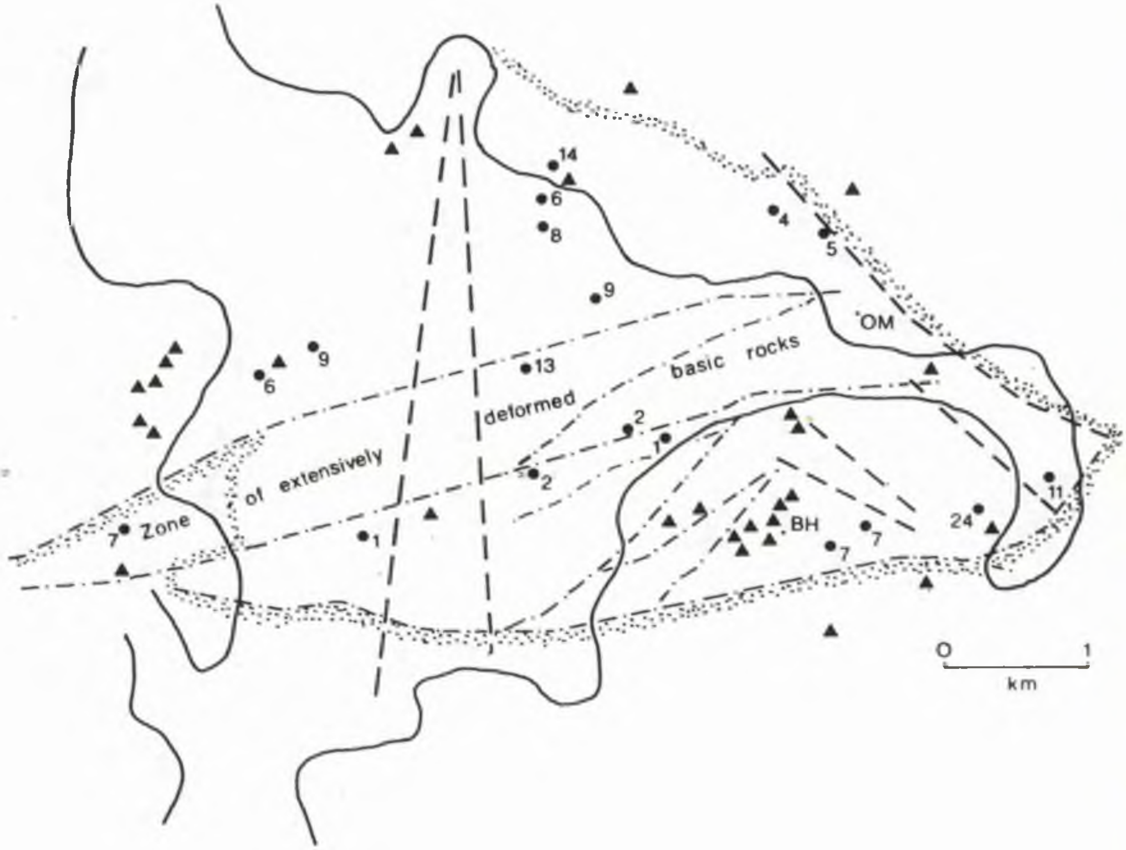


Fig. 12.5.ii. Structure and weathering in the Barra basined valley

(Adapted from Ashcroft and Munro 1978, Figs 4 and 6)

Floor margin

Fault

Shear zone

OM Oldmeldrum

Depths of weathering in boreholes (UADG)

Fresh outcrop

Psammitic and pelitic country rocks

BH Barra Hill

Table 12.5.i Morphometric index values for basined valleys

	Area (km^2)	Length (km)	Rc	K	E	E_x
Durno	5.2	2.8	0.81	0.38	0.92	0.85
Oldmeldrum	15.7	5.6	0.36	0.50	0.80	0.91
Womblehill	3.4	2.3	0.63	0.39	0.90	0.93
Fintray	5.9	4.0	0.47	0.68	0.69	0.83
Newmachar	9.1	5.3	0.49	0.77	0.64	0.92
Straloch	2.9	2.5	0.66	0.54	0.77	0.85
Blackburn	4.0	2.2	0.45	0.30	1.03	0.92
Clinterty	1.5	1.3	0.85	0.28	1.06	0.85

Method	Derived by	Source
Basin circularity	$Rc = \frac{4\pi A}{p^2}$ where p = basin perimeter length	Miller (1953)
Basin elongation	$E = \frac{2\sqrt{A/\pi}}{L}$	Schumm (1956)
Lemniscate index	$K = \frac{L^2}{4A}$	Chorley, Malin and Pogorzelski (1959)
Degree of Enclosure	$E_x = \frac{\text{Length of enclosed perimeter}}{\text{Length of perimeters}}$	-

in the Blair and Straloch basined valleys (Fig. 12.5.iii) and the deep hollow at Clinterty is located on deeply weathered diorites set within hills of foliated granite (Fig. 12.5.iv).

12.5.3 Origin and age

The development of the basined valleys is in many ways analogous to that of the basins. Localised zones of deep weathering have been exploited by the tributary streams, after breaching of rock thresholds, to produce a series of enlarged valleys and small basins whose outlines are governed by the structural lineations which initially guided the weathering (cf. Waters 1957). The termination of some basined valleys in steep valley heads indicates that enlargement took place by headward growth and sapping at the tips of the drainage net. Certain basined valleys retain potential for further development. Considerable depths of weathering remain on the floors and sides of the Barra and Blair basined valleys and, given suitable conditions, these two features can be further lowered and enlarged. The floor of the Newmachar basined valley has been largely swept clean of regolith but grusses remain around the margins and continued enlargement can be predicted.

The age of the basined valleys can be established with some certainty. Holocene processes have failed to remove covers of till and congeliturbate from the floors and the basined valleys must predate the last glaciation. The grusses in which these landforms are developed provide a maximal age, but, as the grusses are probably only the remnants of deeper, structurally-induced zones of weathering, the basined valleys may have been opened out long after formation of the gruss. However the deep and narrow valley sections connecting

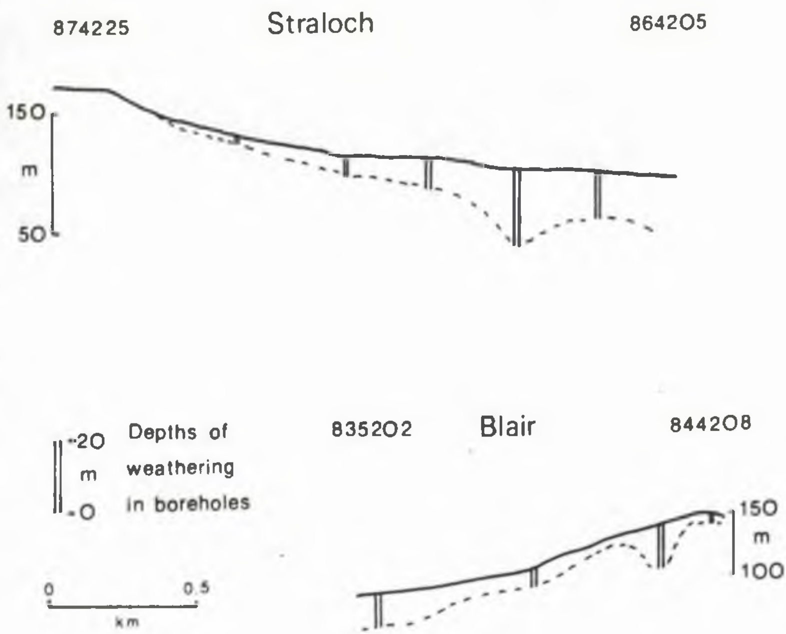


Fig. 12.5.iii. Weathering in two basined valleys

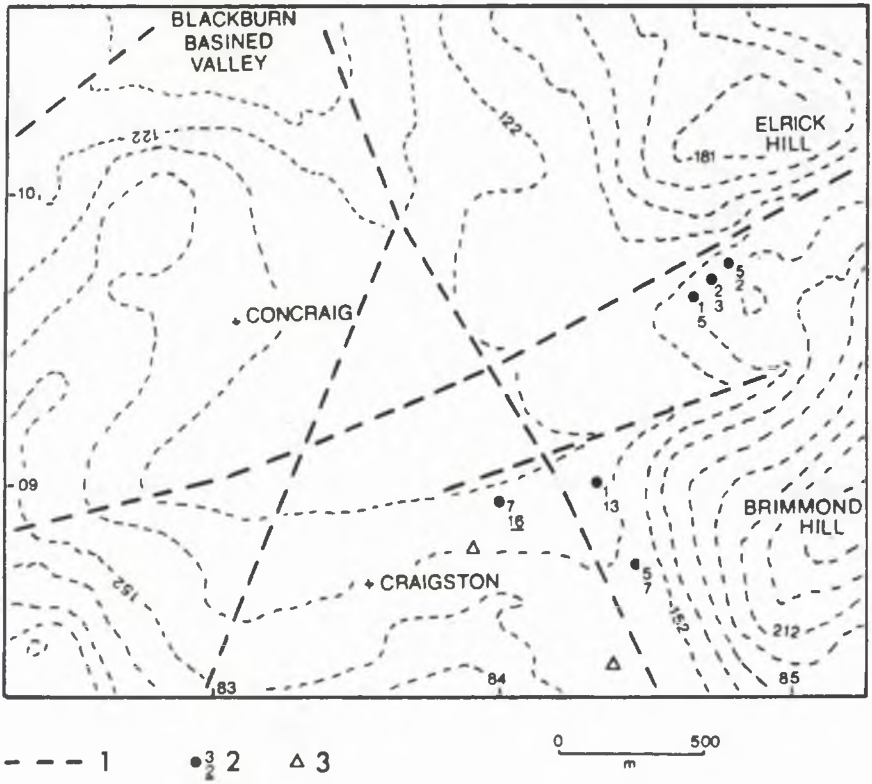


Fig. 12.5.iv. Weathering and fractures in the Clinterty basined valley.

1. Fractures inferred from topographic lineaments
2. Depths of weathering(m) in UADG boreholes
Upper case - drift thickness Lower case - minimum depth of weathering Bar - borehole bottomed on fresh rock. 3. Exposure of weathered rock

the basined valleys to the Don and Urie show that the main stimulus for excavation of these hollows was provided by incision of the major rivers. It is concluded that the basined valleys are products of fluvial exploitation of pre-existing zones of deep weathering during successive non-glacial phases in the Pleistocene.

12.6 Weathering and development of basins

Basins are a distinctive element in the regional relief, occupying considerable areas and exhibiting a wide variety of forms. At least 17 basins can be identified east of the Cairngorms with a total area of over 900km^2 (Fig. 12.6.i). The basins range in size from macro-scale forms, such as the Insch depression (213km^2) and the Skene basin (184km^2), to much smaller features of similar size to the basined valleys.

12.6.1 Morphology

The basin floors are no more rounded in plan than those of the basined valleys:-

	Mean Shape Indices			Mean Enclosure Index
	$\bar{R}_c$	$\bar{K}$	$\bar{E}$	$\bar{E}_x$
Basins	0.58	0.51	0.91	0.83
Basined Valleys	0.59	0.48	0.85	0.88

However the Feugh, Insch and Kirkney basinal forms have E values below 0.65 and are better termed linear depressions than basins (Table 12.6.i). Elsewhere the characteristic 'tear drop' shape associated with drainage basins is only approached by a small number of basins, reflecting the fact that many basins are strongly recti-linear in outline due to the influence of structural controls.

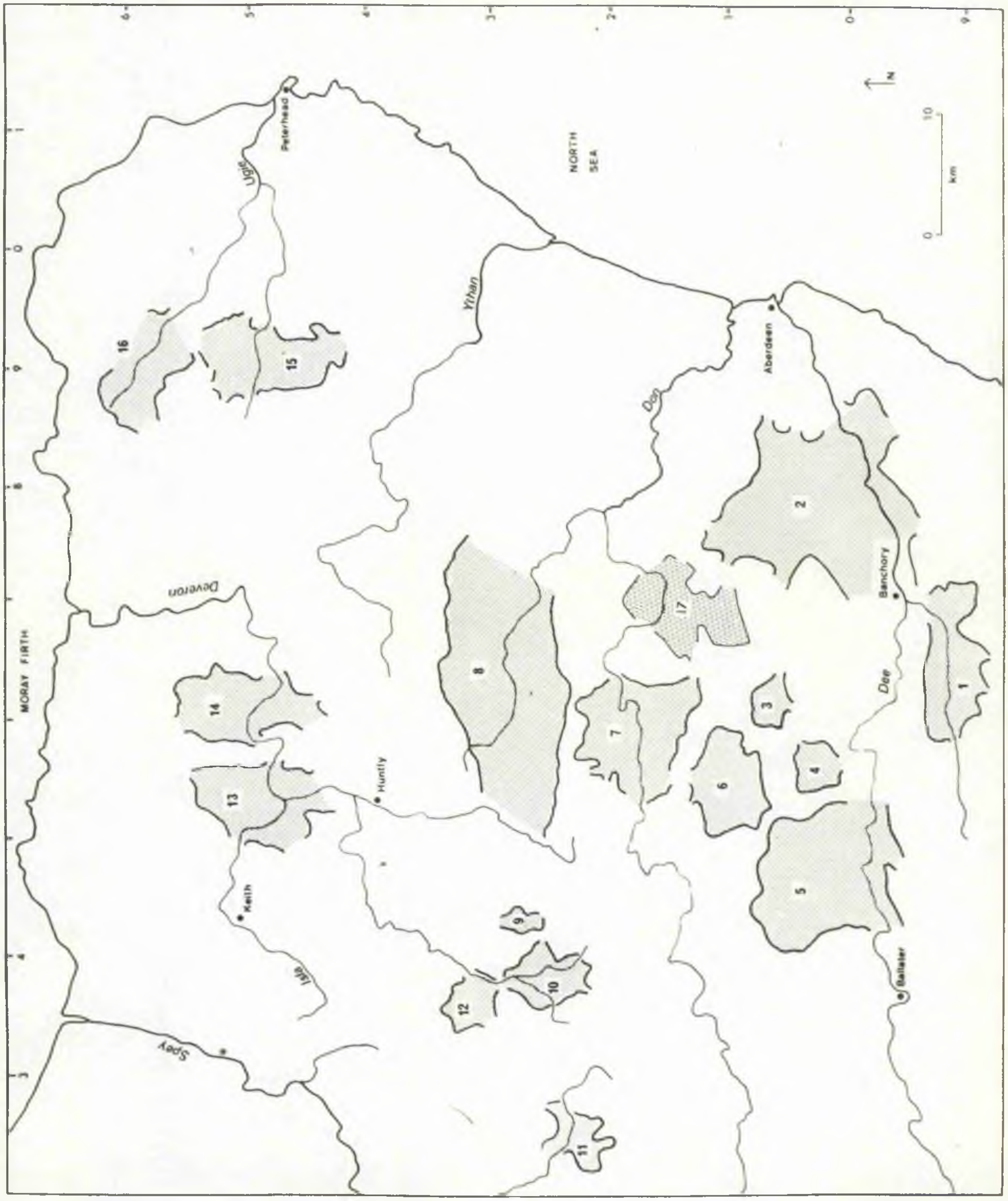
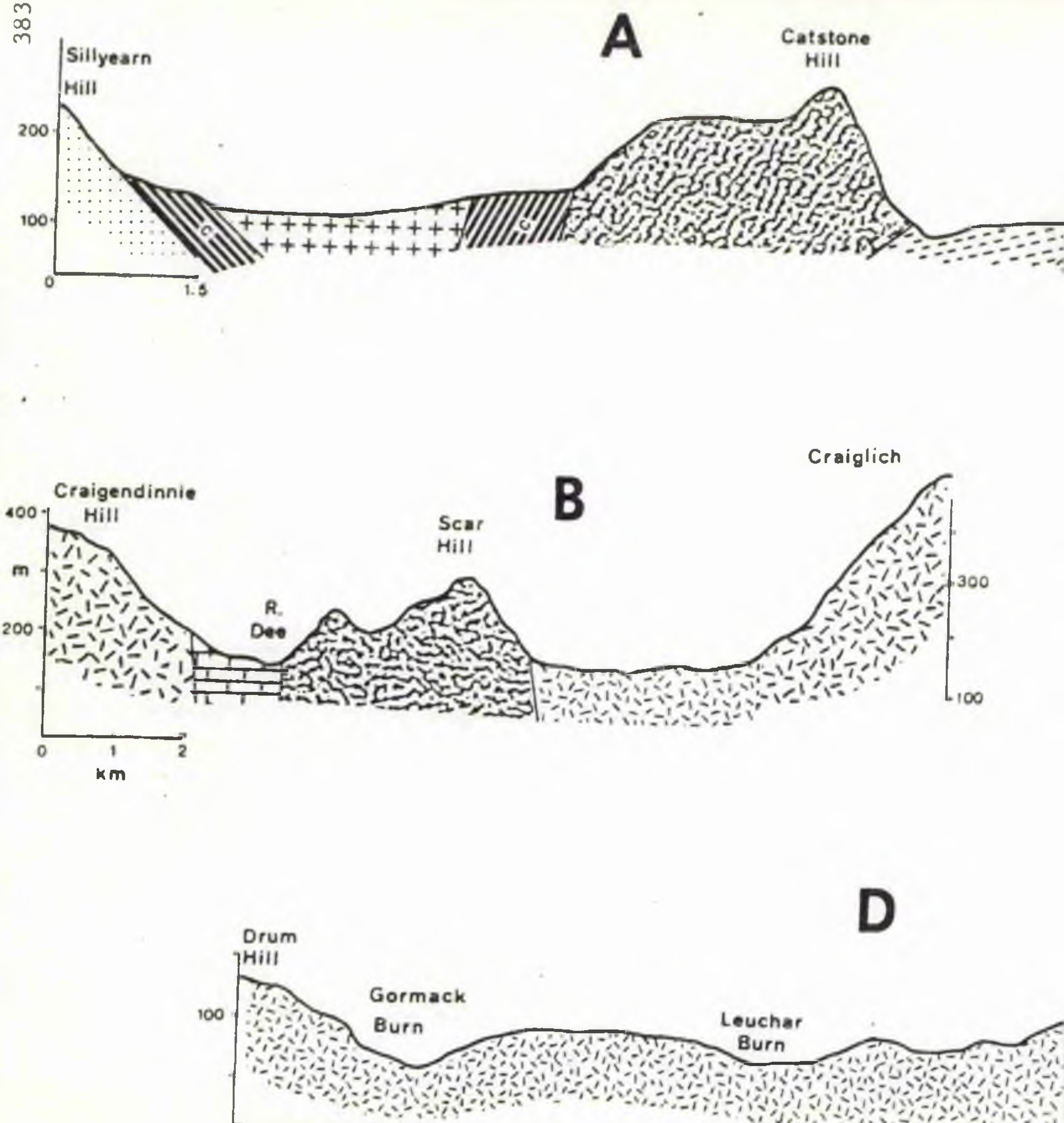


Fig. 12.6.i. Basins in north-east Scotland. Key on p. 385.


A
Sillyearn
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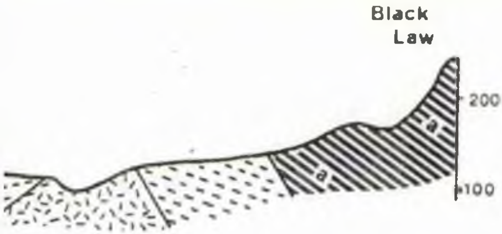
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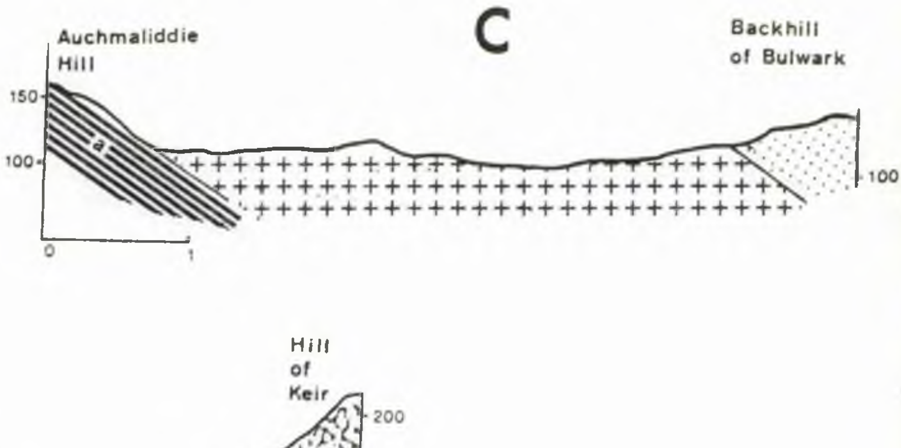
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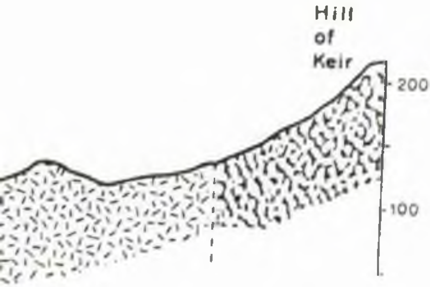
Hill of Keir
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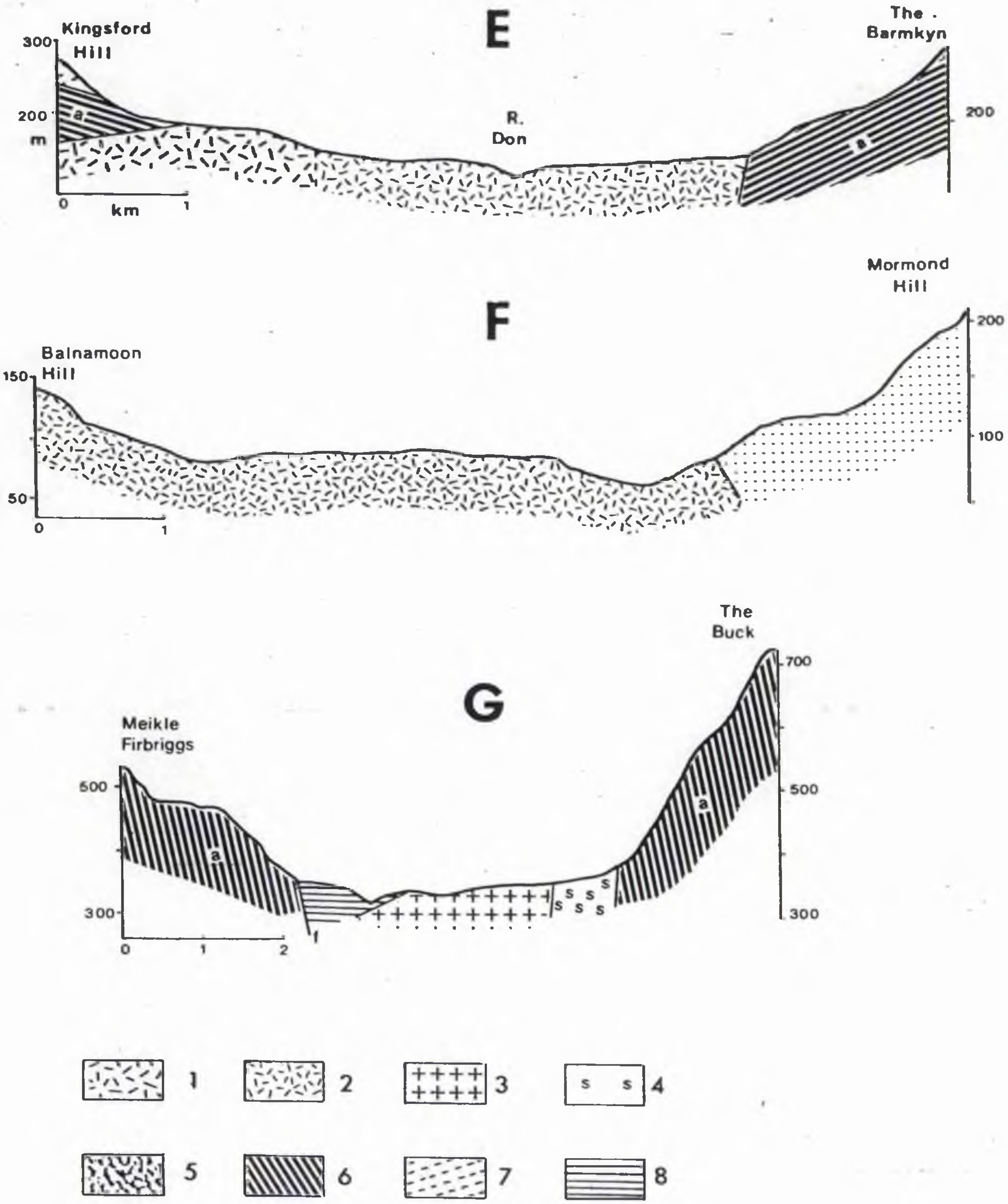

Fig. 12.6.ii. Geological cross-sections across the basins. Key overleaf.

Fig. 12.6.i. Basins in north-east Scotland.

1. Feugh 2. Skene 3. Tornaveen 4. Lumphanan

5. Tarland 6. Cushnie 7. Alford 8. Insch

9. Kirkney 10. Cabrach 11. Braes of Glenlivet

12. Black Hill 13. Knock 14. Aberchirder

15. Maud 16. New Pitsligo 17. Monymusk

Fig. 12.6.ii. Geological cross-sections across the basins.

A. Knock and Aberchirder basins B. Tarland basin

C. Maud basin D. Skene basin E. Alford basin

F. New Pitsligo basin G. Cabrach basin

1. Acid granite 2. Biotite granite 3. Gabbro

4. Serpentinite 5. Biotite gneisses 6. Pelitic chists a- andalusite c- calc 7. Flags

8. Old Red Sandstone Dots Quartzite

Note differences in vertical scales.

Table 12.6.i Morphometric Index values for basins, including present and former floors

Basin	Area (km^2)	Length (km)	R_c	E	K	Ex
Feugh	36.3	10.9	0.32	0.62	0.82	0.91
Skene	184.0	19.5	0.38	0.78	0.52	0.74
Lumphanan	7.6	3.2	0.76	0.97	0.34	0.85
Tarland	88.5	13.7	0.59	0.77	0.53	0.84
Cushnie	38.9	6.8	0.57	1.03	0.30	0.93
Alford (F1)	61.0	9.5	0.49	0.93	0.37	0.69
(F2)	47.7	9.3	0.69	0.84	0.45	0.76
(F3)	23.9	6.8	0.55	0.81	0.48	0.80
Insch	213	26.2	0.41	0.63	0.81	0.84
Kirkney	3.8	3.5	0.30	0.64	0.81	0.70
Cabrach	12.7	5.0	0.50	0.80	0.49	0.91
Braes of Glenlivet	16.3	5.9	0.45	0.77	0.53	0.92
Knock	56.0	7.3	0.55	1.16	0.24	0.70
Aberchirder (F1)	53.8	8.3	0.66	1.00	0.32	0.50
(F2)	44.8	8.0	0.71	0.94	0.36	0.70
Maud	44.1	6.1	0.59	1.22	0.21	0.79
New Pitsligo	48.6	10.4	0.76	0.76	0.56	0.56
Monymusk	47.0	10.0	0.52	0.77	0.53	0.85

Method	Derived by	Source
Basin circularity	$Rc = \frac{4\pi A}{p^2}$ where p = basin perimeter length	Miller (1953)
Basin elongation	$E = \frac{2\sqrt{A/\pi}}{L}$	Schumm (1956)
Lemniscate index	$K = \frac{L^2}{4A}$	Chorley, Malin and Pogorzelski (1959)
Degree of Enclosure	$E_x = \frac{\text{Length of enclosed perimeter}}{\text{Length of perimeters}}$	–

The 3-dimensional shapes of the basins are complex. Most basins have a gently undulating floor which slopes towards the main drainage line or exit (Fig. 12.6.ii). A few basin interiors exhibit high relief, notably in the Tarland basin, where the summits of the central metamorphic hills stand some 150m above the floor (Plate 12.6.i). The margins of the floor are usually defined by a sharp break to steeper bounding slopes. In several basins, the marginal slopes are stepped by benches indicating that the present forms have been opened out in formerly more extensive features to give basin-in-basin forms (Gjessing 1967). The reduction in area can be impressive, as in the Alford basin (Fig. 12.6.iii), where the two benches at 230-270m and 170-190m indicate a reduction in basin floor area from 61.0km^2 and 47.7km^2 to 23.9km^2 for the latest 125-155m floor (Table 12.6.i).

The degree of basin enclosure (E_x) shows considerable variation. In general, E_x is highest for the interior basins and declines eastwards, reflecting the shallowing of the basins towards the coast. The values of E_x have also changed over time in some basins. The extrapolation of the 150-180m bench in the Aberchirder basin gives an E_x value of 0.50 for the former floor, suggesting that a corridor, and not a true basin, existed at the time the bench was cut.

Many basin floors are dissected by the drainage network, especially closer to the coast, demonstrating that the present drainage is modifying or destroying these forms. In the extreme cases of the Black Hill and Tornaveen degraded basins, dissection has reduced the earlier floors to a series of perched remnants of limited extent. However not all basin floors have been left standing above

Plate 12.6.i. The Tarland Basin. View SW from Craskins, with smooth floor developed across the Tomnaverie biotite granite in the middle ground and the abrupt break of slope against the hills of the Central Metamorphic Complex in the background. Mount Keen in far left, rising above the Eastern Grampian Surface.

Plate 12.6.ii. The Maud Basin. View E from New Deer. Hill in foreground developed in andalusite schist. Basin floor corresponds with the outcrop of the Maud norite. White Cow Wood ridge, on the skyline, is formed in quartzites. Area of deep and extensive weathering covers.

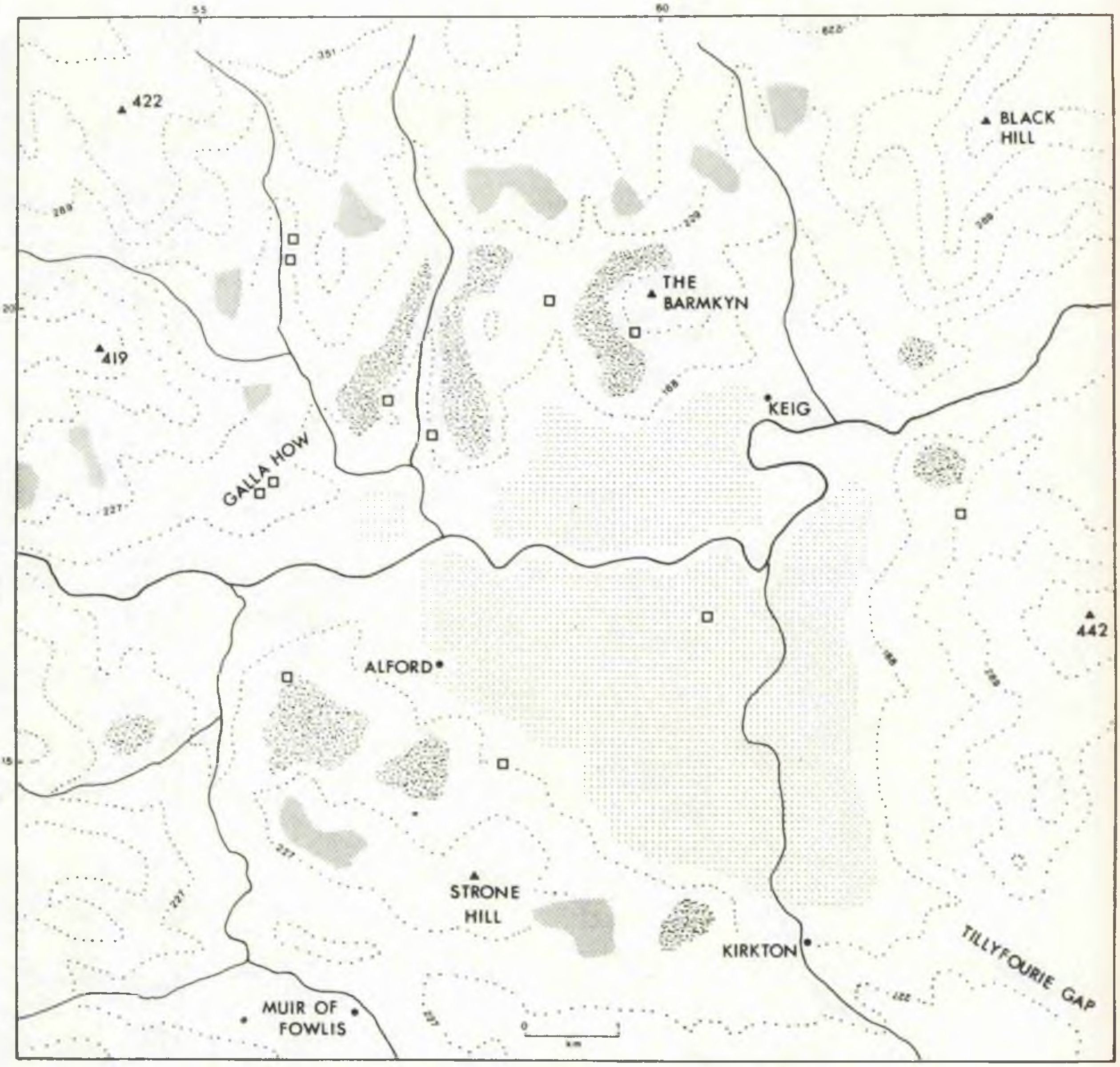

Fig. 12.6.iii. Weathering and benches in the Alford basin.

□ Exposures of weathered rock

The different shadings depict the 125–155m floor and the 170–190m and 230–270m benches(see p. 387).

their drainage. The floors of the Alford and Tarland basins lie close to the levels of the rivers crossing them, the Don and the Dee, and floor lowering has kept pace with drainage incision. Similarly the headwaters of the Deveron flow across the smooth floor of the Cabrach basin, although the deep gorge through which the drainage leaves the basin indicates an earlier phase of substantial lowering.

12.6.2 Geological relationships

Lithology and structure exercise a strong control over the location and morphology of the basins (Fig. 12.6.ii). Many basins are markedly rectilinear in outline,with the positions of the bounding breaks of slope corresponding to known petrographic and structural discontinuities. Basin floors are preferentially developed across granitic and gabbroic rocks to the extent that only the Howe of Cushnie possesses a floor which is not wholly or partly underlain by these rocks. Such pervasive geological control suggests that differential weathering and denudation has had an important influence over basin development. However the control of geology is rarely total and it is clear that other factors must be involved.

Basins predominantly formed in granitic rocks include the Skene, Alford, Tarland, Glenlivet and New Pitsligo basins. The basin floors are associated with biotite and hornblende granites, varieties highly susceptible to grussification (Isherwood and Street 1976; Bustin and Matthews 1979). Basins in basic igneous rocks often show a close correspondence between the outline of the intrusion and the margin of the basin floor (Plate 12.6.ii).

Yet there exist many instances where rocks of apparently similar composition underlie parts of both the basin floor and rim (see also Hack 1982). Structural factors are involved in certain cases and the corridor in which the Aberchirder basin stands is almost certainly the topographic expression of a northward extension of the Drumblade Shear Zone (Ashworth 1975). Elsewhere unrecognised, detailed petrographic differences may influence morphology but are unlikely to account for all the discordant examples.

Another possibility is that the present form is partly inherited from earlier and higher levels when the basins were better adjusted to geology. The floors of some inland basins now lie over 200m below imperfectly levelled rims belonging to the Eastern Grampian Surface. These basins have had a long and complex history and evidence of the nature and disposition of the rocks on which the depressions first developed has been destroyed by later denudation.

A few basins may have been exhumed from beneath a cover of Old Red sediments. However it is unwise to invoke exhumation as a general explanation (Linton 1951) unless Old Red rocks outcrop within or adjacent to the basins, for the base of the Old Red in this area is highly irregular (Section 11.2). Down-faulted Devonian outliers aligned along deep-seated Dalradian structures (Fettes 1968) are found in the Cabrach basin and close to the western edges of the Insch depression and the Glenlivet basin and a tiny outlier of Old Red Sandstone has been recorded from the Feugh valley (Bremner 1942). A degree of exhumation is a firm possibility in these cases, though the manner in which the present floors of the

Cabrach and Feugh basins transect sedimentary and crystalline rocks implies that, if these are ancient features, then considerable modification of the exhumed forms has taken place.

The basins are at different stages of development and, in some, floor lowering continues. The apparent independence of form and geology evident in certain basins may be a temporary phenomenon, persistent only until such time as equilibrium basin forms are produced. Also, if renewed lowering intervenes before such equilibrium forms are established then retreating scarp faces may become fixed in position (Wahrhaftig 1965). Differential weathering rates between the free-draining scarps and the moist foot-slope zones (Budel 1957; Bremmer 1975) will ensure the survival of these scarp positions. Phases of lowering will have occurred repeatedly in response to changes in late Cenozoic base level and climatic fluctuations and the relatively brief time spans available for readjustment may be one reason why many basins have been progressively reduced in area.

The geological influence over basin form may have varied over time for the benches fringing several basins are cut across more resistant rocks than those which now occupy their floors. Considerable difficulties in interpretation are involved here as basin floors and marginal benches may develop simultaneously on rocks of different resistances (Hack 1960). A situation of this type occurs in the Knock basin, where a low step on the floor separates slightly-upstanding calc and mica schists from lower-lying basic intrusives (Munro 1970). However where the benches are accordant in altitude with erosional forms outside the basins, as at New Pitsligo and Alford, then it seems likely that the marginal benches do indicate former floor levels. In these cases, differential weathering has become increasingly selective in its attack over time.

12.6.3 Weathering patterns in the basins

Sections and boreholes show that weathered rock is present in all but 3 basins:- the Feugh, Lumphanan and Black Hill basins. Despite the poor exposure on many basin floors, it is clear that the incidence of weathering varies between basins. Bare ice-smoothed surfaces are found at many points within the Tarland basin and the occasional exposures of weathered rock are confined to sheltered positions around the edges of the floor. In the New Pitsligo basin, up to 5m of granite gruss with corestones is present in quarry faces set in the western slopes but rare sections on the floor show only thin blocky granitic till resting on hard rock. Elsewhere saprolites are more widespread and the floors of the Alford basin (Fig. 12.6.iii) and of the Insch depression (Basham 1968) contain large areas of grussified bedrock.

Depths of weathering in the basins are generally less than 10m, although boreholes around Auchnagatt in the Maud basin show that weathering locally extends below 30m (Fig. 5.4.i). The general impression is that only the roots of former weathering profiles remain beneath the basin floors. In many cases, grusses are confined to pockets protected by bosses of hard rock, notably in the Knock basin where boreholes reveal a highly irregular basal surface of weathering (Fig. 12.6.iv). In the Insch depression and the Kirkney basin, a zone of corestones with granular grusses is widely exposed, confirming that only the basal parts of earlier saprolites remain.

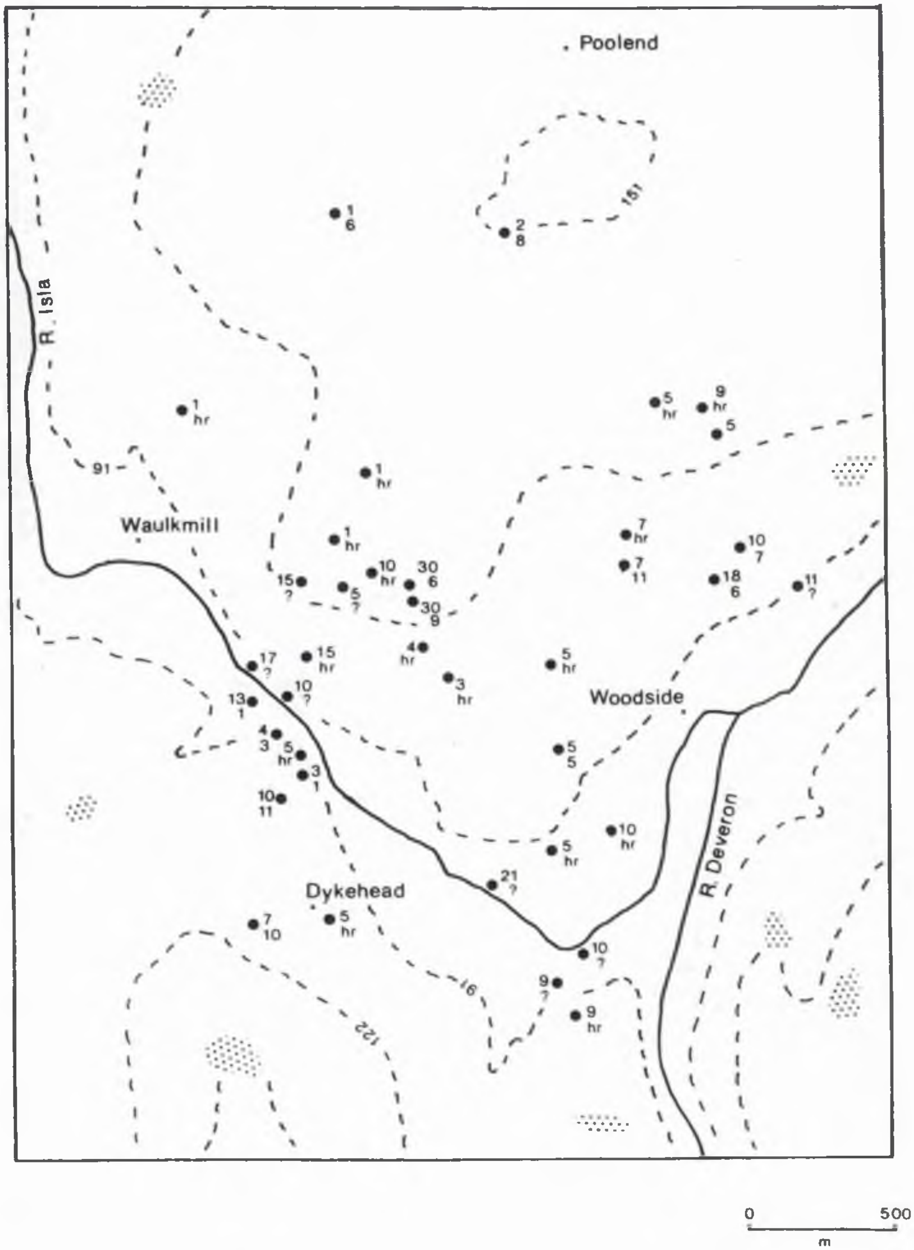

Fig. 12.6.iv. Weathering patterns in the Knock basin

9 Drift thickness (probably often including saprolite)
5 Saprolite thickness
hr Hard rock
? Hole terminated in 'drift'

UADG / RioFinEx boreholes

Fresh outcrop

It is difficult to gain an accurate picture of the distribution of weathering within individual basins. Hard rocks occur at or close to the surface of most marginal slopes, although decomposed rocks are found beneath steep slopes around the Insch depression and the New Pitsligo basin. Grusses are scattered at all levels in the Alford basin and the presence of grusses on basin rims indicates that weathering has affected the entire basin forms. However deeper profiles are confined to the present or former basin floors and the sound rocks of the bounding slopes would not readily allow the extension of the basin margins. The grusses appear to be largely relict and basin development has effectively ceased wherever the weathering cover has been stripped and bare rock surfaces exposed.

12.6.4 Modes of development

Differential weathering is a major element in basin formation (Waters 1957; Thorp 1967; Thomas 1974a and b; Bremmer 1975). The locations of the basins have been influenced by geological factors through their effects on weathering patterns. In several basins, the break of slope at the edge of the floors follows structural alignments. These are equilibrium slopes fixed in position on geological discontinuities. Where the alignments of all the basin margins are structurally determined, as in the Maud basin, then the entire basin has become an equilibrium form (Hack 1960) under present conditions, which may be deepened but which will maintain its area.

Yet only a few basins display precise geological control (see also Hack 1982). The instances where marginal slope positions are independent of geology may be due to a variety of factors including inheritance, exhumation, lack of time for adjustment and the emergence of edaphically dry slopes during basin lowering. In basins with benched margins, the higher floor levels have ignored structural boundaries which delimit the latest floors and the latest floors are largely confined to rocks susceptible to grussification. This change in the effectiveness of weathering over time is probably related to late Neogene climatic and base level fluctuations (Chapter 3). Falling temperatures will have reduced the rate of chemical weathering. Moreover fluctuations in climate and base level will have favoured stripping rather than development of weathering covers. The increasingly frequent environmental changes may have lead to a divergence in levels of rock resistance, with rapid chemical decomposition restricted to rocks which readily disintegrate, chiefly biotite granites and gabbros. Episodic lowering of higher floors cut across rocks of variable resistance would tend to locate the later floors on these zones of selective decomposition.

The processes responsible for evacuating weathered materials from the basins are obscure. The characteristics of the relict grusses indicate that the latest floors were opened out under humid temperate environments. The drainage network was probably the main agent of stripping and channel migration in both the main rivers and the lower order tributary streams will have facilitated the removal of regolith. Headward growth and spring sapping will also have contributed to lowering. The timing and continuity of stripping was determined by pulses of incision arriving at the drainage outlets. These energy inputs will have been received at different times depending on the positions of the basins in the drainage network and lowering of headwater basins, such as Kirkney, Cabrach and Glenlivet, will have lagged far behind regional changes of base level. In these interior locations, rock barriers at the basin exits may have been the dominant controls over rates of floor lowering (Ollier 1965).

Although there is little doubt that the basins were established prior to glaciation, it is important to recognise the continuity of basin development through the Pleistocene. Glacial erosion, although modest, must have removed much weathered material and contributed to basin lowering. Moreover the geomorphic effects of interglacial and interstadial episodes are largely unknown but it can be suggested that fluvial and slope processes acting under periglacial conditions would have been highly effective in removing regolith from the basin floors.

A distinction must also be made between the ages of many basin floors and the antiquity of the overall basin forms. Certain inland basins were undoubtedly established during the Tertiary and the depressions have been maintained through several cycles of uplift and landscape lowering (Fig. 12.6.v).in a manner suggestive of dynamic etchplanation (Wayland 1933; Thomas 1974a). The basins were originally located on structurally controlled compartments of deep weathering and later extended across rocks of variable resistance, perhaps due to moisture concentration and sapping at the base of the marginal slopes under warm climates (Budel 1957; Bremmer 1975; Jahn 1980). Once in existence the basins became largely self-perpetuating as a result of their preferential development on zones of low resistance and of the continual moistening of the floors by radial drainage into the basins.

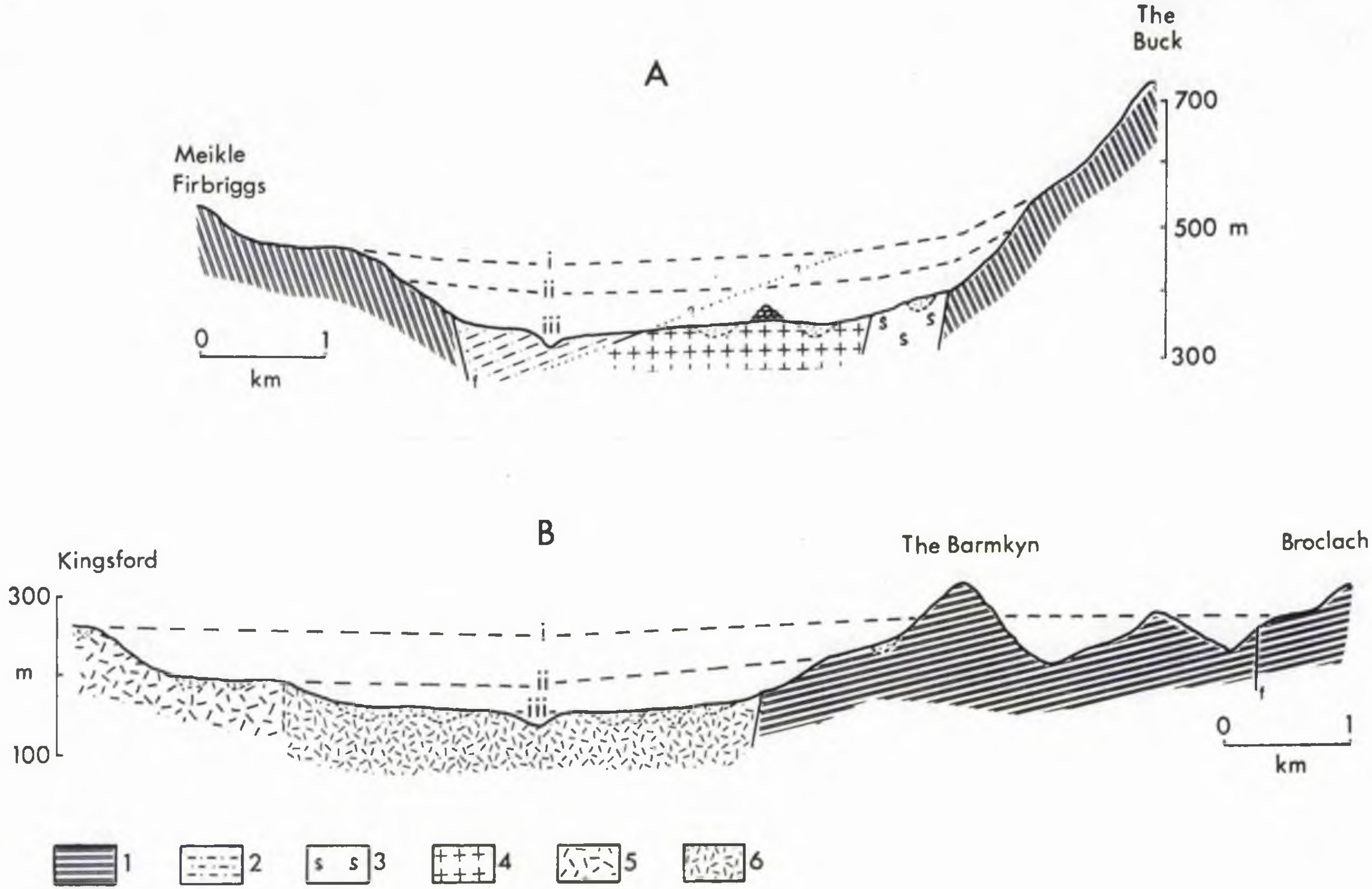

Fig. 12.6.v. Evolution of the Cabrach and Alford basins.

1. Schists 2. Old Red Sandstone 3. Serpentinite

4. Gabbro 5. Acid granite 6. Biotite granite

The latest basin floors are compound features whose location, elevation and detailed morphology reflect the progressive interaction of varied geomorphic processes from the late Neogene to the present. The locations of many floors have been inherited from earlier levels but deep grussification and episodic lowering has lead to a contraction of the floors on to rocks of low resistance. The floors have been lowered by their drainage and by Pleistocene periglacial and glacial processes. The depth of lowering has been controlled by regional and local base levels and by the thickness of the grusses. Away from the headwater basins, many floor elevations are within the altitudinal range of the latest regional erosion surface, the Buchan Surface (Linton 1951; Walton 1963). These floors represent compartments of levelling penetrating inland from a coastal erosion surface along the main drainage routes. Subsequent differential lowering of the floors reflects local variations in depths of weathering, rates of drainage incision and the efficiency of glacial erosion. Many basins have been reduced close to a hard rock floor and further lowering will be dependent on renewed weathering.

12.7 Weathering and valley formation

12.7.1 Valley-in-valley forms and drainage incision

There is considerable morphological evidence that many sections of the major valleys have remained fixed in position over long time periods and that valley forms were modified, rather than destroyed, by glacial and fluvioglacial activity. In section, many valleys show a deeply-incised inner channel flanked by broad benches rising, in turn, to steeper backing slopes. This characteristic morphology is displayed at intervals along the entire lengths of the major rivers (Figs. 11.7.i., 11.9.iii., and 12.7.i), although the rock benches at high levels are replaced by flats cut across both hard and weathered rock in the lowlands. The valley forms resemble closely those described from parts of Scandinavia, where broad 'paleic' valley floors are dissected by Pleistocene 'canyons of adjustment' (Gjessing 1966; 1967; Kaitenen 1969). The benches may also be compared with the Late Pliocene-Early Pleistocene 'Breitterassen' of the Rhenish Schiefergebirge (Budel 1977). Along the lower Deveron and middle Ythan, the age of the benches is given by the overlying patches of Middle to Late Pliocene gravel of the Windyhills Formation. In the North Ugie valley, benches are cut across deeply weathered quartz-mica schists containing hydromorphic minerals formed prior to valley incision and benches elsewhere in Buchan are also underlain by pockets of gruss. Towards the coast, the rivers flow across fluvioglacial and glaciolacustrine sediments which infill earlier channels cut deeply into bedrock and extending below O.D. (Aitken et al 1979; McMillan and Aitken 1981). These factors suggest that drainage incision dates from the younger Pleistocene. Similar valley deepening occurred throughout Europe at this time in response to climatic change, high meltwater discharges and episodically low sea levels (Kaitenen 1969; Budel 1977).

12.7.2 Penetration of weathering beneath valley floors

The links between valley formation and weathering have been obscured by glacial erosion and by deep incision of the drainage system. Weathered rock may penetrate beneath river level at Ythanbank and boreholes in the inner rock channel of the Ugie valley

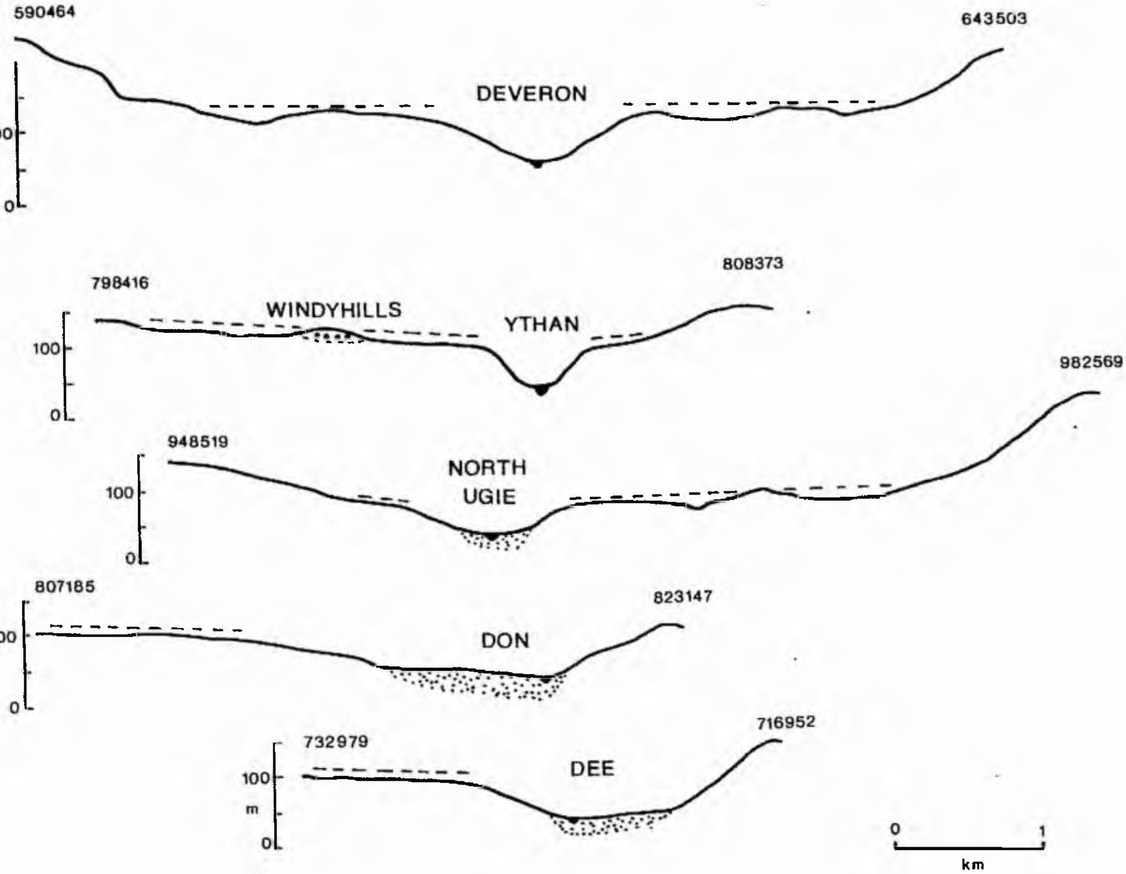

Fig. 12.7.i. Cross-sections across the lower valleys of the main rivers.

Fluvioglacial deposits infilling the inner channels are stippled.

have bottomed on decomposed rocks (McMillan and Aitken 1981). However the extensive outcrops of fresh rock elsewhere in these inner valleys indicate that fluvial and fluvioglacial erosion in the younger Pleistocene has generally succeeded in clearing out any pre-existing weathered material.

As at least some of the weathering found on the valley benches formed before drainage incision and lowering of the water table, alteration must have extended below the level of these earlier valley floors. East of Huntly, alteration is known to penetrate at least 30m below a broad valley floor, now occupied by the grossly-misfit Knightland Burn. This valley almost certainly provided a more direct route for the Deveron before diversion west of Greenfold Hill. The valley is constrained by the topography and the opportunities for channel migration are restricted. Superimposition of the river onto a pre-existing weathering trough is unlikely and it appears that the deep weathering must have developed whilst the Deveron occupied the valley.

This view is somewhat surprising in view of experience in warmer environments, where rivers generally flow across fresh rock floors (Thomas 1966; Feininger 1971; Dixon and Young 1981). Shallow weathering is known to extend locally beneath river levels (Ollier 1965; Thomas 1966; Nieuwenhuis 1971), but deep weathering beneath valley floors has only been described from areas of recent uplift, where drainage is regarded as superimposed (Ollier 1965; Thomas 1974b). Yet there is no theoretical reason why weathering should not extend beneath the valley floor, for alteration is found beneath the water table both in north-east Scotland and more generally (Ollier 1969). In this context, it is significant that the Deveron has here followed the Drumblade Shear Zone, where unhindered movement of groundwater can be predicted (Niini 1968; Rolland 1975). Clearly deep weathering cannot develop whilst rivers are actively downcutting but it is suggested that sub-valley weathering may occur along fracture zones where channel widening is dominant. Sub-valley weathering may be more widespread than is generally realised, especially in areas which combine high relief with deep troughs of weathering, such as the Snowy Mountains of Australia (Ollier 1965) and the Separation Point Massif of South Island, New Zealand (Thomas 1974b).

12.8 Summary of links between weathering patterns and landforms

A number of general points emerge from investigation of the relationships between weathering and landforms:-

A. Glacial, periglacial and fluvioglacial processes in the younger Pleistocene have merely modified a pre-existing landsurface.

Although the depth of erosion has been spatially variable, the importance of established weathering patterns in guiding erosional processes in the younger Pleistocene is everywhere apparent. Moreover the degree of modification of landforms declines as their size increases. Individual slopes must be seen in terms of processes acting under cold environments, although slopes are commonly developed across materials reworked from temperate weathering covers. These processes have exploited weathering patterns to produce a number of meso-scale landforms, including basined valleys and certain melt-water channels, but glacial and periglacial activity has also prevented the development of forms, such as tors, which are considered typical of weathered terrains undergoing stripping (Linton 1955; Thomas 1974b). Macro-scale landforms, notably basins and major valleys have been lowered but not greatly disrupted and their origins lie wholly in the development of the preglacial relief.

B. Differential weathering has given topographic expression to geological and structural trends.

Despite its subdued relief, the topography of the lowlands closely reflects variations in rock type and the disposition of major structures. This accordance is a direct result of the progressive exploitation during landscape lowering of weathering patterns developed in response to differential resistance.

C. Macro-scale landforms have tended to retain their form and position during landscape lowering.

Many basins, valleys and hills have been fixed in position over long periods. The continuity of morphological development can generally be linked to differential rock resistance, with the most persistent forms of negative and positive relief located on rocks on particularly low or high susceptibility to chemical weathering. Similar weathering patterns have formed during successive phases of levelling and lowering, a trend which has been reinforced by the control of the evolving topography over ground-water movement. This continuity indicates strongly that the landscape has developed through some form of etchplanation (Wayland 1933; Thomas 1974a).

The development of these landforms will now be considered in the wider framework of landscape evolution.

CHAPTER 13 Landscape Evolution in the Lowlands

13.1 Introduction

There have been few studies of the geomorphic evolution of the lowland landscape. The preglacial relief has been described briefly by several writers (Bremner 1942; Linton 1951; Gemmell 1975; Clapperton and Sugden 1977) and others have recognised a series of erosional levels (Glentworth 1954; Glentworth and Muir 1963; Walton 1963). None of this work aims to provide detailed description and analysis of the topography and, given the geomorphic significance of the region, further study is urgently required.

This Chapter seeks to look at some of the wider problems of landscape evolution in the lowlands. The morphology of the area is first described in terms of characteristic landform types and landform systems. The reality of previously-identified erosion surfaces is examined using hypsometric and geomorphic evidence and a case is presented for the existence of a single complex surface in the lowlands. The relationships between weathering types, sediments and morphology are then discussed in order to elucidate the origins and age of this surface. Finally, the various lines of geomorphic evidence are brought together in a model of long-term relief development.

13.2 Landform assemblages

13.2.1 Introduction

An objective and accurate description of the preglacial morphology of the lowlands is no easy task. Although a variety of landforms can be recognised and locally integrated into wider landform systems, the subdued topography of many areas is composed of subtle and often ill-defined features. A further difficulty is that where the amplitude of the local relief is less than 50m, even modest glacial and periglacial erosion can have significantly modified the pre-existing topography. In this account, emphasis will be placed on the relative positions of palaeoforms in the topography and on their relations with geology. To define topographic position, the terms 'upper', 'lower' and, often, 'middle' relief are used but the existence of stepped erosional levels is not implied. Each relief category may include more than one storey of relief and the categories frequently merge without break of slope. The reality of erosion surfaces recognised by the Soil Survey of Scotland (Glentworth 1954; Glentworth and Muir 1963) and by Walton (1963) will be discussed after preliminary description of the morphology of specific lowland areas.

13.2.2 Buchan

The upper relief of Buchan, the area east of the Deveron and north of the Ythan, contains three main elements:- <u>isolated hills</u>, <u>interfluval ridges</u> and <u>plateaux</u>. Of the <u>isolated hills</u>, only Mormond Hill (234m) is sufficiently prominent to be termed an inselberg and other hills, such as Hill of Dens (168m) and Hill of Dudwick (174m), rise less than 50m above the surrounding terrain. More extensive are the <u>interfluval ridges</u>, such as the Buchan Ridge which runs eastwards from Kinknockie Hill (137m) to Stirling Hill (87m) and the Monquhitter Ridge which runs south-west from the Hill of Turlundie (199m), overlooking New Pitsligo, and turning southwards beyond Balthangie to Deer's Hill (178m). These broad, convex and featureless ridges form important drainage divides and pass gently downslope into forms of the middle relief. The most significant plateau area comprises the tabular summits of the Hill of Fishrie (227m), Windyheads Hill (231m) and Hill of Troup (201m). This Windyheads Plateau is developed on a block of Old Red Sandstone bounded to the west and east by faults and was earlier tentatively referred to the Marginal Surface. Another smaller plateau occurs around White Cow Wood at a much lower elevation of about 120m.

Parts of this upper relief can be related to zones of resistance, with the Mormond Hill Quartzite, for example, forming an important N-S belt of high ground. More unusual is the Buchan Ridge, which appears to owe its present elevation to a former cover of flint gravels. Yet in other cases the links between positive relief and differential resistance are poorly-defined and even missing. The Turriff Old Red Sandstone outlier supports not only plateau and interfluval ridges of the upper relief but also elements of the middle and lower relief. More striking is the instance of Skelmuir Hill (149m), formed in schists and diorites weathered to depths of at least 20m. These features of the upper relief appear to owe their prominence to positions at the head of local drainage networks rather than to any lithological control.

The middle relief is dominated by concavities of various dimensions. Substantial drainage basins, like those of the Water of Fedderate and Little Water, take the form of shallow, saucer-like depressions whose floors are dissected but not disrupted by networks of meltwater channels. Similar features, commonly with peat-covered floors, occur at scales of 1-2km^2 at the heads of drainage nets throughout central Buchan. However with decreasing size, there is growing doubt as to the antiquity of the forms and there has been significant modification, at least, by mass movement of loose regoliths under periglacial conditions.

The lower relief comprises basins, basined valleys, valleys and benches. Set below the middle relief are the major basins of Maud and New Pitsligo. The margin of the smooth floor of the Maud basin is closely defined by the outcrop of the Maud morite (Smith 1933) and the contact with the surrounding schists is marked by low scarps. To the north, however, the Maud basin is separated by only a narrow band of country rocks from the biotite granite of the New Pitsligo basin, whose smooth floor Wilson (1882) likens to the site of an old lake basin (Plate 13.2.i). The northern margin of this basin rises first to a bench at around 145m and then to scarps bounding the Windyheads Plateau. The peat-covered floor of the New Pitsligo basin lies between 80 and 110m and merges with a broad bench along the side of the North Ugie valley, which here follows a band of quartz-mica schists through the quartzite belt. East of Mormond Hill, this bench becomes a broad surface of low relief, whose uniform morphology gives little indication of the complexity of glacial deposits locally underlying it (Connell et al 1982).

In the lower Ythan valley, features of similar origin to basined valleys have developed on unresistant norites and biotite granites at the expense of earlier valley benches, as along the Ebrie Burn and at Haddo House. The benches become less dissected upstream but beyond Woodhead the valley narrows to a width of around 3km. The benches, however, continue northwards to merge with similar features above the Deveron at Turriff.

Plate 13.2.i

Plate 13.2.i. The New Pitsligo basin. View E from New Pitsligo. Thick peat covers a floor developed across biotite granite. Quartzite residual of Mormond Hill in the background.

13.2.3 The Don-Ythan interfluve

The upper relief of the area between the lower courses of the Don and Ythan includes isolated hills and an interfluval ridge. The basic and gneissose rocks forming the masses of Hill of Barra (193m) and Pitgavenny Hill (236m) owe prominence to their unsheared condition relative to similar rocks west of Oldmeldrum (Ashcroft and Munro 1978). These hills, and others further east, such as Change Hill (186m) and Beauty Hill (168m), rise above an important scarp marking the northern edge of a dissected interfluval ridge, sloping south-eastwards from Hill of Crimond (170m) to Hill of Middleton (146m).

The middle and lower relief is most extensively developed around Udny, where subparallel ridges rise gradually from broad valley floors. Around Barthol Chapel, the drainage basin shows a shallow, concave form similar to those found in Buchan. Along the Don valley, the middle relief is represented by valley benches at around 100m but these benches and the higher interfluval ridge are greatly disrupted by the sequence of basined valleys described earlier.

13.2.4 The Skene lowlands

Between the Don and the Dee, the topography has been more significantly modified by glaciation but the gross preglacial morphology remains clear. The granitic terrain is dominated by intersecting NW-SE and NE-SW fractures which define the rectilinear outline of the Monymusk basin and the alignments of major scarps rising to remnants of the Mounth Surface on Hill of Fare, Cairn William and Bennachie. The upper relief of the Skene lowlands is largely composed of broken ridges and isolated hill masses, such as Brimmond Hill (266m). This irregular relief is developed in foliated granites and migmatites and forms the northern and eastern margins of the main element of the middle relief, the Skene basin. Cut across granodiorites, the floor of the basin lies between 80 and 110m and stands well above the trough occupied by the Dee. A lower relief of the broad valley floors of the Gormack and Leuchar Burns is set into the basin floor. Further north, the lower relief includes the floors of the Monymusk basin and of the Womblehill, Blackburn and Clinterty basined valleys, all developed on biotite-bearing granites.

13.2.5 Northern Banffshire

North of the middle Deveron, the topography is dominated by structural landforms. Remnants of the Marginal Surface form an upper relief of quartzite and gneissose ridges following the Caledonian trend. These ridges present bold, inward-facing scarps to intervening basins and corridors which form a lower relief which can be traced along the Deveron and into Buchan. The Aberchirder corridor marks a northern continuation of the Drumblade Shear Zone (Ashworth 1975) and contains two elements, an upper bench at 155-180m and a lower basin floor at 120-150m. Fracturing is also the dominant control on relief in the Huntly area, where the masses of The Bin (313m), Ordiquhill (249m) and Hill of Greenfold (219m) represent unsheared blocks bounded by valleys following rectilinear shear zones (Fig. 13.2.i). This structural influence probably extends northwards, for the Knock basin and its wedge-shaped continuation, north of Glen Barry, are tracts of lower relief developed across not

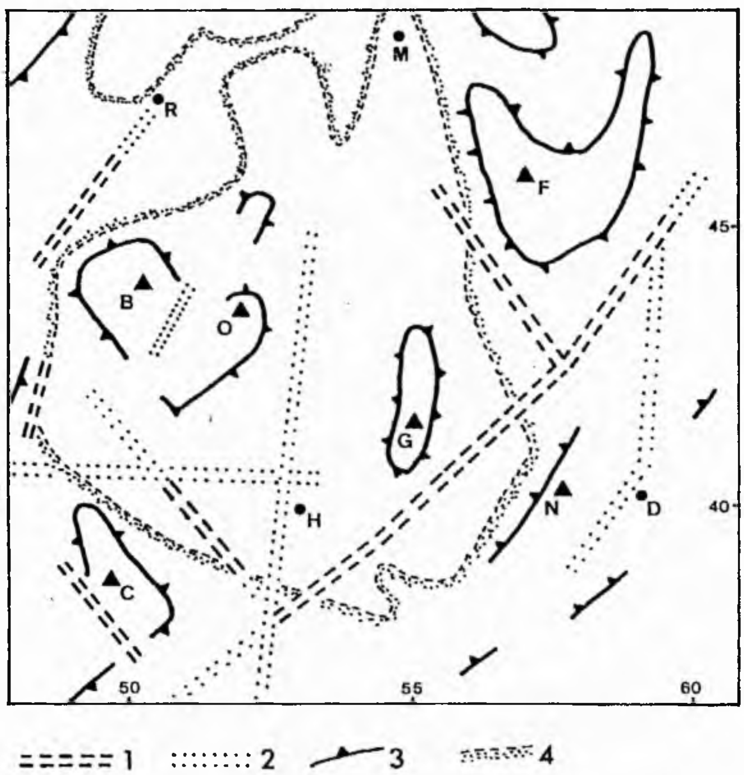

Fig. 13.2.i. Fracturing and relief in the Huntly district.

1. Known shear zones   2. Probable fracture continuations

3. Major scarps   4. Contact between the Huntly and Knock basic masses and the schistose country rocks (stippled).

B. The Bin   C. Clasmach Hill   D. Drumblade

F. Fourman Hill   G. Green Hill   H. Huntly

M. Marnoch   O. Ordiquhill   R. Ruthven

Geological information from Munro (1970) and Ashworth (1975).

only the Knock and Portsoy basics but also neighbouring metamorphic rocks of higher resistance (Munro 1970).

13.2.6 North of the Foudland Ridge to the Deveron

In this area, the upper relief is provided by the Foudland Ridge and the Wind's Eye bench, a part of the Marginal Surface. Around Wells of Ythan, this bench drops some 70m to a middle relief, where the headwaters of the Ythan flow within open valleys, as around Fisherford. These streams soon become incised below the general level and the middle relief is increasingly represented by broad interfluves between 150 and 200m. Along the Turriff-Woodhead valley, which formerly connected the Deveron and Ythan, these interfluves present subdued scarps to valley benches of the lower relief. These benches may be followed into the Howe of Auchterless, a down-faulted and partially-exhumed Devonian valley.

West of Wells of Ythan, the increased dissection of the middle relief reflects the importance of shearing in this area. The most important element of the lower relief is the flat valley floor of the Knightland Burn, following the Drumblade Shear, which forms an important topographic corridor that is continued northwards across the Deveron and into the Aberchirder basin.

13.2.7 The Insch Depression

The massive Insch depression contains three well-defined topographic storeys (Fig. 13.2.ii). Above Strathbogie, the eastward-sloping Clatt Level at 200-230m is a small plateau developed on gabbroic rocks which has been preserved behind a line of syenite hills which have retarded drainage incision. Beyond Insch, this is

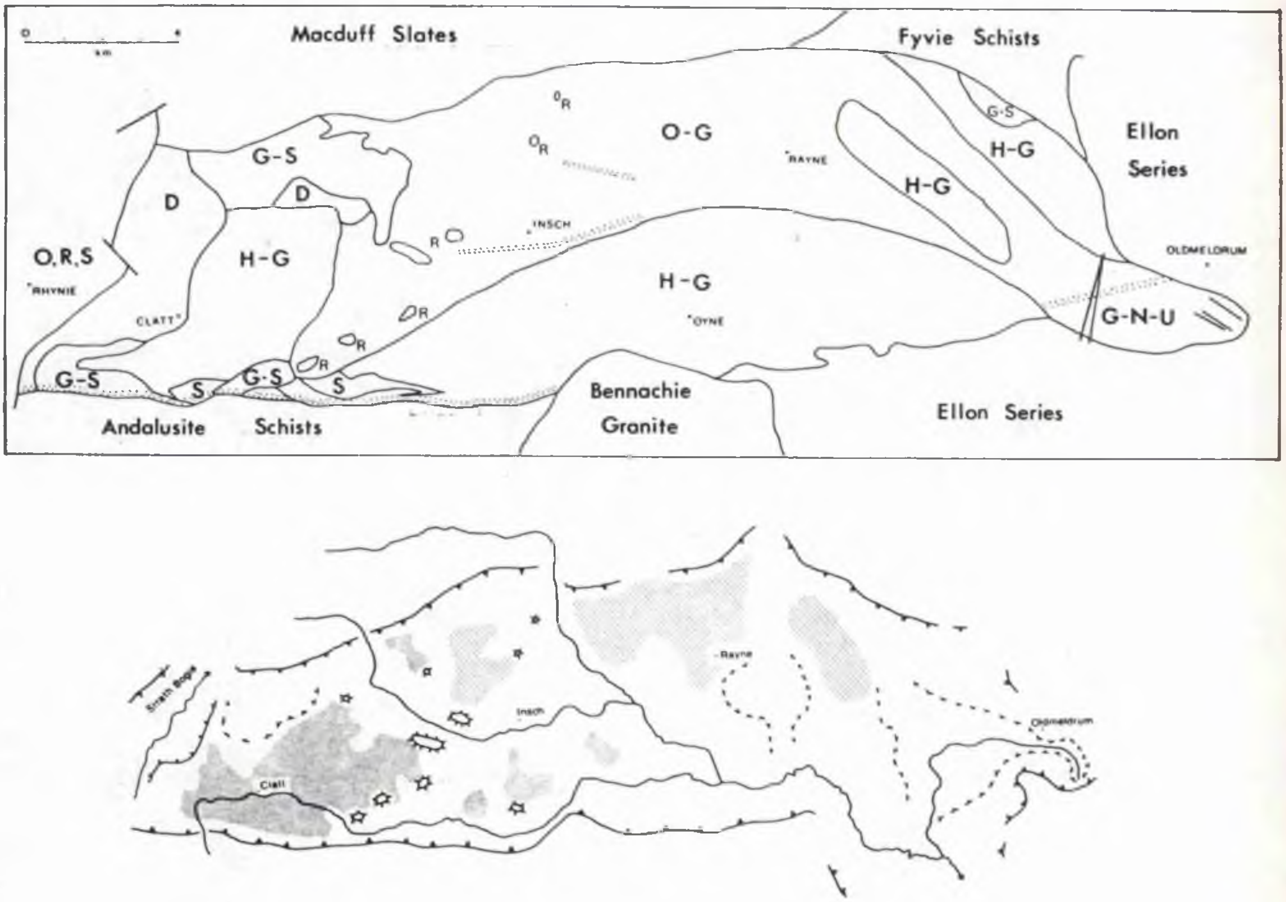

Fig. 13.2.ii. Geology and morphology in the Insch depression.

D. Diorite G-N-U. Gabbros, norites and ultrabasics

G-S. Granite-syenite H-G. Hypersthene gabbro O-G. Olivene gabbro ORS. Old Red Sandstone R. Syenitic Red Rock S. Serpentinite

Main shear zones shown by dotted lines. Geological information from Read et al(1961) and Ashcroft and Munro(1978).

replaced by the Rayne Level, an equally flat bench at 145m along the northern edge of the depression. In turn, the glacis-like slopes of the Rayne Level have been disrupted by encroachment of the Durno and Barra basined valleys. The small basin on the dioritic rocks around Kennethmont is a similar feature and its position beneath the Clatt Level is evidence for the comparatively recent diversion of drainage through the Gartly Gap.

13.2.8 The basins of the Don and Dee

The basins along the valleys of the Don and Dee are extensions of the lowlands formed by levelling of compartments of unresistant rocks. Although their main characteristics have already been described, it is useful to reiterate a number of points:-

(i) The latest floors of the Alford, Tarland and Lumphanan basins all lie between 125 and 155m and are thought by Linton (1951) and Walton (1963) to be accordant with erosion surfaces in the lowlands. However the more restricted floors of the Cushnie and Tornaveen basins and benches in the Alford basin and along the Don valley comprise a distinctly higher storey at 220-270m.

(ii) The basins are probably ancient forms established during, or even before uplift of the Eastern Grampian Surface.

(iii) The floors of the Alford and Tarland basins have been progressively reduced in area during lowering and the outlines of the present floors are tightly controlled by geology. The strength of this rock control (Yatsu 1966) does not support the model of scarp retreat, basin enlargement and surface extension suggested by Linton (1951).

This account of landform assemblages has emphasised the relative position of landform types in the lowland topography. Yet the height differences between upper and lower storeys of relief are often limited and if the landscape is viewed at a broader scale, there is no doubt that extensive areas of levelled terrain occur in the lowlands. Indeed the preglacial morphology of the lowlands has been described mainly in terms of erosional levels and the question of the number and morphology of these levels must now be considered.

13.3 Erosion surfaces in the lowlands

13.3.1 Introduction

Earlier workers have claimed to recognise a number of erosion surfaces in the lowlands. The Soil Survey of Scotland (Glentworth 1954; Glentworth and Muir 1963) distinguish two main topographic levels:- the Lower and Upper Buchan Platforms. The Lower Platform includes all areas of the eastern lowlands lying between 15 and 140m and is termed a tilted peneplain. Along the major valleys, the Lower Platform was thought to tongue into a higher level at between 140 and 230m. This Upper Platform is represented by the smooth summits of the main hills of Buchan and is most extensive in areas west of Maud and Udny. Walton (1963) also recognises two erosion surfaces but at different elevations. A marginal surface in coastal districts was seen to penetrate up the major valleys to form flats at 60-75m. This level is surmounted by a much more widely-developed surface, the Buchan Platform, with an upper limit put at between 120 and 150m. This extensive surface gave way inland to basins with floors at accordant altitudes (see also Linton 1951). Walton considered that his Buchan Platform was a marine erosion surface of Pliocene age, relying mainly on an earlier interpretation of the Buchan Gravels as beach deposits belonging to this period (Flett and Read 1921).

These supposed erosion surfaces are identified in generalised descriptions of the regional relief. No detailed topographic analysis has been made to establish the existence of distinct morphological levels. Moreover no detailed examination has been attempted of the links between geology and morphology to isolate structural flats and the forms of differential resistance. In the following sections, hypsometric and geomorphic evidence for stepped erosion surfaces in the lowlands will be discussed.

13.3.2 Hypsometric evidence for erosional levels

Hypsometric curves for ground below 300m were constructed by sampling the elevations of kilometre grid intersections on the 1:50 000 Ordnance Survey First Series maps. The regional curve shows that some 49% of the sampled area lies between 70 and 140m (Fig. 13.3.i). Local curves for the northern half of the lowlands show sharp peaks indicative of extensive levelled areas (Fig. 13.3.ii). These peaks decline in elevation from 110-130m in the west to 60-90m in central Buchan and 10-40m in the drift-covered lowlands. No clear levels are apparent in curves for southwestern areas but a distinctive peak at 60-80m occurs in areas east of Bennachie.

The hypsometry supports the existence of an important morphological break at about 140m, as suggested by the Soil Survey (Glentworth 1954; Glentworth and Muir 1963) and by Walton (1963). However the Upper Buchan Platform recognised by the Soil Survey at between 140 and 230m

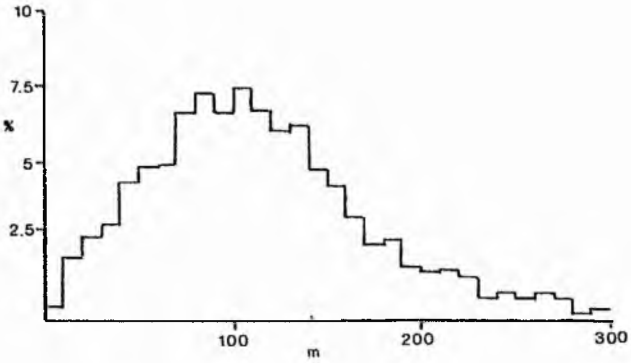

Fig. 13.3.i. Regional hypsometric curve.

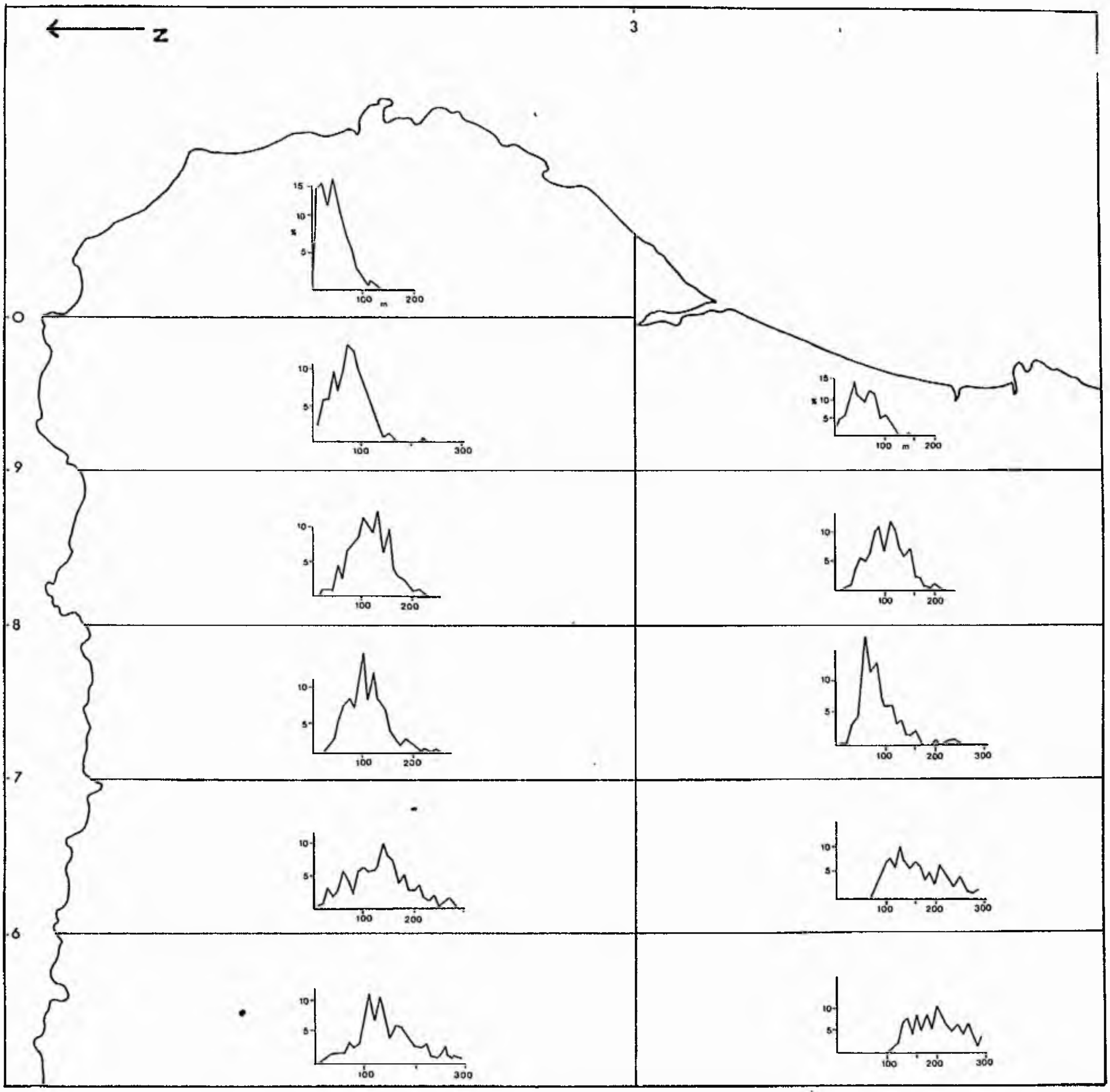

Fig. 13.3.ii. Sub-regional hypsometric curves.

is not reflected in the area-height curves. Only a limited area of the lowlands falls within this range of elevations and no major peaks occur above 150m in the local curves. This Upper Platform, if it exists, can only be a restricted feature. Similarly there is little evidence of the topographic break at around 80m identified by Walton at the base of his Buchan Platform. Instead the hypsometry supports the existence of a single eastward-sloping morphological level with an upper limit at about 140m and no well-defined lower limit.

13.3.3 Geomorphic evidence for erosional levels

Hypsometry, however, offers only a rough guide to morphology (Clarke 1966) and there is some local morphological evidence for the marginal surface of Walton and the Upper Buchan Platform of the Soil Survey. In the eastern lowlands, the lower storey of relief, described earlier, comprises basins, basined valleys, valley benches and valley floors. These forms generally lie below 100m and could be seen as parts of an incipient surface in the process of extension along the major valleys, following the interpretation of Walton (1963). However there are a number of reasons for rejecting such a model:-

(i) The forms of the lower relief are of more than one age.

Along the Don valley, the basined valleys have been opened out at the expense of pre-existing valley benches. Similarly the benches along the Dee are extensions to the main floor of the Skene basin and are breached by lower, open valley floors of later origin.

(ii) Elements of this lower relief commonly merge with forms of higher topographic storeys without discontinuity.

Many forms of the lower relief grade into higher topography and the absence of breaks of slope suggests that both lower and upper slopes are part of larger landform systems. This continuity is well-illustrated along the North Ugie valley, where the floor of the New Pitsligo basin first merges with valley benches which, in turn, join a broad surface of low relief reaching to within 5km of the coast. The resultant morphological level falls smoothly from 110 to 50m over a distance of 18km and owes its remarkable uniformity to the local base level provided by the North Ugie Water prior to incision.

(iii) The basins and basined valleys are forms of differential resistance.

The differences in elevation between the floors of the New Pitsligo and Maud basins and the surrounding relief are an expression of differential rock resistance. The basins can be viewed as forms of dynamic equilibrium (Hack 1960) and both upper and lower relief may be of common age. Many basined valleys, however, are not equilibrium forms as they have yet to exploit neighbouring areas of deep weathering. Nevertheless, in common with the basins, the basined valleys will not extend beyond the zones of weakness which ultimately determine their location and cannot coalesce to produce new erosional levels.

There is therefore little hypsometric or geomorphic evidence for an incipient erosion surface below 80m in the lowlands, as envisaged by Walton (1963). However the lower relief does include at least two generations of forms. The older suite of landforms includes basins and valley benches and forms the lowermost storey of complex landform systems. Set below these forms are younger features, such as basined valleys and certain valley floors, which are the products of drainage incision in the younger Pleistocene.

Although there is a lack of hypsometric corroboration, the concept of an Upper Buchan Platform is apparently supported by the existence of numerous, though areally-restricted, topographic flats above 140m and by the widespread presence of a break of slope at this height. This break of slope is independent of structure where it backs the benches in the upper Ythan valley but elsewhere shows various degrees of structural control (Fig. 13.3.iii). These subdued scarps represent the 'degraded cliff line' identified by Walton (1963) at the rear of his Buchan Platform but in the absence of any evidence of former marine planation in the lowlands, an alternative explanation for these accordant scarps must be sought. It is significant that many of these scarps are found in positions remote from the main drainage lines, where subdued lowland surfaces interdigitate with higher relief. This distribution suggests that the scarps mark the inland limit of an important phase of levelling moving up the major rivers.

The widely-scattered interfluval ridges and flats found above 140m but below the extensive plateaux of the Marginal Surface are regarded by the Soil Survey as remnants of a former erosion surface. These levelled areas are most widely developed around Auchterless and in the western half of the Insch depression but smaller fragments occur widely in the upper relief of Buchan (Fig. 13.3.iv). However these fragments occur over a wide range of elevations, from 120-140m for the White Cow Wood plateau in eastern Buchan to 220-270m

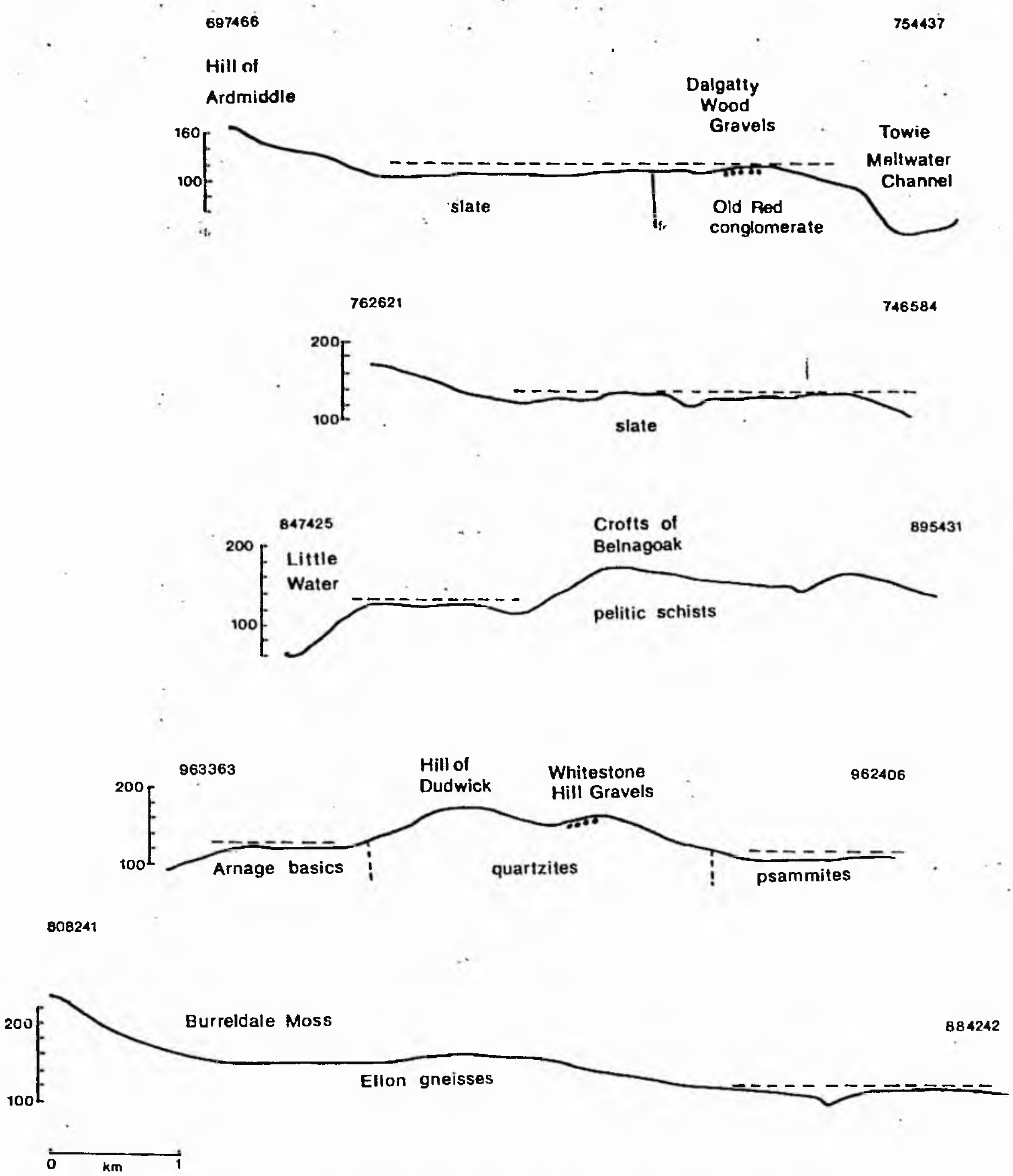

Fig. 13.3.iii. The backing slope of the Buchan Surface.

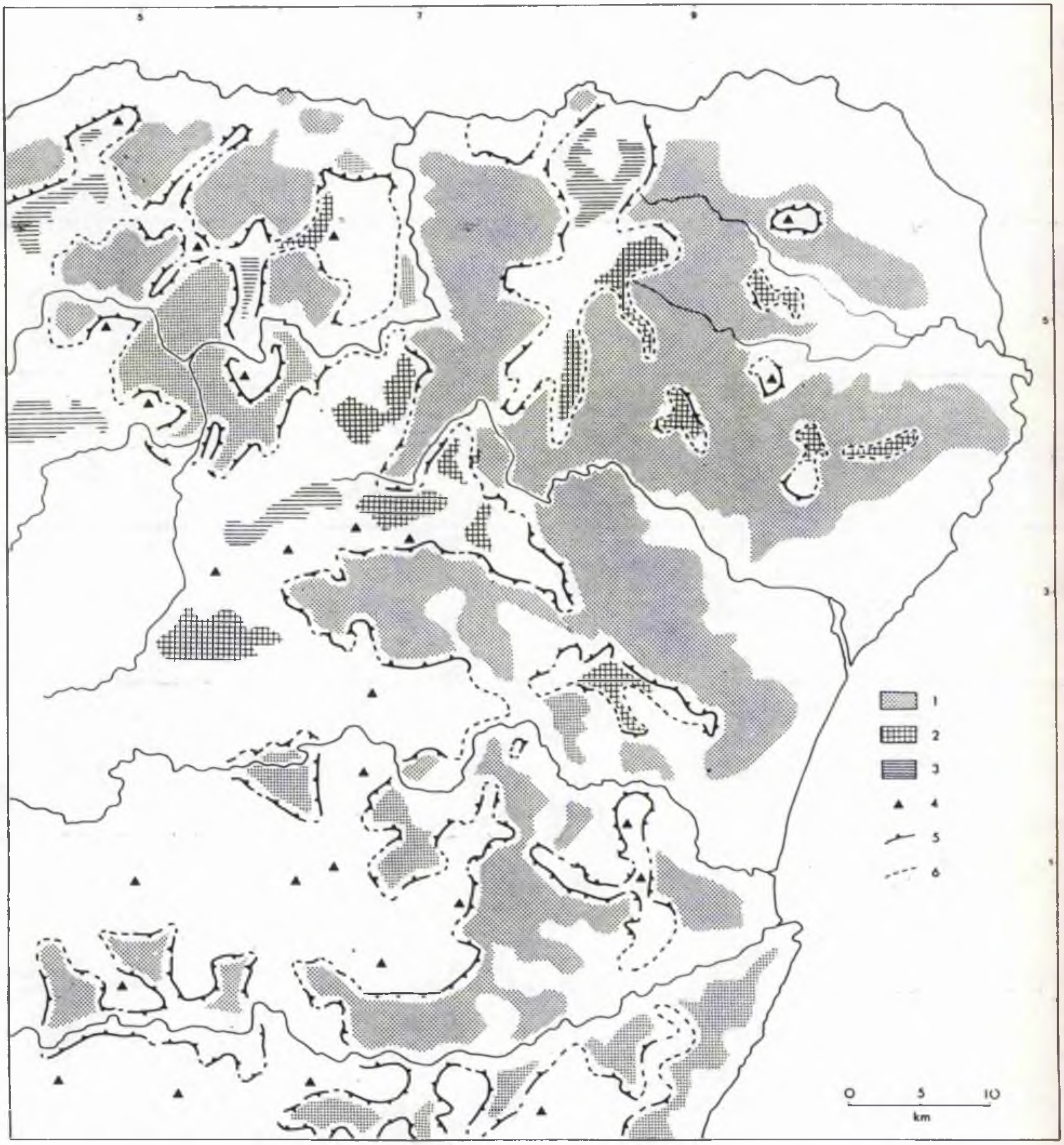

Fig. 13.3.iv. The Buchan Surface.

1. The Buchan Surface 2. Local levels standing above the Buchan Surface 3. Fragments of the Marginal Surface 4. Isolated hills 5. Backing scarps 6. Inner limit ill-defined.

for benches and basin floors around Alford, suggesting the existence of multiple local levels. This impression is particularly strong in the Insch depression, where the Rayne Level is contiguous with the Auchterless Level, the type area for the Upper Buchan Platform, yet is surmounted in the west by the equally broad Clatt Level. A further problem is that many of the ridges in Buchan owe prominence to rock resistance and often grade downslope into forms of the lower relief, suggesting that these forms are part of complex landsurfaces incorporating both positive and negative relief. These isolated flats are best regarded as local levels preserved on resistant rocks or behind rock barriers and left as residuals by the later phase of regional levelling that produced the scarps.

13.3.4 The Buchan Surface : the fundamental morphological level in the lowlands.

The Soil Survey and Walton agree that the most extensive levelled areas in the lowlands are found below the morphological break at 140m. Hypsometry indicates that 70% of the total area below 300m in the lowlands lies below this elevation and points to the existence of a single, though complex erosion surface: the Buchan Surface (Fig. 13.3.iv). The principal characteristics of this Surface are a subdued, but varied relief with partial adjustment to heterogeneous geology and structure and widespread development of landforms of differential resistance. In detail, the Buchan Surface resolves into a multi-storey landscape. An upper relief consisting of both forms of resistance and forms of position (Birot 1978) passes downslope into broad, levelled areas incorporating open, saucer-like drainage basins. Set into this middle relief are the forms of negative resistance located on zones of structural weakness. Inland, the Surface interdigitates with higher relief and extends along the main rivers and into a number of large basins. These inner compartments of levelling and the forms of position in the lowlands demonstrate that the drainage has been the principal agent of surface extension.

The local levels lying above the low scarps at the inner margins of the Buchan Surface suggest development by lowering of an earlier subdued relief. The contrast between the disregard of the Buchan Surface for the complex regional geology (Fitzpatrick 1969; 1972) and the local importance of rock control can also be seen in terms of inheritance. In the basins, the divergence in levels of rock resistance can be related to gradual climatic cooling. The trend towards an increasingly compartmented relief in the lowlands is probably also an expression of the growing selectivity of weathering processes towards the end of the Tertiary. Moreover it is significant that the Windyheads Plateau, referred to the Marginal Surface, stands only 90m above neighbouring elements of the Buchan Surface, indicating that tilting has greatly reduced the height differences between surfaces in eastern areas.

Morphological evidence for lowering during formation of the Buchan Surface is provided by the gently stepped topography of many areas and by the benches found in several of the basins. This lowering has been achieved apparently without disruption of the smooth relief. The only significant morphological break occurs in the coastlands, where deep incision of the drainage has created young forms which dismember the lower relief of the Surface.

13.4 Weathering types, sediments and morphology

The role of weathering in the development of some of the typical landforms of the lowlands has already been considered but little attention has been given to the wider links between weathering, sediments and the origins of the landsurface. Investigations of weathering covers have been an integral part of studies of relief development in parts of Europe south of the limits of the Pleistocene glaciations (Godard 1972; 1978; Bibus 1973; Klein 1975; Coincon et al 1976) and this approach offers considerable potential in the weathered terrain of north-east Scotland. The regional distribution of weathering can be used to test the validity of morphological divisions. The geomorphic position of the weathering types of the Buchan Gravels also supplies important information on the way in which the land-surface has evolved. Finally, the saprolites and sediments allow general estimates to be made of the age of certain relief forms.

In terms of altitude, 57% of the weathering sites lie between 60 and 140m but as hypsometric analysis indicates that around 53% of the total lowland area lies between these elevations, it can be seen that there is no concentration of weathering sites within the altitudinal range of the Buchan Surface. However the ground lying between O.D. and 60m comprises around 23% of the lowland area and yet only 10.3% of weathering sites fall within this range. Part of this discrepancy is due to enhanced erosion by the coastal ice streams but the relative shallowness and infrequency of weathering in areas below 60m may also be a reflection of the shorter time periods available for saprolite formation during and since development of the young relief of the coastlands.

The gruss weathering type is found at all elevations between sea level and the Cairngorm summits and is not associated with any single morphological level. In the lowlands, depths of gruss development locally exceed 50m and profiles up to 15m deep remain even on the highland surfaces (Barrow et al 1913). The mineralogical characteristics of the grusses indicate formation under humid-temperate environments and the former existence of extensive forest covers can be inferred. The ubiquitous distribution, depth of development and characteristics of the grusses demonstrates that morphogenic processes acting under temperate environments has substantially modified the regional relief at all elevations.

The older clayey gruss weathering type has a much more restricted distribution and its common juxtaposition with less-altered saprolites indicates that only the basal zones of these kaolinitic weathering profiles have escaped erosion (Bakker and Levelt 1964). Of 14 known exposures, 12 occur in more elevated parts of central Buchan, where kaolinisation affects quartzites, quartz-mica schists, granites, diorites and quartz porphyry. To these may be added a further 8 possible sites, where zones of clayey alteration are recorded in UADG and IMAU borehole logs (Fig. 13.4.i). Outlying exposures comprise the rubefied and kaolinised granite at Bennachie Car Park and the highly-altered meta-sediment described by Koppi (1977) from the Clashindarroch Forest. These two exposures lie at elevations of around 150m and 350m respectively. Excluded from consideration are saprolites affected by late-stage alteration and the thin zones of kaolinised bedrock produced by acidulated groundwater movement beneath the Buchan Gravels.

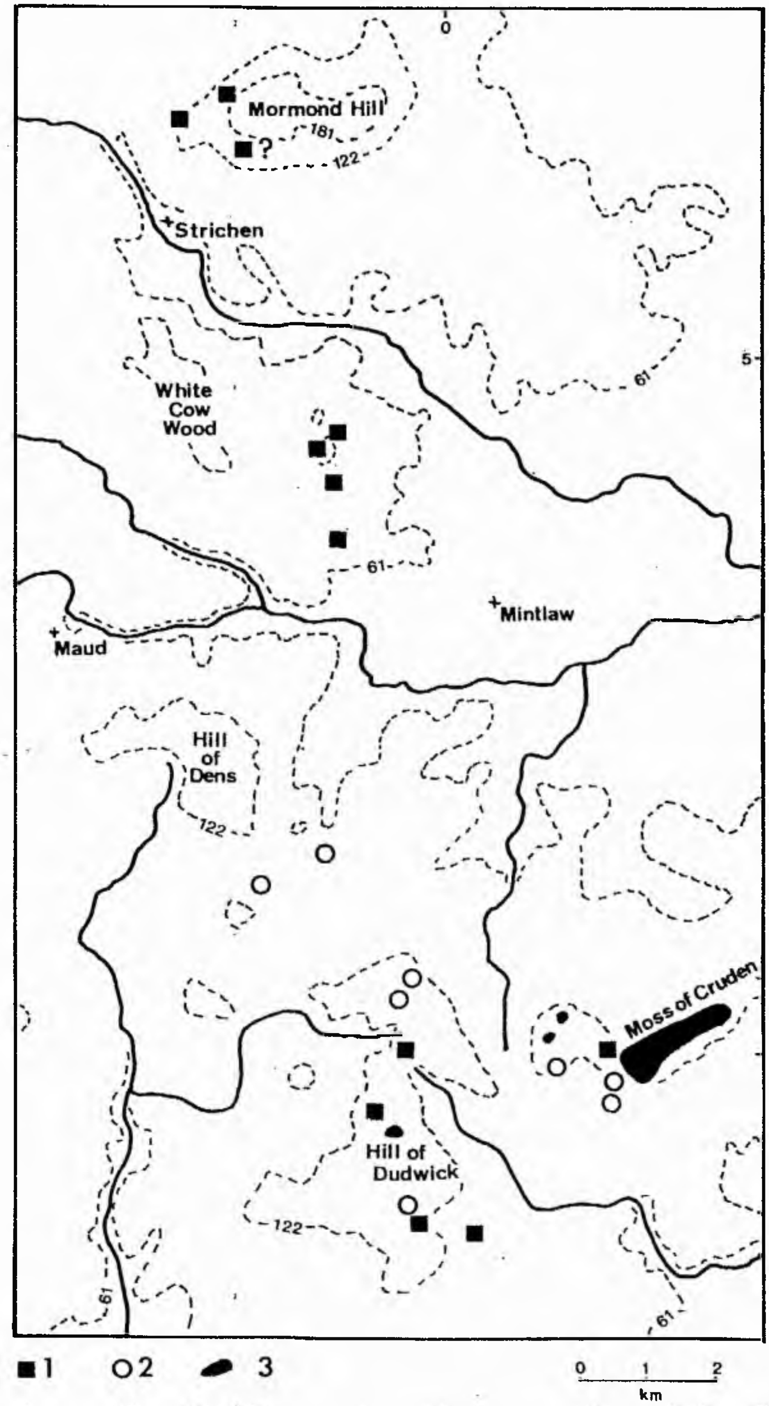

Fig. 13.4.i. Distribution of clayey grusses and the Buchan Ridge Formation in central Buchan.

1. Exposure of clayey gruss 2. Clayey weathered rock recorded in boreholes 3. Buchan Ridge gravels

The frequency of clayey gruss occurrence in central Buchan is of some significance for the age of the relief in this area. The clayey grusses are strongly associated with areas standing above the general level of the Buchan Surface, such as Mormond Hill, the Forest of Deer plateau, the Dudwick-skelmuir ridge and the Moss of Cruden ridge. These latter two ridges are also capped by gravels of the Buchan Ridge Formation deposited by rivers flowing eastwards across an earlier landsurface (Fig. 13.4.i). Evidence from morphology, weathering types and sediments demonstrates that these are areas of residual relief which predate development of the Buchan Surface.

The distribution of clayey grusses suggests that the Buchan Surface has developed by lowering of earlier surfaces formed in kaolinitic weathering covers. The fundamental importance of lowering in the geomorphic evolution of the lowlands is well-illustrated by the topographic position of the Buchan Ridge flint gravels. These deposits have provided an armoured surface for a subjacent valley floor which now forms a prominent ridge. Although the course of the river which deposited these gravels has not been traced west of Whitestone Hill, it seems likely that much of the ground between these deposits and the lower Ythan valley has been affected by the migration of a proto-Ythan river system. This combination of fluvial migration and topographic lowering is analogous to situations found in crystalline terrain in the humid tropics, where rounded pebbles and diamonds of alluvial origin may occur at many levels in the landscape (Thomas and Thorp, in press).

During development of the Buchan Surface, mature weathering covers were progressively replaced by grusses. Deep saprolites were probably maintained until incision of the drainage in the younger Pleistocene. In this latest period, rates of saprolite renewal lagged far behind surface lowering and the forms of the younger relief developed excavation of pre-existing zones of weathering.

In terms of age, the association of the clayey grusses and the Buchan Ridge Formation with the residual relief of central Buchan suggests development prior to the middle Pliocene and perhaps as early as the Miocene. The deeper grusses were earlier referred to the late Pliocene and early Pleistocene and as the Buchan Surface is overlain by the middle to late Pliocene Windyhills Formation along the former Deveron-Ythan drainage route, it is suggested that the Buchan Surface is a product of morphogenesis during the Pliocene and early Pleistocene.

13.5 Towards a model of relief development in the lowlands

The lowland landscape has developed by progressive lowering in response to gradual uplift. Weathering covers have been maintained during lowering despite the fact that major episodes of stripping have occurred involving the transport of coarse gravels in the drainage system. Conservation of regoliths has allowed inheritance of subdued relief from earlier land-surfaces. Many larger landforms have remained fixed in position over long time periods and this continuity of form reflects the repeated and sustained exploitation of differential rock resistance by groundwater weathering. In short, the lowland relief has evolved by a form of etchplanation.

13.5.1 The etchplain concept

The concept of the 'etched-plain' was formulated by Wayland (1933). In the humid tropical environment of Uganda, Wayland recognised that extensive peneplains were underlain by deep alterites. In his view, reactivation of these plains by uplift would lead to removal of weathering covers and the reproduction of plain forms at lower levels in the landscape. Emphasis was placed on alternating phases of etching (differential weathering) and stripping (the removal of weathering products). Repetition of these processes allowed the conservation of surfaces of low relief during uplift.

The original concept has been broadened by later workers to include landscapes at various stages of weathering and stripping (Budel 1957; Thomas 1965; 1974a; Finkl 1979). Increasing attention has been given to the role of climatic change and, in particular, the switch from humid to semi-arid or arid conditions in promoting the stripping of regolith. Although the importance of the alternating phases of stability and instability envisaged by Wayland (1933) continues to be recognised (Erhart 1955), there is growing emphasis on 'dynamic etchplanation' (Thomas 1974a), where weathering penetration is more or less balanced by surface denudation and the landscape is maintained close to dynamic equilibrium (Hack 1960) during lowering.

Thomas (1977) has argued for the wider application of the etchplain model to problems of relief development in recently glaciated regions. The model has been used with some success in studies of the geomorphic evolution of central Europe (Budel 1977; 1979) and southern Sweden (Lidmar-Bergstrom 1982) and aspects of the etchplain concept are implicit in the accounts of the paleic relief of northern Europe (Gjessing 1967; Kaitenen 1969).

However the etchplain model has been developed and applied mainly in humid tropical areas (Thomas 1965; 1974a; Thorp 1975) or to areas where the main features of the relief are inherited from earlier humid tropical environments (Finkl and Churchward 1973; Finkl 1979). Its application to the rather different environment of north-east Scotland involves significant changes in emphasis in order to accommodate the particular conditions for relief generation in the region.

13.5.2 Application to problems of relief development in NW Europe

Perhaps the greatest contrasts lie in the climates prevailing during morphogenesis. Evidence from weathering covers and the Buchan Gravels indicates that no part of the lowland relief pre-dates the Neogene and that only restricted areas lying above the Buchan Surface can predate the Pliocene. The Neogene climates of north-west Europe were dominated by two features: the prevalence of temperate conditions and the frequency and increasing severity of climatic change (see Chapter 3). Phases of extreme warmth and cold occurred only at the beginning and end of the Neogene, with subtropical conditions persisting only until the Middle Miocene (Buchardt 1978) and with the first establishment of tundra vegetation at the Plio-Pleistocene boundary (van der Hammen et al 1971). The intervening period saw fluctuating cool to warm temperate climates without marked seasonality of precipitation. In the Netherlands, these equable environments supported alternating successions of pine and mixed-oak forest (Zagwijn 1960). The frequency of climatic fluctuation is unclear but cold-warm cycles of 1.2 to 1.5 x 10^5yr duration can be traced back to at least 2.5m.y. Whatever their frequency, these oscillations undoubtedly became increasingly severe through the Pliocene and culminated in fluctuations between warm temperate and tundra environments in the Early Pleistocene (West 1980).

These climatic environments are clearly quite different from those prevailing in the humid tropics. During most of the Neogene, Scotland will have come within the forested midlatitude morphogenic zone of Tricart and Cailleux (1972). The models of tropical landform development so widely applied in recently-glaciated areas of north-west Europe (Budel 1977; 1978; 1980; Godard 1965; Gjessing 1967; Kaitenen 1969) ignore the importance of humid temperate environments in the Neogene climatic record (Birkenhauer 1970; 1972). These cooler climates have major morphogenic implications for the twin processes at the heart of the etchplain model: weathering and stripping.

Although the nature of weathering reactions is temperature-independent (Pickering 1962), the rate and intensity of chemical alteration is closely related to temperature and humidity (Tardy et al 1973) and weathering profiles can be expected to develop more quickly and to greater depths in humid tropical, as opposed to temperate environments (Thomas 1974b). However perhaps of greater importance are the differences in the physical properties of saprolites between these morphoclimatic zones. Tropical alterites generally contain high proportions of fines and are inherently more stable than the sandy saprolites of higher latitudes. Moreover the surface horizons of mature alterites in the tropics are frequently indurated and protect underlying fragile materials from erosion. Surfaces developed across thick saprolites in the temperate zone can therefore be expected to be far more responsive to minor environmental perturbations and may be less persistent in the landscape.

Significant differences also exist between the mechanisms of stripping, particularly the role of climatic change. In the tropics, the geomorphic effectiveness of arid phases lies in the reduction or disappearance of the vegetation cover and the exposure of regolith to surface wash processes (Tricart and Cailleux 1972). Yet episodes of severe aridity are not a feature of the maritime Neogene climate of north-west Europe (van der Hammen et al 1971). Furthermore, although climatic change is one of the principal characteristics of Neogene palaeoclimates at higher latitudes, there is considerable doubt as to whether climatic oscillations will have resulted in substantial losses in ground cover at lower elevations before the first decline into tundra conditions in the earliest Pleistocene. In the Netherlands, coniferous and deciduous forests were maintained throughout the Pliocene despite repeated climatic fluctuations (Zagwijn 1960). Without major disruption of the vegetation, the geomorphic effects of climatic change will have been comparatively limited.

Yet although direct process comparisons with the tropics may be invalid, the etchplain concept does remain directly relevant to problems of Neogene relief development in north-west Europe. The changes in saprolite characteristics in the later Tertiary are not of fundamental geomorphic significance as deep gruss covers continued to develop throughout this period (Durand 1960; Esteouelle-Choux 1967; Bakker 1967). Moreover the persistent tectonic activity around the North Sea ensured that Palaeogene surfaces were substantially modified. Deformation continued in the British Isles throughout the Neogene (George 1974; Reffay et al 1982), with exhumation and reactivation of polygenetic Palaeogene surfaces in southern England (Jones 1980) and Wales (Battiau-Queney 1978) and post-Miocene vertical movements of up to 500m of mid-Cenozoic surfaces developed across the Carboniferous of the southern Pennines (Walsh et al 1972). Oblique uplift of Fennoscandia after the Late Oligocene lead to degradation of a complex Palaeogene relief (Peulvast 1978) and intrusive activity in the Rhineland continued into the Pleistocene (Lidmar-Bergstrom 1982). Stripping of gruss-type weathering covers in response to uplift produced an influx of immature sediments to the North Sea (Karllson et al 1979; Berstad and Dypvik 1982) and the extent of the re-modelling of the relief of surrounding areas can be judged from the thicknesses of Neogene strata in the basin, with at least 1200m of sediments in the Central Graben (Pegrum et al 1975). Major morphogenesis continued, with etching of earlier relief by further weathering and stripping in response to tectonic and, less importantly, climatic rhythms.

13.5.3 Application to north-east Scotland

The significance of the etchplain model to north-east Scotland, in particular, lies in three main areas:-

(i) Attention is focussed on the continuity of surface development

The distant origins of the lowland plain can be glimpsed beneath Upper Cretaceous and even beneath earlier Mesozoic sediments (Johnstone 1966). The Formartine Block escaped substantial tectonic movements in the Palaeogene and remained an area of generally low relief. The latest erosion surface, the Buchan Surface, has evolved by lowering of an earlier, possibly Miocene, plain which retains traces of its Palaeogene origins. The inheritance of gross morphology from as far back as the Mesozoic stands in stark contrast with Neogene age of the relief of the Western Highlands (George 1966) and reflects the singular structural position of the region at the boundary between the intermittently-rising Grampians and the subsiding North Sea Basin.

(ii) Links between weathering and morphology are emphasised

The long term (10^6yr) evolution of the lowland landscape can be seen in terms of geochemically-controlled differential denudation. Weathering patterns developed in response to structural and lithological diversity have been exploited during lowering of the landsurface to give a variety of landforms of differential erosion. Emergence of these forms has been encouraged by the growing control of a varied topography over patterns of groundwater movement, favouring continued penetration of weathering in depressions and reinforcement of weathering patterns. Weathering covers have been maintained during lowering and the relief has developed by dynamic etchplanation without significant exposure of grundhockerrelief before glaciation.

(iii) The model provides a descriptive terminology which integrates weathering and slope development

The incidence of weathering is used as an indicator of slope form and as a guide to landscape type. Information is also provided about the degree of stage of weathering penetration or surface lowering. These spatial patterns of weathering can help elucidate the origins of a variety of relief forms and are particularly useful in the identification of zones of glacial erosion.

Although one of the principal advantages of the etchplain model is its emphasis on the continuity of weathering penetration and landform evolution, there is also a need to stress the importance of stage in the lowland landscape. Many landforms can be identified which are not adjusted to geology, such as the deeply-weathered ridges of central Buchan, many of the flats standing above the backing scarp of the Buchan Surface and several of the inland basins. The landscape cannot be interpreted solely in terms of dynamic equilibrium (Hack 1960), despite the fact that many macro-scale landforms have been maintained in crude equilibrium during lowering. In discussion of the origins of the basins, a number of possible reasons were given for the incompleteness of rock control (Yatsu 1966) or differential rock resistance over morphology, including inheritance, exhumation, lack of time for adjustment and the random emergence of edaphically-dry slopes during lowering. More generally, the arrival time of pulses of morphogenic activity moving across the landscape differs according to location relative to the drainage system and rock barriers may cause prolonged delay. The various parts of the landscape are kept at different stages of adjustment and if energy pulses are quickly repeated, the landscape will merely tend towards equilibrium with geology. The immutability of rock control is in any case illusory for levels of rock resistance have changed with climatic cooling and the lowland landscape has only begun to adjust to the increasing selectivity of weathering.

The etchplain model provides only a general framework in which to consider problems of geomorphic development and several major questions remain outstanding about the relief-generating processes. Although the principal characteristics of the weathering covers should be evident, long-term rates of weathering are largely unknown. The agents of stripping are also obscure, for whilst the drainage has clearly played a major part in the evacuation of the products of denudation, the processes responsible for carrying detritus to the stream channels beneath apparently continuous forest covers are unclear. The view that the temperate environment forms a zone of low morphogenic intensity (Tricart and Cailleux 1972) must also be challenged in view of the evidence for complete topographic inversion in parts of the lowlands since deposition of the Buchan Ridge gravels in the Late Miocene or Early Pliocene. Certain of these questions may be resolved when the unfortunate reliance on tropical models in studies of preglacial geomorphic evolution in northern Europe begins to be abandoned.

13.6 Summary

A single erosion surface is identified in the lowlands: the Buchan Surface. In detail, this complex etchplain consists of multi-storey landscapes incorporating a variety of forms of differential resistance. The Buchan Surface is developed across deep grusses and rises to a locally well-defined morphological break at 140m. Standing above the Surface are resistant hills and residual areas of levelled relief which possess fragmented covers of the older clayey gruss weathering type. The lowland landscape has developed by dynamic etchplanation, with lowering and maintenance of the subdued topography during gradual uplift and perpetuation of the major relief forms. Below the Buchan Surface in coastal areas are younger features related to the exploitation of largely relict weathering compartments during drainage incision. The upper relief may date from the Miocene and has distant origins in the Palaeocene and even Mesozoic. The Buchan Surface was elaborated through the Pliocene and early Pleistocene and is disrupted by younger Pleistocene forms.

CHAPTER 14 Regional Denudation Chronology

14.1 Introduction

In the preceding Chapters, the highland and lowland relief forms have been treated separately. Yet it was emphasised earlier that there are important morphological links between these areas (Section 11.1). Similar types of saprolite and landform occur over a wide range of elevations and models of basin and valley development formulated in the lowlands are directly relevant to more elevated terrain. Moreover the highland relief shows many signs of the progressive lowering and continuity of form which has characterised the evolution of the lowland landscape. Major residual hill masses, such as Mount Keen, Morven and Ben Rinnes, were probably in existence prior to formation of the Eastern Grampian Surface. Many basins and valleys have also remained fixed in position since uplift of this surface and several have origins in the Devonian. The etchplain model is thus applicable to problems of relief development at all elevations and both highland and lowland terrain can be described in terms of the degree of stripping of regolith.

These links are further emphasised by the recognition that the position of the highlands and lowlands is in large part due to differential movements of underlying structural units in the Tertiary. The main erosion surfaces, the Eastern Grampian, Marginal and Buchan Surfaces, have common origins in a single dislocated master surface of polygenetic origin. Moreover along the Moray Firth coast, the Buchan Surface has developed by lowering of the uplifted and tilted Marginal Surface and, in eastern Buchan, gravel-capped hills and ridges lie close to the original level of this surface. These associations between highland and lowland surfaces underline the fundamental unity of the regional relief.

The main stages in the development of relief in both highland and lowland areas have been outlined in previous Chapters. However the timing of these geomorphic events remains to be established. Much of the morphological and geological evidence relevant to regional denudation chronology has already been noted but one traditional line of enquiry remains to be examined:- the evolution of the drainage.

14. 2. Drainage Evolution

Bremner (1942), Linton (1951) and Sissons (1967; 1976) have put forward reconstructions of the drainage evolution of north-east Scotland which are parts of larger models dealing with the whole of the Highlands. Bremner (1942 and Fig. 14.2.i) recognises two main drainage trends in areas south of the Moray Firth:-
(i) a series of streams flowing from W-E across the area lying east of the present Spey, and (ii) centripetal drainage towards the Moray Firth in districts further west. This pattern of ancestral drainage was largely accepted by Linton (1951). However these reconstructions can be questioned on a number of grounds, notably their over-reliance on superimposition as a mechanism to account for apparent discordance between drainage patterns and structural trends and for their failure to place drainage evolution in an adequate framework of long-term geomorphic change. This section seeks to identify the regional and local factors which have influenced the drainage patterns and to trace its sequential development.

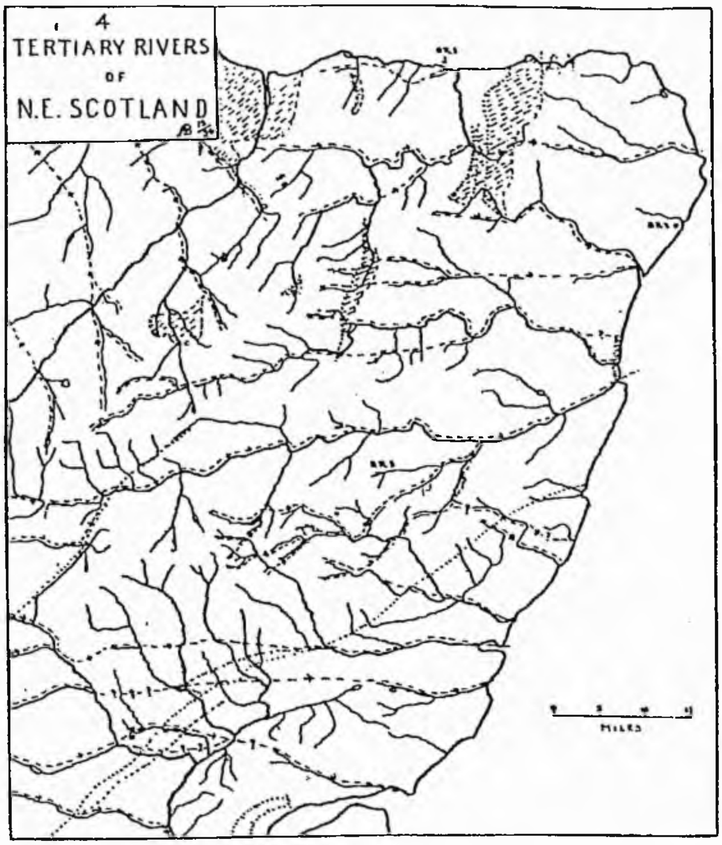

Fig. 14.2.i. Ancestral drainage according to Bremner(1942 Fig. 4).

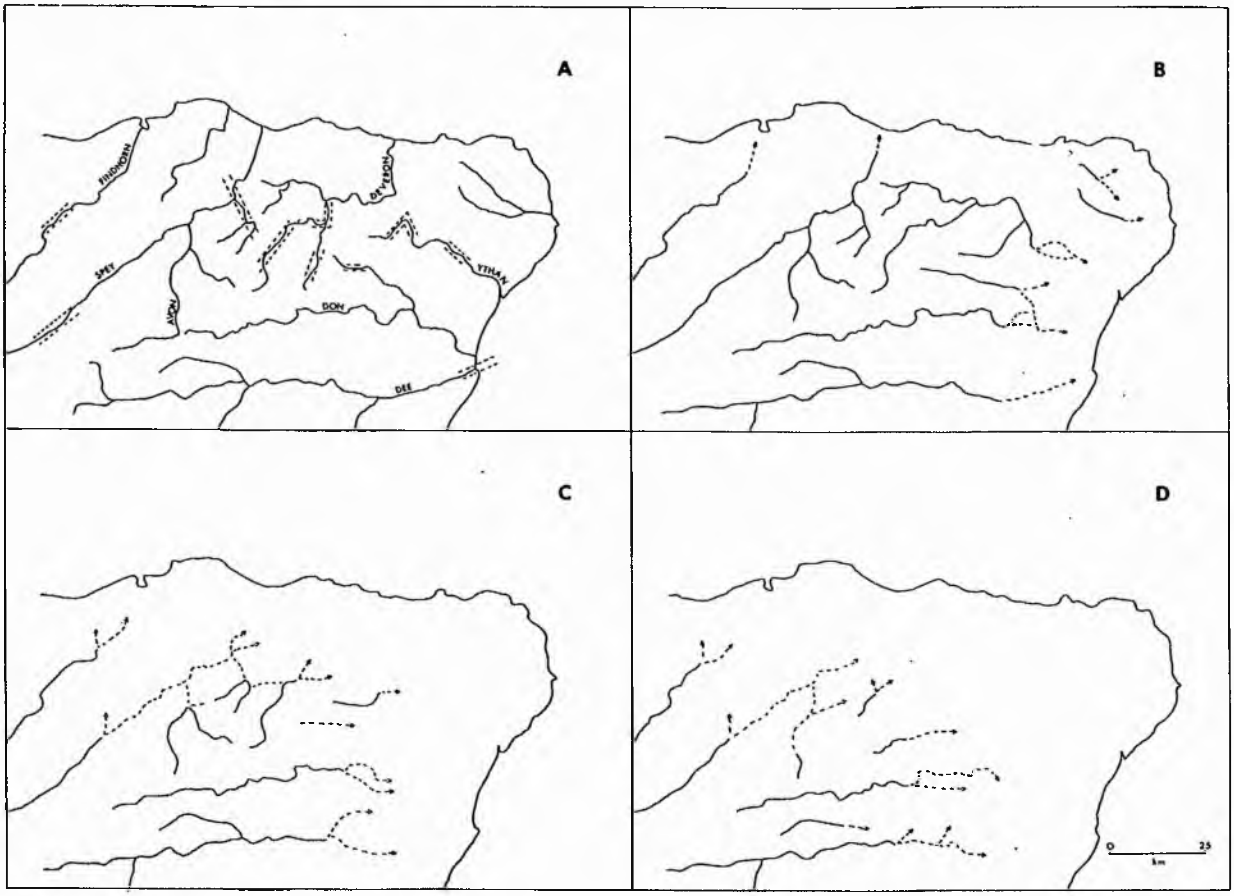

Fig. 14.2.ii. Sequential drainage development

A. Present drainage and structurally-aligned links B. Drainage of the Buchan Surface C. Drainage of the Marginal Surface D. Drainage of the Eastern Grampian Surface.

14.2.1 Superimposition, structural control and tectonic factors

Both Bremner and Linton recognised that the drainage of the Highlands was largely discordant with the dominant Caledonian structural trend. This discordance was seen as a result of superimposition from a former Upper Cretaceous cover and tilting of the exhumed sub-Cenomanian peneplain towards the North Sea in the early Tertiary. However it was shown earlier, following George (1966), that the bulk of the Highlands remained a positive area throughout the Upper Cretaceous and that only marginal transgression took place. Indeed the composition of Mesozoic and later Palaeozoic sediments on the edges of the basement indicates that large parts of the Highlands were last submerged in the Dalradian (Owen 1978). The drainage of the Highlands has evolved continuously through the Mesozoic and Cenozoic and the concept of superimposition onto an emergent surface must be rejected.

However the suggestion that the Highland Block was tilted towards the east in the Tertiary has been confirmed (see Chapter 3) and the drainage pattern can be largely explained by the persistance of styles of tectonic movement over very long time periods. Tilting of the Highlands towards the North Sea Basin occurred repeatedly in the Tertiary and probably originated in the Mesozoic. Similarly the comparatively recent differential movements between the Moray Firth Basin and the surrounding basement are the latest expression of a dominant pattern of movement extending back possibly to the Devonian. The importance of W-E links in the drainage of the eastern Grampians and the centripetal drainage into the Moray Firth further north can be seen as representing adjustment to tectonically-induced regional gradients over periods of 10^7 or even 10^8 yr.

In north-east Scotland, the dominance of W-E drainage links was seen by Bremner (1942) and Linton (1951) as part of the more general disregard of the Highland drainage for Caledonian SW-NE structural trends. However recent work suggests that the drainage is more accordant with structure than was previously realised (Fig. 14.2.ii). In particular, a series of W-E fractures have been recognised in the Moray Firth Basin (Chesher and Bacon 1975), the Insch Mass (Read 1956) and along the lower Dee valley and fracturing along these trends may be of regional importance (Ashcroft and Munro 1978 and see Section 2.4). Elsewhere major shears guide the upper Deveron (Fettes 1968; 1970) and the middle Ythan (Farquhar 1950) and the courses of the middle Findhorn and Spey and the Bogie follow local faults. The frequent sub-parallel alignment of fractures and drainage links suggests that many portions of the network have been fixed in their courses over long time periods.

However the recognition of greater structural accordance does not explain why W-E links should be so prominent in the drainage network. Caledonian structural trends are strong throughout north-east Scotland but are under-represented by drainage link orientation. Regional tilting is probably a significant factor underlying this pattern but the potential significance of superimposition must also be considered in view of the evidence for formerly extensive sedimentary covers in the region.

The number and wide distribution of Old Red Sandstone outliers convinced Bremner (1942) that the regional drainage was superimposed from a cover of these rocks. However the composition of the Middle

Old Red Sandstone shows that much of the basement was never buried and contemporary sedimentation was confined to valleys and depressions set within accidented relief. However around the lower Strath Spey area, the Old Red Sandstone was probably more continuous, for several valleys contain patches of Old Red sediments (Fig. 11.2.i) and were occupied by Devonian rivers exploiting Caledonian structures. The present courses of the lower Findhorn, the middle Avon and upper Strath Isla are largely products of superimposition and other sub-parallel streams in this area now flowing across crystalline rocks may also have re-excavated Devonian valleys (Hinxman and Wilson 1902). Elsewhere sedimentation was localised and the major rivers draining eastwards to the North Sea cross basement areas never covered by the Old Red Sandstone. Only the Bogie and upper Ythan valleys follow down-faulted troughs of Devonian rocks and the Don completely disregards the corridor provided by the Rhynie Old Red Sandstone basin. Superimposition from the Old Red is therefore of considerable local importance but is not a major factor in the development of the regional drainage network.

Although the concepts that the drainage of the Highlands has been superimposed from Mesozoic (Sissons 1967; 1976) or Cretaceous (Linton 1951) covers must be rejected due to lack of evidence for such covers (King 1962; Godard 1965; George 1965; 1966; Morton 1979), the survival of Chalk flints and silicified Greensand in the Buchan Gravels means that the possibility of drainage superimposition from the Cretaceous must still be considered in north-east Scotland. There is no sign that Cretaceous rocks originally extended far to the west of Buchan (Section 10.5) and drainage in areas west of the

Bennachie-Fare Fracture almost certainly evolved within basement terrain during the Tertiary. However superimposition of the lower courses of the main rivers on the Formartine Block remains feasible, as the Cretaceous sea may have transgressed across much of this area. Yet even here there are few indications of any links between drainage and former sedimentary covers. The Buchan Ridge gravels rest on fragments of a Miocene landsurface which retains no in situ Cretaceous material and Cretaceous sediments probably disappeared during the Palaeogene. Any superimposed drainage had most, if not all of the Neogene to re-adjust to basement structures and the courses of the middle Ythan and lower Don are now aligned along major fractures. Other drainage links may not have been established much before the Pleistocene, for the lower Ythan has migrated well to the south since deposition of the Buchan Ridge gravels and the numerous wind gaps along the lower Dee and Don valleys indicate that these rivers may have followed very different courses prior to incision (Bremner 1912; 1921; Walton 1963). It must be concluded that drainage routes in the lowlands are largely of Neogene origin and no trace of any Cretaceous inheritance can be recognised.

Several striking examples of local structural discordance occur where evidence of superimposition from sedimentary covers is absent. Examples include the passage of the middle Deveron through the Craigbourach Moss-Fourman Hill ridge, the course of the Don through the Bennachie-Correen Hills plateau and the manner in which the middle Isla and Deveron run parallel to the Moray Firth coast without exploiting the potential SW-NE lines of weakness provided by the Knock and Portsoy basic intrusions and the Drumblade-Aberchirder shear. These discordant links appear to be a product of differential tectonic movements. The incision of the Don gorge reflects horst-like uplift of the Bennachie-Fare granites relative to the Skene lowlands, probably in the Neogene. The deep valley of the lower Spey also related partly to late Tertiary uplift of the Marginal Surface. The behaviour of the Isla-Deveron drainage suggests that this latest differential movement between the basement and the Moray Firth Basin has involved a component of southerly tilt. Such movement would help to explain the former continuation of the Deveron drainage southeastwards into the Ythan system, a preglacial connection demonstrated by the composition of the Buchan Gravels (Kesel and Gemmell 1981).

14.2.2 The sequential development of the drainage network

A major criticism of earlier reconstructions is that they refer to drainage on some unspecified preglacial landsurface. The drainage is shown passing through cols at a wide range of elevations and the reconstructions include links of different age. Moreover several proposed W-E links, such as those between the Spey and Isla and the Deveron and Ugie (Fig. 14.2.i),are at variance with available geomorphic evidence and appear to have been dictated by rigid adherence to a regional model of subparallel drainage lines. However many of the observations about valley form, misfit valleys, wind gaps and drainage diversion made by early workers (Hinxman 1901; 1907; Bremner 1912; 1919; 1921; 1942; Linton 1949; 1954) remain valid and provide a basis from which to trace drainage evolution.

The sequential development of the drainage network can be reconstructed using evidence of abandoned drainage links. Topographic corridors, underfit streams and wind gaps are found at many levels in the landscape and their elevation gives an indication of age relative to the main relief forms. In order to relate drainage evolution to the principal phases of relief development, the drainage network is reconstructed for periods during formation of the Buchan, Marginal and Eastern Grampian Surfaces.

A. Drainage during development of the Buchan Surface

The drainage of the Buchan Surface can be reconstructed by considering the extent of Pleistocene glacial and fluvioglacial modification of the drainage network. Two main types of modification can be observed:- (i) Diversion - due to glacial and fluvioglacial erosion and (ii) Incision - in response to periodically lowered base levels and high meltwater discharges.

Examples of glacial diversion are uncommon and confined to the Cairngorm Mountains and to the high ground south of the Dee. Glacial breaching of drainage divides has lead to substantial losses of mountain catchment areas from the Don and Dee systems. The Don has been truncated by loss of headwaters in the Cairngorms to the Avon (Bremner 1921; Linton 1954). The drainage area of the Dee has also been significantly reduced with diversion of its upper tributaries into the Feshie (Bremner 1912; Linton 1949) and the loss of the major Tarf Water tributary to the Bruar Water and Tilt (Bremner 1919).

Fluvioglacial activity has remodelled the pattern of tributary drainage in many areas (Clapperton and Sugden 1977). However the main routes of the present network were established before glaciation and maintained their courses through the Pleistocene. Perhaps the most significant change was the severance of the link between the Ythan and Deveron systems. The Buchan Gravels at Windyhills contain heavy minerals and quartzite originating in the drainage basin of the Deveron (see Chapter 10). The former link between the systems lay along the line of the Towie meltwater channel and is marked by a continuous valley bench at around 120m. Diversion of the Deveron drainage into the Moray Firth was probably a result of fluvioglacial erosion associated with ice retreat into the Moray Firth (Peacock 1971).

The drainage area of the Urie has also been substantially reduced since the development of the Buchan Surface, with loss of headwaters to the Bogie. The floor of the eastern part of the Insch depression slopes gently eastwards but drops sharply to the Strathbogie corridor. The tributaries of the Bogie have yet to dissect the Clatt Level (Fig. 13.2.ii) or the floor of the Kirkney basin, 5km to the west. The limited dissection indicates that the Bogie is a comparatively recent development in the drainage pattern, produced by capture of easterly-flowing drainage after lowering of the Old Red lavas of the Gartly Gap.

Evidence of Pleistocene incision below the Buchan Surface is ubiquitous. Large amounts of fluvioglacial and glaciolacustrine sediments infill rock-cut channels descending below O.D. in the lower courses of the Dee, Don, Ythan and Ugie Water (Gemmell 1975;

Peacock et al 1977). A rock channel at the mouth of the Spey extends more than 25m below accumulations of glacial, fluvioglacial and channel-fill deposits to at least-12 O.D. (Aitken et al 1979). Inland, the channels of the main rivers are incised below broad valley benches associated with the Buchan Surface (Fig. 12.7.i). The Ythan gorge at Gight has been incised by more than 50m since deposition of the Windyhills gravels and valley benches and perched basin floors along the Deveron, Ugie and Don indicate Pleistocene valley deepening by 40 to 70m.

The reconstructed drainage of the Buchan Surface (Fig. 14.2.ii) shows that the upper and middle Deveron was established in its present course, although the river probably followed the Drumblade Shear Zone rather than the more circuitous route it now uses around Fourman Hill. The Deveron then joined the Ythan system around Turriff and flowed towards the North Sea. The presence of Banffshire quartzites in the Buchan Ridge gravels (Kesel and Gemmell 1981) suggests that this major river migrated across large areas of Buchan before becoming fixed in a Fyvie-Ellon valley.

The Don was a substantially larger river at this time, receiving drainage from headwaters in the Cairngorms and from an enlarged Urie system. The behaviour of the Don after leaving the gorge section at Monymusk is in doubt.

The Dee has lost a large part of its mountain catchment area by glacial diversion (Bremner 1912; Linton 1949). The river followed its present course at least as far east as Banchory and probably continued along the same fault zone which now guides its route to the coast.

B. Drainage during development of the Marginal Surface

The drainage pattern of the Marginal surface can be reconstructed with some confidence (Fig. 14.2.ii). The Dee valley contains no cols below 300m west of Lumphanan and the river followed its present course, with a possible deviation to the north of the Hill of Fare via the gap occupied by the degraded basin at Tornaveen (Walton 1963). Benches around 240m in the Alford basin suggest that the Don also flowed along the same route as today, west of Bennachie. The col at 250m at Tillyfourie, above the notch of a large meltwater channel, may represent the former drainage outlet of the Don from the basin (Bremner 1921). Drainage of the Insch depression was eastwards but benches above 300m along the upper Deveron valley (Fig. 11.9.iii) show that the Cabrach basin already drained towards the NE. Exploitation of intersecting structures by glacial erosion obscures the former river pattern N and E of the Ladder Hills. The series of embayments with floors above 300m along the Spey valley demonstrate that the Spey was already a substantial river, with headwaters extending far to the west. The Spey may have turned northwards at Lochindorb but the prominent valley benches at Knockando (Hinxman 1901; Bremner 1939 and Fig. 11.9.iv) indicate that the river followed its present route at least as far north as Rothes.

C. Drainage during development of the Eastern Grampian Surface

Evidence for drainage associated with the Eastern Grampian Surface is confined to areas around the Cairngorms. There are few alternative drainage routes available to the Dee, Don, Spey and Findhorn above 600m and the upper reaches of these rivers almost certainly flowed within their present valleys. Drainage of the Cabrach hills was probably to the east along the line now occupied by the Insch depression.

Holgate (1969) has suggested that the headwaters of the Findhorn and Spey lay across the Great Glen Fault prior to sinistral movement in the early Eocene. However the cross-valleys identified by Holgate were most unlikely to have been in existence so soon after injection of the dyke swarms. The valleys were probably opened out much later along sub-parallel fractures displaced by sinistral faulting.

14.2.3 Summary of drainage evolution

The reconstruction of the sequential development of the drainage network emphasises the continuity of valley occupation. The upper courses of the main rivers have been fixed in their present valleys since formation of the Eastern Grampian Surface. The rivers of the lowlands have migrated more freely but many drainage links are now aligned along fracture zones. The dominant influence over regional drainage evolution has been the repeated tilting of the Highlands towards the North Sea. Superimposition from the Old Red Sandstone is locally significant but no trace of drainage inheritance from the Cretaceous is evident. Parts of the drainage network reflect late Tertiary differential tectonic movements and uplift along the Moray Firth border has caused southward diversion of drainage.

14.3 Denudation Chronology I : Palaeogene Geomorphic Evolution

14.3.1 Types of evidence

Much of the available information bearing on the denudation chronology of north-east Scotland is fragmentary and involves difficulties of interpretation. However by combining information from a variety of sources, including morphology, onshore and offshore geology, weathering types and the Buchan Gravels, it is possible to gain an accurate, if somewhat generalised picture of the long-term geomorphic evolution of the region.

The bulk of previous work on the geomorphic evolution of the Scottish Highlands has been based largely on morphological evidence (Fleet 1938; Bremner 1942; Linton 1951; Walton 1963; Godard 1965) and this approach can also be profitably applied in north-east Scotland. Yet although morphological analysis is of considerable benefit in the identification of the principal stages of relief development, it provides evidence only of the relative age of the major landforms. This problem of dating is exacerbated by the absence of post-Jurassic rocks onshore, although important statements can be made about the level of Cenozoic denudation based on the distributions of Old Red outliers and flint residues. The paucity of the onshore record is, however, offset to some extent by increasing knowledge of offshore Tertiary sequences. The sediments of the North Sea Basin provide evidence of a series of major tectonic and palaeoclimatic events affecting north-west Europe in the Cenozoic and give indirect information about styles of weathering and rates of denudation on surrounding land areas (Chapter 3). However there are difficulties involved in relating these regional events to particular problems of relief development in north-east Scotland. The only local information about the age of the regional relief is that provided by the weathering types and by the Buchan Gravels and this evidence is specific to certain limited areas and refers solely to the later Tertiary history. As a result, the denudation chronology of the Palaeogene and Neogene tends to be reconstructed from rather different types of evidence, with the main Palaeogene geomorphic events inferred from the offshore record and with the Neogene chronology more firmly based on local morphological and geological evidence.

14.3.2 The end-Cretaceous landsurface

At the close of the Cretaceous, the landsurface of north-east Scotland was probably one of low relief, rising gently westward. The Cenomanian sea transgressed into the Buchan area and may have spread more widely across the Formartine Block but the bulk of the Grampian High was not submerged (Morton 1979). Elsewhere in north-west Europe, the Chalk overstepped on to deeply-weathered and planed basement surfaces (Lidmar-Bergstrom 1982) and the purity of the Chalk in the Moray Firth Basin demonstrates that the Highlands was an area of subdued relief in the Late Cretaceous. Beyond the limits of the Cretaceous transgression, the dominance of biostatic conditions (Erhart 1955), with warm climates (Bakker and Levelt 1964) and limited tectonic activity (Ziegler 1981) will have lead to continued base-levelling. Marine regression in the early Palaeogene (Ziegler 1982) probably left an extensive peneplain in north-east Scotland. In the west, this end-Cretaceous surface will have comprised an etchplain developed across crystalline rocks and localised areas of Old Red Sandstone. The etchplain merged eastwards with a marine-trimmed sub-Cenomanian surface and then with surfaces bevelled across the newly-emergent Chalk.

14.3.3 Geomorphic effects of early Palaeogene earth movements

In western Scotland, the sub-Cenomanian and end-Cretaceous surfaces were completely remodelled during the early Palaeogene earth movements (Godard 1965; George 1966; 1974). The highest of a staircase of erosional levels now truncates intrusive and volcanic rocks of Palaeocene to Early Eocene age and these rocks provide a firm datum for the commencement of relief development in these areas.

Although no rocks of comparable age occur in the eastern Highlands, this datum has been widely adopted as the starting point for geomorphic evolution in the Highlands as a whole (King 1962; Godard 1965; George 1966; 1974; Sissons 1967; 1976). Yet this extrapolation involves certain untested assumptions about regional tectonic history. In particular, the view that uplift of the Highlands in the early Tertiary took place by some form of arching (Linton 1951; King 1962; George 1966; Owen 1978) must now be rejected in the light of offshore evidence. The pattern of Palaeocene deposition in the central North Sea indicates instead that the Highlands were tilted, with the main axis of movement lying towards the west and north-west (Knox et al 1981), and this style of movement was probably repeated in the more modest phase of uplift at the end of the Palaeogene. The dominance of tilting in movements of the Highland area in the early Tertiary is of considerable geomorphic significance, for the western summit surfaces need no longer be regarded as equivalent in age to the highest relief in the Eastern Grampians. Moreover relief found at low elevations close to the hinge-line of tilt along the edge of the North Sea Basin may be of similar antiquity to that carried to considerable altitudes in the west.

It is also becoming clear that Palaeogene uplift involved major differential movements (Knox et al 1981). In north-east Scotland, considerable differential movements are indicated by the middle (?) Palaeocene activity along the Banff and Highland Boundary Faults (Heybroek et al 1967; Evans et al 1981; Ziegler 1982). Subsidence of the Moray Firth Basin was synchronous with uplift of the Western Highlands (Knox in discussion of Rochow 1981) and proximity to this rapidly subsiding basin appears to have lead to downwarping of the Formartine Block to the north-east. These opposing movements continued into the Early Eocene when the inner Moray Firth area was uplifted at the same time as the Western Highlands had begun to subside (Threlfall 1981; Ziegler 1981). The pattern of differential movement is strongly reminiscent of that found later in the Tertiary and implies that the Bennachie-Fare Fracture was already in existence.

The recognition that tilting and downwarping may have combined to maintain parts of north-east Scotland close to base-level during the early Palaeogene earth movements means that the fate of the end-Cretaceous relief requires reassessment. Upper Cretaceous rocks escaped erosion in areas downwarped towards the Moray Firth and major denudation of the Chalk and release of flints probably began after uplift of areas bordering the Moray Firth in the Early Eocene. The Formartine Block and the Moray Firth Border Zone remained close to base level and the earlier subdued relief was little modified. West of the Bennachie-Fare Fracture, however, the end-Cretaceous surface was probably more severely disrupted. As no major fractures are known to cut across the Caledonian trend between the Western Highlands and the Cairngorm area, it can be assumed that the Grampians acted as a single structural unit during early Palaeogene uplift and that, even allowing for tilting, eastern parts of the Grampians were significantly raised. The reactivation of elements of Devonian positive relief, such as the Bennachie and Ben Rinnes granites, probably dates from this period and substantial local differential movements are implied. Uplift, dislocation and resultant denudation make it unlikely that any vestige of the end-Cretaceous surface survives in the Eastern Grampians (George 1966).

14.3.4 Later Palaeogene Events

The Middle Eocene saw the beginning of a long period lasting until the Middle Oligocene when tectonic and climatic conditions became highly favourable for levelling of the accidented early Palaeogene relief. The Highlands subsided after the Early Eocene and remained comparatively stable for the next 10 m.y. (Ziegler 1981). Major marine transgressions occurred in the Eocene in western Scotland (Inst. Geol. Sci. 1981) and around the North Sea Basin (Ziegler 1982). Eocene climates were similar to those in the contemporary humid tropics, although temperatures dropped abruptly at the Oligocene boundary (Daley 1972; Buchardt 1978). These conditions of tectonic stability combined with warm and humid climates approach the optimum for etching and levelling of relief (Erhart 1955; Fairbridge and Finkl 1980; Lidmar-Bergstrom 1982) and substantial reduction of the Highland relief can be inferred.

Direct evidence for regional planation after the Early Eocene comes from the North Sea Basin, where there was a major reduction in rates of sedimentation (Walmsley 1975) and a switch to fine-grained deposition (Sutter 1980; Ziegler 1981). Deep weathering and etching of relief around the North Atlantic in the Eocene is evidenced by the widespread development of latosols (Nilsen and Kerr 1978) and formation of siallitic saprolites in the Scottish area is shown by the increase in kaolinite contents in North Sea sediments (Karllson et al 1979). The Middle Eocene to Middle Oligocene interval saw development of etchplains throughout north-west Europe (Millot 1970; Budel 1977; 1982; Peulvast 1978; Battiau-Queney 1978; Lidmar-Bergstrom 1982) and this period marks the starting point for the geomorphic evolution of much of the Scottish Highlands.

Widespread levelling almost certainly occurred in north-east Scotland in the middle Palaeogene period. Subsidence of the Grampian area (Ziegler 1981) and uplift of regions bordering the Moray Firth in the Early Eocene (Threlfall 1981) will have reduced and perhaps nullified the earlier height differences between the Cairngorms and Formartine Blocks. In the west, the accidented and tilted early Palaeogene relief was levelled to a position well below that of the end-Cretaceous plain and isolation of a central area of residual relief, now represented by the Cairngorm Massif, may have begun. On the Formartine Block, the Chalk was exposed and substantially denuded and stripping of Old Red Sandstone lead to the exhumation of restricted areas of basement terrain, possibly including the Insch depression. The lower courses of the main rivers were let down on to a crystalline floor and began to adjust to local structures. Intense etching during a prolonged period of tectonic stability allowed the development of a single erosion surface across much of north-east Scotland : the Mid-Palaeogene Surface.

This regional etchplain was composed of various diachronous elements. West of the Bennachie-Fare Fracture, no part of the end-Cretaceous surface survived and the new etchplain developed without significant inheritance. In the east, however, denudation exposed areas of sub-Devonian and sub-Cenomanian topography and fragments of the end-Cretaceous basement etchplain were further lowered. The precise form of this composite surface is unknown, for the present relief stands tens or perhaps hundreds of metres below its former level. However the Mid-Palaeogene Surface can be regarded as the master surface from which have evolved the stepped erosion surfaces which now dominate the relief.

14.4 Denudation Chronology II : Neogene Geomorphic Evolution

In the reconstruction of Neogene denudation chronology, the reliance on inferences about regional geomorphic events drawn from the offshore record is reduced. Although the North Sea Basin remains an important source of information about tectonic movements and climatic change, evidence of landscape evolution is increasingly provided by the local morphology and by its associated sediments and weathering covers. It becomes possible to build up a fairly detailed picture of the development of the lowland terrain, allowing correlations to be made with the principal stages in the evolution of the highland relief established earlier (Section 11.11).

14.4.1 Effects of Late Oligocene to Early Miocene Uplift

In western Scotland and the Shetland area, uplift was resumed in the Middle Oligocene (Smythe and Kenolty 1975; Ziegler 1982). These local movements culminated in a phase of regional tectonic activity in the Late Oligocene and Early Miocene (Morner 1980). The continuance of fine-grained sedimentation in parts of the central North Sea (Pegrum et al 1975) indicates that uplift was on a more modest scale than in the Early Palaeogene and evidence of marine transgression later in the Miocene off north-west Scotland (Evans et al 1981) suggests that tectonic activity was short-lived. In north-east Scotland, the phase of uplift around 22Ma represents the first of two main stages in the dislocation and remodelling of the Mid-Palaeogene Surface.

Although the main axis of uplift lay once again to the W and NW, the style of movement of the Highland area is less certain than in the Palaeocene. In north-east Scotland, the pattern of uplift west of the Bennachie-Fare Fracture can be judged from the relationships between the Eastern Grampian Surface, the lowered derivative of the Mid-Palaeogene Surface, and the Marginal Surface, the surface which developed around its margins after this phase of uplift. The height difference between the two surfaces is 150-200m around the lower Spey valley and c. 200m in the basins along the middle Don and Dee and movement by at least this magnitude is indicated. The style of movement is shown by the gradient of the Eastern Grampian Surface. This surface has a gradient towards the north of c. 7m/km north of the Cairngorms and c. 6m/km on the Monadhliath. East of Lochnagar, the surface slopes at c. 5m/km towards the Highland Boundary Fault. These gradients indicate that uplift of the Mid-Palaeogene Surface in western areas involved tilting towards the Moray Firth in the north and towards the North Sea in the east. However there was only limited movement of the Formartine Block at this time. Along the Moray Firth border, the Marginal Surface was initiated close to base-level yet has a similar elevation, relative to the Eastern Grampian Surface, as the benches and former basin floors west of the Bennachie-Fare Fracture which were formerly graded to the Marginal Surface in the Skene lowlands. Reactivation of this fracture can be inferred and uplift of the eastern lowlands was modest.

These differential movements lead to major differences in the pattern of modification of the Mid-Palaeogene Surface. Towards the North Sea coast, the earlier surface was lowered and may not have been greatly disrupted, although some removal and redistribution of siallitic regoliths must have occurred. Along the inner Moray Firth border, a new level was initiated which was to replace the northern margin of the Mid-Palaeogene Surface. In the Eastern Grampians, however, modification of the Surface was delayed. Remoteness from regional base levels will have restricted, at first, the effects of uplift to areas along the main drainage lines. Many of the major basins originated during this period and the main rivers became entrenched in earlier generations of their present valleys. With time, however, the Mid-Palaeogene Surface came to be substantially lowered, although the maintenance of its subdued form was ensured by the importance of local base levels.

14.4.2 Levelling in the middle Miocene

Parts of western Scotland subsided after the early Miocene and broadly synchronous subsidence of eastern basement areas is indicated by the overstep of Neogene sediments on to the offshore continuation of the Grampian High (Evans et al 1981). In north-west Europe, climatic conditions returned to subtropical levels in the Middle Miocene (Sudijono 1975; Buchardt 1978). Siallitic weathering profiles developed widely under warm and humid environments (Bakker and Levelt 1964) and kaolinite contents rose again in North Sea sediments (Karllson et al 1979; Berstad and Dypvik 1982). Biostatic conditions were re-established throughout the region (Lidmar-Bergstrom 1982) and the middle Miocene marks the second major period of Tertiary base-levelling in the Highlands.

The main erosion surfaces of north-east Scotland began to take on their present form in the long middle Miocene period. West of the Bennachie-Fare fault scarp, areas of low relief inherited from the Mid-Palaeogene Surface were further reduced by etchplanation. Higher surfaces were gradually replaced by lowering and wearing back to give a complex surface with interdigitating local levels, of which the Eastern Grampian Surface is the pared-down equivalent. Along its inner margin, the elevated peneplain was extended by scarp retreat and basin enlargement to produce a mountain front against the Cairngorm Massif. The major hills rising out of the peneplain were emphasised by lowering of surrounding terrain but isolation of these residual features probably dates from the Palaeogene. The lower storey of relief initiated during the preceding phase of uplift continued to encroach on the evolving highland etchplain. Along the main drainage lines, basins and valleys were widened and deepened, with new floors graded to developing surfaces in the eastern lowlands. Many basin floors probably reached their maximum extent during this period and have since contracted (Section 12.6).

Along the coast of the inner Moray Firth, the uplifted and tilted Mid-Palaeogene Surface was transformed. A new surface, the Marginal Surface, was extended southwards by the same processes of scarp retreat, valley widening and basin enlargement which were simultaneously moulding the terrain of more elevated areas inland. Around the lower Spey valley area, an irregular sub-Devonian surface was progressively levelled as it emerged from beneath a wasting Old Red Sandstone cover. Inland and particularly along the proto-Spey valley, basins initiated during end-Palaeogene uplift were deepened. Prolonged levelling over a period of some 10 m.y. allowed basin and embayment floors stretching almost to the main Highland watershed to become graded to the developing coastal surface.

The scattered occurrences of the clayey gruss weathering type in the lowlands probably represent the basal zones of Miocene weathering profiles (see Chapter 9). The survival of these kaolinitic saprolites indicates that the gross form of the lowlands is inherited from the Miocene and that little-modified elements of Miocene relief may survive in central Buchan. However only restricted areas of residual relief can be recognised and elsewhere lowering has obscured the form of the Middle Miocene terrain.

Yet there is little doubt that the lowland landsurface during this period was one of low relief. The Mid-Palaeogene etchplain was not greatly disrupted in eastern areas during the subsequent tectonic phase due to the limited degree of movement of the Formartine Block. In the Middle Miocene, this moderately-dissected relief was again subjected to intense etch-processes and all remnants of Cretaceous sediments were finally removed. The clayey grusses give evidence of mobilisation of iron and silica and their development in quartzitic parent rocks demonstrates that deep weathering affected all but the most resistant lithologies. Pervasive weathering coupled with modest rates of long-term surface lowering did not favour the emergence of major landforms of resistance and a rolling landscape subtly-adjusted to complex geology gradually developed. The earlier etchsurface was re-levelled and a Middle Miocene etchplain, surmounted by only occasional residual masses such as Mormond Hill and Brimmond Hill, was extended across eastern areas.

14.4.3 Relief development in the late Neogene

There is widespread evidence of renewed tectonic activity in north-west Europe after the Middle Miocene. Subsidence of the North Sea Basin accelerated and sediment inputs increased (Clarke 1973). In southern Britain, vertical movements of the order of several hundreds of metres occurred, causing major dislocation of Palaeogene relief (Walsh et al 1972; George 1974; Battiau-Queney 1978; Reffay et al 1982). Uplift of Fennoscandia continued

(Ziegler 1982) and weathering products stripped from shield areas around the Baltic were transported southwards to the eastern edge of the North Sea Basin (Bijlsma 1981). The scale of Neogene denudation indicated by the volume of offshore sediments (see Section 3.5) and the importance of stepped erosion surfaces and topographic basins in the landscape of the Highlands suggests that tectonic activity also affected the Scottish area, although the timing and pattern of uplift is uncertain (George 1966; Owen 1978).

Major changes in climate also occurred towards the end of the Miocene. Temperatures dropped sharply in the sea surrounding northern Britain and did not return to the subtropical levels attained in the Middle Miocene (Poore and Berggren 1975; Buchardt 1978). On land, humid temperate environments prevailed throughout the late Neogene, although frequent cold-warm oscillations became increasingly severe towards the Pleistocene boundary (van der Hammen 1971). Climatic cooling brought a fundamental shift in styles of weathering in north-west Europe. The combination of regional tectonic activity and climatic change promoted the stripping of earlier siallitic saprolites and their replacement by deep weathering profiles containing significant proportions of detrital felspar and biotite (Bakker and Levelt 1964; Esteouelle-Choux 1967). The growing immaturity of regoliths is reflected in the mineralogy of North Sea sediments by increases in the contents of less stable clay minerals (Karllson et al 1979; Berstad and Dypvik 1982).

In north-east Scotland, the late Neogene was a period of renewed tectonic activity. Movement along the fractures bounding the main structural blocks recurred but styles of movement differed slightly from earlier tectonic episodes. Reactivation of the Banff Fault caused major dislocation in the inner Moray Firth area, with uplift of the Marginal Surface relative to the adjacent sedimentary basin by at least 300m. Along the southern border of the Moray Firth, a series of small horsts developed and formed a raised rim to the basin which subsequently greatly retarded the southward penetration of the Buchan Surface and which probably produced diversion of the proto-Isla-Deveron-Ythan drainage. The Marginal Surface has an easterly gradient of c. 2m/km east of the Spey but the likely correlation of this surface with the Grampian Valley Benches (Fleet 1938) in the Great Glen (Linton 1951; Walton 1963) indicates that the Middle Miocene etchplain was warped, rather than tilted towards the North Sea. Moreover the elevations of embayment floors along the Spey valley graded to the Marginal Surface fall by only 110m in 90km and tilting towards the Moray Firth was negligible.

The Eastern Grampian Surface was further uplifted but, in contrast with earlier episodes, substantial movement of the Formartine Block also occurred. In the Dee and Don basins, benches at c. 250m graded to the Marginal Surface stand only 100m above later basin floors graded to the Buchan Surface. As the area west of the Bennachie-Fare Fracture must have been raised with the Marginal Surface in the north, it can be suggested that the Skene area was uplifted by at least 150m. This general figure is confirmed by reference to the present topographic position of the Buchan Ridge Formation. Even in this relatively down-warped eastern area, the gravels have been uplifted by c. 100m since deposition in the late Miocene or early Pliocene.

In the lowlands, the Middle Miocene etchplain was slowly replaced by a new level, the Buchan Surface, whose form and structural relationships reflect the pattern of uplift of the earlier surface. Towards the North Sea coast, easterly warping contrived to minimise the impact of late Neogene tectonic activity. The subdued form of the Middle Miocene etchplain was maintained during gradual lowering and the new level was extended across rocks of highly variable resistance. However along the Moray Firth coast, warping lead to a progressive westerly divergence between the two surfaces. In northern Banffshire, the pared-down and dissected Miocene plain is represented by accordant ridge tops bevelled across resistant metasediments. The Buchan Surface forms a separate topographic storey some 150m below these fragments and comprises compartments of levelling associated exclusively with weak rocks, mainly sheared basic igneous rocks. The contrasting structural relationships of the Buchan Surface in western and eastern parts of the lowlands is a reflection of differences in long-term rates of uplift and denudation and the planing of quartzitic rocks by an end-Tertiary surface in Buchan can be seen as an inherited characteristic.

Uplift of the Mounth and Cairngorm Blocks lead to further dissection of their eastern edges and extensive remnants of the Eastern Grampian Surface are now confined to areas west of Mount Battock and The Buck. The floors of certain inland basins, including the Tarland and Alford basins and the Insch depression, were lowered by around 100m in the period between initial uplift in the late Miocene and the onset of drainage incision in the

Pleistocene. Yet lowering was not accompanied by basin widening and encroachment on surrounding plateaux, as envisaged by Linton (1951). Instead many basin floors were reduced in area and became gradually confined to rocks of low resistance. In the cases of the Tornaveen and Cushnie basins, floor lowering failed to keep pace with drainage incision and the basin forms were severely modified (Section 12.6). Rapid incision by the drainage also prevented widening of valleys and allowed extensive fragments of the Eastern Grampian Surface to be maintained.

Renewal of uplift triggered stripping of middle Miocene weathering covers. Deep siallitic weathering profiles were progressively thinned and disappeared from many areas. Kaolin clays, quartz sand and vein quartz were released to join other resistant materials, notably flint and quartzite, which had been accumulating on the landsurface since the start of the Tertiary. These siliceous residues were concentrated by the drainage system and transported eastwards by rivers vigorous enough to entrain boulder-sized fragments. Remnants of these deposits are now represented by the Buchan Gravels.

In areas of modest uplift and areas remote from the main drainage lines, deeply weathered terrain was maintained during lowering. The clayey grusses were gradually replaced by less mature saprolites whose mineralogical characteristics reflected the lower prevailing temperatures. These grusses formed extensive weathering covers at all levels in the region and locally reached depths of 50m or more. Renewal of grusses occurred more or less continuously beneath a temperate forest cover, allowing the further etching of structural and lithological variations.

The Pliocene saw the emphasis of major pre-existing relief forms and the elaboration of meso-scale landforms. In many areas, surface lowering was balanced by renewal of regolith and the landscape evolved by dynamic etchplanation. The increasing selectivity of weathering lead to divergent patterns of weathering and erosion (Budel 1982). Shallow depressions formed in zones of weaker rocks, particularly biotite-bearing varieties, whilst areas underlain by resistant lithologies, notably quartzites and migmatites, became more prominent and the relief in general became more compartmented. However because patterns of local denudation differed according to location relative to the drainage network, the landscape remained only crudely adjusted to geology. The spatial variability of geomorphic activity was enhanced by rock barriers which retarded the stripping of basins of weathering. Along the watershed of central Buchan, fragments of the Middle Miocene etchplain capped by the Late Miocene-Early Pliocene flint gravels survived with only limited modification.

Closer to the main drainage lines, the amount of surface lowering was more substantial. In Buchan, valley floors are preserved from at least two periods. The fluviatile Buchan Ridge Formation overlies one floor at between 100 and 140m (McMillan and Aitken 1981; Merritt 1981), whilst benches along the lower Ythan at c. 60m represent the valley floor prior to drainage incision in the Pleistocene. These height relationships indicate that parts of Buchan were lowered by 40 - 80m during the

Pliocene. Basin floors in northern Banffshire and west of the Skene lowlands have been lowered by 100 - 150m since formation of the Marginal Surface and it is clear that rates of denudation increased westwards across the tilted Miocene surface.

Continued deep weathering and steady removal of weathering products from a gently-rising landsurface lead to the development of the latest etchplain in the lowlands, the Buchan Surface. The relief of the etchplain was quite varied and consisted of multi-storey landscapes incorporating both landforms of position and landforms of resistance. The drainage migrated widely, leaving spreads of gravel which locally armoured the surface and eventually produced inversion of topography. The new level was extended westwards via the main drainage lines but became increasingly confined to zones of low resistance. The innermost representatives of the Buchan Surface are the graded floors of the basins and depressions along the middle courses of the Dee, Don and Deveron.

Similar kinds of relief modification were occurring simultaneously on the broad highland surfaces around the Cairngorms. Deep gruss covers developed widely and rates of surface lowering were probably similar to those in the lowlands. The Pliocene form of these surfaces has been obscured by glacial erosion but the presence of shallow basins and open tributary valleys suggests that etching lead to the development of landform assemblages comparable to those in the lowlands. However in areas closer to the major scarps bounding the highlands, drainage incision outspaced surface lowering and the Eastern Grampian Surface was further dissected.

Towards the end of the Pliocene, the increasing severity of climatic fluctuations brought major morphogenic changes. In north-west Europe, development of extensive bedrock levels had effectively ceased. The onset of cold environments promoted incision of drainage and episodic reduction of forest covers (Zagwijn 1960; van der Hammen et al 1971) lead to accelerated stripping of regolith (Budel 1977). In north-east Scotland, rates of weathering probably fell behind rates of denudation and weathering covers were reduced in many cases. Along the main valleys, entrenchment may have caused local exposure of the basal surface of weathering and thinning of saprolites elsewhere will have encouraged the emergence of tors and related features. However the basal surface cannot have been extensively exposed for thick grusses have survived quite widely. Moreover the incompletely-disaggregated transition zones at the base of many profiles will have resisted erosion and encouraged further granular disintegration. Yet although regeneration of grusses continued, the late Pliocene marks the beginning of a phase lasting throughout the Pleistocene when weathering covers were progressively thinned to expose basal etchsurfaces in many districts. The pattern and agents of relief modification in the Pleistocene are considered in the next Chapter.

14.5 Correlations with neighbouring areas

The alternating phases of biostasy and rhexistasy recorded in the offshore stratigraphy make it reasonable to search for regional correlations between major erosion surfaces. Optimal conditions for levelling occur when tectonic stability is combined with warm and humid climates to allow deep etching of bedrock surfaces

(Erhart 1955; Fairbridge and Finkl 1980). In the Scottish area, such conditions have prevailed during only two periods in the Tertiary, the middle Palaeogene and the middle Miocene, and the main surfaces in north-east Scotland are inherited from these biostatic intervals. As these were regional geomorphic events, broadly synchronous surfaces will have developed in many parts of the Highlands and examination of the extent, relative position and morphological characteristics of the surfaces should allow correlations to be made.

As the degree of surface modification will increase with age, correlations are most readily established between younger Tertiary levels. There are striking similarities between the latest surface in north-east Scotland, the Buchan Surface, and the Niveau Pliocene recognised by Godard (1965) in areas north of the Great Glen. Both surfaces are peripheral levels rising from around 60m at the coast to inner limits at 140m and 180m respectively. The surfaces have been extended via the main valleys and give way inland to graded basin floors developed across rocks of low resistance. The Niveau Pliocene retains pockets of saprolite whose mineralogy and granulometry is directly comparable to the gruss weathering type in north-east Scotland (Godard et al 1961; Godard 1965; Omand 1973; Zauyah 1976). From its morphology, structural relationships, weathering covers and soils, Godard (1965) concluded that the Niveau Pliocene formed by episodic stripping of immature regoliths under humid temperate environments. Their common characteristics leave little doubt that the Niveau Pliocene and the Buchan Surface are synchronous features marking a single phase of late Tertiary base-levelling.

The Grampian Valley Benches of Fleet (1938) have been correlated with the Marginal Surface (Linton 1951; Walton 1963) and can be traced from the Elgin area into and across the Great Glen. Inland, the latest floor of the Rannoch basin is at a similar elevation to embayment floors along the Spey valley and it is clear that an important phase of basin lowering has penetrated deep into the Grampians. In northern Scotland, Godard (1965) identifies an extensive surface at around 300m, the Surface Ecossaise, whose principal characteristics, namely a general indifference to geology and development of major basins far inland, recall those of the Marginal Surface. One significant contrast, however, is the far greater extent of the Surface Ecossaise but this can be explained by differences in the amount of uplift of earlier levels. It seems likely that the Grampian Valley Benches, the Grampian basins, the Surface Ecossaise and the Marginal Surface are of similar age and represent the prolonged phase of regional planation in the middle Miocene. These correlations indicate that uplift of the Highlands in the late Neogene was uncomplicated by differential movements,except for limited downwarping in eastern areas.

Correlations between higher surfaces are less certain. The Eastern Grampian Surface was linked by Linton (1951) with more elevated plateaux in the Monadhliath and the Gaick Forest. In this first area, the interdigitation between a lower relief, typically represented by the great linear depression of A'Chraidhlaig, and an upper relief of low rolling hills is certainly strongly reminiscent of the relationships between the Avon-Clova and Mounth Surfaces in their type areas. However a correlation between the Eastern Grampian and Gaick surfaces is less likely, even though a projection of the eastern level would pass not far above the western plateau (Linton 1951). The innermost representatives of the Eastern Grampian Surface are the broad benches in the former valley of the upper Dee and these features lie some 300m below the Gaick plateau. Moreover the perched floor of the Atholl basin can be traced from Glen Garry via benches south of Glas Maol to surfaces overlooking Glen Clova (Fleet 1938; Linton 1951) and the basin floor again stands some 350m beneath the adjacent plateau. The Atholl basin and its western continuation, the Rannoch basin, were probably opened out during the same period of regional base-levelling that produced the Eastern Grampian and Monadhlaith surface and the Gaick Plateau is best regarded as a separate level.

There is no obvious equivalent of the Eastern Grampian Surface at similar elevations north of the Great Glen. Godard (1965) notes a number of isolated fragments at between 610 and 700m but this surface is only of limited extent. More widely developed and standing immediately above the Surface Ecossaise is the Surface Intermediare, an etchsurface preferentially developed across granitoid rocks. The Surface Intermediare lies between 375 and 500m and significant differential movement across the Great Glen Fault would have to be admitted before a common age with the Eastern Grampian Surface could be accepted. However the more limited displacement of this surface would help to explain the relatively greater extent of its successor, the Surface Ecossaise, and it is suggested that the Eastern Grampian Surface and the Surface Intermediare are contemporaneous features.

The view that the highest summits of the Western Highlands and the Cairngorms form part of an upwarped master surface (Linton 1951; King 1962) must now be rejected. Tilting has been of such importance in the early Tertiary development of the Highland relief that any equivalent of the Cairngorm summit surface would have been carried well above the present altitude of the Western Highlands. The depths of sediments in the Oligocene basins of the Sea of the Hebrides (Smythe and Kenolty 1975) and the recognition of an important phase of uplift at the Oligo-Miocene boundary (Morner 1980) adds further weight to the conclusion of George (1966) that the scenery of the Western Highlands is wholly of Neogene age. In contrast, the emergence of an area of residual relief around the Cairngorms can be traced back to the middle Palaeogene and, although subsequent lowering has been considerable, the position of the massif towards the eastern edge of a repeatedly-tilted block has allowed prolonged inheritance of form.

These preliminary correlations can be used as a basis from which to consider the geomorphic evolution of the Highlands as a whole. Detailed work on long-term relief development in the Grampian area is urgently required and earlier studies need reassessment in the light of evidence for major Neogene differential earth movements in north-east Scotland. Nevertheless by combining study of major relief forms with the increasing information about regional geomorphic events coming from offshore, it should soon be possible to develop a far more precise understanding of the principal stages in the geomorphic evolution of the Scottish Highlands.

14.6 Summary of the geomorphic evolution of north-east Scotland

The geomorphic evolution of north-east Scotland through the Tertiary is summarised in Table 14.6.i and in a sequence of six schematic profiles extending SW-NE and W-E across the region (Fig. 14.6.i).

Upper Cretaceous

In the Upper Cretaceous, a transgressive sea deposited a cover of Greensand and Chalk on the Formartine Block. The eastern Grampian area was not submerged but was extensively levelled under the prevailing tropical climates. Marine regression in the early Palaeocene left a polygenetic peneplain, the end-Cretaceous Surface, incorporating, from west to east, a deeply-weathered etchplain, a marine-trimmed sub-Cenomanian surface and a depositional surface developed across the Chalk.

Palaeocene-Early Eocene

During the early Palaeogene tectonic phase, the Highlands were uplifted and tilted towards the North Sea, the Moray Firth Basin and the Midland Valley were downfaulted and important differential movements occurred in north-east Scotland. In the middle Palaeocene, the eastern Grampian area was substantially uplifted and the end-Cretaceous Surface was greatly disrupted. However regional tilting together with dislocation along a major fracture zone, the Bennachie-Fare Fracture, reduced the amount of displacement of the Formartine Block and the Buchan area was downwarped towards the outer Moray Firth. Exposure of the Chalk and modification of the end-Cretaceous Surface was delayed until the Early Eocene, when the directions of movement were reversed and the inner Moray Firth area was modestly uplifted.

m.y			PALAEO-CLIMATES	EASTERN GRAMPIANS	
2.5	PLIO-CENE	L	cool temp.		
		E	warm temp.		
5	MIO-CENE	L	cool temp.	uplift, tilt to E	Dissection extends E. Basin and valley deepening. Thick grusses form.
10		M	warm temp. to subtropical	stable	Etching and lowering of Mid-Palaeogene Surface. Basin and valley widening.
20		E	warm temp.	uplift, tilt to E.	Dissection. Basin initiation.
	OLIGO-CENE	L		stable	Extensive etching. Formation of Mid-Palaeogene Surface. Isolation of inselbergs and Cairngorm massif.
		M			
30		E	cool temp.		
	EOCENE	L	humid tropical		
40		M			
		E		subsidence	Destruction of End-Cretaceous Surface
50	PALAEO-CENE	L		major uplift, tilt to E	
		M			
60		E	warm		
70	CRETACEOUS			stable	Etching.

Table 14.6.1. Summary of
of the reli

NORTHERN GRAMPIANS		EASTERN LOWLANDS	
uplift, tilt to E.	Tectonic scarps develop. Basin deepening. Thick grusses form.	uplift	Dynamic etchplanation and development of Buchan Surface. Mobilisation of siliceous residues. Thick grusses form.
stable	Etching. Marginal Surface extended across sub-ORS relief. Basin and valley widening.	stable	Etching and extensive levelling. Resistant hills emerge. Clayey grusses form. Final removal of Chalk(?).
uplift, tilt to N.	Dissection. New level initiated.	minor uplift	Some stripping and lowering.
stable	Extensive etching. Formation of Mid-Palaeogene Surface. Isolation of inselbergs.	stable	Etching. Lowering of sub-Cenomanian and end-Cretaceous Surfaces.
subsidence	Destruction of End- Cretaceous Surface.	uplift	Conservation of End-Cretaceous Surface.
uplift, dislocation and tilt to NE		down-warping to NE	
stable	Etching	subsidence	marine transgression.

the main stages in the Tertiary evolution
ef in north-east Scotland.

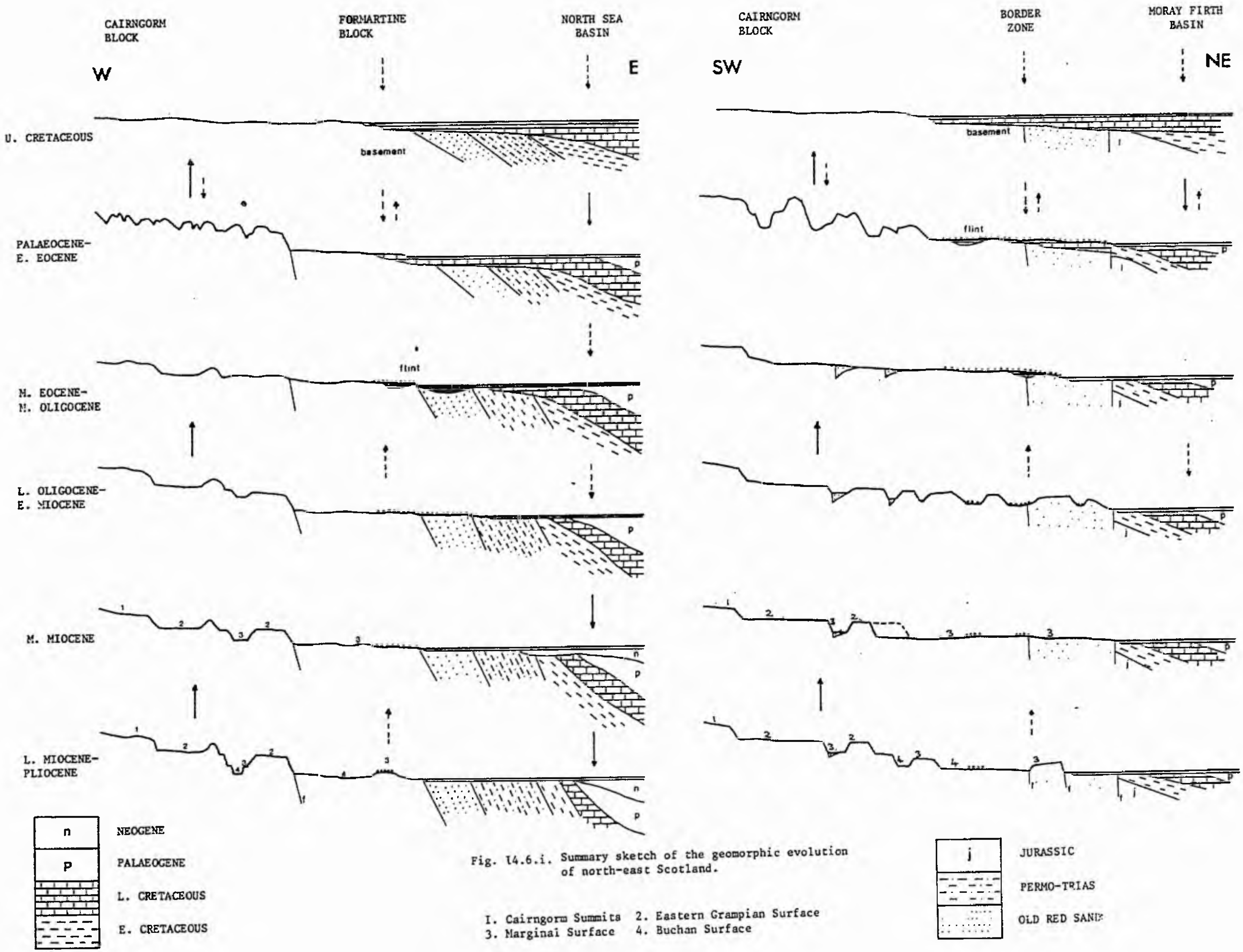

Fig. 14.6.i. Summary sketch of the geomorphic evolution of north-east Scotland.

1. Cairngorm Summits 2. Eastern Grampian Surface
3. Marginal Surface 4. Buchan Surface

Middle Eocene-Middle Oligocene

After the Early Eocene, the establishment of tectonic stability and tropical climates facilitated the development of a polygenetic etchplain of regional extent: the Mid-Palaeogene Surface. The eastern Grampian area had subsided and a new level was gradually extended across the earlier accidented relief. On the Formartine Block, elements of the sub-Cenomanian and sub-Devonian surfaces were exposed. The basement floor was etched and the smooth form of the end-Cretaceous Surface was maintained. Although the present topography stands well below its former level, the Mid-Palaeogene Surface represents the master surface from which the main erosion surfaces were subsequently derived.

Late Oligocene-Early Miocene

At the end of the Palaeogene, the Highlands were again uplifted and tilted towards the North Sea. The Mounth, Cairngorm and Monadhliath Blocks were raised by at least 200m but reactivation of the Bennachie-Fare Fracture lead to more limited displacement of eastern areas. Along the inner Moray Firth, a new level was initiated which subsequently consumed the mid-Palaeogene Surface. In the eastern Grampians, drainage incision and basin development began the dissection of the raised etchplain but in areas remote from drainage lines, the surface was lowered without major modification. Total denudation was also modest in relatively-stable eastern areas, although the final disappearance of the Chalk may date from this period.

Middle Miocene

After the Early Miocene, the Scottish area remained relatively stable for a period of around 10 m.y. and climates returned to subtropical levels. In north-east Scotland, the Middle Miocene was a period of widespread levelling when the principal features of the present relief began to emerge. In the eastern Grampians, valley and basin floors were widened and higher surfaces were re-levelled. To the north, a new etchplain, the Marginal Surface, progressively bevelled an emergent sub-Devonian topography and basin floors graded to the developing coastal surface were extended far inland. Weathering covers from the Middle Miocene biostatic interval survive in central Buchan and rare pockets of clayey gruss elsewhere indicate that kaolinitic saprolites formed widely. Deep weathering affected all but the most resistant rocks and an etchplain was extended across the complex basement geology, leaving only occasional residual hill masses.

Late Miocene and Pliocene

In the late Neogene, tectonic activity was renewed and differential movements probably continued throughout the Pliocene. The Eastern Grampian and Marginal Surfaces were raised by at least 250m and tilted towards the North Sea. In the eastern lowlands, the amount of displacement was less, around 100m, but local movements along the Moray Firth border lead to southward diversion of drainage.

Uplift caused stripping of kaolinitic weathering covers. Accumulations ofsiliceous residues, notably flint and quartzite, were mobilised and transported eastwards by the main rivers and remnants of these gravel bodies are now represented by the Buchan Gravels. Due to major climatic cooling in the Late Miocene, kaolinitic saprolites were gradually replaced by weathering covers containing much higher proportions of detrital felspar and biotite. In many areas, regoliths were maintained despite the de-stabilising effects of uplift and climatic change and gruss-type profiles developed to depths of several tens of metres.

In the eastern lowlands, the latest level, the Buchan Surface, evolved by lowering of the Middle Miocene etchplain. Dynamic etchplanation produced a subdued multi-storey relief, whose detail only loosely reflects the variability of the underlying geology due to the inequality of geomorphic activity across the landscape. Further west, tilting of the Miocene surface prevented conservation of form and the Buchan Surface became confined to depressions preferentially developed on zones of weaker rocks. Along the Dee and Don valleys, earlier basins were deepened and new floors largely located on biotite-rich rocks became graded to the evolving surface in the Skene lowlands. Dissection of the Eastern Grampian Surface continued and was progressively extended westwards from the Bennachie-Fare fault-scarp. However in areas bordering the Cairngorm Massif, the smooth form of the surface was maintained across gruss covers, with development of landform assemblages similar to those of the lowlands.

CHAPTER 15 Landscape modification in the Pleistocene

Although the essential features of the regional relief were established by the end of the Pliocene, the volumes of sediment in the North Sea Basin (Caston 1977) leave no doubt that the landscape was significantly modified in the Pleistocene. In the course of this long period, two fundamental geomorphic thresholds were passed, namely the first appearance of tundra environments and the onset of regional glaciation. The timing of these events is obscure and the terms 'older' and 'younger' Pleistocene will be used to denote the periods before and after the start of regional glaciation. This Chapter seeks to examine the pattern of landscape modification throughout the Pleistocene but attention is inevitably focussed on the effects of glacial erosion.

15.1 Modification in the older Pleistocene

In the absence of any stratigraphic framework for the older Pleistocene, discussion of the nature of morphological changes during this period is necessarily generalised. In western Europe, the Early Pleistocene was characterised by frequent and increasingly severe cold-temperate climatic oscillations, with perhaps as many as 20 cool phases in the Lower and Middle Pleistocene (Evans 1971). Each stadial was accompanied by reduction of forest covers and the episodic establishment of tundra conditions lead to frequent replacement by herb-dominated vegetation (van der Hammen et al 1971; West 1980). Exposed regoliths were highly susceptible to mass movement and slope forms in many areas south of the limits of Pleistocene glaciation reflect the past action of periglacial processes (Tricart and Cailleux 1972). Fluctuating climates produced major hydrological changes and periodic lowering of sea level caused deep entrenchment of drainage systems (Jones 1981).

In north-east Scotland, the initial establishment of tundra conditions at the Plio-Pleistocene boundary must have induced an important phase of stripping. Thereafter renewed weathering within temperate episodes failed to match rates of surface lowering and regoliths were progressively thinned and little-altered granular grusses were exposed at the landsurface for the first time. Stripping emphasised major relief forms, such as basins and hills of resistance, and lead to the emergence of lesser features, notably tors. Exploitation of basins of weathering by fluvial and slope processes produced the distinctive basined valleys described earlier (Section 12.5) and the saucer-like drainage basins found in parts of Buchan are strongly suggestive of mass movement of loose regoliths under periglacial conditions. Along the main valleys, the drainage exploited pre-existing troughs of weathering located along fracture zones and became deeply-incised, leaving prominent benches throughout the lowlands.

Yet the very survival of deep saprolites in parts of the lowlands argues against profound stripping of regoliths under periglacial conditions. In many areas, the subdued nature of the relief will have suppressed erosion until rejuvenation of local drainage networks. Moreover the availability of moisture is a critical control over the efficiency of two principal periglacial mechanisms, frost-shattering and gelifluction (Tricart and Cailleux 1972). The relatively low precipitation received by north-east Scotland both at the present time and in the Loch Lomond Stadial (Sissons 1976) suggests that older Pleistocene stadials may have tended towards aridity, thereby reducing the potential of periglacial denudation. However the most important limiting factor was probably the irregularity of the weathering front. Stripping of regoliths unbuttressed by risers of fresh rock will have proceeded rapidly but where rock thresholds enclosed basins and troughs of weathering, rates of regolith removal will have been greatly reduced. Regoliths behind such local base levels are effectively lost to periglacial mass movement until such time as the rock barriers are breached or lowered by the tributary drainage. Many of these basins of weathering, particularly away from the main valleys, persisted through the older Pleistocene until excavation by the less-discriminating processes of glacial erosion.

15.2 Modification in the younger Pleistocene I : Patterns of glacial erosion

15.2.1 Introduction

The second major geomorphic threshold in the Pleistocene was the commencement of regional glaciation. The timing of this event is unknown, although extensive glaciation of southern Britain may have been delayed as late as 0.6 Ma (Bowen 1978). There is stratigraphic evidence for at least 3 separate glaciations of north-east Scotland (Chapter 4) and comparisons with extraglacial areas indicate possibly as many as 17 glacial events (Fink and Kukla 1977).

Repeated glaciation has truncated weathering profiles and stripped regoliths from wide areas. The products of weathering were redistributed as till sheets and renewal of saprolites in brief interglacial intervals was insignificant. Preglacial land-forms were significantly modified by glacial erosion, with lowering and fragmentation of erosion surfaces, deepening of valleys, diversion of drainage, lowering of basin floors and destruction of many smaller erosional forms. Fluvioglacial erosion has produced deep incision along the main drainage routes, some drainage diversion and fine dissection of the relief. Finally, periglacial activity during interstadial episodes has carried unknown amounts of regolith down slopes and into the stream channels.

At the regional scale, the degree of glacial modification of the landscape of north-east Scotland has been far less than in other parts of the country (Linton 1959; 1963; Clayton 1974; Sissons 1976). Yet locally glacial erosion has had highly variable effects. In some areas, glacial processes have largely remodelled pre-existing relief whereas elsewhere glacial erosion has amounted to no more than the removal of a few metres of regolith. These patterns of glacial modification have yet to be fully investigated and this Section attempts to establish the nature of these patterns and to examine their wider implications.

15.2.2 Types of evidence

Patterns of glacial erosion can be established using a number of lines of evidence. Firstly, the distribution of landforms and landscapes can be mapped and analysed in terms of ice-sheet dynamics (Sugden 1974; 1977; 1978; Sugden and John 1976; Gordon 1979). Secondly, general estimates of glacial modification can be derived by considering the degree of disruption of preglacial relief forms (Godard 1961; 1965; Battiau-Queney 1981). Thirdly, a further approach which has yet to be widely applied is to draw inferences about depths of glacial erosion from the composition of tills

(Godard 1961; 1965). The mineralogy of the tills may be compared with that of crushed fresh bedrock to estimate incorporated components of pre-weathered material (Rosenqvist 1975). Alternatively, the distance of carry of till matrix from parent rocks can be used as an indicator of the efficiency of entrainment at the ice-sheet bed (Whillans 1978). Fourthly and at the regional scale, the volume of offshore sediments can be used to calculate depths of Pleistocene denudation (Matthews 1975; Halstead 1979; Laine 1980 and see Section 3.5). Finally, an approach that has particular relevance to the study area is the use of the distribution of weathered rock as an indicator of glacial erosion (Battiau-Queney 1981). In this study, a composite picture of patterns of glacial erosion will be built up using evidence from landforms of glacial erosion, modification of preglacial morphology, till characteristics and the distribution of weathering.

15.2.3 Landscapes of glacial erosion

Landforms and landscapes of glacial erosion provide evidence of the pattern and degree of modification of the ice-sheet bed. The distribution can be related to ice-sheet dynamics (Sugden 1974; 1977; Sugden and John 1976; Gordon 1979), and to zones of glacial erosion (Linton 1959; 1963; Clayton 1974; Sugden 1978). In north-east Scotland, the characteristic mesoforms of glacial erosion, such as scoured and polished surfaces, rock drumlins and rock basins, have restricted development and their presence is a reliable indicator of locally-enhanced activity.

Clapperton and Sugden (1977) recognise three main types of glacial landscapes in the region:- (i) landscapes of areal scouring,

(ii) landscapes of linear erosion and (iii) landscapes of local mountain glacierisation. To these can be added a further type:- (iv) landscapes of weak or localised scouring. Consideration should also be given to landscapes with few signs of glacial action. Each of these landscape types provides information on the pattern and depth of glacial erosion.

A. Landscapes of areal scouring

Landscapes of areal scouring bear marks of extensive and intensive glacial erosion (Sugden and John 1976). The landscapes are typically composed of low knolls and closed depressions, developed in fresh rocks, whose form and orientation is controlled by lines of structural weakness (Gordon 1981). Areal scouring operates most efficiently where the glacier base is at the pressure melting point (Sugden and John 1976; Gordon 1979) and able to flow rapidly over its bed.

Areally-scoured relief has only a limited distribution in north-east Scotland. Ice-moulded topography is largely absent from the high plateau of the Cairngorms and only becomes widespread on the lower surfaces fringing the massif (Clapperton and Sugden 1977). Elsewhere ice-scouring is largely confined to zones where ice-flow has been channelled by the preglacial relief, as along the Dee and middle Spey valleys. Tracts of moulded and polished bedrock are also found at a number of locations around the coasts (Fig. 15.2.i). Ice-scoured surfaces occur beneath till in the Elgin area (Peacock et al 1968) and around Banff (Clapperton and Sugden 1977), on the shore at Cairnbulg Point (Wilson 1882), at the mouth of the Ythan (Merritt 1981), beneath till in the Aberdeen

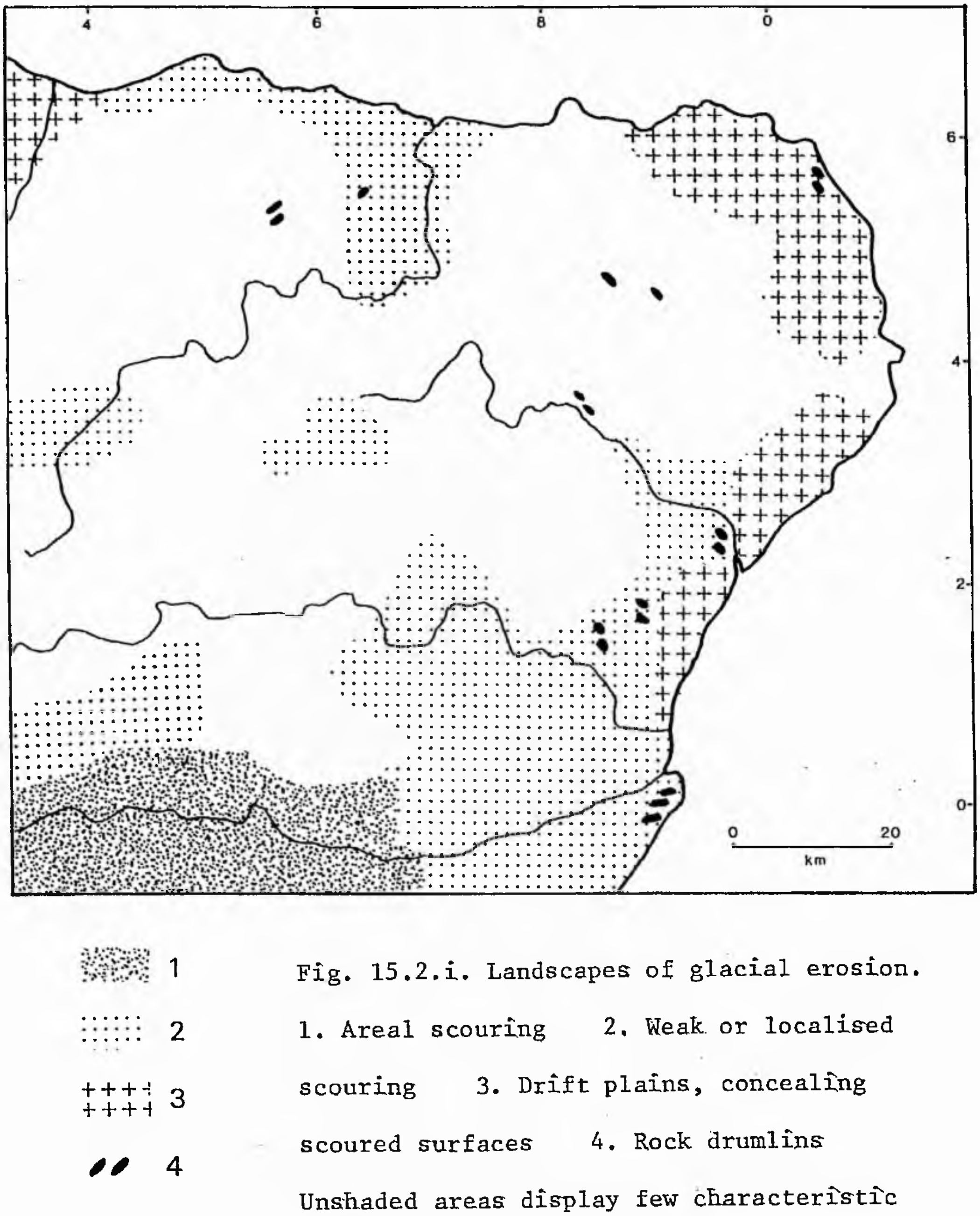

Fig. 15.2.i. Landscapes of glacial erosion.

1. Areal scouring 2. Weak or localised scouring 3. Drift plains, concealing scoured surfaces 4. Rock drumlins

Unshaded areas display few characteristic landforms of glacial erosion.

area (Murdoch 1975; McLean 1977) and southwards across the Kincardine plateau (Clapperton and Sugden 1977). These moulded surfaces emerging from beneath the thick deposits of the Moray Firth and Strathmore ice streams indicate vigorous scouring by the coastal glaciers.

The significance of areally-scoured landscapes in terms of glacial erosion is unclear. At minimum, the existence of areal scouring demonstrates the removal of all preglacial regolith. Feininger (1971) considers that glacial erosion in shield areas has done little more than polish this basal surface of weathering. Other writers (Godard 1965; Stewart 1972; Sugden 1976) have also produced morphological evidence for limited glacial lowering below ancient landsurfaces. Alternatively, such topography may represent an equilibrium bed-form maintained during deep erosion of the ice-sheet bed, a view implicit in the work of White (1972) and supported by a recent study of sediment volumes in the western North Atlantic (Laine 1980).

In north-east Scotland, the restricted development of areal-scouring demonstrates that many areas have not been deeply eroded by ice. Yet within zones of scouring, surface lowering may have been considerable. Around Torphins in the Dee valley, streamlined hills stand as much as 100m above adjacent peat-filled basins. Here glacial erosion has undoubtedly exploited pre-existing morphology and weathering patterns but localised erosion of several tens of metres is indicated. Downvalley, however, in the Skene lowlands, scoured surfaces merge without significant change of elevation with little-modified bedrock levels retaining pockets of weathering. These contrasts emphasise that scoured surfaces are equilibrium forms and demonstrate that the existence of such surfaces allows no simple estimation of depths of glacial erosion.

B. Landscapes of linear glacial erosion

Landscapes of linear erosion are restricted to the Cairngorms and to the south-east Grampians. In these areas, localised ice-streaming (Sugden and John 1976) into and along pre-existing valleys has lead to marked widening and deepening and to the creation of trough forms. In several cases, glacial modification has been insufficient to erase spurs and benches from the sides of the preglacial valleys. Elsewhere, troughs have cut across and diverted earlier drainage lines (Bremner 1919) and the major breach of the Lairig Ghru is cut through the main watershed of the Cairngorms. Away from the Cairngorm and Lochnagar massifs, many valleys show few signs of ice action and rates of ice-flow were clearly insufficient to produce major changes.

C. Landscapes of mountain glacierisation

The main landforms of local mountain glacierisation are corries. These forms are largely confined to the Cairngorms and to areas west of Lochnagar and Glen Clova, where several generations can be recognised (Sugden 1969). More subdued corrie-like features are found in the eastern Grampians and at the heads of valleys in the Ladder Hills (Clapperton and Sugden 1977). The position of the corries often reflects preglacial morphology (Klimaszewski 1964), with corries developed on breaks of slope between the main high-level erosion surfaces wherever aspect was favourable to ice-accumulation.

D. Landscapes of weak or localised scouring

Areas of weakly-scoured topography show many signs of glacial abrasion but the development of ice-moulded forms is much more restricted than in landscapes of areal-scouring. Weakly-scoured terrain is characteristic of much of the country south of the Don and parts of the Moray Firth coast, notably the area of ice-roughened topography on the Macduff Slates east of Aberchirder. Around the Skene depression, many hills are ice-roughened and certain basins, such as those at Monymusk and Loch of Skene, may be the products of localised scouring. However the topography is only weakly streamlined and ice-action has picked out structural trends perpendicular and oblique to the direction of flow. The overall impression is that glacial erosion has exposed a grund-hocker relief (Budel 1977; 1979) but failed to greatly modify this surface.

The weakly-streamlined topography in the lower Ythan valley represents an even more subtle form of glacial modification. The low hills and interfluves are developed in fresh rocks but intervening hollows are cut in weakened or decomposed rocks (Fig. 5.4.i). Streamlining is not a product of ice-moulding in the usual sense but a result of the exploitation of linear zones of weathering.

The characteristics of small groups of drumlinoid forms found in several parts of the lowlands (Fig. 15.2.i) demonstrates that similar landforms may develop at different stages of glacial erosion. Only certain of these features are true roche moutonées, produced by the scouring of solid bedrock by ice. The scattered drumlinoid forms north of the Deveron at Craigbourach Moss, Wether Hill and Fattahead give the appearance of being sculpted from solid rock. More generally, low rock protruberances are found to be closely associated with weathered rocks. This is the case along the Ythan valley between Ellon and Methlick where the isolated exposures used for mapping the solid geology rise from a cover of weathered rocks (Gribble 1965 and Fig. 5.4.i). In the area west and north-west of Aberdeen, rock drumlins and small peat-filled basins are common, again often in close proximity to and even developed across decomposed rocks (Murdoch 1975; Clapperton and Sugden 1977 and Fig. 5.4.iv). These examples represent a stage of ice erosion where regolith has not yet been completely excavated and polishing has commenced on the bosses of sound rock projecting upwards from the surrounding saprolites. Similar landforms have been described from Lewis (Godard 1965) and southern Sweden (Hillefors 1973). They are not roche moutonées sensu stricto, but convergent dome-like forms, produced by the exhumation of zones of fresh rock from within otherwise rotten material.

E. Landscapes with few landforms of glacial erosion

Over quite large areas, repeated glaciation has failed to produce characteristic erosional landforms. Even in areas of relatively high relief, as in the hills surrounding the Cabrach basin and on eastern parts of the Mounth, many valleys appear to have been largely unaffected by ice erosion and retain V-shaped cross-sections. The smooth outlines of these hills was considered by early-writers to be a result of severe ice action (Wilson and Hinxman 1890; Bremner 1912) but the lack of significant moulding suggests instead a low degree of modification.

Typical erosional forms are also absent from much of Buchan and from districts north of Oldmeldrum and east of Huntly (Fig. 15.2.i). This is partly a reflection of the low competence of the ice-sheet bed in these areas, for rocks weakened by weathering or close fissuration will not support ice-moulded mesoforms but give rise instead to broadly streamlined terrain (Linton 1962). Subtle streamlining of the western Insch depression is suggested by the general W-E trend of low ridges developed in weathered gabbro. However in terms of depths of glacial erosion, such detailed moulding is not significant and it is clear that these weathered landscapes have experienced very limited glacial modification.

15.2.4 Modification of preglacial landforms

A. Introduction

In previous Chapters, a wide variety of landforms have been described whose basic features predate glaciation. The survival of these preglacial palaeoforms is a further indication that glacial erosion has only modified a pre-existing landsurface. However the degree of glacial modification varies according to location and these contrasts can be referred to patterns of glacial erosion.

In order to gain an accurate impression of the spatial variability of modification, it is necessary to compare similar types and sizes of palaeoform. Moreover due to the influence of topography over rates of ice flow (Sugden and John 1976), it is important to compare palaeoforms in equivalent topographic positions. Although the range of palaeoform types suitable for comparison is reduced, these constraints allow more precise observations on patterns of glacial erosion.

However such comparisons are complicated by the apparent reversal of the topographic positions of zones of maximum erosion in highland and lowlands areas. The highlands are dominated by landscapes of selective linear erosion, where broad upland surfaces are dissected by deep troughs (Sugden 1968; Clapperton and Sugden 1977). These topographic contrasts are particularly marked in the type area, east of Lochnagar, for the Avon-Clova and Mounth Surfaces. Here the smooth plateau carries integrated tributary drainage systems and shallow basins of differential resistance but is bounded in sharp discontinuity by the glacial troughs of Glens Muick and Clova, cut through preglacial drainage divides (Bremner 1919).

Conversely, in at least some lowland areas, it is the interfluves which display the clearest marks of glacial activity. Along the lower Don valley, ice-moulding is largely confined to the interfluval ridge running south-east from Pitgavenny Hill to Hill of Middleton. Towards the river, the landscape takes on a more fluviatile aspect. Valley benches are dissected by shallow basined valleys retaining deep zones of weathering and the river itself is located in a narrow trench which is predominantly a product of meltwater discharge. Similar relationships occur around the Skene depression, where the surrounding hills are scoured, yet the lower floors of basins and basined valleys show few signs of vigorous ice action. Whilst the sharp contrasts in the degree of glacial erosion between valley and interfluve locations in the highlands can be quite readily explained by the effects of pressure differences on basal melting (Sugden 1974), it is not clear why similar, though reduced differences do not persist in lowland locations. Nevertheless, if useful comparisons are to be made, then attention must focus on valley form in the highlands and interfluve types in the lowlands.

B. Valley form in the highlands

The majority of major valleys east and north-east of the Cairngorms acted as conduits for ice-flow (Wilson and Hinxman 1890; Hinxman 1896). Ice discharge tended to be greatest along the valleys and the degree of glacial modification gives an indication of the magnitude of downvalley discharge (Gjessing 1966).

In the former valley of the upper Dee, the preservation of broad benches indicates only modest vertical erosion by ice (Fig. 11.7.i). Beyond Inverey, however, the benches are greatly disrupted and the valley narrows and deepens until, at Crathie, it becomes a deep trough. When the valley opens out again at Dinnet, the trough form is lost but ice-scoured surfaces remain extensive downvalley as far as Banchory. Off the main axis of the valley, the rock-floored Tarland, Lumphanan and Feugh basins contain moulded and polished surfaces but the survival of over 10m of weathered granite at 3 nearby locations, Mill Maud, Glen Cat and Etnach, indicates that the zone of enhanced erosion followed a narrow corridor along the preglacial valley. Glacial erosion has substantially remodelled the form of the middle Dee valley but the numerous rock outcrops close to the river suggest limited deepening.

The form of the middle Don valley is quite different. Below Cockbridge, the river enters an incised valley section in which weathered and shattered rock is exposed in the valley sides at a number of locations. The valley broadens for a short distance as it crosses the Rhynie Old Red Sandstone basin but then enters a further constricted valley reach containing prominent benches. The river is incised only 15-20m below the latest floor of the Alford basin, which retains extensive gruss covers (Fig. 12.6.iii), and leaves the basin by a deep gorge to pass into the lowlands. The middle Don valley has been modified mainly by meltwater activity and the survival of its preglacial forms indicates that ice discharge was substantially less than along the equivalent portion of the Dee corridor.

To the north, the ice-stream moving along the Insch depression failed to significantly modify its bed. Local levels developed across gabbroic grusses remained largely undisturbed and glacial activity appears to have been restricted to the destruction of tor groups and some quarrying of grusses. Limited ice-roughening is found on the slopes above the upper Deveron valley but the valley itself is little modified and retains a well-defined series of benches (Fig. 11.9.iii). The failure to exploit deeply-altered shear zones further downstream around Huntly (Fig. 13.2.i) also indicates restricted erosive capability (Godard 1961).

Apart from the middle Dee valley, the limited glacial modification of these valleys indicates modest rates of ice-flow. As these were corridors of relatively enhanced discharge, only slight erosion of interfluval areas can be expected (Godard 1961; Battiau-Queney 1981). The preservation of summit tors on The Buck and Bennachie, the local derivation of hilltop soils (Heslop and Bown 1969; Dare-Edwards and Livesey 1976), the existence of deep grusses in exposed positions and the scarcity of scoured surfaces confirm that these upland surfaces have been only weakly modified by glacial erosion.

C. Interfluve types in the lowlands

Glacial erosion has weakly-scoured the hills forming the Dee-Don interfluve and picked out structural lineations. To the north, the Pitgavenny-Middleton interfluve shows more restricted signs of moulding but fresh rock is widely exposed. The interfluves in Buchan, however, retain deep weathering covers and erosion has been minimal. Fresh outcrops reappear on interfluves towards the Moray Firth coast and west of the upper Deveron, many ridges are ice-roughened. These changes indicate declining glacial activity northward from the Dee and eastward from Aberchirder.

15.2.5 Till composition and glacial erosion

Many tills in north-east Scotland contain high proportions of pre-weathered material in each of the main size fractions (Fitzpatrick 1963; Basham 1968; 1974; Wilson and Tait 1977). In soils developed on undisturbed and cryoturbated tills, clay mineralogy is frequently independent of drainage status and the clays are relict and inherited from the underlying drift (Glentworth 1954; Glentworth and Muir 1963; Wilson and Tait 1977). In Soil Associations developed on superficial deposits composed predominantly of detritus derived from single rock types, the soil clay assemblages show close similarities to saprolite clay assemblages found on these lithologies (Table 15.2.i). This correspondence between soil, drift and saprolite clay mineralogy demonstrates that the bulk of the clays are ultimately derived from the saprolites.

Table 15.2.i Comparison of dominant clay minerals in soils and saprolites

Parent Material	Soil Association	Dominant Soil Clays	Dominant Saprolite Clays
Granite and Granite Gneiss	Countesswells	Illite	Illite Kaolinite
Basic igneous	Insch	Illite Montmorillonite Vermiculite	Illite Vermiculite
Buchan Gravels	Skelmuir	Kaolinite	Kaolinite
Quartzite and Quartz Schist	Durnhill	Kaolinite	Kaolinite Illite
Quartz Schist and Quartz Mica Schist	Strichen	Kaolinite	Kaolinite Illite

Data on soil clays from Glentworth and Muir (1963). Each Soil Association is developed on superficial deposits predominantly composed of a single major rock type. The dominant clays in the soils are compared with the dominant clays in saprolites formed on these rock types (see Chapter 8).

Inherited material may also dominate the sand and gravel fractions. Abundant partially-altered primary minerals occur in till horizons unaffected by Holocene soil development (Mitchell 1963; Basham 1968). Corestones are also a conspicuous component of tills in areas down-ice from rock types which produce corestones during weathering (Wilson and Hinxman 1890). It is clear that many tills are predominantly composed of preglacial weathered rock reworked by glacial processes (Fitzpatrick 1963).

The abundance of reworked material would appear to preclude deep erosion of fresh rock by ice. Indeed in a few rather unusual situations, it can be demonstrated from the composition of superficial deposits that glacial entrainment of fresh debris has been negligible. Examination of the mineralogy of soils and tills developed on certain basic rocks and on the Buchan Gravels shows that these superficial deposits are virtually entirely composed of minerals derived from the immediate vicinity. In a recent study of hilltop soils on the Morvern-Cabrach basic intrusion, it was found that:-

> "On the summits of all the hills above about 450m the stones and boulders show no evidence of extraneous material except that which can be explained by downslope movement from nearby localities of different rock type" (Dare-Edwards and Livesey 1976, p. 151).

Similarly, analysis of the fine sand fraction of tills derived from basic rocks at 3 locations in the Insch depression has shown the tills to be almost entirely free of quartz (Hendrick and Newlands 1923; Glentworth 1954). Parallel situations are found on the outcrops of the Buchan Gravels at Windyhills and Moss of Cruden. Overlying tills have virtually identical clay and sand mineralogy to the subjacent deposits and glacial disturbance has been identified, not by contrasts in lithology, but on the basis of quartz textures, disruption of sedimentary structures and the very occasional presence of erratics (McMillan and Merritt 1980; Kesel and Gemmell 1981 and see Chapter 10). In each of these cases, tills almost wholly uncontaminated by minerals exotic to the locality lie in positions 1-10km down-ice from rock outcrops of quite different composition. In the case of the till at Auchinbradie Quarry, Insch (Hendrick and Newlands 1923), the site stands some 7km from the Kennethmont granite-diorite and a mere 2.5km from the syenite of Candle Hill and these distances are reduced for the Buchan Gravels. If glacial processes have failed to carry exotic minerals over such short distances, it can be assumed that entrainment and transport by ice has been extremely limited. The composition of superficial deposits in the Cabrach hills, the Insch depression and in Buchan thus suggests that, in certain restricted areas, glacial erosion has been minimal.

In contrast, the thick tills of the Moray Firth and Strathmore ice-sheets incorporate much higher proportions of erratic material, including many rocks derived from offshore (see Chapter 4). The relative abundance of comparatively far-travelled material indicates major differences in the entrainment and transporting power of the coastal and inland ice-streams and significant differences in erosional potential can be inferred (Whillans 1978).

15.2.6 Weathered rock as an indicator of patterns of glacial erosion

Although the presence of weathered rock has been widely used to delimit zones of modest glacial erosion (Linton 1951; Godard 1961; 1965; Ford 1967; Gjessing 1967; Sugden 1968; Clayton 1974; Lidmar-Bergstrom 1982; McKeague et al 1983), there have been few attempts to use the distribution of weathering as an indicator of regional and local erosional variations (Gauthier 1980; Battiau-Queney 1981). Many glaciated regions, of course, are not suited to this approach due to the scarcity of residual weathered material but in north-east Scotland, where weathering is extensive and its distribution is quite well-known, there is considerable potential for studies of this kind.

In order to discuss patterns of regolith removal by ice, it is necessary to have a model of the distribution and general thickness of regoliths prior to glaciation and reference should be made to the examination of the lithological, structural and topographic controls over weathering patterns in Chapters 5, 12 and 13. In the lowlands, weathering extended across virtually the whole area before glaciation, affecting all but the most resistant rock types. Depths of weathering may have commonly exceeded 20m and generally increased towards interfluves. In the more compartmented relief of the highlands, the distribution was more varied. Steep slopes between erosional levels retained only thin regoliths and the relative resistance of many rock types underlying the smooth upland surfaces restricted formation of thick weathering covers. Deep profiles were largely confined to topographic lows located on weak rocks and along shear zones and former weathering depths of over 10m can be predicted.

At the regional scale, there is no doubt that glacial and fluvioglacial erosion has had a fundamental effect on the pattern of saprolite occurrence (Chester 1978). Where zones of enhanced erosion can be inferred from morphological evidence, these zones almost invariably contain fewer weathering sites (Fig. 5.2.i). The incidence of weathering is sharply reduced in coastal areas crossed by the Moray Firth and Strathmore ice-streams and also along the Dee corridor. In contrast, continuous weathering covers have survived in a number of inland areas and nowhere, except in areas of steep slopes and resistant rocks, have preglacial regoliths been entirely stripped away (Fig. 5.5.i). The regional distribution of weathering indicates major differences in the erosive power of the various ice-streams.

At more local scales, the incidence of weathering alone gives only a rough guide to erosional patterns. However by also considering the topographic positions of the weathering sites relative to directions of ice-flow, it is possible to gain a detailed impression of the degree of glacial modification of the landscape (Godard 1961; Battiau-Queney 1981). Chester (1978) has attempted to quantify these relationships by classifying weathering sites in terms of their geomorphological situation and shows that out of 45 sites, only 6 occur in situations unfavourable to preservation from glacial erosion, such as streamlined hills, interfluve hummocks and troughs. However whilst there is no doubt that weathering is preferentially preserved in ice-lee locations (Hillefors 1973), the reliability of these figures is reduced by the inclusion of sample sites from throughout Formartine and Buchan, where the impact of glacial erosion has been highly variable. Ideally sample sites should be confined within single zones of glacial erosion (Clayton 1974) so that the degree of regolith removal from similar topographic situations can be compared between areas. Unfortunately, in most of north-east Scotland, such structured sampling reduces the sample size so greatly that quantification of these relationships becomes impossible.

Perhaps the most useful way to identify local variations in the efficiency of glacial erosion is to look at a number of case studies from the various weathering zones identified earlier (Fig. 5.5.i) to see how these zones relate to landscapes of glacial erosion. The following areas will be briefly examined:- central Buchan (Zone 1), the Daugh of Invermarkie (Zone 2), the area north-west of Aberdeen (Zones 3 and 4) and the middle Dee valley (Zone 4a).

A. Central Buchan

In this area, weathering covers are essentially continuous (Fig. 5.4.i). Saprolites are found in all topographic situations from the tops of the main hills and interfluves to the floor of the Maud basin and outcrops of fresh rock are virtually confined to resistant quartzites and to the floors of a few of the deeper melt-water channels. Of particular interest are the deposits and saprolites around the Hill of Dudwick, where an outcrop of Late

Miocene-Early Pliocene flint gravels occurs in close proximity to saprolites of possible Miocene age with depths of greater than 20m. Glacial erosion of this summit area has been negligible and even in surrounding districts profile truncation has been modest.

B. Daugh of Invermarkie

To the north of Haugh of Glass, weathered rock is largely absent from hill summits and interfluves but survives widely in more sheltered locations. Saprolites are exposed beneath slopes of up to 10° on the middle and lower flanks of hills and along the sides of upper Deveron valley. To the east, deeply-altered shatter belts around The Bin have remained largely unexploited by ice (Fig. 13.2.i). The general impression is that glacial erosion has stripped regolith from the most exposed sites but failed to excavate loose materials from minor topographic lows.

C. The area north-west of Aberdeen

The glacial and fluvioglacial landforms around Aberdeen are well known (Synge 1956; Clapperton and Sugden 1972; 1977; Murdoch 1975) and the relationship of weathering sites to these features is instructive (Fig. 15.2.ii). As might be expected, exposures and boreholes show that weathered rock is generally not found in association with ice-scoured surfaces, or beneath fluvioglacial deposits or along the floors of meltwater channels. However although a number of weathering sites are found in the lee of Tyrebagger Hill, deep weathering also occurs on the stoss-side of the hill mass around Wynford (Fig. 12.5.iv). Moreover shafts of

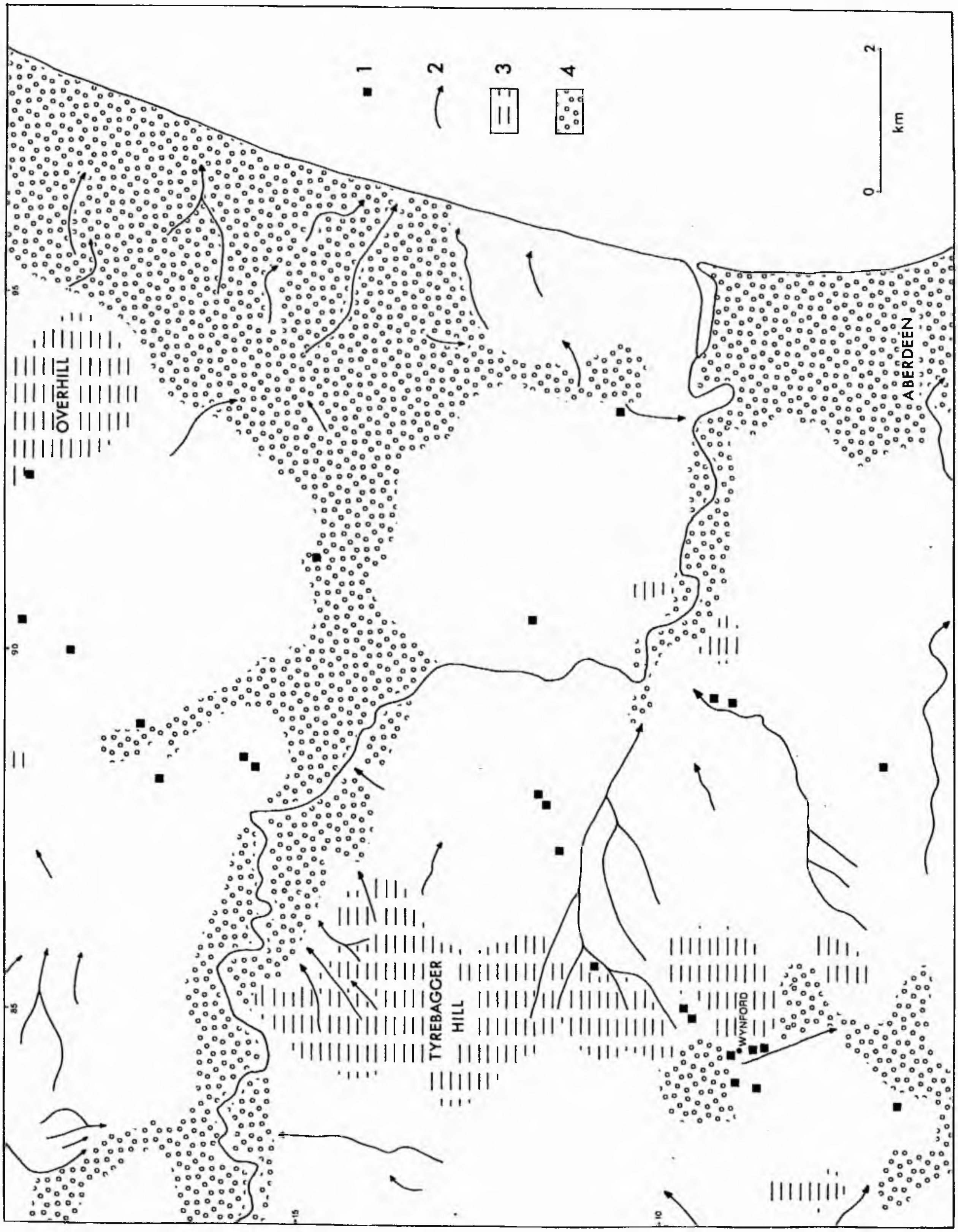

Fig. 15.2.ii. Distribution of weathering. glacially-scoured surfaces ahd fluvioglacial deposits in the area NW of Aberdeen. Key overleaf.

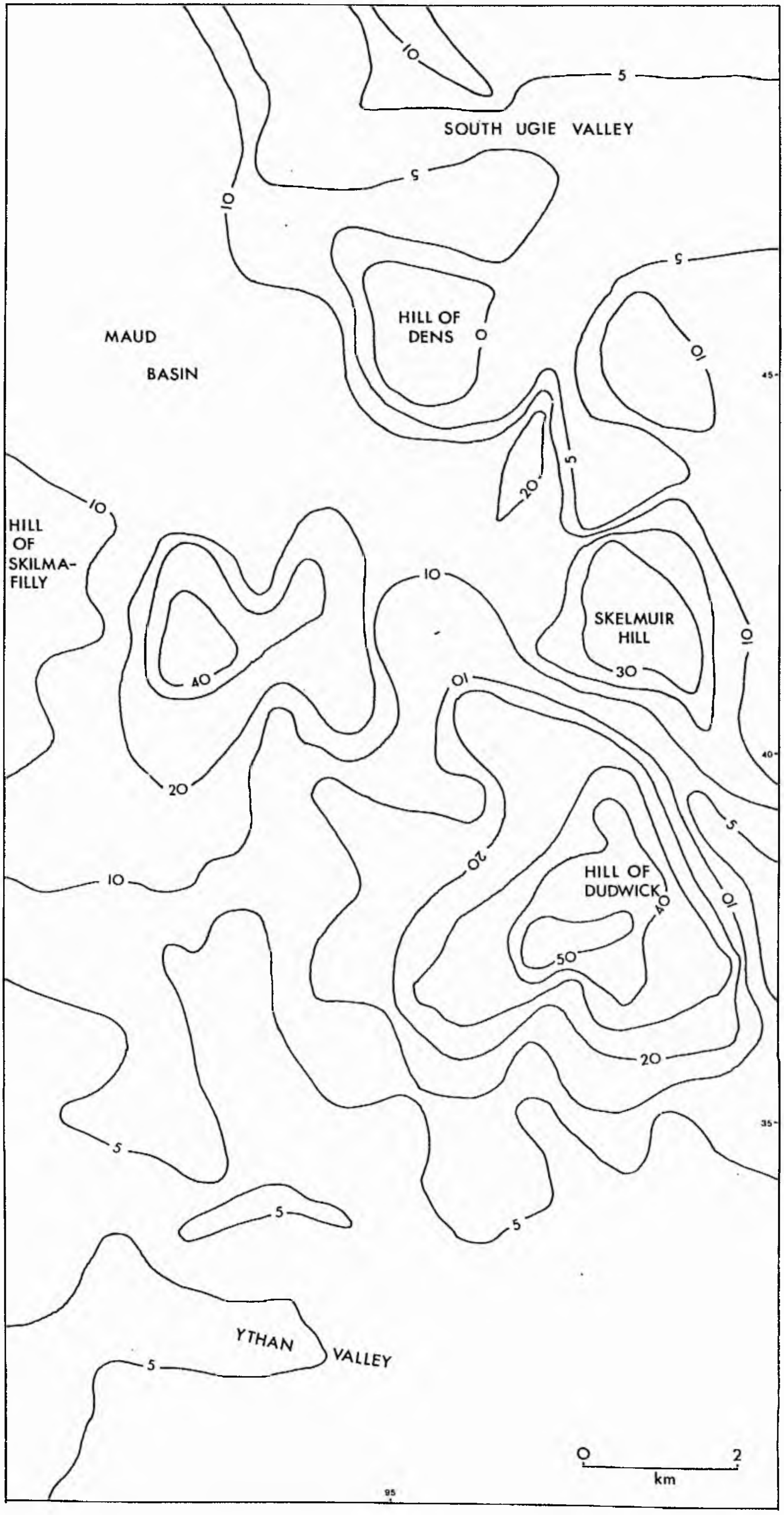
SOUTH UGIE VALLEY
HILL OF DENS
MAUD
BASIN
HILL OF SKILMA-FILLY
SKELMUIR HILL
HILL OF DUDWICK
YTHAN VALLEY
5
10
20
30
40
50
45
40
35
95
0
2
km

Fig. 15.2.iii.

Fig. 15.2.i. Distribution of weathering, glacially-scoured surfaces and fluvioglacial deposits in the area NW of Aberdeen.

1. Occurrence of weathered rock
2. Major meltwater channels
3. Glacially-scoured surfaces
4. Fluvioglacial deposits

Data on glacial and fluvioglacial features from Clapperton and Sugden (1975; 1977) and the Drift Edition of the 1 : 50 000 Geological Survey Sheet 77.

Fig. 15.2.iii. Sketch of the depths of glacial erosion (m) that would be required to remove weathered rock from all but the deepest fracture zones in central Buchan.

Note that removal of weathered rock would lead to remodelling of the preglacial relief.

alteration of up to 11m deep exist in juxtaposition with rock drumlins at Harestone Moss (Fig. 5.4.iv). In this area, glaciation has removed all regoliths from upstanding relief forms and roughened the exposed surfaces. However saprolites persist in ice-lee locations and occasional pockets of weathering survive even in open situations due to the inability of glacial processes to entirely plane-down the irregular basal surface of weathering.

D. The middle Dee valley

Along this section of the valley, no weathered rock survives and significant quarrying of bedrock has taken place. Weathering sites are found only away from the main axis of the valley in occasional sheltered locations at the foot of the western and northern scarps of the Tarland basin and in the narrow valley of Glen Cat. Glacial erosion has severely modified the preglacial form of the valley.

These case studies indicate that each of the weathering zones show clear contrasts in the local topographic situations of weathering sites. The weathering zones are therefore broadly equivalent to zones of glacial erosion.

15.2.7 Depths of glacial erosion and implications for ice-sheet dynamics

A. Depths of glacial erosion

Each of the indicators examined, namely the distribution of landforms of glacial erosion, the degree of modification of pre-glacial landforms, till composition and the distribution of weathering, gives a broadly similar picture of the patterns of glacial erosion in the region. For example, the Insch depression displays few erosional forms and contains little-modified palaeoforms, locally-derived tills and extensive weathering covers. Conversely, the coastal strip between the Don and the Ythan encompasses numerous partially-concealed glacially-moulded surfaces, no obvious palaeoforms, far-travelled till materials and little weathered rock. As the weathering sites provide by far the greatest number of point observations, the distribution of weathering is probably the most precise of these indicators and the map of weathering zones (Fig. 5.5.i) is adopted as a base-map for zones of glacial erosion.

Although it is often necessary to refer in rather general terms to degrees of glacial modification, it is important to try to give figures for depths of erosion. By referring to models of weathering patterns prior to glaciation, it is possible to derive rough estimates for each of the zones of glacial erosion. By way of illustration, Fig. 15.2.iii attempts to show the depths of glacial erosion that would be required to remove preglacial weathered material from all but the deepest fracture belts in central Buchan. The contours are schematic for deep basins of weathering undoubtedly exist in areas not explored by drilling. Nevertheless the diagram shows that at least 40m of erosion would be required in a few localities. Although the preglacial depths of weathering in this interfluve area may be atypical, it can be suggested that areas falling within glacial erosion Zone 4a, with no significant survival of pockets of weathering, have experienced at least this order of erosion. On the other hand, in Zone 1, the preservation of the

Buchan Gravels and the depths of surviving saprolites seem to preclude more than 25m of surface lowering and in many localities actual lowering may have been considerably less.

B. Implications for ice-sheet dynamics

Basal thermal regime is a fundamental constraint on effective glacial erosion (Sugden 1978; Gordon 1979). Unless basal ice is at the pressure-melting point, no basal slip can occur (Boulton 1972) and rates of erosion beneath cold-based Arctic glaciers may be an order of magnitude less than beneath warm-based temperate glaciers (Andrews 1972). Several studies have established general relationships between basal regime and zones of glacial erosion in which landscapes with few signs of glacial modification are related to areas where basal ice was below the pressure-melting point (Sugden 1974; 1978; Sugden and John 1976; Gordon 1979). In view of the abundant evidence for limited glacial erosion in north-east Scotland, it can be suggested that the region was covered by predominantly cold-based ice-sheets during successive glaciations.

Yet according to Clapperton and Sugden (1977, p. 8), "the last ice sheet over the region was warm-based during at least the later stages of its life." This view is based on the interpretation of certain meltwater channels with up-down long profiles and arranged in anastomosing networks as "ice-directed". This term refers to channels formed under hydrostatic pressure within a temperate ice-sheet and aligned along the general direction of ice-flow (Clapperton and Sugden 1977). However the limited extent of glacial erosion in the region is inconsistent with the existence of a warm-based ice-sheet during the last glaciation. It is suggested instead that these meltwater channels formed during the initial phases of decay of a cold-based ice-sheet when the englacial drainage network became functional and discharged large volumes of meltwater under hydrostatic pressure.

15.3 Modification in the younger Pleistocene II : Fluvioglacial and Periglacial Erosion

15.3.1 Fluvioglacial Erosion

The contribution of meltwater activity to relief modification has been mainly through its effect on drainage patterns. High meltwater discharges during periods of low sea level have caused incision of all the major rivers and lead to a number of important drainage diversions. Drainage networks feeding the main rivers owe much of their form to fluvioglacial erosion and meltwater channels are a striking element of the Buchan landscape (Clapperton and Sugden 1977), where they provide some of the steepest slopes in an area of otherwise monotonous relief. Despite their frequency, meltwater channels have failed to significantly modify the larger preglacial landforms. The main effect of meltwater activity has been to produce fine dissection of broad surfaces, without contributing greatly to the stripping and lowering of these surfaces.

15.3.2 Periglacial Erosion

The geomorphic impact of fluvial and slope processes acting under periglacial environments in the younger Pleistocene has yet to be fully assessed. Stratigraphic evidence for at least 2 phases of periglacial activity prior to the last glaciation comes from a single site (Connell et al 1982) and the wider effects of these episodes is unknown. During the decay of the Late Devensian ice sheet and during the Loch Lomond Stadial, permafrost in Scotland extended down to sea level (Sissons 1976). Features relating to cryoturbation, frost-shattering and solifluction during these periods occur throughout north-east Scotland (Fitzpatrick 1958; 1975; Galloway 1961a, b and c). However organic materials dating from the Late Glacial Interstadial at Garral Hill (Galloway 1961a), Tarves (Clapperton and Sugden 1977) and Woodhead (Connell et al in prep.) are overlain by only 1-1.5m of congeliturbate and, more generally, head deposits do not usually reach depths of more than 2m, even at the foot of slopes. Erosion by periglacial processes in the Late Glacial was modest, although mass movement has contributed significantly to the smoothing of relief.

15.4 Summary

During the older Pleistocene regoliths were gradually thinned but the irregularity of the weathering front prevented deep stripping. Major pre-existing landforms were emphasised and exploitation of compartmented weathering patterns lead to the development of shallow basins, basined valleys and tors. Zones of glacial erosion are identified using evidence from landscapes of glacial erosion, the degree of modification of the preglacial relief, till composition and the distribution of weathering. Only in restricted areas of enhanced ice-flow has glacial erosion exceeded 40m and it is concluded that successive ice sheets were cold-based. Fluvioglacial and periglacial erosion has not greatly modified the preglacial relief.

CHAPTER 16 Final Remarks

16.1 Conclusions

The main conclusions of this study are:-

(i) Weathered rock has been located at over 450 sites in north-east Scotland.. Depths of weathering locally exceed 30m but the weathering front is often highly irregular. Weathering profiles display little horizon development and frequently pass downwards into thick transition zones of partially-disaggregated rock. Many deep profiles are free-draining but alteration can also extend below the water table.

The region is divided into weathering zones on the basis of the frequency of weathering sites and their topographic position. The weathering zones reflect variable rock resistance, the disposition of major fracture belts, slopes and patterns of glacial erosion.

(ii) Two weathering types, grusses and clayey grusses, are identified after examination of granulometry, soluble base losses and clay mineralogy. The grusses are characterised by low clay contents and high proportions of little-altered felspar and biotite. Losses of CaO are high but Na_2O and MgO contents remain substantial. Clay mineral assemblages are varied and strongly influenced by rock type. A sub-type is recognised, granular grusses, which includes disaggregated rocks in the first stages of chemical alteration. The grusses are equivalent to the 'sandy weathering type' recognised by Bakker (1967) in Europe.

The clayey grusses are virtually restricted to central Buchan. Clay contents are above 7% and can exceed 20%. Detrital primary mineralogy is dominated by quartz. CaO and Na_2O are almost totally depleted, losses of MgO are high, SiO_2 is reduced and Al_2O_3 is enriched. Kaolinite-illite clay mineral assemblages are dominant on all rock types. Several profiles are rubefied due to the presence of goethite and haematite. The clayey grusses are similar to the 'clay weathering type' of Bakker (1967).

(iii) The grusses and clayey grusses represent weathering covers of different age. The grusses are products of humid temperate weathering environments. Although regeneration of shallow granular grusses occurred in interglacial periods, the bulk of the grusses predate glaciation and several profiles have experienced a major change in drainage status. Gruss development continued throughout the late Pliocene and early Pleistocene but may have begun as early as the late Miocene.

The clayey grusses reflect prolonged alteration under humid conditions when temperatures were higher than at present. Comparisons with the mineralogy of North Sea sediments and with saprolites elsewhere in western Europe suggest that the clayey grusses are of Miocene age, but formation in the early Pliocene cannot be ruled out.

(iv) The division of the Buchan Gravels into two separate formations by recent workers (McMillan and Merritt 1980; Kesel and Gemmell 1981) is accepted. The Windyhills Formation consists of fluvial gravels of Middle to Late Pliocene age. The Buchan

Ridge Formation comprises glacially-disturbed masses of fluviatile deposits of Late Miocene to Early Pliocene age.

(v) The hypothesis of Kesel and Gemmell (1981) that clasts of Chalk flint and silicified Greensand within the Buchan Gravels are glacial erratics of offshore provenance is rejected. Derivation from a former Cretaceous cover in Buchan is proposed as an alternative.

(vi) The relationships between weathering patterns and a number of preglaciation meso-scale landforms are discussed. Basins are preferentially located on zones of low resistance and many are long-established features with origins in the Devonian and the middle Tertiary. The smaller basined valleys are related forms produced by exploitation of pre-existing zones of deep weathering in the Pleistocene. Many valleys are structurally-aligned and retain their preglacial forms. Prior to drainage incision, weathering locally extended below the valley floors.

(vii) The characteristics of offshore sediments indicate alternating phases of biostasy and rhexistasy (Erhart 1955) through the Tertiary in north-east Scotland. Prolonged periods when warm and humid climates were combined with stable tectonic regimes allowed extensive etchplains to develop in three intervals, the Late Cretaceous, the Middle Eocene to Middle Oligocene, and the Middle Miocene. Inter-vening episodes of tectonic activity involved major differential movements which continued into the late Tertiary. However the position of the region towards the eastern edge of the repeatedly-tilted Highland block ensured that the amount of movement was reduced and areas close to the North Sea coast have experienced only limited uplift since the Lower Cretaceous.

(viii) Two major erosion surfaces are identified in the highlands east of the Cairngorms. The Eastern Grampian Surface lies between 450 and 750m and is an etchsurface produced by lowering of the raised and tilted Mid-Palaeogene etchplain. The Marginal Surface at 280 - 370m consists of coastal plateaux bevelled across accidented sub-Devonian relief and a string of embayments along the Spey valley. This surface has origins in the Middle Miocene etchplain and was tilted gently towards the east in the late Neogene. The highlands are bounded by a number of Neogene tectonic scarps.

(ix) A single erosion surface, the Buchan Surface, is identified in the lowlands. The survival of Chalk flints indicates maintenance of low relief since the Cretaceous and fragments of the Miocene landsurface capped by the Buchan Ridge gravels survive in central Buchan. The Buchan Surface was elaborated under temperate environments during the Pliocene and early Pleistocene, when gradual uplift allowed continuous renewal of grusses and the perpetuation of relief forms.

(x) The distribution of weathering is an indicator of zones of glacial erosion. Only in restricted areas has glacial erosion exceeded 40m and the survival of preglacial saprolites and sediments indicates that successive ice sheets were cold-based.

16.2 Wider implications of the study

North-east Scotland is a key area for the study of long-term landform development within the limits of Pleistocene glaciations. The region belongs to a small group of areas around the North Atlantic in which weathering covers have survived glaciation, including parts of eastern Canada (Chalmers 1898; Gauthier 1980; McKeague et al 1983), the Kola peninsula (Kiselev 1975), southern Sweden (Lidmar-Bergstrom 1982) and south-west Wales (Battiau-Queney 1978; 1981). In several districts in north-east Scotland, preglacial weathering profiles are virtually intact. The characteristics of these saprolites can be compared with those of pockets of sandy weathering which occur quite widely elsewhere in Scotland (Fitzpatrick 1963; Godard 1965; Walsh et al 1972; Omand 1973) and in other glaciated regions (Billings and Roy 1933; Goldthwait and Kruger 1938; Virkhalla 1955; Gjems 1963; Ford 1967; Feininger 1971; Bullock et al 1973; Peulvast 1978), but whose significance is not yet understood. Weathering patterns identified in the study area also have clear relevance to questions of the form and origins of stripped preglacial landsurfaces (Gjessing 1967; Kaitenen 1969; Feininger 1971; Lidmar-Bergstrom 1982).

This study has perhaps three main implications for models of long-term landform development in glaciated regions. Firstly, the etchplain concept stresses the continuity of weathering and landscape evolution and allows morphological levels to be correlated with morphogenic events identified from styles of sedimentation in offshore basins. Glaciation is regarded simply as the latest phase of stripping and relief development and no fundamental break with earlier events need be recognised. Little-modified preglacial landsurfaces have been identified widely in northern latitudes (Virkhalla 1955; Rudberg 1966; Bird 1967; Gjessing 1967; Kaitenen 1969; Sugden 1974) and models of etchplanation have considerable potential for elucidating the polycyclic origins of these rock-floored terrains (Thomas 1978; Lidmar-Bergstrom 1982). Secondly, although precursors of the main erosion surfaces can be traced back to the Palaeogene and even to the Mesozoic, the regional landscape is dominated by Neogene landforms, many of which were fashioned entirely under temperate environments. In other parts of north-west Europe, emphasis has been placed on relief development under tropical climates (Godard 1965; Gjessing 1967; Kaitenen 1969; Budel 1978; 1982; Birot 1978; Lidmar-Bergstrom 1982) and the role of morphogenesis under the temperate conditions which have prevailed since the Middle Miocene has been under-stated. Finally, the recognition that differential earth movements continued into the late Tertiary in north-east Scotland forms part of the "Rehabilitation de la tectonique recente" noted by Reffay et al (1982 p.16). Tectonic activity probably occurred throughout north-west Europe in the Neogene (Durand and Milon 1962; Walsh et al 1972; George 1974; Battiau-Queney 1978; Ziegler 1982) and most highland landforms in this region were probably elaborated wholly within the late Tertiary.

16.3 Recommendations for further work in north-east Scotland

Although many aspects of this study require further elaboration, there are perhaps four areas in which future work would be most valuable:-

(i) Although only the bulk clay mineralogy of the weathered rocks has been considered, it is clear that rock type exerts a major influence over mineralogical transformations in the early stages of weathering. Given the variety of rock types affected by chemical alteration in the region, it should be possible to examine the influence of lithology in detail. Recent studies of biotite weathering in granites (Seddoh 1973; Flageollet 1977) suggest that analysis of the alteration products of similar primary minerals in different rock types would allow stages of weathering to be identified within the gruss weathering type.

(ii) Absolute dating of mica clays is already possible (Bray 1980; Ugolini 1976) and the extension of fission-track dating to saprolite alteration products could revolutionise the study of weathering covers.

(iii) Lidmar-Bergstrom (1982) has recently demonstrated the potential of studies of flint types. Jamieson (1858) suggested that different types of flint occurred in the Windyhills and Buchan Ridge gravels and comparisons of these flint populations with types found on the coast (Kesel and Gemmell 1981) may resolve the question of their provenance.

(iv) New information on offshore sediments is appearing rapidly and the framework of Tertiary morphogenic events proposed in this study will require revision.

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APPENDIX 1 Grouping of sampled sections into Granulometric Types

Type 1 Granular Grusses

	Granites	Basic Igneous	Quartzites	Metasediment
1.	Aberchirder	Boddam		
2.	Avochie	Brankstone		
3.	Blackpots	Milton		
4.	Blackrigg	Silverford		
5.	Cairnlochan	Skilmafilly		
6.	Cairn o'Mount	Whitehills		
7.	Coire Raibert			
8.	East Den			
9.	Glen Cat			
10.	Kingsford			
11.	Longhaven			
12.	Mill Maud			
13.	Mormond Quarry - North Side			
14.	Sandford Bay			
15.	Tulloch			

Type 2 Grusses

1.	Aikey Brae	Bruxie	Balchimmy	Auchintool Mos
2.	Braeside	Fedderate	Cairnbarrow	Bonnykelly
3.	Cairnlea	Forestry Hut	Fetterangus	Boyne Quarry
4.	Cruden 1,2,3,4	Huntly Roadside	Howe of Dens	Bruxie
5.	Dens Hill	Kirkhill	Rannas	Cairnhill
6.	New Pitsligo XR	Maud C.P.	Sunnyside	Forglen
7.	PX 48	Sinsharnie		Hillfoot
8.		Weetingshill		Kinmuck
9.				Montgrew
10.				Northseat
11.	Redhouse			Oldmeldrum
12.				PX 53
13.				PX 54
14.				PX 69
				PX 78
				Toddlehills
				Wardhead
				Ythanbank

APPENDIX 1 (contd)

Type 3 Clayey Grusses

	Granites	Basics	Quartzites	Metasediments
1.	Bennachie C.P.	Gaval	Howe of Dens	Clamandswells
2.	Cairngall		Mormond Quarry	Howford
3.	Cruden 5		Mormond Trench	
4.			Sunnyside	
5.			Whitestones	

Type 4 Clayey Alterites

1.	QX 114	Howe of Dens - schist bands	
2.		Sunnyside - schist bands	
3.		Drinnies Wood	
4.		PX 61	
5.		QX 48	
6.		QX 50	

APPENDIX 2 Details of exposures of weathered rock

GR.	Rock Type	(m) Depth of Weatherg Exposed	Particle Size	Geochem.	Clay Minerals	Other Refs.	Name in Text
472634	Quartzite	2.0	x	-	x	-	Rannas
444530	Flags	3.0	x	-		-	Montgrew
434534	Flags	4.0	-	-	-	-	-
490440	Younger Basic	2.5	x	-	x	-	Sinsharnie
499425	"	1.8	x	-	-	-	Huntly Roadside
418412	Quartzite	2.3	x	-	x	-	Cairnbarrow
445404	Older Basic	2.0	x	-	-	-	Both Hill
435316	Mica Schist	5.0	-	-	-	Koppi (1977)	Clashindarroch
430270	Gabbro	3.0	x	-	x	-	Whitehills
491278	Gabbro	2.0	x	-	-	-	-
432253	Gabbro	1.7	x	x	x	-	Silverford
423110	Mica Schist	3.0	-	-	-	-	-
497117	Qtz Schist	2.5	x	-	x	-	Balchimmy
417917	Granite	c.5.0	-	-	-	Milne (1952)	-
542470	Granite	2.2	x	-	x	-	Avochie
593316	Gabbro	2.0	x	-	x	-	Brankston
513258	Gabbro	3.0	-	-	-	-	-
552243	Epidiorite	2.5	x	-	x	-	Knockerspoch
559205	Flags	4.0	x	-	-	-	Shieburn
577203	Granite	3.0	x	-	x	-	Redhouse
634177	Granite	1.5	x	-	x	-	Tulloch
566139	Granite	2.0	x	-	x	-	Kingsford
591073	Mica Schist	2.0	-	-	-	-	-
566067	Granite	10.0	x	x	x	-	Mill Maud
574949	Granite	8.0	x	-	x	-	Glen Cat
615536	Schist	2.0	x	-	x	-	Auchintoul
632528	Granite	1.8	x	-	x	-	Aberchirder
693512	Slate	1.5	x	-	x	-	Forglen (X)
683404	Slate	8.0	-	-	-	-	-
626334	Gabbro	3.3	x	-	-	-	Boddam
693245	Granite	3.0	x	x	x	Wilson et al (1981)	Bennachie Car Park
796507	ORS	2.0	-	-	-	-	-
755419	ORS	1.5	-	-	-	-	-
870569	Granite	2.0	x	-	x	-	New Pitsligo X Roads
897560	Granite	1.5	x	-	-	-	-
871557	Granite	1.2	x	-	-	-	-
887553	Granite	2.0	x	-	x	-	-
857538	Schist	2.5	x	-	x	-	Bonnykelly
888505	Norite	2.5	x	x	x	-	Fedderate

APPENDIX 2 (contd)

GR.	Rock Type	(m) Depth of Weatherg Exposed	Analyses in Text: Particle Size	Geochem.	Clay Minerals	Other Refs.	Name in Text
898394	Gabbro	1.8	x	–	x	–	Skilmafilly
808280	Schist	3.0	x	–	x	–	Oldmeldrum
835258	Mica Schist	2.0	–	–	–	–	–
893093	Granite	3.4	x	–	x	–	Bucksburn
912600	Granite	2.5	x	x	x	–	Blackrigg
950568	Quartzite	15.0	x	x	x	–	Mormond Quarry
973565	Mica Schist	2.0	x	–	x	–	Hillfoot
954547	Mica Schist	3.0	x	x	x	Koppi (1977)	Howford
901537	Granite	3.0	x	–	x	–	Cairnlea
925526	Mica Schist	1.5	x	–	x	–	Wardhead
974513	Quartzite/ Basic	2.0	x	–	x	–	Gaval (X)
904503	Diorite	2.0	x	–	x	–	Weetingshill
989516	Quartzite	1.0	x	–	x	–	Fetterangus
975805	Quartzite	2.8	x	x	x	x	Howe of Dens
953493	Schist/Norite	4.0	x	–	x	–	Bruxie
973497	Quartzite	2.0	x	x	x	–	Drinnies Wood
927479	Granite/Norite	4.0	–	–	–	–	–
963578	Granite	2.0	x	–	x	–	Aikey Brae
952413	Granite	1.5	x	–	x	–	Blackpots
930408	Schist	12.0	x	–	x	–	Northseat
981403	Quartzite	2.7	x	x	x	–	Whitestones
951371	Schist	3.0	–	–	–	–	–
983372	Quartzite	2.5	x	x	x	–	Sunnyside
993369	Quartzite Schist	1.5	x	–	x	–	Clamandswells (X)
991341	Schist	1.5	x	–	x	–	Kinmuck
913332	Schist	6.0	x	–	x	–	Ythanbank
012528	Diorite	5.0	x	–	x	Connell et al (1982)	Kirkhill (X)
NK 053471	Granite	15.0	x	x	x	x	Cairngall
NK 035444	Granite	2.5	x	–	x	–	Braeside
NK 082443	Granite	3.5	x	–	x	–	East Den
NK 124435	Granite	2.0	–	–	–	–	–
NK 076424	Granite	2.2	x	–	x	–	Hill of Dens
NK 084423	Granite	6.0	x	x	x	–	Hill of Longhaven

NOTES: All Grid References are NJ, unless stated

(X) – Exposure lost due to infilling

Publications of the Institute of Geological Sciences

Maps

One-inch, 1:50 000 and larger scales. One inch to one mile (1:63 360) geological maps have been published for practically the whole of Great Britain, but many of the early ones are no longer in print. The maps appear in two editions, as **Drift** (including the superficial or Quaternary deposits) and **Solid** (showing only pre-Quaternary rocks), or as **Solid and Drift** where only one is published. The later one-inch colour-printed maps are now being replaced by 1:50 000 maps; most Scottish sheets on enlargement to 1:50 000 will be issued in two parts, east and west. The index to the maps is on the back cover and where published most can be purchased either flat or folded. The earliest maps were surveyed directly on the one-inch scale, but since the latter part of the nineteenth century one-inch maps have been compiled from surveys made on a scale of six inches to one mile (1:10 560). Six-inch maps may be consulted in the main libraries of the Institute. A large number of these maps covering special areas, including the coalfields and London, are published; and dyeline or photographic copies of the rest can be purchased.

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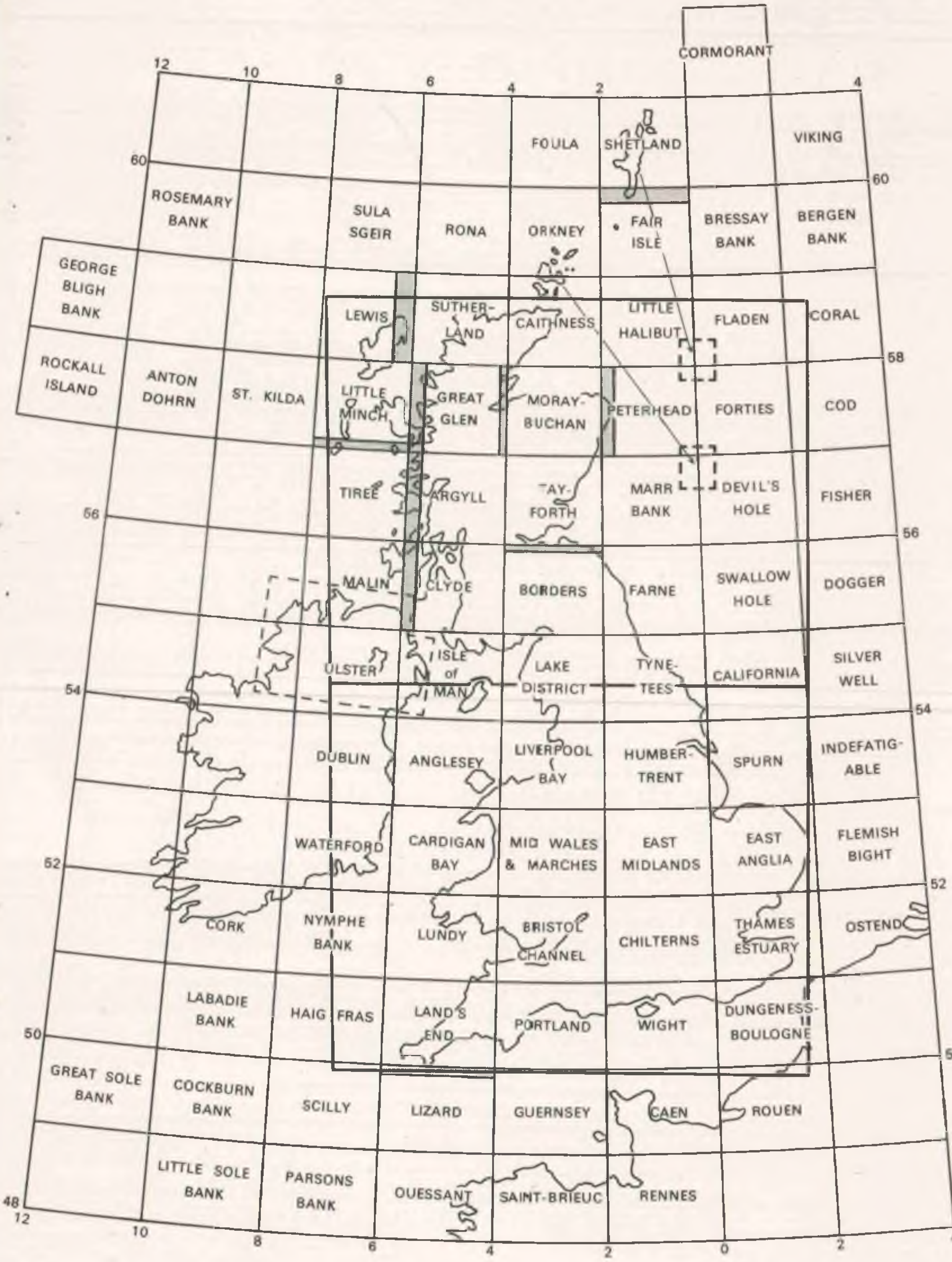

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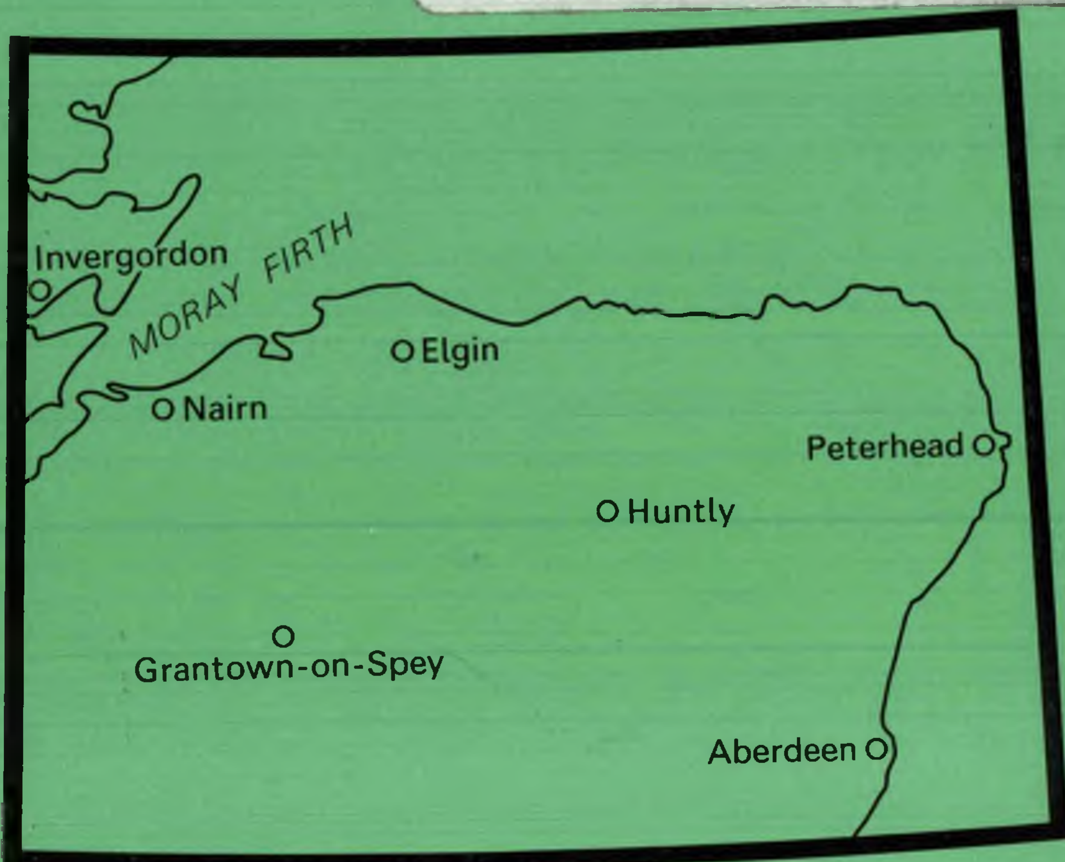

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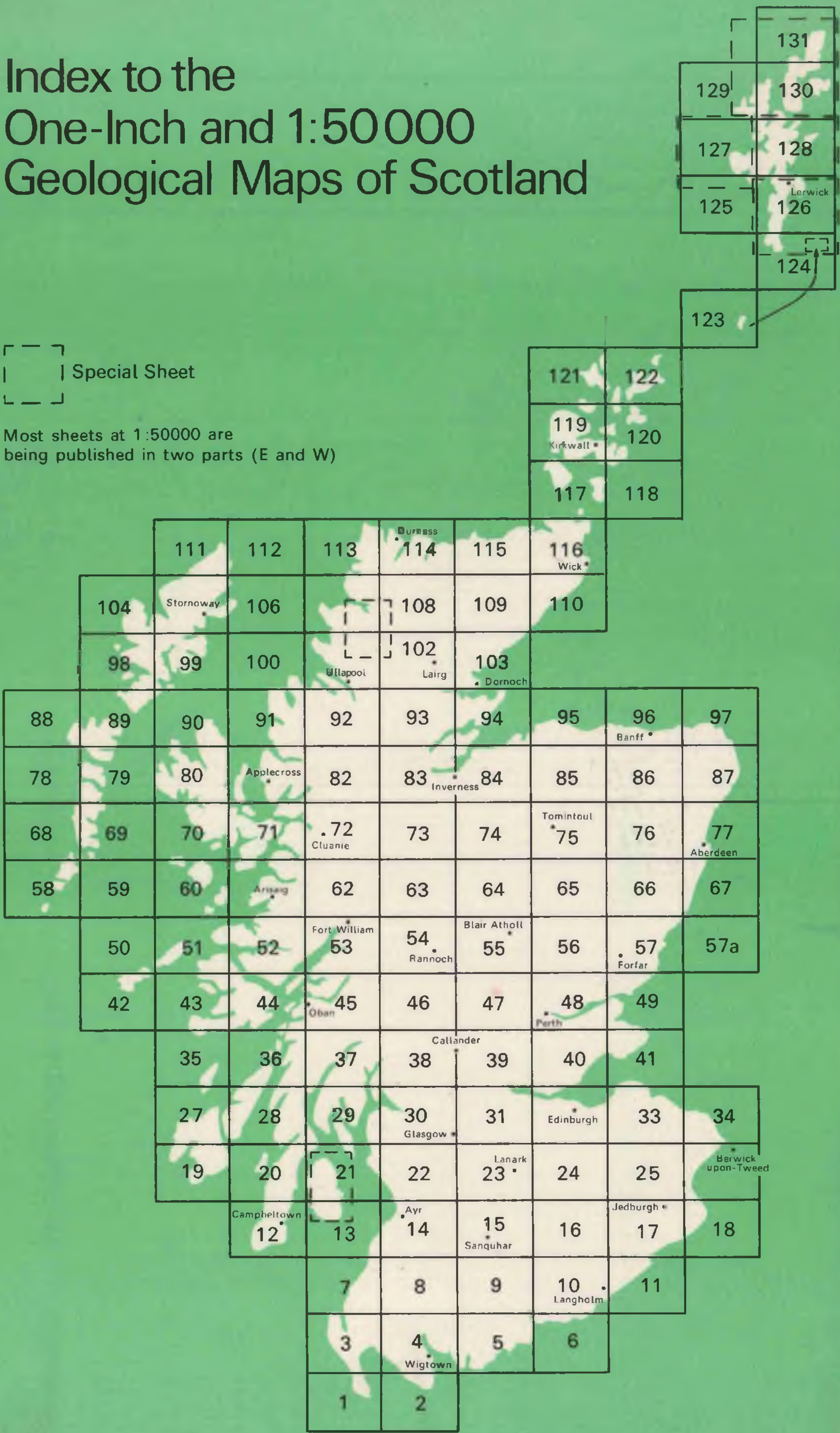

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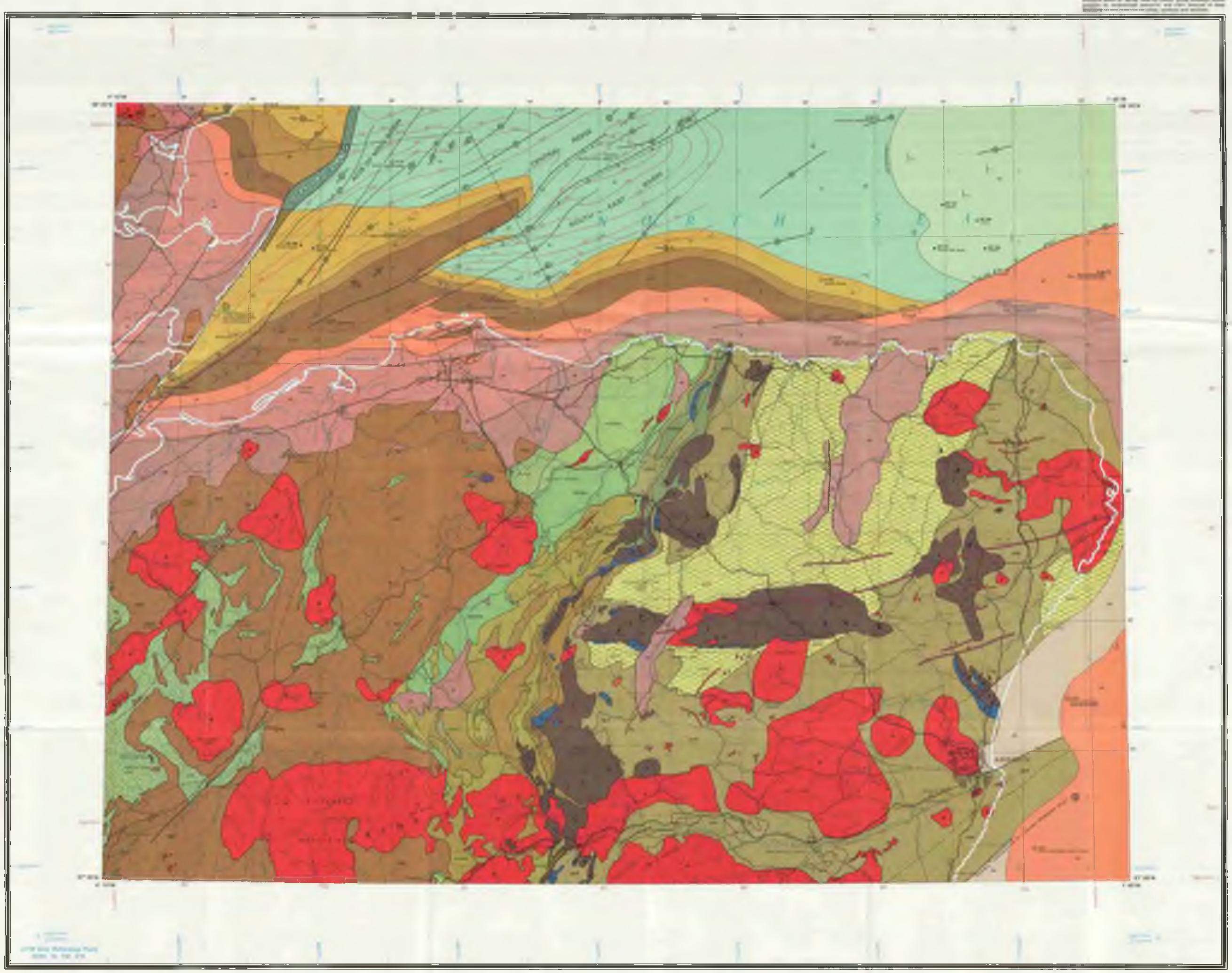
EXPLANATION OF LITHOLOGICAL ORNAMENT

NOTES ON STRATIGRAPHICAL SYMBOLS AND DIVISIONS

NOTES ON THE USE OF LITHOLOGICAL ORNAMENT



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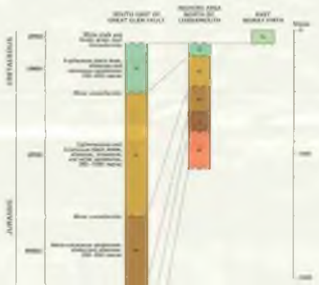

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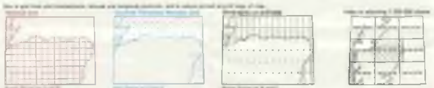

EXPLANATORY NOTES TO THE GEOLOGY

Circled numbers refer to locations on the map

1 JURASSIC SECTION

2 GREAT GLEN FAULT

3 HIGHLAND BOUNDARY FAULT

BOUNDARIES OF THE METASEDIMENTARY DIVISIONS

SURVEY DATA