Deep weathering patterns in north-east Scotland and their geomorphological significance

by

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with 6 figures and 1 table


Die geomorphologische Bedeutung der Verwitterungsmuster wird für die regionale Reliefgenese und für Modelle der Landschaftsentwicklung in anderen vergletscherten Gebieten diskutiert.

Summary. Deep chemical weathering of Neogene and early Pleistocene age occurs extensively in north-east Scotland. Saprolite mineralogy indicates development under temperate environments yet, despite a moderate degree of alteration, depths of weathering locally exceed 50 m. Weathering profiles and local weathering patterns differ in several important aspects from tropical weathering patterns at similar scales. Depths of weathering may vary greatly over short distances and a sharp, smooth basal surface of weathering is rarely found. However, at scales of 1-10 km², basins and troughs of alteration and scarp-foot weathering zones are recognised which are broadly equivalent to patterns reported from humid tropical weathering systems. At scales of 10-250 km², variations in the incidence, depth and continuity of weathering covers reflect geological, topographical and glaciological controls. The geomorphological significance of the weathering patterns is discussed for regional relief development and for models of landscape evolution in other glaciated areas.

Résumé. Une profonde altération chimique du Néogène et du Pléistocène inférieur est largement répandue dans le nord-est de l’Ecosse. La minéralogie des matériaux altérés atteste que cette désagrégation s'est produite sous des environnements tempérés, mais en dépit d'un degré modéré d'altération, elle se retrouve...
Introduction

The existence of deeply weathered rock in north-east Scotland is well-known (Fitzpatrick 1963, Peacock & Michie 1975, Chester 1978). Weathering affects many rock types including Precambrian, Moinian and Dalradian schists and gneisses, Caledonian intrusives, Devonian sandstones and conglomerates, Triassic sandstones and unconsolidated gravels of possible Pliocene age. Clay mineral assemblages in the weathered rocks or saprolites indicate development under humid temperate to subtropical environments (Basham 1974, Wilson & Tait 1977, Hall 1983) and a Neogene to early Pleistocene age for the deep weathering is generally favoured (e.g. Fitzpatrick 1963, Hall 1985).

Recent pipeline excavations and drilling surveys have provided important new information on the distribution of weathering in the region. Over 500 weathering sites are now known (fig. 1) and weathering extends to depths of at least 60 m. Weathering patterns can be identified at a variety of scales which reflect geological, geomorphological and glaciological controls and which have had a profound influence on the development of the relief. Weathering of crystalline rocks on this scale has not been reported previously from the British Isles and this study provides the first detailed account of deep weathering patterns from an area within the limits of the Pleistocene glaciations.

Geology and geomorphology

The oldest rocks are Precambrian biotite gneisses which form an allochthonous core within an overfolded and dislocated sequence of Dalradian metasediments. The Dalradian succession includes mica schists, quartzites, flags, slates and minor limestones and reflects diverse sedimentary environments and different grades of metamorphism (Johnstone 1966). These basement rocks are intruded by numerous Caledonian acid and basic igneous masses. The only extensive sedimentary rocks are Old Red sandstones and conglomerates which occupy a series of down-faulted basins.

The regional relief consists of a stepped and interdigitated succession of erosion surfaces which rise westward towards the Cairngorm massif. Each surface subsuemes tiered relief which is often subtly adjusted to geology. The lower storeys comprise basins, corridors and valleys opened out along lines of structural weakness and within rocks of low resistance to chemical weathering, notably biotite granites and gabbros. Above lies the main surface level which, in turn, is surmounted by resistant hills and hill masses which often represent the residual relief of higher surfaces (fig. 2).

Deep weathering occurs at all topographic levels but is particularly associated with the lowest surface, the Buchan Surface. In Buchan, this Surface retains deposits of highly weathered quartzite and flint gravels, the Buchan Gravels, of probable Tertiary age (Koppi & FitzPatrick 1980, McMillan & Merritt 1980, Hall 1982). The preservation of these gravels and the widespread survival of deeply weathered rocks beneath tills demonstrates that, despite multiple glaciation, the main elements of the relief predate the glacial Pleistocene.
3 Characteristics of the weathering profiles

The characteristics of the saprolites are given elsewhere (Hall 1985) but may be briefly summarised. In most cases the rocks have disintegrated to a granular sand and original structures are preserved. The degree of chemical alteration is modest with clay contents of 0.7% and retention of varying proportions of little-altered Ca-feldspar and biotite, minerals of low resistance in standard weathering sequences. Weathering took place under humid temperate environments (Basham 1974), probably during the Pliocene and early Pleistocene (Hall 1985). These saprolites occur throughout north-east Scotland and are termed the gruss weathering type. A second, older type of more advanced alteration occurs at a few sites in central Buchan but, as weathering patterns appear to be identical in both weathering types, no distinction is made between them in the text which follows.

The saprolites are overlain generally by thin superficial deposits. These comprise mainly till and head and frequently contain an abundance of material reworked from subjacent saprolites (Fitzpatrick 1963).

In deep exposures, there are few signs of horizon development within the saprolites and colour, granulometry and clay mineralogy change gradually down the weathering profile (fig. 3). Depths of alteration are variable. Over 50 m of weathered rock is recorded from a fault zone in the Peterhead granite (Edmond & Graham 1977) and from the sheared margins of the Arnage and Insch (Leslie 1984) basic masses. In central Buchan, 19 boreholes record weathering to depths in excess of 20 m (Hall 1985, fig. 2) and alteration may extend more than 10 m below the water table in this area. Similar thicknesses of saprolite are known from the Huntly, Knock and Maud basic masses, the Skene and Peterhead granites and schists near Aberdeen and Tomintoul but these depths tend to be exceptional and often correspond to fracture zones. Nonetheless the survival of 10 m or more of weathered rock despite profile truncation in over 80 boreholes and in six sections demonstrates original weathering covers of considerable thickness.

At the base of weathering profiles, thick transitions zones frequently separate wholly disaggregated and fresh rock. These features are not generally associated with deep weathering in warmer environments, where a sharp boundary, termed the basal surface (Ruxton & Berry 1959) or weathering front (Mabbutt 1961), is common. In north-east Scotland, these terms can be applied to only about a third of the borehole records. In the remaining cases, weathered rock grades into fresh rock and incipient alteration may reduce the mechanical strength of the rock at depths far below the surficial disaggregated zones.

4 Weathering patterns, landforms and scale

Weathering patterns can be identified at a number of scales in north-east Scotland. In individual exposures the most striking characteristic is the rapid lateral variation in weathering depths. However as larger areas are considered, these irregularities become less apparent and attention switches firstly to major depressions and risers in rockhead profiles and finally to regional variations in the continuity and depths of...
Deep weathering patterns in north-east Scotland

4.1 Weathering patterns and slopes

At scales of less than 1 km\(^2\), weathering depths are highly variable. On the Arnage and Knock basic masses, shafts of weathering reaching depths of at least 35 m occur within 250 m of fresh outcrops. Rockhead profiles are particularly irregular where rocks of contrasting resistance are juxtaposed, most notably where bands of quartzite occur beside other metasediments more susceptible to alteration. Minor shear zones are also frequently associated with trench-like zones of deeper weathering. The magnitude of lateral variations prevents the construction of isoline maps of weathering depths.

Given the irregularity of many rockhead profiles in north-east Scotland, it might be expected that stripping of saprolites would have produced slopes dominated by emergent rock forms. In fact, slopes often show a striking disparity with weathering patterns. Lowland areas north of the Don valley are characterised by gentle convexo-concave slopes with few rock outcrops. In section, smooth slopes are seen to be developed across thin drift covers resting on rocks at widely different stages of alteration. Bosses of fresh rock have protected adjacent pockets of weathering from erosion yet these risers commonly fail to have topographic expression. Many exposures of grussified granite and gabbro display groups of corestones apparently in the process of exhumation. Yet although tors occur widely on the summits of the Grampian foothills, these features are found at only a few localities in the lowlands.

This discordance between slope form and weathering patterns seems to be largely a result of glacial and periglacial activity. The former existence of tor landscapes can be inferred from the abundance of corestones found both on the surface and within tills in a down-ice direction from those areas of granitic and gabbroic rocks which produce corestones on weathering (Wilson & Hinman 1890: 32). Along the Insch depression, the Cabrach torfield is developed on gabbros of identical composition to those found 20 km to the east around Insch (Read, Sadashivaiah & Haq 1961) which display no tors. This relationship probably reflects a progressive, though modest, increase in the intensity of glacial erosion eastwards along this topographic corridor. Although glacial erosion has been incapable of the complete removal of saprolites, it appears that ice action was generally effective enough to destroy small, upstanding rock forms.

Periglacial activity has contributed to the smoothing of slopes in two ways. Firstly, the trains of frost-shattered debris which often extend downslope from risers of fresh rock testify to the reduction and even elimination of small rock protruberances. Secondly, soliflucted tills provide a drape over less regular surfaces developed across fresh and weathered rocks. As these saprolites are largely composed of materials derived from subjacent saprolites (FitzPatrick 1963), the rounded slopes developed across them are similar to those found in extra-glacial areas of extensively-weathered terrain (Thomas 1976).
4.2 Weathering and major landforms

At scales of 1–10 km², rockhead profiles show three main features: (i) alternating low risers and depressions, (ii) linear zones of deep alteration and (iii) scarp-foot weathering zones. Each of these distinctive weathering patterns has topographic expression and each reflects the control of differential rock resistance, fracturing and relief on the progress of weathering.

In the lower Ythan valley, topography appears to reflect the progressive stripping of saprolites from a gently undulating rockhead surface (fig. 4), with the gradual emergence of broad risers of fresh rock as small hills as the intensity of glacial erosion increases towards the axis of the valley. Whether this terrain is a result of two distinct phases of weathering and stripping, with formation of deep saprolites prior to Pleistocene glaciation followed by thinning of saprolites during glaciation, or whether more continuous etching has been involved is unclear. However the latter process almost certainly as been dominant in the formation of the Barra basin, one of a series of small basins along the lower Don valley. The lowest part of the basin floor corresponds with a zone of intense shearing (ASHCROFT & MUNRO 1978, figs. 4 and 5) and is underlain by deep grusses. In contrast, the mass of Barra Hill is composed of dislocated yet relatively unweathered basic cumulates which have remained little weathered. Over time these differences in resistance have lead to the progressive opening out of the basin form and the lowering of its floor to over 50 m below the crest of the marginal slopes.

Linear zones of deep alteration exist at a variety of scales. Trenches up to 300 m wide in the weathering front at Crichtie and Minnes appear to relate to localised fracturing and have been excavated by meltwater to create deep channels. Around Folla Rule in the Insch depression, linear zones of deeper and more advanced alteration correspond with shear zones up to 1 km across in which uralitisation and serpentinisation of the gabbro have predisposed the rock to subaerial weathering (LESLIE 1984). Segments of the Dee, Deveron and Ythan valleys are aligned along major faults and shear zones and it is likely that many large topographic corridors in north-east Scotland were already locked into belts of low resistance offered by major fractures well before the Pleistocene (c.f. ROLLAND 1975).

Scarp-foot weathering zones occur widely in the compartmented relief of inland areas and may reach depths of up to 50 m in the gabbros beneath the northern scarp of the Insch depression (LESLIE 1984). These zones may be found at various stages of exploitation by the drainage (fig. 5). The alignment of the scarps can generally be related to structural or lithological boundaries but differential weathering alone does not explain the decrease in weathering depths away from the scarp-foot. Rather it is the concentration and rapid throughput of groundwater at the base of scarps that promotes deep decomposition (BREMER 1975).

At the district scale, the relief of local assemblages of hills, basin and valleys generally exceeds that of the basal surface even in areas of the deepest surviving saprolites. These landforms are multi-cyclic features produced by a form of dynamic etchplanation (THOMAS 1976) in which geochemical controls on differential denudation are reinforced through time by the growing influence of the evolving topography on patterns of groundwater movement.

5 Regional weathering patterns and relief

The depth, incidence and continuity of the weathering covers remains spatially variable at the regional scale. Compilation of data from sections, boreholes and outcrops allows four weathering zones to be identified (fig. 6):
ZONE 1: Deep and continuous saprolites with few fresh outcrops. Saprolite thicknesses generally are at least 3 m and commonly exceed 10 m. Fresh outcrops are confined to highly resistant rocks.

ZONE 2: Thinner and discontinuous saprolites with fresh outcrops. Pockets of deep alteration remain but saprolites are generally less than 3 m thick. Fresh outcrops are common, especially on steep slopes and along valley floors.

ZONE 3: Fresh rocks with frequent pockets of weathering. Fresh rocks underlie most of the area. Weathering generally is found only in ice-lee locations on interfluvves and along valleys and is common only in tributary valleys and basins.

ZONE 4: Fresh rocks with rare pockets of weathering. Fresh rock predominates and occasional pockets of weathering usually relate to fracture zones.

A distinction is made between areas of gentle slopes and/or rocks of low to moderate resistance in which weathering was probably extensive prior to glaciation (Zone 4a) and areas of steep slopes and/or resistant rocks in which weathering probably was thinly or sporadically developed prior to glaciation (Zone 4b).

The regional distribution of these weathering zones reflects two basic controls, geology and the variable intensity of glacial erosion, each of which is related to topographic factors.

5.1 Geology

Grouping of section data shows that the incidence of weathering varies according to rock type (table 1).

The low resistance of biotite-bearing acid and basic igneous rocks is to be expected. The anomalously low apparent resistance of quartzite reflects the import-

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Table 1 Percentage of sections in weathered rock for different rock types.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>A</th>
<th>B</th>
<th>A/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite, biotite-rich</td>
<td>32.6</td>
<td>9</td>
<td>3.6</td>
</tr>
<tr>
<td>Granite, biotite-poor</td>
<td>8.5</td>
<td>8</td>
<td>1.1</td>
</tr>
<tr>
<td>Basic Igneous</td>
<td>20.6</td>
<td>10</td>
<td>2.1</td>
</tr>
<tr>
<td>Schist and gneiss</td>
<td>25.8</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>Quartzite</td>
<td>7.1</td>
<td>6</td>
<td>1.2</td>
</tr>
<tr>
<td>Slate</td>
<td>3.4</td>
<td>11</td>
<td>0.3</td>
</tr>
<tr>
<td>Old Red Sandstone</td>
<td>2.0</td>
<td>6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

(A) Percentage of total number of sections
(B) Percentage of total study area occupied by each rock type

n = 206
Vigorous, warm-based ice streams -+ Sluggish, cold-based tee streams

Regional weathering patterns and their relation to ice flow lines.

5.2 Variable intensity of glacial erosion

The distribution of weathering zones also reflects differences in the intensity of glacial erosion across the region. The Dee valley falls entirely within Zone 4a and ice streams moving out of the Cairngorms have swept the valley axis clear of weathered rock and locally lowered and moulded the basal surface. Coastal districts covered by the Moray Firth and Strathmore ice masses (CLAPPERTON & SUGDEN 1977) also have been significantly eroded, for few weathering sites are known from these areas (fig. 1) and bedrock surfaces emerging from beneath thick coastal till sheets are seen to be fresh and ice-moulded. In contrast, inland ice generally has been an ineffective agent of erosion and has allowed the preservation of deep saprolites and Tertiary gravels in Zone 1 areas. Consideration of preserved weathering depths, the degree of modification of preglacial palaeoforms and the intensity of glacial scour suggests that depths of glacial erosion have ranged from less than 10 m in parts of Zone 1 to 30-80 m in Zone 4a. These contrasts almost certainly relate to differences in ice sheet basal thermal regimes with inactive, cold-based ice covering most inland areas and significant erosion confined to warm-based ice streams flowing along the Moray Firth and North Sea coasts and along the Dee valley.

6 Discussion

The state of preservation of temperate weathering covers in north-east Scotland despite multiple glaciation is remarkable. Although the degree of chemical alteration generally is modest, disaggregation and weakening of rock reaches depths of several tens of metres. Whilst thick arenaceous weathering covers occur widely in warm temperate extra-glacial areas, there are few records of weathering to depths of more than 10 m within the limits of the Pleistocene glaciations (GODARD 1965, GAUTHIER 1980). However there are abundant references to shallow, isolated pockets of chemically weathered rock from regions bordering the North Atlantic (for a summary see HALL 1985). These are widely thought to represent truncated preglacial saprolites and the evidence from north-east Scotland suggests that these weathering covers were originally both deep and extensive.
Available mineralogical evidence indicates that most relict saprolites in glaciated areas are comparable in type and degree of alteration to the gruss weathering type found throughout north-east Scotland. The view of some writers (e.g. Büdel 1982) that the Pleistocene ice sheets first advanced over a lateritic blanket therefore is incorrect. This distinction is important for the the Scottish weathering patterns differ in several morphologically-significant aspects from weathering patterns reported from the humid tropics. In Scotland, (i) horizonation is not well-developed and colour, granulometry and clay mineralogy change gradually down-profile, (ii) thick transition zones frequently separate wholly disaggregated and fresh rock and a well-defined basal surface of weathering is atypical and (iii) rockhead profiles are often highly irregular, with depths of weathering varying by up to 35 m over distances of 100-1000 m.

In contrast, the main elements of meso-scale weathering patterns, namely alternating basins and risers, troughs of alteration and scarp-foot weathering zones, are directly comparable to features found in the humid tropics (Thomas 1966, Bremer 1975). That such similarities exist between temperate and humid tropical weathering systems indicates that weathering patterns at this scale primarily are a result of geological and, to a lesser extent, topographic controls.

In north-east Scotland, exploitation of weathering patterns has created a diversity of landforms and landscapes largely adjusted to lithological and structural variations. Many meso-scale relief forms are direct products of progressive thinning of weathering covers during the Pleistocene. In zones of relatively enhanced glacial erosion, such as the granite-floored Skene depression, ice action has scoured out zones of deep weathering from around resistant cores to give a structurally-aligned and weakly ice-moulded landscape of hills and ridges separated by elongate hollows. Over wide areas, however, glacial erosion has proved incapable of the complete or even partial removal of preglacial saprolites. Landforms such as the small, shallow basins common in central Buchan and along the lower Don valley seem to owe their essential characteristics to pre-existing weathering patterns and reflect stripping of friable regoliths in response to regional drainage incision and phases of periglacial activity. Such features are more a legacy of Pleistocene interstadial and interglacial periods than of glacial conditions.

At the regional scale the relief is well-adjusted to complex geology, with the margins of large topographic basins closely-defined by lithological boundaries and the main valleys preferentially-aligned along major faults and shear zones. North-east Scotland can be regarded as an etched landsurface and the weathering zones outlined earlier can be used to describe the variable degrees of glacial modification of this surface. Etching, or the bringing into relief of differential rock resistance by alternating phases of chemical weathering and stripping (Thomas 1978), was underway as early as the Devonian for several structurally-controlled basins and valleys are occupied by outliers of Old Red Sandstone (Sissons 1967). However the present outlines of the relief took shape during the Tertiary when phases of stripping induced by periodic uplift and climatic change removed saprolites developed during preceding phases of relative environmental stability. That the final phases, at least, of preglacial relief development took place under temperate climates is shown by the mineralogical characteristics of the arenaceous weathering covers (c.f. Godard 1965, 1969). Indeed the depths of gruss development, despite truncation, and the absence of more highly altered saprolites outside central Buchan indicates that all but the largest preglacial palaeoforms owe their present form to temperate, and not tropical, morphogenetic processes.

Acknowledgements

This work was carried out during tenure of a Research Scholarship at the University of St. Andrews. A grant towards the cost of illustrations (drawn by Mr. C. B. Bremer) was given by the Carnegie Trust for the Universities of Scotland. Borehole information was provided by the Department of Geology and Mineralogy, University of Aberdeen, RioFinEx Ltd and the British Geological Survey, Edinburgh. Unpublished data on sections was provided by Dr. M. Munro and Dr. E. A. FitzPatrick. Thanks are due to all these individuals and institutions an to the many other colleagues who have given advice and encouragement.

References


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