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The clay mineralogy and age of deeply weathered rock in north-east Scotland

by

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with 2 figures and 2 tables

Summary. The clay mineralogy of saprolites developed on a wide range of igneous and metamorphic rock types is described. In the less evolved gruss weathering type, clay mineral assemblages vary according to rock type but kaolinite and mica clays are usually dominant; gibbsite is occasionally present in the early stages of alteration of both quartz-rich and basic igneous rocks. The more evolved clayey gruss weathering type is more kaolinitic and often contains small amounts of hematite. Gibbsite is never associated with clayey gruss. The age of the saprolites is assessed using evidence from clay mineralogy, sediments and morphology. The clayey grusses probably developed under subtropical conditions in the Miocene as kaolinite contents in North Sea sediments dropped sharply after this period. Formation of grusses probably spans most of post-Miocene time, with formation of thick profiles under warm temperate conditions before the onset of regional glaciation and formation of shallow profiles during Quaternary interglacials.

Introduction

The occurrence of deeply weathered rock in formerly glaciated areas is now increasingly recognised. In north-east Scotland chemically-weathered rock is particularly widespread with over 500 weathering sites known, and is remarkably deep and continuous in areas like central Buchan, with maximum recorded depths of weathering of over 50 m (Hall 1985). The region is clearly a key area for the understanding of weathering and long-term relief development. The widespread availability of subsurface information has allowed preglacial weathering patterns to be identified at different scales in North-east Scotland (Hall 1986). These patterns have been related to the development of differentially weathered and eroded preglacial landscapes (Hall 1986, 1987) and also to the variable glacial transformation of a deeply weathered land surface (Hall & Sugden 1987). This paper is concerned with the clay mineralogy of the saprolites and its bearing on the problem of dating the period or

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periods under which the weathering took place. An outline of the geology and geomorphology of north-east Scotland is given in Hall (1986).

Clay Mineralogy

Previous work on the clay mineralogy of saprolites in north-east Scotland has concentrated on basic igneous rocks and clay formation during the initial stages of alteration of these rocks is now reasonably well understood (Wilson 1966, 1967, 1970, Basham 1974). The more common granite weathering profiles have received far less attention. Apart from the important early study of Milne (1952) in the Aberdeen area, the only recent study of granite weathering has been a detailed mineralogical analysis of a haematite/layer silicate clay mineral from a weathering profile on the Bennachie granite (Wilson et al. 1981). Similarly, the clay mineralogy of weathered metamorphic rocks has not been studied in detail, despite the extensiveness of these rocks in the region. Available information is confined to an investigation of two schist weathering profiles (Koppi 1977). Finally, mineralogical data are available for the weathering of granite and granulite clasts in an Old Red Sandstone boulder conglomerate (Wilson et al. 1971) and in the late Tertiary Buchan Ridge Gravels Formation (Koppi & FitzPatrick 1980).

In an effort to extend information on saprolite clay mineralogy and to aid in the characterisation of different weathering types, Hall (1983) analysed the mineralogy of the <2 μm fraction for 62 sites using X-ray diffractometry. Weathering of a wide range of rock types as considered and rock type was found to be a fundamental control on clay mineralogy. Important variations in clay mineralogy were also identified, however, within major lithological groups which reflected different degrees of chemical alteration and, to a lesser extent, differences in former drainage status.

This paper aims to build on this work by presenting detailed data for 29 sites (Fig. 1) on the clay mineralogy of saprolites in different rock types and at different stages of chemical alteration. Granulometry is used as an index of the degree of chemical alteration. Previous studies (Wambeke 1962, Seddoh 1933) have shown that the clay (<2 μm) and silt (2–63 μm) fractions increase as alteration progresses and geochemical analyses of 10 profiles in north-east Scotland have confirmed that soluble base losses increase with clay contents (Hall 1983). Here 3 granulometric groups are defined, following established French terminology (Flageollet 1977), which are taken to represent different levels of chemical alteration:

Granular Grusses	median grain sizes are >1000 μm, silt contents are $<15\%$ and clay contents are $<3\%$.
Grusses	median grain sizes are <1000 μm, silt contents are 15–25% and clay contents are $<6\%$.
Clayey Grusses	median grain sizes are <1000 μm and may be <500 μm. Silt contents are $>25\%$ and clay contents are $>6\%$ and may exceed 15%.

This classification is readily applicable to coarse-grained rocks, notably granite, gabbro and psammitic metamorphic rocks, all of which break down initially by

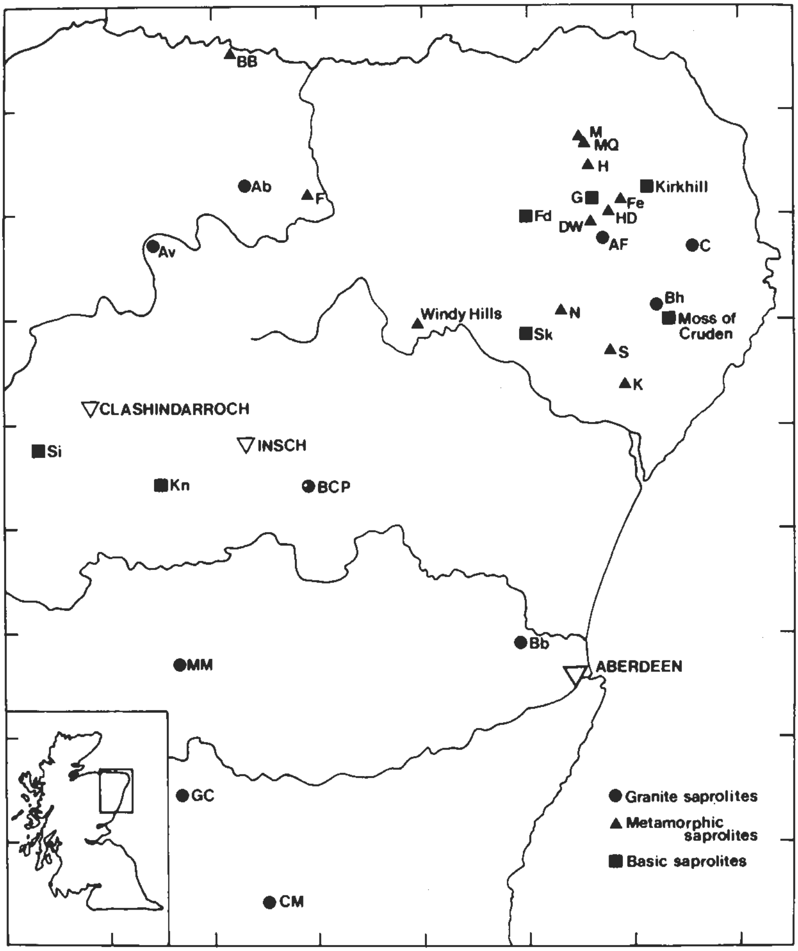

Fig. 1. Location Map.
Ab Aberchirder, AF Aikey Fair, Av Avochie, Bb Bucksburn, BB Boyne Bay, BCP Bennachie Car Park, Bh Backhill, C Cairngall, CM Cairn o'Mount, DW Drinnies Wood, F Forglen, Fd Fedderate, Fe Fetterangus, G Gaval, GC Glen Cat, H Howford, HD Howe of Dens, K Kinmuck, Kn Knockespock, M. Moss-side, MQ Mormond Quarry, MM Mill Maud, N Northseat, S Sunnyside, Si Silverford, Sk Skilmafilly.

granular disintegration. It is less useful with pelitic metamorphic rocks which produce saprolites with relatively high silt contents reflecting release of primary minerals during weathering.

The clay mineralogy of a matrix of weathering sites has been examined which allows the influence of both rock type and increasing chemical alteration on clay mineralogy to be considered (Table 1). Clay mineralogy has been examined as

Table 1. Clay mineralogy of major rock types

Rock-Type	Site	Grid Ref.	% < 2 μ	% < 63 μ	Granitic Saprolites										
						K	H	M	S	M/S	C	G	Hm	Q	F
Acid Granite	Cairn o'Mount	NO 652830	1.2	7.3	GG	XX	–	XXX	–	–	–	X	–	–	TR
	Glen Cat	NO 574949	2.2	8.3	GG	XX	X	–	–	–	XX	–	–	X	TR
	Mill Maud	NJ 566067	2.1	17.5	G	XXX	–	XX	–	–	–	–	–	–	TR
	Bennachie Car Park	NJ 693245	17.0	45.0	CG	XXX	–	XX	–	–	–	–	X	–	–
Biotite Granite	Avochie	NJ 542470	1.3	8.6	GG	XX	–	XX	–	–	–	–	–	TR	TR
	Aberchirder	NJ 632528	1.9	7.0	GG	X	–	XX	–	X	X	–	–	–	TR
	Aikey Fair	NJ 963578	0.5	15.4	GG	–	XX	XX	–	–	–	–	–	TR	–
	Bucksburn	NJ 893093	3.4	16.0	G	?	XX	XX	–	–	–	–	–	X	TR
	Backhill	NK 026407	3.6	26.1	G	XX	X	XX	X	–	–	–	–	–	–
	Cairngall	NK 053471	6.4	26.0	CG	XXX	–	X	–	–	–	–	–	TR	–
					Basic Igneous Saprolites										
						K	H	M/V	S	M/S	C	G	Hm	Q	F
Norite	Fedderate	NJ 885505	1.8	11.3	GG	X	–	X	–	–	–	XX	–	–	–
	Kirkhill	NK 012528	3.4	18.3	G	–	XX	XXX	–	–	–	–	–	X	–
Diorite	Cruden Borehole	NK 028402	43.5	75.5	CG	XX	–	XX	–	–	–	–	–	–	–
Gabbro	Silverford	NJ 432253	0.2	6.7	GG	–	–	XX	–	–	–	–	–	–	–
	Skilmafilly	NJ 898394	2.5	33.1	G	–	X	X	–	–	X	–	–	–	–
	Gaval	NJ 974513	9.0	34.0	CG	–	XX	XX	–	–	–	–	–	–	–
Serpentinite	Knochespock	NJ 552243	3.8	16.0	G	–	–	–	XXX	–	–	–	–	–	–
					Metamorphic Saprolites										
						K	H	M	S	M/S	C	G	Hm	Q	F
Quartz Psammite	Moss-side	NJ 949568	2.1	9.1	GG	–	XX	XX	–	–	–	XX	–	X	X
	Fetterangus	NJ 989516	4.9	12.0	G	XX	–	XXX	–	–	–	TR	–	TR	TR
	Howe of Dens	NJ 975805	13.7	49.8	CG	XXX	–	X	–	–	–	–	X	TR	–
	Mormond Quarry	NJ 950568	12.0	32.0	CG	XXX	–	X	–	–	–	–	X	X	–
	Sunnyside	NJ 983372	15.4	43.0	CG	XXX	–	XX	–	–	–	–	X	TR	–
Feldspar Biotite Psammite	Northseat	NJ 930408	4.5	22.8	G	X	X	XX	–	–	X	–	–	TR	–
	Howford	NJ 954547	8.2	41.3	CG	XX	X	XX	–	–	–	–	–	–	–
	Drinnies Wood	NJ 973497	19.2	39.9	CG	XXX	–	X	–	–	–	–	TR	TR	–
Pelite	Kinmuck	NJ 991341	7.1	20.1	G	XX	–	XX	–	XX	–	–	–	TR	–
	Forglen	NJ 693512	3.9	34.4	G	XX	–	XXX	–	–	–	–	–	X	–
	Windy Hills Borehole	NJ 793393	22.2	94.7	CG	XXX	–	XX	–	–	–	–	–	X	–
Calc schist	Boyne Bay	NJ 615660	4.8	36.1	G	TR	–	X	–	XXX	–	–	–	TR	–

XXX, Dominant (> 50%); XX, Abundant (25–50%); X, Subordinate (5–25%); TR, Trace (< 5%); GG, Granular Gruss; G, Gruss; CG, Clayey Gruss; C, Chlorite; G, Gibbsite; Hm, Haematite; Q, Quartz; F, Feldspar; K, Kaolinite; H, Halloysite; M, Mica; S, Smectite; M/S, Mica-Smectite; M/V, Mica-vermiculite.

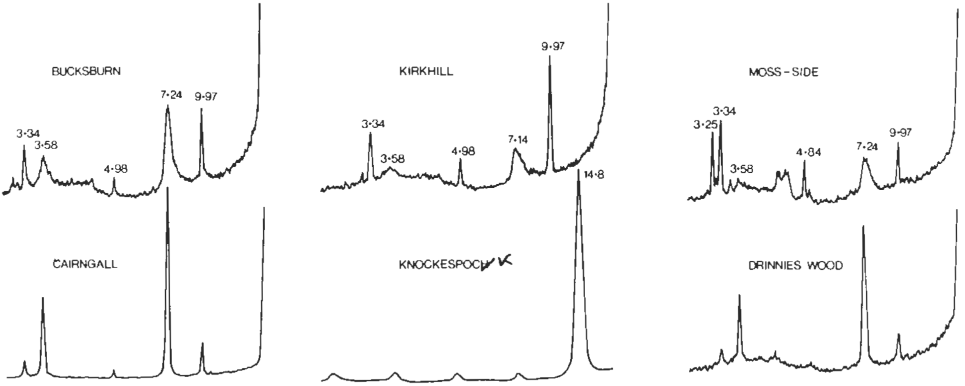

Fig. 2. Representative XRD traces. Oriented runs on glass slides, untreated. Interpretations given in Table 1.

follows. Weathered rock samples were gently disaggregated so that the original particle size distribution was preserved. The samples were then ultrasonically dispersed in distilled water and the clay fraction (<2 μm) separated by centrifugation. Oriented clay samples were prepared by sedimentation on to glass slides. X-ray diffraction was conducted on a Philips 2 kW diffractometer using Co$k\alpha$ radiation at a scanning speed of $2°2\theta$ min^{-1}. The clay samples were scanned through the range $3-35°2\theta$ before and after glycol saturation and heat treatments (300° ad 500 °C). Representative XRD traces are shown in Fig. 2.

Granitic saprolites contain kaolinite-mica clay mineral assemblages which are largely independent of the degree of granulometric evolution and chemical alteration. In the initial stages of weathering feldspar is little affected and kaolinite and occasionally gibbsite are associated with feldspar. Biotite may be altered to vermiculite (Milne 1952). In grusses, kaolinite dominates on acid granites whereas halloysite tends to be more important on biotite granites. At Bennachie Car Park advanced alteration of acid granite has lead to the complete replacement of many feldpsars by kaolinite and to the development of a hematite-layer silicate clay mineral (macaulayite) which is associated with zones of intense rubefaction (Munsell Colour IOR 5/8) in the saprolite (Wilson et al. 1981, Wilson et al. 1984).

Basic igneous saprolites contain a wide range of clay minerals. Basham (1974) has shown that weathering of the Insch gabbro leaves feldspar and hornblende largely unaffected, that pyroxene alters initially to iron oxides and later to vermiculite, and that biotite weathers to hydrobiotite and vermiculite and, occasionally, kaolinite and gibbsite. Vermiculite may also dominate on the norites and gabbros of Buchan, but kaolinite is also present commonly, in significant proportions, and occasional gibbsite may be found, as at Fedderate. Only two sites are known where basic igneous rocks are altered to clayey grusses and both may have been affected by acid groundwaters. At Gaval a gabbroic dyke within quartzites is altered to halloysite and illite, with minor vermiculite, and at Moss of Cruden a borehole through the kaolinitic Buchan Ridge gravels met highly altered diorite or norite dominated by kaolinite and illite. Smectite dominates the clay fraction of the serpentinite at Knockespock but is generally not present in significant amounts in other basic saprolites.

On metamorphic rocks, quartz psammites show similar transformations to those found in acid granites, with dominance of kaolinite and with occasional presence of gibbsite during the early stages of alteration. Feldspar-biotite-psammites are dominated by kaolinite, halloysite and illite clays, and biotite may be converted to vermiculite (KOPPI 1977). With increasing contents of ferro-magnesian primary minerals, weathered metamorphic rocks often show decreasing kaolinite and increasing smectite contents. Altered metalimestones are dominated by smectite, partly inherited from the parent rock (WILSON et al. 1968). Inheritance is also of considerable importance in the weathering of pelites, with release of illite and chlorite during rock breakdown, and kaolinite appears to be the most important weathering product.

The dominant transformations at different stages of weathering for primary minerals of the main rock types are shown in Table 2. A number of general points can be made about the clay mineralogy.

1. *Gibbsite* is sometimes present in the early stages of alteration but is apparently absent from more evolved saprolites.

It is most common in granular grusses and grusses developed on acid granites and quartz schists and may be pseudomorphed after plagioclase. The association of gibbsite with acid rocks has previously been noted in arenes from the Massif Central (DEJOU, GUYOT & ROBERT 1974, PEDRO, SEDDOH & DELMAS 1975). Gibbsite also appears, however, as a minor constituent of clay fractions on basic granular grusses and grusses where it is derived from biotite (WILSON 1966, BASHAM 1974) and plagioclase (WILSON 1969).

Table 2. Dominant transformations for primary minerals in different rock groups

		Granular Gruss	Gruss	Clayey Gruss
Acid	Na-feldspar	k, g	k	k
Granite	K-feldspar	–	k	k
Biotite	Na-feldspar	h, k, g	h, k	k
Granite	K-feldspar	–	k	k
	Biotite	m/v	c, k	k
Gabbro	Ca-feldspar	g, k, h	h, k, g	k, h
	Pyroxene	m/v	m/v	?
	Biotite	m/v	m/v, k, g	m/v
Quartz	Na-feldspar	g, h	k	k
Psammite	K-feldspar	–	k	k
Feldspar	Na-feldspar	N/A	k, h	k
Biotite	K-feldspar	N/A	k, h	k
Psammite	Biotite	N/A	c	k, hm

N/A Not applicable. Other abbreviations as for Table 1.

Gibbsite will only form when drainage is good and silica concentrations in groundwater are low (GARDNER 1972), conditions that may be encountered in the highly permeable medium produced by granular disintegration of rocks containing only small amounts of weatherable minerals, for example acid crystalline rocks with low quantities of Ca-feldspar and ferromagnesian minerals. In basic grusses the situation is different for here aluminous hydroxides may be left as residues from the desilicification of plagioclase (WILSON 1969).

2. *Kaolinite and halloysite* may be present in the early stages of alteration.

Kaolinite (usually disordered) dominates the clay fractions in granular grusses derived from granites and quartz-schists. Halloysite is associated with less acid parent rocks and its formation is apparently favoured by the higher concentrations of basic cations (c.f. DEJOU et al. 1972). Kaolinite also occurs in relatively small amounts in basic granular grusses where it is derived from biotite (WILSON 1966, BASHAM 1974) and, perhaps, also Ca-feldspar. The presence of kaolinite/halloysitic clays during initial alteration is again a reflection of the high permeability of the granular grusses (DEJOU & PEDRO 1967).

3. *Mature kaolinite/illite assemblages* dominate at the later stages of alteration on all rock types.

Kaolinite is generally dominant and may be of the well-ordered or disordered types. It is probably derived from Ca-feldspar, K-feldspar and, to a lesser extent, biotite. Biotite is also partly altered to haematite and geothite. This has contributed to the rubefaction of certain clayey grusses but the main source of pigmentary iron was probably at higher levels of these weathering profiles, now denuded (WILSON et al. 1981).

The age of the saprolites

Using data on granulometry and clay mineralogy, backed by geochemistry, HALL (1983, 1985) has identified two weathering types in north-east Scotland. The more evolved but spatially-restricted *clayey gruss* weathering type includes saprolites in the clayey gruss granulometric group which also show high (> 50%) soluble base losses and, at some sites, rubefaction and etching of quartz. The dominance of kaolinitic-illitic clay mineral assemblages on different rock types for these mature saprolites has been described above. The less altered gruss weathering type is known at several hundred sites throughout north-east Scotland. The gruss weathering type includes the granular gruss and gruss granulometric groups and contains abundant little-altered primary minerals. Soluble base losses are generally 50%. The varied and relatively immature clay mineral assemblages of the grusses have already been described. The gruss and clayey gruss weathering types described above correspond closely with the 'sandy' and 'clayey' saprolites widely recognised in continental Europe (BAKKER 1967, MILLOT 1970).

The greater degree of chemical alteration of the clayey grusses implies that saprolites of this type are older than those of the gruss weathering type. The question of age, however, is complicated by the fact that boreholes in central Buchan show that thick saprolites of gruss type may occasionally underlie clayey gruesses as p of single weathering profiles. In this area, therefore, grusses may represent the b parts of profiles whose upper horizons were originally of clayey gruss type, prio truncation. Outside central Buchan, however, it is likely that the grusses repres a separate phase of deep weathering. Evidence for this includes:

1. the rarity of clayey grusses outside central Buchan. Only two exposures known. These are the rubefied and kaolinised granite at Bennachie Car F (WILSON et al. 1981), described earlier, and a highly altered metasediment fı Clashindarroch Forest (KOPPI 1977) (Fig. 1).
2. the lack of evidence from soil and drift mineralogy for the widespread gla reworking of former highly kaolinitic saprolites (WILSON et al. 1984).
3. the thicknesses of gruss weathering profiles, with depths of over 20 m recor in numerous boreholes (HALL 1986).
4. the clay mineralogy of the grusses, which generally indicates clay forma under free draining conditions which are unlikely to have prevailed towards base of weathering profiles.

The gruss weathering type can thus generally be regarded as the product separate, prolonged phase of deep weathering which took place after formatio clayey grusses had effectively ceased. The possible ages of these two period weathering must now be assessed.

Clayey Gruss Weathering Type

The degree of alteration shown by the clayey grusses of north-east Scotland beyond that of most saprolites reported from formerly glaciated areas and beyond that of Pleistocene arenaceous saprolites found south of the limits of gl tion in France and West Germany. The clayey grusses most closely resemble in and degree of alteration mature Late Tertiary arenes in Brittany (ESTEOUELLE-CH 1967) and Limousin (SEDDOH 1973) which show elevated silt contents, kaoli mica clay mineral assemblages and marked rubefaction.

The mineralogical changes found in the clayey grusses are similar to those fo in weathered granites in humid tropical environments (TARDY et al. 1973) and al certainly reflect warmer climates than those which prevailed in Scotland durin Pleistocene. Humid temperate conditions dominated during the Neogene in North Sea area (BUCHARDT 1978) and it is possible that the clayey grusses re prolonged alteration on stable sites over this period. Evidence from the minera of North Sea sediments suggests, however, that intense kaolinisation had alı ceased, for kaolinite is progressively replaced by chlorite and illite from the Miocene onwards (KARLLSON et al. 1979, BERSTAD & DYPVIK 1982). The ma change in mineralogy corresponds with abrupt cooling from subtropical to ter ate environments at c. 10 Ma (MUDIE & HELGASON 1983) and presumably re the progressive stripping of kaolinitic regoliths developed under warm clir earlier in the Tertiary and their gradual replacement by sandy saprolites (BA 1967).

The Mio-Pliocene boundary defines a probable minimum age for the c grusses. These saprolites may be considerably older than this. Warm and h environments prevailed in Britain during much of the Palaeogene and Miocene. Palaeogene kaolinitic weathering profiles are observed in south-west England and these, together with high kaolinite contents in contemporaneous sediments, provide evidence of prolonged and deep kaolinisation (Isaac 1983). In central Buchan clayey grusses are found juxtaposed with and locally underlying gravels of the Buchan Ridge Gravels Formation, fluvial deposits of probable Late Tertiary age. These gravels incorporate large volumes of Cretaceous flint, some of it cavernous and little-travelled, and demonstrate that this part of Buchan has not been greatly lowered in the Tertiary (Hall 1987). A Mesozoic age for the underlying kaolinised bedrock is therefore possible. Such a great age in unlikely, however, as

1. no in situ Mesozoic sediments have yet been found in Buchan,
2. development of the clayey gruss at the isolated site at the foot of Bennachie must post-date uplift of this granite in the Early Tertiary and
3. the flint gravels are themselves intensely weathered (Koppi & Fitzpatrick 1980), with kaolinisation of non-resistant clasts through 25 m of deposit at Moss of Cruden (McMillan & Merrit 1980).

The simplest view is that the clayey grusses need be no older than the Miocene. Subtropical climates suited to kaolinisation prevailed in Scotland during the Miocene (Buchardt 1978) and kaolinitic clays of this age are known in offshore boreholes (Evans et al. 1981). A greater age is possible but is currently without support.

Gruss Weathering Type

The type and degree of alteration shown by the grusses in north-east Scotland is similar to that of other saprolites in formerly glaciated areas and to that of certain Pleistocene arenes beyond the glacial limits in France. The appearance of kaolinite in the early stages of alteration has been noted in central Finland (Lahti 1985) and from the Morvan, France (Dejou 1967). The presence of gibbsite in arenaceous granite weathering profiles is recorded from several extra-glacial areas, including south-west England (Green & Eden 1971), the Morvan (Pedro et al. 1975) and west-central Spain (Torrent & Benayas 1977). Mica-schist arenes from the Massif Central are dominated by kaolinite/halloysitic clays (Dejou et al. 1974), as in north-east Scotland. Finally, the mineralogy of the basic grusses is comparable to those found in western Norway (Roaldset et al. 1982). In short, clay mineralogy and granulometry show that the gruss weathering type belongs to the family of 'sandy' weathered rocks (Bakker 1967) which occur throughout western Europe, both within and beyond the Pleistocene glacial limits.

The clay mineralogy of the grusses indicates development under humid temperate environments. The importance of kaolinite and presence of gibbsite in the grusses, even on basic parent rocks, demonstrates humid conditions during weathering. Temperatures may have been somewhat higher than at present (Basham 1974) as the clay mineral transformations in the more evolved grusses are more advanced than those in Holocene soils in north-east Scotland (Wilson et al. 1984) and are comparable to those found in young arenes in France (Tardy et al. 1973).

Humid temperate conditions prevailed in Scotland during the Pliocene, the preglacial Pleistocene and interglacial periods. The depths of gruss development, with numerous boreholes recording over 20 m of gruss, indicates that many gruss profiles reflect prolonged weathering, probably dating from the Pliocene. Many thin grusses must represent the truncated remnants of former preglacial deep profiles. Specific support for a preglacial age for grussification at some sites is provided by

1. the presence of norite gruss beneath a sequence of Middle Pleistocene glacial, fluvioglacial and periglacial sediments at Kirkhill (Fig. 1) (HALL 1984) and
2. the presence of hydromorphic Fe and Mn minerals in gruss weathering profiles which now occupy free-graining sites on valley sides. Weathering must, therefore, predate regional drainage incision during the middle Pleistocene.

General support for preglacial grussification is given by the strong influence which pre-existing weathering patterns have exerted over the morphology of land forms of glacial and fluvioglacial erosion (HALL 1986, 1987, HALL & SUGDEN 1987).

Bedrock grussification almost certainly continued during Pleistocene interglacials. Evidence for this is provided by granular disintegration of clasts in weathered Saalian tills (HALL 1984) and frequently also of suseptible biotite-rich clasts in Weichselian tills and gravels. The continuity of grussification seems assured but the depth of gruss development during interglacials is uncertain. BOARDMAN (1985) describes interglacial weathering of the pre-Devensian Thronsgill Till in Cumbria, England, with grussification of andesite and microgranite clasts down to 15 m at one site. The depth of weathering of this till far exceeds that recorded in pre-Weichselian weathered tills in north-east Scotland or, indeed, anywhere else in Britain and may reflect unusual site conditions. Bedrock weathering appears to have been very limited during the present interglacial in north-east Scotland and even shallow granular grusses can often be shown to be of pre-Weichselian age by the incorporation of weathering products into overlying Weichselian glacial and periglacial deposits. Gruss development during earlier interglacials of similar climate and duration must also have been slight and thick gruss development would seem to require periods considerably in excess of 10 ka.

References

BAKKER, J. P. (1967): Weathering of granite in different climates, particularly in Europe. – In: MACAR, P. (ed.): L'évolution des versants. – Congr. Coll. L'Univ. Liège **40:** 51–68.

BASHAM, I. R. (1974): Mineralogical changes associated with deep weathering of gabbro in Aberdeenshire. – Clay Minerals **10:** 189–200.

BERSTAD, S. & H. DYPVIK (1982): Sedimentological evolution and natural radioactivity of Tertiary sediments from the central North Sea. – J. Petroleum Geol. **5:** 77–88.

BOARDMANN, J. (1985): The Troutbeck Paleosol. Cumbria, England. – In: BOARDMAN, J. (ed.): Soils and Quaternary Landscape Evolution, 231–260.

BUCHARDT, B. (1978): Oxygen isotope palaeo-temperatures from the Tertiary period in the North Sea area. – Nature **275:** 121–123.

CARLLSON, W., J. VOLLSET, K. BJØRLYKKE & P. JORGENSEN (1979): Changes in the mineralogical composition of Tertiary sediments from North Sea wells. – Proc 6th Internat. Clay Conf. **27:** 281–289.

DEJOU, J. (1967): Sur l'alteration des granites à deux micas du massif de la Pierre-qui-Vire (Yvonne-Nievre). – C. R. Acad. Sc. Paris **264:** 37–40.

DEJOU, J. & G. PEDRO (1967): A propos de la formation des arènes dans les pays temperées et de la presence de kaolinite au sein de la zone l'alteration. – Bull. Assoc. fr. Etude Sol **1:** 1–4.

DEJOU, J., J. GUYOT & C. CHAUMONT (1972): Alteration superficielle des diorites dans les regions temperées humides: exemples choisis dans le Limousin. – Bull. Serv. Carte Géol. Als. Lorr. **25:** 259–286.

DEJOU, J., J. GUYOT & M. ROBERT (1974): Differenciations observées du cours de l'évolution géochimique superficielle entre les roches acides (granites, micaschists) et les roches basiques (diorites) dans les régions temperées humides. – C. R. Acad Sci. Ser. D **279:** 233–226.

ESTÉOUELLE-CHOUX, J. (1973): Contribution à l'étude des argiles due massif Amoricain. – Thesis. Univ. of Rennes, 319 pp.

EVANS, D., J. A. CHESHER, C. E. DEEGAN & N. G. T. FANNIN (1981): The offshore geology of Scotland in relation to the IGS shallow drilling programme, 1970–1978. – Rep. Inst. Geol. Sci. No. **81/12.**

FITZPATRICK, E. A. (1963): Deeply weathered rock in north-east Scotland, its occurrence, age and contribution to the soils. – J. Soil Sci. **14:** 33–42.

FLAGEOLLET, J. C. (1977): Origine des reliefs, alterations et formations superficielle; contribution à l'étude géomorphologique des massifs ancien cristallines; l'example du Limousin et de la Vendee du Nord-Ouest. – Science de la Terre Mém. No. **35.**

GARDNER, L. R. (1972): Conditions for direct formation of gibbsite from K-feldspar: Further discussion. – Amer. Mineral. **57:** 294–300.

GREEN, C. P. & M. J. EDEN (1971): Gibbsite in the weathered Dartmoor granite. – Geoderma **6:** 315–317.

HALL, A. M. (1983): Weathering and landform evolution in north-east Scotland. – Unpub. Ph. D. thesis, Univ. of St. Andrews.

– (1984): Buchan Field Guide. – Quat. Res. Assoc., Cambridge.

– (1985): Cenozoic weathering covers in Buchan. Scotland, and their significance. – Nature **315:** 392–395.

– (1986): Deep weathering patterns in north-east Scotland and their geomorphological significance. – Z. Geomorph. N. F. **30:** 407–422.

– (1987): Weathering and relief development in Buchan, Scotland. – In: GARDINER, V. (ed.): International Geomorphology 1986 Part II. – Wiley, 991–1005.

HALL, A. M. & D. E. SUGDEN (1987): Limited modification of mid-latitude landscapes by ice sheets: The case of north-east Scotland. – Earth Surface Processes and Landforms **12:** 531–542.

ISAAC, K. P. (1983): Tertiary lateritic weathering in Devon, England, and the Palaeogene continental environment of South-west England. – Proc. Geol. Assoc. **94:** 105–114.

KOPPI, A. J. (1977): Weathering of Tertiary gravels, a schist and a meta-sediment in north-east Scotland. – Ph. D. thesis, Univ. of Aberdeen.

KOPPI, A. J. & E. A. FITZPATRICK (1980): Weathering in Tertiary gravels in north-east Scotland. – J. Soil Sci. **31:** 525–532.

LAHTI, S. I. (1985): Porphyritic pyroxene-bearing granitoids – a strongly weathered rock group in central Finland. – Fennia **163:** 315–321.

LIDMAR-BERGSTRÖM, K. (1982): Pre-Quaternary geomorphological evolution in southern Fennoscandia. – Sver. Geol. Unders. Ser. C. No. **785,** 202 pp.

MCMILLAN, A. A. & J. MERRITT (1980): A reappraisal of the Tertiary deposits of Buchan, Grampian region. – Rep. Inst. Geol. Sci. No. **80**/1.

MILLOT, G. (1970): The Geology of Clays. – Chapman and Hall, London.

MILNE, A. (1952): An investigation of the mineralogical changes involved in the weathering of granites in the vicinity of Aberdeen. – Ph. D. thesis, Univ. of Aberdeen.

Mudie, P. J. & J. Helgason (1983): Palynological evidence for Miocene climatic cooling in eastern Iceland about 9.8 Myr ago. – Nature **303:** 689–692.

Peulvast, J.-P. (1985): In situ weathered rocks on plateaus, slopes and strandflat areas of the Lofoten-Vesteralen, North Norway. – Fennia **163:** 333–340.

Roaldset, E., E. Pettersen, O. Longva, & J. Mangerud (1982): Remnants of preglacial weathering in western Norway. – Norsk Geologisk Tiddskrift **62:** 169–178.

Seddoh, F. (1973): Altération des roches cristallines du Morvan. – Mem. Geol. Univ. Dijon. No. 1.

Tardy, Y., G. Bocquier, H. Pacquet & G. Millot (1973): Formation of clay from granite and its distribution in relation to climate and topography. – Geoderma **10,** 271–284.

Torrent, J. & J. Benayas (1977). Origin of gibbsite in a weathering profile from granite in west-central Spain. – Geoderma **19:** 37–49.

Wambeke, A. R. van (1962): Criteria for classifying tropical soils by age. – J. Soil Science **13:** 124–132.

Wilson, M. J. (1966): The weathering of biotite in some Aberdeenshire soils. – Miner. Mag. **25:** 269–276 and 1080–1093.

– (1967): The clay mineralogy of some soils derived from a biotite-rich quartz gabbro in the Strathdon area, Aberdeenshire. – Clay Minerals **7:** 91–100.

– (1970): A study of the weathering in a soil derived from biotite-hornblende rock. – Clay Minerals **8:** 291–303.

Wilson, M. J., D. C. Bain & W. A. Mitchell (1968): Saponite from the Dalradian metalimestones of north-east Scotland. – Clay Minerals **7:** 343–349.

Wilson, M. J., D. C. Bain & W. J. McHardy (1971): Clay mineral formation in a deeply weathered boulder conglomerate in north-east Scotland. – Clays and Clay Minerals **19:** 345–352.

Wilson, M. J. & J. M. Tait (1977): Halloysite in some soils from north-east Scotland. – Clay Minerals **12:** 59–66.

Wilson, M. J., J. D. Russell, J. M. Tait, D. R. Clark, A. R. Fraser & I. Stephen (1981): A swelling haematite/layer silicate complex in weathered granite. – Clay Minerals **16:** 261–278.

Wilson, M. J., D. C. Bain & D. M. L. Duthie (1984): The soil clays of Great Britain: II. Scotland. – Clay Minerals **19:** 709–735.

Wilson, M. J., J. D. Russell, J. M. Tait, D. R. Clark & A. D. Fraser (1984): Macaulayite, a new mineral from north-coast Scotland. – Miner. Mag. **48:** 127–129.

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