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Cenozoic weathering covers in Buchan, Scotland and their significance

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Isolated occurrences of chemically weathered rock or saprolite are common in many formerly glaciated areas around the North Atlantic[1-6]. These pockets of saprolite are widely regarded as remnants of Cenozoic deep-weathering covers which existed before the first extensive Northern Hemisphere glaciations at ~2.4 Myr (ref. 7) and their apparent survival has long been used as evidence for the local ineffectiveness of glacial erosion[2,4,8,9]. However, the scarcity of correlative deposits means that the age and significance of these fragmented saprolites are uncertain. I report here the results of a detailed survey which shows that in Buchan, Scotland, a combination of Cenozoic tectonic stability and extremely limited Pleistocene glacial erosion has allowed the preservation of deep-weathering covers of probable Miocene to early Pleistocene age on a scale not previously reported from any other formerly glaciated area.

Buchan is an area of subdued relief lying at the angle of north-east Scotland (Fig. 1). The geology consists largely of Precambrian to Dalradian metamorphic rocks intruded by Caledonian acid and basic igneous masses[10]. The only sedimentary rocks onshore are Devonian Old Red Sandstones but thick accumulations of Mesozoic and Palaeogene sediments lie offshore.

In Buchan, saprolites are continuous over wide areas[11] and maximum depths exceed 60 m in boreholes[12,13] (Fig. 2). All major rock types are affected and alteration decreases with depth, indicating that weathering is a product of subaerial rather than hydrothermal alteration.

Within major lithologies, saprolite characteristics vary widely and reflect important differences in the degree of chemical alteration. Data on granulometry and clay mineralogy, backed by geochemistry, indicate that two main weathering types exist. Most widespread is the gruss weathering type in which a relatively low degree of alteration has caused disintegration into a granular sand. Gruss is characterized by an abundance of little-altered primary minerals, low fines contents, low soluble base losses and heterogeneous and immature clay mineral assemblages (Table 1). The second weathering type, clayey gruss, is virtually confined to central Buchan. Here advanced alteration has reduced parent rocks to a sticky, clayey silty sand. Detrital primary mineralogy is dominated by quartz, fines contents are relatively high, and clay mineral assemblages consist of mature kaolinite–illite suites. At several sites, clayey grusses are rubefied due to the presence of haematite and goethite. This distinction between grusses and clayey grusses is comparable with others made for granite weathering covers in Europe south of the limits of Pleistocene glaciation[5,14,15].

The relative ages of the two weathering types can be established using evidence from correlative deposits, saprolite mineralogy and geomorphology. All deep weathering in north-

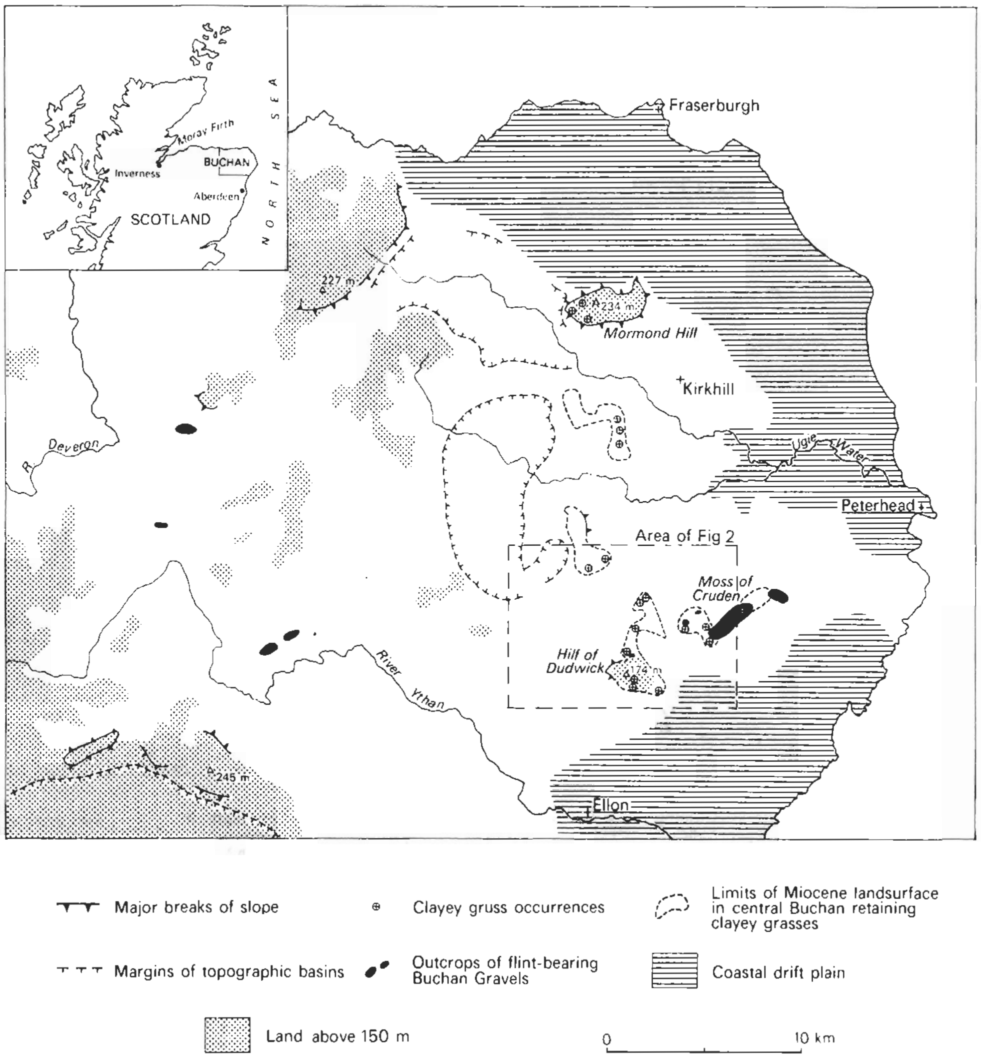

Fig. 1 Location and relief.

east Scotland must predate the last glaciation as materials reworked from subjacent and adjacent saprolites form a major component of Devensian tills and congeliturbates[11,16,17]. Evidence that many gruss weathering profiles are of middle Pleistocene age or older is provided by: (1) the presence of weathered biotite and feldspar and inherited clays throughout the middle to late Pleistocene sequence of glacial, glacifluvial and periglacial deposits at Kirkhill[18,19]; and (2) the presence of hydromorphic iron and manganese minerals in weathering profiles now occupying free-draining sites[20]. These minerals indicate that weathering had already extended close to and probably below the water table before a major change in groundwater drainage status during the Pleistocene in response to regional drainage incision.

Suggestions that deep weathering is wholly of interglacial age[21] may also be rejected in view of the disparity between rates of rock alteration during the present interglacial[2], the relatively short durations (~10-30 kyr) of previous interglacials[22] and observed depths of weathering. Formation before the glacial Pleistocene is indicated.

The dominance of kandite and illite clay mineral assemblages in acid igneous and metamorphic grusses[20] and hydrous mica-amorphous iron oxide assemblages in basic igneous grusses[16] indicates weathering under humid temperate environments. However, the intensity of alteration shown by the clayey grusses requires warmer, probably subtropical climates[14,15]. Marine palaeotemperatures[23] and terrestrial palynology[24] indicate that subtropical climates last prevailed in the Scottish area during the middle Miocene (10 Myr). Major climatic cooling after this time[23,24] is reflected in the mineralogy of North Sea well samples, with appearance of chlorite and amphibole and increases in illite and feldspar contents[25,26], and in a transformation in styles of rock weathering throughout western Europe with the first development in the Tertiary of sandy saprolites retaining significant amounts of detrital feldspar and biotite[5,14]. I conclude that the clayey gruss weathering type predates the late Miocene and that the gruss weathering type developed continuously throughout the Pliocene and early Pleistocene.

The clayey grusses are virtually confined to a north-south belt of high ground in central Buchan (Fig. 1) which represents the remnants of a Miocene or older landsurface. Around Hill of Dudwick, the clayey grusses are juxtaposed with and underlie outcrops of the Buchan Ridge Formation. These intensely-weathered gravel deposits comprise clasts of rolled Cretaceous flint and Dalradian quartzite with a matrix of quartz sand and kaolinitic fines[27], and are widely regarded as Tertiary in age[28-30]. At Moss of Cruden, the gravels are >25 m thick and include clasts of little-travelled nodular flint. The preservation of such large volumes of flint suggests that Buchan has remained close to base-level since marine transgression in the late Cretaceous. This reflects the position of Buchan at the stable eastern extremity of the Scottish Highlands, an area repeatedly tilted westwards towards the rapidly subsiding North Sea basin in the Tertiary[31].

Tectonic stability has been a major factor in the extraordinary development and state of presevation of Cenozoic weathering covers. However, the survival of friable saprolites also demonstrates the singular ineffectiveness of Pleistocene glacial erosion

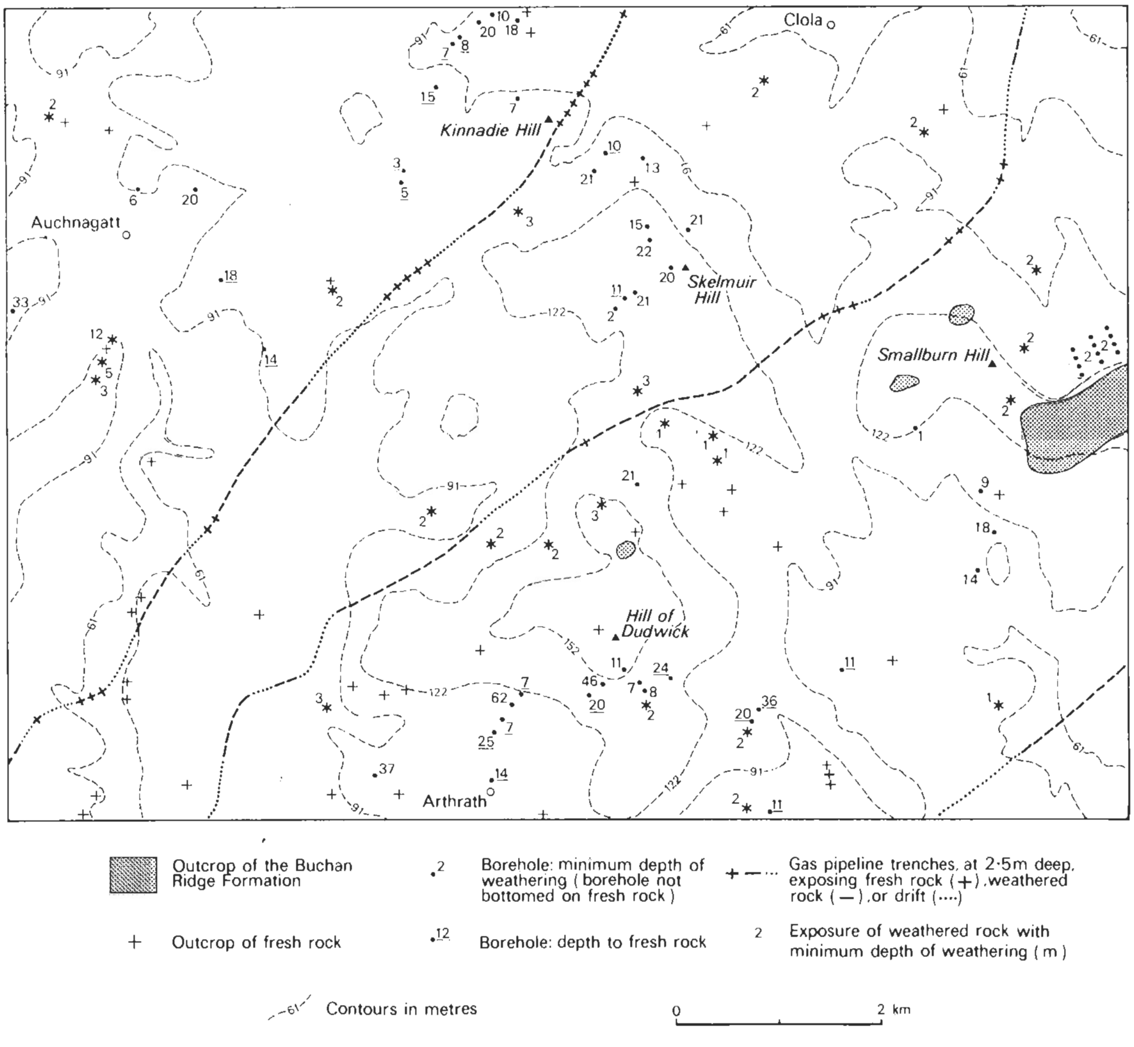

Fig. 2 Deep weathering patterns in central Buchan.

Table 1 Summary characteristics of weathering types

Rock type	Granite						Basic igneous			Quartz schist					Pelite	
Site and grid reference	Hill of Longhaven NK 084423	Cairnlea NJ 901537	Blackrigg NJ 912600	Mill Maud NJ 566067	Backhill NK 026407	Pittodrie NJ 693245	Silverford NJ 432253	Fedderate NJ 888505	Cruden borehole NK 028402	Moss-side NJ 949568	Howford NJ 954547	Mormond Quarry NJ 950568	Sunnyside NJ 983372	Howe of Dens NJ 975805	Kinmuck NJ 991341	Windy Hills borehole NJ 793393
Weathering type	G	G	G	G	G	CG	G	G	CG	G	G	CG	CG	CG	G	CG
% <2 μm	0.2	1.9	1.7	2.1	3.6	17.0	0.2	1.8	43.5	2.1	8.2	12.0	15.4	13.7	7.1	22.2
% <63 μm	2.5	14.4	12.7	17.5	26.1	45.0	6.7	11.3	75.5	9.1	41.3	32.0	43.0	49.8	20.1	94.7
Feldspar/quartz ratio	1.2	0.9	1.2	1.8	1.1	0.1	ND	ND	ND	0.5	0.7	0.1	0.1	0.2	ND	ND
% MgO	0.36	0.36	0.44	0.34	0.53	0.11	6.60	4.52	0.49	0.51	1.23	0.24	0.15	0.14	ND	0.18
% CaO	1.34	0.08	0.12	0.14	0.37	0.07	8.44	4.66	0.49	0.20	0.23	0.07	0.07	0.07	ND	0.10
% Na_2O	3.36	1.13	1.58	2.14	1.81	0.14	1.98	1.59	0.05	1.22	0.18	0.15	0.10	0.05	ND	0.55
% K_2O	6.03	5.3	4.65	5.63	3.56	3.00	0.56	0.55	0.45	2.71	3.84	1.24	0.63	2.80	ND	0.72
% Soluble base losses	5.9	53.4	58.6	48.6	ND	95.4	19.0	31.1	ND	ND	ND	ND	ND	ND	ND	78.9
Rubefaction	—	—	—	—	—	X	—	—	—	—	—	X	X	X	—	—
Etching of quartz	—	—	—	—	—	—	—	—	—	—	—	X	X	—	—	—
Clay mineralogy	I K H C	H	1	K I C	K H V S	K I Hm	I V	Gi K I	K I	Gi I K	I K H V	K I	K I Hm	K I Go	M C I	K I

C, Chlorite; Gi, gibbsite; Go, goethite; H, halloysite; I, illite; M, mixed-layers; S, smectite; V, vermiculite; G, gruss; CG, clayey gruss; ND, not determined.

in Buchan, where a succession of cold-based ice sheets have done little to modify Neogene landsurfaces[19].

Pockets of gruss-type saprolites occur widely in other glaciated areas bordering the North Atlantic[1–6]. Analogies with Buchan suggest that during the Neogene, lowland crystalline terrains were extensively weathered under temperate environments, with depths of weathering exceeding 30 m on interfluves. Where saprolites have survived glaciation and can be shown not to be the products of hypogene alteration[32] or exceptionally deep alteration down fault zones[12,20], it can be proposed that local Pleistocene glacial erosion has amounted to at most the removal of a few tens of metres of regolith and exposure of the basal surface of weathering. Such estimates can be reconciled with regional evidence of deep Pleistocene erosion deduced from the volumes of offshore sediments[33,34] by recognizing the selectivity of glacial erosion. Enclaves of little-modified Neogene relief have survived in parts of eastern Canada[4,35], eastern Greenland[36], Fennoscandia[5,37–39] and the British Isles[2,9,40] where local factors, including remoteness from ice accumulation centres, low gradients and diffluent flow patterns, have combined to maintain basal ice below its pressure melting point and so prevent significant glacial erosion[36]. Finally, the thicknesses of saprolite reported here would suggest that material reworked from preglacial Cenozoic weathering profiles forms a major, but largely overlooked component of glacial tills[37,41].

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