NATURE AND SOURCE OF AEOLIAN DEPOSITS NEAR THE SUMMIT OF BEN ARKLE, NORTHWEST SCOTLAND[1]

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ABSTRACT

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An extensive blanket of white sandy silt near the summit of Ben Arkle, northwest Scotland, consists of recent wind-transported material derived from frost-weathered quartzite regolith. Cryogenic processes are operative to a limited extent at present, but much of the weathered debris may have formed during the Last Glacial period. The aeolian silt grains are predominantly sub-angular and have irregular blocky surface textures with numerous adhering particles of clay-size quartz and kaolinite. Current aeolian reworking of the formerly-vegetated frost-weathered debris may be due to a slight climatic deterioration or to grazing by animals introduced since the late 19th century.

INTRODUCTION

Although coversands and loess in the lowlands of northwest Europe have been extensively studied, there are few published reports of aeolian deposits in upland environments. Some authors (e.g. SMALLEY, 1980) have suggested that cold weathering processes in mountain regions provide the main source of silt found in the world's major loess deposits, but little field or laboratory evidence is available to support this claim. In this paper we present analytical data concerning the nature and formation of aeolian deposits derived from weathered quartzite near the summit of Ben Arkle (altitude 757 m) in northwest Scotland. Arkle is one of a series of sandstone mountains in western Sutherland which consist largely of Cambrian quartzite and Precambrian Torridonian Sandstone (Fig. 1). The slopes of the mountain are mantled by angular quartzite blockfields, boulder banks and solifluction terraces (MOTTERSHEAD & WHITE, 1969; WHITE & MOTTERSHEAD, 1972), but on a gently sloping area between a cairn at national grid reference 311449 and the summit at 310453 there is a blanket of unvegetated white sandy silt. The maximum thickness of the silt is not known, but in several places exceeds 1 m. Similar deposits, though generally more sandy, occur on many neighbouring mountains including Foinaven, Quinag and An Teallach (SISSONS, 1976; BALLANTYNE, 1981).
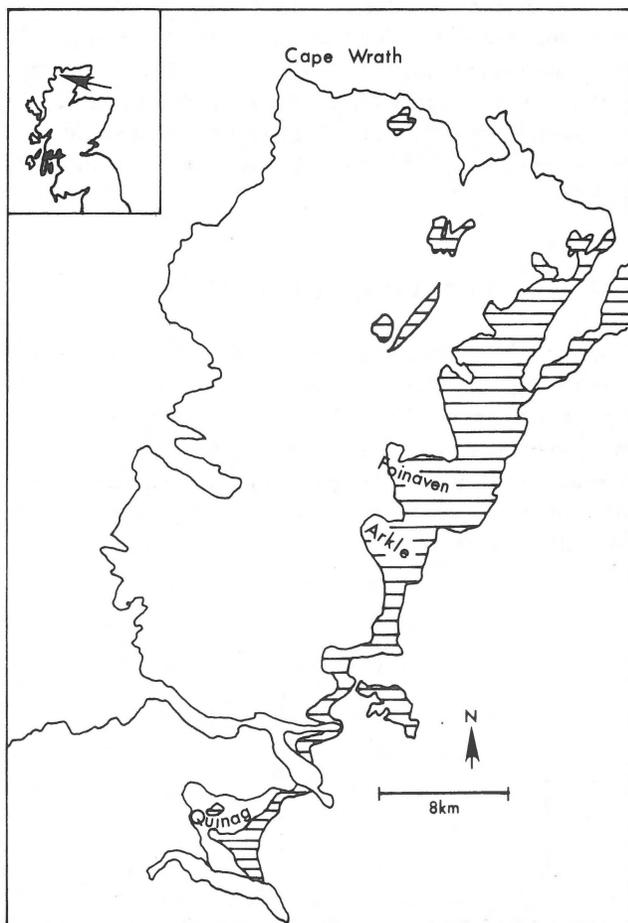

Fig. 1
Map showing location of study area and outcrops of Cambrian quartzite in northwest Sutherland.

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ANALYTICAL METHODS

The sandy silt deposit, together with quartzite pebbles which occur adjacent to and sometimes within it, were sampled for comparative analysis as part of a wider investigation of weathering and slope processes on Scottish mountains (PAINE, 1982). After dispersion with sodium hexametaphosphate the grain size distribution of the > 63 μm fraction of the deposit was determined by dry-sieving at quarter-phi intervals using a mechanical Ro-tap shaker. The silt and clay fractions (< 63 μm) were removed by wet sieving and analyzed by Coulter Counter. The cumulative grain size frequency curves were plotted graphically and the statistical parameters according to FOLK & WARD (1957) calculated. Separate size fractions were prepared for scanning electron microscope (SEM) examination by mounting on double sided adhesive tape and sputter-coating with gold. Grain shape was estimated from SEM images by the visual comparative method of POWERS (1953). The mineralogical composition of the silt was determined by X-ray powder diffraction. A sub-sample was impregnated with araldite and thin sectioned for optical microscope examination. Two quartzite pebbles collected adjacent to the silt deposit were also thin-sectioned and examined optically and under the SEM using both the secondary electron (SE) and cathodoluminescence (CL) modes. Natural fracture surfaces on the pebbles were also examined by SEM. For comparison with the mineralogy of the silt, part of each pebble was crushed and analyzed by X-ray powder diffraction (XRD).

SEDIMENTARY CHARACTERISTICS OF THE SILT

The results of XRD indicated that > 85% of the silt consists of quartz (Fig. 2). Feldspars, muscovite/illite and kaolinite are present up to about 5% each. Traces of anatase and chlorite were found in two specimens. The crushed quartzite pebbles revealed an identical mineralogy. This suggests that the silt is derived from nearby weathered quartzite rather than an allochthonous source.
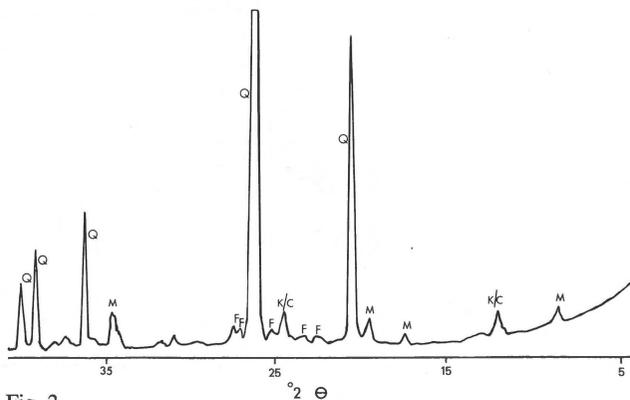
Fig. 2
X-ray diffraction trace of Ben Arkle silt (CuK α radiation). Q = quartz, F = feldspar, M = mica, K = kaolinite, C = chlorite.
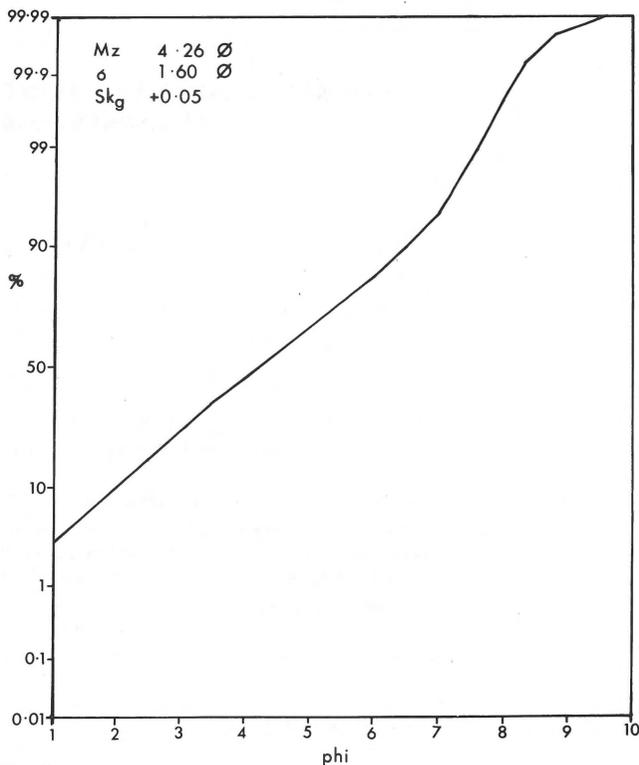
Fig. 3
Cumulative grain size frequency curve (arithmetic-probability paper) of sandy silt collected near the summit of Ben Arkle.

Grain size analysis showed the sediment to consist of approximately 6% medium sand, 40% fine sand, 54% silt and less than 1% clay (Fig. 3). The mean size was calculated to be 4.26 phi (52 μm) and the median 4.23 phi (55 μm). The sediment is poorly sorted according to FOLK & WARD's (1957) classification (phi sorting 1.60), slightly positively skewed (+0.05) and platykurtic (Kg = 0.86). The grain size distribution is unimodal in the coarse silt range and approximates a log-normal distribution. These characteristics suggest that the sediment has been transported and sorted, rather than representing weathering debris *in situ*, since the latter is typically strongly negatively skewed and approximates a Rosin's distribution (KRUMBEIN & TISDEL, 1940; KITTLEMAN, 1964). Weathering debris on the adjacent summital area of Ben Arkle has a pronounced mode in the medium to coarse sand range, contains numerous pebbles > 10 mm, and consists of less than 15% silt and clay (WHITE & MOTTERSHEAD, 1972). The weathering profiles typically show vertical size sorting due to frost action and podzolization. These characteristics are not found in the sandy silt deposits analyzed here. The small grain size, positive skewness and blanket morphology strongly suggest that the material has been transported and deposited by wind. The weathered debris near the summit is only thinly vegetated and shows evidence of active deflation in the form of turf scarps and shallow hollows. Sand and silt apppear to be selectively winnowed from this area by northwesterly winds and deposited on the relatively more sheltered slopes southeast and east of the summit.
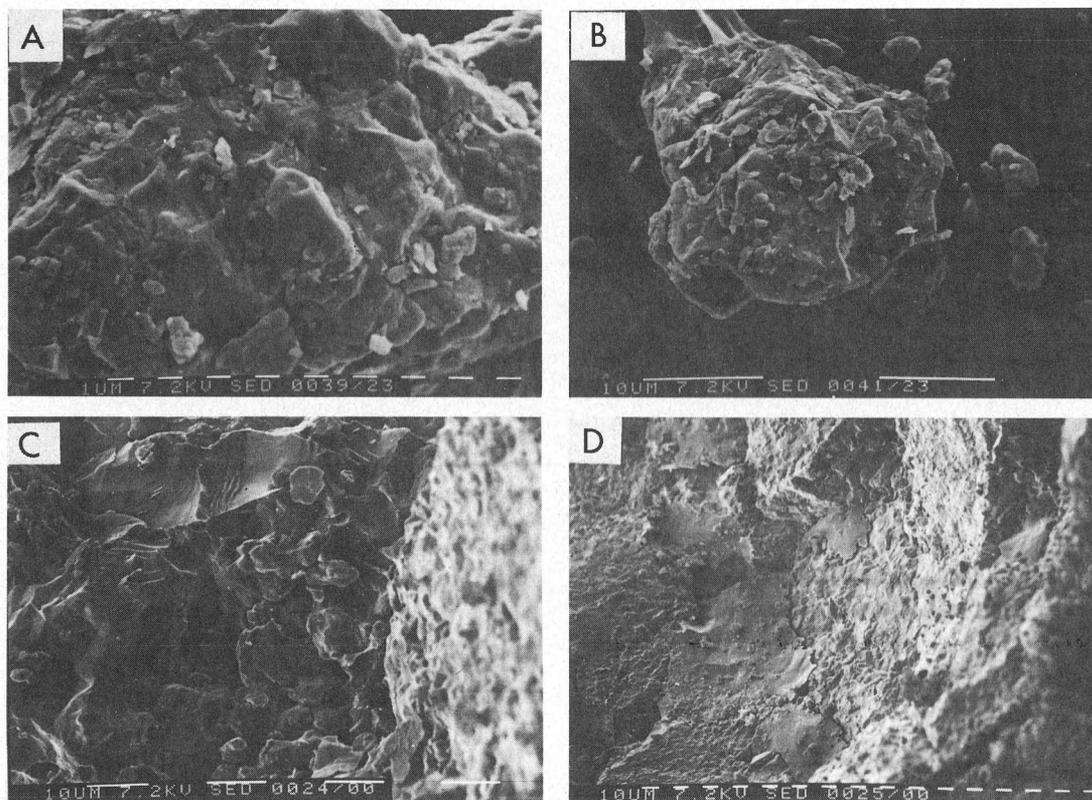
Fig. 4
A: SEM micrograph of a silt grain with 'microblock' texture (scale bar = 1 μm).
B: Silt grain surface with adhering clay-size quartz debris. Note that the fracture edges appear to have been slightly rounded by chemical action (scale bar = 10 μm).
C: SEM micrograph of a natural fracture surface on a quartzite pebble from Ben Arkle, showing both conchoidal (smooth) cross-grain fracture surfaces and plucked (grain marginal) fracture surfaces (scale bar = 10 μm).
D: Detail of natural fracture surfaces on a quartzite pebble. The flat, smooth area in the centre of the photograph is a fragment of silica cement (scale bar = 10 μm).

Most of the sand grains in the deposit are sub-rounded or sub-angular, while the silt grains are predominantly subangular. SEM examination showed that many grains have an irregular 'blocky' surface texture and are covered by numerous adhering grains of fine quartz, mica and kaolinite (Figs. 4A & 4B). Some grains have clean, conchoidal fracture surfaces. These features can be attributed to the nature of breakage during weathering of the quartzite (Figs. 4C & 4D).

Although the material is considered to be aeolian, aeolian abrasion plates (KRINSLEY & WELLENDORF, 1980) have been identified only on the surfaces of a few of the larger sand grains. The rarity of these features probably reflects the short duration of aeolian transport experienced by the grains. Silt grains rarely show textural evidence of aeolian abrasion, unless they are chips from larger aeolian sand grains, because insufficient energy is released during particle collisions to cause surface breakage (KRINSLEY & MCCOY, 1978).

Many of the particles examined showed evidence of silica solution in the form of edge rounding and incipient etch pits (Fig. 4B). Although quartz is often regarded as a stable mineral, it may dissolve rapidly under the right conditions (PYE, 1983; CHALCRAFT & PYE, 1983). The pH of the regolith soils on Ben Arkle lies in the range 3.0 – 3.8 and peaty organic acids are abundant (WHITE & MOTTERSHEAD, 1972). Under these circumstances, quartz solution can be expected (cf. CLEARY & CONOLLY, 1971; PYE, 1983).

SAND AND SILT PARTICLE FORMATION

The mechanisms responsible for the formation of silt and fine sand particles on Ben Arkle are probably both mechanical and chemical. Substantial evidence indicates that periglacial processes are operative on the higher parts of Scottish mountains at the present day (MILLER ET AL., 1954; FITZPA-TRICK, 1958; RAGG & BIBBY, 1966; ROMANS ET AL., 1966; RYDER & MCCANN, 1971; WHITE & MOTTERSHEAD, 1972). According to BIRSE (1980), the effects of freeze-thaw processes appear in soils above 600 m and are prevalent above 900 m. SISSONS (1976) concluded that the quartzite screes on Ben Arkle are still partly active. Air temperature data on Scottish mountains above 600 m are sparse, but what evidence there is suggests 30-40 freezing cycles per year at about 700 m (BALLANTYNE,

1981). However, short term ground temperature measurements indicate that diurnal freeze-thaw cycles affect only the uppermost 5-6 cm when snowcover is absent and are virtually eliminated at this altitude when snow is present (HALSTEAD, 1974; BALLANTYNE, 1981). Only on the highest mountain summits is freezing likely to extend to depths of more than 50 cm.

Although some frost weathering occurs on Ben Arkle at the present day, it must have taken place on a larger scale during the Late Glacial. WHITE & MOTTERSHEAD (1972) have argued that the large amounts of weathered debris on the upper slopes of Ben Arkle indicate that the mountain was not completely overrun by ice during the last glaciation. Although glacially smoothed and striated slopes are present on the lower parts of the mountain, these are not present at higher levels. Some, if not much of the debris currently being deflated near the summit may therefore be of Late Glacial or earlier age.

The effectiveness of frost action in forming fine sand and silt-size particles has been demonstrated in a number of experimental investigations (TRICART, 1956; WIMAN, 1963; MARTINI, 1967; POTTS, 1970; FAHEY & GOWAN, 1979; MOSS ET AL., 1981; LAUTRIDOU & OZOUF, 1982). Few of these studies, however, have specifically examined the frost weathering of quartzite. Susceptibility to frost action depends on a number of factors including rock strength (degree and nature of cementation, extent of microfracturing, degree of chemical alteration), rock porosity and permeability, moisture availability, and frequency and rate of freezing (MCGREEVY, 1981; LAUTRIDOU & OZOUF, 1982). Highly porous rocks with low permeability, such as chalks, and weathered rocks, are normally most susceptible to frost damage, but may not necessarily produce silt-size material unless other criteria are met.

In the case of quartzite, frost action operates in two ways and at two different scales. First, frost-wedging in larger joints may cause splitting and form large angular blocks (the 'macrogelivation' of TRICART, 1956). Second, frost may penetrate small microcracks between and within individual mineral grains, forming loose sand and silt grains ('microgelivation' of TRICART, 1956). The latter process is responsible for the slow rounding and surface weathering of fracture faces formed on large jointed blocks by macrogelivation.

Because of its low porosity and the high strength of silica cement, quartzite is more resistant to microgelivation than many other rocks. The efficiency of small-scale frost action (and associated crack-tip stressing by adsorbed water) is dependent on the ability of moisture to penetrate small microcracks (MOSS ET AL., 1981). In well-cemented and frequently recrystallized quartzite the principal entry points for water are the crystal boundaries between diagenetically altered quartz grains (Fig. 5A). These boundaries bear little relation to the outlines or internal structures of the original detrital grains, as shown by comparing the secondary electron and cathodoluminescene micrographs of the same area in Figs. 5A & 5B. The CL image reflects small differences in the concentration of ionic impurities or lattice ordering and allows former detrital grain 'cores' to be distinguished from later overgrowths (SIPPEL, 1968; TOVEY & KRINSLEY, 1980).

Experimental work has shown that relatively little silt and clay is produced by frost weathering of quartzite blocks in comparison, for example, with limestones and argillaceous sedimentary rocks (LAUTRIDOU & OZOUF, 1982). The predominantly sand and coarse silt particles formed are highly suitable for aeolian deflation. On other rocks types, however, field and experimental evidence indicates that frost action produces grains in the size range 20-60 μm (ZEUNER, 1949; ST. ARNAUD & WHITESIDE, 1963; MOSS ET AL., 1981; KONISHCHEV, 1982).
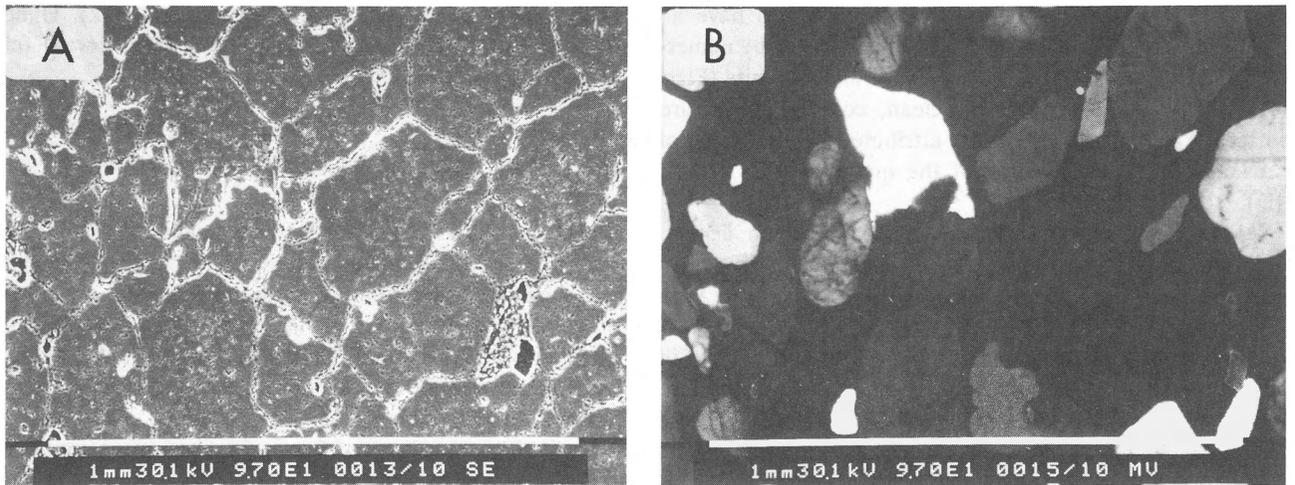
Fig. 5
A. Secondary electron image of part of a polished thin section of Arkle quartzite, showing diagenetic inter-grain boundaries (scale bar = 1 mm).
B. Cathodoluminescence image of the same area shown in Fig. 5A. The outlines of original detrital grains can be distinguished from later overgrowths and bear little relationship to the present intergrain boundaries (scale bar = 1 mm).

AEOLIAN PROCESSES ON SCOTTISH MOUNTAINS

Aeolian sand sheets up to several metres thick occur on several Torridonian mountains in northwest Scotland, notably Quinag, An Teallach and Beinn Bhan. Aeolian deposits are also found on mountains in Orkney and Shetland (BALL & GOODIER, 1974), in parts of the Cairngorms (KING, 1971), and in the Western Isles. The upper west-facing slopes and summits experience high wind velocities which result in deflation of quite coarse material and re-deposition in topographic hollows and sheltered areas on the leeward side. The deposits usually take the form of low sand blankets rather than dunes (BIRSE, 1980).

The Ben Arkle deposits appear to be finer than those on some other mountains. On An Teallach, for example, BALLANTYNE (1981) found that only 2 of 57 samples contained >4% silt. Some of these samples contained particles larger than 10 mm, indicating that extremely strong wind gusts must periodically be experienced. In this case the fines probably were winnowed and carried away in suspension, rather than being deposited close to the source as on Ben Arkle.

The timing and duration of aeolian sedimentation on Scottish mountains is poorly documented. BALL & GOODIER (1974) suggested that the present phase of wind erosion and sedimentation in Shetland may have been initiated by climatic deterioration during the 'Little Ice Age'. BALLANTYNE (1981) suggested that introduction of grazing animals in the 19th century may have played an important part in reactivating aeolian deflation and sedimentation on An Teallach. It remains to be established whether these and earlier events on different mountains were synchronous and shared a common cause. At least one pre-modern period of aeolian sand deposition is recorded on An Teallach (BALLANTYNE, 1981), and possibly equivalent deposits are found within a solifluction terrace sequence on the eastern side of Ben Arkle, though an aeolian origin for the latter is not proven (WHITE & MOTTERSHEAD, 1972, 479).

CONCLUSIONS

Frost-weathered regolith near the thinly-vegetated summit of Ben Arkle is currently being reworked by aeolian processes and deposited in relatively sheltered sites on the southeastern side of the mountain. Similar deposits are forming on other sandstone mountains in northern Scotland. Weathering of sandstone produces debris with a low clay content in the size range suitable for wind transport (4 μm-1 mm). SEM and XRD analyses confirm that the Ben Arkle sandy silt deposits are derived from Cambrian orthoquartzite which caps the mountain. The sand and silt grains are predominantly subangular and have blocky textures which reflect the pattern of fracture during frost weathering of quartzite. Many of the particles have suffered edge rounding by solution of silica, but surface textural features indicative of aeolian abrasion are rare.

Although frost action is operative on the mountain at the present day, its intensity is much less than in the past. Much of the weathered debris on Ben Arkle probably formed during the Late Pleistocene (WHITE & MOTTERSHEAD, 1972). The causes of the current phase of aeolian reworking are not certain but may be related to a slight climatic deterioration or to the effects of grazing animals in reducing the vegetation cover.

REFERENCES

Ball, D. F. & R. Goodier 1974 Ronas Hill, Shetland: a preliminary account of its ground pattern features resulting from the action of frost and wind. In: Goodier (ed.): The Natural Environment of Shetland – Nature Conservancy Council (Edinburgh): 89-106.

Ballantyne, C. K. 1981 Periglacial landforms and environments on mountains in the northern Highlands of Scotland – PhD Thesis, Univ. Edinburgh: 593 pp.

Birse, E. L. 1980 Suggested amendments to the world soil classification to accommodate Scottish mountain and aeolian soils – J. Soil Sci. 31: 117-124.

Chalcraft, D. & K. Pye (in press) Humid tropical weathering of quartzite on Mount Roraima, southeastern Venezuela – Z. Geomorphol.

Cleary, W. J. & J. R. Conolly 1971 Embayed quartz grains in soils and their significance. – J. Sediment Petrol. 42: 899-904.

Fahey, B. D. & R. J. Gowan 1979 Application of the sonic test to experimental freeze-thaw studies in geomorphic research – Arct. Alp. Res. 11: 253-260.

Fitzpatrick, E. A. 1958 An introduction to the periglacial geomorphology of Scotland – Scot. Geogr. Mag. 74: 28-36.

Folk, R. L. & W. C. Ward 1957 Brazos River Bar: a study in the significance of grain size parameters – J. Sediment Petrol. 27: 3-26.

Halstead, C. A. 1974 Soil freeze-thaw in the Southern Uplands of Scotland – Weather 29: 261-265.

King, R. B. 1971 Vegetation destruction in the subalpine zones of the Cairngorm mountains – Scot. Geogr. Mag. 87: 103-115.

Kittleman, L. R. Jr. 1964 Application of Rosin's Distribution to size-frequency analysis of clastic rocks – J. Sediment Petrol. 34: 483-502.

Konishchev, V. N. 1982 Characteristics of cryogenic weathering in the permafrost zone of the European USSR – Arct. Alp. Res. 14: 261-265.

Krinsley, D. H. & F. W. McCoy 1978 Aeolian quartz sand and silt. In: W. B. Whalley (ed.): Scanning Electron Microscopy in the Study of Sediments – Geoabstracts (Norwich): 249-274.

Krinsley, D. H. & W. Wellendorf 1980 Wind velocities determined from the surface textures of sand grains – Nature 283: 372-373.

Krumbein, W. C. & F. W. Tisdel 1940 Size distributions of source rocks of sediments – Am. J. Sci. 238: 296-305.

Lautridou, J. P. & J. C. Ozouf 1982 Experimental frost shattering: 15 years of research at the Centre de Géomorphologie du CNRS – Prog. Phys. Geogr. 6: 215-232.

Martini, A. 1967 Preliminary experimental studies of frost shattering of certain rock types from the West Sudetes – Biul. Peryglac. 16: 147-194.

McGreevy, J. P. 1981 Some perspectives on frost shattering – Progr. Phys. Geogr. 4: 56-75.

Miller, R., R. Common & R. W. Galloway 1954 Stone stripes and other surface features of Tinto Hill – Geogr. J. 120: 216-219.

Moss, A. J., P. Green & J. Hutka 1981 Static breakage of granitic detritus by ice and water in comparison with breakage by flowing water – Sedimentology 28: 261-272.

Mottershead, D. N. & I. D. White 1969 Some solifluction terraces in Sutherland – Bot. Soc. Edinb. Trans. 40: 604-620.

Paine, A. D. M. 1982 Origin and development of blockfields in the Cairngorm Mountains. Part II – Dissertation, Univ. Cambridge, unpublished: 90 pp.

Potts, A. S. 1970 Frost action in rocks: some experimental data – Inst. Br. Geogr. Trans. 49: 109-124.

Powers, M. C. 1953 A new roundness scale for sedimentary particles – J. Sediment Petrol. 23: 117-119.

Pye, K. 1983 Formation of quartz silt during humid tropical weathering of dune sands – Sediment Geol. 34: 267-282.

Ragg, J. M. & J. S. Bibby 1966 Frost weathering and solifluction products in southern Scotland – Geogr. Ann. 48A: 12-23.

Romans, J. C. C., J. H. Stevens & L. Robertson 1966 Alpine soils of northeast Scotland – J. Soil Sci. 17: 184-199.

Ryder, R. H. & S. B. McCann 1971 Periglacial phenomena on the island of Rhum in the Inner Hebrides – Scot. J. Geol. 7: 293-303.

Sippel, R. F. 1968 Sandstone petrology, evidence from luminescence petrography – J. Sediment Petrol 38: 530-554.

Sissons, J. B. 1976 Scotland – Methuen (London): 150 pp.

Smalley, I. J. 1980 The formation of loess materials and loess deposits: some observations on the Tashkent loess – Geophys. Geol. Geophys. Veröff. K.M.U. Leipzig Bd. II, 2: 247-257.

St. Arnaud, R. J. & E. P. Whiteside 1963 Physical breakdown in relation to soil development – J. Soil Sci. 14: 267-281.

Tovey, N. K. & D. H. Krinsley 1980 A cathodoluminescent study of quartz sand grains – J. Microsc. 120: 279-289.

Tricart, J. 1956 Étude expérimentale du problème de la gelivation – Biul. Peryglac. 4: 285-318.

White, I. D. & D. N. Mottershead 1972 Past and present vegetation in relation to solifluction on Ben Arkle, Sutherland – Bot. Soc. Edinb. Trans. 41: 475-489.

Wiman, F. 1963 A preliminary study of experimental frost weathering – Geogr. Ann. 45A: 113-121.

Zeuner, F. 1949 Frost soils on Mount Kenya, and the relation of frost soils to aeolian deposits – J. Soil Sci. 1: 20-30.