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Grus weathering mantles—problems of interpretation

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Abstract

Grus is an ill-defined product of deep weathering of coarse-grained rocks whose relationships to other weathering changes remain unclear. This paper attempts to address this issue by reviewing a number of examples of coarse saprolites from a variety of climatic and topographic settings. Grus is the category of weathering mantle that possesses the following characteristics: sand + gravel 75–100%; silt + clay <25%; clay <10%; Chemical Index of Alteration (CIA) 60–70; Chemical Weathering Index (CWI) 15–20. The origin of grus is connected with weakening of rock fabric by development of microcracks, biotite expansion, and initial alteration of plagioclase. It may originate either beneath the surface or at greater depths within a weathering profile. The climatic approach to the formation of grus mantles offers limited explanation of field occurrences, as these materials are widespread across climatic zones, from the humid tropics to cool temperate areas, although rates of grusification are likely to be influenced by climatic parameters. By contrast, topographic and also petrographic factors appear to play key roles in the development of grus, which may be regarded as a response of weathering systems to rapid relief differentiation. Grus mantles are preferentially associated with moderate to high relief; hence, they are essentially azonal and their development is under way in many areas of the world. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Among weathering processes, granular disaggregation of coarse-grained rocks, particularly granite, is one of the most frequently referred to in standard textbooks or regional descriptions. Yet its resultant in situ product is surrounded by ambiguity and escapes an

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unequivocal explanation. It is often called 'grus', sometimes spelled 'gruss', and if it forms a residual mantle, seems to be an equivalent of 'sandy saprolites' (arènes) or 'arenaceous saprolites'.

There are two major reasons why the origin of grus mantles remains unclear and poorly understood. First, 'grus' is an ill-defined term, apparently used with various meanings and contexts (see Migoń, 1997a), which is not helpful if regional correlations and genetic comparisons are to be established. Moreover, the relationship between near-surface grus and the zone of grusification at depth remains poorly investigated. Second, controls on the development of thick grus mantles are uncertain, with studies often following a climatic approach, while little or no reference to other potential controlling factors, such as geologic predisposition or local relief, is provided.

Although not all of the uncertainties can be resolved here, we shall nevertheless attempt to refine the definition of grus and relate it to other weathered products and discuss the role of climatic and geomorphic controls on the distribution of grus mantles at the regional and global scales.

2. Grus as a weathering product

2.1. The nature of 'grus' and its definition

It is difficult to be precise about the distribution of 'grus' because as noted by Migoń (1997a), different definitions have been offered in the literature. Furthermore, existing definitions consider a variety of characteristics such as grain size, parent rock, degree of chemical change, or environment. An operational description used by Migoń (1997a, pp. 57–58) was based solely on grain size characteristics, stating that grus is: a product of in situ rock weathering, characterised by its specific grain size distribution, where the sand (0.1–2.0 mm) and gravel (> 2.0 mm) fraction may constitute up to 100% of the material, while the percentage of silt+clay will not exceed 25%.

French authors often distinguish between 'arènes' and 'altérites' (Bourgeon, 1991), the latter being associated with extensive kaolinisation (Millot, 1970; Tardy et al., 1973; Tardy and Roquin, 1998), but also refer to arènes as 'altérites sableuses' or 'altérites ménagés' (Lageat and Lagasquie, 1994). According to these authors, such materials should have less than 10% clay, exhibit the presence of illite and vermiculite with only small amounts of kaolinite, and show only slight mobilisation of major cations. The SiO_2/Al_2O_3 ratio should be in the region of 2.7. This is contrasted with highly evolved materials with 15–20% clay and 45–50% kaolinite in the clay fraction, and a SiO_2/Al_2O_3 ratio of 2.17:2.22 (Lageat and Lagasquie, 1994). Sequeira-Braga et al. (1990) in their review of arènes from Atlantic Europe corroborate these findings regarding textural characteristics (clay plus silt <20%), but demonstrate that 20–46% of original rock constituents may be lost. They characterise the arènes as 'fabric skeleton' materials to distinguish them from plasma-based saprolites, resulting from 'argillization'.

One problem in this area is the difficulty of estimating the clay mineral content. This is because clay minerals commonly aggregate and appear as silt-sized 'particles'. However, non-clay minerals, mostly quartz, will dominate the silt fraction of a grus mantle. The lack of uniformity in pretreatments before measurement of the clay fraction makes comparisons between published analyses difficult.

The application of weathering indices offers an alternative approach to the characterisation of weathered materials and tends to emphasise a continuum of change from fresh to highly altered rock, and to give numerical expression to the chemical or mineralogical changes taking place during weathering.

The Chemical Weathering Index (CWI) was proposed by Sueoka (1988), in which

$$\mathrm{CWI} = \frac{\mathrm{Al_2O_3 + Fe_2O_3 + TiO_2 + H_2O(\pm)}}{\text{(All chemical components)}}\,\mathrm{mol} \times 100\% \tag{1}$$

He matched the CWI values to the common sixfold zonation of the weathering profile. In this scheme, fresh granite scores 13–15% and moderately weathered granite 15–20%, rising to 60% for residual lateritic soil.

Nesbitt and Young (1989) proposed a Chemical Index of Alteration (CIA) in which

$$\mathrm{CIA} = \mathrm{Al_2O_3/Al_2O_3 + CaO + Na_2O + K_2O(molar)} \tag{2}$$

CIA values for feldspar and biotite are 50–55 so that unweathered granitic rocks have CIA values close to 50. Secondary minerals such as kaolinite and gibbsite have values of 100 and smectites 70–85.

Nesbitt and Markovics (1997) found that the CIA of a granodiorite rose from 50/51 in a fresh corestone to 86.5 within the altered material beneath the corestone and to 93/95 within material filling subhorizontal and near-vertical joints. Nossin (1967) found similar relationships around corestones on Singapore Island and numerous observations confirm the rapid transition from corestones to highly altered material in tropical areas. In these cases, the alteration of the corestones clearly did not produce significant grus.

In summary, grus mantles should posses the following characteristics: sand+gravel 75–100%; silt+clay <20%; clay <10%; CIA 60–70; CWI 15–20. The presence of specific clay minerals may not be diagnostic but some interstratified minerals (chlorite, vermiculite) and possibly illite are usually present in small quantities.

2.2. Surface grus and transitional zones of weathering profiles

Migoń (1997a) emphasised the occurrence of weathering profiles in central and northern Europe that consist almost entirely of grus. These profiles show no clear gradation towards more advanced alteration near the surface (except perhaps for pedogenesis in the top 0.1–2.0 m). By contrast, it is frequently suggested that grus is found at depth in profiles with more advanced weathering in higher zones or horizons. The well-known diagram by Strakhov (1967) implies such a relationship and a broadly similar model was adopted by the Engineering Group of the Geological Society of London (Geological Society of London, 1990; Fookes, 1997). This view is also specifically expressed by Robertson and Butt (1997) in their Atlas of Weathered Rocks, based largely on experience in Australia. They comment: “grus is the fragmental disintegration product of largely unweathered granitic rock. It is commonly applied to surface products, but it is also present as a porous horizon ranging in thickness from a few centimeters to 10 m or more at the base of the saprolite. Grus differs from saprock in that it is friable rather than compact." Despite this last comment, the authors make grus equivalent to saprock and separate from 'saprolite'. The use of the term saprock in this context distinguishes these materials from saprolite. This distinction is based on the degree of alteration; less than 20% of the weatherable minerals being altered in the saprock and grus.

This transition was clearly demonstrated from granite weathering profiles in Ghana by Ruddock (1967) who found an inverse correlation with depth (surface to 15 m; 36 samples) for the grading parameter, percentage <0.2 mm+percentage <0.002 mm. Thus in this humid tropical environment, there is a clear transition with depth towards coarser material containing aggregates of quartz crystals, kaolin pseudomorphs and actual plagioclase.

However, it may not always be possible to equate the properties of surface grus to those of transitional saprock at depth. This is because the water relations in thick weathering mantles change with depth and saturated zones with slow moving solutions occur beneath many cratonic and other surfaces of low relief. In different conditions, either highly kaolinised (mostly into halloysite) or smectitic clays can be found close to the weathering front. This contrast may be between humid regions, usually in the tropics, where there is both saturation and water movement at depth, leading to white kaolinitic residues low in bases and Fe (Dubroeucq and Volkoff, 1998; Thomas et al., 1999) and seasonally dry areas, where early alteration products formed at the weathering front are not rapidly removed in the ground water (Bourgeon, 1991). According to Clayton (1974), smectite clays are favoured where the SiO_2/Al_2O_3 ratio >10 (whereas a ratio of 2:1 can theoretically be proposed).

In granites and other crystalline rocks, a characteristic zonation of the weathering profile is widely accepted. Ruxton and Berry (1957) developed a fourfold division for granite profiles in Hong Kong, later extended to the recognition of six zones by Dearman et al. (1978) and used by many agencies and other authors (Geotechnical Control Office, 1988; Geological Society of London, 1990; Fookes, 1997; Irfan 1996). These schemes recognise and define a sequence of changes from fresh rock towards a residual soil. Terms such as slightly, moderately, highly, and completely decomposed are used (e.g., by Irfan, 1996). Variations of mineral composition with depth for Hong Kong show that there is little alteration in slightly decomposed granite but progressive loss of plagioclase and biotite (mirrored by sharp declines in MgO, CaO, and Na_2O) in moderately to highly decomposed rocks.

3. Petrographic factors in grus weathering

3.1. Microcrack systems and possible hydrothermal alteration

Spatial anisotropy in weathered rocks is nearly always observed and this can occur on widely varying scales, from petrographic and structural zones, commonly 1 to >10 km across to joint bounded blocks <1 to >100 m in diameter. Within apparently undivided rock masses, planes of weakness can occur from 1 μm–1 m. Such variations will reflect rock mineralogy, grain size, and especially the nature of the fracture system. Shear zones, faults, and joint systems have long been identified as factors guiding the weathering agents and processes. But the microcrack system may be the most effective preconditioning factor throughout a rock mass (Pye, 1985; Irfan, 1996). The origins of microcracks lie in palaeostress fields imposed by crystallization, hydrofracturing during hydrothermal activity, and tectonism. In some studies, feldspars contain the most microcracks with quartz also commonly fractured. But cracks can be intergranular (IGC) as well as transgranular (TGC) (Zang, 1993a,b).

The importance of microcrack systems can be seen in three contexts: (1) they are often associated with fluid movement in the Earth's crust and therefore cannot be separated from hydrothermal alteration processes; (2) they increase access to rock surfaces by groundwater, thereby accelerating the weathering processes; and (3) by aiding water penetration, they increase rock disintegration by frost weathering in cold pedoclimatic conditions. In some instances, the presence of little altered but friable or disintegrated rock in high latitudes or altitudes may potentially be a reflection of all three of these factors operating sequentially or in the cases of (2) and (3), simultaneously.

Irfan (1996) demonstrates solution of feldspars along grain boundaries and transgranular microcracks developed in the vicinity of joints within slightly decomposed granite. This suggests extension of microcrack systems, from pre-existing intra- and intergranular cracks and voids, due to de-stressing of quartz and feldspars during weathering (Irfan, 1996). The important role of microcracks at initial stages of grusification was also emphasised by Pye (1985). Furthermore, it is suggested that expansion of biotite may occur as secondary minerals are formed in the biotite, leading to an increase in interlayer spacing, a phenomenon described by Wahrhaftig (1965) from the Sierra Nevada (USA) and by Isherwood and Street (1976) from Colorado. There is loss of rock strength in moderately decomposed granite yet mineralogical change is still small (Irfan, 1996). As the microfractures increase, voids are enlarged as solution of the alkali feldspars develops and halloysite tubes form by the hydrolysis of the plagioclase. This process allows access to more of the rock mass; eluviation becomes important and clay minerals and sesquioxides subsequently form bridges within an open fabric. It is notable that these changes are in one sense, independent of the occurrence of corestones within the rock mass. But the existence of microcracks in the fresh rock not only accelerates its decomposition but also leads to early disaggregation, such that corestones either do not form or survive for short periods in the profile.

Several studies, such as those by Eggler et al. (1969) in Wyoming, Dixon and Young (1981) in southeastern Australia, and Evans and Bothner (1993) in New Hampshire, USA, have proposed the preconditioning of granite to weathering by slight, hydrothermal alteration along microcrack systems. Some studies of kaolin deposits (Sheppard, 1977; Dominy and Camm, 1998; Psyrillos et al., 1998) suggest that a simple distinction between hydrothermal alteration and meteoric weathering cannot be made. The view is now forming that many kaolins are a function of a two-phase alteration of the granite, starting with the injection of hydrothermal veins. This process can cause hydrofracturing, which favours subsequent supergene alteration (weathering). The identification of 'low temperature' alteration at 70–100 °C (Sheppard, 1977; Psyrillos et al., 1998) raises the whole issue of the water cycle in rocks, including the long distance transport of brines. Deep penetration of groundwater will lead to warming at depth by geothermal heat flow and interaction with hydrothermal fluids can occur. However, many kaolin-rich weathered residues are considered to be the products of humid tropical weathering (Dubroeucq and Volkoff, 1998; Thomas et al., 1999; Da Costa and Moraes, 1998).

3.2. Influence of rock fabric and mineralogy

These considerations demonstrate important geological factors favouring grusification of granites. In addition, factors such as the rock fabric and mineralogy are likely to be important. These seldom operate on a regional scale but can lead to differential weathering within and between plutons. Factors such as large grain size, the presence of biotite and hornblende, and an absence of silicification due to metasomatism all favour weathering in granites (Brook, 1978). Coarse granites appear subject to grusification, possibly because intra- and intergranular tensions can be higher than in fine-grained rocks. However, potash-rich granites containing microcline phenocrysts, by contrast, often form massive, high relief forms (Marmo, 1956; Pye et al., 1984). Disruption of the rock fabric can result from the early alteration of biotite and hornblende and is more pervasive in coarse-grained rocks. Foliation can increase weathering penetration in fissile rocks, but granite–gneiss subjected to high-grade metamorphism can be effectively sealed against water penetration. It is therefore obvious that detailed studies of all forms of weathering must consider petrographic detail, but in this review we consider mainly the regional distribution and landscape setting of grus mantles.

4. Distribution of grus in relation to present-day climatic zones

4.1. Grus mantles and present-day climates

Although grus mantles are widespread in areas of temperate climate, they have been reported from a variety of climatic zones and it seems they may be found in every climatic regime (Table 1, Figs. 1–3), both in humid and semiarid variants. However, in humid temperate areas such as western and northern Europe or northeast Canada, grus mantles appear to be the most characteristic outcome of rock weathering, whereas in low latitudes they occur alongside products of more advanced alteration, such as ferrallitic saprolites, as recorded for instance in SE Brazil (Power and Smith, 1994; Thomas, 1994) and Uganda (Taylor and Howard, 1999). The reasons for this coexistence are not entirely clear, although Taylor and Howard (1999) noted that sandy weathering similar to grus occurs in the lower zones of ferricreted profiles and also as near-surface materials in dissected areas. They considered the inhibition of geochemical advance below the water table and the exposure of the coarse grained, sandy weathering at the surface by stripping, as the factors leading to the observed distribution.

Although the general phenomenon of deep grusification seems not to be climate dependent, as demonstrated in Table 1, regional climate is likely to exert a control on how fast and in which settings grus mantles develop. This secondary role of climate may be inferred from patterns of grus weathering in different climates (Table 2).

If the climate is warm and humid (>1500 mm year^{-1}), such as in SE Brazil, Nepal, or Uganda, then the rate of weathering is high and profile deepening progresses relatively fast.

Table 1
Occurrence of grus mantles in relation to climatic zones and climatic types

Climate	Area of occurrence	Selected references
Temperate		
Cool humid	EUROPE: Scotland, Fennoscandia	Söderman et al., 1983; Kejonen, 1985; Lahti, 1985; Lundqvist, 1985; Peulvast, 1985, 1989; Hall, 1986; Le Coeur, 1989; Lidmar-Bergström et al., 1997, 1999
	NORTH AMERICA: Labrador, N Appalachians	Bouchard and Godard, 1984; Wang and Ross, 1989; Bouchard and Jolicoeur, 2000
Humid	EUROPE: Ireland, SW England, Massif Central, Central Europe	Hövermann, 1950; Wilhelmy, 1958; Jahn, 1962; Demek, 1964; Franz, 1969; Eden and Green, 1971; Nieuwenhuis, 1971; Macaire, 1985; Kubiniok, 1988; Pierre, 1990; Migoń, 1997a
	NORTH AMERICA: Appalachians, Sierra Nevada	Wahrhaftig, 1965; Pavich, 1985; Cleaves, 1993
Warm humid	EUROPE: Portugal, NW Spain, S Italy	Molina et al., 1987; Pedraza-Gilsanz, 1989; Sequeira-Braga et al., 1990; Le Pera and Sorriso-Valvo, 2000
	SOUTHERN HEMISPHERE: SE Australia, New Zealand, South Africa	Thomas, 1974, 1978; Dixon and Young, 1981
Semiarid	ASIA: Mongolia	Kotarba, 1986
	NORTH AMERICA: Wyoming	Eggler et al., 1969
Warm semiarid	NORTH AMERICA: Texas	Folk and Patton, 1982
Subtropical and tropical		
Humid	ASIA: Nepal, SE China	Gardner and Walsh, 1996.
	SOUTHERN HEMISPHERE: SE Brazil, NE Australia	Power and Smith, 1994; Thomas, 1994; Robertson and Scott, 1997
Semiarid	ASIA: Deccan	Brunner, 1969; Bourgeon, 1991 (quoted in Pedro, 1997); Gunnell and Bourgeon, 1997

Please note that the table is intended to give a general picture of grus distribution and is not a complete reference list.

Moreover, grain size and abundance of kaolinite in the saprolites in these environments indicate that alteration is more advanced than in grus from higher latitudes (Ruddock, 1967; Taylor and Howard, 1999). Hence, the resultant arenaceous mantles occupy an intermediate position between a ‘typical’ grus and saprolites, in which kaolinite starts to appear in larger quantities. They appear similar to the ‘clayey grus’ as described from NE Scotland (Hall, 1986). In these areas, it is difficult to sustain the view that arenization fundamentally differs from other weathering systems. Rather, it is an early stage of weathering, and clay-rich saprolites develop at the expense of grus and sandy material if the surface of the grus mantle is not eroded. High efficacy of grusification is also demonstrated by the occurrence of low hills (<50 m high), which are weathered throughout.

Warm but drier areas have grus profiles relatively undeveloped. They are thinner because the weathering front advances rather slowly while stripping is efficient. Hills, if not built of an ancient saprolite capped by duricrust, are cut in unweathered rock, while grus emerges around them. This pattern is characteristic for hilly land surfaces and inselberg landscapes also in the temperate zone. Little grus can be found in the mountains, where rock slopes mantled by talus prevail. In the drier areas of the Karnataka Plateau, India (Gunnell and Bourgeon, 1997), the composition of the grus varies with topographic position, with greater

Fig. 1. Grus with corestones exposed in a quarry near Peterhead, NE Scotland.

decomposition of plagioclase to kaolinite evident beneath upper slopes. In Uganda (Taylor and Howard, 1999), grus samples from depth may contain vermiculite and smectite, in addition to kaolinite, while in surface samples both smectite and kaolinite occur with minor amounts of plagioclase and mica.

Grus mantles in the temperate and humid areas, such as large parts of Europe or the eastern part of the United States, are of moderate thickness, often 5–15 m. Grus is almost ubiquitous, although on steeper mountain slopes (>20–30°) it is usually absent. In higher latitudes, grus mantles become shallower and more granular. They seldom exceed 10 m, but they were almost certainly subjected to frequent erosion by periglacial and glacial processes (cf. Braun, 1989; Peulvast, 1989; Cleaves, 1993), so their present thickness might not be a reliable indicator of the effectiveness of grusification. Furthermore, there is a considerable uncertainty concerning possible inheritance of grus from the Pliocene or even earlier times.

Temperate semiarid areas are least favourable for grus mantle development, although the strong possibility of periglacial inheritance prohibits generalizations. Grus is produced by weathering of granitoid rocks in these environments (cf. Kotarba, 1986, for the Mongolian steppes), but scarce vegetation does not afford sufficient protection and surface erosion and redeposition of grus are almost instantaneous. As a result, grus mantles are thin.

4.2. Climatic inheritance

Any generalization of the relationship of deep grusification to climate is inhibited by the possibility that many grus mantles are not the result of weathering under contemporary climatic conditions but are inherited from a distant past and different climatic regimes. This issue is particularly important in present-day temperate areas, which are known to

Fig. 2. Grus developed from serpentinites in central Cyprus.

have experienced drastic climate changes in the last few million years. Moreover, stratigraphic relationships show that many of the grus occurrences are of pre-Quaternary, or even of pre-Pliocene age, increasing the probability of climatic inheritance.

In Britain, Linton (1955) claimed that grus in Dartmoor originated in a tropical environment; a view later challenged as more data about the mineralogy and texture of the grus mantle appeared (Eden and Green, 1971; Doornkamp, 1974). However, grus in the Bavarian Forest and Sumava range, Central Europe, is locally overlain by Miocene deposits and, hence, has also been interpreted as a (sub-)tropical residuum (Pippan, 1969; Chabera, 1972; Kubiniok, 1988). Hillefors (1985) proposed that grus mantles found in SW Sweden are in fact the roots of much older, tropical mantles. Furthermore, Hall (1986) distinguished three categories of grus in NE Scotland on the basis of grain size and secondary minerals, and suggested different ages for each type, from the Miocene age for ‘clayey grus’, through a possible Pliocene age for the main grus occurrences, to the Holocene for ‘granular grus’.

Similar problems in the North American context have recently been discussed by Bouchard and Jolicoeur (2000). They review a number of papers in which the presence of

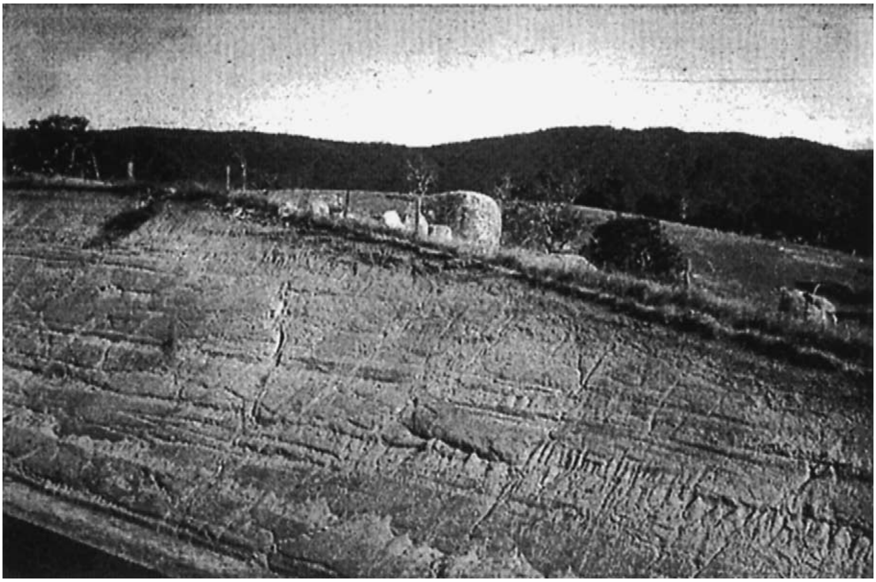

Fig. 3. Thick grus developed in granite, exposed below the Table Mountain Group sandstones of the Cape Peninsula, South Africa.

kaolinite and gibbsite has been used to argue for warm and humid weathering environment and an unspecified Tertiary age of grus. However, in their own opinion, grus profiles and their mineralogy are consistent with the temperate climate of the present day.

These variations and uncertainties undermine any attempt to establish direct links between grus weathering and climate, and therefore zonation of grus products with respect to climatic differences within the temperate zone must be regarded as premature.

5. Geomorphological context of grus mantles

From the geomorphological point of view, grus mantles occur in a variety of settings. Nevertheless, they seem to be preferentially associated with some relief and rarely appear to underlie low-lying plains or occupy the lowest parts of basins. There may, however, be a sampling problem here because exposures depend on some degree of relief elevation. Thus in the Buchan area of NE Scotland, relief is subdued and most grus exposures occur beneath middle or lower slopes of residual or enclosing hills within and surrounding the basin-shaped lowlands.

Grus profiles occur in three major types of setting (Table 3). First, they are common within elevated plateaux and uplands, beneath gentle slopes and along valley sides. In these areas, grus is often absent on upland tops, becomes thicker downslope (Fig. 4), but may disappear again on steep slopes of fluvial incisions. However, in the Appalachians, the thickest saprolites are often reported from beneath the wide flattened interfluves (Stolt et al., 1992; Cleaves, 1993).

Table 2
Profile behaviour, patterns, and characteristics of grus and sandy mantles in different climates

	Warm	Temperate to cool
Humid	rapid profile deepening and lowering	relatively rapid profile deepening in moderate relief
	rate of weathering front advance very fast (>10 m/Ma)	slow profile deepening on steeper slopes
	corestones at depth abundant	rate of weathering front advance intermediate (ca. 5–10 m/Ma)
	grus mantles thick (>20 m)	grus mantles thin to medium thick (5–20 m)
	clayey grus and arène common	grus and granular grus prevails, clayey grus rare
Semiarid	profile deepening restricted, frequent truncation	slow profile deepening in moderate relief
	rate of weathering front advance slow	non-saprolitic weathering on steeper slopes, talus development
	grus mantles thin to medium thick (5–20 m)	grus mantles thin (< 5 m)
	grus and granular grus prevails	granular grus prevails

Second, they occur in hilly and inselberg landscapes, although details of grus distribution vary. In SW Poland (Migoń, 1997b) and in some parts of the Bohemian Massif (Ivan, 1983), the hills themselves are built of unweathered massive granite, but their lower slopes are underlain by a grus mantle, the thickness of which locally exceeds 10 m. Many of the south Swedish sites seem also to be in a footslope position, yet other hills are weathered throughout into grus (Lidmar-Bergström et al., 1997).

Third, grus mantles are associated with highly dissected mountain areas. Again, their distribution patterns vary. In northern European mountains, grus mantles occur beneath passes and valley benches (Peulvast, 1985, 1989; Le Coeur, 1989), while in the subtropical mountains of Serra do Mar, watershed ridges, spurs, and isolated hills are very often deeply weathered. Only the cores of unweathered granite–gneiss (Thomas, 1995) protrude as massive domes from the widespread saprolitic mantle. The geomorphic setting of grus mantles in the Separation Point granite of the Abel Tasman National Park, New Zealand, is worth special emphasis. A summit plateau with an elevation of ca. 1000 m largely stripped of regolith, rapidly gives way to ridge and valley topography, falling in altitude to sea level within 12–15 km. Field and air photo interpretations indicate that zones of pale, sandy

Table 3
The occurrence of weathering mantles in relation to regional and local relief (based on various sources quoted in the paper and our own observations)

Topographical setting	Examples
Elevated plateaux, upland slopes and valleys sides	Dartmoor (England), Massif Central (France), Harz and Fichtelgebirge (Germany), Karkonosze (Poland), Serra da Estrela (Portugal), Sila Massif (Italy), Appalachians (USA)
Inselberg landscapes and residual hills	Bohemian Massif (Czech Republic, Poland), southern Sweden, eastern Portugal
Highly dissected mountain area	Scottish Highlands, Scandinavian Mountains (Norway), Serra do Mar (Brazil), Middle Hills (Nepal), New Zealand, South Africa

Fig. 4. Grus developed beneath lower slopes of granite valleys, central Portugal.

weathering are followed by the main streams and influence the pattern of bays and headlands along the coast (Thomas, 1974). The arcuate plan of this relief suggests a strong structural control over the zones of weathering. Small pockets of a more highly altered saprolite occur in protected locations, mostly close to sea level. In the Cape Peninsula, South Africa, the Silurian/Ordovician Table Mountain Group, mainly sandstone, overlies a Cambrian/Precambrian granite suite and the combination forms an area of strong relief with high sandstone cliffs overlooking granite piedmonts and lowlands. At certain points, near-vertical cliffs cut across the granite contact and in these locations there is no visible development of weathering above the sound granite. But where the sandstone cliffs have receded, ramp-like slopes carrying rockfall debris and associated hillslope deposits from the cliffs are underlain by thick sandy grus (Fig. 3). The implication of this situation is that the granite weathering could have developed synchronously with scarp retreat. Subsequently, these ramp-slopes may become highly dissected, as in the Valley of the Thousand Hills near Durban and local watershed ridges are then built largely of deeply disintegrated granite, within which corestones and domes can be found (Thomas, 1978). However, in this latter area, a few drill records indicate weathering below the sedimentary cover, which is quite thin.

5.1. The morphotectonic setting of grus mantles

The above observations may now be placed into a morphogenetic and morphotectonic context. Moderate to high relief is in most cases the product of relatively recent relief differentiation and a component of differential surface uplift is usually involved. The morphotectonic settings of grus mantles are assigned to four categories although partial overlap between them is possible.

(1) Grus mantles occur in block-faulted topography, which is the result of differential uplift of an old surface. Examples include Fichtelgebirge in Germany, where uplift took place chiefly in the Miocene (Peterek et al., 1996), the Massif Central and the Sudetes, whose uplift is Mid- to Late Tertiary (Dyjor, 1986), the rift margin zone of western Uganda (Taylor and Howard, 1999), and Sierra Nevada, the uplift of which is still under way (Wahrhaftig, 1965). Although there are grus sites on elevated palaeosurfaces within the horsts, many occur within fault-generated escarpments, where their thickness often attains local maxima (cf. Karkonosze in Poland; Migoń, 1997a).

(2) Grus mantles occur within uplifted (upwarped) and dissected terrains typified by passive continental margins. Their morphology in detail either resembles an all-slope topography (Serra do Mar, Valley of the Thousand Hills, Abel Tasman Park) or consists of elevated plateaux separated by deep incisions (Appalachians, Scandinavian Mountains). In contrast to (1) above, relief differentiation (compartmentalization) here is more due to the action of exogenic agents of erosion and dissection rather than due to tectonic processes. Deep grus weathering is found in various places within the landscape and in low latitudes no preferential location for grus can be observed.

In both these cases, it is important to consider whether the grus is entirely a remnant of an old weathering mantle, possibly truncated since surface denudation has accelerated or is forming simultaneously with and subsequent to uplift and dissection. Although there are occasional claims that grus in such areas may be inherited (Kubiniok, 1988), it often coexists with more advanced, kaolinised saprolites, usually located in grabens or on extensive watershed surfaces (cf. Fichtelgebirge—Peterek et al., 1996; Sudetes—Migoń, 1999). It is these kaolinitic saprolites, quite distinct from grus, which are likely to be of pre-uplift age. In some cases, the former kaolinitic and 'lateritic' covers have been eroded and deposited in adjacent basins as well as within interior grabens. Millot's (1970) analysis of sediments found in the Aquitaine basin and derived from the Massif Central is the classic example, while similar sediments have been found in fault-bound Palaeogene basins adjacent to Dartmoor (Bristow and Robson, 1994).

(3) Grus is also found in some orogenic terrains. The South Island of New Zealand was cited above and although the Separation Point granite lies in a less active tectonic zone, it has experienced strong Neogene uplift and dissection. The Sila Massif in Italy is a further example (Le Pera and Sorriso-Valvo, 2000). It can be noted that Haantjens and Bleeker (1970) referred to skeletal and smectitic weathering of volcanic rocks in Papua New Guinea and considered the former to take place within a time scale of ca. 5 ka. Although not specifically described as grus, such occurrences demonstrate the reality of effective weathering in orogenic terrains. Stallard (1995) has also pointed out that weathering processes may be rapid in such terrain as a consequence of the occurrence of susceptible rocks, including volcanic and epithermal igneous rocks, widespread fracturing, and free drainage. Widespread grus mantles are unlikely to form in these conditions but occurrences are found in favourable locations.

(4) The final category is essentially one of subdued relief and includes undulating, often multi-convex landscapes, and dominantly concave basin landforms, perhaps with steep rims. Some of these subdued landscapes contain isolated, steep hills or inselbergs that stand above extensive plains. None of these landscapes necessarily involves recent tectonics. Yet, long-term relief differentiation does take place here and is being

accomplished by weathering, mass movement, and erosion, producing moderate relief in the range of 100–200 m (Thomas, 1974). Grus mantles can penetrate deeply below convex compartments, but in other cases are confined mainly to lower slopes.

5.2. Grus and relief-interpretation

The common association of thick grus mantles with areas of moderate to high relief, often with a recent history of uplift across the morphoclimatic belts of the world, requires special explanation. Rapid, deep penetration of low grade weathering (one that involves rather modest changes in mineralogy and chemistry of parent rock) in such settings seems to be facilitated by the following circumstances.

- Tectonic preconditioning of the rock, including extensive fissuration, development of fault zones with associated breccias, and possibly enhanced microfracturing.
- Tensional stresses within the rock, which lead to joint opening during relief formation, promoting deeper infiltration and groundwater circulation.
- Increased relief accompanied by lowering of groundwater levels and increase in hydraulic gradient; accelerating access of water within the rock mass.
- Moderate to high relief areas containing a variety of local topographic settings, which offer at least some protection against surface erosion, thus enabling profile deepening. These include summit flats, plateau surfaces, cols and saddles, moderately inclined slopes and footslopes.
- The occurrence of susceptible rocks, including high-level intrusives and volcanic rocks in both recent and older orogenic terrains.

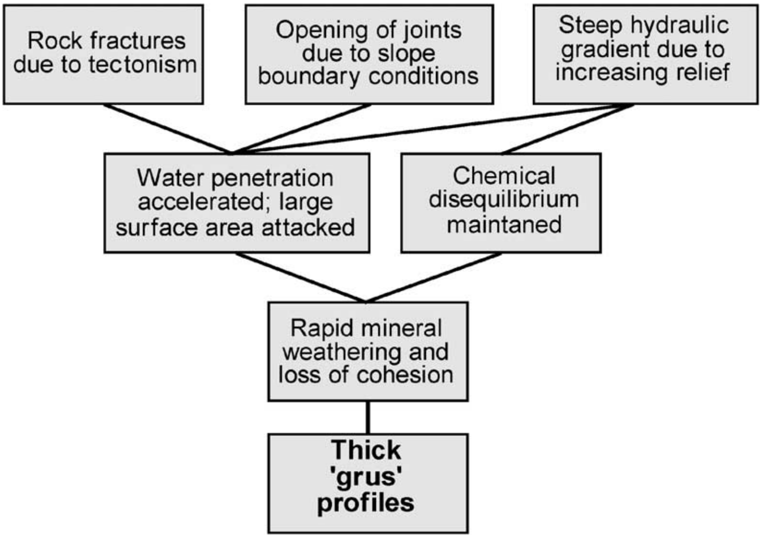

Fig. 5. Conceptual diagram to show principal influences on the origin and development of thick grus mantles in areas of moderate to high relief, subjected to recent uplift.

How all these factors may combine to produce thick grus is diagrammatically illustrated in Fig. 5.

The rates at which grusification occurs are not known with any great precision, although they are likely to be in the order of 5–20 m/Ma (e.g., Pavich, 1989; Cleaves, 1993). They are possibly distinctly higher in warm and humid environments and may increase exponentially with time. For grus weathering profiles to survive, they have to be higher than, or at least comparable with, average rates of surface denudation. But on the other hand, surface erosion must be fast enough to prevent profiles from attaining greater maturity in their mineralogical evolution.

Hence, it may be proposed that much of the deep grus phenomenon is a response of weathering systems to rapid relief differentiation, whether by tectonics, erosion, or both, and associated enhancement of groundwater circulation. Grus is not exclusive to such settings but at the same time, other categories of deep weathering mantles are seldom encountered in areas of high relief, except perhaps the humid tropics.

6. Conclusions

There is little justification for the recognition of grus as the product of a distinctive weathering system. Gradations between different degrees of alteration are apparent in many circumstances: along regional rainfall gradients, down profile, and across local landscapes. Grus mantles vary in composition and character from almost wholly granular (lithic) fragments to fersiallitic residues (clayey grus). The alteration products include vermiculites and smectites, and significant kaolinite. Al and Fe sesquioxides are generally absent, but these only appear as the weathering stage advances beyond any reasonable definition of grus. Close definition of grus is therefore hardly justified. Nonetheless, the widespread recognition of arenisation or grusification in granites and some other rocks justifies retention of the term. Whether these materials should be regarded as in equilibrium with any prevailing environment is very doubtful. There may be a theoretical balance possible between grus formation and removal, which is capable of maintaining a sandy regolith on a hillslope. But the time frame required to produce tens of metres of grus (10^5–10^6 years) is such that both climatic and tectonic disturbances will have been major influences on weathering systems.

Surface exposures of grus therefore depend critically on landscape histories. We do not argue the case for or against the progress of weathering in cool climates towards lateritic or bauxitic residues (Taylor et al., 1992) because the time required would similarly span fundamental environmental changes. Regolith or saprolite age remains ill defined for most occurrences and proposed rates of weathering, even within a single climatic zone, can span orders of magnitude. Deep weathering outside the cratonic interiors and their ferrallitic mantles can be broadly Neogene. In SE Brazil, Vasconcelos et al. (1992) proposed minimum ages based on ^{40}K–^{40}Ar and $^{40}Ar/^{39}Ar$ analyses of potassium manganese oxides, of 10.1–5.6 Ma, for deep regoliths (>20 m) in a zone of dissection. It is possible that a late Miocene age for much deeply weathered rock will be found consistent with many tectonic and climatic histories, but weathering processes are continuous and secondary minerals are continually formed and modified through time. Grus is unlikely to be of geologically ancient origin and outside recently glaciated areas most occurrences are likely to be Quaternary or late Tertiary in age. However, some grus mantles, especially in formerly glaciated terrains, may have resulted from the truncation of thicker weathering profiles. Consequently, their present characteristics may reflect the weathering environment close to the weathering front and are not indicative of near-surface conditions in either present or past.

A purely climatic approach to the explanation of grus is not helpful, since grus mantles can be found in a variety of climates, from subtropical to cool temperate, and beneath high-grade weathering materials in the tropics. However, there is some zonation of grus properties with respect to climate, climatic change, and climate-dependent subaerial processes. An integrated, geomorphological approach, which emphasises topographical factors at the local and regional scales and takes into account the history of uplift and dissection, seems to be more appropriate. Dissected terrains of moderate relief are particularly suitable for thick grus to develop. This is because of free drainage, strong hydraulic gradient, and rock dilatation. In many rocks, systems of microcracks increase

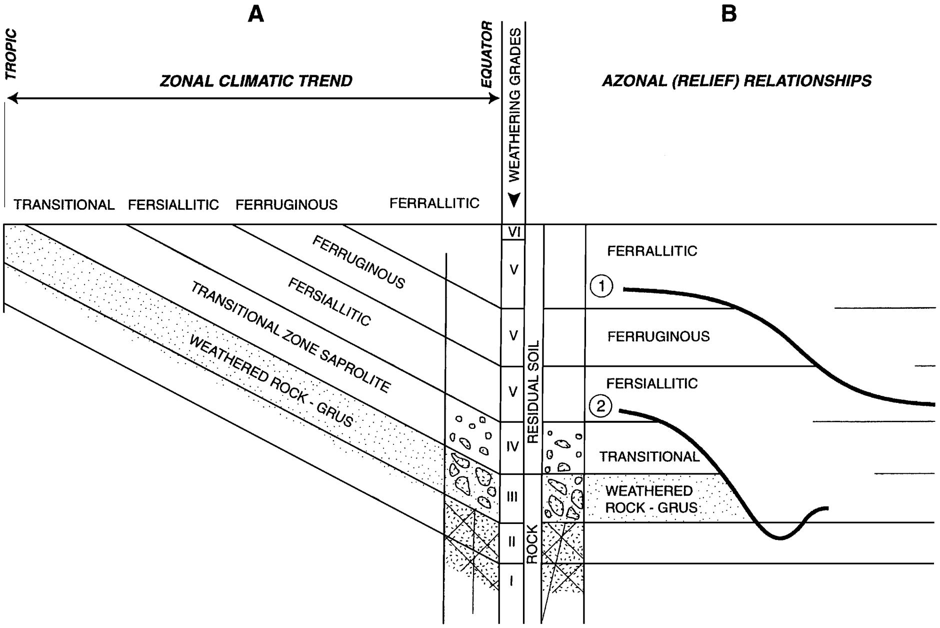

Fig. 6. Schematic diagram to illustrate relationships between weathering depth, grade, and surface exposure of residual materials in the tropics. Grus (with or without corestones) is equated to weathered rock—mainly Grade III in engineering classifications. Surface exposures of grus in tropical areas are confined to semiarid zones and dissected relief, but a varying thickness of grus may be found at depth in all climates. Weathering stages (fersiallitic, ferruginous, ferrallitic) as proposed by Duchaufour (1982) and used in Fookes (1997). (A) shows the potential surface outcrop and depth transition along a humidity transect, following the ideas of Strakhov (1967); curves 1 and 2 in (B) illustrate how surface outcrop may occur in relation to slope and valley forms, following dissection. Diagram modified from Fig. 2.3 in Fookes (1997), constructed by M.F.T. for Geological Society of London (1990). Reproduced with permission.

permeability, favouring deep penetration of water, which can lead to early grusification. Surface instability prevents the profiles from attaining geochemical and mineralogical maturity.

A model of regolith development, based on relative rates of uplift, weathering penetration, and surface denudation, needs to be considered alongside established models of profile evolution based on climatic parameters and gradients. But even when this is attempted (see Thomas, 1997, Fig. 6), several circumstances have to be recognised. Variations in rock mineralogy and fabric, along with local variations in stress fields and fracturing, may obscure any linear relationship with uplift rate.

Furthermore, most landscapes have passed through periods of stability and weathering advance and episodes of instability and stripping. Long-term stability, whether defined in tectonic or climatic terms (and these may be linked) has not been a characteristic of the Neogene and evidence worldwide suggests that many weathering profiles formed or truncated since the mid-Miocene have not advanced far beyond the stage of grus formation. Exceptions come mainly from the humid tropics, where copious precipitation and high biological productivity ensure rapid biogeochemical evolution of regoliths towards a ferrallitic stage.

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