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Deep weathering through time in central and northwestern Europe: problems of dating and interpretation of geological record

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Abstract

Upland and shield areas of central and northwestern Europe are characterised by an abundance of relict weathering mantles (saprolites). These saprolites, if accurately dated and interpreted, may serve as an important complementary source of information about long-term environmental history. In this paper, methods used to establish ages of weathering mantles are reviewed, such as stratigraphic and morphostratigraphic dating, clay mineral and stable isotope analysis, K–Ar and cosmogenic isotope dating, particularly with reference to European examples. The record of deep weathering in the Mesozoic and Cainozoic is examined to explain the peculiarities of the evidence and controls on the changing style of weathering through time. Weathering has been a continuous process through time, but general and local geological conditions have resulted in different ages of preserved mantles. An apparent trend from an earlier kaolinitic/ferrallitic style of weathering in the Mesozoic and Early Tertiary, towards a grussic style by the end of the Cainozoic, does not only reflect climate change, but it is also broadly consistent with tectonic/geomorphic history and related changes in land surface stability. Miocene and Plio–Pleistocene saprolites, in particular, show that in different geomorphological and lithological circumstances, different types of weathering mantles could have evolved. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Weathering; Saprolites; Dating methods; Europe

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1. Introduction

Upland areas of central and western Europe as well as northern European shields are characterised by an abundance of weathering mantles (saprolites), generally considered as relict, and inherited from various geological epochs, from Early Palaeozoic up to the Pleistocene (Figs. 1 and 2). These saprolites occur in a variety of topographic and stratigraphic settings, and can be found on different types of bedrock. Their potential for research on long-term geological evolution has long been recognised and outlined in a number of papers (e.g. Bakker and Levelt, 1964; Thomas, 1978; Godard, 1989; Lidmar-Bergström, 1995).

One of the persisting problems in such studies, however, is the accurate dating of weathering mantles. Dating becomes critical in any attempts to use saprolites as means of

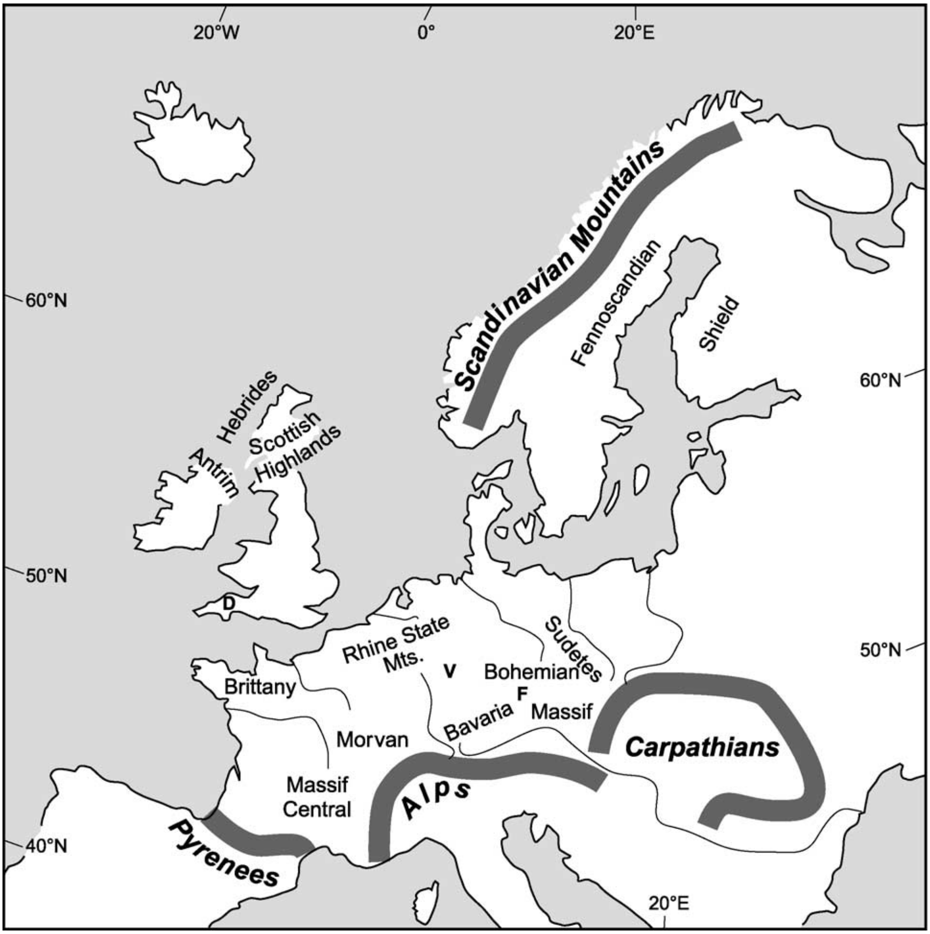

Fig. 1. Location map indicating areas and localities mentioned in the paper. V-Vogelsberg, F-Fichtelgebirge.

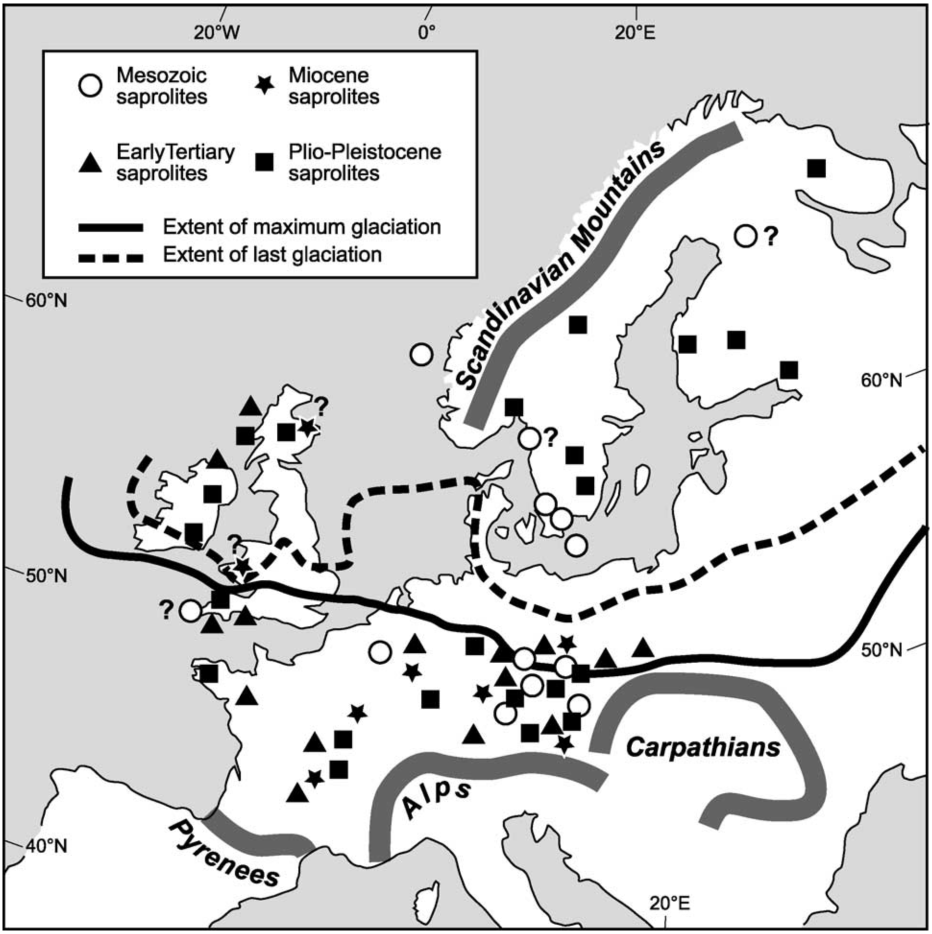

Fig. 2. Distribution of relict weathering mantles in central and northwestern Europe, classified according to their most likely ages. Question marks indicate ages inferred from circumstantial evidence such as long-distance correlations with saprolites of known ages or morphostratigraphic dating.

deciphering the course of long-term landform evolution and of establishing its chronological framework. A number of methods have been used to provide ages of saprolites, varying in the resolution offered, reliability and availability of application. Moreover, the very concept of the 'age' of saprolite mantles is rather poorly developed and different components of saprolites may have, and yield, different 'ages' (Ollier, 1991; Thomas, 1994a). Therefore, the 'age' as given in most papers is usually quite a long period during which a saprolite may have developed (cf. 'Early Tertiary kaolins of central Europe'). In reality, the profiles could have attained their principal characteristics in much shorter time, but the resolution of dating methods is insufficient.

This paper principally intends to serve two purposes. Firstly, it provides a brief review of dating methods applied to weathering mantles, with special reference to European examples, although it is not meant to describe the methods themselves in detail. Rather, it aims to point out the implications of the results for attempts to establish a geochronology of weathering. Secondly, it looks at the phenomenon of deep weathering as present in the geological record of the Mesozoic and Cainozoic, and tries to explain the peculiarity of the evidence and controls on the changing style of weathering through time. It has to be noted that given space limitations, references will be inevitably selective, especially those concerning long-term denudation and sedimentation histories.

2. Dating weathering mantles

Methods of dating saprolites can be broadly divided into two major groups. In one group, ages are inferred from the geological and/or geomorphological context of weathering mantles and these ages are usually upper or lower time limits of saprolite formation. In the other one, the age of weathering is derived from properties of the saprolites themselves. The procedure to obtain the age may follow an indirect or direct path. In the former, selected characteristics of a saprolite such as clay mineral assemblages or stable isotope ratios are correlated with independently established palaeoclimatic histories or sediment ages, and in this way, periods of weathering are identified. In the latter, absolute ages are provided. These include dating of Mn oxides and calculations of abundance of cosmogenic isotopes.

2.1. Stratigraphic dating

This method relies on the classic stratigraphic principle of superposition, according to which the age of overlying sediments or volcanic rocks provide the minimum age of weathering. Equally, the age of rock subjected to weathering provides the maximum age, which in the case of extrusive rocks is almost equal to the actual onset of weathering. The resultant time interval may be significantly narrowed through the examination of exposure time of saprolite hosting rock unit. For example, in Bavaria (Germany) kaolinitic saprolites are developed on Variscan rock complexes but apatite fission track ages exclude any possibility that these saprolites could be older than mid-Tertiary (Schröder et al., 1997; Gilg, 2000).

The resolution of stratigraphic dating is highly varied and depends on local geological circumstances. Locally, weathering episodes could be dated very precisely, as in the case of Early Palaeocene intra-basaltic saprolites in Antrim, Northern Ireland (Smith and McAlister, 1987), and in the Inner Hebrides off the west coast of Scotland (Jolley, 1997). However, over much of the Fennoscandian Shield saprolites are overlain by Late Weichselian till, and except for southern Sweden, where Cretaceous sediments occur on top of kaolinitic saprolites (Lidmar-Bergström, 1989), ages obtained from the application of stratigraphic principles alone are virtually meaningless. The stratigraphic method works most effectively in areas subjected to protracted volcanic activity, where consecutive lava flows may fossilise weathering horizons of different ages. The Massif Central (Pierre, 1990; Pierre and Dejou, 1990) and the Antrim lava field in Northern Ireland (Smith and McAlister, 1987; Hill et al., 2000) are the best European examples of such conditions.

The reliability of the method is generally good, unless dating of overlying sediments is at serious fault, but it has limited application to many upland and shield areas where saprolites occur at the surface, or beneath very recent deposits. Moreover, stratigraphic dating implies an effective halt of weathering at the time of burial by younger sediments, whereas such an assumption is not necessarily always correct. If overlying strata are thin and permeable and the site is freely drained, water may still have access to the saprolite below and cause further weathering. In particular, ongoing weathering beneath peat blankets is very probable as suggested by Smith and McAlister (1987) in Northern Ireland. Schmidt and Ollier (1988) have described instances of Tertiary weathering mantles below Jurassic lava flows in Australia and documented such reverse ages by palaeomagnetism, whereas Pavich and Obermeier (1985) argued for Late Cainozoic subsurface weathering under Cretaceous and Miocene strata in the Coastal Plain in eastern United States.

2.2. Morphostratigraphic approach

In this approach, the key to the age of weathering is the age of a geomorphic surface which is weathered, or which truncates a saprolite. In the former situation, weathering postdates the origin of the surface; in the latter, weathering is of an earlier date. Obviously, the procedure of morphostratigraphic dating relies heavily on the accuracy of dating geomorphic surfaces. Unfortunately, their ages are usually very poorly constrained and the method faces the danger of circular reasoning.

In only a few examples, ages obtained from the relationships between saprolites and landforms can be considered meaningful. In the Scottish Highlands, Hall and Mellor (1988) demonstrated that weathering mantles, which had developed within shallow upland valleys, were subsequently incised by glacial troughs, hence these mantles are probably of pre-Pleistocene age. Another area is southern Sweden where distinctive landscapes associated with specific saprolites evolved at different times within the Phanerozoic. This is shown by the relationships between erosional landscapes and cover rocks (Lidmar-Bergström, 1995), and these associations could then be used to infer ages of saprolites in other, not too distant areas.

2.3. Secondary mineral interpretation

Palaeoclimatic analysis of secondary minerals formed during weathering is perhaps the most commonly used means of unravelling the age of saprolites, if stratigraphic constraint is not possible or its resolution is unsatisfactory. The method is actually based on a sequence of assumptions, of which the critical one holds that some secondary minerals, or their associations, are diagnostic for certain types of climatic environments. Clay minerals are considered most useful. The next step involves the identification of a period (or periods) within the geological record, for which such climatic conditions have been independently established. Local and regional geological circumstances may then assist in selecting the most likely alternative within possible weathering periods.

Palaeoclimatic interpretation of clays is championed mostly by the French who established a school of comprehensive clay mineral analysis in respect to climate (e.g.

Millot, 1964; Pedro, 1968; Tardy et al., 1973; Righi and Meunier, 1995). However, several notes of caution have been subsequently introduced by various authors who emphasised the role of other factors such as parent rock composition, site factors, including local geomorphology and hydrology, stage of weathering, and duration of weathering. These may all upset the supposed relationships and result in spurious conclusions if not adequately considered (cf. Singer, 1980; Gerrard, 1994; Power and Smith, 1994). Results of recent studies from Australia in particular (Bird and Chivas, 1989; Taylor et al., 1992) show that kaolins and laterites may form even in a cool climate, given general surface stability over a long time scale, and as such may not have a definite palaeoclimatic value. Furthermore, it has been stressed that the presence of a mineral itself, such as gibbsite, is not sufficient to infer paleoenvironments, for which it needs to occur in at least larger quantities.

Nonetheless, in the European context there seems to be a consensus that thick kaolinite-rich saprolites are inherited from humid and warm climate and are not younger than Miocene. Ferrallitic profiles would testify to humid tropical conditions, and thus they need to be Early Tertiary in age or older. By contrast, sandy saprolites (*arènes*, grus) retain most of the original rock structure and would point to a less aggressive environment, for example, the temperate climate of the Pliocene, although the actual meaning of sandy weathering mantles remains a contentious issue (Gerrard, 1994; Migoń and Thomas, 2002). Palaeoclimatic interpretation becomes much more problematic if weathering mantles have survived in isolated patches, have unclear relationship to local geomorphic history, or are potentially truncated. Many ‘ages’ derived from mineralogical analyses of such incomplete and isolated profiles could be seriously inaccurate, yet much of regional geochronology of weathering in Europe is based on such an imperfect approach.

2.4. Stable isotope analysis

The essence of this indirect method is the assumption that D/H and $^{18}O/^{16}O$ ratios in secondary minerals formed during weathering, chiefly in kaolinite, reflect primarily the isotopic composition of groundwater in the presence of which they originated and the temperature of formation. The stable isotope ratios in groundwater in turn reflect the average isotope ratio of rainfall, itself dependent on the mean annual temperature (Bird and Chivas, 1988). Hence, through the analysis of stable isotope geochemistry of weathering products, one can establish the likely temperature ranges of weathering environments and correlate them with the climatic history of a given area. This technique has been used most successfully in Australia where residual clays with distinctive oxygen isotopic signatures have been recognised, consistent with Permian, pre mid-Tertiary and post mid-Tertiary ages of weathering (Bird and Chivas, 1988, 1993).

In the European context, stable isotope analysis of weathering products to infer their age has been rare. More often, stable isotope studies have aimed at the recognition of the origin of kaolins, whether of supergene or hydrothermal origin (Sheppard, 1977; Boulvais et al., 2000). One of the examples of geochronological work is that by Gilg (2000) who analysed hydrogen isotope ratios in saprolites and sedimentary clays to obtain a geochronology of kaolin formation in Bavaria, southern Germany. Both mid-Cretaceous and mid-Tertiary ages have been suggested.

The success of the method is heavily dependent on the availability and quality of reference data used in age derivation such as the occurrence of well-dated sedimentary clays. Otherwise, it is very difficult to ascribe geochronological meaning to the obtained isotopic values. However, Gilg (2000) suggests that in the context of central European uplands, Jurassic and Cretaceous kaolins would have δD values from around $-60‰$ to $-70‰$, whereas mid-Tertiary kaolins would have from -75 to $-90‰$.

2.5. K–Ar and $^{40}Ar/^{39}Ar$ dating

During weathering, supergene minerals belonging to the alunite group, sulphates (alunite, jarosite) and Mn^{+4} oxides (cryptomellane, hollandite), may form and these can be dated using the and $^{40}Ar/^{39}Ar$ technique of the K–Ar method (Vasconcelos, 1999; Vasconcelos et al., 1992, 1994). By applying this technique, one can determine the ages of neoformed minerals, their distribution within the profiles and the length of time necessary for the formation of laterite blankets.

Again, few investigations of this sort have been carried out in Europe. Most recently, Hautmann and Lippolt (2000) have investigated more than 30 manganese ore deposits from central Europe, chiefly from Germany. The oldest ages, ca. 25 Ma, have been obtained for samples collected in the Massif Central, but most samples yielded Middle and Late Miocene ages. Gilg and Frei (1996) applied K–Ar and Rb/Sr dating to kaolins in Brittany and eastern Germany. The results obtained, point to Eocene (45–50 Ma) and Lower Cretaceous (ca. 110 Ma) ages, respectively, and are consistent with the regional stratigraphy of kaolinite-rich sediments.

2.6. Cosmogenic isotope dating

Within the recent advent of cosmogenic isotope techniques to date land surfaces and rates of erosion, a technique using the cosmogenic ^{10}Be inventories in soils and saprolites, may be used for dating (Pavich et al., 1985; Bouchard and Pavich, 1989). ^{10}Be is delivered by rainfall and accumulates in soils due to slow radioactive decay until it may reach an equilibrium value, which would take about 5 Ma. However, ^{10}Be inventories are simultaneously depleted by soil erosion and solution transport and these need to be considered alongside with delivery rates. Therefore, the application of this method provides information about the length of accumulation time, hence the minimum age of a saprolite, provided it is exposed at the topographic surface. For buried saprolites, the method yields data about the length of exposure time and should not be confused with the actual age.

Several attempts to use ^{10}Be method have been made in eastern North America (the Appalachians and the Piedmont) to constrain the ages of presumably ‘old’ saprolites. Most of the obtained ‘residence times’ proved quite young, pointing to Quaternary rather than to Tertiary weathering (Pavich et al., 1985; Brown et al., 1988; Bouchard and Pavich, 1989). However, specific problems have been recognised if the method is applied in formerly glaciated areas, of which the probable shielding effect of ice caps is the most important. It appears as if no cosmogenic isotope studies of European saprolites exposed at the surface have been attempted so far.

3. Deep weathering in the geological record

3.1. Phases of deep weathering—convention or reality?

Specifically named time intervals (‘phases’) in which weathering processes have operated are often seen in the literature. In Europe, much research has been made into the origin of kaolins because of their commercial importance. Störr et al. (1977) identified several phases of kaolinisation in central Europe from the Ordovician to the Miocene, based on the occurrence of kaolin in the sedimentary record and to some extent also in preserved weathering crusts. These kaolinisation periods coincide with periods of humid climate, while during arid phases other clay minerals were preferentially formed such as chlorites, smectites, and mixed layer minerals (Norin, 1949; Sellwood and Sladen, 1981; Sladen and Batten, 1984). However, because of poorly constrained ages for many kaolin deposits, the phases recognised by Störr et al. (1977) are protracted in time; the last one encompasses the Late Mesozoic and Tertiary, ca. 100 Ma in total. Hence, the time intervals give only a broad outline over a very long time perspective. Furthermore, they do not refer to weathering in general, but only to kaolinisation. There is a high probability that weathering was time and space continuous, although it operated with different intensities and there may have been shifts in the balance between rates of saprolite production and surface erosion. Thus, most of the ‘phases’ recognised within the literature are snapshots that happen to be captured because of specific geologic circumstances such as burial by lava or by transgressive marine sediments. Termination of deep weathering in a place affected by burial does not mean that weathering came to a halt in exposed areas. In southern Sweden, there is kaolinised bedrock buried beneath Jurassic sediments but weathering continued until Late Cretaceous as shown by thick kaolins covered by Campanian limestone (Lidmar-Bergström, 1989, 1995). Another example may be found in the Massif Central, where lava flows of ages ranging from Middle Miocene to Late Pleistocene overlie sandy saprolites derived from granite, with each saprolite having distinctive mineralogy and geochemistry (Pierre, 1990). This demonstrates that grus mantles have been produced in the Massif Central from at least the Middle Miocene until now. In addition, no support for the concept of phases of accelerated weathering has come from the geochronological studies of Mn oxides (Hautmann and Lippolt, 2000), in which no clear clustering of ages has been demonstrated. Minor concentrations could be accidental and reflect the time of denudational exposure of bedrock rather than intensified weathering.

Even if such age clustering is obtained, it should not lead automatically to the recognition of phases of deep weathering, but should provoke questions of why there is a gap in the record. Here, the concept of the diversity of evolutionary pathways of weathering profiles is helpful (Thomas, 1994b). The record of weathering may disappear altogether if profiles are completely eroded or lose its palaeoenvironmental value if significantly truncated. Similarly, no older ages will be obtained if weathering was concurrent with erosion and profile lowering was dominant, this is the case for the passive margin along the SW Brazilian coast (Vasconcelos et al., 1992; Thomas, 1995), and has been proposed for northwestern coast of Norway (Peulvast, 1989). This suggestion is reinforced by the recent recognition that thick weathering profiles may in fact need significantly less time to develop than previously suspected and are time dynamic (Thomas, 1994a). Furthermore, short-term climatic changes, probably characteristic for the Neogene, may have retarded the progress of weathering, but were unlikely to stop it completely.

3.2. Specific times—specific saprolites?

Most of the European weathering mantles of Mesozoic ages are thick kaolinite-rich saprolites (Rasmussen, 1966; Sturt et al., 1979; Störr, 1983; Lidmar-Bergström, 1989; Dupuis, 1992; Bosák, 1995). They have survived under the protective cover of Late Cretaceous, or less often Jurassic, sediments, hence their ages are well constrained by local stratigraphy. The existence of thick Mesozoic saprolites is usually linked with hot and humid conditions (Kužvart and Konta, 1968), although long-term surface stability and low rates of denudation characteristic of the Mesozoic in central Europe are factors not to be ignored. The quite widespread occurrence of pre-Late Cretaceous kaolins, if taken together with the unconstrained ages of many residual kaolin deposits, has promoted thinking that Mesozoic saprolites may in fact be more common and were stripped of their sedimentary cover relatively recently. For example, this has been suggested in respect to Dartmoor (SW England) by Lidmar-Bergström (1986) who drew attention to the presence of land-derived kaolins in the Jurassic and Early Cretaceous sediments in Southeast England (Sellwood and Sladen, 1981; Sladen and Batten, 1984). In this interpretation, the kaolinitic mantle of Dartmoor was formed in the Mesozoic, then buried in the Late Cretaceous, and uncovered and re-exposed in the Tertiary. Similarly, kaolinised bedrock in Finland bears similarities to Cretaceous saprolites in Sweden (Söderman, 1985). A wider application of stable isotope dating to European kaolinitic saprolites may assist in determining the extent of Mesozoic deep weathering (cf. Gilg and Frei, 1996; Gilg, 2000), whereas apatite fission track dating of host rocks may provide an independent time constraint.

Weathering mantles ascribed to bedrock alteration during the Palaeogene are similarly predominantly kaolinitic and occur over extensive areas in western (e.g. Bristow, 1977; Sheppard, 1977; Esteoule-Choux, 1983; Boulvais et al., 2000) and central Europe (e.g. Kužvart, 1969; Surowce kaolinowe, 1982; Störr, 1983; Felix-Henningsen, 1994). They form regional covers attaining tens of metres in thickness. Lateritic-like profiles have developed on basalts (Nilsen and Kerr, 1978; Smith and McAlister, 1987; Bell et al., 1996; Hill et al., 2000) and some sedimentary rocks (Isaac, 1983). In the majority of instances, Early Tertiary ages of kaolins and laterites are derived from their occurrence beneath dated sediments or lava flows, whose ages range from Palaeocene (lava flows in Northern Ireland) through Eocene (marine deposits in Brittany; terrestrial sands in eastern Germany) to Middle Miocene (sands and clays in the foreland of the Sudetes, SW Poland). Most authors seek reasons for the extensive development of saprolites in the Tertiary in suitable climatic conditions that were warm and humid (cf. Kužvart and Konta, 1968; Büdel, 1977).

There is no doubt that weathering continued on upland surfaces during the Miocene, but the nature of Miocene weathering is controversial. These controversies partly stem from uncertainties in dating, yet some saprolites have ages rather tightly constrained. A specific group of Miocene weathering mantles is the one developed at the expense of

Miocene volcanic rocks. They occur in the Massif Central in France (Pierre and Dejou, 1990), Vogelsberg and Fichtelgebirge in Germany (Schwarz, 1997), and in the Sudetes and their foreland in Poland (Kościówko and Morawski, 1986). The depth of basalt weathering varies from a few metres up to 30 m, and locally there could be as many as six separate weathering horizons sandwiched between the lavas (Pierre and Dejou, 1990). In Vogelsberg, the Middle Miocene (17–15 Ma) basalt is weathered to a depth of 50 m, with the weathering zone vertically divided into three distinct horizons. They include a lower one rich in smectitic clays, a kaolinitic middle one, and an upper one that bears features of a lateritic bauxite cap; the latter is a few metres thick (Schwarz, 1997). In Fichtelgebirge, pisolithic gravels, found close to weathered basalt outcrops, are taken as evidence for the former existence of a lateritic profile (Sobanski and Valeton, 1996). This type of advanced weathering is interpreted to indicate a climatic optimum and short-term return of 'greenhouse' conditions in the Middle Miocene (Schwarz, 1997). Advanced alteration of crystalline rocks and kaolin formation extending into the Miocene is also inferred from stable isotope analysis (Gilg, 2000).

On the other hand, there is evidence available that Miocene weathering did not reach the kaolinitic stage, and sandy saprolites began to appear in the geological record. In the Massif Central, Pierre (1990) used the stratigraphic principle (burial by dated lava) to show that *arènes* were formed as early as 16 Ma ago. Grus mantles beneath Miocene deposits are also known from the southeastern border of the Bohemian Massif (Pippan, 1969). In other cases, a Miocene age for grus is argued on the basis of palaeoclimatic interpretation of mineralogy such as for 'clayey' grus in Scotland (Hall et al., 1989), grus in Germany (Borger, 1992) and Morvan in France (Nieuwenhuis, 1971).

Sandy saprolites are considered to be characteristic of the end of the Tertiary and the Quaternary. In many regional studies, they are regarded as a distinctive generation of saprolites, different from earlier kaolins or laterites (e.g. Bakker, 1967; Smith and McAlister, 1987; Godard, 1989; Eden and Green, 1971; Lidmar-Bergström et al., 1997; Migoń, 1999). However, dating of grus usually relies on palaeoclimatic interpretation or other circumstantial evidence, such as their occurrence on exposed slopes prone to denudation, which would imply a young age. Stratigraphic principles are of limited help as most grus mantles are developed on Carboniferous or older granites and are covered by Later Pleistocene slope or fluvial deposits. Therefore, interpretations of grus vary. Some authors claim that sandy saprolites are remnants of much truncated ancient saprolites and do not have any relation to the weathering environment in the Late Tertiary (Hillefors, 1985; Kubiniok, 1988), whereas others suggest rapid deepening in the Quaternary (Peulvast, 1989; Migoń, 1997). Grus development is probably active today, especially under blankets of peat (Smith and McAlister, 1987), and Sequeira-Braga et al. (1989) relate clay mineral suites in western European *arènes* to the present-day latitudinal climatic gradient.

It appears that there is no simple interpretation of sandy saprolites, as they seem to form in various settings and circumstances. Observations from low latitudes demonstrate that arenaceous (sandy) and clayey saprolites may co-exist (Power and Smith, 1994; Thomas, 1994a; Migoń and Thomas, 2002) and there is no need to classify them into separate age categories in palaeoweathering studies if no unequivocal evidence is available. On the other hand, the recent evidence from cosmogenic dating (Bouchard and Pavich, 1989) and other calculations (reviewed by Thomas, 1994a) suggest that grus mantles form quickly, at rates of 2–50 m/Ma; therefore their very young age is not impossible.

In summary, although there appears to be a general trend from an earlier kaolinitic/ferrallitic style of weathering towards a grussic style by the end of the Tertiary, the many uncertainties in dating provide a warning that the general model based on a solely climatic approach could be flawed. Given the long-term context of weathering, there is no doubt that there must have been a linkage between climate, weathering and tectonics; hence, the interpretation of the trend is not necessarily climatic. Surface stability and magnitude of erosion form another set of key variables in the weathering history of European oldlands.

3.3. Weathering style changes—discussion

The geological record of weathering on European oldlands and shields may reflect the history of long-term environmental (climatic) change, but the nature of the geological record of weathering is such, that it appears broadly consistent with the tectonic/geomorphic history. It is generally accepted that the Mesozoic was a period of tectonic stability within low relief surfaces located close to base-level, and that protracted conditions of biostasie facilitated weathering profile deepening, achievement of geochemical maturity, formation of spatially extensive saprolitic mantle and development of a planed relief in specific lithostructural circumstances. In most areas referred to in this paper, the development of surface relief was interrupted by Cretaceous transgression, the deposits of which (predominantly carbonate, but locally clastic) covered weathered land surfaces and sealed the record of Mesozoic weathering. However, the transgression must not be regarded as the termination of the 'phase' of deep weathering, as the composition of latest Cretaceous sediments suggests a steady supply of pre-weathered materials from remaining lands (Skoček and Valečka, 1983; Störr, 1983).

The turn of the Mesozoic and the beginning of the Tertiary were periods of increasing tectonic instability, resulting in sea withdrawal, uplift and deep denudation over many of the European uplands (e.g. Lewis et al., 1992; Hejl et al., 1997). Although it is likely that deep weathering in tropical climate played a key role in the progress of denudation, no extensive saprolites could have survived from that time because of both the denudation regime itself and the fact that most of weathering attack was concentrated upon newly emerged carbonate deposits, which do not leave thick residues. However, wherever a protective cover existed, as within the British Tertiary Volcanic Province, thick Palaeocene saprolites survived.

Much of the subsequent Early Tertiary in mainland Europe was again the period of general tectonic and geomorphic stability, and climate was predominantly warm and humid. Under these conditions, thick weathering mantles of kaolinitic type could have formed, and abundant silcretes reinforce the view that extensive deeply weathered and low relief surfaces typified the Palaeogene (Summerfield and Goudie, 1980; Thiry and Simon-Coinçon, 1996). The situation changed in the Neogene, which was dominated by uplift, dissection and erosion of older surfaces, although geologically brief intervals of stability have been noted, for instance in the Bohemian Massif. The ensuing rhexistasie conditions resulted in widespread stripping of older saprolites, the phenomenon well recorded in sedimentary basins (cf. Simon-Coinçon et al., 1997), but also in more rapid relief differentiation that is not conducive to laterally extensive kaolinisation. In the Middle Miocene, sandy saprolites started to appear in the record in some uplands (Massif Central, Bohemian Massif, possibly Scottish Highlands), but their origin was perhaps more related to changing surface conditions, under which mineralogical maturity was difficult to achieve, rather than climatic change. This supposition is corroborated by stable isotope studies by Gilg (2000) who demonstrated the origin of kaolins in the Miocene and by the ferrallitic-like and fersiallitic saprolites on Miocene basalts (Kościówko and Morawski, 1986; Sobanski and Valeton, 1996; Schwarz, 1997). It seems that different types of weathering mantles could have formed in different geomorphological and lithological circumstances.

Pliocene climate cooling may have eventually retarded extensive kaolinisation, especially in northern Europe (British Isles, Fennoscandian Shield), although there is evidence for ongoing kaolinite formation in more southerly parts of western Europe (Sequeira-Braga et al., 1989). But at the same time, erosional dissection and relief differentiation were proceeding, or even intensified, in many upland terrains, favouring the origin of shallow and spatially discontinuous grus. Long-term profile lowering has been inferred as the dominant evolutionary way in many settings (e.g. Peulvast, 1989; Thomas, 1995; Migoń, 1997).

Environmental conditions during the Quaternary, with its climatic cooling and repetitive glaciations, did not prove optimal for weathering mantle development, and much of the record of earlier weathering could have been lost. It is true that glacial erosion was highly selective and some ‘preglacial’ saprolites survive up to the present-day, yet certainly most other weathering mantles suffered from truncation or complete erosion by glacial and periglacial processes. Shallow sandy saprolites are consistent with these geomorphological, glaciological and climatic circumstances.

In summary, it appears unhelpful to insist on a simple climatic explanation of the general weathering history from the Mesozoic until present. Complex explanations that take into account tectonic, geomorphic and environmental factors—with the emphasis on the first—are more adequate and consistent with current knowledge of weathering mechanisms and factors.

4. Conclusions

The long-term record of deep weathering reviewed in this paper consists of two types of evidence. First, there are buried saprolites that are ‘snapshots’ which happen to be captured because of specific geologic circumstances, and whose stratigraphic dating often has poor resolution. Second, there are weathering mantles in exposed positions whose ages are inferred from a number of assumptions. Neither forms of evidence can have wider palaeoenvironmental significance. It appears clear that a fuller understanding of the role of weathering in geological evolution will be achieved through: (1) a wider application of dating techniques to the saprolites themselves, among which stable isotope analysis and K–Ar and ^{40}Ar/^{39}Ar dating seem most promising; and (2) an investigation of linkages between weathering, history of long-term denudation and sedimentation. Understanding the history of denudation may provide important time constraints on the ages of saprolites, whereas sedimentary basin analysis should supplement the fragmentary record preserved in areas of net denudation. Especially, an integration of onshore and offshore records of saprolite production and stripping is one of the main challenges for the future.

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