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Weathering of granites in a temperate climate (NW Portugal): granitic saprolites and arenization

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Abstract

Saprolites or in situ weathering products from granitoid rocks of Northwest Portugal were studied by means of X-ray diffraction (XRD) of their clay fraction and observations of polished thin sections combined with transmission electron microscopy (TEM), scanning electron microscopy with energy dispersive spectrometer (SEM-EDS) microanalyses. Their principal features are: (1) depths of more than 10 m; (2) mean material loss of 40% as calculated by an isovolumetric method; (3) low clay content (mean value of 7%) and a high degree of mineralogical evolution. The clay fraction is characterized by a predominance of kaolinite and gibbsite, with subordinate 2:1 minerals (illite, chlorite, vermiculitic mixed layers, vermiculite). The significance of the secondary minerals in granitic saprolites from Northwest Portugal is compared to published data from Atlantic Europe. This allows the definition of a climatic zonality for weathering products and identifies 'arenization' as an important weathering process. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Granitic saprolites; Kaolin minerals; Gibbsite; Arenization; Temperate climate

1. Introduction

The material generated by the weathering of coarse-grained rocks, especially granites, is usually referred to as 'granitic saprolite'. Power and Smith (1994) used terms such as arenaceous and sandy regoliths on the basis of both the weathering products and the mechanisms responsible for their formation. Similarly, 'arène' in French and 'arena' in Portuguese have been used as substitute terms for granitic saprolite. These terms were

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ultimately derived from the Latin word meaning ‘sand’ and the corresponding weathering process which results to their formation has been termed ‘arenization’ (Sequeira Braga et al., 1989). According to Pédro (1997), arenization occurs in the weathering zone of deeply weathered profiles, i.e. level III, just above the unweathered rock. This level is only affected by geochemical weathering, without pedological and biological activity, and the original rock structure can be easily recognized. The widespread occurrence of these profiles is indicated by the significant number of published studies on granitic saprolites and arenization (e.g. Collier, 1961; Millot, 1964; Tardy, 1969; Seddoh, 1973; Dejou et al., 1977; Meunier, 1980; Gaussen, 1981; Sequeira Braga, 1988; Molina, 1991; Pédro, 1997). In this study, our concern is to extend the range of available information through a study of Quaternary granitic saprolites from temperate Northwest Portugal, characterized by an average annual rainfall between 1200 and 1600 mm and an average annual temperature between 14.5 and 17 °C. In doing so, our aims are to identify the physical, mineralogical, and chemical characteristics of the granitic saprolites and the weathering mechanisms responsible for arenization. This information will be used to compare the nature and regional significance of the secondary minerals found with those identified in other studies from Atlantic Europe and to attempt to define any climatic zonality in the weathering products of the granites. Ultimately, it is hoped to show that arenization should be considered an important weathering system that ranks in significance in temperate areas with processes such as podzolization.

2. Materials and methods

2.1. Field observations

Variscan two-mica granites and biotite granitoids with calcium-rich plagioclase (and associated rocks) (Pereira, 1992) occupy significant areas of Northwest Portugal. The landscapes found on these rocks are characterized by isolated groups of well-rounded boulders and joint-bounded blocks forming areas of elevated relief, surrounded by deeply weathered bedrock. Such landscapes are common on such lithologies across the world and Romaní and Twidale (1998) suggest that, because of their worldwide distribution, such granitic boulders have no climatic significance. They do, however, acknowledge that some authors express a contradictory opinion, and in the Serra do Gerês and in Serra da Peneda in Northwest Portugal, Gaussen (1981) observed three units that Godard (1977) proposed as typical for the temperate regions of western Europe. These are, in situ granitic saprolites, removed granitic saprolites and periglacial solifluction block fields which, in mountainous areas of Portugal, were affected by postglacial fluvial erosion.

This study concentrates primarily on in situ granitic saprolites corresponding to the C-horizons of weathering profiles. Typically, these saprolites are characterized by the preservation of the original granitic structure and texture, the isovolumetric nature of the arenization process and their ability to be broken by hand. However, within some profiles, it was possible to distinguish between saprolite and ‘weathered rock’, particularly around corestones. The latter is more compact and shows greater cohesion than the saprolite, has a greater bulk density, and can only be broken up with a hammer. Samples of both weathering products were collected using the same procedures from two areas, the River Cávado basin and Oporto (Fig. 1). In the River Cávado basin, the study area is located between the city of Braga and the shoreline. In this area, 30 weathering profiles from five different granitic rocks were studied, located at the base and at the top of the slopes of the River Cávado basin (Sequeira Braga, 1988). In Oporto, samples were obtained from 13 weathering profiles on the two-mica Oporto granite (Begonha, 1997). The weathering profiles show great vertical and horizontal heterogeneity independent of the type of granite. The weathering front at the base of the profiles is not continuous and the thickness of the granitic saprolites differs from place to place. In Fig. 2, two examples of weathering profiles are shown from the two-mica porphyritic Perelhal granite and the Oporto granite (leucogranite). Most granitic saprolite profiles exceed 10 m and some are more than 20 m deep. Corestones occur in some, but not all profiles, and can have distinctive, 20 to 50 cm thick weathering rinds with a yellow-brownish colour.

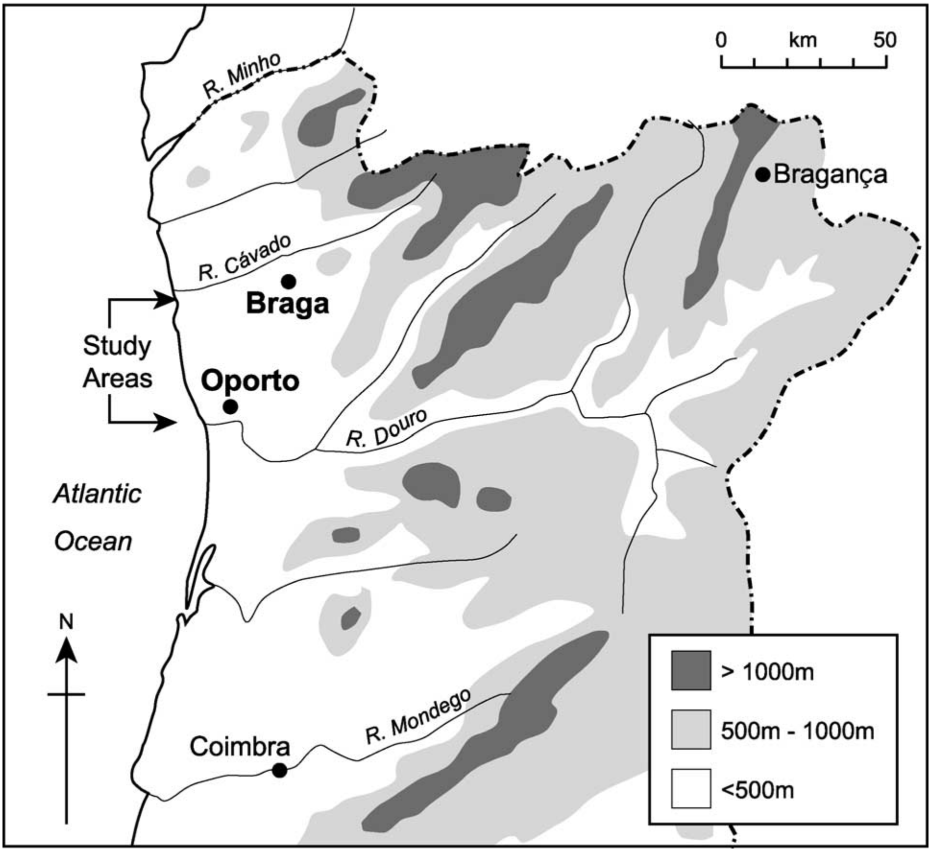

Fig. 1. Geographic location of study areas: Cávado river basin and Oporto, Portugal.

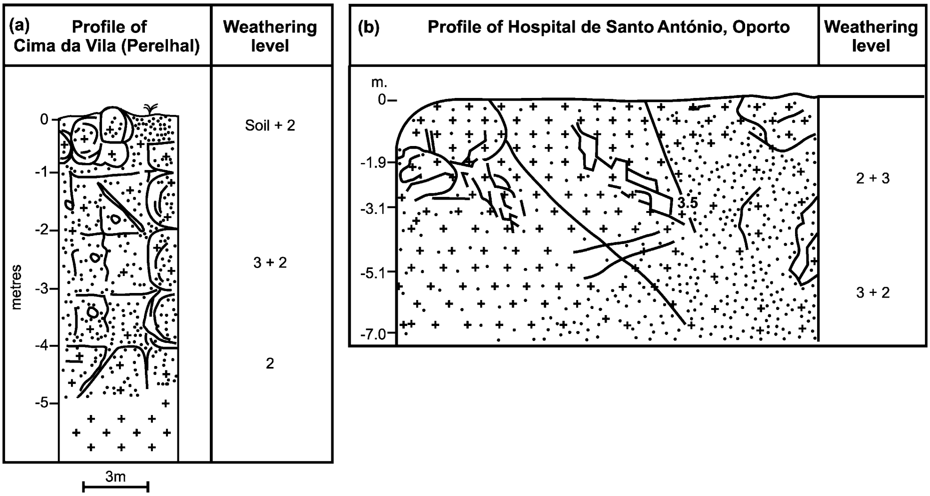

Fig. 2. Sketch of weathering profiles; (a) Cávado river basin — Perelhal granite — Cima da Vila profile; (b) Oporto granite — Hospital de Santo António profile. 2 = Weathered rock; 3 = granitic saprolite.

2.2. Analytical procedures

Optical microscopy, X-ray diffraction (XRD), scanning electron microscopy with energy dispersive spectrometer (SEM-EDS), transmission electron microscopy (TEM), electron microprobe, and plasma and atomic absorption spectrometry analyses were used in order to mineralogically and chemically characterize fresh rock, weathered granite, and granitic saprolite in the bulk rock and in the < 2 μm fraction. The studies by optical microscopy and SEM-EDS were carried out on polished thin sections and also on fragments of weathered rock and granitic saprolites. Chemical analyses of the bulk rock and dry bulk density were carried out on samples showing different degrees of weathering in order to establish the geochemical budget calculated through the isovolumetric method (Millot and Bonifas, 1955). The different element oxides can be measured in the same volume of fresh rock and corresponding weathering products and their content compared because of the conservation of the original petrographic textures and geological structures (Sequeira Braga et al., 1990; Begonha, 1997). The grain-size distributions of the granitic saprolites were also determined.

3. Physical characteristics of granitic saprolites

Dry bulk density varies between 2.54 and 2.69 in the fresh rock, between 1.94 and 2.65 in the weathered rock, and between 1.33 and 2.25 in the saprolites for the 43 weathering profiles that have been studied. The variation in the values of dry bulk density from the base to the top of the profiles corroborates their heterogeneity. Typically, the saprolites (Fig. 2) can be classified as sand with coarse particles (0.25–2 mm), between 27% and

53%, and low percentages of the < 2 μm fraction (7% in the 30 weathering profiles of the River Cávado basin and 6% in the 13 profiles of the Oporto granite). According to the classification of Brewer (1964), the saprolites on all types of granitic rocks of Northwest Portugal are fabric skeleton materials, essentially composed by grains of quartz, feldspar, and some mica. Granitic saprolites are therefore almost aplasmogenic (Pédro, 1984), meaning that the content of secondary minerals or "plasma" is very low as pointed out by Sequeira Braga et al. (1989, 1990).

4. Geochemical budget during arenization

Elemental analyses show that sodium and calcium are the most leached elements from the granitic saprolites. Calcium loss varies between 90% and 100% and sodium between

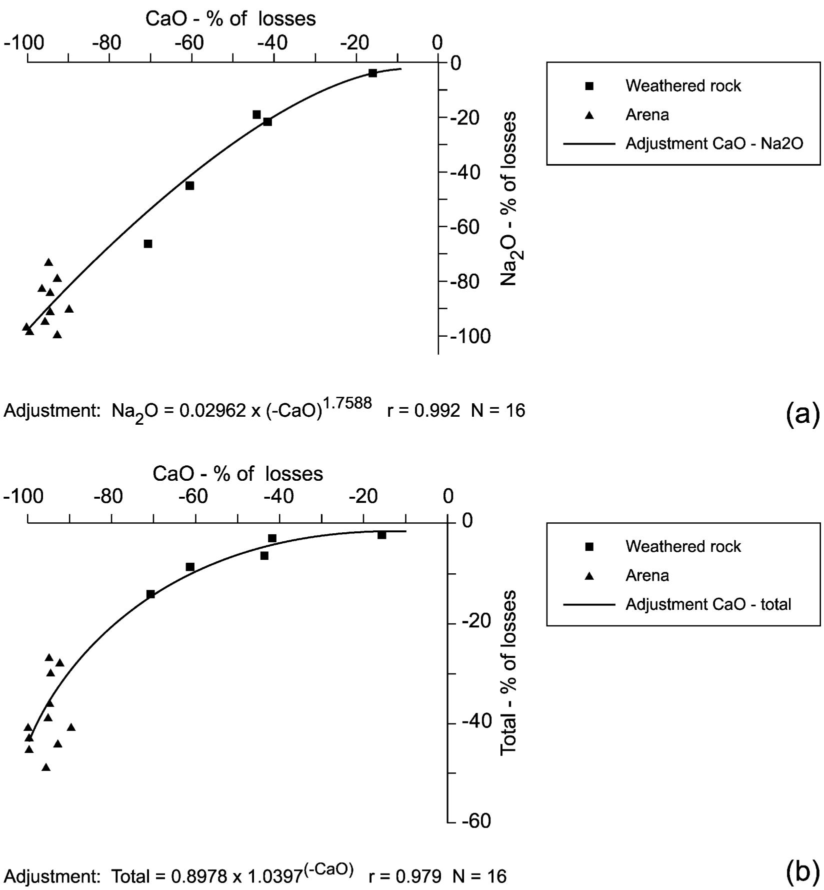

Fig. 3. Variation of loss of material (isovolumetric balance) during weathering of Oporto granite between CaO and Na_2O (a); CaO and total losses (b).

73% and 99%, primarily due to the complete alteration of the plagioclase. The high coefficient of correlation between the sodium and calcium losses ($r = 0.992$, Fig. 3a) in the arenization process of the Oporto granite confirms a similar behaviour of these two elements. Calcium is also a good indicator of total element loss. A good correlation ($r = 0.979$, Fig. 3b) was also obtained by Begonha (1997) between this element and total loss during weathering. Removal of magnesium, potassium, and silicon is less significant. Weak to medium loss of K_2O in the granitic saprolites of the River Cávado basin (45.5%) and in the saprolites of the Oporto granite (38.5%) is explicable in terms of the presence and low vulnerability to weathering of potassium feldspars that comprise one of the components of the skeleton fabric of the saprolites (microcline is the dominant feldspar). Aluminium and iron are the least leached elements.

In Fig. 4, the curves fitted to the volumetric concentrations of SiO_2 and Al_2O_3 (g cm^{-3}) and the dry bulk density illustrates variations in the concentration of these elements during the arenization of the Oporto granite and demonstrates that it is possible to show that the leaching of aluminium (losses between 15% and 46%) is smaller than those for silicon (29–53%). These values are similar to those calculated by Sequeira Braga (1988) for the different granites of the River Cávado basin (10–40% for aluminium and 32–51% for silicon) and they appear to confirm Gardner's (1980) earlier objections to the use of the isoaluminium method in the determination of the geochemical budget during rock weathering, as both aluminium and titanium are partly leached, contrary to what is frequently assumed. As an example (Fig. 2), leachings of Al_2O_3 and SiO_2 in the saprolites in the top of the Cima da Vila profile are 14% and 32%. In the saprolites in the top of the Hospital de Santo António profile, the losses are 46% for Al_2O_3 and 50% for SiO_2. The geochemical budget also shows that during the formation of the saprolites, the total loss of material varies between 26% and 46% with an average value of 40%. This is somewhat

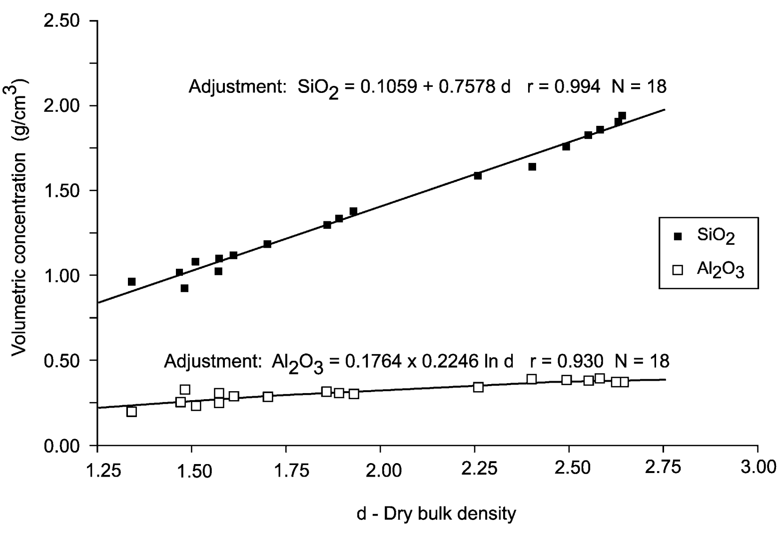

Fig. 4. Variation of volumetric concentrations of SiO_2 and Al_2O_3 (g cm^{-3}) versus dry bulk density.

higher than the values obtained from studies of other granitic saprolites in countries of Atlantic Europe and could have a regional significance (Sequeira Braga et al., 1989). It is worth noting, however, that if 40% of the material is removed, this means that 60% of the parent rock remains in situ, principally as quartz and feldspar. If the clay fraction typically represents approximately 7% of the 60%, this means that only some 4.2% of the parent rock contributed to the formation of secondary minerals that are retained within the saprolite.

5. Secondary minerals

5.1. Clay fraction characterization

The clay fractions (< 2 μm) of the saprolites have been previously examined by means of X-ray diffraction (Sequeira Braga, 1988) and were found to contain between 0% and 45% of 2:1 clay minerals (illite, chlorite, I/V, I/Sm, C/V, and C/Sm mixed layers) and between 10% and 85% of 1:1 clay minerals (kaolinite, metahalloysite) as well as iron and aluminium oxy-hydroxides. The latter include goethite (5–15%) and gibbsite (up to 85% in granitic saprolite and up to 75% in weathered rock, especially the weathering rinds of boulders). Totals for kaolin minerals plus gibbsite vary between 35% and 95% in the saprolite and between 15% and 70% in weathered rock. These results corroborate data obtained in earlier studies from the northwest part of the Iberian Peninsula and represent the highest values of kaolin minerals and above all of gibbsite recorded in Atlantic Europe (Sequeira Braga et al., 1989).

In spite of the homogeneous composition of each parent rock in the outcrop, the distributions of kaolin minerals and gibbsite vary significantly between profiles. In some cases, kaolin minerals or gibbsite are alternately predominant, while elsewhere, concentrations are similar. In some profiles, gibbsite content increases from the base to the top, while other profiles are characterized by an apparently random variation. The latter could reflect the mineralogical heterogeneity of the parent rock and it is possible that for the same parent rock, in a region with the same climate, these variations can only be explained by local factors. At the outcrop scale, these could include the local slope, fracture characteristics, and external drainage. At the hand specimen scale, relevant controls might include the size of mineral grains, possible microfracturing, porosity, and internal drainage. Therefore, although the parent rock is generally considered to be homogeneous within each type of granitoid at the outcrop scale, metre scale composition is not necessarily a determinant factor in the genesis and distribution of secondary minerals within the saprolites.

5.2. Detailed mineralogy and habits

5.2.1. Kaolinite and metahalloysite

XRD analyses of the saprolites often show a large peak centered at 7.3 Å and a small peak at 3.56 Å. The asymmetry of the 7.3 Å reflection and its shifting to 10.4 Å by hydration denotes the major presence of metahalloysite. Observation by TEM and SEM-

EDS (Fig. 5) confirms the tubular morphology of metahalloysite and its dominance compared to kaolinite. The reflections obtained by X-ray microdiffraction correspond to those for metahalloysite (4.42, 3.58, 2.60, 1.72, 1.51, and 1.29 Å) and accord with those given by Brindley and Brown (1980). SEM-EDS examination of biotite crystals from a granitic saprolite sample (Fig. 5) shows that between exfoliated layers of the mica 1:1 minerals have developed with different types of growth and habits. Thin 2–6 μm tubes grow perpendicular to the cleavage planes of biotite, thick straight tubes grow parallel to the crystallographic *c* axis and to the cleavage planes of the biotite whilst tubular forms grow from the corroded borders of mica crystals and rare pseudohexagonal lamellae of kaolinite appear between the metahalloysite tubes.

5.2.2. Gibbsite

Gibbsite is typically well crystallized and shows characteristic reflections for XRD, the most important and best defined of which are the 4.83 and 4.37 Å peaks. SEM-EDS examination shows the occurrence of two distinct crystalline habits for gibbsite in the

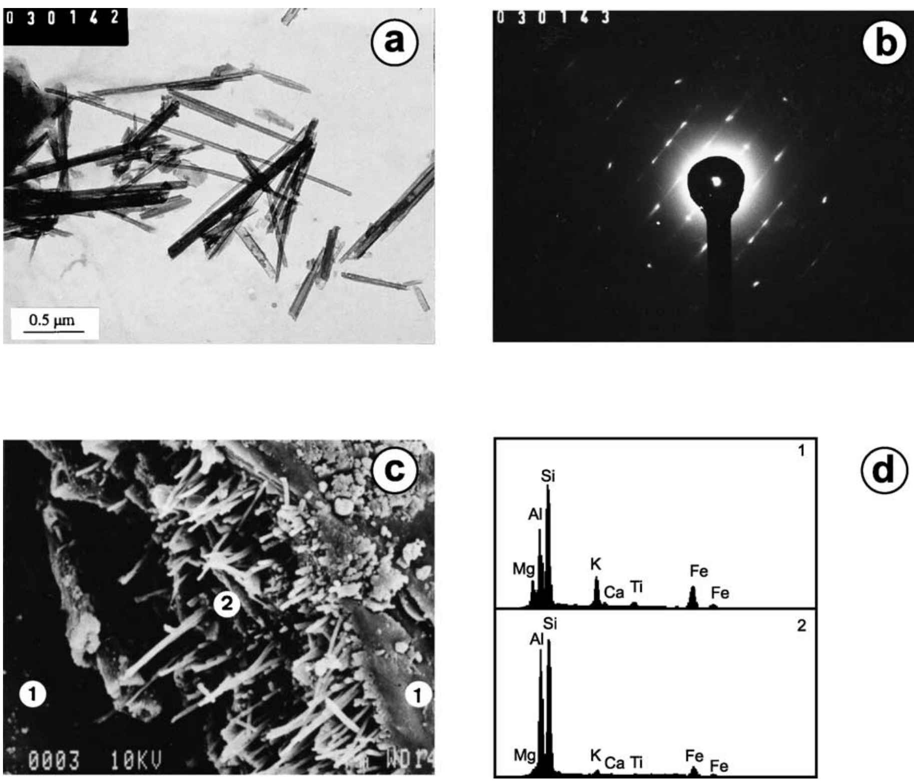

Fig. 5. TEM images: (a) double tubes of metahalloysite, (b) X-ray microdiffraction diagram within a tube from image (a). SEM-EDS images, (c) weathered biotite from granitic saprolite, (d) chemical spectrum of biotite-position 1 and kaolinite–metahalloysite-position 2.

granitic saprolites, hexagonal plates with more or less corroded borders, and more abundant long prisms locked in one of the extremities and with a stacking-like aspect (Fig. 6). TEM study of the < 2 μm fraction reveals that gibbsite particles frequently exhibit a wedge shape (Fig. 6) and X-ray microdiffraction diagrams (Fig. 6) permit the identification of 3.33, 2.14, 1.59, 1.48, and 1.47 Å reflections for gibbsite.

5.3. Intramineral weathering: microsites and microsystems

Secondary mineral formation was studied through the examination of polished thin sections of weathered rock and saprolite. The micromorphological study of weathered rock, particularly weathering rinds, shows that fissure systems are characterized by inter-, intra-, and transgranular microcracks. These microcracks evolve in a dendritic manner during weathering (Bisdom, 1967) and increase in number and thickness. Plagioclase is the mineral most affected by this process and its porosity increases significantly compared with microcline (Fig. 7). In contrast, quartz is the least affected mineral, showing some

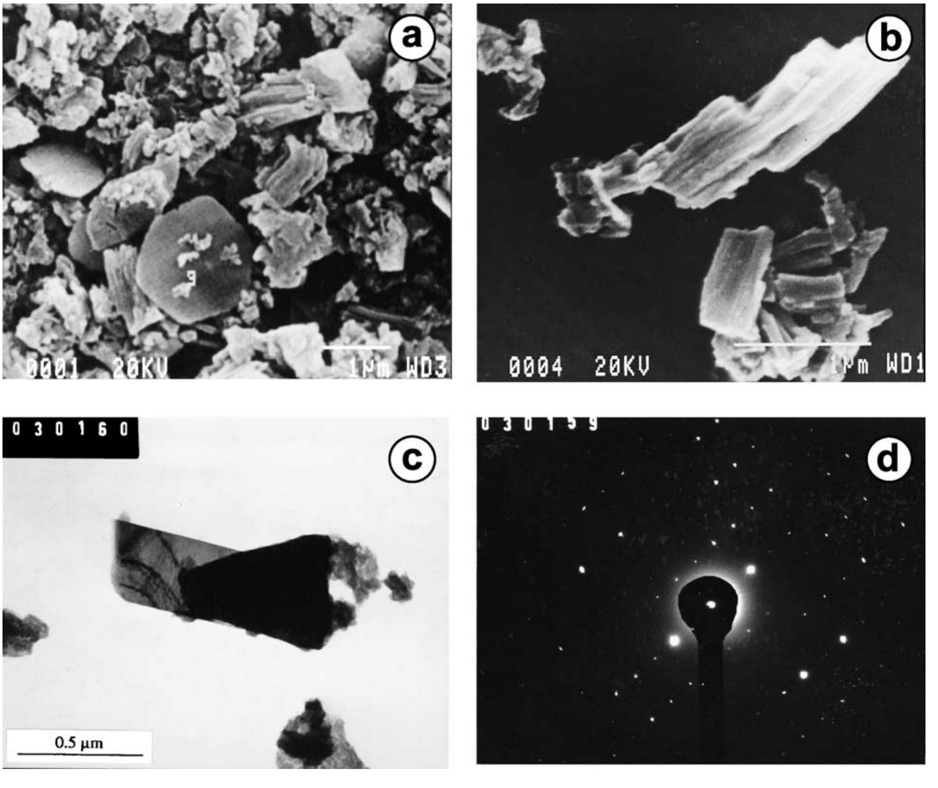

Fig. 6. Micromorphology of gibbsite in granitic saprolites from Cávado river basin, SEM-EDS images: (a) hexagonal plates and (b) prisms or lathes. TEM images: (c) wedge like particle and (d) X-ray microdiffraction diagram of gibbsite.

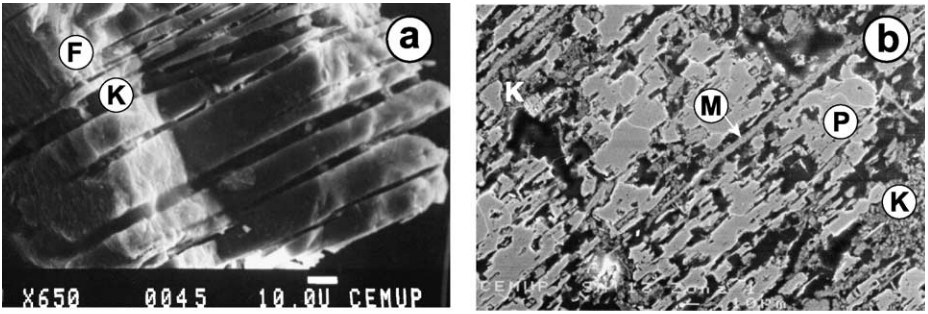

Fig. 7. SEM-EDS images of granitic saprolites: (a) weathered feldspar (microcline) from Cávado river basin, showing kaolinite plasma between the cleavage surfaces; (b) etch-pits on plagioclase from Oporto granite and kaolinite in its weathering microsites. F = feldspar; P = plagioclase; M = muscovite; K = kaolinite.

fissures but no evidence of chemical dissolution (etch pits). Differences between the physical modifications of primary minerals are also reflected in their chemical alteration.

5.3.1. Feldspars

According to Berner and Holdren (1979), Nixon (1979), Wilson and McHardy (1980), Eggleton and Buseda (1980), Eggleton and Smith (1983), Anand et al. (1985), and Banfield and Eggleton (1990), feldspar destabilization starts on the crystal surface at already structurally disturbed microsites (e.g. dislocations, etch-pits, cleavages, and fractures). Fig. 7a, for example, shows the occurrence of kaolinite between the cleavage planes of microcline in the Campados kaolin deposit in the River Cávado basin (Brilha, 1992). In saprolites from the Oporto granite, plagioclase is reduced to small-sized and very corroded fragments embedded in a kaolinitic matrix (Fig. 7b) and at weathering microsites on feldspars, only kaolin minerals have been identified. Gibbsite, considered by many to be the end member of the weathering sequence for aluminosilicate minerals (e.g. Harriss and Adams, 1996; Meunier and Velde, 1979; Penven et al., 1983; Anand et al., 1985), was not identified.

5.3.2. Biotite

There are numerous studies dedicated to the examination of biotite weathering and its evolution to either kaolinite (e.g. Wilson, 1966; Meunier and Velde, 1979; Sequeira Braga et al., 1989) or gibbsite (e.g. Wilson, 1966; Dejou et al., 1970; Furtado, 1973; Macias, 1981; Sequeira Braga et al., 1989). For our part, a striking example is presented of differential weathering at microsites on a unique biotite crystal from the granitic saprolite of the Cima da Vila profile (Fig. 2). Fig. 8a shows a polished section of the biotite crystal with a corresponding distribution map of principal constitutive elements (Fig. 8b). The highest percentages of K, Fe, Mg, and Ti correspond to the less weathered layers, with likely incipient formation of vermiculitic mixed-layers. The highest percentages of Si and Al correspond to more weathered exfoliated and separated layers and the formation of kaolin minerals. Concentration of Al at some microsites is related to the presence of gibbsite. Thus, in a single biotite crystal, it is possible to observe at different microsites the formation of 10–14 Å minerals, of kaolin minerals, or of gibbsite.

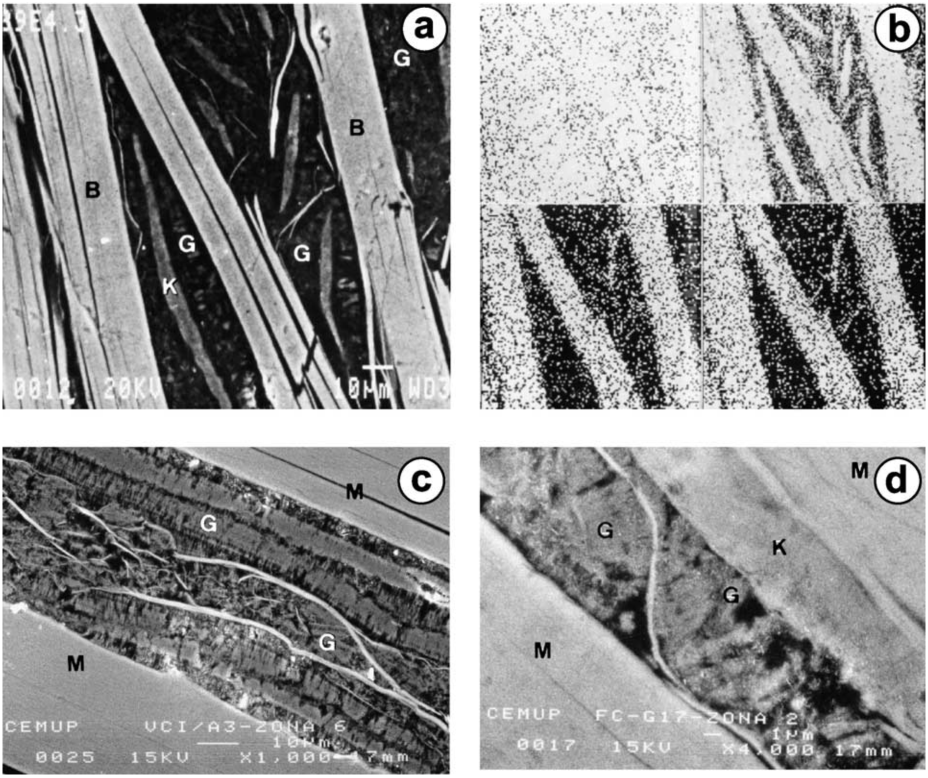

Fig. 8. SEM-EDS images of polished thin section: (a) weathered biotite from granitic saprolites of Perelhal granite; (b) Al, Si, K, and Fe distribution mapping, showing kaolinite elongated shapes inside a gibbsite plasma in a biotite crystal; (c) and (d) weathered muscovite from granitic saprolites of Oporto granite, showing an oriented crystalliplasma of gibbsite in muscovite cleavage surfaces (c) and kaolinite + gibbsite disorder crystalliplasma (d). B = biotite; M = muscovite; K = kaolinite; G = gibbsite.

5.3.3. *Muscovite*

Muscovite kaolinization has been referred to by, for example, Jiang and Peacor (1991) and Robertson and Eggleton (1991). Muscovite crystals may, however, exhibit differential weathering at microsites as shown by Fig. 8c and d. In this case, an oriented crystalliplasma of gibbsite (lamellae more or less perpendicular to the cleavage planes of muscovite—Fig. 8c) was observed, together with an irregularly distributed crystalliplasma (Fig. 8d). In addition, a kaolinite crystalliplasma was also observed (Fig. 8d) in alignment with the unweathered exfoliate layers of the muscovite (Begonha, 1997).

Chemical analyses by electron microprobe (Sequeira Braga, 1988) and semiquantitative chemical analyses by SEM-EDS of biotite and muscovite weathering (Sequeira Braga, 1988; Sequeira Braga et al., 1989; Begonha, 1997) have shown the existence of two generations of gibbsite: a purer phase of interlamellar gibbsite (irregular crystalliplasma) and a phase that includes SiO_2 as well as Al_2O_3 and which corresponds with the oriented lamellae of gibbsite.

5.3.4. Summary

It would appear that the secondary minerals identified in the clay fractions of the saprolites (10–14 Å minerals, kaolin minerals, and gibbsite) represent three stages of increasing weathering of feldspars and micas, in accordance with the mineral weathering sequence detailed by Tardy (1969) and many others (Sequeira Braga, 1988). The weathering of rock is not, however, an equilibrium system (Buol and Weed, 1991) and it is likely that an individual weathering profile will exhibit a sequence of weathering stages and that differences in primary minerals and microenvironmental conditions may result in different end products. Tardy et al. (1973) and Tardy (1997) have therefore described granitic saprolites as a dynamic system made up of a population of closed or partly open microenvironments hardly dependent on each other. Seddoh and Pédro (1975) similarly highlighted the polygenesis of secondary minerals in primary minerals such as plagioclases in relation with intramineral or extramineral transfers and Nahon (1991) described intra-crystalline and inter-crystalline transfers at two scales, which define geochemical nano- and microsystems. This, as emphasized by Romero et al. (1992), can result in very different secondary weathering products. Thus, each secondary mineral of a given mixture or association should be thought of as characteristic of a combination of temperature, openness of the system, water/rock ratio, and rate of renewal of solutions. All of these govern the composition of solutions responsible for the weathering of primary minerals, the further breakdown of secondary minerals, and the removal of weathering products. In Northwest Portugal, the main association of secondary minerals deriving from these complex interactions is gibbsite + kaolinite, in many cases, gibbsite predominating. Gibbsite is seen as representing advanced weathering corresponding to intense hydrolysis even if, according to Pédro (1997), the degree of weathering as measured by the ratio of secondary constituents to primary minerals is low.

6. Climatic zonality of secondary minerals in saprolites

A review of literature on secondary minerals found in the clay fractions of the C-horizons of granitic saprolites from the Atlantic (Sequeira Braga et al., 1989) has identified a southward gradation from Scandinavia to Portugal, in terms of weathering type, as defined by Pédro (1997). Under present-day cold and wet climates in northern Europe (Scandinavia and Scotland) and at higher altitudes (e.g. the Vosges, France), the dominant secondary minerals are vermiculites and 2:1 mixed layer clays. Under more temperate climates (e.g. Cornwall and the Armorican and Central massifs of France), 2:1 minerals (vermiculites and associated mixed layers) compete for dominance with 1:1 minerals of the kaolinite group, and gibbsite, if present, is generally found only in small quantities. Under the wetter and warmer climatic conditions of southwest Europe (e.g. Northwest Portugal and Galicia), kaolin minerals and gibbsite are the dominant secondary minerals and gibbsite can reach 40–80% in the <2 μm fraction. It would seem, therefore, that at a large scale, secondary minerals can be related to present-day climate and that a southward climatic zonality or latitudinal zonation of these minerals from Scandinavia to Portugal can be recognized. Variations can be observed as related to the diversity of sites, geomorphologic location, and tectonic history of the parent rocks (Sequeira Braga et al., 1989; Gerrard, 1994).

However, at a micro-scale, for instance that of an individual biotite crystal, the nature of the secondary minerals is more closely related to particular leaching conditions than to specific climatic conditions (Gerrard, 1994), or depends more on the initial primary minerals than on general bioclimatic conditions (Pédro, 1997). The zonality of secondary minerals in the granitic saprolites of Atlantic Europe can thus be characterized by: an increased loss of material from the cold climates in the north to the warmer climates in the south, material loss averages of 40%, and a corresponding increase in the degree of mineralogical evolution from north to south where gibbsite is frequently dominant.

7. Arenization: age and climatic implications

Dating arenization in Northwest Portugal is not simple. However, Sequeira Braga et al. (1990) have described terraces of arenaceous granitic saprolites that are younger than Pliocene fluviatile and lacustrine deposits along the River Cávado basin. Daveau (1977), Diniz (1984), and Pereira and Pais (1987) have also referred to the existence of a humid temperate climate in Portugal during the early Quaternary, not very different from the present. Meanwhile, in mountainous areas, Gaussen (1981) has described periglacial solifluction block fields overlying granitic saprolites, which were affected by postglacial fluvial incision. The suggestion is, therefore, that arenization has encompassed much of the Quaternary under climatic conditions that facilitate the neoformation of the end members of the granitic weathering sequence (kaolin minerals and gibbsite). Field observation of numerous weathering profiles has not revealed any modification in their normal evolution such as profile truncation. Weathering proceeds primarily along widespread joint and fissure systems, initially forming weathering rinds that eventually develop into saprolites. Mineralogical evidence of the weathering of biotite to gibbsite and/or kaolinite in the microenvironments of these weathering rinds suggests that weathering is continuing under present-day conditions in much the same way as it acted in the early Quaternary.

In summary, our observations from Northwest Portugal support the general conclusions of Power and Smith (1994), who highlighted the need for a distinction between climatic and nonclimatic influences and between the effects of present-day climates and paleoclimates during the formation of weathering products.

8. Conclusions

The granitic saprolites of Northwest Portugal are typically more than 10 m deep, have an average material loss of 40%, and have a low clay content (average of 7%) composed of secondary minerals testifying to intense alteration of primary minerals. This clay fraction is characterized by a predominance of kaolinite plus gibbsite formed by excessive leaching of profiles. Subordinate 2:1 minerals include illite, chlorite, vermiculitic mixed layers, vermiculite. The wide range of secondary minerals exists within individual profiles because of the differential transformation of the primary minerals. However, they also coexist within biotite and muscovite crystals due to the presence of a variety of intramineral weathering microsites.

The principal mechanisms responsible for the weathering primary minerals are the transformation of mica into illite, chlorite, vermiculite, and their mixed-layer counterparts and the pseudomorphic recrystallization of kaolinite and gibbsite (oriented crystalliplasma) from exfoliated layers of biotite, vermiculated biotite, and muscovite. Crystallization of tubular metahalloysite, interlamellar kaolinite in plate shapes by epitaxic growth, in the microsites of biotite, and muscovite is also observed, as is gibbsite crystallization between exfoliated layers of biotite and muscovite and in pores that occur within the kaolinite crystalliplasma. In broader terms, this and other studies by the principal author have identified a climatic zonality of secondary minerals in granitic saprolites across Atlantic Europe, from Scandinavia to Portugal. Fundamental to this zonality is a southwards increase in the degree of weathering of primary minerals, with gibbsite dominant in the southernmost saprolites in association with the greatest loss of material from the parent rocks.

Finally, arenization in temperate countries is a form of skeleton weathering that consists of the separation of the mineral grains and negligible clay formation. This is in contrast to deep weathering under humid tropical conditions, which is comparatively rapid and in which abundant argillization (or clay formation) is involved. According to Tardy (1997), arenaceous regoliths are most strongly developed and permanent in temperate environments and are thin and ephemeral in the Tropics. If this is so, then arenization, like podzolization, should be considered to be a major weathering process of the temperate zone, just as ferrallitization or bauxitization is seen as a major influence upon tropical saprolites.

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